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Charmless b-hadron decays at LHCb

I. Nasteva on behalf of the LHCb collaboration
Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil.

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Measurements of *CP* asymmetries in charmless two-body B-meson decays can provide stringent tests of the Standard Model. In multibody decays, short and long-distance dynamics along with a sizeable effective weak phase in the interference between tree and penguin amplitudes can lead to a rich structure of *CP* violation as a function of the phase space. We present here the latest studies of *CP* violation in charmless b-hadron decays, in particular those with baryons in the initial and final states.

Keywords: LHCb; charmless B meson decays; hadronic B decays; multibody B decays; *CP* violation.

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1. Introduction

Charmless hadronic B decays have been the subject of great theoretical and experimental interest [1]. They are suppressed in the Standard Model (SM) and proceed through $b \to u$ tree and $b \to s, d$ loop (penguin) transitions, which have similar size amplitudes. Because the tree and penguin amplitudes have a relative weak phase, their interference can lead to *CP* violation in decay. In addition, new particles could contribute to the loop amplitude, leading to discrepancies with the SM prediction and possible additional sources of CP violation that could be accessed through precise measurements of charmless decays.

The LHCb experiment [2, 3] was designed to measure and identify the characteristic signatures of b-hadron decays. Their long lifetimes lead to displaced decay vertices, which are reconstructed by the Vertex Locator subdetector. In most of the analyses presented here, charged final-state hadrons are combined to form secondary vertices and the selections use multivariate analyses to reject combinatorial bakgrounds. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors, while photons and neutral pions are reconstructed by the Electromagnetic Calorimeter. The flavour of neutral b-hadrons is identified using flavour-tagging algorithms based on the final-state particle charges of the decay of the b-hadron (same-side) or of its pair-produced companion (opposite-side tagging).

Here, we present highlights from the recent results on charmless b-meson and b-baryon decays from the LHCb experiment, focusing on *CP* violation.

2. *CP* violation in two-body B-meson decays

Neutral B-meson decays to two charged hadrons have been studied extensively and have exhibited large *CP* violation effects. The recent study [4] represents an update on the LHCb results using a partial Run 2 data sample of 1.9 fb^{-1} integrated luminosity. A simultaneous fit is perfoned to the invariant mass, decay time, flavour tagging decision and mistag probability for the three different final states: $K^+\pi^-$, $\pi^+\pi^-$ and K^+K^-, and a second per-candidate method is also applied as a validation. The time-dependent asymmetry is measured for $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays (Fig. 1, left), and the *CP* -violating quantities C_f, S_f and $A_f^{\Delta\Gamma}$ are extracted from the fit,

$$\begin{aligned} C_{\pi\pi} &= -0.311 \pm 0.045 \pm 0.015\,, \\ S_{\pi\pi} &= -0.706 \pm 0.042 \pm 0.013\,, \\ C_{KK} &= 0.164 \pm 0.034 \pm 0.014\,, \\ S_{KK} &= 0.123 \pm 0.034 \pm 0.015\,, \\ A_{KK}^{\Delta\Gamma} &= -0.83 \;\; \pm 0.05 \;\; \pm 0.09\,, \end{aligned}$$

where the first uncertainties are statistical and the second systematic. These results are the most precise from a single experiment and agree with previous measurements. They represent the first observation of time-dependent *CP* violation in B_s^0 decays.

In addition to time-dependent *CP* violation, the direct *CP* asymmetry is measured for $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays, and the resulting significant asymmetries are consistent with previous measurements,

$$\begin{aligned} A_{CP}\,(B^0 \to \pi^+\pi^-) &= -0.0824 \pm 0.0033 \pm 0.0033\,, \\ A_{CP}\,(B_s^0 \to K^+K^-) &= 0.236 \;\; \pm 0.013 \pm 0.011\,. \end{aligned}$$

Another measurement of a two-body decay is that of *CP* violation in $B^+ \to K^+\pi^0$ [5], performed at LHCb for the first time with a sample of 5.4 fb^{-1} of Run 2 data. The decay reconstruction is very challenging due to the single charged track, neutral pion and lack of a displaced vertex. The invariant mass distributions of the selected candidates, separated by charge, are shown in Fig. 1 (middle and right). The *CP* asymmetry is found to be

$$A_{CP}\,(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003\,,$$

where the last uncertainty is due to external inputs. The result is more precise than the world average and consistent with zero within 1.5 standard deviations (σ).

