The Flavor structure of UED with KK-parity

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Outline

Goal:

A model of UED with KK-parity with

1. anarchic Yukawas
2. mass hierarchies from localization

Outline:

- Reminder: How does RS-GIM work?
- Mass Hierarchy in UED with KK-parity
  or: KK-parity and the problem of light modes
- Bounds from FCNC in UED with KK-parity

Motivation: Hierarchy Problem vs. Flavor Physics

- "tension" between EWSB & flavor

Unitarity

$m_{Higgs} \lesssim 1$ TeV

Flavor

$\Lambda_{new} \gtrsim 10^4 - 10^5$ TeV

$\Rightarrow$ We need new physics $\lesssim 1$ TeV to ensure that Higgs is light, but it must not violate flavor.

- Does a model of EWSB naturally respect flavor?

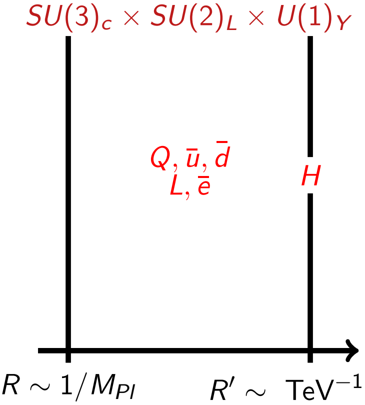
$\Rightarrow$ In general: No. In some cases: Yes.

Reminder: Flavor in RS

Randall-Sundrum

- warped metric
$$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$$
- Higgs on the IR brane.
- SM fields in the bulk.

- Higgs mass is suppressed by $\frac{R'}{R} \sim 10^{16}$



Flavor in RS: The Yukawa couplings

- Fermion bulk mass: $\sim \frac{c^i}{z}\bar{\Psi}_i\Psi_i$

Normalized zero mode solutions

$$g_0 \sim z^{2-c} f(c) \qquad \text{and} \qquad f_0 \sim z^{2+c} f(-c)$$

with $f(c) = \sqrt{\frac{1-2c}{1-(R'/R)^{2c-1}}}$

- $f(c)$ strongly hierarchical for SM fermions.
- Yukawa couplings:

$$\mathcal{L}_Y = -\frac{v}{\sqrt{2}}\frac{R^4}{R'^3}\left[\bar{\Psi}_q \tilde{Y}_u \Psi_u + \bar{\Psi}_q \tilde{Y}_d \Psi_d + h.c.\right]\Big|_{z=R'}$$

$\tilde{Y}_u, \tilde{Y}_d$ are both $\mathcal{O}(1)$, anarchic flavor matrices.

Flavor in RS: The SM masses

⇒ Mass matrices are given by

$$m_u = \frac{v}{\sqrt{2}} f_q \tilde{Y}_u f_u \qquad \text{with} \qquad f_c = \text{diag}[\{f(c_i)\}]$$
$$m_d = \frac{v}{\sqrt{2}} f_q \tilde{Y}_d f_d$$

- Now usual SM prescription applies (here: $U_{ij} \sim f_i/f_j$)

$$m^{SM} = U_L m U_R^\dagger \qquad \text{and} \qquad V_{CKM} = U_{Lu}^\dagger U_{Ld}$$

$$\Rightarrow \left(m^{SM}_{u,d}\right)_{ii} \sim \frac{v}{\sqrt{2}} Y_* f_{q_i} f_{u_i,d_i}$$

⇒ We got flavor hierarchy, but what about new FCNC contributions?

Flavor in RS: Hierarchy of f_i's

- First let us check the order the f_i's:

Left-handed f_i's are determined from $V_{CKM} \sim f_{qi}/f_{qj}$

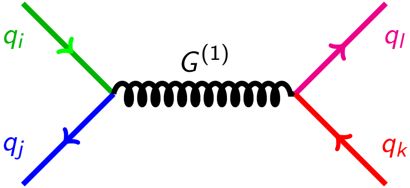
$$\frac{f_{q_2}}{f_{q_3}} \sim \lambda^2, \quad \frac{f_{q_1}}{f_{q_3}} \sim \lambda^3 \qquad \text{with } \lambda \sim \sin\theta_c \sim 0.2$$

