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# Gauge-invariant implications of the LHCb measurements on Lepton-Flavour Non-Universality

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We study the implications of the recent measurements of  $R_K$  and  $R_{K^*}$  by the LHCb collaboration. We do that by adopting a model-independent approach based on the Standard Model Effective Field Theory (SMEFT), with the dominant New Physics (NP) effects encoded in the coefficients of dimension-six operators respecting the full Standard Model (SM) gauge symmetry. After providing simplified expressions for  $R_K$  and  $R_{K^*}$ , we determine the implications of the recent LHCb results for these observables on the coefficients of the SMEFT operators at low and high energies. We also take into account all  $b \rightarrow s\ell\ell$  data, which combined lead to effective NP scenarios with SM pulls in excess of  $5\sigma$ . Thus the operators discussed in this paper would be the first dimension-six terms in the SM Lagrangian to be detected experimentally. Indirect constraints on these operators are also discussed. The results of this paper transcend the singularity of the present situation, and set a standard for future analyses in  $b \rightarrow s$  transitions when the NP is assumed to lie above the electroweak scale.

*Introduction.*— An absolute priority in particle physics is to detect and measure the effects of dimension-six terms in the SM Lagrangian. These *must* be there since the SM is only valid up to a physical scale  $\Lambda > \mu_{\text{EW}}$ , where  $\mu_{\text{EW}} \simeq 100 \text{ GeV}$  is the electroweak scale. These effects are suppressed by a factor  $\mu_{\text{EW}}^2/\Lambda^2$ , so if  $\Lambda$  is very large precision tests are needed.

Lepton-flavour universality (LFU) –lepton gauge interactions being identical for  $e, \mu, \tau$ – is a strong test of certain dimension-six terms. One such test is given by the observables  $R_{K^{(*)}}$ , defined as [1]

$$[R_{K^{(*)}}]_{[q_1^2, q_2^2]} = \frac{\int_{q_1^2}^{q_2^2} d\Gamma(B \rightarrow K^{(*)}\mu^+\mu^-)}{\int_{q_1^2}^{q_2^2} d\Gamma(B \rightarrow K^{(*)}e^+e^-)}, \quad (1)$$

with  $q^2$  the dilepton squared invariant mass. For  $q^2 \gg 4m_\mu^2$ , lepton-mass effects are negligible and LFU predicts  $R_{K^{(*)}} \simeq 1$ , making these ratios exceptional probes of dimension-six terms breaking LFU.

The LHCb collaboration has measured some of these ratios, finding values significantly smaller than one [2, 3]:

$$R_K = 0.745_{-0.074}^{+0.090} \pm 0.036, \quad q^2 \in [1, 6] \text{ GeV}^2,$$

$$R_{K^*} = 0.660_{-0.070}^{+0.110} \pm 0.024, \quad q^2 \in [0.045, 1.1] \text{ GeV}^2,$$

$$R_{K^*} = 0.685_{-0.069}^{+0.113} \pm 0.047, \quad q^2 \in [1.1, 6.0] \text{ GeV}^2. \quad (2)$$

Comparing these results to their LFU predictions [4–6],

$$R_K^{\text{SM}} = 1.00 \pm 0.01, \quad q^2 \in [1, 6] \text{ GeV}^2,$$

$$R_{K^*}^{\text{SM}} = 0.92 \pm 0.02, \quad q^2 \in [0.045, 1.1] \text{ GeV}^2,$$

$$R_{K^*}^{\text{SM}} = 1.00 \pm 0.01, \quad q^2 \in [1.1, 6.0] \text{ GeV}^2, \quad (3)$$

one concludes that the LHCb measurements represent deviations from LFU at the level of  $2.6\sigma$ ,  $2.2\sigma$  and  $2.4\sigma$ , respectively. The Belle collaboration has also found slight differences between  $e$  and  $\mu$  channels in their  $B \rightarrow K^*\ell^+\ell^-$  angular analysis [9], most notably in the pioneering measurement of the clean observables  $Q_4$  and  $Q_5$  [10]. While each individual measurement is not very significant in itself, their combination constitutes an intriguing set of anomalies. Recent studies analysing these new measurements in terms of models and the Weak Effective Theory (WET) can be found in Refs. [7, 8, 11–14].

Dimension-six operators breaking LFU will manifest also in  $b \rightarrow s\ell^+\ell^-$  ( $\ell = \mu$  or  $e$ ) observables such as branching ratios and angular distributions. Notably, anomalies have been observed in  $b \rightarrow s\mu^+\mu^-$  transitions too [15–17] and these are consistent with the anomaly in  $R_K$  [18–20]. Global analyses of  $b \rightarrow s\mu^+\mu^-$  data lead to scenarios that can accommodate  $R_K$  and  $R_{K^*}$  [4, 21, 22].

