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Measurements of CP violation in charmless two-body B decays at LHCb

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Direct and mixing-induced CP violation observables in charmless charged two-body B decays may provide valuable information in the quest for physics beyond the Standard Model. Owing to the large beauty production cross-section at the LHC and to the unique characteristics of the LHCb detector and trigger, unprecedented samples of such decays are becoming available. We present updated measurements of direct CP violation in $B^0_{(s)} \to K\pi$ decays as well as of direct and mixing-induced CP violation in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays. Furthermore, we report measurements of the branching fractions of these decays, notably including those of the annihilation modes $B^0 \to K^+K^-$ and $B^0_s \to \pi^+\pi^-$.

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1. Introduction

The study of charmless $H_b \to h^+h^-$ decays, where H_b is a b-flavoured meson or baryon, and h is either a pion, kaon or proton, plays an important role in the search of physics beyond the Standard Model (SM) in the flavour sector. These processes are mediated by tree and penguin diagrams, which give non-negligible contributions to the decay amplitude that introduce unknown hadronic factors [1]. While this poses theoretical challenges for an accurate determination of CKM phases, it also allows to test for contributions from physics beyond the SM [2, 3, 4].

In this paper we present the results from the LHCb experiment [5] on charmless two-body B and Λ_b decays. Section 2 will describe measurements of the branching fractions of $B^0 \to h^+h^-$ and $B_s^0 \to h^+h^-$, where $h = \pi, K$, $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$. Section 3 includes measurements of direct CP violation in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays and Section 4 describes measurements of time-dependent CP violation in two-body charmless decays $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$.

2. $B \to h^+h^-$ branching fractions

Using data corresponding to an integrated luminosity of 0.37 fb^{-1} collected by the LHCb experiment in 2011, we report measurements of the branching fractions in charmless two-body decays [6]. Three different sets of kinematic requirements were used to discriminate against combinatorial background (see ref. [6] for details). Particle identification (PID) variables using the two LHCb RICH detectors were used to identify each of the final states. The PID efficiencies were determined in a data-driven method, by reweighting the efficiencies from tagged calibration samples of $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $\Lambda \to p\pi^-$.

Figure 1 shows the invariant mass spectra for the mass hypotheses $K^+\pi^-$, $\pi^+\pi^-$, K^+K^-, pK^- and $p\pi^-$ for a loose kinematic selection and $K^+\pi^-$ for a tighter selection. Figure 2 shows the invariant mass spectra for the mass hypotheses K^+K^-, and $\pi^+\pi^-$ for the tightest event selection. Unbinned maximum likelihood fits are overlaid for all hypotheses. The signal yields are extracted from the fits and the ratios of efficiencies are extracted using Monte Carlo simulated data, reweighted for the PID hypotheses. Systematic uncertainties considered are PID calibration, final state radiation, the fitting model, three-body decays and cross-feed backgrounds due to a mass-scale bias and mass resolutions. Results are normalised to the $B^0 \to K^+\pi^-$ decay, using the result from the Heavy Flavour Averaging Group (HFAG), $B(B^0 \to K^+\pi^-) = (19.4 \pm 0.6) \times 10^{-6}$ [7]. We also use the ratio of strange B meson to light neutral B meson production f_s/f_d obtained in LHCb: $f_s/f_d = 0.267^{+0.021}_{-0.020}$ [8]. We finally obtain the following branching ratios:

$$B(B^0 \to \pi^+\pi^-) = (5.08 \pm 0.17 \pm 0.37) \times 10^{-6} \quad (2.1)$$
$$B(B_s^0 \to K^+K^-) = (23.0 \pm 0.7 \pm 2.3) \times 10^{-6} \quad (2.2)$$
$$B(B_s^0 \to \pi^+K^-) = (5.4 \pm 0.4 \pm 0.6) \times 10^{-6} \quad (2.3)$$
$$B(B^0 \to K^+K^-) = (0.11^{+0.05}_{-0.04} \pm 0.06) \times 10^{-6} \quad (2.4)$$
$$B(B_s^0 \to \pi^+\pi^-) = (0.95^{+0.21}_{-0.17} \pm 0.13) \times 10^{-6} \quad (2.5)$$

The results for $B(B_s^0 \to K^+K^-)$, $B(B_s^0 \to \pi^+K^-)$ and $B(B^0 \to K^+K^-)$ are the world's most precise and $B(B_s^0 \to \pi^+\pi^-)$ is the first evidence for this decay (5.3σ). Also, we obtain the world's most precise results for: $B(\Lambda_b^0 \to p\pi^-)/B(\Lambda_b^0 \to pK^-) = 0.86 \pm 0.08 \pm 0.05$.

