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CP violation measurements in two-body charmless decays at LHCb

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This report concerns the two most recent measurements, performed by the LHCb experiment, of the *CP*-violation observables in charmless two-body decays of B mesons. The first analysis determines the time-integrated *CP* asymmetry in the $B^+ \to K^+\pi^0$ decays. The corresponding dataset is collected between 2016 and 2018 for a total integrated luminosity of $5.4\,\text{fb}^{-1}$ at a centre-of-mass energy of 13 TeV. This is the most precise determination of this quantity, even exceeding the precision of the previous world average. The second analysis determines the time-integrated *CP* asymmetries in the $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$ decays, and the time-dependent *CP* asymmetries in the $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays. The utilised data are collected in 2015 and 2016 for a total integrated luminosity of $1.9\,\text{fb}^{-1}$. Once these results are combined with the previous measurement by LHCb (additional $3.1\,\text{fb}^{-1}$), the most precise determinations of these quantities by a single experiment are obtained. Furthermore, time-dependent *CP* violation is observed for the first time in the B^0_s sector.

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1. Introduction

The decays of hadrons containing b quarks into final states where the c quark is missing are excellent probes for the indirect research for new physics (NP). Due to the values of the elements of the Cabibbo-Kobayashi-Maskawa matrix [1, 2], tree-level and loop-level Feynman diagrams provide comparable contributions to the decay amplitudes. NP may emerge through virtual contributions inside the loops and produce deviations of the measured quantities from the Standard Model (SM) predictions. Relevant observables are the branching fractions, the time-integrated and the time-dependent *CP* asymmetries. However, the loop-level topologies introduce additional strong parameters which are not easily calculable. To remove the unknown quantities and provide stringent tests of the SM consistency, it is often necessary to combine observables from different decays and exploit approximate flavour symmetries. This report concerns the measurement of the asymmetries between the charge-conjugated instantaneous decay rates ($\Gamma_{B\to f}$ and $\Gamma_{\overline{B}\to\bar{f}}$) of the $B^+ \to K^+\pi^0$, $B^0 \to K^+\pi^-$, and $B^0_s \to \pi^- K^+$ decays, and the charge-conjugated time-dependent decay rates ($\Gamma(t)$) of the $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays[1] [3, 4]. The time-integrated *CP* asymmetry is defined as

$$A^f_{CP} = \frac{\Gamma_{\overline{B}\to\bar{f}} - \Gamma_{B\to f}}{\Gamma_{\overline{B}\to\bar{f}} + \Gamma_{B\to f}} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2},$$

where A_f is the amplitude of the flavour-specific decay into the final state f and $\bar{A}_{\bar{f}}$ is the amplitude of the *CP*-conjugated process. Assuming *CPT* invariance and negligible *CP* violation in the $B^0_{(s)}$-$\overline{B}{}^0_{(s)}$ mixing, the time-dependent *CP* asymmetries of the $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays are

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

where the final state is a *CP* eigenstate, while $\Delta m_{d,s}$ and $\Delta\Gamma_{d,s}$ are the mass and width differences of the mass eigenstates in the $B^0_{(s)}$-$\overline{B}{}^0_{(s)}$ two-state systems. The parameters C_f and S_f encode the *CP* violation in the decay and in the interference between mixing and decay, respectively. The parameter $A^{\Delta\Gamma}_f$ is related to them by the constraint $(C_f)^2 + (S_f)^2 + (A^{\Delta\Gamma}_f)^2 = 1$, which is not imposed in these measurements, but checked *a posteriori* as a robustness test.

