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# Charmless charged two-body $B$-decays at LHCb

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Using data collected by the LHCb detector during the 2010 run we reconstruct a sample of the main charmless charged two-body $B$ hadron decay modes, namely $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, $B_s^0 \to K^+K^-$, $B_s^0 \to \pi^+K^-$, $\Lambda_b \to pK^-$ and $\Lambda_b \to p\pi^-$. We provide preliminary values of the direct $CP$ asymmetries in the $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays, and of the $B_s^0 \to K^+K^-$ lifetime: $A_{CP}(B^0 \to K^+\pi^-) = -0.074 \pm 0.033(\mathrm{stat}) \pm 0.008(\mathrm{syst})$, $A_{CP}(B_s^0 \to \pi^+K^-) = 0.15 \pm 0.19(\mathrm{stat}) \pm 0.02(\mathrm{syst})$ and $\tau(B_s^0 \to K^+K^-) = 1.440 \pm 0.096(\mathrm{stat}) \pm 0.010(\mathrm{syst})$ ps, respectively.

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## 1. Introduction

The LHCb detector is a forward spectrometer covering the pseudo-rapidity range $1.8 < \eta < 4.9$, designed to perform flavour physics measurements at the LHC. It is composed of a vertex detector close to the interaction region, a set of tracking stations in front of and behind a dipole magnet that provides a field integral of 4 Tm, two Ring-Imaging Cherenkov (RICH) detectors, electromagnetic and hadronic calorimeters complemented with pre-shower and scintillating pad detectors, and a set of muon chambers. LHCb is equipped with a trigger system organized in two levels. The first level (Level 0) is a hardware trigger implemented with custom electronic boards. Its goal is to select particles with high transverse energy and momentum using partial detector information, in particular from the calorimeter system and the muon chambers. Then, at a maximum output rate of 1.1 MHz, the full detector is read out into a computing farm running a software trigger application. This constitutes the so-called High Level Trigger (HLT), reducing the recorded data to a rate of about 2 kHz. Details on the LHCb detector and trigger can be found in Ref. [1]. An overview of its performance during the 2010 data taking can be found in Ref. [2].

The family of charmless $H_b \to h^+h'^-$ decays, where $H_b$ can be either a $B^0$ meson, a $B_s^0$ meson or a $\Lambda_b$ baryon, while $h$ and $h'$ stand for $\pi$, $K$ or $p$, is of great interest and has been extensively studied at the $B$ factories and the Tevatron [3, 4, 5, 6, 7, 8]. Such decays are sensitive probes of the Cabibbo-Kobayashi-Maskawa matrix and have the potential to reveal the presence of New Physics [9, 10, 11]. The LHCb experiment has an excellent potential to improve dramatically the world knowledge of such decays. We present preliminary values of the direct $CP$ asymmetries in the $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays, defined in terms of decay rates as $A_{CP} = [\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)]/[\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)]$, as well as a measurement of the $B_s^0 \to K^+K^-$ lifetime (see also Refs. [12] and [13]). The analyses are based on the data collected by LHCb during 2010 at a centre of mass energy of 7 TeV, corresponding to an integrated luminosity $\int \mathscr{L} dt \simeq 37\ \mathrm{pb}^{-1}$.

## 2. Measurement of $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B_s^0 \to \pi^+K^-)$

The events used for this analysis are extracted from the triggered data through a stripping algorithm that employs a set of loose selection criteria, followed by a tighter event selection, optimized and performed offline. Signal events are discriminated from the combinatorial background by means of some kinematic variables, such as the transverse momenta and impact parameters of the daughter tracks, the transverse momentum of the $B$-hadron candidate and its lifetime. We have determined two sets of selection criteria, where each set is targeted to achieve the best sensitivity on $A_{CP}(B^0 \to K^+\pi^-)$ or on $A_{CP}(B_s^0 \to \pi^+K^-)$. The $H_b \to h^+h'^-$ sample passing the kinematic event selection is then subdivided into different final states using the particle identification (PID) capabilities of the two RICH detectors. PID variables are used to subdivide the events passing the kinematic selection into eight mutually exclusive categories corresponding to distinct final state hypotheses, namely $K^+\pi^-$, $K^-\pi^+$, $\pi^+\pi^-$, $K^+K^-$, $p\pi^-$, $\bar{p}\pi^+$, $pK^-$ and $\bar{p}K^+$.

