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

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The study of charmless two-body B decays provides valuable information for testing the Cabibbo-Kobayashi-Maskawa paradigm of CP violation in the Standard Model. In addition, as the contribution of loop diagrams to the decay amplitudes are sizeable, the CP violation observables may be sensitive to physics beyond the Standard Model. In this paper we present the latest measurements performed by the LHCb Collaboration in this sector. Of particular note are the first evidence of the $B^0 \to p\bar{p}$ decay, the best measurement to date of the direct CP asymmetry of the $B^+ \to K^0_S K^+$ decay, the first observation of CP violation in the decays of the B^0_s mesons with the measurement of $A_{CP}(B^0_s \to \pi^+ K^-)$ and the first measurement of the coefficients of the time-dependent CP asymmetry of the $B^0_s \to K^+ K^-$ decay.

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1. Introduction

Charmless charged two-body B decays are a matter of great interest in the sector of flavour physics, and have been extensively studied in the past both at e^+e^- colliders and at the TeVatron. On the one hand, their *CP* violation observables, that can be either direct or time-dependent *CP* asymmetries, are sensitive to the parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1, 2], that accommodates *CP* violation and quark-flavour mixing within the Standard Model (SM). On the other hand, the study of these decays can probe the presence of non-SM physics. In fact, as the contributions of penguin topologies to the decay amplitudes are sizeable, new particles not present in the SM may appear in the loops as virtual contributions, leading to different values of the *CP* violation observables with respect to SM predictions. However, a precise calculation of these quantities within the SM is challenging, because of theoretical uncertainties affecting the hadronic factors in the decay amplitudes. In this respect it is crucial to combine different measurements from several charmless two-body B decays, exploiting approximate flavour symmetries, in order to constrain the values of the unknown hadronic parameters. In this paper we present the latest results on charmless two-body B decays obtained by the LHCb Collaboration [3] analyzing the pp collisions recorded during 2011 and 2012.

2. First evidence for the two-body charmless baryonic decay $B^0 \to p\bar{p}$

The $B^0_{(s)} \to p\bar{p}$ decays are still unobserved, despite various searches performed in the past at e^+e^- colliders. The theoretical predictions of the branching ratio of the $B^0 \to p\bar{p}$ decay vary within a wide range ($10^{-7}-10^{-6}$), and depend on the method used for the calculation. Up to now, no theoretical predictions have been published for the branching ratio of the $B^0_s \to p\bar{p}$ decay mode.

The branching ratios of the two decay modes are determined using the $B^0 \to K^+\pi^-$ decay[1] as a normalization channel. Event selection for signal modes is performed using a boosted decision tree (BDT) algorithm as a multivariate classifier to separate signal from combinatorial background, on the basis of kinematic and geometric variables. Normalization channel is selected using individual requirements on a set of variables similar to that used for the BDT. The optimization of the selection criteria is performed taking into account the output of the BDT and the particle identification (PID) criteria used to identify protons, kaons and pions. While the efficiency of the BDT requirement is determined from fully simulated events (and cross-checked using background-subtracted candidates of $B^0 \to K^+\pi^-$ decay), the particle identification efficiencies are estimated using calibration samples of $\Lambda \to p\pi$ (for protons) and $D^{*+} \to [K^-\pi^+]_{D^0}\pi^+$ decays (for kaons and pions). Yields of signal modes and normalization channel are extracted from unbinned maximum likelihood fits to the $p\bar{p}$ and $K\pi$ invariant mass spectra. In Figure 1 the $K\pi$-mass (left) and $p\bar{p}$-mass (right) spectra of selected events are shown, with the result of the fit superimposed. The statistical significances of the $B^0_{(s)} \to p\bar{p}$ signals, evaluated using Wilks' theorem [4], are $3.3\,\sigma$ and $1.9\,\sigma$ for the $B^0 \to p\bar{p}$ and $B^0_s \to p\bar{p}$ decays, respectively. Main contributions to the systematic uncertainties are the goodness of PID calibration and the modelling of invariant mass shapes that affect the extraction of signal yields. In the case of the $B^0_s \to p\bar{p}$ decay a relevant rôle is played by the uncertainty on the hadronization probabilities ratio between B^0 and B^0_s: $f_s/f_d = 0.256 \pm 0.020$ [5].

