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R_K and R_{K^*} beyond the standard model

Gudrun Hiller[*] and Ivan Nišandžić[†]

Institut für Physik, Technische Universität Dortmund, D-44221 Dortmund, Germany

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Measurements of the ratio of $B \to K^* \mu\mu$ to $B \to K^* ee$ branching fractions, R_{K^*}, by the LHCb Collaboration strengthen the hints from previous studies with pseudoscalar kaons, R_K, for the breakdown of lepton universality, and therefore the Standard Model (SM), to $\sim 3.5\sigma$. Complementarity between R_K and R_{K^*} allows us to pin down the Dirac structure of the new contributions to be predominantly SM-like chiral, with possible admixture of chirality-flipped contributions of up to $\mathcal{O}(\text{few}10\%)$. Scalar and vector leptoquark representations (S_3, V_1, V_3) plus possible $(\tilde{S}_2, V_2)$ admixture can explain R_{K,K^*} via tree-level exchange. Flavor models naturally predict leptoquark masses not exceeding a few TeV, with couplings to third-generation quarks at $O(0.1)$, implying that this scenario can be directly tested at the LHC.

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I. INTRODUCTION

Gauge interactions of the leptons within the Standard Model (SM) exhibit exact universality. The only known source of lepton nonuniversality (LNU) are the Yukawa couplings of the leptons to the Higgs. Tests of lepton universality are provided by rare (semi)leptonic $|\Delta B| = |\Delta S| = 1$ transitions, which are induced in the SM at one loop and additionally suppressed by the Glashow-Iliopoulos-Maiani mechanism, therefore allowing us to probe physics from scales significantly higher than the weak scale. Useful observables are the ratios of branching fractions of B meson decays into strange hadrons H and muon pairs over electron pairs [1]

$$R_H = \frac{\mathcal{B}(B \to H\mu^+\mu^-)}{\mathcal{B}(B \to He^+e^-)}, \qquad H = K, K^*, X_s, \ldots \quad (1)$$

in which (lepton universal) hadronic effects cancel. The ratios are therefore predicted within the SM to be very close to 1 and provide a clean test of the SM [1].

The LHCb Collaboration measured R_K in the dilepton-invariant mass-squared (q^2) bin $1\ \text{GeV}^2 \le q^2 \le 6\ \text{GeV}^2$ using the $1\ \text{fb}^{-1}$ data set [2]

$$R_K^{\text{LHCb}} = 0.745^{+0.090}_{-0.074} \pm 0.036, \quad (2)$$

and, very recently, R_{K^*} within $1.1\ \text{GeV}^2 \le q^2 \le 6\ \text{GeV}^2$ [3]

$$R_{K^*}^{\text{LHCb}} = 0.69^{+0.11}_{-0.07} \pm 0.05, \quad (3)$$

with deviation from $R = 1$ by 2.6σ each. (Here and in the following we add statistical and systematic uncertainties in quadrature.) Corrections to $R = 1 + O(m_\mu^2/m_B^2)$ [1] arise from electromagnetic interactions [4–7]. This affects the SM prediction at low q^2 at the percent level [8], not qualitatively altering the fact that the data, Eqs. (2) and (3), constitute a challenge to universality and the SM.

Moreover, the importance of the measurement of R_{K^*} in addition to R_K is in its diagnosing power regarding different beyond the SM (BSM) contributions [9]. Left-handed and right-handed $b \to s$ currents enter $B \to K\ell\ell$ and $B \to K^*\ell\ell$ in almost orthogonal combinations in both regions of q^2 sensitive to LNU. Comparison of R_K with R_{K^*}, for instance through a double ratio $X_{K^*} = R_{K^*}/R_K$ [9], probes directly right-handed LNU currents. The aim of this paper is to exploit this in a model-independent manner and pursue interpretations within leptoquark extensions of the SM.

