Towards establishing lepton flavor universality violation in $\bar{B} \to \bar{K}^* \ell^+ \ell^-$ decays

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Rare semileptonic $b \to s\ell^+\ell^-$ transitions provide some of the most promising frameworks to search for new physics effects. Recent analyses of these decays have indicated an anomalous behavior in measurements of angular distributions of the decay $B^0 \to K^* \mu^+ \mu^-$ and lepton-flavor-universality observables. Unambiguously establishing if these deviations have a common nature is of paramount importance in order to understand the observed pattern. We propose a novel approach to independently and complementary probe this hypothesis by performing a simultaneous amplitude analysis of $\bar{B}^0 \to \bar{K}^{*0} \mu^+ \mu^-$ and $\bar{B}^0 \to \bar{K}^{*0} e^+ e^-$ decays. This method enables the direct determination of observables that encode potential non-equal couplings of muons and electrons, and are found to be insensitive to nonperturbative QCD effects. If current hints of new physics are confirmed, our approach could allow an early discovery of physics beyond the standard model with LHCb run II data sets.

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Flavor changing neutral current processes of B meson decays are crucial probes for the standard model (SM), since as yet undiscovered particles may contribute to these transitions and cause observables to deviate from their SM predictions [1–4]. The decay mode $\bar{B} \to \bar{K}^* \ell^+ \ell^-$ is a prime example (i.e., $\ell = \mu,\ e$), which offers a rich framework to study from differential decay widths to angular observables. An anomalous behavior in angular and branching fraction analyses of the decay channel $\bar{B}^0 \to \bar{K}^{*0} \mu^+ \mu^-$ has been recently reported [5–8], notably in one of the observables with reduced theoretical uncertainties, P_5' [9,10]. Several models have been suggested in order to interpret these results as new physics (NP) signatures [11–17]. Nonetheless, the vectorlike nature of this pattern could be also explained by non-perturbative QCD contributions from $b \to sc\bar{c}$ operators (i.e., charm loops) that are able to either mimic or camouflage NP effects [18–20]. Nonstandard measurement in ratios of $b \to s\ell^+\ell^-$ processes—such as of R_K [21] and R_{K^*} [22]—indicate a suppression of the muon channel which is also compatible with the P_5' anomaly. In this case an immediate interpretation of lepton flavor universality (LFU) breaking is suggested due to the small theoretical uncertainties in their predictions [23,24]. Whilst the individual level of significance of the present anomalies is still inconclusive, there is an appealing nontrivial consistent pattern shown in global analysis fits [25–29].

The formalism of b decays is commonly described within an effective field theory [30], which probes distinct energy scales; with regimes classified into short-distance (high energies) perturbative and noncalculable long-distance effects. These can be parametrized in the weak Lagrangian in terms of effective operators with different Lorentz structures, $\mathcal{O}_i$, with corresponding couplings $\mathcal{C}_i$—referred to as Wilson coefficients (WC). Only a subset of the operators that are most sensitive to NP is examined in this work [31], i.e., $\mathcal{O}_7$ (virtual photon exchanges), $\mathcal{O}_{9,10}$ (vector and axial currents) and corresponding right-handed couplings with flipped helicities. In this framework, NP effects are incorporated by introducing deviations in the WCs [32] from their SM predictions, i.e., $\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP}$. For instance, the anomalous pattern seen in semileptonic decays can be explained by a shift in the coefficient $\mathcal{C}_9$ only, or $\mathcal{C}_9$ and $\mathcal{C}_{10}$ simultaneously [25–27]. A direct experimental determination of the WCs is currently bounded by sizeable uncertainties that arise from nonfactorizable hadronic matrix elements that are difficult to assess reliably from first principles. Some promising approaches suggest to extract this contribution from data-driven analyses [33,34] and by exploiting analytical properties of its structure [31]. However, these models still have intrinsic limitations, in particular in the assumptions that enter in parametrization of the dilepton invariant mass distribution.

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In this article, we propose a new model-independent approach that from a simultaneous unbinned amplitude analysis of both $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ and $\bar{B}^0 \to \bar{K}^{*0}e^+e^-$ decays can, for the first time, unambiguously determine LFU-breaking from direct measurements of WCs. This work builds on the generalization of Ref. [31], but it is insensitive to the model assumptions of the parametrization. This effect relies on the strong correlation between the muon and electron modes imposed by the lepton-flavor universality of the hadronic matrix elements. Furthermore, in this method the full set of observables (e.g., R_{K^*}, P_5' and branching fraction measurements) available in $\bar{B} \to \bar{K}^*\ell^+\ell^-$ decays is exploited, providing unprecedented precision on LFU in a single analysis.

