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Unified flavor symmetry from warped dimensions

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ABSTRACT

In a model of warped extra-dimensions with all matter fields in the bulk, we propose a scenario which explains all the masses and mixings of the SM fermions. In this scenario, the same flavor symmetric structure is imposed on all the fermions of the Standard Model (SM), including neutrinos. Due to the exponential sensitivity on bulk fermion masses, a small breaking of this symmetry can be greatly enhanced and produce seemingly un-symmetric hierarchical masses and small mixing angles among the charged fermion zero-modes (SM quarks and charged leptons), thus washing out visible effects of the symmetry. If the Dirac neutrinos are sufficiently localized towards the UV boundary, and the Higgs field leaking into the bulk, the neutrino mass hierarchy and flavor structure will still be largely dominated and reflect the fundamental flavor structure, whereas localization of the quark sector would reflect the effects of the flavor symmetry breaking sector. We explore these features in an example based on which a family permutation symmetry is imposed in both quark and lepton sectors.

1. Introduction

The original motivation for warped extra-dimensions, or Randall–Sundrum models (RS), was to address the hierarchy problem. In RS the fundamental scale of gravity is exponentially reduced from the Planck mass scale to a TeV size due to a Higgs sector localized near the boundary of the extra dimension [1]. If SM fermions are allowed to propagate in the extra dimension [2], and become localized towards either boundary, the scenario also addresses the flavor problem of the SM and suppresses generic flavor-violating higher-order operators present in the original RS setup. However, KK-mediated processes still generate dangerous contributions to electroweak and flavor observables (including dangerous deviations to the $Zb\bar{b}$ coupling) [3–5], pushing the KK scale to 5–10 TeV [6]. The usual mechanisms employed to lower the KK scale involve using a custodial gauge $SU(2)_R$ symmetry [7], which insures a small contribution to electroweak precision parameters, lowering the KK scale to around 3 TeV, and rendering this scenario visible at the LHC. Alternatively, introducing a dilatonic scalar such that the warping of the 5-th dimension is strongly modified near the infrared (IR) brane while behaving as an Anti-de-Sitter space near the ultraviolet region, (so-called soft-wall metrics) is another solution [8]. There, the hierarchy problem imposes constrains on the Higgs profile which are stronger than in the original model, while electroweak constraints are milder, allowing a KK scale as low as 1–3 TeV.

One realization of the warped space model is based on the so-called flavor anarchy [5], in which one assumes that no special structure governs the flavor of Yukawa couplings and bulk fermion masses, as natural $\mathcal{O}(1)$ values for these 5D parameters already generate viable masses and mixings. However the neutrino sector must behave differently, first due to the possibility of Majorana mass terms, and second because this setup generates large mass hierarchies and small mixing angles, at odds with neutrino observations. An interesting property of flavor anarchy warped scenarios was investigated in [9], for the case of a bulk Higgs wave function leaking into the extra dimension. There one would obtain small mixing angles and hierarchical masses for all charged fermions, and at the same time very small Dirac masses, with large mixing angles and negligible mass hierarchy for neutrinos. Thus the flavor anarchy paradigm could still work in these scenarios. The case of Majorana neutrinos in this setup was also addressed in [9] where small and almost degenerate masses can be generated for IR localized Majorana neutrinos, out of higher-order interactions in the Lagrangian. The problem is that the warping necessary to

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obtain the correct neutrino masses would be too small, and not enough to solve the hierarchy problem. Adding UV-localized Majorana masses (via some $SU(2)$ triplet representation in the UV region) can also generate small and almost degenerate masses [10]. As our goal here is to treat neutrinos on equal footing as quarks and charged leptons, we prefer not to add neutrino-specific extensions and assume that Dirac neutrino masses give the dominant contribution to neutrino masses.

