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New tests of short-distance dynamics in $b \to s\bar{\ell}\ell$ decays

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The rare $B \to K^{(*)}\bar{\ell}\ell$ decays exhibit a long-standing tension with Standard Model (SM) predictions, which can be attributed to a lepton-universal short-distance $b \to s\bar{\ell}\ell$ interaction. We present two novel methods to disentangle this effect from long-distance dynamics: one based on the determination of the inclusive $b \to s\bar{\ell}\ell$ rate at high dilepton invariant mass ($q^2 \geq 15$ GeV^2), the other based on the analysis of the q^2 spectrum of the exclusive modes $B \to K^{(*)}\bar{\ell}\ell$ (in the entire q^2 range).

Using the first method, we show that the SM prediction for the inclusive $b \to s\bar{\ell}\ell$ rate at high dilepton invariant mass is in good agreement with the result obtained summing the SM predictions for one- and two-body modes (K, K^*, $K\pi$). This observation allows us to perform a direct comparison of the inclusive $b \to s\bar{\ell}\ell$ rate with data. This comparison shows a significant deficit ($\sim 2\sigma$) in the data, fully compatible with the deficit observed at low-q^2 on the exclusive modes. This provides independent evidence of an anomalous $b \to s\bar{\ell}\ell$ short-distance interaction, free from uncertainties on the hadronic form factors. To test the short-distance nature of this effect we use a second method, where we analyze the exclusive $B \to K\bar{\ell}\ell$ differential branching ratio data in the entire q^2 region. Here, after using a dispersive parametrization of the narrow charmonia resonances, we extract the non-SM contribution to the universal Wilson coefficient C_9 for every bin in q^2. The q^2-independence of the result, and its compatibility with the inclusive determination, provide a consistency check of the short-distance nature of this effect.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

PoS(EPS-HEP2023)368

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1. Introduction

Exclusive and inclusive $b \to s\bar{\ell}\ell$ decays are sensitive probes of physics beyond the Standard Model (SM). The flavor-changing neutral-current (FCNC) structure implies a strong suppression of the decay amplitudes within the SM and, correspondingly, enhanced sensitivity to short-distance physics. On the theory side, the presence of narrow charmonium resonances poses challenges if the invariant mass of the dilepton pair, $q^2 = (p_{\bar{\ell}} + p_\ell)^2$, is close to the resonance masses. This is why precise SM tests are confined to $q^2 \lesssim 6-8\,\mathrm{GeV}^2$ (low-q^2 region) and $q^2 \gtrsim 14-15\,\mathrm{GeV}^2$ (high-q^2 region). On the experimental side, in the last few years measurements of rates and angular distributions of the exclusive $B \to K^{(*)}\bar{\mu}\mu$ decays by LHCb [1, 2] have shown significant tensions with the corresponding SM predictions, especially in the low-q^2 region. The goal of this study is to better understand the nature of this tension by trying to disentangle long-distance dynamics from possible short-distance dynamics using two different approaches [3, 4].

2. First approach: semi-inclusive $b \to s\bar{\ell}\ell$ transitions at high q^2

The effective Lagrangian valid below the electroweak scale relevant to $b \to s\bar{\ell}\ell$ transitions is conventionally written as

$$\mathcal{L}_{\text{eff}}^{b\to s\bar{\ell}\ell} = \frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left(V_{ts}^* V_{tb}\sum_i C_i O_i + \text{h.c.}\right) + \mathcal{L}_{\text{QCD}\times\text{QED}}^{N_f=5}\,, \tag{1}$$

where we have used CKM unitarity, and neglected the tiny $O(V_{us}^* V_{ub})$ terms. The only O_i with $b \to s\bar{\ell}\ell$ matrix elements that are non-vanishing at tree level are the electric-dipole operator O_7 and the two FCNC semileptonic operators O_9 and O_{10}:

$$O_7 = \frac{m_b}{e}(\bar{s}_L\sigma_{\mu\nu}b_R)F^{\mu\nu}\,, \quad O_9 = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,, \quad O_{10} = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,. \tag{2}$$

