PROCEEDINGS OF SCIENCE

Charm mixing and CP violation at LHCb

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The LHCb experiment has collected the world's largest sample of charmed hadrons in pp collisions at the LHC. Using data corresponding to an integrated luminosity of 1.0 fb^{-1} recorded in 2011, measurements of direct and indirect CP violation in the charm sector and of D^0 mixing parameters were performed. Results from several decay modes are presented with complementary time-dependent and time-integrated analyses.

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1. Introduction

The charm sector of particle physics is a promising place to probe for the presence of physics beyond the Standard Model (SM) because CP violation (CPV) in the charm sector is expected to be very small in the SM [1]. Since evidence of $D^0-\bar{D}^0$ oscillations was first reported [2, 3, 4, 5] there is growing interest in this subject. Until recently, no single mixing measurement had reached a precision above 5σ significance. In combinations of all measurements, however, a 10σ significance of $D^0-\bar{D}^0$ oscillations has been obtained [6]. The first observation of $D^0-\bar{D}^0$ mixing in a single measurement was recently achieved at the LHCb experiment, with a significance of above above 9σ [7]. The LHCb detector is presented in Sec. 2. Details of the measurement of $D^0-\bar{D}^0$ oscillations are discussed in Sec. 3. The time-integrated CP asymmetry measurements in two-body D^0 decays are discussed in Sec. 4. A search for CPV asymmetry in $D^+\to\phi\pi^+$ decays is discussed in Sec. 5. Conclusions are presented in Sec. 6.

2. The LHCb detector

The LHCb detector [8] is a single-arm forward spectrometer covering pseudorapidity range $2<\eta<5$, designed for the study of particles containing b or c quarks. Displaced vertices of c-hadron decays can be measured with 20 μm resolution. The decay time resolution of 10% of the D meson lifetime is achieved using a silicon vertex locator. The tracking system measures the charged particles with momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV to 0.6% at 100 GeV, corresponding to a typical mass resolution of approximately 8 MeV for a two-body charm meson decay. The $c\bar{c}$ cross-section in 4π in pp collisions of $\sim$6 mb measured with the LHCb detector at $\sqrt{s}=7$ TeV [9] is about 20 times larger than the $b\bar{b}$ cross-section [10]. For all these reasons, the LHCb experiment has great potential for charm physics studies.

3. Observation of $\mathbf{D^0-\bar{D}^0}$ oscillations

To measure $D^0-\bar{D}^0$ oscillations, the D^0 flavour has to be identified at both the production and decay. The flavour of the D^0 meson at the production time is identified in the process of $D^{*+}\to D^0(\to K\pi)\pi_s^+$ decays in which the charge of the slow pion (π_s) tags the initial D^0 or $\bar{D}^0$. The flavour at the D^0 decay is tagged by the charge of the K meson. The $D^0\to K^+\pi^-$ decays are called wrong-sign (WS) decays and the $D^0\to K^-\pi^+$ decays are called right-sign (RS) decays. The RS decays are dominated by the Cabibbo-favoured (CF) decay amplitude, whereas the WS amplitude includes contributions from both the doubly-Cabibbo-suppressed (DCS) $D^0\to K^+\pi^-$ decay and $D^0-\bar{D}^0$ mixing followed by the favoured $\bar{D}^0\to K^+\pi^-$ decay. Assuming negligible CPV, the time-dependent ratio, R, of WS to RS decay rates is approximated by [11]

$$R(t)=R_D+\sqrt{R_D}y'\frac{t}{\tau}+\frac{x'^2+y'^2}{4}(\frac{t}{\tau})^2, \tag{3.1}$$

where t/τ is the decay time expressed in units of the average D^0 lifetime (τ), R_D is the ratio of DCS to CF decay rates, $x'=x\cos\delta+y\sin\delta$, $y'=y\cos\delta-x\sin\delta$, where δ is the strong phase difference between DCS and CF amplitudes. The parameters $x=\Delta m/\Gamma$ and $y=\Delta\Gamma/2\Gamma$, where Δm and $\Delta\Gamma$ are the mass and the decay width differences between the two mass eigenstates and Γ is the average D^0 decay width.

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The measurement is performed with 1.0 fb^{-1} of data recorded by the LHCb detector during 2011. Events are selected by requiring two oppositely charged tracks to form a D^0 candidate with a decay vertex well separated from the associated pp collision vertex. Further criteria on the quality of the reconstructed tracks are described in [7].

The time-integrated $D^0\pi_s^+$ mass distributions, $M(D^0\pi_s^+)$, for the selected RS and WS candidates are shown in Fig. 1. A binned χ^2 fit is used to separate the D^{*+} signal and the background component. From the fits about 3.6×10^4 WS and 8.4×10^6 RS decays are obtained.

