

Pati–Salam and lepton universality in B decays

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Recent hints for lepton-flavor non-universality in B -meson decays can be interpreted as hints for the existence of leptoquarks. We show that scalar leptoquarks unavoidably arise in grand unified theories, using the well-known Pati–Salam model as an example. These GUT-motivated leptoquarks can have a number of appealing features including automatic absence of proton decay, purely chiral couplings, and relations between the various leptoquark couplings. We show that $R(K^{(*)})$ can be connected to the neutrino mass matrix that arises via type-II seesaw, resulting in testable lepton flavor violation. In order to also explain $R(D^{(*)})$ one instead has to assume the existence of light right-handed neutrinos, once again with testable predictions in other B -meson decays and at the LHC.

1 Introduction

The strongest hints for physics beyond the Standard Model (SM) in the recent past have emerged in rare B -meson decays, probed by BaBar, Belle, and LHCb. Particularly clean observables are given by double ratios such as $R(K^{(*)})$ and $R(D^{(*)})$. These ratios are sensitive probes of lepton-flavor non-universality and show small but persistent deviations from their SM values. Updated results presented at this Moriond conference (see contributions by M. Prim, T. Humair and G. Caria) have already been included in several global fits (see Refs. 1, 2, 3, 4, 5, 6) and have been discussed by D. Straub (see these proceedings). We use the opportunity these proceedings offer and also update our analysis below. The difference from the published version in Ref. 7 is however small and mainly quantitative.

New-physics explanations of $R(K^{(*)})$ ($R(D^{(*)})$) require Z' (W') vector bosons or leptoquarks. A popular *combined* explanation uses the vector leptoquark (LQ) $U_1 \sim (\mathbf{3}, \mathbf{1})_{2/3}$, which is unfortunately rather difficult to obtain in UV-complete models (see A. Angelescu’s contribution to these proceedings). In Ref. 7 we pointed out that *scalar* LQs on the other hand can be found in abundance in grand unified theories, the simplest example being the Pati–Salam (PS) model based on the gauge group $SU(4)_{LC} \times SU(2)_L \times SU(2)_R$ (Ref. 8). The most general PS model that abandons quark–lepton mass unification actually already contains *all* scalar LQs and is thus perfectly suited to explain the B -meson anomalies by lowering the relevant LQ masses to the TeV scale. In addition, these PS-motivated LQs do not cause proton decay, which is usually a major problem in simple SM extensions that requires the imposition of an additional proton-stabilizing symmetry based on baryon or lepton number (see Ref. 9). Furthermore, the Pati–

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Salam symmetry imposes restraints on the LQ couplings and relates them to other couplings, thus providing testable predictions despite not being a one-particle combined explanation like U_1 . We will highlight some of these predictions below but stress that the general idea goes beyond our examples and should be explored in other grand unified theories as well.

2 $R(K^{(*)})$ and neutrino mass

The SM fermions as well as right-handed neutrinos reside in the PS representations

$$\Psi_L \sim (\mathbf{4}, \mathbf{2}, \mathbf{1}) \rightarrow (\mathbf{3}, \mathbf{2})_{\frac{1}{6}} \oplus (\mathbf{1}, \mathbf{2})_{-\frac{1}{2}} \equiv Q_L \oplus L_L, \quad (1)$$

$$\Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}) \rightarrow (\mathbf{3}, \mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{3}, \mathbf{1})_{-\frac{1}{3}} \oplus (\mathbf{1}, \mathbf{1})_{-1} \oplus (\mathbf{1}, \mathbf{1})_0 \equiv u_R \oplus d_R \oplus \ell_R \oplus N_R, \quad (2)$$

which allow us to define a parity left–right exchange symmetry $\Psi_L \leftrightarrow \Psi_R$ that maximizes the predictive power of the framework and will be imposed below. In order to break the PS group to the SM and provide masses to the right-handed neutrinos we introduce the scalar fields

$$\Delta_L \sim (\overline{\mathbf{10}}, \mathbf{3}, \mathbf{1}) \rightarrow (\mathbf{6}, \mathbf{3})_{-\frac{1}{3}} \oplus (\overline{\mathbf{3}}, \mathbf{3})_{\frac{1}{3}} \oplus (\mathbf{1}, \mathbf{3})_1 \equiv \Sigma_3 \oplus S_3 \oplus \delta_3, \quad (3)$$

