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Charmless B Decays into Three Bodies at LHCb

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Studies of charmless decays of neutral B mesons into three-body final states have led to branching fraction measurements of $B^0_{d,s} \to K^0_S h^{\pm} h^{\mp}$ and the first observation of the decay $B^0_s \to K^0_S K^{\pm} \pi^{\mp}$. Studies of charged B meson decays have provided branching fraction measurements of the $B^+ \to p\overline{p}K^{+\ddagger}$ intermediate states. The studies have also yielded positive charge asymmetries measurements in the channels $B^+ \to \pi^+\pi^+\pi^-$ (4.2σ) and $B^+ \to K^+\pi^+\pi^-$ (2.8σ) and negative charge asymmetries in the channels $B^+ \to K^+K^-\pi^+$ (3.0σ) and $B^+ \to K^+K^+K^-$ (3.7σ). Very large charge asymmetries have also been seen in certain areas of the $B^+ \to \pi^+\pi^+\pi^-$ and $B^+ \to K^+K^-\pi^+$ phase space.

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PoS(Beauty 2013)014

1. Charmless decays of neutral B meson

The study of charmless decays of neutral B into three-body final states containing a K^0_S meson can be used to analyze some interesting physics scenarios. The decays $B^0 \to K^0_S\pi^+\pi^-$ and $B^0 \to K^0_S K^+K^-$ are dominated by $b \to q\bar{q}s$ ($q = u,d,s$) loop transitions and mixing-induced *CP* asymmetries in such decays are predicted to be similar to those in $b \to c\bar{c}s$ transitions, *e.g.* $B^0 \to J/\psi K^0_S$ [1, 2]. However, several extensions of the Standard Model (SM) may enhance the loop diagram contributions, which could introduce additional weak phases [3, 4, 5, 6].

In addition, the Dalitz plot analysis of the decay $B^0_s \to K^0_S\pi^+\pi^-$ is of particular interest to measure the CKM weak phase γ with a theoretically clean method [7]. Recent results revealed evidence of *CP* violation in the $K^{*-}\pi^+$ intermediate state of the decay $B^0 \to K^+\pi^-\pi^0$ [8]. Since the $K^{*-}\pi^+$ state is also shared between $B^0_s \to K^-\pi^+\pi^0$ and $B^0_s \to K^0_S\pi^+\pi^-$, the same method used by the BaBar collaboration can be applied to measure *CP* violation in these modes through a Dalitz plot analysis.

The K^0_S candidates are reconstructed in their decays to the $\pi^+\pi^-$ final state. Due to their lifetime, only one third of the reconstructed K^0_S mesons decays inside the VELO detector at the LHCb experiment [9]. Hence, two categories of reconstructed candidates are defined: daughter tracks with ("Long-Long") and without ("Down-Down") VELO detector information. Measurements of the $B^0_{d,s} \to K^0_S h^\pm h^\mp$ decay branching fractions relative to the normalization mode $B^0 \to K^0_S\pi^+\pi^-$ have been performed using LHCb data corresponding to an integrated luminosity of 1 fb^{-1} recorded at $\sqrt{s} = 7$ TeV during the 2011 run. The decay $B^0_s \to K^0_S K^\pm\pi^\mp$ has been observed for the first time while the decay $B^0 \to K^0_S K^\pm\pi^\mp$ has been observed with a statistical significance of 7.3σ, confirming the previous result in this channel from the BaBar collaboration [10]. The preliminary measured ratios of branching fractions are [11]

$$\frac{\mathscr{B}(B^0 \to K^0_S K^\pm\pi^\mp)}{\mathscr{B}(B^0 \to K^0_S\pi^+\pi^-)} = 0.117 \pm 0.018\,(\text{stat}) \pm 0.018\,(\text{syst}),$$

$$\frac{\mathscr{B}(B^0 \to K^0_S K^+K^-)}{\mathscr{B}(B^0 \to K^0_S\pi^+\pi^-)} = 0.53 \pm 0.04\,(\text{stat}) \pm 0.04\,(\text{syst}),$$

$$\frac{\mathscr{B}(B^0_s \to K^0_S\pi^+\pi^-)}{\mathscr{B}(B^0 \to K^0_S\pi^+\pi^-)} = 0.24 \pm 0.06\,(\text{stat}) \pm 0.04\,(\text{syst}),$$