[1] The inclusion of charge conjugated decay modes is implied throughout this paper unless otherwise stated.

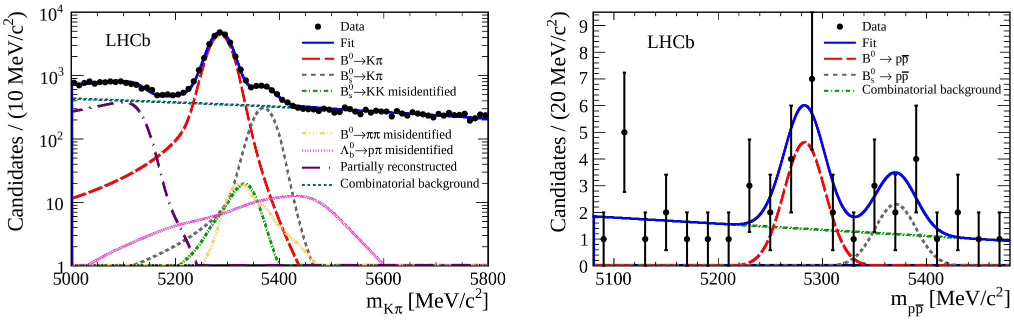

Figure 1: Invariant mass distribution of $K\pi$ (left) and $p\bar{p}$ (right) candidates after full selection. The fit result is superposed together with each fit model component as described in the legend.

Using the Feldman-Cousins frequentist method [6] the 68.3% and 90% confidence level (CL) intervals on the branching ratios of signal modes are evaluated to be [7]:

$$\mathscr{B}\left(B^0 \to p\bar{p}\right) = (1.47\,^{+0.62}_{-0.51}\,^{+0.35}_{-0.14}) \times 10^{-8} \text{ at } 68.3\% \text{ CL},$$
$$\mathscr{B}\left(B^0 \to p\bar{p}\right) = (1.47\,^{+1.09}_{-0.81}\,^{+0.69}_{-0.18}) \times 10^{-8} \text{ at } 90\% \text{ CL},$$
$$\mathscr{B}\left(B^0_s \to p\bar{p}\right) = (2.84\,^{+2.03}_{-1.68}\,^{+0.85}_{-0.18}) \times 10^{-8} \text{ at } 68.3\% \text{ CL},$$
$$\mathscr{B}\left(B^0_s \to p\bar{p}\right) = (2.84\,^{+3.57}_{-2.12}\,^{+2.00}_{-0.21}) \times 10^{-8} \text{ at } 90\% \text{ CL},$$

where the first uncertainties are statistical and the second are systematic. In particular, an excess of $B^0 \to p\bar{p}$ candidates with respect to background expectations is observed with a statistical significance of 3.3 σ, that represents the first evidence for a two-body charmless baryonic B^0 decay.

3. Branching ratio and *CP* asymmetry of the decays $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$

Candidates of $B^+ \to K^0_S K^+$ and $B^+ \to K^0_S\pi^+$ decays are selected from the 3 fb^{-1} of pp collisions collected during 2011 and 2012. The candidates are formed combining a $K^0_S \to \pi^+\pi^-$ decay with a track displaced from the primary pp interaction region and identified as a pion or a kaon by PID requirements. The event selection is further refined using a BDT classifier. A looser requirement has been defined on the BDT output for the $B^+ \to K^0_S\pi^+$ mode, while tighter criterion is used for the $B^+ \to K^0_S K^+$ decay mode.

