ANGULAR OBSERVABLES IN THE $B^0 \to K^{*0}\mu^+\mu^-$ DECAY AT LHCb*

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This contribution summarizes the most recent results of measurements of the angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ decays using data samples from the LHCb experiment. Measurement of P_5' observable shows 2.5 and 2.9σ deviation from the Standard Model prediction in two q^2 bins. Also for the value of $\mathcal{R}e(C_9)$ parameter 3.3σ deviation was observed.

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1. Introduction

Modern particle physics achieved extraordinary results in explaining how the Universe works at the level of subatomic particles. Standard Model (SM) has been built throughout many years, and in its present form classifies all known elementary particles and describes interactions between them, except for the gravitational force. Despite its great success, the SM has few issues that have to be explained, such as matter–antimatter asymmetry or hierarchy problem. It does not incorporate dark matter particles, dark energy and describes neutrinos as massless particles. To understand these phenomena and to make progress in particle physics, it is necessary to search for the so-called physics Beyond the Standard Model (BSM). One way of doing it is the investigation of flavour-changing neutral current (FCNC) processes such as $B^0 \to K^{*0}\mu^+\mu^-$ decay. These transitions, where the quark changes its flavour without changing its electric charge, are highly suppressed in the SM by the so-called GIM mechanism and can proceed only through electroweak penguin or box diagrams. It is possible that some new, heavy

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particle can enter the loop which can be observed indirectly, even if new physics particle is too heavy for direct searches. Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay and observed anomalies with respect to the SM may reveal yet unknown contributions, for instance, an additional vector or axial–vector which are introduced by new physics models [1]. It is also debated that those anomalies may arise due to the hadronic uncertainties, associated with the transition form factors or some other long-distance effects [2].

Results presented in this paper are based on 4.7 fb^{-1} data set of pp collisions collected by the LHCb experiment in Run 1 and 2016 [3]. The corresponding center-of-mass energies were 7, 8 TeV (Run 1) and 13 TeV (2016).

2. The LHCb detector

The LHCb detector [4] is a single-arm forward spectrometer designed to study heavy flavour physics. It contains ring-imaging Cherenkov detectors (RICH1, RICH2), hadronic and electromagnetic calorimeters (HCAL, ECAL), muon identification system (M1–M5), and tracking detectors of high precision (vertex locator — VELO, TT and T1–T3) (see Fig. 1). The fact that it covers a pseudorapidity range of $2 < \eta < 5$, where the most final-state particles from B-meson decay can be found, makes it an exceptional detector to study rare processes.

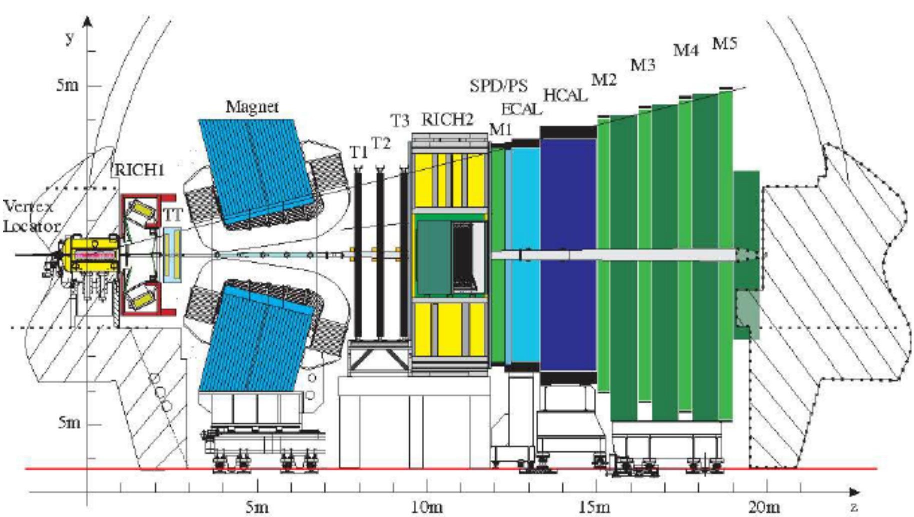

Fig. 1. The LHCb detector [4].