2. *CP* violation in $B^0 \to K^+\pi^0$ decays

Isospin relations would suggest the same value for the time-integrated *CP* asymmetries in $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$ decays. However, their world averages, without including the results discussed in this report, are separated by 5.5 standard deviations [3]. This peculiarity constitutes the long-standing *Kπ-puzzle*. As explained in Ref. [5], a more accurate examination of this anomaly leads to the following sum rule, which also concerns the time-integrated *CP* asymmetries in the $B^0 \to K^0\pi^0$ and $B^+ \to K^0\pi^+$ decays

$$A^{K^+\pi^-}_{CP} + A^{K^0\pi^+}_{CP} \frac{\mathcal{B}(B^+ \to K^0\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} \frac{\tau_0}{\tau_+} = A^{K^+\pi^0}_{CP} \frac{2\mathcal{B}(B^+ \to K^+\pi^0)}{\mathcal{B}(B^0 \to K^+\pi^-)} \frac{\tau_0}{\tau_+} + A^{K^0\pi^0}_{CP} \frac{2\mathcal{B}B^0 \to K^0\pi^0)}{\mathcal{B}(B^0 \to K^+\pi^-)},$$

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[1] Charge-conjugate decay modes are implied throughout except for the asymmetries definitions.

where τ_0 and τ_+ are the lifetimes of the B^0 and B^+ mesons, and $\mathcal{B}(\cdot)$ indicates the branching fraction of the process between parentheses. Discrepancies in this sum rule could be a sign of NP. The measurement of $A_{CP}^{K^+\pi^0}$ involves the data collected by the LHCb experiment from 2016 to 2018 for a total integrated luminosity of 5.4 fb^{-1} obtained with proton-proton collisions at the center-of-mass energy $\sqrt{s} = 13$ TeV. The association of the mass hypothesis to the final-state particles benefits from the considerable particle identification performance of the LHCb detector [6]. It permits the background due to final-state misidentification (*misID* background) to be suppressed. The main complication for reconstructing the signal candidates is due to the final-state pattern. It comprises a single charged track and lacks a reconstructible secondary vertex with a significant displacement from any primary proton-proton interaction (primary vertex): a signature typically used to identify the decays of B hadrons. Therefore, the reconstruction algorithm looks for K^+ candidates inconsistent with any primary vertex, but consistent with a B^+ candidate. In particular, both the π^0 momentum and the B^+ trajectory are calculated assuming the primary vertex closest to the K^+ track as their origin vertices. The main background components are due to random association of final-state particles (combinatorial background) and decays of B hadrons to more than two bodies, which are only partially reconstructed. To optimise the background rejection a Boost-Decision-Tree technique is exploited [7]. As inputs, it takes variables concerning the kinematic and the geometry of the signal candidates, and quantities related to the isolation of the K^+ candidates. The time-integrated *CP* asymmetry corresponds to the difference between the raw asymmetry of the $B^\pm \to K^\pm\pi^0$ samples and the nuisance asymmetries affecting the initial and final states: $A_{CP}^{K^+\pi^0} = A_{\text{raw}}^{K^+\pi^0} - (A_{\text{prod.}}^{B^\pm} + A_{\text{det.}}^{K^\pm})$. The $A_{\text{raw}}^{K^+\pi^0}$ quantity is the asymmetry between the yields of the *CP* conjugated signal modes: $A_{\text{raw}}^{K^+\pi^0} = \frac{N(B^+\to K^+\pi^0)-N(B^-\to K^-\pi^0)}{N(B^+\to K^+\pi^0)+N(B^-\to K^-\pi^0)}$. It is extracted by an unbinned maximum likelihood fit to the invariant-mass spectrum of the dataset described above. Figure 1 shows the distribution of the data with the result of best-fit superimposed. The components of the fit model corresponding to the signal, the combinatorial, the *misID*, and the partially-reconstructed background are also shown. The latter background category involves also a peaking component due to resonance intermediate states, like $B^+ \to (K^{*+} \to K^+\pi^0)\pi^0$ decays. The overall signal yield is approximately 16×10^3. The nuisance asymmetries are due to the different production rates