We find it convenient to perform a change of basis $\{O_9, O_{10}\} \to \{O_V, O_L\}$, where

$$O_V = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,, \quad O_L = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\ell_L)\,, \tag{3}$$

such that $C_V = C_9 + C_{10}$ and $C_L = -2C_{10}$. The new basis allows us to separate effective interactions that originate from different underlying dynamics, and behave differently in the evolution from high scales ($\mu_0 \sim m_t$) down to low scales ($\mu_b \sim m_b$). Throughout the computation we use the following values:

$$C_L(m_b) = 8.38 \pm 0.04 \qquad C_V(m_b) = -0.01 \pm 0.26. \tag{4}$$

Our goal is to compare the inclusive rate in the high-q^2 region with a semi-inclusive determination based on data, as an inclusive measurement is not yet available. In order to validate this procedure, we first show that, within the SM, the sum of a few exclusive modes (the leading $B^0 \to K^0\bar{\ell}\ell$, $B^0 \to K^{0*}\bar{\ell}\ell$, and the sub-leading $B^0 \to K\pi\bar{\ell}\ell$) can approximate well the inclusive rate in the high-q^2 region. As pointed out in [5], a convenient way to estimate the inclusive rate is by computing the ratio of the FCNC transition and the $b \to u$ charged-current decay,

$$R_{\text{incl}}^{(\ell)}(q_0^2) = \int_{q_0^2}^{m_B^2} dq^2 \frac{d\Gamma(B \to X_s\bar{\ell}\ell)}{dq^2} \Bigg/ \int_{q_0^2}^{m_B^2} dq^2 \frac{d\Gamma(B \to X_u\bar{\ell}\nu)}{dq^2}\,, \tag{5}$$

where q_0^2 is the lower cut on q^2 (we choose $q_0^2 = 15$ GeV^2). The hadronic structure of the two transitions is very similar, leading to a significant cancellation of non-perturbative uncertainties. For the inclusive rate $B \to X_u \bar{\ell}\nu$ we use the measurements from Belle [6].

To provide an updated numerical prediction of $R_{\rm incl}(q_0^2)$ within the SM we re-express the result of [5] in the $C_{L,V}$ basis:

$$R_{\rm incl}(q_0^2) = \frac{|V_{tb}V_{ts}^*|^2}{|V_{ub}|^2}\left[\mathcal{R}_L + \Delta\mathcal{R}_{[q_0^2]}\right] = \frac{|V_{tb}V_{ts}^*|^2}{|V_{ub}|^2}\left[\frac{\alpha_e^2 C_L^2}{16\pi^2} + \Delta\mathcal{R}_{[q_0^2]}\right] \tag{6}$$

where $\Delta\mathcal{R}_{[q_0^2]}$ is the correction to the limit of purely left-handed interactions dominating $b \to s\bar{\ell}\ell$ and identical hadronic distributions in $b \to u\ell\bar{\nu}$ compared to $b \to s\bar{\ell}\ell$. We find:

$$\mathcal{R}_L^{\rm SM} = (2.538 \pm 0.024) \times 10^{-5}\,, \quad \Delta\mathcal{R}_{[15]}^{\rm SM} = (-0.03 \pm 0.22) \times 10^{-5}\,, \tag{7}$$

and with this, we finally obtain for the branching ratio:

$$\mathcal{B}(B \to X_s\bar{\ell}\ell)_{[15]}^{\rm SM} = (4.5 \pm 1.0) \times 10^{-7} = 4.5 \times 10^{-7}\left[1 \pm 0.16_{\rm exp} \pm 0.11_{\rm CKM} \pm 0.09_{\Delta\mathcal{R}}\right]. \tag{8}$$

