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A flavor sector for the composite Higgs

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ABSTRACT

We discuss flavor violation in large N Composite Higgs models. We focus on scenarios in which the masses of the Standard Model fermions are controlled by hierarchical mixing parameters, as in models of Partial Compositeness. We argue that a separation of scales between flavor and Higgs dynamics can be employed to parametrically suppress dipole and penguin operators, and thus effectively remove the experimental constraints arising from the lepton sector and the neutron EDM. The dominant source of flavor violation beyond the Standard Model is therefore controlled by 4-fermion operators, whose Wilson coefficients can be made compatible with data provided the Higgs dynamics approaches a "walking" regime in the IR. Models consistent with all flavor and electroweak data can be obtained with a new physics scale within the reach of the LHC. Explicit scenarios may be realized in a 5D framework, the new key ingredient being the introduction of flavor branes where the wave functions of the bulk fermions end.

1. Introduction

Flavor violation in Composite Higgs (CH) models [1] was originally implemented via Extended Ultracolor interactions [2],[1] and only more recently via the paradigm of Partial Compositeness [3].

The Extended Ultracolor picture postulates the existence of a *flavor sector* that mediates flavor-violating interactions between Standard Model (SM) and Ultracolor fermions at some high scale m_F. The effective field theory, renormalized at the scale $m_\rho \leqslant m_F$ where Ultracolor confines and the Higgs doublet H is formed, contains operators of the form

$$\mathscr{L}_{\text{EUC}} = \alpha\left(\frac{m_\rho}{m_F}\right)^{\Delta-1}\overline{f}Hf + \beta m_\rho^2\left(\frac{m_\rho}{m_F}\right)^{\Delta_{4\psi}-4}H^\dagger H + \frac{\gamma}{m_F^2}\overline{f}f\overline{f}f + \frac{\delta}{m_F^2}\left(\frac{m_\rho}{m_F}\right)^{\Delta-1}\overline{f}\sigma_{\mu\nu}F^{\mu\nu}Hf + \cdots. \quad (1)$$

Here f collectively refers to the SM fermion fields, whereas α, β, γ, δ are matrices in flavor space. In (1) we included the renormalization group effects induced by the strong Higgs dynamics and assumed that Ultracolor is in an approximate conformal phase below m_F, with Δ and $\Delta_{4\psi}$ denoting the scaling dimensions of the fields interpolating the Higgs and Higgs mass operators, respectively.

The picture (1) has very general applicability, but does not tell us anything about the actual flavor structure of the couplings α, β, γ, δ unless some assumption on the short distance physics is made. Partial Compositeness provides an efficient organizing principle for these couplings.

In models of Partial Compositeness one assumes the SM fermions couple *linearly* to composite operators of the Ultracolor sector via flavor-violating, anarchic couplings. [4] If the Higgs dynamics is nearly conformal for a large range of energies above m_ρ, then the mixing parameters can naturally be made hierarchical at low energies. The resulting effective field theory may still be formally written as in (1), but now with two important differences. First, in this model the flavor sector responsible for generating (1) is Ultracolor itself, so that the scale m_F coincides with m_ρ and the renormalization group factors in (1) disappear. Second, the matrices α, β, γ, δ are *hierarchical*, and can be employed to explain the SM fermion masses (see [5,6] for an implementation of this idea within 5D dual scenarios).

The assumption $m_F = m_\rho$ has the very attractive feature of relating flavor violation to the weak scale, and thus leading to a very predictive scenario. However, the stringent experimental bounds on the Wilson coefficients of the *dipole operators* – especially from $\mu \to e\gamma$, the electron EDM, and the neutron EDM – severely constrain such program [7–10].

The aim of this Letter is to show that these constraints can be significantly alleviated by considering scenarios in which both SM *and* Ultracolor fermions are partially composite states of a strongly

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[1] Following [1] we will refer to the theory of the fundamental constituents of the CH as Ultracolor, to distinguish it from Technicolor theories where the electroweak symmetry is not broken by a Higgs doublet.

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coupled, nearly conformal flavor sector characterized by a large dynamical mass m_F. In these scenarios the SM flavor problem can be addressed at a higher scale $m_F > m_\rho$, and the dangerous dipole operators in (1) suppressed by a renormalization group factor of order m_ρ^2/m_F^2 compared to conventional models of Partial Compositeness.

In Section 2 we present the model in detail. We then identify a class of realistic scenarios in Section 3, and discuss their dual 5D picture in Section 4. We finally conclude in Section 5.

2. The model

The main building blocks of our model are the SM fermion and gauge fields, a Higgs sector, and a *flavor sector*.

The Higgs sector is basically a copy of the one postulated in CH models [1], and consists of a strongly coupled Ultracolor theory that after chiral symmetry breaking delivers a Nambu–Goldstone boson (NGB) multiplet containing a field with the quantum numbers of the Higgs doublet.

The existence of a separate flavor sector is the main novelty of our approach to Partial Compositeness. The flavor sector is a strongly coupled and approximately conformal field theory. Its couplings to the SM fermions control the only source of flavor violation in the model.

The quantum numbers of the Ultracolor and flavor sectors are chosen in such a way that the SM and Ultracolor fermions dominantly communicate with each other via the weak gauging of the SM group and the nearly conformal flavor theory. At some high UV cutoff scale Λ the SM fermions f and the ultra-fermions ψ are assumed to couple linearly to composite operators $O_{f,\psi}$ of the flavor sector:

$$\lambda_f O_f f + \lambda_\psi O_\psi \psi + \text{h.c.}, \tag{2}$$

with $\lambda_{f,\psi}$ dimensionless parameters. No direct coupling between the fs and the ψs is present, up to irrelevant terms suppressed by inverse powers of the cutoff. These assumptions should be compared to those of the Partial Compositeness scenario of [4], where the operators $O_{f,\psi}$ themselves are composites of the ψs.