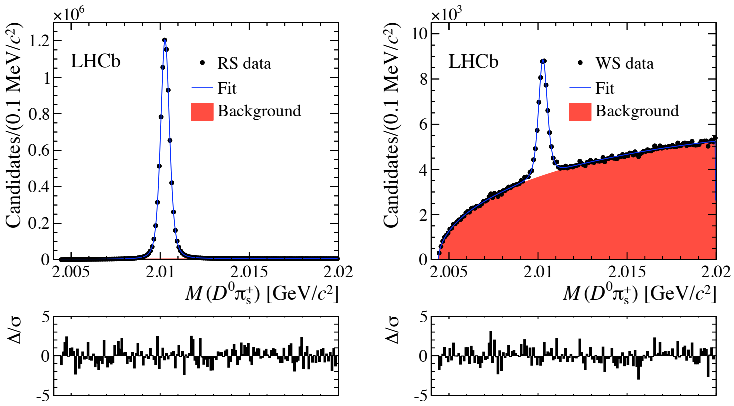

Figure 1: Time-integrated $D^0\pi_s^+$ mass distributions for the selected RS $D^0\to K^-\pi^+$ (left) and WS $D^0\to K^+\pi^-$ (right) candidates with fit projections overlaid. The bottom plots show the residuals between the data points and the fits.

The measurement of the time-dependent WS/RS ratio is performed in thirteen bins of D^0 decay time, chosen to have a similar number of candidates in each bin. The number of RS and WS decays are determined using fits to the $M(D^0\pi_s^+)$ distributions in each bin to calculate the WS/RS ratios. The measured WS/RS ratios are shown in Fig. 2a) [7]. The mixing parameters are obtained from the binned χ^2 fit to the time-dependence given in Eq. 3.1 (solid line in Fig. 2a)) and are listed in Table 1. Most of the systematic uncertainties cancel in the WS/RS ratio since the WS and RS events are expected to have the same decay time acceptance and the measurement is therefore dominated by the statistical uncertainties. Two main sources of systematic uncertainties have been identified. One is related to the secondary D decays. It is found that when the secondary component is not accounted for the measured WS/RS ratio could be biased by at most 3%. A second source is related to a background from charm decays, where both daughters are reconstructed with the wrong particle type which gives a peak in $M(D^0\pi_s^+)$. It is found that the dominant peaking background is from RS events that survive the requirements of the WS selection. The peaking background is estimated to constitute $(0.4\pm0.2)\%$ of the WS signal.

The fit to the measured WS/RS ratios with the no-mixing hypothesis does not describe the data (dashed line in Fig. 2a)). The χ^2 difference between mixing and no-mixing assumption excludes the no-mixing hypothesis with a probability corresponding to 9.1σ. This analysis is therefore the first observation of $D^0-\bar{D}^0$ oscillations in a single measurement. In Fig. 2b) the 1σ, 3σ and 5σ confidence regions of the measured mixing parameters x'^2 and y' are shown. The measurements are compatible with and have substantially better precision than those from previous measurements [2, 4, 12].

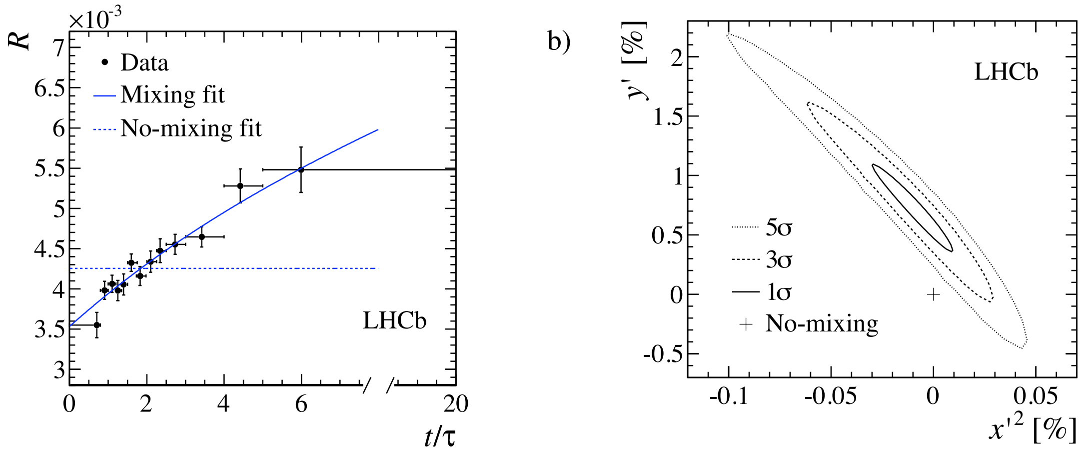

Figure 2: **a)** Decay time-dependence of the WS/RS ratios, R, with the projection of the mixing allowed (solid line) and no-mixing (dashed line) fits overlaid; **b)** Estimated confidence-level (CL) regions in the (x'^2, y') plane for $1-\mathrm{CL} = 0.317(1\sigma)$, $2.7\times10^{-3}(3\sigma)$ and $5.73\times10^{-7}(5\sigma)$.