The branching fractions for the leading exclusive modes in the high-q^2 region can be computed using the form factors calculated in Refs. [7, 8]. Integrating for $q^2 \geq 15$ GeV, we find

$$\mathcal{B}(B \to K\bar{\ell}\ell)_{[15]}^{\rm SM} = \left(1.31 \pm 0.12\right) \times 10^{-7}\,, \quad \mathcal{B}(B \to K^*\bar{\ell}\ell)_{[15]}^{\rm SM} = \left(3.19 \pm 0.30\right) \times 10^{-7}\,, \tag{9}$$

The subleading $B \to K\pi$ branching ratio is estimated via heavy-hadron chiral perturbation theory. In order to avoid double-counting the resonant contributions from $B \to (K^* \to K\pi)\bar{\ell}\ell$, we only include the s-wave contribution assuming K^*-dominance for the $p-$wave. We find

$$\mathcal{B}\big(B \to (K\pi)_s\bar{\ell}\ell\big)_{[15]}^{\rm SM} = (5.8 \pm 2.5) \times 10^{-8}\,, \tag{10}$$

where the narrow-width approximation is used. Combining (9) and (10), we arrive at the following SM estimate of the semi-inclusive branching fraction:

$$\sum_i \mathcal{B}(B \to X_s^i\bar{\ell}\ell)_{[15]}^{\rm SM} = \left(5.07 \pm 0.42\right) \times 10^{-7}\,. \tag{11}$$

This result is well-compatible with the truly inclusive estimate presented in Eq. (8).

Having established the validity of this procedure, we now compare the inclusive determination (8) with a semi-inclusive sum based on the available experimental data from LHCb [2] (for $\ell = \mu$):

$$\mathcal{B}(B \to K\bar{\mu}\mu)_{[15]}^{\rm exp} = (8.47 \pm 0.50) \times 10^{-8}\,, \quad \mathcal{B}(B \to K^*\bar{\mu}\mu)_{[15]}^{\rm exp} = (1.58 \pm 0.35) \times 10^{-7}\,. \tag{12}$$

Applying a correction factor coming from the sub-leading $B \to K\pi$ mode in (10), we determine the following result:

$$\sum_i \mathcal{B}(B \to X_s^i\bar{\mu}\mu)_{[15]}^{\rm exp} = (2.74 \pm 0.41) \times 10^{-7}\,. \tag{13}$$

As summarized in Fig. 1, this result is significantly below the (consistent) SM predictions in Eqs. (8) and (11). This provides an independent verification of the known suppression in the $b \to s\bar{\mu}\mu$,

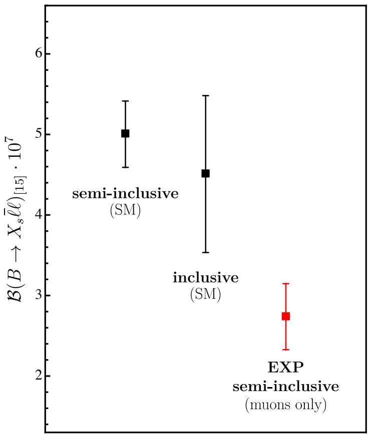

Figure 1: SM predictions vs. experimental data for the inclusive branching ratio, $\mathcal{B}(B \to X_s\bar{\ell}\ell)$, in the region $q^2 \geq 15$ GeV^2.