The calibration of PID observables is one of the crucial aspects of this analysis. As we use the same set of kinematic cuts to select all the various $H_b \to h^+h'^-$ channels, the only difference in selecting each decay mode is due to cuts on PID variables. Hence, in order to determine the amount of background for a given channel, due to all the other channels where at least one particle

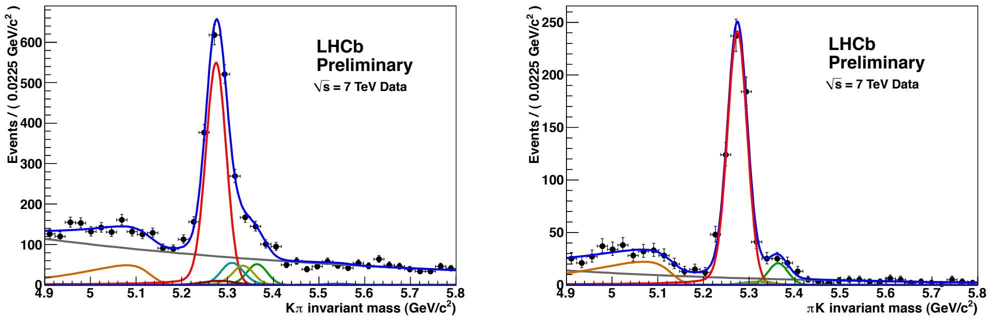


**Figure 1:** Left: $K^+\pi^-$ (plus charge conjugate) invariant mass spectrum for events surviving the event selection optimized for the best sensitivity on $A_{CP}(B^0 \to K^+\pi^-)$. Right: same plot as that on the left, but for events surviving the event selection optimized for the best sensitivity on $A_{CP}(B_s^0 \to \pi^+K^-)$. The result of the unbinned maximum likelihood fit is superimposed. The main components contributing to the fit model explained in the text are also visible: $B^0 \to K\pi$ (red), wrong sign $B^0 \to K\pi$ combination (dark red), $B^0 \to \pi^+\pi^-$ (light blue), $B_s^0 \to K^+K^-$ (dark yellow), $B_s^0 \to \pi K$ (green), combinatorial background (grey), 3-body partially reconstructed decays (orange).

has been mis-identified (cross-feed background), the relative PID efficiencies amongst the various final states play a key role. The high production rate of charged $D^*$ mesons at the LHC and the kinematic characteristics of the $D^{*+} \to D^0(K^-\pi^+)\pi^+$ decay chain (and its charge conjugate) make such events an ideal calibration sample for the PID of kaons and pions. In addition, for calibrating the RICH response for protons, a sample of $\Lambda \to p\pi^-$ decays can be used. In both cases, no use of PID information needs to be made in selecting the samples, as the selection of highly pure final states can be realized by means of kinematic cuts alone. Since the production and decay kinematics of the $D^0 \to K^-\pi^+$ and $\Lambda \to p\pi^-$ channels differ from those of $H_b \to h^+h'^-$ decays, the distributions obtained from calibration samples have been reweighted in $p$ and $p_T$ in order to match the corresponding distributions of daughter particles in $H_b \to h^+h'^-$ decays.

We perform unbinned maximum likelihood fits to the mass spectra of offline selected events passing the kinematic and PID selections optimized for the measurements of $A_{CP}(B^0 \to K^+\pi^-)$ or of $A_{CP}(B_s^0 \to \pi^+K^-)$. The extraction of the two signal decays $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ from the $K^\pm\pi^\mp$ mass spectra must take account of three distinct sources of background: combinatorial background, that is a non-peaking component present over the whole mass window; 3-body $B$-decay background, e.g. composed of $B \to \rho\pi$ decays where one of the pions from the $\rho$ decay is missed, which occurs below the signal mass peaks due to the missing mass; cross-feed background, i.e. the background determined by all the other charmless two-body $H_b$ decay modes, where one or both decay products have been mis-identified.

