Gauge-invariant implications of the LHCb measurements on lepton-flavor nonuniversality

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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-6 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 $b \to s\ell\ell$ data, which combined lead to effective NP scenarios with SM pulls in excess of 5σ. Thus, the operators discussed in this paper would be the first dimension-6 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 $b \to s$ transitions when the NP is assumed to lie above the electroweak scale.

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I. INTRODUCTION

An absolute priority in particle physics is to detect and measure the effects of dimension-6 terms in the Standard Model (SM) Lagrangian. These *must* be there since the SM is only valid up to a physical scale $\Lambda > \mu_{\rm EW}$, where $\mu_{\rm EW} \simeq 100$ GeV is the electroweak scale. These effects are suppressed by a factor $\mu_{\rm EW}^2/\Lambda^2$, so if Λ is very large, precision tests are needed.

Lepton-flavor universality (LFU)—lepton gauge interactions being identical for e, μ, τ—is a strong test of certain dimension-6 terms. One such test is given by the observables $R_{K^{(*)}}$, defined as [1]

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

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-6 terms breaking LFU.

The LHCb Collaboration has measured some of these ratios, finding values significantly smaller than 1 [2,3]:

$$\begin{aligned} R_K &= 0.745^{+0.090}_{-0.074} \pm 0.036, \quad && q^2 \in [1,6]\ \text{GeV}^2, \\ R_{K^*} &= 0.660^{+0.110}_{-0.070} \pm 0.024, \quad && q^2 \in [0.045, 1.1]\ \text{GeV}^2, \\ R_{K^*} &= 0.685^{+0.113}_{-0.069} \pm 0.047, \quad && q^2 \in [1.1, 6.0]\ \text{GeV}^2. \end{aligned} \tag{2}$$

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

$$\begin{aligned} R_K^{\rm SM} &= 1.00 \pm 0.01, \quad && q^2 \in [1,6]\ \text{GeV}^2, \\ R_{K^*}^{\rm SM} &= 0.92 \pm 0.02, \quad && q^2 \in [0.045, 1.1]\ \text{GeV}^2, \\ R_{K^*}^{\rm SM} &= 1.00 \pm 0.01, \quad && q^2 \in [1.1, 6.0]\ \text{GeV}^2, \end{aligned} \tag{3}$$

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

Dimension-6 operators breaking LFU will manifest also in $b \to s\ell^+\ell^-$ ($\ell = \mu$ or e) observables such as branching ratios and angular distributions. Notably, anomalies have been observed in $b \to s\mu^+\mu^-$ transitions too [15–17], and these are consistent with the anomaly in R_K [18–20]. Global analyses of $b \to s\mu^+\mu^-$ data lead to scenarios that can accommodate R_K and R_{K^*} [4,21,22].

Many models have been proposed to address the $b \to s$ 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]. References [91–94] have explored renormalizable models that explain R_K at the one-loop level, while the minimal supersymmetric SM with R-parity conservation was considered in Ref. [95].

We interpret these measurements in the context of the Standard Model effective field theory (SMEFT) [96,97]. This is the most convenient framework when the new degrees of freedom are much heavier than $\mu_{\rm EW}$ 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 $\mu_{\rm EW}$ and at the scale Λ 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 us 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.

II. EFFECTIVE FIELD THEORY

At energies relevant for the B decay, the most general Hamiltonian for semileptonic $b \to s$ transitions contains the terms

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

where $\lambda_t^{ij} = V_{ti}^* V_{tj}$, with V the Cabibbo-Kobayashi-Maskawa 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

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

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 $\Lambda \gg \mu_{\rm EW}$, one can describe deviations from the SM in a general way using the SMEFT. Dominant new physics (NP) effects are parametrized by effective operators of canonical dimension 6,

$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda^2}\sum_k \mathcal{C}_k Q_k, \tag{6}$$

where the sum extends over all operators in the *Warsaw basis* [97], $\mathcal{C}_k$ being the WCs and Q_k being 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., Refs. [18,100].

