Leptons, Loops and Dipoles in Randall-Sundrum Models

J. Rohrwild

Rudolf Peierls Centre for Theoretical Physics
University of Oxford

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Outline:

1. Brief intro to RS
2. General strategy
3. Calculations in 5D
4. Lepton phenomenology

Minimal RS model: Setup

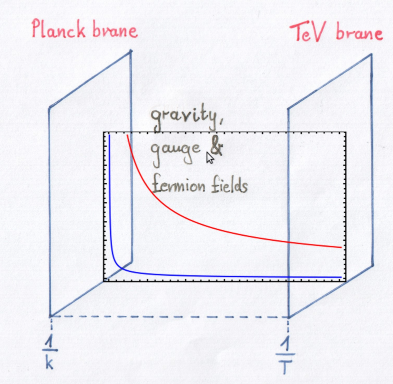
Slice of AdS_5 in interval ($[1/k, 1/T]$ in conformal coordinates)

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

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

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

proper distance between branes (= boundaries):
$1/k \times \ln(k/T)$

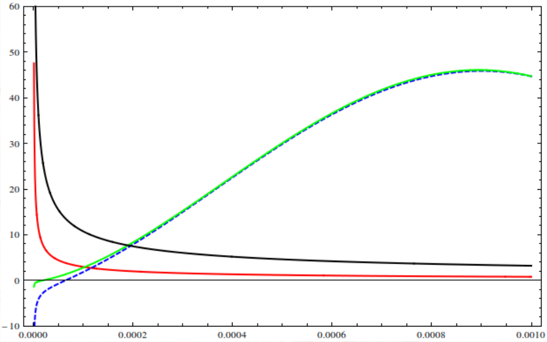


Minimal RS model: All SM fields except the Higgs in the bulk; no additional fields
Custodially protected RS: Add $SU(2)_R$ gauge fields and increase fermion content

lowest KK resonance mass $\sim 2.5T$

Minimal RS model: Setup

- in the KK mode language

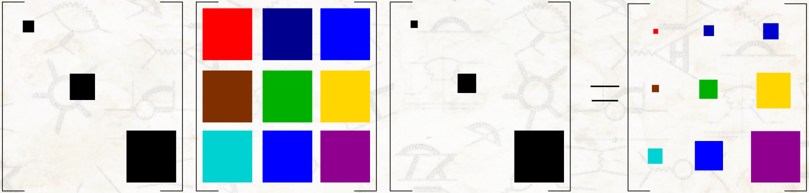


- Note that:

$$Y_{ij}^{4D} \sim f_{L_i}^{(0)}(1/T)\, y_{ij}^{(5D)}\, g_{E_i}^{(0)}(1/T)$$

Minimal RS model: Setup

- the equation in a picture



- Note that:

$$Y_{ij}^{4D} \sim f_{L_i}^{(0)}(1/T)\, y_{ij}^{(5D)}\, g_{E_i}^{(0)}(1/T)$$

Boundary Conditions and Spectrum

- Boundary conditions ($\equiv$ parities under S^1/Z_2 orbifold Z_2 symmetries)

$$\partial_z A_\mu|_{z=1/T,1/k} = 0 \qquad A_5|_{z=1/T,1/k} = 0$$
$$L_R|_{z=1/T,1/k} = 0 \qquad E_L|_{z=1/T,1/k} = 0$$

  Only L_L , E_R have zero modes ($m_0 = 0$). KK excitations describe massive gauge bosons and vector-like fermions.

- 5D gauge fixed such that A_μ and A_5 decouple $\to \xi$
- wrong-chirality Higgs couplings (WCHC)

$$\int d^4x \, [(\bar{L}\Phi)E + h.c.]|_{z=1/T} = \int d^4x \, [(\bar{L}_L\Phi)E_R + (\bar{L}_R\Phi)E_L + h.c.]|_{z=1/T}$$

  The WCHC $(\bar{L}_R\Phi)E_L$ vanishes for a brane-localized Higgs due to the boundary condition. Too naive!

RS & Lepton-flavour observables

- Exhaustive phenomenology of tree-level processes (electroweak, flavour) from gluon FCNCs KK gluon mass ~ 20 TeV w/o extra flavour structure [e.g. Csaki, Falkowski, Weiler, 2008]
- Higgs production in gluon-gluon fusion [Casagrande et al., 2010; Azatov et al., 2010; Carena et al., 2012; Malm et al.,2013, Archer et al. 2014]
- quark FCNCs: $b \to s\gamma$, $b \to sg$ [Gedelia, Isidori, Perez 2009; Blanke et al., 2012], and $c \to ug$ [Delaunay et al., 2012]
- lepton observables
  - $a_\mu - a^{SM} = 239(63)(48) \times 10^{-11}$
  - $\mathrm{Br}\,(\mu \to e\gamma) < 5.7 \times 10^{-13}(10^{-14})$ MEG (upgraded)
  - $\mathrm{Br}\,(\mu \to 3e) < 1.0 \times 10^{-12}$ SINDRUM
  - $\mathrm{Br}^{\mathrm{Au(Al)}}\,(\mu N \to eN) < 7 \times 10^{-13}(10^{-16})$ SINDRUM II (DeeMe, Mu2E,COMET)

