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Measurement of *CP* violation in the phase space of $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ and $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ decays

LHCb collaboration

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The charmless decays $B^{\pm} \to K^+K^-\pi^{\pm}$ and $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ are reconstructed in a data set, corresponding to an integrated luminosity of 1.0 fb^{-1} of pp collisions at a center-of-mass energy of 7 TeV, collected by LHCb in 2011. The inclusive charge asymmetries of these modes are measured to be $A_{CP}(B^{\pm} \to K^+K^-\pi^{\pm}) = -0.141 \pm 0.040\,(\text{stat}) \pm 0.018\,(\text{syst}) \pm 0.007(J/\psi\,K^{\pm})$ and $A_{CP}(B^{\pm} \to \pi^+\pi^-\pi^{\pm}) = 0.117 \pm 0.021\,(\text{stat}) \pm 0.009\,(\text{syst}) \pm 0.007(J/\psi\,K^{\pm})$, where the third uncertainty is due to the CP asymmetry of the $B^{\pm} \to J/\psi\,K^{\pm}$ reference mode. In addition to the inclusive CP asymmetries, larger asymmetries are observed in localized regions of phase space.

Charmless decays of B mesons to three hadrons are dominated by quasi-two-body processes involving intermediate resonant states. The rich interference pattern present in such decays makes them favorable for the investigation of charge asymmetries that are localized in the phase space [1, 2]. The large samples of charmless B decays collected by the LHCb experiment allow direct CP violation to be measured in regions of phase space. In previous measurements of this type, the phase spaces of $B^{\pm} \to K^{\pm}K^{+}K^{-}$ and $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ decays were observed to have regions of large local asymmetries [3]. Concerning baryonic modes, no significant effects have been observed in either $B^{\pm} \to p\bar{p}K^{\pm}$ or $B^{\pm} \to p\bar{p}\pi^{\pm}$ decays [4]. Large CP-violating asymmetries have also been observed in charmless two-body B meson decays such as $B^0 \to K^{+}\pi^{-}$ and $B_s^0 \to K^{-}\pi^{+}$ (and the corresponding $\overline{B}^0$ and $\overline{B}_s^0$ decays) [5].

Some recent efforts have been made to understand the origin of the large asymmetries. For direct CP violation to occur, two interfering amplitudes with different weak and strong phases must be involved in the decay process [6]. Interference between intermediate states of the decay can introduce large strong phase differences, and is one mechanism for explaining local asymmetries in the phase space [7, 8]. Another explanation focuses on final-state $KK \leftrightarrow \pi\pi$ rescattering, which can occur between decay channels with the same flavor quantum numbers [3, 8, 9]. Invariance of CPT symmetry constrains hadron rescattering 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. Effects of SU(3) flavor symmetry breaking have also been investigated and partially explain the observed patterns [8, 10, 11].

The $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ decay is interesting because $s\bar{s}$ resonant contributions are strongly suppressed [12–14]. Recently, LHCb reported an upper limit on the ϕ contribution to be $\mathcal{B}(B^{\pm} \to \phi\pi^{\pm}) < 1.5 \times 10^{-7}$ at the 90% confidence level [15]. The lack of $K^{+}K^{-}$ resonant contributions makes the $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ decay a good probe for rescattering from decays with pions. The $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ mode, on the other hand, has large resonant contributions, as shown in an amplitude analysis by the BaBar collaboration, which measured the inclusive CP asymmetry to be (0.03 ± 0.06) [16]. For $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ decays, the inclusive CP-violating asymmetry was measured by the BaBar collaboration to be (0.00 ± 0.10) [17], from a comparison of B^{+} and B^{-} sample fits. Both results are compatible with the no CP-violation hypothesis.

