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CP violation in $B^0_{(s)} \to h^+h^-$

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An important test of the Standard Model is represented by the charmless charged two-body b-hadron decays to final states with kaons and pions. In fact the *CP* asymmetries measured using these decays are sensitive to new physics beyond the Standard Model since the decay amplitudes receive contributions from loop-level diagrams with magnitudes similar to those from tree-level transitions. We report the most recent results on the charmless b-hadron two-body decays obtained by the LHCb experiment using the data collected in Run 1 (3 fb^{-1}).

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1. Introduction

The study of the *CP* violation using charmless two-body *b*-hadron decays represents a very important test to validate the Standard Model (SM) [1, 2]. On the one hand the time-dependent (TD) *CP* asymmetries are sensitive to the Cabibbo-Kobayashi-Maskawa (CKM) matrix angle γ and the mixing phases ϕ_s and ϕ_d, thus a precision measurement allows to determine the value of these observables with high accuracy. On the other hand the time-integrated *CP* asymmetries of the $B^0_{(s)} \to K^{\pm}\pi^{\mp}$ provide a validity test of the U-spin symmetry [3]. A rich set of physic processes, including both tree-level and one-loop diagrams, contribute to the $B^0_{(s)} \to h^+h^-$ decays, where h stands for a pion or a kaon. The presence of loops makes the *CP* violating observables sensitive to new physics processes beyond the SM [4, 5]. In the SM the presence of *CP* violation in the weak sector is linked to the existence of at least three different flavour families and to the presence of non-zero complex phase in the CKM quark mixing matrix. The CKM matrix allows to describe the transitions between the three quark families by means of charged current processes. In order to completely understand the mechanisms behind the *CP* violation a precise measurement of the CKM elements is required. According to the SM, the *CP* violation can raise in three different ways. The first mode, called "*CP* violation in decays", appears when the decay-rates of a process and its own conjugate are different. In this case it is possible to measure the time-integrated *CP* asymmetry, defined as:

$$A_{CP} = \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f})}{\Gamma(B \to f) + \Gamma(\overline{B} \to \overline{f})} = \frac{1 - \left|\frac{\overline{A}_{\overline{f}}}{A_f}\right|^2}{1 + \left|\frac{\overline{A}_{\overline{f}}}{A_f}\right|^2} \tag{1.1}$$

The second way is named "*CP* violation in mixing" and occurs in case the probabilities of a $B^0_{(d,s)}$ meson to oscillate into their corresponding $\overline{B}^0_{(d,s)}$ anti-meson and viceversa are different. The third *CP* violation mode is named "*CP* violation in interference" and can raise when both the $B^0_{(s)}$ meson and $\overline{B}^0_{(s)}$ anti-meson decay to the same final state and *CP* violation arises from the interference between the mixing and the decay of the neutral B mesons. Thus it is possible to measure the time-dependent *CP* asymmetry defined as:

$$A_{CP}(t) = \frac{C_f \cos(\Delta M t) + S_f \sin(\Delta M t)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma}{2}t\right)} \tag{1.2}$$

where f represents a certain final state, the parameters C_f, S_f are defined as:

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \qquad S_f = \frac{2Im(\lambda_f)}{1 + |\lambda_f|^2}, \tag{1.3}$$

and $A_f^{\Delta\Gamma}$ satisfy the following relation: $|C_f|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1$

2. Measurements with charmless two-body B decays

In LHCb experiment, the time-dependent *CP* asymmetries of the $B^0_d \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays and the time-integrated *CP* asymmetries of the $B^0_d \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$ decays are measured simultaneously by means of an analysis of the three different final states: $\pi^+\pi^-$, K^+K^-

and $K^{\pm}\pi^{\mp}$. The information provided by the RICHs allows to fulfil the efficient discrimination between pions and kaons which is required by such analysis. However small cross-feed contributions due to mis-identification between pions and kaons remain at the level of 10% relatively to the signals. These contributions, in addition to the random combination of two tracks and to the partially reconstructed 3-body decays, represent the main contaminations to be dealt with. The signal purity of the sample is maximized by means of an event selection performed in two steps: firstly a set of particle identification (PID) requirements is applied, then a boosted-decision-tree classifier based on kinematic and geometrical variables is exploited. The selected sample, which is used in the analysis, contains approximately 28600 $B^0_d \to \pi^+\pi^-$, 36800 $B^0_s \to K^+K^-$, 94200 $B^0_d \to K^+\pi^-$, and 7000 $B^0_s \to \pi^+K^-$ signal candidates. The flavour tagging (FT) tool plays a fundamental role in the measurement of the time-dependent *CP* asymmetries of the $B^0_d \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays. The purpose of this tool consists in the determination of the flavour of the neutral $B_{(s)}$ meson at the production. The FT algorithms are able to predict, within a certain probability, the initial flavour of the $B_{(s)}$ meson exploiting the informations of the other particles in the event. In this analysis both "Same Side" algorithms, using the particles generated in the B-signal fragmentation [6, 7], and "Opposite Side" algorithms, exploiting particles coming from the decay of the other B in the event, are employed [8]. The effective tagging efficiency provided by the FT algorithms can be evaluated as:

$$\varepsilon_{eff} = \varepsilon_{tag} \cdot (1-2\omega)^2 \tag{2.1}$$

where ε_{tag} represents the fraction of the events for which the algorithm is able to provide a tagging decision and ω indicates the mistag probability. The amount of tagging power available in a certain dataset represents a very important parameter to be taken into account in time-dependent precision measurements, since it is inversely proportional to statistic uncertainty of the *CP* observables. The time-dependent *CP* asymmetries and their corresponding statistical uncertainties can be written as:

$$\begin{aligned} C_f^{obs} &= (1-2\omega)C_f & S_f^{obs} &= (1-2\omega)S_f \\ \sigma(C_f^{obs}) &= \frac{1}{\sqrt{\varepsilon_{tag}(1-2\omega)^2}}\sigma(C_f) & \sigma(S_f^{obs}) &= \frac{1}{\sqrt{\varepsilon_{tag}(1-2\omega)^2}}\sigma(S_f) \end{aligned} \tag{2.2}$$