$$\begin{aligned} \Delta_R \sim (\overline{\mathbf{10}}, \mathbf{1}, \mathbf{3}) &\rightarrow (\mathbf{6}, \mathbf{1})_{-\frac{1}{3}} \oplus (\mathbf{6}, \mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{6}, \mathbf{1})_{-\frac{4}{3}} \oplus (\overline{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}} \oplus (\overline{\mathbf{3}}, \mathbf{1})_{-\frac{2}{3}} \oplus (\overline{\mathbf{3}}, \mathbf{1})_{\frac{4}{3}} \\ &\oplus (\mathbf{1}, \mathbf{1})_0 \oplus (\mathbf{1}, \mathbf{1})_1 \oplus (\mathbf{1}, \mathbf{1})_2 \equiv \Sigma_1 \oplus \tilde{\Sigma}_1 \oplus \bar{\Sigma}_1 \oplus S_1 \oplus \tilde{S}_1 \oplus \bar{S}_1 \oplus \delta_1 \oplus \tilde{\delta}_1 \oplus \bar{\delta}_1, \end{aligned}$$

which contain amongst other things all S_j LQs (using the notation of Ref. 10). The SM-singlet δ_1 will obtain a large vacuum expectation value (VEV) that breaks $PS \rightarrow SM$, whereas the triplet δ_3 will obtain a small SM-breaking VEV that generates type-II seesaw neutrino masses

$$M_\nu \simeq -\sqrt{2}\langle\delta_3\rangle V_L^* y^L V_L^\dagger. \quad (4)$$

Here V_L is the standard Cabibbo–Kobayashi–Maskawa matrix and $\langle\delta_3\rangle$ the sub-GeV triplet VEV. Since the neutrino mixing angles and mass-squared differences are well known from neutrino-oscillation measurements, we can determine y^L as a function of the unknown neutrino phases and lightest neutrino mass. However, y^L is not only the (symmetric) Yukawa coupling of δ_3 to the neutrinos, but thanks to PS also the S_3 LQ coupling:

$$\mathcal{L} = \overline{Q}_L^c y^L L_L S_3 + \frac{1}{\sqrt{2}} \overline{L}_L^c y^L L_L \delta_3 + \text{h.c.} \quad (5)$$

The S_3 coupling is relevant for $R(K^{(*)})$ as it generates the desired Wilson coefficients

$$\Delta C_9 = -\Delta C_{10} = \frac{\pi v^2}{\alpha} \frac{1}{V_{L,tb} V_{L,ts}^*} \frac{1}{M_{S_3}^2} y_{23}^L y_{22}^{L*}. \quad (6)$$

Using the Moriond-updated results of Ref. 5 we require $\text{Re}(\Delta C_9) \stackrel{!}{\simeq} -0.53 \pm 0.08$. Here we are assuming all scalars except for S_3 to be sufficiently heavy to be irrelevant for the processes under consideration.

PS thus relates the neutrino mass parameters of Eq. (4) to the $R(K^{(*)})$ couplings of Eq. (6). While it is trivial to accommodate both simply by playing with $\langle\delta_3\rangle$ and M_{S_3} , it is non-trivial to evade the numerous additional S_3 -mediated processes, in particular the lepton-flavor-violating $\mu \rightarrow e$ conversion in nuclei. The existing limit of Ref. 11 requires rather small y_{11}^L and y_{12}^L couplings compared to y_{23}^L and y_{22}^L , which in turn leads to a prediction of the so-far unknown CP phases in the neutrino sector. This is in direct analogy to the often-studied texture zeros in the neutrino mass matrix, which here translate into coupling zeros of the LQ S_3 . Fitting the unknown neutrino parameters together with $R(K^{(*)})$ allows us to make the predictions shown in Fig. 1 (left), in particular a rather small Dirac CP phase.

