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CP violation and branching fraction measurements of three-body charmless $B^{\pm}$ decays at LHCb

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Three independent analysis are reported based on a data sample corresponding to an integrated luminosity of 3 fb^{-1} of pp collisions recorded with LHCb detector. Firstly, the relative branching fractions of $B^{+} \to h^{+}h'^{+}h'^{-}$ decays, where $h^{(\prime)}$ is a pion or kaon, are measured. The results obtained improve significantly on previous measurements of these quantities, and are important for the interpretation of Dalitz plot analyses of three-body charmless hadronic decays of B^{+} mesons. Furthermore, the amplitude analysis of $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ and $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ are also reported. Regarding the $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ decay, the rescattering amplitude produces a negative *CP* symmetry of $(-66 \pm 4 \pm 2)\%$, which is the largest *CP* violation effect observed from a single amplitude. Whereas in the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay a large *CP* asymmetry is observed in the decay amplitude involving the tensor $f_2(1270)$ resonance, as well as in the $\pi^{+}\pi^{-}$ *S*-wave at low invariant mass. The presence of *CP* violation related to interference between the $\pi^{+}\pi^{-}$ *S*-wave and the *P*-wave $B^{+} \to \rho(770)^{0}\pi^{\pm}$ amplitude is also established.

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1. Introduction

In the last decades, B meson decays have attracted attention due to CP violation phenomena, denoted CPV, as well as the sensitivity to new physics in rare B decays. A matter of great interest is the study of charmless three-body $B^{\pm}$ decays, whose leading diagram contributions proceed through a $b \to s(d)$ penguin transition and a $b \to u$ tree transition. These decays offer the additional possibility to study the weak phase interference patterns between two-body resonances in the Dalitz plot, and a novel scenario to spot rescattering effects that connect different final states. Most of these channels have branching ratios of the order of 10^{-5} to 10^{-6}, and therefore, large data samples are needed to provide precision measurements.

Large CP asymmetries localised in regions of phase space of $B^+ \to h^+h'^+h'^-$, where $h^{(\prime)}$ is a pion or kaon, decays were observed in model-independent analysis [1–3], and until recently there has been no description of these effects with an accurate model of the contributing resonances. In addition, the results of Dalitz-plot analyses typically include fit fractions of contributing resonances, which can be converted to quasi-two-body branching fractions. Interpretation of the data requires both branching fractions and CP asymmetries through the phase space to be considered. This document presents the latest results from LHCb regarding the asymmetries in the phase space via amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ decays [4–6] and the measurement of the relative branching fractions of $B^+ \to h^+h'^+h'^-$ decays [7].

The results presented below are based on a data sample corresponding to an integrated luminosity of 3 fb^{-1} of pp collision data collected with the LHCb detector [8, 9], between 2011 and 2012. The procedure to select signal candidates is similar to those used in previous LHCb analyses of $B^+ \to h^+h'^+h'^-$ decays and it is optimized for the set of relative branching fraction and amplitude analysis measurements (please check Refs. [4–7] for more details).

2. Relative branching fractions of $B^+ \to h^+h'^+h'^-$ decays

The relative size of the branching fractions, denoted $\mathcal{B}$, of $B^+ \to h^+h'^+h'^-$ decays can be understood to first approximation through the Cabibbo-Kobayashi-Maskawa matrix elements that enter the relevant Feynman diagrams. Interference between different amplitudes contributing to the same process can cause CP violation.

Since currently $\mathcal{B}(B^+ \to K^+K^+K^-)$ is known most precisely, results are presented primarily as ratios with this mode as the denominator. However, determinations of all ratios of one mode to another are also presented, as are the correlations between the results, in order to profit from future improvements of any of the individual branching fraction measurements. In this work, any $B^+ \to h^+h'^+h'^-$ decay where the three final-state particles originate from the same vertex is considered to be part of the signal. This definition thus includes all charmonium resonances, since all have negligible lifetimes, and excludes all contributions from weakly decaying charm mesons.

The relative branching fractions of the signal modes are determined, for example with $B^+ \to K^+K^+K^-$ as denominator, as

$$\frac{\mathcal{B}(B^+ \to h^+h'^+h'^-)}{\mathcal{B}(B^+ \to K^+K^+K^-)} = \frac{\mathcal{N}^{\rm corr}_{hh'h'}}{\mathcal{N}^{\rm corr}_{KKK}} \quad (1)$$

where $\mathcal{N}^{\mathrm{corr}}$ is the efficiency-corrected signal yield accounting both for the variation of the total efficiency across the SDP and for the charm vetoes that completely remove certain regions of the phase space. In fact, in order to avoid a dominant systematic uncertainty due to lack of knowledge of the Dalitz-plot distributions, a model-independent approach is pursued whereby an efficiency correction is applied to each candidate depending on its Dalitz-plot position. These efficiency-corrected yields are [10]

