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Charmless B decays: Dalitz

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The charmless decays of B mesons offer a fertile ground to measure CP violation, by studying the Dalitz plot structure. We report about the most recent measurements in this sector, performed by LHCb using proton-proton data, recorded in 2011 and 2012 and corresponding to an integrated luminosity of 3.0 fb^{-1}. The inclusive CP asymmetries and local asymmetries in specific regions of the phase space are measured for the $B^{\pm} \to h^{\pm}h^{+}h^{-}$ (where $h = \pi, K$) decays. In addition the first evidence for CP violation in charmless $B^{+} \to p\bar{p}K^{+}$ decays is reported. Finally, a more accurate measurement of the branching fraction of the $B^{+} \to \Lambda(1520)p$ (with $\Lambda(1520)$ decaying into a $K^{+}p$ final state) is shown.

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1. Introduction

The violation of *CP* symmetry in the quark sector is well explained in the Standard Model (SM) by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1, 2], through the presence of a single complex phase. Despite the success of the SM to describe all *CP* asymmetries observed experimentally, the amount of *CP* violation within the SM is not enough to explain the matter-antimatter asymmetry present in the universe.

The charmless *b*-hadron decays offer an interesting opportunity to search for different sources of *CP* violation. In these decays the violation of *CP* can be observed as an asymmetry in the decay rate of a particle and its *CP* conjugate. In order to occur the existence of at least two amplitudes with different weak and strong phases is necessary. The weak phases are sensitive to physics beyond the Standard Model and can be studied through the interference between tree-level and penguin contributions. The strong phases can originate from different mechanisms. One source is related to short-distance processes [3], while the other sources are due to long-distance effects, like $KK \leftrightarrow \pi\pi$ rescattering [4], occurring in the final state, or interference between intermediate states of the decay [5]. The measurement of *CP* asymmetries over the Dalitz plane is useful to better understand the generation of such phases and to constrain the parameters describing the hadronic interactions.

In these proceedings we report the latest results obtained using a data sample corresponding to an integrated luminosity of 3.0 fb^{-1} collected by the LHCb experiment in proton-proton collisions at center-of-mass energies of 7 and 8 TeV.

2. *CP* violation in $B^\pm \to h^\pm h^+ h^-$ decays

The studies of direct *CP* violation in $B^\pm \to h^\pm h^+ h^-$ decays[1], performed at the B-factories through amplitude analyses, have shown evidence of *CP* asymmetries in $B^+ \to \rho^0(770)K^+$ [6, 7] and $B^+ \to \phi(1020)K^+$ [8] decays. Moreover the LHCb collaboration measured non-zero inclusive *CP* asymmetries and larger local asymmetries in the decays $B^\pm \to K^\pm\pi^+\pi^-$, $B^\pm \to K^\pm K^+ K^-$ [10], $B^\pm \to \pi^\pm K^+ K^-$ and $B^\pm \to \pi^\pm\pi^+\pi^-$ [11] using a data sample corresponding to 1.0 fb^{-1}. The results presented in this document constitute an update of the previous analysis, making use of the entire data set recorded by LHCb. Additional information can be found in [12]. The signal candidates are selected by making use of a multivariate technique and efficient particle identification variables, thus improving the performance.

The observed asymmetry (raw asymmetry) is defined as

$$\mathscr{A}_{raw} = \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}}\,, \tag{2.1}$$

where N represents the signal yields, extracted with an unbinned maximum likelihood fit to the mass spectra of the selected candidates. By measuring the $\mathscr{A}_{raw}$ asymmetries and correcting for $B^\pm$ production asymmetry and for other detector effects due to unpaired hadron $h^\pm$, using control decays, it is possible to measure the *CP* violation

$$\mathscr{A}_{CP} = \mathscr{A}_{raw} - \mathscr{A}_P - \mathscr{A}_D\,, \tag{2.2}$$

[1]Throughout the document, the inclusion of charge conjugate processes is implied, except in the definition of *CP* asymmetries.

whose results, integrated over the Dalitz plot, read

$$\begin{aligned}
\mathscr{A}_{CP}(B^\pm \to K^\pm\pi^+\pi^-) &= +0.025 \pm 0.004 \pm 0.004 \pm 0.007, \\
\mathscr{A}_{CP}(B^\pm \to K^\pm K^+ K^-) &= -0.036 \pm 0.004 \pm 0.002 \pm 0.007, \\
\mathscr{A}_{CP}(B^\pm \to \pi^\pm K^+ K^-) &= +0.058 \pm 0.008 \pm 0.009 \pm 0.007, \\
\mathscr{A}_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) &= -0.123 \pm 0.017 \pm 0.012 \pm 0.007,
\end{aligned}$$

where the first uncertainty is statistical, the second systematic and the third is due to the error on the CP asymmetry of the $B^\pm \to J/\psi K^\pm$ decay, used as a control channel.

