SM theoretical predictions for $B^0 \to \phi\ell^+\ell^-$ decay

Alexander Parkhomenko & Irina Parnova

parkh@uniyar.ac.ru, parnova.irina@yandex.ru

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Abstract

In the Standard Model (SM), the $b \to s$ and $b \to d$ flavor-changing neutral currents (FCNC), being loop-induced, are standard experimental channels for testing the SM precisely and searching for possible physics beyond the SM. Purely annihilation decays of B-mesons are of significant interest as in the SM they are extremely suppressed and New Physics effects can increase substantially their decay widths.

Radiative and semileptonic decays of bottom hadrons with the ϕ-meson production, being a subject of experimental searches at the LHC and SuperKEKB, are typical examples of annihilation-type processes. The upper limit on the radiative decay branching fraction, $\mathcal{B}(B^0 \to \phi\gamma) < 1.0 \times 10^{-7}$, obtained by the Belle collaboration in 2016, was the only one for quite some time [1]. This year, the LHCb collaboration obtained the upper limit on its semileptonic counterpart, $\mathcal{B}(B^0 \to \phi\mu^+\mu^-) < 3.2 \times 10^{-9}$ [2]. It would be desirable to consider the annihilation-type semileptonic $B^0 \to \phi\ell^+\ell^-$ decay, where ℓ is a charged lepton, and present SM theoretical predictions for the branching fraction within the Effective Electroweak Hamiltonian approach for the $b \to d\ell^+\ell^-$ transitions.

Introduction

An experimental observation of significant deviations from the SM predictions in rare decays of bottom hadrons may lead to a New Physics discovery. At present, the majority of experimental data on rare B-meson decays is in good agreement with the SM. For example, the LHCb, CMS and ATLAS collaborations at the LHC measured the branching fraction of the ultra-rare annihilation-type decay $\mathcal{B}_{\rm exp}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.4) \times 10^{-9}$ [3], which agrees within the uncertainties with the SM prediction $\mathcal{B}_{\rm th}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ [4]. There are also active experimental searches of the similar $B^0 \to \mu^+\mu^-$ decay with the recent PDG branching fraction $\mathcal{B}_{\rm exp}(B \to \mu^+\mu^-) = (0.7^{+1.3}_{-1.1}) \times 10^{-10}$ [3]. Rare semileptonic annihilation-type decays of $B^0_{(s)}$-mesons, assuming that the ω- and ϕ-mesons are pure states, $\omega = (\bar{u}u + \bar{d}d)/\sqrt{2}$ and $\phi = \bar{s}s$, include $B^0 \to \phi\ell^-\ell^+$, $B^0_s \to \rho^0\ell^-\ell^+$, $B^0_s \to \omega\ell^-\ell^+$, where $\ell = e,\ \mu,\ \tau$, as well as their radiative counterparts $B^0 \to \phi\gamma$, $B^0_s \to \rho^0\gamma$, $B^0_s \to \omega\gamma$. Due to the smallness of their decay widths, there are only experimental limits on the branching fraction of $B^0 \to \phi\gamma$ [1] and $B^0 \to \phi\mu^-\mu^+$ [2].

Theoretical analysis of radiative annihilation-type decays $B^0 \to \phi\gamma$ and $B_s \to \rho^0(\omega)\gamma$, including the $\omega - \phi$ mixing effect was undertaken in [5], where predictions for the B_s-meson indicate a significant contribution from this effect. For semileptonic annihilation-type $B^0 \to \phi\ell^+\ell^-$ decay we present Standard Model predictions, so far, without taking into account $\omega - \phi$ mixing. We estimate also the dependence on the choice of theoretical models for the B-meson distribution amplitudes entering decay width through their first inverse moments.

Theoretical analysis

Calculatons are done in the Effective Electroweak Hamiltonian approach. The effective Lagrangian density for $b \to d$ flavor-changing neutral current (FCNC) is derived from the SM by integrating out heavy particles — the top quark, W-, Z- and Higgs bosons:

$$\mathcal{L}_{\rm eff}(x) = \mathcal{L}_{\rm QED}(x) + \mathcal{L}_{\rm QCD}(x) - \mathcal{H}^{b\to d}_{\rm weak}(x),$$

