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

LHCb collaboration

Abstract

The first amplitude analysis of the $B^\pm \rightarrow \pi^\pm K^+K^-$ decay is reported based on a data sample corresponding to an integrated luminosity of 3.0 fb$^{-1}$ of $pp$ collisions recorded in 2011 and 2012 with the LHCb detector. The data is found to be best described by a coherent sum of five resonant structures plus a nonresonant component and a contribution from $\pi\pi \leftrightarrow KK$ $S$-wave rescattering. The dominant contributions in the $\pi^\pm K^\mp$ and $K^+K^-$ systems are the nonresonant and the $B^\pm \rightarrow \rho(1450)^0\pi^\pm$ amplitudes, respectively, with fit fractions around 30%. For the rescattering contribution, a sizeable fit fraction is observed. This component has the largest $CP$ asymmetry reported to date for a single amplitude of $(−66\pm 4\pm 2)\%$, where the first uncertainty is statistical and the second systematic. No significant $CP$ violation is observed in the other contributions.


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Charge-parity (CP) symmetry is known to be violated in the weak interaction. In charged $B$-meson decays, only direct CP violation (CPV) is possible. Its simplest manifestation is a difference in the rate of $B^-$ and $B^+$ mesons to a given decay mode. For multibody hadronic charged decays, more sophisticated direct CPV observables can be explored. Indeed, it is natural to expect that CP asymmetries are enhanced in specific regions of the phase space.

The LHCb collaboration has reported sizeable localised CP asymmetries in the phase space of three-body charmless $B^\pm$ decays $^1$. Among the channels studied, the $B^\pm \rightarrow \pi^\pm \pi^+\pi^-$ and $B^\pm \rightarrow \pi^\pm K^+K^-$ decays have the same quantum numbers and weak coupling, but have different intermediate states and differ by a factor of three in their total branching fractions. The $B^\pm \rightarrow \pi^\pm \pi^+\pi^-$ decay, which has a larger branching fraction, can proceed through resonances from direct (tree) $b \rightarrow u \ (\bar{b} \rightarrow \bar{u})$ transitions as well as from $b \rightarrow d \ (\bar{b} \rightarrow \bar{d})$ loop-induced (penguin) processes. On the other hand, the production of resonances in the $B^\pm \rightarrow \pi^\pm K^+K^-$ decay is limited: $\pi^\pm K^\mp$ resonances can only be obtained from penguin transitions; $K^+K^-$ resonances can come from tree-level transitions but with the $s\bar{s}$ contribution highly suppressed by the OZI rule $^2$.$^4$. Nonetheless, contributions from rescattering processes $^5$.$^6$ could be present.

In the $B^\pm \rightarrow \pi^\pm K^+K^-$ decay, no significant $\phi(1020) \rightarrow K^+K^-$ contribution has been seen $^7$, but a concentration of events is observed just above the $\phi(1020)$ region in the $K^+K^-$ invariant-mass spectrum. This corresponds to the region where the well-known $S$-wave $\pi^+\pi^- \leftrightarrow K^+K^-$ rescattering effect is seen, as shown by elastic scattering experiments $^8$.$^9$. Interestingly, in this same region, large CP asymmetry effects have been observed $^1$.$^10$. As proposed in Refs. $^11$.$^12$, this could be a manifestation of CPV arising from the dynamically produced rescattering strong-phase differences between amplitudes with different weak phases.

A better understanding of the CPV mechanisms occurring in three-body hadronic $B$ decays can be achieved through full amplitude analyses. In this Letter, the first amplitude analysis of the decay $B^\pm \rightarrow \pi^\pm K^+K^-$ is performed based on a data sample corresponding to an integrated luminosity of 3.0 fb$^{-1}$ collected in 2011 and 2012. The isobar model formalism $^13$, which assumes that the total decay amplitude is a coherent sum of intermediate two-body states, is applied. A rescattering amplitude is also included. The magnitudes and phases of the coupling to intermediate states are determined independently for $B^+ \rightarrow \pi^+ K^+ K^- \pi^-$ and $B^- \rightarrow \pi^- K^+ K^- \pi^+$ decays, allowing for CP violation.