II. MODEL-INDEPENDENT INTERPRETATION

We employ the usual effective Hamiltonian for $b \to s\ell\ell$, $\ell = e, \mu, \tau$ transitions

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha}{4\pi}\sum_i C_i^\ell \mathcal{O}_i^\ell + \text{H.c.}, \quad (4)$$

where $C_i^\ell, \mathcal{O}_i^\ell$ denote lepton-specific Wilson coefficients and dimension-six operators, respectively, renormalized at the scale $\mu \sim m_b$. Furthermore, G_F, α, and $\lambda_t = V_{tb}V_{ts}^*$ stand for Fermi's constant, the fine-structure constant and the product of relevant Cabibbo-Kobayashi-Maskawa matrix elements, respectively. The semileptonic operators read

$$\mathcal{O}_9^\ell = (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell), \qquad \mathcal{O}_9'^\ell = (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \ell),$$
$$\mathcal{O}_{10}^\ell = (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5 \ell), \qquad \mathcal{O}_{10}'^\ell = (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu\gamma_5 \ell), \quad (5)$$

with chiral projectors $P_{L,R} = 1/2(1 \mp \gamma_5)$. The operators with chiral lepton currents,

$$\mathcal{O}_{AB}^\ell = (\bar{s}\gamma^\mu P_A b)(\bar{\ell}\gamma_\mu P_B \ell), \qquad A, B = L, R, \quad (6)$$

[*] ghiller@physik.uni-dortmund.de
[†] ivan.nisandzic@tu-dortmund.de

are related to the $\mathcal{O}^{(\prime)\ell}_{9,10}$ as

$$C_9^\ell = \frac{1}{2}(C_{LL}^\ell + C_{LR}^\ell), \qquad C_{10}^\ell = \frac{1}{2}(C_{LR}^\ell - C_{LL}^\ell),$$
$$C'^\ell_9 = \frac{1}{2}(C_{RL}^\ell + C_{RR}^\ell), \qquad C'^\ell_{10} = \frac{1}{2}(C_{RR}^\ell - C_{RL}^\ell). \quad (7)$$

Within the SM the (lepton-universal) Wilson coefficients are $C_9^{\rm SM} = 4.07$, $C_{10}^{\rm SM} \simeq -4.31$ [10]; thus $C_{LL}^{\rm SM} = C_9^{\rm SM} - C_{10}^{\rm SM} \simeq 8.4$, while scalar or tensor Wilson coefficients are negligible. We define $C_{LL}^\ell = C_{LL}^{\rm SM} + C_{LL}^{\rm NP\ell}$ [9] and drop the label "NP" (new physics) for Wilson coefficients negligible within the SM.

In the $B \to K^{(*)}\ell\ell$ branching fractions contributions from photon exchange enter, notably from charm loops and dipole operators. These contributions are numerically small at high and low q^2, sufficiently away from the photon pole, and lepton universal. Within current accuracy of R_{K,K^*} these contributions can be safely neglected. In this limit [9]

$$R_K = 1 + \Delta_+ + \Sigma_+,$$
$$R_{K^*} = 1 + \Delta_+ + \Sigma_+ + p(\Sigma_- - \Sigma_+ + \Delta_- - \Delta_+), \quad (8)$$

where

$$\Delta_\pm = 2\Re\left(\frac{C_{LL}^{\rm NP\mu} \pm C_{RL}^\mu}{C_{LL}^{\rm SM}} - (\mu \to e)\right),$$
$$\Sigma_\pm = \frac{|C_{LL}^{\rm NP\mu} \pm C_{RL}^\mu|^2 + |C_{LR}^\mu \pm C_{RR}^\mu|^2}{|C_{LL}^{\rm SM}|^2} - (\mu \to e). \quad (9)$$

Since BSM contributions in $|\Delta B| = |\Delta S| = 1$ transitions are smaller than the SM ones [10] the dominant BSM effect is captured by the linear (interference) terms $\Delta_\pm$.

The coefficient p in Eq. (8) denotes the fraction of transverse parallel and longitudinal contributions to the $B \to K^*\ell\ell$ branching ratio [9]. Due to helicity arguments, $p \sim 1$ both at low recoil (high q^2) and at low q^2. Consequently, $\mathcal{B}(B \to K^*\ell\ell)$ is dominated by contributions proportional to $|C - C'|^2$. Since $\mathcal{B}(B \to K\ell\ell) \propto |C + C'|^2$ due to parity invariance of the strong interaction, both modes are complementary and deviations of R_K from R_{K^*} probe primed operators [9].

