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Measurement of time-dependent *CP*-violating asymmetries in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays at LHCb

Stefano Perazzini[*†]
CERN, Switzerland
E-mail: stefano.perazzini@cern.ch

Using a data sample of pp collisions corresponding to an integrated luminosity of 3 fb^{-1}, collected with the LHCb detector at a centre-of-mass energies of 7 and 8 TeV, the *CP*-violating asymmetries in the decay and in the interference between mixing and decay in the $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ modes are measured. The results are $C_{\pi^+\pi^-} = -0.24 \pm 0.07 \pm 0.01$, $S_{\pi^+\pi^-} = -0.68 \pm 0.06 \pm 0.01$, $C_{K^+K^-} = 0.24 \pm 0.06 \pm 0.02$, $S_{K^+K^-} = 0.22 \pm 0.06 \pm 0.02$, and $A^{\Delta\Gamma}_{K^+K^-} = -0.75 \pm 0.07 \pm 0.11$, where the first uncertainties are statistical and the second systematic.

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[*] on behalf of LHCb Collaboration
[†] Speaker.

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The $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays[1] represent an interesting laboratory to probe the Cabibbo-Kobayashi-Maskawa (CKM) picture [1,2] of the Standard Model (SM) and to investigate the presence of possible contributions of new physics beyond it. The time-dependent *CP* asymmetries of these decays are sensible to the CKM phases γ, β and β_s, but the presence of relevant penguin contributions to the decay amplitudes introduces theoretical uncertainties in terms of additional hadronic parameters. However, the hadronic parameters of the two decays are related by U-spin symmetry [3–5], *i.e.* by the exchange of d and s quarks in the decay diagrams. It has been shown that a combined analysis of the branching ratios and *CP* asymmetries in two-body B-meson decays, accounting for U-spin breaking effects, allows for the determination of the CKM phases γ and $-2\beta_s$ [6,7].

In this document, the measurements of the time-dependent *CP*-violating asymmetries in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays are presented. The analysis is based on a data sample of pp collisions corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$ collected with the LHCb detector [8,9] at centre-of-mass energies of 7 and 8 TeV.

The time-dependent *CP* asymmetry between $B^0_{(s)}$ and $\bar{B}^0_{(s)}$ mesons decaying to a *CP* eigenstate f is given by

$$\mathscr{A}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right)},$$

where $\Delta m_{d,s}$ and $\Delta\Gamma_{d,s}$ are the mass and width differences of the mass eigenstates in the $B^0_{(s)} - \bar{B}^0_{(s)}$ system. Assuming negligible *CP* violation in the $B^0_{(s)} - \bar{B}^0_{(s)}$ mixing, C_f and S_f parameterise *CP* violation in the decay and in the interference between the mixing and the decay, respectively.

Event selection is optimised against two main sources of backgrounds: other two-body b-hadron decays with misidentified pions, kaons or protons in the final state (cross-feed background), and combinatorial background. A third source of background, due to partially reconstructed three-body B decays (three-body background), is found to populate an invariant mass region well separated from the signal mass peak, hence no selection is optimised against this component.

The acquired events are filtered using a loose preselection, mainly reducing the amount of combinatorial background. Candidates passing the preselection are then classified into mutually exclusive samples corresponding to the $\pi^+\pi^-$, K^+K^- and $K^+\pi^-$ final states by means of the particle identification (PID) information provided by the two RICH detectors of LHCb. The $K^+\pi^-$ sample, containing the flavour-specific $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays, is used as a calibration sample. Finally, a boosted decision tree (BDT) algorithm [10, 11] is used to further reduce the amount of combinatorial background.

The main cross-feed background contributing to the $\pi^+\pi^-$ and K^+K^- spectra is represented by the $B^0 \to K^+\pi^-$ decay with one of the two final-state particles misidentified. The PID requirements are optimised in order to reduce the amount of this cross-feed background to approximately 10% of the $B^0 \to \pi^+\pi^-$ ($B_s^0 \to K^+K^-$) signal in the $\pi^+\pi^-$ (K^+K^-) sample. Similarly, the PID requirements used to select the $K^+\pi^-$ sample are optimised to reduce the amount of the $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ cross-feed backgrounds to about 10% of the $B_s^0 \to \pi^+K^-$ yield.