Consider the differential decay rate for $\bar{B} \to \bar{K}^*\ell^+\ell^-$ decays (dominated by the on-shell $\bar{K}^{*0}$ contribution) fully described by four kinematic variables; the di-lepton squared invariant mass, q^2, and the three angles $\vec{\Omega} = (\cos\theta_\ell, \cos\theta_K, \phi)$ [30]. The probability density function $(p.d.f.)$ for this decay can be written as

$$p.d.f. = \frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}^3\Omega}, \quad \text{with} \quad \Gamma = \int_{q^2} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}, \tag{1}$$

with different q^2 intervals depending on the lepton flavor under study. For a complete definition of $\mathrm{d}^4\Gamma/(\mathrm{d}q^2\mathrm{d}^3\Omega)$ we refer to [30,35] and references therein. It is convenient to explicitly write the WC dependence on the decay width by the transversity amplitudes ($\lambda = \perp, \parallel, 0$) as [31]

$$\mathcal{A}_\lambda^{(\ell)L,R} = \mathcal{N}_\lambda^{(\ell)} \bigg\{ (C_9^{(\ell)} \mp C_{10}^{(\ell)}) \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[C_7^{(\ell)} \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \bigg\}, \tag{2}$$

where $\mathcal{N}_\lambda^{(\ell)}$ is a normalization factor, and $\mathcal{F}_\lambda^{(T)}(q^2)$ and $\mathcal{H}_\lambda(q^2)$ are referred to "local" and "nonlocal" hadronic matrix elements, respectively. The $\mathcal{F}_\lambda^{(T)}(q^2)$ are form factors, while $\mathcal{H}_\lambda(q^2)$ encode the aforementioned nonfactorizable hadronic contributions and are described using two complementary parametrizations [31,34]—for brevity only a subset of results is shown for the latter approach. In the following, this function is expressed in terms of a "conformal" variable $z(q^2)$ [31,36,37], with an analytical expansion truncated at a given order z^n (herein referred to as $\mathcal{H}_\lambda[z^n]$), after removing singularities related to the $J/\psi(1S)$ and $\psi(2S)$. Further information about the formalism is given in Appendix A. One of the drawbacks of this expansion is that *a priori* there is no physics argument to justify the order of the polynomial to be curtailed at—which in turn currently limits any claim on NP sensitivity.

In order to overcome these points, we investigate the LFU-breaking hypothesis using direct determinations of the difference of Wilson coefficients between muons and electrons, i.e.,

$$\Delta\mathcal{C}_i = \tilde{\mathcal{C}}_i^{(\mu)} - \tilde{\mathcal{C}}_i^{(e)}, \tag{3}$$

where the usual WCs $\mathcal{C}_i^{(\mu,e)}$ are renamed as $\tilde{\mathcal{C}}_i^{(\mu,e)}$, since an accurate disentanglement between the physical meaning of $\mathcal{C}_i^{(\mu,e)}$ and the above-mentioned hadronic pollution cannot be achieved at the current stage of the theory [38]. The key feature of this strategy is to realize that all hadronic matrix elements are known to be lepton-flavor universal, and thus are shared among both semileptonic decays. This benefits from the large statistics available for $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ decays that is sufficient to enable the determination of these multispace parameters. Note that an amplitude analysis of the electron mode only has been previously disregarded, given the limited data set in either LHCb or Belle experiments. In a common framework the hadronic contributions are treated as nuisance parameters, while only the Wilson coefficients $\tilde{\mathcal{C}}_9^{(\mu,e)}$ and $\tilde{\mathcal{C}}_{10}^{(\mu,e)}$ are kept separately for the two channels. For consistency, the WC $\tilde{\mathcal{C}}_7$ is also shared in the fit and fixed to its SM value, given its universal coupling to photons and the strong constraint from radiative B decays [39]. In the following, all the right-handed WCs are fixed to their SM values, i.e., $\mathcal{C}_i'^{(\mu,e)} = 0$, while sensitivity studies on the determination of the WCs $\mathcal{C}_9'^{(\mu)}$ and $\mathcal{C}_{10}'^{(\mu)}$ are detailed in Appendix B.

Signal-only ensembles of pseudoexperiments are generated with sample size corresponding roughly to the yields foreseen in LHCb run II [8 fb^{-1}] and future upgrades [50–300 fb^{-1}] [40], and Belle II [50 ab^{-1}]. These are extrapolated from Refs. [5,6,22] by scaling, respectively, with luminosity and $\sigma_{b\bar{b}} \propto \sqrt{s}$ for LHCb, where s denotes the designed center-of-mass energy of the b-quark pair, and exclusively with luminosity for Belle II. Note that for brevity most of the results are shown for the representative scenario of LHCb run II. The studied q^2 range corresponds to $1.1\ \mathrm{GeV}^2 \le q^2 \le 8.0\ \mathrm{GeV}^2$ and $11.0\ \mathrm{GeV}^2 \le q^2 \le 12.5\ \mathrm{GeV}^2$ for the muon mode and $1.1\ \mathrm{GeV}^2 \le q^2 \le 7.0\ \mathrm{GeV}^2$ for the electron mode in LHCb, while in Belle II the same kinematic regions are considered for both semileptonic channels, namely, $1.1\ \mathrm{GeV}^2 \le q^2 \le 8.0\ \mathrm{GeV}^2$ and $10.0\ \mathrm{GeV}^2 \le q^2 \le 13.0\ \mathrm{GeV}^2$. This definition of q^2 ranges are broadly consistent with published results and assumes improvements in the electron mode resolution for LHCb [41].

