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Rare radiative-and-leptonic B_s-meson decay within and beyond the Standard Model

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The rare-and-radiative B_s-meson decay is a promising channel to test hypothetical New Physics effects in $b \to s$ quark transitions besides semileptonic rare $B_{(s)}$-meson transitions. In this proceedings, we review the state-of-the-art of theoretical computations of the branching ratio of the decay $B_s \to \mu^+\mu^-\gamma$ and the existing experimental bounds on this physical quantity. In particular, we will describe a peculiar parametrization of the hadronic form factors, namely a HQET-based procedure to infer the behaviour of these quantities in the B_s-sector starting from lattice QCD data available in the D_s-sector at high momentum transfer. We argue that such an approach will be particularly relevant in the near future to develop global fits of all the available lattice data on the hadronic form factors. Finally, we will review the results of the first sensitivity study of $B_s \to \mu^+\mu^-\gamma$ beyond the Standard Model.

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1. Introduction

The radiative-and-leptonic B_s-meson decay is an interesting example of a $b \to s$ quark transition. From the phenomenological point of view, there are several advantages which arise from the study of this transition, namely:

- the absence of a chirality suppression (due to the presence of the final-state photon), which, instead, affects the purely leptonic $B_s \to \mu^+\mu^-$ counterpart;
- the sensitivity to a larger set of Wilson Coefficients (WCs) entering in the $b \to s$ effective Hamiltonian, if compared with the $B_s \to \mu^+\mu^-$ case;
- the possibility to study this channel in two different experimental ways, namely through or without the reconstruction of the final-state photon.

In this proceeding, we will firstly review the state-of-the-art of the theoretical computations of the hadronic form factors (FFs) and the properties of a new phenomenological approach to the FFs themselves. After a brief overview of the available experimental bounds on the Branching Ratio (BR) of this transition, such a parametrization will be then used for a dedicated sensitivity study beyond the SM (BSM).

2. A new parametrization for the hadronic form factors

In order to compute a theoretical expectation value of the BR of $B_s \to \mu^+\mu^-\gamma$, it is necessary to have a proper control of the hadronic FFs, which enter in the definition of the hadronic matrix elements of quark 4-currents as

$$\langle \gamma(k,\epsilon)|\bar{s}\gamma_\mu\gamma^5 b|\bar{B}_s(p)\rangle = ie\left(\epsilon^*_\mu p\cdot k - k_\mu \epsilon^* \cdot p\right)\frac{F_A(q^2)}{m_{B_s}}\,, \quad (1)$$

$$\langle \gamma(k,\epsilon)|\bar{s}\gamma_\mu b|\bar{B}_s(p)\rangle = e\,\varepsilon_{\mu\epsilon^* pk}\,\frac{F_V(q^2)}{m_{B_s}}\,, \quad (2)$$

and analogously for tensor currents. Note that we will be mainly interested in the study of the high-q^2 region (where $q^2 \equiv (p-k)^2$ is the squared momentum transfer), in which $F_{V,A}(q^2)$ are the FFs mainly contributing to the BR. An explicit expression of the differential decay width in terms of such FFs can be found, for instance, in Refs. [1–3].

Precise computations of the hadronic FFs in Eq. (1) in the case of radiative D_s- and B_s-meson decays have been performed in different theoretical frameworks, including, for instance, quark models [1, 2, 4, 5], QCD factorization and soft-collinear effective theory [6], light-cone sum rules [7, 8], and dispersion relations [9]. Recently, novel non-perturbative computations on the lattice have been performed in Refs. [10, 11] for the D_s-meson case and in Ref. [12] for the B_s-meson one. Furthermore, interesting methodological inputs for further non-perturbative and highly precise simulations on the lattice have been proposed in Refs. [13, 14].

In this proceeding, we will review the main properties of a novel parametrization of the hadronic FFs, originally proposed in Ref. [15]. Hereafter, we will refer to it as the “GNSV approach" to the FFs. The main idea is to perform a Heavy Quark Effective Theory (HQET) scaling of some parameters describing the FFs themselves from the D_s-sector to the B_s-sector, starting from the available lattice QCD data in the D_s-sector at high momentum transfer.

