

CP Violation in *b*- and *c*-hadron decays at LHCb

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Abstract. Testing the Standard Model of particle physics by precision measurements of *CP* violating observables in the decays of *b* and *c* hadrons has been one of the design goals of the LHCb experiment. World-leading measurements have been performed of the semileptonic asymmetry, a_s^{sl} , and of the mixing-induced *CP*-violating phase ϕ_s in the $B_s^0\bar{B}_s^0$ system. The CKM angle γ is still the least known angle of the Unitarity Triangle, and the only one easily accessible using tree-level decays. A recent combination of LHCb measurements in various $B \rightarrow DK$ decay modes has yielded the most precise determination of γ from a single experiment to date. The LHCb experiment is collecting unprecedented samples of beauty baryons, allowing for the first time to study *CP* violating observables in their decays. A recent analysis provided the first evidence for *CP* violation in the beauty baryon sector. Finally, LHCb has the largest samples of charmed hadron decays collected by any experiment to date. These samples yield some of the world's most sensitive searches for direct and indirect *CP* violation in the charm sector.

1. Introduction

The main goal of the LHCb experiment [1] at CERN's Large Hadron Collider (LHC) is to perform precision measurements in *CP* violating observables and rare decays of hadrons containing beauty or charm quarks. This contribution to the proceedings is focused on LHCb measurements of *CP* violating observables. The comparison of these measurements with predictions from the Standard Model (SM) of particle physics tests the SM and can reveal the presence of contributions from physics Beyond the Standard Model (BSM).

The single source of *CP* violation in the SM is a complex phase in the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix [2, 3]. The CKM matrix parametrises transitions between the three quark families in charged current interactions. It is fully described by four independent real parameters, namely three rotation angles and one complex phase. A non-zero value of this complex phase can induce *CP* violating asymmetries in processes in which two or more amplitudes with different weak phases interfere. Usually, one of the interfering amplitudes involves loop diagrams with internal quark lines, such as box diagrams or penguin diagrams.

Most BSM physics models predict the existence of hitherto unobserved heavy particles. Such particles can appear in the internal lines of the loop diagrams and modify observed *CP* asymmetries with respect to SM predictions. Precision measurements of such asymmetries therefore test the SM and can reveal the presence of BSM physics. The pattern of observed deviations from SM predictions can hint at the underlying dynamics of the BSM physics at play. Since the deviations that these measurements search for are caused by the appearance of virtual particles in internal lines of loop diagrams, the sensitivity of these searches extends to



mass scales that exceed the centre of mass energy of the accelerator at which the measurement is performed.

The B^+B^- , $B^0\bar{B}^0$ and $B_s^0\bar{B}_s^0$ meson systems give rise to a wide range of CP violating observables for which precise SM predictions can be made. CP violating observables can also be measured in the decays of b baryons and in the charm sector, although predictions are less precise here.

The CKM mechanism gives rise to three possible sources of CP violating asymmetries:

CP violation in mixing in the $B^0\bar{B}^0$ and $B_s^0\bar{B}_s^0$ systems is caused by the interference of box diagrams with different internal quark lines. The mixing phase in the $B_s^0\bar{B}_s^0$ system is predicted with good precision to be close to zero in the Standard Model and is therefore particularly sensitive to possible contributions from New Physics.

CP violation in decay is caused by the interference of decay diagrams with different weak and strong phases leading to the same final state. This is the only possible source of CP violation for in the $B^+ - B^-$ system. In general, poorly known strong phases limit the precision with which the weak phase can be extracted from the measured asymmetry. There are, however, cases in which the weak phase can be cleanly extracted using a combination of several related decay modes and exploiting symmetries of the strong interaction between these modes.

CP violation in the interference of mixing and decay to a final state that is accessible to both the B^0 or B_s^0 meson and its respective antiparticle is caused by the interference of the direct decay amplitude of a B^0 or B_s^0 meson to the given final state and the process where the B^0 or B_s^0 meson first mixes to a \bar{B}^0 or \bar{B}_s^0 , which then decays to the same final state. A prominent example is the “golden” decay mode $B^0 \rightarrow J/\psi K_S^0$, which allowed the precise measurement of the mixing phase $\sin 2\beta$ in the $B^0\bar{B}^0$ system by the B factories BaBar [4] and Belle [5].

All three sources of CP violation will play a role in the measurements that are discussed in the remainder of this contribution, which is organized as follows. Section 2 is dedicated to a recent LHCb measurement of the CP violating phase in $B_s^0 - \bar{B}_s^0$ mixing using semileptonic B_s^0 decays, Sec. 3 to the measurement of the CP violating phase ϕ_s in the decay channel $B_s^0 \rightarrow J/\psi K^+ K^-$, and Sec. 4 to measurements of the CKM phase γ from $B^\pm \rightarrow DK^\pm$ tree decays; Sec. 5 and Sec. 6 briefly touch on recent measurements of CP violating asymmetries in the decays of Λ_b^0 baryons and of charmed mesons, respectively. Unless mentioned otherwise, all measurements discussed here have been performed using the full LHCb Run-I data set, corresponding to an integrated luminosity of 3.0 fb^{-1} of pp collisions collected at pp centre of mass energies of 7 TeV in 2011 and 8 TeV in 2012.