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 flavor. Contrary to Eq. (5), here ℓ denotes a lepton $SU(2)_L$ doublet.

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
$[Q_{\varphi\ell}^{(1)}]_{aa}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{\ell}_a\gamma^\mu\ell_a)$	$\mathcal{O}_{9,10}$	One-loop
$[Q_{\varphi\ell}^{(3)}]_{aa}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{\ell}_a\gamma^\mu\tau^I\ell_a)$	$\mathcal{O}_{9,10}$	One-loop
$[Q_{\ell u}]_{aa33}$	$(\bar{\ell}_a\gamma_\mu\ell_a)(\bar{u}_3\gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	One-loop
$[Q_{\varphi e}]_{aa}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_a\gamma^\mu e_a)$	$\mathcal{O}_{9,10}$	One-loop
$[Q_{eu}]_{aa33}$	$(\bar{e}_a\gamma_\mu e_a)(\bar{u}_3\gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	One-loop

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

$$\mathcal{C}_{9a}^{\rm NP} = \frac{\pi}{\alpha\lambda_t^{sb}}\frac{v^2}{\Lambda^2}\{[\tilde{\mathcal{C}}_{\ell q}^{(1)}]_{aa23} + [\tilde{\mathcal{C}}_{\ell q}^{(3)}]_{aa23} + [\tilde{\mathcal{C}}_{qe}]_{23aa}\},$$
$$\mathcal{C}_{10a}^{\rm NP} = -\frac{\pi}{\alpha\lambda_t^{sb}}\frac{v^2}{\Lambda^2}\{[\tilde{\mathcal{C}}_{\ell q}^{(1)}]_{aa23} + [\tilde{\mathcal{C}}_{\ell q}^{(3)}]_{aa23} - [\tilde{\mathcal{C}}_{qe}]_{23aa}\},$$
$$\mathcal{C}_{9a}' = \frac{\pi}{\alpha\lambda_t^{sb}}\frac{v^2}{\Lambda^2}\{[\tilde{\mathcal{C}}_{\ell d}]_{aa23} + [\tilde{\mathcal{C}}_{ed}]_{aa23}\},$$
$$\mathcal{C}_{10a}' = -\frac{\pi}{\alpha\lambda_t^{sb}}\frac{v^2}{\Lambda^2}\{[\tilde{\mathcal{C}}_{\ell d}]_{aa23} - [\tilde{\mathcal{C}}_{ed}]_{aa23}\}. \tag{7}$$

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 $\mu_{\rm EW}$. The tilde over the SMEFT WCs denotes that they are given in the fermion mass basis (see Ref. [101]). Throughout the paper, we adopt the weak basis where $V_{d_L} = \mathbb{1}$ and $V_{d_R,u_R} = \mathbb{1}$.

III. 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 linearizing in the NP coefficients. We find

$$[R_K]_{[1,6]} \simeq 1.00(1) + 0.230(\mathcal{C}^{\rm NP}_{9\mu-e} + \mathcal{C}'_{9\mu-e}) - 0.233(2)(\mathcal{C}^{\rm NP}_{10\mu-e} + \mathcal{C}'_{10\mu-e}), \quad (8)$$

$$[R_{K^*}]_{[0.045,1.1]} \simeq 0.92(2) + 0.07(2)\mathcal{C}^{\rm NP}_{9\mu-e} - 0.10(2)\mathcal{C}'_{9\mu-e} - 0.11(2)\mathcal{C}^{\rm NP}_{10\mu-e} + 0.11(2)\mathcal{C}'_{10\mu-e} + 0.18(1)\mathcal{C}^{\rm NP}_7, \quad (9)$$

$$[R_{K^*}]_{[1.1,6]} \simeq 1.00(1) + 0.20(1)\mathcal{C}^{\rm NP}_{9\mu-e} - 0.19(1)\mathcal{C}'_{9\mu-e} - 0.27(1)\mathcal{C}^{\rm NP}_{10\mu-e} + 0.21(1)\mathcal{C}'_{10\mu-e}, \quad (10)$$

