CP Violation in B Decays at LHCb

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A selection of recent results from studies of CP violation in the decays of B mesons are presented, which were performed using pp collision data at $\sqrt{s} = 7$ TeV and 8 TeV collected by the LHCb experiment during Run I, corresponding to an integrated luminosity of 3.0 fb^{-1}.

1 Model-independent measurement of γ with $B^\pm \to D(\to K^0_S\pi^+\pi^-, K^0_S K^+K^-)K^\pm$ decays

Indirect searches for New Physics (NP) can be performed at LHCb with precision measurements of the CKM Unitarity Triangle parameters. One of these, the angle $\gamma \equiv \arg[-(V_{ud}V^*_{ub})/(V_{cd}V^*_{cb})]$, can be measured in $B^\pm \to DK^\pm$ decays, where D is an admixture of D^0 and $\overline{D}^0$ mesons decaying to the same final state. The ratio of amplitudes $A(B^\pm \to \overline{D}^0 K^\pm)/A(B^\pm \to D^0 K^\pm)$ is $r_B e^{i(\delta_B \pm \gamma)}$, where r_B is the colour-suppression factor, δ_B is the strong-phase difference and γ is the weak-phase difference. LHCb has measured γ in $B^\pm \to DK^\pm$ decays with many D final states. These are summarised in [1] and have a combined measurement of $\gamma = (72.9^{+9.2}_{-9.9})^\circ$.

In the case $D \to K^0_S h^+h^-$, where $h = \pi$ or K, the strong-phase difference between the D^0 and $\overline{D}^0$ decay, δ_D, varies in the Dalitz plot. A model-independent method is used, in which averaged values of δ_D in bins of the Dalitz plot are provided externally. The relative signal yield in each Dalitz plot bin is given by the Cartesian parameters $x_\pm = r_B\cos(\delta_B \pm \gamma)$ and $y_\pm = r_B \sin(\delta_B \pm \gamma)$; the relative yield of flavour-tagged $D^0 \to K^0_S h^+h^-$ decays, which is measured using $\overset{(-)}{B}{}^0 \to (D^{*\pm} \to \overset{(-)}{D}{}^0\pi^\pm)\mu^\mp X$ decays (X are any other particles produced in the $\overset{(-)}{B}{}^0$ decay that are not reconstructed); and the amplitude-weighted values of $\cos\delta_D$ and $\sin\delta_D$ integrated over the bin, which are obtained with quantum-correlated $\psi(3770) \to D\overline{D}$ decays by the CLEO experiment [2]. A model-dependent measurement of γ with $D \to K^0_S\pi^+\pi^-$ decays, in which the values of δ_D are obtained with an amplitude model of the D^0 decay, has also been performed at LHCb using 1.0 fb^{-1} of data [3].

Approximately 2260 (320) $B^\pm \to DK^\pm$, $D \to K^0_S\pi^+\pi^-$ ($K^0_S K^+K^-$) decays are selected. The Cartesian parameters $x_\pm$ and $y_\pm$ are directly measured and found to be $x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \times 10^{-2}$, $x_- = (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \times 10^{-2}$, $y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \times 10^{-2}$ and $y_- = (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \times 10^{-2}$ [4], where the uncertainties are statistical, experimental systematic, and the systematic due to the CLEO measurements, respectively. These are the most accurate measurements of $x_\pm, y_\pm$ to date. Figure 1 shows the measured values of $x_\pm$ and $y_\pm$ with likelihood contours corresponding to statistical uncertainties only. The CP observables are extracted and found to be $\gamma = (62^{+15}_{-14})^\circ$, $\delta_B = (134^{+14}_{-15})^\circ$ and $r_B = (8.0^{+1.9}_{-2.1}) \times 10^{-2}$ [4].

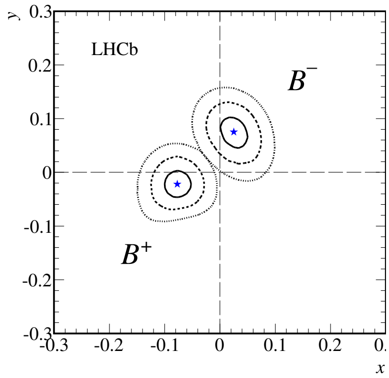

Figure 1: Central values (stars) of $x_\pm$ and $y_\pm$ and the 1-, 2- and 3-standard deviation regions for statistical uncertainties only [4].