The LHCb detector $^14$.$^15$ is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the $pp$ interaction region $^16$, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes $^17$ placed downstream of the magnet. The tracking system provides a measurement of the momentum, $p$, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/$c$. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu$m, where $p_T$ is the component of the momentum transverse to the beam, in GeV/$c$. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors $^18$. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are
identified by a system composed of alternating layers of iron and multiwire proportional chambers \[19\]. The online event selection is performed by a trigger \[20\], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, in which all tracks with \( p_T > 500 \) \( (300) \) MeV/c are reconstructed for data collected in 2011 \( (2012) \). The software trigger used in this analysis requires a two-, three- or four-track secondary vertex with a significant displacement from any PV. At least one charged particle must have a transverse momentum \( p_T > 1.6 \) GeV/c and be inconsistent with originating from any PV. A multivariate algorithm \[21\] is used for the identification of secondary vertices consistent with the decay of a \( b \) hadron.

Simulated samples, needed for obtaining the signal efficiency as well as for background studies, are generated using PYTHIA \[22\] with a specific LHCB configuration \[23\]. Decays of hadronic particles are produced by EvtGen \[24\], in which final-state radiation is generated using PHOTOS \[25\]. The interaction of the generated particles with the detector and its response is implemented using the GEANT4 toolkit \[26\] as described in Ref. \[27\].

A multivariate selection based on a boosted decision tree (BDT) algorithm \[29, 30\] is applied to reduce the combinatorial background (random combination of tracks). The BDT is described in Ref. \[1\]; it is trained using a combination of \( B^- \rightarrow h^\pm h^\mp h^- \) samples of simulated events (where \( h \) can be either a pion or a kaon) as signal, and data in the high-mass region \( 5.40 < m(\pi^\pm \pi^\mp \pi^-) < 5.58 \) GeV/c\(^2\) of a \( B^\pm \rightarrow \pi^\pm \pi^\mp \pi^- \) sample as background. The samples contributing to the signal, namely \( B^\pm \rightarrow \pi^\pm K^-K^- \), \( B^\pm \rightarrow \pi^\mp \pi^+ \pi^- \), \( B^\pm \rightarrow K^\pm \pi^\mp \pi^- \) and \( B^\pm \rightarrow K^\pm K^-K^- \), share a similar topology allowing for a common optimization. The \( B^\pm \rightarrow \pi^\pm \pi^\mp \pi^- \) sample is used as a proxy for the combinatorial background because, among the various \( B^\pm \rightarrow h^\pm h^\mp h^- \) channels, it is the only one whose high mass region is populated just by combinatorial background. The selection requirement on the BDT response is chosen to maximize the ratio \( N_S/\sqrt{N_S + N_B} \), where \( N_S \) and \( N_B \) represent the expected number of signal and background candidates in data, respectively, within an invariant mass window of approximately 40 MeV/c\(^2\) around the \( B^\pm \) mass in the data \[1\].

Particle identification criteria are used to reduce the crossfeed from other \( b \)-hadron decays, in particular to reduce \( K \leftrightarrow \pi \) misidentification. Muons are rejected by a veto applied to each track \[31\]. After the full selection, events with more than one candidate in the range \( 5.08 < m(\pi^\pm K^\mp K^-) < 5.58 \) GeV/c\(^2\) are discarded. This removes approximately 1% of the selected candidates.

An unbinned extended maximum-likelihood fit is applied simultaneously to the \( \pi^+K^-K^+ \) and \( \pi^-K^+K^- \) mass spectra in order to obtain the total signal yields and the raw asymmetry, defined as the difference of \( B^- \) and \( B^+ \) signal yields divided by their sum. Three types of background sources are identified: the residual combinatorial background, partially reconstructed decays (mostly from four-body decays) and cross-feed from other \( B \)-meson decays due to misidentification of one or more particles. The parametrization of crossfeed and partially reconstructed backgrounds is performed using
This description for the total decay amplitude is known as the isobar model. In the amplitude fit, the complex coefficients \( c_i \) are described by

\[
\mathcal{M}_i(m_{\pi^+K^-},m_{K^+K^-}) = \sum_{i=1}^{N} c_i \mathcal{M}_i(m_{\pi^+K^-},m_{K^+K^-}),
\]

where \( \mathcal{M}_i(m_{\pi^+K^-},m_{K^+K^-}) \) is the decay amplitude for an intermediate state \( i \). The analogous amplitude for the \( B^- \) meson, \( \overline{\mathcal{A}}_i \), is written in terms of \( \overline{c}_i \) and \( \overline{\mathcal{M}}_i(m_{\pi^-K^+},m_{K^+K^-}) \).