2. CP violation in $B_s^0 - \bar{B}_s^0$ mixing from $B_s^0 \rightarrow D_s^- \mu^+ X$ decays

Second-order weak transitions (box diagrams) induce particle-antiparticle mixing in the $K^0\bar{K}^0$, $D^0\bar{D}^0$, $B^0\bar{B}^0$ and $B_s^0\bar{B}_s^0$ systems. The time evolution of the coupled $B_s^0\bar{B}_s^0$ system can be described by an effective Schrödinger equation of the form

$$-i \frac{\partial}{\partial t} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = H \cdot \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix} \cdot \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

(and similar for the other neutral meson–antimeson systems). The eigenstates of the effective Hamiltonian, H , are the heavy and light mass eigenstates, B_H and B_L , which have well defined masses, m_H and m_L , and lifetimes, Γ_H and Γ_L . Relevant observables are the mass difference $\Delta m_s \equiv m_H - m_L$ and the lifetime difference $\Delta\Gamma_s \equiv \Gamma_H - \Gamma_L$. Particle–antiparticle mixing is described by the off-diagonal elements of H , where M_{12} describes the dispersive part of

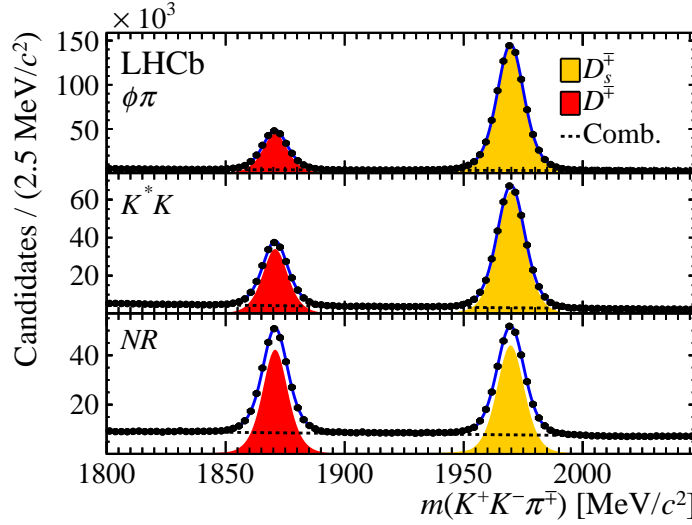


Figure 1. Combined invariant mass spectra of $K^+K^-\pi^-$ and $K^+K^-\pi^+$ candidates for each of the three kinematical regions used in the measurement of a_{sl}^s . Top: $\phi\pi^-$ with $\phi \rightarrow K^+K^-$, middle: $K^{0*}K^-$ with $K^{0*} \rightarrow K^+\pi^-$, bottom: non-resonant (NR) $K^+K^-\pi^-$. In all three samples a clear D_s^- signal is visible as well as a D_s^+ signal at lower invariant mass.

the transition amplitude, i.e. transitions via off-shell intermediate states, and Γ_{12} describes its absorptive part, i.e. transitions via on-shell intermediate states. A relative phase ϕ_M between M_{12} and Γ_{12} causes CP violation in the mixing process, causing the probability for the transition $B_s^0 \rightarrow \bar{B}_s^0$ to be different from that for the transition $\bar{B}_s^0 \rightarrow B_s^0$.

This CP asymmetry can be measured in the time-integrated semileptonic asymmetry

$$a_{\text{sl}}^s \equiv \frac{\Gamma(\bar{B}_s^0 \rightarrow \ell^+ X) - \Gamma(B_s^0 \rightarrow \ell^- X)}{\Gamma(\bar{B}_s^0 \rightarrow \ell^+ X) + \Gamma(B_s^0 \rightarrow \ell^- X)} = \frac{\Delta\Gamma_s}{\Delta m_s} \tan \phi_M,$$

where ℓ^\pm stands for a positively or negatively charged lepton. In the SM, the phase ϕ_M in the $B_s^0\bar{B}_s^0$ system is small and the semileptonic asymmetry is predicted to be $a_{\text{sl}}^s = (1.9 \pm 0.3) \times 10^{-5}$ [6]. This makes measurements of a_{sl}^s sensitive to possible contributions from BSM physics in $B_s^0 - \bar{B}_s^0$ mixing.