Within the SM setup, the Wilson coefficients are set to $\mathcal{C}_9^{\mathrm{SM}} = 4.27$, $\mathcal{C}_{10}^{\mathrm{SM}} = -4.17$ and $\mathcal{C}_7^{\mathrm{SM}} = -0.34$ (see [31] and references therein), corresponding to a fixed renormalization scale of $\mu = 4.2$ GeV. This baseline model is modified for two NP benchmark points (BMP), $\Delta\mathcal{C}_9 = -1$ and

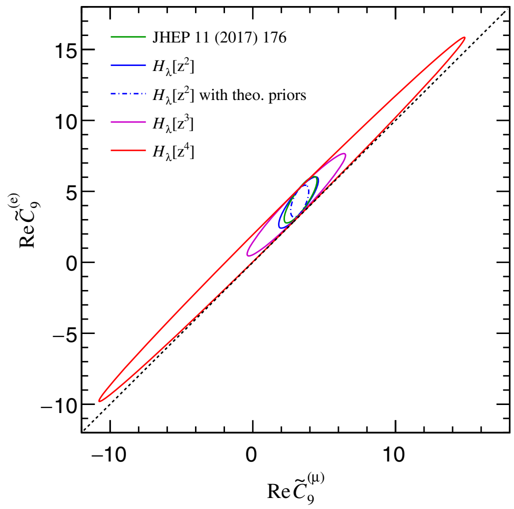

FIG. 1. Two-dimensional sensitivity scans for the pair of Wilson coefficients $\tilde{\mathcal{C}}_9^{(\mu)}$ and $\tilde{\mathcal{C}}_9^{(e)}$ for different nonlocal hadronic parametrization models evaluated at $\mathtt{BMP}_{\mathcal{C}_9}$, and with the expected statistics after LHCb run II. The contours correspond to 99% confidence level statistical-only uncertainty bands and the dotted black line indicates the LFU hypothesis.

$\Delta\mathcal{C}_9 = -\Delta\mathcal{C}_{10} = -0.7$, referred to, respectively, as $\mathtt{BMP}_{\mathcal{C}_9}$ and $\mathtt{BMP}_{\mathcal{C}_{9,10}}$, where NP is inserted only in the case of muons, i.e., $\mathcal{C}_i^{(e)} = \mathcal{C}_i^{\mathrm{SM}}$. These points are favored by several global fit analyses with similar significance [25–27].

An extended unbinned maximum likelihood fit is performed to these simulated samples, in which multivariate Gaussian terms are added to the log-likelihood to incorporate prior knowledge on the nuisance parameters. In order to probe the model-independence of the framework, the nonlocal hadronic parametrization is modified in several ways (see Appendix A for a detailed discussion), i.e.,

(i) baseline $\mathcal{H}_\lambda[z^2]$ SM prediction [31] included as a multivariate Gaussian constraint;
(ii) no theoretical assumption on $\mathcal{H}_\lambda[z^2]$ and with free-floating parameters;
(iii) higher orders of the analytical expansion of $\mathcal{H}_\lambda[z^n]$ up to z^3 and z^4—free floating;
(iv) and re-parametrization of the nonlocal hadronic matrix elements as proposed in Ref. [34], i.e., including them as multiplicative factors to the corresponding leading hadronic terms.

On the other hand, form factors parameters are taken from [42] and, in order to guarantee a good agreement between Light-Cone Sum Rules [43,44] and Lattice results [45,46], their uncertainties are doubled with respect to Ref. [42].

Figure 1 shows the fit results for several alternative parametrizations of the nonlocal hadronic contribution for the $\mathtt{BMP}_{\mathcal{C}_9}$ hypothesis, with yields corresponding to LHCb run II scenario. We observe that the sensitivity to $\tilde{\mathcal{C}}_9^{(\mu,e)}$ is strongly dependent on the model assumption used for the nonlocal matrix elements. Nonetheless, it is noticeable that the high correlation of the $\tilde{\mathcal{C}}_9^{(\mu)}$ and $\tilde{\mathcal{C}}_9^{(e)}$ coefficients is sufficient to preserve the true underlying physics at any order of the series expansion $\mathcal{H}_\lambda[z^n]$ and without any parametric theoretical input, i.e., the two-dimensional pull estimator with respect to the LFU hypothesis is unbiased. We note that, as commonly stated in the literature (see e.g., recent review in Ref. [47]), the determination of $\mathcal{C}_{10}^{(\mu,e)}$ is insensitive to the lack of knowledge on the nonlocal hadronic effects. Nevertheless, its precision is still bounded to the uncertainties on the form factors, that are found to be the limiting factor by the end of run II.