Lepton Flavour Observables

- $g-2$
  pure loop-induced effect in RS; flavour diagonal; [Davoudiasl et al. 2000]
- d_e
  pure loop-induced effect in RS; flavour diagonal, CP violating;
- $\mu \to e\gamma$
  pure loop-induced effect in RS; LFV [Agashe et al., 2006, Csaki et al., 2010]
- $\mu \to 3e$
  tree-dominated effect (?) [Agashe et al., 2006, Grojean et al., 2003; Csaki et al., 2010]
- $\mu \to e$ in Au
  tree-dominated effect (?); provides “orthogonal” information [Agashe et al., 2006; Chang & Ng, 2005; Csaki et al., 2010]

This talk:
$\to$ a general strategy
$\to$ How do you calculate loops in 5D?

Lagrangian (minimal model)

$$S_{5\mathrm{D}} = \int d^4x \int_{1/k}^{1/T} dz\,\sqrt{G}\,\Bigg\{ -\frac{1}{4}F^{MN}F_{MN} - \frac{1}{4}W^{a,MN}W^{a}_{MN}$$

$$+ \sum_{\psi=E,L} \left(e^M_m \left[\frac{i}{2}\,\bar{\psi}_i\,\Gamma^m (D_M - \overleftarrow{D}_M)\psi_i \right] - M_{\psi_i}\bar{\psi}_i\psi_i \right) \Bigg\} + S_{\mathrm{GF+ghost}}$$

$$+ \int d^4x \left\{ (D^\mu\Phi)^\dagger D_\mu\Phi - V(\Phi) - \left(\frac{T}{k}\right)^3 \left[y^{(5\mathrm{D})}_{ij}(\bar{L}_i\Phi)E_j + \mathrm{h.c.} \right] \right\}$$

$$\Gamma^m = (\gamma^\mu, i\gamma_5) \qquad e^M_m = (kz)\delta^M_m \qquad M_{\psi_i} = c_{L/E_i}\cdot k$$

Two scales:

k determines the size of all parameters

T put in by hand to address the quantum corrections to the Higgs mass

Strategy

- distinct scale hierarchy $\underbrace{k \gg T}_{UV} \gg \underbrace{v \gg m_\ell}_{IR}$

  matching scale μ

- strategy:

  1. Step (in symmetric phase $\rightarrow$ no vev):
  integrate out the "bulk" $\rightarrow$ match onto an $SU(2)_L \times U(1)_Y$ symmetric effective theory

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

[Buchmüller & Wyler]

  2. Step: change into the "broken" phase

  3. Step: compute observables in using 4d effective theory

1. Step: 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:

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

- relevant operators include

$$\begin{aligned}
\sum_i C_i \mathcal{O}_i \supset\ & a_{B,ij}\, \bar{L}_i \Phi \sigma_{\mu\nu} E_j B^{\mu\nu} + a_{W,ij}\, \bar{L}_i \tau^a \Phi \sigma_{\mu\nu} E_j\, W^{a,\mu\nu} + \text{h.c.} \\
& + c_{1,i}\, (\bar{E}_i \gamma_\mu E_i)(\Phi^\dagger i D^\mu \Phi) + c_{2,i}\, (\bar{L}_i \gamma_\mu L_i)(\Phi^\dagger i D^\mu \Phi) \\
& + c_{3,i}\, (\bar{L}_i \gamma^\mu \tau^a L_i)(\Phi^\dagger i \overleftrightarrow{\tau^a D_\mu} \Phi) \\
& + b_{1,ijkl}\, (\bar{L}_i \gamma_\mu L_i)(\bar{L}_k \gamma^\mu L_l) + b_{2,ij}\, (\bar{L}_i \gamma_\mu L_i)(\bar{E}_j \gamma^\mu E_j) \\
& + b_{3,ij}\, (\bar{E}_i \gamma_\mu E_i)(\bar{E}_j \gamma^\mu E_j) + \ldots \\
& + b_{L\tau Q,ij}\, (\bar{L}_i \gamma_\mu \tau^a L_i)(\bar{Q}_j \gamma^\mu \tau^a Q_j) + b_{LQ,ij}\, (\bar{L}_i \gamma_\mu L_i)(\bar{Q}_j \gamma^\mu Q_j) \\
& + b_{EQ,ij}\, (\bar{E}_i \gamma_\mu E_i)(\bar{Q}_j \gamma^\mu Q_j) + b_{Lu,ij}\, (\bar{L}_i \gamma_\mu L_i)(\bar{u}_j \gamma^\mu u_j) \\
& + b_{Ld,ij}\, (\bar{L}_i \gamma_\mu L_i)(\bar{d}_j \gamma^\mu d_j) + b_{Eu,ij}\, (\bar{E}_i \gamma_\mu E_i)(\bar{u}_j \gamma^\mu u_j) \\
& + b_{Ed,ij}\, (\bar{E}_i \gamma_\mu E_i)(\bar{d}_j \gamma^\mu d_j) + \ldots
\end{aligned}$$

