Flavor Anarchy in a Randall-Sundrum Model with 5D Minimal Flavor Violation and a Low Kaluza-Klein Scale

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A variant of a warped extra dimension model is presented. It is based on 5D minimal flavor violation, in which the only sources of flavor breaking are two 5D *anarchic* Yukawa matrices. These matrices also control the bulk masses, which are responsible for the resulting flavor hierarchy. The theory flows to a next to minimal flavor violation model where flavor violation is dominantly coming from the 3rd generation. Flavor violation is also suppressed by a parameter that dials the violation in the up or down sector. There is therefore a sharp limit in which there is no flavor violation in the down-type quark sector which, remarkably, is consistent with the observed flavor parameters. This is used to eliminate the current Randall-Sundrum flavor and *CP* problem. Our construction suggests that strong dynamic-based, flavor models may be built based on the same concepts.

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Introduction.—The standard model (SM) hierarchy between the Planck scale and the electroweak (EW) symmetry breaking scale is unnatural since the Higgs boson mass is ultraviolet (UV) sensitive. Solutions to the hierarchy problem generically spoil the agreement of the SM with data when trying to explain flavor as well. This tension motivates new physics frameworks with the approximate symmetries of the SM.

We consider the Randall-Sundrum scenario (RS1) [1], which provides a solution to the hierarchy problem. Because of warped geometry, the mass scales in an effective 4D description depend on location in an extra dimension: the Higgs sector is localized near the "TeV" brane where it is protected by a low warped-down scale of order a TeV while gravity is localized near the UV brane with a Planckian fundamental scale. In the original model, the SM was localized on the TeV brane. Thus, flavor issues [e.g., flavor hierarchy, smallness of flavor-changing neutral currents (FCNCs)] and predictions regarding EW tests are UV sensitive. Allowing the SM fields to propagate in the bulk can explain flavor, and makes flavor issues UV insensitive: Light fermions are localized near the Planck brane [2] so FCNCs from higher-dimensional operators are suppressed [2,3]. Fermion localization also explains the hierarchy of fermion masses (and mixing) without hierarchies, solving the flavor puzzle [4].

However, with bulk fields, exchange of gauge Kaluza-Klein (KK) modes induces FCNCs. Unlike the flat case, there is a significant protection from a built-in RS1-GIM (Glashow-Iliopoulos-Maiani) [5] due to approximate flatness of the KK gauge boson wave functions in the UV and hierarchic fermion wave functions in the IR; nevertheless, the contributions to FCNCs are non-negligible. At low energies this class of models flows to next to minimal flavor violation (NMFV) [6]; flavor-changing effects are primarily induced via mixing with the third generation. In this framework flavor violation is due to sources with a typical scale of $\Lambda_{\rm NMFV}$, which breaks the SM flavor group from $U(3)_Q \times U(3)_u \times U(3)_d$ down to $U(2)_Q \times U(2)_u \times U(3)_d \times U(1)_{\rm top}$, where Q, u, d stand for quark doublets and up- and down-type singlets, respectively. The extra sources are quasialigned with the SM flavor breaking and the misalignment is of order of the Cabibbo-Kobayashi-Maskawa (CKM) matrix where new sources of *CP* violation (CPV) are present. Thus, transitions between the first [second] and third generation are suppressed by $\mathcal{O}(\lambda_C^3)$ $[\mathcal{O}(\lambda_C^2)]$, where $\lambda_C \sim 0.23$ is the Cabibbo angle. Nevertheless, given an IR localized Higgs sector, additional right-handed (RH) currents yield a stringent bound, $\Lambda_{\rm NMFV} \geq 8$ TeV [7]. This implies a severe little hierarchy problem.