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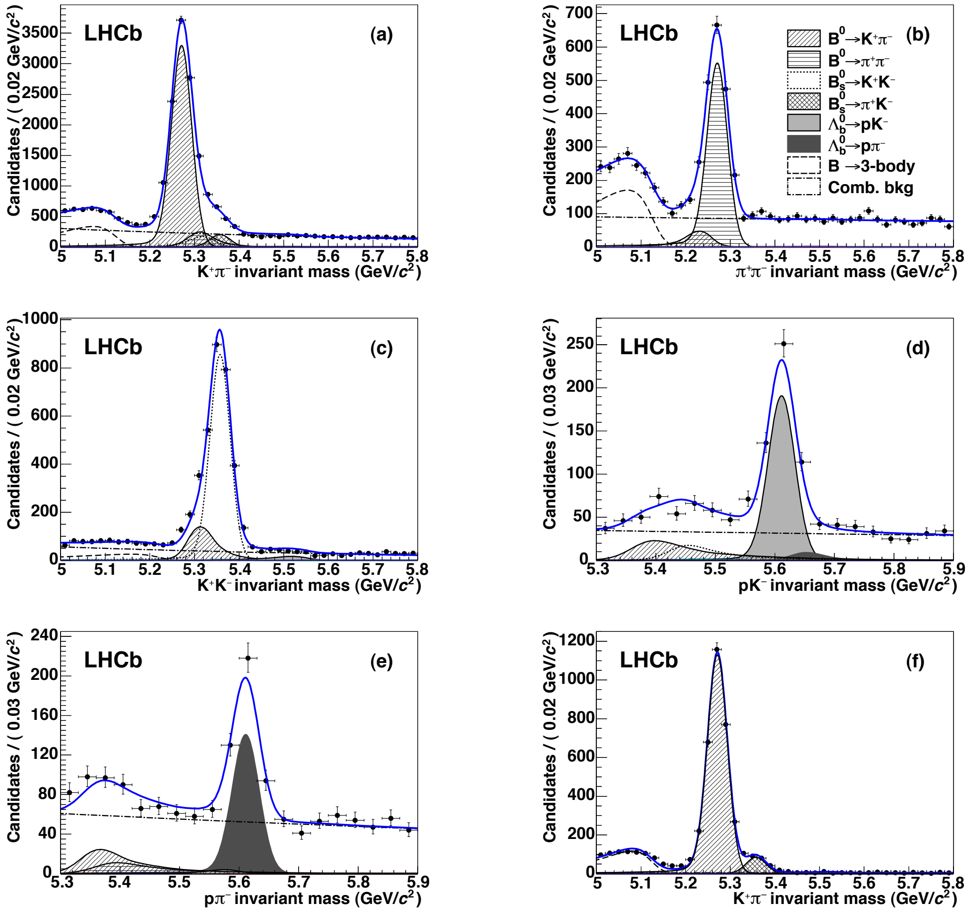

Figure 1: Invariant mass spectra corresponding to the mass hypotheses (a) $K^+\pi^-$, (b)$\pi^+\pi^-$, (c) K^+K^-, (d) pK^-, (e) $p\pi^-$ for a loose kinematic selection and (f) $K^+\pi^-$ for a tighter selection. The results of the unbinned maximum likelihood fits are overlaid.

