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Time-integrated CP violation measurements in the B mesons system at the LHCb experiment

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Summary. — Time-integrated CP violation measurements in the B meson system provide information for testing the CKM picture of CP violation in the Standard Model. A review of recent results from the LHCb experiment is presented.

1. – Introduction

By measuring CP asymmetries in different processes, it is possible to set constraints on the CKM angles and look for deviations from the CP violation expected in the Standard Model (SM) uncovering possible contributions of new physics beyond the SM. An interesting place to look for CP violation is the B hadron system. And the Large Hadron Collider is currently the largest source of b-hadron ever built, thanks to the large $b\bar{b}$ production cross-section at the LHC energy. The produced 3×10^{11} $b\bar{b}$ pairs per nominal year (10^7) are studied by the LHCb experiment.

2. – Charmless three-body decays

Three-body charmless B decays are a good laboratory to search for different sources of CP violation, through the study of the signature of these sources in the Dalitz plot. Direct CP violation requires the existence of amplitudes with differences in both their weak and their strong phases. Interference between intermediate states of the decay can introduce large strong-phase differences, and therefore induce local asymmetries in the phase space. Another mechanism is final-state $KK \leftrightarrow \pi\pi$ rescattering, which can occur between decay channels having the same flavour quantum numbers. The LHCb collaboration has already measured non-zero inclusive CP asymmetries and larger local asymmetries in the decays $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to K^{\pm}K^{+}K^{-}$, $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ and $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ using a data sample corresponding to $1.0\,\text{fb}^{-1}$ [1, 2]. These results suggested that final-state interactions may be a contributing factor to CP violation. An update of these analyses [3], which includes an optimization of the selection procedure

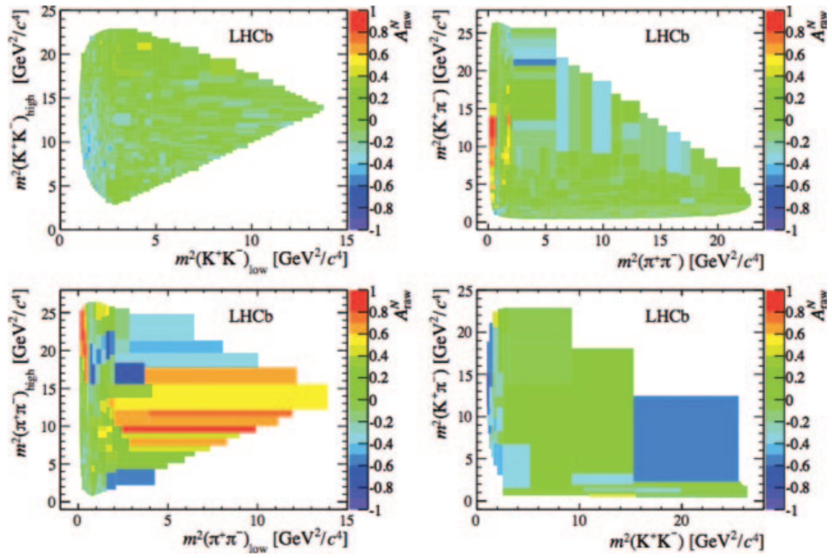

Fig. 1. – Measured raw asymmetry in bins of the Dalitz plot for background-subtracted and acceptance corrected events for $B^\pm \to K^\pm K^+K^-$ (top-left), $B^\pm \to K^\pm\pi^+\pi^-$ (top-right), $B^\pm \to \pi^\pm\pi^+\pi$ (bottom-left) and $B^\pm \to \pi^\pm K^+K$ (bottom-right).

using a multivariate algorithm, and of the $B^+ \to p\bar{p}h^\pm$ with $h = \pi, K$ [4] using $3.0\,\mathrm{fb}^{-1}$ of data is reported.

2˙1. $B^\pm \to h^\pm h^+h^-$. – The difference in the decay rates of charge conjugate decays is given by $A_{\mathrm{raw}} = \frac{N_{B^-}-N_{B^+}}{N_{B^-}+N_{B^+}}$. The raw asymmetry has to be corrected for detection efficiency of the unpaired hadron $h^\pm$ and B meson production asymmetries. The $B^\pm \to J/\psi K^\pm$ channel, which has similar topology and negligible CP violation, as a reference, thus allowing corrections to be made for production and instrumental asymmetries. Different sources of systematic uncertainties have been considered including potential mismodellings in the mass fits, the phase-space acceptance corrections and the trigger composition of the samples. The results for the integrated CP asymmetries are

$$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007,$$
$$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007,$$
$$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007,$$
$$A_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007,$$

where the first uncertainty is statistical, the second systematic, and the third is due to the limited knowledge of the CP asymmetry of the $B^\pm \to J/\psi K^\pm$ reference mode with significances of 2.8σ, 4.3σ, 4.2σ and 5.6σ, respectively. The CP asymmetries are not uniformly distributed in the phase space. Figure 1 shows the distribution of the raw asymmetry, after background subtraction and correction for acceptance effects. The binning is chosen adaptively, in order to have approximately the same number of entries in each bin. For each of the channels, we observe a significant CP asymmetry in the

