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A three-site gauge model for flavor hierarchies and flavor anomalies

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ABSTRACT

We present a three-site Pati–Salam gauge model able to explain the Standard Model flavor hierarchies while, at the same time, accommodating the recent experimental hints of lepton-flavor non-universality in B decays. The model is consistent with low- and high-energy bounds, and predicts a rich spectrum of new states at the TeV scale that could be probed in the near future by the high-p_T experiments at the LHC.

1. Introduction

Recent data on semileptonic B decays indicate anomalous violations of Lepton Flavor Universality (LFU) of short-distance origin. The statistical significance of each anomaly does not exceed the 3σ level, but the overall set of deviations from the Standard Model (SM) predictions is very consistent. The evidences collected so far can naturally be grouped into two categories, according to the underlying quark-level transition: i) deviations from τ/μ (and τ/e) universality in $b \to c\ell\bar{\nu}$ charged currents [1–4]; ii) deviations from μ/e universality in $b \to s\ell\bar{\ell}$ neutral currents [5,6]. The latter turn out to be consistent [7,8] with the anomalies reported in the angular distributions of the $B^0 \to K^{*0}\mu^+\mu^-$ decay [9,10].

A common origin of the two set of anomalies is not obvious, but is very appealing from the theoretical point of view. Severals attempts to provide a combined explanation of the two effects have been presented in the recent literature [11–29]. Among them, a class of particularly motivated models are those based on TeV-scale new physics (NP) coupled mainly to the third generation of SM fermions, with subleading effects on the light generations controlled by an approximate $\mathrm{U(2)_Q} \times \mathrm{U(2)_L}$ flavor symmetry [30]. As recently shown in [31] (see also [13,17,26]), an Effective Field Theory (EFT) based on this flavor symmetry allows us to account for the observed semileptonic LFU anomalies taking into account the tight constraints from other low-energy data [32,33]. Moreover, the EFT fit singles out the case of a vector leptoquark (LQ) field $U_\mu \sim (\mathbf{3},\mathbf{1})_{2/3}$, originally proposed in [17], as the simplest and most successful framework with a single TeV-scale mediator (taking into account also the direct bounds from high-energy searches [34]).

While the results of Ref. [31] are quite encouraging, the EFT solution and the simplified models require an appropriate UV completion. In particular, the vector LQ mediator could be a composite state of a new strongly interacting sector, as proposed in [17,25], or a massive gauge boson of a spontaneously broken gauge theory, as proposed in [35–37]. In this paper we follow the latter direction.

Ultraviolet completions for the vector LQ mediator U_μ naturally point toward variations of the Pati–Salam (PS) gauge group, $\mathrm{PS} = \mathrm{SU(4)} \times \mathrm{SU(2)_L} \times \mathrm{SU(2)_R}$ [38], that contains a massive gauge field with these quantum numbers. The original PS model does not work since the (flavor-blind) LQ field has to be very heavy in order to satisfy the tight bounds from the coupling to the light generations. An interesting proposal to overcome this problem has been put forward in Ref. [36], with an extension of the PS gauge group and the introduction of heavy vector-like fermions, such that the LQ boson couples to SM fermions only as a result of a specific mass mixing between exotic and SM fermions.

A weakness of most of the explicit SM extensions proposed so far to address the B-physics anomalies, including the proposal of Ref. [36], is the fact that the flavor structure of the models is somehow ad hoc. This should be contrasted with the EFT solution of Ref. [31], which seems to point toward a common origin between flavor anomalies and the hierarchies of the SM Yukawa couplings. In this paper we try to address these problems together, proposing a model that is not only able to address the anomalies, but is also able to explain in a natural way the observed flavor hierarchies.