The total \( B^+ \rightarrow \pi^+K^-K^+ \) decay amplitude, \( \mathcal{A} \), can be expressed as function of \( m_{\pi^+K^-}^2 \) and \( m_{K^+K^-}^2 \) as

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\mathcal{A}(m_{\pi^+K^-}^2,m_{K^+K^-}^2) = \sum_{i=1}^{N} c_i \mathcal{M}_i(m_{\pi^+K^-}^2,m_{K^+K^-}^2),
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The distributions of the selected \( B^\pm \) candidates, represented by the Dalitz plot, are shown in Fig. 1. The distributions are due to combinatorial background and the \( \phi \) mesons randomly associated with a pion, with negligible charge asymmetry.

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The contribution of the possible intermediate states in the composition of the total decay amplitude is tested through a procedure in which each component is taken in and out of the model, and that which provides the best likelihood is then maintained, and the process is repeated. In some regions of the phase space the observed signal yields could not be well described with only known resonance states and lineshapes, and thus alternative parameterisations were also tested.

In the $\pi^\pm K^\mp$ system, a nonresonant amplitude involving a single-pole form factor of the type $(1 + m^2(p^2 + 1)/\Lambda^2)^{-1}$, as proposed in Ref. [10], is included. This component, hereafter called single-pole amplitude, is a phenomenological description of the partonic interaction. The parameter $\Lambda$ sets the scale for the energy dependence and the proposed value of $1$ GeV/$c^2$ is used.
In the $K^+K^-$ system, a dedicated amplitude accounting for the $\pi\pi \leftrightarrow KK$ rescattering is used. It is expressed as the product of the nonresonant single-pole form factor described above and a scattering term which accounts for the $S$-wave $\pi\pi \leftrightarrow KK$ transition amplitude, with isospin equal to 0 and $J = 0$, given by the off-diagonal term in the $S$-matrix for the $\pi\pi$ and $KK$ coupled channel. The scattering term is expressed as $\sqrt{1 - \nu^2}e^{2\delta}$. The functional forms of the inelasticity ($\nu$) and phase shift ($\delta$) are taken from Ref. [39]. For the mass range 0.95 to 1.4 GeV/$c^2$, where the coupling $\pi\pi \rightarrow KK$ is known to be important, these parameters are given by

$$\nu = 1 - \left(\epsilon_1 \frac{k_2}{s^{1/2}} + \epsilon_2 \frac{k_2^2}{s}\right) \frac{M^2 - s}{s}$$  \hspace{1cm} (5)$$

and

$$\cot \delta = C_0 \left(\frac{s - M_f^2}{M_f^2 - s}\right) \frac{|k_2|}{k_2^2},$$  \hspace{1cm} (6)$$

where $s = m_{K^+K^-}^2$, $k_2 = \frac{1}{2} \sqrt{s - 4m_K^2}$, $m_K = 0.495$ GeV/$c^2$, $M_f = 1.5$ GeV/$c^2$, $M_s = 0.92$ GeV/$c^2$, $M_f = 1.32$ GeV/$c^2$, $\epsilon_1 = 2.4$, $\epsilon_2 = -5.5$ and $C_0 = 1.3$ [39].

The $B^+ \rightarrow \pi^+K^+K^-$ resonant structure is studied using the LAURA$^+$ package [40,41]. For all models tested in the analysis, the channel $B^+ \rightarrow \overline{K}^*(892)^0K^+$ is used as reference, with its real part $x$ fixed to one, $y$ and $\Delta y$ fixed to zero, while the $\Delta x$ parameter is free to vary. The values of $x, y, \Delta x$ and $\Delta y$ for all other contributions are free parameters in the fit. The masses and widths of all resonances are fixed in the fit [28].