Many models have been proposed to address the  $b \rightarrow s$  anomalies. These models involve a  $Z'$  boson from an extended gauge group [23–58], leptoquarks (or R-parity violating supersymmetry) [57, 59–81], a massive resonance from a strong dynamics [82–86] or Kaluza-Klein excitations [87–90]. Refs. [91–94] have explored renormalizable models that explain  $R_K$  at the one-loop level, while the MSSM with R-parity conservation was considered in Ref. [95].

We interpret these measurements in the context of the SMEFT [96, 97]. This is the most convenient framework when the new degrees of freedom are much heavier than  $\mu_{\text{EW}}$ , and allows for a more transparent connection to possible ultraviolet scenarios as it incorporates the full electroweak gauge symmetry. We start by providing simplified analytical expressions for the observables of interest

and for the SMEFT Wilson coefficients (WCs) at low and high energies. With these expressions at hand, we study the implications of the LHCb measurements on the coefficients of the SMEFT operators both at  $\mu_{\text{EW}}$  and at the scale  $\Lambda$  where the (unknown) heavy degrees of freedom decouple. For this purpose we use `DsixTools` [98], implementing the complete SMEFT one-loop Renormalization Group Equations (RGEs). This allows to study the appearance of other effective operators at low energies due to renormalization, leading to indirect constraints on the scenarios that explain the LHCb measurements.

*Effective Field Theory.*— At energies relevant for the  $B$  decay the most general Hamiltonian for semileptonic  $b \rightarrow s$  transitions contains the terms

$$\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \lambda_t^{sb} \sum_i \mathcal{C}_i \mathcal{O}_i, \quad (4)$$

where  $\lambda_t^{ij} = V_{ti}^* V_{tj}$ , with  $V$  the CKM matrix,  $\lambda_t^{sb} \sim -0.04$  [99], and the sum runs over all the relevant operators for semileptonic  $\Delta B = \Delta S = 1$  observables, including

$$\begin{aligned} \mathcal{O}_9^{(\prime)} &= (\bar{s} \gamma_\alpha P_{L(R)} b) (\bar{\ell} \gamma^\alpha \ell), \\ \mathcal{O}_{10}^{(\prime)} &= (\bar{s} \gamma_\alpha P_{L(R)} b) (\bar{\ell} \gamma^\alpha \gamma_5 \ell). \end{aligned} \quad (5)$$

The dipole operator  $\mathcal{O}_7 = (\bar{s} \sigma_{\alpha\beta} P_R b) F^{\alpha\beta}$  is only marginally relevant for  $[R_{K^*}]_{[0.045, 1.1]}$ . Assuming now that the SM degrees of freedom are the only ones present below a certain mass scale  $\Lambda \gg \mu_{\text{EW}}$ , one can describe deviations from the SM in a general way using the SMEFT. Dominant NP effects are parametrized by effective operators of canonical dimension six,

$$\mathcal{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda^2} \sum_k \mathcal{C}_k Q_k, \quad (6)$$

where the sum extends over all operators in the *Warsaw basis* [97],  $\mathcal{C}_k$  being the WCs and  $Q_k$  the operators. This effective theory is more suitable to describe NP above the electroweak scale, since it incorporates the restrictions imposed by gauge invariance and leads to relations among operators that would otherwise be missing, see e.g. [18, 100].

Matching the SMEFT onto the operators in Eq. (4) at tree level, one obtains the following matching conditions at  $\mu_{\text{EW}} \sim \mathcal{O}(M_W)$  [18, 101] (with  $a = e, \mu$ ):

$$\begin{aligned} \mathcal{C}_{9a}^{\text{NP}} &= \frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ [\tilde{\mathcal{C}}_{\ell q}^{(1)}]_{aa23} + [\tilde{\mathcal{C}}_{\ell q}^{(3)}]_{aa23} + [\tilde{\mathcal{C}}_{qe}]_{23aa} \right\}, \\ \mathcal{C}_{10a}^{\text{NP}} &= -\frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ [\tilde{\mathcal{C}}_{\ell q}^{(1)}]_{aa23} + [\tilde{\mathcal{C}}_{\ell q}^{(3)}]_{aa23} - [\tilde{\mathcal{C}}_{qe}]_{23aa} \right\}, \\ \mathcal{C}'_{9a} &= \frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ [\tilde{\mathcal{C}}_{\ell d}]_{aa23} + [\tilde{\mathcal{C}}_{ed}]_{aa23} \right\}, \end{aligned}$$