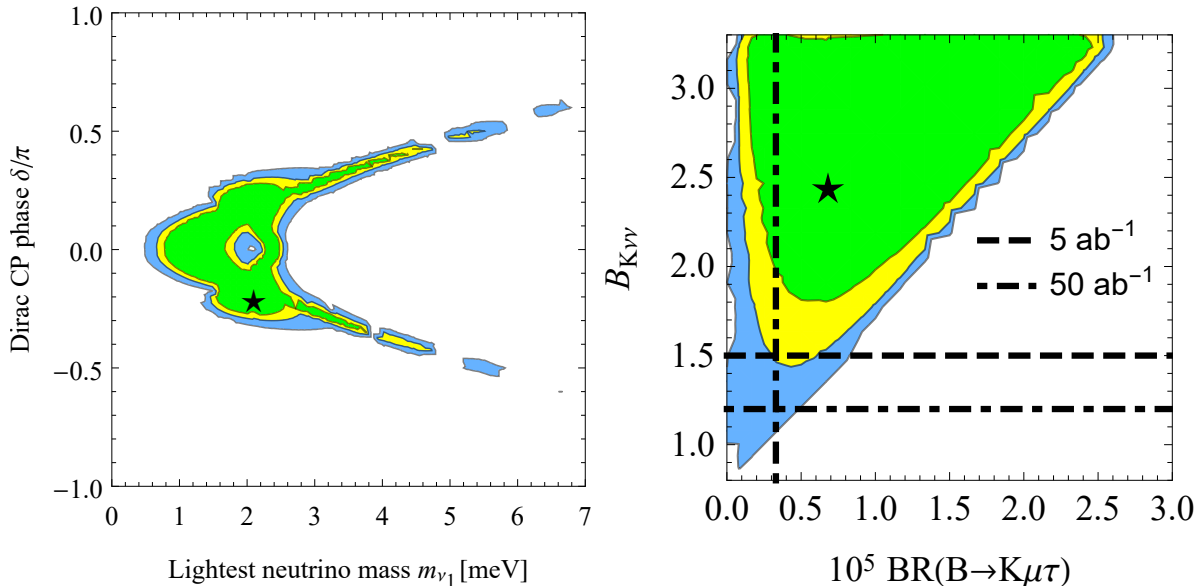


Figure 1 – Left: Results of the fit for the neutral-current anomalies and type-II neutrino masses, fixing $\langle \delta_3 \rangle = 50$ meV and normal ordering. The star denotes the best-fit point; we show the $\Delta\chi^2 < 2.3$ (1σ), 6.2 (2σ), 11.8 (3σ) regions in green, yellow, and blue, respectively, marginalizing over all other parameters. Right: Results of the fit for the combined explanation of $R(K^{(*)})$ and $R(D^{(*)})$, also showing Belle-II prospects for certain luminosities.

We want to stress that it is highly non-trivial that the M_ν – $R(K^{(*)})$ connection is successful. It only works because M_ν with normal mass ordering has a peculiar hierarchical structure: a dominant 23 block with potentially tiny 11 and 12 entries. This makes it possible for S_3 to explain $R(K^{(*)})$ (which resides in the 23 sector) without running into problems with muonic lepton flavor violation (which resides in the 12 sector). If we had instead assumed *inverted* mass ordering we would have found an S_3 coupling matrix that is impossible to reconcile with $R(K^{(*)})$ and $\mu \rightarrow e$ processes. The same is true if we assume type-I seesaw dominance, as shown in Ref. 7. The M_ν – $R(K^{(*)})$ connection is thus a rather surprising and non-trivial feature that would be a strong hint at grand unification if confirmed. In this regard we note that the above suppression of muonic lepton flavor violation is not expected to hold far below the existing limits, so upcoming experiments such as Mu2e, COMET, and Mu3e should see signs of new physics if our explanation is correct.

3 $R(K^{(*)})$ and $R(D^{(*)})$

While $R(K^{(*)})$ is relatively easy to accommodate in SM-extensions, $R(D^{(*)})$ requires a rather low new-physics scale around TeV and is thus subject to many more constraints. Particularly constraining is the so-far unobserved decay $B \rightarrow K\nu\nu$, which is connected to $B \rightarrow D\tau\nu$ via $SU(2)_L$ and typically requires a cancellation. As pointed out in Refs. 12, 13, 14, 15, 16, one way out is to explain $R(D^{(*)})$ via an additional decay mode $B \rightarrow D\tau N_R$, which automatically evades the $B \rightarrow K\nu\nu$ constraint and should lead to similar differential distributions as long as N_R is lighter than about 100 MeV.