At much smaller scales the approximate conformal invariance of the flavor sector is broken and a dynamical mass of order $m_F \ll \Lambda$ is generated. We will assume that this phenomenon is not accompanied by the formation of light exotic states (see however the end of this section).

According to Naive Dimensional Analysis (NDA) [14], the low energy theory renormalized at the scale m_F contains (up to corrections suppressed by powers of m_F/Λ) the SM and Ultracolor Lagrangians plus

$$\mathscr{L}_{\text{EUC}} = \frac{m_F^4}{g_F^2}\widehat{\mathscr{L}}\left(\frac{\varepsilon_f g_F f}{m_F^{3/2}}, \frac{\varepsilon_\psi g_F \psi}{m_F^{3/2}}, \frac{D_\mu}{m_F}\right) + \cdots, \tag{3}$$

where $\widehat{\mathscr{L}}$ is a functions with order one entries and D_μ a covariant derivative. Here g_F is the coupling characterizing the strength of the flavor sector, and by NDA it satisfies

$$g_F \lesssim 4\pi, \tag{4}$$

with $g_F \ll 4\pi$ only in theories with a large number of fundamental constituents. Possible loop corrections of order $g_F^2/16\pi^2$ are included in the dots of (3).

The assumption that the theory can be characterized by a single coupling and a single scale is very restrictive, but should suffice to provide a quantitative understanding of the model.

The coefficients

$$\varepsilon_{f,\psi} \sim \frac{\lambda_{f,\psi}(m_F)}{g_F} \lesssim 1 \tag{5}$$

measure the amount of compositeness of the associated field, such that for $\varepsilon_{f,\psi} \sim 1$ the corresponding fermion behaves like a bound state of the strong flavor dynamics. The magnitude of the $\varepsilon_{f,\psi}$s is controlled by the RG evolution of the $\lambda_{f,\psi}$s from the cutoff scale down to $m_F \ll \Lambda$, and can naturally be hierarchical. The existence of hierarchical mixing parameters is at the heart of the Partial Compositeness solution to the SM flavor puzzle.

The Lagrangian (3) describes the dominant interactions (beyond those induced by the SM gauge group) between the Higgs sector fields ψ and the SM fermions f. The formal structure of $\mathscr{L}_{\text{EUC}}$ is analogous to the one in Extended Ultracolor models, see Eq. (1). The crucial new feature is the presence of the *hierarchical* flavor-violating parameters $\varepsilon_{f,\psi}$.

The rest of the Letter will be devoted to a detailed analysis of the effective field theory (3). While we derived (3) from the principles of Partial Compositeness, our results will be more general and will in fact apply to any theory of flavor leading to the form (3), such as for example Froggatt–Nielsen models.

The scenarios of Partial Compositeness studied in the previous literature can be recovered from (3) in the limit in which the mass scales and couplings of the flavor and Ultracolor sectors coincide, and $\varepsilon_\psi \to 1$.

2.1. Yukawa interactions

The ultra-fermion bilinear $\overline{\psi}\psi$ is assumed to be the operator with the lowest scaling dimension that interpolates the composite Higgs field. Using (3), we thus see that in our model the Yukawa matrices for the charged SM fields are effectively described by the following operators:

$$\frac{g_F^2}{m_F^2}\varepsilon_\psi^2 \varepsilon_{f_i^a}\varepsilon_{f_j^b}(\overline{\psi}\psi)_{m_F}\left(\overline{f_i^a} f_j^b\right) + \text{h.c.}, \tag{6}$$

with $f_i^a = q_i, u_i, d_i, \ell_i, e_i$ the five SM fermion representations and $i, j = 1, 2, 3$ family indices. Note that the above relation constrains the spurionic symmetries carried by the $\lambda_{f,\psi}$s. (The Yukawa operator (6) should be compared to the one found in the Partial Compositeness model of [4], where multiple insertions of the ultra-fermion bilinear typically appear.)

Non-hierarchical neutrino masses and mixing may be generated as discussed in [10]. In this Letter we will only be interested in the physics of the charged leptons and quarks, for which much stronger experimental constraints exist.

Including the RG flow down to the scale m_ρ at which the Ultracolor theory becomes strong and the Higgs doublet H emerges, and assuming approximate conformal invariance in the mass range $m_\rho < \mu < m_F$, we find that the Yukawa matrices arising from (6) have the structure anticipated in Eq. (1), namely

$$y_{ij} \sim \frac{g_F^2}{g_\rho}\varepsilon_\psi^2 \varepsilon_{f_i^a}\varepsilon_{f_j^b}\left(\frac{m_\rho}{m_F}\right)^{\Delta-1}. \tag{7}$$

Δ is the scaling dimension of the ultra-fermion bilinear, and g_ρ is the typical coupling among the resonances of the Higgs sector. Again, NDA suggests that $g_\rho \sim 4\pi$ in maximally strong theories, while $g_\rho < 4\pi$ in large N Ultracolor. In deriving (7) from (6) we adopted the NDA estimate $(\overline{\psi}\psi)_{m_\rho} \sim m_\rho^2 H/g_\rho$.

As in the standard scenarios of Partial Compositeness, the Yukawa matrix (7) can elegantly generate the SM flavor hierarchy. The new feature of our model is the existence of a universal suppression $(m_\rho/m_F)^{\Delta-1}$, which can be traced back to the irrelevance of the Yukawa interaction (6). Because of this suppression, it is generally *impossible* to decouple the flavor sector while keeping the SM fermion masses fixed. This is especially true in theories