In this Letter we report measurements of the inclusive CP-violating asymmetries for $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ and $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ decays. The CP asymmetry in $B^{\pm}$ decays to a final state $f^{\pm}$ is defined as

$$A_{CP}(B^{\pm} \to f^{\pm}) \equiv \Phi[\Gamma(B^{-} \to f^{-}), \Gamma(B^{+} \to f^{+})], \quad (1)$$

where $\Phi[X, Y] \equiv (X - Y)/(X + Y)$ is the asymmetry function, Γ is the decay width, and the final states $f^{\pm}$ are $\pi^{+}\pi^{-}\pi^{\pm}$ or $K^{+}K^{-}\pi^{\pm}$. The asymmetry distributions across the phase space are also investigated.

The LHCb detector [18] 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 analysis is based on pp collision data, corresponding to an integrated luminosity of $1.0\,\text{fb}^{-1}$, collected in 2011 at a center-of-mass energy of 7 TeV.

Events are selected by a trigger [19] that consists of a hardware stage, based on information from a calorimeter system and five muon stations, followed by a software stage, which applies a full event reconstruction. Candidate events are first required to pass the hardware trigger, which selects particles with a large transverse energy. The software trigger requires a two-, three- or four-track secondary vertex with a high sum of the transverse momenta, p_{T}, of the tracks and significant displacement from the primary pp interaction vertices (PVs). At least one track should have $p_{\mathrm{T}} > 1.7\,\text{GeV}/c$ and χ^2_{IP} with respect to any primary interaction greater than 16, where χ^2_{IP} is defined as the difference between the χ^2 of a given PV reconstructed with and without the considered track, and IP is the impact parameter. A multivariate algorithm [20] is used for the identification of secondary vertices consistent with the decay of a b hadron.

Further criteria are applied offline to select B mesons and suppress the combinatorial background. The $B^{\pm}$ decay products are required to satisfy a set of selection criteria on their momenta, their p_{T}, the χ^2_{IP} of the final-state tracks, and the distance of closest approach between any two tracks. The B candidates are required to have $p_{\mathrm{T}} > 1.7\,\text{GeV}/c$, $\chi^2_{\mathrm{IP}} < 10$ (defined by projecting the B candidate trajectory backwards from its decay vertex), decay vertex $\chi^2 < 12$, and decay vertex displacement from any PV greater than 3 mm. Additional requirements are applied to variables related to the B-meson production and decay, such as the angle θ between the B-candidate momentum and the direction of flight from the primary vertex to the decay vertex, $\cos(\theta) > 0.99998$. Final-state kaons and pions are further selected using particle identification information, provided by two ring-imaging Cherenkov detectors [21], and are required to be incompatible with a muon [22]. The kinematic selection is common to both decay channels, while the particle identification selection is specific to each final state. Charm contributions are removed by excluding the regions of $\pm 30\,\text{MeV}/c^2$ around the world average value of the D^0 mass [23] in the two-body invariant masses $m_{\pi^{+}\pi^{-}}$, $m_{K^{\pm}\pi^{\mp}}$ and $m_{K^{+}K^{-}}$.

The simulated events used in this analysis are generated using PYTHIA 6.4 [24] with a specific LHCb configuration [25]. Decays of hadronic particles are produced by

