PROCEEDINGS OF SCIENCE

Confronting quark-lepton unification with LFUV

Matěj Hudec[a,*]

[a] *Insitute of Particle and Nuclear Physics, Charles University, V Holešovičkách 2, Prague, Czechia*

E-mail: hudec@ipnp.mff.cuni.cz

Quark-lepton $SU(4)$ symmetry is an appealing paradigm, a step towards grand unification. It has been identified decades ago that the minimal potentially realistic models with the quark-lepton symmetry have the $SU(4) \times SU(2) \times U(1)$ gauge structure and naturally contain both gauge and scalar leptoquarks. Such models have been thoroughly studied by several authors.

In recent years, a lot of interest have been aroused by the experimental hints of lepton flavour universality violation (LFUV) in the B-meson decays. These are often interpreted as signals of existence of leptoquarks. We will present the study of the capability of the minimal $SU(4)$ models to accommodate the LFUV. In particular, we will argue that leptoquark interactions in the considered models can partially accommodate subsets of the anomalous B-meson decay data, unavoidably predicting lepton flavour violating processes which will be testable at Belle II during the next years. On the other hand, the models are unable to explain the current central values of the B-anomalies and, thus, will be disproved if these are confirmed as signals of New Physics.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

*Speaker

https://pos.sissa.it/

PoS(ICHEP2020)380

The hints of new physics (NP) in B-meson decays, such as the deviations in lepton flavour universality test $R_{K^{(*)}} = \mathrm{BR}(B \to K^{(*)}\mu^+\mu^-) \,/\, \mathrm{BR}(B \to K^{(*)}e^+e^-)$, gave rise to a variety of tailor-made extensions of the Standard Model (SM). Many of them employ some kind of leptoquark (LQ) as the key – and usually the only – part of the NP sector (see, e.g., [1]). In our work [2], we have chosen a different approach, adopting elsewhere-motivated models and investigating to which extent could they be compatible with the data.

We have studied the minimal quark-lepton symmetry model (*MQLSM*) [3] and its small extension suggested in Ref. [4] which we call the *FPW model* in this contribution. The motivation for these models is simple – they are the most modest reasonable implementations the quark-lepton unification à la Pati-Salam. The models naturally contain several types of leptoquarks, interactions and masses of which are constrained by the extended gauge symmetry. It is therefore not trivial to tell whether these models could effectively reproduce some of the well fitting simple leptoquark scenarios mentioned above.

The notion of *minimality* of the considered models is three-fold:

(i) They are based on the $G_{421} = SU(4)_C \times SU(2)_L \times U(1)_R$ gauge group – the smallest extension of $G_{\mathrm{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$ containing the Pati-Salam factor $SU(4)_C$.

(ii) No extra charged fermions are present. The MQLSM only contains 3 generations of the tetraplets

$$F_L = \begin{pmatrix} Q_L \\ L_L \end{pmatrix}, \qquad f_R^u = \begin{pmatrix} u_R \\ \nu_R \end{pmatrix}, \qquad f_R^d = \begin{pmatrix} d_R \\ e_R \end{pmatrix}, \tag{1}$$

which unify three colors of quarks with leptons.[1] The extension to the FPW model consists in including three gauge singlets N_L which take part in the inverse seesaw mechanism.

(iii) The minimal scalar sector necessary to reproduce the SM at low energies is employed. It consists of a field $\chi \sim (4, 1, +1/2)_{421}$ which breaks the gauge symmetry to that of the SM, a Higgs doublet $H \sim (1, 2, +1/2)_{421}$ and an $SU(4)_C$ adjoint $\Phi \sim (15, 2, +1/2)_{421}$ which contains another Higgs doublet, necessary to give different masses to leptons and quarks from the same tetraplets.

At the level of the G_{SM} group, the model features the gauge leptoquark $U_1 \sim (3, 1, +2/3)_{\mathrm{SM}}$, an excellent candidate to address the B-anomalies if its interaction matrices could be chosen arbitrarily (see, e.g., [6]). However, in an $SU(4)_C$ gauge model with minimal fermion content, the interaction matrices of U_1 must be unitary. In such a case, the first signal of the vector LQ would be some of the purely leptonic meson decays $P \to ll'$ which set the limit on the LQ mass way above [7] the level of relevance for the processes of our interest. The models contains also several *scalar* LQs. In particular, the χ tetraplet incorporates an $\bar{S}_1 \sim (\bar{3}, 1, -2/3)_{\mathrm{SM}}$ field which, however, cannot interact with charged leptons and, moreover, mostly forms the Goldstone boson eaten by U_1. Furthermore, there are two weak doublets $R_2 \sim (3, 2, +7/6)_{\mathrm{SM}}$ and $\widetilde{R}_2 \sim (3, 2, +1/6)_{\mathrm{SM}}$ which reside in Φ. Only the latter is at least partially eligible in adressing the neutral current B-meson anomalies [1] and we will thus focus on it.