where $\mathcal{C}^{\rm NP}_{9\mu-e} \equiv \mathcal{C}^{\rm NP}_{9\mu} - \mathcal{C}^{\rm NP}_{9e}$, etc., and all WCs are defined at the scale $\mu_b = 4.8$ GeV. We have linearized the dependence with respect to the WCs, consistently assuming that contributions from dimension-8 SMEFT operators interfering with the SM and the self-interference of dimension-6 terms are both negligible. For $[R_K]_{[1,6]}$ and $[R_{K^*}]_{[1.1,6]}$, we have good agreement with Ref. [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 $b \to s\gamma$ transitions ($-0.05 \lesssim \mathcal{C}^{\rm NP}_7 \lesssim 0.08$ at 3σ [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:

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

All the other operators fail:

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

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

(iii) $\mathcal{C}_{qe} \to \mathcal{C}^{\rm NP}_{9\mu-e} = \mathcal{C}^{\rm NP}_{10\mu-e}$: has a very small effect on R_K. For reasonable values of the WC, it holds that $R_K \simeq R_K^{\rm SM}$.

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

(i) $\mathcal{C}^{(1,3)}_{\ell q}, \mathcal{C}_{qe} \to \mathcal{C}^{\rm NP}_{9\mu-e}, \mathcal{C}^{\rm NP}_{10\mu-e}$

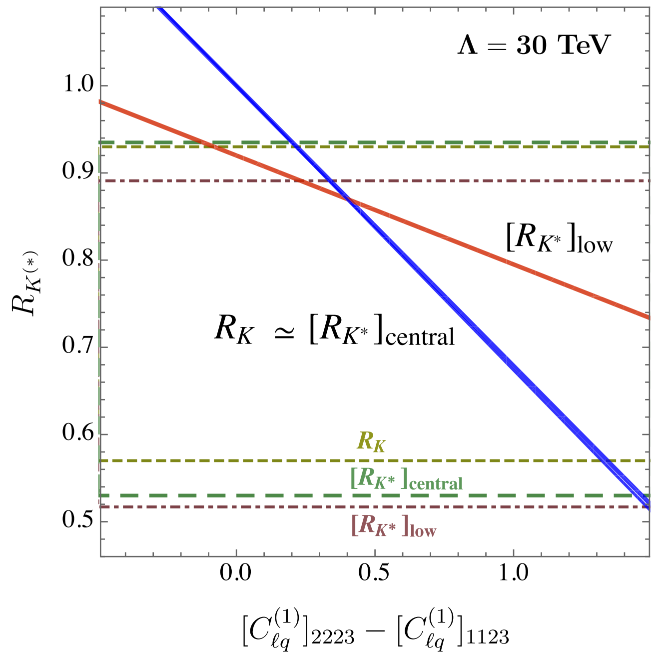

FIG. 1. R_K and R_{K^*} as a function of the SMEFT WC $\mathcal{C}^{(1)}_{\ell q}$ with $\Lambda = 30$ TeV. The experimental ranges for R_K and R_{K^*} at 95% C.L. are also shown for comparison.

(ii) $\mathcal{C}^{(1,3)}_{\ell q}, \mathcal{C}_{\ell d} \to \mathcal{C}^{\rm NP}_{9\mu-e} = -\mathcal{C}^{\rm NP}_{10\mu-e}, \mathcal{C}'_{9\mu-e} = -\mathcal{C}'_{10\mu-e}$

(iii) $\mathcal{C}^{(1,3)}_{\ell q}, \mathcal{C}_{ed} \to \mathcal{C}^{\rm NP}_{9\mu-e} = -\mathcal{C}^{\rm NP}_{10\mu-e}, \mathcal{C}'_{9\mu-e} = -\mathcal{C}'_{10\mu-e}$

(iv) $\mathcal{C}^{(1)}_{\ell q}, \mathcal{C}^{(3)}_{\ell q} \to \mathcal{C}^{\rm NP}_{9\mu-e} = \mathcal{C}^{\rm NP}_{10\mu-e}$