Fit type (χ^2/ndf)	Parameter	Fit results (10^{-3})	Correlation coefficient R_D	y'	x'^2
Mixing (9.5/10)	R_D	3.52 ± 0.15	1	-0.954	$+0.882$
	y'	7.2 ± 2.4		1	-0.973
	x'^2	-0.09 ± 0.13			1
No mixing (98.1/12)	R_D	4.25 ± 0.04			

Table 1: Results of the time-dependent fit to the WS/RS ratios. The uncertainties include statistical and systematic sources.

4. A search for time-integrated CPV in $\mathbf{D^0 \to h^- h^+}$ decays

The CP asymmetry of a decay of a D^0 meson to a CP eigenstate, $A_{CP}(f)$, can be expressed in terms of two contributions, a direct component associated with CPV in the decay amplitudes and an indirect component associated with CPV in the mixing or in the interference between mixing and decay. It can be written to the first order as [13]

$$A_{CP}(f) = a_{CP}^{dir}(f) + \frac{\langle t\rangle}{\tau} a_{CP}^{ind}, \tag{4.1}$$

where $a_{CP}^{dir}(f)$ is a direct CPV for the decay, $\langle t\rangle$ is the average proper time of the reconstructed sample, τ is the D^0 lifetime, and a_{CP}^{ind} is the indirect CPV originating from the mixing and/or the interference between mixing and decay. The indirect component is universal for CP eigenstates in the SM and is expected to be small. The direct component depends in general on the final state. In the SM, direct CPV in $D^0 \to K^-K^+$ and the $D^0 \to \pi^-\pi^+$ decays is expected to be 10^{-3} or less [1]. In the presence of physics beyond the SM, however, the rate of CPV could be enhanced.

The time-integrated CPV asymmetry between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ has been measured in the LHCb experiment with data collected in 2011 (1 fb^{-1}) using two methods: where the D^0 comes from promptly produced charged D^* decays (the pion-tagged method) and where the D^0 comes from inclusive semileptonic B decays (the muon-tagged method).

4.1 The pion-tagged method

The flavour of the initial state (D^0 or $\bar{D}^0$) is tagged by the charge of the slow pion (π_s) in the decay chain of charged D^* decays ($D^{*+} \to D^0\pi_s^+$ or $D^{*-} \to \bar{D}^0\pi_s^-$), similar to the $D^0 - \bar{D}^0$ oscillation analysis (Sec. 3). At first order, the measured raw time-integrated asymmetry may be written as a sum of various components both from physics and detector effects,

$$A_{RAW}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_P(D^{*+}), \tag{4.2}$$

where $A_{CP}(f)$ is an intrinsic physics CP asymmetry, $A_D(f)$ is the asymmetry for selecting the D^0 decay into the final state f, $A_D(\pi_s^+)$ is the asymmetry for selecting a slow pion from the D^{*+} decay chain, and $A_P(D^{*+})$ is the production asymmetry of the D^{*+} mesons.

Since the decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ are charge symmetric the D^0 detection asymmetries vanish. The difference $\Delta A_{CP} = A_{RAW}(K^-K^+) - A_{RAW}(\pi^-\pi^+)$ is measured since the asymmetries $A_D(\pi_s^+)$ and $A_P(D^{*+})$ are cancel in the subtraction. Than the quantity ΔA_{CP} is a difference of CP asymmetries, $\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$.

The selection criteria to isolate the decays of interest are related to the decay time, the track quality, the vertex quality, the transverse momentum of the D^0 candidates, and the angle between the D^0 momentum in the lab frame and its daughters' momenta in the rest frame. The full selection description can be found in [14]. Defining the mass difference as $\delta m \equiv m(h^-h^+\pi_s^+) - m(h^-h^+) - m(\pi^+)$ for $h = K, \pi$, the fits to the δm distributions in $1844 < m(h^-h^+) < 1884$ MeV/c^2 range of mass give D^{*+} signal yields of 2.24×10^6 $D^0 \to K^-K^+$ decays, and 0.69×10^6 $D^0 \to \pi^-\pi^+$ decays. The fractional difference in average decay time of the D^0 candidates passing the selection for the two decay modes is $\Delta\langle t\rangle/\tau = (11.27 \pm 0.13)\%$. The measured ΔA_{CP} is primarily sensitive to the direct CPV.

