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# Collider Signals of Top Quark Flavor Violation from a Warped Extra Dimension

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## Abstract

We study top quark flavor violation in the framework of a warped extra dimension with the Standard Model (SM) fields propagating in the bulk. Such a scenario provides solutions to both the Planck-weak hierarchy problem and the flavor puzzle of the SM without inducing a flavor problem. We find that, generically,  $tcZ$  couplings receive a huge enhancement, in particular the right handed ones can be  $\mathcal{O}(1\%)$ . This results in BR ( $t \rightarrow cZ$ ) at or above the sensitivity of the Large Hadron Collider (LHC). At the International Linear Collider (ILC), single top production, via  $e^+e^- \rightarrow t\bar{c}$ , can be a striking signal for this scenario. In particular, it represents a physics topic of critical importance that can be explored even with a relatively low energy option, close to the  $tc$  threshold. At both the LHC and the ILC, angular distributions can probe the above prediction of dominance of right-handed couplings.

**Introduction.** In a few years, the Large Hadron Collider (LHC) is expected to unravel the mystery of electroweak symmetry breaking (EWSB) and also perhaps the mechanism of stabilizing the enormous hierarchy between the Planck and EWSB scales. Can this TeV-physics give us clues to the origin of flavors? The answer to this question depends on the scale of dynamics which mediates flavor physics,  $\Lambda_F$ . It is the top quark contributions to the Higgs mass squared which yield the most severe fine tuning within the SM due to large top mass. In almost any natural SM extension, therefore, the top quark is likely to have significant couplings to the new physics (NP) sector at TeV. Generic couplings of the NP sector to the light quarks are in tension with the constraints from flavor changing neutral currents (FCNC) processes which require the NP scale to be of  $\mathcal{O}(1000)$  TeV. However, in models which have a high  $\Lambda_F$ , the flavor structure in TeV scale physics is described entirely by the up and down Yukawa matrices – these models belong to the minimal flavor violation (MFV) framework [1]. Such a scenario is rather easily consistent with FCNC data even with TeV NP scale and on the flip side, it is difficult to obtain clues to the origin of flavors from the NP at TeV in this case.

However, references [2, 3] studied a different possibility that new sources of flavor and CP violation are present in the NP at TeV. It was shown that, as long as the NP dynamics respect the SM approximate flavor symmetries and is *quasi*-aligned (i.e., has at most CKM-like misalignment) with SM Yukawa matrices, such a low flavor scale is still allowed by the FCNC data. The corresponding framework was denoted as next to MFV (NMFV) [2]. Thus an exciting case is possible in which flavor violation arises from the same NP at TeV scale which is re-

lated to the solution of the hierarchy problem [2]. All of the precise data constraining this framework, available at present, is due to processes which involve down type quarks. However, the most direct way to test the above paradigm is via a careful study of the top couplings. For the first time such a test will be possible at the LHC since millions of top quarks will be produced per year. In particular we will mainly focus here on  $\Delta F = 1$  top FCNC processes related to  $t \rightarrow c$  transition which are highly GIM and CKM-suppressed within the SM, but yet are theoretically clean due to the fact that the top decays before being hadronized.

In this letter, we study one such scenario which combines solutions to the Planck-weak hierarchy and flavor puzzle, namely the Randall-Sundrum (RS1) framework of warped extra dimension [4]. We show that sizable  $tcZ$  coupling is induced which can lead to observable effects at both the upcoming LHC and at the proposed International Linear Collider (ILC).

The framework involves a slice of  $AdS_5$ . Due to the warped geometry, the relationship between the  $5D$  mass scales (taken to be of order the  $4D$  Planck scale) and those in an effective  $4D$  description depends on the location in the extra dimension. The  $4D$  (or zero-mode) graviton is localized near the “UV/Planck” brane which has a Planckian fundamental scale, whereas the Higgs sector is localized near the “IR/TeV” brane where it is protected by a warped-down fundamental scale of  $\sim$  TeV. This large hierarchy of scales can be generated via a modest-size radius of the extra dimension. Furthermore, based on the AdS/CFT correspondence [5], RS1 is conjectured to be dual to  $4D$  composite Higgs models [6].

In the RS1 model, the entire SM (including the

fermions and gauge bosons) are assumed to be localized on the TeV brane. Thus, it provides no understanding of the flavor puzzle. Moreover, the higher-dimensional operators in the 5D effective field theory (from cut-off physics) are suppressed only by the warped-down scale  $\sim \text{TeV}$ , giving too large contributions to FCNC processes and observables related to SM electroweak precision tests (EWPT).