As follows from the chirality structure of the Yukawa Lagrangian for the considered leptoquark

$$\mathcal{L}^{\mathrm{Yuk}}_{R_2} = \left(\overline{u_R}\, Y_2 L_L{}^j \varepsilon_{ji} + \overline{Q_L}{}_i Y_4 e_R\right) R_2{}^i + \mathrm{h.c.} \tag{2}$$

[1]Talking about unification of 3 colors with the lepton *number* may be misleading (see, e.g., the appendix in Ref. [5]).

(with i, j standing for the $SU(2)_L$ indices), the R_2 interaction with down-type quarks involves the *right-handed* leptons only. The corresponding tree-level amplitudes therefore contribute to the Weak effective theory as $C_9^{\rm NP} = +C_{10}^{\rm NP}$ and thus essentially do not interfere with those from the SM weak interactions for which $C_9^{\rm SM} \approx -C_{10}^{\rm SM}$ approximately holds. Thus, in order to achieve $R_K < 1$ as measured [8], the LQ must couple via Y_4 to electrons more than to muons. As there are several stringent bounds on lepton flavour violation (LFV) between e and μ from decays such as $K_L^0 \to e\mu, \mu \to e\gamma$ or $\mu \to eee$, the coupling of R_2 to muons must be strongly suppressed. Despite the fact that such a scenario cannot explain the additional discrepancies which suggest that the NP is in the $b \to s\mu\mu$ channel, this scenario ranked the 2nd position in the comparison of simplified scenarios explaining the neutral current anomally [1].

To investigate if such a scenario can be achieved within the unified models considered, we have found the most general form of the scalar potential build from χ, H and Φ and verified that the situation where R_2 is much lighter than the rest of the BSM spectrum is feasible [5]. Then, we have studied the constraints on the shapes of the Yukawa matrices Y_2 and Y_4 stemming from the extended gauge symmetry.

In the MQLSM, the largest Yukawa elements, enhanced by m_t/m_b with respect to the others, always reside in Y_2 [9]. The MQLSM is thus incompatible with the first signal of NP being in $R_{K^{(*)}}$.

Further on, we will concentrate on the FPW model in which the extra fields N_L bring also new free parameters. These, consequently, lead to releasing the theoretical constraints on Y_2. In Ref. [2], we have identified a region in the parameter space consistent with the stringent bounds on LFV in the μ-e sector. In its "safest" part, the relevant Yukawas in the d-type quark and charged lepton mass basis read

$$Y_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad Y_4 \simeq \frac{\sqrt{3/2}}{v_{\rm ew}\cos\beta} \begin{pmatrix} 0 & 0 & m_\tau e^{i\delta_4}\sin\phi \\ m_s e^{i\delta_1}/\sqrt{2} & 0 & m_\tau e^{i\delta_5}\cos\phi \\ m_b e^{i\delta_2}/\sqrt{2} & 0 & -m_b e^{i\delta_3}/\sqrt{2} \end{pmatrix}, \tag{3}$$

where β, ϕ and δ_i's are, together with the LQ mass m_{R_2}, the remaining relevant free parameters of the situation. Apparently, while all couplings to muons vanished, there is some LQ interaction in the τ sector which cannot be avoided at the same time. This leads to various LFV $\tau \to eX$ decays. Varying the free parameters in Eq. (3), we have found that the R_K as given in Ref. [8] is inconsistent with the experimental limit on BR($\tau \to e\pi^+\pi^-$) – see Fig. 1. Hence, if the current value of R_K is confirmed by future measurements, the FPW model will be ruled out as a whole.

In what follows, we assume that the real value of R_K is closer to but still significantly below 1. For such a case, the model predicts that several LFV observables are close to their current limits. Apart from $\tau \to e\pi^+\pi^-$ let us mention BR($\tau \to e\gamma$) which is bound to be discovered on Belle II.

