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Long-distance QCD effects in FCNC $B \to \gamma l^+ l^-$ decays

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Abstract. This presentation reviews the main results of our recent work [1] on rare radiative leptonic decays $B_{d,s} \to \gamma\mu^+\mu^-$ and $B_{d,s} \to \gamma e^+ e^-$ induced by flavour-changing neutral currents (FCNC) in the Standard Model.

Rare FCNC decays of B-mesons are forbidden at the tree level in the Standard Model and occur only via loop diagrams. Respectively, their branching ratios are very small, of order $10^{-8} - 10^{-10}$ [2]. New particles can propagate in the loops and hence such processes are expected to be sensitive to the possible effects of New Physics. Several FCNC decays have been observed experimentally, exhibiting a few deviations from the Standard Model at the level of $2 - 3\ \sigma$ (see discussion in [3, 4]).

An appropriate framework for the theoretical description of FCNC B-decays is the effective field theory: virtual heavy particles of the SM with the masses much greater than m_b (i.e., W, Z, and t-quark) are integrated out yielding the $b \to q$ effective Hamiltonian [5–7]

$$H_{\rm eff}^{b\to q} = \frac{G_F}{\sqrt{2}} V_{tq}^* V_{tb} \sum_i C_i(\mu) O_i^{b\to q}(\mu). \tag{1}$$

The basis operators $O_i^{b\to q}(\mu)$ contain only dynamical light degrees of freedom (u, d, s, c, and b-quarks, leptons, photons and gluons). These light particles appear as dynamical degrees of freedom in the diagrams for the amplitudes of rare FCNC B-decays. The Wilson coefficients $C_i(\mu)$ absorb the contributions of the heavy particls (W, Z, and t in the SM) given by the box and the penguin digrams; taking account of hard gluon exchanges in the Feynman diagrams leads to the dependence of C_i on the scale μ.

Finally, the amplitude of the radiative leptonic B-decay is given by

$$A(B_q \to \gamma ll) = \langle \gamma ll | H_{\rm eff}^{b\to q} | B_q \rangle. \tag{2}$$

The presence of the B-meson in the initial state leads to the necessity of treating nonperturbative QCD effects; the amplitudes of FCNC rare leptonic B-decays involve a great variety of such nonperturbative QCD contributions.

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Top-quark contributions

The diagrams generated by the t-quarks (as well as other heavy particles of the SM) in the loops are presented in Fig. 1 and Fig. 2. The B-decay amplitudes corresponding to these diagrams are described in terms of $B \to \gamma$ transition form factors:

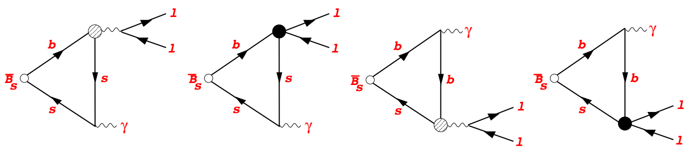

Figure 1. Real photon emission from the valence quark.

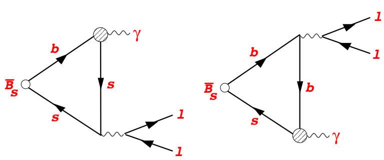

Figure 2. Real photon emission from the penguin FCNC vertex.

The diagrams of Fig. 1 yield contributions that have no singularities in the physical decay region. For these contributions, we made use of the dispersion approach based on the relativistic constituent quark picture [8–12]: within this approach, the form factors are given by relativistic spectral representations via the meson relativistic wave functions. The transition form factors from the dispersion approach satisfy all rigorous constraints known from QCD for these quantities [9, 13]. The model parameters (i.e., the constituent quark masses and the hadron wave functions) have been fixed by the requirement to reproduce the known values of meson weak decay constants [1]. The left diagram of Fig. 2 leads to the contributions to the form factors that do have singularities (resonances and cuts) in the physical decay region. To calculate these contributions, we combined the results from the dispersion approach at $q^2 < 0$ with the gauge-invariant version of vector meson dominance [14].

Finally, Fig. 3 displays the Bremsstrahlung contribution to the $B_{s,d} \to \gamma \ell^+ \ell^-$ amplitude; it is given in terms of the B-meson decay constant f_B and is proportional to the mass of the lepton in the final state [15].