The model we propose is a three-site version of the original PS model. At high energies, the gauge group is $\mathrm{PS}^3 \equiv \mathrm{PS}_1 \times \mathrm{PS}_2 \times \mathrm{PS}_3$, where each PS group acts on a single fermion family. The spontaneous symmetry breaking (SSB) down to the SM group occurs in a series of steps characterized by different energy scales, which

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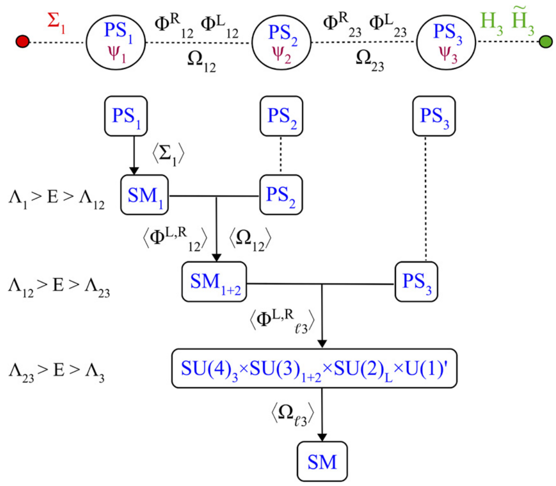

Fig. 1. Moose diagram of the model (up) and symmetry breaking sequence.

allow us to decouple the heavy exotic fields coupled to the first two generations at very high energies. As a result, the gauge group controlling TeV-scale dynamics contains a LQ field that is coupled mainly to the third generation (see Fig. 1). A key aspect of this construction is the hypothesis that electroweak symmetry breaking (EWSB) occurs via a Higgs field sitting only on the third-generation site: this assumption allows us to derive the hierarchical structure of the Yukawa couplings as a consequence of the hierarchies of the vacuum expectation values (VEVs) controlling the breaking of the initial gauge group down to the SM. In particular, the $U(2)_Q \times U(2)_L$ global flavor symmetry appears as a subgroup of an approximate flavor symmetry of the system emerging at low energies [$U(2)^5$]. Last but not least, the localization of the Higgs field on the third-generation site provides a natural screening mechanism for the Higgs mass term against the heavy energy scales related to the symmetry breaking of the heavy fields coupled to the light generations.

2. The model

The gauge symmetry of the model holding at high energies is $PS^3 \equiv PS_1 \times PS_2 \times PS_3$, where

$$PS_i = SU(4)_i \times [SU(2)_L]_i \times [SU(2)_R]_i \,. \tag{1}$$

The fermion content is the same as in the SM plus three right-handed neutrinos, such that each fermion family is embedded in left- and right-handed multiplets of a given PS_i subgroup:

$$\Psi_L^{(i)} \sim (\mathbf{4},\mathbf{2},\mathbf{1})_i \,, \qquad \Psi_R^{(i)} \sim (\mathbf{4},\mathbf{1},\mathbf{2})_i \,. \tag{2}$$

The subindex $i = 1, 2, 3$ denotes the site that, before any symmetry breaking, can be identified with the generation index.

The SM gauge group is a subgroup of the diagonal group, $PS_{diag} = PS_{1+2+3}$, which corresponds to the original PS gauge group. The SSB breaking $PS^3 \to SM$ occurs in a series of steps at different energy scales (see Fig. 1) with appropriate scalar fields acquiring non-vanishing VEVs, as described below.

I. High-scale *vertical breaking* [$PS_1 \to SM_1$].

At some heavy scale, $\Lambda_1 > 10^3$ TeV, the PS_1 group is broken to SM_1, where

$$SM_i = SU(3)_i \times [SU(2)_L]_i \times [U(1)_Y]_i \,, \tag{3}$$

by the VEV of a scalar field $\Sigma_1 \sim (\mathbf{4},\mathbf{1},\mathbf{2})_1$, charged only under PS_1 (or localized on the first site). Via this breaking 9 gauge fields with exotic quantum numbers (6 LQ fields, a $W_R^\pm$, and a Z', all coupled only to the first generation) acquire a heavy mass and decouple.

