Lepton Flavour Violation in the Randall-Sundrum Model

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Outline:

- Introduction
- Strategy and formalism
- Phenomology

Theory setup

Five dimensional Anti de Sitter spacetime with compact extra dimension:

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

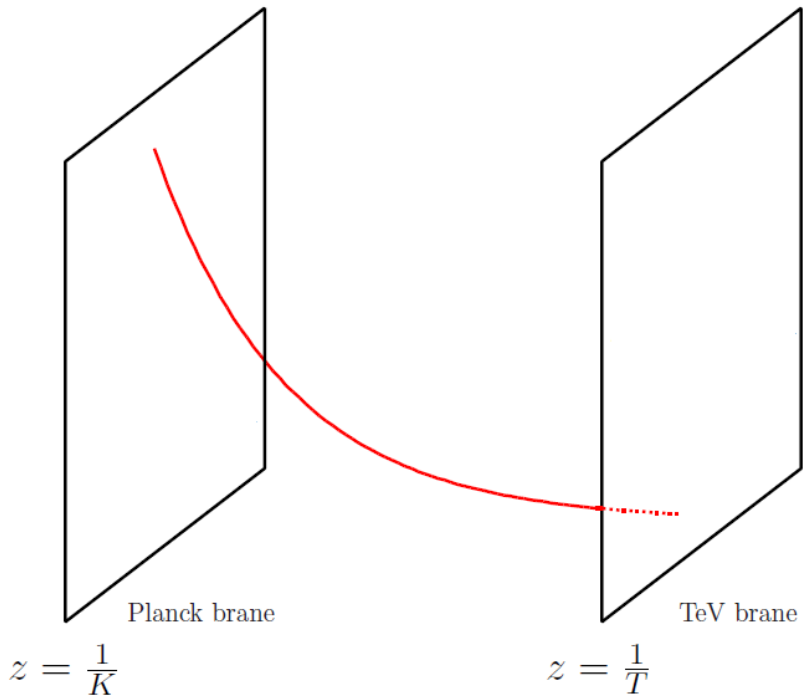
$$M_{Pl}^{4d\,2} \approx \frac{M_{Pl}^{5d\,3}}{k}$$

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

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

proper distance between branes (= boundaries):

$$1/k \times \ln(k/T)$$



- Higgs localization to address the hierachy problem [Randall, Sundrum 1999]
- natural generation of flavour hierachy [Huber, Safi 2000,2001]

Models and particle content

- minimal RS: SM fields promoted to 5D fields and Higgs localized close to the IR brane
- custodially protected RS: extended symmetry group
  $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_X \times P_{L,R}$
  $\Rightarrow$ BC break custodial symmetry only on UV brane
  $\Rightarrow$ extended fermion sector

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

Constraints

- from direct production $M_{kk} \sim$ 2.7 TeV
- from EWPT $M_{kk} \gtrsim$ 5.6 TeV (10 TeV) for the costudial protected (minimal) RS model [e.g. Agashe et al., 2003; Duling et al., 2009; Casagrande et al., 2010]

- from gluon FCNCs $\sim$ 20 TeV without additional flavour structure
- Lepton flavour violating processes
  We investigate:
  - Flavour changing radiative transition like $\mu \to e\gamma$ [Agashe et al., 2006; Csaki et al., 2010]
  - Flavour changing processes also mediated by FCNCs like $\mu \to \bar{e}ee$
  - Flavour preserving: muon g-2 [Rohrwild, Moch, 2014]

Strategy: EFT before EWSB

- distinct scale hierarchy $\underbrace{k \gg T}_{UV} \gg \underbrace{v \gg m_\ell}_{IR}$
- strategy: integrate out the "bulk" by matching onto an $SU(3) \times SU(2) \times U(1)_Y$ invariant Lagrangian at a scale $T \gg \mu \gg v$ in the unbroken theory:

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

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

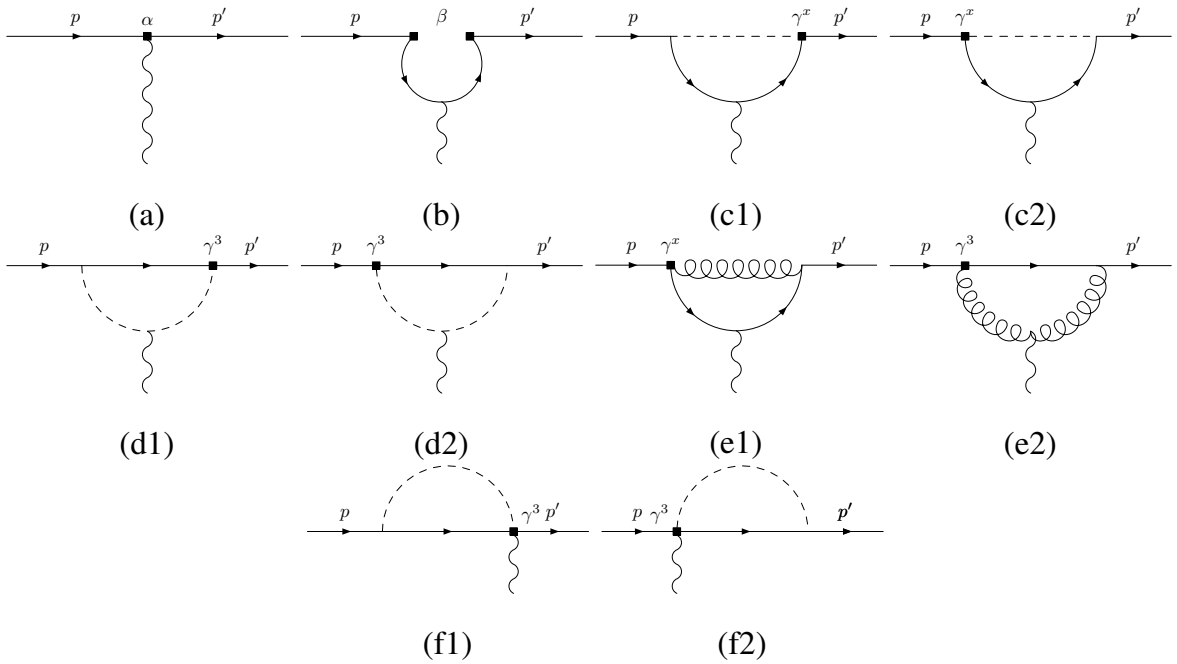
- relevant dim. six operators include

$$\begin{aligned}
\sum_i C_i \mathcal{O}_i \supset\ & a_{B,ij}\, \bar{L}_i \Phi \sigma_{\mu\nu} E_j B^{\mu\nu} + a_{W,ij}\, \bar{L}_i \tau^a \Phi \sigma_{\mu\nu} E_j\, W^{a,\mu\nu} + \text{h.c.} \\
& + b_{ij}\, (\bar{L}_i \gamma^\mu L_i)(\bar{E}_j \gamma_\mu E_j) + c_{1,i}\, (\bar{E}_i \gamma_\mu E_i)(\Phi^\dagger i D^\mu \Phi) \\
& + c_{2,i}\, (\bar{L}_i \gamma_\mu L_i)(\Phi^\dagger i D^\mu \Phi) + c_{3,i}\, (\bar{L}_i \gamma^\mu \tau^a L_i)(\Phi^\dagger i \tau^a \overleftrightarrow{D}_\mu \Phi) \\
& + b_{1,ij}\, (\bar{L}_i \gamma_\mu \tau^a L_i)(\bar{L}_j \gamma^\mu \tau^a L_j) + b_{2,ij}\, (\bar{L}_i \gamma_\mu L_i)(\bar{L}_j \gamma^\mu L_j) \\
& + b_{3,ij}\, (\bar{E}_i \gamma_\mu E_i)(\bar{E}_j \gamma^\mu E_j) + h_{ij}\, (\Phi^\dagger \Phi)(\bar{L}_i \Phi E_j) + h.c.
\end{aligned}$$

