Measurements of $CP$ violation in charmless 3-body B-meson decays at LHCb

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Charmless 3-body B-meson decays can present significant $CP$ asymmetries. Large raw charge asymmetries were observed in $B^+ \rightarrow \pi^+ K^+ K^-$ and $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays by the LHCb collaboration. The most recent results from LHCb are discussed here. They include amplitude analyses of $B^+ \rightarrow \pi^+ K^+ K^-$ and $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays. The study of $B^0 \rightarrow \pi^+ K^+ K^-$ reported a large $CP$ asymmetry arising from the S-wave. In the case of the $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ decay analysis, the first observation of $CP$ violation in a process involving a tensor was made.
1. Introduction

In charmless 3-body B-meson decays, large CP asymmetries can occur due to interference between contributions to a single amplitude from penguin and tree diagrams with comparable magnitudes. The LHCb collaboration observed large raw charge asymmetries in $B^+ \rightarrow \pi^+ K^+ K^-$ and $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays\(^1\) [1], providing a strong motivation to perform amplitude analyses for both $B^+ \rightarrow \pi^+ K^+ K^-$ [2] and $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ [3, 4]. These two decays are coupled through the rescattering process $\pi\pi \leftrightarrow KK$. Rescattering allows decays via one channel ($e.g.$ $B \rightarrow X\pi^+\pi^-$) to appear as a second, coupled final state ($e.g.$ $XX K^-\pi^+$). Both of the amplitude analyses have been performed with the Run 1 data sample, corresponding to 3 fb\(^{-1}\) of $pp$ collisions at $\sqrt{s} = 7,8$ TeV collected by LHCb. One way to describe the effect of interfering amplitudes is based on the isobar model [5, 6]. In this formalism, the overall amplitude is described as a sum of individual contributions with index $j$, each of which is the product of two terms:

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

where $A^+$ and $A^-$ are the amplitudes for $B^+$ and $B^-$ at a given point in phase space, and $c_j^\pm$ is constant over the phase space (the Dalitz plot) and are the free parameters of the model. $m_{ab}^2$ is the squared invariant mass of particle $a$ and $b$. $F_j(m_{13}^2, m_{23}^2)$ is a form factor given by

$$F_j(m_{13}^2, m_{23}^2) = R(m_{13}) \times T(\bar{p}, \bar{q}) \times X(|\bar{p}|r_{BW}) \times X(|\bar{q}|r_{BW}),$$

and is the product of a mass line-shape $R$ ($e.g.$ a Breit-Wigner), an angular dependence $T$, and the barrier factors $X$, and does not distinguish between $B^+$ and $B^-$. CP violation occurs if $c_j^+ \neq c_j^-$ for any of the components.

2. Amplitude analysis of $B^+ \rightarrow \pi^+ K^+ K^-$ decays

The isobar model (Eq. 1) is used to describe the charmless three-body decay $B^+ \rightarrow \pi^+ K^+ K^-$. The resulting amplitude provides a good description of the data (Fig. 1). To describe the $\pi^+ K^-$ system, the model includes three contributions. They consist of the $K^*(892)^0$ and $K_0^*(1430)^0$ resonances, plus a nonresonant with a single-pole form factor [7] providing a phenomenological description of the partonic interaction. The nonresonant term is the single largest contribution to the amplitude, with a fit fraction of about 32\% [2]. Four contributions are used to describe the $K^+ K^-$ system, namely three resonances——$\rho(1450)^0$, $f_2(1270)$ and $\phi(1020)$——and a rescattering amplitude. The latter has yielded a CP asymmetry of $(-66 \pm 4 \pm 2)\%$ [2], the largest such asymmetry observed for a single contribution in an amplitude analysis.

3. Amplitude analysis of $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays

While the isobar formalism is conceptually simple and has been used successfully in numerous past studies, it has some known limitations, particularly when describing multiple overlapping

\(^1\)Charge-conjugate processes are included implicitly.
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Figure 1: Distribution of $m_{K^+K^-}^3$ up to 3.5 $GeV^2/c^4$. Data are represented by points for $B^+$ and $B^−$ separately, with the result of the fit overlaid [2].

contributions (in which case it can violate unitarity). This is a particular concern for the $\pi^+\pi^−$ S-wave component. Therefore, to complement the result, this component was described with three different approaches: the isobar model, the K-matrix formalism [8–10] and a quasi-model-independent (QMI) procedure [11–16]. The fits obtained with all three approaches are in good agreement with the data and with each other (Fig. 2). In the fits, it is found that the $\rho(770)^0$ resonance has a CP asymmetry compatible with 0. By contrast, significant CP violation was observed in the interference between the $\rho(770)^0$ P-wave and the S-wave contribution. All three approaches gave a good description of this effect, which marks the first time that CP violation in an amplitude analysis has been observed originating purely in the interference between two components (as opposed to asymmetries in the components themselves). In addition, a clear CP asymmetry, around 15% [3, 4], which is not associated with the interference process described above, is seen below the $K^+K^-$ threshold. The $f_2(1270)$ resonance also exhibited significant CP violation of about 40% [3, 4]; this is the first time that CP violation linked to a tensor tensor has been reported.

4. Conclusion

Challenging amplitude analyses were performed to better understand the CP violation observed in $B^+ → \pi^+K^+K^-$ and $B^+ → \pi^+\pi^+\pi^−$ decays. In the $B^+ → \pi^+K^+K^−$ amplitude analysis, large CP violation was observed in the S-wave contribution. This is consistent with what is observed
in the coupled channel $B^+ \rightarrow \pi^+\pi^+\pi^-$. In the $B^+ \rightarrow \pi^+\pi^+\pi^-$ amplitude analysis, consistent descriptions of the S-wave contribution were obtained with three different frameworks. Significant CP violation was observed in the S-wave component, and in the interference between the S- and P-wave components. For the first time, CP violation was observed in a process involving a tensor.

Further, exciting results can be expected for these and other multi-body charmless $b$-hadron decays with the addition of the Run 2 data sample (which has both an integrated luminosity and a $b$-hadron production cross-section two times larger). The upgraded LHCb detector will collect data with even greater luminosity and efficiency from Run 3.

References


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