$$\frac{\mathscr{B}(B^0_s \to K^0_S K^\pm\pi^\mp)}{\mathscr{B}(B^0 \to K^0_S\pi^+\pi^-)} = 1.96 \pm 0.15\,(\text{stat}) \pm 0.20\,(\text{syst}),$$

$$\frac{\mathscr{B}(B^0_s \to K^0_S K^+K^-)}{\mathscr{B}(B^0 \to K^0_S\pi^+\pi^-)} = 0.084 \pm 0.031\,(\text{stat}) \pm 0.019\,(\text{syst}),$$

where the fragmentation fraction ratio f_s/f_d used in these results has been accurately determined by the LHCb experiment to be 0.267 ± 0.021 [12]. The main sources of systematic uncertainties are the fit model applied to signal and background, the selection efficiency determination and the particle identification efficiency. For $B^0_s \to K^0_S K^\pm\pi^\mp$ the f_s/f_d ratio uncertainty also contributes significantly to the final systematic.

Using the world average of $\mathscr{B}(B^0 \to K^0\pi^+\pi^-) = (4.96 \pm 0.20) \times 10^{-5}$ [13] the time-integrated branching fractions

$$\mathscr{B}(B^0 \to K^0_S K^\pm\pi^\mp) = (5.8 \pm 0.9 \pm 0.9 \pm 0.2) \times 10^{-6},$$

$$\mathscr{B}(B^0 \to K^0_S K^+ K^-) = (2.63 \pm 0.20 \pm 0.20 \pm 0.11) \times 10^{-5},$$
$$\mathscr{B}(B^0_s \to K^0_S \pi^+ \pi^-) = (1.19 \pm 0.30 \pm 0.20 \pm 0.05) \times 10^{-5},$$
$$\mathscr{B}(B^0_s \to K^0_S K^\pm \pi^\mp) = (9.7 \pm 0.7 \pm 1.0 \pm 0.4) \times 10^{-5},$$
$$\mathscr{B}(B^0_s \to K^0_S K^+ K^-) = (4.2 \pm 1.5 \pm 0.9 \pm 0.2) \times 10^{-6},$$

were obtained, where the first uncertainty is statistical, the second is systematic and the last is due to the uncertainty on $\mathscr{B}(B^0 \to K^0_S \pi^+ \pi^-)$. Figure 1 shows the mass spectra for $K^0_S K^\pm \pi^\pm$ candidates.

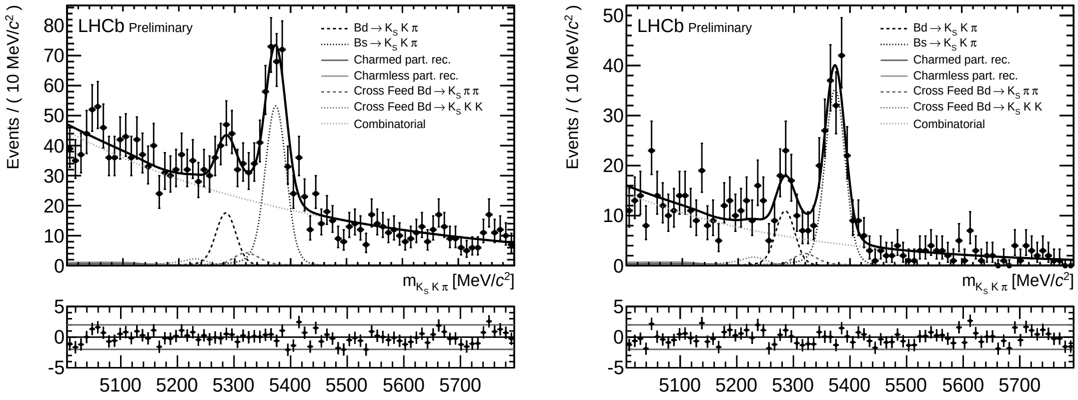

Figure 1: Invariant mass spectra of $B \to K^0_S K^\pm \pi^\pm$ candidates for K^0_S reconstructed in the (left) "Down-Down" and (right) "Long-Long" categories. The data are described by the points and each component of the fit model is displayed on the plot.

2. Charmless decays of charged B meson

Several studies of charmless decays of charged B mesons into three-body final states have been performed at the LHCb experiment and the main results are detailed in the next sections.

