Collider signals of top quark flavor violation from a warped extra dimension

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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$(t \to cZ)$ at or above the sensitivity of the Large Hadron Collider (LHC). At the International Linear Collider (ILC), single top production, via $e^+e^- \to t\bar{c}$, 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.

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I. 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 hierarchy between the Planck and EWSB scales. Can this TeV-physics give us clues to the origin of flavors? This depends on the scale of dynamics which mediates flavor physics, Λ_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 $O(1000)$ TeV. However, in models with a high Λ_F, the flavor structure at low energies 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 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.

It was shown, however, in [2,3] that, as long as the NP dynamics respect the SM approximate flavor symmetries and is *quasi*-aligned with SM Yukawa matrices, a few TeV flavor scale is still allowed by the data. The corresponding framework was denoted as next to MFV (NMFV) [2]. Thus an exciting case is possible in which flavor violation (FV) arises from the same NP at TeV scale which is related 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 $t \to c$ transition which are highly GIM and CKM-suppressed within the SM, but yet are theoretically clean due to the top high mass.

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. Because of 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 ~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 ~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 [7–9]. 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. The 1st and 2nd generation fermions can be localized near the Planck brane so that the FCNC's from higher-dimensional operators are suppressed by scales $\gg$ 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 [8–10]: 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 nonuniversal due to the different profiles for the SM fermions. However, the gauge KK modes are localized near the TeV brane and hence it can be shown that the nonuniversal 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 $\gtrsim 1000$ 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 ~ 3 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 nonuniversal shift in its coupling to the SM Z via mixing of KK Z with zero-mode Z [12]: $\delta g_Z^{b_L} \sim g_{Z^{\rm KK}}^{b_L} \xi \frac{m_Z^2}{m_{\rm KK}^2}$ where $\xi \equiv \sqrt{\log(M_{\rm Pl}/{\rm TeV})}$ and $g_{Z^{\rm KK}}^{b_L}$ is the corresponding nonuniversal KK Z coupling. 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 $Z\bar{b}_L b_L$ 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., $Z\bar{b}_L b_L$ coupling) which can be relaxed by the following setup: (i) $(t, b)_L$ quasilocalized 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 FV involving b_L which has been studied in [11,14,15] along with FV in lepton and light quark sectors.

In the rest of this paper, we focus on *top* quark FV 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 nonuniversal 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): $g_{Z^{\rm KK}}^{t_R} \sim g_Z \xi$. A similar size effect is found from mixing of zero-mode t_R with KK t_L which then couples to the Z [16]: $\delta g_Z^{t_R}|_{t_L^{\rm KK}} \sim (\lambda_{5D} v/\sqrt{2})^2/m_{\rm KK}^2$. 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, γ. 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 ξ 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.

II. FLAVOR VIOLATION

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

We assume that the $5D$ Yukawa matrices are anarchic, i.e., all entries (including off-diagonal ones) are of similar size. The idea is that the hierarchies in both the SM fermion masses and mixing angles originate entirely from the fermion profiles, which, in turn, can be quite different (or hierarchical) even with *small* changes (i.e., no hierarchies) in the $5D$ mass parameters. Note that this is the standard (or usual) assumption in flavor models, i.e., explaining hierarchies in the *SM* Yukawas with *out* hierarchies in the *fundamental* Yukawa couplings. With this assumption and 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 $U_L^\dagger D_L = V_{\rm CKM}$ 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 Ref. [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:

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

with

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

and similarly for $\bar{t}uZ$ couplings which are further suppressed. Note that the above models makes a sharp prediction that top FV 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:

$$\mathcal{L}^{t}_{FC} \ni \frac{m_t}{m_W^2} (\sqrt{4\pi\alpha_{em}}, g_s)(F^{\mu\nu}, G^{\mu\nu}) \times \bar{t} \sigma_{\mu\nu} (C^{t}_{7\gamma,8G} P_L + C'^{t}_{7\gamma,8G} P_R) c, \tag{3}$$

