

Results on direct CP violation in B decays in LHCb

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I present three studies from the LHCb experiment on the subject of direct CP violation in B^0 and B_s^0 decays. First, we measure the CP asymmetry in $B^\pm \rightarrow \psi K^\pm$ decays, with $\psi = J/\psi, \psi(2S)$, using 0.35 fb^{-1} of pp collisions at $\sqrt{s} = 7 \text{ TeV}$. We find no evidence for CP violation. Second, using the same data sample, we see the first evidence of CP violation in the decays of B_s^0 mesons to $K^\pm \pi^\mp$ pairs, $A_{CP}(B_s^0 \rightarrow K\pi) = 0.27 \pm 0.08(\text{stat}) \pm 0.02(\text{syst})$ (3.3σ). Third, using 1.0 fb^{-1} of data, measurements of CP sensitive observables of the $B^\pm \rightarrow DK^\pm$ system are presented. They include the first observation of the suppressed mode $B^\pm \rightarrow [\pi^\pm K^\mp]_D K^\pm$. Combining several D final states, CP violation in $B^\pm \rightarrow DK^\pm$ decays is observed with a significance of 5.8σ .

1 Measurement of CP asymmetries in $B^\pm \rightarrow \psi h^\pm$ decays

The $B^\pm \rightarrow \psi h^\pm$ decays, with $\psi = (J/\psi, \psi(2S))$ and $h = K, \pi$, receive contributions from both tree and penguin diagrams. If these contributions have different weak phases, direct CP violation may occur. The Standard Model predicts that for $b \rightarrow c\bar{c}s$ decays the tree and penguin contributions have the same weak phase and thus no direct CP violation is expected in $B^\pm \rightarrow \psi K^\pm$. For $b \rightarrow c\bar{c}d$ transitions, however, both contributions have different weak phases, and CP violation in $B^\pm \rightarrow \psi \pi^\pm$ decays may occur. Their branching fractions are expected to be about 5% of the favoured $B^\pm \rightarrow \psi K^\pm$ modes. In our paper [1] we analyse a data sample of 0.35 fb^{-1} of pp collisions at $\sqrt{s} = 7 \text{ TeV}$, taken in 2011 with the LHCb detector. We define the CP asymmetry and the charge-averaged ratio of branching ratios as

$$A^{\psi\pi} = \frac{\mathcal{B}(B^- \rightarrow \psi\pi^-) - \mathcal{B}(B^+ \rightarrow \psi\pi^+)}{\mathcal{B}(B^- \rightarrow \psi\pi^-) + \mathcal{B}(B^+ \rightarrow \psi\pi^+)} , \quad R^\psi = \frac{\mathcal{B}(B^\pm \rightarrow \psi\pi^\pm)}{\mathcal{B}(B^\pm \rightarrow \psi K^\pm)} . \quad (1)$$

The ψ resonance is reconstructed in the $\mu^+\mu^-$ final state, and the well known and abundant decay $B^\pm \rightarrow J/\psi K^\pm$ is used as a control channel. It is crucial to control its cross feed into the $B^+ \rightarrow J/\psi \pi^+$ channel. Here we benefit from LHCb's two ring imaging Cherenkov (RICH) detectors that provide strong K/π separation. We obtain the signal yields from a simultaneous fit to the B candidate invariant mass distribution in eight independent subsamples, defined by the charge ($\times 2$), the ψ state ($\times 2$) and the flavour of the bachelor hadron ($K, \pi, \times 2$). The fit projections for the $\psi(2S)$ subsamples are shown in Figure 1. The measured ratios of branching fractions are $R^{J/\psi} = (3.83 \pm 0.11 \pm 0.07) \times 10^{-2}$ and $R^{\psi(2S)} = (3.95 \pm 0.40 \pm 0.12) \times 10^{-2}$, where the first uncertainty is statistical and the second systematic. $R^{\psi(2S)}$ is compatible with the one existing measurement [2], $(3.99 \pm 0.36 \pm 0.17) \times 10^{-2}$. The measurement of $R^{J/\psi}$ is 3.2σ lower than the

