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A three-site model for B anomalies and flavour hierarchies

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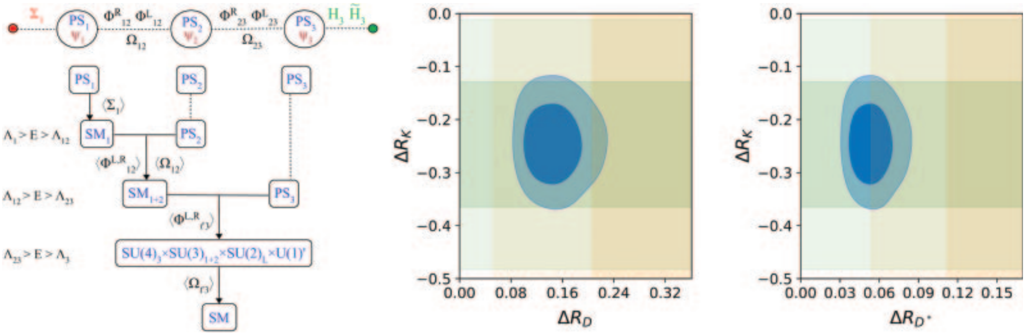
Summary. — We present a New Physics model based on a three-site deconstruction of the Pati-Salam gauge group. The model addresses the recent experimental hints of lepton-flavour non-universality in B decays, connecting the observed anomalies to the origin of the flavour hierarchies in the Standard Model. Moreover, it predicts a well-defined pattern of non-standard effect in low-energy observables and presents a rich spectrum of new states at the TeV scale. Such signatures could be probed in present and future low- and high-energy experiments.

1. – Introduction

In the recent years, various experimental Collaborations reported hints of Lepton Flavour Universality (LFU) violation in semileptonic B decays. These results can be grouped into two main categories: i) deviations from τ/μ (and τ/e) universality in $b \to c\ell\nu$ charged-current transitions, encoded in the ratio $R_{D^{(*)}}$ [1-4]; ii) deviations from μ/e universality in $b \to s\ell\ell$ neutral currents, measured in $R_{K^{(*)}}$ [5, 6]. The latter are consistent [7, 8] with the anomalies reported in the angular distributions of the $B^0 \to K^{*0}\mu^+\mu^-$ decay [9, 10].

Taken together, B anomalies represent a very coherent set of deviations from the Standard Model (SM), hence a common origin of both anomalies in terms of New Physics (NP) is very interesting from the theoretical point of view. Models aiming at such a combined explanation typically rely on TeV-scale NP coupled mainly to the third generation of SM fermions. Particularly motivated are attempts involving a vector leptoquark (LQ) $U_\mu \sim (\mathbf{3}, \mathbf{1})_{2/3}$ [11-17]. If interpreted as massive gauge boson of a spontaneously broken gauge symmetry, possible UV completions for the LQ naturally point towards variations of the Pati-Salam (PS) gauge group, PS $= SU(4) \times SU(2)_L \times SU(2)_R$ [18]. However, the PS leptoquark couples universally to the three fermion families, hence the tight bounds arising from light generation couplings force it to be too heavy to be a good candidate for the explanation of B anomalies.

Here we present a three-site variation of the original PS model, $\mathrm{PS}^3 \equiv \mathrm{PS}_1 \times \mathrm{PS}_2 \times \mathrm{PS}_3$, where each PS_i acts on a different fermion family [19, 20]. The spontaneous symmetry



(a) (b)

Fig. 1. – (a) Moose diagram of the model (top) and symmetry breaking sequence. (b) 68% (dark blue) and 95% (light blue) posterior probabilities of the NP shifts in $R_{D^{(*)}}$ *vs.* ΔR_K. The experimental values at 1σ (2σ) are indicated by the dark (light) coloured bands.

breaking (SSB) $\mathrm{PS}^3 \to \mathrm{SM}$ occurs in steps characterized by different energy scales, yielding a TeV-scale LQ coupled dominantly to the third family. This breaking also controls the breaking of the accidental $U(2)^5$ flavour symmetry of the gauge sector, implying an interesting connection among B anomalies and SM flavour hierarchies. After describing the model structure, we discuss its phenomenological implications, focusing in particular on low-energy observables.