The bounds obtained for the WCs in the scenario $(\mathcal{C}^{(1)}_{\ell q}, \mathcal{C}_{\ell d})$ are shown in Fig. 2. Here, we have used the exact expressions for the observables, without linearizing in the NP coefficients. The results are identical for the scenario $(\mathcal{C}^{(3)}_{\ell q}, \mathcal{C}_{\ell d})$. In order to accommodate the anomalies, one needs a positive NP contribution to $\mathcal{C}^{(1)}_{\ell q} + \mathcal{C}^{(3)}_{\ell q}$. The bound obtained on $\mathcal{C}_{\ell d}$ arises because the measurements are compatible with $[R_{K^*}]_{\rm central}/R_K \simeq 1$, 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:

(i) $\mathcal{C}_{qe}, \mathcal{C}_{\ell d} \to \mathcal{C}^{\rm NP}_{9\mu-e} = \mathcal{C}^{\rm NP}_{10\mu-e}, \mathcal{C}'_{9\mu-e} = -\mathcal{C}'_{10\mu-e}$: within this scenario, it is not possible to accommodate both R_{K^*} and R_K simultaneously.

(ii) $\mathcal{C}_{\ell d}, \mathcal{C}_{ed} \to \mathcal{C}'_{9\mu-e}, \mathcal{C}'_{10\mu-e}$: again, it is not possible to accommodate both R_{K^*} and R_K simultaneously.

(iii) $\mathcal{C}_{qe}, \mathcal{C}_{ed} \to \mathcal{C}^{\rm NP}_{9\mu-e} = \mathcal{C}^{\rm NP}_{10\mu-e}, \mathcal{C}'_{9\mu-e} = \mathcal{C}'_{10\mu-e}$: 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-6 operators requires the presence of $\mathcal{C}^{(1)}_{\ell q}$ and/or $\mathcal{C}^{(3)}_{\ell q}$.

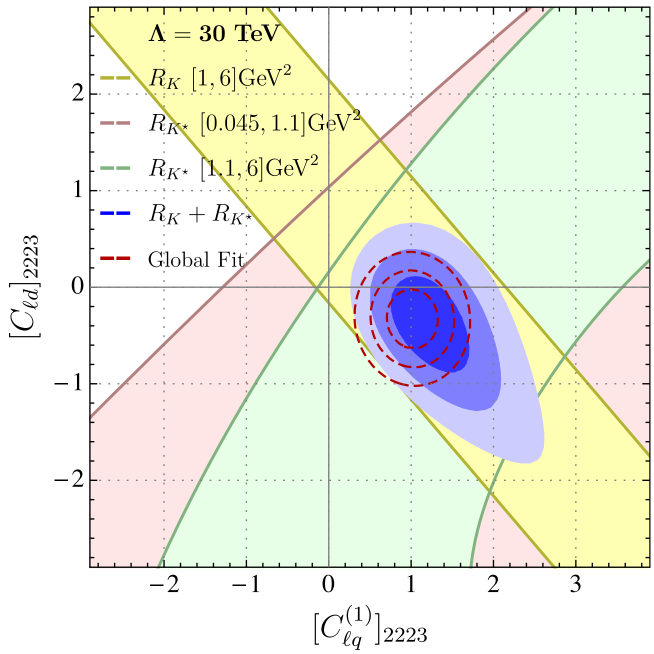

FIG. 2. Constraints on the SMEFT WCs $\mathcal{C}^{(1)}_{\ell q}$ and $\mathcal{C}_{\ell d}$ with $\Lambda = 30$ TeV, assuming no NP in the electron modes. The individual constraints from R_K and R_{K^*} at the 3σ level are represented by filled bands. The combined fit to R_K and R_{K^*} is shown in blue (1,2 and 3σ contours). The result of a global fit with all $b \to s\ell^+\ell^-$ data included in [9] is shown in a similar way as red dashed contours.

