PROCEEDINGS OF SCIENCE

Time integrated and time dependent asymmetries in $B \to hh^{'}$ ($h = K, \pi$) decays at LHCb

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During 2011, LHCb has collected an integrated luminosity of 1.0 fb^{-1}, giving rise to a large variety of measurements. Amongst these, measurements of *CP* violation in *B* decays play a central role. In particular *CP* violation measurements in charmless transitions of *B* mesons are of interest since they provide new or improved constraints on new physics contributions. These proceedings summarise LHCb results made public in the year 2012 and 2013, with particular emphasis on the first observation of direct *CP* violation in the B_s^0 system.

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1. Introduction

The LHCb detector [1] is a single arm spectrometer designed to accurately measure decay products of B and D mesons for precision measurements at the LHC. In the following, an overview of recent studies in B decays to two pseudoscalar particles performed by the LHCb collaboration is presented. Other measurements conducted with the LHCb detector are summarised in the relevant contributions to these proceedings, in particular other charmless decays are covered in [2, 3].

Key ingredients for the analyses presented in the following are the ability to trigger on [4] and to disentangle different modes owing to dedicated ring-imaging Cherenkov detectors [5]. Some measurements additionally require good tagging capabilities and excellent proper time resolution [6]. The data samples used for the analyses presented here are based on pp collision data collected in 2011 at $\sqrt{s} = 7\,\text{TeV}$ corresponding to integrated luminosities ranging from $0.35\,\text{fb}^{-1}$ to $1.0\,\text{fb}^{-1}$.

2. General strategy

CP violation in charmless B decays allows important information to be extracted on phases of the Unitarity Triangle, in particular the angle γ. These measurements are generally sensitive to new physics effects, since the involved processes are characterised by dominant loop contributions. The drawback lies in the numerous diagram topologies that contribute to these decays. Thus the extraction of the weak phases is considered as more complicated than in the Standard Model benchmark measurements of these quantities performed with $B^0 \to J/\psi K^0_S$ and open charm decays.

The $B \to hh'$ decays are key channels to develop this strategy at LHCb [7]. Tagged time dependent analyses are also targeted to maximally exploit the information contained in these decays. In particular the four observables in the time dependent analyses must be combined with additional constraints to reduce the initial amount of unknown parameters from 7 to 4. This can be done by using U-spin symmetry to relate hadronic parameters [7]. This assumption can be controlled by measuring the direct *CP* asymmetry in the flavour specific U-spin partners $B^0_s \to K^-\pi^+$ and $B^0 \to K^+\pi^-$. Moreover the size of the suppressed polluting amplitudes in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays is measured in the rare $B^0 \to K^+K^-$ and $B^0_s \to \pi^+\pi^-$ decays.

Information about weak phases in these decays can only be obtained providing that all the decays of the $B \to hh'$ family are measured, including direct *CP* violation in flavour specific decays.

3. Branching fraction measurements of $B \to hh'$ decays

With $0.37\,\text{fb}^{-1}$, the rare $B^0 \to K^+K^-$ and $B^0_s \to \pi^+\pi^-$ decay modes, dominated by exchange and penguin annihilation diagrams, are searched for [8]. The first observation of $B^0_s \to \pi^+\pi^-$ is obtained and its branching fraction measured to be

$$\mathscr{B}\left(B^0_s \to \pi^+\pi^-\right) = (0.95\ {}^{+0.21}_{-0.17}\,(\text{stat.})\ \pm 0.13\,(\text{syst.})) \times 10^{-6}, \tag{3.1}$$

while the $B^0 \to K^+K^-$ branching fraction is found equal to

$$\mathscr{B}\left(B^0 \to K^+K^-\right) = (0.11\ {}^{+0.05}_{-0.04}\,(\text{stat.})\ \pm 0.06\,(\text{syst.})) \times 10^{-6}. \tag{3.2}$$

