Modified Pati-Salam model for flavor anomalies

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1. Introduction

One of the most significant direct evidences of physics beyond the standard model (SM) are the recently observed anomalies in B meson decays, which suggest a lepton flavor universality (LFU) violation. Assuming that those anomalies are not the product of systematic errors, they can be explained by a vector leptoquark (LQ) $(3,1)_{2/3}$, which can arise from grand unification theories such as the Pati-Salam model. We study a Pati-Salam based model that aims at explaining the LFU violations. It is based on the local gauge group $\mathrm{SU}(4)_L \times \mathrm{SU}(4)_R \times \mathrm{SU}(2)_L \times \mathrm{U}(1)'$ and its key feature is that $\mathrm{SU}(4)_R$ breaks at a much higher energy scale than $\mathrm{SU}(4)_L$, avoiding right handed flavor changing currents and allowing a mass of the LQ as low as 10 TeV. The model does not require the introduction of quarks or leptons mixings with new vector-like fermions. We present a detailed study of this model, obtain constraints from the C_9 and C_{10} pseudo-observables, and constrast them against a model independent analysis.

2. Local Gauge group

The model was first proposed in [1] and it includes two $\mathrm{SU}(4)_{L/R}$ groups which break to $\mathrm{SU}(3)_C$

$$\underbrace{\mathrm{SU}(4)_L \otimes \mathrm{SU}(4)_R}_{\text{color}} \otimes \underbrace{\mathrm{SU}(2)_L}_{\text{isospin}} \otimes \mathrm{U}(1)' .$$

The key feature of the model is that $\mathrm{SU}(4)_R$ breaks at a much higher energy scale than $\mathrm{SU}(4)_L$, avoiding right-handed flavor changing currents and lowering the mass of the LQ.

3. Particle content

The decomposition of the initial gauge group into SM particles results in

$$\begin{aligned} \hat{\Psi}_L &= (4,\,1,\,2,\,0) &&= (3,\,2)_{\frac{1}{6}} \oplus (1,\,2)_{-\frac{1}{2}} ,\\ \hat{\Psi}^u_R &= (1,\,4,\,1,\,\tfrac{1}{2}) &&= (3,\,1)_{\frac{2}{3}} \oplus (1,\,1)_0 ,\\ \hat{\Psi}^d_R &= (1,\,4,\,1,\,-\tfrac{1}{2}) &&= (3,\,1)_{-\frac{1}{3}} \oplus (1,\,1)_{-1} , \end{aligned}$$

Where $\hat{\Psi}_L$, $\hat{\Psi}^u_R$, $\hat{\Psi}^u_L$ contain the fields Q_L, L_L, u_R, d_R, e_R and a right-handed neutrino ν_R.

4. SU(4) generators

The generators are normalized according to $\mathrm{Tr}(T_i T_j) = (1/2)\delta_{ij}$.
The first eight generators are constructed such that their first three rows and columns coincide with the Gell-Mann matrices, which are the usual SU(3) group generators. They describe color interactions, for instance

$$T_1 = \frac{1}{2}\tilde{\lambda}_1 = \frac{1}{2}(C_{12}+C_{21}) = \frac{1}{2}\begin{pmatrix} 0&1&0& \\ 1&0&0& \\ 0&0&0& \\ &&& \end{pmatrix} .$$

The generators describing transitions between quarks and leptons have non-zero entrances in their fourth row and column, for instance

$$T_9 = \frac{1}{2}\tilde{\lambda}_9 = \frac{1}{2}(C_{14}+C_{41}) = \frac{1}{2}\begin{pmatrix} &&&1 \\ &&&0 \\ &&&0 \\ 1&0&0& \end{pmatrix}$$

And the diagonal generator, which gives the charge of the U(1) resulting upon the breaking of SU(4) to the color group

$$T_{15} = \frac{1}{2\sqrt{6}}\tilde{\lambda}_{15} = \frac{1}{2\sqrt{6}}\begin{pmatrix} 1&&& \\ &1&& \\ &&1& \\ &&&-3 \end{pmatrix} .$$

5. Charge operator

Decomposition of SU(4)

$$\mathrm{SU}(4)_{L/R} \to \mathrm{SU}(3)_{L/R} \otimes \mathrm{U}(1)_{L/R\,31} .$$

Charge operator defined as

$$Q = (t^3) + A(T^{15}_L + T^{15}_R) + BY' ,$$

For instance, for $\hat{\Psi}_L$

$$(Q\Psi_L)^{i\alpha} = \left[(t^3)^\alpha_\beta \delta^i_j + A(T^{15}_L)^i_j \delta^\alpha_\beta + 0\right]\Psi^{j\beta}_L .$$

