$\mathrm{SU}(4)$ weak singlet leptoquark in $R_{K^{(*)}}$ flavor anomalies

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Contenido

Introduction

Introduction

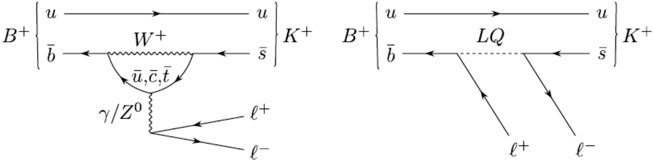
- The standard model (SM) provides a remarkably successful description of nature at the level of elementary particles.
- Most significant experimental hints of physics beyond the SM are the anomalies in B-meson decays $\rightarrow$ Lepton flavor universality (LFU) violation.
- These anomalies can be explained with a $(3,1)_{2/3}$ vector leptoquark (LQ).
- Goal of this work: to study a viable model based upon the Pati-Salam unification that does not involve mixing with new vector-like fermions.

Introduction

B-meson decays and flavor anomalies

B-meson decays and flavor anomalies

- New physics (NP) searches from comparisons between observed measurements and the SM predictions.
- Measurable quantities can be predicted accurately predicted in decays of a charged B^+ meson $(u\bar{b})$ into a kaon $K^+(u\bar{s})$ and two charged leptons ℓ^-, ℓ^+.
- LFU is an accidental symmetry of the SM.



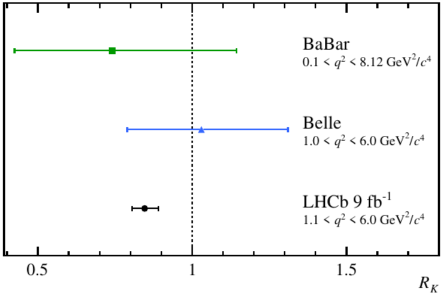
Contributions of the SM and NP to B-meson decays (Source: Nature Phys. 18 (2022) 3, 277-282).

B-meson decays and flavor anomalies

- Branching fractions for two semi-leptonic decay modes

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} .$$

- LHCb 2021 measurements: $R_K = 0{,}846\,^{+0{,}044}_{-0{,}041}$, $3{,}1$ standard deviations away from SM predictions.



Comparison between R_K measurements (Source: Nature Phys. 18 (2022) 3, 277-282).

Study of the model

Model and particle content

The model we study was proposed by Fornal, et.al. (Phys. Rev. D 99, 055025 (2019)), it is based on the gauge local group

$$\mathrm{SU}(4)_L \otimes \mathrm{SU}(4)_R \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)'$$

Decomposition into the SM particles

$$\Psi_L = (4,1,2,0) = (3,2)_{\frac{1}{6}} \oplus (1,2)_{-\frac{1}{2}}$$
$$\Psi_R^u = (1,4,1,\tfrac{1}{2}) = (3,1)_{\frac{1}{6}} \oplus (1,1)_0$$
$$\Psi_R^d = (1,4,1,-\tfrac{1}{2}) = (3,1)_{-\frac{1}{3}} \oplus (1,1)_{-1}$$

Contain Q_L, L_L, u_R, d_R, e_R and a right-handed neutrino ν_R.

Higgs sector

$$\Sigma_L = (4,1,1,\tfrac{1}{2}), \quad \Sigma_R = (1,4,1,\tfrac{1}{2}),$$
$$\Sigma = (\bar{4},4,1,0)$$

The key feature of this model is that $\mathrm{SU}(4)_R$ breaks at a much higher energy scale than $\mathrm{SU}(4)_L$.

Left-handed fermions

The SM fermions are combined into fundamental representations of $\mathrm{SU}(4)_L$

$$\begin{pmatrix} u^1 \\ u^2 \\ u^3 \\ \nu \end{pmatrix}_{Lf} , \quad \begin{pmatrix} d^1 \\ d^2 \\ d^3 \\ \ell \end{pmatrix}_{Lf} , \quad f = 1, 2, 3 \, .$$

Left-handed fermions form fundamental representations of $\mathrm{SU}(2)_L$

$$\begin{pmatrix} u^c \\ d^c \end{pmatrix}_L , \quad \begin{pmatrix} \nu \\ \ell \end{pmatrix}_L .$$

The three fermion generations are grouped into the $\{4, 2\}$ representation of the $\mathrm{SU}(4)_L \otimes \mathrm{SU}(2)_L$ group:

$$\begin{pmatrix} u^c & d^c \\ \nu & \ell \end{pmatrix}_f ,$$

Charge operator

Following sponteneous symmetry breaking of the $\mathrm{SU}(4)_{L/R}$ groups to $\mathrm{SU}(3)_c$:

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

six massive gauge bosons decouple from the initial 15-plet of gauge fields and form three charged coloured leptoquarks.