SMEFT operator	Definition	Matching	Order
$[Q_{\ell q}^{(1)}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \ell_a) (\bar{q}_2 \gamma^\mu q_3)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell q}^{(3)}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \tau^I \ell_a) (\bar{q}_2 \gamma^\mu \tau^I q_3)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{qe}]_{23aa}$	$(\bar{q}_2 \gamma_\mu q_3) (\bar{e}_a \gamma^\mu e_a)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell d}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \ell_a) (\bar{d}_2 \gamma^\mu d_3)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{ed}]_{aa23}$	$(\bar{e}_a \gamma_\mu e_a) (\bar{d}_2 \gamma^\mu d_3)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{\varphi \ell}^{(1)}]_{aa}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{\ell}_a \gamma^\mu \ell_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi \ell}^{(3)}]_{aa}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{\ell}_a \gamma^\mu \tau^I \ell_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\ell u}]_{aa33}$	$(\bar{\ell}_a \gamma_\mu \ell_a) (\bar{u}_3 \gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi e}]_{aa}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{e}_a \gamma^\mu e_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{eu}]_{aa33}$	$(\bar{e}_a \gamma_\mu e_a) (\bar{u}_3 \gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	1-loop

TABLE I. List of relevant operators (see Ref. [97] for definitions) that contribute to the matching to  $\mathcal{C}_{9,10}^{(\prime)}$ , either at tree-level or through one-loop running. The index  $a = e, \mu$  denotes the lepton flavour. Contrary to Eq. (5), here  $\ell$  denotes a lepton  $\text{SU}(2)_L$  doublet.

$$\mathcal{C}'_{10a} = -\frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ [\tilde{\mathcal{C}}_{\ell d}]_{aa23} - [\tilde{\mathcal{C}}_{ed}]_{aa23} \right\}. \quad (7)$$

Only operators that break LFU have been included. These matching conditions are summarized in Table I, where the operators of the SMEFT are defined. We also show in this table the operators that contribute via one-loop running, but leave out a few others that contribute with finite terms to the matching. Here we implicitly assume that the WCs are defined at the matching scale  $\mu_{\text{EW}}$ . The tilde over the SMEFT WCs denotes that they are given in the fermion mass basis (see [101]). Throughout the paper we adopt the weak basis where  $V_{dL} = \mathbb{1}$  and  $V_{dR, uR} = \mathbb{1}$ .

*Explaining the LHCb measurements.*— For the phenomenological discussion we derive approximate formulas for  $R_{K, K^*}$  in terms of the relevant WCs. These formulas are obtained with the same approach as Ref. [4], but neglecting terms that are not important for the present discussion and linearising in the NP coefficients. We find:

$$\begin{aligned} [R_K]_{[1,6]} &\simeq 1.00(1) + 0.230(\mathcal{C}_{9\mu-e}^{\text{NP}} + \mathcal{C}'_{9\mu-e}) \\ &\quad - 0.233(2)(\mathcal{C}_{10\mu-e}^{\text{NP}} + \mathcal{C}'_{10\mu-e}), \\ [R_{K^*}]_{[0.045, 1.1]} &\simeq 0.92(2) + 0.07(2)\mathcal{C}_{9\mu-e}^{\text{NP}} - 0.10(2)\mathcal{C}'_{9\mu-e} \\ &\quad - 0.11(2)\mathcal{C}_{10\mu-e}^{\text{NP}} + 0.11(2)\mathcal{C}'_{10\mu-e} + 0.18(1)\mathcal{C}_7^{\text{NP}}, \\ [R_{K^*}]_{[1.1, 6]} &\simeq 1.00(1) + 0.20(1)\mathcal{C}_{9\mu-e}^{\text{NP}} - 0.19(1)\mathcal{C}'_{9\mu-e} \end{aligned} \quad (8)$$

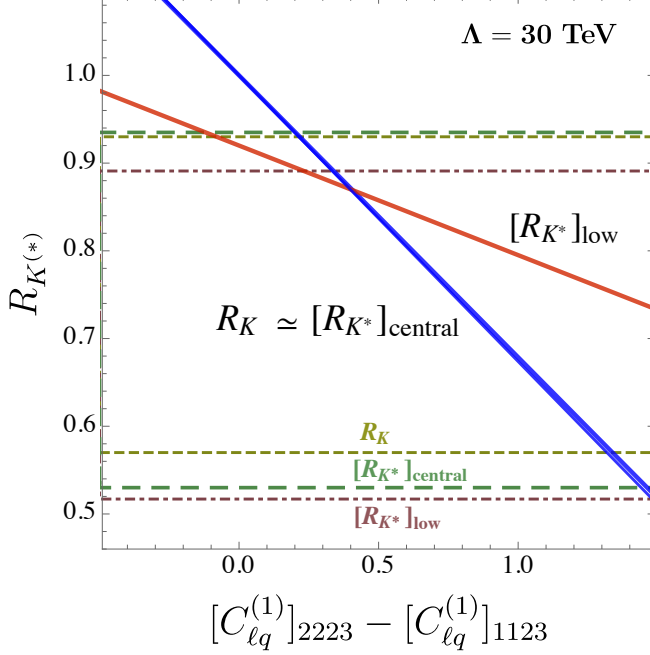


FIG. 1.  $R_K$  and  $R_{K^*}$  as a function of the SMEFT WC  $\mathcal{C}_{\ell q}^{(1)}$  with  $\Lambda = 30$  TeV. The experimental ranges for  $R_K$  and  $R_{K^*}$  at 95% CL are also shown for comparison.