1. Step: EFT before EWSB

- relevant operators include

$$\sum_i C_i \mathcal{O}_i \supset a_{B,ij}\, \bar{L}_i \Phi \sigma_{\mu\nu} E_j B^{\mu\nu} + a_{W,ij}\, \bar{L}_i \tau^a \Phi \sigma_{\mu\nu} E_j\, W^{a,\mu\nu} + \text{h.c.}$$
$$+ c_{1,i}\, (\bar{E}_i \gamma_\mu E_i)(\Phi^\dagger i D^\mu \Phi) + c_{2,i}\, (\bar{L}_i \gamma_\mu L_i)(\Phi^\dagger i D^\mu \Phi)$$
$$+ c_{3,i}\, (\bar{L}_i \gamma^\mu \tau^a L_i)(\Phi^\dagger i \tau^a \overleftrightarrow{D}_\mu \Phi)$$
$$+ b_{1,ijkl}\, (\bar{L}_i \gamma_\mu L_i)(\bar{L}_k \gamma^\mu L_l) + b_{2,ij}\, (\bar{L}_i \gamma_\mu L_i)(\bar{E}_j \gamma^\mu E_j)$$
$$+ b_{3,ij}\, (\bar{E}_i \gamma_\mu E_i)(\bar{E}_j \gamma^\mu E_j) + \ldots$$
$$+ b_{L\tau Q,ij}\, (\bar{L}_i \gamma_\mu \tau^a L_i)(\bar{Q}_j \gamma^\mu \tau^a Q_j) + b_{LQ,ij}\, (\bar{L}_i \gamma_\mu L_i)(\bar{Q}_j \gamma^\mu Q_j)$$
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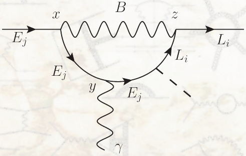
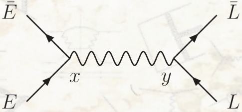
$$+ b_{Ed,ij}\, (\bar{E}_i \gamma_\mu E_i)(\bar{d}_j \gamma^\mu d_j) + \ldots$$





2. Step: After EWSB

Changing to the 'broken' phase

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

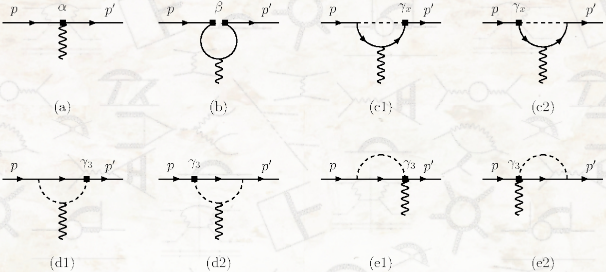
gives

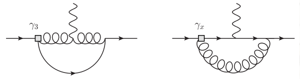
$$\begin{aligned}\sum_i C_i \mathcal{O}_i \to\ & \frac{\alpha_{ij}+\alpha_{ij}^\star}{2} \frac{v}{\sqrt{2}} \bar{\psi}_i \sigma_{\mu\nu} \psi_j F^{\mu\nu} + \frac{\alpha_{ij}-\alpha_{ij}^\star}{2i} \frac{v}{\sqrt{2}} \bar{\psi}_i \sigma_{\mu\nu} i\gamma_5 \psi_j F^{\mu\nu} \\ & + \beta_{ijkl} (\bar{\psi}_i \gamma^\mu P_L \psi_j)(\bar{\psi}_k \gamma_\mu P_R \psi_l) \\ & + \gamma_{1,ij} \frac{v}{2} (\bar{\psi}_i P_L \gamma_\mu \psi_j)(i\partial^\mu H) + [\gamma_{2,ij}+\gamma_{3,ij}] \frac{v}{2} (\bar{\psi}_i P_R \gamma_\mu \psi_i)(i\partial^\mu H) \\ & + \gamma_{3,ij} \frac{v}{\sqrt{2}} (\bar{\psi}_i P_R \gamma^\mu \nu_i)(-i\partial_\mu \phi^-) + \gamma_{3,ij} \frac{v}{\sqrt{2}} (\bar{\psi}_i P_R \gamma^\mu \nu_i)(eA_\mu \phi^-) \\ & + \text{h.c. of previous line} + \ldots\end{aligned}$$

the Greek Wilson coefficients are Latin ones dressed with flavour rotation matrices

