Dalitz plot analyses of charmless $b$-hadron decays at LHCb

Stefano Perazzini, on behalf of LHCb Collaboration

Abstract

Charmless $b$-hadron decays are suppressed in the Standard Model by tiny CKM matrix elements which brings the tree amplitudes to levels comparable with loop amplitudes, and potentially New Physics amplitudes. CP violation measurements using Dalitz plot analyses in multi-body decays allow to disentangle these various contributions. In this document we report about the most recent measurements from LHCb in this sector. Firstly, the study of direct CP asymmetries over the Dalitz plane of the $B^+ \rightarrow \pi^+ h^+ h^-$ decays and the $B^+ \rightarrow K^+ h^+ h^-$ decays (where $h = \pi, K$), will be presented (through this document the inclusion of charge conjugate is always implied, unless explicitly stated). Then the results obtained studying the $B^+ \rightarrow p\bar{p}h^+$ decays will be shown. The measurements of the branching ratio of the $B^+ \rightarrow \bar{\Lambda}(1520)p$ (with $\bar{\Lambda}(1520) \rightarrow \bar{p}K^+$), of the forward-backward asymmetry of the light meson ($\pi$ or $K$) in the $p\bar{p}$ rest frame and of the direct CP asymmetry over the $B^+ \rightarrow p\bar{p}h^+$ Dalitz plane will be discussed.

Keywords: CP violation, $b$-hadron decays, Dalitz plot analysis

1. Introduction

Decays of $B$ mesons to three-body hadronic charmless final states provide an interesting environment to probe the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1, 2] that generates CP violation in the Standard Model (SM). Moreover these decays receive non-negligible contributions from loop topologies. New particles beyond the SM may appear as virtual contributions inside the loops leading to discrepancies of the CP violation observables with respect to their predictions. Even if on the one hand the loop diagrams represent a good laboratory for discovery, on the other hand the interpretation of the observables in terms of CKM parameters is non-trivial. In fact, CP violation arises from the interference between processes with different weak and strong phases. Since the source of the strong phase difference in these processes is not well understood, the potential for discovery provided by charmless charged three-body $B$ decays is limited by theoretical uncertainties. Possible sources of the strong phase difference are the interference between intermediate states of the decay [3, 4], or final-state $KK \leftrightarrow \pi\pi$ rescattering, which can occur in decay channels with the same quantum numbers [5, 6, 7, 8]. Effects of SU(3) flavour symmetry breaking can also be used to explain the observed patterns of asymmetries [9, 4, 10]. The analysis of CP asymmetries over the Dalitz plane provides additional information to probe these hypotheses and to better constrain the hadronic parameters.

In this document we present the most recent and most relevant results obtained by the LHCb experiment [11] in the study of these decays performed using the $p-p$ collisions recorded during 2011 and 2012, corresponding to an integrated luminosity of 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 2 fb$^{-1}$ at $\sqrt{s} = 8$ TeV.

2. Direct CP violation in $B^+ \rightarrow \pi^+ h^+ h^-$ and $B^+ \rightarrow K^+ h^+ h^-$ decays

Theoretical predictions regarding direct $CP$ violation in three-body charmless $B$ decays are mostly based on quasi-two-body decays to intermediate states [12]. Thanks to the rich set of resonances and to their interference pattern these decays favour the investigation of charge asymmetries localized in the phase space. In the past the BaBar and Belle experiments at the $B$-factories
performed amplitude analyses of the $B^{+} \rightarrow \pi^{+}K^{+}K^{-}$ and $B^{+} \rightarrow K^{+}K^{-}K^{-}$ decays reporting evidence of $CP$ violation in the intermediate channel $\rho^{0}K^{+}$ [13, 14] and more recently in the channel $\phi K^{+}$ [15]. However, the inclusive $CP$ asymmetries of all the four final states considered, namely $K^{+}\pi^{+}\pi^{-}$, $K^{+}K^{-}K^{-}$, $\pi^{+}K^{-}K^{-}$ and $\pi^{+}\pi^{-}\pi^{0}$, were found to be consistent with zero [16, 17]. LHCb, using the data sample collected in $p$$p$ collisions during 2011, measured the inclusive $CP$-violating asymmetries for $B^{+} \rightarrow \pi^{+}\pi^{+}\pi^{-}$, $B^{+} \rightarrow \pi^{+}K^{+}K^{-}$, $B^{+} \rightarrow K^{+}\pi^{+}\pi^{-}$ and $B^{+} \rightarrow K^{+}K^{-}K^{-}$ decays. The $CP$ asymmetry in $B^{+}$ decays to a final state $f^{+}$ is defined as

