Radion Mediated Flavor Changing Neutral Currents

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In the context of a warped extra-dimension with Standard Model fields in the bulk, we obtain the general flavor structure of the Radion couplings to fermions and show that the result is independent on the particular nature of the Higgs mechanism (bulk or brane localized). These couplings will be generically misaligned with respect to the fermion mass matrix when the fermion bulk mass parameters are not all degenerate. When the Radion is light enough, the generic size of these tree-level flavor changing couplings will be strongly constrained by the experimental bounds on $\Delta F = 2$ processes. At the LHC the possibility of a heavier Radion decaying into top and charm quarks is then considered as a promising signal to probe the flavor structure of both the Radion sector and the whole scenario.

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Introducing a warped extra-dimension in such a way as to create an exponential scale hierarchy between the two boundaries of the extra dimension [1] has generated a lot of attention in the recent years as a novel approach to solve the hierarchy problem. By placing the Standard Model (SM) fermions in the bulk of the extra dimension it was then realized that one can simultaneously address the fermion mass hierarchy puzzle [2]. In this context the main constraints come from precision electroweak processes [3, 4, 5, 6], pushing the scale of new physics (the mass of the lowest KK excitations) to several TeV. In these scenarios, the metric fluctuations contain a scalar degree of freedom - the Radion, whose mass and couplings could make it the first new physics state to be discovered at the LHC. In the original RS1 setup [1], the Radion phenomenology was extensively studied and analyzed including the possibility of some amount of mixing with the Higgs scalar [7, 8, 9]. But it wasn’t until relatively recently [10, 11, 12] that Radion interactions with bulk SM fields were fully considered. In this letter we want to extend these last investigations to include the full fermion flavor structure to the Radion couplings and show that as opposed to the original RS1 scenario, there is a prediction for generic flavor violating Radion couplings to fermions. The spacetime we consider takes the usual Randall-Sundrum form [1]:

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2), \quad (1)$$

with the UV (IR) branes localized at $z = R$ ($z = R'$). The Radion can be parametrized by the following scalar perturbation of metric:

$$ds^2 = \left(\frac{R}{z}\right)^2(e^{-2F}\eta_{\mu\nu}dx^\mu dx^\nu - (1 + 2F)^2dz^2) \quad (2)$$

Demanding that the perturbed metric solves the Einstein equation and that the Radion field is canonically normalized, we get

$$F = \frac{r(x)^2}{\Lambda_r R^2} \quad (3)$$

where $r(x)$ is the corresponding canonically normalized Radion graviscalar with its associated interaction scale $\Lambda_r = \sqrt{\frac{M_{Pl}}{r_0}}$. We assume that some unknown dynamics (e.g. the Goldberger-Wise mechanism [13]) will fix the inter-brane distance and give a positive mass squared to the Radion, and that it gives negligible back-reaction to the metric. The couplings between bulk SM fermions and the Radion are calculated in [11] in the case of one generation, with a brane localized Higgs. We are interested here in the flavor structure of these couplings when all families of fermions are considered, and for the more general case of a 5D bulk Higgs $H$ [14]. To this end let us focus on the up-sector of the simple setup in which we consider the 5D fermions $Q_i$, $U_i$, with flavor indices $i, j = 1, 2, 3$. They contain the 4D SM $SU(2)_L$ doublet and singlet fermions respectively with a 5D action

$$S_{\text{fermion}} = \int d^4x dz \sqrt{g} \left[ \frac{1}{2}(\bar{Q}_i\Gamma^A D_A Q_i - D_A \bar{Q}_i\Gamma^A Q_i) + \frac{c_0}{R} \bar{Q}_i Q_i + (Q \rightarrow U) + \left( Y_{ij} \sqrt{R} \bar{Q}_i H U_j + h.c. \right) \right] \quad (4)$$