3. Angular distribution

The $B^0 \to K^{*0}\mu^+\mu^-$ final state is described by the invariant mass squared of a dimuon system q^2, the three decay angles: $\cos(\theta_K)$, $\cos(\theta_\ell)$ and ϕ, and by the invariant mass of the $K^+\pi^-$ system. In the present paper, K^{*0} refers to the $K^*(982)^0$ resonance which is reconstructed through the $K^{*0} \to K^+\pi^-$ decay. The θ_K angle is the angle between the direction of K^+ (K^-) and the direction of B^0 ($\bar{B}^0$) in K^{*0} rest frame. The angle θ_ℓ is the angle between the direction of μ^+ (μ^-) and the direction opposite to that of the B^0 ($\bar{B}^0$) in the rest frame of the dimuon system. The angle ϕ is the angle between planes constructed from $K^+\pi^-$ system and dimuon pair in the B^0 ($\bar{B}^0$) rest frame. Details of the angular basis can be found in Ref. [5]. The differential decay rates of the B^0 and $\bar{B}^0$ decays are given by [6]

$$\begin{aligned} \frac{\mathrm{d}^4\Gamma\left(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-\right)}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} &= \frac{9}{32\pi}\sum_i I_i\left(q^2\right) f_i\left(\vec{\Omega}\right) , \\ \frac{\mathrm{d}^4\bar{\Gamma}\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} &= \frac{9}{32\pi}\sum_i \bar{I}_i\left(q^2\right) f_i\left(\vec{\Omega}\right) , \end{aligned} \tag{1}$$

where I_i and $\bar{I}_i$ are the angular observables and $f_i(\vec{\Omega})$ are combinations of spherical harmonics.

By introducing CP-averaged observables as

$$S_i = \left(I_i + \bar{I}_i\right) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right) , \tag{2}$$

the angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$ decay can be rewritten as

$$\begin{aligned} &\frac{1}{\mathrm{d}\left(\Gamma+\bar{\Gamma}\right)\mathrm{d}q}\frac{\mathrm{d}^4\left(\Gamma+\bar{\Gamma}\right)}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}}\bigg|_P = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K\right. \\ &+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ &+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell \\ &\left.+S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\right] , \end{aligned} \tag{3}$$

where A_FB is a forward–backward asymmetry and F_L is a fraction of longitudinal polarization of K^{*0}.

The angular distribution in Eq. (3) refers to the decay where $K^+\pi^-$ system is in a P-wave configuration. In order to add a contribution for an S-wave decay, one has to modify the angular distribution to the form where a fraction of S-wave, F_S, appears. Additional coefficients which arise from interference between S- and P-wave amplitudes also appear.

In order to eliminate the leading $B^0 \to K^{*0}$ form-factor uncertainties, an additional set of observables was proposed — $P_{1,2,3}$ and $P'_{4,5,6,8}$ [7] . These theoretically clean observables are constructed from ratios of CP-averaged angular observables like the famous $P'_5 = S_5/\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}$.

4. Effective field theory

Results of angular measurements can be expressed in terms of the effective field theory. In the SM, transitions of b quarks to s quarks are governed by the effective Hamiltonian

$$\mathcal{H}_{\mathrm{eff}} = -\frac{4G_{\mathrm{F}}}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i^{10} \mathcal{C}_i \mathcal{O}_i \,, \tag{4}$$