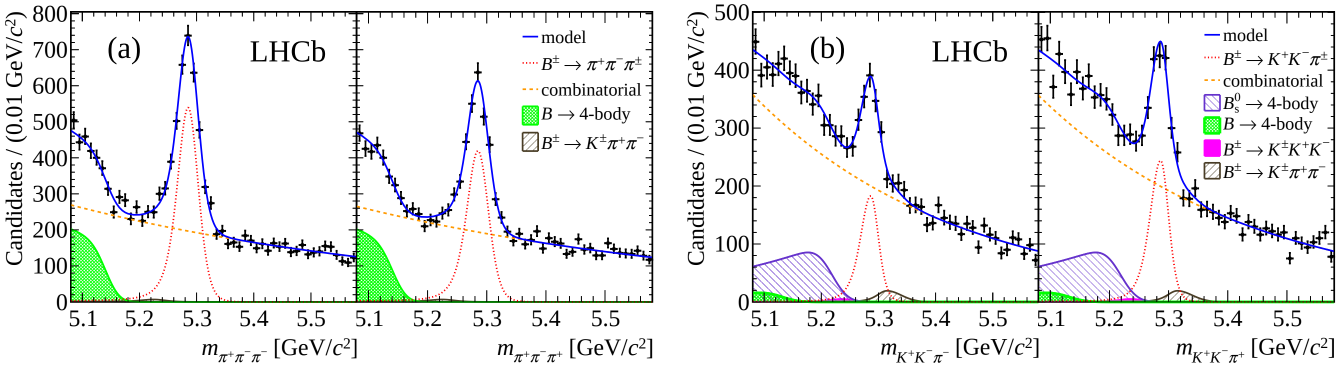

FIG. 1. Invariant mass spectra of (a) $B^\pm \to \pi^+\pi^-\pi^\pm$ decays and (b) $B^\pm \to K^+K^-\pi^\pm$ decays. The left panel in each figure shows the B^- modes and the right panel shows the B^+ modes. The results of the unbinned maximum likelihood fits are overlaid. The main components of the fit are also shown.

EvtGen [26], in which final-state radiation is generated using Photos [27]. The interaction of the generated particles with the detector and its response are implemented using the Geant4 toolkit [28] as described in Ref. [29].

Unbinned extended maximum likelihood fits to the mass spectra of the selected $B^\pm$ candidates are performed to obtain the signal yields and raw asymmetries. The $B^\pm \to K^+K^-\pi^\pm$ and $B^\pm \to \pi^+\pi^-\pi^\pm$ signal components are parametrized by a Cruijff function [30] with equal left and right widths and different radiative tails to account for the asymmetric effect of final-state radiation on the signal shape. The means and widths are left to float in the fit, while the tail parameters are fixed to the values obtained from simulation. The combinatorial background is described by an exponential distribution whose parameter is left free in the fit. The backgrounds due to partially reconstructed four-body B decays are parametrized by an ARGUS distribution [31] convolved with a Gaussian resolution function. For $B^\pm \to \pi^+\pi^-\pi^\pm$ decays the shape and yield parameters describing the backgrounds are varied in the fit, while for $B^\pm \to K^+K^-\pi^\pm$ decays they are taken from simulation, due to a further contribution from four-body B_s^0 decays such as $B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+$. We define peaking backgrounds as decay modes with one misidentified particle, namely the channels $B^\pm \to K^\pm\pi^+\pi^-$ for the $B^\pm \to \pi^+\pi^-\pi^\pm$ mode, and $B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+K^-$ for the $B^\pm \to K^+K^-\pi^\pm$ mode. The shapes and yields of the peaking backgrounds are obtained from simulation. The yields of the peaking and partially reconstructed background components are constrained to be equal for B^+ and B^- decays. The invariant mass spectra of the $B^\pm \to K^+K^-\pi^\pm$ and $B^\pm \to \pi^+\pi^-\pi^\pm$ candidates are shown in Fig. 1.

The signal yields obtained are $N(KK\pi) = 1870 \pm 133$ and $N(\pi\pi\pi) = 4904 \pm 148$, and the raw asymmetries are $A_{\rm raw}(KK\pi) = -0.143 \pm 0.040$ and $A_{\rm raw}(\pi\pi\pi) = 0.124 \pm 0.020$, where the uncertainties are statistical. The CP asymmetries are expressed in terms of the measured raw asymmetries, corrected for effects induced by the detector acceptance and interactions of final-state pions with matter $A_{\rm D}(\pi^\pm)$, as well as for a possible B-meson production asymmetry $A_{\rm P}(B^\pm)$,