Two fits have been done, either using the selection optimized for the best sensitivity on $A_{CP}(B^0 \to K^+\pi^-)$ (Fig. 1, left) or on $A_{CP}(B_s^0 \to \pi^+K^-)$ (Fig. 1, right). The dominant signal visible in the plots is due to the $B^0 \to K^+\pi^-$ decay. As is apparent, the tighter selection optimized for $A_{CP}(B_s^0 \to \pi^+K^-)$ causes a stronger suppression of the combinatorial background, with respect to the selection optimized for $A_{CP}(B^0 \to K^+\pi^-)$. From the mass fits we can extract raw asymmetries between $CP$-coniugated final states. Such asymmetries must then be corrected for instrumental and production asymmetries in order to determine the corresponding physical *CP* asymmetries, as we will discuss in the following.

The *CP* asymmetries we want to measure are related to the raw asymmetries measured in data by

$$A_{CP} = A_{CP}^{RAW} - A_D - \kappa A_P, \tag{2.1}$$

where $A_D$ is the instrumental asymmetry in reconstructing $K^+\pi^-$ and $K^-\pi^+$ final states, $A_P$ is the production asymmetry defined in terms of the $B$ and $\bar{B}$ production rates as

$$A_P = \frac{R_{\bar{B}} - R_B}{R_{\bar{B}} + R_B}, \tag{2.2}$$

and $\kappa$ is a factor that takes into account the $B - \bar{B}$ oscillation and is given by

$$\kappa = \frac{\int \left(e^{-\Gamma t} \cos \Delta m t\right) \varepsilon(t) dt}{\int \left(e^{-\Gamma t} \cosh \frac{\Delta\Gamma}{2} t\right) \varepsilon(t) dt}. \tag{2.3}$$

In this last equation, $\varepsilon(t)$ is the acceptance for the decay of interest, expressed as a function of the proper decay time.

The $\kappa$ factors for $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B_s^0 \to \pi^+K^-)$ are calculated by determining the acceptance function from Monte Carlo simulations, using the event selections optimized for the respective $A_{CP}$ measurements. In the calculation we assume $\Delta\Gamma_d = 0$ and we use the central values of the current world averages for $\Gamma_d$, $\Gamma_s$, $\Delta m_d$, $\Delta m_s$ and $\Delta\Gamma_s$ [15]. Owing to the fast $B_s^0$ oscillations, the $\kappa$ factor for the case of the $B_s^0 \to \pi^+K^-$ decay is small (1.5%), i.e. the possible presence of a $B_s^0$ production asymmetry would not affect the measurement of $A_{CP}(B_s^0 \to \pi^+K^-)$ in a sizeable way. In contrast, the $\kappa$ factor for the case of the $B^0 \to K^+\pi^-$ decay is 33%, hence the presence of a $B^0$ production asymmetry would have a non-negligible effect when extracting $A_{CP}(B^0 \to K^+\pi^-)$ from the respective raw asymmetry.

We determine $A_D$ by using high statistics samples of tagged $D^{*+} \to D^0(K^-\pi^+)\pi^+$, $D^{*+} \to D^0(K^+K^-)\pi^+$ and $D^{*+} \to D^0(\pi^+\pi^-)\pi^+$, and untagged $D^0 \to K^-\pi^+$ decays (plus their charge conjugate modes). A simultaneous analysis of the integrated raw asymmetries of all these decays is necessary to disentangle the various contributions to the raw asymmetries of each individual mode. The presence of open charm production asymmetries arising from the primary proton-proton interaction and the subsequent hadronization phase constitutes an additional complication which needs to be considered [16]. We determine the value of $A_D$ to be $A_D = -0.004 \pm 0.004$.

Since $B^+$ and $B^0$ mesons share valence quarks with the initial protons, it is expected that they are produced at a higher rate than $B^-$ and $\bar{B}^0$ mesons [17]. We estimate the size of such a production asymmetry by reconstructing a sample of $B^\pm \to J/\psi(\mu^+\mu^-)K^\pm$ decays, where the flavour of the decaying $B$ is tagged via the sign of the $K$ meson. As we need the production asymmetry for neutral $B$ mesons, we assume that $A_P(B^0)$ is equal to $A_P(B^+)$, but introducing a systematic error of 0.01 to account for possible differences, and obtain $A_P(B^0) = -0.024 \pm 0.013 \pm 0.010$. Such an additional systematic uncertainty has been determined by studying the predictions of different Monte Carlo fragmentation models [17].