LHCb has published [7] a measurement of a_{sl}^s using the decay mode $B_s^0 \rightarrow D_s^- \mu^+ X$ with $D_s^- \rightarrow K^+ K^- \pi^-$. The measured raw asymmetry was defined as

$$A_{\text{raw}} \equiv \frac{N(D_s^- \mu^+ X) - N(D_s^+ \mu^- X)}{N(D_s^- \mu^+ X) + N(D_s^+ \mu^- X)},$$

where the numbers of candidates were extracted from a fit to the $K^+K^-\pi^-$ and $K^+K^-\pi^+$ invariant mass spectra, as illustrated in Fig. 1. A total of about 1.6 million $D_s^\pm \mu^\pm$ candidates was reconstructed in the 3 fb $^{-1}$ sample from run I. No attempt was made to determine the initial flavour of the B_s^0 or \bar{B}_s^0 meson at the time of its production. This reduces the measured asymmetry by a factor of two but avoids the significantly larger loss in statistical precision due to flavour-tagging algorithms. The $B_s^0 - \bar{B}_s^0$ production asymmetry in pp collisions is expected to be of the order of a few percent, but is diluted to a negligible level by the rapid $B_s^0 - \bar{B}_s^0$ oscillations. Taking into account trigger and detection asymmetries, A_D , as well as the fraction of backgrounds peaking at the D_s^\pm mass in the $K^+K^-\pi^\pm$ mass spectra, f_{bkg} , and

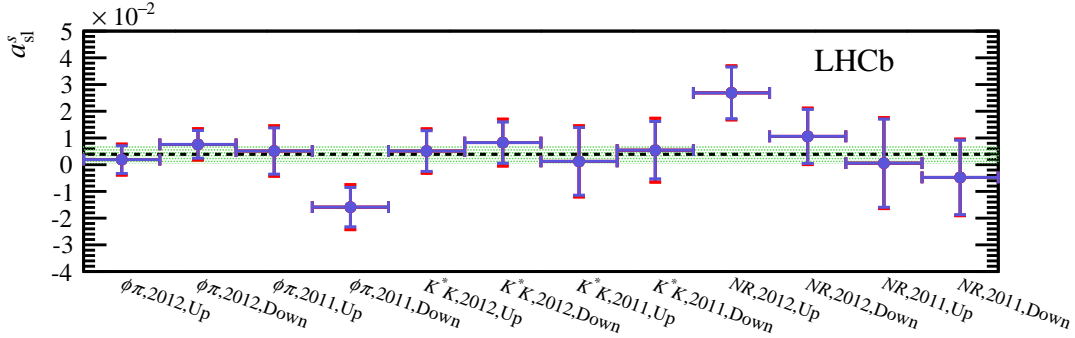


Figure 2. Results for a_{sl}^s from each of the twelve disjoint data samples used in the analysis. The inner (blue) vertical error bars indicate statistical uncertainties, while the outer (red) error bars indicate the combined statistical and systematic uncertainties. The dashed (black) horizontal line indicates the combined result and the shaded (green) horizontal band its uncertainty.

possible charge asymmetries in these backgrounds, A_{bkg} ,

$$\frac{a_{\text{sl}}^s}{2} = \frac{1}{1 - f_{\text{bkg}}} (A_{\text{raw}} - A_{\text{D}} - f_{\text{bkg}} A_{\text{bkg}}) .$$

Detection asymmetries cancel to first order between the two oppositely charged final-state kaons on the one hand and between the oppositely charged pion and muon on the other hand. Small remaining asymmetries due to different kinematical properties of the four final-state particles, particle-identification criteria and trigger requirements on the muon were estimated and corrected for using data-driven techniques in a variety of control channels. The fractions of peaking backgrounds and charge asymmetries were derived from known branching fractions and production asymmetries. The analysis was performed separately for three disjoint kinematic regions of the D_s^- decay products, namely $\phi\pi^-$ with $\phi \rightarrow K^+K^-$, $K^{0*}K^-$ with $K^{0*} \rightarrow K^+\pi^-$ and non-resonant $K^+K^-\pi^-$. The polarity of the LHCb spectrometer magnet was reversed in regular intervals throughout the data taking periods and the analysis was performed separately for the data collected with the magnetic field pointing up and down. Finally, the analysis was performed separately for the data collected in 2011 and 2012. The results obtained for the in total twelve disjoint data samples are in good agreement with each other, as is illustrated in Fig. 2. The twelve individual measurements were combined to yield the final result,

$$a_{\text{sl}}^s = (0.39 \pm 0.26(\text{stat}) \pm 0.20(\text{syst})) \times 10^{-2} ,$$

which is the most precise measurement of the CP violating asymmetry in $B_s^0 - \bar{B}_s^0$ mixing to date and is in good agreement with the SM prediction. The result is still limited by statistical uncertainties and a more precise measurement can be expected from extending the analysis to include run-II data.