3.Step: Compute Observables

Example: $g-2$ & $\mu \to e\gamma$ correspond to the flavour conserving and violating part of





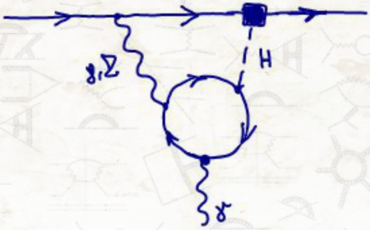
UV and IR divergences require regularisation

BUT finite due to $\frac{1}{\epsilon} \times \epsilon$

Scheme dependent $\to$ dependence must cancel with the dependence of the 5D loop in α

3.Step: Compute Observables

Example: $g-2$ & $\mu \to e\gamma$ also receive enhanced contributions at two loops

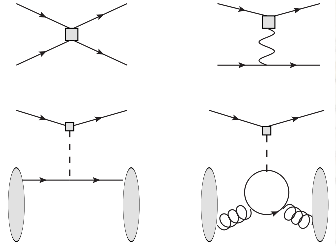


- Barr-Zee type contributions
- arise from FCNC Higgs couplings (effect on $g-2$ negligible)
- effect on e.g. $\mu \to e\gamma$ studied

Chang, Hou, Keung '93

3.Step: Matching from effective theory onto effective theory

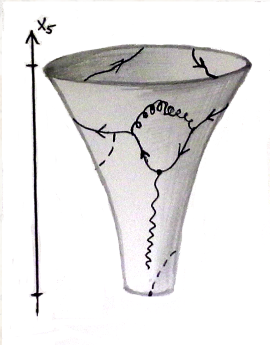
Example: $\mu \to e$ & $\mu \to 3e$



- computation straightforward
- must include insertions of the flavour-changing dipole that also mediates $\mu \to e\gamma$ (same order in the $1/T$ counting)

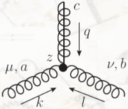
So all we need is …

Wilson Coefficents



- treat RS as (non-renormalisable) QFT in 5D
  derive Feyman rules for 5D theory [Randall & Schwartz 2001]
  for the moment we do not consider metric fluctuations

- vertices are simple, e.g.



$$-i\frac{1}{kz}\, g_5\, \epsilon^{abc}\, \eta_{\mu\nu} \left(\partial_z|_{\text{on `a'}} - \partial_z|_{\text{on `b'}} \right)$$

- propagators are only treated in Fourier space in the flat directions
  $\rightarrow$ mixed representation
  $\rightarrow$ each vertex is accompanied by an integral over the fifth dimension

5D Formalism

- work in a 5D QFT
  no KK sums; vertices and propagators are five dimensional [Randall, Schwartz, 2001]
- zero-mode ($\sim$ SM fields) must be separated explicitly

$$f_L^{(0)}(z) = \sqrt{\frac{1-2c_L}{1-\epsilon^{1-2c_L}}}\sqrt{T}(kz)^2(Tz)^{-c_L} \qquad g_E^{(0)}(z) = \sqrt{\frac{1+2c_E}{1-\epsilon^{1+2c_E}}}\sqrt{T}(kz)^2(Tz)^{c_E}$$

- 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 fifth dimension, e.g.
  conventions follow Csaki 2010 v1-v6

$$\left[\frac{1}{kz}\right]^4 \mathcal{D}\Delta_L(p,z,z') = i\delta(z-z')\mathbb{1} \qquad \mathcal{D} = \not{p} + i\Gamma^5\left(\partial_z - \frac{2}{z}\right) - \frac{c_L}{z}$$

$$\Delta_L(p,z,z') = -\underbrace{P_L F_L^+(p,z,z')\not{p}P_R}_{\text{contains to-be SM field}} - P_R F_L^-(p,z,z')\not{p}P_L$$
$$+\underbrace{P_L d^+ F_L^-(p,z,z')P_L + P_R d^- F_L^+(p,z,z')P_L}_{\sim\text{mass term}}$$

5D Formalism

- exact solution in the unbroken phase

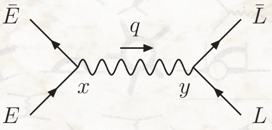
$$F_L^+(p,x,y) = \Theta(x-y)\,\frac{ik^4 x^{5/2} y^{5/2} \tilde{S}_+(p,x,1/T,c_L)\tilde{S}_+(p,y,1/k,c_L)}{S_-(p,1/T,1/k,c_L)} + \Theta(y-x)\,\frac{ik^4 x^{5/2} y^{5/2} \tilde{S}_+(p,y,1/T,c_L)\tilde{S}_+(p,x,1/k,c_L)}{S_-(p,1/T,1/k,c_L)}$$

$$S_\pm(p,x,y,c) = I_{c\pm 1/2}(px)K_{c\pm 1/2}(py) - K_{c\pm 1/2}(px)I_{c\pm 1/2}(py)$$

$$\tilde{S}_\pm(p,x,y,c) = I_{c\pm 1/2}(px)K_{c\mp 1/2}(py) + K_{c\pm 1/2}(px)I_{c\mp 1/2}(py)$$

