b-s Anomaly Decays in Covariant Quark Model

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Abstract—The work is devoted to the study of b-s anomaly decays. We evaluated branching fractions of $B \to K^+\mu^+\mu^-$, $B^0 \to \phi\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ decays and compared them with available experimental data and with results from other theoretical approaches.

Keywords: b-s anomaly, covariant quark model, branching fractions, deviations

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1. INTRODUCTION

Worth noting that Standard model has been extremely successful in explaining the results of experiments for particle physics. The outstanding success of SM in the description of almost all experimental data in particle physics is manifested in the electroweak pool for different observables. Nevertheless, in recent years observed discrepancies in $B$-meson rare decays with the predictions of SM. Flavour-changing neutral currents have been prominent tools in high-energy physics in the search for new degrees of freedom, due to their quantum sensitivity to energies much higher than the external particles involved and can be instrumental in order to determine where to look for new physics. During the last decade a lot of observables, including the branching ratios, CP and the angular asymmetry in inclusive and exclusive decay modes of $B$-meson were measured by B-factories and at LHC experiments. These data allow to explore the spiral structure in the interactions with the flavour-changing and a possible existence of new sources of CP violation.

In 2013 it has been paid much attention to the rare flavor-changing neutral current decay $B \to K^*\mu^+\mu^-$. One of the reason was the first measurement of form-factor independent angular observables performed by LHCb Collaboration [1, 2]. It has been claimed that there is a 3.7$\sigma$ deviation from the Standard Model for so-called $p^*$ angular observable.

The $B_s^0 \to \phi\ell^+\ell^-$ decay is similar to the $B \to K^*\ell^+\ell^-$ decay. The $B_s$ meson production is suppressed compared to the $B^0$ meson by the relation $f_s/f_d \approx 1/4$, but the narrow resonance $\phi$ provides a clean set of data with low background. The main difference between $B_s^0 \to \phi\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$ decays is that the final state do not contain information about the initial state of the meson, whether it was $B_s$ or $B$. $B_s^0 \to \phi\ell^+\ell^-$ decay channel was first discovered and studied by CDF Collaboration in 2011 [3, 4], later been studied by LHCb Collaboration [5, 6]. Despite the fact that the angular distributions are in good agreement with the SM expectations, branching ratio of decay had a 3.1$\sigma$ disagreement with the prediction of the SM [5, 7].

Our goal was to check all this deviations of theoretical predictions taken into account the last experimental data.

2. THE $B \to K^*\pi\ell^+\ell^-$ DECAY

The study of the rare $B \to K^*\ell^+\ell^-$ decay in the framework of the covariant quark model with infrared confinement was made in [8]. The obtained results compared with available experimental data and the results from other theoretical approaches. We give in Table 1 the numerical value for the total branching ratio $\mathcal{B}(B \to K^*\mu^+\mu^-)$ and compare them with available experimental data and with other approaches.

Also we explored the influence of the intermediate scalar $K_0^*$ meson on the angular decay distribution of the cascade decay $B \to K\pi + \mu^+\mu^-$ in [15]. In the wake of exploring uncertainty in the full angular distribution of the $B \to K\pi + \mu^+\mu^-$ decay caused by the
presence of the intermediate scalar $K^*_0$ meson. We give in Table 1 the numerical values for the total branching ratios of $B \to K^* \mu^+ \mu^-$ and $B_d^0 \to K^*_0(800)\nu \bar{\nu}$ decays and compare with another theoretical prediction.

Let us briefly discuss the impact of scalar resonance on decay. As well known, the narrow vector resonance is described by a Breit-Wigner parametrization and the given cascade $B$-decay can be calculated by using the narrow width approximation. But it is not true in the case of the broad scalar $K^*_0(800)$ meson. We will use for the time being the parametrization accepted in Ref. [17] which integrated value in the $K^*$-resonance region is equal to

$$\int \frac{dm_{K^*}}{(m_{K^*-\delta_m})^2} = 0.17,$$

(1)

Then we scale the calculated value for the differential decay rate $d\Gamma(B \to K^*_0(800)\mu^+\mu^-)$ by this factor and compare with those for $B \to K(892)\mu^+\mu^-$ decay. The integrated ratio

$$R(q^2) = \frac{2/3 d\Gamma(B \to K^*(892)\mu^+\mu^-)}{2/3 d\Gamma(B \to K^*(892)\mu^+\mu^-) + 0.17 d\Gamma(B \to K_0^*(800)\mu^+\mu^-)},$$

(2)

(numerator and denominator are integrated separately in the full kinematical region of $q^2$) gives the size of the $S$-wave pollution to the branching ratio of the $B \to K^* \ell^+ \ell^-$ decay only about 6%.

