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DESCRIPTION OF HADRONIC EFFECTS IN WEAK DECAYS OF BEAUTY MESONS USING COVARIANT QUARK MODEL*

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Description of rare B-meson decays in the Standard Model requires an appropriate description of hadronic effects. Covariant quark model with infrared confinement represents a suitable framework for doing it. In this text, we briefly describe the model and its application to the $B \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$ decays, including numerical results.

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1. Introduction

Many new-physics (NP) scenarios modify the Standard Model (SM) predictions for rare flavor-changing decays of B mesons. This expected sensitiveness to NP motivates theoretical and experimental research. New high-luminosity machines nowadays in operation allow for unprecedented measurements of rare decays: not only are they observed but, for some processes, also angular distributions are being extracted with increasing precision.

The experimental progress is followed by theoretical investigations where possible effects of NP are searched for. As for today, the SM is confirmed, however with some tensions (reaching up to $\sim 3\sigma$ for certain observables). These so-called anomalies provide additional motivation for a careful cross-check of the SM computations.

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The covariant quark model (CQM) is a Lagrangian-based approach with full Lorentz invariance which provides an alternative way of including the hadronic effects into an SM computation. It has limited number of free parameters and can be easily extended to higher multi-quark states (baryons, tetraquarks).

2. Covariant quark model

In the CQM, a quark–hadron interaction is introduced

$$\mathcal{L}_{\rm int} = g_H\, H(x)\, J_H(x) \tag{1}$$

with the quark current (mesons[1])

$$J_M(x) = \int \mathrm{d}x_1 \int \mathrm{d}x_2\, F_M(x, x_1, x_2)\, \bar{q}^a_{f_1}(x_1)\, \Gamma_M\, q^a_{f_2}(x_2)\,, \tag{2}$$

where the invariant vertex function takes the form

$$F_H(x, x_1, \ldots, x_n) = \delta\left(x - \sum_{i=1}^{n} w_i x_i\right) \Phi_H\left[\sum_{i<j} (x_i - x_j)^2\right]. \tag{3}$$

The weights

$$w_i = m_i / \sum_{j=1}^{n} m_j \tag{4}$$

match quark-system barycenter with the hadron position and the Gaussian form of the second term

$$\bar{\Phi}_H\left(-k^2\right) = \exp\left(k^2/\Lambda_H^2\right) \tag{5}$$

is chosen for computational convenience. It contains one free parameter Λ_H which can be related to the size of the hadron H. In addition, the model contains as parameters four constituent quark masses and one universal cutoff parameter which will be addressed later. The values of parameters relevant for our case are (all in GeV):

$$\begin{aligned} m_{u,d} &= 0.235\,, \quad m_s = 0.424\,, \quad m_c = 2.16\,, \quad m_b = 5.09\,, \quad \lambda_{\rm cutoff} = 0.181\,, \\ \Lambda_B &= 1.95\,, \quad \Lambda_{B_s} = 2.05\,, \quad \Lambda_{K*} = 0.75\,, \quad \Lambda_\phi = 0.88\,. \end{aligned} \tag{6}$$

Two important ingredients are built into the model: compositeness condition and infrared confinement. The first one reflects hadrons as being

[1] Expressions for baryons and tetraquarks can be found in *e.g.* [1].

compounds of quarks and, within the model, it can be expressed in terms of the meson mass operator derivative (the ˜ character refers to the Fourier transform into the momentum space)

$$Z_M = 1 - \frac{3g_M^2}{4\pi^2} \tilde{\Pi}'_M(m_M^2) = 0\,, \tag{7}$$

where Z_M is the renormalization constant which can be interpreted as the matrix element between the physical state and the corresponding bare state. Being set to zero implies that the physical state does not contain bare state and is, therefore, properly described as a bound state. In this way, the coupling constants g_M are determined from model parameters.

The infrared confinement is introduced via an integration cutoff in the space of Schwinger parameters which come from in the Schwinger representation of quark propagators. Appropriate techniques allow to transform the multidimensional improper integral into a convolution of an integration over a finite volume (simplex) and a single improper integral, to which the cutoff is applied

$$\Pi = \int\limits_0^{\infty \to 1/\lambda^2} \mathrm{d}t\, t^{n-1} \int\limits_0^1 \mathrm{d}^n\alpha\, \delta\left(1 - \sum_{i=1}^n \alpha_i\right) F(t\alpha_1, \ldots, t\alpha_n)\,, \tag{8}$$

where F stands for the whole structure of the corresponding Feynman diagram. In this way, Π becomes a smooth function with thresholds in the quark loop diagrams and corresponding branch points removed. The cutoff value λ is considered to be universal.

The model allows us to predict the behavior of meson form factors (FF) and, in the next step, the value of observables.