Right-handed f_{u_i,d_i}'s fixed by fermion masses hierarchy

$$\begin{aligned} \frac{f_{u_1}}{f_{u_3}} &\sim \frac{m_u}{m_t}\frac{1}{\lambda^3}, & \frac{f_{u_2}}{f_{u_3}} &\sim \frac{m_c}{m_t}\frac{1}{\lambda^2} & & \\ \frac{f_{d_1}}{f_{u_3}} &\sim \frac{m_d}{m_t}\frac{1}{\lambda^3}, & \frac{f_{d_2}}{f_{u_3}} &\sim \frac{m_s}{m_t}\frac{1}{\lambda^2}, & \frac{f_{d_3}}{f_{u_3}} &\sim \frac{m_b}{m_t} \end{aligned}$$

Flavor in RS: New Contributions to FCNC

- Strongest bound: FCNC due to KK-gluon exchange:



$$\sim \; g_{L,u}^{ij}\, \bar{u}_L^i \gamma^\mu G_\mu^{(1)} u_L^j \; + \; g_{L,d}^{kl}\, \bar{d}_L^k \gamma^\mu G_\mu^{(1)} d_L^l \; + \; (L \to R)$$

- Plug in the wave function: In original (gauge) basis = diagonal

$$g_x \approx g_{s*} \Big[\underbrace{-\frac{1}{\log R'/R}}_{\text{universal}} + \underbrace{f_x^2\, \gamma(c_x)}_{\text{non-universal: } \gamma \sim 1} \Big]$$

$\Rightarrow$ Universal part does not contribute: $U^\dagger \mathbb{1} U = \mathbb{1}$.

$\Rightarrow$ Non-universal part: New source of FCNCs.

Flavor in RS: RS-GIM

- How big is the size of flavor violation?
- Rotate with $U \sim f_i/f_j$
  $\Rightarrow$ Off-diagonal KK-gluon couplings

$$g^{ij} \sim g_{s*} f_i f_j \gamma \qquad \text{(for } q, u, d\text{)}$$

RS - GIM $\hat{=}$ g^{ij} is automatically suppressed

- for L: by ratios of CKM-elements.
- for R: by mass hierarchy.

Flavor in RS: How strong is RS-GIM?

- How strong is this suppression for $\Delta F = 2$ operators?

Effective Hamiltonian

$$\mathcal{H} = C^1(\bar{q}_L^i q_L^j)(\bar{q}_L^k q_L^l) + C^4(\bar{q}_R^i q_L^k)(\bar{q}_L^l q_R^j) + C^5(\bar{q}_R^i q_L^l)(\bar{q}_L^k q_R^j)$$

- Strongest bound comes from the Kaon system: $|C_K^4|$ suppressed by $10^4 - 10^5$ TeV.

$\Rightarrow$ in RS:

$$C_K^4 \sim \frac{g_{s*}^2}{M^2} f_{q1} f_{q2} f_{d1} f_{d2} \sim \frac{g_{s*}^2}{M^2} \frac{m_d m_s}{v^2}$$

$$\Rightarrow \boxed{M \sim 20 \text{ TeV}}$$

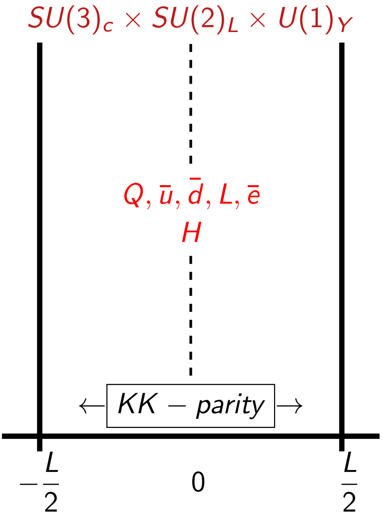
Does a similar mechanism exist in UED?

UED with KK-parity

UED

- Flat metric
  $ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$
- All SM fields in the bulk.

- SM fields are flat.
- Add KK-parity: $y \to -y$
  + Improves EWPC.
  + DM candidate.



