**$R_K$ and $R_{K^*}$ beyond the Standard Model**

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Measurements of the ratio of $B \to K^*\mu\mu$ to $B \to K^*\ell\ell$ 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 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 $O$(few10%).

Scalar and vector leptoquark representations $(\bar{S}_3, V_1, V_3)$ plus possible $(\bar{S}_2, V_2)$ admixture can explain $R_{K^*}$ 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.

**Introduction.** Gauge interactions of the leptons within the Standard Model (SM) exhibit exact universality. The only known source of lepton non-universality (LNU) are the Yukawa couplings of the leptons to the Higgs. Tests of lepton universality are provided by rare (semi)lepton $|\Delta B| = |\Delta S| = 1$ transitions, which are induced in the SM at one loop and additionally suppressed by the Glashow-Iliopoulos-Maiani mechanism, therefore allowing 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]

$$R_H = \frac{B(B \to H\mu^+\mu^-)}{B(B \to H\ell^+\ell^-)}, \quad H = K, K^*, X_s, \ldots$$

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

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

$$R_K^{\text{LHCb}} = 0.745_{-0.073}^{+0.090} \pm 0.036,$$

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

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

with deviation from $R = 1$ by $2.6\sigma$ 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 percent level [8], not qualitatively altering the fact that the data, (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 model-independently and pursue interpretations within leptoquark extensions of the SM.

**Model-independent interpretation.** We employ the usual effective Hamiltonian for $b \to s\ell\ell$, $\ell = e, \mu, \tau$ transitions

$$H_{\text{eff}} = -\frac{4G_F\lambda_\ell}{\sqrt{2}} \alpha \sum_i \tilde{C}_i^\ell O_i^\ell + \text{h.c.},$$

where $C_i^\ell, O_i^\ell$ denote lepton-specific Wilson coefficients and dimension-six operators, respectively, renormalized at the scale $\mu \sim m_b$. Furthermore, $G_F, \alpha$, and $\lambda_\ell = V_{tb}V_{ts}^\dagger$ stand for Fermi’s constant, the finestructure constant and the product of relevant Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, respectively.

The semileptonic operators read

$$O_9^\ell = (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell), \quad O_9^{\ell \dagger} = (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \ell),$$

$$O_{10}^\ell = (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell), \quad O_{10}^{\ell \dagger} = (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \gamma_5 \ell),$$

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

$$O_{AB}^\ell = (\bar{s}\gamma_\mu P_A b)(\bar{\ell}\gamma_\mu P_B \ell), \quad A, B = L, R,$$

are related to the $O_{9,10}^{\ell \dagger}$ as

$$C_9 = \frac{1}{2}(C_{LL}^\ell + C_{LR}^\ell), \quad C_{10} = \frac{1}{2}(C_{LR}^\ell - C_{LL}^\ell),$$

$$C_{9}^{\ell \dagger} = \frac{1}{2}(C_{RL}^\ell + C_{RR}^\ell), \quad C_{10}^{\ell \dagger} = \frac{1}{2}(C_{RR}^\ell - C_{RL}^\ell).$$

Within the SM the (lepton universal) Wilson coefficients are $C_{SM}^{B_L} = 4.07$, $C_{SM}^{B_R} \approx -4.31$ [10], thus $C_{LL}^{B_L} = C_{SM}^{B_L} - C_{10}^{B_L} \approx 8.4$, while scalar or tensor Wilson coefficients are negligible. We define $C_{LL}^\ell = C_{SM}^{B_L} + C_{NP}^{B_L}$ [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]