$$\mathcal{L}_{\rm QED}(x) = e\sum_f Q_f\left[\bar{f}(x)\gamma^\mu f(x)\right]A_\mu(x), \quad \mathcal{L}_{\rm QCD}(x) = g_{\rm st}\sum_q\left[\bar{q}(x)\gamma^\mu T^a q(x)\right]G^a_\mu(x),$$

where e is the elementary charge, Q_f is the relative charge of the fermion $f(x) = \{\ell(x), q(x)\}$, $A_\mu(x)$ is the photon field, g_{st} is the strong coupling constant, T^a ($a = 1, \dots, 8$) are the generators of the color $SU(3)_C$ group, $G^a_\mu(x)$ is the gluon field. The FCNC term $\mathcal{H}^{b\to d}_{\rm weak}$ describes the $b \to d$ transition:

$$\mathcal{H}^{b\to d}_{\rm weak} = -\frac{4G_F}{\sqrt{2}}\sum_{p=u,c}\lambda^{(d)}_p\sum_j C_j(\mu)\mathcal{P}_j(\mu) + \text{h. c.},$$

where G_F is the Fermi constant, $C_j(\mu)$ are Wilson coefficients, $\mathcal{P}_j(\mu)$ are the $b \to d$ transition operators, $\lambda^{(d)}_p = V^*_{pd}V_{pb}$ is the product of the Kabibbo-Kobayashi-Maskawa matrix elements. The standard basis of the $\mathcal{P}_j(\mu)$ operators includes 10 operators [6]. The leading-order contribution to the $B^0 \to \phi\ell^+\ell^-$ decay amplitude is given by the penguin operators:

$$\mathcal{P}_3 = (\bar{d}\gamma_\mu Lb)\sum_q(\bar{q}\gamma^\mu q), \qquad \mathcal{P}_5 = (\bar{d}\gamma_\mu\gamma_\nu\gamma_\rho Lb)\sum_q(\bar{q}\gamma^\mu\gamma^\nu\gamma^\rho q),$$

where $L = 1 - \gamma_5$ is the fermionic left-handed projector. On the tree level, $B^0 \to \phi\ell^+\ell^-$ amplitude is represented by 8 diagrams. The largest contribution is from the diagram with the ϕ-meson emission from the light quark line, shown in Fig. 1. The diagram with the meson emission from the b-quark is $1/m_b$ suppressed. Contributions of other 6 diagrams are also suppressed by α_s and α_s/m_b.

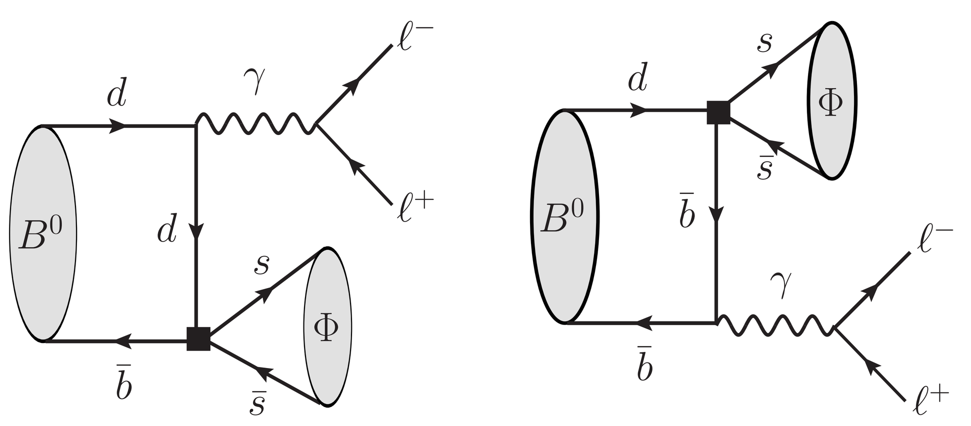

Figure 1: Diagrams given the largest contribution to the $B^0 \to \phi\ell^+\ell^-$ amplitude on the tree level