$$-0.27(1)\mathcal{C}_{10\mu-e}^{\text{NP}} + 0.21(1)\mathcal{C}'_{10\mu-e}, \quad (10)$$

where  $\mathcal{C}_{9\mu-e}^{\text{NP}} \equiv \mathcal{C}_{9\mu}^{\text{NP}} - \mathcal{C}_{9e}^{\text{NP}}$  etc., and all WCs are defined at the scale  $\mu_b = 4.8$  GeV. We have linearised the dependence with respect to the WCs, consistently assuming that contributions from dimension-eight SMEFT operators interfering with the SM and the self interference of dimension-six terms are both negligible. For  $[R_K]_{[1,6]}$  and  $[R_{K^*}]_{[1.1,6]}$  we have good agreement with [19].

We now investigate the implications of the LHCb measurements by considering the measured 95% confidence level intervals. We start with *single-operator scenarios* where only one of the relevant operators is assumed to be present at the electroweak scale. The effect of the dipole operator  $\mathcal{O}_7$  on the low- $q^2$  bin of  $R_{K^*}$  is very small given the bound it receives from  $b \rightarrow s\gamma$  transitions ( $-0.05 \lesssim \mathcal{C}_7^{\text{NP}} \lesssim 0.08$  at  $3\sigma$  [4]). The deviations from the SM in these three observables must then be caused mainly by the four-fermion semileptonic operators of the WET. In what follows we discuss single-operator scenarios that can potentially explain the anomalies:

►  $\mathcal{C}_{\ell q}^{(1,3)} \rightarrow \mathcal{C}_{9\mu-e}^{\text{NP}} = -\mathcal{C}_{10\mu-e}^{\text{NP}}$ : these scenarios accommodate the experimental measurements of  $R_{K,K^*}$  for  $\mathcal{C}_{9\mu-e}^{\text{NP}} \lesssim -0.2$ , corresponding to  $\mathcal{C}_{\ell q}^{(1,3)} \gtrsim 0.3$  with  $\Lambda = 30$  TeV, see Figure 1.

All the other operators fail:

►  $\mathcal{C}_{\ell d} \rightarrow \mathcal{C}'_{9\mu-e} = -\mathcal{C}'_{10\mu-e}$ : gives rise to  $R_{K^*} > 1$  in the central-bin when  $R_K < 1$ .  $R_{K^*}$  in the low-bin is also

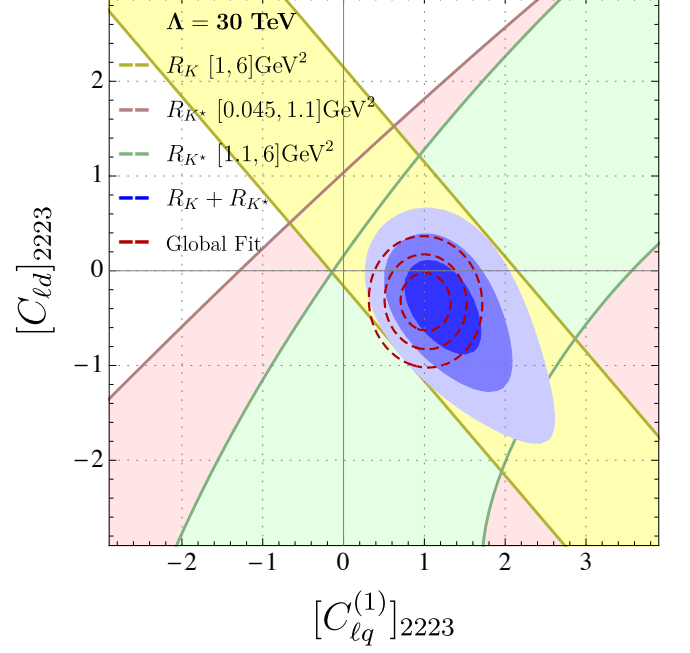


FIG. 2. Constraints on the SMEFT WCs  $\mathcal{C}_{\ell q}^{(1)}$  and  $\mathcal{C}_{\ell d}$  with  $\Lambda = 30$  TeV, assuming no NP in the electron modes. The individual constraints from  $R_K$  and  $R_{K^*}$  at the  $3\sigma$  level are represented by filled bands. The combined fit to  $R_K$  and  $R_{K^*}$  is shown in blue (1,2 and 3  $\sigma$  contours). The result of a global fit with all  $b \rightarrow s\ell^+\ell^-$  data included in [7] is shown in a similar way as red dashed contours.

above the experimental range when  $R_K < 1$ .