To be more specific, each FF has to obey a dispersion relation of the form[1]

$$V^{D_s}_{\perp[\parallel]} = \frac{1}{\pi}\int_0^{\infty} \frac{\Im[V^{D_s}_{\perp[\parallel]}(t)]}{t-q^2} = \frac{r^{D_s^*[D_{s1}]}_{\perp[\parallel]}}{1-q^2/m^2_{D_s^*[D_{s1}]}} + \cdots$$

where the residues $r^{D_s^*[D_{s1}]}_{\perp[\parallel]}$ are related to the tri-couplings $g_{D_s^* D_s \gamma}$ and $g_{D_{s1} D_s \gamma}$ as

$$r^{D_s^*}_{\perp} = m_{D_s} f_{D_s^*} g_{D_s^* D_s \gamma}/m_{D_s^*}, \qquad r^{D_{s1}}_{\parallel} = m_{D_s} f_{D_{s1}} g_{D_{s1} D_s \gamma}/m_{D_{s1}}.$$

Thus, one can use available lattice QCD data in order to test different pole structures, e.g. single pole (P) or double pole (PP), and to infer the values of the residues from the data themselves at high q^2. Let us highlight that, when Ref. [15] came out, only the lattice QCD results published in Ref. [10] were available and were used as inputs. As stated in Ref. [15], while a P ansatz was found to be sufficient to properly describe the FF $V^{D_s}_{\parallel}$, a PP structure was, instead, necessary for the FF $V^{D_s}_{\perp}$.

Then, the tri-couplings can, in turn, be parameterized as the sum of the magnetic moments of the valence quarks, each term in the sum being weighted with the electric charge of the corresponding quark [16]. In this way, the behavior of the FFs $V^{B_s}_{\perp[\parallel]}$ can be properly inferred at high-q^2.

In order to derive an estimate of the BR, it is also necessary to include the effects of broad charmonia as properly normalized Breit-Wigner poles. Their effect is to produce a shift in the WC C_9 as [17]

$$C_9 \to C_9 - \frac{9\pi}{\alpha^2}\overline{C}\sum_V |\eta_V| e^{i\delta_V} \frac{\hat{m}_V \mathcal{B}(V\to\mu^+\mu^-)\hat{\Gamma}^V_{tot}}{\hat{q}^2 - \hat{m}_V^2 + i\hat{m}_V \hat{\Gamma}^V_{tot}}$$

where $\overline{C} = C_1 + C_2/3 + C_3 + C_4/3 + C_5 + C_6/3$ can be inferred from the analysis carried out in Ref. [6], the values of the physical parameters identifying the charmonia are collected in Appendix B of Ref. [15], the reference value for all of $|\eta_V|$ is taken unity and, finally, the central values from the BESIII measure in Ref. [18] were used for δ_V .

Once we put all these ingredients together in the expression of the decay width[2], our final result at high-q^2 reads $\mathcal{B}(B_s \to \mu^+\mu^-\gamma)[4.2\,\text{GeV}, m_{B_s}] = (1.63 \pm 0.80)\cdot 10^{-10}$. We highlight that *the GNSV procedure has to be applied at high-q^2*, since an expansion of the FFs in terms of P or PP expressions is completely reliable only in this region of momentum transfer. It is also worth highlighting that this parametrization of the hadronic FFs may be used in the future to develop interesting global analyses of all the available $D_s \to \gamma$ and/or $B_s \to \gamma$ data. In this respect, the results obtained in Ref. [12] constitute a fundamental benchmark to compare with.

3. State-of-the-art of experimental searches for $B_s \to \mu^+\mu^-\gamma$

From the experimental point of view, searches for the rare radiative-and-leptonic B_s-meson decay can be developed in two complementary ways, namely through the reconstruction of the

[1] Note that $V_\perp(q^2) = -F_V(q^2)$ and $V_\parallel(q^2) = -F_A(q^2)$.