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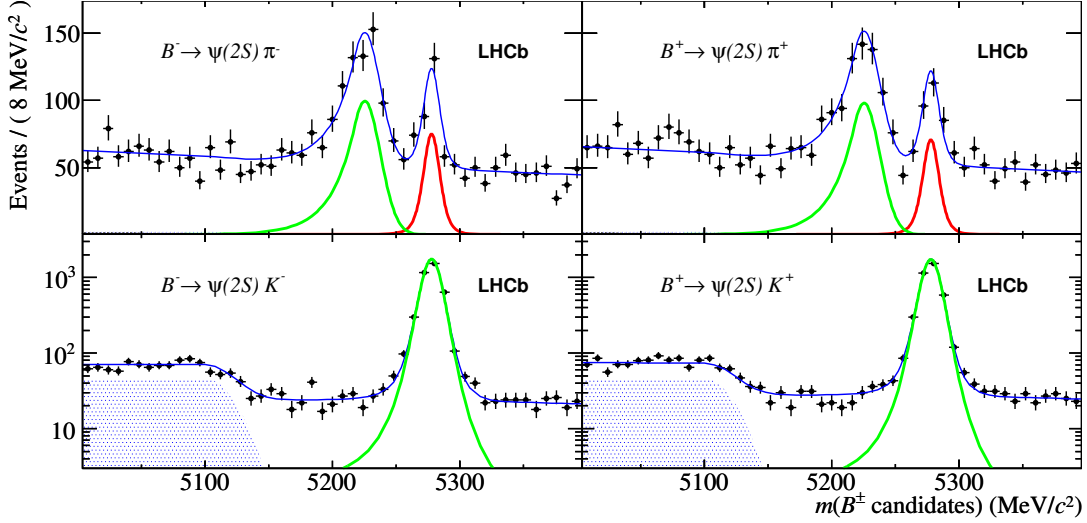


Figure 1: $B^\pm \rightarrow \Psi(2S)h^\pm$ invariant mass distributions, overlaid by the total fitted PDF (thin line). Pion-like events are reconstructed as $J/\psi\pi^\pm$ and enter in the top plots. All other events are reconstructed as $J/\psi K^\pm$ enter the bottom plots (shown in logarithmic scale). B^- decays are shown on the left, B^+ on the right. The dark [red] curve shows the $B^\pm \rightarrow \psi(2S)\pi^\pm$ component, the light [green] curve represents $B^\pm \rightarrow \psi(2S)K^\pm$. Partially reconstructed backgrounds are shaded.

current world average [3], $(5.2 \pm 0.4) \times 10^{-2}$. Using the established measurements of the Cabibbo-favoured branching fractions [3], we deduce $\mathcal{B}(B^\pm \rightarrow J/\psi\pi^\pm) = (3.88 \pm 0.11 \pm 0.15) \times 10^{-5}$, $\mathcal{B}(B^\pm \rightarrow \psi(2S)\pi^\pm) = (2.52 \pm 0.26 \pm 0.15) \times 10^{-5}$. The measured CP asymmetries,

$$A_{CP}^{J/\psi\pi} = 0.005 \pm 0.027 \pm 0.011, \quad (2)$$

$$A_{CP}^{\psi(2S)\pi} = 0.048 \pm 0.090 \pm 0.011, \quad (3)$$

$$A_{CP}^{\psi(2S)K} = 0.024 \pm 0.014 \pm 0.008, \quad (4)$$

have comparable or better precision than previous results, and no evidence of direct CP violation is seen.

2 Direct CP violation in $B^0(B_s^0) \rightarrow K^-\pi^+$ decays

CP violation is well established in the K^0 and B^0 meson systems. Recent results from LHCb have also provided evidence for CP violation in the D^0 system [4]. In our paper [5] we report evidence of direct CP violation in the last neutral meson system, the B_s^0 system. We reconstruct both $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow K^-\pi^+$ decays in 0.35 fb^{-1} of data collected with the LHCb detector in 2011. The considered decays have contributions from both tree and penguin diagrams, and are sensitive to contribution of new physics in the penguins. The CP asymmetry in the $B^0 \rightarrow K^+\pi^-$ is well established [3]. The probability of a b quark to decay as $B_s^0 \rightarrow K\pi$ is about 14 times smaller than that to decay as $B^0 \rightarrow K\pi$. However, both tree and penguin diagrams are roughly of the same magnitude, so CP violation effects can potentially be large. We define the CP asymmetries as