The measured value of ΔA_{CP} is found to be $\Delta A_{CP} = [-0.34 \pm 0.15(stat) \pm 0.10(syst)]\%$. Systematic uncertainties are assessed as follows. The analysis was repeated with the asymmetry extracted through the sideband subtraction in δm instead of a fit, removing all candidates but one (chosen at random) in events with multiple candidates, loosing requirement on the soft pion detection and use the fits to the $m(K^-K^+)$ and $m(\pi^-\pi^+)$ spectra to test for potential peaking background. Each uncertainty is taken as the full difference in the result from the baseline value.

The ΔA_{CP} was measured with the pion-tagged method previously at the LHCb experiment using 0.6 fb^{-1}, about 60% of 2011 data [15]. This updated analysis uses improved detector calibration and vertex reconstruction. The results obtained on the first 0.6 fb^{-1} are consistent within the uncorrelated uncertainties between the two analyses. Further, the updated measurement is consistent between the first 0.6 fb^{-1} and the last 0.4 fb^{-1}. The measured value on full 2011 statistics does not confirm the evidence for CPV in the charm sector that had previously been reported.

4.2 The muon-tagged method

A measurement of ΔA_{CP} has been performed [16] in which the D^0 mesons are produced in inclusive semileptonic B meson decays to the $D^0\mu^-\bar{\nu}_\mu X$ final state, where X means other possible particles. The charge of the accompanying muon is used to identify the flavour of the D^0 meson ($\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ or $B \to \bar{D}^0\mu^+\nu_\mu X$). Similar to the pion-tagged method, the measured raw time-integrated asymmetry is a sum of physics and detector asymmetries,

$$A_{RAW}(f) = A_{CP}(f) + A_D(f) + A_D(\mu^+) + A_P(B), \tag{4.3}$$

where $A_D(\mu^+)$ is the detection asymmetry for selecting a muon from semileptonic B decay chain and $A_P(B)$ is the production asymmetry of the B mesons. Both detection and production asymmetries differ from those in the pion-tagged method.

The two measurements of ΔA_{CP} are statistically independent and due to the different production environment and tagging technique the systematic uncertainties are also essentially uncorrelated. A binned maximum likelihood fit to the mass distributions is performed to determine the numbers of signal candidates as $(558.9 \pm 0.9) \times 10^3$ for $D^0 \to K^- K^+$ decays and $(221.6 \pm 0.8) \times 10^3$ for $D^0 \to \pi^- \pi^+$ decays. The fractional difference in an average decay time of the D^0 candidates for the two samples is $\Delta\langle t\rangle/\tau = 0.018 \pm 0.002(stat) \pm 0.007(syst)$. The small value of $\Delta\langle t\rangle/\tau$ implies that the measured ΔA_{CP} is equal to the difference in direct CPV with negligible indirect CPV correction.

The measured value of ΔA_{CP} is found to be $\Delta A_{CP} = [0.49 \pm 0.30(stat) \pm 0.14(syst)]\%$. A detailed description of the systematic uncertainties can be found in [16]. The result does not confirm the evidence for direct CPV in the charm sector.

The measured ΔA_{CP} obtained using the pion-tagged method and the muon-tagged method are compatible at the 3% level, $\chi^2 = 4.85$ (2.2σ).

5. Search for CPV in $\mathbf{D^+ \to \phi\pi^+}$ and $\mathbf{D_s^+ \to K_s^0\pi^+}$ decays

In D^+ Cabibbo-suppressed decays a CP asymmetry will occur if tree and penguin processes interfere with different strong and weak phases. In these decays, a non-zero CP asymmetry would indicate the presence of direct CPV. The $D^+ \to \phi\pi^+$ decay is a particularly promising channel for CP asymmetry searches due to its large branching ratio of $(2.65 \pm 0.09) \times 10^{-3}$ [18].