$$A_{CP} = A_{\rm raw} - A_{\rm D}(\pi^\pm) - A_{\rm P}(B^\pm). \tag{2}$$

The pion detection asymmetry, $A_{\rm D}(\pi^\pm) = 0.0000 \pm 0.0025$, has been previously measured by LHCb [32]. The production asymmetry $A_{\rm P}(B^\pm)$ is measured from a data sample of approximately 6.3×10^4 $B^\pm \to J/\psi\,(\mu^+\mu^-)K^\pm$ decays. The $B^\pm \to J/\psi\,K^\pm$ sample passes the same trigger, kinematic, and kaon particle identification selection criteria as the signal samples, and it has a similar event topology. The $A_{\rm P}(B^\pm)$ term is obtained from the raw asymmetry of the $B^\pm \to J/\psi\,K^\pm$ mode as

$$A_{\rm P}(B^\pm) = A_{\rm raw}(J/\psi\,K) - A_{CP}(J/\psi\,K) - A_{\rm D}(K^\pm), \tag{3}$$

where $A_{CP}(J/\psi\,K) = 0.001 \pm 0.007$ [23] is the world average CP asymmetry of $B^\pm \to J/\psi\,K^\pm$ decays, and $A_{\rm D}(K^\pm) = -0.010 \pm 0.003$ is the kaon interaction asymmetry obtained from $D^0 \to K^\pm\pi^\mp$ and $D^0 \to K^+K^-$ decays [33], and corrected for $A_{\rm D}(\pi^\pm)$. The CP asymmetries of the $B^\pm \to K^+K^-\pi^\pm$ and $B^\pm \to \pi^+\pi^-\pi^\pm$ channels are then determined using Eqs. 2 and 3.

Since the detector efficiencies for the signal modes are not uniform across the Dalitz plot, and the raw asymmetries are also not uniformly distributed, an acceptance correction is applied to the integrated raw asymmetries. It is determined by the ratio between the B^- and B^+ average efficiencies in simulated events, reweighted to reproduce the population of signal data over the phase space. Furthermore, the detector acceptance and reconstruction depend on the trigger selection. The efficiency of the hadronic hardware trigger is found to have a small charge

