Interpreting hints for lepton flavor universality violation

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We interpret the recent hints for lepton flavor universality violation in rare B meson decays. Based on a model-independent effective Hamiltonian approach, we determine regions of new physics parameter space that give a good description of the experimental data on R_K and R_{K^*}, which is in tension with Standard Model predictions. We suggest further measurements that can help narrowing down viable new physics explanations. We stress that the measured values of R_K and R_{K^*} are fully compatible with new physics explanations of other anomalies in rare B meson decays based on the $b \to s\mu\mu$ transition. If the hints for lepton flavor universality violation are the first signs of new physics, perturbative unitarity implies new phenomena below a scale of ~ 100 TeV.

I. INTRODUCTION

The wealth of data on rare leptonic and semileptonic b hadron decays that have been accumulated at the LHC so far allows the Standard Model (SM) Cabibbo-Kobayashi-Maskawa picture of flavor and CP violation to be tested with unprecedented sensitivity. Interestingly, current data on rare $b \to s\ell\ell$ decays show an intriguing pattern of deviations from the SM predictions both for branching ratios [1–3] and angular distributions [4,5]. The latest global fits find that the data consistently points with high significance to a nonstandard effect that can be described by a four-fermion contact interaction $C_9(\bar{s}\gamma^\nu P_L b)(\bar{\mu}\gamma_\nu\mu)$ [6] (see also earlier studies [7–9]). Right now the main obstacle towards conclusively establishing a beyond-SM effect is our inability to exclude large hadronic effects as the origin of the apparent discrepancies (see e.g., [10–16]).

In this respect, observables in $b \to s\ell\ell$ transitions that are practically free of hadronic uncertainties are of particular interest. Among them are lepton flavor universality (LFU) ratios, i.e., ratios of branching ratios involving different lepton flavors such as [17–19]

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}, \quad R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)}. \quad (1)$$

In the SM, the only sources of lepton flavor universality violation are the leptonic Yukawa couplings, which are responsible for both the charged lepton masses and their interactions with the Higgs.[1] Higgs interactions do not lead to any observable effects in rare b decays and lepton mass effects become relevant only for a very small dilepton

invariant mass squared close to the kinematic limit $q^2 \sim 4m_\ell^2$. Over a very broad range of q^2 the SM accurately predicts $R_K = R_{K^*} = 1$, with theoretical uncertainties of $O(1\%)$ [20]. Deviations from the SM predictions can be expected in various models of new physics (NP), e.g., Z' models based on gauged $L_\mu - L_\tau$ [21–24] or other gauged flavor symmetries [25–29], models with partial compositeness [30–33], and models with leptoquarks [34–42].

A first measurement of R_K by the LHCb Collaboration [43] in the dilepton invariant mass region $1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$,

$$R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036, \quad (2)$$

shows a 2.6σ deviation from the SM prediction. Very recently, LHCb presented first results for R_{K^*} [44–46],

$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03, \quad (3)$$

$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05, \quad (4)$$

where the superscripts indicate the dilepton invariant mass bin in GeV^2. These measurements are in tension with the SM at the level of 2.4 and 2.5σ, respectively. Intriguingly, they are in good agreement with the recent R_{K^*} predictions in [6] that are based on global fits of $b \to s\mu\mu$ decay data, assuming $b \to see$ decays to be SM-like.

In this paper we interpret the $R_{K^{(*)}}$ measurements using a model-independent effective Hamiltonian approach (see [47–53] for earlier model-independent studies of R_K). We also include Belle measurements of LFU observables in the $B \to K^*\ell^+\ell^-$ angular distributions [5]. We do not consider early results on $R_{K^{(*)}}$ from *BABAR* [54] and Belle [55] which, due to their large uncertainties, have little impact. We identify the regions of NP parameter space that give a good description of the experimental data. We show how future

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[1]Neutrino masses provide another source of lepton flavor nonuniversality, but the effects are negligible here.

measurements can lift flat directions in the NP parameter space and discuss the compatibility of the $R_{K^{(*)}}$ measurements with other anomalies in rare B meson decays.