In the same analysis the $B_s^0 \to K^-\pi^+$ and $B_s^0 \to K^+K^-$ branching fractions are determined,

$$\mathscr{B}\left(B_s^0 \to K^-\pi^+\right) = (5.4 \pm 0.4 \text{ (stat.) } \pm 0.6 \text{ (syst.)}) \times 10^{-6}, \tag{3.3}$$

$$\mathscr{B}\left(B_s^0 \to K^+K^-\right) = (23.0 \pm 0.7 \text{ (stat.) } \pm 2.3 \text{ (syst.)}) \times 10^{-6}, \tag{3.4}$$

with the best precision to date. The ratio of branching fractions of similar Λ_b decays is also extracted,

$$\mathscr{B}\left(\Lambda_b \to pK^-\right) / \mathscr{B}\left(\Lambda_b \to p\pi^-\right) = 0.86 \pm 0.08 \text{ (stat.) } \pm 0.05 \text{ (syst.)}. \tag{3.5}$$

4. First observation of direct *CP* violation in the B_s^0 system

Searches for direct *CP* violation in the flavour specific $B_s^0 \to K^-\pi^+$ decays are performed using an integrated luminosity of $1.0\,\text{fb}^{-1}$ [9], in a recent update of a $0.35\,\text{fb}^{-1}$ analysis [10]. Small corrections to the raw *CP* asymmetries, clearly visible by eye in Fig. 1, are introduced to account for detection and production asymmetries. Detection asymmetries, induced by different reconstruction efficiencies and by different cross sections in the interactions of oppositely charged particles with the detector material, are determined by means of large samples of two-body D meson decays. A potential *CP* asymmetry in the $D^0 \to K^+K^-$ decays is also accounted for in this correction according to the HFAG [11] average. Finally the kinematics of the D decays are reweighted to match those of the B decays. The corresponding corrections amount to approximately $(1.2 \pm 0.2)\%$. The production asymmetry of B^0 mesons is directly extracted from the decay time dependence of the observed asymmetry as $A_{raw}(t) \simeq A_{CP} + A_{det.} + A_{prod.} cos(\Delta m_{d(s)} t)$. The obtained $A_{prod.}(B^0) = (0.1 \pm 1.0)\%$ and $A_{prod.}(B_s^0) = (4 \pm 8)\%$ are further diluted by mixing and the shape of the proper time acceptance by factors of 0.303 ± 0.005 and -0.033 ± 0.003 respectively.

The B_s^0 and B^0 *CP*-violating asymmetries are thus determined to be [9]:

$$A_{CP}^{B_s^0 \to K\pi} = \frac{\mathscr{B}\left(\bar{B}_s^0 \to K^+\pi^-\right) - \mathscr{B}\left(B_s^0 \to K^-\pi^+\right)}{\mathscr{B}\left(\bar{B}_s^0 \to K^+\pi^-\right) + \mathscr{B}\left(B_s^0 \to K^-\pi^+\right)} = 0.27 \pm 0.04 \text{ (stat.)} \pm 0.01 \text{ (syst.)}, \tag{4.1}$$

$$A_{CP}^{B^0 \to K\pi} = \frac{\mathscr{B}\left(\bar{B}^0 \to K^-\pi^+\right) - \mathscr{B}\left(B^0 \to K^+\pi^-\right)}{\mathscr{B}\left(\bar{B}^0 \to K^-\pi^+\right) + \mathscr{B}\left(B^0 \to K^+\pi^-\right)} = -0.080 \pm 0.007 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \tag{4.2}$$

For the first time, an observation of (direct) *CP* violation in the B_s^0 system is obtained. The dominating systematics are linked to the modeling of the B invariant mass in the B_s^0 case and to the polluting asymmetries in the B^0 case. Both will be reduced with larger integrated luminosities. These results are in agreement and more precise with respect to previous measurements [12, 13, 14].

5. Effective lifetime measurement of the B_s^0 meson in the $B_s^0 \to K^+K^-$ decay

A measurement of the effective lifetime of the B_s^0 meson in the $B_s^0 \to K^+K^-$ decay is performed with $1\,\text{fb}^{-1}$. This quantity, sensitive to *CP* violation and potential new physics effects, has already been measured at LHCb [15].