[2] The CKM inputs have been taken from the latest "global Standard-Model analysis' and "New-Physics fit' perfomed by the UTfit Collaboration in Refs. [19–21]

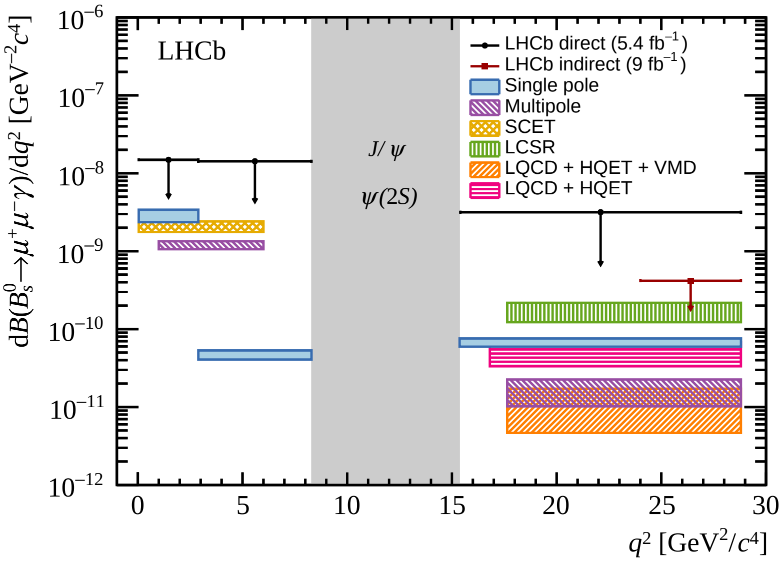

Figure 1: Differential branching fraction of the rare radiative-and-leptonic B_s-meson decay vs. the squared momentum transfer. The black arrows represent the limits (in the three aforementioned q^2-regions) coming from the direct measurement [22], while the red one is the result of the indirect measurement in Refs. [24, 25]. The colored areas are the various SM predictions available in literature and summarized in the previous Section. Taken from Ref. [22].

produced photon (*direct* measurement) [22] of without such a reconstruction (*indirect* measurement) [23]. We will synthetically describe these two procedures in what follows.

3.1 Direct measurement

The direct measurement of $B_s \to \mu^+\mu^-\gamma$ allows to investigate the low-, the intermediate- and the high-q^2 regions. However, the reconstruction of the photon unavoidably worsens the resolution, making this kind of analysis very challenging.

In Ref. [22], three different kinematic regions have been investigated, namely $4m_\mu^2 \leq q^2 \leq 2.89$ GeV^2, 2.89 GeV$^2 \leq q^2 \leq 8.29$ GeV^2 and, finally, 15.4 GeV$^2 \leq q^2 \leq m_{B_s}^2$. The measured BRs are not statistically significant in any of these three regions, thus allowing only to put some upper limits. The results of this measurement are summarized in Fig. 1, where the upper bounds on the BR resulting from the direct method are compared with the available theoretical predictions summarized in the previous Section. It is worth highlighting that the uncertainties on the measured BRs are presently dominated by statistics. Thus, an important improvement in this kind of measurements is expected from the future LHCb runs.

3.2 Indirect measurement

The upper limit on the BR coming from the indirect measurement [24, 25] is shown as well in Fig. 1. The underlying idea, originally proposed in Ref. [23], is to measure the $B_s \to \mu^+\mu^-\gamma$ signal from the non-radiative counterpart, namely from $B_s \to \mu^+\mu^-$. In fact, to the extent that the final state radiation contribution can be systematically subtracted off (as is the case for leptonic B_s searches), one can measure the initial state radiation component of the radiative-and-leptonic spectrum as a “contamination” of the non-radiative candidate events (as the signal window is enlarged downwards). This means that a perfect control of all the backgrounds is absolutely mandatory in this case. Nevertheless, the advantage of this proposal is that such procedure works at high-q^2 [23, 26], i.e. in the same region where lattice QCD data are available [12].