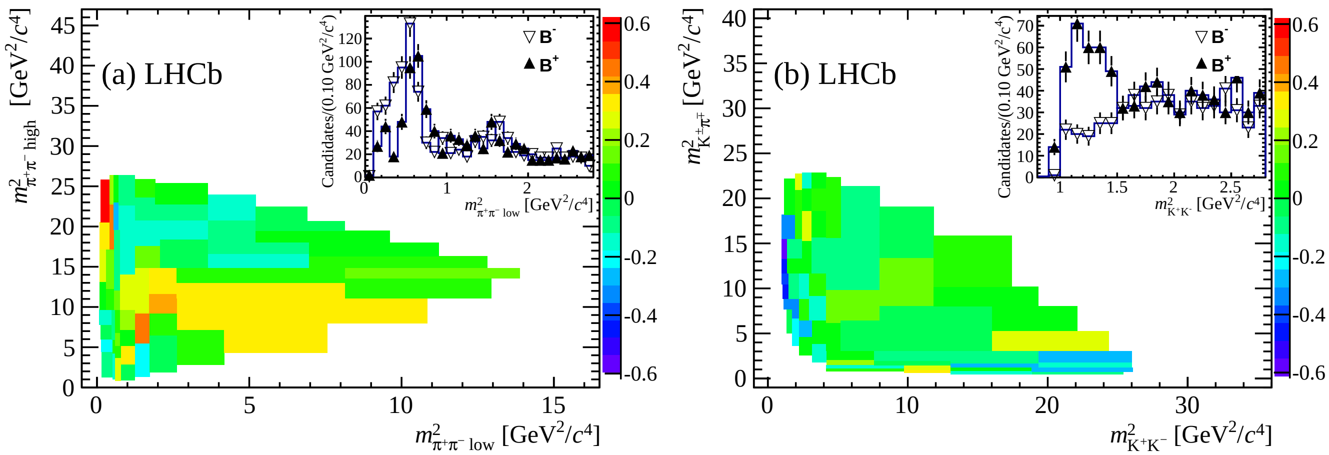

FIG. 2. Asymmetries of the number of events (including signal and background) in bins of the Dalitz plot, A^N_{raw}, for (a) $B^\pm \to \pi^+\pi^-\pi^\pm$ and (b) $B^\pm \to K^+K^-\pi^\pm$ decays. The inset figures show the projections of the number of events in bins of (a) the $m^2_{\pi^+\pi^-\,\mathrm{low}}$ variable for $m^2_{\pi^+\pi^-\,\mathrm{high}} > 15\,\mathrm{GeV}^2/c^4$ and (b) the $m^2_{K^+K^-}$ variable. The distributions are not corrected for efficiency.

asymmetry for kaons. Therefore, the data are divided into two samples: events with candidates selected by the hadronic trigger and events selected by other triggers independently of the signal candidate. The acceptance correction and subtraction of the $A_{\mathrm{P}}(B^\pm)$ term is performed separately for each trigger configuration. The trigger-averaged value of the production asymmetry is $A_{\mathrm{P}}(B^\pm) = -0.004 \pm 0.004$, where the uncertainty is statistical only. The integrated CP asymmetries are then the weighted averages of the CP asymmetries for the two trigger samples.

The methods used in estimating the systematic uncertainties of the signal model, combinatorial background, peaking background, and acceptance correction are the same as those used in Ref. [3]. For $B^\pm \to K^+K^-\pi^\pm$ decays, we also evaluate a systematic uncertainty due to the partially reconstructed background model by varying the mean and resolution according to the difference between simulation and data obtained from the signal component. The $A_{\mathrm{D}}(\pi^\pm)$ and $A_{\mathrm{D}}(K^\pm)$ uncertainties are included as systematic uncertainties related to the procedure. A systematic uncertainty is also evaluated to account for the difference in kaon kinematics between the $B^\pm$ and D^0 decays. The systematic uncertainties for the measurements of $A_{CP}(B^\pm \to K^+K^-\pi^\pm)$ and $A_{CP}(B^\pm \to \pi^+\pi^-\pi^\pm)$ are summarized in Table I.

The results obtained for the inclusive CP asymmetries of the $B^\pm \to K^+K^-\pi^\pm$ and $B^\pm \to \pi^+\pi^-\pi^\pm$ decays are

$$A_{CP}(B^\pm \to K^+K^-\pi^\pm) = -0.141 \pm 0.040 \pm 0.018 \pm 0.007,$$
$$A_{CP}(B^\pm \to \pi^+\pi^-\pi^\pm) = 0.117 \pm 0.021 \pm 0.009 \pm 0.007,$$

where the first uncertainty is statistical, the second is the experimental systematic, and the third is due to the CP asymmetry of the $B^\pm \to J/\psi\, K^\pm$ reference mode [23]. 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 standard deviations (σ) for $B^\pm \to K^+K^-\pi^\pm$ and 4.9σ for $B^\pm \to \pi^+\pi^-\pi^\pm$ decays.

In addition to the inclusive charge asymmetries, we study the asymmetry distributions in the two-dimensional phase space of two-body invariant masses. The Dalitz plot distributions in the signal region, defined as the three-body invariant mass region within two Gaussian widths from the signal peak, are divided into bins with approximately equal numbers of events in the combined B^- and B^+ samples. Figure 2 shows the raw asymmetries (not corrected for efficiency), $A^N_{\mathrm{raw}} = \Phi[N^-, N^+]$, computed using the number of negative (N^-) and positive (N^+) entries in each bin of the $B^\pm \to \pi^+\pi^-\pi^\pm$ and $B^\pm \to K^+K^-\pi^\pm$

TABLE I. Systematic uncertainties on $A_{CP}(B^\pm \to K^+K^-\pi^\pm)$ and $A_{CP}(B^\pm \to \pi^+\pi^-\pi^\pm)$. The total systematic uncertainties are the sum in quadrature of the individual contributions.