By using the central value of $A_{CP}^{RAW}(B^0 \to K^+\pi^-)$ extracted from the mass fit, we can then get the corrected central value of the *CP* asymmetry $A_{CP}(B^0 \to K^+\pi^-) = -0.074$. For the case of the

| Systematic uncertainty | $A_{CP}(B^0 \to K^+\pi^-)$ | $A_{CP}(B^0_s \to \pi^+K^-)$ |
|---|---|---|
| PID calibration | 0.0021 | 0.001 |
| Final state radiation | 0.0034 | 0.011 |
| Signal model | 0.0019 | 0.009 |
| Combinatorial background model | negligible | 0.013 |
| Cross-feed background model (shift) | 0.0009 | 0.005 |
| Cross-feed background model (smearing) | 0.0006 | 0.006 |
| Instrumental asymmetry | 0.0042 | 0.004 |
| Production asymmetry | 0.0054 | negligible |
| Total | 0.0082 | 0.021 |

**Table 1:** Summary of systematic uncertainties on $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B^0_s \to \pi^+K^-)$. The total systematic uncertainties given in the last row are obtained by summing in quadrature all the contributions.

$B^0_s \to \pi^+K^-$ decay, even assuming conservatively that the $B^0_s$ production asymmetry is as large as that used above, one gets a negligible systematic shift, due to the very small value of the factor $\kappa$ in this case. The value of $A^{RAW}_{CP}(B^0_s \to \pi^+K^-)$ determined from the mass fit is practically unaffected by corrections due to instrumental and production asymmetries, given the large statistical error. The central value of the $CP$ asymmetry is $A_{CP}(B^0_s \to \pi^+K^-) = 0.15$.

The systematic errors on $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B^0_s \to \pi^+K^-)$ that we identify fall into three main categories, related to PID calibration, modelling of the signal and background components in the maximum likelihood fits, and instrumental and production asymmetries. The various contributions are summarized in Tab. 1.

Taking into account the systematic uncertainties, we can provide the following values of the direct $CP$ asymmetries:

$$A_{CP}(B^0 \to K^+\pi^-) = -0.074 \pm 0.033(\mathrm{stat}) \pm 0.008(\mathrm{syst}) \tag{2.4}$$

and

$$A_{CP}(B^0_s \to \pi^+K^-) = 0.15 \pm 0.19(\mathrm{stat}) \pm 0.02(\mathrm{syst}). \tag{2.5}$$

The current HFAG average $A_{CP}(B^0 \to K^+\pi^-) = -0.098^{+0.012}_{-0.011}$ [14] and the CDF measurement $A_{CP}(B^0_s \to \pi^+K^-) = 0.39 \pm 0.15 \pm 0.08$ [6, 7] are in agreement with our values.

## 3. Measurement of the effective $B^0_s \to K^+K^-$ lifetime

A measurement of the $B^0_s \to K^+K^-$ lifetime may be used to put constraints on contributions from New Physics to the $B^0_s$ mixing phase and the width difference between the light and heavy states $\Delta\Gamma_s$ [10, 11, 18, 19]. The selection of the sample of $B$ mesons decaying into two hadrons makes minimum requirements on the flight distance of the $B$ meson, both during data-taking and in the final event selection. Consequently, the selection procedure tends to reject candidates which decay after a short proper time. Two independent data-driven approaches have been developed to compensate for the resulting bias. One extracts the acceptance function from the data, and then



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applies this acceptance correction to obtain a measurement of the $B_s^0 \to K^+K^-$ lifetime. The other method cancels the selection bias by taking a ratio of the $B_s^0 \to K^+K^-$ and $B^0 \to K^+\pi^-$ proper decay time distributions. The $B_s^0 \to K^+K^-$ lifetime is then extracted, using the world average measurement of the $B^0 \to K^+\pi^-$ lifetime as input.