3. Form factors, observables, results

The two studied processes $B \to K^* + 2\mu$ and $B_s \to \phi + 2\mu$ differ in the flavor of the spectator quark, but are otherwise very similar, particles have the same quantum numbers. They are described by seven FFs

$$\begin{aligned} &\left\langle V_{[\bar{q}_3,q_2]}\,(p_2,\epsilon_2)\right|\bar{q}_2 O^\mu q_1 \left|P_{[\bar{q}_3,q_1]}\,(p_1)\right\rangle \\ &= \frac{\epsilon_\nu^\dagger}{m_1+m_2}\Big[-g^{\mu\nu} P\,q\boldsymbol{A_0}\left(q^2\right) + P^\mu P^\nu \boldsymbol{A}_+\left(q^2\right) \\ &+q^\mu P^\nu \boldsymbol{A}_-\left(q^2\right) + i\varepsilon^{\mu\nu\alpha\beta} P_\alpha q_\beta \boldsymbol{V}\left(q^2\right)\Big]\,, \end{aligned} \tag{9}$$

$$
\begin{aligned}
&\left\langle V_{[\bar{q}_3,q_2]}\left(p_2,\epsilon_2\right)\left|\bar{q}_2\left[\sigma^{\mu\nu}q_\nu\left(1+\gamma^5\right)\right]q_1\right|P_{[\bar{q}_3,q_1]}\left(p_1\right)\right\rangle \\
&=\epsilon^\dagger_\nu\Bigg[-\left(g^{\mu\nu}-\frac{q_\mu q_\nu}{q^2}\right)P\,q\,\boldsymbol{a_0}\left(q^2\right)+\left(P^\mu P^\nu-q^\mu P^\nu\frac{p\cdot q}{q^2}\right)\boldsymbol{a}_+\left(q^2\right) \\
&+i\varepsilon^{\mu\nu\alpha\beta}P_\alpha q_\beta\,\boldsymbol{g}\left(q^2\right)\Bigg]. \qquad (10)
\end{aligned}
$$

To fully profit from the measured experimental data, we take into account (in the narrow-width approximation) the cascade decay of the final-state mesons: $K^*\to K\pi$ and $\phi\to KK$.

The choice of observables is driven by the desired sensitivity to NP and small sensitivity to hadronic FFs. Besides usual observables A_{FB} (forward–backward asymmetry of the leptonic system) and F_{L} (longitudinal polarization of the final-state meson) also FF-independent observables P_i [2] are studied.

The computation were performed within the helicity framework where, by introducing the so-called helicity basis, one can evaluate leptonic and hadronic tensor in separate frames. All observables are expressed in terms of helicity amplitudes which are related to the model-dependent form factors. The explicit formulas for these relations can be found in [3]. The full four-differential cross section depends on the transferred momentum squared, on one leptonic and one hadronic angle (direction of the outgoing leptons and hadrons), and one angle between hadronic system and leptonic system planes.

The $b\to s$ flavor transition is treated using four-fermion effective theory where the Wilson coefficients are taken from literature.

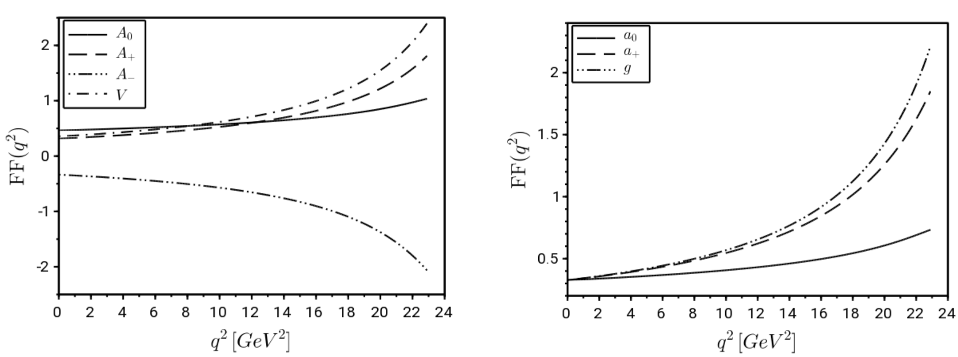

Fig. 1. $B\to K^*$ form factors.

We present the results for both the muons and tau leptons in the final state. A detailed differential information for various bins can be found in Refs. [3] and [4]. The results are presented in form of figures and tables. For the $B \to K^*(\to K\pi) + \ell\ell$ decay, they are summarized in Figs. 1 and 2 and Tables I and II. For $B_s \to \phi(\to KK) + \ell\ell$ decay, the results are presented in Figs. 3 and 4 and Table III. No significant deviation from the SM is observed.