The sensitivity to the two benchmarklike NP scenarios using the proposed pseudo-observables $\Delta\mathcal{C}_i$ is shown in Fig. 2. We quantify the maximal expected significance with

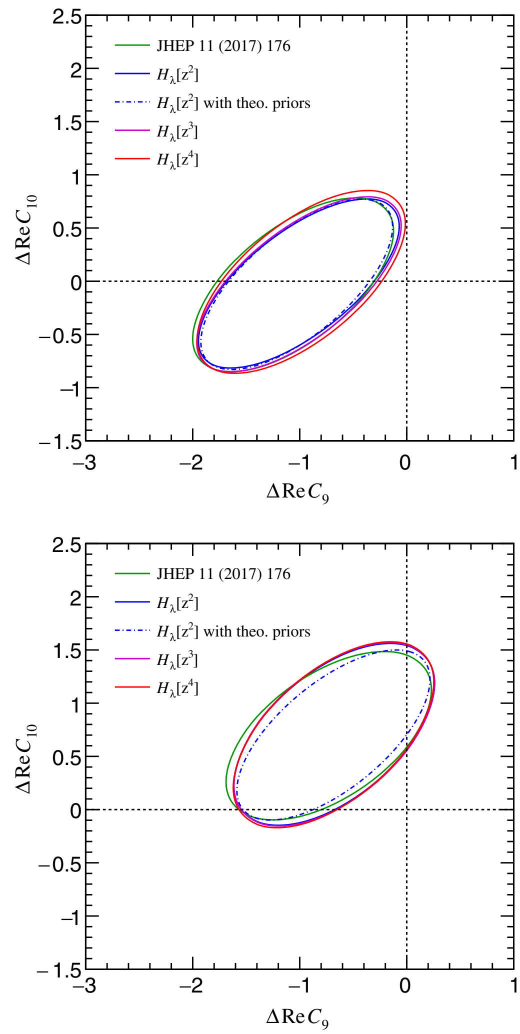

FIG. 2. Two-dimensional sensitivity scans for the proposed observables $\Delta\mathcal{C}_9$ and $\Delta\mathcal{C}_{10}$ for different nonlocal hadronic parametrization models evaluated at (top) $\mathtt{BMP}_{\mathcal{C}_9}$ and (bottom) $\mathtt{BMP}_{\mathcal{C}_{9,10}}$, and with the expected statistics after LHCb run II. The contours correspond to 99% confidence level statistical-only uncertainty bands.

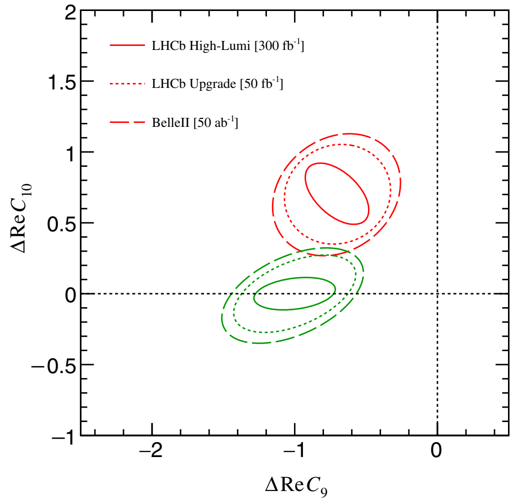

FIG. 3. Two-dimensional sensitivity scans for the proposed observables $\Delta\mathcal{C}_9$ and $\Delta\mathcal{C}_{10}$ for the two considered NP scenarios: (green) $\mathtt{BMP}_{\mathcal{C}_9}$ and (red) $\mathtt{BMP}_{\mathcal{C}_{9,10}}$. The contours correspond to 99% confidence level statistical-only uncertainty bands expected for the (dashed) Belle II 50 ab^{-1} and LHCb Upgrade (dotted) 50 fb^{-1} and (solid) 300 fb^{-1} statistics.