Using Eqs. (2), (3) one obtains

$$X_{K^*} = R_{K^*}/R_K = 0.94 \pm 0.18, \quad (10)$$

$$R_{K^*} + R_K - 2 = -0.54 \pm 0.14, \quad (11)$$

which gives, at 1σ,

$$\mathrm{Re}[C_9^{\rm NP\mu} - C_{10}^{\rm NP\mu} - (\mu \to e)] \sim -1.1 \pm 0.3, \quad (12)$$

$$\mathrm{Re}[C'^\mu_9 - C'^\mu_{10} - (\mu \to e)] \sim 0.1 \pm 0.4. \quad (13)$$

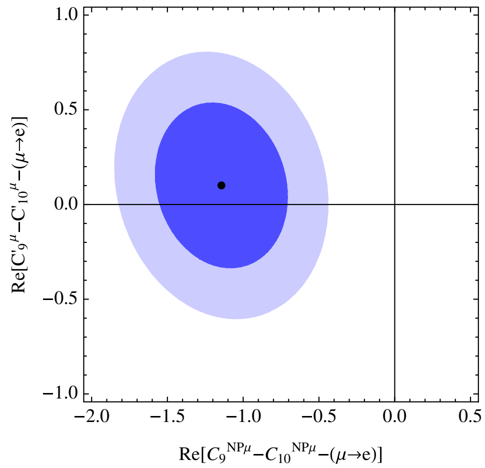

FIG. 1. Fit of left- and right-handed BSM coefficients in $|\Delta B| = |\Delta S| = 1$ transitions to R_K and R_{K^*} data (2), (3). Darker and lighter shaded regions correspond to 68% and 95% C.L. intervals, respectively.

As anticipated, $|C^{\rm NP}| \ll |C^{\rm SM}|$. Therefore, the linear approximation, that is, neglecting the $\Sigma_\pm$ terms, is meaningful within the current experimental precision. Dropping quadratic terms greatly simplifies the interpretation of the data: Only BSM in O_{LL}^ℓ or O_{RL}^ℓ is able to explain R_{K,K^*}.

In Fig. 1 a χ^2 fit for the left- and right-handed Wilson coefficients is shown. The discrepancy with the SM is about $\sim 3.5\sigma$, where we allowed for a few percent deviations from $R = 1$ [8]. Interestingly, solutions with $C_9^{\rm NP\mu} \sim -1$ are also favored by a global fit [10] to $b \to s\mu\mu$ observables. Taking this into account suggests an explanation of R_{K,K^*} anomalies with BSM predominantly residing in the muons.

III. LEPTOQUARK EXPLANATIONS

We consider leptoquark extensions of the SM with tree-level couplings to down-type quarks and leptons. Representations under $SU(3)_C \times SU(2)_L \times U(1)_Y$ with relevant Wilson coefficients are given in Table I for scalar S_i[1] and in Table II for vector leptoquarks V_i, respectively. The index $i = 1, 2, 3$ refers to the dimension of the $SU(2)_L$ multiplet, see, e.g., [11–13] for overviews.

The scalar leptoquarks S_2 and $\tilde{S}_1$ generate only C_{LR} and C_{RR}, respectively, which do not interfere with the SM contribution, see Eq. (9), and lead to R_K, R_{K^*} near 1. We therefore discard these two possibilities as explanations of the R_{K,K^*} anomalies.

In view of the experimental constraints shown in Fig. 1 we focus on leptoquarks that can give a sizable $C_{LL}^{\rm NP\ell} = 2C_9^{\rm NP\ell} = -2C_{10}^{\rm NP\ell}$. This singles out the scalar triplet S_3, the vector singlet V_1, and the vector triplet

[1] In the literature the scalar leptoquarks S_2 and $\tilde{S}_2$ are also denoted by R_2 and $\tilde{R}_2$, respectively.

