Theories with Extra Dimensions and Flavor Physics

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Outline

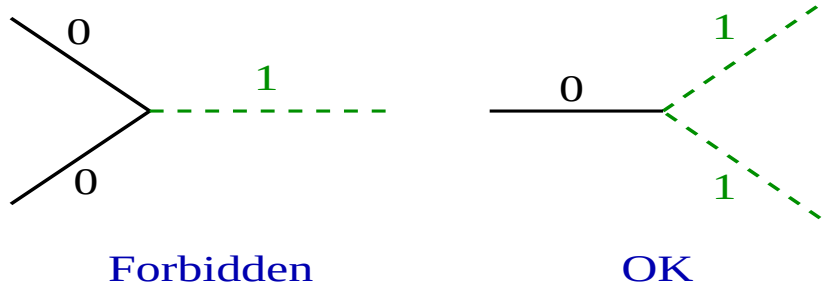
- Why ED ? The hierarchy problem.
- What kind of ED ? UED and WED.
- Flavor and UED
- Flavor and WED
- Conclusions/Outlook

Extra Dimensions and the Hierarchy Problem

- Large Extra Dimensions:
  - Only gravity propagates in the bulk.
  - $\Lambda \simeq \mathrm{TeV}$ is the fundamental scale.
  - Compactification scale $1/R$ can be large ($\mathcal{O}(0.1)$ mm)
- Universal Extra Dimensions (UED):
  - All fields propagate in the bulk.
  - $1/R \lesssim$ TeV.
  - Cutoff $\Lambda \simeq$10's TeV.
- Warped Extra Dimensions (WED):
  - Original Randall-Sundrum: Gravity is localized in AdS_5.
  - Fundamental scale is M_P.
  - Weak scale generated by the AdS_5 metric if we live at κL from M_P.
  - Model building $\Rightarrow$ "bulk life".

Universal Extra Dimensions

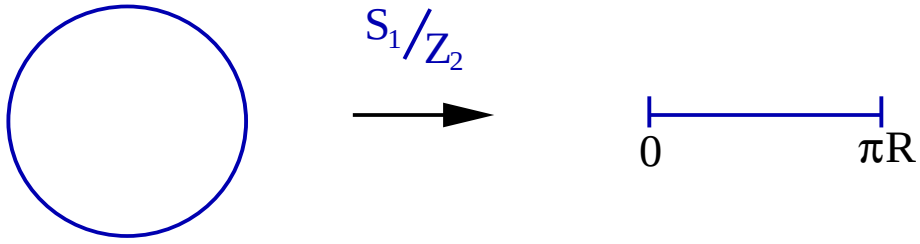
- If some SM fields propagate in the bulk $\Rightarrow$ $1/R \gtrsim 1$ TeV.
- But if we assume *all* fields can propagate in the extra dimensions. What is the allowed R ?
- Momentum conservation in the extra dimensions
  $\Rightarrow$ KK-number conservation E.g.



$\Rightarrow$ KK excitations must be pair produced, direct bounds on $1/R$ are lower.

Universal Extra Dimensions

- Orbifold Compactification: Allows to have chiral fermions



- It breaks KK-number $\longrightarrow$ KK-parity

  $\Rightarrow$ Lightest KK Particle (LKP) is stable $\rightarrow$ Dark Matter candidate

- Direct and EW constraints:

$$1/R \gtrsim 300 \text{ GeV for 5D}$$
$$1/R \gtrsim (400 - 600) \text{ GeV for 6D}$$

UED Phenomenology

- Light KK modes $\Rightarrow$ large cross sections.
- But, almost degenerate KK levels $\Rightarrow$ little energy release: E.g. $q\bar{q} \to Q_1 Q_1 \to Z_1 Z_1 + \not{E}_T \to 4\ell + \not{E}_T$ (Cheng, Matchev, Schmaltz '02).
- Decays to Second KK Level:
  - They couple to 2 zero modes through brane couplings (loop generated). (Datta, Kong, Matchev '05)
  - Signals different in 5D from 6D (Burdman, Dobrescu, Pontón '05)
  - At the LHC is possible to produce 2nd KK level gluon in s-channel.

Flavor Physics in UED

- If we consider the SM in the bulk in d extra dimensions

$$\mathcal{L} = \mathcal{L}_F + (D_M \Phi(x,y))^\dagger D^M \Phi(x,y) + \frac{1}{\Lambda^{d/2}} \bar{\Psi}(x,y) Y \Phi(x,y) \Psi(x,y)$$

  and Y is the only source of flavor violation $\Rightarrow$ MFV. Here Λ is the UV cutoff, and $\Lambda R \gg 1$.