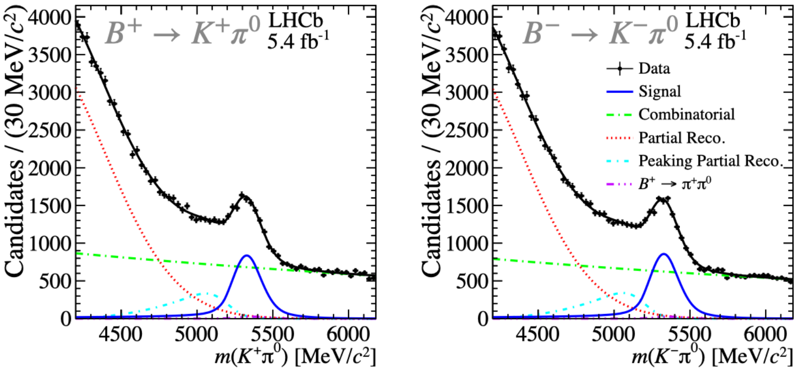

Figure 1: Invariant mass for $B^+ \to K^+\pi^0$ (left) and $B^- \to K^-\pi^0$ (right) candidates. The result of the best fit is superimposed to the data points [3].

of the B^+ and B^- mesons (production asymmetry, $A^{B^\pm}_{\text{prod.}}$) and to the different reconstruction and identification efficiencies of the K^+ and K^- candidates (final-state asymmetry, $A^{K^\pm}_{\text{det.}}$). To determine their sum, $B^+ \to (J/\psi \to \mu^+\mu^-)K^+$ decays are exploited. In this case, the following relation holds: $A^{B^\pm}_{\text{prod.}} + A^{K^\pm}_{\text{det.}} = A^{J/\psi K^+}_{\text{raw}} - A^{J/\psi K^+}_{CP}$. The value of $A^{J/\psi K^+}_{CP}$ is taken from the world average of this quantity [8]. The $A^{J/\psi K^+}_{\text{raw}}$ parameter is measured with a fit to the corresponding invariant-mass spectrum, profiting of its high statistics ($\approx 6.8\times 10^5$ candidates) and purity ($> 99\%$). In conclusion, the LHCb measurement of time-integrated *CP* asymmetry in the $B^+ \to K^+\pi^0$ decay is [3]

$$A^{K^+\pi^0\text{(LHCb)}}_{CP} = (2.5 \pm 1.5 \pm 0.6 \pm 0.3)\%,$$

where the uncertainties are statistical, systematic, and due to external inputs, respectively. This is both the first measurement of this quantity at a hadron collider and the most precise determination of $A^{K^+\pi^0}_{CP}$ to date. With this update the world average (W.A.) for this parameter becomes $A^{K^+\pi^0\text{(W.A.)}}_{CP} = (3.1 \pm 1.3)\%$. The new difference between the time-integrated *CP* asymmetries in the $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$ decays is $A^{K^+\pi^0\text{(W.A.)}}_{CP} - A^{K^+\pi^-\text{(W.A.)}}_{CP} = (11.5 \pm 1.4)\%$, which is different from zero by 8 standard deviations. The $K\pi$-puzzle sum rule now provides $A^{K^0\pi^0\text{(S.R.)}}_{CP} = (-13.8 \pm 2.5)\%$, which deviates from zero by 5.5 standard deviations, while the current experimental determination of the same quantity is $A^{K^0\pi^0\text{(W.A.)}}_{CP} = (1 \pm 10)\%$ [8], strongly requiring for more insight to unveil eventual contributions from NP.