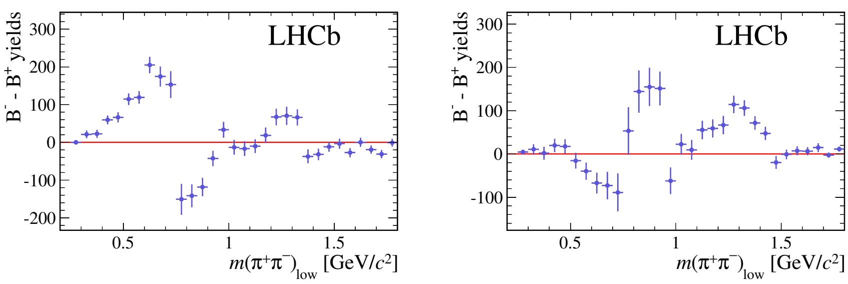

Figure 2: Difference between the number of $B^- \to \pi^-\pi^+\pi^-$ and $B^+ \to \pi^+\pi^+\pi^-$ events as a function of $m(\pi^+\pi^-$ low) in the region (left) $\cos\theta < 0$ and (right) $\cos\theta > 0$, where $\cos\theta$ is the helicity angle between like-sign pions in the $m(\pi^+\pi^-$ low) rest frame. [5]

2 Inclusive and local CP asymmetries in $B \to$ three-body charmless decays

Direct CP violation can occur through the presence of both weak- and strong-phase differences between tree- and loop-level diagrams of a given decay. In decays of charged B mesons to three charged charmless mesons, the CKM matrix elements involved give rise to the weak-phase difference while the strong-phase difference could be due to several sources, the relative strength of which may vary over the phase space. These sources can be classified into two categories, interference and rescattering, which can be studied by measuring local CP asymmetries.

Four channels are studied: $B^\pm \to \pi^\pm\pi^+\pi^-$, $K^\pm\pi^+\pi^-$, $\pi^\pm K^+K^-$ and $K^\pm K^+K^-$. The level of direct CP violation is quantified by A_{CP}, the asymmetry between the observed number of B^- and B^+ mesons, corrected for detection, production and kaon matter-interaction asymmetries. The inclusive A_{CP} measurements are $\mathcal{O}(1\%)$ and incompatible with zero, and are positive for $B^\pm \to \{\pi^\pm, K^\pm\}\pi^+\pi^-$ but negative for $B^\pm \to \{\pi^\pm, K^\pm\}K^+K^-$. Large asymmetries are observed in localised regions of the Dalitz plot: $A_{CP} = \mathcal{O}(10\text{–}30\%)$ in the region

$1.0 < m(\pi^+\pi^-), m(K^+K^-) < 1.5$ GeV/c^2. The oppositely-signed asymmetries for the different modes is a characteristic signature of *CPT* conservation in $\pi\pi \leftrightarrow KK$ rescattering. The dominance of long- over short-distance interference effects can be studied by measuring A_{CP} for $B^\pm \to \pi^\pm\pi^+\pi^-$ as a function of $m(\pi^+\pi^-$ low) for positive and negative $\cos\theta$, where $\cos\theta$ is the angle between the like-sign pions in the $m(\pi^+\pi^-$ low) rest frame. As can be seen in Figure 2, A_{CP} changes sign near the $\rho(770)$ resonance, and in different directions for the two $\cos\theta$ ranges. In this region of phase space, A_{CP} can be as large as 50–60% [5].

These findings reveal that direct *CP* violation is dominated by different physical processes inducing strong-phase differences across the phase space. The study of amplitude analyses is essential to understanding the contributions of these processes.

3 ϕ_s and T-odd triple product asymmetries in $B_s^0 \to \phi\phi$ decays

The $B_s^0 \to \phi\phi$ decay proceeds via loop diagrams only, allowing searches for new heavy particles participating in the quantum loops. This can be probed using the *CP*-violating phase ϕ_s, the phase difference between decays with and without mixing, which is small ($< 10^{-2}$) in the Standard Model (SM) and can be significantly enhanced in NP models [6].