- In this scenario, only flavor physics effects are generated by loops of KK modes in flavor observables: B, D K rare decays and mixing. (Buras, Spranger, Poschenrieder, Weiler '03)

- There is no high p_T signal for flavor

Flavor Physics in UED

But this is not general. Higher dimensional operators $\Rightarrow$ FCNC

- For instance

$$\int d^4x\, dy \left(\frac{1}{\Lambda^3}\right) (\bar{\Psi}(x,y)\Gamma_M \Psi(x,y))\ (\bar{\Psi}(x,y)\Gamma^M \Psi(x,y))$$

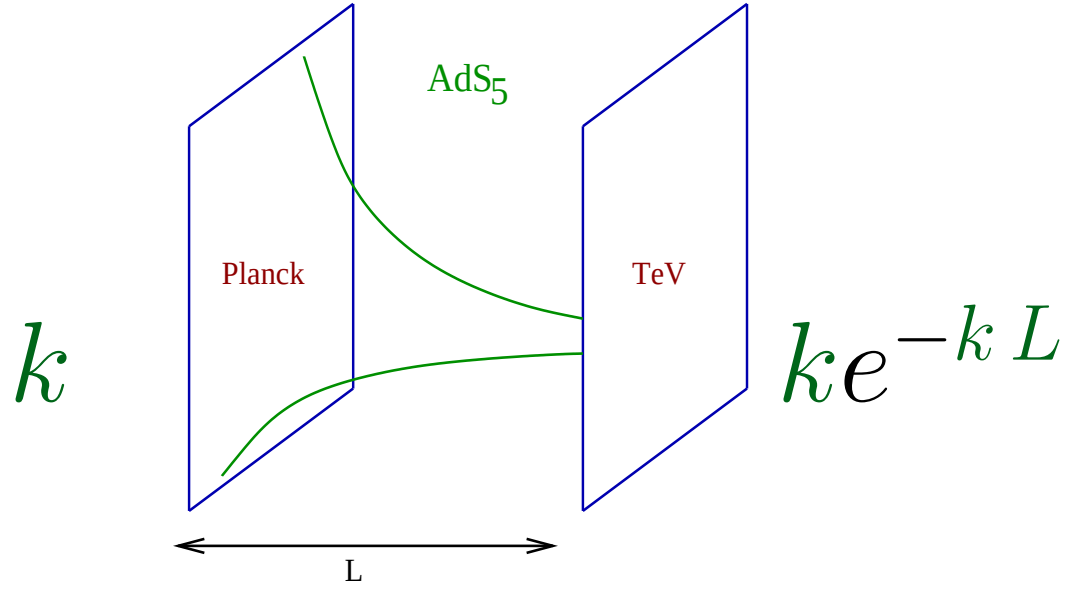
$$\rightarrow \int d^4x \left(\frac{1}{\Lambda^2}\right)\left(\frac{1}{\Lambda R}\right) (\bar{\psi}^{(n)}\gamma_\mu \psi^{(n)})\ (\bar{\psi}^{(n)}\gamma^\mu \psi^{(n)})$$

  $\Rightarrow$ suppressed FCNC.

- But $\Lambda R \simeq 10$, and if $R \simeq 1$ TeV, FCNC's are not suppressed enough.
  $\Rightarrow$ UV couplings could result in FCNC effects.

Warped Extra Dimensions

- One compact extra dimension. Non-trivial metric induces small energy scale from Planck scale (L. Randall, R. Sundrum '99).



- Geometry of extra dimension generates hierarchy exponentially

$$\Lambda_{\rm TeV} \sim M_{\rm Planck}\, e^{-k\,L}$$

with k the curvature

Warped Extra Dimensions

- In original proposal, *only gravity* propagates in 5D bulk.
- RS is a solution of the hierarchy problem. But origin of EWSB? And flavor ? ...
- Allowing gauge fields and matter to propagate in the bulk opens many possibilities: models of EWSB, GUTs, flavor, ...
- The 5D mass of a bulk fermion $=>$ *localization* of zero-mode.
- If Higgs remains on TeV brane:
  Fermions localized toward TeV brane are more massive
  Fermions localized toward the Planck brane are lighter

$\Longrightarrow$ Fermion Geography

WED and Flavor Physics

- Fermion Fields in the bulk: 5D fermion field KK decomposition

$$\Psi_{L,R}(x,y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0} \psi_n^{L,R}(x) e^{2\kappa|y|} f_n^{L,R}(y)$$

- 5D fermion bulk mass term $\longrightarrow$ localization of fermion fields:

$$S_f = \int d^4x\, dy\, \sqrt{-g} \left\{ \cdots - \; c\, \kappa \bar{\Psi}(x,y)\Psi(x,y) \right\} \;,$$

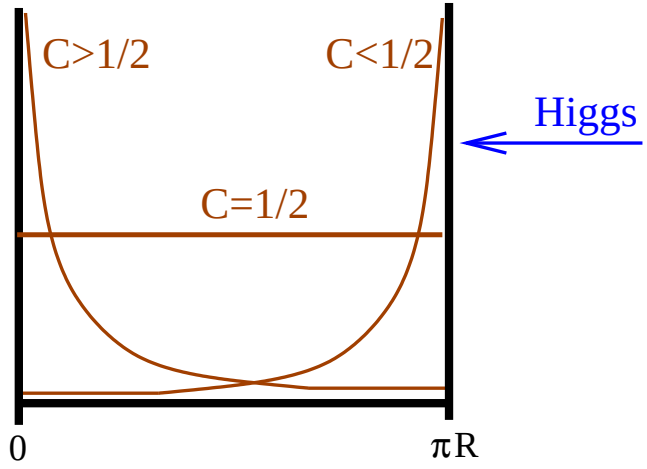
with $c \simeq O(1)$.