$$A_{CP}(B^{\pm} \rightarrow f^{+}) = \frac{\Gamma(B^{-} \rightarrow f^{-}) - \Gamma(B^{+} \rightarrow f^{+})}{\Gamma(B^{-} \rightarrow f^{-}) + \Gamma(B^{+} \rightarrow f^{+})},$$

where $\Gamma$ is the instantaneous decay rate of the process (charge-conjugation is not implied in the equation above) and $f^{\pm}$ can be $\pi^{\pm}\pi^{\mp}$, $\pi^{+}K^{-}K^{+}$, $K^{+}\pi^{+}\pi^{-}$ and $K^{+}K^{-}K^{-}$. A study of $A_{CP}$ over the Dalitz plane of the decays has also been performed.

The events used in this analysis are selected by a multi-level trigger [18], consisting in a hardware stage, selecting events on the basis of information provided by calorimeters and muon detectors, followed by two software stages performing a full event reconstruction. The first software stage performs an inclusive selection of events, requiring the presence of at least one track with large momentum, transverse momentum ($p_{T}$) and impact parameters with respect to the reconstructed $p$$p$ interaction vertex (primary vertex or PV). The second software stage firstly uses the combination of two, three or four tracks with a large sum of their transverse momentum to reconstruct secondary vertices displaced with respect to the PV. Then a multi-variate algorithm is used to select those vertices more consistent with the decay of a $B$ hadron. Three high-$p_{T}$ charged tracks with a small distance of closest approach between any two of them are fitted offline to a common vertex building the $B^{+}$ candidates. Further requirements are applied to the quality of the common vertex fit and to the angle between the $B^{+}$ momentum and its direction of flight in order to reduce the combinatorial background. Finally the various final states are separated by means of particle identification information, provided by the two ring-imaging Cherenkov detectors [19]. Specific background pollutions coming from charm contributions are removed vetoing the invariant mass region around the $D^{0}$ peak in the $\pi^{+}\pi^{-}$, $K^{-}\pi^{+}$ and $K^{+}K^{-}$ final state hypotheses. The contribution of the $B^{+} \rightarrow J/\psi K^{+}$ decay is also excluded from the $K^{+}\pi^{+}\pi^{-}$ final state spectrum removing the mass region $3.05 < m_{\pi^{+}\pi^{-}} < 3.15$ GeV/$c^{2}$.
Unbinned extended maximum likelihood fits to the charge-conjugate invariant mass spectra of the selected $B^+$ candidates are performed, in order to extract the quantity

$$A_{\text{RAW}} = \frac{N(B^- \rightarrow f^-) - N(B^+ \rightarrow f^+)}{N(B^- \rightarrow f^-) + N(B^+ \rightarrow f^+)},$$

where $N(\cdot)$ are the signal yields extracted from the fits. The two charge-conjugated invariant mass spectra (for each of the four final states) are reported in Figure 1, with the result of the best fit overlaid. Extracted signal yields are reported in Table 1. The signal components are parameterised by so-called Cruijff functions [20] to account for the asymmetric effect of final-state radiation on the signal shape. The combinatorial background is described by an exponential function, and the background due to partially reconstructed four-body $B$ decays is parameterised by an ARGUS function [21] convolved with a Gaussian resolution function. Shape and yields of the cross-feed backgrounds (coming from decays with one misidentified particle) are determined using fully simulated events. The direct $CP$ asymmetries are extracted from $A_{\text{RAW}}$ using the relation $A_{\text{CP}} = A_{\text{RAW}} - A_{\Delta}$, where the correction $A_{\Delta} = A_{\text{det.}} + A_{\text{prod.}}$ is a term that takes into account the detection asymmetry ($A_{\text{det.}}$) between the charge-conjugate final states and the asymmetry in the production rate of $B^+$ and $B^-$ mesons ($A_{\text{prod.}}$). For the $B^+ \rightarrow K^+\pi^+\pi^-$ and $B^+ \rightarrow K^+K^+K^-$ decays the correction $A_{\Delta}$ is determined from data using the sample of $B^+ \rightarrow J/\psi K^+$ decays passing the same selection stages of the signal sample (apart from particle identification cuts that are applied only to the kaon). This control channel not only shares the same topology with the signals, but it has also been proven that the kaons from the control channel have similar kinematics with respect to those coming from signal decays. Consequently $A_{\Delta} = A_{\text{RAW}}(J/\psi K^+) - A_{\text{CP}}(J/\psi K^+)$, where $A_{\text{CP}}(J/\psi K^+) = (0.1 \pm 0.7)\%$ is taken from the world average [22]. In the case of the $B^+ \rightarrow \pi^+\pi^+\pi^-$ and $B^+ \rightarrow \pi^+K^+K^-$ decays, the detection asymmetry