The *CP*-summed $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ yields are measured together with the raw charge asymmetries, $A_{\text{raw}}(K^0_S h^+) = \left(N(K^0_S h^-) - N(K^0_S h^+)\right) / \left(N(K^0_S h^-) + N(K^0_S h^+)\right)$, by means of a simultaneous unbinned extended maximum likelihood fit to the $B^\pm$ candidate mass distributions. Figure 2 shows the four invariant mass distributions with the projections of the fit superimposed. The ratio of branching ratios is determined from the fitted yields using relative efficiencies that comprehend trigger, reconstruction, selection and PID effects. The *CP* asymmetries of the $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ decays are related to the raw asymmetries by the relation $A_{CP}(B^+ \to K^0_S h^+) \approx A_{\text{raw}}(B^+ \to K^0_S h^+) - A_{\text{det+prod}}(B^+ \to K^0_S h^+) + A_{K^0_S}$, where $A_{\text{det+prod}}$ is the sum of the detection and production asymmetries between *CP* conjugate decays; $A_{K^0_S}$ is the contribution of *CP* violation in the neutral kaon system. Detection and production asymmetries are

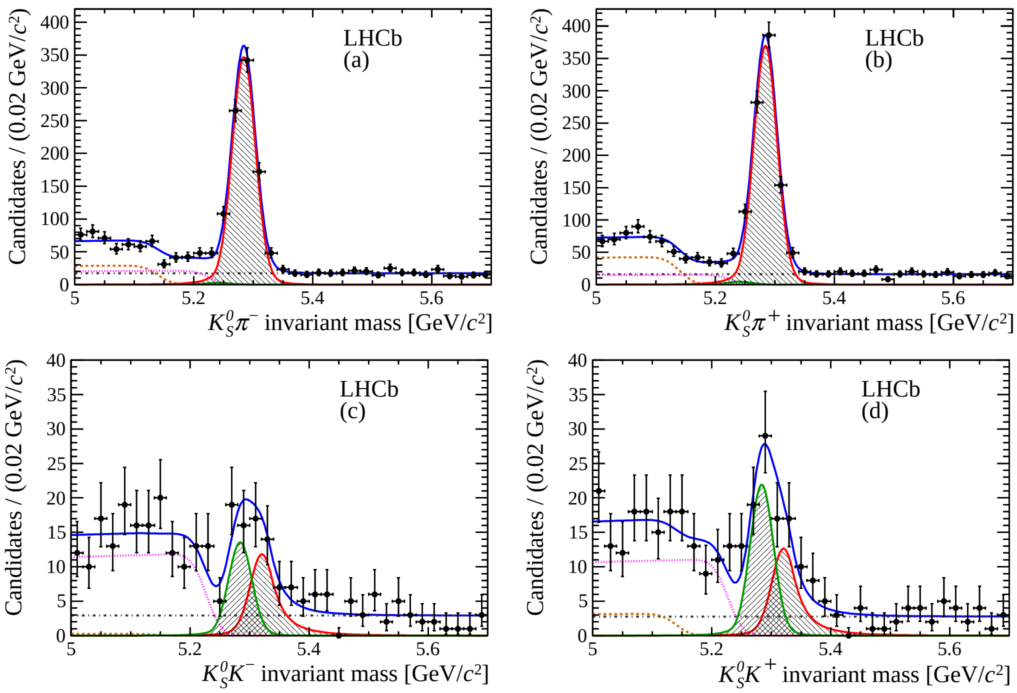

Figure 2: Invariant mass distributions of selected (a) $B^- \to K^0_S\pi^-$, (b) $B^+ \to K^0_S\pi^+$, (c) $B^- \to K^0_S K^-$ and (d) $B^+ \to K^0_S K^+$ candidates. Data are points with error bars, the $B^+ \to K^0_S\pi^+$ ($B^+ \to K^0_S K^+$) components are shown as red falling hatched (green rising hatched) curves, combinatorial background is grey dash-dotted, partially reconstructed B^0_s (B^0, B^+) backgrounds are dotted magenta (dashed orange).