$$A_{CP}(B_{(s)}^0) = \frac{\Gamma(\bar{B}_{(s)}^0 \rightarrow \bar{f}_{(s)}) - \Gamma(B_{(s)}^0 \rightarrow f_{(s)})}{\Gamma(\bar{B}_{(s)}^0 \rightarrow \bar{f}_{(s)}) + \Gamma(B_{(s)}^0 \rightarrow f_{(s)})}, \quad (5)$$

with $f = K^+\pi^-$ and $f_s = K^-\pi^+$. To distinguish the $K^+\pi^-$ and $K^-\pi^+$ final states we rely on the RICH particle identification system. We carefully control the efficiencies and misidentification rates from data, through large control samples of $D^* \rightarrow D\pi \rightarrow (K\pi)_D\pi$ and $\Lambda_b \rightarrow p\pi$

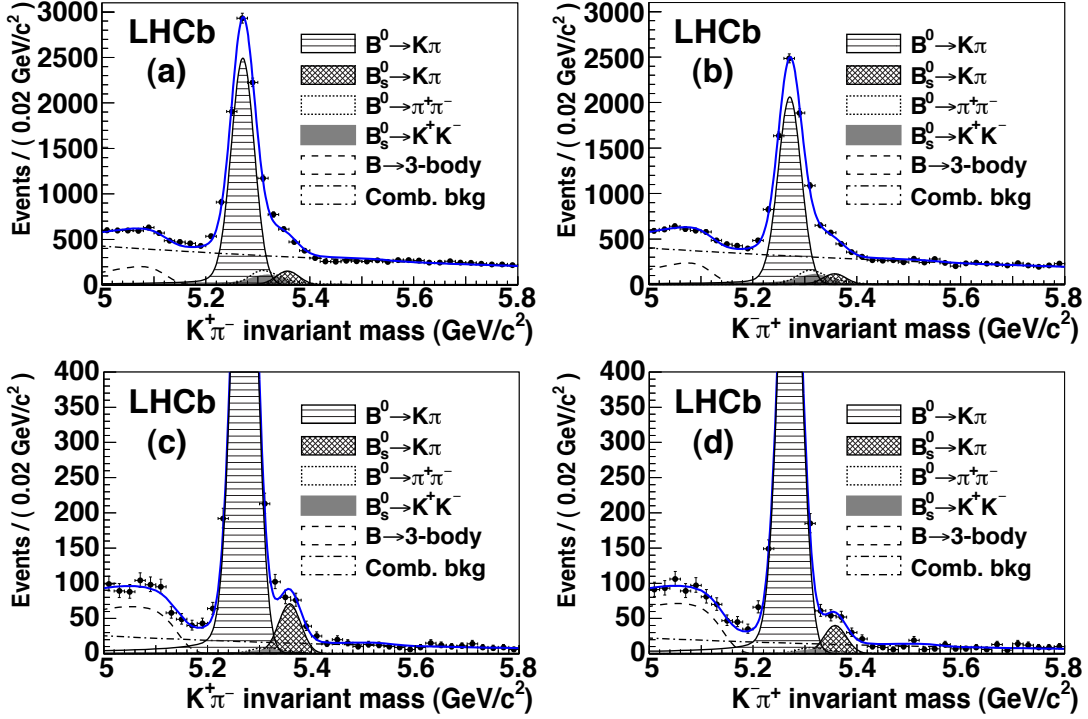


Figure 2: $K\pi$ invariant mass spectra obtained using the event selection adopted for the best sensitivity on (a, b) $A_{CP}(B^0 \rightarrow K\pi)$ and (c, d) $A_{CP}(B_s^0 \rightarrow K\pi)$. Plots (a) and (c) represent the $K^+\pi^-$ invariant mass whereas plots (b) and (d) represent the $K^-\pi^+$ invariant mass. The results of the unbinned maximum likelihood fits are overlaid. The main components contributing to the fit model are also shown.