In this decay the current with the b- and d-quarks determines the initial B-meson, and the other, constructed from s-quarks, is related with the final ϕ-meson. As a result, the total amplitude of the process is factorized as the product of the ϕ-meson decay constant, f_ϕ, and the B-meson wave function defined on the light cone. This wave function is determined by two B-meson distribution amplitudes (DAs) $\varphi^B_+(t)$ and $\varphi^B_-(t)$ through the transition matrix element from the meson state to the vacuum [7]:

$$\langle 0|q_\alpha(z)\,E(0,z)\,h_{v,\beta}(0)|\bar{B}(v)\rangle = -\frac{if_Bm_B}{4}\left[(1+\hat{v})\left\{\tilde{\varphi}^B_+(t) - \left[\tilde{\varphi}^B_+(t) - \tilde{\varphi}^B_-(t)\right]\frac{\hat{z}}{2t}\right\}\gamma_5\right]_{\beta\alpha},$$

where m_B and f_B are the B-meson mass and decay constant, respectively, $t = (vz)$ is the B-meson proper time, $E(0, z)$ is the quark-antiquark Wilson line, $v^\mu = (1, 0, 0, 0)$ is B-meson four-velocity in its rest frame, z^μ is a light-like separation between quarks under assumption of a massless d-quark. The amplitudes of the process considered include the DA Fourier transforms [7, 8]:

$$\tilde{\varphi}^B_\pm(t) = \int_0^\infty d\omega\,\mathrm{e}^{-i\omega t}\phi^B_\pm(\omega),$$

where ω is the light-quark energy. Of two DAs, $\phi^B_+(\omega)$ is the leading amplitude and $\phi^B_-(\omega)$ is subleading one and related to $\phi^B_+(\omega)$ by the Wandzura-Wilczek relation [7]:

$$\phi^B_-(\omega) = \int_\omega^\infty\frac{\phi^B_+(\omega')}{\omega'}d\omega'.$$

If the leading DA is known, the subleading one can be found in this approximation.

$B^0 \to \phi\ell^+\ell^-$ Differential Branching Fraction:

$$\frac{d\mathcal{B}}{dq^2} = \tau_B\frac{G_F^2|V^*_{td}V_{tb}|^2\alpha^2}{216\pi}m_Bf_B^2f_\phi^2Q_d^2\lambda^3(1, m_\phi/m_B, \sqrt{q^2}/m_B)\,|C_3 + 4C_5|^2$$
$$\times\left[\left|\frac{1}{\lambda^B_-(q^2)}\right|^2 + \frac{m_\phi^2}{q^2\left(1 - q^2/M_B^2\right)^2}\left|\frac{1}{\lambda^B_+(q^2)}\right|^2\right],$$

where τ_B is the B-meson mean life, m_ϕ is the ϕ-meson mass, $Q_d = -1/3$ is the relative charge of the d-quark, $\lambda(a, b, c)$ is the kinematical function. The differential branching fraction also depends on the first inverse moments (FIMs) $[\lambda^B_\pm(q^2)]^{-1}$ of the B-meson DAs, $\phi^B_\pm(\omega)$, which are non-perturbative quantities:

$$\lambda^{-1}_{B,\pm}(q^2) = \int_0^\infty\frac{\phi^B_\pm(\omega)d\omega}{\omega - q^2/M_B - i\epsilon}.$$

where q^2 is the momentum squared of the lepton pair. Their momentum-dependence is determined by a choice of DA theoretical models. Here, we use two models of the DAs — Exponential model (GN) [7] and Linear model (KKQT) [9]. The q^2-dependence of the FIMs for each type of model is shown in Fig. 2.

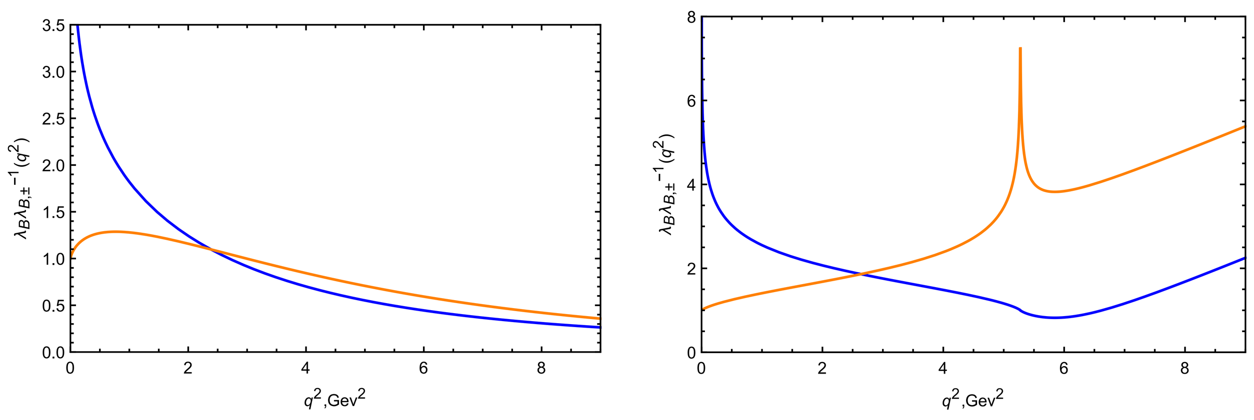

Figure 2: First inverse moments of DAs in Exponential (left) and Linear (right) models