3. *CP* violation in $B^0_{(s)} \to h^+h'^-$ decays

The *CP* violation observables of the $B^0_{(s)} \to h^+h'^-$ decays (where $h, h' \in \{\pi, K\}$) can be used to determine the angles γ and α of the Unitary Triangle, as well as the B^0_s mixing phase, β_s [9]. This analysis utilises the data sample of proton-proton collision collected by LHCb at the centre-of-mass energy $\sqrt{s} = 13$ TeV in 2015 and 2016. The total integrated luminosity is 1.9 fb^{-1}. The background categories are similar to the ones of the previous analysis. The particle identification performance of LHCb [6] permits the *misID* background to be reduced below the 10% of the corresponding signal, keeping and adequate efficiency. The rejection of the combinatorial background is optimised using a Boosted-Decision-Tree classifier [7], involving kinematic and geometrical variables as inputs. The large part of the partially reconstructed background is restricted out of the signal peak, thanks to the good invariant-mass resolution of LHCb [6]. The *CP*-violation observables $A^{K^+\pi^-}_{CP}$, $A^{\pi^-K^-}_{CP}$, $C_{\pi^+\pi^-}$, $S_{\pi^+\pi^-}$, $C_{K^+K^-}$, $S_{K^+K^-}$, $A^{\Delta\Gamma}_{K^+K^-}$ are extracted from the data with an unbinned maximum-likelihood fit[2]. Two fit strategies are developed to validate each other: one called *per-candidate* and the other *simultaneous*. The *per-candidate* method is specific for the time-dependent CP asymmetries. The main difference between the two methods is that the *per-candidate* one uses the calibration of the decay-time resolution and of the decay-time efficiency on a per-candidate basis. In addition, it performs the final fits to background subtracted samples. The results of the two methods are found to be in agreement. In the following, the *simultaneous* method, that is used for the combination with the previous LHCb results, is described in more details. The fit observables are the invariant mass of the two final-state hadrons, the decay time of the $B^0_{(s)}$ candidates, and the flavour-tagging

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[2] The parameter $A^{\Delta\Gamma}_{\pi^+\pi^-}$ is not measured because of the almost null value of $\Delta\Gamma_d$ [8].

decision and per-candidate mistag probabilities. The invariant mass is essential to disentangle the signal and background yields. The decay time provides necessary information for the time-dependent *CP* asymmetries. The flavour tagging is a set of algorithms exploited to discriminate between $B^0_{(s)}$ and $\overline{B}^0_{(s)}$ candidates at the instant of their production [10]. The fit of the four exclusive final-state samples ($K^+\pi^-$, π^+K^-, $\pi^+\pi^-$, K^+K^-) is simultaneous. This feature permits the *misID* backgrounds to be handled even if their invariant-mass peaks are very close to the signal ones. The production asymmetries are estimated exploiting the decay time information from the $B^0 \to K^+\pi^-$ decays. The final state asymmetries are corrected thanks to $D^+ \to K^+\pi^-$, $D^+ \to K^-\pi^+\pi^-$, and $D^+ \to \overline{K}^0\pi^+$ samples. Wrong flavour-tagging decisions and finite decay-time resolution dilute the time-dependent *CP* asymmetries. The flavour-tagging algorithms provide a raw expectation of the mistag probability for each candidate. This quantity is calibrated directly in the final fit exploiting $B^0 \to K^+\pi^-$ and – to a minor extent – $B^0_s \to \pi^+K^-$ decay modes. Additional information is obtained from a sample of $B^0_s \to D_s\pi^+$ decays. Studies on $J/\psi \to \mu^+\mu^-$ and $\Upsilon(4S) \to \mu^+\mu^-$ decays and fully simulated $B^0_s \to K^+K^-$ decays allow the decay-time resolution for the $B^0_{(s)} \to h^+h'^-$ decays to be determined and included in the fit. The reconstruction efficiency of the signal candidates depends on their decay time. Hence, effective efficiency function are extracted from a background-subtracted

