PROCEEDINGS OF SCIENCE

Measurements of *CP* violation in charmless 2-body *B*-meson decays at LHCb

Davide Fazzini*, **on behalf of the LHCb collaboration**

Universitá degli studi & INFN Milano-Bicocca
Milano, Italy

E-mail: davide.fazzini@cern.ch

Charmless charged two-body b-hadron decays, with kaons and pions in the final state, are an optimal test of the Standard Model validity. Indeed these decays receive important contributions from loop-level processes making the *CP* asymmetries sensitive to transitions beyond the Standard Model. A precise measurement of these *CP* observables is crucial for a better determination of the quark-flavour mixing phases. In this article we report the results obtained by LHCb on the time-dependent and time-integrated *CP* asymmetries using events of charmless b-hadron two-body decays collected during the Run 1 data taking period and corresponding to 3 fb^{-1}.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

*Speaker

1. Introduction

Charmless two-body b-hadron decays provide an excellent scenario for studying the *CP* violation within the Standard Model (SM) [1], to test the U-spin symmetry [2], and the Cabibbo-Kobayashi-Maskawa (CKM) picture [3] of the quark-flavour mixing in the SM as well as to investigate the presence of new physic processes beyond it [4]. It has been demonstrated that a combined analysis of the *CP* asymmetries with the branching fractions in these kind of decays, taking into account the U-spin breaking effects, allows us to set more stringent constraints on the *CP*-violating phase $-2\beta_s$ and the CKM angle γ [5]. Similarly, a combination of the *CP* violation on the $B^0 \to \pi^+\pi^-$ with the branching fractions from the isospin-related decays $B^{0,+} \to \pi^{0,+}\pi^0$ allow a better determination of the CKM angle α [6].

In this work, the measurements of the time-integrated *CP* asymmetries in $B^0_{(s)} \to K^\pm\pi^\mp$ decays and the time-dependent *CP* asymmetries in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays are discussed. The analysis is based on a data sample of pp collisions corresponding to an integrated luminosity of 3.0 fb^{-1}, collected at LHCb with a centre-of-mass energy of 7 and 8 TeV. The *CP* asymmetry as a function of the decay-time for $B^0_{(s)}$ mesons decaying to a *CP* eigenstate f, assuming *CPT* invariance, is given by:

$$A_{CP}(t) = \frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right)}, \tag{1}$$

where $\Delta m_{d,s}$ and $\Delta\Gamma_{d,s}$ are the mass and width differences of the mass eigenstates in the $B^0_{(s)} - \overline{B}^0_{(s)}$ system. The quantities C_f, S_f and $A_f^{\Delta\Gamma}$ are defined as

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}, \qquad A_f^{\Delta\Gamma} \equiv -\frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2}, \qquad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}, \tag{2}$$

where q/p is related to $B^0_{(s)} - \overline{B}^0_{(s)}$ mixing and A_f ($\bar{A}_f$) is the B ($\bar{B}$) decay amplitudes. Assuming negligible *CP* violation in mixing, as predicted by the SM and confirmed experimentally, the two parameters C_f and S_f represent the direct and the mixing-induced *CP* violation, respectively. The parameters C_f, S_f and $A_f^{\Delta\Gamma}$ are linked by an unitary relation $|C_f|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1$ which is not imposed in the analysis. The time-integrated *CP* asymmetry for a $B^0_{(s)}$ mesons decaying to a flavour-specific final state f is defined as:

$$A_{CP} = \frac{\Gamma(B^0_{(s)} \to f) - \Gamma(\overline{B}^0_{(s)} \to \overline{f})}{\Gamma(B^0_{(s)} \to f) + \Gamma(\overline{B}^0_{(s)} \to \overline{f})} = \frac{1-\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right|^2}{1+\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right|^2}. \tag{3}$$

2. Measurements with charmless two-body B decays

The analysis is performed simultaneously on the three final states: $\pi^+\pi^-$, K^+K^- and $K^\pm\pi^\mp$, which are efficiently selected by means of the information provided by Ring Imaging Cherenkov detectors. However small cross-feed contributions due to mis-identification between pions and kaons remain at the level of 10% relative to the signals. Beside the cross-feed contributions, other background contamination comes from the random combination of two tracks and from partially reconstructed 3-body decays. The signal event are selected by means of a two-step procedure: initially a set of particle identification (PID) requirements is applied then a boosted-decision-tree classifier, trained using kinematic and geometrical variables, is exploited to get rid of the combinatorial background which is the remaining dominant background component. After this selection, the sample used in the analysis contains approximately 28600 $B^0 \to \pi^+\pi^-$, 36800 $B^0_s \to K^+K^-$, 94200 $B^0 \to K^+\pi^-$, and 7000 $B^0_s \to \pi^+K^-$ signal candidates as shown in Fig. 1.