An attractive solution to this problem is to allow the SM fields to propagate in the extra dimension [7, 8, 9]. In such a scenario, the SM particles are identified with the zero-modes of the 5D fields and the profile of a SM fermion in the extra dimension depends on its 5D mass parameter. We can then choose to localize 1st and 2nd generation fermions near the Planck brane so that the FCNC's from higher-dimensional operators are suppressed by scales  $\gg \text{TeV}$  which is the cut-off at the location of these fermions [9, 10]. As a bonus, we obtain a solution to the flavor puzzle in the sense that hierarchies in the SM Yukawa couplings arise without introducing hierarchies in the fundamental 5D theory [8, 9, 10]: the 1st/2nd generation fermions have small Yukawa couplings to Higgs which is localized near the TeV brane. Similarly, the top quark can be localized near the TeV brane to account for its large Yukawa.

In this scenario, there is a new source of FCNC's from the couplings of SM fermions to gauge KK modes since these couplings are non-universal due to the different profiles for the SM fermions. However, the gauge KK modes are localized near the TeV brane while the light fermions are near the Planck brane and hence it can be shown that the non-universal part of these couplings are proportional to the SM Yukawa couplings [9, 10]. Thus, most of the couplings to the NP degrees of freedom are small and hierarchical, leading to the same symmetry structure which suppresses the SM flavor-violating contributions [11]. This is in sharp contrast to similar models in a flat extra dimension which are problematic since they require the KK scale  $\gtrsim 1000 \text{ TeV}$  to satisfy FCNC constraints. Since the top Yukawa is large, we expect FCNC's involving top (and also its partner,  $b_L$ ) to be sizable, especially given that the KK scale must be a few TeV based on naturalness. The gauge KK modes also give contributions to EWPT: the constraints from the  $S$  and  $T$  parameters can be satisfied with KK mass scale as low as  $\sim 3 \text{ TeV}$  if a custodial isospin symmetry is incorporated [12].

Let us examine the top/bottom sector in detail. It is clear that both  $t_{L,R}$  being near the Planck brane gives too small top Yukawa. On the other hand,  $(t, b)_L$  being close to the TeV brane leads to its coupling to KK  $Z$  being large and, in turn, results in a non-universal shift in its coupling to the SM  $Z$  via mixing of KK  $Z$  with zero-mode  $Z$  [12]:  $\delta g_Z^{b_L} \sim g_{Z\text{KK}}^{b_L} \xi \frac{m_Z^2}{m_{\text{KK}}^2}$  where  $\xi \equiv \sqrt{\log(M_{\text{Pl}}/\text{TeV})}$  and  $g_{Z\text{KK}}^{b_L}$  is the corresponding non-universal KK  $Z$  cou-

pling. There is also a contribution from the exchange of KK modes of the extra  $U(1)$  arising from the extended 5D gauge symmetry; here and below “KK  $Z$ ” will represent both these effects. Such corrections to  $Z b_L b_L$  coupling can be suppressed by suitable choice of representation of top and bottom quarks under the custodial isospin symmetry [13], but in this paper we will consider models with the assignment of [12]. The constraint from data is that  $\delta g_Z^{b_L}/g_Z \lesssim 1/4\%$ . Thus, for few TeV KK scale, there is a tension between obtaining large top mass and EWPT (i.e.,  $Z b_L b_L$  coupling) which can be relaxed by the following setup: (i)  $(t, b)_L$  quasi-localized near TeV brane so that the shift in coupling of  $b_L$  to  $Z$  is on the edge, (ii)  $t_R$  localized very close to TeV brane to obtain large top quark mass and (iii) largest dimensionless 5D Yukawa,  $\lambda_{5D} \sim 4$ , consistent with perturbativity. Note that the resulting coupling of  $b_L$  to gauge KK modes (including gluon) is comparable to the SM couplings and thus is still larger than what is expected on the basis of  $m_b$  alone (since it is dictated by the large top mass instead). Thus, we obtain sizable flavor violation involving  $b_L$  which has been studied in [11, 14, 15] along with flavor violation in lepton and light quark sectors.

In the rest of this paper, we focus on *top* quark flavor violation since as mentioned above, it is likely to be sizeable and in a few years, the LHC will provide us a copious source of tops.