The 15th $\mathrm{SU}(4)_{L/R}$ generator contributes to the charge operator. Normalized as $\mathrm{Tr}\left(T^i T^j\right) = \frac{1}{2}\delta^{ij}$, this generator is given by

$$T_L^{15} = T_R^{15} = \frac{1}{2\sqrt{6}} \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -3 \end{pmatrix}. \tag{2}$$

Charge operator

The charge operator of the model is given by

$$Q = t^3 + \underbrace{\frac{\sqrt{6}}{3}\left(T_L^{15} + T_R^{15}\right) + Y'}_{\text{SM hypercharge } Y}, \tag{3}$$

In the fundamental representation of $\mathrm{SU}(4)$ this operator can be represented by two matrices

$$Q^u = \begin{pmatrix} \frac{2}{3} & & & \\ & \frac{2}{3} & & \\ & & \frac{2}{3} & \\ & & & 0 \end{pmatrix}, \quad Q^d = \begin{pmatrix} -\frac{1}{3} & & & \\ & -\frac{1}{3} & & \\ & & -\frac{1}{3} & \\ & & & -1 \end{pmatrix} \tag{4}$$

Charge eigenvalues of the $\mathrm{SU}(4)$ gauge bosons

Considering the adjoint representation of $\mathrm{SU}(4)$, to which the leptoquarks belong,

$$4 \times \bar{4} = 1 + 15\,.$$

The eigenvalues of the charge operators in this representation are given by

$$Q^{[15]}_{kl} = Q^{[4]}_{k} + Q^{[\bar{4}]}_{l} = +Q^{[4]}_{k} - Q^{[4]}_{l}$$

$$Q^{[4]\,u} = \begin{pmatrix} \frac{2}{3} & & & \\ & \frac{2}{3} & & \\ & & \frac{2}{3} & \\ & & & 0 \end{pmatrix}, \quad Q^{[4]\,d} = \begin{pmatrix} -\frac{1}{3} & & & \\ & -\frac{1}{3} & & \\ & & -\frac{1}{3} & \\ & & & -1 \end{pmatrix} \qquad Q^{[15]}_{kl} = \begin{pmatrix} 0 & 0 & 0 & \frac{2}{3} \\ 0 & 0 & 0 & \frac{2}{3} \\ 0 & 0 & 0 & \frac{2}{3} \\ -\frac{2}{3} & -\frac{2}{3} & -\frac{2}{3} & 0 \end{pmatrix}$$

Interaction Lagrangian

From the initial symmetry of the model we infer the following 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 has the form

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

$\mathrm{SU}(4)$ gauge bosons

Taking the $\mathrm{SU}(4)_{L/R}$ terms of the interaction Lagrangian

$$\mathrm{i} g_L G^A_{L\mu} T^A_L + \mathrm{i} g_R G^A_{R\mu} T^A_R \tag{5}$$

Let

$$\mathbb{G}_{L/R\,\mu} \equiv G^A_{L/R\,\mu} T^A_{L/R} \,. \tag{6}$$

$$\mathbb{G}_\mu = \frac{1}{\sqrt{2}} \left(\begin{array}{ccc|c} & & & X^1_\mu \\ & \frac{1}{\sqrt{2}} \sum_{A=1}^{8} G^A_\mu T^A & & X^2_\mu \\ & & & X^3_\mu \\ \hline X^{1*}_\mu & X^{2*}_\mu & X^{3*}_\mu & \frac{\sqrt{3}}{2} G^{15}_\mu \end{array} \right) , \quad X_\mu = \begin{pmatrix} X^1_\mu \\ X^2_\mu \\ X^3_\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(G^9_\mu - \mathrm{i}\, G^{10}_\mu\right) \\ \frac{1}{\sqrt{2}}\left(G^{11}_\mu - \mathrm{i}\, G^{12}_\mu\right) \\ \frac{1}{\sqrt{2}}\left(G^{13}_\mu - \mathrm{i}\, G^{14}_\mu\right) \end{pmatrix} .$$