The fit results are summarized in Table 1. Seven components are required to provide an overall good description of data; three of them correspond to the structure in the $\pi^+K^+$ system, and four for the $K^+K^-$ system. Statistical uncertainties on the presented results are derived from the fitted values of $x, y, \Delta x, \Delta y$, with correlations and error propagation taken into account; sources of systematic uncertainty are also evaluated as described later.

The $\pi^+K^+$ system in the data is well described by the contributions from the $K^*(892)^0$ and $K^0_0(1430)^0$ resonances plus the single-pole amplitude. The inclusion of the latter provides a better description of the data than that obtained from the $K^0_0(700)$, $K^0_1(1430)^0$, $K^*(1410)^0$, and $K^*(1680)^0$ resonances. The largest contribution, as seen in Table 1, is from the single-pole amplitude, with a total fit fraction of about 32%. The vector $K^*(892)^0$ and the scalar $K^0_0(1430)^0$ amplitudes contribute to 7.5% and 4.5%, respectively. Given that they originate from penguin-diagram processes, their contributions to the total rate are expected to be small. The projection of the data onto $m_{\pi\piK}$ with the fit model overlaid, is shown in Fig. 2.

In the $K^+K^-$ system, two main signatures can be highlighted: a strong pattern of destructive interference localised between 0.8 and $3.3 \text{ GeV}^2/c^4$ in $m_{K^+K^-}^2$ and projected between 12 and $20 \text{ GeV}^2/c^4$ in $m_{\pi\piK}^2$, as shown in Fig. 1, and the large CP asymmetry for $m_{K^+K^-}^2$ below $1.5 \text{ GeV}^2/c^4$, corresponding to the $\pi\pi \leftrightarrow KK$ rescattering region, as shown in Fig. 3. For the former, a good description of the data is achieved only when a high-mass vector amplitude is included in the Dalitz plot fit, producing the observed pattern through the interference with the $f_2(1270)$ amplitude. The data are well described by assuming this contribution to be the $\rho(1450)^0$ resonance, included in the fit with mass and width fixed to their known values [28]. The corresponding $B^+ \rightarrow \rho(1450)^0\pi^+$ fit fraction is approximately 30%, a rather large contribution not expected for the $K^+K^-$
Table 1: Results of the Dalitz plot fit, where the first uncertainty is statistical and the second systematic. The fitted values of $c_i$ ($\bar{c}_i$) are expressed in terms of magnitudes $|c_i|$ ($|\bar{c}_i|$) and phases arg($c_i$) (arg($\bar{c}_i$)) for each $B^+$ ($B^-$) contribution. The top row corresponds to $B^+$ and the bottom to $B^-$ mesons.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Fit Fraction(%)</th>
<th>$A_{CP}(%)$</th>
<th>Magnitude ($B^+/B^-$)</th>
<th>Phase[°] ($B^+/B^-$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^0$</td>
<td>7.5 ± 0.6 ± 0.5</td>
<td>+12.3 ± 8.7 ± 4.5</td>
<td>0.94 ± 0.04 ± 0.02</td>
<td>0 (fixed)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.06 ± 0.04 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$K_S^0(1430)^0$</td>
<td>4.5 ± 0.7 ± 1.2</td>
<td>+10.4 ± 14.9 ± 8.8</td>
<td>0.74 ± 0.09 ± 0.09</td>
<td>−176 ± 10 ± 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.82 ± 0.09 ± 0.10</td>
<td>136 ± 11 ± 21</td>
</tr>
<tr>
<td>Single pole</td>
<td>32.3 ± 1.5 ± 4.1</td>
<td>−10.7 ± 5.3 ± 3.5</td>
<td>2.19 ± 0.13 ± 0.17</td>
<td>−138 ± 7 ± 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.97 ± 0.12 ± 0.20</td>
<td>166 ± 6 ± 5</td>
</tr>
<tr>
<td>$\rho(1450)^0$</td>
<td>30.7 ± 1.2 ± 0.9</td>
<td>−10.9 ± 4.4 ± 2.4</td>
<td>2.14 ± 0.11 ± 0.07</td>
<td>−175 ± 10 ± 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.92 ± 0.10 ± 0.07</td>
<td>140 ± 13 ± 20</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>7.5 ± 0.8 ± 0.7</td>
<td>+26.7 ± 10.2 ± 4.8</td>
<td>0.86 ± 0.09 ± 0.07</td>
<td>−106 ± 11 ± 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.13 ± 0.08 ± 0.05</td>
<td>−128 ± 11 ± 14</td>
</tr>
<tr>
<td>Rescattering</td>
<td>16.4 ± 0.8 ± 1.0</td>
<td>−66.4 ± 3.8 ± 1.9</td>
<td>1.91 ± 0.09 ± 0.06</td>
<td>−56 ± 12 ± 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.86 ± 0.07 ± 0.04</td>
<td>−81 ± 14 ± 15</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>0.3 ± 0.1 ± 0.1</td>
<td>+9.8 ± 43.6 ± 26.6</td>
<td>0.20 ± 0.07 ± 0.02</td>
<td>−52 ± 23 ± 32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.22 ± 0.06 ± 0.04</td>
<td>107 ± 33 ± 41</td>
</tr>
</tbody>
</table>