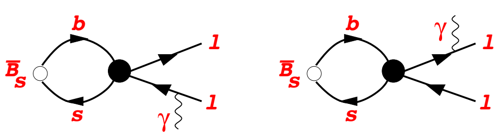

Figure 3. The Bremsstrahlung contribution.

Charm-quark contributions

Whereas heavy degrees of freedom (t, W, Z) are described by the effective Hamiltonian, light degrees of freedom, in particular c and u quarks, remain dynamical and their contributions in the loops should be taken into account. The diagrams for the charm-loop contributions are presented in Fig. 4: the numerically dominant penguin diagram (left) and the weak-annihilation diagram (right). When the W-boson line is shrinked to a point, and the soft-gluon exchanges between the charm-loop and the B-meson loop are taken into account, the charming penguin is reduced to two classes of diagrams shown in Fig. 5.

The structure of the charm-loop contributions to the $B_s \to \gamma l^+ l^-$ amplitude has the form:

$$H_{\mu\alpha}(k', k) = -\frac{G_F}{\sqrt{2}} V_{cb} V^*_{cs} e \Big[\epsilon_{\mu\alpha k' k} H_V - i \left(g_{\alpha\mu}\, kk' - k'_\alpha k_\mu \right) H_A \Big], \qquad (3)$$

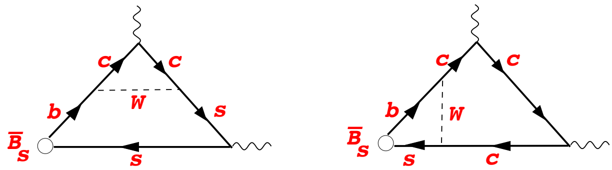

Figure 4. Diagrams with c-quarks in the loops: penguin diagram (left), weak annihilation diagram (right)

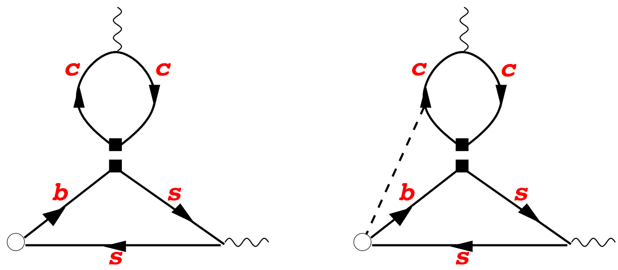

Figure 5. Factorizable (left) and nonfactorizable (right) charming loops. Dashed line in the right figure stands for the soft gluon.

with $0 < q^2 < M_B^2$, including the region of the charmonium resonances. Perturbative QCD cannot be applied here and non-perturbative approaches based on hadron degrees of freedom are necessary, see discussion in [16–23]. For $H_i(q^2, 0)$ one may write dispersion representation in q^2 with two subtractions [18]:

$$H_i(q^2, 0) = a_i + b_i q^2 + (q^2)^2 \left\{ \sum_{\psi=J/\psi,\psi'} \frac{f_\psi \mathcal{A}^i_{B\psi\gamma}}{m^3_\psi (m^2_\psi - q^2 - i m_\psi \Gamma_\psi)} + h_i(q^2) \right\}, \quad i = V, A, \quad (4)$$

where the functions $h_i(q^2)$ describe the hadron continuum including the broad charmonium states lying above the DD threshold. At $q^2 > 4M_D^2$, we take into account the known broad vector ψ_n $(n = 3, \ldots, 6)$ resonances. The subtraction constants a_i and b_i are determined by matching to the known results from light-cone sum rules at $q^2 \leq 4m_c^2$, including nonfactorizable corrections calculated in [18]. The absolute values of the amplitudes $\mathcal{A}^i_{B\psi\gamma}$ may be measured in $B \to \psi_i \gamma$ decays. It should be understood, however, that nonfactorizable gluons may generate complex relative phases between the contributions of different charmonia [19]. These possible non-universal (i.e., process-dependent and thus in general different in $B \to \gamma ll$ and $B \to Vll$) relative phases cannot be determined by pQCD-based calculations and provide one of the main sources of the theoretical uncertainties for rare radiative leptonic decays. Further details and subtleties see [1, 24].