We present a novel variant of the RS1 framework, where at leading order flavor violation in the down-type quark sector is eliminated. Our main idea is that the 5D theory follows the minimal flavor violation (MFV) paradigm where flavor violation is due only to two 5D up and down anarchical Yukawa matrices. The theory has four flavor violating parameters: three mixing angles and a CPV phase. It allows for extra protections against flavor and *CP* violation, following from a simple symmetry argument. In the limit where the doublet quark bulk mass is controlled only by the down-type 5D Yukawa matrix there is an enhanced $U(1)^3$ flavor symmetry. Thus, the whole down-type flavor sector can be simultaneously diagonalized so that the contributions to flavor violating processes in the down sector vanish. We will show how our model realizes approximately this limit. Moreover, additional CPV phases which induced a RS1 *CP* problem [5] are eliminated. Unlike in the SM, in our model the flavor violating parameters are $\mathcal{O}(1)$.

Model.—The only sources of flavor breaking are the 5D up and down Yukawa matrices $Y_{u,d}$ to a bulk Higgs boson H. However, unlike the 4D MFV [8] case in our framework the 5D Yukawa matrices are "anarchic," defined basis-independently as follows: The eigenvalues of $Y_{u,d}$ are all of the same order, and the unitary matrix that transforms from the eigenbasis of $Y_u Y_u^\dagger$ to the eigenbasis of $Y_d Y_d^\dagger$ is $\mathcal{O}(1)$ in each entry (an example is given below).

In addition, the theory contains 5D vectorlike, 3×3, mass matrices $C_{Q,u,d}$ for each of the quark representations. Bulk MFV implies that the only vectorlike flavor-breaking spurions for the doublets [singlets] are $Y_{u,d}Y_{u,d}^\dagger$ [$Y_{u,d}^\dagger Y_{u,d}$]. $V_5^{\rm KM}$ is the only source of flavor and CPV in our theory. Under the global symmetry $U(3)_Q \times U(3)_u \times U(3)_d$, either Y_u or Y_d can be brought to diagonal form, and $V_5^{\rm KM}$ resides in the remaining one. According to our MFV assumption we can expand the 5D mass matrices as a power series in $Y_{u,d}$:

$$C_{u,d} = Y_{u,d}^\dagger Y_{u,d} + \cdots, \qquad C_Q = rY_u Y_u^\dagger + Y_d Y_d^\dagger + \cdots, \tag{1}$$

where universal terms and overall order one coefficients were omitted for simplicity and the dots stand for subdominant higher order terms (as discussed below). The relevant part of the 5D Lagrangian is given by

$$\mathcal{L}_{\rm gen} = C_{Q,u,d}(\bar{Q}, \bar{u}, \bar{d})(Q, u, d) + HY_{u,d}\bar{Q}(u, d), \tag{2}$$

where C_i are in units of k the anti–de Sitter curvature, and we will assume that the Higgs boson is a bulk field (see later) so that Y_i are measured in units of $1/\sqrt{k}$.

Our first result is that although the UV theory is anarchic MFV the low energy theory is hierarchic. This is since the eigenvalues of the C_i matrices induce geometrical separation in the extra dimension or large anomalous dimension in the dual conformal field theory (CFT) [9].