Systematic uncertainty	$A_{CP}(KK\pi)$	$A_{CP}(\pi\pi\pi)$
Signal model	0.001	0.0005
Combinatorial background	0.003	0.0008
Peaking background	0.001	0.0025
Acceptance	0.014	0.0032
Part. rec. background	0.005	–
$A_{\mathrm{D}}(\pi^\pm)$ uncertainty	0.003	0.0025
$A_{\mathrm{D}}(K^\pm)$ uncertainty	0.003	0.0032
$A_{\mathrm{D}}(K^\pm)$ kaon kinematics	0.008	0.0075
Total	0.018	0.0094

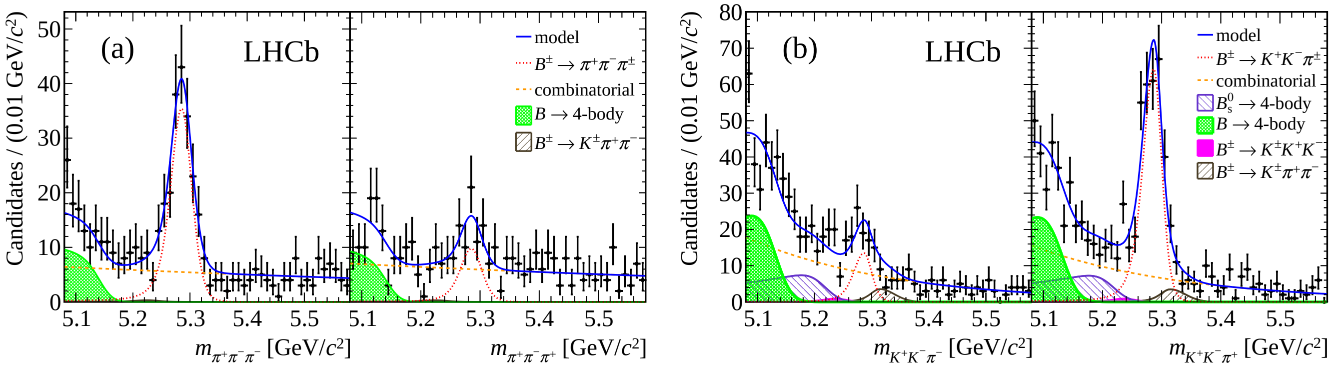

FIG. 3. Invariant mass spectra of (a) $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ decays in the region $m^2_{\pi^+\pi^- \text{ low}} < 0.4\,\text{GeV}^2/c^4$ and $m^2_{\pi^+\pi^- \text{ high}} > 15\,\text{GeV}^2/c^4$, and (b) $B^{\pm} \to K^+K^-\pi^{\pm}$ decays in the region $m^2_{K^+K^-} < 1.5\,\text{GeV}^2/c^4$. The left panel in each figure shows the B^- modes and the right panel shows the B^+ modes. The results of the unbinned maximum likelihood fits are overlaid.

Dalitz plots. The $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ Dalitz plot is symmetrized and its two-body invariant mass squared variables are defined as $m^2_{\pi^+\pi^- \text{ low}} < m^2_{\pi^+\pi^- \text{ high}}$. The A^N_{raw} distribution in the Dalitz plot of the $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ mode reveals an asymmetry concentrated at low values of $m^2_{\pi^+\pi^- \text{ low}}$ and high values of $m^2_{\pi^+\pi^- \text{ high}}$. The distribution of the projection of the number of events onto the $m^2_{\pi^+\pi^- \text{ low}}$ invariant mass (inset in Fig. 2(a)) shows that this asymmetry is located in the region $m^2_{\pi^+\pi^- \text{ low}} < 0.4\,\text{GeV}^2/c^4$ and $m^2_{\pi^+\pi^- \text{ high}} > 15\,\text{GeV}^2/c^4$. For $B^{\pm} \to K^+K^-\pi^{\pm}$ we identify a negative asymmetry located in the low K^+K^- invariant mass region. This can be seen also in the inset figure of the K^+K^- invariant mass projection, where there is an excess of B^+ candidates for $m^2_{K^+K^-} < 1.5\,\text{GeV}^2/c^4$. Although $B^{\pm} \to K^+K^-\pi^{\pm}$ has no $\phi(1020)$ contribution [15, 34], a clear structure is observed. This structure was also seen by the BaBar collaboration [17] but was not studied separately for B^- and B^+ components. No significant asymmetry is present in the low-mass region of the $K^{\pm}\pi^{\mp}$ invariant mass projection.