\begin{table}[h]
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<table>
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<tr>
<th>Decay</th>
<th>Yields</th>
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<tr>
<td>$B^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>4904 \pm 148</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+K^+K^-$</td>
<td>1870 \pm 133</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+\pi^+\pi^-$</td>
<td>35901 \pm 327</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+K^+K^-$</td>
<td>22119 \pm 164</td>
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\end{tabular}
\caption{Signal yields extracted from the fits reported in Figure 1.}
\end{table}
The production asymmetry, determined in [24], using background, and green dash-dotted (partially reconstructed background) curves. In the bottom plot: background-subtracted and acceptance-corrected Dalitz-plot distributions for $B^+ \rightarrow \phi K^+$ decays (left) and $B^+ \rightarrow p\bar{p}\pi^+$ decays (right).

In order to take into account the variation of detection efficiencies across the Dalitz plane, an acceptance correction is applied to the integrated raw asymmetries. Simulated samples of $B^+$ and $B^-$ decays are reweighted in order to reproduce the population observed in data over the phase space. Then the ratio between the average efficiencies determined for the reweighted samples of $B^+$ and $B^-$ is used as correction factor. Moreover, in order to take into account an asymmetry introduced by the hadronic trigger, the analysis is performed on two separate subsamples: one composed by the candidates responsible for firing the hadronic trigger, and the other composed by the events where any other trigger would have fired independently on the signal candidates. The final values for the integrated $CP$ asymmetries are then obtained from a weighted average of the results from the two sub-samples. Fit model, trigger induced asymmetries and phase-space acceptance corrections are considered as possible sources of systematic uncertainties. The impact of the chosen fitting model is estimated fitting data with alternative parameterization for the shapes of signal, combinatorial background, partially reconstructed background and cross-feed background components. The deviation from the nominal results are accounted for as systematic uncertainties. Systematic uncertainties due to trigger asymmetries are estimated using the $B^+ \rightarrow J/\psi K^+$ decays as control channel. An incorrect modelling of the acceptance correction has been taken into account summing in quadrature the uncertainty coming from the limited statistics of the simulated samples and the variation observed changing the binning scheme of the acceptance map.

The results obtained for the inclusive $CP$ asymmetries are

\[
\begin{align*}
A_{CP}(\pi^+K^+K^-) &= -0.141 \pm 0.040 \pm 0.018 \pm 0.007 [25], \\
A_{CP}(\pi^+\pi^+\pi^-) &= 0.117 \pm 0.021 \pm 0.009 \pm 0.007 [25], \\
A_{CP}(K^+\pi^+\pi^-) &= 0.032 \pm 0.008 \pm 0.004 \pm 0.007 [25], \\
A_{CP}(K^+K^-K^+) &= -0.043 \pm 0.009 \pm 0.003 \pm 0.007 [26],
\end{align*}
\]
where the first uncertainty is statistical, the second is the experimental systematic, and the third is due to the CP asymmetry of the $B^+ \to J/\psi K^+$ reference mode [22]. The significances of the inclusive charge asymmetries, calculated by dividing the central values by the sum in quadrature of the statistical and both systematic uncertainties, are $3.2\sigma$ for the $B^+ \to \pi^+ K^+ K^-$ decay, $4.9\sigma$ for the $B^+ \to \pi^+ \pi^- \pi^- \pi^-$ decay, and $2.8\sigma$ for the $B^+ \to K^+ \pi^+ \pi^- \pi^-$ decay and $3.7\sigma$ for the $B^+ \to K^+ K^+ K^-$ decay.

