Variants of warped geometry: leptons on a soft wall

With Michael Atkins, arXiv/1002.5044 [hep-ph]

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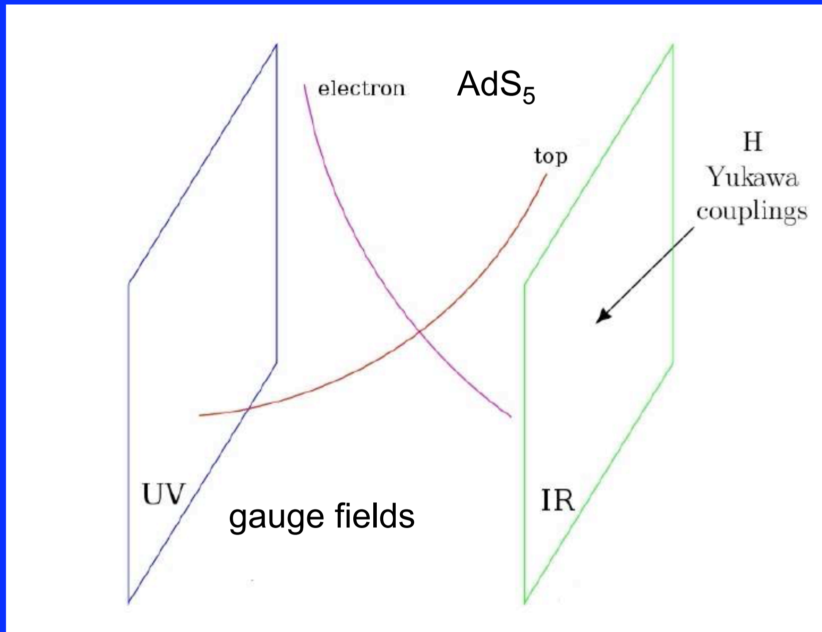
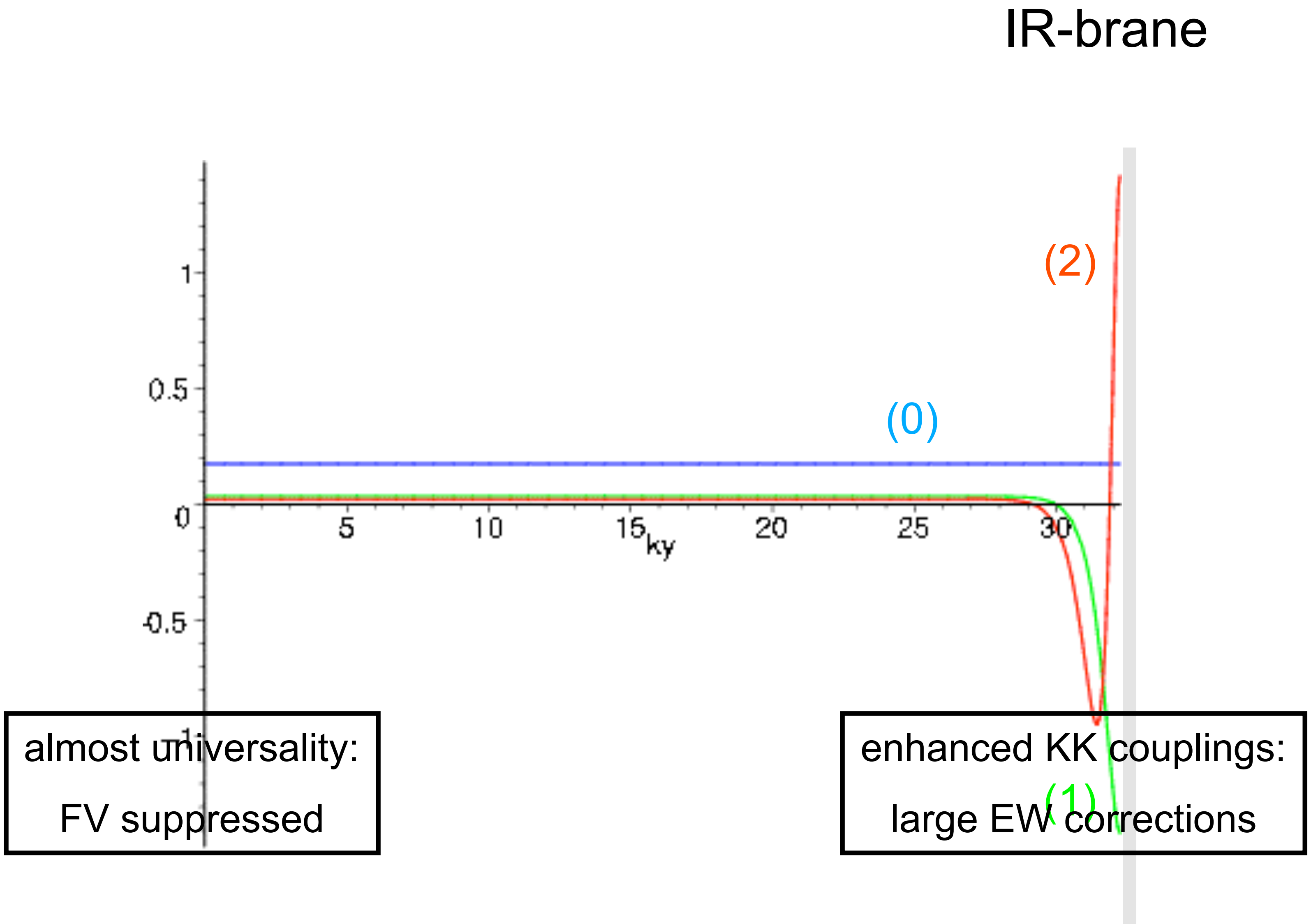
Planck'10, Cern, June '10

