ANGULAR ANALYSIS OF $B_d^0 \to K^{\star 0}\mu^+\mu^-$ DECAYS AT ATLAS*

MARTIN SÝKORA

on behalf of the ATLAS Collaboration

Institute of Particle and Nuclear Physics, Faculty of Mathematics and Physics
Charles University, V Holešovičkách 2, 18000 Prague, Czech Republic

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The large amount of heavy flavour data collected by the ATLAS experiment at the LHC allows the analysis of rare processes potentially sensitive to New Physics, which could be evident in processes that are naturally suppressed in the Standard Model. The results of the analysis of the angular distribution parameters describing the $B_d^0 \to K^{\star 0}\mu^+\mu^- \to K^+\pi^-\mu^+\mu^-$ decay based on full Run 1 data are presented. They are consistent with the Standard Model predictions.

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1. Introduction

Flavor-changing neutral currents (FCNC), including the $b \to s$ transition presented within this paper, are forbidden at the tree level and thus can be sensitive to new physics. If potential heavy new particles exist, the FCNC decay amplitudes may be noticeably affected by their contributions. A deviation up to 3.4σ from the Standard Model (SM) prediction was observed by the LHCb experiment in the measurement of angular observables in the $B_d^0 \to K^{\star 0}\mu^+\mu^-$ decays, as depicted in figure 1. The same measurement [1] was performed by ATLAS [3] using 20.3 fb^{-1} of LHC pp collision data at $\sqrt{s} = 8$ TeV, focusing on the interesting regions of low di-muon invariant masses (q).

2. Analysis method

The convention defined by the LHCb Collaboration was chosen using three primary angular observables as shown in figure 1. The angular differ-

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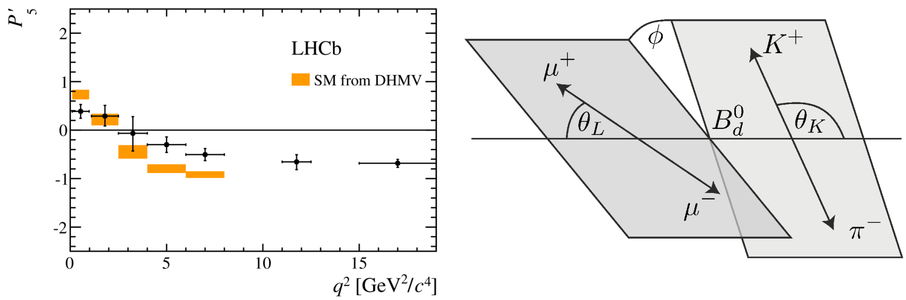

Fig. 1. Left: The LHCb results for $P_5^{\prime}$ angular observable in different q^2 regions [2]. Right: An illustration of the helicity angles in the $B_d^0 \to K^{\star 0} \mu^+ \mu^-$ decay [1].

ential decay rate can be derived as a function of q^2 and angular variables $\phi, \cos\theta_L$, and $\cos\theta_K$ [4]

$$\begin{aligned}
&\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L \mathrm{d}\cos\theta_K \mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\left[\frac{3\,(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K\right.\\
&+\frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L - F_L\cos^2\theta_K\cos 2\theta_L\\
&+S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_L\cos\phi\\
&+S_5\sin 2\theta_K\sin\theta_L\cos\phi + S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi\\
&\left.+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\right]. \qquad (1)
\end{aligned}$$

The helicity basis form introduces angular coefficients S_i and a fraction of longitudinally polarized K^* meson F_L. The angular coefficients depend on hadronic form-factors that suffer from significant uncertainties at the leading order. To cancel these, specific ratios $P_j^{(\prime)}$ are constructed [4, 5]

$$P_1 = \frac{2S_3}{1-F_L}\,, \qquad P_2 = \frac{S_6}{2\,(1-F_L)}\,,$$
$$P_3 = -\frac{S_9}{1-F_L}\,, \qquad P_{j=4,5,6,8}^{\prime} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L\,(1-F_L)}}\,.$$

The ATLAS analysis was performed in 6 bins of q^2 in the range between 0.04 and 6 GeV^2. The regions with peaking backgrounds from the decay channels $\phi \to \mu\mu$, $B^0 \to J/\psi K^*$, and $B^0 \to \psi\,(2S)\,K^*$ are excluded as well as the radiative tails of the $c\bar{c}$ resonances. An illustration of the investigated regions is shown in figure 2. To validate the fitting procedure described in

Section 3, both three-level $c\bar{c}$ resonances are used as control channels. The control samples are in addition used to determine nuisance parameters for the B-candidate mass signal probability density function (p.d.f.).