Here we present an alternative scenario where instead of adopting flavor anarchy, we propose that all fermions share the same flavor symmetry. We assume that the flavor violating effects in the 5D Lagrangian can be parametrized by a small coefficient whose size is controlled by a ratio of scales, $\frac{\langle\phi\rangle^n}{\Lambda^n}$, with $\langle\phi\rangle$ the vacuum expectation value (VEV) of some flavon field, and Λ some cut-off mass scale, or the KK mass of some other flavon fields. This small breaking of the flavor symmetry is enough to reproduce correctly the flavor structure of the SM in both the quark and lepton sectors. We proceed by introducing the model, followed by an example of a flavor symmetry to showcase our results.

2. The model

The (stable) static spacetime background is:

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2, \tag{1}$$

where the extra coordinate y ranges between the two boundaries at $y = 0$ and $y = y_{\text{TeV}}$, and where $A(y)$ is the warp factor responsible for exponentially suppressing mass scales at different slices of the extra dimension. In the original RS scenario $A(y) = ky$, with k the curvature scale of the AdS_5 interval, while in general warped scenarios $A(y)$ is a more general (growing) function of y. The appeal of more complicated metrics lies on the possibility of having light KK resonances matter fields (∼1 TeV), while keeping flavor and precision electroweak bounds at bay [8,11]. For simplicity we will take $A(y) = ky$, but with the assumption that the same general features arise in more complicated metric scenarios (this will be addressed in a longer companion paper). Assuming invariance under the usual SM gauge group, the 5D quark Lagrangian is

$$\begin{aligned}\mathcal{L}_q = {} & \mathcal{L}_{kinetic} + M_{q_i}\bar{Q}_iQ_i + M_{u_i}\bar{U}_iU_i + M_{d_i}\bar{D}_iD_i \\ & + \big(Y^{5D}_{ij_u}H\bar{Q}_iU_j + \text{h.c.}\big) + \big(Y^{5D}_{ij_d}H\bar{Q}_iD_j + \text{h.c.}\big)\end{aligned} \tag{2}$$

where Q_i, U_i and D_i are 5D quarks (doublets and singlets under $SU(2)$). In the lepton sector, we assume that Majorana mass terms are forbidden, and so the Lagrangian can be trivially obtained from the previous one by substituting Q_i by L_i, U_i by N_i and D_i by E_i, where L_i are lepton doublets, and N_i and E_i are neutrino and lepton singlets, respectively. The Higgs field H is a bulk scalar that can acquire a nontrivial vacuum expectation value (VEV) $v(y) = v_0e^{aky}$, and is exponentially localized towards the TeV boundary, with delocalization controlled by the parameter a. Such nontrivial exponential VEVs appear naturally in warped backgrounds with simple scalar potentials and appropriate boundary conditions [8,12,13].

This extra dimensional scenario has two sources of flavor. One arises from the usual Yukawa couplings Y^u_{ij}, Y^d_{ij}, Y^e_{ij} and Y^ν_{ij} (dimensionless parameters defined in units of the curvature out the dimension-full 5D Yukawa couplings as $Y^{5D}_{ij} = \sqrt{k}Y_{ij}$). The other flavor parameters come from the fermion bulk mass terms, diagonal in flavor space, taken to be constant bulk terms written in units of the curvature k, i.e. $M_i = c_ik$ ($M_i = M_{q_i}, M_{u_i}, M_{d_i}, M_{L_i}, M_{\nu_i}, M_{e_i}$).