The phase ϕ_s is measured by tagging the initial flavour of the B_s^0 meson at production, using flavour-tagging algorithms that have a combined tagging efficiency of 26% with a 33% mistag rate. The $\phi\phi$ final state is a linear combination of *CP*-even and *CP*-odd final states with different decay-time and angular distributions, hence an angular analysis in the helicity angle basis is performed to distinguish the various states, as seen in Figure 3. The data are corrected for their angular acceptance using simulated data and for their decay-time acceptance using $B_s \to D_s\pi$ decays. The B_s^0 mixing parameters are constrained to LHCb measurements. It is found that $\phi_s = -0.17 \pm 0.15\,(\text{stat.}) \pm 0.03\,(\text{syst.})$, which is in agreement with SM theory predictions. The level of direct *CP* violation $|\lambda|$, defined as the absolute ratio between the decay amplitudes of $B_s^0 \to \phi\phi$ and $\overline{B}_s^0 \to \phi\phi$, is found to be $|\lambda| = 1.04 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.})$. This is consistent with the hypothesis of no direct *CP* violation.

The $B_s^0 \to \phi\phi$ decay offers a second complementary probe of *CP* violation that is independent of decay time or initial B_s^0 flavour, and instead relies on a simple counting experiment. Two T-odd triple-product quantities can be constructed from the kinematics of the decay, $U \equiv \sin\Phi\cos\Phi$ and $V \equiv \pm\sin\Phi$, where Φ is the angle between the two $\phi \to K^+K^-$ decay planes. The sign of V depends on the value of $\cos\theta_1\cos\theta_2$, where $\theta_{1,2}$ is the angle between the K^+ track momentum in the $\phi_{1,2}$ meson rest frame and the $\phi_{1,2}$ momentum in the B_s^0 rest frame. The asymmetries in the signs of U and V, A_U and A_V, are *CP*-violating quantities with SM expectations close to zero. A non-zero asymmetry would indicate either the presence of *CP* violation or final state interactions. The results are consistent with the hypothesis of *CP* conservation, $A_U = -0.003 \pm 0.017 \pm 0.006$ and $A_V = -0.017 \pm 0.017 \pm 0.006$ [6], where the first uncertainty is statistical and the second uncertainty is systematic.

4 Conclusions

There is a broad and exciting programme of studies of *CP* violation in *B* decays at LHCb. Using data collected from Run I, many of these results have been comparable to those obtained

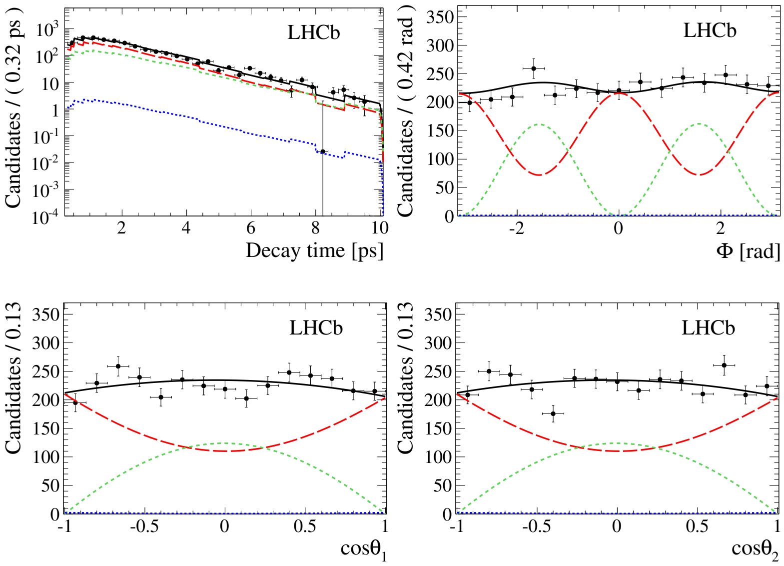

Figure 3: Decay time and helicity angle distributions of $B_s^0 \to \phi\phi$, where Φ is the angle between the two $\phi \to K^+K^-$ decay planes and $\theta_{1,2}$ is the angle between the K^+ track momentum in the $\phi_{1,2}$ meson rest frame and the $\phi_{1,2}$ momentum in the B_s^0 rest frame. The (black points) background-subtracted data are shown with the (solid black) result of the fit, and the (long-dashed red) CP-even P-wave, (short-dashed green) CP-odd P-wave and (dotted blue) S-wave contributions [6].

by the B-factories. Many of these results are statistically-limited and will be improved with the data collected during Run II in 2015–2018, which is expected to collect data corresponding to an integrated luminosity of 5 fb^{-1}.

Acknowledgments

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