3. The CP -violating phase ϕ_s in $B_s^0 \rightarrow J/\psi K^+ K^-$

The final state $J/\psi K^+ K^-$ is accessible to decays of both B_s^0 and \bar{B}_s^0 . The interference between the decay amplitudes and the $B_s^0 - \bar{B}_s^0$ mixing amplitude can give rise to a CP violating phase

$$\phi_s = \phi_M - 2\phi_D ,$$

where ϕ_M is the $B_s^0 - \bar{B}_s^0$ mixing phase discussed in the previous section and ϕ_D is the weak phase between the B_s^0 and \bar{B}_s^0 decay amplitudes. In the SM, both ϕ_M and ϕ_D are very small,

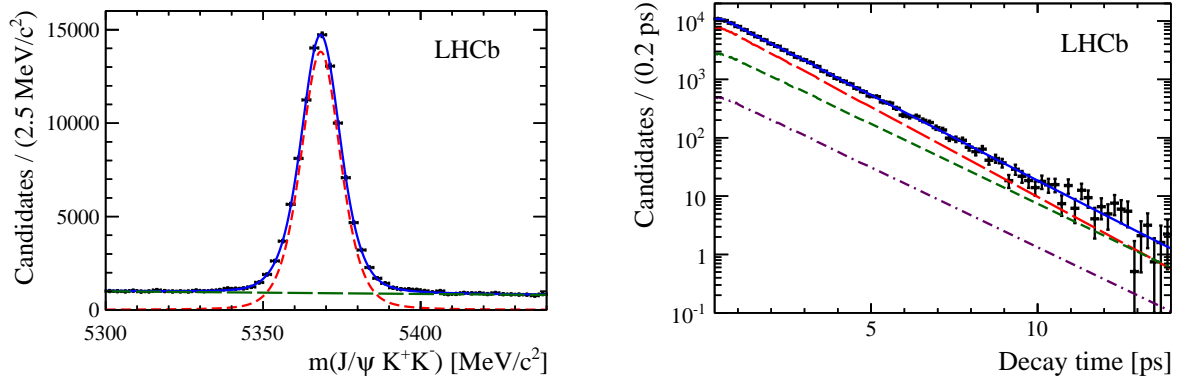


Figure 3. Left: $J/\psi K^+ K^-$ invariant mass distribution of the event sample employed for the ϕ_s measurement. Overlaid is the result of the invariant-mass fit. Right: decay time distribution with the projection of the time-dependent angular fit overlaid. The long-dashed (red) line indicates the CP even contribution, while the short-dashed (green) and dash-dotted (purple) lines indicate CP odd contributions.

resulting in a prediction of $\phi_s = -0.038 \pm 0.001$ rad [8]. This makes measurements of ϕ_s sensitive to possible contributions from BSM physics in $B_s^0 - \bar{B}_s^0$ mixing.

Measurements of ϕ_s proceed through the time-dependent CP asymmetry

$$A_{CP}(t) \equiv \frac{\frac{\partial \Gamma}{\partial t}(\bar{B}_s^0 \rightarrow J/\psi K^+ K^-) - \frac{\partial \Gamma}{\partial t}(B_s^0 \rightarrow J/\psi K^+ K^-)}{\frac{\partial \Gamma}{\partial t}(\bar{B}_s^0 \rightarrow J/\psi K^+ K^-) + \frac{\partial \Gamma}{\partial t}(B_s^0 \rightarrow J/\psi K^+ K^-)} = \frac{-\eta_f \sin \phi_s \sin(\Delta m_s t)}{\cosh(\Delta \Gamma_s \frac{t}{2}) - \eta_f \cos \phi_s \sinh(\Delta \Gamma_s \frac{t}{2})},$$

where B_s^0 and \bar{B}_s^0 depict the initial flavour of the decaying meson at the time of its production, η_f is the CP eigenvalue of the final state, and Δm_s and $\Delta \Gamma_s$ are the mass and lifetime differences between the heavy and light mass eigenstates in the $B_s^0 \bar{B}_s^0$ system.

Reconstructing the J/ψ in its decay to two muons provides for a clear trigger signature and clean event samples. Several factors, however, make this a challenging measurement:

- The initial flavour of the beauty meson at the time of its production has to be derived using information from the remainder of the event. This flavour tagging is not perfect and the associated mis-tag fraction dilutes the oscillation amplitude. The dilution factor has to be known precisely in order to extract $\sin \phi_s$ from the measured oscillation amplitude.
- An excellent decay time resolution is required to resolve the rapid $B_s^0 - \bar{B}_s^0$ oscillation. The decay-time resolution causes a dilution of the oscillation amplitude and has to be known precisely.
- The final state in the decay $B_s^0 \rightarrow J/\psi K^+ K^-$ is not a CP eigenstate. A time-dependent angular analysis of the four final state particles is required to statistically separate the CP odd and CP even contributions.
- The value of the decay-width difference $\Delta \Gamma_s$ has to be determined simultaneously with that of ϕ_s .