II. MODEL-INDEPENDENT IMPLICATIONS FOR NEW PHYSICS

We assume that NP in the $b \to s\ell\ell$ transitions is sufficiently heavy such that it can be model-independently described by an effective Hamiltonian, $\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \mathcal{H}_{\text{eff}}^{\text{NP}}$,

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i,\ell} (C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell) + \text{H.c.},$$

(5)

with the following four-fermion contact interactions,

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad O_9'^\ell = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell), \quad (6)$$

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

(7)

and the corresponding Wilson coefficients C_i^ℓ, with $\ell = e$, μ. We do not consider other dimension-six operators that can contribute to $b \to s\ell\ell$ transitions. Dipole operators and four-quark operators [56] cannot lead to violation of LFU and are therefore irrelevant for this work. Four-fermion contact interactions containing scalar currents would be a natural source of LFU violation. However, they are strongly constrained by existing measurements of the $B_s \to \mu\mu$ and $B_s \to ee$ branching ratios [57,58]. Imposing $SU(2)_L$ invariance, these bounds cannot be avoided [59]. We have checked explicitly that $SU(2)_L$ invariant scalar operators cannot lead to any appreciable effects in $R_{K^{(*)}}$ (cf. [60]).

For the numerical analysis we use the open source code flavio [61]. Based on the experimental measurements and theory predictions for the LFU ratios $R_{K^{(*)}}$ and the LFU differences of $B \to K^* \ell^+ \ell^-$ angular observables $D_{P'_{4,5}}$ (see below), we construct a χ^2 function that depends on the Wilson coefficients and that takes into account the correlations between theory uncertainties of different observables. We use the default theory uncertainties in flavio, in particular $B \to K^*$ form factors from a combined fit to light-cone sum rule and lattice results [62]. The experimental uncertainties are presently dominated by statistics, so their correlations can be neglected. For the SM we find $\chi^2_{\text{SM}} = 24.4$ for 5 degrees of freedom.

Table I lists the best-fit values and pulls, defined as the $\sqrt{\Delta\chi^2}$ between the best-fit point and the SM point for scenarios with NP in one individual Wilson coefficient. The plots in Fig. 1 show contours of constant $\Delta\chi^2 \approx 2.3, 6.2, 11.8$ in the planes of two Wilson coefficients for the scenarios with NP in C_9^μ and C_{10}^μ (top), in C_9^μ and C_9^e

TABLE I. Best-fit values and pulls for scenarios with NP in one individual Wilson coefficient, taking into account only LFU observables.

Coefficient	Best fit	1σ	2σ	Pull
C_9^μ	-1.56	$[-2.12, -1.10]$	$[-2.87, -0.71]$	4.1σ
C_{10}^μ	$+1.20$	$[+0.88, +1.57]$	$[+0.58, +2.00]$	4.2σ
C_9^e	$+1.54$	$[+1.13, +1.98]$	$[+0.76, +2.48]$	4.3σ
C_{10}^e	-1.27	$[-1.65, -0.92]$	$[-2.08, -0.61]$	4.3σ
$C_9^\mu = -C_{10}^\mu$	-0.63	$[-0.80, -0.47]$	$[-0.98, -0.32]$	4.2σ
$C_9^e = -C_{10}^e$	$+0.76$	$[+0.55, +1.00]$	$[+0.36, +1.27]$	4.3σ
$C_9^\mu = C_{10}^\mu$	-1.91	$[-2.30, -1.51]$	$[-2.71, -1.10]$	3.9σ
$C_9'^\mu$	-0.05	$[-0.31, +0.21]$	$[-0.57, +0.46]$	0.2σ
$C_{10}'^\mu$	$+0.03$	$[-0.21, +0.27]$	$[-0.44, +0.51]$	0.1σ
$C_9'^e$	$+0.07$	$[-0.21, +0.37]$	$[-0.49, +0.69]$	0.2σ
$C_{10}'^e$	-0.04	$[-0.30, +0.21]$	$[-0.57, +0.45]$	0.2σ

(center), or in C_9^μ and $C_9'^\mu$ (bottom), assuming the remaining coefficients to be SM-like.