where $\frac{1}{\sqrt{R}}, \frac{c_0}{R}$ are the 5D fermion masses, and we choose to work in the basis where they are diagonal in 5D flavor
space. The bulk Higgs acquires a nontrivial VEV \( v(z) \) localized towards the IR brane solving the Planck-hierarchy problem. Note that the special case of brane-localized Higgs case can be treated as a limit of the bulk Higgs case. After writing the 5D fermions in two component notation, \( Q_i = (Q_{L}^{i}, Q_{R}^{i}) \) and \( U_i = (U_{L}^{i}, U_{R}^{i}) \), we perform a “mixed” KK decomposition as
\[
\begin{align*}
Q_{L}(x, z) &= Q_{L}^{ij}(z) q_{L}^{i}(x) + \cdots, \quad (5) \\
Q_{R}(x, z) &= Q_{R}^{ij}(z) q_{R}^{i}(x) + \cdots, \quad (6) \\
U_{L}(x, z) &= U_{L}^{ij}(z) U_{L}^{i}(x) + \cdots, \quad (7) \\
U_{R}(x, z) &= U_{R}^{ij}(z) U_{R}^{i}(x) + \cdots, \quad (8)
\end{align*}
\]
where we have only written the 4D SM fermions \( q_{L}^{i}(x) \) and \( u_{R}^{i}(x) \) and where \( Q_{L,R}^{ij}(z) \) and \( U_{L,R}^{ij}(z) \) are the corresponding profiles along the extra dimension. The fields \( q_{L}^{i}(x) \) and \( u_{R}^{i}(x) \) verify the Dirac equation
\[
\begin{align*}
-\bar{\psi}_{i} \gamma^{\mu} \partial_{\mu} \psi_{i} + m_{ij} \bar{u}_{i}^{j} &= 0, \\
-\bar{\psi}_{i} \gamma^{\mu} \partial_{\mu} \psi_{i} + m_{ij} \bar{q}_{i}^{j} &= 0,
\end{align*}
\]
with the 4D SM fermion mass matrix \( m_{ij} \) not necessarily diagonal in flavor space. The couplings between Radion and SM fermions can be calculated by inserting the perturbed metric of Eq. (2) and the 5D fermion KK decompositions of Eqs. (5-8) into the action of Eq. (4). To proceed we used a perturbative approach treating the 4D fermion masses \( m_{ij} \) as small expansion parameters (i.e. we assumed \( m_{ij}/R' \ll 1 \) keeping only first order terms. In this limit, the profiles \( Q_{L}^{ij}(z) \) and \( U_{L}^{ij}(z) \) match the simple wave-functions for massless zero-modes. No other explicit profile solution is required since we just need to properly insert and use the KK extra dimensions for \( Q_{L}^{ij}(z) \) and \( U_{L}^{ij}(z) \) into Eq. (4). A subtlety however is that the 5D bulk Higgs field perturbation contains itself some Radion dependence on \( \mathcal{H}(x, z) = v(z) - \frac{z^{2}v'(z)}{R'^{2}} \left[ 1 - \left( \frac{R'}{z} \right)^{2} \right] \frac{r(x)}{\Lambda_{r}} + \cdots \) (11)
where the \( \cdots \) contain the 4D light Higgs and the rest of the Higgs KK modes. This result gives an additional contribution to the Radion coupling to fermions. It is possible to show that the general formula for the Radion coupling to SM fermions is
\[
\begin{align*}
\mathcal{H}(x, z) &= v(z) - \frac{z^{2}v'(z)}{R'^{2}} \left[ 1 - \left( \frac{R'}{z} \right)^{2} \right] \frac{r(x)}{\Lambda_{r}} + \cdots \tag{11}
\end{align*}
\]
where we have defined
\[
\mathcal{I}(c) = \left[ \frac{1}{2} - c \right] / \left( 1 - (R/R')^{1-2c} \right) + c \approx \begin{cases} 
1 & (c > 1/2) \\
\frac{1}{2} & (c < 1/2)
\end{cases} \tag{13}
\]
For one generation of fermions, this result agrees with the formulae obtained in [11] and it can also be understood from the following intuitive argument. When the 4D SM fermion mass is generated near the IR brane, its dependence on \( \frac{1}{R} \) is
\[
m_{ij} \propto f(c_{q_{i}})f(-c_{u_{j}}) \frac{R}{R'} \tag{14}
\]
with \( f(c) \) proportional to the zero mode wavefunction of the fermions evaluated at IR brane
\[
f(c) = \sqrt{\frac{1 - 2c}{1 - (R/R')^{1-2c}}} \tag{15}
\]
Since the Radion is basically a fluctuation of the IR brane location, its couplings with SM fermions can also be obtained by replacing \( \frac{1}{R} \rightarrow \frac{1}{R}(1 - \frac{1}{R}) \) in the fermion mass matrix [11]. Then it is easy to check that we reproduce the result of Eq. (12). Non-universalities in the term \( \mathcal{I}(c_{q_{i}}) + \mathcal{I}(-c_{u_{j}}) \) will lead to a misalignment between the Radion couplings and the fermion mass matrix. After diagonalization of the fermion mass matrix, flavor violating couplings will be generated and can be parametrized as
\[
\mathcal{L}_{FV} = \frac{r}{\Lambda_{r}} (\bar{u}_{L}^{i} u_{R}^{i} a_{ij} \sqrt{m_{i} m_{j}} + h.c.) \quad (i \neq j) \tag{16}
\]
where \( u^{i} \) are the quark mass eigenstates with masses \( m_{i} \). The extension to the down quark sector and charged leptons is immediate.