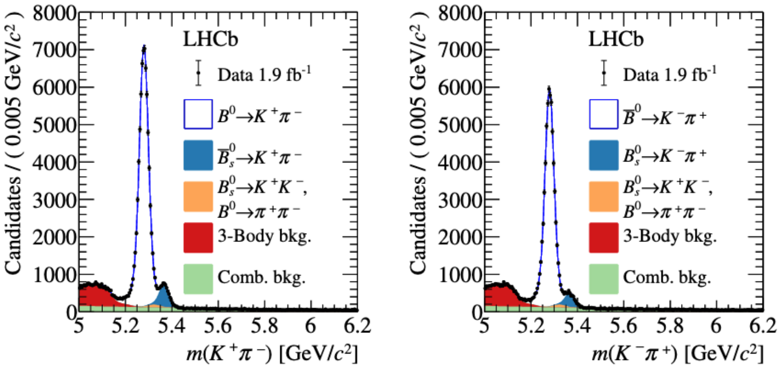

Figure 2: Invariant mass for the $K^+\pi^-$ (left) and $K^-\pi^+$ (right) final states. The projection of the best fit is superimposed [4].

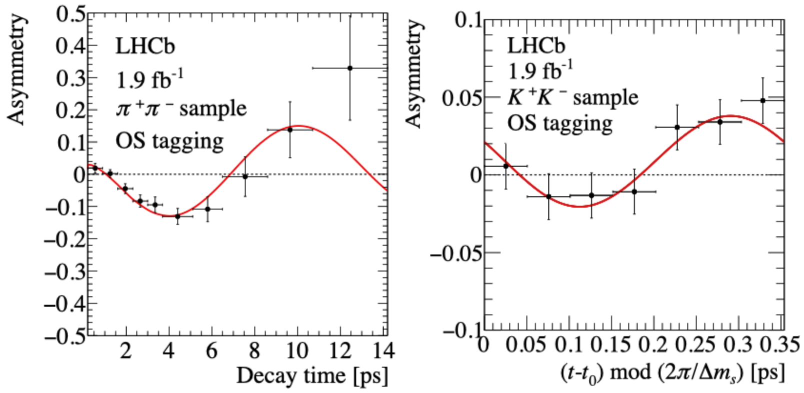

Figure 3: Time-dependent *CP* asymmetries for $B^0 \to \pi^+\pi^-$ (left) and $B^0 \to K^+K^-$ decays (right). The data points are obtained from the invariant mass regions $m(\pi^+\pi^-) \in [5.20, 5.35]$ GeV/c^2 and $m(K^+K^-) \in [5.30, 5.44]$ GeV/c^2, respectively. The red lines show the results of the best fit [4].

$B^0 \to K^+\pi^-$ sample: when the flavour-tagging decision is neglected, its decay-time shape is the product of a pure exponential with the decay-time efficiency. Figure 2 shows the invariant-mass distributions for the $K^+\pi^-$ and π^+K^- final-states samples. The difference between the yields of the *CP*-conjugated signal modes is visible. Figure 3 illustrates the time-dependent *CP* asymmetries as obtained from the data in the invariant mass region dominated by the signal component. In both the figures, the results of the best fits are superimposed. The results of this analysis are combined with the previous measurements by LHCb [11]. The final determinations are [4]

$$\begin{aligned} A_{CP}^{K^+\pi^-} &= (-8.31 \pm 0.34)\%, & C_{\pi^+\pi^-} &= (-32.0 \pm 3.8)\%, & C_{K^+K^-} &= (+17.2 \pm 3.1)\%, \\ A_{CP}^{\pi^+K^-} &= (+22.5 \pm 1.2)\%, & S_{\pi^+\pi^-} &= (-67.2 \pm 3.4)\%, & S_{K^+K^-} &= (+13.9 \pm 3.2)\%, \\ & & & & A^{\Delta\Gamma}_{K^+K^-} &= (-89.7 \pm 8.7)\%. \end{aligned}$$

To date, these are the most precise measurements of these quantities from a single experiment. The significance for $(C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-}) \neq (0, 0, -1)$ is 6.5 standard deviations. This is the first observation of time-dependent *CP* violation in the decays of the B_s^0 mesons. The just presented results involve a total integrated luminosity of 5 fb^{-1}. Now, 4 more inverse femtobarns are available thanks to the data collected by LHCb in 2017 and 2018, and the analysis of this sample is ongoing.

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