The asymmetries are as well studied in bins of the Dalitz plot. Figure 1 shows the distributions of the raw asymmetry, calculated according to Eq. 2.1. The plots are obtained after the subtraction of the background and the correction for acceptance effects. The binning is chosen adaptively, in order to have approximately the same number of entries in each bin. The distributions show a very

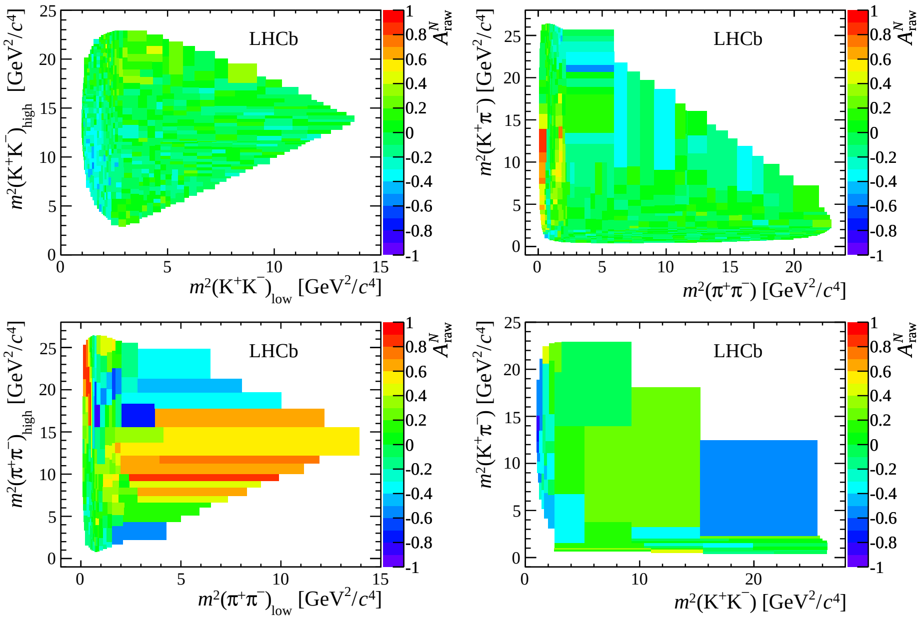

Figure 1: Measured raw asymmetry in bins of the Dalitz plot for background-subtracted and acceptance-corrected events. Top left: $B^\pm \to K^\pm K^+ K^-$. Top right: $B^\pm \to K^\pm\pi^+\pi^-$. Bottom left: $B^\pm \to \pi^\pm\pi^+\pi^-$. Bottom right: $B^\pm \to \pi^\pm K^+ K^-$.

rich structure, with very large asymmetries localised in certain regions. The sign of the asymmetry is positive for the channels which include two pions in the final state and negative for those which include two kaons. The asymmetry calculations, performed in the $m(K^+K^-)$ or $m(\pi^+\pi^-)$ invariant mass region between 1.0 and 1.5 GeV/c^2, leads to the following results

$$\begin{aligned}
\mathscr{A}_{CP}(B^\pm \to K^\pm\pi^+\pi^-) &= +0.121 \pm 0.012 \pm 0.017 \pm 0.007, \\
\mathscr{A}_{CP}(B^\pm \to K^\pm K^+ K^-) &= -0.211 \pm 0.011 \pm 0.004 \pm 0.007, \\
\mathscr{A}_{CP}(B^\pm \to \pi^\pm K^+ K^-) &= +0.172 \pm 0.021 \pm 0.015 \pm 0.007, \\
\mathscr{A}_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) &= -0.328 \pm 0.028 \pm 0.029 \pm 0.007.
\end{aligned}$$

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The results have a significance of 5σ. A possible explanation for the generation of the strong phase differences is the role played by hadron rescattering.

Another interesting feature can be observed plotting the yield asymmetry as a function of the $m(hh)$ invariant mass, splitted according to the sign of the cosine of the angle θ_p, defined by the momenta of the unpaired hadron and the resonant daughter with the same-sign charge. As an example Figure 2 shows, for the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay, the distribution of the yield asymmetry in bins of $m(\pi^{+}\pi^{-})$, according to the sign of $\cos(\theta_p)$. The charge asymmetry changes sign at a