A new analysis has been performed employing a strategy that attempts to minimise systematic uncertainties associated with the decay time acceptance, by ensuring this acceptance is kept as flat

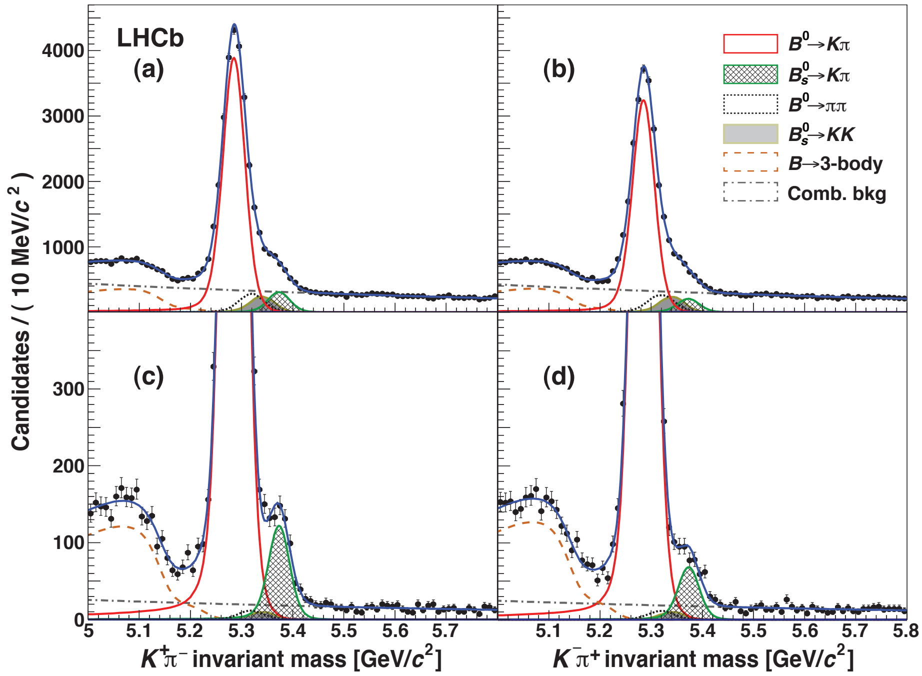

Figure 1: The $K^+\pi^-$ (left) and $K^-\pi^+$ (right) invariant mass spectra optimised for the B^0 asymmetry measurement (top), and for the B_s^0 asymmetry measurement (bottom), see [9] for details.

as possible at all stages in the analysis [16]. The acceptance of the reconstructed B_s^0 candidates as a function of the decay time is shown in Fig. 2. The result of the analysis

$$\tau_{KK} = 1.455 \pm 0.046 \text{ (stat.) } \pm 0.006 \text{ (syst.) ps}, \tag{5.1}$$

for which the systematic uncertainty is still dominated by a proper time reconstruction bias, is in agreement with the expectation assuming no NP contributions $\tau_{KK} = 1.40 \pm 0.02$ [16, 17].