In addition to the inclusive charge asymmetries, also a study of the asymmetry distributions in the Dalitz plane is performed. In Figure 2 (top) the raw asymmetry of the number of candidates in the $\pi^+ K^+ K^-$ and $\pi^+ \pi^- \pi^-$ spectra is plotted across the Dalitz plane. No background subtraction or acceptance correction is applied, but the candidates are requested to lie within $\pm 3$ times the invariant mass resolution around the $B^+$ mass. In the analysis of $B^+ \to K^+ \pi^- \pi^-$ and $B^+ \to K^+ K^- K^-$ decays a background subtraction (but not an acceptance correction) is applied to the candidates in order to produce the asymmetry plots over the Dalitz plane shown in Figure 2 (bottom). The CP asymmetries are further studied, following the same strategy used for the global asymmetries, in regions of the Dalitz planes where large raw asymmetries have been evidenced. These regions, that are not obviously associated with any resonance, are defined as: $m_{\pi^+ \pi^-}$, high $> 15$ GeV$^2$/c$^4$ and $m_{\pi^+ \pi^-}$, low $< 0.4$ GeV$^2$/c$^4$ for the $\pi^+ \pi^- \pi^-$ mode; $m_{K^+ K^-}$, high $< 1.5$ GeV$^2$/c$^4$ and $m_{K^+ K^-}$, low $< 2.0$ GeV$^2$/c$^4$ for the $K^+ K^- K^-$ mode; $m_{K^+ \pi^-}$, high $< 15$ GeV$^2$/c$^4$ and $0.08 < m_{K^+ \pi^-}$, low $< 0.66$ GeV$^2$/c$^4$ for the $K^+ \pi^- \pi^-$ mode. The local charge asymmetries are found to be very large:

\[
A_{\text{CP}}^{\text{reg}} (\pi^+ K^+ K^-) = -0.648 \pm 0.070 \pm 0.013 \pm 0.007 \quad [25],
\]

\[
A_{\text{CP}}^{\text{reg}} (\pi^+ \pi^- \pi^-) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007 \quad [25],
\]

\[
A_{\text{CP}}^{\text{reg}} (K^+ \pi^- \pi^-) = 0.678 \pm 0.078 \pm 0.032 \pm 0.007 \quad [26],
\]

\[
A_{\text{CP}}^{\text{reg}} (K^+ K^- K^-) = -0.226 \pm 0.020 \pm 0.004 \pm 0.007 \quad [26].
\]

3. Measurements of CP violation and decay dynamics in $B^+ \to p\bar{p}h^+$ decays

The large values of the CP asymmetries reported in the previous section, triggered interest in the study of CP violation in $B^+ \to p\bar{p}h^+$ decays. In fact the large localized asymmetries, not associated with any particular resonance, suggest the presence of a large strong phase difference due to the rescattering between $\pi^- \pi^-$ and $K^- K^-$ decays. The baryonic $B^+ \to p\bar{p}h^+$ decays, although sharing the same quark-level diagrams, may exhibit different behaviour due to the baryonic nature of two out of the three final-state particles. Using the data sample collected by LHCb during 2011 and 2012, LHCb studied these baryonic decays in the region with invariant mass $m_{p\bar{p}} < 2.85$ GeV/c$^2$, i.e. below the charmonium resonances threshold. In addition, an accurate measurement of the branching fraction of the decay $B^+ \to \Lambda(1520)p$ (where $\Lambda(1520) \to K^+ \bar{p}$) is performed. Finally an improved determination of the forward-backward asymmetry of the light meson of the decay in the $p\bar{p}$ rest frame is provided.

The event selection is similar to that presented in the previous section, but in this case the final refinement of the candidates is performed using a Boosted Decision Tree (BDT) multivariate algorithm, that discriminates between signal and background on the basis of kinematic and geometrical variables. The invariant mass spectra for the $p\bar{p}K^+$ and $p\bar{p}\pi^+$ final states are reported in Figure 3 (top), with the result of the maximum likelihood fits overlaid. Signal, combinatorial background, partially reconstructed background and cross-background components have been considered in the definition of the fitting model. Signal yields are $N(p\bar{p}K^+) = 18721 \pm 142$ and $N(p\bar{p}\pi^+) = 1988 \pm 74$ [27].