- similar expressions for the different boson propagators

Tree-level coefficients are 'for free'



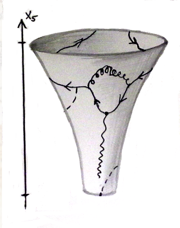
$$b_{ij} = -i(-g_5')^2 \frac{Y_L Y_E}{4} T^2 \int_{1/k}^{1/T} \mathrm{d}x\, \mathrm{d}y \frac{{f_{L_i}^{(0)}}^2(y)}{(ky)^4} \frac{{g_{E_j}^{(0)}}^2(x)}{(kx)^4} \Delta_\perp(q=0,x,y)$$

the hypercharge boson zero-momentum propagator is

$$\Delta_\perp(q,x,y) \overset{q\to 0}{=} \Theta(x-y) \frac{ik}{\ln\frac{k}{T}} \left(-\frac{1}{q^2} + \frac{1}{4} \left\{ \frac{1/T^2 - 1/k^2}{\ln\frac{k}{T}} - x^2 - y^2 + 2x^2 \ln(xT) + 2y^2 \ln(yT) + 2y^2 \ln\frac{k}{T} \right\} + \mathcal{O}(q^2) \right) + (x \leftrightarrow y),$$

all integrals are elementary
very similar to computation of $\Delta F = 2$ tree-level processes
$\hookrightarrow$ agrees with KK sum calculation [Casagrande et al. 2008]

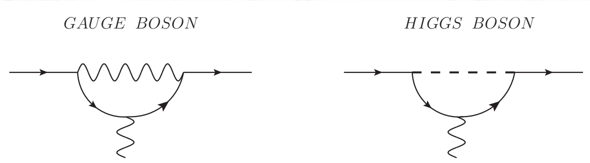
So all we need is . . .



the dipole operator(s) $\cos\Theta_W a^B - \sin\Theta_W a^W$

$$\mathcal{L} \supset a^B \bar{L}\Phi\, \sigma_{\mu\nu} B^{\mu\nu}\, E + a^W \bar{L}\Phi\, \tau^A \sigma_{\mu\nu} W_A^{\mu\nu}\, E$$

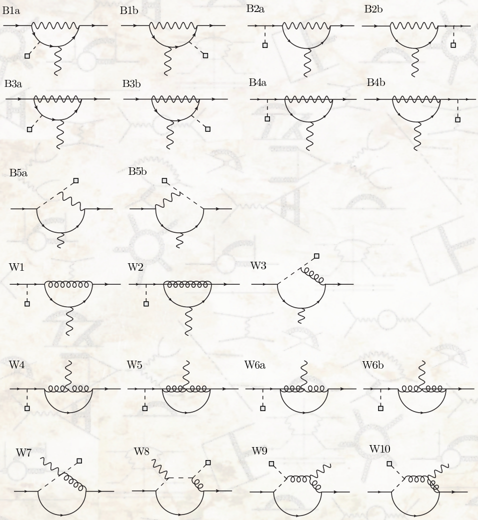
- actual 5D loop with different particle species in the loop
- two (3?) different diagram classes



one Yukawa interaction to contribute to $\bar{L}\Phi\, \sigma \cdot F\, E$

three Yukawa interactions to contribute to $\bar{L}\Phi\, \sigma \cdot F\, E$

Dipole operator matching–gauge part



- in external line put Φ in vev, and take the superposition of B and W^3 corresponding to the photon

$\leftarrow$ diagrams in minimal model

- in the custodial model there are 24 non-abelian diagrams and 23 abelian diagrams in 15 distinct topologies

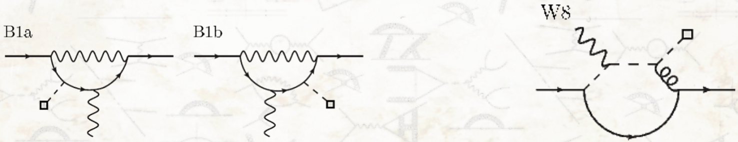
gauge part – extraction the short-distance contribution

There are three different contributions from each diagram
$\hookrightarrow$ identify à la expansion by regions Beneke, Smirnov '97

(1) the SM corrections; all 5D propagators propagate the zero mode. The loop integral does not contain the short-distance scales T, k explicitly, and is **purely** long-distance

needs to be eliminated by subtraction of the zero-mode from **one** gauge boson propagator

(2) contributions from momentum scales $l \ll T$, at least one of the 5D propagators propagates a KK mode. One-loop long-distance matrix element of tree insertion of four-fermion and fermion-Higgs operator.