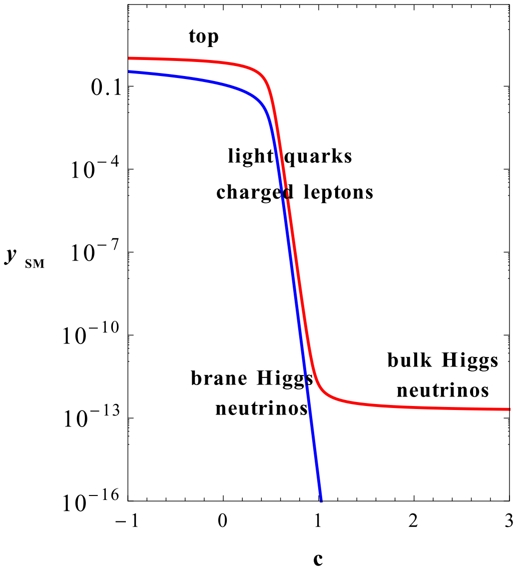

Fig. 1. Effective 4D Yukawa couplings for fermions as a function of the fermion bulk mass parameter c. For simplicity, we have taken the c-parameters for the doublet and the singlet to be equal.

It has been observed before in [9] that, whenever the bulk Higgs localization parameter a is small enough in comparison with the c_i parameters (i.e., for the Higgs sufficiently delocalized from the TeV brane), the 4D effective masses depend exponentially on a rather than on the c_i parameters. The effective 4D masses for all the SM fermions become

$$m_t \simeq v\tilde{Y}_{33} \quad c_{q_3}, c_{u_3} < 1/2 \tag{3}$$

$$(m_f)_{ij} \simeq v\epsilon^{(c_{L_i}-\frac{1}{2})}\epsilon^{(c_{R_j}-\frac{1}{2})}\tilde{Y}_{ij} \quad a > c_{L_i} + c_{R_j} \tag{4}$$

$$(m_\nu)_{ij} \simeq v\epsilon^{a-1}\tilde{Y}_{ij} \quad a < c_{l_i} + c_{\nu_j}, \tag{5}$$

where m_t is the top quark mass, $(m_f)_{ij}$ represents mass matrices for light quarks and charged leptons, and $(m_\nu)_{ij}$ is the Dirac neutrino mass matrix. Note that the couplings $\tilde{Y}_{ij}$ still retain a mild dependence on the c_i-parameters as follows $\tilde{Y}_{ij} = Y_{ij}\frac{\sqrt{2(a-1)(1-2c_{L_i})(1-2c_{R_j})}}{a-c_{L_i}-c_{R_j}}$, with Y_{ij} being the original 5D Yukawa couplings. The parameters $c_{L_i} \equiv c_{q_i}, c_{l_i}$ correspond to the $SU(2)$ doublets, and $c_{R_j} \equiv c_{u_j}, c_{d_j}, c_{e_j}, c_{\nu_j}$ are for the $SU(2)$ singlets. The warp factor ϵ defined by the background parameters as $\epsilon = e^{-ky_{\text{TeV}}} \sim 10^{-15}$ encapsulates the hierarchy between the UV (gravity) brane and the TeV (SM) brane. The c-parameters dependence on masses is shown in Fig. 1 for the case of a brane localized Higgs VEV ($a = 30$) and for a delocalized (bulk) Higgs VEV ($a = 1.9$), where the appearance of a plateau in the neutrino mass region reflects the insensitivity to the values of the c_i's in that limit.

Tension arises since, in order to generate viable neutrino masses from Eq. (5), one requires that $a \sim 1.80$–1.95. Values of $a < 2$ reintroduce some amount of tuning in the model and, for example, for $a = 1.95$, some ostensibly independent parameters of the 5D Higgs potential must be fixed to be equal to within about 1%. However this same tuning will also be responsible for generating a light enough Higgs mode compared to the KK scale [8]. In more general warped backgrounds this tension would easily disappear due to an enlarged parameter space, justifying the choice $a = 1.9$ throughout the rest of the paper.

We assume that all Yukawa matrices and fermion bulk masses from the 5D Lagrangian share the same symmetry structure, further broken by small terms i.e.

$$\mathbf{c}_f = \mathbf{c}^0_f + \delta\mathbf{c}_f \tag{6}$$

$$Y_Y = Y^0_Y + \delta Y_Y, \tag{7}$$