TABLE I. Scalar leptoquarks and relations between Wilson coefficients, assuming a single leptoquark at the time. The last column shows implications for R_{K^*} assuming $R_K < 1$, as suggested by data (2).

	Representation	C_{AB}	Relation	$R_{K^{(*)}}$
$\tilde{S}_2$	$(3, 2, 1/6)$	C_{RL}	$C_9' = -C_{10}'$	$R_K < 1, R_{K^*} > 1$
S_3	$(\bar{3}, 3, 1/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$
S_2	$(3, 2, 7/6)$	C_{LR}	$C_9 = C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$	C_{RR}	$C_9' = C_{10}'$	$R_K \simeq R_{K^*} \simeq 1$

V_3. This scalar and the vectors have been considered as a possible explanation of R_K (2) in [12,14–17] and in [12,17–21], respectively. Subdominant contributions from right-handed currents can be provided by additional leptoquarks $\tilde{S}_2$ or V_2, which induce $C_{RL}^{\ell} = 2C_9'^{\ell} = -2C_{10}'^{\ell}$. In these models [12,13]

$$C_{LL}^{\mathrm{NP}\ell} = \frac{k_{\mathrm{LQ}}\pi\sqrt{2}}{G_F\lambda_t\alpha}\frac{YY^*}{M^2},$$
$$k_{\mathrm{LQ}} = 1, -1, -1 \quad \text{for } S_3, V_1, V_3, \tag{14}$$

$$C_{RL}^{\ell} = \frac{k_{\mathrm{LQ}}\pi\sqrt{2}}{G_F\lambda_t\alpha}\frac{YY^*}{M^2},$$
$$k_{\mathrm{LQ}} = -1/2, +1 \quad \text{for } \tilde{S}_2, V_2. \tag{15}$$

Here, M (Y) denotes the leptoquark mass (coupling).

Model-independent and leptoquark specific predictions for R_K versus R_{K^*} are shown in Fig. 2. The green and blue band s denote the 1σ band of R_K (2) and R_{K^*} (3), respectively. Also shown are BSM scenarios which can (red solid and dashed lines) or cannot (blue dotted and gray dashed lines) simultaneously explain the data. Concretely, leptoquark $\tilde{S}_2$, corresponding to the blue dotted curve, and which has been considered in the context of R_K [14,22–24], is disfavored as the sole source of LNU by the measurement of R_{K^*}. The numerics are based on the full expressions for the decay rates, for $\ell = \mu$. Recall, however, that to linear approximation only nonuniversality matters.

We find for the dominant, SM-like chiral contribution S_3,

$$\frac{Y_{b\mu}Y_{s\mu}^* - Y_{be}Y_{se}^*}{M^2} \simeq \frac{1.1}{(35\ \mathrm{TeV})^2}, \qquad (S_3) \tag{16}$$

TABLE II. Vector leptoquarks and implications for R_{K^*} assuming $R_K < 1$, as suggested by data (2), see Table I.

	Representation	C_{AB}	Relation	$R_{K^{(*)}}$
V_1	$(3, 1, 2/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$
		C_{RR}	$C_9' = +C_{10}'$	$R_K \simeq R_{K^*} \simeq 1$
V_2	$(3, 2, -5/6)$	C_{RL}	$C_9' = -C_{10}'$	$R_K < 1, R_{K^*} > 1$
		C_{LR}	$C_9 = +C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
V_3	$(3, 3, -2/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$