Conventional RS - SM



Bulk SM: fermion mass pattern from localizations, etc...

Main properties of gauge bosons:



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Ways out:

- brane kinetic terms
- custodial symmetry (bulk left-right symmetry)
- modify 5D warp factor (not much of an effect, Delgado, Falkowski ‘07)
- include more than 5D (can help, depending how the internal space scales, Archer, SH ‘10)
- soft wall

Soft-Wall Extra Dimension

[Batell, Gherghetta, Sword '08]

- Different phenomenology can be found by considering what is known as a "soft wall" extra dimension.
- The soft wall is realised by removing the IR brane and replacing it with a smooth space time cutoff generated by a dilaton field $\Phi(y)$. The action is given by

$$S = \int d^4x \int dy \sqrt{g}\, e^{-\Phi(y)}\, \mathcal{L}.$$

$$\Phi(y) = (\mu y)^2$$

Mass scales:

AdS curvature k

KK scale μ

Randall-Sundrum, $m_n^2 \sim n^2$. Soft-wall model, $m_n^2 \sim n$.

- In the soft wall model the Higgs must necessarily propagate in the bulk.
- It has been found that the soft-wall model is less constrained by EW precision observables than RS. (m_{KK}~2 TeV, Falkowski, Perez-Victoria '08)

Bulk fields on a soft wall:

gauge fields: trapped by the soft wall → discrete spectrum

fermion fields are not trapped

→ need to take the Higgs into account to get a discrete spectrum

$$S = \int dx^4 \int_{y_0}^{\infty} dy\, \sqrt{g} e^{-\Phi} \Big[\frac{1}{2} \left(\overline{\Psi}_L i e_A^M \gamma^A D_M \Psi_L - D_M \overline{\Psi}_L i e_A^M \gamma^A \Psi_L \right) - M_L \overline{\Psi}_L \Psi_L \\ + \frac{1}{2} \left(\overline{\Psi}_R i e_A^M \gamma^A D_M \Psi_R - D_M \overline{\Psi}_R i e_A^M \gamma^A \Psi_R \right) - M_R \overline{\Psi}_R \Psi_R \Big] .$$