2.1 $B^+ \to p\overline{p}K^+$ decays

The $B^+ \to p\overline{p}K^+$ decay allows investigation of many different physical aspects of B meson decays such as charmonium mesons that decay to $p\overline{p}$, excited $\overline{\Lambda}$ states that decay to $\overline{p}K^+$, glueballs or exotic states and also investigate the nature of the intermediate charmonium-like $X(3872)$ [14, 15].

Measurements of the ratios of branching fractions

$$R(mode) = \frac{\mathscr{B}(B^+ \to mode \to p\overline{p}K^+)}{\mathscr{B}(B^+ \to J/\psi K^+ \to p\overline{p}K^+)},$$

where "mode" corresponds to the intermediate states $\eta_c(1S)$, $\psi(2S)$, $\eta_c(2S)$, $\chi_{c0}(1P)$, $h_c(1P)$, $X(3872)$ or $X(3915)$ together with a kaon, have been performed using LHCb data corresponding to an integrated luminosity of 1 fb^{-1}.

Figures 2 and 3 show the $p\overline{p}$ invariant mass for $B^+ \to p\overline{p}K^+$ candidates within the B mass signal window $|M(p\overline{p}K^+) - M_{B^+}| < 50\,\mathrm{MeV}/c^2$, together with the fit results for $p\overline{p}$ intermediate states.

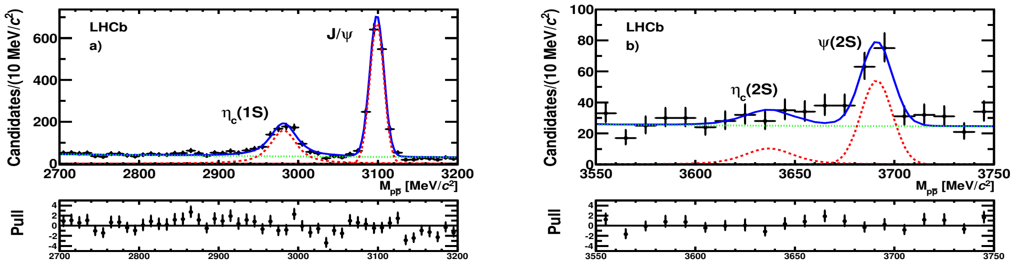

Figure 2: Invariant mass distribution for the $p\overline{p}$ system around (a) the $\eta_c(1S)$ and J/ψ and (b) the $\eta_c(2S)$ and $\psi(2S)$ states.

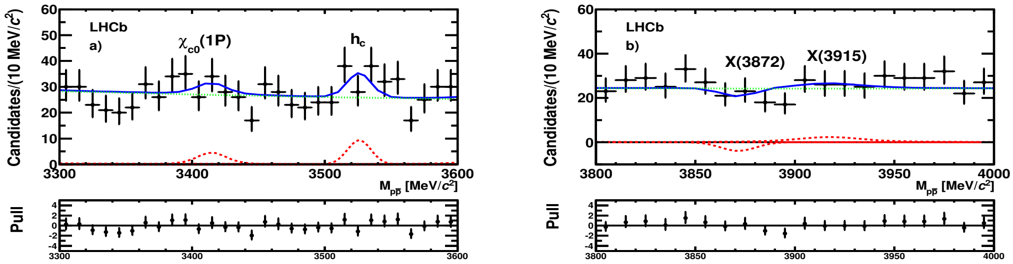

Figure 3: Invariant mass distribution for the $p\overline{p}$ system around (a) the $\chi_{c0}(1P)$ and h_c and (b) the $X(3872)$ and $X(3915)$ states.

The measured ratios of the branching fractions for each intermediate state with respect to the $B^+ \to J/\psi K^+ \to p\overline{p}K^+$ final are [16]

$$\frac{\mathscr{B}(B^+ \to p\overline{p}K^+)_{total}}{\mathscr{B}(B^+ \to J/\psi K^+ \to p\overline{p}K^+)} = 4.91 \pm 0.19\,(\text{stat}) \pm 0.14\,(\text{syst}),$$

$$\frac{\mathscr{B}(B^+ \to p\overline{p}K^+)_{M_{p\overline{p}}<2.85\,\text{GeV}/c^2}}{\mathscr{B}(B^+ \to J/\psi K^+ \to p\overline{p}K^+)} = 2.02 \pm 0.10\,(\text{stat}) \pm 0.08\,(\text{syst}),$$