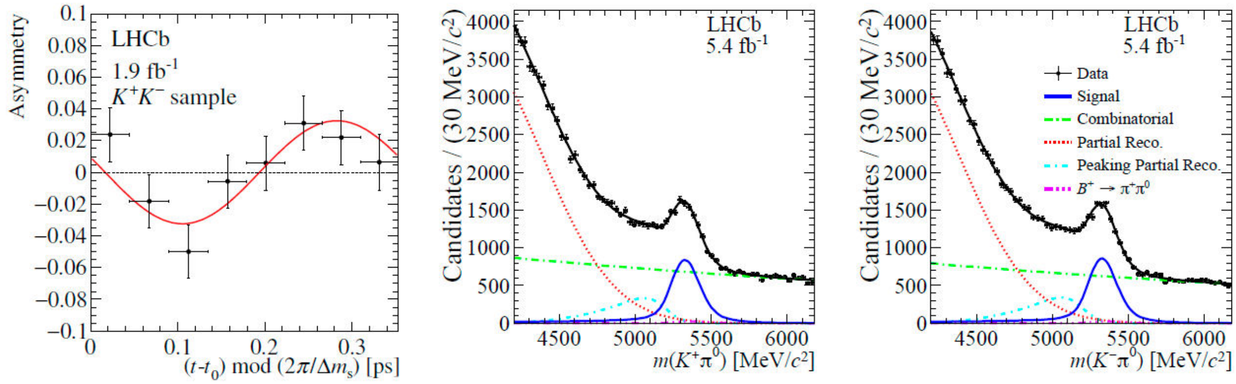

FIGURE 1. Time-dependent asymmetry for $B_s^0 \to K^+K^-$ decays [4] (left). Invariant mass distributions of selected $B^+ \to K^+\pi^0$ (middle) and $B^- \to K^-\pi^0$ (right) candidates [5].

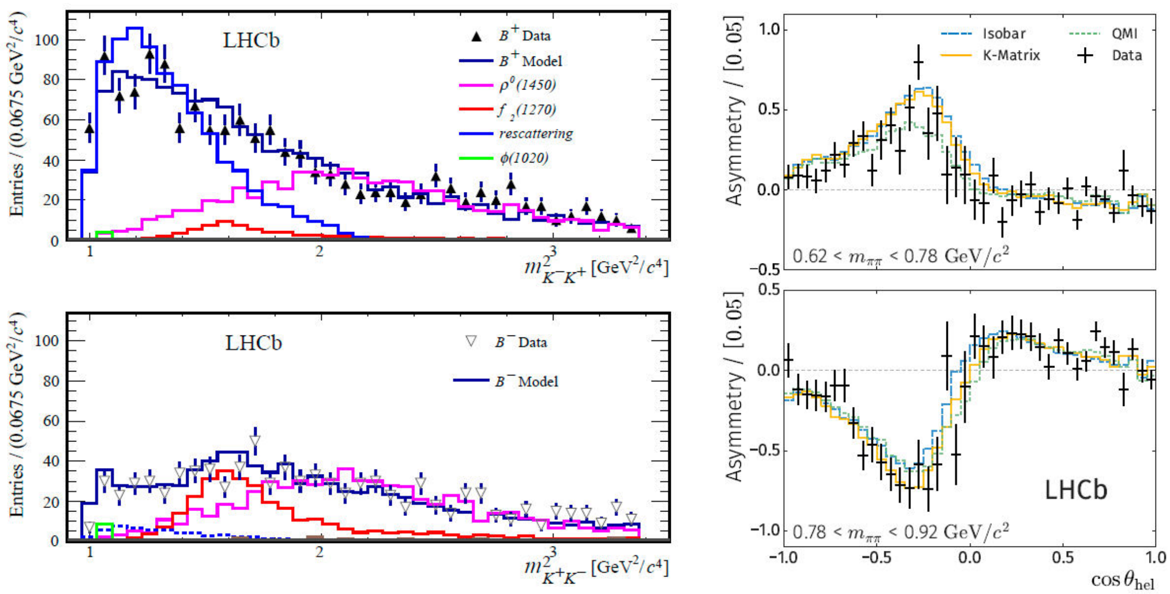

FIGURE 2. Results of the amplitude analysis fit of $B^+ \to \pi^+K^+K^-$ decays [8], showing a projection at low K^+K^- masses (left). The top left plot shows B^+, and the bottom left B^- candidates. Results of the amplitude analysis fit for $B^+ \to \pi^+\pi^+\pi^-$ decays [11] (right), showing the *CP* asymmetry as a function of the cosine of the helicity angle below (top right) and above (bottom right) the $\rho(770)^0$ resonance pole. The fit components are indicated in the plots.