In our PS framework the decay $B \rightarrow D\tau N_R$ can in principle be induced by the S_1 LQ.^b However, the S_1 couplings are related to the N_R mass matrix, in complete analogy to the S_3 couplings and M_ν above. This implies that a light N_R is automatically weakly coupled to S_1 , making it impossible to explain $R(D^{(*)})$. It is thus necessary to extend the PS model and

^bAn alternative solution would be to use the R_2 LQ that resides in the $(\mathbf{15}, \mathbf{2}, \mathbf{2})$ representation typically required for electroweak symmetry breaking. We do not consider this option here because the R_2 couplings are not directly related to the S_3 couplings, which lowers the predictivity of this approach.

Parameter	Best fit	Observable	Best fit	Pull/bound
M_{S_3}	6.1 TeV	$R_{D^{(*)}}$	1.14	-0.1σ
y_{22}	0.030	$\Delta C_9 = -\Delta C_{10}$	-0.53	$+0.0\sigma$
y_{23}	1.02	$R_{D^{(*)}}^{\mu/e}$	1.00	$+0.0\sigma$
y_{33}	0.006	$\delta g_{\tau\tau}^R$	0.4×10^{-4}	-1.3σ
χ^2	2.2	$\delta g_{\mu\mu}^R$	-6.9×10^{-4}	-0.8σ
		$B_{K\nu\nu}$	2.48	3.28
		$\text{BR}(B \rightarrow K\mu\tau)$	0.7×10^{-5}	4.8×10^{-5}
		$\text{BR}(\tau \rightarrow \mu\gamma)$	4.3×10^{-11}	4.4×10^{-8}
		$\text{BR}(\tau \rightarrow 3\mu)$	7.7×10^{-11}	2.1×10^{-8}

Table 1: Results of the fit for the combined explanation of $R(K^{(*)})$ and $R(D^{(*)})$, fixing $M_{S_1} = 1$ TeV.

decouple the S_1 couplings from the N_R mass generation. As shown in Ref. 7 there are numerous ways to achieve this; here we will simply assume that one of the N_R is indeed light (below 100 MeV) and has some unrelated couplings to S_1 . Since we are staying agnostic about the neutrino mass mechanism we no longer have the M_ν - $R(K^{(*)})$ connection from above, so the LQ couplings are now free parameters,

$$\mathcal{L} = \bar{Q}_L^c y^L L_L S_3 - \frac{1}{\sqrt{2}} \left(\bar{d}_R^c y^R V_R^\dagger N_R + \bar{\ell}_R^c y^R V_R^\dagger u_R \right) S_1 + \text{h.c.} \quad (7)$$

Still, parity equates the S_1 and S_3 LQ couplings, $y^L = y^R$, for which we make the Ansatz

$$y^L = y^R \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{23} & y_{33} \end{pmatrix} \quad (8)$$

in order to evade constraints from muonic lepton flavor violation. S_3 will be used to explain $R(K^{(*)})$ via Eq. (6), i.e. using the product of y_{22} and y_{23} . S_1 will induce $B \rightarrow D\tau N_R$ via a large y_{23} , assuming the light N_R mass eigenstate, dubbed \hat{N} , to be aligned with the second generation:

$$R_{D^{(*)}} \equiv \frac{\Gamma(B \rightarrow D\tau\nu, D\tau\hat{N})/\Gamma(B \rightarrow D\tau\nu_\tau)_{\text{SM}}}{\Gamma(B \rightarrow D\hat{\ell}\nu, D\hat{\ell}\hat{N})/\Gamma(B \rightarrow D\hat{\ell}\nu_\ell)_{\text{SM}}} \simeq 1 + \left(\frac{v^2}{4M_{S_1}^2} \frac{V_{R,cs}}{V_{L,cb}} y_{23}^2 \right)^2, \quad (9)$$

with $\hat{\ell} = e, \mu$, see Ref. 7 for more details. Using the updated Belle data on $R(D^{(*)})$ presented at this conference (and now published in Ref. 17), we estimate the preferred region to be $R_{D^{(*)}} \stackrel{!}{\simeq} 1.14 \pm 0.04$, which then determines y_{23}/M_{S_1} .