In general the measured proper time distribution in the untagged $B_s^0 \to K^+K^-$ decay is given by

$$\hat{\Gamma}(B_s^0 \to K^+K^-) = R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t} \tag{3.1}$$

where $R_H$ and $R_L$ are the fractions of the heavy and light states contributing to the $B_s^0 \to K^+K^-$ decay. $\hat{\Gamma}(B_s^0 \to K^+K^-)$ is primarily sensitive to the width of the short-lived light state of the $B_s^0$. We perform a maximum likelihood fit to the lifetime with a function consisting of a single exponential. In the absence of acceptance effects, this yields a value [20]

$$\Gamma_f = \frac{R_L/\Gamma_L + R_H/\Gamma_H}{R_L/\Gamma_L^2 + R_H/\Gamma_H^2}. \tag{3.2}$$

The comparison of such a measurement with a lifetime obtained from a flavour specific decay, allows one to extract $\Delta\Gamma_s$. Any New Physics effect in $B_s^0 \to K^+K^-$ will lead to a reduction in the measured $\Delta\Gamma_s$ with respect to the Standard Model prediction [18].

In the absolute measurement the lifetime is determined by an unbinned maximum likelihood fit using an analytical probability density function (p.d.f.) for the signal lifetime and a non-parametric estimated p.d.f. for the combinatorial background. The measurement is factorised in two independent fits. A first fit is performed to the observed mass spectrum and used to determine the signal and background probabilities of each event. These probabilities are used in the subsequent fit for the lifetime. The p.d.f. describing the lifetime of the signal is calculated analytically taking into account per-event acceptance and the proper time resolution. The per-event acceptance is calculated by re-running the event selection, determining whether an event would have been selected as a function of its proper time. For example, for an event with given kinematics, i.e. fixed track slopes and momenta, there is a direct relation between the proper time and the impact parameters of the tracks. Hence, cuts on impact parameters directly translate into a discrete decision about acceptance or rejection of an event as a function of its proper time. The fitted mass and proper time distributions are shown in Fig. 2.

The relative lifetime measurement is based on the fact that the decays $B_s^0 \to K^+K^-$ and $B^0 \to K^+\pi^-$ are kinematically almost identical. Consequently, the proper time bias due to the trigger and selection is, to a good approximation, equal for both channels and cancels in the ratio of the proper time distributions. It is therefore possible to make an unbiased measurement of the $B_s^0 \to K^+K^-$ lifetime by taking a ratio of the proper time distribution with that of $B^0 \to K^+\pi^-$, using the more precisely constrained $B^0$ lifetime as input.

The two complementary approaches yield two measurements of the $B_s^0 \to K^+K^-$ lifetime which agree well. Our preliminary result is

$$\tau(B_s^0 \to K^+K^-) = 1.440 \pm 0.096(\text{stat}) \pm 0.010(\text{syst}) \text{ ps}. \tag{3.3}$$

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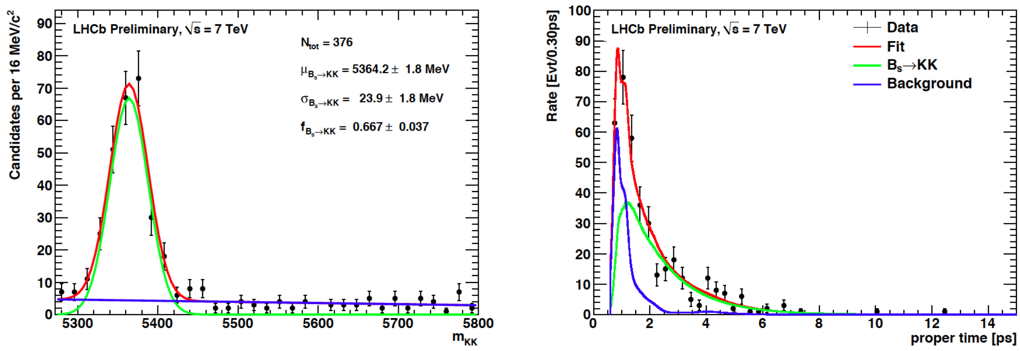


**Figure 2:** Left: Fit to the invariant mass spectrum for $B_s^0 \to K^+K^-$. Right: Fit for the lifetime.


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