II. *Horizontal breaking* 1–2 [$SM_1 \times PS_2 \to SM_{1+2}$].

Gauge fields on different sites are broken to their diagonal subgroup via appropriate *link* fields, or scalar bilinears. On both links (1–2 and 2–3) we introduce the following set of link fields

$$\begin{aligned}
\Phi_{ij}^L &\sim (\mathbf{1},\mathbf{2},\mathbf{1})_i \times (\mathbf{1},\bar{\mathbf{2}},\mathbf{1})_j \,, \\
\Phi_{ij}^R &\sim (\mathbf{1},\mathbf{1},\mathbf{2})_i \times (\mathbf{1},\mathbf{1},\bar{\mathbf{2}})_j \,, \\
\Omega_{ij} &\sim (\mathbf{4},\mathbf{2},\mathbf{1})_i \times (\bar{\mathbf{4}},\bar{\mathbf{2}},\mathbf{1})_j \,,
\end{aligned} \tag{4}$$

such that

$$\begin{aligned}
\langle \Phi_{ij}^L \rangle \neq 0 &\Rightarrow [SU(2)_L]_i \times [SU(2)_L]_j \to [SU(2)_L]_{i+j} \,, \\
\langle \Phi_{ij}^R \rangle \neq 0 &\Rightarrow [SU(2)_R]_i \times [SU(2)_R]_j \to [SU(2)_R]_{i+j} \,, \\
\langle \Omega_{ij} \rangle \neq 0 &\Rightarrow \begin{cases} SU(4)_i \times SU(4)_j \to SU(4)_{i+j} \\ [SU(2)_L]_i \times [SU(2)_L]_j \to [SU(2)_L]_{i+j} \,. \end{cases}
\end{aligned}$$

At a scale $\Lambda_{12} < \Lambda_1$ the 1–2 link fields acquire a VEV. As a result, the vertical breaking occurring on the first site is mediated also to the second site, and the gauge symmetry is reduced to $SM_{1+2} \times PS_3$.

Thanks to this second breaking, 9 exotic gauge fields coupled mainly to the second generation, and 12 SM-like gauge fields coupled in a non-universal way to the first two families acquire a heavy mass and can be integrated out. Below the scale Λ_{12} the residual dynamical gauge sector is invariant under a global $U(2)^5$ flavor symmetry acting on the first two generations of SM fermions.[1]

At this stage there is still no local coupling between the fermions of the first two generations and the scalar fields sitting on the third site (H_3 and $\tilde{H}_3$) that contain the SM Higgs. In other words, we have not yet generated an effective Yukawa coupling for the light generations.

The hierarchy between Λ_1, Λ_{12}, and the VEVs of the 1–2 link fields does not need to be specified. The lower bound on the lowest of such scales, that we fix to be 10^3 TeV, is set by the tight limits on flavor-changing neutral currents involving the first two generations (most notably K–$\bar{K}$ and D–$\bar{D}$ mixing [39], and $K_L \to \mu e$ [40]). With this choice, we can ignore the effect of $d \geq 6$ effective operators generated at this scale.

III. *Horizontal breaking* 2–3 [$SM_{1+2} \times PS_3 \to SM$].

The scale characterizing the dynamics of the 2–3 link fields is $\Lambda_{23} \sim 10^2$ TeV. We assume a specific hierarchy among this scale and the VEVs of the link fields:

$$\Lambda_{23} > \langle \Phi_{23}^{L,R} \rangle > \langle \Omega_{23} \rangle \equiv \Lambda_3 \sim 1 \text{ TeV} \,. \tag{5}$$

This hierarchy is a key ingredient to generate the correct pattern for the Yukawa couplings (discussed in detail below) and, at the same time, address the flavor anomalies.

At energies $\langle \Phi_{23}^{L,R} \rangle > E > \Lambda_3$ we can decouple a $W_L^\pm$, a $W_R^\pm$, and two Z' fields with mass of $\mathcal{O}(10 \text{ TeV})$, that are too heavy to be probed at colliders and have no impact on flavor physics because of the $U(2)^5$ flavor symmetry.

Below Λ_{23}, the dynamical gauge group is reduced to

$$\mathcal{G} = SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)' \,. \tag{6}$$

[1] At $E < \Lambda_{12}$ mass terms for the right-handed neutrinos of the first two generations are allowed. We thus integrate out also $\nu_{1,2}^R$ remaining with 5 independent species of massless fermions charged under SM_{1+2}.