[1] Charge conjugation is implied throughout this document.

PID efficiencies and misidentification probabilities for kaons and pions, used to determine the cross-feed-background contamination, are determined using samples of $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays [12].

The BDT discriminant combines information from kinematical and geometrical properties of the reconstructed candidates. Simulated events and data in the high-mass sideband ($5.6 < m < 5.8\,\mathrm{GeV}/c^2$) are used to model the signals and the combinatorial background, respectively, in the training of the BDT. The optimal threshold on the BDT response is chosen to maximise $S/\sqrt{S+B}$, where S and B represent the numbers of signal and combinatorial background candidates in a window around the signal masses of $\pm 60\,\mathrm{MeV}/c^2$ (corresponding to about ± 3 times the invariant mass resolution).

Time-dependent *CP* asymmetry terms are determined by means of a simultaneous unbinned maximum likelihood fit to the distributions of the selected candidates in the $\pi^+\pi^-$, K^+K^- and $K^+\pi^-$ final-state hypotheses. For each component that contributes to the selected samples, the following distributions are modelled: invariant mass, decay time, assigned flavour of the B candidate (flavour tagging) and associated per-event mistag probability, and per-event decay time error. Crucial inputs to the fit are the calibration of the flavour tagging and of the decay-time resolution. They introduce a dilution factor in the observed amplitude of the time-dependent asymmetry corresponding to $D = (1-2\omega) \times \exp\left(-0.5\Delta m_{(s)}^2 \sigma_t^2\right)$, where ω is the actual mistag probability and σ_t is the width of the decay time resolution.

So-called opposite-side (OS) taggers are used to determine the initial flavour of the signal B meson [13]. Since b quarks are produced in pairs in pp collisions, flavour tagging is achieved by looking at the charge of the lepton, either muon or electron, originating from semileptonic decays, and of the kaon from the $b \to c \to s$ decay transition of the other b in the event. This information is combined into a decision (ξ) and a predicted mistag probability (η) by means of an artificial neural network. The sensitivity to the time-dependent *CP* asymmetry is directly related to the tagging power, defined as $\varepsilon_{\rm eff} = \sum_i |\xi_i|\,(1-2\omega_i)^2/N$, where ω_i and ξ_i are the actual mistag probability and the tagging decision, respectively, of the i-th of the N total candidates. The relation between η and ω is calibrated during the fit itself, from the tagged time-dependent decay rates of the $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays. Notably, from the same rates it is also possible to determine the possible imbalance between the production rates of $B_{(s)}^0$ and $\bar{B}_{(s)}^0$ mesons, the so-called production asymmetry.

The model used to describe the decay-time resolution is studied from fully simulated $B_s^0 \to \pi^+K^-$ and $B_s^0 \to D_s^-\pi^+$ decays. It is found that for both decays the distribution of the difference between the reconstructed and simulated decay time is well described by a double Gaussian function, with zero mean and widths depending on the per-event decay-time error δ_t. In addition the parameters governing the distribution are found to be very similar between the two decay modes. By fitting the tagged decay-time distributions of fully simulated $B_s^0 \to \pi^+K^-$ and $B_s^0 \to D_s^-\pi^+$ decays, the possibility of calibrating the relation between δ_t and σ_t has been proved, once the response of the OS taggers is known. In order to calibrate the decay-time resolution in data, tagged time-dependent fits are performed to $B_s^0 \to D_s^-\pi^+$ decays with the calibration of the OS taggers determined from the study of $B^0 \to D^-\pi^+$ decays.