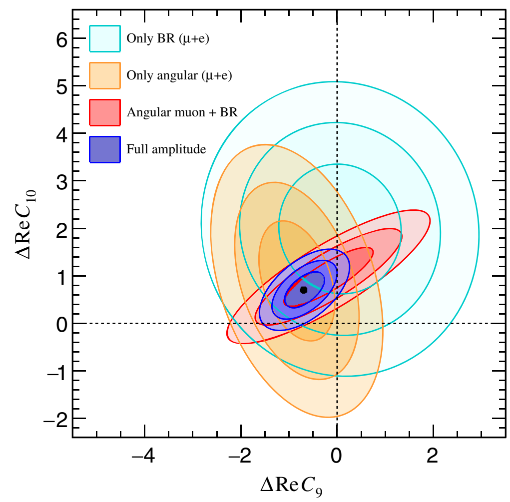

FIG. 4. Sensitivity to $\mathtt{BMP}_{\mathcal{C}_{9,10}}$ scenario for the expected statistics after the LHCb run II. The relative contribution (68%, 95%, 99% confidence level contours) of each step of the analysis is shown in different colors, together with the result of full amplitude method proposed in this article.

respect to the SM to be 4.6 and 5.3σ for $\mathtt{BMP}_{\mathcal{C}_9}$ and $\mathtt{BMP}_{\mathcal{C}_{9,10}}$, respectively. Realistic experimental effects are necessary to determine the exact sensitivity achievable. Nevertheless, these results suggest that a first observation (with a single measurement) of LFU breaking appears to be feasible with the expected recorded statistics by the end of LHCb run II. Furthermore, it is interesting to examine the prospects for confirming this evidence in the upcoming LHCb/Belle upgrades [48]. Figure 3 summarizes the two-dimensional statistical-only significances for the designed luminosities. Both LHCb Upgrade and Belle II experiments have comparable sensitivities (within 8.0–10σ), while LHCb High-Lumi has an overwhelming significance. These unprecedented data sets will not only yield insights on this phenomena but also enable a deeper understanding of the nature of NP—insensitive to both local and nonlocal hadronic uncertainties.

Experimental resolution and detector acceptance/efficiency effects are not considered in this work, as these would require further information from current (nonpublic) or planned B-physics experiments. Nevertheless, the precision on this measurement can remain unbiased either by parametrizing these effects in the amplitude model and/or even recomputing the angles or the q^2 variables constraining the B invariant mass [41]. Moreover, the differential decay width can receive additional complex amplitudes from signal-like backgrounds, e.g., $K\pi$ S-wave from a nonresonant decay and/or a scalar resonance [49]. These contributions are determined to be small [5,50], and in the proposed formalism they benefit from the same description between the muon and electron mode (see detailed discussion in Ref. [38]). Therefore, such contribution does not dilute the expected sensitivity of the measurement.

Another important test to probe the stability of the model consists in analysing potential issues that can rise if the truncation $\mathcal{H}_\lambda[z^n]$ is not a good description of nature. We proceed as follows: we generate ensembles with nonzero coefficients for $\mathcal{H}_\lambda[z^3]$ and $\mathcal{H}_\lambda[z^4]$, and we perform the fit with $\mathcal{H}_\lambda[z^2]$. Despite the mismodeling of the nonlocal hadronic effects in the fit, we observe that the determination of $\Delta\mathcal{C}_9$ and $\Delta\mathcal{C}_{10}$ is always unbiased, thanks to the relative cancellation of all the shared parameters between the two channels. It is worth mentioning that a hypothetical determination of the individual $\tilde{\mathcal{C}}_9^{(\mu,e)}$ and $\tilde{\mathcal{C}}_{10}^{(\mu,e)}$ WCs can also produce a shift in their central values that mimics the behavior of NP [38].

In conclusion, we propose a clean and model-independent method to combine all the available information from $\bar{B}\to\bar{K}^*\ell^+\ell^-$ decays for a precise determination of LFU-breaking differences of WCs, i.e., $\Delta\mathcal{C}_9$ and $\Delta\mathcal{C}_{10}$. This relies on a shared parametrization of the local (form factors) and nonlocal ($\mathcal{H}_\lambda[z^n]$) hadronic matrix elements between the muonic and electronic channels, that in turn enables the determination of the observables of interest free from any theoretical uncertainty. In addition, this simultaneous analysis is more robust against experimental effects such as mismodeling of the detector resolution, since most parameters are effectively determined from the muon mode. This would be an important benefit for LHCb where the electron resolution is significantly worse than that of muons. Figure 4 illustrates the usefulness of the newly-proposed observables by combining the different information from angular analysis to branching ratio measurements. Due to the inclusiveness of the approach, the expected sensitivity surpasses any of the projections for the foreseen measurements of, e.g., R_{K^*} or P_5' alone—given the benchmark points. Therefore, this novel formalism can be the most immediate method to observe unambiguously NP in $\bar{B} \to \bar{K}^* \ell^+ \ell^-$ decays.

