Evidence for *CP* Violation in Time-Integrated $D^0 \to h^- h^+$ Decay Rates

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A search for time-integrated *CP* violation in $D^0 \to h^- h^+$ ($h = K,\ \pi$) decays is presented using 0.62 fb^{-1} of data collected by LHCb in 2011. The flavor of the charm meson is determined by the charge of the slow pion in the $D^{*+} \to D^0 \pi^+$ and $D^{*-} \to \bar{D}^0 \pi^-$ decay chains. The difference in *CP* asymmetry between $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$, $\Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$, is measured to be $[-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\%$. This differs from the hypothesis of *CP* conservation by 3.5 standard deviations.

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The charm sector is a promising place to probe for the effects of physics beyond the standard model (SM). There has been a resurgence of interest in the past few years since evidence for D^0 mixing was first seen [1,2]. Mixing is now well established [3] at a level which is consistent with, but at the upper end of, SM expectations [4]. By contrast, no evidence for *CP* violation in charm decays has yet been found.

The time-dependent *CP* asymmetry $A_{CP}(f;t)$ for D^0 decays to a *CP* eigenstate f (with $f = \bar{f}$) is defined as

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}, \quad (1)$$

where Γ is the decay rate for the process indicated. In general $A_{CP}(f;t)$ depends on f. For $f = K^- K^+$ and $f = \pi^- \pi^+$, $A_{CP}(f;t)$ can be expressed in terms of two contributions: a direct component associated with *CP* violation in the decay amplitudes, and an indirect component associated with *CP* violation in the mixing or in the interference between mixing and decay. In the limit of *U*-spin symmetry, the direct component is equal in magnitude and opposite in sign for $K^- K^+$ and $\pi^- \pi^+$, though the size of *U*-spin breaking effects remains to be quantified precisely [5]. The magnitudes of *CP* asymmetries in decays to these final states are expected to be small in the SM [5–8], with predictions of up to $\mathcal{O}(10^{-3})$. However, beyond the SM the rate of *CP* violation could be enhanced [5,9].

The asymmetry $A_{CP}(f;t)$ may be written to first order as [10,11]

$$A_{CP}(f;t) = a_{CP}^{\text{dir}}(f) + \frac{t}{\tau} a_{CP}^{\text{ind}}, \quad (2)$$

where $a_{CP}^{\text{dir}}(f)$ is the direct *CP* asymmetry, τ is the D^0 lifetime, and a_{CP}^{ind} is the indirect *CP* asymmetry. To a good approximation this latter quantity is universal [5,12]. The time-integrated asymmetry measured by an experiment, $A_{CP}(f)$, depends upon the time acceptance of that experiment. It can be written as

$$A_{CP}(f) = a_{CP}^{\text{dir}}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{\text{ind}}, \quad (3)$$

where $\langle t \rangle$ is the average decay time in the reconstructed sample. Denoting by Δ the differences between quantities for $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ it is then possible to write

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+) \\ &= [a_{CP}^{\text{dir}}(K^- K^+) - a_{CP}^{\text{dir}}(\pi^- \pi^+)] + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\text{ind}}. \end{aligned} \quad (4)$$

In the limit that $\Delta\langle t \rangle$ vanishes, ΔA_{CP} is equal to the difference in the direct *CP* asymmetry between the two decays. However, if the time acceptance is different for the $K^- K^+$ and $\pi^- \pi^+$ final states, a contribution from indirect *CP* violation remains.

The most precise measurements to date of the time-integrated *CP* asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ were made by the CDF, *BABAR*, and Belle collaborations [10,13,14]. The Heavy Flavor Averaging Group (HFAG) has combined time-integrated and time-dependent measurements of *CP* asymmetries, taking account of the different decay time acceptances, to obtain world average values for the indirect *CP* asymmetry of $a_{CP}^{\text{ind}} = (-0.03 \pm 0.23)\%$ and the difference in direct *CP* asymmetry between the final states of $\Delta a_{CP}^{\text{dir}} = (-0.42 \pm 0.27)\%$ [3].

In this Letter, we present a measurement of the difference in time-integrated *CP* asymmetries between $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$, performed with 0.62 fb^{-1} of data collected at LHCb between March and June 2011. The flavor of the initial state (D^0 or $\bar{D}^0$) is tagged by requiring a $D^{*+} \to D^0 \pi_s^+$ decay, with the flavor determined by the charge of the slow pion (π_s^+). The inclusion

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of charge-conjugate modes is implied throughout, except in the definition of asymmetries.

The raw asymmetry for tagged D^0 decays to a final state f is given by $A_{\rm raw}(f)$, defined as

$$A_{\rm raw}(f) \equiv \frac{N(D^{*+} \to D^0(f)\pi_s^+) - N(D^{*-} \to \bar{D}^0(f)\pi_s^-)}{N(D^{*+} \to D^0(f)\pi_s^+) + N(D^{*-} \to \bar{D}^0(f)\pi_s^-)}, \quad (5)$$

where $N(X)$ refers to the number of reconstructed events of decay X after background subtraction.