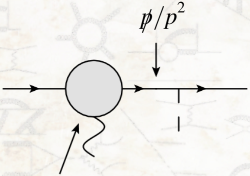
(3) The short-distance contribution: loop momentum of order $l \sim T$ (or k)

expand in external fermion momenta p, p' to linear/quadratic order eliminates region (2) since the denominator no longer contains long-distance scales

gauge part – remarks

off-shell terms

- non-1PR diagrams are necessary!
- obvious if external leg propagates a massive particle →short distance effect
- but even if the particle is on-shell (mass-less mode) the diagram is relevant
- known from B physics → matching of power-suppressed heavy-to-light SCET currents



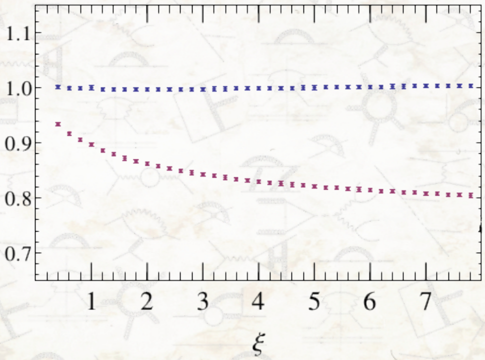
$$\Lambda^\mu = \Lambda^\mu + \not{p}\Lambda_1^{off,\mu} + \Lambda_2^{off,\mu}\not{p}'$$

- after cancelling the propagator the off-shell vertex-function is part of the short-distance coefficient

gauge part – remarks

gauge invariance

- calculation done for general 5d gauge parameter ξ
- one can show analytically that the set of 21 1-loop diagrams is gauge invariant (three gauge invariant subsets) Beneke, Moch, JR 2014



- other checks: scheme independence (naive γ_5 vs general scheme), all integrals can be solved analytically in certain limits (e.g. large loop-momentum)

gauge part – remarks

anapole moment

Most general $U(1)_{\text{em}}$ invariant vertex function for on-shell fermions:

$$\Gamma^\mu(p,p') = ieQ_\mu \bar{u}(p',s')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}}{2m_\ell} q_\nu F_2(q^2) + \frac{i\sigma^{\mu\nu}}{2m_\ell} q_\nu \gamma_5 F_3(q^2) \right.$$
$$\left. + \left(q^2\gamma^\mu - \not{q}q^\mu\right)\gamma^5 F_4(q^2)\right] u(p,s)$$

- F_1 — charge form factor;
- $a_\mu = (g-2)_\mu/2 = F_2(0)$
- F_3 — EDM from factor
- F_4 — anapole moment, $SU(2)\times U(1)_Y$ gauge dependent Musolf, Holstein, 1991
  $\not{q}q^\mu\gamma_5 \to 2m_\mu q^\mu \gamma_5$

The $L[\ldots]EF^{\mu\nu}$ vertex contains both $(p+p')^\mu P_R$ and $(p-p')^\mu P_R$. The latter is associated with the anapole moment.
consistency check (analytical even in RS) coefficient of $(p-p')^\mu P_R$ must be proportional to m_ℓ.

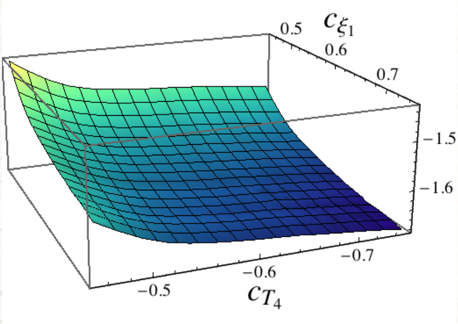
gauge part – result

- general structure of the gauge diagram contibution with full flavour dependence

$$a_{ij}^{gauge} = ieQ_\mu \frac{\alpha_{em}}{4\pi}\frac{1}{T^2} \times \mathrm{Loop}(c_{L_i}, c_{E_j}) \cdot \log\frac{k}{T} \cdot \underbrace{f_{L_i}^{(0)}(1/T)\, Y_{ij}\, g_{E_j}^{(0)}(1/T)\frac{T^3}{k^4}}_{=M_{ij}}$$

- $\mathrm{Loop}(c_{L_i}, c_{E_j})$ (here for csRS, RS min is even less sensitive)