Obtaining the coefficients we arrive at the charge operator

$$Q = t^3 + \frac{\sqrt{6}}{3}(T^{15}_L + T^{15}_R) + Y' .$$

which can be represented as two 4×4 matrices

$$Q^u = \begin{pmatrix} \frac{2}{3}&&& \\ &\frac{2}{3}&& \\ &&\frac{2}{3}& \\ &&&0 \end{pmatrix}, \quad Q^d = \begin{pmatrix} -\frac{1}{3}&&& \\ &-\frac{1}{3}&& \\ &&-\frac{1}{3}& \\ &&&-1 \end{pmatrix}$$

6. Interaction Lagrangian

$$\mathcal{L} \supset \overline{\hat{\Psi}}_L \gamma^\mu \mathrm{D}_\mu \hat{\Psi}_L + \overline{\hat{\Psi}}{}^u_R \mathrm{i}\gamma^\mu \mathrm{D}_\mu \hat{\Psi}^u_R + \overline{\hat{\Psi}}{}^d_R \mathrm{i}\gamma^\mu \mathrm{D}_\mu \hat{\Psi}^d_R ,$$

where the covariant derivative is

$$\mathrm{D}_\mu = \partial_\mu + \mathrm{i}g_L G^A_{L\mu} T^A_L + \mathrm{i}g_R G^A_{R\mu} T^A_R + \mathrm{i}g_2 W^a_\mu t^a + \mathrm{i}g'_1 Y'_\mu Y' ,$$

7. LQ eigenstates

$$\mathbb{G}_{L/R\,\mu} \equiv G^A_{L/R\,\mu} T^A_{L/R} .$$

$$\mathbb{G} = \frac{1}{\sqrt{2}} \left(\begin{array}{ccc|c} & & & X^1 \\ & \frac{1}{\sqrt{2}}\sum_{A=1}^{8} G^A_\mu T^A & & X^2 \\ & & & X^3 \\ \hline X^{1*} & X^{2*} & X^{3*} & \frac{\sqrt{3}}{2} G^{15}_\mu \end{array}\right)$$

$$X = \begin{pmatrix} X^1 \\ X^2 \\ X^3 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(G^9_\mu - \mathrm{i}G^{10}_\mu) \\ \frac{1}{\sqrt{2}}(G^{11}_\mu - \mathrm{i}G^{12}_\mu) \\ \frac{1}{\sqrt{2}}(G^{13}_\mu - \mathrm{i}G^{14}_\mu) \end{pmatrix} .$$

The mass matrix

$$\mathcal{M}^2_X = \frac{1}{4}\begin{pmatrix} g^2_L[v^2_L + v^2_\Sigma(1+z^2)] & -2g_L g_R v^2_\Sigma z \\ -2g_L g_R v^2_\Sigma z & g^2_R[v^2_R + v^2_\Sigma(1+z^2)] \end{pmatrix}$$

8. Phenomenological analysis

$$\mathcal{L} \supset \frac{g_L}{\sqrt{2}} X_L \left[x^{ij}_{Lu}(\overline{u}_i \gamma^\mu \nu_j) + x^{ij}_{Ld}(\overline{d}_i \gamma^\mu \ell_j)\right] + \text{h.c.} ,$$

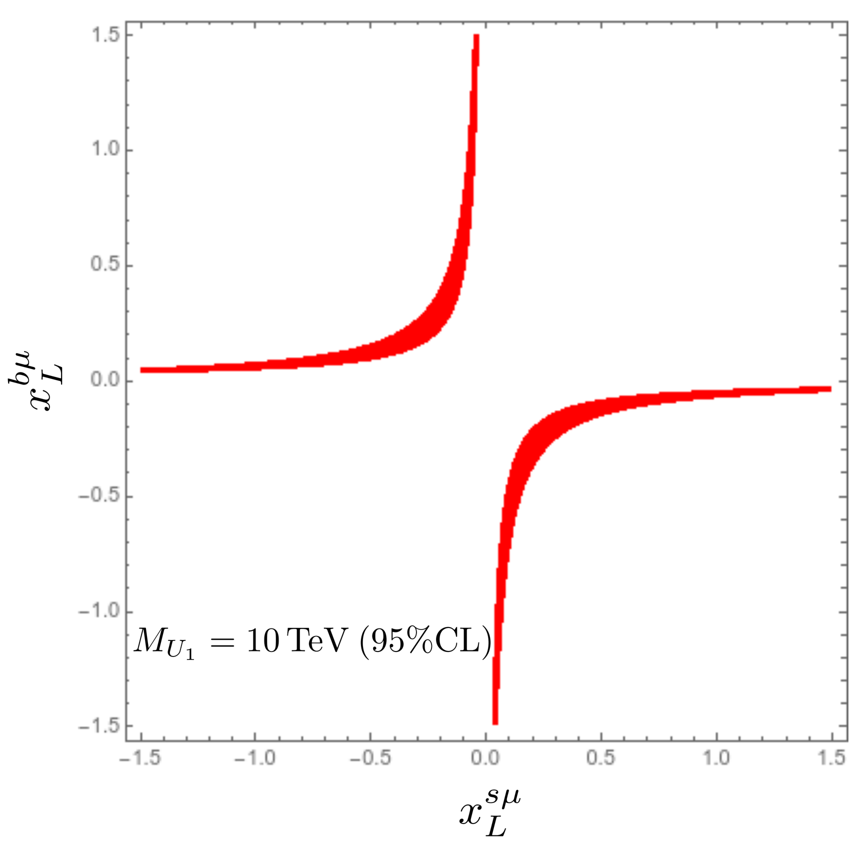
The R_K anomaly involves the transition $b \to s\mu^+\mu^-$ via the effective Hamiltonian