$$\frac{\mathscr{B}(B^+ \to \eta_c(1S)K^+ \to p\overline{p}K^+)}{\mathscr{B}(B^+ \to J/\psi K^+ \to p\overline{p}K^+)} = 0.578 \pm 0.035\,(\text{stat}) \pm 0.025\,(\text{syst}),$$

$$\frac{\mathscr{B}(B^+ \to \psi(2S)K^+ \to p\overline{p}K^+)}{\mathscr{B}(B^+ \to J/\psi K^+ \to p\overline{p}K^+)} = 0.080 \pm 0.012\,(\text{stat}) \pm 0.009\,(\text{syst}),$$

where the main sources of systematic uncertainties are the signal and background fit models and the B mass fit range (for B candidates) and window (for charmonium candidates) applied to the sample.

Using the results obtained for $\eta_c(2S)$ and the branching fraction $\mathscr{B}(B^+ \to \eta_c(2S)K^+) \times \mathscr{B}(\eta_c(2S) \to K\overline{K}\pi) = (3.4^{+2.3}_{-1.6} \times 10^{-6})$ [13] and the upper limit on the ratio $\frac{\mathscr{B}(B^+ \to X(3872)K^+ \to p\overline{p}K^+)}{\mathscr{B}(B^+ \to J/\psi K^+ \to p\overline{p}K^+)} < 0.017$, the following limits are observed:

$$\frac{\mathscr{B}(\eta_c(2S) \to p\overline{p})}{\mathscr{B}(\eta_c(2S) \to K\overline{K}\pi)} < 3.1 \times 10^{-2},$$

$$\frac{\mathscr{B}(X(3872) \to p\overline{p})}{\mathscr{B}(X(3872) \to J/\psi \pi^+\pi^-)} < 2.0 \times 10^{-3}.$$

2.2 $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ decays

The $B^+ \to h^+h^+h^-$ (with $h = K,\pi$) decays offer a good environment to study *CP* violation, enriched by the interference pattern of the two-body intermediate states in the Dalitz plot. The leading contributions to these decays occur through a $b \to s(d)$ penguin and a $b \to u$ tree transition and the interference between these contributions together with the interferences between the intermediate states provide access to the CKM weak phase γ.

The $B^+ \to K^+\pi^+\pi^-$ decay mode has been observed by the Belle and BaBar collaborations [17, 18], which claim evidence of *CP* violation in the channel with final state $B^+ \to \rho^0(770)K^+$, $\rho^0(770) \to \pi^+\pi^-$, and whose current world average is $\mathscr{A}^{CP}(B^+ \to \rho^0(770)K^+) = 0.37 \pm 0.10$ [13]. The present world average experimental value for the $B^+ \to K^+\pi^+\pi^-$ asymmetry is $\mathscr{A}^{CP}(B^+ \to K^+\pi^+\pi^-) = 0.038 \pm 0.022$ [13]. For the $B^+ \to K^+K^+K^-$ mode, the current world average asymmetry value is $\mathscr{A}^{CP}(B^+ \to K^+K^+K^-) = -0.017 \pm 0.030$.

For direct CP violation to occur, two interfering amplitudes (usually referred to as "tree" and "penguin") with different weak and strong phases must be involved in the decay process [19]. Large *CP* violation effects have been observed in charmless two-body B meson decays such as $B^0 \to K^+\pi^-$ and $B^0_s \to K^-\pi^+$ [20]. However, the source of the strong phase difference in these processes is not well understood, which limits the potential to use these measurements to search for physics beyond the Standard Model. One possible source of the required strong phase is from final-state hadron rescattering, which can occur between two or more decay channels with the same flavour quantum numbers, such as $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ [21, 22, 23, 24]. This effect, referred to as "compound CP violation" [25] is constrained by *CPT* conservation so that the sum of the partial decay widths, for all channels with the same final-state quantum numbers related by the S-matrix, must be equal for charge-conjugated decays. Motivated by the *CPT* invariance and experimental resemblance, measurements of charge asymmetries of $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ have been performed together and separately from $B^+ \to K^+K^-\pi^+$ and $B^+ \to \pi^+\pi^+\pi^-$ modes.