The family of $B \to K\pi$ decays are expected to obey relations based on isospin symmetry, one of which involves the *CP* asymmetry difference, $\Delta A_{CP}\,(K\pi) \equiv A_{CP}\,(B^+ \to K^+\pi^0) - A_{CP}\,(B^0 \to K^+\pi^-)$, predicted to be zero but found non-zero in previous measurements. This discrepancy is known as the so-called $K\pi$ puzzle [6]. The two current analyses bring an update to the world average value of $\Delta A_{CP} = 0.115 \pm 0.014$, which stands even further from zero at 8σ. Thus the $K\pi$ puzzle is confirmed and substantially enhanced.

3. *CP* violation and branching fractions in three-body B-meson decays

The decays of B mesons to three hadrons offer the possibility to study their rich spectra of quasi-two-body resonant intermediate states, where *CP* violation effects could appear in addition to the phase-space-integrated global *CP* asymmetries. Indeed, rich distributions of large local *CP* asymmetries, as well as integrated asymmetries, were seen in the $K^+K^-K^+$, $K^+\pi^+\pi^-$, $\pi^+K^+K^-$ and $\pi^+\pi^+\pi^-$ final states at LHCb [7].

To investigate the underlying dynamics of one of the channels, the first amplitude analysis of $B^+ \to \pi^+K^+K^-$ decays at LHCb [8] was performed recently using the isobar model and a 3.0 fb^{-1} sample of Run 1 data. The fit model that best describes the data contains a coherent sum of five amplitudes that represent two-body resonances in the K^+K^+ or π^+K^- system, a nonresonant component of a single-pole form factor [9], and a dedicated amplitude to account for the possible $\pi\pi \leftrightarrow KK$ rescattering at low energies [10]. The results of the fit show that the dominant components are the single-pole and $\rho(1450)^0$ amplitudes with fit fractions of around 30% each, and the rescattering amplitude with around 16%. In addition, the rescattering amplitude *CP* asymmetry is measured to be $(-66 \pm 4 \pm 2)\%$, making it the largest *CP* asymmetry ever observed from a single amplitude. This is illustrated in Fig. 2 (left), where the rescattering component dominates the low-mass region in B^+ and is practically absent in the B^- distribution.

The $B^+ \to \pi^+\pi^+\pi^-$ decay channel was also studied in an amplitude analysis of Run 1 data [11, 12], using the isobar model with three complementary approaches to describe the S-wave amplitude. The first approach uses a coherent sum of a σ pole [13] with a $\pi\pi \leftrightarrow KK$ rescattering term [14], the second is based on the K-matrix formalism with parameters from scattering data [15], and the third is a "quasi-model-independent" (QMI) approach [16] that divides the dipion mass spectrum into bins treated independently in the fit. The analysis observed several different sources of *CP* violation in the phase space of $B^+ \to \pi^+\pi^+\pi^-$ decays, the largest of which involve the tensor $f_2(1270)$ resonance and the S-wave at low mass,

$$A_{CP}\,(f_2(1270)) = 0.468 \pm 0.061 \pm 0.047,$$
$$A_{CP}\,(S\text{-wave}) = 0.144 \pm 0.018 \pm 0.021.$$

This is the first time *CP* violation is observed in these processes and the first observation in any tensor resonance.

CP violation is also observed in the interference between the P-wave $\rho(770)^0$ resonance and the S-wave, appearing as a characteristic change of sign of the asymmetry below and above the $\rho(770)^0$ resonance pole, as shown in Fig. 2 (right). The statistical significance of the *CP* violation associated with this interference is more than 25σ, making it the first observation of *CP* violation in the interference between two quasi-two-body amplitudes.

The precise knowledge of the branching fractions of three-body B-meson decays is of great importance for interpreting the fit fraction data from amplitude analyses and comparing against theoretical predictions. Recently, a measurement of the branching fractions of the four decay modes involving kaons and pions was performed using 3.0 fb^{-1} of LHCb Run 1 data [17]. The candidate yields are determined from a simultaneous invariant mass fit to the four channels, while the selection efficiencies are measured from simulation and calibration data samples. The most precisely known branching fraction, that of $B^- \to K^+K^+K^-$, is used as a reference to which the relative branching fractions of the remaining channels are measured to obtain

$$\frac{\mathcal{B}(B^+ \to \pi^+K^+K^-)}{\mathcal{B}(B^- \to K^+K^+K^-)} = 0.151 \pm 0.004 \pm 0.008\,,$$
$$\frac{\mathcal{B}(B^+ \to K^+\pi^+\pi^-)}{\mathcal{B}(B^- \to K^+K^+K^-)} = 1.703 \pm 0.011 \pm 0.022\,,$$
$$\frac{\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)}{\mathcal{B}(B^- \to K^+K^+K^-)} = 0.488 \pm 0.005 \pm 0.009\,.$$

The results agree with the world average values and represent significant improvements in the precision of these branching fractions.