The CP asymmetries are further studied in the regions where large raw asymmetries are found. The regions are defined as $m^2_{\pi^+\pi^- \text{ high}} > 15\,\text{GeV}^2/c^4$ and $m^2_{\pi^+\pi^- \text{ low}} < 0.4\,\text{GeV}^2/c^4$ for the $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ mode, and $m^2_{K^+K^-} < 1.5\,\text{GeV}^2/c^4$ for the $B^{\pm} \to K^+K^-\pi^{\pm}$ mode. Unbinned extended maximum likelihood fits are performed to the mass spectra of the candidates in these regions, using the same models as for the global fits. The spectra are shown in Fig. 3. The resulting signal yields and raw asymmetries for the two regions are $N^{\text{reg}}(KK\pi) = 342 \pm 28$ and $A^{\text{reg}}_{\text{raw}}(KK\pi) = -0.658 \pm 0.070$ for the $B^{\pm} \to K^+K^-\pi^{\pm}$ mode, and $N^{\text{reg}}(\pi\pi\pi) = 229 \pm 20$ and $A^{\text{reg}}_{\text{raw}}(\pi\pi\pi) = 0.555 \pm 0.082$ for the $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ mode. The CP asymmetries are obtained from the raw asymmetries using Eqs. 2 and 3 and applying an acceptance correction. Systematic uncertainties are estimated due to the signal models, acceptance correction and binning choice in the region, the $A_{\text{D}}(\pi^{\pm})$ and $A_{\text{P}}(B^{\pm})$ statistical uncertainties and the $A_{\text{D}}(K^{\pm})$ kaon kinematics. The local charge asymmetries for the two regions are measured to be

$$A^{\text{reg}}_{CP}(B^{\pm} \to K^+K^-\pi^{\pm}) = -0.648 \pm 0.070 \pm 0.013 \pm 0.007,$$
$$A^{\text{reg}}_{CP}(B^{\pm} \to \pi^+\pi^-\pi^{\pm}) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007,$$

where the first uncertainty is statistical, the second is the experimental systematic and the third is due to the CP asymmetry of the $B^{\pm} \to J/\psi K^{\pm}$ reference mode [23].

In conclusion, we have found the first evidence of inclusive CP asymmetries of the $B^{\pm} \to K^+K^-\pi^{\pm}$ and $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ modes with significances of 3.2σ and 4.9σ, respectively. The results are consistent with those measured by the BaBar collaboration [16, 17]. These charge asymmetries are not uniformly distributed in the phase space. For $B^{\pm} \to K^+K^-\pi^{\pm}$ decays, where no significant resonant contribution is expected, we observe a very large negative asymmetry concentrated in a restricted region of the phase space in the low K^+K^- invariant mass. For $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ decays, a large positive asymmetry is measured in the low $m^2_{\pi^+\pi^- \text{ low}}$ and high $m^2_{\pi^+\pi^- \text{ high}}$ phase-space region, not clearly associated to a resonant state. The evidence presented here for CP violation in $B^{\pm} \to K^+K^-\pi^{\pm}$ and $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ decays, along with the recent evidence for CP violation in $B^{\pm} \to K^{\pm}\pi^+\pi^-$ and $B^{\pm} \to K^{\pm}K^+K^-$ decays [3] and recent theoretical developments [7–10], indicate new mechanisms for CP asymmetries, which should be incorporated in models for future amplitude analyses of charmless three-body B decays.

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