The raw charge asymmetry, $\mathscr{A}^{CP}_{RAW}$, is obtained from the B^- and B^+ candidate yields as

$$\mathscr{A}^{CP}_{RAW} = \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}}.$$

The decay $B^+ \to J/\psi K^+$ is used to correct the raw asymmetry for reconstruction and B production effects. This has similar kinematics to the signal channels and no expected *CP* violation, with the current $\mathscr{A}^{CP}$ world average for $B^+ \to J/\psi K^+$ being $(1 \pm 7) \times 10^{-3}$ [13]. The odd number of kaons in both signal and the control channels leads to a similar effect of the asymmetry due to the differences among K^+ and K^- interaction with matter. The raw asymmetry is also corrected for any possible trigger bias by splitting the data in two subsamples depending on the trigger decision.

Measurements of the inclusive charge asymmetries of $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ have been performed using LHCb data corresponding to an integrated luminosity of 1 fb^{-1}. The final results are [26]

$$\mathscr{A}^{CP}(B^+ \to K^+\pi^+\pi^-) = +0.034 \pm 0.009\,(\text{stat}) \pm 0.004\,(\text{syst}) \pm 0.007(J/\psi K^+),$$
$$\mathscr{A}^{CP}(B^+ \to K^+K^+K^-) = -0.046 \pm 0.009\,(\text{stat}) \pm 0.005\,(\text{syst}) \pm 0.007(J/\psi K^+),$$

where the third uncertainty is the $\mathscr{A}^{CP}(B^+ \to J/\psi K^+)$ uncertainty. The main source of systematic effects are attributed to the use of the $B^+ \to J/\psi K^+$ control channel to account for the production and reconstruction asymmetries and the acceptance correction in the Dalitz plot.

The phase space distribution of the $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ decays have also been investigated. The relevant variables used to represent the Dalitz plot are the two-body invariant masses ($m^2_{\pi^+\pi^-}$, $m^2_{K^+\pi^-}$) for $B^+ \to K^+\pi^+\pi^-$ and ($m^2_{K^+K^-low}$, $m^2_{K^+K^-high}$) for $B^+ \to K^+K^+K^-$ decays, where $m^2_{K^+K^-high} > m^2_{K^+K^-low}$. To inspect the events in phase space in search for *CP* violation, only candidates with invariant mass within $\pm 40\,\mathrm{MeV}/c^2$ around the *B* candidate mass peak are considered. The phase space of these decays are divided into bins with the same number of candidates using an adaptative binning algorithm. For each bin, the variable $\mathscr{A}^{CP}_N \equiv \frac{N^- - N^+}{N^- + N^+}$ is computed using the number of $B^\pm$ candidates, $N^\pm$, which includes both signal and background and is not corrected for efficiency.

The top part of Fig. 4 shows the resulting $\mathscr{A}^{CP}_N$ distribution where large asymmetries are clearly visible in the low $m^2_{K^+K^-low}$and low $m^2_{\pi^+\pi^-}$regions for $B^+ \to K^+K^+K^-$ and $B^+ \to K^+\pi^+\pi^-$ respectively. To analyze the *CP* violation without the background influence, the fit procedure was applied to extract the raw asymmetry in bins of two-body invariant mass projections, as illustrated in the bottom part of Fig. 4. From the figure, it is clear that the charge asymmetries have opposite sign between $m^2_{\pi^+\pi^-}$(positive) and $m^2_{K^+K^-low}$(negative) mass projections.

