CP Violation in Hadronic B Decays at LHCb

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This article describes measurements of CP violation in charmed tree-level and charmless loop-level decays of B mesons. Comparison between these two classes of decay is interesting given the potential for new physics effects appearing in loops and enhancing or suppressing the level of observed CP violation. Firstly a study in tree-level $B^{\pm} \to [hh']_D K^{\pm}$ decays is presented, along with the progress towards a precise measurement of the CKM phase γ at LHCb. Secondly an analysis of $B^0_{(s)} \to hh'$ decays is described where loop diagrams can contribute. The analyses exploit data recorded by the LHCb detector, a forward spectrometer with excellent tracking capability and the ability to distinguish pions and kaons using the Ring Imaging Cherenkov (RICH) detectors.

1 CP violation in tree-level $B^{\pm} \to [hh']_D K^{\pm}$

Standard Model CP violation is parameterised entirely by complex phases in the Cabibbo Kobayashi Maskawa (CKM) matrix. The least well known of these is γ which can be measured with low theoretical uncertainty by studying interference between the amplitudes for $B^{\pm} \to D^0 K^{\pm}$ and $B^{\pm} \to \overline{D}^0 K^{\pm}$ decay processes where the intermediate neutral D meson decays to a common final state F, labelled by $[F]_D$. The complex phase between the two $B^{\pm}$ decay amplitudes is the sum or difference of the strong and weak phases, δ_B and γ respectively. Studies where the D meson decays to a non-CP eigenstate have been described in the proceedings for my poster at this conference entitled 'Observation of CP Violation in $B^{\pm} \to DK^{\pm}$ Decays at LHCb'. In this section I concentrate only on decays of the D meson to CP eigenstates ($D^0 \to K^+K^-, \pi^+\pi^-$ [1]) in a GLW analysis [2]. The observables with sensitivity to γ are $R_{CP+} = \frac{\Gamma(B^{\pm} \to [K^+K^-, \pi^+\pi^-]_D K^{\pm})}{\Gamma(B^{\pm} \to [K^{\pm}\pi^{\mp}]_D K^{\pm})}$ and $A_{CP+} = \frac{\Gamma(B^- \to D_{CP}K^-) - \Gamma(B^+ \to D_{CP}K^-)}{\Gamma(B^- \to D_{CP}K^-) + \Gamma(B^+ \to D_{CP}K^-)}$ where D_{CP} denotes a D meson reconstructed in a final state of known CP. These observables depend on γ e.g. $A_{CP\pm} = \frac{\pm 2 r_B \sin(\delta_B)\sin(\gamma)}{R_{CP\pm}}$.

Candidates were selected from the full 2011 1 fb^{-1} LHCb data set, as described in the poster proceedings referred to earlier. The invariant mass spectra of the $B^{\pm} \to (K^+K^-)_D K^{\pm}$ and $B^{\pm} \to (\pi^+\pi^-)_D K^{\pm}$ are shown in Figure 1 along with the more prevalent $B^{\pm} \to D\pi^{\pm}$ mode used in each case to control aspects of the signal fit. A charge asymmetry is clearly visible in the sizes of the $B^{\pm} \to DK^{\pm}$ signals which translates to the following results for the CP observables where the first uncertainty is statistical and the second is systematic: $R_{CP+} = 1.007 \pm 0.038 \pm 0.012$ and $A_{CP+} = 0.145 \pm 0.032 \pm 0.010$. In these results the dominant source of systematic uncertainty is the knowledge of the $B^{\pm}$ production asymmetries and the kaon and pion detection asymmetries.

Put together, the significance of the CP violation observed is 4.5σ and, combined with the results in the ADS final state, CP violation is observed at the level of 5.8σ. It is interesting to note that the $B^{\pm} \to [\pi^{\pm}K^{\mp}]_D\pi^{\pm}$ ADS mode showed a hint of CP violation at the level of 2.4σ ($R_{ADS(\pi)} = 0.00410 \pm 0.00025 \pm 0.00005$ and $A_{ADS(\pi)} = 0.143 \pm 0.062 \pm 0.011$) where little is expected, but the importance of this effect will be clearer in future analyses.

The ADS and GLW measurements are compatible and competitive with the current world averages [3] and have been combined with analyses of other D final states ($[K^0_S\pi^+\pi^-]_D$, $[K^0_S K^+K^-]_D$ [4] and $[K^{\pm}\pi^{\mp}\pi^+\pi^-]_D$ [5]) to make a measurement of the CKM phase γ using LHCb data [6].

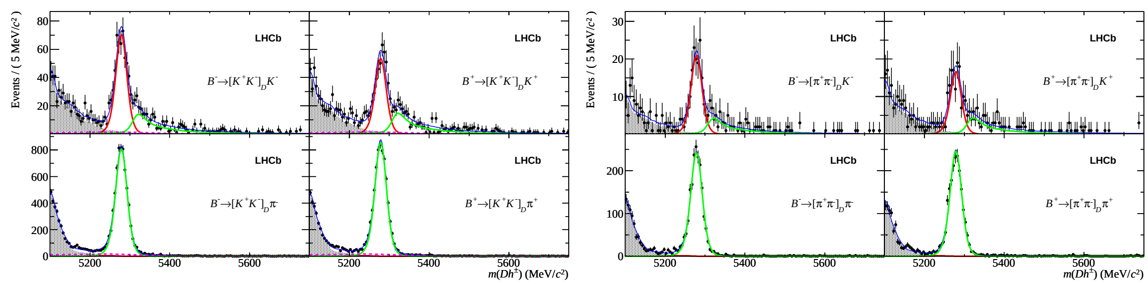

Figure 1: $B^{\pm}$ invariant mass spectrum from GLW modes with $B^{\pm} \to DK^{\pm}$ signal (solid red line) and $B^{\pm} \to D\pi^{\pm}$ control (solid green line) [2].