decays. There are cross feeds from $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ decays, whose line shape we predict from simulation. We compute a raw asymmetry from the yields of a fit to the invariant mass distribution in the positive charge and negative charge subsamples. Figure 2 shows the projections. This raw asymmetry needs to be corrected for two effects: an inherent detector charge asymmetry (which we estimate from our D^* control samples) and a non-zero production asymmetry that is further diluted by B mixing (thus it mostly affects the B^0 channel due to its much slower $B^0-\bar{B}^0$ oscillation). The total corrections to the raw asymmetry are $\Delta A_{CP}(B^0) = -0.007 \pm 0.006$ and $\Delta A_{CP}(B_s^0) = 0.010 \pm 0.002$, where the errors are statistical. The systematic uncertainty of $A_{CP}(B^0)$ is dominated by uncertainties due to instrumentation and production asymmetry, while the systematic uncertainty of $A_{CP}(B_s^0)$ receives a leading contribution from the combinatorial background description. In conclusion we obtain the following measurements of the CP asymmetries:

$$A_{CP}(B^0 \rightarrow K\pi) = -0.088 \pm 0.011 (\text{stat}) \pm 0.008 (\text{syst})$$

and

$$A_{CP}(B_s^0 \rightarrow K\pi) = 0.27 \pm 0.08 (\text{stat}) \pm 0.02 (\text{syst}).$$

The result for $A_{CP}(B^0 \rightarrow K\pi)$ constitutes the most precise measurement available to date. It is in good agreement with the current world average [6]. The significance of the measured deviation from zero exceeds 6σ . The result for $A_{CP}(B_s^0 \rightarrow K\pi)$ is in agreement with the only measurement previously available [7]. The significance computed for $A_{CP}(B_s^0 \rightarrow K\pi)$ is 3.3σ , making this the first evidence for CP violation in the decays of B_s^0 mesons.

3 Observation of CP violation in $B^\pm \rightarrow DK^\pm$

The CKM angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ is the least well known angle of the corresponding unitarity triangle of the CKM matrix V . The angle γ can be measured in $B^\pm \rightarrow DK^\pm$ decays where the D signifies a D^0 or \bar{D}^0 meson. The amplitude for the D^0 contribution is proportional to V_{cb} whilst the \bar{D}^0 amplitude depends on V_{ub} . If the D final state is accessible for both D^0 and \bar{D}^0 mesons, the two amplitudes interfere and give rise to observables that are sensitive to γ . Many different D final states can be used. In our analysis [8] of 1.0 fb^{-1} of $\sqrt{s} = 7 \text{ TeV}$ data collected by LHCb in 2011, we use the CP eigenstates $D \rightarrow K^+K^-$, $\pi^+\pi^-$ (often referred to as “GLW” modes [9, 10]), and the flavour eigenstate $D \rightarrow \pi^-K^+$ (labelled “ADS” mode [11, 12]). The latter requires the favoured, $b \rightarrow c$ decay to be followed by a doubly Cabibbo-suppressed D decay, and the suppressed $b \rightarrow u$ decay to be followed by a favoured D decay. As a consequence, the interfering amplitudes are of similar magnitude and hence large interference can occur. In total, 13 observables are measured: three ratios of partial widths

$$R_{K/\pi}^f = \frac{\Gamma(B^- \rightarrow [f]_D K^-) + \Gamma(B^+ \rightarrow [f]_D K^+)}{\Gamma(B^- \rightarrow [f]_D \pi^-) + \Gamma(B^+ \rightarrow [f]_D \pi^+)} , \quad (6)$$

where f represents KK , $\pi\pi$ and the favoured $K\pi$ mode, six CP asymmetries

$$A_h^f = \frac{\Gamma(B^- \rightarrow [f]_D h^-) - \Gamma(B^+ \rightarrow [f]_D h^+)}{\Gamma(B^- \rightarrow [f]_D h^-) + \Gamma(B^+ \rightarrow [f]_D h^+)} , \quad (7)$$

and four charge-separated partial widths of the ADS mode relative to the favoured mode

$$R_h^\pm = \frac{\Gamma(B^\pm \rightarrow [\pi^\pm K^\mp]_D h^\pm)}{\Gamma(B^\pm \rightarrow [K^\pm \pi^\mp]_D h^\pm)} . \quad (8)$$