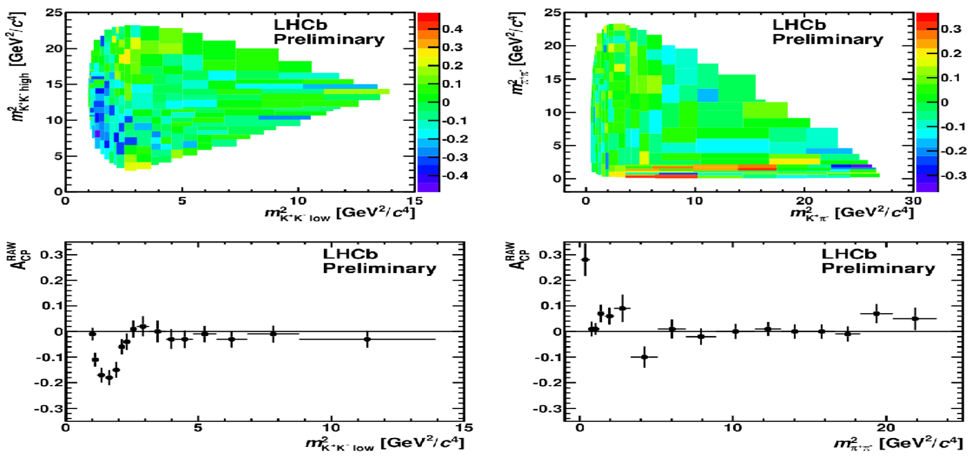

Figure 4: Mass projection of $\mathscr{A}^{CP}_N$ distribution over the Dalitz plot for $B^+ \to K^+K^+K^-$ (top left) and $B^+ \to K^+\pi^+\pi^-$ (top right). Mass projection of $\mathscr{A}^{CP}_{RAW}$ for $m^2_{K^+K^-low}$(bottom left) and $m^2_{\pi^+\pi^-}$(bottom right).

2.3 $B^+ \to K^+K^-\pi^+$ and $B^+ \to \pi^+\pi^+\pi^-$ decays

The $B^+ \to K^+K^-\pi^+$ and $B^+ \to \pi^+\pi^+\pi^-$ decays proceed through a $b \to d$ penguin and a $b \to u$ tree transition and have been measured previously by Belle and BaBar collaborations but no evidence of *CP* violation has been reported [13]. Unlike the $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ case, these two decays have a large background level and a special care to the *CP* violation observable is mandatory. Hence, the raw asymmetry in this case is defined in terms of negative and positive *B*

PoS(Beauty 2013)014

candidates and corrected by the acceptance in the Dalitz plot as

$$^{ACC}\mathscr{A}^{CP}_{RAW} = \frac{(N_{B^-}/R) - N_{B^+}}{(N_{B^-}/R) + N_{B^+}},$$

where R is the ratio between B^+ and B^- data-weighted average efficiency in the Dalitz plot.

The raw charge asymmetry is corrected for production asymmetry as in the previous $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ analysis [26]. Any reconstruction asymmetry effects are corrected using the techniques of the previous LHCb analysis of B and D decays [27, 28]. Using LHCb data corresponding to an integrated luminosity of 1 fb^{-1}, the final charge asymmetries for $B^+ \to K^+K^-\pi^+$ and $B^+ \to \pi^+\pi^+\pi^-$ are measured to be [29]

$$\mathscr{A}^{CP}(B^+ \to K^+K^-\pi^+) = -0.153 \pm 0.046\,(\text{stat}) \pm 0.019\,(\text{syst}) \pm 0.007(J/\psi K^+),$$
$$\mathscr{A}^{CP}(B^+ \to \pi^+\pi^+\pi^-) = +0.120 \pm 0.020\,(\text{stat}) \pm 0.019\,(\text{syst}) \pm 0.007(J/\psi K^+),$$

where the third uncertainty is related to the uncertainty of the world average $\mathscr{A}^{CP}$ value from $B^+ \to J/\psi K^+$ and the main source of systematic effect is the acceptance correction.

The phase space distribution of the $B^+ \to K^+K^-\pi^+$ and $B^+ \to \pi^+\pi^+\pi^-$ decays has also been investigated, revealing a large negative asymmetry at low $m^2_{K^+K^-}$ invariant mass as well as large positive asymmetry at low $m^2_{\pi^+\pi^- low}$. To quantify the charge asymmetries in these regions, the same $\mathscr{A}^{CP}$ measurement procedure is applied to the candidates inside the region $m^2_{\pi^+\pi^- low} < 0.4\,\text{GeV}^2/c^4$ and $m^2_{\pi^+\pi^- high} > 15\,\text{GeV}^2/c^4$ for $B^+ \to \pi^+\pi^+\pi^-$ and $m^2_{K^+K^-} < 1.5\,\text{GeV}^2/c^4$ for $B^+ \to K^+K^-\pi^+$ decays. The inclusive $\mathscr{A}^{CP}$ per region of the Dalitz plot is

$$\mathscr{A}^{CP}(B^+ \to K^+K^-\pi^+ \; region) = -0.671 \pm 0.067\,(\text{stat}) \pm 0.028\,(\text{syst}) \pm 0.007(J/\psi K^+),$$
$$\mathscr{A}^{CP}(B^+ \to \pi^+\pi^+\pi^- \; region) = +0.622 \pm 0.075\,(\text{stat}) \pm 0.032\,(\text{syst}) \pm 0.007(J/\psi K^+).$$