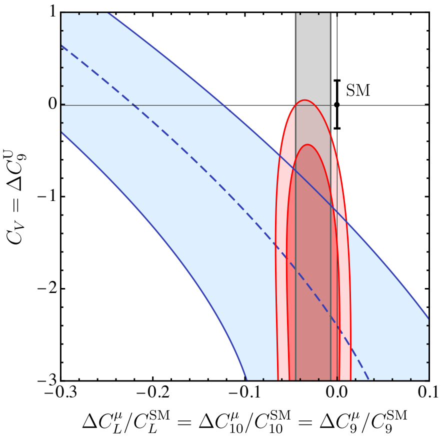

Figure 2: Regions for the Wilson coefficients favored by experimental data. The dark and light red regions give the combined compatibility from the inclusive rate $b \to s\bar{\ell}\ell$ (blue 1σ-band), LFU tests and $B_s \to \bar{\mu}\mu$ (gray band) at 68% and 90% confidence level, respectively.

since, being based on the inclusive rate, it is insensitive to hadronic form factors, and has a different sensitivity to non-perturbative effects associated with charm-rescattering.

In Fig. 2 we plot the region in the C_V–C_L plane favored by present data (blue dashed line with band). Perturbative and non-perturbative contributions due to charm-rescattering can be accounted for via an effective modification to C_V. Assuming $C_L = C_L^{\mathrm{SM}}$, the modification needed is very large; in fact, it is larger than the perturbative estimate of charm-rescattering contributions, and beyond any realistic estimate of non-perturbative charm-rescattering in the high-q^2 region, far from the narrow charmonium resonances. If, instead, we allow for a (lepton-flavor non-universal) modification of C_L, which can occur only beyond the SM, the discrepancy with the data is more easily explained with a small (naturally lepton-flavor universal) modification to C_V. Combining the constraints on C_L coming from LFU tests [9] and $B_s \to \bar{\mu}\mu$ [10] (gray band), leads to a preferred region (red region) in the $C_V - \Delta C_L^\mu$ plane that does not include the SM point at the 90% confidence level.

3. Second approach: bin-by-bin extraction of C_9

As a further hint to the short-distance nature of this effect, we look at the exclusive modes $B^+ \to K^+\bar{\mu}\mu$ and $B^0 \to K^{0*}\bar{\mu}\mu$, and show that the Wilson coefficient C_9 extracted from data does not show a significant q^2– or helicity-dependence.

In order to compute the theory predictions, we effectively modify C_9 by taking into account the perturbative corrections coming from the four-quark operators O_{1-6}. Since in this analysis the entire q^2 region is considered, a parametrization of the $c\bar{c}$ resonances is also needed: we use a dispersive approach (see [14]), where each resonance (J/ψ, $\psi(2s)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4450)$ for the K case, and only J/ψ, $\psi(2s)$ for K^* due to a lack of data) is parameterized by two unknown parameters that are extracted from data.

In the case of $B \to K\bar{\mu}\mu$, we perform a fit of C_9 bin by bin in q^2 by using the measured branching ratio by LHCb [2] and more recently by CMS [11], and the form factors computed in [7] for the theory prediction. In the low-q^2 region, since the experimental bins used by LHCb and by CMS are the same, we combine the two measurements, whereas in the high-q^2 region we carry out two independent fits, using LHCb and CMS data separately. In the case of $B \to K^*\bar{\mu}\mu$, we perform the fit from the branching ratio and the angular observables measured by LHCb [12], using the form factors computed in [13] for the theory predictions.