The simultaneous fit to the invariant mass, decay time, per-event mistag probability and per-event decay time error distributions of the $K^+\pi^-$, $\pi^+\pi^-$ and K^+K^- spectra determines in particular

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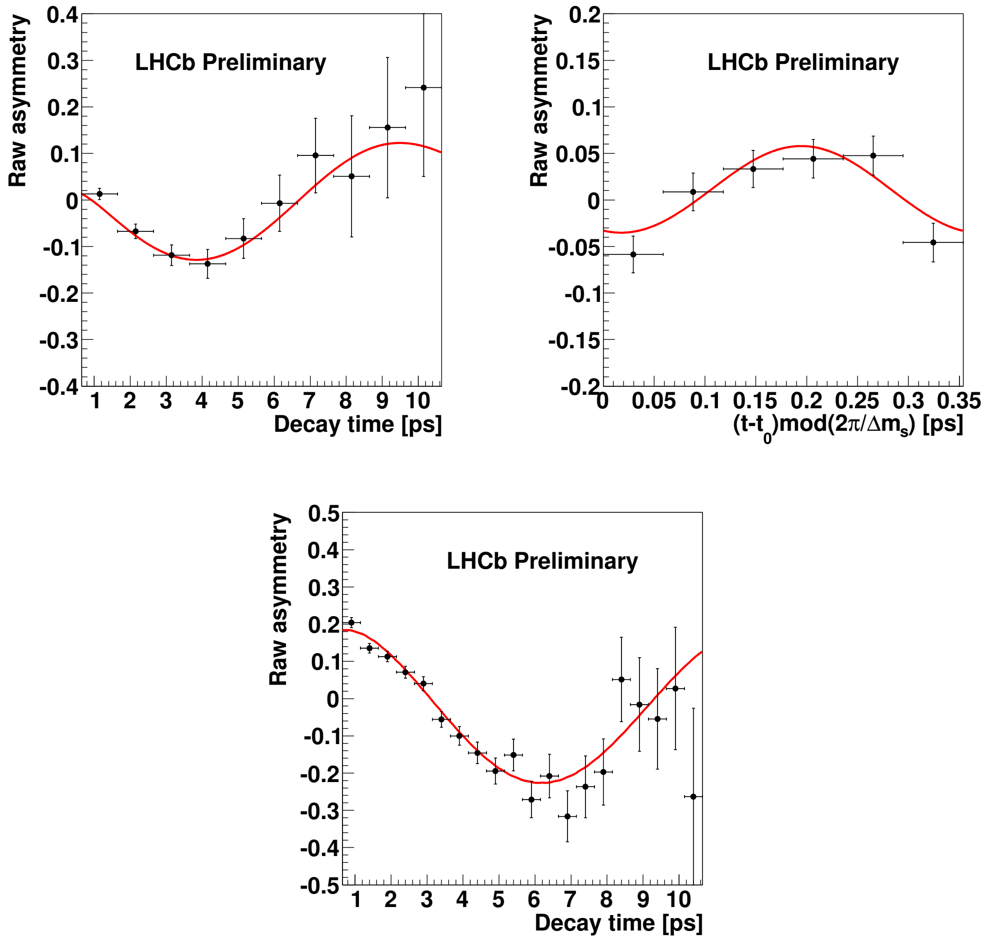

Figure 1: Raw time-dependent asymmetry for the (top left) $\pi^+\pi^-$, (top right) K^+K^- and (bottom) $K^+\pi^-$ spectra for candidates lying in the invariant mass regions dominated by the signals, and corresponding to $5.20 < m < 5.35\,\text{GeV}/c^2$, $5.30 < m < 5.45\,\text{GeV}/c^2$ and $5.20 < m < 5.32\,\text{GeV}/c^2$, respectively.