measured using $B^+ \to J/\psi K^+$ decays selected using kinematic and topological requirements similar to those employed in the signal selection. Effects from *CP* violation in the neutral kaon system are estimated fitting the decay time distribution of $B^+ \to K^0_S\pi^+$ decays. Effects of regeneration of K^0_S from K^0_L interaction with detector material is found small in the LHCb detector acceptance, and thus neglected. PID calibration and invariant mass modelling constitute the dominant contributions to the systematic uncertainty on the relative branching ratio. The main systematic errors for the *CP* asymmetry measurements are the determination of detection and production asymmetries. Final results are [8]:

$$\frac{\mathscr{B}(B^+ \to K^0_S K^+)}{\mathscr{B}(B^+ \to K^0_S \pi^+)} = 0.064 \pm 0.009\ (\text{stat.}) \pm 0.004\ (\text{syst.}),$$
$$A_{CP}(B^+ \to K^0_S\pi^+) = -0.022 \pm 0.025\ (\text{stat.}) \pm 0.010\ (\text{syst.}),$$
$$A_{CP}(B^+ \to K^0_S K^+) = -0.21 \pm 0.14\ (\text{stat.}) \pm 0.01\ (\text{syst.}).$$

The measurements of $A_{CP}(B^+ \to K^0_S K^+)$ and $\mathscr{B}(B^+ \to K^0_S K^+)/\mathscr{B}(B^+ \to K^0_S\pi^+)$ are the best single determinations to date. Using the same selection optimized for the $B^+ \to K^0_S K^+$ decay, but with tighter PID cuts in order to reject protons from B baryon decays, a search for the $B^+_c \to K^0_S K^+$ decay has been also performed with the data sample collected during 2011. Applying the Feldman-Cousins approach to the invariant mass fit of B^+_c candidates the first upper limit on a B^+_c meson

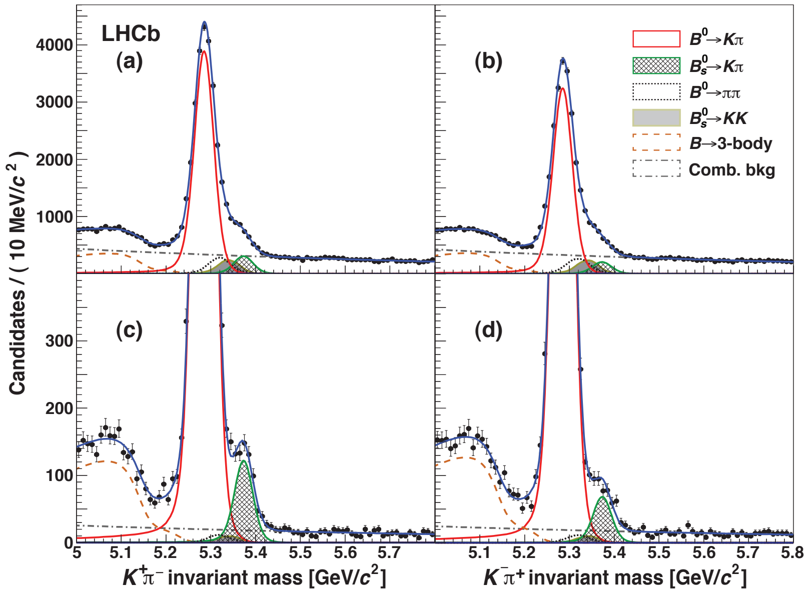

Figure 3: Invariant mass spectra obtained using the event selection adopted for the best sensitivity on (a, b) $A_{CP}(B^0 \to K^+\pi^-)$ and (c, d) $A_{CP}(B_s^0 \to K^-\pi^+)$. Panels (a) and (c) represent the $K^+\pi^-$ invariant mass, whereas panels (b) and (d) represent the $K^-\pi^+$ invariant mass. The results of the unbinned maximum likelihood fits are overlaid. The main components contributing to the fit model are also shown.