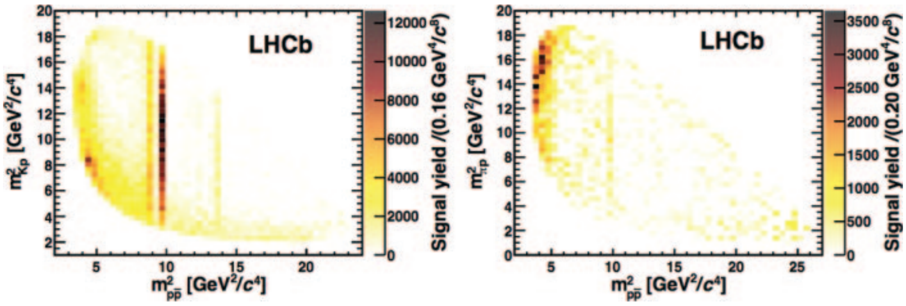

Fig. 2. – Background-subtracted and acceptance-corrected Dalitz-plot distributions for $B^{\pm} \to p\bar{p}K^{\pm}$ (left) and $B^{\pm} \to p\bar{p}\pi^{\pm}$ (right).

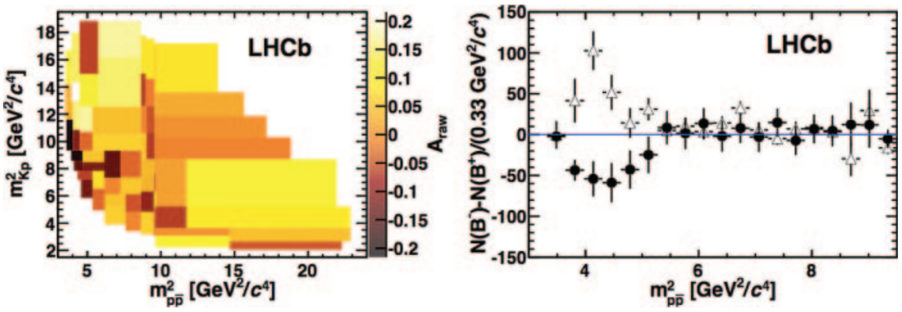

Fig. 3. – Raw asymmetry of signal events in bins of the Dalitz plane for $B^{+} \to p\bar{p}K^{+}$ decays (left). Difference between the number of B^{-} and B^{+} events as a function of $m^2_{p\bar{p}}$ for $m^2_{K^+p} < 10\,\mathrm{GeV}^2/c^4$ (black dots) and for $m^2_{K^+p} > 10\,\mathrm{GeV}^2/c^4$ (empty triangles).

$m(K^+K)$ or $m(\pi^+\pi^-)$ invariant mass region between 1.0 and $1.5\,\mathrm{GeV}/c^2$. These CP asymmetries are positive for the channels that include two pions in the final state and negative for those that include two kaons. A possible explanation of this asymmetry can be associated with the $\pi^+\pi^- \leftrightarrow K^+K^-$ rescattering strong-phase difference. Moreover in both $B^{\pm} \to K^{\pm}\pi^+\pi^-$ and $B^{\pm} \to \pi^{\pm}\pi^+\pi^-$ decays an asymmetry has been observed around the $\rho(770)$ mass region which can be attributed to the final-state interference between the S-wave and P-wave in the Dalitz plot. The dynamical origin of these CP-violating sources can be fully understood only performing a full amplitude analysis.

2·2. $B^{\pm} \to p\bar{p}h^{\pm}$. – The large asymmetries measured in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays motivates the studies on the closely related $B^{\pm} \to p\bar{p}h^{\pm}$ decays, where a smaller $p\bar{p} \leftrightarrow h^+h^-$ is expected. The analysis is based on $3\,\mathrm{fb}^{-1}$ of data and it is an update of the previous published analysis. The distribution of events in the Dalitz plane, defined by $(m^2_{p\bar{p}}, m^2_{hp})$, is shown in fig. 2, after the subtraction of the background and the correction for acceptance effects. The $\Lambda(1520) \to K^+p$ band is visible in the left plot. The measurement of the branching fraction is performed using the $B^+ \to J/\psi(\to p\bar{p})\,K^+$ decay as a reference mode

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

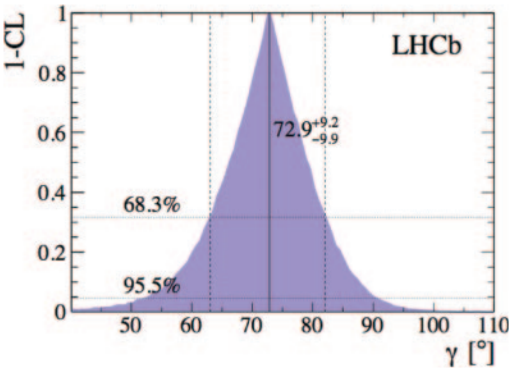

Fig. 4. – Confidence level (CL) curve for the γ combination. The 1σ and 2σ CL bounds are indicated.