Background is subtracted assigning to each candidate a signal weight computed using the sPlot [28] technique. The weights are also corrected for reconstruction efficiencies determined using both fully simulated events and calibration data samples. In Figure 3 (bottom) the distributions of corrected signal weights, over the Dalitz plane are reported. Apart from the regions of clearly visible $J/\psi \to p\bar{p}$, $B^+ \to p\bar{p}$ resonances, events tend to accumulate near the $p\bar{p}$ threshold. While $B^+ \to p\bar{p}K^+$ events occupy the region at low $m_{K^+ p}$, $B^+ \to p\bar{p}\pi^+$ candidates prefer the region at large $m_{\pi^+ p}$. This different behaviour can be observed also in the distribution of the helicity angle $\theta_p$ of the $p\bar{p}$ system, defined as the angle between the light meson $h$ and the oppositely charged baryon in the $p\bar{p}$ rest frame. On the left in Figure 4 the distributions of $\cos \theta_p$ for background subtracted events and corrected for the acceptance effects are reported. From the distributions of $\cos \theta_p$ it is possible to measure the forward-backward asymmetry $A_{\text{FB}}$ defined as

\[
A_{\text{FB}} = \frac{N_{\text{pos}} - N_{\text{neg}}}{N_{\text{pos}} - N_{\text{neg}}},
\]

where $N_{\text{pos}}$ ($N_{\text{neg}}$) are the efficiency corrected signal yields with positive (negative) values of $\cos \theta_p$. Measured values in the charmonium-free region are $A_{\text{FB}}(p\bar{p}K^+, m_{p\bar{p}} < 2.85$ GeV/c$^2) = 0.495 \pm 0.012 \pm 0.007$ and $A_{\text{FB}}(p\bar{p}\pi^+, m_{p\bar{p}} < 2.85$ GeV/c$^2) = -0.409 \pm 0.033 \pm
0.006). Systematic uncertainties are due to the determination of reconstruction efficiencies and are studied using calibration samples and fully simulated events. In particular the value of $A_{FB}(p\bar{p}K^+, m_{p\bar{p}} < 2.85\text{GeV}/c^2)$ contradicts the short-range analysis expectation [29]. A strong dependence of $A_{FB}$ on the value of $m_{p\bar{p}}$ is also observed, as evidenced on the right plot in Figure 4. The determination of the branching ratios of the $B^+ \rightarrow \Lambda(1520)\bar{p}$ (with $\Lambda(1520) \rightarrow K^+\bar{p}$) and of the non resonant decay $B^+ \rightarrow p\bar{p}\pi^+$ (in the $m_{p\bar{p}} < 2.85\text{GeV}/c^2$ region) are obtained relatively to the branching ratio of the $B^+ \rightarrow J/\psi h^+$ decays (with $J/\psi \rightarrow p\bar{p}$). The yields for the various contributions are extracted from two-dimensional extended unbinned maximum likelihood fits to the invariant mass distributions of $p\bar{p}h^+$ and $p\bar{p}$ or $K^+\bar{p}$ spectra. Ratios of yields are corrected for the relative reconstruction efficiencies, determined using fully simulated events (for the reconstruction efficiencies) and calibration samples (for the effect of particle identification requirements). The relative branching ratios are:

$$\frac{BR(B^+ \rightarrow \Lambda(1520)(\rightarrow K^+\bar{p})\bar{p})}{BR(B^+ \rightarrow J/\psi(\rightarrow p\bar{p})K^+)} = 0.033 \pm 0.005 \pm 0.007,$$

$$\frac{BR(B^+ \rightarrow p\bar{p}\pi^+, m_{p\bar{p}} < 2.85\text{GeV}/c^2)}{BR(B^+ \rightarrow J/\psi(\rightarrow p\bar{p})\pi^+)} = 12.0 \pm 1.2 \pm 0.3.$$

Systematic uncertainties also include contributions from the background model. Using as input the external measurements $BR(B^+ \rightarrow J/\psi K^+) = (1.016 \pm 0.033) \times 10^{-3}$, $BR(B^+ \rightarrow J/\psi\pi^+) = (4.1 \pm 0.4) \times 10^{-5}$, $BR(J/\psi \rightarrow p\bar{p}) = (2.17 \pm 0.07) \times 10^{-3}$ [22], and $BR(\Lambda(1520) \rightarrow K^-\bar{p}) = 0.234 \pm 0.016$ [30], the absolute branching ratios are:

$$BR(B^+ \rightarrow \Lambda(1520)(\rightarrow K^+\bar{p})\bar{p}) = (3.15 \pm 0.48 \pm 0.07 \pm 0.26 (BF)) \times 10^{-7},$$

$$BR(B^+ \rightarrow p\bar{p}\pi, m_{p\bar{p}} < 2.85\text{GeV}/c^2) = (1.07 \pm 0.11 \pm 0.03 \pm 0.11 (BF)) \times 10^{-6},$$