Leptoquarks mass eigenstates

$$\mathcal{M}_X^2 = \frac{1}{4}\begin{pmatrix} g_L^2\left[v_L^2 + v_\Sigma^2(1+z^2)\right] & -2g_Lg_Rv_\Sigma^2 z \\ -2g_Lg_Rv_\Sigma^2 z & g_R^2\left[v_R^2 + v_\Sigma^2(1+z^2)\right] \end{pmatrix},$$

Mixing matrix

$$\begin{pmatrix} X_1 \\ X_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_4 & \sin\theta_4 \\ -\sin\theta_4 & \cos\theta_4 \end{pmatrix}\begin{pmatrix} X_L \\ X_R \end{pmatrix}.$$

Making $\mathrm{SU}(4)_R$ break at a much higher energy scale we assume that the vevs of the scalar fields satisfy $v_R \gg v_L$ and $v_R \gg v_\Sigma$, hence the mass matrix becomes diagonal, $\sin\theta_4 = 0$ and the masses of the leptoquarks become

$$M_{X_1} = \frac{1}{2}g_L\sqrt{v_L^2 + v_\Sigma^2(1+z^2)}$$

$$M_{X_2} = \frac{1}{2}g_Rv_R\,.$$

Flavor structure and interaction terms

Left-handed doublets

$$Q_{Li} = \begin{pmatrix} V^{\dagger}_{ki} u_k \\ d_i \end{pmatrix} , \qquad L_{Lj} = \begin{pmatrix} U_{kj} \nu_j \\ \ell_j \end{pmatrix} , \tag{7}$$

Lagrangiano de interacción

$$\boxed{\mathcal{L} \supset \frac{g_L}{\sqrt{2}} X_L \left[x^{ij}_{Lu} (\overline{u}_i \gamma^{\mu} \nu_j) + x^{ij}_{Ld} \big(\overline{d}_i \gamma^{\mu} \ell_j \big) \right] + \text{h.c.}} , \tag{8}$$

where $x_{Lu} \equiv V^{\dagger} x_{Ld} U$.

Phenomenological analysis

Phenomenological analysis

Model-independent analysis

Model-independent analysis

$$\mathcal{L} \supset U_{1\mu} \sum_{i,j=1,2,3} \left[x_L^{ij} \left(\overline{d}_L^i \gamma^\mu e_L^j \right) + \left(V^\dagger x_L U \right)_{ij} \left(\overline{u}_L^i \gamma^\mu \nu_L^j \right) + x_R^{ij} \left(\overline{d}_R^i \gamma^\mu e_R^j \right) \right] + \text{h.c} \,,$$

To avoid constraints arising from $\mu - e$ conversions in the nucleous and parity violations we use the “minimal U_1 model”structure by Angelescu, et.al (JHEP 10 (2018) 183)

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix} \,.$$

Semileptonic decays of B-meson involve a $b \to s\mu^+\mu^-$ via the effective Hamiltonian

$$\mathcal{H}_{\text{eff}}(b \to s\mu^+\mu^-) = -\frac{\alpha_{\text{em}} G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[C_9^{bs\mu\mu} (\overline{s} P_L \gamma_\beta b) \left(\overline{\mu} \gamma^\beta \mu \right) + C_{10}^{bs\mu\mu} (\overline{s} P_L \gamma_\beta b) \left(\overline{\mu} \gamma^\beta \gamma_5 \mu \right) \right]$$

Model-independent analysis

Wilson coefficients:

$$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} = -\frac{\pi}{\sqrt{2}\,G_F\alpha_{\text{em}}\,V_{tb}\,V_{ts}^*}\,\frac{x_L^{s\mu}\left(x_L^{b\mu}\right)^*}{M_{U_1}^2}\,.$$