4. CP and P violation in three- and four-body b-baryon decays

Although no *CP* violation has been observed yet in decays involving baryons, three- and four-body b-baryon decays present similar decay diagrams to b-mesons and are good candidates for *CP* violation searches and investigating the resonant structure and decay dynamics.

A *CP* violation search was performed in $\Xi_b^- \to pK^-K^-$ decays using 5 fb^{-1} of LHCb Run 1 and 2 data [18]. The invariant mass fits of the selected candidates are shown in Fig. 3, where the previously unobserved $\Omega_b^- \to pK^-K^-$ decay is also modeled. No significant yield is obtained for Ω_b^- decay and an upper limit is placed on the product of ratios of its fragmentation and branching fraction to those of Ξ_b^- at 90 (95)% confidence level,

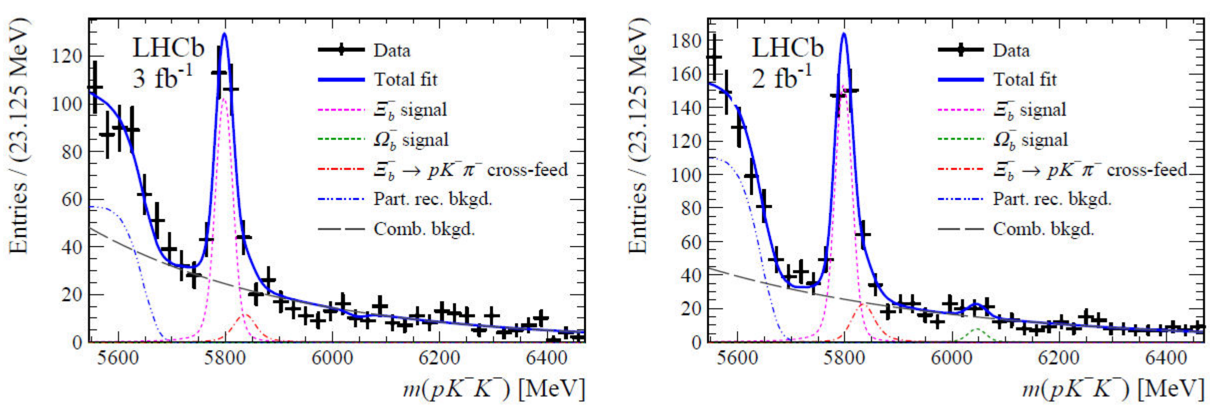

FIGURE 3. Invariant mass distributions of Ξ_b^- candidates from Run 1 (left) and Run 2 data (right) with the fit superimposed [18].