The latest LHCb measurement of ϕ_s in $B_s^0 \rightarrow J/\psi K^+ K^-$ [9] is based on 96'000 signal candidates reconstructed from the 3 fb⁻¹ collected in run I. The $J/\psi K^+ K^-$ invariant mass spectrum and decay-time distribution are shown in Fig. 3.

A combination of flavour tagging algorithms using opposite-side lepton, kaon and vertex charge and same-side kaon charge was employed to derive the initial flavour of the beauty meson. Opposite-side tagging algorithms exploit the fact that b and \bar{b} quarks are predominantly produced

in quark-antiquark pairs. The algorithms search for flavour-specific signatures from the decay of the second beauty hadron in the event, which must have been produced with flavour opposite to that of the signal B_s^0 or \bar{B}_s^0 candidate. The same-side kaon charge algorithm exploits the fact that the strange-type valence quark in the signal B_s^0 or \bar{B}_s^0 meson must have been produced via a $s\bar{s}$ pair during the hadronisation process. The other strange-type quark can give rise to a charged kaon, which should be close in phase space to the signal meson. The charge of that kaon can then be employed to tag the initial flavour of the signal B_s^0 or \bar{B}_s^0 candidate. Mis-tag fractions, i.e. the fractions of events in which the tagging algorithms give a wrong decision, were determined from data, employing control samples of flavour-specific decays $B^+ \rightarrow J/\psi K^+$ for the opposite-side algorithms and $B_s^0 \rightarrow D_s^- \pi^+$ for the same-side kaon algorithm. The decay-time resolution was modeled from data, using random combinations of prompt J/ψ candidates with two oppositely charged kaons from the same primary vertex. The angular acceptance, which needs to be known to correctly estimate the CP even and CP odd contributions in the final state, was extracted from samples of simulated events, which were reweighted to reproduce kinematic distributions observed in collision data.

The projection of the time-dependent angular fit onto the decay time distribution is shown in the right panel in Fig. 3. The different lifetimes of the CP even and CP odd components are clearly visible, indicating a non-zero value of $\Delta\Gamma_s$.

The combination of this measurement with an earlier, less precise, LHCb measurement of ϕ_s using the decay mode $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ [10], yielded $\phi_s = -0.010 \pm 0.039$ rad. This is the most precise determination of ϕ_s from a single experiment to date and it is in excellent agreement with the SM prediction. The uncertainty of the measurement is still large compared to the quoted precision of the SM prediction. The precision of the measurement is limited by statistical uncertainties and is therefore expected to improve significantly as the size of the analysed data sample increases.

4. The CKM angle γ from $B^\pm \rightarrow DK^\pm$ decays

The unitarity of the CKM matrix gives rise to six orthogonality relations, which can be represented as triangles in the complex plane. The triangle derived from multiplying the first and third columns of the CKM matrix is of particular interest since its three sides are of comparable length. Its three angles are closely related to CP violating observables and the lengths of its sides can be measured from CP conserving observables. The overconstrained determination of the sides and angles of this Unitarity Triangle provides a powerful consistency test of the SM picture of CP violation.

The least well determined parameter of the Unitarity Triangle to date is the angle $\gamma \equiv \arg(-(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*))$. The CKMfitter group [11] quotes $\gamma = (73.2_{-7.0}^{+6.3})^\circ$ from a global fit of CKM parameters, while the UTfit group [12] quotes $\gamma = (68.3 \pm 7.5)^\circ$.

A theoretically clean determination of γ can be derived from measurements of time integrated decay rates for different $B^\pm \rightarrow DK^\pm$ tree decays. If the decay is observed in a final state $[f]_D$ that is accessible to both D^0 and \bar{D}^0 decays, the interference of the decay amplitudes

$$B^\mp \rightarrow D^0 K^\mp \rightarrow [f]_D K^\mp \quad \text{and} \quad B^\mp \rightarrow \bar{D}^0 K^\mp \rightarrow [f]_D K^\mp$$

leads to a CP asymmetry that is sensitive to γ . Since the decays involve no loop diagrams, the extracted value for γ should be unaffected by possible contributions from BSM Physics. However, the measurements are experimentally challenging since they involve purely hadronic final states, which are difficult to trigger, and require excellent K/π separation. Moreover, branching fractions for the interesting decays are small.