2 CP violation in loop-level $B^0_{(s)} \to hh'$

CP violation studies in two body $B^0_{(s)}$ decays are of great interest. CP violation has not yet been observed in the B^0_s system and studies of charmless B decays have potential sensitivity to new physics effects which could modify the observed level of CP violation [7]. Time dependent analyses of $B^0 \to \pi^+\pi^-$ have been undertaken at BaBar [8] and Belle [9] but not all the results are in good agreement, motivating further study. The studies outlined here also allow a test of U-spin symmetry breaking. Two CP violation analyses of LHCb data taken in 2011 are described: a time-integrated study of $B^0_{(s)} \to K\pi$ decays (0.35 fb^{-1}) [10] and a time-dependent analysis of $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays (0.69 fb^{-1}) [11].

In the first analysis, the measured observable is $A_{CP} = \frac{\Gamma(\overline{B}^0_{(s)} \to \overline{f}_{(s)}) - \Gamma(B^0_{(s)} \to f_{(s)})}{\Gamma(\overline{B}^0_{(s)} \to \overline{f}_{(s)}) + \Gamma(B^0_{(s)} \to f_{(s)})}$ where $f = K^+\pi^-$, $f_s = K^-\pi^+$. The invariant mass spectra of the selected $B^0_{(s)}$ candidates display a clear raw asymmetry. The CP asymmetries extracted are $A_{CP}(B^0) = -0.088 \pm 0.011(stat) \pm 0.008(syst)$ and $A_{CP}(B^0_s) = 0.27 \pm 0.08(stat) \pm 0.02(syst)$ where the dominant systematic uncertainty originates from the knowledge of the production and detection asymmetries. This is the most precise measurement of CP violation in $B^0 \to K\pi$ decays, with a significance of greater than 6σ, and is the first evidence of CP violation in $B^0_s \to K\pi$ decays, with a significance of 3.3σ.

The time-dependent asymmetries in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ are given by $A(t) = \frac{\Gamma(t)(\overline{B}^0_{(s)} \to h^+h^-) - \Gamma(t)(B^0_{(s)} \to h^+h^-)}{\Gamma(t)(\overline{B}^0_{(s)} \to h^+h^-) - \Gamma(t)(B^0_{(s)} \to h^+h^-)} = \frac{A^{dir}\cos(\Delta m t) + A^{mix}\sin(\Delta m t)}{\cosh(\frac{\Delta\Gamma}{2}t) - A^{\Delta\Gamma}\sinh(\frac{\Delta\Gamma}{2}t)}$ where A^{dir} and A^{mix} are the asymmetries originating from direct CP violation and from the interference between mixing and decay. In this analysis the abundant and kinematically similar mode $B^0 \to K\pi$ was used to determine the mis-tag rate and to account for the production asymmetry. A two dimensional fit to the invariant mass and $B^0_{(s)}$ decay time was then performed to determine the asymmetry (Figure 2 for $B^0_s \to K^+K^-$).

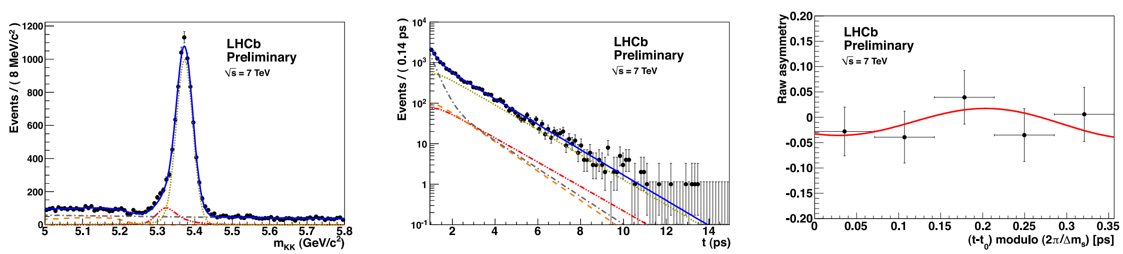

Figure 2: From left to right: $B^0_s \to K^+K^-$ invariant mass distribution, $B^0_s \to K^+K^-$ decay time distribution and measured raw asymmetry.

In the $\pi^+\pi^-$ mode the measurement of A^{dir} was $0.11 \pm 0.21(stat) \pm 0.03(syst)$ which lies closer to the central value measured by BaBar [8]. In $\pi^+\pi^-$, $A^{mix} = -0.56 \pm 0.17(stat) \pm 0.03(syst)$. In the K^+K^- mode, the results were $A^{dir} = 0.02 \pm 0.18(stat) \pm 0.04(syst)$ which, as predicted by U-spin symmetry once bounds are placed on certain exchange/annihilation diagrams [12], is compatible with the time integrated asymmetry in $B^0 \to K\pi$ presented earlier, and $A^{mix} = 0.17 \pm 0.18(stat) \pm 0.05(syst)$. These results form the the first CP violation investigation in $B^0_s \to K^+K^-$.

3 Conclusion and outlook

Analyses in tree-level $B^{\pm} \to [hh']_D K^{\pm}$ and in loop-level $B^0_{(s)} \to hh'$ decays have been described, demonstrating the capabilities of the LHCb experiment in undertaking CP violation studies in hadronic B decay modes. The former has been used in a tree-level LHCb measurement of the CKM phase γ with a low theoretical uncertainty. The charmless modes are also sensitive to the phase γ and future comparison between measurements in the two categories of decay (charmed and charmless) may yield sensitivity to new physics effects entering charmless loop processes. Analysis of the full 2011 and 2012 LHCb data sets is awaited with great interest.

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