The CP asymmetries are studied using control decay modes, in which no CP asymmetry is expected. The production and detector asymmetries cancel in the differences of raw asymmetries defined below. To investigate CPV in the $D^+ \to \phi\pi^+$ and the $D_s^+ \to K_s^0\pi^+$ Cabibbo-suppressed decays, the favoured $D^+ \to K_s^0\pi^+$ and $D_s^+ \to \phi\pi^+$ decays (with $K_s^0 \to \pi^-\pi^+$) are used as a control channel, respectively [17]:

$$A_{CP}(D^+ \to \phi\pi^+) = A_{RAW}(D^+ \to \phi\pi^+) - A_{RAW}(D^+ \to K_s^0\pi^+) + A_{CP}(K^0/\bar{K}^0),$$

$$A_{CP}(D_s^+ \to K_s^0\pi^+) = A_{RAW}(D_s^+ \to K_s^0\pi^+) - A_{RAW}(D_s^+ \to \phi\pi^+) + A_{CP}(K^0/\bar{K}^0).$$

The $A_{CP}(K^0/\bar{K}^0)$ is the correction for CPV in the neutral kaon system.

An amplitude analysis of $D^+ \to K^-K^+\pi^+$ decay shows that a relative strong phase varies rapidly in the region of the ϕ resonance in the Dalitz plot [19], as shown in Fig. 3. The phase is measured relative to that of the $K^*(892)^0$ meson. The variation in phase means that it is possible that CPV asymmetry could be canceled out when the different regions of the ϕ resonance are combined to calculate A_{CP}. Therefore, a complementary observable $A_{CP}|_S$ is defined. The area around the ϕ resonance in the Dalitz plot is divided into four regions, A, B, C and D (Fig. 3). The division is chosen to minimize the change in phase within each region. The observable $A_{CP}|_S$ is defined as the difference between the two diagonals, each made of two regions with similar phases,

$$A_{CP}|_S = 1/2(A^A_{RAW} + A^C_{RAW}) - A^B_{RAW} - A^D_{RAW}.$$

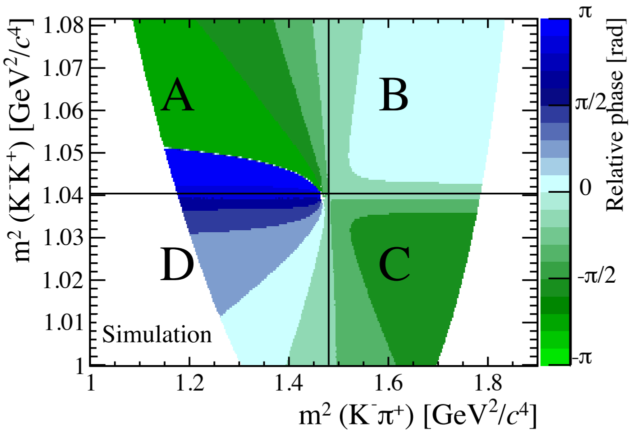

Figure 3: Variation of the overall phase of the D^+ decay amplitude in the ϕ mass region of the Dalitz plot, from a simulation study based on the CLEO-c amplitude model [19] in which the phase is defined relative to that of the $K^*(892)^0$ resonance.

Simulated studies show that, depending on the nature of potential CP violation present, $A_{CP}|_S$ can be more sensitive to CPV than A_{CP} (see [17]).

The data sample used corresponds to 1 fb^{-1} LHCb 2011 data. Signal yields of 1577×10^3 $D^+\to\phi\pi^+$, 3010×10^3 $D_s^+\to\phi\pi^+$, 1058×10^3 $D^+\to K_s^0\pi^+$ and 26×10^3 $D_s^+\to K_s^0\pi^+$ decays are obtained.

The results are consistent with no evidence for CPV in either decay:

$$A_{CP}(D^+\to\phi\pi^+) = (-0.04\pm0.14(stat)\pm0.13(syst))\%,$$

$$A_{CP}|_S(D^+\to\phi\pi^+) = (-0.18\pm0.17(stat)\pm0.18(syst))\%,$$

$$A_{CP}(D_s^+\to K_s^0\pi^+) = (+0.61\pm0.83(stat)\pm0.13(syst))\%.$$

This is the most precise analysis of CP asymmetry in the ϕ resonance region to date.

6. Conclusions

Using 1 fb^{-1} of data collected with the LHCb experiment in 2011 $D^0-\bar{D}^0$ oscillations are observed for the first time in a single measurement by evaluating the time-dependence of the ratio of $D^0\to K^+\pi^-$ and $D^0\to K^-\pi^+$ decays. The no-mixing hypothesis is excluded at 9.1 standard deviations. The time-integrated difference in CP asymmetry between $D^0\to K^-K^+$ and $D^0\to\pi^-\pi^+$ decays has been measured using two methods and the results obtained do not confirm evidence for direct CP violation. No evidence for CP violation is found in searches for CP asymmetries in the Cabibbo suppressed decays $D^+\to\phi\pi^+$ and $D_s^+\to K_s^0\pi^+$.

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