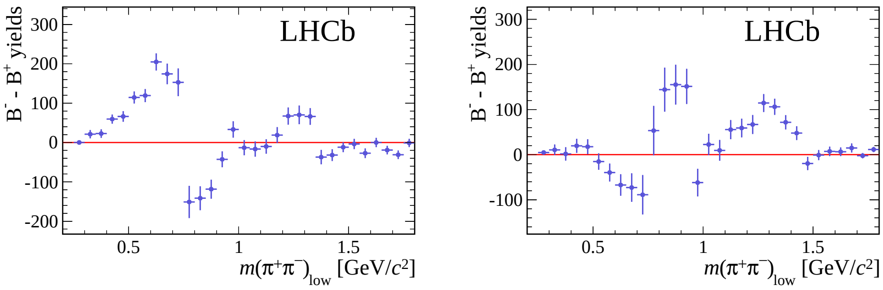

Figure 2: Difference between B^- and B^+ signal events as a function of $m(\pi^+\pi^-)$ invariant mass for $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays. Left: $\cos(\theta_p) > 0$, Right: $\cos(\theta_p) < 0$.

value of $m(\pi^+\pi^-)$ close to the $\rho(770)$ resonance. This can be related to the dominance of the long-distance interference effect in this region of the Dalitz plot. Moreover, the change of sign occurs for both $\cos(\theta_p)$ values, indicating the dominance of the real part of the Breit-Wigner propagator. To understand the dynamical origin of these *CP*-violating sources a full amplitude analysis is needed.

3. *CP* violation in $B^+ \to p\bar{p}h^+$ decays

The large asymmetries measured in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays motivates the studies on the closely related $B^+ \to p\bar{p}h^+$ decays, where a smaller $h^+h^- \leftrightarrow pp$ rescattering is expected. The results presented here are an update of the studies previously performed by in LHCb [13]. It made use of the entire data set, improving the selection with a similar strategy adopted for the $B^{\pm} \to h^{\pm}h^{+}h^{-}$ analysis. More details can be found in [14].

After the selection, the number of signal events are extracted using an unbinned maximum likelihood fit to the $B^+ \to p\bar{p}K^+$ and $B^+ \to p\bar{p}\pi^+$ invariant masses, yielding to $N(ppK) = 18721 \pm 142$ and $N(pp\pi) = 1988 \pm 74$ signal candidates.

The distribution of events in the Dalitz plane, defined by (m^2_{pp},m^2_{hp}), is shown in Figure 3, after the subtraction of the background and the correction for acceptance effects. In the left plot it is possible to observe hints of the $\Lambda(1520) \to K^+\bar{p}$ band. The measurement of the branching fraction is performed using the $B^+ \to J/\psi(p\bar{p})K^+$ decay as a reference mode

$$\mathscr{B}(B^+ \to \bar{\Lambda}(1520)(K^+\bar{p})p) = (3.15 \pm 0.48(\text{stat}) \pm 0.07(\text{syst}) \pm 0.26(\text{BF})) \times 10^{-7}.$$

The enhancements at low $m^2_{p\bar{p}}$ values seen in Figure 3 are observed in other $B \to ppX$ decays. The $B^+ \to p\bar{p}K^+$ events occupy the region at low $m_{K^+\bar{p}}$, while $B^+ \to p\bar{p}\pi^+$ candidates rather the region at large $m_{\pi^+\bar{p}}$.

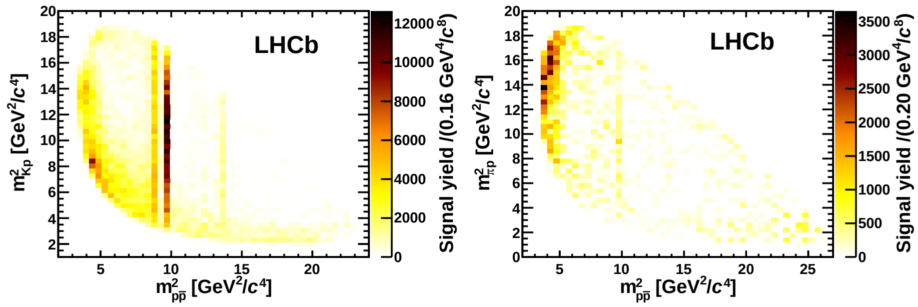

Figure 3: Background-subtracted and acceptance-corrected Dalitz-plot distributions for $B^+ \to p\bar{p}K^+$ (left) and $B^+ \to p\bar{p}\pi^+$ (right).

In Figure 4 is shown (left) the distribution of the helicity angle θ_p, defined as the angle between the daughter meson h and the oppositely charged baryon in the $p\bar{p}$ rest frame of the $p\bar{p}$ system for $p\bar{p}K$ and $p\bar{p}\pi$, in the region with invariant mass $m_{p\bar{p}} < 2.85$ GeV/c^2. The two modes show a clear sign-inversion pattern.