where G_{F} is a Fermi constant, V_{ij} are elements of a CKM matrix and $\mathcal{C}_i$ are the Wilson coefficients of the corresponding four-Fermi operators $\mathcal{O}_i$. In this description, we can distinguish short-distance physics which is encoded in Wilson coefficients $\mathcal{C}_i$ and long-distance physics described by local operators $\mathcal{O}_i$. Semileptonic $b \to s\ell^+\ell^-$ decays receive contributions from $\mathcal{O}_7$, $\mathcal{O}_9$ and $\mathcal{O}_{10}$ operators, with corresponding Wilson coefficients $\{\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}\} = \{-0.34, 4.27, -4.17\}$ at the scale $\mu_b = 4.2$ GeV [8]. In BSM scenarios, new chirally flipped operators, denoted by $\mathcal{O}'_i$, may also be generated. Contributions from scalar $\mathcal{O}_{\mathrm{S}}^{(\prime)}$ and pseudoscalar $\mathcal{O}_{\mathrm{P}}^{(\prime)}$ operators are highly suppressed in the SM due to the small masses of the leptons. Presented analysis focuses on determining the shift of real part of the vector coupling strength C_9 from the SM expectation

$$\Delta\mathcal{R}e(C_9) = \mathcal{R}e(C_9)^{\mathrm{fit}} - \mathcal{R}e(C_9)^{\mathrm{SM}} \,. \tag{5}$$

5. The $K^+\pi^-\mu^+\mu^-$ mass distribution

A simultaneous fit to the mass distribution $m(K^+\pi^-\mu^+\mu^-)$ and three decay angles was performed. An additional fit to the distribution of the $K^+\pi^-$ system invariant mass helped to constrain S-wave fraction F_S. To discriminate signal and background, the invariant mass distribution was used (see Fig. 2), where the signal is modelled by the sum of two Gaussian functions with a common mean and a power-law tail on the low-mass side. The combinatorial background is described by an exponential function. The signal

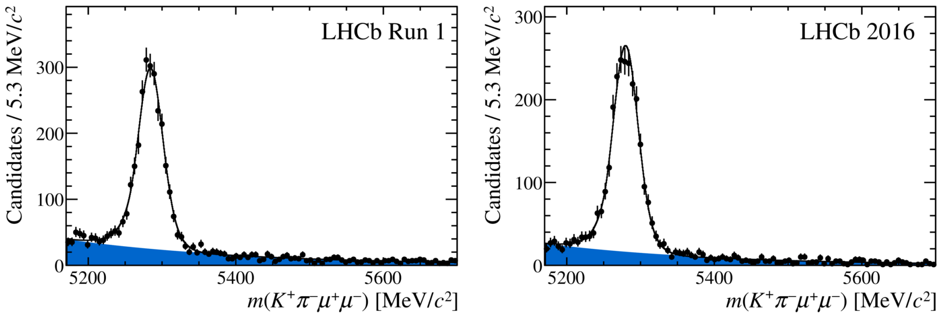

Fig. 2. The $B^0 \to K^+\pi^-\mu^+\mu^-$ mass distribution integrated over $q^2[0.1, 19]$ GeV$^2/c^4$ excluding charmonium modes and $\phi(1200)$, for Run 1 data set (left) and the 2016 data set (right). The shaded area indicates the combinatorial background [3].

yield integrated over broad range of q^2 $0.1 < q^2 < 19$ GeV$^2/c^4$ with exclusion of charmonium modes and $\phi(1200)$ was determined to be 2398 ± 57 in Run 1 data set and 2187 ± 53 in the 2016 data set.

6. CP-averaged observables

Figure 3 shows results of several angular observables measurements F_{L}, A_{FB}, S_5 and P_5' along with their respective SM predictions [9]. SM predictions for P_5' (taken from Ref. [10]) are restricted only for $q^2 < 8$ GeV$^2/c^4$ since the impact of the long-distance contribution remains small in the large recoil region. Results from Run 1, 2016 and combined ones show similar tendencies and are mostly in agreement with the SM predictions. However, there are still visible discrepancies in two q^2 bins ($4 < q^2 < 6$ GeV$^2/c^4$ and $6 < q^2 < 8$ GeV$^2/c^4$) of the P_5' observable. In comparison to the previous results obtained by the LHCb Collaboration [6], these tensions with the SM have reduced from 2.8 and 3.0σ to 2.5 and 2.9σ, respectively. It has been proposed that these discrepancies could be caused by a smaller value of the C_9 Wilson coefficient with respect to the SM.