There is a non-universal shift in the coupling of  $t_R$  to  $Z$  as above, except that, due to its profile, the coupling of  $t_R$  to gauge KK modes is enhanced (just like those for the Higgs):  $g_{Z\text{KK}}^{t_R} \sim g_Z \xi$ . There is also a similar size effect from mixing (via the Higgs vev) of zero-mode  $t_R$  with KK  $t_L$  which then couples to the  $Z$  [16]:  $\delta g_Z^{t_R}|_{t_L^{\text{KK}}} \sim (\lambda_{5D} v/\sqrt{2})^2/m_{\text{KK}}^2$ . The shift in coupling of  $Z$  to  $t_L$  is the same as that for  $b_L$ , i.e., smaller.

There are also 4-fermion operators generated by the direct exchange of KK  $Z$ ,  $\gamma$ . We can use the fact that the coupling of light fermions (for example, the electron) to these KK modes is suppressed compared to the SM gauge couplings by  $\xi$  to obtain the coefficients of these operators. The coupling of the extra  $U(1)$  gauge bosons to light fermions is Yukawa suppressed and hence their exchange is negligible.

**Flavor violation.** The couplings discussed above are in the interaction basis. Flavor violation arises when we rotate to the mass basis. To determine these effects, we need to estimate the corresponding mixing angles.

We assume that the 5D Yukawas are anarchic so that the hierarchies in both the SM fermion masses and mixing angles originate from the profiles. Since  $u_L$  and  $d_L$  have the same profile, we get  $U_L \sim D_L$ , where  $(U, D)_L$  denote unitary transformations to go from interaction to mass basis for LH up and down-type quarks, respectively. Using  $U_L^\dagger D_L = V_{CKM}$  then gives  $(U_L)_{23} \sim V_{ts}$  and  $(U_L)_{13} \sim V_{td}$ . Combining the above information

on left-handed (LH) mixing angles and profile of  $(t, b)_L$ ,  $t_R$  with the observed quark masses, we can estimate the size of profiles of all the quarks near the TeV brane and hence the right-handed (RH) mixing angles as well (see reference [11] for details). We find  $(U_R)_{23} \sim 0.1$  and  $(U_R)_{13} \sim 10^{-3}$ , where  $U_R$  denote unitary transformations for RH up-type quarks.

Thus we find:

$$\mathcal{L}_{\text{FC}}^t \ni \left( g_1 \bar{t}_R \gamma_\mu c_R + g_2 \bar{t}_L \gamma_\mu c_L \right) Z^\mu g_Z, \quad (1)$$

with

$$g_{1,2} \sim \left[ 5 \cdot 10^{-3} \frac{(U_R)_{23}}{0.1}, 4 \cdot 10^{-4} \frac{(U_L)_{23}}{0.04} \right] \left( \frac{3 \text{ TeV}}{m_{KK}} \right)^2, \quad (2)$$

and similarly for  $\bar{t}uZ$  couplings which are further suppressed. Note that the above models makes a sharp prediction that top flavor-violation is mostly right handed.

Next, we consider radiative processes which require chirality flip and hence result from loop diagrams. The dominant contributions involve Higgs and KK fermion in the loop, since the KK fermions have larger couplings to Higgs than the SM ones:

$$\begin{aligned} \mathcal{L}_{\text{FC}}^t \ni & \frac{m_t}{m_W^2} \left( \sqrt{4\pi\alpha_{em}}, g_s \right) (F^{\mu\nu}, G^{\mu\nu}) \times \\ & \bar{t} \sigma_{\mu\nu} \left( C_{7\gamma, 8G}^t P_L + C_{7\gamma, 8G}^{\prime t} P_R \right) c, \end{aligned} \quad (3)$$

where  $F^{\mu\nu}(G^{\mu\nu})$  is the photon (gluon) field strength. Thus we find

$$C_{7\gamma, 8G}^{\prime t} \sim \frac{m_W^2}{m_{KK}^2} \frac{\lambda_{5D}^2}{16\pi^2} (U_R)_{23}. \quad (4)$$

For the operator with  $t_R$ ,  $C_{7\gamma, 8G}^t$ , replace  $(U_R)_{23}$  by  $(U_L)_{23}$  which is further suppressed.