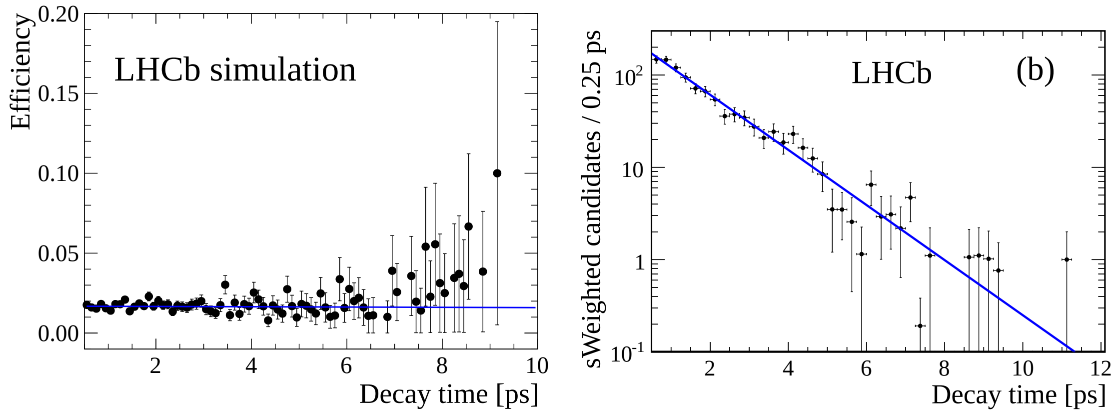

Figure 2: Acceptance of B mesons as a function of the decay time on simulated $B_s^0 \to K^+K^-$ signal candidates (left). A linear fit to the decay time (right) yields an effective lifetime of $\tau_{KK} = 1.455 \pm 0.046$ (stat.) $\pm$ 0.006 (syst.) ps [16].

6. Time dependent *CP* violation measurements of $B \to hh'$ decays

With $0.69\,\mathrm{fb}^{-1}$, the analysis is sensitive to time dependent *CP* violation [18], that is measured by means of opposite side flavour tagging, based on a combination of the electron, muon, kaon and secondary vertex taggers, which exploit the decay products of the other b-hadron produced in the event [6]. In order to calibrate this algorithm, and to exercise the whole analysis, $B^0 \to K^+\pi^-$ is used as a proxy.

From a simultaneous fit of the $K\pi$ invariant mass and the time of flight of the reconstructed B meson, and assuming the B_s^0 mixing parameters are perfectly determined by other LHCb measurements [19, 20] and $\Delta\Gamma_d = 0$, the effective tagging efficiency (or *tagging power*) $\varepsilon D^2 = 2.3 \pm 0.1\%$, the B^0 and B_s^0 production asymmetries $A_P(B^0) = -0.015 \pm 0.013$ and $A_P(B_s^0) = -0.03 \pm 0.06$, where only statistical uncertainties are quoted, are extracted. These quantities are used as input for the $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ time dependent analyses.

In order to extract the time dependent violation in $B^0 \to \pi^+\pi^-$ decays, Δm_d is fixed to the central value measured in $B^0 \to D^-\pi^+$ decays [21], $\Delta m_d = 0.499 \pm 0.032$ (stat.) ± 0.003 (syst.) ps^{-1}, the central value being varied to estimate the related systematic uncertainty. Assuming $\Delta\Gamma_d = 0$, the direct and mixing induced *CP* asymmetries are both extracted together with their statistical correlation factor:

$$A^{dir.}_{\pi^+\pi^-} = 0.11 \pm 0.21\ \text{(stat.)}\ \pm 0.03\ \text{(syst.)}, \tag{6.1}$$

$$A^{mix.}_{\pi^+\pi^-} = -0.56 \pm 0.17\ \text{(stat.)}\ \pm 0.03\ \text{(syst.)}, \tag{6.2}$$

$$\rho(A^{dir.}_{\pi^+\pi^-}, A^{mix.}_{\pi^+\pi^-}) = 0.34\ \text{(stat.)}. \tag{6.3}$$

The dominating sources of (relatively small) systematic uncertainties are the central values used for the input parameters (namely Δm_d and tagging efficiencies) and the model used to parameterise the decay time (both signal and background). The raw mixing asymmetry together with the result of the fit is shown in Fig. 3 (left).