3. THE $B_d^0 \to \phi(\to K^+K^-)\ell^+\ell^-$ DECAY

In paper [18] we calculated all form factors which appear in the $B_d \to \phi$ transition. The expressions for the Wilson coefficients $C_3$ and $C_9$ are taken on the two-loop level of accuracy by using the results obtained in Refs. [19, 20]. Then we evaluated the branching fraction, the forward-backward asymmetry and the so-called optimized observables using form factors in the cascade decay $B \to \phi(\to K^+K^-)\mu^+\mu^-$. We compared our results with the recent experimental data reported in Ref. [21] for various $q^2$-bins.

The level of agreement with experiment can be estimated by combining in quadrature the experimental errors with the theoretical ones: if the difference in observable values is smaller, then it can be seen as compatible with zero.

Using this optics one can address the $3.3\sigma$ deviation seen by [21] for branching fraction in the $1–6$ GeV range. In the covariant confined quark model this discrepancy is much reduced. The remaining deviation $(1.4\sigma)$ shrinks is even further if the two-loop corrections for the Wilson coefficients are taken into account.

| Mode                          | CQM       | Others                   | Expt. [9–11]         |
|-------------------------------|-----------|--------------------------|----------------------|
| $B \to K^* \mu^+ \mu^-$       | $12.7 \times 10^{-3}$ | $(11.9 \pm 3.9) \times 10^{-3}$ | $(9.24 \pm 0.93)\text{stat} \pm 0.67\text{sys}) \times 10^{-7}$ |
|                               |           | $11.5 \times 10^{-3}$    |                      |
|                               |           | $14 \times 10^{-3}$      |                      |

| Decay modes                  | Branching fractions |
|-------------------------------|---------------------|
|                               | CQM                 | [16]                |
| $B_d^0 \to K^*_0(800)\mu^+\mu^-$ | $3.47 \times 10^{-7}$ | $(7.31 \pm 1.21) \times 10^{-7}$ |
| $B_d^0 \to K^*_0(800)\tau^+\tau^-$ | $0.61 \times 10^{-7}$ | $(1.33 \pm 0.36) \times 10^{-7}$ |
| $B_d^0 \to K_0^*(800)\nu \bar{\nu}$ | $2.53 \times 10^{-6}$ | $(6.30 \pm 0.97) \times 10^{-6}$ |
account, down to 1.1σ. With such error reduction one cannot claim a discrepancy with the SM any longer.

Overall one observes a good description of the data by the covariant quark model and the agreement becomes even better if the two-loop corrections are taken into account. The biggest discrepancy of observed for $B_s^-$ in the lowest bin $0.1 \leq q^2 \leq 2$ GeV is reduced to 1.7σ when these corrections are taken into account.

4. THE $B_s^0 \to \ell^+\ell^-$ DECAY

As it was shown in [23] the rare decays are fully dominated by internal top quark contributions. We used next definition for the branching ratio of $B_s^0 \to \ell^+\ell^-$ to check the sensitivity to the top quark mass [23]:

$$B(B_s \to \ell^+\ell^-) = \frac{\mathcal{B}(B_s) G_F^2}{\pi} \left( \frac{\alpha}{4\pi \sin^2 \theta_W} \right)^2$$

$$\times F_{B_s}^2 m_{B_s}^2 m_{\ell} \left( 1 - \frac{m_{\ell}^2}{m_{B_s}^2} \right) \sum_{i=1}^2 Y^2(\alpha_i),$$

where $B_s$ denotes the flavor eigenstate ($\bar{b}_s$) and $F_{B_s}$ is the corresponding decay constant. The function $Y(x_i)$ is given by

$$Y(x_i) = \eta_f Y_0(x_i), \quad \text{Eq. (4)}$$

where

$$Y_0(x_i) = \frac{4-x + \frac{3x}{1-x} \ln x}{8 (1-x)^2 \ln x},$$

$$x = m^2/M^2_{W}, \quad \eta_f = 1.028.$$

There are predictions within the covariant quark model for the branching ratio of $B_s^0 \to \ell^+\ell^-$ decay with top quark contribution given in Table 4.

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