**Experimental Signals: LHC.** At the LHC  $\sim 10^8$  top quark pairs will be produced, which will allow to search for FCNC top decays with a significantly improved sensitivity [17]. The  $tcZ$  coupling in Eq. (1) results in

$$\text{BR}(t \rightarrow cZ) \sim 10^{-5} \left( \frac{3 \text{ TeV}}{m_{KK}} \right)^4 \left( \frac{(U_R)_{23}}{0.1} \right)^2. \quad (5)$$

Here and below the quantities in parentheses are  $O(1)$  for natural regions of parameter space. With  $100 \text{ fb}^{-1}$  luminosity, the expected upper limit on  $\text{BR}(t \rightarrow cZ)$  is  $\sim$  a few  $10^{-5}$  [17]. Thus, we see that the (relatively) huge  $\text{BR}(t \rightarrow cZ)$  in this model, much larger than the expectation from the SM of  $\approx 10^{-13}$  [18], is on the edge of current LHC sensitivity, providing a motivation to refine the analysis since an improvement by an order of magnitude will definitively test this framework. Also, with enough statistics, angular analysis will be able to distinguish between LH or RH coupling in  $tcZ$  [19]: the above models predicts that RH coupling dominates. At the

LHC,  $q\bar{q} \rightarrow tc$  (single top production) via  $tcZ$  coupling or direct KK  $Z$  exchange is likely to be overwhelmed by the large background [20]. However, similar to KK  $Z$ , there are also flavor violating couplings to the KK *gluon* which can give observable effects in  $q\bar{q} \rightarrow tc$  via KK gluon exchange (see reference [21]).

The dipole operators give

$$\text{BR}(t \rightarrow c\gamma, G) \sim 10^{-10, -9} \times \left( \frac{3 \text{ TeV}}{m_{KK}} \right)^2 \left( \frac{(U_R)_{23}}{0.1} \right) \left( \frac{\lambda_{5D}}{4} \right)^4, \quad (6)$$

dominated by LH operator. Thus, again we see that  $\text{BR}(t \rightarrow c\gamma, G)$  in this model is much larger than in the SM [18], but still too small to be observed: the sensitivities at the LHC are  $\text{BR}(t \rightarrow c\gamma, G) \sim 10^{-5, -4}$  [17].

**ILC.** Indeed the FC- $Ztc$  effective interaction, Eq.(3) has the capacity to also lead to a striking and clean signature via the reaction:  $e^+e^- \rightarrow t\bar{c}$  accessible to the ILC. One finds that

$$R_{tc} = \frac{\zeta_{tc}(a_{Ztc}^2 + b_{Ztc}^2)(a_{Zee}^2 + b_{Zee}^2)}{[(1 - m_Z^2/s)4\pi\alpha_{em}]^2}, \quad (7)$$

where  $R_{tc} = \frac{\sigma(e^+e^- \rightarrow [t\bar{c} + c\bar{t}])}{\sigma(e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-)}$ ,  $\zeta_{tc} = \frac{9}{2} y_c^2 y_t [1 + \frac{y_c}{3y_t}]$ ,  $y_{c,t} = [\text{energy of the charm, top quark} / \text{energy of the } e^- \text{ or } e^+]$  and  $a$ 's,  $b$ 's are the coefficient of vector and axial pieces respectively [ $a_{Ztc}$ ,  $b_{Ztc} = g_Z(g_1 \pm g_2)/2$ ].

The above cross-section is from  $tcZ$  coupling and is dominant at low energies. Using the couplings given above and dimensional analysis, we can show that at higher energies, namely,  $\sqrt{s} \gtrsim m_Z \xi \sim 500 \text{ GeV}$ , direct KK  $Z$ ,  $\gamma$  exchange is more important and has a different energy dependence than the SM  $Z$  exchange [22]. This transition in the energy dependence of the cross-section may be probed experimentally providing a clear signature for our framework.

Numerically  $R_{tc}$  starts being around  $2 \times 10^{-5}$  at energies close to threshold, *i.e.*  $\approx 200 \text{ GeV}$ , reaching about  $2 \times 10^{-4}$  at higher energies. It is worth stressing again [23] that at the ILC this reaction leads to very interesting and unique signal at relatively low energy, *i.e.*  $\lesssim 2m_t$ . Note also the kinematics of these class of events is extremely constrained which should help in their identification. At such center of mass energies, due to its huge mass, the top quark takes up well over half (in-fact most of) the energy, signifying that it is a single top event, with the opposite side being an essentially massless (charm) jet, in particular, it must not contain a b-quark.