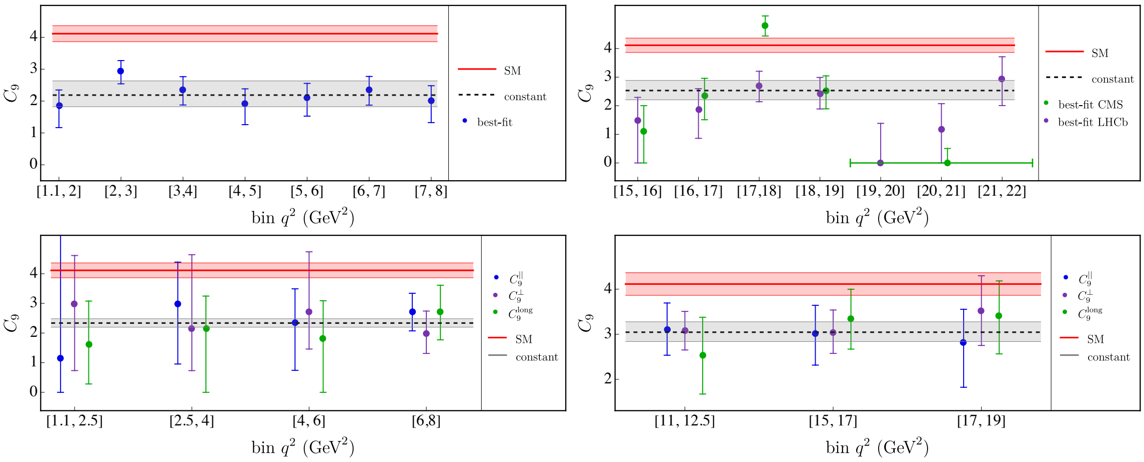

Figure 3: Determinations of C_9 in different q^2 bins from $B \to K\bar{\mu}\mu$ (top) and $B \to K^*\bar{\mu}\mu$ (bottom) data. The red and gray bands denote the SM value and the value extracted assuming a constant (q^2-independent) C_9, respectively.

The results of the fit are shown in Fig. 3. The best-fit results under the assumption of a q^2-independent C_9 are also shown (gray lines). We do not notice a significant q^2- or polarization-dependence, which would be present if we were missing the contribution of dominant long-distance QCD effects. In Fig. 4 we show the best-fit results with the assumptions of q^2-independent C_9, in the low- and high-q^2 regions and for the different modes and polarizations.

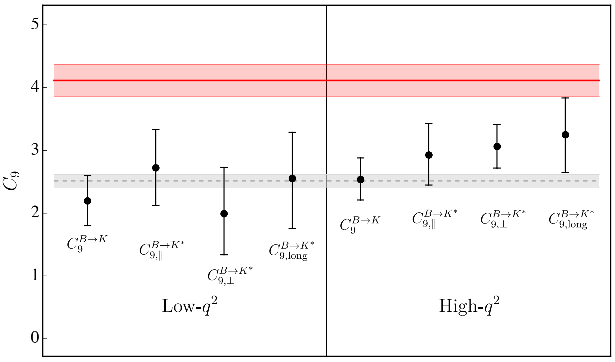

Figure 4: Independent determinations of C_9.

We also combine $B \to K$ and $B \to K^*$ in the full q^2 spectrum (gray dashed line). These eight independent determinations of C_9 are in good agreement with each other, providing another consistency check of the short-distance nature of the tension between the SM and $b \to s\bar{\ell}\ell$ data.

References

[1] R. Aaij *et al.* [LHCb], *Measurement of Form-Factor-Independent Observables in the Decay* $B^0 \to K^{*0}\mu^+\mu^-$ Phys. Rev. Lett. **111** (2013), 191801 doi:10.1103/PhysRevLett.111.191801 [arXiv:1308.1707 [hep-ex]].

R. Aaij *et al.* [LHCb], *Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity*, JHEP **02** (2016), 104 doi:10.1007/JHEP02(2016)104 [arXiv:1512.04442 [hep-ex]].

[2] R. Aaij *et al.* [LHCb], *“Differential branching fractions and isospin asymmetries of $B \to K^{(*)}\mu^+\mu^-$ decays,* JHEP **06** (2014), 133 doi:10.1007/JHEP06(2014)133 [arXiv:1403.8044 [hep-ex]].

[3] G. Isidori, Z. Polonsky and A. Tinari, *Semi-inclusive $b \to s\bar{\ell}\ell$ transitions at high q^2,* [arXiv:2305.03076 [hep-ph]].

[4] M. Bordone, G. Isidori, S. Mächler and A. Tinari, [To appear].