decay into two light quarks has been established:

$$\frac{f_c}{f_u} \cdot \frac{\mathscr{B}(B_c^+ \to K_S^0 K^+)}{\mathscr{B}(B^+ \to K_S^0 \pi^+)} < 5.8 \times 10^{-2} \text{ at 90\% confidence level.}$$

4. First observation of *CP* violation in the decays of B_s^0 mesons

The measurement of the direct *CP* asymmetries $A_{CP}\left(B^0 \to K^+\pi^-\right)$ and $A_{CP}\left(B_s^0 \to \pi^+K^-\right)$ is performed on the 1 fb^{-1} of *pp* collisions collected during the 2011 run. In this analysis charmless charged two-body *B* decays are discriminated from combinatorial background using kinematic and geometrical cuts. Then, PID criteria are used to separate the $K^+\pi^-$ and $K^-\pi^+$ final states. Different values for the kinematic, geometrical and PID requirements have been optimized in order to achieve the best sensitivity on $A_{CP}\left(B^0 \to K^+\pi^-\right)$ (looser cuts) and $A_{CP}\left(B_s^0 \to \pi^+K^-\right)$ (tighter cuts). Raw asymmetries are extracted from data performing a simultaneous unbinned maximum likelihood fit of invariant mass spectra. In Figure 3 the $K^+\pi^-$ and $K^-\pi^+$ mass spectra for the events passing the two selections are shown, with the results of the best fit superimposed. Similarly to what is described in the previous section, raw asymmetries and *CP* violation asymmetries are connected by the relation $A_{CP}(B_{(s)}^0 \to K^+\pi^-) = A_{(s)}^{\text{RAW}} - A_{(s)}^D - \kappa_{(s)} A_{(s)}^P$, where $A_{(s)}^D$ is the asymmetry of reconstruction efficiencies between $K^+\pi^-$ and $K^-\pi^+$ pairs, $A_{(s)}^P$ is the production asymmetry of $B_{(s)}^0$ mesons and $\kappa_{(s)}$ is a dilution factor that depends on the decay time evolution of the neutral *B* meson. Detection asymmetries are determined studying D^*-tagged $D^0 \to K^+K^-$ and $D^0 \to K^-\pi^+$ and un-tagged $D^0 \to K^-\pi^+$ decays. The production asymmetries are determined directly from the signals, by means of a fit of the time-dependent decay rates of neutral B meson to the untagged decay time distributions. The main sources of systematic uncertainties are the determination of A^D in the case of $B^0 \to K^+\pi^-$ decay and the modelling of invariant mass shapes in the case of $B_s^0 \to K^-\pi^+$ decays. Final results are [9]:

$$\begin{aligned} A_{CP}(B^0 \to K^+\pi^-) &= -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst}), \\ A_{CP}(B_s^0 \to K^-\pi^+) &= 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}). \end{aligned}$$

The former is the most precise measurement of $A_{CP}(B^0 \to K^+\pi^-)$ to date, whereas the latter represents the first observation of CP violation in decays of B_s^0 mesons with a significance of 6.5σ.

5. First measurement of time-dependent *CP* violation in $B_s^0 \to K^+K^-$ decays

The time-dependent CP asymmetry of a generic neutral B meson decay, $B \to f$, can be written as:

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) + D_f \sinh\left(\frac{\Delta\Gamma}{2}t\right)}, \tag{5.1}$$

where $\Gamma(t)$ represents the time dependent decay rate of the initial B or $\bar{B}$ meson to the final state f, Δm and $\Delta\Gamma$ are the B meson oscillation frequency and decay width difference respectively, and where the relation $C_f^2 + S_f^2 + D_f^2 = 1$ holds. With this parameterization, C_f and S_f account for CP violation in the decay and in the interference between mixing and decay, respectively. Using the data sample corresponding to 1 fb^{-1} of pp collisions collected during 2011, LHCb measured the C and S coefficients for the $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays. PID requirements are used to separate $\pi^+\pi^-$ and K^+K^- final states. Two BDT classifiers (each one optimized for one of the two decays under study) refine the combinatorial background rejection. Crucial aspects of the analysis are the flavour tagging and the determination of the decay time resolution, as both effects dilute the observed amplitude of the time-dependent asymmetry. The determination of the initial flavour of the signal B meson (the so-called ”flavour tagging”) is obtained using a multivariate algorithm that analyzes the decay products of the other B hadron in the event. The response of the algorithm is calibrated by measuring the oscillation of the flavour specific decay $B^0 \to K^+\pi^-$, in which the amplitude is related to the effective mistag rate. The non perfect determination of the decay time of the B meson is studied by means of charmonium and bottomonium states decaying into $\mu^+\mu^-$ pairs. The values for $C_{\pi^+\pi^-}$, $S_{\pi^+\pi^-}$, $C_{K^+K^-}$ and $S_{K^+K^-}$ are extracted from a two dimensional (invariant mass and tagged decay time) maximum likelihood fit of the $\pi^+\pi^-$ and K^+K^- spectra. The raw time-dependent asymmetries are shown in Figure 4 for candidates with invariant mass in the region dominated by signal events, corresponding to $5.20 < m < 5.36$ GeV/c^2 for the $\pi^+\pi^-$ spectrum and $5.30 < m < 5.44$ GeV/c^2 for the K^+K^- spectrum. Measured values for the CP violation amplitudes are [10]:

$$\begin{aligned} C_{KK} &= 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst}), \\ S_{KK} &= 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst}), \end{aligned} \tag{5.2}$$

with a statistical correlation coefficient of 0.02;

$$\begin{aligned} C_{\pi\pi} &= -0.38 \pm 0.15\,(\text{stat}) \pm 0.02\,(\text{syst}), \\ S_{\pi\pi} &= -0.71 \pm 0.13\,(\text{stat}) \pm 0.02\,(\text{syst}), \end{aligned} \tag{5.3}$$

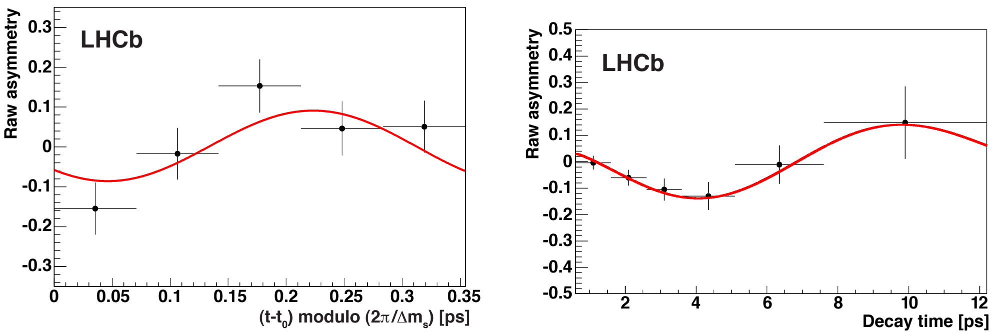

Figure 4: Time-dependent raw asymmetry for candidates in the $B_s^0 \to K^+K^-$ (left) and $B^0 \to \pi^+\pi^-$ signal mass region with the result of the fit overlaid. In the left plot, offset $t_0 = 0.6$ ps corresponds to the selection requirement on the decay time.

with a statistical correlation coefficient of 0.38. Dividing the central values of the measurements by the sum in quadrature of statistical and systematic uncertainties, and taking correlations into account, the significances for (C_{KK}, S_{KK}) and $(C_{\pi\pi}, S_{\pi\pi})$ to differ from $(0, 0)$ are determined to be 2.7σ and 5.6σ, respectively. The parameters C_{KK} and S_{KK} are measured for the first time.

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