►  $\mathcal{C}_{ed} \rightarrow \mathcal{C}'_{9\mu-e} = \mathcal{C}'_{10\mu-e}$ : has a very small effect on  $R_K$ . For reasonable values of the WC it holds  $R_K \simeq R_K^{\text{SM}}$ . Furthermore when  $R_{K^*} < 1$  in both bins,  $R_K > 1$ .

►  $\mathcal{C}_{qe} \rightarrow \mathcal{C}_{9\mu-e}^{\text{NP}} = \mathcal{C}_{10\mu-e}^{\text{NP}}$ : has a very small effect on  $R_K$ . For reasonable values of the WC it holds  $R_K \simeq R_K^{\text{SM}}$ .

We now consider *two-operator scenarios*. In this case, assuming that only two operators are non-zero at a time, it is possible to accommodate  $R_{K,K^*}$  with:

- $\mathcal{C}_{\ell q}^{(1,3)}, \mathcal{C}_{qe} \rightarrow \mathcal{C}_{9\mu-e}^{\text{NP}}, \mathcal{C}_{10\mu-e}^{\text{NP}}$
- $\mathcal{C}_{\ell q}^{(1,3)}, \mathcal{C}_{\ell d} \rightarrow \mathcal{C}_{9\mu-e}^{\text{NP}} = -\mathcal{C}_{10\mu-e}^{\text{NP}}, \mathcal{C}'_{9\mu-e} = -\mathcal{C}'_{10\mu-e}$
- $\mathcal{C}_{\ell q}^{(1,3)}, \mathcal{C}_{ed} \rightarrow \mathcal{C}_{9\mu-e}^{\text{NP}} = -\mathcal{C}_{10\mu-e}^{\text{NP}}, \mathcal{C}'_{9\mu-e} = \mathcal{C}'_{10\mu-e}$
- $\mathcal{C}_{\ell q}^{(1)}, \mathcal{C}_{\ell q}^{(3)} \rightarrow \mathcal{C}_{9\mu-e}^{\text{NP}} = -\mathcal{C}_{10\mu-e}^{\text{NP}}$

The bounds obtained for the WCs in the scenario  $(\mathcal{C}_{\ell q}^{(1)}, \mathcal{C}_{\ell d})$  are shown in Figure 2. Here we have used the exact expressions for the observables, without linearising in the NP coefficients. The results are identical for the scenario  $(\mathcal{C}_{\ell q}^{(3)}, \mathcal{C}_{\ell d})$ . In order to accommodate the anomalies one needs a positive NP contribution to

$\mathcal{C}_{\ell q}^{(1)} + \mathcal{C}_{\ell q}^{(3)}$ . The bound obtained on  $\mathcal{C}_{\ell d}$  arises because the measurements are compatible with  $[R_{K^*}]_{\text{central}}/R_K \simeq 1$  and this double ratio is mainly sensitive to  $\mathcal{C}_{\ell d}$  [19].

The following scenarios with two operators fail to accommodate the data with reasonable values of the WCs:

- $\mathcal{C}_{qe}, \mathcal{C}_{\ell d} \rightarrow \mathcal{C}_{9\mu-e}^{\text{NP}} = \mathcal{C}_{10\mu-e}^{\text{NP}}, \mathcal{C}'_{9\mu-e} = -\mathcal{C}'_{10\mu-e}$ : within this scenario it is not possible to accommodate both  $R_{K^*}$  and  $R_K$  simultaneously.
- $\mathcal{C}_{\ell d}, \mathcal{C}_{ed} \rightarrow \mathcal{C}'_{9\mu-e}, \mathcal{C}'_{10\mu-e}$ : again, it is not possible to accommodate both  $R_{K^*}$  and  $R_K$  simultaneously.
- $\mathcal{C}_{qe}, \mathcal{C}_{ed} \rightarrow \mathcal{C}_{9\mu-e}^{\text{NP}} = \mathcal{C}_{10\mu-e}^{\text{NP}}, \mathcal{C}'_{9\mu-e} = \mathcal{C}'_{10\mu-e}$ : this scenario cannot generate the needed deviation on  $R_K$ .

In summary, the explanation of the  $R_{K,K^*}$  anomalies within the SMEFT at the level of dimension-six operators requires the presence of  $\mathcal{C}_{\ell q}^{(1)}$  and/or  $\mathcal{C}_{\ell q}^{(3)}$ .