Figure 2: Distribution of $m^2_{\pi^+K^+}$. Data are represented by points for $B^+$ and $B^-$ candidates separately, with the result of the fit overlaid.
Figure 3: Distribution of $m_{K^+K^-}^2$ 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.

A second solution is found in the fit, presenting a large positive CP asymmetry of 76% in the $K^*_0(1430)^0$ component, which is compensated by a similarly large negative asymmetry in the interference term between $K^*_0(1430)^0$ and the single-pole amplitudes, such that the net effect is a negligible CP asymmetry near the $K^*_0(1430)^0$ region, as seen in data. As such, this solution is interpreted as an unphysical solution. More data are necessary to understand this feature.
Several sources of systematic uncertainty are considered. These include the possible mismodelling in the mass fit, the efficiency variation across the DP and background models, the uncertainty associated to the fixed parameters in the Dalitz plot fit and possible biases in the fitting procedure. The model developed to describe the dynamics of $B^\pm \to \pi^\pm K^+ K^-$ decays is an approximation, and hence could also be considered a source of systematic uncertainty. With the currently available sample size there is limited scope to explore the impact of alternative models, and therefore no uncertainty has been assigned due to this assumption.

The systematic uncertainty associated to efficiency variation across the Dalitz plot is evaluated by performing several fits to data with efficiency maps obtained by varying the bin content of the original efficiency histogram according to a Gaussian function, with mean and width taken as the central value and uncertainty, respectively, of each bin. The systematic uncertainty due to the background models is evaluated with a similar procedure. Its main contribution is due to the combinatorial background modelling. The production and kaon detection asymmetry effects are taken into account following Ref. [43].

The main contribution to the systematic uncertainty comes from the variation of the masses and widths of the resonances; their central values and uncertainties are taken from the PDG [28] and are randomised according to a Gaussian function. This systematic uncertainty is particularly important for the $K^*_0(1430)^0$ and nonresonant components, the two broad scalar contributions in the $\pi^\pm K^\mp$ system. A systematic uncertainty is also evaluated due to the differences in the nominal model when the $\rho(1450)^0$ component is set with parameters fixed to known values [28] and when these are free to vary. No differences with the nominal solution structure are observed. All uncertainties are added in quadrature and represent the second uncertainty in Table 1.

In summary, the resonant substructure of the charmless three-body $B^\pm \to \pi^\pm K^+ K^-$ decay is determined using the isobar model formalism, providing an overall good description of the observed data. Three components are obtained for the $\pi^\pm K^\mp$ system: two resonant states ($K^*(892)^0$, $K^*_0(1430)^0$) with a $CP$ asymmetry consistent with zero, and a nonresonant single-pole form factor contribution with a fit fraction of about 30%. Two other components are found, $\rho(1450)$ and $f_2(1270)$, which provide a destructive interference pattern in the Dalitz plot. The rescattering amplitude, acting in the region $0.95 < m(K^+ K^-) < 1.42$ GeV/$c^2$, produces a negative $CP$ asymmetry of $(-66 \pm 4 \pm 2)\%$, which is the largest $CP$ violation effect observed from a single amplitude.

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National Research University Higher School of Economics, Moscow, Russia, associated to 39
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