2. – The PS^3 model

We assume that the gauge symmetry of the model holding at high energy is $\mathrm{PS}^3 \equiv \mathrm{PS}_1 \times \mathrm{PS}_2 \times \mathrm{PS}_3$, where $\mathrm{PS}_i = SU(4)_i \times [SU(2)_L]_i \times [SU(2)_R]_i$. Each fermion family is embedded in a left- and a right-handed multiplet of a given PS_i subgroup: $\Psi_L^i \sim (\mathbf{4},\mathbf{2},\mathbf{1})_i$ and $\Psi_R^i \sim (\mathbf{4},\mathbf{1},\mathbf{2})_i$. Spontaneous symmetry breaking to the SM occurs stepwise via scalar fields acquiring a non-vanishing vev, as shown in fig. 1(a). In particular we distinguish among vertical breakings, corresponding to the breaking of the gauge group within a given site, and horizontal breakings, which refer to the breaking of gauge groups of adjacent sites to the diagonal subgroup. The latter occur via scalar bilinears or *link* fields, $\Phi_{ij}^L \sim (\mathbf{1},\mathbf{2},\mathbf{1})_i \times (\mathbf{1},\bar{\mathbf{2}},\mathbf{1})_j$, $\Phi_{ij}^R \sim (\mathbf{1},\mathbf{1},\mathbf{2})_i \times (\mathbf{1},\mathbf{1},\bar{\mathbf{2}})_j$ and $\Omega_{ij} \sim (\mathbf{4},\mathbf{2},\mathbf{1})_i \times (\bar{\mathbf{4}},\bar{\mathbf{2}},\mathbf{1})_j$, with $i,j =$ 1-2 and 2-3. The vertical breaking $\mathrm{PS}_1 \to \mathrm{SM}_1$ occurs at some heavy scale $\Lambda_1 > 10^3$ TeV due to the vev of the scalar field $\Sigma_1 \sim (\mathbf{4},\mathbf{1},\mathbf{2})_1$; such breaking is propagated to the second site by the vev of the 1-2 link fields. At this stage the gauge symmetry is $\mathrm{SM}_{1+2} \times \mathrm{PS}_3$, hence the gauge sector of the theory has an accidental $U(2)^5$ flavour symmetry acting on the first and second generation of fermions. The breaking to the SM occurs via the vevs of the 2-3 link fields, among which we assume the hierarchical pattern $\langle \Phi_{23}^{L,R} \rangle > \langle \Omega_{23} \rangle$. Finally, electroweak symmetry breaking is achieved via an effective $SU(2)_L$ Higgs field, emerging as a light component from two scalar fields sitting on the third site, $H_3 \sim (\mathbf{15},\mathbf{2},\bar{\mathbf{2}})_3$ and $\tilde{H}_3 \sim (\mathbf{1},\mathbf{2},\bar{\mathbf{2}})_3$.

The new massive gauge bosons relevant for phenomenology are those generated in the second to last step of this breaking chain, namely $SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)' \to$ SM, triggered by $\langle \Omega_{23} \rangle \neq 0$. This breaking occurs at the TeV scale and gives rise to three new massive spin-1 fields, with masses in the range 1–3 TeV: a leptoquark $U \sim (\mathbf{3},\mathbf{1})_{2/3}$, a coloron $G' \sim (\mathbf{8},\mathbf{1})_0$ and a $Z' \sim (\mathbf{1},\mathbf{1})_0$.

An important aspect of the model is the deep connection among the Yukawa couplings structure and the breaking pattern. Since the Higgs is localised on the third site, only Yukawa terms for third-generation fermions are allowed at a renormalizable level; Yukawa couplings for lighter families arise from higher-dimensional operators generated below $\Lambda_{23} \sim 100$ TeV, as the vevs of the 2-3 link fields break the $U(2)^5$ flavour symmetry. Including operators up to dimension six, the resulting structure for the Yukawa couplings is

$$Y_f = \begin{pmatrix} y_\ell^f \dfrac{\langle \Phi_{\ell 3}^L \rangle \langle \Phi_{3\ell}^R \rangle}{\Lambda_{23}^2} & y_{3\ell}^f \dfrac{\langle \Omega_{\ell 3} \rangle}{\Lambda_{23}} \\ 0 & y_3^f \end{pmatrix}, \tag{1}$$

which leads to a good description of SM Yukawa couplings in terms of vev ratios and $\mathcal{O}(1)$ parameters.

