Lepton flavour violation in RS models

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Theoretische Physik 1
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Outline:

- Introduction
- Strategy and formalism
- Results

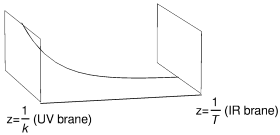
General Theory Overview

Five dimensional Anti de Sitter spacetime with compact extra dimension

$$ds^2 = \left(\frac{1}{kz}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - d^2 z)$$

$$\varepsilon \equiv \frac{T}{k} \approx 10^{-16} \approx \frac{1 \text{ TeV}}{M_{Pl}^{4d}}$$

$$z \in [1/k, 1/T]$$



- Geometric solution of the gauge–gravity hierarchy problem [Randall, Sundrum (1999)]
- Natural mechanism for generation of flavour hierarchies
  [Grossman et al. (2000), Gherghetta et al. (2000), Huber et al. (2000)]
- Compact fifth dimension quantises the 5th component of the momenta
  ⇒ Kaluza-Klein towers for all bulk fields

typical KK mass scale $m_{KK} \sim 2.45T$

Models & Particle Content

- Minimal RS: only SM fields (promoted to 5D) + Higgs localised near IR branes
- Custodial protected RS: extended gauge group
  $\mathrm{SU}(3)_{\mathrm{c}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}} \times \mathrm{U}(1)_{\mathrm{X}} \times \mathbb{Z}_2$
  $\rightarrow$ custodial symmetry only broken by UV brane boundary conditions
  $\rightarrow$ extended fermion sector (but no unique choice for fermion reps.)

$$
\begin{aligned}
\xi^i_{1L} &= \begin{pmatrix} \chi_L^{\nu_i}\,(-,+)_1 & l_L^{\nu_i}\,(+,+)_0 \\ \chi_L^{l_i}\,(-,+)_0 & l_L^{l_i}\,(+,+)_{-1} \end{pmatrix} \\
\xi^i_{2R} &= \nu_R\,(+,+)_0 \\
\xi^i_{3R} &= T^i_{3R} \otimes T^i_{4R} = \begin{pmatrix} \tilde{\lambda}^i_R\,(-,+)_1 \\ \tilde{N}^i_R\,(-,+)_0 \\ \tilde{L}^i_R\,(-,+)_{-1} \end{pmatrix} \otimes \begin{pmatrix} \lambda^i_R\,(-,+)_1 \\ N^i_R\,(-,+)_0 \\ E^i_R\,(+,+)_{-1} \end{pmatrix} .
\end{aligned}
$$

- Models where the Higgs leaks into the bulk (Bulk Higgs with KK Higgs modes)

Model Constraints

- Direct production: $m_{KK} > 2.45$ TeV
- Higgs decay: $m_{KK} \sim 4.9\,(10)$ TeV for the minimal (custodial protected) model
  [Hahn, Hörner, Malm, Neubert, Novotny, Schmell (2014)]
- Gluon FCNCs: $m_{KK} \sim 32$ TeV for a fully anarchic Yukawa [Csaki, Falkowski, Weiler (2008)]
- Electroweak precision observables S and T : $\sim\ 4.9\,(10)$ TeV for the minimal (custodial protected) model [B. Duling; S. Casagrande, F. Goertz, U. Haisch, M. Neubert, T. Pfoh]

$\rightarrow$ Direct production off KK excitations at the LHC not likely

Lepton Transitions

- $(g-2)_\mu$ and d_e
  pure loop-induced effects in RS; flavour diagonal [M.Beneke, P. Dey , J. Rohrwild (2012)]

- $\mu \to e\gamma$
  pure loop-induced effects in RS; LFV [Agashe et al. (2006); Csaki et al. (2010)]

- $\mu \to 3e$
  tree + loop induced effects [Grojean et al. (2003); Csaki et al. (2010)]

- $\mu \to e$ in nuclei
  tree dominated effects; [Chang & Ng (2005); Csaki et al. (2010)]