$$S_{\text{Yuk}} = - \int dx \int_{y_0}^{\infty} dy \sqrt{g} e^{-\Phi} \frac{\lambda_5}{\sqrt{k}} \left[\overline{\Psi}_L(x,y) h(y) \Psi_R(x,y) + \overline{\Psi}_R(x,y) h(y) \Psi_L(x,y) \right]$$

$$h(y) = \eta k^{3/2} \mu^2 y^2$$

Using the KK reduction

$$\psi_{L,R\pm}(x,y) = \sum_{n=0}^{\infty} \psi_{\pm}^{(n)}(x)\, f_{L,R\pm}^{(n)}(y),$$

and requiring the $\psi_{\pm}^{(n)}(x)$ to be mass eigenstates, the $f^{(n)}$s will be given by

$$\pm\,\partial_y \begin{pmatrix} f_{L\pm}^{(n)} \\ f_{R\pm}^{(n)} \end{pmatrix} + e^{-A} \begin{pmatrix} M_L & m(y) \\ m(y) & M_R \end{pmatrix} \begin{pmatrix} f_{L\pm}^{(n)} \\ f_{R\pm}^{(n)} \end{pmatrix} = m_n \begin{pmatrix} f_{L\mp}^{(n)} \\ f_{R\mp}^{(n)} \end{pmatrix}.$$

remarks: - the dilaton does not enter, i.e. no trapping

- we solve these equations numerically for the wave functions

- other approaches

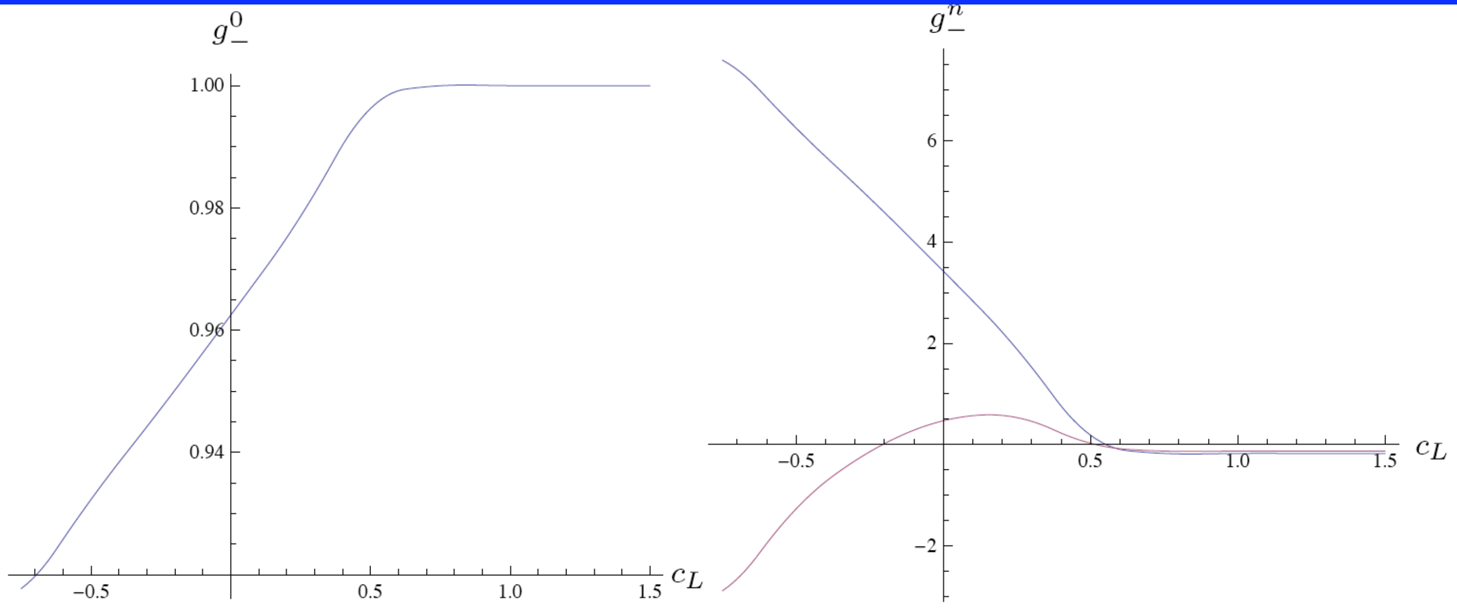
Gherghetta, Sword ‘09

Delgado, Diego ‘09

Aybat, Santiago ‘09

Gauge to fermion couplings:

$$g_{\pm}^{n} = g_5 \int_{y_0}^{\infty} dy\, f_A^{(n)} \left[\left(f_{L\pm}^{(0)} \right)^2 + \left(f_{R\pm}^{(0)} \right)^2 \right]$$



(a) (b)

Again there is a region of almost universal couplings: FV suppressed?

Fermion mass hierarchy:

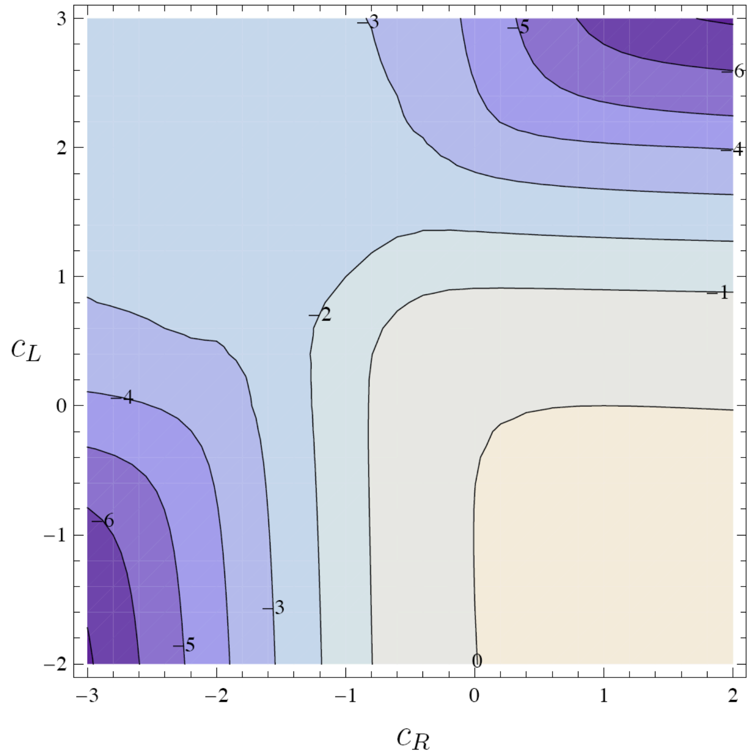


Figure 3: Contour plot of $\log_{10}(m_0/\mu)$ for the zero mode masses of fermions $\mu = 1$ TeV and $k = 10^3$ TeV.

For one Dirac fermion, the zero mass does depend on c_R and c_L

Smallest mass to be obtained in the universal region: ~ μ^2/k

→ accommodating tiny masses needs a huge hierarchy (e.g. for neutrinos)

Charged leptons and Dirac neutrinos on the soft wall:

We consider 3 generations of leptons with different Dirac mass parameters and random Yukawa couplings. The mass hierarchies are obtained by

In the case where we are not interested in generating neutrino masses via locations, we take only a moderate hierarchy of scales, $k/\mu = 10^7$. In this regime we choose the following three scenarios:

$$\text{(A)}: \quad c_{L1} = 0.700, \quad c_{L2} = 0.700, \quad c_{L3} = 0.700,$$
$$c_{R1} = -1.376, \quad c_{R2} = -0.903, \quad c_{R3} = -0.703,$$

$$\text{(B)}: \quad c_{L1} = 0.720, \quad c_{L2} = 0.700, \quad c_{L3} = 0.680,$$
$$c_{R1} = -1.373, \quad c_{R2} = -0.903, \quad c_{R3} = -0.704,$$