The fit prefers NP in the Wilson coefficients corresponding to left-handed quark currents with high significance $\sim 4\sigma$. Negative C_9^μ and positive C_{10}^μ decrease both $\mathcal{B}(B \to K\mu^+\mu^-)$ and $\mathcal{B}(B \to K^*\mu^+\mu^-)$ while positive C_9^e and negative C_{10}^e increase both $\mathcal{B}(B \to Ke^+e^-)$ and $\mathcal{B}(B \to K^*e^+e^-)$, allowing a good description of the data in each case. Also along the direction $C_9^\ell = -C_{10}^\ell$ that corresponds to a left-handed lepton current, we find excellent fits to the data. As can be seen from the top plot in Fig. 1, right-handed muon currents ($C_9^\mu = C_{10}^\mu$) cannot describe the data. We find that right-handed electron currents can explain R_K and R_{K^*} if the corresponding Wilson coefficients are sizable ($C_9^e = C_{10}^e \sim -2$ or $+3$).

The primed Wilson coefficients, that correspond to right-handed quark currents, cannot improve the agreement with the data by themselves. As is well known [19], the primed coefficients imply $R_{K^*} > 1$ given $R_K < 1$ and vice versa. The complementary sensitivity of R_{K^*} and R_K to right-handed currents is illustrated in the bottom plot of Fig. 1 for the example of C_9^μ vs $C_9'^\mu$. In combination with sizable unprimed coefficients, the primed coefficients can slightly improve the fit.

Among the unprimed Wilson coefficients, there are approximate flat directions. We find that a good description of the experimental results is given by

$$C_9^\mu - C_9^e - C_{10}^\mu + C_{10}^e \simeq -1.4, \qquad (8)$$

unless some of the individual coefficients are much larger than 1 in absolute value. The flat direction is clearly visible in the top and center plot of Fig. 1. In many NP models one has relations among these coefficients. In models with leptoquarks one finds $C_9^\ell = \pm C_{10}^\ell$ [34,63]; models based
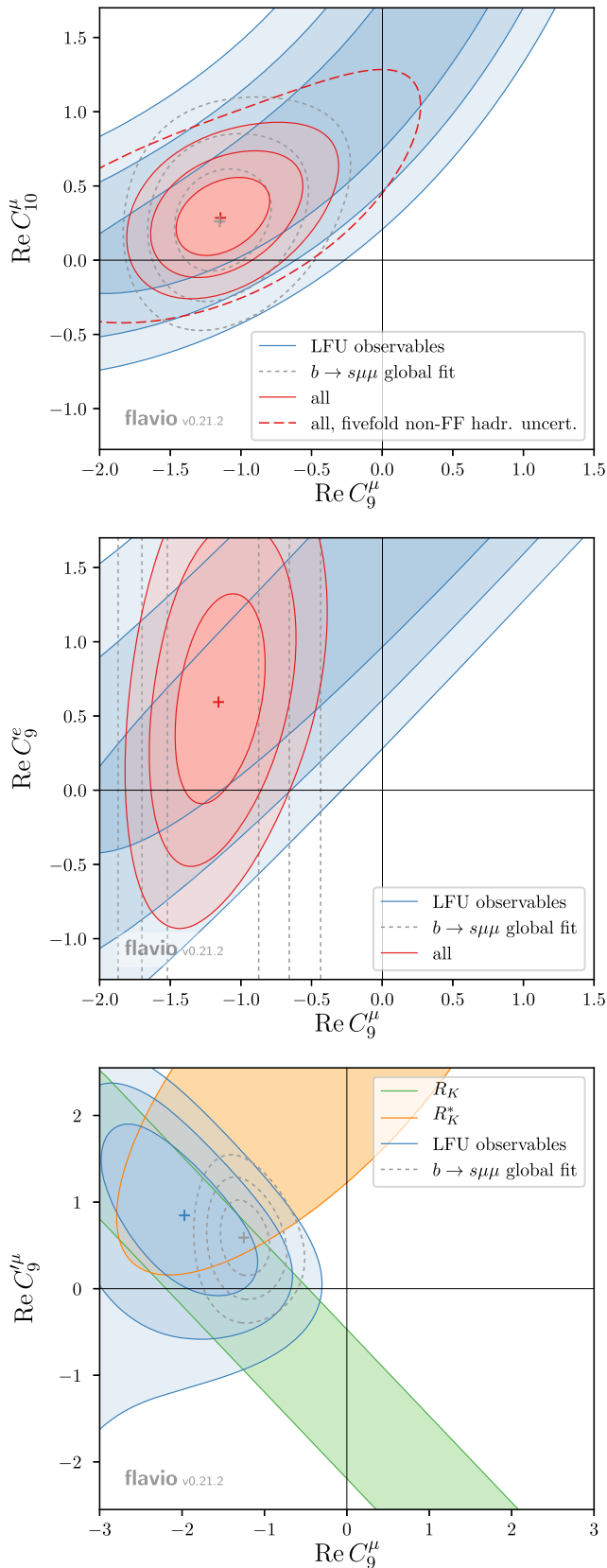
FIG. 1.   Allowed regions in planes of two Wilson coefficients, assuming the remaining coefficients to be SM-like.