3. $B^0_{(s)} \to K^\pm\pi^\mp$ direct CP violation

In this section we report direct CP violating asymmetries in $B^0 \to K^+\pi^-$ and $B^0_s \to K^-\pi^+$ time-integrated decays using 0.35 fb^{-1} of data collected with LHCb in 2011 [9]. The direct CP asymmetry in the $B^0_{(s)}$ decay rate to the f final states $f = K^+\pi^-$ and $f = K^-\pi^+$ is:

$$A_{CP} \equiv \frac{\Gamma\left(\bar{B}\to\bar{f}\right) - \Gamma\left(B\to f\right)}{\Gamma\left(\bar{B}\to\bar{f}\right) + \Gamma\left(B\to f\right)}. \tag{3.1}$$

Optimised kinematic and PID criteria were used to select the events. Maximum likelihood fits to the two channels yield 13250 ± 150 events for $B^0 \to K\pi$ and 314 ± 27 events for $B^0_s \to K\pi$. The raw CP asymmetries were corrected for detector acceptance, event reconstruction, final state interactions and the raw $B^0_{(s)} - \bar{B}^0_{(s)}$ production asymmetries to yield: $A_{CP}\left(B^0 \to K^+\pi^-\right) = -0.088 \pm 0.011 \pm 0.008$, which is the first $> 5\sigma$ observation of direct CP violation at a hadron machine (6.4σ significance), and $A_{CP}\left(B^0_s \to K^+\pi^-\right) = 0.27 \pm 0.08 \pm 0.02$, which is the first evidence for CP violation in B^0_s decays (3.3σ significance).

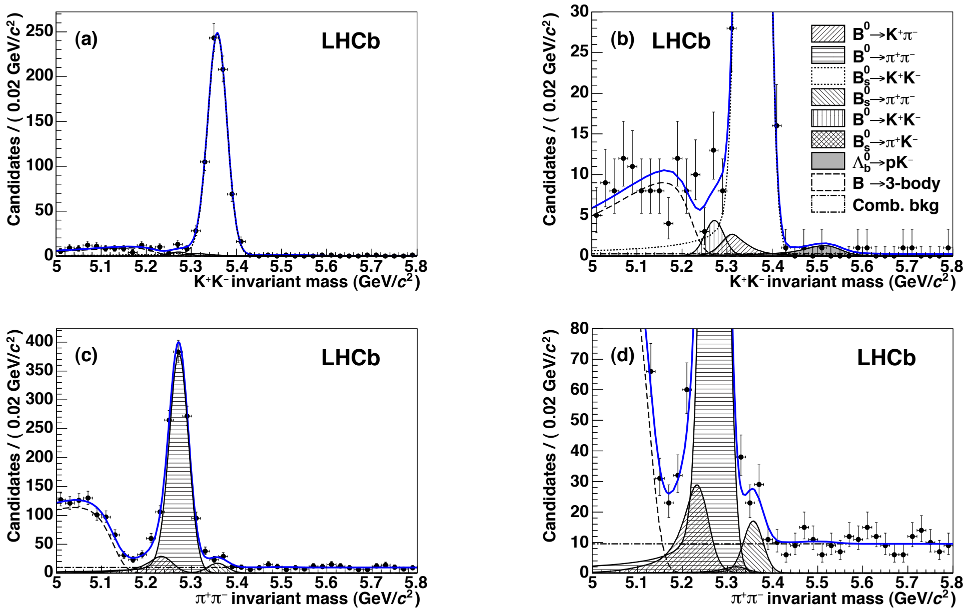

Figure 2: Invariant mass spectra corresponding to the mass hypotheses (a) and (b) K^+K^-, and (c) and (d) $\pi^+\pi^-$ for the tightest event selection. The results of the unbinned maximum likelihood fits are overlaid.

4. Time-dependent CP violation in $B^0 \to \pi^+\pi^-$

In this section, we present the first measurement of time-dependent CP violation in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays at LHCb. The time-dependent CP asymmetries are:

$$A_{CP}(t) = \frac{A_f^{dir}\cos(\Delta mt) + A_f^{mix}\sin(\Delta mt)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) - A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right)}, \tag{4.1}$$

where A_f^{dir} and A_f^{mix} parameterise direct and mixing-induced CP violation, with $f = \pi\pi$ or KK and $A_f^{\Delta\Gamma}$ is given by: $\left(A_f^{dir}\right)^2 + \left(A_f^{mix}\right)^2 + \left(A_f^{\Delta\Gamma}\right)^2 = 1$. The world average for the $\pi\pi$ channel is: $A_{\pi\pi}^{dir} = 0.38 \pm 0.06$ and $A_{\pi\pi}^{mix} = -0.65 \pm 0.07$ [7], but there exists tension between the Belle [10] and Babar [11] results. CP violation in $B_s^0 \to K^+K^-$ decays has not been previously measured.