Similar analyses have found evidence of the $B^\pm \rightarrow [\pi^\pm K^\mp]_D K^\pm$ decay [13–15]. The abundant $B^- \rightarrow D\pi^-$ decays have limited sensitivity to γ and provide a large control sample from which probability density functions are shaped. The analysis method benefits greatly from a boosted decision tree, which combines 20 kinematic variables to effectively suppress combinatorial backgrounds. Charmless backgrounds are suppressed by exploiting the large forward boost of the D meson through a cut on its flight distance. The signal yields are estimated by a simultaneous fit to 16 independent subsamples, defined by the charges ($\times 2$), the D final states ($\times 4$), and the K or π nature of the bachelor hadron ($\times 2$). Figures 3 and 4 show the projections of the $\pi^+\pi^-$ and suppressed $\pi^\pm K^\mp$ subsamples, respectively. It is crucial to control the cross feed of the abundant $B^- \rightarrow D\pi^-$ decays into the signal decays. For this we rely on the two RICH detectors, which allow to place particle identification cuts on the bachelor hadron. These cuts are 87.6% efficient for kaons at a rate of 3.8% misidentified pions. Many systematic uncertainties cancel in the ratios Eqns. 6-8. The remaining systematic uncertainties are dominated by an intrinsic charge asymmetry of the detector, and by the uncertainty on the particle identification. From the measured 13 observables the following established quantities can be deduced (the full set is contained in our paper [8]):

$$\begin{aligned} R_{CP+} &= 1.007 \pm 0.038 \pm 0.012 , \\ A_{CP+} &= 0.145 \pm 0.032 \pm 0.010 , \\ R_K^- &= 0.0073 \pm 0.0023 \pm 0.0004 , \\ R_K^+ &= 0.0232 \pm 0.0034 \pm 0.0007 , \end{aligned}$$

where the first error is statistical and the second systematic; R_{CP+} is computed from $R_{CP+} \approx \langle R_{K/\pi}^{KK}, R_{K/\pi}^{\pi\pi} \rangle / R_{K/\pi}^{K\pi}$ with an additional 1% systematic uncertainty assigned to account for the