The fit of the angular observables varying parameter $\mathcal{R}e(C_9)$ was performed using the flavio software package [11]. Generally, NP contribution to the Wilson coefficients are complex numbers, but here they are assumed to be aligned in phase with the SM (*i.e.* they are real). Analysis of only the Run 1 data set found 3.0σ deviation from the SM value of $\mathcal{R}e(C_9)$ (previous analysis [6] showed a discrepancy of 3.4σ). With additional data from 2016, this deviation has increased to 3.3σ. The best fit to the angular coefficients was obtained with the shift $\Delta\mathcal{R}e(C_9) = -0.99^{+0.25}_{-0.21}$.

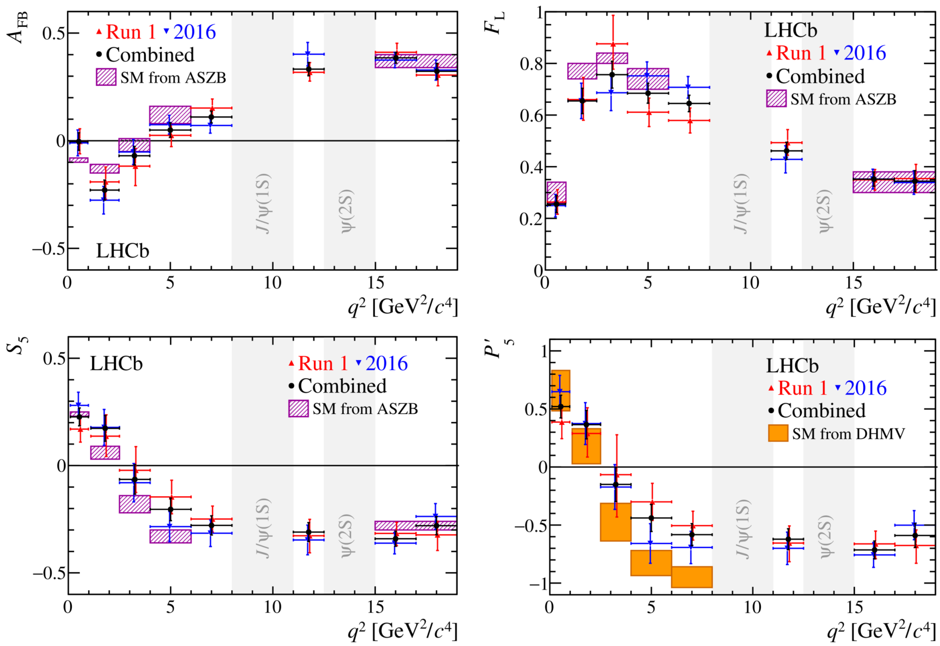

Fig. 3. The CP-averaged observables $F_{\rm L}$, $A_{\rm FB}$, S_5 and P'_5 as functions of q^2 and their respective SM predictions [3].

7. Summary

Recent results of angular measurements of the $B^0 \to K^{*0}\mu^+\mu^-$ decay have been presented. They are predominantly in agreement with the SM predictions. The discrepancies from the SM of P'_5 observable in two q^2 bins have reduced with comparison to the previous analysis [6]. However, tension with the SM of $\mathcal{R}e(C_9)$ parameter is observed to increase. These are the most precise measurements to date.

Presented deviations with respect to the SM predictions are very promising and could be explained by contributions from NP particles. For better understanding of these deviations, a further analysis with bigger data sample is needed.

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