UED with KK-parity: Fermion zero mode

- Let's add a bulk mass for the fermions like we did in RS:

$$S = \int d^4x \int dy \left[\frac{i}{2}(\bar{\Psi}\,\Gamma^M \overleftrightarrow{\partial}_M \Psi) - m\bar{\Psi}\Psi \right]$$

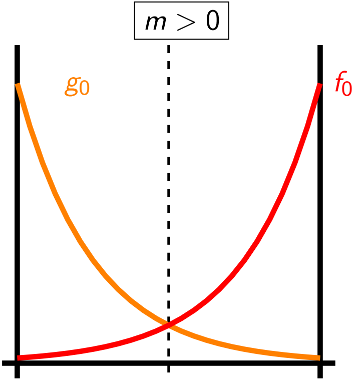
  - Equations of motion

$$\frac{dg_n}{dy} + m\,g_n - m_n\,f_n = 0$$
$$\frac{df_n}{dy} - m\,f_n - m_n\,g_n = 0$$

  - Zero mode solutions

left-handed: $g_0 \sim e^{-my}$

right-handed: $f_0 \sim e^{+my}$



$\Rightarrow$ not KK-Parity invariant

Split-UED

- To maintain KK-parity and also allow bulk masses choose

$$m = m(y) = \begin{cases} \mu & , y < 0 \\ -\mu & , y > 0 \end{cases}$$

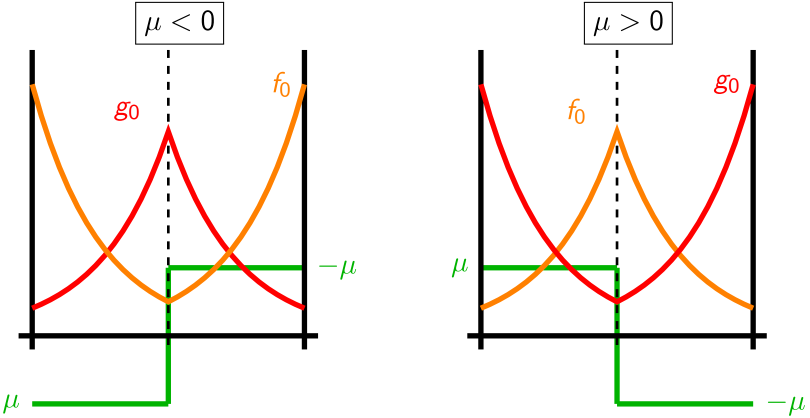
- For $y \neq 0$, we still have

$$g_n' + m(y)\, g_n - m_n f_n = 0$$
$$f_n' - m(y)\, f_n - m_n g_n = 0$$

$\Rightarrow$ Invariant under KK-parity: $m(y) \to -m(y)$

Split-UED: Fermion zero mode

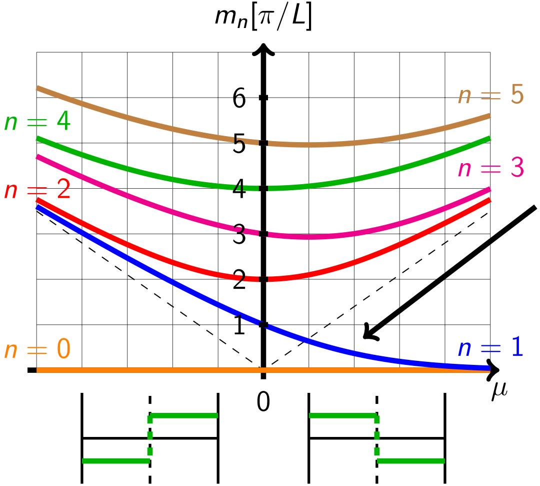
Different localization, depending on sign of μ.



$\Rightarrow$ Could give mass hierarchy due to small overlap.