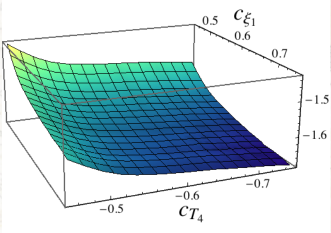
Moch, JR 2014



$\rightarrow$ expect contribution to $g-2$ to be independent of the Yukawa structure & FCNCs are suppressed

Phenomenology and Results (gauge part)

- a_{ij}^{gauge} relative to the mass matrix



$$a_{ij}^{gauge} = \text{Const} \times \text{Loop}(c_{L_i}, c_{E_j}) \cdot M_{ij}$$

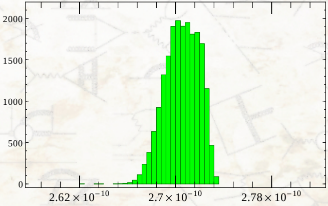
$\hookrightarrow$ supressed FCNCs

- $g_\mu - 2$

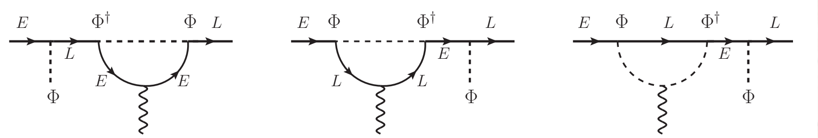
$$\Delta a_\mu^{gauge} = 27.2(8.8) \cdot 10^{-11} \frac{1\ \text{TeV}^2}{T^2}$$

compared to

$$a_\mu^{exp} - a_\mu^{the} = 287(63)(49) \times 10^{-11}$$



Dipole operator matching– Higgs part



- subtlety: a brane localised Higgs should be described as having a delta-function-like profile

$$\delta(z - 1/T) = \lim_{\delta \to 0} \frac{T}{\delta} \Theta(z - \frac{1-\delta}{T}).$$

$\rightarrow$ limit of a distribution of width δ/T for $\delta \to 0$
$\rightarrow$ introduces an additional large scale $\frac{T}{\delta}$ for any finite value

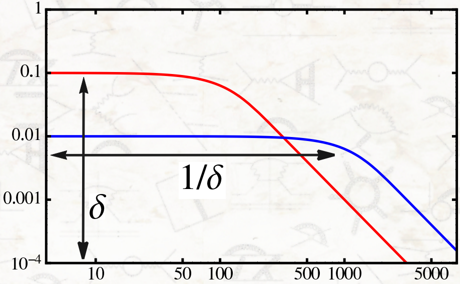
- BUT we also have a dimensional regulator $\rightarrow \epsilon \rightarrow 0$ before or after $\delta \rightarrow 0$?

Dipole operator matching– Higgs part

- answer both options are valid part of the RS model

Beneke, Moch, JR & Malm et al.

- the order of limits determines if the Higgs can be resolved or not



- simple answer (minimal RS):

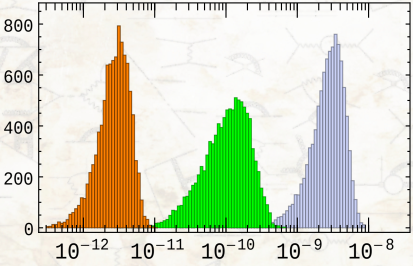
$$\begin{aligned}\Delta a_{ij} = \; & (iQ_\mu e) \times \frac{1}{6} \times \frac{1}{16\pi^2}\frac{1}{T^2} \times f_{L_i}^{(0)}(1/T)[YY^\dagger Y]_{ij}\, g_{E_j}^{(0)}(1/T)\frac{T^3}{k^4} \\ & + (iQ_\mu e)\frac{1}{192\pi^2} \times f_{L_i}^{(0)}(1/T) Y_{ik}\, iF^-_{E_k}(0,1/T,1/T) Y^\dagger_{kh} {f^{(0)}_{L_h}}^2 (1/T) Y_{hj}\, g^{(0)}_{E_j}(1/T) \\ & + (iQ_\mu e)\frac{1}{192\pi^2} \times f_{L_i}^{(0)}(1/T) Y_{ik}\, {g^{(0)}_{E_h}}^2(1/T) Y^\dagger_{kh}\, iF^+_{L_h}(0,1/T,1/T) Y_{hj}\, g^{(0)}_{E_j}(1/T)\end{aligned}$$

Phenomenology— $g-2$

- gauge diagram contribution is independent of all model parameters (only overall scales T, k matter)

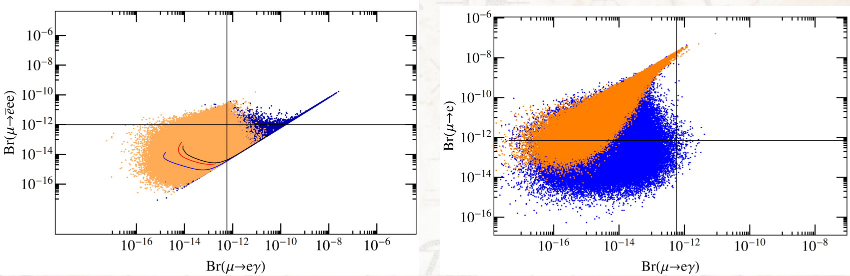
$$\Delta a_\mu \approx 27 \times 10^{-11} \frac{1\ \mathrm{TeV}^2}{T^2}$$

- Higgs contribution depends on the Yukawa size
  $\to$ smaller than gauge contribution for Yukawas < 1
  $\to$ but can reach $1 \cdot 10^{-9}$ for $Y^{>} = 3$.



