Time dependent CPV in the beauty sector

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Time-dependent CP violating phenomena probe the time evolution and the decay of beauty hadrons and allow access to the underlying dynamics. We present various time-dependent CP violation measurements in the B^0 and B_s^0 meson systems that are performed using pp collisions by LHCb and using e^+e^- collisions by the B factory experiments BaBar and Belle. For LHCb, we report measurements of the quantum-loop mediated $B_s^0 \rightarrow (K^-\pi^+)(K^+\pi^-)$ and $B_s^0 \rightarrow \phi\phi$ decays, and measurements of $B^0 \rightarrow D^\mp\pi^\pm$ and $B_s^0 \rightarrow h^+h^-$ decays. For Belle, we report new results for the charmless $B^0 \rightarrow \pi^0\pi^0K_S^0$ and $B^0 \rightarrow K_S^0\eta\gamma$ decays. In addition, we present a measurement of $\cos 2\beta$ obtained by a time-dependent Dalitz plot analysis of $B^0 \rightarrow D^*h^0$ with $D \rightarrow K_S^0\pi^+\pi^-$ that combines the final BaBar and Belle data sets.

1 Introduction

Measurements of CP asymmetries in neutral B mesons probe the interference of the mixing and decay Feynman diagrams. The CP asymmetry as a function of time can be described as

$$A_{CP} = \frac{\Gamma_{\bar{B}(d,s)^0 \rightarrow f} - \Gamma_{B(d,s)^0 \rightarrow f}}{\Gamma_{\bar{B}(d,s)^0 \rightarrow f} + \Gamma_{B(d,s)^0 \rightarrow f}} = \frac{-C_f \cos(\Delta m_{d,s}t) + S_f \sin(\Delta m_{d,s}t)}{\cosh(\Delta \Gamma_{d,s}t/2) + A_f^{\Delta \Gamma} \sinh(\Delta \Gamma_{d,s}t/2)}, \quad (1)$$

where

$$C_f \equiv \frac{1-|\lambda_f|}{1+|\lambda_f|}, \quad C_f \equiv \frac{2Im\lambda_f}{1+|\lambda_f|}, \quad A_f^{\Delta \Gamma} \equiv -\frac{2Re\lambda_f}{1+|\lambda_f|}, \quad \lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f}.$$

In the above equation, f represents the final state, A_f the $B_{s,d}$ decay amplitude, and $\bar{A}_f$ the $\bar{B}_{s,d}$ decay amplitude.

In the Standard Model (SM), the weak phase from B_s^0 - $\bar{B}_s^0$ mixing is given by $\phi_s^{c\bar{c}s} \approx -2\beta_s = 2arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$. The SM prediction for $\phi_s^{c\bar{c}s}$ has been obtained from global fits to experimental data yielding a value of -0.0360 ± 0.0006 rad [1]. There are however beyond-the-SM theories that could provide additional contributions to B_s^0 mixing diagrams which alter this value [2, 3].

In addition to decays with a tree-level contribution, measurements of decays in which the leading order contribution is a flavour changing neutral current (FCNC)

interaction are important in the search for physics beyond the SM. The CP -violating phase measured in the $B_s^0 \rightarrow \phi\phi$ decay results from $b \rightarrow s\bar{s}s$ transitions and is therefore expected to be close to zero in the SM due to the effective cancellation of the CP -violating weak phase between the B_s^0 mixing diagrams and the penguin decay diagrams [5, 6]. The $B_s^0 \rightarrow K^{*0}\bar{K}^{*0}$ (892) decay is an example of a $b \rightarrow d\bar{d}s$ transition and the associated CP -violating phase is expected to be zero for similar reasons as the $B_s^0 \rightarrow \phi\phi$ decay.

Time-dependent CP violation measurements in the B^0 system are mainly performed using b-factory data. The high flavour tagging efficiency of the b-factories makes many analyses of decay channels with event yields of as little as a hundred events possible. For time-dependent analyses in the B^0 system at the b-factories, the decay time difference with respect to the other $\bar{B}^0$ decay produced in the event is measured and denoted as Δt . The time-dependent decay rate is then of the form

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 + q[S \sin(\Delta m_d \Delta t) + \mathcal{A} \cos(\Delta m_d \Delta t)]\}, \quad (2)$$

where q is the B^0 meson flavour, S and $\mathcal{A}$ are the S_f and C_f parameters in eq. 1, respectively. Time-dependent analyses in the B^0 system are sensitive to the CKM angle $\beta \equiv \phi_1$, the current central value of $\sin(2\beta)$ is -0.699 ± 0.017 [4]. Measurements of $\sin(2\beta)$ result in an ambiguity in the sign of $\cos(2\beta)$.