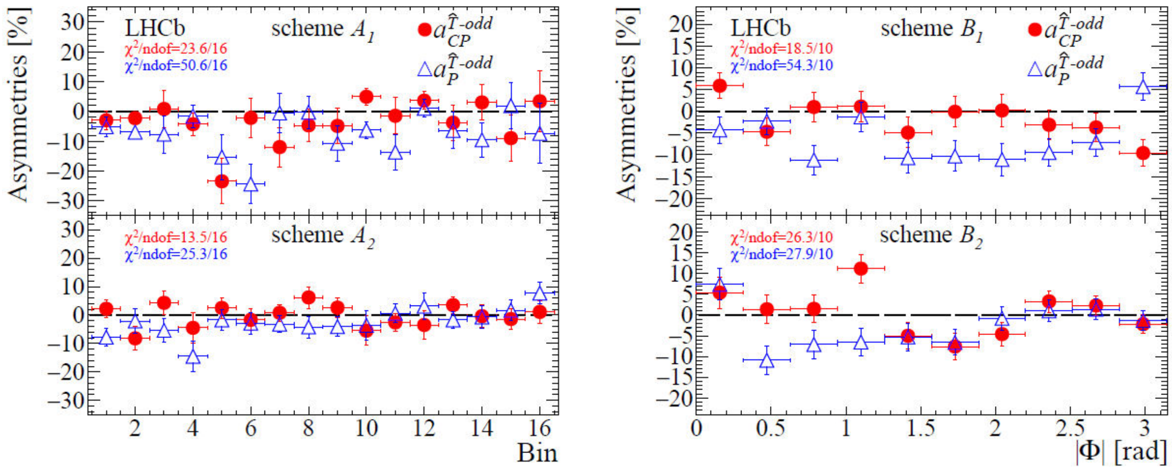

FIGURE 4. Measured *CP* - and P-violating asymmetries in four different binning schemes in the phase space of $\Lambda_b^0 \to p\pi^-\pi^+\pi^+$ decays [21], as indicated in the plots.

$$\frac{f_{\Omega_b^-}}{f_{\Xi_b^-}} \times \frac{\mathcal{B}(\Omega_b^- \to pK^-K^-)}{\mathcal{B}(\Xi_b^- \to pK^-K^-)} < 62\ (71) \times 10^{-3}\,.$$

CP violation in $\Xi_b^- \to pK^-K^-$ decays is probed by means of an amplitude analysis of the sample of about 460 candidates in the signal region. Many possible Λ^* and Σ^* resonant states that decay to pK^- are studied, and six are found to have relevant contributions and considered in the fit model. The *CP* asymmetries of the components are extracted from the fit, and are found to be consistent with zero. From the fit fractions, the branching fractions of the resonant components are measured, of which two have significance larger than 5σ,

$$\begin{aligned}
&\mathcal{B}(\Xi_b^- \to \Lambda(1520)K^-) \\
&\quad = (0.76 \pm 0.09 \pm 0.08 \pm 0.30) \times 10^{-6}, \\
&\mathcal{B}(\Xi_b^- \to \Lambda(1670)K^-) \\
&\quad = (0.45 \pm 0.07 \pm 0.13 \pm 0.18) \times 10^{-6}.
\end{aligned}$$

This is the first amplitude analysis of any b-baryon decay that allows for *CP* violation effects.

The other b-baryon mode, studied recently by LHCb, is the four-body decay $\Lambda_b^0 \to p\pi^-\pi^+\pi^+$. Previously, the LHCb collaboration reported evidence of *CP* violation in this mode with 3.3σ significance [19]. The current analysis [21], based on a larger data sample of 6.6 fb^{-1} of Run 1 and 2 data and an optimised selection, supersedes the previous results. Two independent methods are applied to probe *CP* and P violation, a triple product asymmetries (TPA) measurement sensitive to both global and local asymmetries, and the unbinned energy test method [20] sensitive to local effects. In the TPA method, scalar triple products are formed from the momenta of the three final-state particles, and are used to divide the data into four statistically independent subsamples, related by *CP* or P transformations, which then yield T-odd asymmetries and the resulting *CP* - and P-violating asymmetry observables.

The phase-space-integrated TPA values are obtained from the fit to the full data sample,

$$a_{CP}^{\hat{T}-\text{odd}} = (-0.7 \pm 0.7 \pm 0.2)\%\,,$$
$$a_{P}^{\hat{T}-\text{odd}} = (-4.0 \pm 0.7 \pm 0.2)\%\,,$$

where the former is consistent with *CP* symmetry at 2.9σ, not confirming the previous evidence. The latter is the P-violating asymmetry, which has a nonzero value with a significance of 5.5σ and establishes the observation of parity violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^+$ decays.

The local TPA values are studied in two binning schemes in phase space, shown in Fig. 4. They agree with the global values and indicate that the P-violation has a large contribution from $\Lambda_b^0 \to pa_1(1260)^-$ decay at 5.5σ. The energy test method also confirms the observation of local P violation (5.3σ) and the conservation of *CP* symmetry (3.0σ) in $\Lambda_b^0 \to p\pi^-\pi^+\pi^+$ decays.

5. Perspectives

The LHCb experiment has obtained a plethora of interesting *CP* violation measurements of charmless b-hadron decays so far, including time-dependent *CP* violation and large asymmetries in two-body B-meson decays that deepen the $K\pi$ puzzle, a rich pattern of large local asymmetries in the phase space of three-body B-meson decays, and the observation of P violation in b-baryon decays. New studies are still underway using Run 2 data and are expected to present results with improved precision and analyses of new decay channels and observables. After the completion of the current detector upgrade, the experiment will be able to record even larger data samples and expand its *CP* -violation physics reach to novel precision measurements, new SM tests and discoveries.

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