The time-dependent charmless two-body decay asymmetries were determined from 0.69 fb^{-1} of 2011 LHCb data at 7 TeV [12]. A common event selection, with additional PID cuts and a fixed decay time resolution ($\sigma_t = 50$), was used. The acceptance was derived from Monte Carlo simulations. Opposite side flavour tagging [13] was used to determine the tagging efficiency ε, mistag rate ω and tagging power $\varepsilon_{eff} = \varepsilon(1-2\omega)^2$. The $B_{(s)}^0 \to K\pi$ channels were used as controls, to extract Δm_d and $\tau(B^0)$, which agree with the world average, and to determine: $\varepsilon_{eff} = (2.3 \pm 0.1)\%$. The production asymmetries were $A_P(B^0) = (-1.5 \pm 1.3)\%$ and $A_P(B_s^0) = (-3 \pm 6)\%$, with $\sigma_m = 22.4$ MeV/c^2. Figure 3 shows the $B^0 \to K\pi$ invariant mass and mixing asymmetry.

The $B^0 \to \pi^+\pi^-$ invariant mass and CP asymmetries can be seen in Figure 4, with the fits overlaid. The results of the fit are: $A_{\pi\pi}^{dir} = 0.11 \pm 0.21 \pm 0.03$ and $A_{\pi\pi}^{mix} = -0.56 \pm 0.17 \pm 0.03$ (3.2σ significance), with a correlation coefficient of $\rho\left(A_{\pi\pi}^{dir}, A_{\pi\pi}^{mix}\right) = -0.34$. The preliminary LHCb results are the first evidence of time-dependent CP violation at a hadron collider and currently favour the Babar results. The main systematic uncertainty is due to the input of Δm_d in the fit.

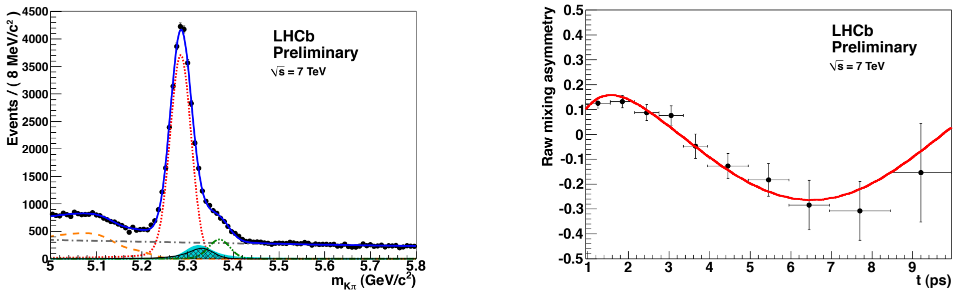

Figure 3: Invariant mass (left) and raw mixing asymmetry (right) in the $B^0 \to K\pi$ signal mass region.

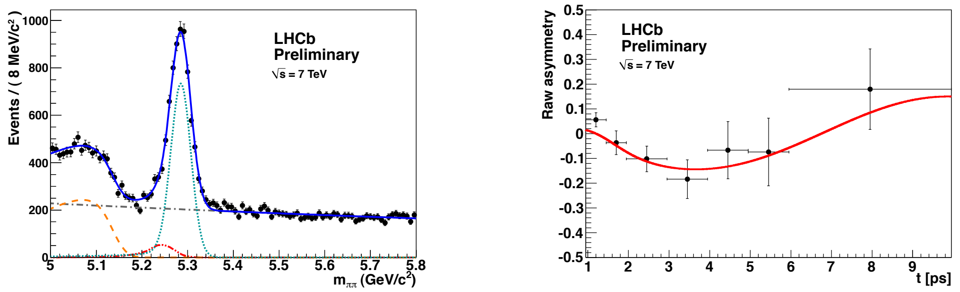

Figure 4: Invariant mass (left) and raw mixing asymmetry (right) in the $B^0 \to \pi\pi$ signal mass region.

