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Extra-Dimensional EWSB and Fermion Masses

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– Research done in collaboration with David E. Kaplan *

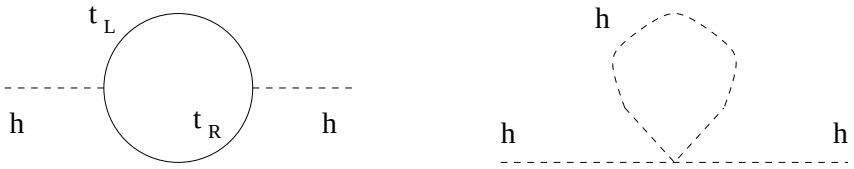
Outline:

1. Hierarchy
2. Flavor
3. Experimental Constraints
4. Outlook

* JHEP **0006** 020,2000, and more to appear soon!

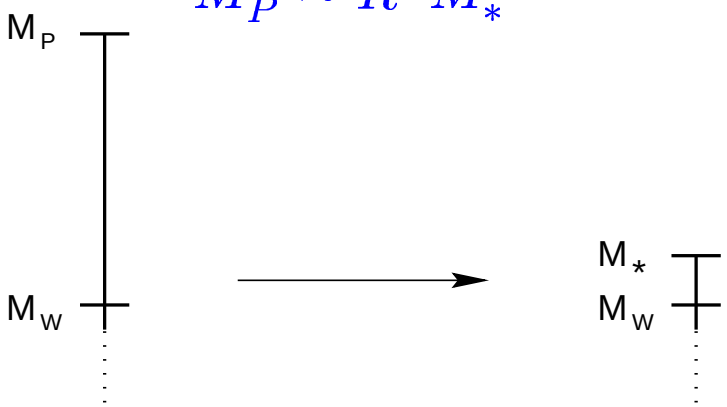
The Hierarchy Problem

- As we all know, the hierarchy between M_W and M_P is puzzling
  - *Why* is the weak scale so much smaller than the Planck scale?
  - *How* is the hierarchy maintained in the face of radiative corrections?



- The ADD solution: There is NO Hierarchy
  - Gravity seems weak because it is "diluted" in n extra dimensions

$$M_P^2 \sim R^n M_*^{n+2}$$



The Flavor Puzzle

- Our goal is to see if extra dimensions can also shed some light on flavor:
  - Large Hierarchy of Masses

$$M_u \ll M_c \ll M_t$$

$$M_d \ll M_s \ll M_b$$

  - Shouldn't we expect all the quarks to have masses of order M_t ?
  - Puzzling Pattern of Mixings