Fermion spectrum: For a LH zero mode

- Let's examine the complete fermion spectrum: Lefthanded zero mode.



$$m_1 \approx 2\,\mu\, e^{-\mu L/2}$$

$\Rightarrow$ too light
(we need $\mu L \approx 10$)

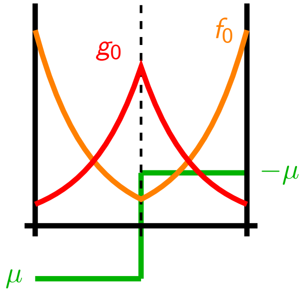
Fermion spectrum: Origin of the extra light mode

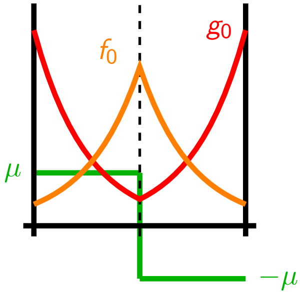
- Where does this light mode come from?

Solve:

$$g_n' + mg_n - m_n f_n = 0$$
$$f_n' - mf_n - m_n g_n = 0$$

with BC: $f_n(\pm L/2) = 0$





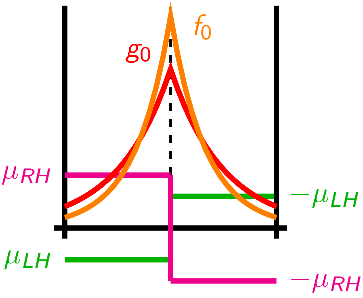
BC: $f_0 \neq 0 \quad \Rightarrow$ gets heavy.

BC: $f_0 \approx 0 \Rightarrow f_0$ remains light
[Equivalently, take the limit $L \to \infty$.]

Fermion spectrum: Consequences

- What does this mean for our model?
  - Need to choose $\mu_{LH} < 0$ to localize g_0 in the middel
  - For same reason we need f_0 in middle ($\mu_{RH} > 0$)

  $\Rightarrow$ Need all SM localized at $y = 0$ to avoid light modes.



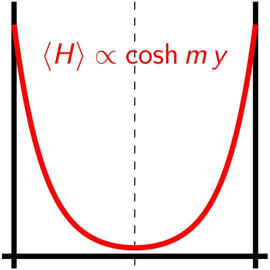
$\Rightarrow$ No small overlap: How will we get the hierarchy now?

Localizing the Higgs

- To obtain hierarchy:
  Need to exponentially localize the Higgs at the boundaries
  (or put it directly on the boundary)

Localizing the Higgs

- Add bulk potential
  $\mathcal{V} = m^2|H|^2$
- Add boundary potentials
  $V \propto \lambda(|H|^2 - v^2)^2$



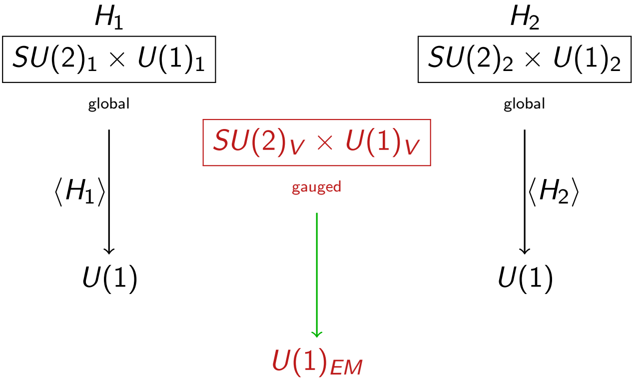
$\Rightarrow$ Gives hierarchy:

$$\mathcal{L}_Y \approx -\frac{v}{\sqrt{2}} \left[\bar{\Psi}_q \tilde{Y}_u \Psi_u + \bar{\Psi}_q \tilde{Y}_d \Psi_d + h.c. \right] \Big|_{y=\pm\frac{L}{2}}$$

- BUT, also gives very light, KK-odd mode.

Localizing the Higgs: Two site model

- Where are these (Pseudo)Goldstones from?
- For simplicity, consider a 2 site model: $H \to H_1$ & H_2



- Two independent H_i + global symmetries $\doteq$ 6 Goldstones
  - 3 KK-even: $\pi_1 + \pi_2 \to$ get eaten
  - 3 KK-odd: $\pi_1 - \pi_2 \to$ remain in spectrum!