on gauged $L_\mu - L_\tau$ predict $C_9^e = C_{10}^e = 0$ [21], while in some Z' models one finds $C_9^\ell = aC_{10}^\ell$, where a is a constant of $\mathcal{O}(1)$ (see e.g., [64]).

We find that a nonstandard C_{10}^ℓ (C_9^ℓ) leads to slightly larger (smaller) effects in R_{K^*} than in R_K. Therefore, $R_{K^*} \lesssim R_K < 1$ is best described by a nonstandard C_{10}^ℓ. The opposite hierarchy, $R_K \lesssim R_{K^*} < 1$, would lead to a slight preference for NP in C_9^ℓ.

A more powerful way to distinguish NP in C_9^ℓ from NP in C_{10}^ℓ is through measurements of LFU differences of angular observables [23,65,66]. We find that the observables

$$D_{P_4'} = P_4'(B \to K^*\mu^+\mu^-) - P_4'(B \to K^*e^+e^-), \quad (9)$$

$$D_{P_5'} = P_5'(B \to K^*\mu^+\mu^-) - P_5'(B \to K^*e^+e^-), \quad (10)$$

are particularly promising (for a definition of the observables $P_{4,5}'$ see [67]). Predictions for the observables $D_{P_{4,5}'}$ as functions of q^2 in the SM and various NP scenarios are shown in the plots of Fig. 2. The SM predictions are close to zero with very high accuracy across a wide q^2 range. In the presence of NP, $D_{P_{4,5}'}$ show a nontrivial q^2 dependence. If the discrepancies in $R_{K^{(*)}}$ are explained by NP in C_9^ℓ, we predict a negative $D_{P_4'} \sim -0.1$ at low $q^2 \lesssim 2.5$ GeV^2 and a sizable positive $D_{P_5'} \sim +0.5$. With NP in C_{10}^ℓ we predict instead a positive $D_{P_4'} \sim +0.15$ and a small negative $D_{P_5'} \sim -0.1$. We observe that $D_{P_5'}$ has even the potential to distinguish between NP in C_9^e and C_9^μ. For $q^2 \gtrsim 5$ GeV^2, a negative C_9^μ leads to a sizable increase of $P_5'(B \to K^*\mu^+\mu^-)$, while a positive C_9^e can decrease $P_5'(B \to K^*e^+e^-)$ only slightly, as the SM prediction for P_5' in this q^2 region is already close to its model-independent lower bound of -1. The recent measurements by Belle, $D_{P_4'}^{[1,6]} = +0.498 \pm 0.553$ and $D_{P_5'}^{[1,6]} = +0.656 \pm 0.496$ [5], have still sizable uncertainties and are compatible with NP both in C_9^ℓ and in C_{10}^ℓ. They slightly favor NP in C_9^ℓ. We note that, while the SM prediction for these observables has a tiny uncertainty, for fixed values of LFU violating Wilson coefficients, form factor and other hadronic uncertainties do play a role, as also shown in Fig. 2. However, these uncertainties are still so small that sufficient experimental precision could allow a clean identification of the underlying NP contact interaction.