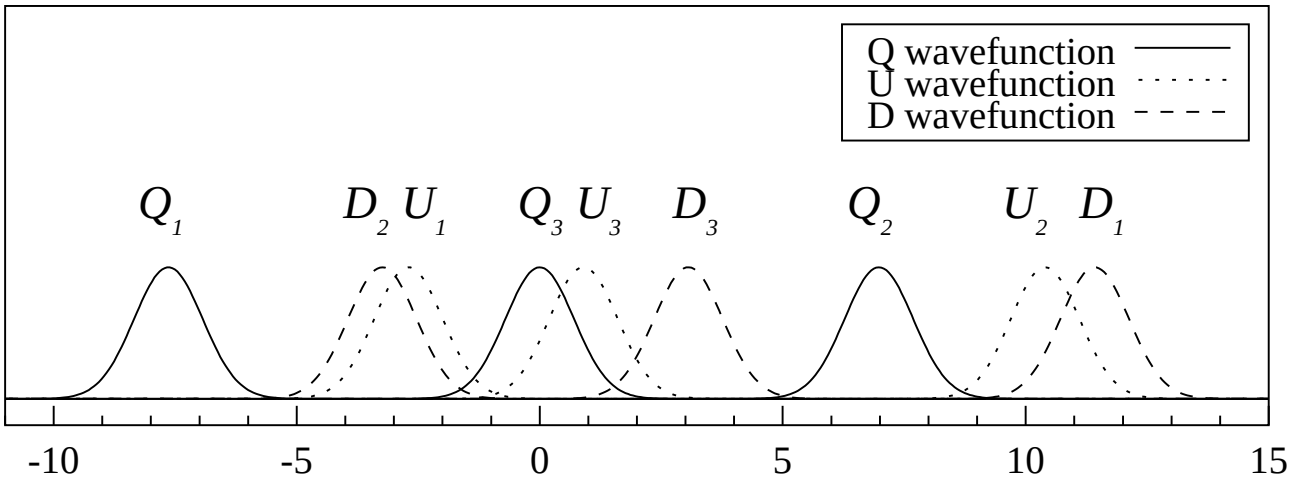
$$V_{us} \sim 1/5$$

$$V_{cb}, V_{ub} \ll 1$$

$$V_{us} \times V_{cb} \sim V_{ub}$$

- Can we solve the flavor puzzle and the hierarchy problem at the same time?
- Maybe a hybrid model with flavor from one extra dimension and gravity in *even* more? [J. Lykken & S. Nandi]

The Arkani-Hamed & Schmaltz Model



[E. Mirabelli & M. Schmaltz]

- Fermion zero-modes localized in an extra dimension
- $SU(2)$ singlets and doublets at different locales
- Higgs (VEV) distributed evenly in the bulk
- Gauge fields in the bulk
- Small overlap of the wave functions

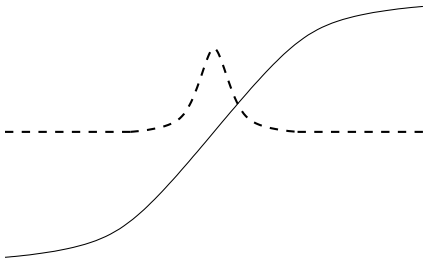
  $\rightarrow$ small 4d Yukawa couplings
- Some fine-tuning for M_t
- Empty Matrices $\rightarrow$ ϵ_K?

Localizing Fermions

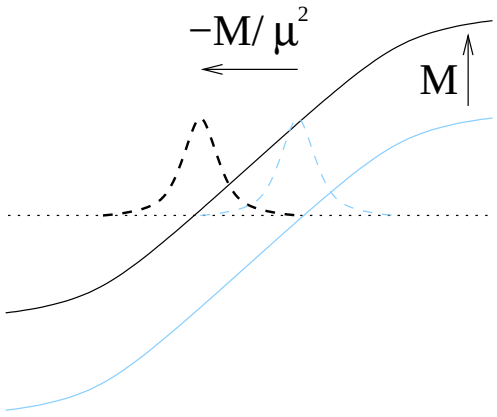
- 5d fermion Ψ coupled to scalar Φ

$$\overline{\Psi}(i\ \partial\!\!\!/ - \gamma^5 \partial_5 + f\Phi)\Psi$$

- Notice a massless Ψ is a 4-component field
- A non-trivial $\langle \Phi \rangle$ that crosses zero somewhere localizes a zero mode about that point:

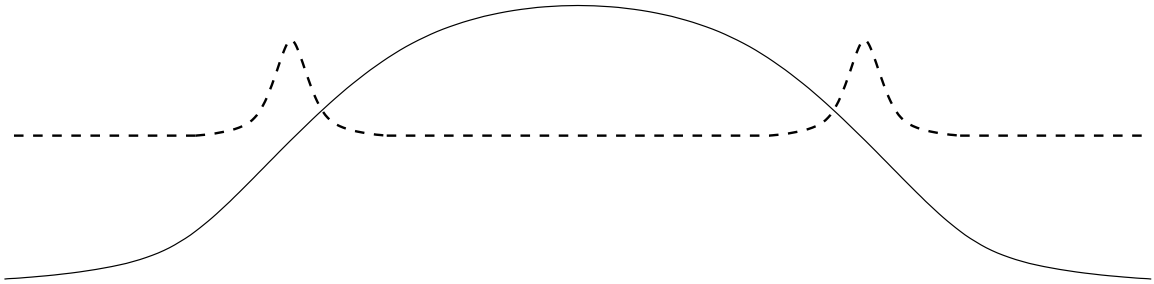


- We can split fermions by adding masses:



Compactification

- In order for the theory to look 4d at low energies, we want to compactify the extra dimension
- For example, on a circle: S^1
- ...but this causes other problems:



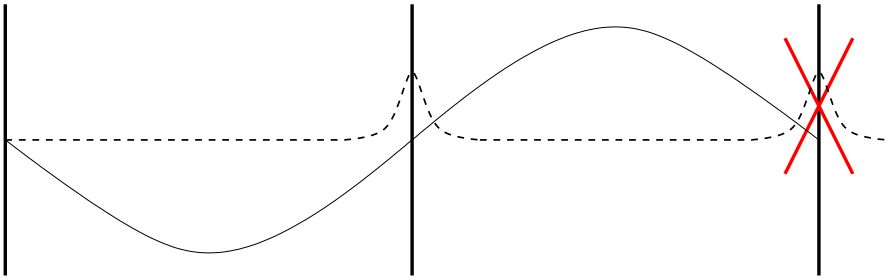
  - Generally, 5d theories are not chiral
  - Each SM fermion has a mirror partner
  - The VEV $\langle \Phi \rangle$ is unstable
- We address these problems with orbifold boundary conditions

Orbifold

- For example, $S^1/\mathcal{Z}_2$:

$$\begin{aligned}
\Psi(x, x_5) &= \gamma_5 \Psi(x, -x_5) \\
\Psi(x, L + x_5) &= \gamma_5 \Psi(x, L - x_5) \\
\Phi(x^\mu, -y) &= -\Phi(x^\mu, y) \\
\Phi(x^\mu, L/2 + y) &= -\Phi(x^\mu, -L/2 + y)
\end{aligned}$$

- This mods out the zero mass mirror partner:

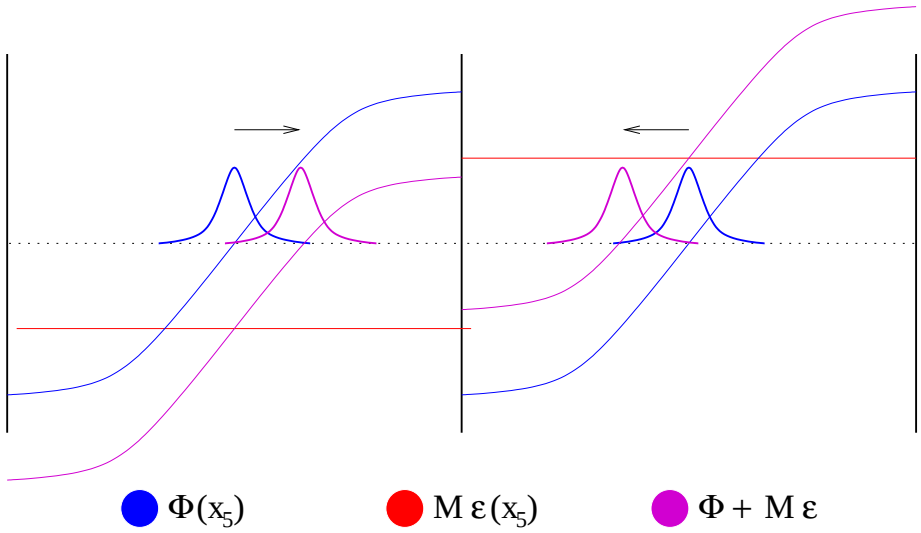


- A bulk scalar potential $(\Phi^2 - u^2)^2$ clashes with the boundary conditions [H. Georgi, A. Grant, G. Hailu]

- Fermion mass terms forbidden by the orbifold

Odd Mass Term

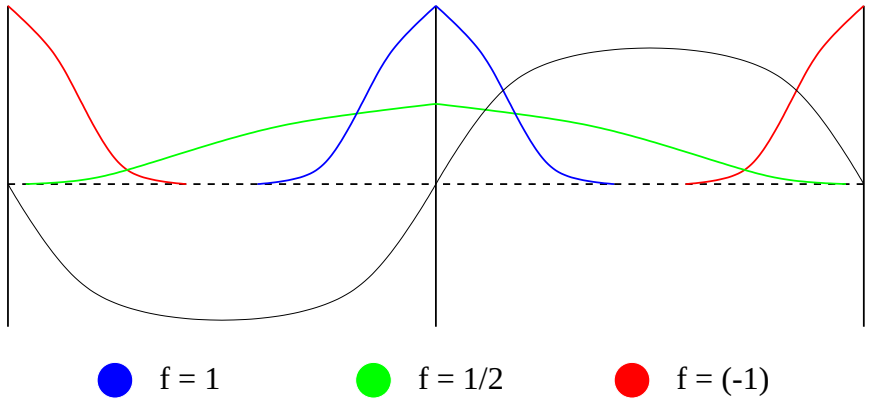
- We can build the AS model with an orbifold by adding an “odd” mass:



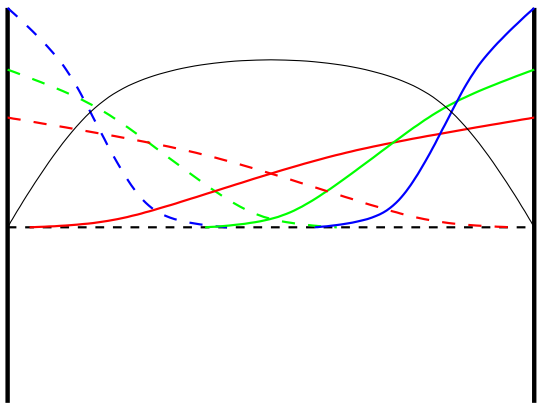
- For example, the odd mass can arise from another bulk scalar coupled to the fermions
- The EWSB Higgs can be even or odd under the orbifold, and might have a non-trivial VEV as a result

Flavor on an Orbifold I: Bulk Higgs

- Another flavor model does not invoke the odd mass but different ($\mathcal{O}(1)$) couplings to Φ



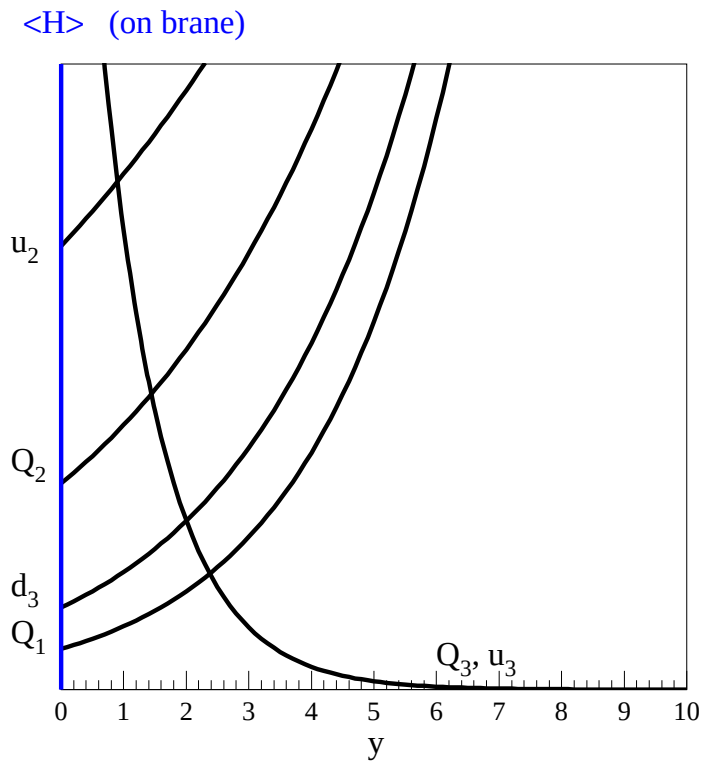
- Zero modes go like $1/\mathrm{Cosh}^{2f}[x_5/2]$
- Doublets at $x_5 = 0$, singlets at $x_5 = L/2$:



- For $M_* L \sim 20$, the widths range from $1/5$ to $3/2$, and 5d Yukawas from $1/3$ to 3

Model II: Higgs on a Boundary

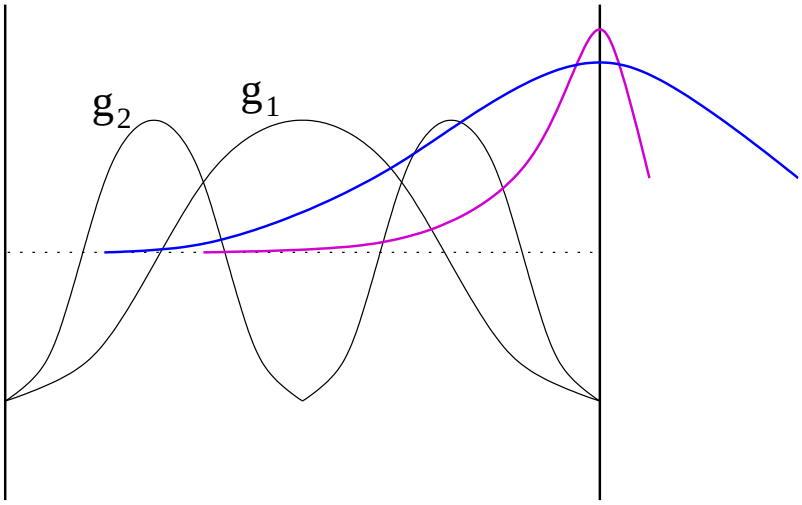
- Higgs (VEV) only at a boundary ($x_5 = 0$)