The second result is that, if the Yukawa couplings are localized on the TeV brane or if the Higgs profile is peaked toward the TeV brane, this theory flows to approximate NMFV with additional sources of flavor and CPV. To see that, given this assumption, the 4D zero mode mass matrices are [5] $m_{u,d} \simeq 2v F_Q Y_{u,d} F_{u,d}$, where F_x correspond to the value of the quark zero modes on the TeV brane. More explicitly, the eigenvalues f_{x^i} of the F_x matrices are [2,5] $f_{x^i}^2 = (1/2 - c_{x^i})/(1 - \epsilon^{1-2c_{x^i}})$, where c_{x^i} are the eigenvalues of the C_x matrices, $k\pi r_c = \log[M_{\bar{\rm Pl}}/{\rm TeV}]$, $\epsilon = \exp[-k\pi r_c]$, $M_{\bar{\rm Pl}}$ is the reduced Planck mass, and $v \simeq 174$ GeV. The f_{x^i} signify the amount of compositeness of the different generations. The $Y_{u,d}$ are anarchic, and thus the corresponding mixing angles are given by ratios of the F_i eigenvalues. For instance, $m_{u,d}$ satisfy $(m_{u,d}m_{u,d}^\dagger)_{ij} = 4v^2(F_Q Y_{u,d} F_{u,d} F_{u,d}^\dagger Y_{u,d}^\dagger F_Q^\dagger)_{ij} \sim f_{Q^i} f_{Q^j}$. The rotation matrices to the mass eigenbasis of the left-handed up- and down-type quarks are thus parametrically $(V_{u,d})_{ij} \sim (m_{u,d}^2)_{ij}/|(m_{u,d}^2)_{ii} - (m_{u,d}^2)_{jj}|$ which implies $(V_{\rm CKM})_{ij} \sim f_{Q^i}/f_{Q^j}$. Thus the c_{Q^i} eigenvalues control the CKM mixing angles in models with anarchic Yukawa matrices [5]. We checked explicitly [10] that nonuniversal corrections, in a case of a quasilocalized bulk Higgs boson, to the f_{x^i} values are small of $\mathcal{O}(10\%)$ and thus subdominant.

The couplings of zero modes to the gauge KK states (which are localized near the TeV brane) are proportional to $F_{Q,u,d}^2$, which is misaligned with $m_{u,d}$. Thus new flavor and CPV phases appear in the low energy theory. However, the NMFV limit arises since one eigenvalue of $(F_{u,Q,d})$ is much larger than the others, preserving an approximate $U(2)$ (so that F_Q^2 and $m_{u,d}$ are quasialigned) [6]. There are RH currents since in the mass basis the $C_{u,d}$ matrices are not diagonal. Our third result is that in the limit where r in Eq. (1) goes to zero, C_Q, C_d, and Y_d can all be simultaneously diagonalized. Therefore, flavor violation in the down sector vanishes, where in this case flavor conversion (including the CKM part) is due to the up quark sector. Within our scheme and by Eq. (1) the value of r is not a free parameter but rather a function of the flavor parameters. For concreteness, we present a numerical example satisfying our scheme. In Table I we present the eigenvalues of C_i and F_i that yield the quark masses and mixing angles. We further need to show that there is a consistent solution to the following relation:

$${\rm diag}\,(C_Q) = a{\rm diag}[rV_5^{\rm KM\dagger}(\theta_{ij}, \delta)C_u V_5^{\rm KM}(\theta_{ij}, \delta) + C_d], \tag{3}$$

that is in accordance with the mass values in Table I, where θ_{ij} is a mixing angle between the ith and jth generations and δ is the 5D CKM phase. To see that our setup is self-consistent we need to verify that the eigenvalues of the three mass matrices $C_{Q,u,d}$ can be derived from only two anarchical matrices $Y_{u,d}$. As an example, the following numbers were found to solve the above relation, a, r, θ_{12}, θ_{23}, θ_{13}, $\delta \approx 0.8$, 0.25, $143°$, $43°$, $48°$, $45°$. In this example, the 5D Yukawa matrices were taken to be

$$\begin{aligned} {\rm diag}(Y_u Y_u^\dagger) &\simeq 1.5c_u - 1.8 \approx (0.8, 1, 1.9), \\ {\rm diag}(Y_d Y_d^\dagger) &\simeq 4.1c_d - 1.3 \approx (1.4, 1.2, 1.1). \end{aligned} \tag{4}$$

We see explicitly that $Y_d Y_d^\dagger$ and $V_5^{\rm KM\dagger} Y_u Y_u^\dagger V_5^{\rm KM}$ are anar-

TABLE I. The eigenvalues, of C_x, F_x, which roughly yield the right masses and CKM elements at the M_Z scale (for slightly different set of viable parameters, see [3,5]).