We stress that the NP contact interactions in (5) lead also to a characteristic q^2 shape in the LFU ratios $R_{K^{(*)}}$. In Fig. 3 we show $R_{K^{(*)}}$ as functions of q^2 in the SM and in the same NP scenarios as in Fig. 2. In the SM, $R_{K^{(*)}}$ are to an excellent approximation q^2 independent. For very low $q^2 \simeq 4m_\mu^2$ they drop to zero, due to phase space effects. NP contact interactions lead to an approximately constant shift
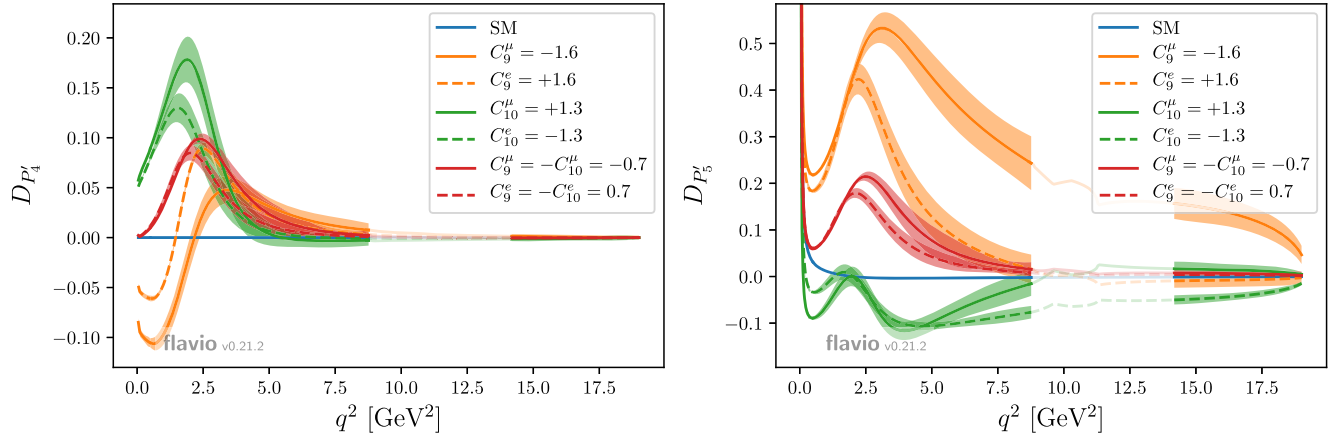
FIG. 2.   The $B \to K^* \ell^+ \ell^-$ LFU differences $D_{P'_4}$ and $D_{P'_5}$ in the SM and various NP benchmark models as functions of q^2. The error bands contain all theory uncertainties including form factors and nonfactorizable hadronic effects. In the region of narrow charmonium resonances, only the short-distance contribution is shown, without uncertainties.

in R_K. The ratio R_{K^*}, on the other hand, shows a nontrivial q^2 dependence in the presence of NP. In contrast to $B \to K\ell\ell$, the $B \to K^*\ell\ell$ decays at low q^2 are dominated by the photon pole, which gives a lepton flavor universal contribution. The effect of NP is therefore diluted at low q^2. Given the current experimental uncertainties, the measured q^2 shape of R_{K^*} is compatible with NP in the form of a contact interaction. Significant discrepancies from the shapes shown in Fig. 3 would imply the existence of light NP degrees of freedom around or below the scale set by q^2 and a breakdown of the effective Hamiltonian framework.

Assuming that the description in terms of contact interactions holds, we translate the best-fit values of the Wilson coefficients into a generic NP scale. Reparametrizing the effective Hamiltonian (5) as $\mathcal{H}_{\text{eff}}^{\text{NP}} = -\sum_i \mathcal{O}_i / \Lambda_i^2$, one gets