The mass of the LQ isodoublet cannot be predicted based on rare decays since the low-energy observables are only sensitive to the product $m_{R_2}\cos\beta$. On the other hand, regardless of the choice of the free parameters in Eq. (3), its decays are essentially uniquely determined. In particular, the

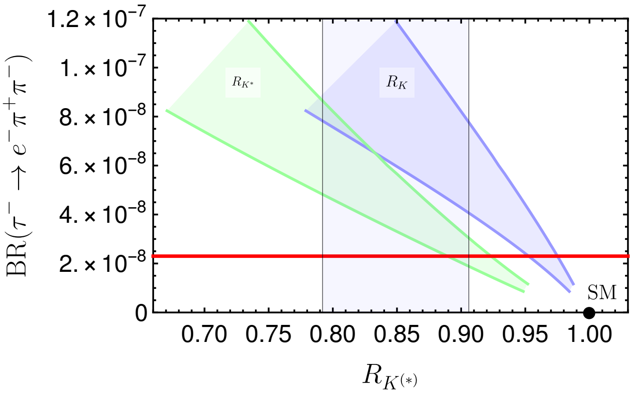

Figure 1: Correlation between $R_{K^{(*)}}$ and a lepton flavour violating decay of the τ-lepton in the otherwise allowed region of the parameter space. The 1-σ interval of R_K as measured in Ref. [8] as well as the 90 % C.L. limit on the considered τ decay [10] are denoted. The figure has been adopted from Ref. [2].

non-negligible LQ decay channels are related by

$$\mathrm{BR}(R_2^{+5/3} \to e^+ t) \simeq \mathrm{BR}(R_2^{+5/3} \to \tau^+ t) \simeq \frac{m_b^2}{2m_\tau^2}\mathrm{BR}(R_2^{+5/3} \to \tau^+ j), \tag{4}$$

$$\mathrm{BR}(R_2^{+2/3} \to e^+ b) \simeq \mathrm{BR}(R_2^{+2/3} \to \tau^+ b) \simeq \frac{m_b^2}{2m_\tau^2}\mathrm{BR}(R_2^{+2/3} \to \tau^+ j) \tag{5}$$

where j denotes a light quark jet. We have found that, for such a LQ, the current experimental searches set limit no stronger than $m_{R_2} > 900$ GeV.

Acknowledgements

We acknowledge the support from the *Charles University Research Center UNCE/SCI/013*, from *Grant agency of the Czech Republic, project no. 20-17490S* and from *Grant Agency of Charles University (GAUK), project no. 1248119*.

References

[1] G. D'Amico, M. Nardecchia, P. Panci, F. Sannino, A. Strumia, R. Torre et al., *Flavour anomalies after the R_{K^*} measurement*, *JHEP* **09** (2017) 010 [1704.05438].

[2] T. Faber, M. Hudec, H. Kolešová, Y. Liu, M. Malinský, W. Porod et al., *Collider phenomenology of a unified leptoquark model*, *Phys. Rev. D* **101** (2020) 095024 [1812.07592].

[3] A.D. Smirnov, *The minimal quark-lepton symmetry model and the limit on Z'-mass*, *Phys. Lett.* **B346** (1995) 297 [hep-ph/9503239].

[4] P. Fileviez Pérez and M.B. Wise, *Low Scale Quark-Lepton Unification*, *Phys. Rev.* **D88** (2013) 057703 [1307.6213].

[5] T. Faber, M. Hudec, M. Malinský, P. Meinzinger, W. Porod and F. Staub, *A unified leptoquark model confronted with lepton non-universality in B-meson decays*, Phys. Lett. **B787** (2018) 159 [1808.05511].

[6] A. Angelescu, D. Bečirević, D. Faroughy and O. Sumensari, *Closing the window on single leptoquark solutions to the B-physics anomalies*, JHEP **10** (2018) 183 [1808.08179].

[7] A.D. Smirnov, *Vector leptoquark mass limits and branching ratios of $K_L^0, B^0, B_s \to l_i^+ l_j^-$ decays with account of fermion mixing in leptoquark currents*, Mod. Phys. Lett. **A33** (2018) 1850019 [1801.02895].

[8] LHCb collaboration, *Search for lepton-universality violation in $B^+ \to K^+ \ell^+ \ell^-$ decays*, Phys. Rev. Lett. **122** (2019) 191801 [1903.09252].

[9] P. Popov, A.V. Povarov and A.D. Smirnov, *Fermionic decays of scalar leptoquarks and scalar gluons in the minimal four color symmetry model*, Mod. Phys. Lett. **A20** (2005) 3003 [hep-ph/0511149].

[10] Belle collaboration, *Search for Lepton-Flavor-Violating and Lepton-Number-Violating $\tau \to \ell h h'$ Decay Modes*, Phys. Lett. B **719** (2013) 346 [1206.5595].