Time dependent *CP* violation is also looked for in $B_s^0 \to K^+K^-$ decays by fixing $\Delta m_s = 17.63 \pm 0.11$ (stat.) ± 0.02 (syst.) ps^{-1} [19] and $\Gamma_s = 0.657 \pm 0.009$ (stat.) ± 0.008 (syst.) ps^{-1} [20] to their respective central values. A determination of $\Delta\Gamma_s = 0.076 \pm 0.019\,\mathrm{ps}^{-1}$, where only statistical uncertainty is quoted, is also obtained as a side product of the analysis. This is in agreement with a previous measurement of the same quantity by another LHCb analysis [20], with similar uncertainty and thus consists in a suitable cross-check. The direct and mixing induced *CP* asymmetries are both extracted together with their statistical correlation factor:

$$A^{dir.}_{K^+K^-} = 0.02 \pm 0.18\ \text{(stat.)}\ \pm 0.04\ \text{(syst.)}, \tag{6.4}$$

$$A^{mix.}_{K^+K^-} = 0.17 \pm 0.18\ \text{(stat.)}\ \pm 0.05\ \text{(syst.)}, \tag{6.5}$$

$$\rho(A^{dir.}_{K^+K^-}, A^{mix.}_{K^+K^-}) = 0.10\ \text{(stat.)}, \tag{6.6}$$

where the contributions to the systematic uncertainties are again dominated by the uncertainty on the input parameters and the decay time model. The raw mixing asymmetry together with the result of the fit is shown in Fig. 3 (right).

Hence a first measurement of the time dependent asymmetry in $B_s^0 \to K^+K^-$ decays is obtained, as well as an evidence of mixing-induced *CP* violation in the $B^0 \to \pi^+\pi^-$ decays. This last result is in agreement with previous determinations but it does not yet reach their precision [12, 22, 23].

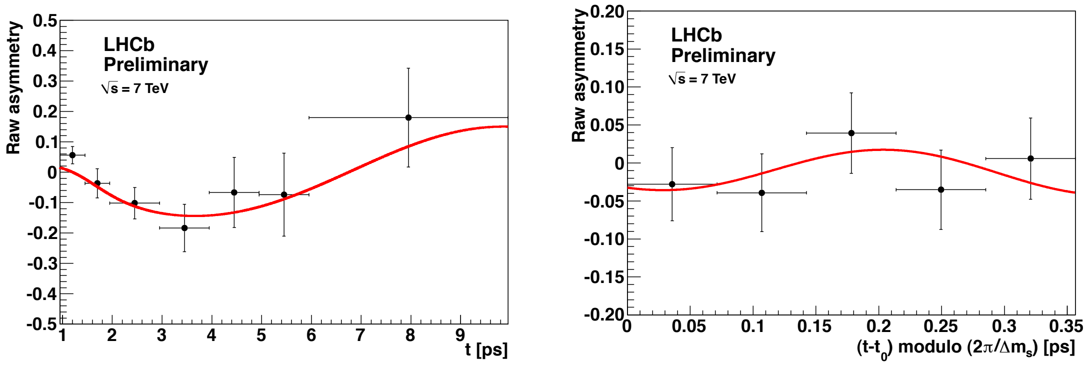

Figure 3: Raw mixing asymmetry in the $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ signal mass regions respectively on the left and right hand side of the figure, with the result of the fit overlaid [18].

7. Conclusion

With at most 1 fb^{-1} of data analysed by LHCb, time integrated $B \to hh'$ decays are measured with world leading precisions. In particular the rare $B_s^0 \to \pi^+\pi^-$ mode has been observed for the first time and typically 10% precise determinations of the branching fractions of the U-spin partners of the $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays are obtained. Direct *CP* asymmetries in the flavour specific $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays are now determined with unprecedented precision. In particular, the first observation of (direct) *CP* violation in B_s^0 decays is reported, allowing for a comparison with its U-spin related quantity, the direct *CP* asymmetry in $B^0 \to \pi^+\pi^-$. Moreover $B_s^0 \to K^+K^-$ time dependent asymmetries are measured for the first time. These measurements give some confidence about the validity of the hypotheses needed for a loop-dominated measurement of the weak $\gamma(\varphi_3)$ angle. Another approach to constrain new physics in the $B \to hh'$ decays consist in measuring the effective lifetime of $B_s^0 \to K^+K^-$ and to compare it to $\Delta\Gamma_s$ and ϕ_s measurements. All these measurements are compatible with the Standard Model, and will improve with updates of these analyses.

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