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

where

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

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 $B \rightarrow K^*\ell\ell$ branching ratio [9]. Due to helicity arguments $p \sim 1$ both at low recoil (high $q^2$) and at low $q^2$. Consequently, $\mathcal{B}(B \rightarrow K^*\ell\ell)$ is dominated by contributions proportional to $|C - C'|^2$. Since $\mathcal{B}(B \rightarrow K\ell) \propto |C + C'|^2$ 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 (2),(3) one obtains

$$
X_{K*} = R_{K^*}/R_K = 0.94 \pm 0.18, \tag{10}
R_{K^*} + R_K - 2 = -0.54 \pm 0.14, \tag{11}
$$

which gives, at $1\sigma$

$$
\Re[C_{10}^{NP,\mu} - C_{10}^{NP,\mu} - (\mu \rightarrow e)] \sim -1.1 \pm 0.3, \tag{12}
\Re[C_{10}^{NP,\mu} - C_{10}^{NP,\mu} - (\mu \rightarrow e)] \sim 0.1 \pm 0.4. \tag{13}
$$

As anticipated, $|C_{NP}| \ll |C_{SM}|$. 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 $O_{LL}^\ell$ or $O_{RL}^\ell$ is able to explain $R_{K,K^*}$.

In Fig. 1 a $x^2$ 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 $C_{10}^{NP,\mu} \sim -1$ are also favored by a global fit [10] to $b \rightarrow s\mu\mu$ observables. Taking this into account suggests an explanation of $R_{K,K^*}$ anomalies with BSM predominantly residing in the muons.

**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 $S_i$ 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 $C_{NP}^{LL} = 2C_9^{NP} = -2C_{10}^{NP}$. This singles out the scalar triplet $S_3$, the vector singlet $V_1$ and the vector triplet $V_3$. 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 $C_{RL}^{\mu} = 2C_{10}^{\mu} = -2C_{10}^{\mu}$.

\[1\text{ In the literature the scalar leptoquarks } S_2 \text{ and } \tilde{S}_2 \text{ are also denoted by } R_2 \text{ and } R_2 \text{, respectively.}\]
Table II: Vector leptoquarks and implications for $R_K$ assuming $R_K < 1$, as suggested by data (2), see Table I.

| $V_i$ | $(3, 1, 2/3)$ | $C^{NP}_{LL}$ | $C_0 = -C_{10}$ | $R_K \simeq R_K^* < 1$ |
|-------|---------------|----------------|-----------------|--------------------------|
| $V_1$ | $(3, 2, -5/6)$ | $C_{RL}$ | $C_0 = -C_{10}$ | $R_K < 1$, $R_K^* > 1$ |
| $V_2$ | $(3, 3, -2/3)$ | $C'^{NP}_{LL}$ | $C_0 = -C_{10}$ | $R_K \simeq R_K^* \simeq 1$ |

In these models [12, 13]

$$C^{NP}_{LL} = \frac{k_{LQ} \sqrt{2} Y Y^*}{G_F \lambda \alpha} \frac{k_{LQ}}{M^2}, k_{LQ} = 1, -1, -1$$

$$C'^{LL}_{RL} = \frac{k_{LQ} \sqrt{2} Y Y^*}{G_F \lambda \alpha} \frac{k_{LQ}}{M^2}, k_{LQ} = -1/2, +1$$

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 denote the $1\sigma$ 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 $S_2$, corresponding to the blue dotted curve, and which has been considered in the context of $R_K$ [14, 22–24], is disfavoured 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, to linear approximation only non-universality matters.

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

$$\frac{Y_{\mu} V_{s\mu}}{M^2} - \frac{Y_{\mu} V_{se}}{M^2} \simeq \frac{1.1}{(35 \text{ TeV})^2}, \quad (S_3) \quad (16)$$

and similarly for $V_1$ or $V_3$. To accommodate an admixture of right-handed currents we need contributions from another leptoquark, such as $S_2$

$$\frac{Y_{\mu} V_{s\mu}}{M^2} - \frac{Y_{\mu} V_{se}}{M^2} \simeq \frac{-0.1}{(24 \text{ TeV})^2}, \quad (S_2) \quad (17)$$