A promising feature of this framework is the possibility to extend the analysis to include other decay channels involving flavor changing neutral currents. For instance, the charged decay $\bar{B}^+ \to \bar{K}^{*+} \ell^+ \ell^-$ undergoes the same physics and is easily accessible at the B-factories, while other rare semi-leptonic decays such as $B^+ \to K^+ \ell^+ \ell^-$ and $\Lambda_b \to \Lambda^{(*)} \ell^+ \ell^-$ have a different phenomenology but access the same NP information in terms of WC description. Thus, an unbinned global simultaneous fit to all data involving $b \to s \ell^+ \ell^-$ transitions is a natural and appealing extension of this work. Moreover, the parameter space of the investigated WCs can also be broadened to incorporate direct measurement of the right-handed $\mathcal{C}_i'$—currently weakly constrained by global fits [25–27].

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APPENDIX A: FORMALISM

The nonlocal hadronic matrix elements $\mathcal{H}_\lambda(q^2)$ are investigated using two complementary parametrizations [31,34].

The nominal parametrization [31] is obtained through the mapping

$$q^2 \mapsto z(q^2) \equiv \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \tag{A1}$$

where $t_+ = 4M_D^2$ and $t_0 = t_+ - \sqrt{t_+(t_+ - M^2_{\psi(2S)})}$, which leads to the functions $\mathcal{H}_\lambda(z)$ that are characterized by two singularities at $z_{J/\psi}$ and $z_{\psi(2S)}$. These can be expressed as

$$\mathcal{H}_\lambda(z) = \frac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z), \tag{A2}$$

where the functions $\hat{\mathcal{H}}_\lambda(z)$ are analytical and can be Taylor-expanded around $z = 0$ as

$$\hat{\mathcal{H}}_\lambda(z) = \left[\sum_{k=0}^{n} \alpha_k^{(\lambda)} z^k\right] \mathcal{F}_\lambda(z). \tag{A3}$$

Several orders of the polynomials are studied in the text. Note that any additional order k introduces a complex parameter, $\alpha_k^{(\lambda)}$, for each of the polarizations $\lambda = \perp, \parallel, 0$. These nuisance parameters can be either free floated in the fit (nominal configuration labeled as $\mathcal{H}_\lambda[z^2, \ldots, z^4]$) or Gaussian constrained to their SM prediction (labeled as $\mathcal{H}_\lambda[z^2]$ with theo. priors in the plots).

Finally, the nonlocal hadronic matrix elements are reparametrized following Ref. [34], in which these nonlocal hadronic contributions are included as multiplicative factors, leading to a reformulation of the amplitudes of Eq. (2) as

$$\mathcal{A}_\lambda^{(\ell)L,R} = \mathcal{N}_\lambda^{(\ell)} \left\{ (C_9^{(\ell)} \mp C_{10}^{(\ell)}) \mathcal{F}_\lambda(q^2) \left[1 + a_\lambda + b_\lambda \frac{q^2}{6\,\mathrm{GeV}^2}\right] + \frac{2 m_b M_B}{q^2} C_7^{(\ell)} \mathcal{F}_\lambda^T(q^2) \right\}, \tag{A4}$$

where a_λ and b_λ are complex coefficients Gaussian constrained around zero.

APPENDIX B: RIGHT-HANDED WILSON COEFFICIENTS

An extension of the physics case of the proposed method is to investigate the sensitivity to the chirality-flipped counterparts of the usual Wilson coefficients, i.e., $\mathcal{C}_9'^{(\mu)}$ and $\mathcal{C}_{10}'^{(\mu)}$. Following the formalism discussed in this article, the primed WCs are examined by considering in addition to the $\mathtt{BMP}_{\mathcal{C}_{9,10}}$ three different modified NP scenarios for the muon only: $\mathcal{C}_{9,10}'^{(\mu)} = \mathcal{C}_{9,10}'^{\mathrm{SM}} = 0$; $\mathcal{C}_9'^{(\mu)} = \mathcal{C}_{10}'^{(\mu)} = 0.3$; and $\mathcal{C}_9'^{(\mu)} = -\mathcal{C}_{10}'^{(\mu)} = 0.3$. Notice that for the electron mode the $\mathcal{C}_{9,10}'^{(e)}$ is set and fixed to the SM value $\mathcal{C}_{9,10}'^{\mathrm{SM}} = 0$.

Figure 5 shows the fit results for different order of the analytic expansion for the nonlocal hadronic contribution for a NP scenario with $\mathcal{C}_9'^{(\mu)} = \mathcal{C}_{10}'^{(\mu)} = 0.3$, and yields corresponding to the LHCb run II expected statistics. The dependency on the determination of $\mathcal{C}_9'^{(\mu)}$ and $\mathcal{C}_{10}'^{(\mu)}$ on the order of the expansion clearly saturates after $\mathcal{H}_\lambda[z^3]$ and allows a measurement of the primed Wilson coefficients for the muon decay channel $B^0 \to K^{*0} \mu^+ \mu^-$ independent on the theoretical hadronic uncertainty. Figure 6 shows the prospects for the sensitivity to the $\mathcal{C}_9'^{(\mu)}$ and $\mathcal{C}_{10}'^{(\mu)}$ Wilson coefficients corresponding to the expected statistics at the LHCb upgrade with 50and 300 fb^{-1}. Note that only with the full capability of the LHCb experiment it is possible to start disentangling the different NP hypotheses.