$$\mathcal{N}^{\mathrm{corr}} = \frac{1}{\epsilon^{\mathrm{veto}}} \sum_{j}^{N_{\mathrm{bins}}} \frac{cM_j + \sum_{i\subset \mathrm{bin}\, j} w_i}{\epsilon_j^{\mathrm{tot}}} \tag{2}$$

where the index j runs over the N_{bins} of the square Dalitz plot, ϵ_{veto} is the charm veto efficiency, $\epsilon_j^{\mathrm{tot}}$ is the corresponding total efficiency in bin j, and for each value of j the index i runs over the candidates in that bin. The per-candidate signal *sWeights* w_i, which implement the background subtraction, are obtained from individual fits to the B-candidate mass distribution of each mode in which all nuisance parameters are fixed to the values obtained in the simultaneous fit. In these fits the only varying parameters are the yields of the signal and all background components except those of the cross-feed background contributions, which are fixed. The term cM_j accounts for these fixed components.

The three independent measured ratios relative to the $B^+ \to K^+K^+K^-$ channel are

$$\begin{aligned}
\mathcal{B}(B^+ \to \pi^+K^+K^-)/\mathcal{B}(B^+ \to K^+K^+K^-) &= 0.151 \pm 0.004(\mathrm{stat}) \pm 0.008(\mathrm{syst}),\\
\mathcal{B}(B^+ \to K^+\pi^+\pi^-)/\mathcal{B}(B^+ \to K^+K^+K^-) &= 1.703 \pm 0.011(\mathrm{stat}) \pm 0.022(\mathrm{syst}),\\
\mathcal{B}(B^+ \to \pi^+\pi^+\pi^-)/\mathcal{B}(B^+ \to K^+K^+K^-) &= 0.488 \pm 0.005(\mathrm{stat}) \pm 0.009(\mathrm{syst}),
\end{aligned}$$

whereas the other nine measurements, for which statistical and systematic correlations between the ratios are taken into account, can be found in Ref. [7].

The dominant systematic uncertainties are related to knowledge of the background shapes in the invariant-mass fit, and are reducible if knowledge of the various sources of background can be improved or if the background can be suppressed in future analyses. Several other sources of systematic uncertainty are, however, not negligible compared to the statistical uncertainty of these results, so that further significant reduction in uncertainty will be challenging.

Comparisons with the current world averages are given, for the three measurements above, in Fig. 1 All measurements are in good agreement with the previous world average results and, furthermore, significant improvement in the precision of all measured ratios is obtained.

3. Amplitude analysis of the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay

This section documents the analysis of the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay amplitude in the Dalitz plot. Previous studies of this decay mode indicate that the amplitude contains a sizable $\rho(770)^0$ component [12, 13]. The amplitude analysis performed by the *BABAR* Collaboration [13] additionally observed a large S-wave contribution. However, measurements of CP-violating quantities were limited by statistical precision.

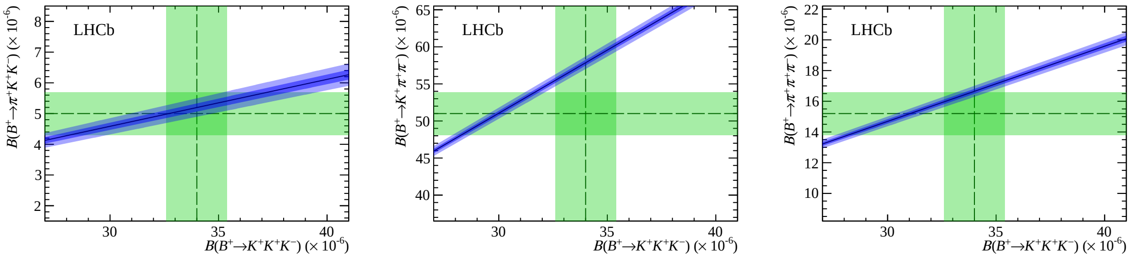

Figure 1: Comparisons of the measured branching fraction ratios, with $\mathcal{B}(B^+ \to K^+K^+K^-)$ as denominator, with the current world averages [11]. Light (dark) bands associated with the branching fraction ratio correspond to the 1σ total (statistical) uncertainty intervals. For horizontal and vertical bands taken from the PDG only the total uncertainty is shown.