Understanding the mass range is linked to flavor. The leptoquark coupling matrix $Y$ is a $3 \times 3$ 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 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 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 $\mu - e$ conversion, 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 $\ell$-isolation, $\ell = e, \mu$, [12, 16] with $Y_{q_3\ell} \sim c_1$, $Y_{q_2\ell} \sim c_2 \lambda^2$, $q_3 = b, t$, $q_2 = s, c$, \quad (18)

where $c_1 \sim \lambda \sim 0.2$. Note that the FN-mechanism is only able to explain parametric suppressions in specific powers of the parameter $\lambda$ up to numbers of order one. Irrespective of the concrete flavor symmetry, each coupling $Y$ to lepton doublets brings in a non-abelian spurion insertion suppression, the factor $c_1$, which is unavoidable as lepton doublets are necessarily charged under the non-abelian group to obtain a viable PMNS-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 $Y_{b\ell} Y_{s\ell} \sim \lambda^2 \simeq \text{few} \times 0.01$. Eq. (16) implies $M \sim 5 \sim 10 \text{ TeV}$, accessible at the LHC at least partly with single production.

Eq. (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

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

We assume vector leptoquarks to be gauge-like and employ the usual Hamiltonian

$$H_{\text{eff}}^{B=2} = (C_1^{SM} + C_1^{LQ})(\bar{b}\gamma_\mu(1-\gamma_5)s)(\bar{b}\gamma_\mu(1-\gamma_5)s) + \text{h.c.} \quad (20)$$

where

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

see, e.g [31]. In general, $(YY^*)^2 \to \sum_{i,\ell}(Y_{bi,\ell}Y_{bi,\ell}^*)(Y_{bi,\ell}Y_{bi,\ell}^*)$. It follows that

$$\Delta m_{B_s}^{LQ}/\Delta m_{B_s}^{SM} = \frac{p_{LQ}(YY^*)^2}{8M^2G_F^2m_W^2\lambda^2S_0(x)} \quad (22)$$

where $S_0$ is an Inami-Lim function, $x_t = m_t^2/m_W^2$. We use $\Delta m_{B_s}^{LQ}/\Delta m_{B_s}^{SM} = 1.02 \pm 0.10$ [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.

**UV considerations.** The main challenge for embedding light scalar leptoquarks into (complete) short-distance models is proton decay. From Table I only $S_2, S_3$ 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

$$L_{QQ} = Y_\kappa \bar{Q}_L^\kappa (i\sigma^\alpha)(\sigma^\beta)(S_3^\dagger)^{\beta\gamma}Q_\gamma^L + \text{h.c.} \quad (23)$$

with isospin indices $\alpha, \beta, \gamma$. The Yukawa coupling $Y_\kappa$ is anti-symmetric in flavor space [37, 38], thus $S_3$ does not introduce proton decay at tree level, however, couplings to $ut(e)$ can induce the process via higher orders 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 2 spurion fields $\xi$ and $\xi'$, see [16] for details. Including the FN-suppression for the up-quark this amounts to $\lambda^4\kappa^\xi \lesssim 10^{-4}$. Viable patterns for $R_K$ are obtained with second generation quarks in non-trivial representations of $A_3$. This way, however, the $ut(e)$ coupling cannot be suppressed further.

If the evidence for LNU in $C_{LL}^{NP}$ 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 $126U$ scalar multiplet of $SO(10)$ [13, 39]. The dangerous couplings to quark bilinears are forbidden by $SO(10)$-invariance - the corresponding Yukawa coupling to fermion multiplets is $y_{ij,16}16, 16. 126$ 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 non-gauge spin-1 leptoquarks might be obtained as composite states from strongly coupled dynamics, in which case they are accompanied by other composite states.

**Conclusions.** The recent measurement of $R_K \sim 3$ by the LHCb collaboration challenges lepton universality, an inbuilt 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 $|\Delta B| = |\Delta S| = 1$ FCNCs 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

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

consistent with earlier findings by Belle $R_{X_s} = 0.42\pm0.25$ [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 (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 $b\mu, t\nu$. 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 $b \to s\ell\ell$. In this case modes into final state electrons (and corresponding neutrinos) are dominant.

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