- Yukawa suppression from overlap with “Higgs brane”
- For $M_* L \sim 20$, this requires widths and 5d Yukawas between $1/3$ and 3
- No fine-tuning for M_t
- Automatically have: $V_{us} \times V_{cb} \sim V_{ub}$

Flavor-changing Neutral Currents

- The gauge boson zero modes couple universally to all of the fermions, but the higher modes do not:



- After CKM rotation, this introduces flavor-violating interactions

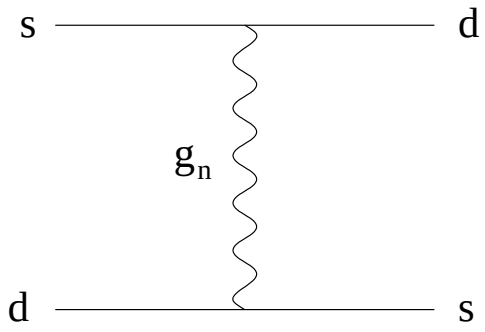
$$\left(\begin{array}{ccc} \overline{d} & \overline{s} & \overline{b} \end{array} \right) L_d^\dagger \left(\begin{array}{ccc} c_1^n & 0 & 0 \\ 0 & c_2^n & 0 \\ 0 & 0 & c_3^n \end{array} \right) L_d \left(\begin{array}{c} d \\ s \\ b \end{array} \right)$$

- The flavor-violating terms are proportional to rotation matrices (left- or right-handed) and Δc^n

K^0-$\overline{K^0}$ Mixing

- For example, consider a contribution to K^0-$\overline{K^0}$ mixing from KK gluons

  [A. Delgado, A. Pomarol, M. Quiros]



- In the SM these processes are weak loop effects
- The $\Delta S = 2$ effective Hamiltonian

$$H^{\Delta S=2} \sim \frac{\alpha_S}{M_c^2} \sum_{n=1}^{n^*} \frac{V^\dagger C V}{n^2}$$

- KK mass scale $M_c = L^{-1}$
- The sum is cut off at n^* (but results basically independent of n^*)

Limits on Models of Flavor

- By requiring the right order of magnitude for Δm_K and ϵ_K, we derive limits on M_c
- In specific models, this is related to the fundamental scale M_*

Model	AS	KT(I)
Δm_K	120 TeV	5 TeV
$\Delta \epsilon_K$	3000 TeV	80 TeV
L	$50/M_*$	$10/M_*$

- One can obtain similar bounds from ϵ'_K/ϵ_K (somewhat weaker than the ϵ_K ones)
- $M_* \sim (10^4 - 10^6) \times M_W$: Extra-dimensional flavor seems unlikely to coexist with a hierarchy solution
- SUSY models?

What about the Higgs?

- If the Higgs field lives in the extra dimension, this may impact Higgs phenomenology
- Kaluza-Klein modes for the Higgs (n-Higgs doublet model) [J. Gunion]
- EWSB VEV could be "shared":
  - Reduced Z-Z-h (W-W-h) interaction strengths
  - Processes like $t\bar{t}h$ and $b\bar{b}h$ could become more important as discovery modes
  - Rare decays like $h \to \gamma\gamma$ could be enhanced (or suppressed)
- Some Higgs modes may have flavor-violating couplings like the gauge boson KK modes did
  - $h \to \tau\mu$? [T. Han]
- Some modes may couple strongly to *light* fermions

Outlook

- An extra dimension can provide interesting solutions to the flavor puzzle
- FCNC constraints are quite strong, and seem to disfavor a combined extra-dimensional solution of hierarchy and flavor
- Unusual Higgs phenomenology can result!