where the last errors are due to the external inputs for the branching ratios. The dependence of the direct $CP$ asymmetry over the phase space of the $B^+ \rightarrow p\bar{p}K^+$ decays (the $B^+ \rightarrow p\bar{p}\pi$ sample has not enough statistics to perform this kind of studies) has been investigated using signal weights inferred from the fits shown in Figure 3. The raw asymmetry is reported in Figure 5 (left). A clear pattern can be observed near the $m_{p\bar{p}}$ threshold, where the raw asymmetry results to be negative in the region $m_{K^+\bar{p}}^2 < 10\text{GeV}^2/c^4$ and positive in the region $m_{K^+\bar{p}}^2 < 10\text{GeV}^2/c^4$. Figure 5 (right) shows the value of $N(B^+) - N(B^+)$ in bins of $m_{p\bar{p}}$ for the two $m_{K^+\bar{p}}$ regions. The effect is quantified extracting raw asymmetries from unbinned maximum likelihood fits to the $p\bar{p}K^+$ invariant mass in different bins of the Dalitz plane. The raw asymmetries are corrected for acceptance, by taking into account the small difference in average efficiency due to the $B^-$ and $B^+$ samples and populating differently the Dalitz plane. Detection asymmetry and production asymmetry corrections are studied from $B^+ \rightarrow J/\psi(\rightarrow p\bar{p})K^+$ decays, accounting also for differences in the $p\bar{p}$ momentum asymmetries. In Table 2 the values of $A_{CP}$ for different regions of the phase space are reported (including those of resonant modes). In the region $m_{p\bar{p}} < 2.85\text{GeV}/c^2$, $m_{K^+\bar{p}}^2 > 10\text{GeV}^2/c^4$, the measured asymmetry is positive with a significance of nearly $4\sigma$, which represents the first evidence of $CP$ violation in $B$-mesons decays with baryons in the final state. For the $B^+ \rightarrow p\bar{p}\pi^+$ decays a value of $A_{CP}$ in the charmonium free region defined by $m_{p\bar{p}}^2 < 2.85\text{GeV}/c^2$...
Figure 5: In the left plot: raw asymmetry of signal events in bins of the Dalitz plane for $B^+ \rightarrow p\bar{p}K^+$ decays. In the right plot: difference between the number of $B^+$ and $B^-$ events in bins of $m_{p\bar{p}}^2$ for $m_{K^+p}^2 < 10 \text{ GeV}^2/c^4$ (black dots) and for $m_{K^+p}^2 > 10 \text{ GeV}^2/c^4$ (empty triangles).

Table 2: $CP$ asymmetries for $B^+ \rightarrow p\bar{p}K^+$ and $B^+ \rightarrow p\bar{p}\pi^+$ decays, in different regions of the phase space. The systematic uncertainties are dominated by the precision on the measurement $A_{CP}(B^+ \rightarrow J/\psi K^+)$. 

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<tr>
<th>Mode/region</th>
<th>$A_{CP}$</th>
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<tbody>
<tr>
<td>$\eta_c(\rightarrow p\bar{p})K^+$</td>
<td>0.040 ± 0.034 ± 0.004</td>
</tr>
<tr>
<td>$\psi(2S)(\rightarrow p\bar{p})K^+$</td>
<td>0.092 ± 0.058 ± 0.004</td>
</tr>
<tr>
<td>$p\bar{p}K^+$, $m_{p\bar{p}} &lt; 2.85 \text{ GeV}/c^2$</td>
<td>0.021 ± 0.020 ± 0.004</td>
</tr>
<tr>
<td>$p\bar{p}K^+$, $m_{p\bar{p}} &lt; 2.85 \text{ GeV}/c^2$, $m_{K^+p}^2 &lt; 10 \text{ GeV}^2/c^4$</td>
<td>$-0.036 \pm 0.023 \pm 0.004$</td>
</tr>
<tr>
<td>$p\bar{p}K^+$, $m_{p\bar{p}} &lt; 2.85 \text{ GeV}/c^2$, $m_{K^+p}^2 &gt; 10 \text{ GeV}^2/c^4$</td>
<td>0.096 ± 0.024 ± 0.004</td>
</tr>
<tr>
<td>$p\bar{p}\pi^+$, $m_{p\bar{p}} &lt; 2.85 \text{ GeV}/c^2$</td>
<td>$-0.041 \pm 0.039 \pm 0.005$</td>
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has been measured. The systematic uncertainties are estimated by using alternative fit functions and splitting the data sample according to trigger requirements and magnet polarity. Overall systematic uncertainties are dominated by the value used for $A_{CP}(B^+ \rightarrow J/\psi K^+)$. 

References