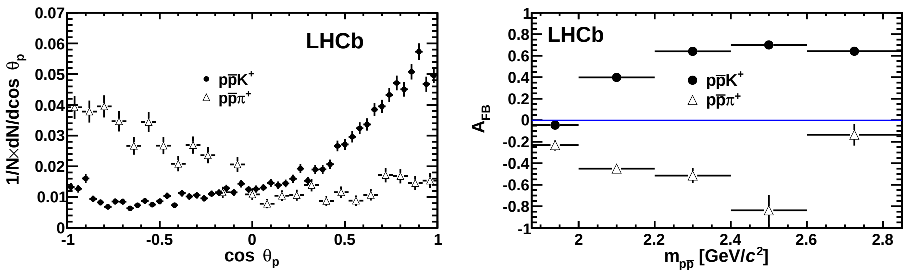

Figure 4: Left: background-subtracted and acceptance-corrected normalized distributions of $\cos(\theta_p)$ for $m_{p\bar{p}} < 2.85$ GeV/c^2. Right: Forward-backward asymmetry as a function of $m_{p\bar{p}}$.

The forward-background asymmetry is defined as

$$\mathscr{A}_{FB} = \frac{N(\cos\theta_p > 0) - N(\cos\theta_p < 0)}{N(\cos\theta_p > 0) + N(\cos\theta_p < 0)}, \tag{3.1}$$

where N represents the efficiency-corrected signal yields. The $\mathscr{A}_{FB}$ distribution is shown in Figure 4 on the right and the measurements, for $m_{p\bar{p}} < 2.85$ GeV/c^2, are

$$\mathscr{A}_{FB}(B^+ \to p\bar{p}K^+) = +0.495 \pm 0.012(\text{stat}) \pm 0.007(\text{syst}),$$
$$\mathscr{A}_{FB}(B^+ \to p\bar{p}\pi^+) = -0.409 \pm 0.033(\text{stat}) \pm 0.006(\text{syst}).$$

These asymmetries can be interpreted as being due to the dominance of non-resonant $p\bar{p}$ scattering [9].

The CP asymmetry variation across the Dalitz plane has been studied for the $B^+ \to p\bar{p}K^+$ decay only, since for the $B^+ \to p\bar{p}\pi^+$ decay the statistics of the data sample was not enough. Figure 5 shows on the left the distribution of the raw asymmetry over the Dalitz plot. The sign of the asymmetry is positive for $m^2_{K^+\bar{p}} > 10$ GeV^2/c^4 and negative for $m^2_{K^+\bar{p}} < 10$ GeV^2/c^4.

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This trend is shown in Figure 5 on the right, where the yield asymmetry between B^- and B^+ for the corresponding regions of $m^2_{K^+\bar{p}}$ is shown. The raw asymmetries are corrected for detection and

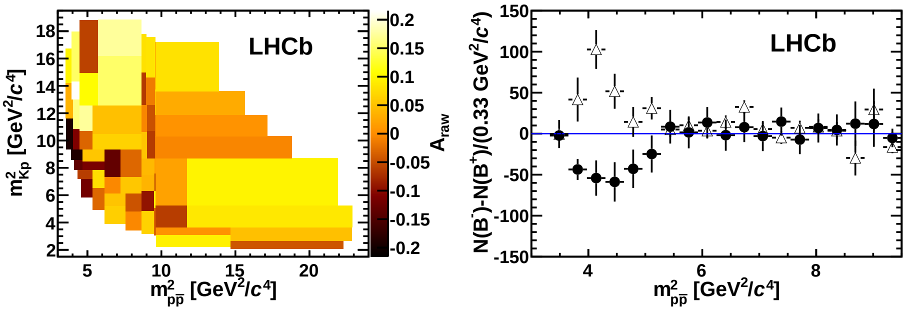

Figure 5: Left: raw asymmetry of signal events in bins of the Dalitz plane for $B^+ \to p\bar{p}K^+$ decays. Right: difference between the number of B^- and B^+ events as a function of $m^2_{p\bar{p}}$ for $m^2_{K^+\bar{p}} < 10$ GeV^2/c^4 (black dots) and for $m^2_{K^+\bar{p}} > 10$ GeV^2/c^4 (empty triangles).

production effects, using the $B^+ \to J/\psi(p\bar{p})K^+$ decay as a control channel. The *CP* asymmetry measurement, in the region where $m_{p\bar{p}} < 2.85$ GeV/c^2 and $m^2_{K^+\bar{p}} > 10$ GeV^2/c^4, leads to

$$\mathscr{A}_{CP}(B^+ \to p\bar{p}K^+) = +0.096 \pm 0.024(\text{stat}) \pm 0.004(\text{syst}),$$

which corresponds to a 4σ evidence of *CP* violation in *B* decays with baryons in the final state.

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