Results

The differential branching ratios are shown in Fig. 6. The plots in Fig. 6 correspond to the description of the charm-loop effects according to Eq. (4), and further assuming that all charmonia contribute with the same positive sign (coinciding with the sign of the factorizable contribution).

In the region $q^2 \leq 6\ \text{GeV}^2$, the charming loops provide a small contribution at the level of a few percent, so the distributions in this region may be predicted with a good accuracy, mainly limited by the form-factor uncertainty. Our estimates [1] read

$$\mathcal{B}(\bar{B}_s \to \gamma l^+ l^-)|_{q^2 \in [1,6]\,\text{GeV}^2} = (6.01 \pm 0.08) 10^{-9}$$
$$\mathcal{B}(\bar{B}_d \to \gamma l^+ l^-)|_{q^2 \in [1,6]\,\text{GeV}^2} = (1.02 \pm 0.15) 10^{-11}. \quad (5)$$

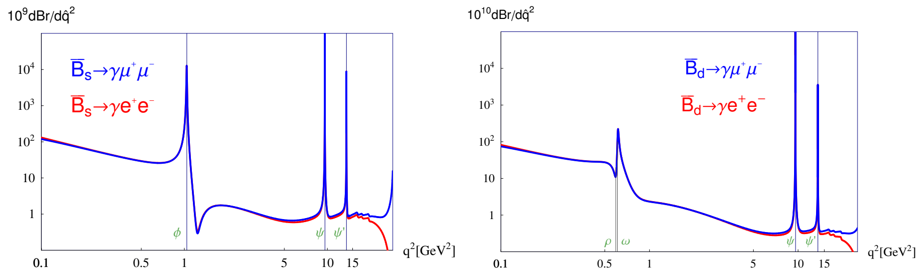

Figure 6. Differential branching fractions for $B_s \to \gamma l^+ l^-$ (left) and $B_d \to \gamma l^+ l^-$ (right) decays. Blue lines - $\mu^+\mu^-$ final state, red lines - e^+e^- final state.

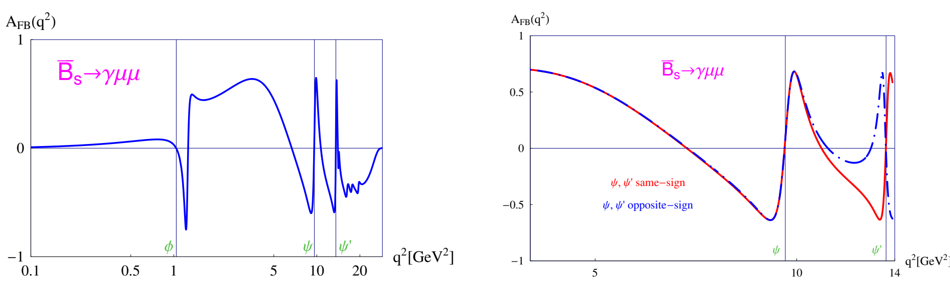

Figure 7. Forward-backward asymmetry for $B_s \to \gamma\mu\mu$ decays. The left plot shows the asymmetry for all q^2 for the contributions of all charmonia taken of the same positive sign, equal to that of the factorizable contribution; the right plot shows the sensitivity of $A_{\rm FB}$ to the relative signs of ψ and ψ': solid (red) line - both signs positive, dashed (blue) line - the ψ contribution taken positive, whereas the ψ' contribution negative.

For the $B_s \to \gamma l^+ l^-$ transition, the dominant contribution is given by the ϕ-meson. Its parameters are known well, leading to the small uncertainty in the $B_s \to \gamma l^+ l^-$ decay rate integrated over the range of $q^2 = [1, 6]$ GeV^2. For the $B_d \to \gamma l^+ l^-$ transition, the known contribution of the vector resonances is less important, and the branching ratio uncertainty reflects to a large extent the 10% uncertainty in the form factor contributions given by Fig. 1.

The A_{FB} for $\bar{B}_s \to \gamma\mu\mu$ is shown in Fig. 7. The right plot exhibits the sensitivity of A_{FB} in the region between ψ and ψ' to the relative signs of the contributions of these states.

Further results and details see our paper [1].

Acknowledgments

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