The following sections summarise updated and most accurate measurements of the CP -violating weak phases in $b \rightarrow c\bar{c}s$ and $b \rightarrow s\bar{s}s$ transitions [9, 10, 11], in addition to a first measurement of the weak phase in $b \rightarrow d\bar{d}s$ transitions from LHCb data [11]. Decay time dependent measurements of $B^0 \rightarrow \pi^0\pi^0 K_S^0$ and $B^0 \rightarrow K_S^0\eta\gamma$ decays are presented using Belle data [12, 13], along with a new measurement of $\cos(2\beta)$ using a combination of BaBar and Belle data that provides first evidence that $\cos(2\beta) > 0$ [14].

2 Time-dependent CP violation in B_s^0 decays

2.1 The $B_s^0 \rightarrow J/\psi K^+ K^-$ decay

The $B_s^0 \rightarrow J/\psi K^+ K^-$ decay requires the use of decay angles in the helicity basis to disentangle the four polarisation amplitudes contributing to the decay (3 P -wave and an S -wave). The four observables are shown in Figure 1.

A good understanding of the efficiencies as a function of each observable is important in keeping measurements dominated by statistical uncertainties. The measurement uses 95690 candidates obtained from 3 fb^{-1} of LHCb data collected in 2011 and 2012 [9]. The decay gives access to the B_s^0 - $\bar{B}_s^0$ oscillation frequency, Δm_s , the decay width and decay width difference, Γ_s & $\Delta\Gamma_s$, in addition to the decay amplitudes, $|A_0|^2$ & $|A_\perp|^2$, and the CP -violating parameters, $\phi_s^{c\bar{c}s}$ & $|\lambda|$. The results of

Fig. 1 Decay-time and helicity-angle distributions for $B_s^0 \rightarrow J/\psi K^+ K^-$ decays (data points) with the one-dimensional fit projections overlaid. The solid blue line shows the total signal contribution, which is composed of CP -even (long-dashed red), CP -odd (short-dashed green) and S-wave (dotted-dashed purple) contributions [9].

the measurement are provided in Table 1. Results are consistent with SM predictions and result in stringent constraints on physics beyond the SM [15].

Table 1 Values of the principal physics parameters determined from the polarisation-independent fit. The first uncertainty is statistical and the second systematic.

Parameter	Value
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0032$
$ A_\perp ^2$	$0.2504 \pm 0.0049 \pm 0.0036$
$ A_0 ^2$	$0.5241 \pm 0.0034 \pm 0.0067$
$\phi_s^{c\bar{c}s}$ [rad]	$-0.058 \pm 0.049 \pm 0.006$
$ \lambda $	$0.964 \pm 0.019 \pm 0.007$
Δm_s [ps^{-1}]	$17.711^{+0.055}_{-0.057} \pm 0.011$

2.2 The $B_s^0 \rightarrow \phi\phi$ decay

The $B_s^0 \rightarrow \phi\phi$ decay requires an angular analysis to disentangle the polarisation states, as for the $B_s^0 \rightarrow J/\psi K^+ K^-$ decay. In total, approximately 9000 decay candidates are used to make the measurement, from 5.0 fb^{-1} of data collected between 2011 and 2016 [10]. The number of candidates is much smaller than that used for the measurement of $B_s^0 \rightarrow J/\psi K^+ K^-$ decays, therefore external constraints are taken

Table 2 Values of the principal physics parameters determined from the polarisation-independent fit. The first uncertainty is statistical and the second systematic.

Parameter	Value
ϕ_s^{ss} [rad]	$-0.07 \pm 0.13 \pm 0.03$
$ \lambda $	$1.02 \pm 0.05 \pm 0.03$
$ A_0 ^2$	$0.382 \pm 0.008 \pm 0.011$
$ A_\perp ^2$	$0.287 \pm 0.008 \pm 0.005$

Fig. 2 Decay-time and helicity-angle distributions for $B_s^0 \rightarrow \phi\phi$ decays (data points) with the one-dimensional fit projections overlaid. The solid blue line shows the total signal contribution, which is composed of CP -even (long-dashed red), CP -odd (short-dashed green) and S-wave (dotted-dashed purple) contributions [10].

from the best known values of Δm_s , Γ_s , and $\Delta\Gamma_s$. The four observables describing the decay are shown in Figure 2 along with the corresponding fit projections. Numerical results for the polarisation amplitudes, $|A_0|^2$ and $|A_\perp|^2$, are given in Table 2, along with the CP -violating parameters, ϕ_s^{ss} and $|\lambda|$. Results are consistent with CP conservation and consequently SM predictions.