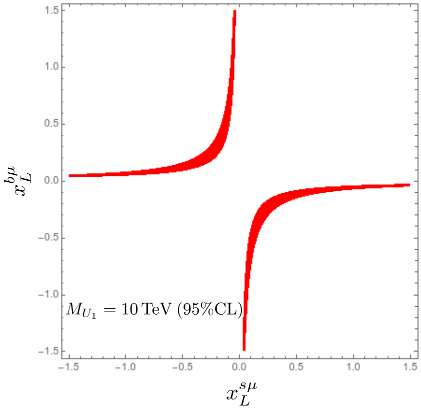
2021 values found by Altmannshofer & Stangl (Eur.Phys.J.C 81 (2021) 10, 952) for $C_9 = -C_{10}$ from all rare decays of the B-meson give

$$C_{9\text{ ex}}^{bs\mu\mu} = -C_{10\text{ ex}}^{bs\mu\mu} = -0{,}39 \pm 0{,}07\,.$$

Model-independent analysis

1σ interval for the flavor couplings obtained from a χ^2 analysis for a LQ with $M_{U_1} = 10\ \mathrm{TeV}$:

$x_L^{s\mu}$	$x_L^{b\mu}$
$[0{,}23, 0{,}30]$	$[-0{,}26, -0{,}20]$



Phenomenological analysis

Model-specific phenomenology

Wilson coefficients

The LQ states X_{1_μ}, $X_{2\mu}$ introduce the following modifications to the Wilson coefficients

$$C_9^{\mu\mu} = -C_{10}^{\mu\mu} = -\frac{\sqrt{2}\pi^2 g_L^2 x_{Ld}^{s\mu} x_{Ld}^{b\mu\,*}}{G_F e^2 V_{tb} V_{ts}^*}\left[\frac{\cos^2\theta_4}{M_{X_1}^2} + \frac{\sin^2\theta_4}{M_{X_2}^2}\right]. \tag{9}$$

With the restriction on the breaking energy of $\mathrm{SU}(4)_R$ we get

$$C_9^{\mu\mu} = -C_{10}^{\mu\mu} = -\frac{\pi}{\sqrt{2}\,G_F\alpha_{\text{em}}\,V_{tb}V_{ts}^*}\frac{1}{M_X^2}\left(\frac{g_L}{\sqrt{2}}x_{Ld}^{s\mu}\right)\left(\frac{g_L}{\sqrt{2}}x_{Ld}^{b\mu}\right), \tag{10}$$

Coupling matrix parametrization

From an analisis of $K_L^0 \to e^{\pm}\mu^{\mp}$ searches and $e - \mu$ conversions, Fornal et.al. parametrize the copling matrix as

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

where $|\delta_i| \ll 1$.

From constraints for $R_{K^{(*)}}$ anomalies it can be stablished that

$$\cos(\phi_1 + \phi_2) \approx 0{,}18\,,$$

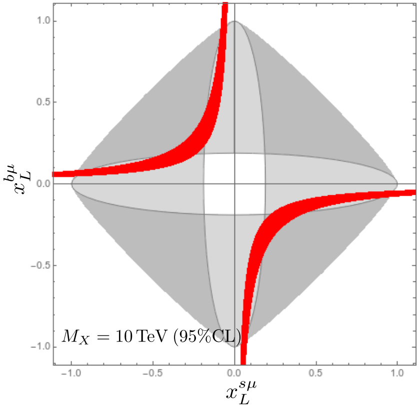
Furthermore, the coupling constant

$$g_L \approx 1{,}06 g_s\,,$$

with $g_s \approx 0{,}96$ being the strong coupling constant at 10 TeV.

Allowed region

Allowed region at $95\,\%\mathrm{CL}$ for a LQ with $M_X = 10\mathrm{TeV}$



Concluding remarks

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- Leptoquarks arising from a $\mathrm{SU}(4)$ symmetry offer a possible explanation for LFU violation. The new vertex admits direct transitions between quarks and leptons with different couplings.
- For the R_K anomaly, involving a $b \to s\mu^+\mu^-$ transition we determined $x_L^{s\mu}$, $x_L^{b\mu}$ in the interval $[0{,}23, 0{,}30]$ y $[-0{,}26, -0{,}20]$ for a $10\mathrm{TeV}$ LQ.
- The parametrization of the coupling matrix in Fornal's model admits a wide range of values. The data from the model-independent analysis are within this range.
- The value range of the model-specific analysis is still quite broad. It is required a more thorough analysis that studies the pertinence of this parametrization.

Thank you