Another interesting aspect of this class of events is that the RS1 framework with a generic effective interaction, Eq. (1), leads to a sizeable forward-backward asymmetry due to one helicity (in this case RH) being dominant. For unpolarized beams, we find that

$$A_{FB}(e^+e^- \rightarrow t\bar{c}) = \frac{2 \zeta_{FB} a_{Ztc} b_{Ztc} a_{Zee} b_{Zee}}{(a_{Ztc}^2 + b_{Ztc}^2)(a_{Zee}^2 + b_{Zee}^2)}, \quad (8)$$

where  $\zeta_{FB} = \frac{1+(y_c/y_t)}{1+[y_c/(3y_t)]}$ .  $A_{FB}$  is around 7% at low energies and asymptotically reaches about 11%. Note that the asymmetry should be larger with polarized beams. Furthermore, the sign of the forward-backward asymmetry distinguishes dominance of RH vs. LH  $Z$  coupling: it is positive for RH dominating as in the case of the above models with a warped extra dimension. At energies above 500 GeV we expect additional contributions from the direct KK  $Z$ ,  $\gamma$  exchange to modify the form of the asymmetry.

The consensus of the community is that the ILC should be initially usable with energies in the range of 200 to 500 GeV and subsequently it should be able to run at around 1 TeV. Also, the hope is that the integrated luminosity will be around  $500 \text{ fb}^{-1}$  after the first few years of running [24, 25]. If these characteristics are fulfilled then one can anticipate tens of FC- $tc$  events.

We end with the following brief comments:

(i) Another interesting feature of the flavor-changing  $tc$  vertex in RS1 is that the mixing coefficient,  $(U_R)_{23}$ , is actually complex and in general we should expect  $O(1)$  CP-odd phase [11]. In this context the expected beam polarization (80% for electrons and up-to about 60% for positrons [24, 25]) at the ILC would become a very valuable probe. Since, at these energies, the final state CP-even phases are likely to be small,  $T_N$  (naive time-reversal)-even observables such as partial rate asymmetry are likely to be rather small. But the several momenta available (in the decay products of the  $tc$  complex), in addition to the beam polarization, should allow us to write down many  $T_N$ -odd observables [26, 27] which will not require final state phases and could be amenable to experimental study.

(ii) With regard to the CP-odd phases a concern in the RS1 type scenario is that in fact one naturally expects neutron electric dipole moment (NEDM) of  $O(10^{-25} \text{ e-cm})$  which exceeds existing experimental bounds by about  $O(10)$ ; therefore there is a CP “problem” [11]. However, there can be significant differences in the size of the CP phases since the ones that enter the NEDM are from different sectors  $D_R, U_R, U_L, D_L$  than the ones which are relevant to this paper (which mostly arise from  $U_R, U_L$ ).

(iii) ILC can also have sensitivity to modifications of flavor *preserving* couplings of top to SM gauge bosons: to  $Z$  [16, 28] and to photon (anomalous magnetic moment/EDM-form factors: see below) via  $e^+e^- \rightarrow \bar{t}t$  (ILC will do better here than LHC). In addition, there is a modification of top quark coupling to the Higgs (from that in the SM) due to the mixing of zero and KK fermions mentioned earlier [29]. There are also direct gauge KK exchanges modifying  $\bar{t}t$  cross-sections at the ILC (from KK  $Z, \gamma$ ) [28] and at the LHC (from KK gluon). Diagrams similar to those giving  $t \rightarrow c\gamma$ , gluon, but without flavor violation, give anomalous magnetic moment for top quark and also EDM in the presence of

$O(1)$  CP violating phases:

$$d_t \sim 10^{-19} \left( \frac{3 \text{ TeV}}{m_{KK}} \right)^2 \left( \frac{\lambda_{5D}}{4} \right)^2 \text{ e-cm}. \quad (9)$$

Needless to say, the (CP-conserving) magnetic form-factor is likely to be dominated by the standard 1-loop QCD contribution but the CP-violating electric form factor, originating from the CKM-phase is expected to be severely suppressed as it cannot contribute at 1-EW loop order; therefore the RS1 contribution of 1-loop order estimated above is much larger. Note also that in this scenario, for  $q^2 = s \ll m_{KK}^2$ ,  $d_t$  is essentially a constant (to  $O(q^2/m_{KK}^2)$ ). It is thus extremely interesting that the ILC with the parameters mentioned above should be able to study top electric dipole moment form factors of  $O(10^{-19} \text{ e-cm})$  [26, 27, 30].

**Conclusions.** Summarizing, the framework of warped extra dimension provides a novel and very interesting resolution to the Planck-weak *and* flavor hierarchy problem of the SM. It tends to generically single out the top quark with properties significantly different from the SM. In particular, the flavor-changing  $tcZ$  interactions could lead to spectacular signatures at the LHC as well as at the ILC that would be very worthwhile to explore.

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