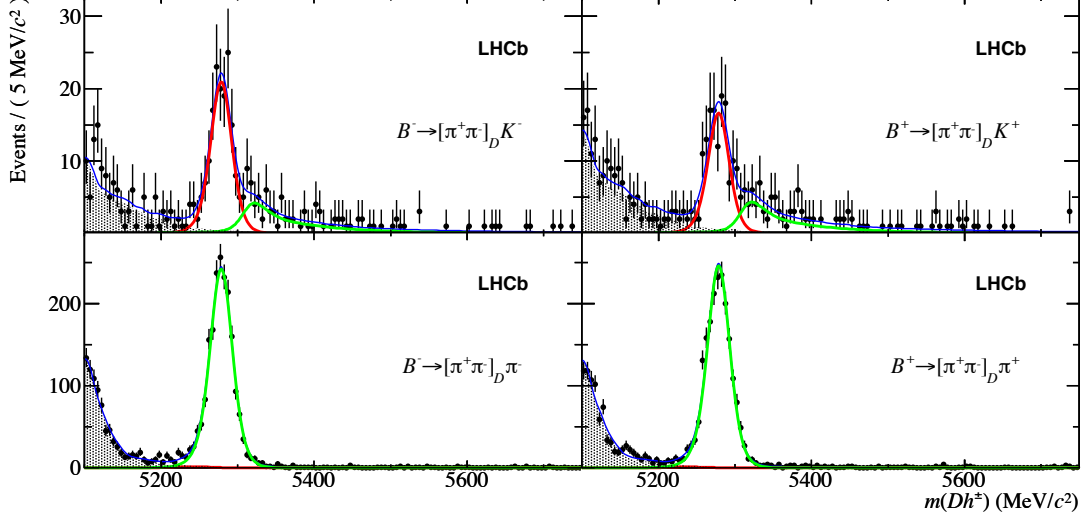


Figure 3: The invariant mass distribution of selected $B^\pm \rightarrow [\pi^+\pi^-]_D h^\pm$ candidates. The left plots are B^- candidates, B^+ are on the right. In the top plots, the bachelor track passes the kaon RICH cut and the B candidates are reconstructed assigning this track the kaon mass. The remaining events are placed in the bottom row and are reconstructed with a pion mass hypothesis. The dark (red) curve represents the $B \rightarrow DK^\pm$ events, the light (green) curve is $B \rightarrow D\pi^\pm$. The shaded contribution are partially reconstructed events and the thin line shows the total PDF which also includes a linear combinatoric component.

approximation; A_{CP+} is computed as $A_{CP+} = \langle A_K^{KK}, A_K^{\pi\pi} \rangle$. From the R_K^\pm we also compute

$$R_{ADS(K)} = 0.0152 \pm 0.0020 \pm 0.0004 ,$$

$$A_{ADS(K)} = -0.52 \pm 0.15 \pm 0.02 ,$$

as $R_{ADS(K)} = (R_K^- + R_K^+)/2$ and $A_{ADS(K)} = (R_K^- - R_K^+)/(R_K^- + R_K^+)$.

To summarise, the $B^\pm \rightarrow DK^\pm$ ADS mode is observed with $\approx 10\sigma$ statistical significance when comparing the maximum likelihood to that of the null hypothesis. This mode displays evidence (4.0σ) of a large negative asymmetry, consistent with previous experiments [13–15]. The combined asymmetry A_{CP+} is smaller than (but compatible with) previous measurements [16, 17]. It is 4.5σ significant. We compare the maximum likelihood with that under the null-hypothesis in all three D final states where the bachelor is a kaon, diluted by the non-negligible correlated systematic uncertainties. From this we observe, with a total significance of 5.8σ , direct CP violation in $B^\pm \rightarrow DK^\pm$ decays.

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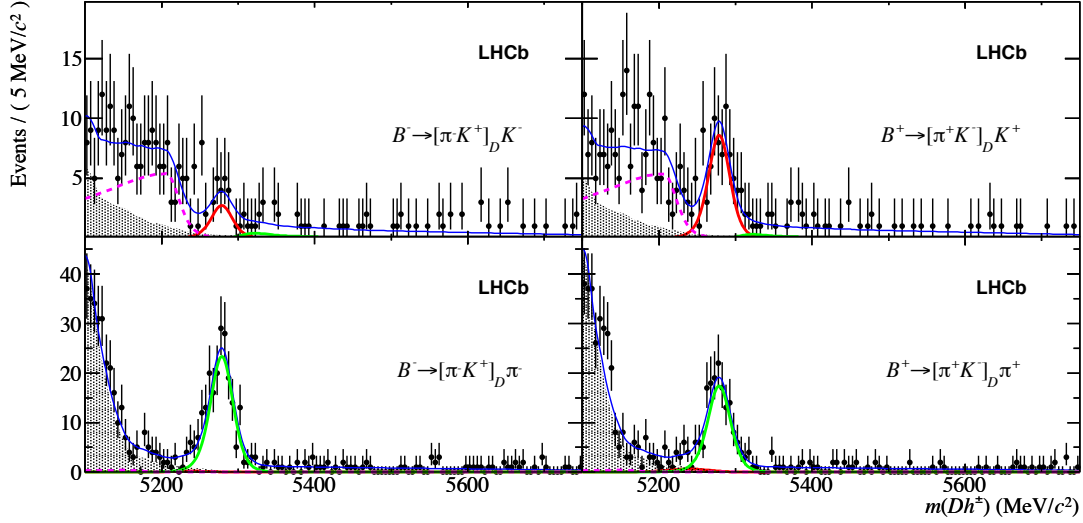


Figure 4: The invariant mass distribution of selected $B^\pm \rightarrow [\pi^\pm K^\pm]_D h^\pm$ candidates. See the caption of Fig. 3 for a full description. The broken line here represents the partially reconstructed, but Cabibbo favoured, $B_s^0 \rightarrow D^0 K^+ \pi^-$ decays where the pion is lost.

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