2.3 The $B_s^0 \rightarrow K^+\pi^-K^-\pi^+$ decay

A further example of a decay channel that requires an angular analysis is given by the $B_s^0 \rightarrow K^+\pi^-K^-\pi^+$ decay. The decay mode is further complicated by the many contributions to the $K\pi$ mass spectrum. These contributions consist of non-resonant S -wave, K^{*0} P -wave, in addition to that of a tensor $\overline{K}_2^*(1430)^0$ along with associated interferences. In order to properly disentangle so many contributions, the decay-time dependent fit incorporates the $K\pi$ invariant mass as an observable. The $K\pi$ invariant mass along with the associated fit is shown in Figure 3. The dataset used for the analysis consists of 3 fb^{-1} of LHCb data collected in 2011 and 2012 [11].

Fig. 3 One-dimensional projections of the decay-time-dependent, flavour-tagged fit to (black points) the sPlot weighted data for the $K^+ \pi^-$ invariant mass. The solid gray line represents the total fit model along with the iCP -averaged components for each contributing decay [11].

The results of the CP -violation parameters, $\phi_s^{d\bar{d}s}$ and $|\lambda|$, are given in Table 3. CP violation is consistent with the SM expectation. The analysis is dominated by systematic uncertainties, the largest contribution of which originates from the size of the simulation sample.

Table 3 Values of the CP violation parameters determined from the polarisation-independent fit. The first uncertainty is statistical and the second systematic.

Parameter	Value
$\phi_s^{d\bar{d}s}$ [rad]	$-0.10 \pm 0.13 \pm 0.14$
$ \lambda $	$1.035 \pm 0.034 \pm 0.089$

2.4 CP violation in $B \rightarrow hh$ decays

The measurement of CP violation in $B \rightarrow hh$ decays is a measurement of time-dependent CP violation in both B_s^0 and B^0 decays, as different mesons are the main contributors to different final states. The $\pi\pi$ final state is studied with B^0 decays and the KK final state with B_s^0 decays. The $B^0 \rightarrow K^- \pi^+$ decay is used to understand the decay time acceptance and calibrate the incorrect flavour assignment probability. The fit to all final states simultaneously allows for mis-identified pions and kaons to be accounted for. The analysis used 3.0 fb^{-1} of data collected in 2011 and 2012 [16].

The results of the CP violation parameters defined in eq. 1 are shown in Table 4. The significance for $(C_{KK}, S_{KK}, A_{CP}^{B_s^0})$ to deviate from $(0, 0, -1)$ has been determined from a χ^2 test statistic to be 4.0 standard deviations. This result constitutes the strongest evidence for CP violation in the B_s^0 system to date.

Table 4 Values of the principal physics parameters determined from the polarisation-independent fit. The first uncertainty is statistical and the second systematic.

Parameter	Value
$C_{\pi\pi}$	$-0.34 \pm 0.06 \pm 0.01$
$S_{\pi\pi}$	$-0.63 \pm 0.05 \pm 0.01$
C_{KK}	$0.20 \pm 0.06 \pm 0.02$
S_{KK}	$0.18 \pm 0.06 \pm 0.02$
$A_{KK}^{\Delta\Gamma}$	$-0.79 \pm 0.07 \pm 0.10$
$A_{CP}^{B^0}$	$-0.084 \pm 0.004 \pm 0.003$
$A_{CP}^{B_s^0}$	$0.213 \pm 0.015 \pm 0.007$

3 Time-dependent CP violation in B^0 decays

3.1 The $B^0 \rightarrow K_S^0 \pi^0 \pi^0$ decay

The known energy of electron-positron collisions results in a fully kinematically constrained decay. This allows the use of the beam-constrained mass, $M_{bc} \equiv \sqrt{(E_{beam}/c^2)^2 - |\mathbf{p}_B^{CM}/c|^2}$, and the energy difference $\Delta E \equiv E_{beam} - E_B^{CM}$, to isolate the signal candidates from the background candidates, where $\mathbf{p}_B^{CM}$ and E_B^{CM} are the B momentum and energy respectively in the centre-of-mass (CM) frame. A common variable used in addition to isolate signal is a likelihood ratio calculated from modified Fox-Wolfram moments, $\mathcal{R}_{s/b}$ [13].