To study the consequences of this result, we will consider models with flavor anarchy i.e. where all the hierarchies in the fermion sector are explained by the warped factors and all 5D Lagrangian parameters are of the same order [5]. In this class of models the natural size of \( a_{ij} \) is
\[
a_{ij} \sim (\Delta \mathcal{I}_{ij}) \sqrt{\frac{f(c_{q_{i}})f(-c_{u_{j}})}{f(c_{q_{i}})f(-c_{u_{j}})}} \tag{17}
\]
where \( \Delta \mathcal{I}_{ij} \sim O(0.1)^{2} \) is the deviation of \( \mathcal{I}(c_{q_{i}}) + \mathcal{I}(-c_{u_{j}}) \) from its mean value. We perform a scan over the 5D fermion masses and “ anarchical” Yukawa couplings leading to the observed SM fermion masses and CKM mixing angles and obtain a distribution for the parameters \( a_{ij}^{2} \). For example, the average values of the parameter \( a_{12}^{2} \) and \( a_{21}^{2} \) are of order \( \sim 0.07 \) and 70% of the time they are distributed between

\[1\] This will remain true in the presence of fermion brane kinetic mixings although the flavor structure of Eq. (12) will be modified.

\[2\] This estimate is only valid for models that explain the Planck weak hierarchy. But for little RS models, the deviation could be a few times larger.
FIG. 1: Bounds in the $(m_r - \Lambda_r)$ plane coming from $\epsilon_K$ for different values of the flavor violating parameter $a_{ds} = \sqrt{|a_{21}^d a_{21}^s|}$. In flavor anarchy models, typical values for $a_{21}$ range between 0.03 and 0.12. In Little RS the parameter can reach values a few times larger. One can relate the scale $\Lambda_r$ to the mass of the lightest KK gluon as $M_1^{KKG} \approx \Lambda_r/(M_{Pl} R)$, as shown on the RHS of the figure.

0.03 < $a_{12}^d$, $a_{21}^d < 0.12$. The average value of the parameter $a_{23}^d(a_{32}^s)$ are ~ 0.08(0.05) and 70% of the times they are between 0.03 < $a_{23}^d < 0.13$ (0.01 < $a_{32}^s < 0.09$).

The first thing to study is how constrained are the Radion parameters due to low energy observables such as $\Delta F = 2$ processes. The processes mediated by virtual Radion exchange will have the following flavor structure

$$ q_i^\alpha L_j^\beta \bar{q}_k^\alpha R_q^\beta $$  

(18)

$\alpha, \beta$ are color indices and $i, j, k, n$ are flavor indices. One can see that this interaction can be parametrized by standard $Q_2, Q_4$ operators (see for example [15]). The strongest constraints will come from $\epsilon_K$; and the model independent constraint on the size of new physics contributions to the imaginary part of the Wilson coefficient $C_{4KK}$, renormalized at the scale 50 GeV, is $\text{Im} C_4 \lesssim 1.2 \times 10^{-3} \text{ TeV}^{-2}$ [11]. From Eq. (16) it is easy to compute the contribution from a tree-level Radion exchange as $\text{Im}(C_{4}^{\text{Radion}}) \approx m_d m_s \text{Im}(a_{12}^d a_{21}^s)/(\Lambda_r^2 m_2^2)$ and therefore the experimental bound requires that $a_{ds}/(\Lambda_r m_r) < 0.44 \text{ TeV}^{-2}$, where we define $a_{ds} \equiv \sqrt{|a_{21}^d a_{21}^s|}$ and assume order one phase. In Fig. 1 we show the bounds for different values of $a_{ds}$ in the $(m_r, \Lambda_r)$ plane. The scale $\Lambda_r$ is directly related to the lightest KK gluon mass by $M_1^{KKG} \approx \Lambda_r/(M_{Pl} R)$, and so one can easily convert bounds on the KK mass into bounds on $\Lambda_r$. It is also interesting to note that the bounds from flavor physics give strong constraints for a very light Radion, precisely the hardest possibility to probe at the LHC due to its dominant hadronic decay channels. A light Radion with flavor violating couplings can also become a top quark decay product, in processes such as $t \rightarrow rc$ or $t \rightarrow ru$, where $u$ and $c$ are the up and charm quarks. We have checked that, due to the suppressed couplings coming from $\Lambda_r$, this signal [19] will not be visible at the LHC unless the flavor violating parameters $a_{13}$ or $a_{34}$ take unnaturally large values ($O(1)$).