Figures 5 and 6 show the $m^2_{K^+K^-}$ and $m^2_{\pi^+\pi^- low}$ invariant mass distributions together with the B^- and B^+ mass distribution for $B^+ \to K^+K^-\pi^+$ and $B^+ \to \pi^+\pi^+\pi^-$ decays respectively.

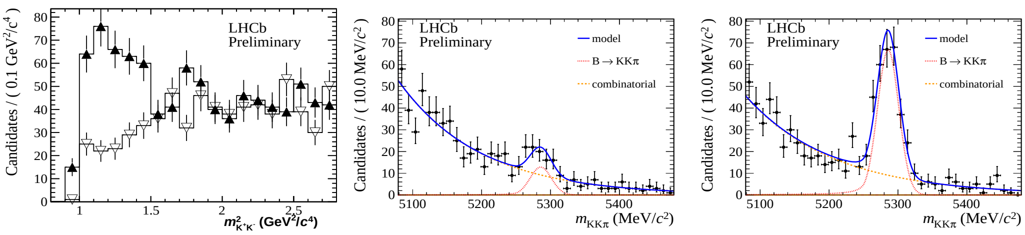

Figure 5: $B^\pm \to K^\pm K^+\pi^-$ candidate yields (signal and background) as a function of $m^2_{\pi^+\pi^- low}$ for candidates with $m^2_{\pi^+\pi^- high} > 15\,\text{GeV}^2/c^4$ (left), where empty triangles represent B^- and filled triangles represent B^+; and mass distribution for B^- (middle) and B^+ (right) for candidates with $m^2_{\pi^+\pi^- low} < 0.4\,\text{GeV}^2/c^4$ and $m^2_{\pi^+\pi^- high} > 15\,\text{GeV}^2/c^4$.

3. Conclusions

The LHCb collaboration has recently produced new results in B meson decays to charmless 3-body final states. The first observation of the $B^0_s \to K^0_S K^\pm \pi^\mp$ decay and measurements of the ratio

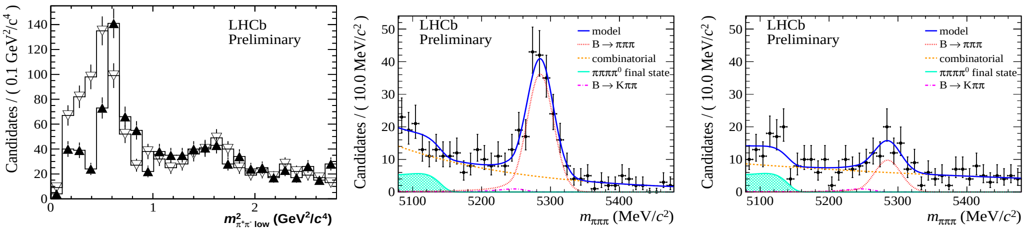

Figure 6: $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ candidate yields (signal and background) as a function of $m^2_{K^+K^-}$(left), where empty triangles represent B^- and filled triangles represent B^+; and mass distribution for B^- (middle) and B^+ (right) for candidates with $m^2_{K^+K^-} < 1.5\,\mathrm{GeV}^2/c^4$.

of the branching fractions of the $p\overline{p}$ intermediate states with respect to the $B^+ \to J/\psi K^+$ decays in the $B^+ \to p\overline{p}K^+$ final state have been reported. Also, an intriguing large opposite sign $\mathscr{A}^{CP}$ has been observed for the pairs $B^+ \to K^+\pi^+\pi^-/B^+ \to K^+K^+K^-$ and $B^+ \to K^+K^-\pi^+/B^+ \to \pi^+\pi^+\pi^-$ decays. For the latter, an even larger opposite sign $\mathscr{A}^{CP}$ has been reported in regions of the Dalitz plot not clearly related to resonant states. The LHCb experiment tripled its sample with the data collected during the 2012 run, allowing all these analyses to improve the results and other modes to be studied.

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PoS(Beauty 2013)014