4. New Physics

The phenomenological relevance of $B_s \to \mu^+\mu^-\gamma$ is particularly evident in the context of BSM physics. At high-q^2, this decay is sensitive, in fact, to the same WCs (i.e. C_9 and C_{10}) entering in the semileptonic neutral-current transitions $B \to K^{(*)}\ell\ell$ and $B_s \to \phi\ell\ell$. While all the experimental indications of LFU violation in these semileptonic transitions have now completely disappeared [27], many $b \to s\mu\mu$ data (including the measurements of BRs and angular observables) still show some tensions with the SM in the *low* di-muon invariant mass squared region, see e.g. Refs. [28–34]. Note that the confirmation of the existence of these discrepancies is strongly influenced by the description of the hadronic FFs governing both the short- and the long-distance contributions, see e.g. the discussion in Ref. [35] and references therein.[3]

For what concerns BSM studies of $B_s \to \mu^+\mu^-\gamma$, the key idea is that, if BSM physics really affects rare semileptonic $B_{(s)}$-meson decays, such an effect should be also manifest in $B_s \to \mu^+\mu^-\gamma$. In particular, high-q^2 observables have to be sensitive to the very same short-distance physics present in rare semileptonic $B_{(s)}$-meson transitions, without being affected by the same long-distance effects. In Ref. [39] a first sensitivity study was performed in this sense. From the experimental point of view, the most important assumption is that all the backgrounds are considered well under control, i.e. that the uncertainty on the rare-and-radiative signal is basically dominated by the sheer amount of data collected. From the theoretical point of view, the uncertainties on the FFs computed in Ref. [15] have been shrinked at the $O(5\%)$ level, as motivated by the precision reached by computations of these FFs on the lattice as in Refs. [11, 12][4].

To summarize, the main message is as follows. Let us assume for simplicity that the NP contributions to C_9 and C_{10} are both real and universal in the light lepton flavours. Let us call them $\delta C_9^{u(e,\mu)}$ and $\delta C_{10}^{u(e,\mu)}$, respectively. Under these assumptions, if one uses the values of $\delta C_9^{u(e,\mu)}$ and $\delta C_{10}^{u(e,\mu)}$ inferred from a global fit of $b \to s\mu\mu$ data to compute the pull to the SM of the BR of $B_s \to \mu^+\mu^-\gamma$ (as a function of the acquired data), then one finds that the pull itself reaches the 2σ level at the border of the 1σ region for the WC C_9 shift. Such a finding is graphically illustrated in Figure 2.

5. Conclusions

To conclude, the rare-and-radiative $B_s \to \mu^+\mu^-\gamma$ decay is a promising channel to develop interesting phenomenological analyses both within and beyond the SM in the near future.

[3]The FFs governing long-distance contributions are affected by the presence of sub-threshold cuts, whose impact on unitarity and analiticity has been recently reconsidered in Refs. [36, 37], and of anomalous thresholds, as pointed out in [38]. It would be interesting to apply the proposal contained in Refs. [36, 37] in the context of a novel study of hadronic FFs entering in $B \to K^{(*)}\ell\ell$ and $B_s \to \phi\ell\ell$ decays.

[4]In our sensitivity study, it is also assumed that the uncertainties on broad charmonia play an entirely negligible role at high-q^2. Only a direct and fully non-perturbative computation of charming penguings will give us a reliable indication of these uncertainties. A first proposal to achieve this goal on the lattice has been recently presented in Ref. [40].