[5] Z. Ligeti and F. J. Tackmann, *Precise predictions for $B \to X_s l^+l^-$ in the large q^2 region,* Phys. Lett. B **653** (2007), 404-410 doi:10.1016/j.physletb.2007.07.070 [arXiv:0707.1694 [hep-ph]].

[6] L. Cao *et al.* [Belle], *Measurement of Differential Branching Fractions of Inclusive $B \to X_u \ell^+ \nu_\ell$ Decays,* Phys. Rev. Lett. **127** (2021) no.26, 261801 doi:10.1103/PhysRevLett.127.261801 [arXiv:2107.13855 [hep-ex]].

[7] W. G. Parrott *et al.* [HPQCD collaboration], *$B\to K$ and $D\to K$ form factors from fully relativistic lattice QCD,* Phys. Rev. D **107** (2023) no.1, 014510 doi:10.1103/PhysRevD.107.014510 [arXiv:2207.12468 [hep-lat]].

[8] R. R. Horgan, Z. Liu, S. Meinel and M. Wingate, *Rare B decays using lattice QCD form factors,* PoS **LATTICE2014** (2015), 372 doi:10.22323/1.214.0372 [arXiv:1501.00367 [hep-lat]].

[9] R. Aaij *et al.* [LHCb], *Test of lepton universality in $b \to s\ell^+\ell^-$ decays,* Phys. Rev. Lett. **131** (2023) no.5, 051803 doi:10.1103/PhysRevLett.131.051803 [arXiv:2212.09152 [hep-ex]].
R. Aaij *et al.* [LHCb], *Measurement of lepton universality parameters in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays,* Phys. Rev. D **108** (2023) no.3, 032002 doi:10.1103/PhysRevD.108.032002 [arXiv:2212.09153 [hep-ex]].
R. Aaij *et al.* [LHCb], *Tests of lepton universality using $B^0 \to K^0_S\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$ decays,* Phys. Rev. Lett. **128** (2022) no.19, 191802 doi:10.1103/PhysRevLett.128.191802 [arXiv:2110.09501 [hep-ex]].

[10] A. Tumasyan *et al.* [CMS], *Measurement of the $B^0_S\to\mu^+\mu^-$ decay properties and search for the $B^0\to\mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s}$ = 13 TeV,* Phys. Lett. B **842** (2023), 137955 doi:10.1016/j.physletb.2023.137955 [arXiv:2212.10311 [hep-ex]].

[11] CMS collaboration, *Test of lepton flavor universality in* $\mathrm{B}^\pm \to \mathrm{K}^\pm\ell^+\ell^-$ *decays* CMS-PAS-BPH-22-005, 2023,"https://cds.cern.ch/record/2868987"

[12] R. Aaij *et al.* [LHCb], *Measurements of the S-wave fraction in $B^0 \to K^+\pi^-\mu^+\mu^-$ decays and the $B^0 \to K^*(892)^0\mu^+\mu^-$ differential branching fraction,* JHEP **11** (2016), 047 [erratum: JHEP **04** (2017), 142] doi:10.1007/JHEP11(2016)047 [arXiv:1606.04731 [hep-ex]].

R. Aaij *et al.* [LHCb], *Measurement of CP-Averaged Observables in the $B^0 \to K^{*0}\mu^+\mu^-$ Decay,* Phys. Rev. Lett. **125** (2020) no.1, 011802 doi:10.1103/PhysRevLett.125.011802 [arXiv:2003.04831 [hep-ex]].

[13] A. Bharucha, D. M. Straub and R. Zwicky, *$B \to V\ell^+\ell^-$ in the Standard Model from light-cone sum rules,* JHEP **08** (2016), 098 doi:10.1007/JHEP08(2016)098 [arXiv:1503.05534 [hep-ph]].

[14] A. Khodjamirian, T. Mannel and Y. M. Wang, JHEP **02** (2013), 010 doi:10.1007/JHEP02(2013)010 [arXiv:1211.0234 [hep-ph]].