Flavor	c_Q, f_Q	c_u, f_u	c_d, f_d
I	0.64, 0.002	0.68, 7×10^{-4}	0.65, 2×10^{-3}
II	0.59, 0.01	0.53, 0.06	0.60, 0.008
III	0.46, 0.2	−0.06, 0.8	0.58, 0.02

chic. We have checked that this set of parameters approximately reproduces the SM quark masses, mixing angles, and an $\mathcal{O}(1)$ CKM phase. To avoid additional flavor structure from operators localized on the UV brane, we assume that UV brane localized terms are either proportional to the Yukawa matrices or just small, in agreement with their naive dimensional analysis size. Thus our flavor structure is not spoiled by Planckian physics [11].

The full three-generation system, which is necessary to obtain a *CP*-violating phase, is complicated and the allowed range of $|r|$ must be found numerically. In general, the resulting r can be described, according to Eq. (3), by various branches (corresponding to different permutations of C_x) as a function of a, θ_{ij}, δ, and a universal term [11]. In our numerical scan, for simplicity, a universal term in (3) was not included and we typically find $r = 0.1$–0.4, this corresponds to a slice of the most general solution [11]. Thus, remarkably we find multiple solutions in which flavor violation in the down sector is suppressed by $\mathcal{O}(0.25)$ while fitting all the data.

The typical size of the Yukawa matrix eigenvalues is $y \approx 3$ (slightly bigger than was used in [5] with a Higgs boson on the brane). In theories where the Higgs boson is a bulk field, such as the holographic composite Higgs models [12], y is within the perturbative region for at least three KK modes, $N_{\rm KK}$, below the cutoff [13], $N_{\rm KK}(2y/4\pi)^2 < 1$. As we shall see next, this choice yields a suppression (not due to symmetry) of order $r_y \sim 2/3$ which together with a moderate value of r completely relaxes the present tension with flavor and CPV precision bounds. As mentioned above, in terms of flavor violating parameters, whether the Higgs boson is strictly an IR field or quasilocalized towards the IR brane makes very little difference [10].

FCNC and electric dipole moment.—Let us briefly review the status of the strongest constraints on bulk RS1 models. These are from $\Delta F = 2$ processes due to tree level exchange of KK gluon. In [5] it was shown that the ratio between the RS1, $(V-A)^2$, contributions and the SM is proportional to $(F_Q^2)_{ij}^2$ (in the down quark mass basis). Using the relation $(V_{\rm CKM})_{ij} \sim f_{Q^i}/f_{Q^j}$ the ratio of contributions can be written as

$$h^{\rm RS} = \frac{M_{12}^{\rm RS}}{M_{12}^{\rm SM}} \sim 0.5 \times \left(\frac{3\ \text{TeV}}{m_{\rm KK}}\right)^2 \left(\frac{f_{Q^3}}{0.3}\right)^4. \tag{5}$$

The above contribution is proportional to $f_{Q^3}^4$ because to leading order all flavor violation comes through the third generation. At present, $h^{\rm RS} \lesssim 0.3$ [6,7,14]. However, in models where RH currents are present, the dominant contributions to ϵ_K involve operators with $(V-A)\times(V+A)$ structure [7]. Such contributions are proportional to $(F_Q^2)_{12}(F_d^2)_{12} \propto m_d m_s/(vy)^2$ which apparently is smaller by a factor of $\mathcal{O}(20)$. This is not enough due to the following two sources of enhancement: $\mathcal{O}(11)$ from chiral enhancement of the matrix element and $\mathcal{O}(7)$ from the running from the KK scale to the weak scale. These overcome the suppression and yield the largest contributions which imply that the KK masses have to be above 8 TeV.

In our class of models both the $(V-A)^2$ and the $(V-A)\times(V+A)$ contributions are suppressed by r^2. In addition, due to the larger overall scale for the Yukawa matrices the value of f_{Q^3} is smaller by $r_y \sim 2/3$ than in the brane-localized-Higgs case. Because of the RS1-GIM mechanism left-handed flavor violation is proportional to f_{Q^3}. Thus, $(V-A)^2[(V-A)\times(V+A)]$ contributions are suppressed by $\mathcal{O}(r_y^4)$ $[\mathcal{O}(r_y^2)]$. So, altogether we expect a suppression of down quark $\Delta F = 2$ currents to be of the order $(2/3)^{4,2}(0.25)^2 = \mathcal{O}(1, 3\%)$ in the $(V \mp A)\times(V-A)$ case, respectively. This allows KK masses below the 2 TeV scale without violating any of the current constraints, significantly below the value allowed by EW tests [15].