A plausible scenario is that the NP enters mainly through muons. Under this hypothesis, which will be taken in the following, all the viable explanations of the  $R_{K,K^*}$  anomalies provide a good fit of the  $b \rightarrow s\mu^+\mu^-$  data [4, 21, 22]. This observation is non-trivial given that a large fraction of the  $b \rightarrow s\mu^+\mu^-$  decay observables probe different combinations of the WCs. Note also that having only the operator  $\mathcal{C}_{9\mu}^{\text{NP}}$  of the WET, which alone provides a very good fit of  $b \rightarrow s\mu^+\mu^-$  data, requires at least two SMEFT operators of the Warsaw basis,  $\mathcal{C}_{\ell q}^{(1)}$  (or  $\mathcal{C}_{\ell q}^{(3)}$ ) and  $\mathcal{C}_{qe}$ . Other benchmark scenarios of the WET that provide a good fit, for instance  $\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}'_{9\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = \mathcal{C}'_{10\mu}$ , are more involved to realize within the SMEFT due to the constraints imposed by electroweak gauge symmetry.

In Table II we use the result from the global fit to  $b \rightarrow s\ell\ell$  in [7] to give the corresponding bounds on the WCs for the scenarios that can accommodate the  $R_{K,K^*}$  anomalies. The involved WCs are  $\mathcal{O}(1)$  for  $\Lambda \sim 30$  TeV. The result of the global fit in the scenario  $(\mathcal{C}_{\ell q}^{(1,3)}, \mathcal{C}_{\ell d})$  is shown in Figure 2 as red dashed contours.

*Renormalization group effects.*— The SMEFT WCs in the previous equations, given at  $\mu = \mu_{\text{EW}}$ , can be obtained in terms of their values at the NP scale  $\Lambda$  by means of the SMEFT RGEs [102–104]. Using a first leading log approximation we find

$$\begin{aligned}
[\Delta\mathcal{C}_{\ell q}^{(1)}]_{aa23} &= -\frac{y_t^2\lambda_t^{sb}}{16\pi^2}L\left([\mathcal{C}_{\varphi\ell}^{(1)}(\Lambda)]_{aa} - [\mathcal{C}_{\ell u}(\Lambda)]_{aa33}\right), \\
[\Delta\mathcal{C}_{\ell q}^{(3)}]_{aa23} &= \frac{y_t^2\lambda_t^{sb}}{16\pi^2}L\left([\mathcal{C}_{\varphi\ell}^{(3)}(\Lambda)]_{aa}\right), \\
[\Delta\mathcal{C}_{qe}]_{23aa} &= -\frac{y_t^2\lambda_t^{sb}}{16\pi^2}L\left([\mathcal{C}_{\varphi e}(\Lambda)]_{aa} - [\mathcal{C}_{eu}(\Lambda)]_{aa33}\right), \\
[\Delta\mathcal{C}_{\ell d}]_{aa23} &= [\Delta\mathcal{C}_{ed}]_{aa23} = 0,
\end{aligned} \tag{11}$$

where  $\Delta\mathcal{C}_i \equiv \mathcal{C}_i(\mu_{\text{EW}}) - \mathcal{C}_i(\Lambda)$  and  $L \equiv \log\left(\frac{\Lambda}{\mu_{\text{EW}}}\right)$ . We have made use of *top dominance* assumptions, only keeping Yukawa terms including  $y_t = \sqrt{2}m_t/v \sim 1$ , the top quark Yukawa coupling, neglecting other Yukawa-driven terms. These expressions agree very well with precise numerical calculations when the dominant terms are the direct (tree-level) ones, while they may deviate slightly when the one-loop induced terms dominate due to the running of the top Yukawa coupling. In the following we only take them as guiding tool and obtain all our numerical results using **DsixTools** [98]. We observe that, in principle, it is possible to achieve an explanation of the  $R_{K,K^*}$  anomalies via operator mixing effects with a NP scale  $\Lambda \sim 1$  TeV and WCs of  $\mathcal{O}(1)$ . Specifically, by generating  $[\mathcal{C}_{\ell u}(\Lambda)]_{2233} \sim -1$ ,  $[\mathcal{C}_{\varphi\ell}^{(1)}(\Lambda)]_{22} \sim 1$ , or  $[\mathcal{C}_{\varphi\ell}^{(3)}(\Lambda)]_{22} \sim -1$ . However, we will see later that the possibility of  $[\mathcal{C}_{\varphi\ell}^{(1,3)}(\Lambda)]_{22}$  is ruled out by experimental data. For the interesting scenario,  $[\mathcal{C}_{\ell u}(\Lambda)]_{2233}$ , we note that for matching scales  $\mu_{\text{EW}} \simeq m_t$ , NLO corrections vanish to a good approximation and the leading RGE contribution dominates, see [105] for similar observations.