Mass of Pseudo-Goldstones

Global $[SU(1)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$ is explicitly broken by

- Having localized Higgs, not 2-site model (small correction)

$$\langle H \rangle \propto \cosh(m\,y) \quad \Rightarrow \quad m_0 \propto m\,e^{-mL/2}$$

- Gauging $SU(2)_V \times U(1)_V$
- Introducing Yukawa couplings:

$$\mathcal{L}_Y \sim \bar{\Psi}_q H_1 \Psi_u + \bar{\Psi}_q H_2 \Psi_u + (down)$$

Coleman-Weinberg potential

$\Rightarrow$ All the KK-odd Goldstones get mass from fermion (and gauge) loops.

[If you don't like loops: Modify setup slightly (e.g. extra $U(1)$ in bulk,...)]

Flavor in UED with KK-parity

- Now, we can proceed analogous to the RS case:

Normalized zero mode solutions

$$g_0, f_0 \sim f(c)\, \exp\left[-c\left(\frac{|y|}{L} - \frac{1}{2}\right)\right] \qquad \text{with } c = \mu L$$

$$\text{with } f(c) = \sqrt{\frac{c}{e^c - 1}} = \frac{1}{\log R'/R} f^{RS}(c_{RS})$$

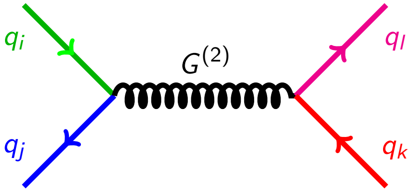
- Yukawa couplings are given by

$$\mathcal{L}_Y = -\frac{v}{\sqrt{2}}\left[\bar{\Psi}_q \tilde{Y}_u \Psi_u + \bar{\Psi}_q \tilde{Y}_d \Psi_d + h.c.\right]\Big|_{y=\pm L/2}$$

- $\tilde{Y}_u$, $\tilde{Y}_d$ are both $\mathcal{O}(1)$, anarchic flavor matrices.

$\Rightarrow$ This is completely analogous to the RS case ...

... until



- Plug in the wave function: In original basis = diagonal

$$g_x \approx g^{4D}\sqrt{2}\Big[\underbrace{1}_{\text{universal}} - \underbrace{f_x^2\,\gamma(c_x)}_{\text{non-universal}}\Big]$$

- Here $\gamma \propto \frac{e^c}{c^3}$, but to obtain mass hierarchy we need $c \sim 0 \ldots 15$.

Unlike RS: $\gamma \not\approx 1$ $\Rightarrow$ NO protection from FCNCs.

[There is a way of fixing this, but that leads back to RS.]

Conclusion

- UED with KK-parity can localize fermions (but only in the middle).
- Localizing the Higgs on the boundaries gives Pseudo-Goldstones: but they get loop masses $\rightarrow$ no problem.

$\Rightarrow$ Get flavor hierarchy, but no protection from FCNC.

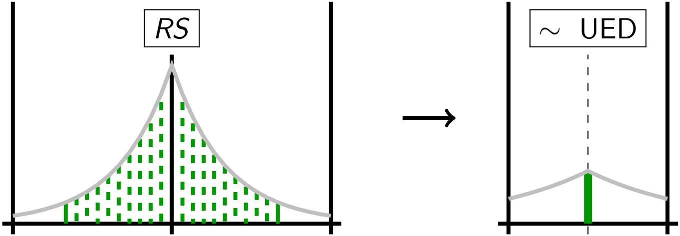
Anarchic flavor in UED is difficult.

The End

Thank you.

RS vs. UED with KK-parity

- So why does this work in RS, but not in UED with KK-parity?
- Can't we think of UED as integrated out RS?



$\Rightarrow$ Effect of integrating out: Add "boundary" kinetic term

$$S_{\text{fermion}} = \int d^5x \left\{ \frac{i}{2} \bar{\Psi}\, \Gamma^{\mu} \overleftrightarrow{\partial}_{\mu} \Psi \right\} \kappa L \delta(y)$$

RS vs. UED with KK-parity

- Only changes the function $f(c,\kappa) = \sqrt{\dfrac{c}{(1+c\kappa)e^c - 1}}$.
- Form of γ_x is not changed.

Can suppress $f \sim 1/\kappa$, while keeping $\gamma \sim \dfrac{e^c}{c} \sim 1$.

- However, this is basically RS and not UED!