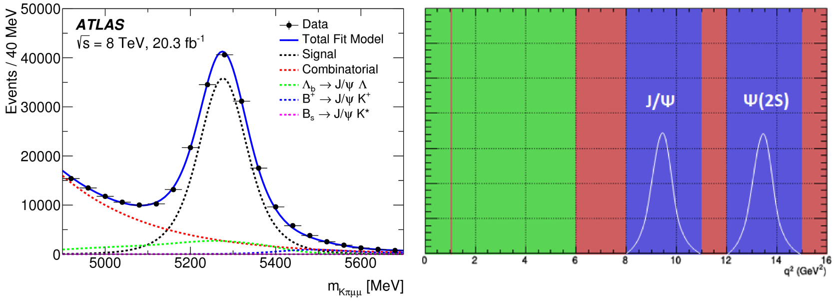

Fig. 2. Left: The B-candidate mass distribution in the $B^0 \to J/\psi K^*$ control channel [1]. Right: The analyzed regions of q^2 are in green, while the control regions are in blue. The radiative tails of the $c\bar{c}$ resonances and the region of $\phi \to \mu\mu$ decay, all in red, are excluded from the analysis.

The data is combined from 19 trigger chains with the most dominant contribution from $B^0 \to \mu^+\mu^- X$ requirement together with the transverse momentum cut $p_{\mathrm{T}} > 4$ GeV for one muon and $p_{\mathrm{T}} > 6$ GeV for the other muon, which ensures sensitivity down to the kinematic threshold. The suppression of the combinatorial background is achieved by cut-based selection criteria for a number of the B-candidate kinematic variables, in particular, including B^0 lifetime significance, secondary vertex fit quality, and B-hadron momentum pointing from the decay vertex towards the primary vertex.

As the investigated Run 1 dataset contained a limited number of signal events after the selection (342±39 for the full q^2 range up to 6 GeV^2), the full angular distribution fit would lead to unstable results and large systematic uncertainties. Therefore, a trigonometric folding scheme (equations (2)–(5)) is used, which allows for the simplification of equation (1) using certain symmetries. Nevertheless, it causes a loss of sensitivity for the angular parameters S_6 and S_9

$$F_L, S_3, S_4, P_4^{'} : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \end{cases} \quad \text{and} \quad \begin{cases} \cos\theta_L \in [0,1] \\ \cos\theta_K \in [-1,1] \\ \phi \in [0,\pi] \end{cases} \tag{2}$$

$$F_L, S_3, S_5, P_5^{'} : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \end{cases} \quad \text{and} \quad \begin{cases} \cos\theta_L \in [0,1] \\ \cos\theta_K \in [-1,1] \\ \phi \in [0,\pi] \end{cases} \tag{3}$$

$$F_L, S_3, S_7, P_6^{\prime}: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \frac{\pi}{2} \\ \phi \to -\pi - \phi & \text{for } \phi < -\frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \end{cases} \quad \text{and} \begin{cases} \cos\theta_L \in [0,1] \\ \cos\theta_K \in [-1,1] \\ \phi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \end{cases} \tag{4}$$

$$F_L, S_3, S_8, P_8^{\prime}: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \frac{\pi}{2} \\ \phi \to -\pi - \phi & \text{for } \phi < -\frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_K \to \pi - \theta_K & \text{for } \theta_L > \frac{\pi}{2} \end{cases} \quad \text{and} \begin{cases} \cos\theta_L \in [0,1] \\ \cos\theta_K \in [-1,1] \\ \phi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \end{cases} \tag{5}$$

3. Fitting method

An extended unbinned maximum-likelihood fit is performed in each bin of q^2 using the function

$$\mathcal{L} = \frac{\mathrm{e}^{-n}}{N!} \prod_{k=1}^{N} \sum_{l} n_l P_{kl} \left(m_{K\pi\mu\mu}, \cos\theta_K, \cos\theta_L, \phi; F_L, S_i, \hat{\theta} \right) , \tag{6}$$

where P_{kl} is the p.d.f. of the B-candidate mass, helicity angles, angular coefficients, and other nuisance parameters $\hat{\theta}$, N is the number of events, and n is the sum over the fitted yield n_l of the l^{th} component. Firstly, per-candidate Gaussian pre-fit fixes the parameters describing the B-mass distribution, while the consequent full mass-angular fit lets free only the parameters related to the helicity angles distributions. Detector sculpting of the angular distributions is compensated by polynomial acceptance functions extracted from the signal Monte Carlo (MC) simulation. The combined angular distributions $\epsilon\left(\cos\theta_K, \cos\theta_L, \phi\right)$ are described by the product of sixth-order polynomial distributions in each angle. The p.d.f. is then defined as

$$P_{kl} = \epsilon\left(\cos\theta_K\right) \epsilon\left(\cos\theta_L\right) \epsilon\left(\phi\right) g\left(\cos\theta_K, \cos\theta_L, \phi\right) G\left(m_{K\pi\mu\mu}\right) , \tag{7}$$

where $\epsilon\left(\cos\theta_K\right)$, $\epsilon\left(\cos\theta_L\right)$, and $\epsilon\left(\phi\right)$ are the factorized acceptance functions, g is the differential decay rate function defined by one of the folding schemes and G is the signal mass distribution.