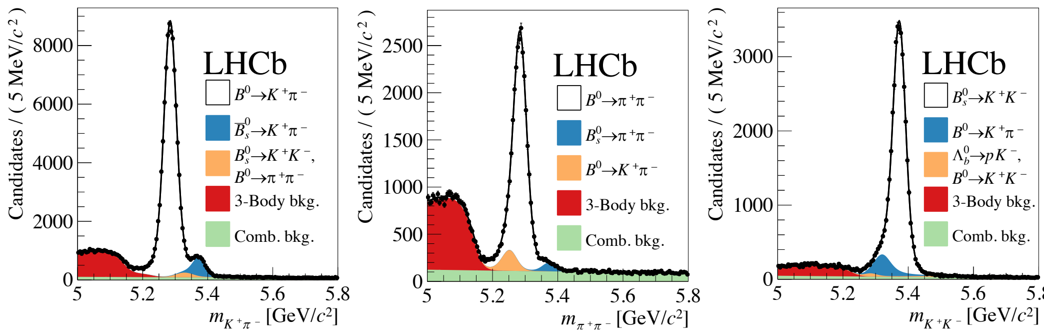

Figure 1: Invariant mass distribution for the $K^\pm\pi^\mp$, $\pi^+\pi^-$ and K^+K^- final state. For each final state, the individual components are also shown.

2.1 Key features for the time-dependent measurement

A key ingredient for the measurement of the time-dependent *CP* asymmetries with neutral B-meson decaying to a *CP* final state is the flavour tagging (FT). The FT tool consists of various algorithms which are able to infer, within a certain probability, the flavour of the $B^0_{(s)}$ meson at production, using information from the other particles in the event. These algorithms are defined as 'Same Side" (SS) if they exploit the particles generated in the B-signal fragmentation [7][8] and as "Opposite Side" (OS) if they use particles coming from the decay of the other B in the event [9]. As a consequence of this distinction, the SS taggers turn out to be specific to the nature of the neutral meson of interest while the OS taggers, in first approximation, act equally on B^0 and B^0_s mesons. Each FT algorithm is trained using specific B-meson decay channels and selections which are different from the ones used in this analysis. Therefore, a more accurate estimate is obtained by means of a calibration procedure taking into account the specific kinematics of the selected signal $B^0_{(s)}$ mesons. The OS tagging response is calibrated using the $B^0_{(s)} \to K^\pm\pi^\mp$ decays, while the SS algorithms are calibrated using the $B^0 \to K^\pm\pi^\mp$ and $B^0_s \to D^\mp_s\pi^\pm$ decay channel, in order to take into account the differences between B^0 and B^0_s. For the B^0_s case, the $B^0_s \to D^\mp_s\pi^\pm$ mode has been chosen since the small yield of $B^0_s \to \pi^\pm K^\mp$ is not sufficient for obtaining a reliable calibration. The sensitivity to the quantities C_f and S_f governing the time-dependent *CP* asymmetry is directly related to the effective tagging power defined as: $\varepsilon_{eff} = \sum_i \epsilon_i(1-2\omega_i)^2/N$, where ϵ_i and ω_i are the tagging decision and the associated calibrated mistag probability for the i-th of N candidates, respectively. The total tagging powers available for the $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays are $(4.08 \pm 0.20)\%$ and $(3.65 \pm 0.21)\%$ respectively.

Other two important features to be considered in a time-dependent analysis are the calibration of the decay-time resolution and the time-dependent efficiency in reconstructing the signal candidates. The decay-time resolution calibration is performed using an OS-tagged time-dependent fit to a sample of $B^0_s \to D^{\mp}_s\pi^{\pm}$ decays, where the combined response of the OS algorithms is calibrated using a sample of $B^0 \to D^{\mp}\pi^{\pm}$ decays. The signal efficiency is determined by fitting the ratio between the untagged time-dependent decay-rate of $B^0 \to K^{\pm}\pi^{\mp}$ decay and a pure exponential with a lifetime $1/\Gamma_d$ with $\Gamma_d = 0.6588 \pm 0.0017$ ps^{-1}. For the other two-body charmless B decay modes the same time-dependent efficiency is used but corrected for differences between the decay modes. The results of the fit related to both these features are reported in Fig. 2