$$\mathcal{H}_{\text{eff}}(b \to s\mu^+\mu^-) = -\frac{\alpha_{\mathrm{em}G_F}}{\sqrt{2}\pi} V_{tb} V^*_{ts} \times \Big[C^{bs\mu\mu}_9 (\overline{s}P_L \gamma_\beta b)(\overline{\mu}\gamma^\beta \mu) + C^{bs\mu\mu}_{10} (\overline{s}P_L \gamma_\beta b)(\overline{\mu}\gamma^\beta \gamma_5 \mu)\Big]$$

where

$$C^{bs\mu\mu}_9 = -C^{bs\mu\mu}_{10} = -\frac{\pi}{\sqrt{2}G_F \alpha_{\mathrm{em}} V_{tb} V^*_{ts}} \frac{x^{s\mu}_L \left(x^{b\mu}_L\right)^*}{M^2_{U_1}}$$

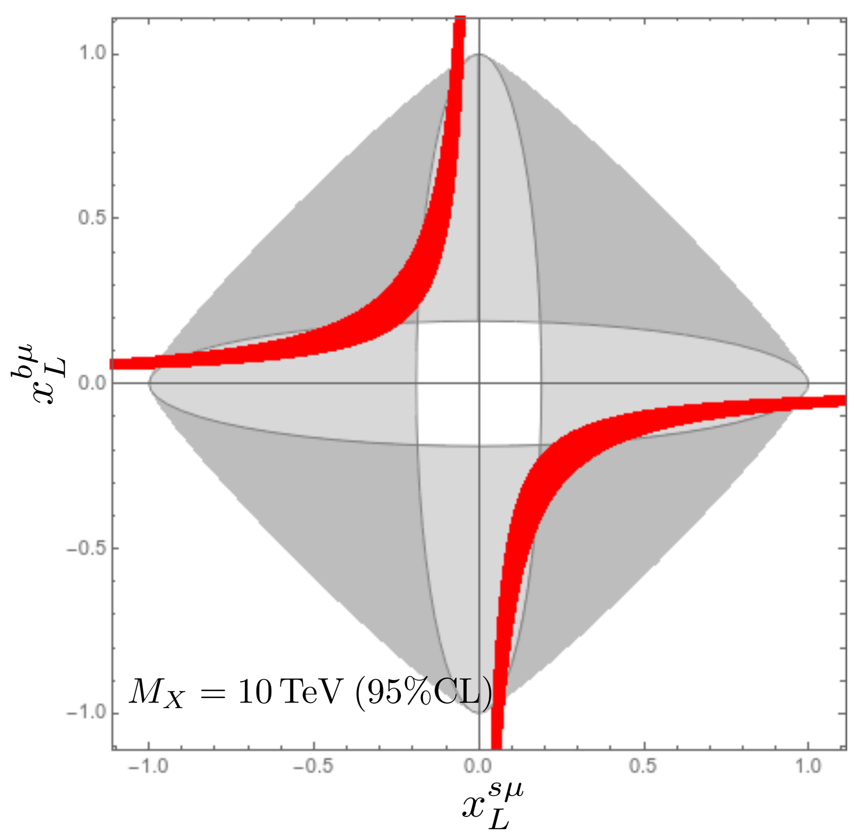
Model independent:



Parameterizing the couplings matrix as

$$x_{Ld} \approx \mathrm{e}^{\mathrm{i}\phi}\begin{pmatrix} \delta_1 & \delta_2 & 1 \\ \mathrm{e}^{\mathrm{i}\phi_1}\cos\theta & \mathrm{e}^{\mathrm{i}\phi_2}\sin\theta & \delta_3 \\ -\mathrm{e}^{\mathrm{i}\phi_2}\sin\theta & \mathrm{e}^{\mathrm{i}\phi_1}\cos\theta & \delta_4 \end{pmatrix} ,$$

we find for this model



9. References

[1] B. Fornal et al. Left-Right SU(4) Vector Leptoquark Model for Flavor Anomalies. *Phys. Rev. D*, 99(5):055025, 2019.