We now analyse the implications of the WCs required to explain the anomalies in other low-energy observables. In particular we focus on the bounds from other LFUV observables and from Electroweak Precision Data (EWPd). We separate the discussion in two cases: when the operators that explain the anomalies are generated at tree-level and when they are induced at one-loop.

► **Tree-level generated operators:** First we focus on the observables that can give a direct constraint on the operators given in Table II. As noted in Refs. [106, 107], the operators  $Q_{\ell q}^{(1,3)}$  could modify the ratio  $R_{K^{(*)}}^{\nu\nu} = \Gamma(B \rightarrow K^{(*)}\nu\bar{\nu})/\Gamma(B \rightarrow K^{(*)}\nu\bar{\nu})_{\text{SM}}$ . Moreover, the WC  $\mathcal{C}_{\ell q}^{(3)}$  also affects the LFUV ratio  $\Gamma_{B \rightarrow D^{(*)}\mu\nu}/\Gamma_{B \rightarrow D^{(*)}e\nu}$ . However we find that the contributions to these observables are always below the experimental sensitivity. This result is consistent with the analysis done in Ref. [108]. We do not find any other direct constraint on these scenarios. Furthermore, we also consider the case where the relevant operators explaining the anomalies are generated at the NP scale and use **DsixTools** [98] to obtain the pattern of RGE-induced operators. We find that the new WCs generated in the running are sufficiently small to avoid the experimental constraints from EWPd and LFUV observables.

► **One-loop induced operators:** We now consider operators at the NP scale that cannot explain the anomalies directly. In this case the relevant contributions can still be generated through renormalization-group effects. Due to the loop suppression, the size of the WCs necessary to account for the anomalies should be larger and/or the NP scale should be lower, yielding more interesting bounds at low energies. In fact, requiring WCs to be  $\mathcal{O}(1)$  or smaller implies  $\Lambda \lesssim \mathcal{O}(1)$  TeV in this case. We find that among



Operator(s) $\times (30 \text{ TeV}/\Lambda)^2$	Fit from $b \rightarrow s\ell\ell$ observables		
	Best fit	$1\sigma$	$2\sigma$
$\mathcal{C}_{\ell q}^{(1,3)}$	0.95	[0.75, 1.14]	[0.56, 1.36]
$(\mathcal{C}_{\ell q}^{(1,3)}, \mathcal{C}_{qe})$	(1.03, 0.80)	[(0.89, 1.18], [0.61, 0.98]]	[(0.74, 1.32], [0.42, 1.17]]
$(\mathcal{C}_{\ell q}^{(1,3)}, \mathcal{C}_{\ell d})$	(1.02, -0.33)	[(0.80, 1.23], [-0.54, -0.12]]	[(0.59, 1.44], [-0.75, 0.10]]
$(\mathcal{C}_{\ell q}^{(1,3)}, \mathcal{C}_{ed})$	(1.02, 0.20)	[(0.81, 1.22], [-0.00, 0.41]]	[(0.60, 1.43], [-0.21, 0.62]]

TABLE II. Constraints on the SMEFT WCs obtained from the global fit to  $b \rightarrow s\ell\ell$  in terms of the WET operators from [7].

WC ( $\mu = \Lambda$ )	$R_K$ and $R_{K^*}$	Constraints
$[\mathcal{C}_{\ell q}^{(1)}]_{2223}$	✓	No relevant constraints
$[\mathcal{C}_{\ell q}^{(3)}]_{2223}$	✓	No relevant constraints
$[\mathcal{C}_{\varphi\ell}^{(1)}]_{22}$	✗	Excluded due to EWPd
$[\mathcal{C}_{\varphi\ell}^{(3)}]_{22}$	✗	Excluded due to EWPd
$[\mathcal{C}_{\ell u}]_{2233}$	✓	No relevant constraints

TABLE III. SMEFT operators at  $\mu = \Lambda$  that can potentially explain the anomalies. The first two WCs contribute to  $R_K$  and  $R_{K^*}$  at tree-level while the last three contribute at the one-loop level. We find that  $[\mathcal{C}_{\varphi\ell}^{(1,3)}]_{22}$  cannot work due to constraints from EWPd.