Several methods, using different combinations of final states $[f]_D$, have been proposed. The GLW (Gronau-London-Wyler) method [13, 14] uses CP eigenstates such as $[K^+ K^-]_D$. The disadvantage of this method is that the decay amplitude for $B^- \rightarrow \bar{D}^0 K^-$ is suppressed with

respect to $B^- \rightarrow D^0 K^-$ by a factor of $r_B \approx 0.1$, limiting possible interference effects and the sensitivity to γ . The ADS (Atwood-Dunietz-Soni) method [15, 16] uses quasi flavour-specific final states such as $[\pi^- K^+]_D$, where the decay $\bar{D}^0 \rightarrow \pi^- K^+$ is Cabibbo favoured while the decay $D^0 \rightarrow \pi^- K^+$ is doubly Cabibbo suppressed. The ratio of magnitudes of the D^0 and \bar{D}^0 decay amplitudes, $r_D \approx 0.05$, compensates for the small value of r_B and leads to similar overall magnitudes for the two $B^- \rightarrow [f]_D K^-$ decay paths. Large interference effects are therefore possible, giving better sensitivity to γ . Disadvantages of the ADS approach are the very small total branching fraction for the doubly Cabibbo suppressed final states and the introduction of two additional parameters that have to be determined experimentally, namely r_D and the strong phase δ_D between the D^0 and \bar{D}^0 decay amplitudes. The GGSZ or Dalitz-plot method [17, 18] exploits interference patterns across the phase space for self-conjugate three-body decays $D^0 \rightarrow K_S^0 \pi^+ \pi^-$. A rich resonance structure is observed in these decays, giving rise to potentially large interference effects and good sensitivity to γ . However, variations of the strong phase δ_D across the phase space can be large and have to be taken into account in the extraction of γ . The associated systematic uncertainties ultimately limit the achievable precision of the measurement.

All three methods are pursued in LHCb. Measurements of GLW and ADS observables in $B^\mp \rightarrow DK^\mp$ decays, based on the 3 fb^{-1} collected in Run I, have been published in Ref. [19]. Invariant mass distributions for the GLW modes and for the suppressed ADS modes are shown in Figs. 4 and 5, respectively. In both cases, the effect of the CP asymmetry is visible as different event yields for the respective B^- and B^+ decay modes. As expected, the suppressed ADS modes give smaller event yields but the observed asymmetry is significantly larger than in the GLW modes. The deviation from a vanishing asymmetry in the suppressed ADS modes corresponds to eight Gaussian standard deviations, making this the first observation of CP violation in a single $B \rightarrow DK$ decay mode. The lower panels in the two figures show invariant mass spectra for $B^\mp \rightarrow D\pi^\mp$ decays. In these decays, CP asymmetries are expected to be significantly smaller than in $B \rightarrow DK$, due to a smaller value of r_B . In addition to the classic GLW and ADS decay modes discussed above, Ref. [19] also includes measurements using four-body D -meson decays to $\pi^\mp K^\pm \pi^+ \pi^-$ and $\pi^+ \pi^- \pi^+ \pi^-$. A recent analysis employing GLW and ADS approaches to $B^\pm \rightarrow DK^{*\pm}$ decay modes [20] is one of the first LHCb measurements to include data from Run II, adding another 1 fb^{-1} to the 3 fb^{-1} from Run I. Dalitz-plot analyses have been performed using $B^\mp \rightarrow DK^\mp$ decays with D mesons decaying to $K_S^0 \pi^+ \pi^-$ and $K_S^0 K^+ K^-$ [22] and, more recently, using $B^0 \rightarrow DK^{*0}$ decays with D mesons decaying to $K_S^0 \pi^+ \pi^-$ [23] and to $K_S^0 \pi^+ \pi^-$ or $K_S^0 K^+ K^-$ [24].

A different approach to measuring γ is via the time-dependent CP asymmetry in the decay $B_s^0 \rightarrow D_s^+ K^-$. The final state is accessible for B_s^0 and \bar{B}_s^0 decays and CP violation can be caused by interference of mixing and decay. The two decay amplitudes are of similar magnitude and the mixing is strong, such that large asymmetries can be expected. The CP -violating weak phase is given by $\gamma - 2\beta_s$, where $-2\beta_s$ is the $B_s^0 - \bar{B}_s^0$ mixing phase. Independent measurements of this mixing phase can be employed to extract γ . LHCb has presented a preliminary measurement [21] of γ using 6'000 $B_s^0 \rightarrow D_s^\pm K^\mp$ candidates extracted from the 3 fb^{-1} collected in Run I.

A combined fit to the results of several recent LHCb analyses using $B \rightarrow DK$ -like decay modes, including several of those mentioned above, has yielded [25]

$$\gamma = (72.2_{-7.3}^{+6.6})^\circ,$$

which is the most precise determination of γ from a single experiment to date. The result is in good agreement with SM expectations.

