Modified Pati-Salam model for flavor anomalies

Oscar Rosero and Eduardo Rojas

Department of Physics, Universidad de Nariño, Pasto, Colombia

odroseroc@gmail.com

Universidad de Nariño FUNDADA EN 1904

Departamento de Física

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 model within the Pati-Salam unification framework 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

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

8. Phenomenological analysis

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

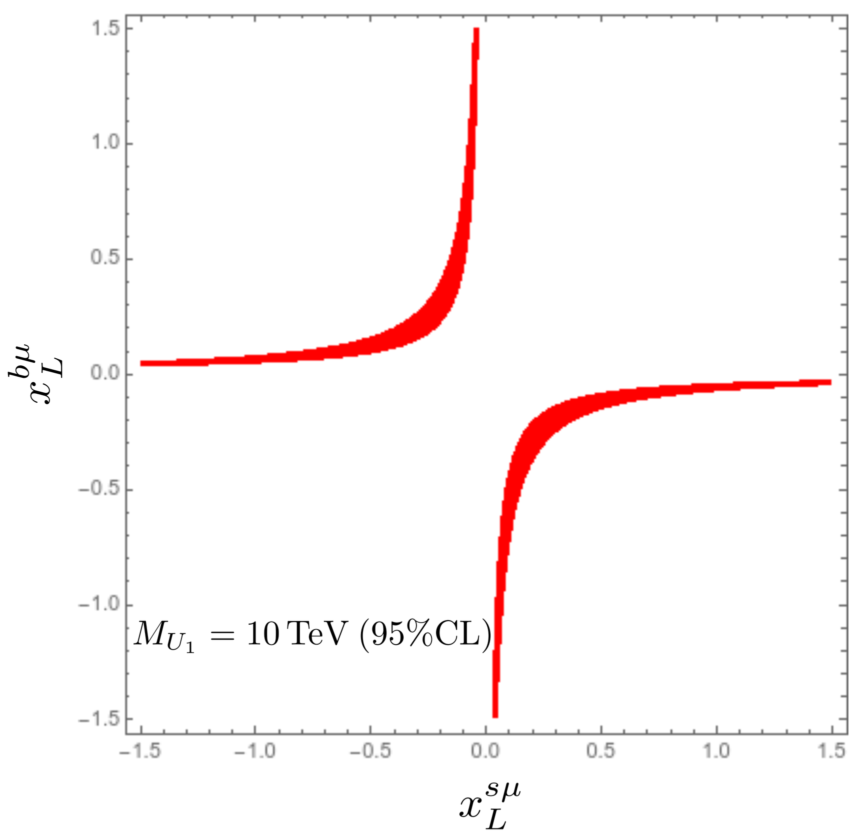
The R_K anomaly involves the transition $b \to s\mu^+\mu^-$ via the effective Hamiltonian

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

where

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

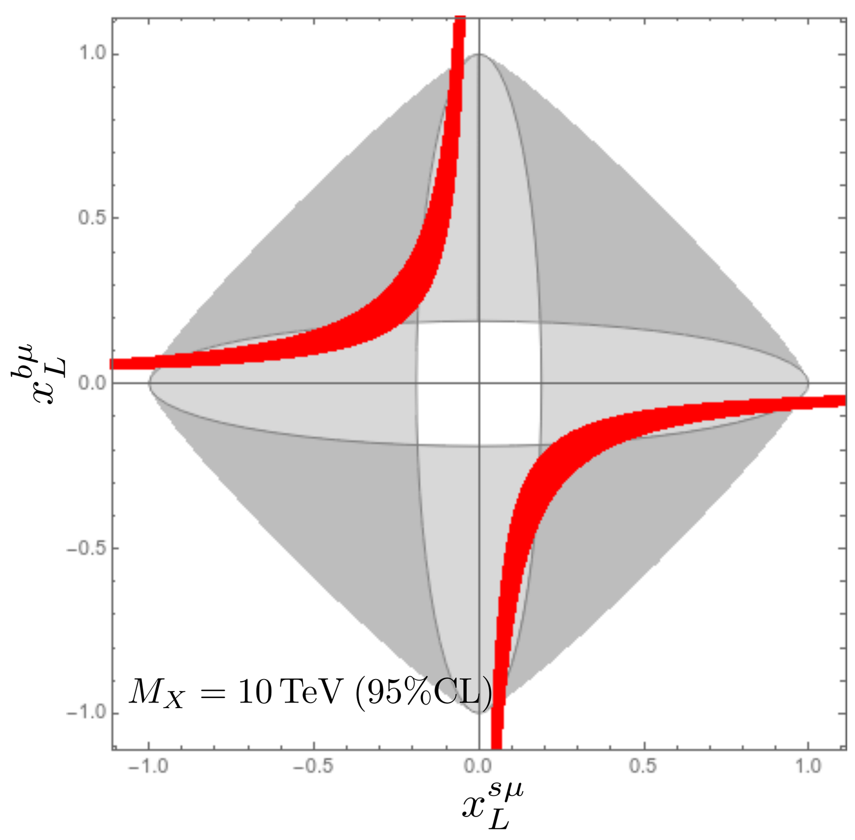
Model independent:



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.