Numerical results

Experimentally, partially integrated branching fractions are measured:

$$\Delta\mathcal{B}(q^2_{\rm min} < q^2 < q^2_{\rm max}) = \int_{q^2_{\rm min}}^{q^2_{\rm max}}\frac{d\mathcal{B}}{dq^2}dq^2.$$

Theoretical predictions for the partially integrated branching fraction in the region $q^2 \in [1\ \text{GeV}^2, 8\ \text{GeV}^2]$ are estimated where Long Distance (LD) contributions from light vector mesons can be neglected. For Exponential (GN) and Linear (KKQT) models, partially integrated branching fractions are:

$$\Delta\mathcal{B}^{\rm GN}(1\ \text{GeV}^2 < q^2 < 8\ \text{GeV}^2) = (2.14^{+1.57}_{-0.96}) \times 10^{-13},$$
$$\Delta\mathcal{B}^{\rm KKQT}(1\ \text{GeV}^2 < q^2 < 8\ \text{GeV}^2) = (3.88^{+2.85}_{-1.75}) \times 10^{-13}.$$

The results obtained demonstrate a strong dependence on the choice of the DA model. The difference in the model predictions is of the order of the factorization scale uncertainty. The estimation of the total branching fraction due to the perturbative contribution is as follows:

$$\mathcal{B}_{th}(B^0 \to \phi\ell^+\ell^-) \sim 10^{-12},$$

which is three orders of magnitude lower than the upper limit obtained by LHCb [2].

Conclusions

- The theoretical analysis of the $B^0 \to \phi\ell^-\ell^+$ decay in the leading order within the Effective Electroweak Hamiltonian approach is presented.
- The branching fraction is perturbatively calculated in the region of small q^2 and its dependence on the theoretical model of the B-meson DAs is demonstrated numerically.
- Theoretical prediction for the total branching fraction $\mathcal{B}_{\rm th}(B^0 \to \phi\ell^+\ell^-) \sim 10^{-12}$ agrees with the experimental restriction $\mathcal{B}_{\rm exp}(B^0 \to \phi\mu^+\mu^-) < 3.2 \times 10^{-9}$ by LHCb Collaboration [2].

Forthcoming Research

This analysis should be extended by taking into account all the tree-level amplitudes. A more precise prediction for the total branching fraction which covers the entire kinematically allowed region is under derivation. Since the $\omega - \phi$ mixing effects significantly on the $B^0 \to \phi\gamma$ branching fraction, it is necessary to take into account an impact of this effect on the decay considered.

References

[1] Z. King et al. (Belle Collaboration). Search for the decay $B^0 \to \phi\gamma$. PRD 93 (2016) 111101.
[2] R. Aaji et al. (LHCb Collaboration). Search for the decay $B^0 \to \phi\mu^+\mu^-$. JHEP 05 (2022) 067.
[3] P. A. Zyla et al. (Particle Data Group) Review of Particle Physics. PTEP 2020 (2020) 083C01.
[4] C. Bobeth et al. $B_{s,d} \to \ell^+\ell^-$ in the Standard Model with Reduced Theoretical Uncertainty. PRL 112 (2014) 101801.
[5] H. Deng, J. Gao et al. Study on pure annihilation type $B \to V\gamma$ decays. PRD 103 (2021) 076004.
[6] K. G. Chetyrkin, M. Misiak, M. Munz. Weak radiative B-meson decay beyond leading logarithms. PLB 400 (1997) 206.
[7] A. G. Grozin, M. Neubert. Asymptotics of heavy-meson form factors. PRD 55 (1997) 272.
[8] M. Beneke, T. Feldmann, D. Seidel. Systematic approach to exclusive $B \to V\ell^+\ell^-, V\gamma$ decays. NPB 612 (2001) 25.
[9] H. Kawamura, J. Kodaira et al. B-Meson Light-Cone Distribution Amplitudes in the Heavy-Quark Limit. PLB 523 (2001) 111.