Strategy: Effective Field Theory

- Distinct hierarchy of scales $\underbrace{k \gg m_{KK}}_{UV} \gg \underbrace{v \gg m_\ell}_{IR}$
- Strategy: integrate out the "bulk" by matching onto an $SU(3) \times SU(2) \times U(1)_Y$ invariant Lagrangian at a scale $m_{KK} \gg \mu \gg v$:

$$\mathcal{L}_{RS} \to \mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{m_{KK}^2} \sum_i C_i \mathcal{O}_i$$

[M.Beneke, P. Dey J, Rohrwild],(2012)

- Relevant dim. six operators include

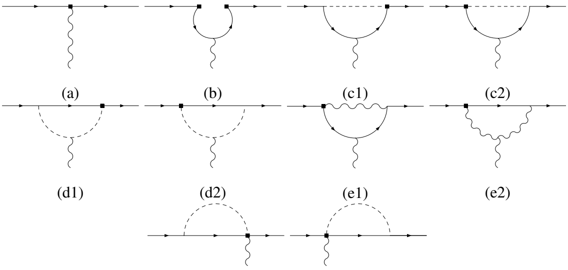
$$\sum_i C_i \mathcal{O}_i \supset a_{B,ij}\, \bar{L}_i \Phi \sigma_{\mu\nu} E_j B^{\mu\nu} + a_{W,ij}\, \bar{L}_i \tau^a \Phi \sigma_{\mu\nu} E_j\, W^{a,\mu\nu}$$ Dipole Operators

$$+ b_{LE,\,ij}\, (\bar{L}_i \gamma^\mu L_i)(\bar{E}_j \gamma_\mu E_j) + c_{1,i}\, (\bar{E}_i \gamma_\mu E_i)(\Phi^\dagger i D^\mu \Phi)$$
$$+ c_{2,i}\, (\bar{L}_i \gamma_\mu L_i)(\Phi^\dagger i D^\mu \Phi) + c_{3,i}\, (\bar{L}_i \gamma^\mu \tau^a L_i)(\Phi^\dagger i \tau^a \overleftrightarrow{D}_\mu \Phi)$$ Tree Operators
$$+ h_{ij}\, (\Phi^\dagger \Phi)(\bar{L}_i \Phi E_j) + b_{L\tau L,ij}\, (\bar{L}_i \gamma_\mu \tau^a L_i)(\bar{L}_j \gamma^\mu \tau^a L_j)$$
$$+ b_{LL,ij}\, (\bar{L}_i \gamma_\mu L_i)(\bar{L}_j \gamma^\mu L_j) + b_{EE,ij}\, (\bar{E}_i \gamma_\mu E_i)(\bar{E}_j \gamma^\mu E_j) + \ldots$$

EFT after EWSB

$$\Phi \to \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + H + iG) \end{pmatrix} \qquad E_i \to V_{ij} P_R \psi_j, \qquad L_i \to U_{ij} P_L \begin{pmatrix} \nu_j \\ \psi_j \end{pmatrix}$$

- Set of Diagrams contributing to radiative LFV



(a) (b) (c1) (c2) (d1) (d2) (e1) (e2) (f1) (f2)

- similar set for $\mu \to \bar{e}ee$ [Crivelin et al., 2014]

$\to$ TASK: determine the Wilson coefficients

5d Formalism

- Work in a five dimensional QFT
  no KK sums; vertices and propagators are 5D [Randall, Schwartz, 2001]
- Use mixed coordinate-momentum representation for propagators in the unbroken theory [Randall, Schwartz, 2001]
  $\rightarrow$ propagators depend on 4D momentum and start/end coordinate in the 5th dimension

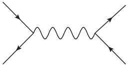
$$\Delta_L(p,x,y) = -\underbrace{P_L F_L^+(p,x,y)\not{p}P_R}_{\text{contains zero mode SM field}} - P_R F_L^-(p,x,y)\not{p}P_L$$
$$+\underbrace{P_L d^+ F_L^-(p,x,y)P_L + P_R d^- F_L^+(p,x,y)P_L}_{\sim\text{mass term}}$$

Exact solution in the unbroken phase:

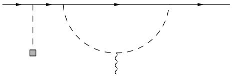
$$F_L^-(p,x,y) = \frac{ik^4 x^{5/2} y^{5/2}\theta(x-y)\left(K_{c-\frac{1}{2}}\left(\frac{p}{k}\right) I_{c-\frac{1}{2}}(py) - I_{c-\frac{1}{2}}\left(\frac{p}{k}\right) K_{c-\frac{1}{2}}(py)\right)}{K_{c-\frac{1}{2}}\left(\frac{p}{k}\right) I_{c-\frac{1}{2}}\left(\frac{p}{T}\right) - I_{c-\frac{1}{2}}\left(\frac{p}{k}\right) K_{c-\frac{1}{2}}\left(\frac{p}{T}\right)}$$
$$\times\left(I_{c-\frac{1}{2}}\left(\frac{p}{T}\right) K_{c-\frac{1}{2}}(px) - K_{c-\frac{1}{2}}\left(\frac{p}{T}\right) I_{c-\frac{1}{2}}(px)\right) + (x \leftrightarrow y)$$

EFT Matching: Diagram Classes

- Tree level diagrams: four–fermion etc.

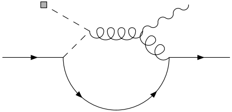


- Higgs contribution to dipole operator:



strong dependence on Higgs and 5D parameters localisation (bulk Higgs vs. brane Higgs).

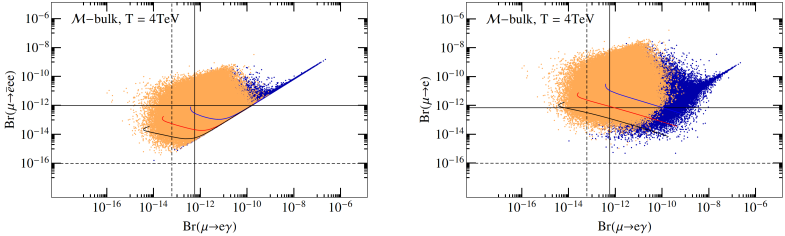
- Gauge contribution to dipole operator:



numerically computed to one permille precision[Rohrwild, Moch, 2014].
RS contribution UV insensitive

LVF Minimal RS Model

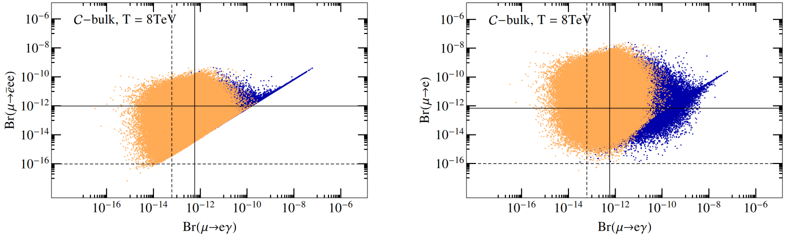
- No significant reduction of the possibe range due to experimental d_e constraint



- $M_{KK} > 5\,\text{TeV}$ constraint due experimental limits
- Exclusion range of future Mu2e experiment up to M_{KK} of 20 TeV

  [M. Beneke, P. Moch, J. Rohrwild, 1508.01705 (2015)]

LVF Custodial Protected RS model



- $M_{KK} > 20\,\text{TeV}$ due to experimental constraints

  [M. Beneke, P. Moch, J. Rohrwild, 1508.01705 (2015)]

Conclusion

- Complete 5D computation of all dominant Wilson coefficients contributing to LVF
- First time fully 5D computation of the Higgs KK contribution
- $M_{KK} > 5\,(20)$ TeV from the LVF for the minimal (custodial) RS model
- Potential reach of future LVF experiment up too KK masses of 20 TeV
- 5D Wilson coefficients adaptable for further projects, for example $\bar{B} \to X_s \gamma$ [P. Moch, J. Rohrwild Nucl.Phys. B902 (2016)]
- EFT programs usable for different models [T. Feldmann, C. Luhn, P. Moch (2016)]