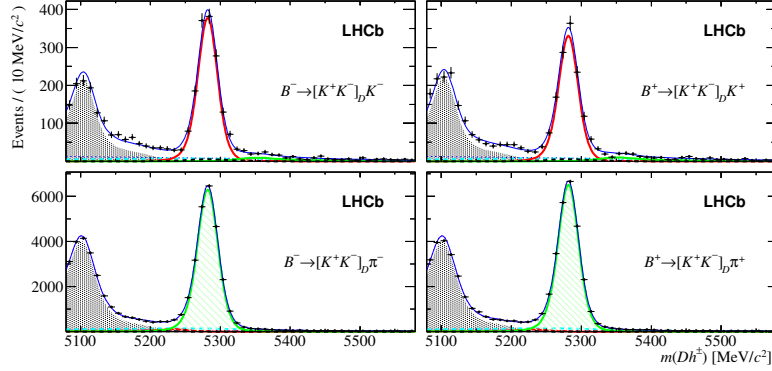


Figure 4. Invariant mass distributions for GLW modes, upper left: $B^- \rightarrow [K^+K^-]_D K^-$ and upper right: $B^+ \rightarrow [K^+K^-]_D K^+$. The lower panels show the corresponding distributions for $B^\mp \rightarrow D\pi^\mp$ decays.

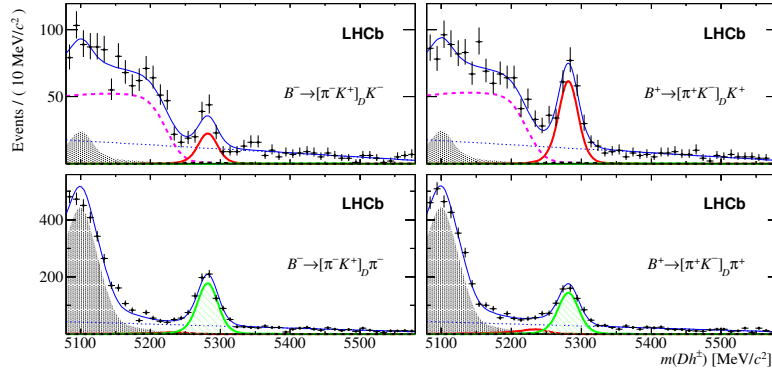


Figure 5. Invariant mass distributions for the suppressed ADS modes, upper left: $B^- \rightarrow [\pi^- K^+]_D K^-$, upper right: $B^+ \rightarrow [\pi^+ K^-]_D K^+$. The lower panels show the corresponding distributions for $B^\mp \rightarrow D\pi^\mp$ decays.

5. CP violation in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays

In the SM, sizeable CP asymmetries are predicted to occur in decays of beauty baryons to final states that contain no charmed hadrons. Asymmetries as large as 20% can be expected in some three-body decay modes. The LHCb experiment has collected an unprecedented number of beauty baryon decays, which allows for the first time to perform sensitive studies of CP violating observables. A systematic study of CP violation in beauty baryon decays can test the validity of the CKM mechanism in the baryon sector, for example by comparing measured asymmetries with those measured in B meson decays with identical underlying quark transitions.

LHCb has published a study of CP violating observables in the decay $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$, based on 6'650 signal candidates reconstructed in the 3 fb^{-1} collected in Run I [26]. In this decay, direct CP violation can arise from the interference of a tree amplitude and a penguin amplitude. The two decay amplitudes are of similar magnitude and large interference effects are therefore possible. The weak phase between the two amplitudes corresponds to the angle α of the CKM Triangle. However, the poorly known relative strong phase between the two decay amplitudes makes predictions of the expected CP asymmetry challenging.

The search for a CP violating asymmetry in this decay cannot rely on a comparison of Λ_b^0 and $\bar{\Lambda}_b^0$ decay rates, due to the poorly known $\Lambda_b^0 - \bar{\Lambda}_b^0$ production asymmetry in pp collisions. Instead, the four-body topology of the decay is exploited to combine momenta of final-state particles into a triple products, $C_{\hat{T}}$ and $\bar{C}_{\hat{T}}$, which are odd under parity and time reversal. For

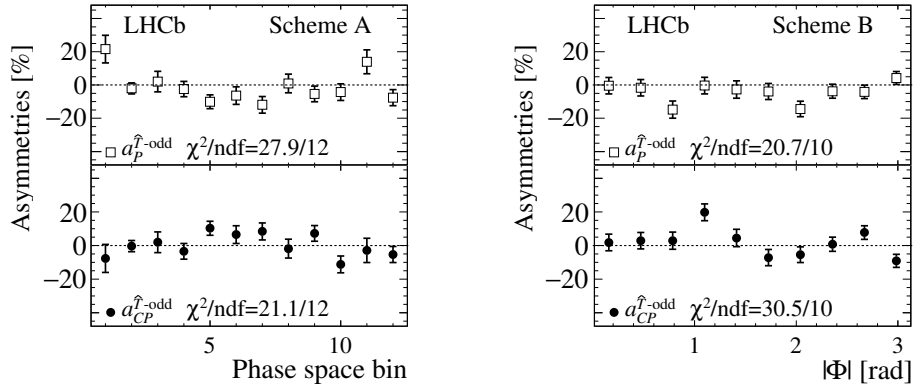


Figure 6. The asymmetry $a_P^{\hat{T}\text{-odd}}$ (upper panels) and $a_{CP}^{\hat{T}\text{-odd}}$ (lower panels) in bins of left: phase space and right: Φ .