Phenomenology—minimal model

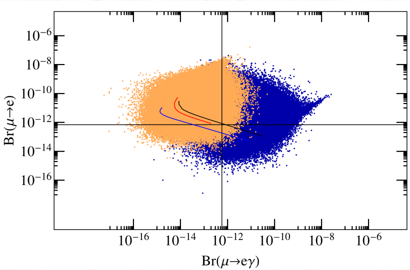
- $\mu \to e\gamma$ and $\mu \to 3e$ ($T = 8$ TeV)

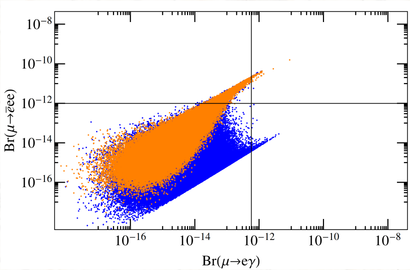


- dipole boundary ($\mu \to 3e$ dominated by dipole operate)
- in general both tree-level operators (Higgs-fermion and four-fermion) and 5D dipoles are important (esp. in the more natural bulk Higgs case tree-approximation [used in all RS analyses up to now] does not work)
- gauge-contributions prevent reducing $\mu \to e\gamma$ by just changing the Yukawa magnitude

Phenomenology—minimal model

- $\mu \to e\gamma$ and $\mu \to e$ ($T = 8$ TeV)

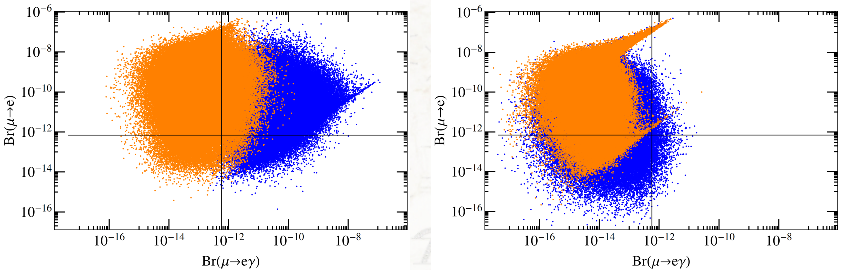




- essentially no correlations → genuinely “orthogonal” constraints

Phenomenology—custodial model

- $\mu \to e\gamma$ and $\mu \to e$ conversion ($T = 8$ TeV)



Agashe et al. 2006

- Yukawa size cannot help to escape bounds
- next generation experiments can rule out the parameters space $m^{(1)}_{gluon} < 20$ TeV
- one can invent flavour symmetries to avoid bounds, but it is quite hard to avoid all bounds (different operators contribute differently)

Comparisons

- Davoudiasl, Hewett, Rizzo [hep-ph/9911262]
  - + KK sums
  - + dropped external insertion and half the internal ones
  - + Higgs diagrams appear when they should not
  - + subset of abelian diagrams remains
  - + similar order of magnitude but negative sign
- Csaki, Grossman, Tanedo, Tsai [hep-ph/1004.2037]
  - + 5D calculation but no matching onto the effective lagrangian
  - + depending on version without external Higgs insertions
  - + fixed gauge
  - + extracts dominant contributions

Comparisons

- K. Agashe, A. E. Blechman and F. Petriello, [hep-ph/0606021]
  - \+ studies all LFV muon observables
  - \+ only Higgs loop-diagrams
  - \+ consider radiative transition for bulk Higgs
  - \+ do not include loop contributions to $\mu \to e$, $\mu \to 3e$
  - \+ general conclusions ✓
  - \+ first to find that Yukawa size cannot be used to evade bounds
  - ▸ first to mention wrong chirality couplings

Summary

- complete computation of the leptonic dimension-six Wilson coefficients including the dipole operators without approximations
- without imposing very specific flavour structures the new experiments will rule out KK modes in excess of 20 TeV
- 'gauge' corrections to $g-2$ is model independent (like S and T parameter) but too small to help
- Higgs contribution is doubly model-dependent
- unmentioned: dimension-eight contributions, gravity, electric dipole moments, ...