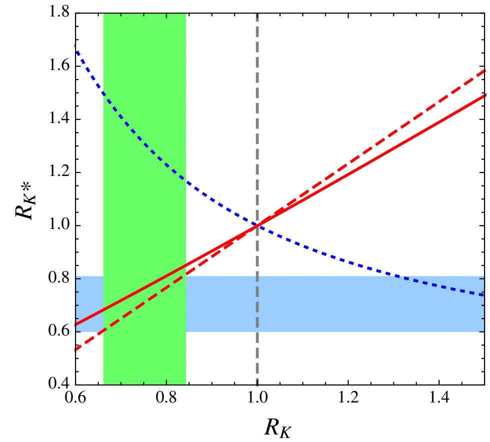

FIG. 2. R_K versus R_{K^*} in BSM scenarios. Solid red curve: C_{LL}^{NP} ($C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}}$) corresponding to S_3, V_1, or V_3; blue dotted curve: C_{RL} ($\tilde{S}_2$ or V_2); gray dashed curve: $C_{RL} = -C_{LL}^{\mathrm{NP}}$ (no single leptoquark); and red dashed curve: C_{LL}^{NP} and $C_{RL} = -1/10 C_{LL}^{\mathrm{NP}}$ (for instance, S_3 plus 10% admixture of $\tilde{S}_2$). The colored bands correspond to the LHCb measurements of R_K (2) and R_{K^*} (3).

and similarly for V_1 or V_3. To accommodate an admixure of right-handed currents we need contributions from another leptoquark, such as $\tilde{S}_2$,

$$\frac{Y_{b\mu}Y_{s\mu}^* - Y_{be}Y_{se}^*}{M^2} \simeq \frac{-0.1}{(24\ \mathrm{TeV})^2}. \qquad (\tilde{S}_2) \tag{17}$$

Understanding the mass range is linked to flavor. The leptoquark coupling matrix Y is a 3×3 matrix in generation space, with rows corresponding to quark flavor and columns corresponding to lepton flavor. The presence of both kinds of fermions in one vertex is beneficial; it allows us to probe flavor in new ways beyond SM fermion masses and mixings. Viable models are those employing a Froggatt-Nielsen $U(1)_{FN}$ to generate mass hierarchies for quarks and charged leptons together with a discrete, non-Abelian group such as A_4, which allows us to accommodate neutrino properties [25,26]. Applied to leptoquark models this allows to select lepton species—for instance, having only couplings to one lepton species, muons, or electrons [16]. Corrections to lepton isolation arise from rotations to the mass basis and at higher order in the spurion expansion, and induce lepton flavor violation [12,16,27–30] such as $B \to K\mu\tau$, which can be probed with B-physics experiments, but also $\mu - e$ converison and rare K and $\ell \to \ell'$ decays. Together with $B \to K^{(*)}\nu\bar{\nu}$ modes the latter constitute the leading constraints on flavor models and LNU anomalies, and improved experimental study is promising.

A generic prediction for S_3, V_1, V_3—all of them couple quark doublets to lepton doublets—is obtained from simple flavor patterns such as ℓ-isolation, $\ell = e, \mu$ [12,16],

$$Y_{q_3\ell} \sim c_l, \qquad Y_{q_2\ell} \sim c_l\lambda^2,$$
$$q_3 = b, t, \qquad q_2 = s, c, \tag{18}$$

where $c_l \sim \lambda \sim 0.2$. Note that the FN mechanism is only able to explain parametric suppressions in specific powers of the parameter λ up to numbers of order 1. Irrespective of the concrete flavor symmetry, each coupling Y to lepton doublets brings in a non-Abelian spurion insertion suppression, the factor c_l, which is unavoidable as lepton doublets are necessarily charged under the non-Abelian group to obtain a viable Pontecorvo-Maki-Nakagawa-Sakata matrix. The suppression of the additional couplings to right-handed leptons in $V_{1,2}$ can be achieved using flavor symmetries [12,20].

Putting lepton and neutrino properties aside, a minimal prediction is $Y_{s\ell}/Y_{b\ell} \sim m_s/m_b$; hence $Y_{b\ell}Y^*_{s\ell} \sim \lambda^2 \simeq$ few $\times\, 0.01$. Equation (16) implies $M \sim 5$–10 TeV, accessible at the LHC at least partly with single production.