The $B_s^0 \to K^+K^-$ invariant mass and CP asymmetries can be seen in Figure 5. The results of the fit are $A_{KK}^{dir} = 0.02 \pm 0.18 \pm 0.04$ and $A_{KK}^{mix} = 0.17 \pm 0.18 \pm 0.05$ (3.2σ), with a correlation coefficient of $\rho\left(A_{KK}^{dir}, A_{KK}^{mix}\right) = -0.10$. The values of Δm_s and Γ_s are inputs to the fit. The preliminary LHCb results do not show evidence for CP violation and agree with the world average. Under the assumption of U-spin symmetry, we expect $A_{KK}^{dir} \approx A_{CP}\left(B^0 \to K^+\pi^-\right) = -0.088 \pm 0.011 \pm 0.008$, from the LHCb measurement. The Standard Model prediction is $A_{KK}^{dir} \approx 0.15$. The main systematic errors are due to decay time acceptance and resolution, and the input of Δm_s to the fit.

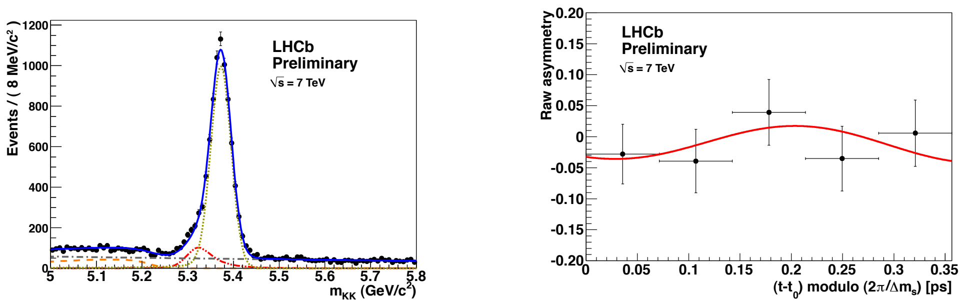

Figure 5: Invariant mass (left) and raw mixing asymmetry in the $B_s^0 \to KK$ signal mass region.

The LHCb results for $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ time-dependent asymmetries are shown in Figure 6, and these are compared to results by previous experiments.

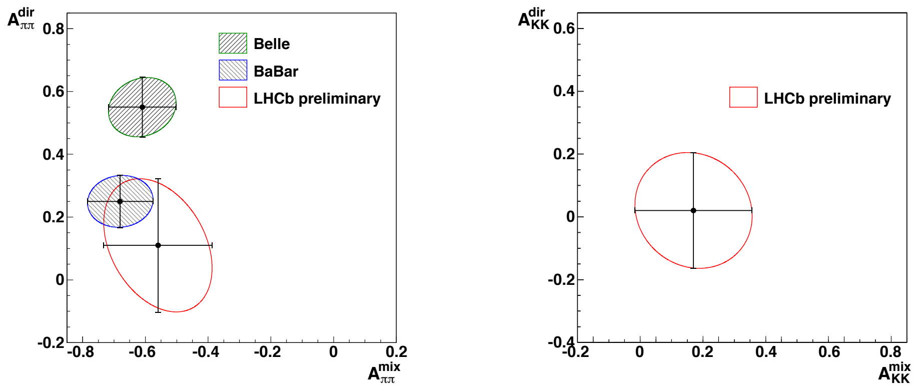

Figure 6: Present experimental status for (left) $A^{dir}_{\pi\pi}$ and $A^{mix}_{\pi\pi}$ and (right) A^{dir}_{KK} and A^{mix}_{KK}. Data points with error bars and standard error ellipses (39% C.L.) are shown.

5. Conclusions

The branching fractions of two-body charmless B^0, B^0_s and Λ_b decays were established by measurements from 0.37 fb^{-1} of LHCb data from 2011. Four channels are the world's most precise and $B\left(B^0_s \to \pi^+\pi^-\right)$ is observed for the first time (5.3σ). The first $> 5\sigma$ observation of direct CP violation in $B^0 \to K\pi$ decays at a hadron collider and the first evidence of CP violation in $B^0_s \to K\pi$ decays were observed by LHCb from 0.35 fb^{-1}. Finally, time-dependent CP violation in two body charmless B decays using 0.69 fb^{-1} of LHCb data from 2011 was also observed. The CP asymmetries from $B^0 \to \pi^+\pi^-$ are the first evidence (3.2σ) for time-dependent CP violation at a hadron collider and agree with the world average. The CP asymmetry in $B^0_s \to K^+K^-$ was measured for the first time, with no evidence for CP violation. All analyses are statistically limited, and with 3.0 fb^{-1} collected in 2011 and 2012, LHCb should improve on all these results.

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