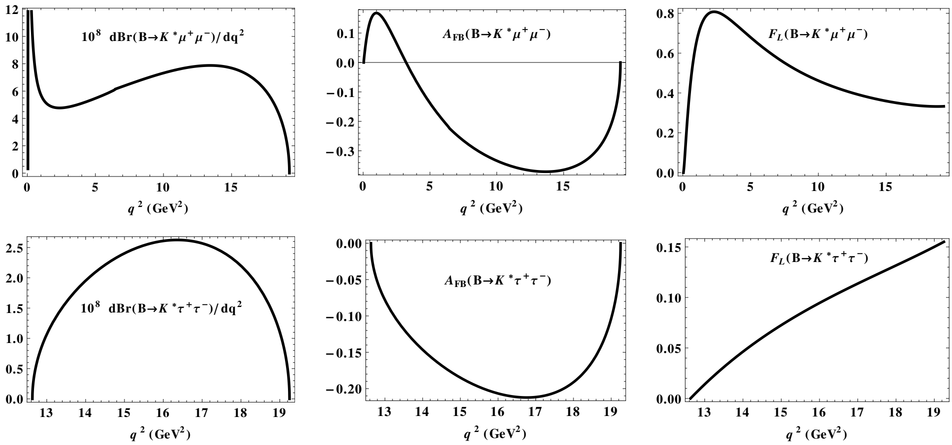

Fig. 2. Differential branching fraction, A_{FB} and F_{L} observables.

TABLE I

The q^2-integrated predictions and measurements (1–6 GeV^2) for $B \to K^*(\to K\pi)+2\mu$ decay.

	Belle [5]	LHCb [6]	CDF [7]	CQM
$\mathcal{B} \times 10^7$	1.49 ± 0.44	0.42 ± 0.07	—	2.58
A_{FB}	0.26 ± 0.29	-0.06 ± 0.14	0.29 ± 0.23	-0.02
F_{L}	0.67 ± 0.24	0.55 ± 0.10	0.69 ± 0.22	0.75

TABLE II

q^2-averaged polarization observables over the whole kinematic region.

	$B \to K^*\ell^+\ell^-$						
	$\langle A_{\mathrm{FB}}\rangle$	$\langle F_{\mathrm{L}}\rangle$	$\langle P_1\rangle$	$\langle P_2\rangle$	$\langle P_3\rangle$	$\langle P_4'\rangle$	$\langle P_5'\rangle$
μ	-0.23	0.47	-0.48	-0.31	0.0015	1.01	-0.49
τ	-0.18	0.092	-0.74	-0.68	0.00076	1.32	-1.07

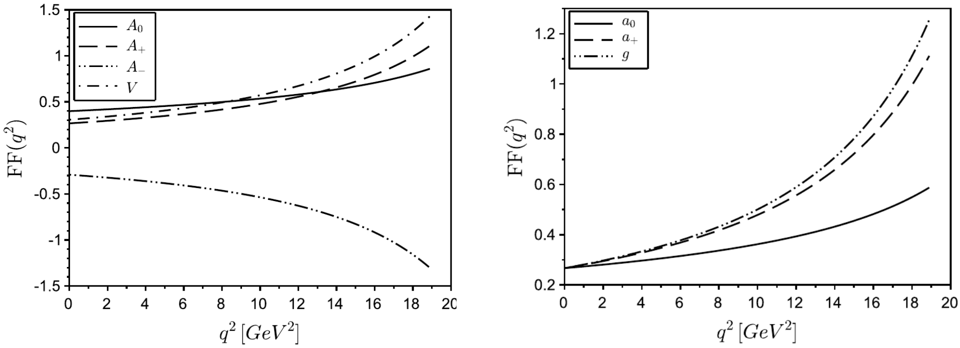

Fig. 3. $B_s \to \phi$ form factors.

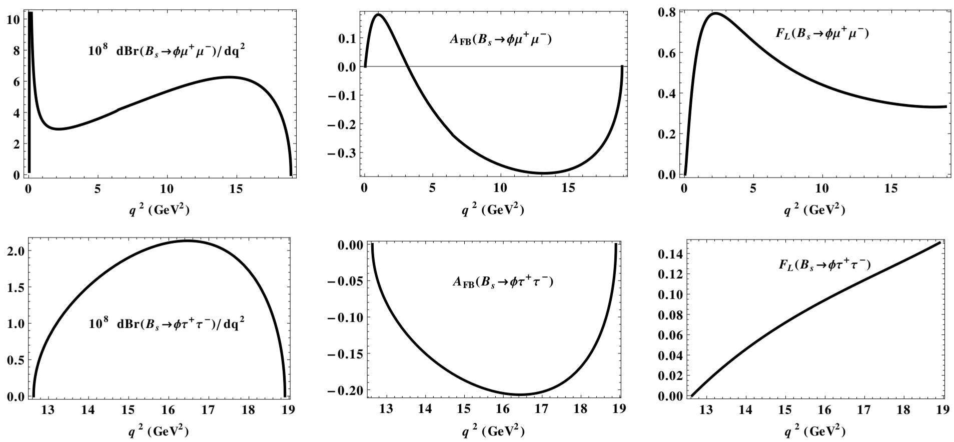

Fig. 4. Differential branching fraction, A_{FB} and F_{L} observables.

TABLE III

Total branching fractions.

	This work	Ref. [8]
$10^7\mathcal{B}(B_s \to \phi\mu^+\mu^-)$	9.11 ± 1.82	7.97 ± 0.77
$10^7\mathcal{B}(B_s \to \phi\tau^+\tau^-)$	1.03 ± 0.20	

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