$$\Lambda_i = \frac{4\pi}{e} \frac{1}{\sqrt{|V_{tb}V_{ts}^*|}} \frac{1}{\sqrt{|C_i|}} \frac{v}{\sqrt{2}} \simeq \frac{35 \text{ TeV}}{\sqrt{|C_i|}}. \quad (11)$$
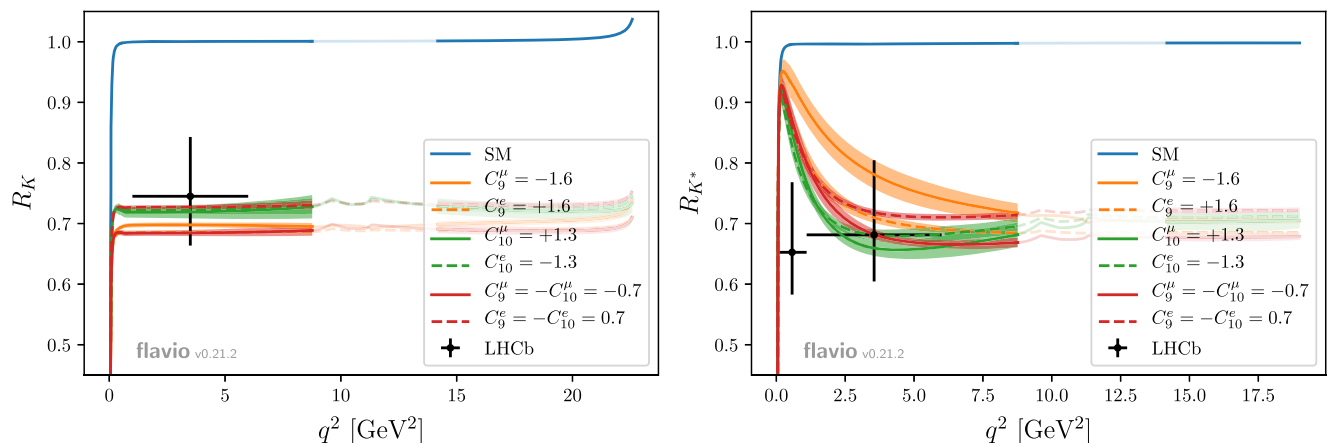
Based on perturbative unitarity we therefore predict the existence of NP degrees of freedom below a scale of $\Lambda_{\text{NP}} \sim \sqrt{4\pi} \times 35 \text{ TeV} / \sqrt{|C_i|} \sim 100 \text{ TeV}$.

III. COMPATIBILITY WITH OTHER RARE B DECAY ANOMALIES

It is natural to connect the discrepancies in $R_{K^{(*)}}$ to the other existing anomalies in rare decays based on the $b \to s\mu\mu$ transition. In the plots of Fig. 1 we show in dotted gray the $1, 2,$ and 3σ contours from our global $b \to s\mu\mu$ fit that does *not* take into account the measurements of the LFU observables $R_{K^{(*)}}$ and $D_{P_{4,5'}}$ [6]. We observe that the blue regions preferred by the LFU observables are fully compatible with the $b \to s\mu\mu$ fit. We have also performed a full fit, taking into account all the observables from the $b \to s\mu\mu$ fit, the branching ratio of $B_s \to \mu^+\mu^-$ (assuming it not to be affected by scalar NP contributions), and the *BABAR* measurement of the $B \to X_s e^+ e^-$ branching ratio [68]. This fit, shown in red, points to a nonstandard $C_9^\mu \simeq -1.2$ with very high

FIG. 3.   The LFU ratios $R_{K^{(*)}}$ in the SM and two NP benchmark models as function of q^2. Concerning the error bands, the same comments as for Fig. 2 apply.

significance. Wilson coefficients other than C_9^μ are constrained by the global fit.

Compared to the LFU observables, the global $b \to s\mu\mu$ fit depends more strongly on estimates of hadronic uncertainties in the $b \to s\ell\ell$ transitions. To illustrate the impact of a hypothetical, drastic underestimation of these uncertainties, we also show results of a global fit where uncertainties of nonfactorizable hadronic contributions are inflated by a factor of 5 with respect to our nominal estimates. In this case, the global fit becomes dominated by the LFU observables, but the $b \to s\mu\mu$ observables still lead to relevant constraints. For instance, the best-fit value for C_{10}^μ in Table I would imply a 50% suppression of the $B_s \to \mu^+\mu^-$ branching ratio, which is already in tension with current measurements [57], barring cancellations with scalar NP contributions.

IV. CONCLUSIONS

The discrepancies between SM predictions and experimental results in the LFU ratios R_K and R_{K^*} can be explained by NP four-fermion contact interactions $(\bar{s}b)(\bar{\ell}\ell)$ with left-handed quark currents. Future measurements of LFU differences of $B \to K^*\ell^+\ell^-$ angular observables can help to identify the chirality structure of the lepton currents. If the hints for LFU violation in rare B decays are the first signs of NP, perturbative unitarity implies new degrees of freedom below a scale of $\Lambda_{\rm NP} \sim 100$ TeV. These results are robust; i.e., they depend very mildly on assumptions about the size of hadronic uncertainties in the $B \to K^{(*)}\ell^+\ell^-$ decays.

Intriguingly, the measured values of R_K and R_{K^*} are fully compatible with NP explanations of various additional anomalies in rare B meson decays based on the $b \to s\mu\mu$ transition. A combined fit singles out NP in the Wilson coefficient C_9^μ as a possible explanation.

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