- $=>$ Fermion zero-modes can be localized by choosing c :

$$f_0^{R,L}(y) = \sqrt{\frac{\kappa\pi R\,(1 \pm 2c)}{e^{\kappa\pi R(1\pm 2c)} - 1}}\; e^{\pm c\,\kappa\, y}$$

WED and Flavor Physics

- $O(1)$ flavor breaking in bulk can generate fermion mass hierarchy:

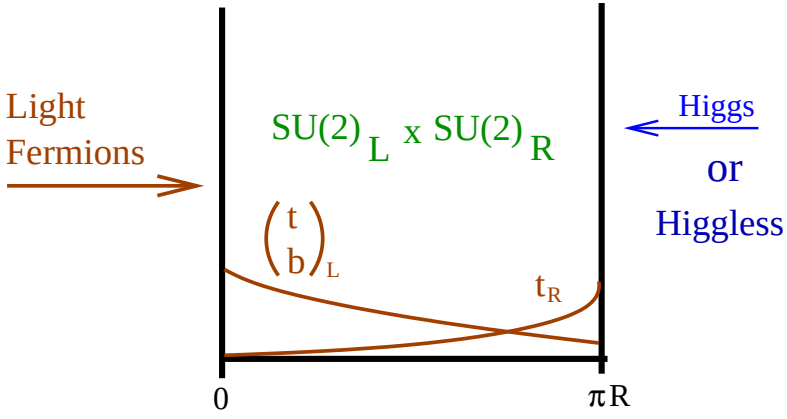


Fermions localized toward the TeV brane can have larger Yukawas, Those localized toward the Planck brane have highly suppressed ones.

- But fermions at $\simeq \pi R =>$ strong couplings to 1st KK gauge bosons!
E.g: 3rd generation quarks might have large couplings $\rightarrow$ flavor violation.

WED and Flavor Physics

Several possibilities for model building:



- Higgs or Higgless (BC breaking)
- Light fermions on Planck brane or off (reduces S)
- Third generation remains a challenge

Agashe, Delgado, Sundrum '03; Csaki, Grojean, Murayama, Terning '03; Barbieri, Pomarol, Rattazzi '03; Burdman, Nomura '03; Cacciapaglia, Csaki, Grojean, Terning '04, '05; $\cdots$,

WED Flavor Signals

Two type of flavor effects:

- FCNC couplings of the Z:
  - Interesting low energy flavor signals. E.g. $b \to s\ell^+\ell^-$ (Burdman, Nomura '03, Agashe, Perez, Soni '04)
  - Deviations in $\bar{t_L} t_L Z$ and $\bar{t_L} b_L W$ are $\mathcal{O}(\text{few}\%)$.
  - Deviations in $\bar{t_R} t_R Z$ could be $\mathcal{O}(1)$.
- FCNC couplings of KK gauge bosons (e.g. KK gluons):
  - E.g. FCNC coupling of the 1st KK gluon $G^{(1)} t\bar{c}$.
  - Effects in non-leptonic B decays and CP Asymmetries (Burdman '03)
  - $\Rightarrow$ Potentially large effect in single-top production at the LHC
  - Kinematics is very different than the SM single-top.
  - Also anomaly in the angular distribution in $b\bar{b}$.

WED Flavor Signals

A possible strategy

- Obtain bounds on (or fits of) c_L and c_R as well as D_{bs} from the $b \to s\ell^+\ell^-$ effect and non-leptonic B decays and asymmetries.
- Compute single top production through s-channel KK gluon for these values of c_L and c_R and U_{tc}.
- Assumptions:
  1. Up and Down rotations similar and $\simeq V_{CKM}$
  2. CKM comes mostly from down sector (U_{tc} negligible)
  3. CKM comes mostly from down sector (D_{bs} negligible)
- (Caveat: RH rotations are not affected by CKM considerations)
- Is the signal observable ?

Summary

- UED: Is a case of MFV if we neglect higher dimensional operators contributing to FCNC. (Model building for flavor at Λ would surely change this.)
- WED: Model of flavor. Signals for flavor both in low and high energies. A case of NMFVness
  - Choose scenarios and constraint parameters from low energy (e.g B decays, CPV, etc.)
  - Correlate with single top production at LHC.