The usual enhancement seen in many baryonic decays is visible at low $m^2_{p\bar{p}}$ values. 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 3 shows on the left the distribution of the raw asymmetry over the Dalitz plot. The sign of the asymmetry is positive for $m^2_{K^+\bar{p}} > 10\,\mathrm{GeV}^2/c^4$ and negative for $m^2_{K^+\bar{p}} < 10\,\mathrm{GeV}^2/c^4$ as shown in fig. 3. The CP asymmetry measurement, correcting for detection and production effects using the $B^+ \to J/\psi(\to p\bar{p})K^+$ decays as control channel, in the region $m_{p\bar{p}} < 2.85\,\mathrm{GeV}/c^2$ and $m^2_{K^+\bar{p}} > 10\,\mathrm{GeV}^2/c^4$ is the first evidence of CP violation in B decays with baryons in the final state

$$A_{CP}(B^+ \to p\bar{p}K^+) = +0.096\,\pm\,0.024(\mathrm{stat})\,\pm\,0.004(\mathrm{syst}),$$

with a 4σ significance.

3. – LHCb γ combination

The unitarity triangle angle $\gamma = \arg[-V_{ud}V^*_{ub}/V_{cd}V^*_{cb}]$ has the weakest experimental constrains and therefore its precise measurement is an important test of the CKM consistency. The LHCb experiment has studied a variety of B decay channels with sensitivity to the CKM angle γ through tree-level diagrams. In particular $B^\pm \to [hh]_D h^\pm$ (GLW/ADS) [6], $B^\pm \to [K\pi\pi\pi]_D h^\pm$ (ADS) [7], $B^\pm \to [K^0_s hh]_D K^\pm$ (GGSZ) [8], $B^\pm \to [K^0_s K\pi]_D K^\pm$ (GLS) [9], $B^0 \to [hh]_D K^{*0}$ (GLW/ADS) [10] and $B^0_s \to D^\pm_s K^\pm$ (time-dependent) [11] decays. A more precise measurement of γ can be achieved through the combination of these results [5]. The combination is performed for the $B \to DK$ decay modes using a frequentist approach. In addition to the effects of $D^0\,\bar{D}^0$ mixing, possible contributions from CP violation in the D0 system (at first order) are considered. The result of the combination is presented in fig. 4. The best-fit value of γ is found to be 72.9° and at the 68% confidence level (CL), γ is measured to be

$$\gamma = (73^{+9}_{-10})^\circ.$$

This measurement is of greater precision with an improvement of 30% with respect to the pre-LHCb measurements. A comparison of the γ measurement from loop processes

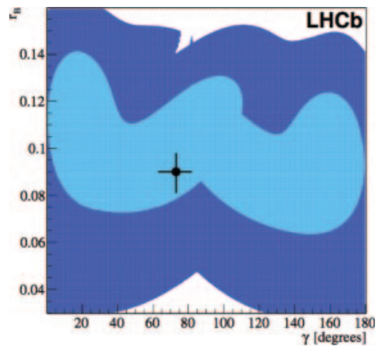

Fig. 5. – Likelihood scan of r_B *vs.* γ. The marker shows the results of the latest LHCb γ combination.

using $B \to hh$ decays $\gamma = (63.5^{+7.2}_{-6.7})$ [12] can be made but a better precision is necessary in order to reveal possible inconsistencies.

4. – $B^\pm \to [hh\pi^0]_D h^\pm$ decays

In order to improve the sensitivity on the γ angles, the study of new decay modes sensitive to γ is performed. The study of the $B^\pm \to [hh\pi^0]_D h^\pm$ decays includes the ADS $B^\pm \to [K\pi\pi^0]_D h^\pm$ decays and the quasi-GLW decays $B^\pm \to [\pi\pi\pi^0]_D h^\pm$ and $B^\pm \to [KK\pi^0]_D h^\pm$ decays [13]. In order to extract the CP observables, the $D \to K^+\pi^-\pi^0$ coherence factor and the average strong-phase difference measured at CLEO-c are taken as external inputs. The results for the ADS observables are the most precise measurements of these quantities. No evidence of CP violation is obtained with the current experimental precision. First observations have been made of the decays $B^\mp \to [\pi^\mp K^\pm \pi^0]_D \pi^\mp$ and $B^\mp \to [K^+K^-\pi^0]_D \pi^\mp$, and first evidence is obtained for the mode $B^\mp \to [\pi^\mp K^\pm \pi^0]_D K^\mp$. Likelihood scans of γ with the parameters of interest r_B and δ_B, as seen in fig. 5, place a bound of $r_B = 0.11 \pm 0.03$ at 1σ. These results will contribute to the overall precision of when combined with other measurements.

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