the coefficients $C_{\pi^+\pi^-}$, $S_{\pi^+\pi^-}$, $C_{K^+K^-}$, $S_{K^+K^-}$ and $A^{\Delta\Gamma}_{K^+K^-}$. In the fits the parameters $\Delta m_{d(s)}$, $\Gamma_{d(s)}$, and $\Delta\Gamma_s$ are fixed to the HFAG averages [14], while the value of $\Delta\Gamma_d$ is fixed to 0. Signal yields are $N(B^0 \to \pi^+\pi^-) = 28\,652 \pm 226$, $N(B_s^0 \to K^+K^-) = 36\,840 \pm 222$, $N(B^0 \to K^+\pi^-) = 94\,220 \pm 339$ and $N(B_s^0 \to \pi^+K^-) = 7032 \pm 119$. Figure 1 shows the time-dependent asymmetry in the $\pi^+\pi^-$, K^+K^- and $K^+\pi^-$ spectra for candidates lying in the invariant mass region dominated by the signals, correponding to $5.20 < m < 5.35\,\text{GeV}/c^2$, $5.30 < m < 5.45\,\text{GeV}/c^2$ and $5.20 < m < 5.32\,\text{GeV}/c^2$, respectively.

Several sources of systematic uncertainties that may affect the determination of the *CP* asymmetry coefficients in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays are considered. Alternative models are used to describe the invariant mass shapes for all the components. A contribution from $\Lambda_b^0 \to pK^-$ decays to the K^+K^- spectrum, with the proton misidentified as a kaon, is estimated to have a size of 2.5% with respect to that of the $B_s^0 \to K^+K^-$ decay. A parameterisation of this component is included in the fit fixing its yield. Systematic uncertainties associated to the calibration of the per-event decay time resolution are determined inserting Gaussian constraints on the calibration parameters used in the fit. The error on the calibration parameters are inflated in order to take into account the small differences between $B_s^0 \to \pi^+K^-$ and $B_s^0 \to D_s^-\pi^+$ observed in simulation. Alternative models are used to describe the decay time resolution and the distribution of the per-event decay time error. The systematic uncertainties related to the decay time acceptance, *i.e.* the dependency of the reconstruction efficiency as a function of the decay time, are estimated by leaving free the parameters governing this function for the $B^0 \to K^+\pi^-$ decay, while keeping fixed the ratio between the decay time acceptances of the $B^0 \to K^+\pi^-$ decay and of the other signals and cross-feed backgrounds. Alternative models are used to describe the decay time distributions of cross-feed, combinatorial and three-body backgrounds. The systematic uncertainty due to the fixed parameters $\Delta m_{d(s)}$, $\Gamma_{d(s)}$, and $\Delta\Gamma_s$ is determined by repeating the fit with Gaussian constraints on these parameters. The systematic uncertainty due to the calibration of the flavour tagging is determined using an alternative model describing the relation between η and ω. The most relevant systematic uncertainties are found to be: the calibration of the decay time resolution for $C_{K^+K^-}$ and $S_{K^+K^-}$, the decay time acceptance and the input parameters for $A^{\Delta\Gamma}_{K^+K^-}$ and the flavour tagging calibration and the model used to describe the cross-feed decay time distributions for $C_{\pi^+\pi^-}$ and $S_{\pi^+\pi^-}$.

Final results are [17]

$$\begin{aligned}
C_{\pi^+\pi^-} &= -0.24 \pm 0.07 \pm 0.01, \\
S_{\pi^+\pi^-} &= -0.68 \pm 0.06 \pm 0.01, \\
C_{K^+K^-} &= 0.24 \pm 0.06 \pm 0.02, \\
S_{K^+K^-} &= 0.22 \pm 0.06 \pm 0.02, \\
A^{\Delta\Gamma}_{K^+K^-} &= -0.75 \pm 0.07 \pm 0.11,
\end{aligned}$$