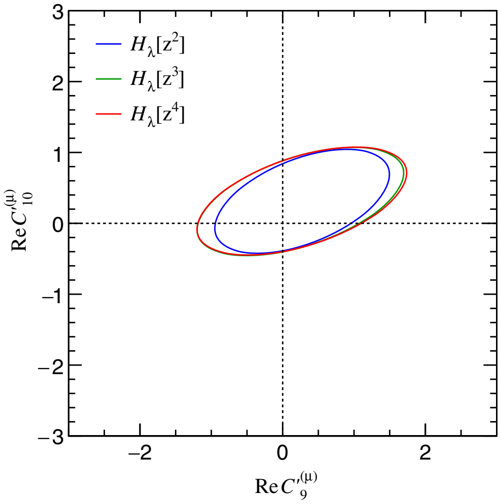

FIG. 5. Two-dimensional sensitivity scans for the pair of Wilson coefficients $\mathcal{C}_9^{\prime(\mu)}$ and $\mathcal{C}_{10}^{\prime(\mu)}$ for different nonlocal hadronic parametrization models for a NP scenario with $\mathcal{C}_9^{\prime(\mu)} = \mathcal{C}_{10}^{\prime(\mu)} = 0.3$. The contours correspond to 99% confidence level statistical-only uncertainty bands evaluated with the expected statistics after LHCb run II.

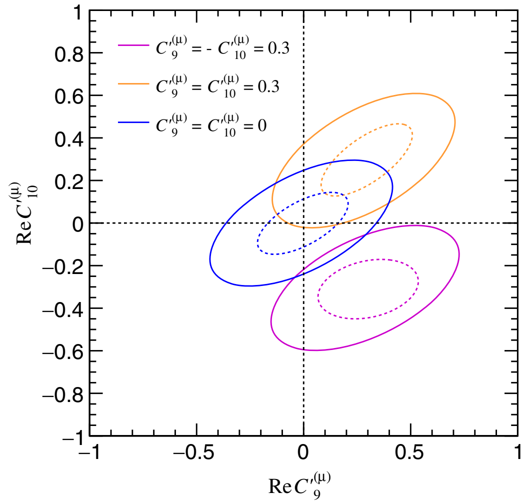

FIG. 6. Two-dimensional sensitivity scans for the pair of Wilson coefficients $\mathcal{C}_9^{\prime(\mu)}$ and $\mathcal{C}_{10}^{\prime(\mu)}$ for three NP scenarios: (blue) $\mathcal{C}_9^{\prime(\mu)} = \mathcal{C}_{10}^{\prime(\mu)} = 0$, (orange) $\mathcal{C}_9^{\prime(\mu)} = \mathcal{C}_{10}^{\prime(\mu)} = 0.3$ and (magenta) $\mathcal{C}_9^{\prime(\mu)} = -\mathcal{C}_{10}^{\prime(\mu)} = 0.3$. The contours correspond to 99% confidence level statistical-only uncertainty bands expected for the LHCb Upgrade (dotted) 50 fb^{-1} and (solid) 300 fb^{-1} statistics.