A combined fit of $R(K^{(*)})$ and $R(D^{(*)})$, imposing all the relevant related constraints, yields the masses and couplings of Tab. 1. Both LQs are in the TeV mass range and y_{23} is of order one, much larger than all the other couplings. The main constraints and predictions then arise from processes involving the lightest LQ (S_1) and its 23 couplings. In particular, $B \rightarrow K\nu\nu$ and $B \rightarrow K\mu\tau$ are predicted large enough that Belle II can exclude the relevant parameter space [see Fig. 1 (right)], while LHC can independently test this model in the channels $pp \rightarrow \tau\nu$ and $pp \rightarrow S_1 \bar{S}_1 \rightarrow \bar{t}\mu t \bar{\mu}$, see Fig. 2 and Ref. 7. Note that we further predict the S_1 branching ratios $\text{BR}(S_1 \rightarrow t\mu) \simeq \text{BR}(S_1 \rightarrow c\tau) \simeq \text{BR}(S_1 \rightarrow b \text{ invisible})$.

4 Conclusions

The tantalizing and persisting B -meson anomalies in the observables $R(K^{(*)})$ and $R(D^{(*)})$ hint at the existence of leptoquarks, which in turn hint at grand unified theories where they arise

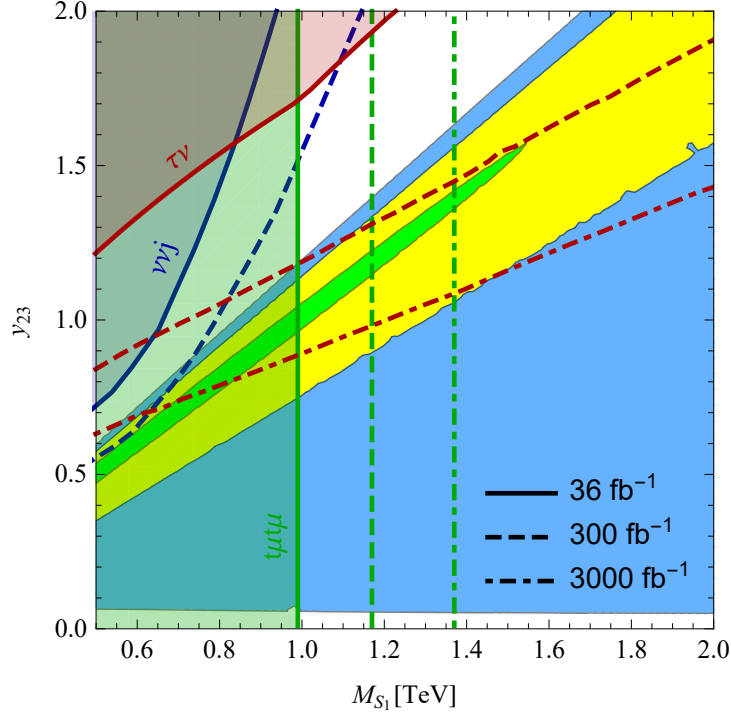


Figure 2 – Collider phenomenology for S_1 . The 1σ , 2σ , 3σ regions where both sets of anomalies are explained are denoted in green, yellow and blue, respectively. Existing LHC bounds are denoted by continuous lines and shaded regions, future prospects by dotted and dot-dashed lines for various LHC luminosities.

naturally. Most grand unified theories actually contain *all* scalar LQs as partners of the scalars required for the gauge-group breakdown. As a simple example we considered the well-known Pati–Salam model and showed that $R(K^{(*)})$ can be accommodated using the S_3 LQ and furthermore connected to the type-II seesaw neutrino mass structure, predicting measurable lepton-flavor violation in the muon sector.

Explaining both $R(K^{(*)})$ and $R(D^{(*)})$ simultaneously is more involved and requires an extension of the Pati–Salam model in order to incorporate one light right-handed neutrino with an order one coupling to the S_1 LQ. The underlying parity-symmetric Pati–Salam structure then identifies the S_1 and S_3 couplings and predicts large rates for $B \rightarrow K\nu\nu$ and $B \rightarrow K\mu\tau$, fully testable in Belle II.

There is hope that the B -meson anomalies are just the first signs of new physics that should show up in other rare decays or even be directly produced at the LHC. Grand unified theories make for a flexible yet predictive framework that allows to connect seemingly disconnected signatures.

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