where the first uncertainties are statistical and the second systematic. The *CP* asymmetry parameters are found to be mostly uncorrelated with the only exception being $C_{\pi^+\pi^-}$ and $S_{\pi^+\pi^-}$ showing a statistical correlation coefficient $\rho(C_{\pi^+\pi^-}, S_{\pi^+\pi^-}) = 0.376$. The measurements of $C_{\pi^+\pi^-}$ and $S_{\pi^+\pi^-}$ are in good agreement with previous measurements by BaBar [15] and Belle [16]. The measurement of $S_{\pi^+\pi^-}$ is the most precise from a single experiment to date. The measurement of $C_{K^+K^-}$ and $S_{K^+K^-}$ are in good agreement with the previous results from LHCb [18] based on a subsample of the data used in this analysis. Neglecting the small correlations between $C_{K^+K^-}$, $S_{K^+K^-}$ and $A^{\Delta\Gamma}_{K^+K^-}$, and dividing the central values of the measurements by the sum in quadrature of the statistical and systematic uncertainties, the significance for $(C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-})$ to differ from $(0,0,1)$ is determined to be 4.7 standard deviations (σ); that of $(C_{K^+K^-}, S_{K^+K^-})$ to differ from $(0,0)$ is found to be 4.6σ; and those of $C_{K^+K^-}$ and $S_{K^+K^-}$ to differ from 0 are found to be 3.6σ and 3.3σ, respectively. Further improvements in precision are expected with the inclusion of same-side flavour tagging information.

References

[1] N. Cabibbo, *Unitary symmetry and leptonic decays*, Phys. Rev. Lett. **10** (1963) 531.

[2] M. Kobayashi and T. Maskawa, *CP violation in the renormalizable theory of weak interaction*, Prog. Theor. Phys. **49** (1973) 652.

[3] R. Fleischer, *New strategies to extract β and γ from $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$*, Phys. Lett. **B459** (1999) 306, arXiv:hep-ph/9903456.

[4] R. Fleischer, *$B_{s,d} \to \pi\pi, \pi K, KK$: Status and prospects*, Eur. Phys. J. **C52** (2007) 267, arXiv:0705.1121.

[5] R. Fleischer and R. Kneigjens, *In pursuit of new physics with $B_s^0 \to K^+K^-$*, Eur. Phys. J. **C71** (2011) 1532, arXiv:1011.1096.

[6] M. Ciuchini, E. Franco, S. Mishima, and L. Silvestrini, *Testing the Standard Model and searching for new physics with $B_d \to \pi\pi$ and $B_s \to KK$ decays*, JHEP **10** (2012) 029, arXiv:1205.4948.

[7] LHCb collaboration, R. Aaij *et al.*, *Determination of γ and $-2\beta_s$ from charmless two-body decays of beauty mesons*, Phys. Lett. **B741** (2015) 1, arXiv:1408.4368.

[8] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.

[9] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, arXiv:1412.6352.

[10] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and regression trees*, Wadsworth international group, Belmont, California, USA, 1984.

[11] B. P. Roe *et al.*, *Boosted decision trees as an alternative to artificial neural networks for particle identification*, Nucl. Instrum. Meth. **A543** (2005) 577, arXiv:physics/0408124.

[12] L. Anderlini *et al.*, *The PIDCalib package*, LHCb-PUB-2016-021.

[13] LHCb collaboration, R. Aaij *et al.*, *Opposite-side flavour tagging of B mesons at the LHCb experiment*, Eur. Phys. J. **C72** (2012) 2022, arXiv:1202.4979.

[14] Heavy Flavor Averaging Group, Y. Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2014*, arXiv:1412.7515, updated results and plots available at http://www.slac.stanford.edu/xorg/hfag/.

[15] BaBar collaboration, J. P. Lees *et al.*, *Measurement of CP asymmetries and branching fractions in charmless two-body B-meson decays to pions and kaons*, Phys. Rev. **D87** (2013) 052009, arXiv:1206.3525.

[16] Belle collaboration, J. Dalseno *et al.*, *Measurement of the CP violation parameters in $B^0 \to \pi^+\pi^-$ decays*, Phys. Rev. **D88** (2013) 092003, arXiv:1302.0551.

[17] LHCb collaboration, *Measurement of time-dependent CP-violating asymmetries in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays at LHCb*, LHCb-CONF-2016-018.

[18] LHCb collaboration, R. Aaij *et al.*, *First measurement of time-dependent CP violation in $B_s^0 \to K^+K^-$ decays*, JHEP **10** (2013) 183, arXiv:1308.1428

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