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

$$C'^{t}_{7\gamma,8G} \sim \frac{m_W^2}{m_{\rm KK}^2} \frac{\lambda_{5D}^2}{16\pi^2} (U_R)_{23}. \tag{4}$$

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

III. 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

$$\mathrm{BR}\,(t \to cZ) \sim 10^{-5} \left(\frac{3\ \rm TeV}{m_{\rm KK}} \right)^4 \left(\frac{(U_R)_{23}}{0.1} \right)^2. \tag{5}$$

Here and below the quantities in parentheses are $O(1)$ for natural regions of parameter space. With 100 $\rm fb^{-1}$ luminosity, the expected upper limit on $\mathrm{BR}(t \to cZ)$ is $\sim$ a few 10^{-5} [17]. Thus, we see that the (relatively) huge $\mathrm{BR}(t \to cZ)$ in this model, much larger than the expectation from the SM of $\approx 10^{-13}$ [18], is on the edge of the LHC sensitivity, providing a motivation to refine the analysis since an $\mathcal{O}(10)$ improvement will test this framework. Note that there is an $O(1)$ uncertainty in the prediction for this BR in this model due to the mixing angles, but such a variation is an inherent feature of this approach to address the flavor puzzle. Also, with enough statistics, angular analysis will be able to tell LH from RH coupling in tcZ [19], where our framework predicts that RH coupling dominates. At the LHC, $q\bar{q} \to tc$ (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 $q\bar{q} \to tc$ via KK gluon exchange (see [21]).

The dipole operators give

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

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

IV. ILC

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

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

where $R_{tc} = \frac{\sigma(e^+e^- \to [t\bar{c} + c\bar{t}])}{\sigma(e^+e^- \to \gamma \to \mu^+\mu^-)}$, $\zeta_{tc} = \frac{9}{2} y_c^2 y_t [1 + \frac{y_c}{3y_t}]$, $y_{c,t} =$ [energy of the charm, top quark/energy of the e^- 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, $\sqrt{s} \gtrsim m_Z \xi \sim 500$ GeV, direct KK Z, γ 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 2×10^{-5} at energies close to threshold, i.e. ≈ 200 GeV, reaching about 2×10^{-4} at higher energies. It is worth stressing again [23] that at the ILC this reaction can lead to a 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 most of the energy, signifying that it is a single top event, with the opposite side being an essentially massless jet.

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

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

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 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. We note that this forward-backward asymmetry (and similarly the angular analysis of $t \to cZ$ decay at the LHC) can allow us to distinguish RS1 from other models which also predict a sizable tcZ vertex. At energies above 500 GeV we expect additional contributions from the direct KK Z, γ 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 fb^{-1} after the first few years of running [24,25]. If these characteristics are fulfilled then one can anticipate tens of flavor-changing (FC) tc events.

We end with the following brief comments:

(i) Another interesting feature of the FC 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 one naturally expects neutron electric dipole moment (NEDM) of $O(10^{-25}$ e-cm) which exceeds existing experimental bounds by $O(10)$; 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 also have sensitivity to modifications of flavor *preserving* couplings of top to SM gauge bosons: to Z [16,28] and to photon (EDM-form factor: see below) via $e^+e^- \to \bar{t}t$ (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, γ) [28] and at the LHC (from KK gluon). Diagrams similar to those giving $t \to c\gamma$, gluon, but without flavor violation, give anomalous magnetic moment for top quark and also EDM in the presence of $O(1)$ CP violating (CPV) phases:

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

The CPV 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 is much larger. Note also that in this scenario, for $q^2 = s \ll m_{\text{KK}}^2$, d_t is essentially a constant (to $O(q^2/m_{\text{KK}}^2)$). 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 $O(10^{-19}$ e-cm) [26,27,30].

V. 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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