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



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

5d formalism

- work in 5d theory before EWSB
  $\rightarrow$vertices and propagators are five dimensional. [Randall, Schwartz, 2001]
- use mixed coordinate-momentum representation for all propagators in the unbroken theory[Randall, Schwartz, 2001]
  SM-doublet propagator:

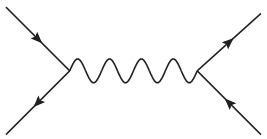
$$\begin{aligned}\Delta_L(p,x,y) &= -F_L^-(p,x,y)\not{p}P_L - F_L^+(p,x,y)\not{p}P_R \\ &\quad + d^+F_L^-(p,x,y)P_L + d^-F_L^+(p,x,y)P_R,\end{aligned}$$

- exact solution in the unbroken phase

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

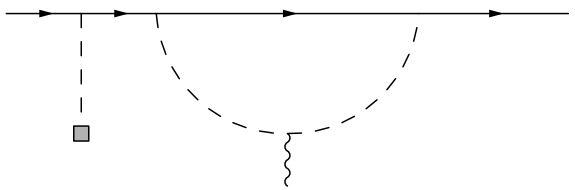
EFT matching: Diagram classes

- Tree level diagrams: four fermion etc.



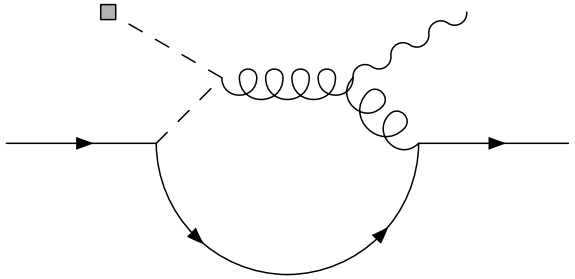
elemantary integrals

- Higgs contribution to dipol operator:



results strongly depend on Higgs localization (bulk Higgs vs. brane Higgs)

- Gauge contribution to dipol operator:

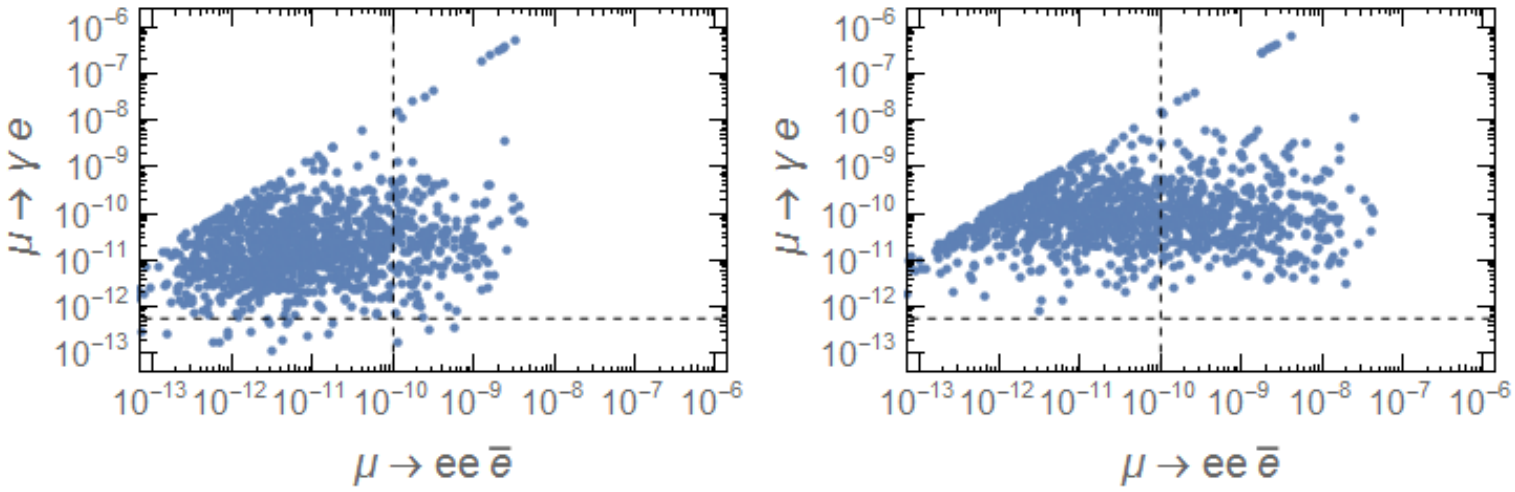


numerically computed to one permille precision[Rohrwild, Moch, 2014]

Preliminary results: Narrow Width Higgs

- $\mu \to e\gamma$ vs $\mu \to eee$ for $M_{kk} \sim 5$ TeV and $\mathcal{O}(1)$ 5D Yukawas

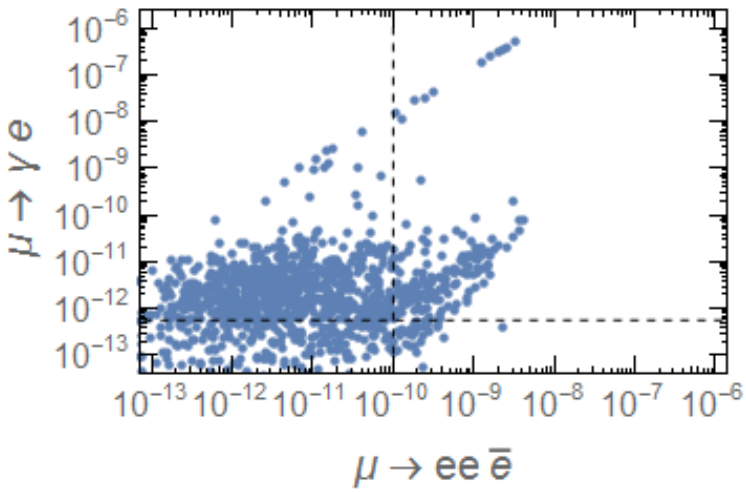
minimal RS model custodial protected RS model



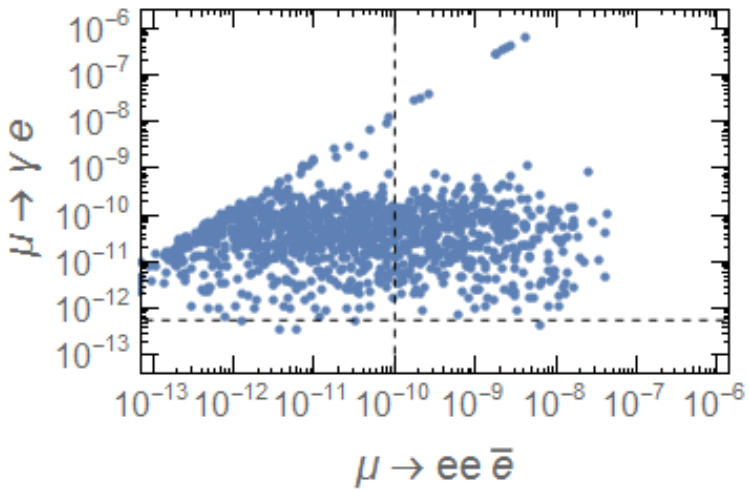
Preliminary results results: Brane Higgs

- $\mu \to e\gamma$ vs $\mu \to eee$ for $M_{kk} \sim 5$ TeV and $\mathcal{O}(1)$ 5D Yukawas

minimal RS model



custodial protected RS model



- impact of specific dim. eight operators potentially large

Conclusion

- complete 5d calculation of all Wilson coefficients of all leptonic dimension six operators contributing to LVF
- results depend on the treatment of the Higgs brane localization
- LVF parameters strongly depend on 5d parameters, huge effects possible
- work in progress: estimating dimension eight operators contribution to $\mu \to e\gamma$