The signal and background distributions of M_{bc} , ΔE , and $\mathcal{R}_{s/b}$ are shown in Figure 4, where 335 $B^0 \rightarrow K_S^0 \pi^0 \pi^0$ signal candidates are seen from a three dimensional fit. The total dataset consists of 742×10^6 $B\bar{B}$ pairs collected with the Belle detector at the $\Upsilon(4S)$ resonance. The high effective flavour tagging power of $29.8 \pm 0.4\%$ makes a decay-time dependent fit possible with the number of candidates found. The resulting decay-time dependent fit measures a values of $\mathcal{S} = -0.92^{+0.31}_{-0.27}(\text{stat}) \pm 0.11(\text{syst})$ and $\mathcal{A} = -0.28 \pm 0.21(\text{stat}) \pm 0.04(\text{syst})$.

3.2 The $B^0 \rightarrow K_S^0 \eta \gamma$ decay

A similar decay time dependent analysis is performed using $B^0 \rightarrow K_S^0 \eta \gamma$ decays as that described in the previous section. The total dataset consists of 772×10^6 $B\bar{B}$ pairs collected with the Belle detector at the $\Upsilon(4S)$ resonance. A total of 92 candidates are used to make the measurement. The CP violation parameters are determined to be $\mathcal{S} = -1.32 \pm 0.77(\text{stat}) \pm 0.36(\text{syst})$ $\mathcal{A} = -0.48 \pm 0.41(\text{stat}) \pm 0.07(\text{syst})$. The 1,

Fig. 4 M_{bc} , ΔE and $\mathcal{R}_{s/b}$ distributions (points with uncertainties) using signal-enhanced selections $M_{bc} > 5.27 \text{ GeV}/c^2$, $0.15 \text{ GeV} < \Delta E < 0.10 \text{ GeV}$, and $\mathcal{R}_{s/b} > 0.9$ except for the variable displayed. The fit result is illustrated by the solid curve, while the total and $B\bar{B}$ backgrounds are shown by broken and dotted curves, respectively [13].

Fig. 5 The solid red, dashed blue, and dotted green curves show the 1σ , 2σ , 3σ confidence contours, respectively. The red dot shows the fit result. The physical boundary $S^2 + A^2 = 1$ is drawn with a thin solid black curve. Our result is consistent with a null asymmetry within 2σ [12].

2, and 3σ confidence contours of the S and $\mathcal{A}$ parameters are shown in Figure 5. The result is consistent with null asymmetry within 2σ .

3.3 Measurement of $\cos(2\beta)$ using $B^0 \rightarrow D^* h^0$ decays

The first evidence for the resolution of the sign of $\cos(2\beta)$ has required the combination of 471×10^6 $B\bar{B}$ pairs collected with the BaBar detector and 772×10^6 $B\bar{B}$ pairs collected with the Belle detector [14]. The measurement of $\cos(2\beta)$ is achieved through the interference of the D^* and $\bar{D}^*$ decay amplitudes, $\mathcal{A}_{D^*}$ and $\mathcal{A}_{\bar{D}^*}$, which can be written as

$$\text{Im}(e^{-i2\beta} \mathcal{A}_{D^*} \mathcal{A}_{\bar{D}^*}) = \text{Im}(\mathcal{A}_{D^*} \mathcal{A}_{\bar{D}^*}) \cos(2\beta) - \text{Re}(\mathcal{A}_{D^*} \mathcal{A}_{\bar{D}^*}) \sin(2\beta). \quad (3)$$

This then gives access to both $\sin(2\beta)$ and $\cos(2\beta)$, which are measured to be $0.80 \pm 0.14 \pm 0.06 \pm 0.03$ and $0.91 \pm 0.22 \pm 0.09 \pm 0.07$, respectively, where the first uncertainty is statistical, the second is systematic and the third is related to the choice

of fit model. The significance of which $\cos(2\beta)$ is greater than zero is determined to be 3.7σ , representing the first evidence.

4 Summary

The most accurate single measurement of CP violation in B_s^0 mixing has been presented along with an updated measurement of the weak phase in the $B_s^0 \rightarrow \phi\phi$ decay and the first measurement of the weak phase in $B_s^0 \rightarrow K^+\pi^-K^-\pi^+$ decays using LHCb data. An LHCb analysis has also revealed the strongest evidence yet of CP violation in the B_s^0 sector, measured from $B_s^0 \rightarrow K^+K^-$ decays to be at the 4.0σ level. Two new decay time dependent measurements have been presented using data collected with the Belle detector, $B^0 \rightarrow K_S^0\pi^0\pi^0$ and $B^0 \rightarrow K_S^0\eta\gamma$. In addition, first evidence has been presented that $\cos(2\beta) > 0$, with a significance of 3.7σ , potentially resolving the long standing ambiguity in the value of the CKM angle β .

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