For a heavier Radion ($\gtrsim 200$ GeV), the most promising discovery channel would be $r \rightarrow ZZ \rightarrow 4f$ due to its clean signal. Translating the LHC Higgs Search analysis [20] into Radion LHC reach, one finds that both CMS and ATLAS should separately be able to claim discovery for $\Lambda_r \lesssim 5$ TeV with 30 fb$^{-1}$ of data [22]. To study the flavor structure of such a heavy Radion, we consider the channel $r \rightarrow tl\bar{t}$ (see for example [21] in top-condensation models). We define $a_{tc} \equiv \sqrt{(a_{21}^d)^2 + (a_{32}^s)^2}/2$ to parametrize the flavor violating coupling between Radion and top charm. The signal we focus on is $pp \rightarrow tl\bar{t} \rightarrow b\bar{c}l\bar{c}$ (where $l$ stands for electrons and muons). And the main backgrounds are: (i) $pp \rightarrow tj \rightarrow bl\bar{v}j$; (ii) $pp \rightarrow Wj j \rightarrow l\nu j\bar{j}$, where one of the light jet is mistagged as b quark; (iii) $pp \rightarrow Wb b \rightarrow b\bar{b}\nu\bar{c}$, where one of the b jet is mistagged; (iv) $pp \rightarrow ft \rightarrow b\bar{l}+\nu\bar{b}\bar{l}+\bar{v}$ where one b jet is mistagged and one of the charged lepton is lost in beam pipe ($|y_l| > 2.5$) or it is merged with one of the jets ($\Delta R_{ij} < 0.6$). We use CalcHEP [23] and PYTHIA 2.6 [24] to obtain both signal and background cross sections and estimate the potential LHC reach for this signal. For this we fix the Radion interaction scale to $\Lambda_r = 2$ TeV, and use three different values for its mass, $m_r = 250, 300$ and 350 GeV. We impose lepton and jet acceptance cuts on transverse momenta $p_T > 20$ GeV, on rapidities, $|y_{jl}| < 2.5$, and on angular separation $\Delta R_{ij} > 0.6$ and $\Delta R_{jj} > 0.6$. We assume that neutrino momentum can be reconstructed. We demand additionally that the total event’s invariant mass reconstructions to the Radion’s mass $M_{bluj} \in (m_r - 5$ GeV, $m_r + 5$ GeV), and that the $bl\nu$ invariant mass reconstructions to the top mass $M_{bl\nu} \in (170$ GeV, $180$ GeV). We also tighten the rapidity cut on the light jet, $|y_j| < 1.5$. We assume that the Radion would have been discovered through $r \rightarrow ZZ$ channel and thus measured its mass $m_r$. Because the Radion decay width is extremely small ($\Gamma_r < 0.15$ GeV in this mass range), the window to use for the total invariant mass is controled by the experimental jet energy resolution (we used a window of $\pm 5$ GeV). The results are shown in Table 1. As noted in [12], a small amount of Higgs-Radion mixing [7], parametrized by the Lagrangian parameter $\xi$, can dramatically reduce the principal Radion decay channels. This could then enhance secondary decay channels, such as $r \rightarrow \gamma\gamma$, and in this case $r \rightarrow tl\bar{t}(c\bar{c})$. In Fig. 2 we plot contours for

\footnote{We used the RG equations in [18]. Constraints on the coefficient $C_2$ are weaker by a factor of five and the bounds from $B_d$ mixing are weaker by an order of magnitude, so we ignored them in the present analysis.}
the LHC reach in the \((a_{tc} \text{ vs. } \xi)\) plane, for \(m_r = 250\) GeV and different values of \(\Lambda_r\). We can see that at least for some ranges of \(\xi\), the LHC should be able to probe typical values of \(a_{tc}\) in flavor anarchy model. Of course a more realistic study of this signal should be carried out, including a full detector simulation as well as the hadronic decay mode of the intermediate W boson.

| \(m_r\) | 250 GeV | 300 GeV | 350 GeV |
|--------|---------|---------|---------|
| Signal | \(a_{tc}^2 \times 21\, fb\) | \(a_{tc}^2 \times 15\, fb\) | \(a_{tc}^2 \times 9\, fb\) |
| Background | 280 fb | 199 fb | 136 fb |

TABLE I: Signal and background for different Radion masses with \(\Lambda_r = 2\) TeV (and no Higgs-Radion mixing). We multiplied by a K-factor of 2.4 for the signal, to account for QCD corrections in the Radion production from gluon fusion.

In this letter we derived the general flavor structure of the Radion couplings to bulk fermions, and showed that the same result holds for both bulk and brane Higgs scenarios. The SM fermion masses and Radion couplings will be misaligned when the 5D fermion bulk mass parameters are non-degenerate. This will then lead to FCNC's that the same result holds for both bulk and brane Higgs of the Radion parameter space could be probed, gaining very valuable information on the flavor substructure of the whole model.

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FIG. 2: Contours in the \((\xi - a_{tc})\) plane of the estimated signal significance \(S/\sqrt{B} = 3\) for the process \((pp \rightarrow r \rightarrow tc)\) at the LHC for 300 fb\(^{-1}\) of data. \(\xi\) is the Higgs-Radion mixing parameter and \(a_{tc}\) is the flavor violating parameter which gives rise to the Radion coupling to top-charm.

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