Equation (18) points to lower values of leptoquark masses, see Fig. 3. Also shown are constraints from $B_s - \bar{B}_s$ mixing, induced at one loop through box diagrams and which constrains the square of YY^* over M^2 [14]. A data-driven upper limit, irrespective of flavor, is obtained as

$$M \lesssim 40\ \text{TeV}, 45\ \text{TeV}, 20\ \text{TeV} \quad \text{for } S_3, V_1, V_3. \tag{19}$$

We assume vector leptoquarks to be gaugelike and employ the usual Hamiltonian

$$\mathcal{H}^{\Delta B=2}_{\text{eff}} = (C_1^{\text{SM}} + C_1^{\text{LQ}})(\bar{b}\gamma_\mu(1-\gamma_5)s)(\bar{b}\gamma_\mu(1-\gamma_5)s) + \text{H.c.} \tag{20}$$

where

$$C_1^{\text{LQ}} = \frac{p_{\text{LQ}}(YY^*)^2}{128\pi^2 M^2},$$
$$p_{\text{LQ}} = 5, 4, 20 \quad \text{for } S_3, V_1, V_3, \tag{21}$$

see, e.g., [31]. In general, $(YY^*)^2 \to \sum_{\ell_i,\ell_j}(Y_{b\ell_i}Y^*_{s\ell_i}) \times (Y_{b\ell_j}Y^*_{s\ell_j})$. It follows that

$$\Delta m^{\text{LQ}}_{B_s}/\Delta m^{\text{SM}}_{B_s} = \frac{p_{\text{LQ}}(YY^*)^2}{8M^2 G_F^2 m_W^2 \lambda_t^2 S_0(x_t)}, \tag{22}$$

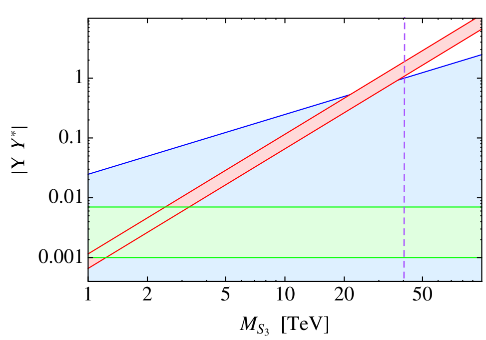

FIG. 3. Allowed values of $|YY^*|$, M_{S_3} by Δm_{B_s} (blue area) and $R_{K^{(*)}}$ (red band) (12). The green band corresponds to flavor model predictions (18). The dashed blue line corresponds to the upper limit on the mass of the S_3 leptoquark (19).

where S_0 is an Inami-Lim function, $x_t = m_t^2/m_W^2$. We use $\Delta m^{\text{exp}}_{B_s}/\Delta m^{\text{SM}}_{B_s} = 1.02 \pm 0.10$ [28,32].

Direct limits for scalar leptoquarks decaying 100% into a muon (electron) and a jet are $M > 1050$ GeV [33] ($M > 1755$ GeV [34]). For vector leptoquarks, the limits are model dependent and read $M > 1200$–1720 GeV ($M > 1150$–1660 GeV) for 100% decays to muon (electron) plus jet [35]. The bounds weaken if decays into neutrinos are taken into account.

IV. UV CONSIDERATIONS

The main challenge for embedding light scalar leptoquarks into (complete) short-distance models is proton decay. From Table I, only S_2, $\tilde{S}_2$ do not couple to quark bilinears ($\bar{q}q$) and, thus, do not induce proton decay at tree level. In addition, dangerous couplings to the Higgs doublet should be suppressed [13,36].

SM gauge invariance allows S_3 to couple to quark bilinears

$$\mathcal{L}_{QQ} = Y_\kappa \bar{Q}_L^{C\alpha}(i\sigma^2)^{\alpha\beta}(S_3^\dagger)^{\beta\gamma}Q_L^\gamma + \text{H.c.}, \tag{23}$$

with isospin indices α, β, γ. The Yukawa coupling Y_κ is antisymmetric in flavor space [37,38], Thus, S_3 does not introduce proton decay at tree level; however, couplings to $ut(c)$ can induce the process via higher-order diagrams [38].

Within flavor models, the dangerous terms in (23) receive suppressions. For $U(1)_{FN} \times A_4 \times Z_3$, and assuming that the quarks transform trivially under A_4, we find that this requires at least two spurion fields ξ and ξ', see [16] for details. Including the FN suppression for the up-quark, this amounts to $\lambda^4\kappa\kappa' \lesssim 10^{-4}$. Viable patterns for R_K are obtained with second-generation quarks in nontrivial representations of A_4. This way, however, the ut coupling cannot be suppressed further.