[1] Y. Grossman and M. P. Worah, Phys. Lett. B **395**, 241 (1997).
[2] R. Fleischer, Int. J. Mod. Phys. A **12**, 2459 (1997).
[3] D. London and A. Soni, Phys. Lett. B **407**, 61 (1997).
[4] M. Ciuchini, E. Franco, G. Martinelli, A. Masiero, and L. Silvestrini, Phys. Rev. Lett. **79**, 978 (1997).
[5] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 02 (2016) 104.
[6] S. Wehle *et al.* (Belle Collaboration), Phys. Rev. Lett. **118**, 111801 (2017).
[7] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 07 (2013) 084.
[8] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 06 (2014) 133.
[9] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **111**, 191801 (2013).
[10] S. Descotes-Genon, L. Hofer, J. Matias, and J. Virto, J. High Energy Phys. 06 (2016) 092.
[11] R. Gauld, F. Goertz, and U. Haisch, J. High Energy Phys. 01 (2014) 069.
[12] A. J. Buras and J. Girrbach, J. High Energy Phys. 12 (2013) 009.
[13] W. Altmannshofer and D. M. Straub, Eur. Phys. J. C **73**, 2646 (2013).
[14] A. Crivellin, L. Hofer, J. Matias, U. Nierste, S. Pokorski, and J. Rosiek, Phys. Rev. D **92**, 054013 (2015).
[15] G. Hiller and M. Schmaltz, Phys. Rev. D **90**, 054014 (2014).
[16] S. Biswas, D. Chowdhury, S. Han, and S. J. Lee, J. High Energy Phys. 02 (2015) 142.
[17] B. Gripaios, M. Nardecchia, and S. A. Renner, J. High Energy Phys. 05 (2015) 006.
[18] S. Jäger and J. Martin Camalich, J. High Energy Phys. 05 (2013) 043.
[19] S. Jäger and J. Martin Camalich, Phys. Rev. D **93**, 014028 (2016).
[20] M. Ciuchini, M. Fedele, E. Franco, S. Mishima, A. Paul, L. Silvestrini, and M. Valli, J. High Energy Phys. 06 (2016) 116.
[21] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **113**, 151601 (2014).
[22] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 08 (2017) 055.
[23] G. Hiller and F. Kruger, Phys. Rev. D **69**, 074020 (2004).
[24] M. Bordone, G. Isidori, and A. Pattori, Eur. Phys. J. C **76**, 440 (2016).
[25] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, and J. Virto, J. High Energy Phys. 01 (2018) 093.
[26] W. Altmannshofer, P. Stangl, and D. M. Straub, Phys. Rev. D **96**, 055008 (2017).
[27] T. Hurth, F. Mahmoudi, D. Martinez Santos, and S. Neshatpour, Phys. Rev. D **96**, 095034 (2017).
[28] M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, Eur. Phys. J. C **77**, 688 (2017).
[29] A. K. Alok, B. Bhattacharya, A. Datta, D. Kumar, J. Kumar, and D. London, Phys. Rev. D **96**, 095009 (2017).
[30] W. Altmannshofer, P. Ball, A. Bharucha, A. J. Buras, D. M. Straub, and M. Wick, J. High Energy Phys. 01 (2009) 019.

[31] C. Bobeth, M. Chrzaszcz, D. van Dyk, and J. Virto, Eur. Phys. J. C **78**, 451 (2018).

[32] A. Ali, G. F. Giudice, and T. Mannel, Z. Phys. C **67**, 417 (1995).

[33] T. Blake, U. Egede, P. Owen, G. Pomery, and K. A. Petridis, Eur. Phys. J. C **78**, 453 (2018).

[34] T. Hurth, C. Langenbruch, and F. Mahmoudi, J. High Energy Phys. 11 (2017) 176.

[35] C. Bobeth, G. Hiller, and G. Piranishvili, J. High Energy Phys. 07 (2008) 106.

[36] C. G. Boyd, B. Grinstein, and R. F. Lebed, Phys. Lett. B **353**, 306 (1995).

[37] C. Bourrely, I. Caprini, and L. Lellouch, Phys. Rev. D **79**, 013008 (2009); **82**, 099902(E) (2010).

[38] M. Chrzaszcz, A. Mauri, N. Serra, R. Silva Coutinho, and D. van Dyk, arXiv:1805.06378.

[39] A. Paul and D. M. Straub, J. High Energy Phys. 04 (2017) 027.

[40] R. Aaij *et al.* (LHCb Collaboration), Expression of Interest for a Phase-II LHCb Upgrade: Opportunities in Flavour Physics, and Beyond, in the HL-LHC Era, Technical Report No. CERN-LHCC-2017-003, CERN, Geneva, 2017.

[41] F. Lionetto, N. Serra, O. Steinkamp, and K. Mueller, Measurements of Angular Observables of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ Decays and the Upgrade of LHCb, (2018), https://cds.cern.ch/record/2624938.

[42] A. Bharucha, D. M. Straub, and R. Zwicky, J. High Energy Phys. 08 (2016) 098.

[43] P. Ball and V. M. Braun, Phys. Rev. D **58**, 094016 (1998).

[44] A. Khodjamirian, T. Mannel, and N. Offen, Phys. Rev. D **75**, 054013 (2007).

[45] D. Becirevic, V. Lubicz, and F. Mescia, Nucl. Phys. **B769**, 31 (2007).

[46] R. R. Horgan, Z. Liu, S. Meinel, and M. Wingate, Phys. Rev. D **89**, 094501 (2014).

[47] B. Capdevila, S. Descotes-Genon, L. Hofer, and J. Matias, J. High Energy Phys. 04 (2017) 016.

[48] J. Albrecht, F. Bernlochner, M. Kenzie, S. Reichert, D. Straub, and A. Tully, arXiv:1709.10308.

[49] D. Becirevic and A. Tayduganov, Nucl. Phys. **B868**, 368 (2013).

[50] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 11 (2016) 047; 04 (2017) 142(E).