Λ_b^0 decays,

$$C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi_{\text{slow}}}^- \times \vec{p}_{\pi^+}) \propto \sin \Phi,$$

where \vec{p}_p , \vec{p}_{π^+} and $\vec{p}_{\pi_{\text{slow}}}^-$ are the three-momenta of the final-state proton, the π^+ and the lower-momentum π^- , respectively, and Φ is the angle between the two decay planes defined by the flight directions of the proton and the higher-momentum π^- on the one hand and by the flight directions of the final-state π^+ and the lower-momentum π^- on the other hand. For $\bar{\Lambda}_b^0$ decays, correspondingly,

$$\bar{C}_{\hat{T}} \equiv \vec{p}_{\bar{p}} \cdot (\vec{p}_{\pi_{\text{slow}}}^+ \times \vec{p}_{\pi^-}) \propto \sin \bar{\Phi}.$$

Defining furthermore asymmetries in event yields,

$$A_{\hat{T}} \equiv \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

for Λ_b^0 decays and

$$\bar{A}_{\hat{T}} \equiv \frac{N(\bar{C}_{\hat{T}} > 0) - N(\bar{C}_{\hat{T}} < 0)}{N(\bar{C}_{\hat{T}} > 0) + N(\bar{C}_{\hat{T}} < 0)}$$

for $\bar{\Lambda}_b^0$ decays, parity is violated if

$$a_P^{\hat{T}\text{-odd}} \equiv \frac{1}{2} (A_{\hat{T}} + \bar{A}_{\hat{T}}) \neq 0$$

and CP is violated if

$$a_{CP}^{\hat{T}\text{-odd}} \equiv \frac{1}{2} (A_{\hat{T}} - \bar{A}_{\hat{T}}) \neq 0.$$

The analysis was performed in ten bins of $|\Phi|$ and in twelve bins of phase-space, as illustrated in Fig. 6. Combining the two binning schemes, and including systematic uncertainties, a p -value of 9.8×10^{-4} was found for the hypothesis of no CP violation. This corresponds to 3.3 Gaussian standard deviations and makes this result the first evidence for CP violation in b baryon decays. No deviation from parity conservation was found.

6. CP violation in the $D^0\bar{D}^0$ system

The $D^0\bar{D}^0$ system is the only neutral meson system that consists of up-type quarks. Measurements therefore probe different quark dynamics from those in the $K^0\bar{K}^0$, $B^0\bar{B}^0$, and $B_s^0\bar{B}_s^0$ systems. In the SM, CP violating effects in the $D^0\bar{D}^0$ system are expected to be small, with asymmetries generally predicted to be no larger than of the order of 10^{-3} . In principle, measurements of CP violating observables therefore provide good sensitivity to possible contributions from BSM physics. A caveat is that predictions suffer from sizeable uncertainties on hadronic form factors, caused by the relatively small mass of the charm quark.

The LHCb experiment is well suited for studies in the charm sector due to its excellent vertex resolution, its excellent kaon/pion identification capabilities, and its flexible trigger scheme, which allows to trigger on purely hadronic states down to small transverse momenta. The $c\bar{c}$ production cross section is about 20 times larger than the $b\bar{b}$ production cross section [27], allowing to collect large event samples. The LHCb collaboration has published various measurements of CP violating observables using 2-body, 3-body and 4-body decays of D^0 and \bar{D}^0 mesons. For a relatively recent overview, see Ref. [28]. A very recent measurement compared the ratios of doubly Cabibbo suppressed “wrong-sign” decays to Cabibbo favoured “right-sign” decays for D^0 and \bar{D}^0 candidates,

$$R^+ \equiv \frac{N(D^0 \rightarrow K^+\pi^-)}{N(D^0 \rightarrow K^-\pi^+)} \quad \text{and} \quad R^- \equiv \frac{N(\bar{D}^0 \rightarrow K^-\pi^+)}{N(\bar{D}^0 \rightarrow K^+\pi^-)}.$$

A non-vanishing difference between R^+ and R^- would imply CP violation. The measurement made use of flavour-tagged samples of D^0 and \bar{D}^0 candidates from $D^{*+} \rightarrow D^0\pi^+$ and $D^{*-} \rightarrow \bar{D}^0\pi^-$ decays as well as samples of doubly-tagged candidates, in which the D^{\pm} was produced in a semileptonic B -meson decay, $B \rightarrow D^{*\pm}\mu^\mp$. The doubly-tagged samples have lower yields, but better purity and better trigger acceptance at small D^0 and \bar{D}^0 decay times. A total of 6'700 wrong-sign and 1'730'000 right-sign candidates was extracted from the 3 fb^{-1} collected in Run 1 and used to determine $R^+ - R^-$ as a function of the reconstructed D^0 or \bar{D}^0 decay time. No significant deviations from zero were found, compatible with the hypothesis of no CP violation.

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