If the evidence for LNU in C^{NP}_{LL} strengthens, it would be important to understand the origin of the leptoquark S_3 which provides an explicit high-energy realization. One possibility was suggested in Ref. [15]. The S_3 appears, along with the Higgs doublet, as a pseudo-Goldstone boson of the strong dynamics around TeV scale, while the proton decay is avoided with a discrete symmetry.

An alternative possibility is to trace the origin of S_3 to a grand unified theory (GUT). The S_3 is contained in the $\overline{126}_H$ scalar multiplet of $SO(10)$ [13,39]. The dangerous couplings to quark billnears are forbidden by $SO(10)$ invariance—the corresponding Yukawa coupling to fermion multiplets is $y_{ij}16_i16_j\overline{126}_H$, which embeds only the couplings to leptons and quarks, but not to quark bilinears. The 16_i denotes the spinor representation of $SO(10)$ that unifies all SM fermions of a single generation and a right-handed neutrino, and $i = 1, 2, 3$ is a flavor index. The S_3 might play a role in correcting the phenomenologically unsuccessful prediction of the relation between the mass matrices of down-type quarks and charged leptons in the minimal $SU(5)$ [40,41].

Vector leptoquarks appear as super-heavy gauge bosons in a GUT, with masses near the unification scale. For example, the state with quantum numbers of V_1 is a gauge boson in models of quark-lepton unification, e.g., the original Pati-Salam model or variants thereof, see [42]. V_1, V_3 do not couple to quark bilinears and are safe with regards to proton decay. If V_1 is a gauge boson, the corresponding left- and right-handed couplings are unitary. It is then more difficult to suppress the unwanted (right-handed) couplings and simultaneously avoid the constraints from the first generation fermions. The embedding of V_3 into a UV complete model is challenging [43].

The low-scale nongauge spin-1 leptoquarks might be obtained as composite states from strongly coupled dynamics, in which case they are accompanied by other composite states.

V. CONCLUSIONS

The recent measurement of R_{K^*} (3) by the LHCb Collaboration challenges lepton universality, an in-built feature of the SM and many of its extensions; further, combined with R_K (2) the discrepancy with the SM is $\sim 3.5\sigma$. The LNU contributions to $|\Delta B| = |\Delta S| = 1$ flavor-changing-neutral-currents are predominantly SM-like chiral, with possible admixture of right-handed contributions up to the order of few 10%, see Fig. 1. Since R_K and R_{K^*} suffice to determine the chiral structure, measurements of further LNU ratios R_H into different final states and angular distributions [9,44] provide consistency checks. Using R_{K,K^*} data we predict the ratio of inclusive $B \to X_s \ell\ell$ branching fractions,

$$R_{X_s} \sim 0.73 \pm 0.07, \tag{24}$$

consistent with earlier findings by Belle, $R_{X_s} = 0.42 \pm 0.25$ [45], and *BABAR*, $R_{X_s} = 0.58 \pm 0.19$ [46].[2]

Leptoquarks naturally induce LNU in semileptonic decays at tree level. The scalar S_3 and the vector $V_{1,3}$ representations can account for the dominant, SM-like chiral contribution (12). Their masses are limited to not exceed the multi-10 TeV range in order to comply with data, see Eq. (19) for details. Leptoquark explanations of R_{K,K^*} within flavor models, which simultaneously address the masses and mixings of SM fermions, require leptoquark masses in the few-TeV region, which can be explored at the LHC, see Fig. 3. The dominant decay modes of the triplets S_3 and V_3 are $b\mu$, $t\mu$, $b\nu$, and $t\nu$, whereas the $SU(2)_L$-singlet V_1 decays predominantly to $b\mu$ and $t\nu$. The respective Yukawa couplings are at the level $O(0.1)$. Ignoring the pull from the global fit to $b \to s\mu\mu$ LNU can also stem from sizable BSM contributions to $b \to see$. In this case modes into final-state electrons (and corresponding neutrinos) are dominant.

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