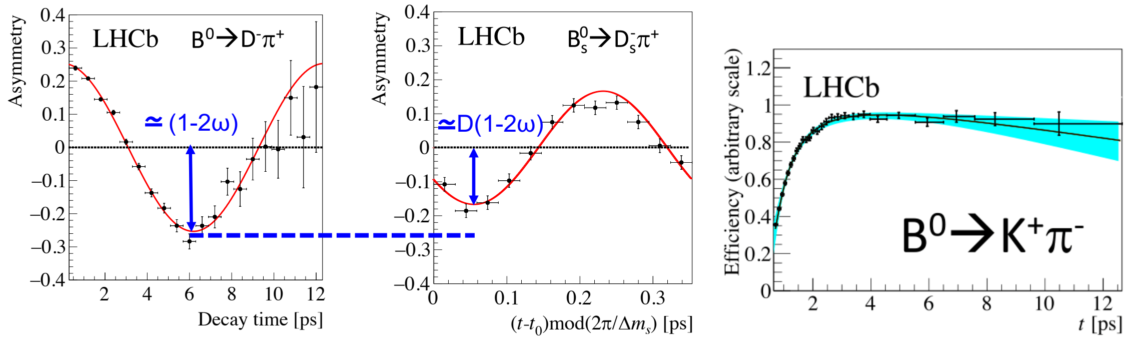

Figure 2: On the left, time-dependent asymmetries of $B^0_{(s)} \to D^{\mp}_{(s)}\pi^{\pm}$, with fit results superimposed. On the right, efficiency as function of the decay time for the $B^0 \to K^{\pm}\pi^{\mp}$. The black line is the result of the fit while the bright area corresponds to the 68% confidence interval.

2.2 Key features for the time-integrated measurement

The time-integrated asymmetries of $B^0_{(s)} \to K^{\pm}\pi^{\mp}$ decays A_{raw}, estimated from data, have to be corrected for the nuisance experimental detection asymmetry, arising from the different detection efficiency of charge-conjugate final states. This nuisance asymmetry can be expressed as the sum of the asymmetry between the efficiencies of the $K^-\pi^+$ and $K^+\pi^-$ final state $A_D(K^{\pm}\pi^{\mp})$, and the asymmetry related to the different efficiency of the particle identification (PID) requirements selecting the two final states $A_{PID}(K^{\pm}\pi^{\mp})$. The final-state detection asymmetry is determined by means of $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \overline{K}^0(\to \pi^+\pi^-)\pi^+$ control modes, taking into account the different kinematic with the $B^0_{(s)} \to K^{\pm}\pi^{\mp}$ decays [10]. The values for $A_D(K^{\pm}\pi^{\mp})$ are reported in Eq. 4. The PID asymmetry is determined using $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays and the values are reported in Eq. 5. No difference is found in the absolute values of the corrections for the $B^0 \to K^{\pm}\pi^{\mp}$ and $B^0_{(s)} \to \pi^{\pm}K^{\mp}$ modes.

$$A_D(K^{\pm}\pi^{\mp}) = (-0.91 \pm 0.14)\%. \tag{4}$$

$$A_{PID}(K^{\pm}\pi^{\mp}) = (-0.04 \pm 0.25)\%. \tag{5}$$

3. Results

The final results for time-integrated *CP* asymmetries and time-dependent *CP* violation parameters in $B^0_{(s)} \to h^+h'^-$ decays are:

$$
\begin{aligned}
A_{CP}^{B^0} &= (-8.4 \pm 0.4 \pm 0.3)\% & A_{CP}^{B_s^0} &= (\ 21.3 \pm 1.5 \pm 0.3)\% \\
C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01 & C_{K^+K^-} &= \ \ 0.20 \pm 0.06 \pm 0.02 \\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01 & S_{K^+K^-} &= \ \ 0.18 \pm 0.06 \pm 0.02 \\
& & A^{\Delta\Gamma}_{K^+K^-} &= -0.79 \pm 0.07 \pm 0.10
\end{aligned}
\tag{6}
$$

where the first uncertainty is statistical and the second systematic. The raw time-dependent asymmetries of the $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$, obtained using both the OS and SS taggers are shown in Fig. 3. All measurements have been performed simultaneously using the full Run 1 data sample, corresponding to an integrated luminosity of 3 fb^{-1} collected with the LHCb detector at centre-of-mass energies of 7-8 TeV. The measurements of $A_{CP}(B^0 \to K^+\pi^-)$, $A_{CP}(B_s \to \pi^+K^-)$, $C_{\pi^+\pi^-}$ and $S_{\pi^+\pi^-}$ are the most precise obtained by a single experiment. Evaluating a χ^2 test, the *CP* parameters of the $B^0_s \to K^+K^-$ decay, obtained in this analysis, turn out to deviate from the no *CP* violation hypothesis, i.e. $(C_{K^+K^-} = 0, S_{K^+K^-} = 0, A^{\Delta\Gamma}_{K^+K^-} = -1)$, by more than 4 standard deviations. Due to the very small value of $\Delta\Gamma_d$ it was not possible to measure the *CP* parameter $A^{\Delta\Gamma}_{\pi^+\pi^-}$, which has been consequently fixed to 0 in the analysis. The values of the production asymmetries for $B^0_{(s)}$ mesons, left free to vary in the final fit, are estimated to be $(0.19 \pm 0.60)\%$ and $(2.4 \pm 2.1)\%$, respectively, and consistent with expectations [11]. As suggested by Ref [2], the measurements of $A^{B^0}_{CP}$ and $A^{B^0_s}_{CP}$ allow a validity test of the SM by checking the equality:

$$
\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B_s^0}} + \frac{\mathcal{B}(B^0_s \to \pi^+K^-)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0, \tag{7}
$$

where $\mathcal{B}(B^0_{(s)} \to K^\pm\pi^\mp)$ are *CP*-averaged branching fractions while $\tau_{d,s}$ are the $B^0_{(s)}$ mean lifetimes. Using the world averages for $f_s/f_d \times \mathcal{B}(B^0_s \to \pi^+K^-)/\mathcal{B}(B^0 \to K^+\pi^-)$ and τ_d/τ_s [12] and the measurement of the relative hadronisation fraction between B^0_s and B^0 mesons f_s/f_d [13], the value $\Delta = -0.11 \pm 0.04 \pm 0.03$ is obtained, where the first uncertainty is from the measurements of the *CP* asymmetries and the second is from the input values mentioned above. No evidence of any deviation from 0 is observed with the current experimental precision.

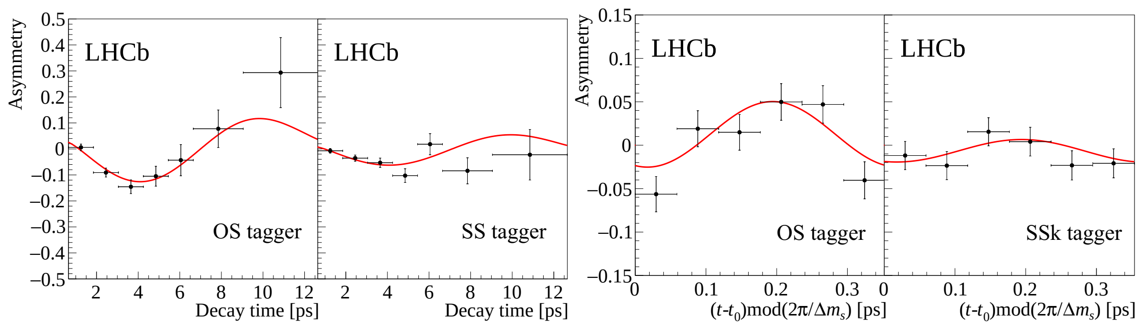

Figure 3: Raw time-dependent asymmetry for the $\pi^+\pi^-$ (left) and K^+K^- (right) final states from the invariant mass signal regions. On the left the asymmetries obtained using the OS tagging algorithms while on the right the asymmetries observed using the SS taggers.

References

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

[2] H. J. Lipkin, *Is observed direct CP violation in* $B_d \to K^+\pi^-$ *due to new physics? Check standard model prediction of equal violation in* $B_s \to K^-\pi^+$, Phys. Lett. **B621** (2005) 126 [hep-ph/0503022].

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

[4] 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 [1205.4948].

[5] LHCb collaboration, R. Aaij et al., *Determination of* γ *and* $-2\beta_s$ *from charmless two-body decays of beauty mesons*, Physics Letters B **741** (2015) 1 .

[6] M. Gronau and D. London, *Isospin analysis of* cp *asymmetries in* b *decays*, Phys. Rev. Lett. **65** (1990) 3381.

[7] LHCb collaboration, R. Aaij et al., *New algorithms for identifying the flavour of* B^0 *mesons using pions and protons*, *Eur. Phys. J. C* **77** (2016) 238. 23 p.

[8] LHCb collaboration, R. Aaij et al., *A new algorithm for identifying the flavour of* b_s^0 *mesons at lhcb*, *Journal of Instrumentation* **11** (2016) P05010.

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

[10] LHCb collaboration, R. Aaij et al., *Measurement of CP asymmetry in* $D^0 \to K^-K^+$ *and* $D^0 \to \pi^-\pi^+$ *decays*, JHEP **07** (2014) 041 [1405.2797].

[11] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht et al., *Measurement of* b^0, b_s^0, b^+ *and* λ_b^0 *production asymmetries in 7 and 8 tev proton–proton collisions*, Physics Letters B **774** (2017) 139–158.

[12] Y. Amhis et al., *Averages of b-hadron, c-hadron, and* τ*-lepton properties as of summer 2016*, The European Physical Journal C **77** (2017) .

[13] R. Aaij, C. Abellan Beteta, A. Adametz, B. Adeva, M. Adinolfi, C. Adrover et al., *Measurement of the fragmentation fraction ratio* f_s/f_d *and its dependence on b meson kinematics*, Journal of High Energy Physics **2013** (2013) .