Three sets of results are presented, corresponding to the cases where the $\pi\pi$ S-wave is described by (i) a coherent sum of specific resonant contributions (isobar), (ii) a monolithic, unitarity-preserving model informed by historical scattering data (K-matrix), and (iii) a quasi-model-independent (QMI) binned approach. All approaches contain identical contributions to higher partial waves, where $L > 0$. As an example, in the isobar model each of the N amplitudes A are described by a function F_j that parametrizes the intermediate resonant or nonresonant processes,

$$A^{\pm}(m_{13}^2, m_{23}^2) = \sum_j^N c_j^{\pm} F_j(m_{13}^2, m_{23}^2), \tag{3}$$

where the complex coefficients c_j represent the relative contribution of component j. The function F contains only strong dynamics. Then, two important quantities comes out from each of the amplitude analysis formalisms mentioned above: the fit fractions $\mathcal{F}$, defined as the integral of the absolute value of the amplitude squared for each intermediate component, j, divided by that of the coherent matrix-element squared for all intermediate contributions,

$$\mathcal{F}_j^{\pm} = \frac{\int_{\rm DP} |A_j^{\pm}(m_{13}^2, m_{23}^2)|^2 {\rm d}m_{13}^2 {\rm d}m_{23}^2}{\int_{\rm DP} |A^{\pm}(m_{13}^2, m_{23}^2)|^2 {\rm d}m_{13}^2 {\rm d}m_{23}^2}, \tag{4}$$

and the quasi-two-body parameter of CP violation in decay associated with a particular intermediate contribution

$$\mathcal{A}_{CP}^j = \frac{|c_j^-|^2 - |c_j^+|^2}{|c_j^-|^2 + |c_j^+|^2}. \tag{5}$$

The results presented in Refs. [4, 5] show that the models exhibit good overall agreement with the data and with each other, both in CP-average projections and in the variation of the asymmetries across the phase space. Three important features are highlighted:

- The interference between the spin-1 $\rho(770)^0$ and $\omega(782)$ resonances is well described by the models and no significant asymmetry is observed in this region when integrating over $\cos\theta_{\rm hel}$, where $\theta_{\rm hel}$ is the helicity angle.

- A small but approximately constant asymmetry at $m(\pi^+\pi^-)$ values below the $\rho(770)^0$ mass. This region is dominated by the S-wave component with a small contribution from the $\rho(770)^0$ low-mass tail; the CP asymmetry in the S-wave in this region is also seen in all three approaches.

- A large CP violation associated with the $f_2(1270)$ resonance.

The main sources of experimental systematic uncertainty are related to the signal, combinatorial and peaking background parametrization in the B^+ invariant-mass fit, and the description of the efficiency variation across the Dalitz plot. The systematic uncertainties related to the physical amplitude models include the variation of masses and widths of established resonances, in addition to the inclusion of more speculative resonant structures.

4. Amplitude analysis of the $B^{\pm} \to \pi^{\pm}K^+K^-$ decay

In the case of the amplitude analysis of the $B^{\pm} \to \pi^{\pm}K^+K^-$ decay, only the isobar model is employed to described the amplitudes.

The $\pi^{\pm}K^{\pm}$ system is well described by the contributions from the $K^*(892)^0$ and $K_0^*(1430)^0$ resonances, plus a single-pole amplitude, which is a phenomenological description of the partonic interaction. The largest amplitude is from the single-pole amplitude, with a total fit fraction of about 32%.

In the K^+K^- system, two main signatures can be highlighted: a strong destructive interference localized between 0.8 and 3.3 GeV$^2/c^4$ in $m^2_{K^+K^-}$ invariant mass and projected between 12 and 20 GeV$^2/c^4$ in $m^2_{\pi^{\pm}K^{\pm}}$; and a large CP asymmetry of $(-66 \pm 4 \pm 2)$% corresponding to the $\pi\pi \leftrightarrow KK$ rescattering region (1-1.5 GeV/c^2 [14]). This is the largest CPV manifestation ever observed for a single amplitude. Since its measured fit fraction is about 16%, this must be directly related to the total inclusive CP asymmetry observed in this channel, which was previously reported to be (-12.3 ± 2.1)%. For the coupled channel $B^{\pm} \to \pi^{\pm}\pi^+\pi^-$, with a branching fraction 3 times larger than that of $B^{\pm} \to \pi^{\pm}K^+K^-$, a positive CP asymmetry has been measured [3]. This gives consistency for the interpretation of the large CPV observed here originates from rescattering effects.

5. Summary

In conclusion, three results were presented in this document using data collected by the LHCb experiment in 2011 and 2012 corresponding to an integrated luminosity of 3.0 fb^{-1}. The measurement of relative branching fractions of $B^+ \to h^+h'^+h'^-$ decays was performed. All measurements are in good agreement with the previous world-average results and significant improvement in the precision of all measured ratios were obtained. The amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^+\pi^-$ and $B^{\pm} \to \pi^{\pm}K^+K^-$ were also presented. With respect to the $B^{\pm} \to \pi^{\pm}\pi^+\pi^-$ decay, significant CP violation is observed in the decay amplitudes associated with the $f_2(1270)$ resonance and with the $\pi^+\pi^-$ S-wave at low invariant mass, in addition to CP violation characteristic of interference between the spin-1 $\rho(770)^0$ resonance and the spin-0 S-wave contribution. Regarding the $B^{\pm} \to \pi^{\pm}K^+K^-$

decay, the main result comes from the $\pi\pi \leftrightarrow KK$ rescattering region, revealing the largest CPV manifestation ever observed for a single amplitude.

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PoS(CKM2021)114