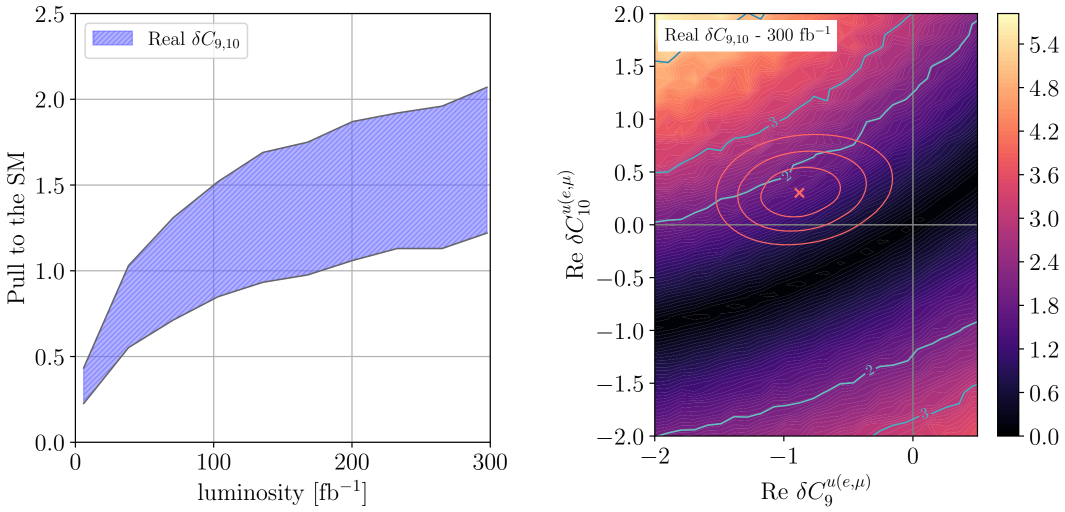

Figure 2: Pull to the SM (left) in the scenario with NP contributions to C_9 and C_{10}, which are assumed to be both real and universal in the light lepton flavours. Let us call them $\delta C_9^{u(e,\mu)}$ and $\delta C_{10}^{u(e,\mu)}$. The colored area is the 1σ region for the pull to the SM of the BR of $B_s \to \mu^+\mu^-\gamma$, as allowed by the values of the WC shift obtained in a global fit of $b \to s\mu\mu$ data. For completeness, we also show the pull to the SM for 300fb^{-1} of collected data as a function of the NP contributions $\delta C_9^{u(e,\mu)}$ and $\delta C_{10}^{u(e,\mu)}$ (right). Taken from Ref. [39].

- For what concerns studies within the SM, we have reviewed a novel HQET-based procedure to infer the behaviour of the FFs in the B_s-sector, starting from LQCD data available for the D_s-sector at high-q^2. This method has been originally proposed in Ref. [15] and its importance relies on the fact that it may be used in the future to develop global analyses of all the available lattice data.

- For what concerns, instead, studies beyond the SM, the analysis of the rare-and-radiative B_s-meson decay offers the opportunity to investigate hypothetical NP effects affecting $b \to s$ quark transitions in a way which is complementary to the usual investigation of rare semileptonic $B_{(s)}$-mesons transitions (see Ref. [41] and references therein for recent results on the semileptonic side). In fact, $B_s \to \mu^+\mu^-\gamma$ is independent of the long-distance effects present, e.g., in $B \to K^{(*)}\ell\ell$ decays, while being characterized by the same short-distance physics. Figure 2 shows a first result for the pull to the SM of the BR of $B_s \to \mu^+\mu^-\gamma$, which is based on assumptions on the experimental and theoretical uncertainties which can be importantly improved in the near future.

Let us finally highlight that, although a measurement of the BR of the $B_s \to \mu^+\mu^-\gamma$ decay is not available at present, the current experimental uncertainties are completely dominated by systematics [22]. Thus, it is very reasonable to expect one measurement of the BR of $B_s \to \mu^+\mu^-\gamma$ in the near future, by exploiting the aforementioned direct and/or indirect methods. In this sense, another interesting step forward would be the development of a dedicated program on searches for $B_s \to \mu^+\mu^-\gamma$ at the CMS experiment, in particular in connection to the High Luminosity LHC program [42].

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