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 $b \to s\mu^+\mu^-$ data [4,21,22]. This observation is nontrivial given that a large fraction of the $b \to s\mu^+\mu^-$ decay observables probe different combinations of the WCs. Note also that having only the operator $\mathcal{C}^{\rm NP}_{9\mu}$ of the WET, which alone provides a very good fit of $b \to s\mu^+\mu^-$ data, requires at least two SMEFT operators of the Warsaw basis, $\mathcal{C}^{(1)}_{\ell q}$ (or $\mathcal{C}^{(3)}_{\ell q}$) and $\mathcal{C}_{qe}$. Other benchmark scenarios of the WET that provide a good fit, for instance $\mathcal{C}^{\rm NP}_{9\mu} = -\mathcal{C}'_{9\mu}, \mathcal{C}^{\rm NP}_{10\mu} = \mathcal{C}'_{10\mu}$, 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 $b \to s\ell\ell$ in Ref. [9] 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 $(\mathcal{C}^{(1,3)}_{\ell q}, \mathcal{C}_{\ell d})$ is shown in Fig. 2 as red dashed contours.

IV. RENORMALIZATION GROUP EFFECTS

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

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

where $\Delta\mathcal{C}_i \equiv \mathcal{C}_i(\mu_{\rm EW}) - \mathcal{C}_i(\Lambda)$ and $L \equiv \log(\frac{\Lambda}{\mu_{\rm EW}})$. 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 $[\mathcal{C}_{\ell u}(\Lambda)]_{2233} \sim -1$, $[\mathcal{C}^{(1)}_{\varphi\ell}(\Lambda)]_{22} \sim 1$, or $[\mathcal{C}^{(3)}_{\varphi\ell}(\Lambda)]_{22} \sim -1$. However, we will see later that the possibility of $[\mathcal{C}^{(1,3)}_{\varphi\ell}(\Lambda)]_{22}$ is ruled out by experimental data. For the interesting scenario, $[\mathcal{C}_{\ell u}(\Lambda)]_{2233}$, we note that for matching scales $\mu_{\rm EW} \simeq m_t$, next-to-leading-order corrections vanish to a good approximation and the leading RGE contribution dominates; see Ref. [105] for similar observations.

TABLE II. Constraints on the SMEFT WCs obtained from the global fit to $b \to s\ell\ell$ in terms of the WET operators from Ref. [9].

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

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.

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

We now analyze the implications of the WCs required to explain the anomalies in other low-energy observables. In particular, we focus on the bounds from other lepton-flavor universality violating (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.

A. 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 $R^{\nu\nu}_{K^{(*)}} = \Gamma(B \to K^{(*)}\nu\bar{\nu})/\Gamma(B \to K^{(*)}\nu\bar{\nu})_{\mathrm{SM}}$. Moreover, the WC $\mathcal{C}_{\ell q}^{(3)}$ also affects the LFUV ratio $\Gamma_{B\to D^{(*)}\mu\nu}/\Gamma_{B\to D^{(*)}e\nu}$. 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.

B. 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 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 $Z \to \mu^+\mu^-$ 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 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]. These findings are summarized in Table III.

V. SUMMARY

An increasing significance for new physics in $b \to s$ transitions has been accumulating since the first LHCb measurements of the $B \to K^*\mu\mu$ angular distribution in 2013 and their later lepton-flavor 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 regard to new physics.

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

(i) 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^*}.

(ii) 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 summarized as:

(i) 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 ~30–50 TeV and still keep the WCs $\lesssim\mathcal{O}(1)$.

(ii) 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-flavor 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 $b \to s\ell\ell$ data, a consistent pattern arises (see Fig. 2), with the new physics scenarios considered in this paper favored with respect to the SM hypothesis by around 5 standard deviations and with a high goodness of fit [9]. 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-flavor universality-violating ratios at *low hadronic recoil*, as well as of other ratios such as R_ϕ and R_{X_s}, clean observables such as Q_5, and improved measurements with increased statistics.

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