4. Results

The full set of analysis results can be found in Ref. [1]. Figure 3 shows the angular distributions and the projections of the likelihood fit of the S_5 folding scheme in q^2 region $[4.0, 6.0]$ GeV^2, which was the one with the largest deviation observed by the LHCb. The resulting distributions for F_L and $P_j^{(\prime)}$ can be found in figure 4. The largest deviation from SM prediction observed in the ATLAS Run 1 analysis is 2.7σ, and it is in the case of the $P_5^{\prime}$ parameter in the q^2 region of $[4.0, 6.0]$ GeV^2.

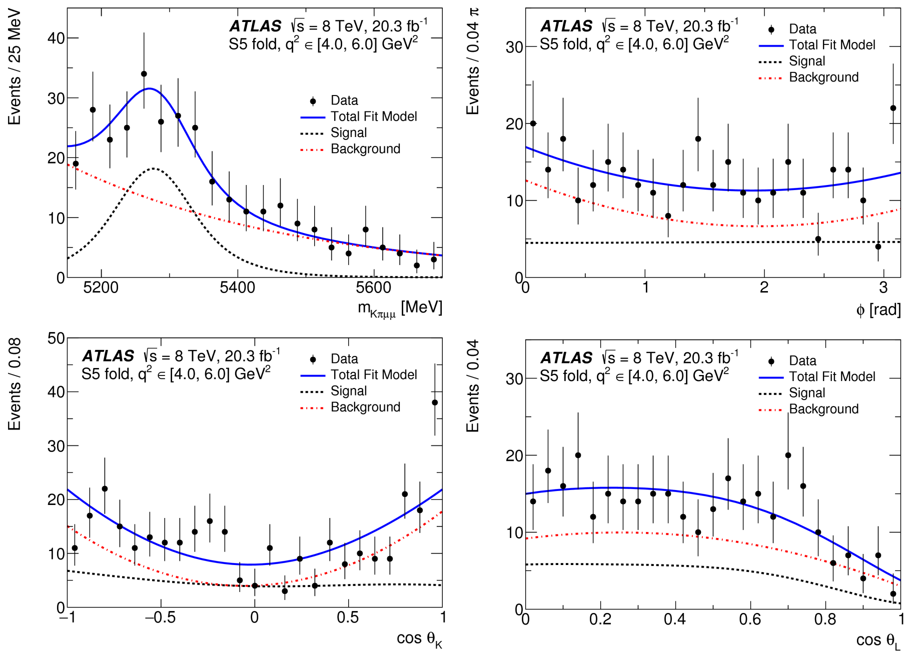

Fig. 3. Mass and angular fits of S_5 folding scheme for q^2 range of $[4, 6]$ GeV^2 [1].

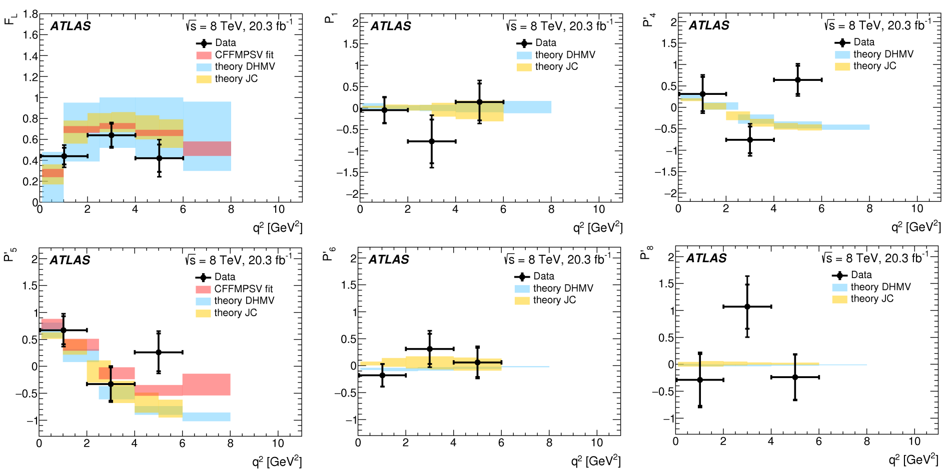

Fig. 4. Measured F_L and $P_j^{'}$ parameters compared with the SM predictions [1] from the theoretical approaches CFFMPSV [6], DHMV [7], and JC [8].

5. Systematic uncertainties

An extensive study of systematic uncertainties was performed and can be found in Ref. [1]. Many of the methods rely on the comparison of the nominal and modified fit. The most significant contributions come from $K\pi$ background peaking at $\cos\theta_K$ around 1.0 (compared with fit results in $\cos\theta_K < 0.9$) and background from partially reconstructed $B \to D^{0(+)}_{(s)} X$ decays resulting in an event accumulation at $|\cos\theta_L|$ around the value of 0.7. This is handled using a 30 MeV veto window around the D-meson masses.

6. Conclusion

The LHC Run 1 ATLAS measurement of the angular parameters in the $B^0_d \to K^{\star 0}\mu^+\mu^-$ decay is consistent within the limited statistical precision with SM, although the largest deviation in P'_5 follows the LHCb observation. The analysis of the much larger Run 2 dataset is ongoing. Better b-hadron decay time resolution is expected due to the installation of an additional IBL pixel layer. Furthermore, studies of the full q^2 range are planned.

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