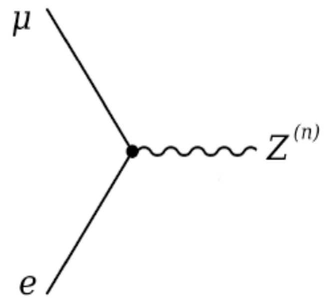
$$\text{(C)}: \quad c_{L1} = 0.600, \quad c_{L2} = 0.600, \quad c_{L3} = 0.600,$$
$$c_{R1} = -1.430, \quad c_{R2} = -0.980, \quad c_{R3} = -0.790.$$

In the regime where we can also generate neutrino masses, $k/\mu = 10^{15}$ we choose:

$$\text{(D)}: \quad c_{L1} = 0.60, \quad c_{L2} = 0.60, \quad c_{L3} = 0.60,$$
$$c_{R1} = -0.82, \quad c_{R2} = -0.64, \quad c_{R3} = -0.55.$$

Flavour Violation

- With three generations of fermions, the transformation from 5D gauge eigenstates to 4D mass eigenstates can produce flavour non-diagonal couplings.
- For example, we could produce flavour non-diagonal couplings between **leptons and KK modes of the Z boson:**



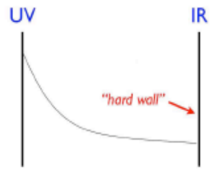
- Define the neutral current gauge couplings in the basis of mass eigenstates as

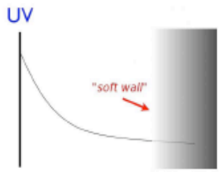
$$\mathcal{B}^{(n)}_{L,R} = \mathcal{U}_{L,R}\, \mathcal{G}^{(n)}_{L,R}\, \mathcal{U}^{\dagger}_{L,R},$$

  where $\mathcal{U}_{L,R}$ diagonalise the full fermion mass matrices and $\mathcal{G}^{(n)}_{L,R}$ contains the couplings to the nth KK state of the Z boson.
- Flavour violation is driven by non-universality of couplings of different flavour states δg_{ij} which are mixed by an angle θ_{ij}

$$\mathcal{B}_{ij} \approx \delta g_{ij} \sin\theta_{ij}$$

Constraints from Lepton Flavour Violation





	RS, $m_{KK} = 10$ TeV [S.J. Huber hep-ph/0303183]	Soft-Wall, $m_{KK} = 2$ TeV [M.A. & S.J. Huber arXiv:1002.5044]	Experiment [PDG]
$\mathrm{Br}(\mu \to e e \bar{e})$:	5.2×10^{-14}	2.5×10^{-15}	$< 1.0 \times 10^{-12}$
$\mathrm{Br}(\tau \to \mu \mu \bar{\mu})$:	1.1×10^{-13}	2.7×10^{-12}	$< 3.2 \times 10^{-8}$
$\mathrm{Br}(\tau \to e e \bar{e})$:	7.5×10^{-15}	2.8×10^{-16}	$< 3.6 \times 10^{-8}$
$\mathrm{Br}(\mu N \to e N)$:	5.0×10^{-16}	1.4×10^{-14}	$< 6.1 \times 10^{-13}$
$\mathrm{Br}(\mu \to e \gamma)$:	2.1×10^{-16}	1.2×10^{-18}	$< 1.2 \times 10^{-11}$
$\mathrm{Br}(\tau \to \mu \gamma)$:	6.7×10^{-16}	4.1×10^{-14}	$< 4.5 \times 10^{-8}$
$\mathrm{Br}(\tau \to e \gamma)$:	2.8×10^{-17}	2.6×10^{-18}	$< 1.1 \times 10^{-7}$

- Similar rates for both models BUT it is very important to compare the KK scales!
- Branching ratios for $l_i \to l_j l_j l_j$ scales as $1/m_{KK}^4$.
- Flavour violation in the soft-wall model is much more suppressed than the Randall-Sundrum model.

Conclusions

Soft wall models provide a rich phenomenology:

- reduced EWPO constraints: KK scale ~2 TeV
- fermion mass “geography” successful
- reduced rates of flavor violation with respect to the hard wall

Next step: generalize to the quark sector (work in progress)