the three possible scenarios, the ones based on  $\mathcal{C}_{\varphi\ell}^{(1,3)}$  are excluded by EWPd since they induce excessively large modifications to the  $W$  mass and/or the  $Z$  couplings. In particular, the required value of  $\mathcal{C}_{\varphi\ell}^{(3)}$  is well beyond the allowed value from the bound on the  $W$  mass, while  $\mathcal{C}_{\varphi\ell}^{(1)}$  induces a large contribution to  $Z \rightarrow \mu^+\mu^-$  that is excluded by the LEP-I measurements, and to  $\mathcal{C}_{\varphi D}$  (the WC of  $Q_{\varphi D} = (\varphi^\dagger D^\mu \varphi)^*(\varphi^\dagger D_\mu \varphi)$ ), which is also constrained by the  $W$  mass [109, 110]. In contrast, we find that the scenario where  $\mathcal{C}_{\ell u}$  is obtained at the NP scale remains as a viable candidate, with  $[\mathcal{C}_{\ell u}(\Lambda)]_{2233} \sim -1$  and  $\Lambda \sim 1$  TeV. RGE evolution down to the electroweak scale generates in this case contributions to  $[Q_{\varphi\ell}^{(1)}]_{22}$  together with the four-lepton operators  $[Q_{\ell\ell}]_{22aa} = (\bar{\ell}_2 \gamma_\mu \ell_2)(\bar{\ell}_a \gamma^\mu \ell_a)$  and  $[Q_{\ell e}]_{22aa} = (\bar{\ell}_2 \gamma_\mu \ell_2)(\bar{e}_a \gamma^\mu e_a)$ , which are found to be well below the experimental limits [109, 110].

*Summary.*— An increasing significance for New Physics in  $b \rightarrow s$  transitions is accumulating since the first LHCb measurements of the  $B \rightarrow K^* \mu\mu$  angular distribution in 2013 and their later lepton-flavour universality violating hint in  $R_K$ . A crucially important confirmation of such hints has appeared just recently with the LHCb measurement of  $R_{K^*}$  in two large-recoil bins, *complementary* to  $R_K$  in regards to New Physics.

In this paper we have analysed the implications of these new measurements, in terms of the SMEFT. Our conclusions on the required WCs at the scale  $\mu = \mu_{\text{EW}}$  can be summarised as follows:

- The  $[\mathcal{C}_{\ell q}^{(1,3)}]_{2223}$  coefficients play a crucial role in the explanation of the anomalies. All solutions (with one or two operators) require their presence to accommodate the LHCb measurements of  $R_K$  and  $R_{K^*}$ .
- The coefficients  $[\mathcal{C}_{\ell d}]_{2223}$ ,  $[\mathcal{C}_{qe}]_{2322}$  and  $[\mathcal{C}_{ed}]_{2223}$  cannot explain the anomalies.

Turning to our conclusions regarding the WCs at the UV scale,  $\mu = \Lambda$ , they can be summarised as:

- When the anomalies are explained with operators that contribute to the  $R_{K,K^*}$  ratios at tree-level ( $[\mathcal{C}_{\ell q}^{(1,3)}]_{2223}$ ), the resulting bounds are not significant. In this case the NP scale can be as high as  $\sim 30$ -50 TeV and still keep the WCs  $\lesssim \mathcal{O}(1)$ .
- In contrast, when the anomalies are explained with operators that contribute via RGE operator-mixing effects ( $[\mathcal{C}_{\varphi\ell}^{(1,3)}]_{22}$  and  $[\mathcal{C}_{\ell u}]_{2233}$ ), the indirect bounds turn out to be very relevant. In fact, the coefficients  $[\mathcal{C}_{\varphi\ell}^{(1,3)}]_{22}$  cannot explain the  $R_{K,K^*}$  ratios since the required values are excluded by EWPd. For the  $[\mathcal{C}_{\ell u}]_{2233}$  coefficient no relevant constraints were found. In this case the NP scale must be very low once we assume  $[\mathcal{C}_{\ell u}]_{2233} \sim \mathcal{O}(1)$ :  $\Lambda \lesssim 1$  TeV, making this scenario potentially testable by other experimental means.

If confirmed, the violation of lepton flavour universality would have far-reaching consequences. In our analysis we have identified the crucial operators that a specific New Physics model would have to induce in order to be able to explain the  $R_{K,K^*}$  anomalies. These minimal requirements can be regarded as a general guideline for model building. In addition, when combining these measurements with all  $b \rightarrow s\ell\ell$  data a consistent pattern arises (see Fig. 2), with the New Physics scenarios considered in this paper favoured with respect to the SM hypothesis by around 5 standard deviations, and with a high goodness of fit [7]. As described in the introduction, these scenarios could be reproduced in extensions of the

SM possibly including leptoquarks, heavy  $Z'$  bosons or other additional heavy states. We look forward for measurements of lepton-flavour universality-violating ratios at *low hadronic recoil*, as well as of other ratios such as  $R_\phi$  and  $R_{X_s}$ , clean observables such as  $Q_5$ , and improved measurements with increased statistics.

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