Finally, we comment that our model does not suffer from a *CP* problem due to constraints from the neutron electric dipole moment since the contributions to this process arise only at two loops and not at one loop as occurs generically [5]. One way to see that two loops are required is to compare the CPV sources of the generic case and our class of models. In the general case even with two generations several CPV phases are present, so that one loop is enough to be sensitive to these extra phases. However, in our case there is a single CPV phase in the fundamental theory which vanishes in the two generations case, as the theory becomes real in that limit. Thus only two loop diagrams can be sensitive to this 5D-CKM phase, and the RS1 *CP* problem is solved. In more technical terms the spurion that generates the leading contributions is $d_N \equiv {\rm Im}[F_Q(Y_u Y_u^\dagger + Y_d Y_d^\dagger) Y_d F_d]_{11} = {\rm Im}[F_Q(C_Q/ar + Y_d Y_d^\dagger(1-1/r))Y_d F_d]_{11}$, where in the RH side we have used Eq. (1). This expression is a function only of $Y_d Y_d^\dagger$ and C_Q where the misalignment between these two spurions is described by a single 5D CKM-like matrix. Thus for CPV all three generations must participate in the process, which is possible only at two loops [16].

Conclusions and outlook.—A warped extra dimension model is presented based on the novel idea of 5D anarchic minimal flavor violation. We point out several features: The low energy theory is anarchic and the model solves the flavor puzzle; however, the theory is not described by MFV but rather by next to MFV. New flavor and *CP* violating phases are generically present. However, they dominantly induce flavor-changing currents only in the up-type sector. In addition CPV occurs only when three generations are considered. Thus the agreement with experimental constraints, both from flavor-changing and dipole moment experiments, is dramatically improved. Our mechanism suppresses only the contributions related to flavor and *CP* violation while the contributions to EW precision observables are unaffected. It would be interesting to extend our mechanism to the lepton sector which also has flavor and *CP* problems [17]. No extra structure was required in our scenario. Rather the number of flavor parameters was reduced. Thus, the LHC collider phenomenology is largely similar to what was discussed in the general framework [18]. Our mechanism ensures by symmetry in the limit of small r that flavor violation is suppressed in the down sector. However, flavor violation in the up sector should be similar to the general case which was analyzed in [5,19]: it yields possible LHC signals in the form of top flavor violation, $t \to cZ$ [19] (the contributions to $D - \bar{D}$ mixing are subdominant as in [5]).

We showed how our scheme solved the RS1 flavor and *CP* problems, but not how to dynamically realize this scheme. One possibility is through shining [20] from the TeV brane, where additional bulk scalars (transform under the flavor symmetry) can couple to the TeV Yukawa matrices. It is possible that the strong *CP* problem can also be solved via the above setup in the spirit of [21].

Our setup can be understood via a 4D point of view: a single flavor-breaking source induces the bulk mass which is responsible for both mixing between elementary and composite fermions and the anomalous dimensions of chiral CFT operators, as well as the structure of composite Higgs-fermion Yukawa interactions. This is similar to anomaly mediated supersymmetry breaking [22] where flavor violation in the squark soft breaking sector is induced by the 4D Yukawa matrices. It would be interesting to construct a realistic supersymmetric version of the above model, along the lines of [23]. In such a case the anomalous dimension of the operators is proportional to the anarchic Yukawa matrices, and nondegenerate squark masses are under better control.

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Note added.—While this work was near completion, Ref. [24] was published which also deals with the RS flavor problem but without addressing the flavor puzzle.

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