The total tagging powers available for the $B^0_d \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays are $(4.08 \pm 0.20)\%$ and $(3.65 \pm 0.21)\%$ respectively. The time-integrated asymmetries of the $B^0_d \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$ decays (A_{raw}) measured from data do not correspond to the effective *CP* asymmetry (A_{CP}): a further correction has to be applied in order to take into account the other nuisance asymmetries coming from various experimental effects. These effects comprise the production asymmetry (A_P) and the detection asymmetry (A_D):

$$A_{raw}(t) \approx A_{CP} + A_D + A_P \cos(\Delta m_{d(s)} t) \tag{2.3}$$

While the production asymmetry can be estimated directly from the final fit to data along with the *CP* asymmetries, the detection asymmetry has to be introduced as an external parameter. The value of the detection asymmetry is determined by means of high-statistics samples of Cabibbo-favoured decays of charmed mesons [9], taking into account the kinematic differences with respect to the $B^0_{(s)} \to h^+h^-$ decay modes. The value of the detection asymmetry for both the $B^0_d \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$ decays has been fixed to:

$$A_D^{K\pi}(B^0_d \to K^+\pi^-) = A_D^{K\pi}(B^0_s \to \pi^+K^-) = (-0.91 \pm 0.14)\%. \tag{2.4}$$

3. Results

The final values of the time-dependent *CP* parameters are

$$\begin{aligned} C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01 \\ S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01 \\ C_{K^+K^-} &= 0.20 \pm 0.06 \pm 0.02 \\ S_{K^+K^-} &= 0.18 \pm 0.06 \pm 0.02 \\ A^{\Delta\Gamma}_{K^+K^-} &= -0.79 \pm 0.07 \pm 0.10 \end{aligned} \tag{3.1}$$

while the values of the time-integrated *CP* asymmetries are

$$\begin{aligned} A_{CP}(B^0 \to K^+\pi^-) &= (-8.4 \pm 0.4 \pm 0.3)\% \\ A_{CP}(B_s \to \pi^+K^-) &= (\ 21.3 \pm 1.5 \pm 0.3)\% \end{aligned} \tag{3.2}$$

In Fig. 1 the raw time-dependent asymmetries of the $B^0_d \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$, obtained using the OS and SS taggers, are shown. All the measurements have been performed using the full Run 1 data sample, corresponding to an integrated luminosity of 3 fb^{-1}. The *CP* parameter $A^{\Delta\Gamma}_{\pi^+\pi^-}$ can not be determined since the value of $\Delta\Gamma_d$ is too small and it is fixed to 0 in the analysis. All the results obtained are in very good agreement with the previous measurements obtained by BaBar [10], Belle [11, 12], CDF [13] and LHCb [14, 15]. 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. In addition, 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. This measurement represents the strongest evidence of *CP* violation in B^0_s system to date.

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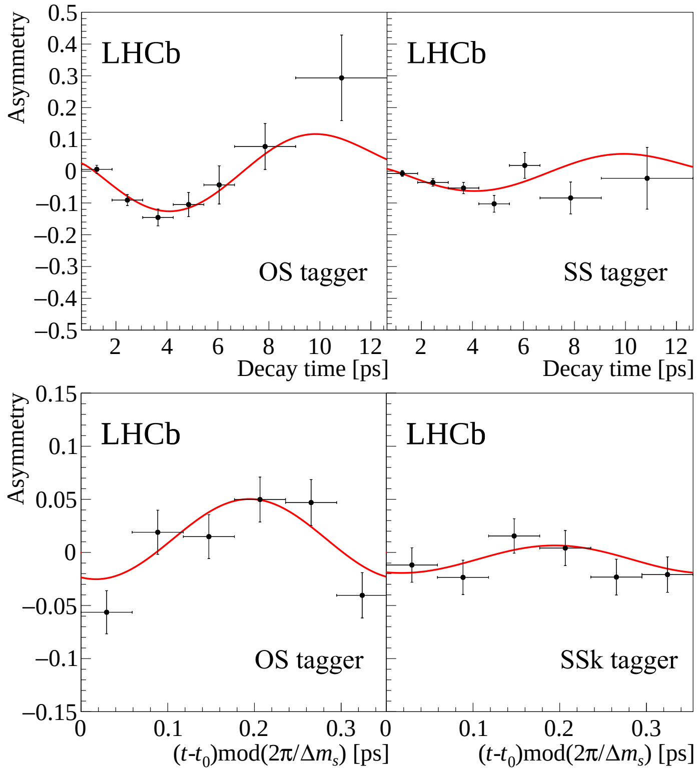

Figure 1: Raw time-dependent asymmetry for the $\pi^+\pi^-$ (top) and K^+K^- (bottom) final states from the invariant mass signal regions. On the left the asymmetries obtained using the OS tagging algorithms while on the right the asymmetries observed using the SS taggers.

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