The breaking of $U(2)^5$ due the heavy 2-3 dynamics generates additional higher-dimensional operators which induce a small interaction among the new massive bosons and light-fermion families, thus playing an essential role in low-energy phenomenology, in particular in the explanation of the anomalies in $b \to s\ell\ell$.

3. – Low-energy phenomenology

Despite the apparent complexity of the construction, NP effects relevant for collider and low-energy phenomenology are ultimately controlled by the TeV-scale breaking of the gauge symmetry. The massive gauge bosons appearing at this scale (U, G and Z') couple dominantly to third-generation fermions; the full flavour structure of their couplings is determined by the $U(2)^5$ symmetry and by the small breaking terms mentioned above. The resulting phenomenology is described in terms of a limited number of parameters, which can be constrained by performing a global fit to low-energy observables.

The NP contribution to $b \to c(u)\tau\nu$ transitions is entirely due to the leptoquark and is encoded in the effective Lagrangian

$$\begin{aligned} \mathcal{L}(b \to u_i \ell \bar{\nu}) = -\frac{4G_F}{\sqrt{2}} \Big(& \big[\mathcal{C}_{\nu edu}^{\mathrm{V,LL}}\big]_{333i}^* (\overline{\tau}_L \gamma^\mu \nu_{L3})(\overline{u}_{iL} \gamma_\mu b_L) \\ & + \big[\mathcal{C}_{\nu edu}^{\mathrm{S,RL}}\big]_{333i}^* (\overline{\tau}_R \nu_{L3})(\overline{u}_{iL} b_R) \Big) . \end{aligned} \tag{2}$$

The scalar operator arises due to the unsuppressed right-handed leptoquark currents and constitutes an important difference with respect to other models aiming at a combined explanation of B anomalies. Its presence determines a departure from a purely $V - A$ structure, hence a non-universal scaling in the NP contribution to R_D and R_{D^*},

$$\begin{aligned} \Delta R_D &\approx 2\, C_U \times (1 + 2.1), \\ \Delta R_{D^*} &\approx 2\, C_U \times (1 + 0.17), \end{aligned} \tag{3}$$

where C_U is a Fermi-like coupling encoding the overall strength of the leptoquark interaction. This operator also induces a chirally enhanced NP contribution to $B \to \tau\nu$, yielding an enhancement of the branching ratio ranging from $\mathcal{O}(30\%)$ up to $\mathcal{O}(100\%)$ of the SM prediction.

Concerning $b \to s\ell\ell$ transitions, the Z'-mediated contribution is negligible due to the constraints arising from $\Delta B = 2$ observables. The main contribution to such transitions comes therefore from the leptoquark, via the dimension-six operators mentioned at the end of the previous section. Moreover, the model predicts a similar NP contribution in $b \to s\mu\mu$ and $b \to s\tau\tau$, as well as large LFV effects in $\tau \to \mu$ transitions, both in τ decays (in particular in $\tau \to \mu\gamma$, $\tau \to 3\mu$) and in B decays ($B_s \to \tau\mu$ and $B \to K\tau\mu$).

Overall, PS^3 is found to be in very good agreement with all existing low-energy bounds. As can be seen from the fit in in fig. 1(b), the model can fully accommodate the anomalies in $b \to s\ell\ell$ transitions. However, the central value for $R_{D^{(*)}}$ cannot be achieved due to the bounds from LFU tests in τ decays.

As to high-p_T phenomenology, we observe that the masses of the new vector bosons predicted by the model lie around the TeV scale, and are therefore within the reach of present and future searches at the LHC. In this regard, an important feature of these states is their large width, which can hinder their detection.

4. – Conclusions

In conclusion, the PS^3 model offers a consistent framework for the explanation of B anomalies, compatible with experimental constraints and connected to the structure of Yukawa couplings. The model has interesting implications for future low-energy measurements: concerning charged current processes, it implies a different scaling of the NP contribution in R_D and R_{D^*}, and a possible large enhancement in $\mathcal{B}(B \to \tau\nu)$; as to neutral currents, it predicts sizeable rates for LFV processes of the type $\tau \to \mu$.

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