To first order the raw asymmetries may be written as a sum of four components, due to physics and detector effects:

$$A_{\rm raw}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_P(D^{*+}). \quad (6)$$

Here, $A_D(f)$ is the asymmetry in selecting the D^0 decay into the final state f, $A_D(\pi_s^+)$ is the asymmetry in selecting the slow pion from the D^{*+} decay chain, and $A_P(D^{*+})$ is the production asymmetry for D^{*+} mesons. The asymmetries A_D and A_P are defined in the same fashion as $A_{\rm raw}$. The first-order expansion is valid since the individual asymmetries are small.

For a two-body decay of a spin-0 particle to a self-conjugate final state there can be no D^0 detection asymmetry, i.e., $A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$. Moreover, $A_D(\pi_s^+)$ and $A_P(D^{*+})$ are independent of f and thus in the first-order expansion of Eq. (5) those terms cancel in the difference $A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+)$, resulting in

$$\Delta A_{CP} = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+). \quad (7)$$

To minimize second-order effects that are related to the slightly different kinematic properties of the two decay modes and that do not cancel in ΔA_{CP}, the analysis is performed in bins of the relevant kinematic variables, as discussed later.

The LHCb detector is a forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, and is described in detail in Ref. [15]. The Ring Imaging Cherenkov (RICH) detectors are of particular importance to this analysis, providing kaon-pion discrimination for the full range of track momenta used. The nominal downstream beam direction is aligned with the $+z$ axis, and the field direction in the LHCb dipole is such that charged particles are deflected in the horizontal (xz) plane. The field polarity was changed several times during data taking: about 60% of the data were taken with the down polarity and 40% with the other.

Selections are applied to provide samples of $D^{*+} \to D^0\pi_s^+$ candidates, with $D^0 \to K^-K^+$ or $\pi^-\pi^+$. Events are required to pass both hardware and software trigger levels. A loose D^0 selection is applied in the final state of the software trigger, and in the offline analysis only candidates that are accepted by this trigger algorithm are considered. Both the trigger and offline selections impose a variety of requirements on kinematics and decay time to isolate the decays of interest, including requirements on the track fit quality, on the D^0 and D^{*+} vertex fit quality, on the transverse momentum ($p_T > 2$ GeV/c) and decay time ($p_T > 100$ m) of the D^0 candidate, on the angle between the D^0 momentum in the lab frame and its daughter momenta in the D^0 rest frame ($|\cos\theta| < 0.9$), that the D^0 trajectory points back to a primary vertex, and that the D^0 daughter tracks do not. In addition, the offline analysis exploits the capabilities of the RICH system to distinguish between pions and kaons when reconstructing the D^0 meson, with no tracks appearing as both pion and kaon candidates.

A fiducial region is implemented by imposing the requirement that the slow pion lies within the central part of the detector acceptance. This is necessary because the magnetic field bends pions of one charge to the left and those of the other charge to the right. For soft tracks at large angles in the xz plane this implies that one charge is much more likely to remain within the 300 mrad horizontal detector acceptance, thus making $A_D(\pi_s^+)$ large. Although this asymmetry is formally independent of the D^0 decay mode, it breaks the assumption that the raw asymmetries are small and it carries a risk of second-order systematic effects if the ratio of efficiencies of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ varies in the affected region. The fiducial requirements therefore exclude edge regions in the slow pion (p_x, p) plane. Similarly, a small region of phase space in which one charge of slow pion is more likely to be swept into the beampipe region in the downstream tracking stations, and hence has reduced efficiency, is also excluded. After the implementation of the fiducial requirements about 70% of the events are retained.

The invariant mass spectra of selected K^-K^+ and $\pi^-\pi^+$ pairs are shown in Fig. 1. The half width at half maximum of the signal line shape is 8.6 MeV/c^2 for K^-K^+ and 11.2 MeV/c^2 for $\pi^-\pi^+$, where the difference is due to the kinematics of the decays and has no relevance for the subsequent analysis. The mass difference (δm) spectra of selected candidates, where $\delta m \equiv m(h^-h^+\pi_s^+) - m(h^-h^+) - m(\pi^+)$ for $h = K,\ \pi$, are shown in Fig. 2. Candidates are required to lie inside a wide δm window of 0–15 MeV/c^2, and in Fig. 2 and for all subsequent results candidates are in addition required to lie in a mass signal window of 1844–1884 MeV/c^2. The D^{*+} signal yields are approximately 1.44×10^6 in the K^-K^+ sample, and 0.38×10^6 in the $\pi^-\pi^+$ sample. Charm from b-hadron decays is strongly suppressed by the requirement that the D^0 originate from a primary vertex, and accounts for only 3% of the total yield. Of the events that contain at least one D^{*+} candidate, 12% contain more than one candidate; this is expected due to background soft pions from the primary vertex and all candidates are accepted. The background-subtracted average decay time of D^0 candidates passing the selection is measured for each final state, and the fractional difference $\Delta\langle t\rangle/\tau$ is obtained.

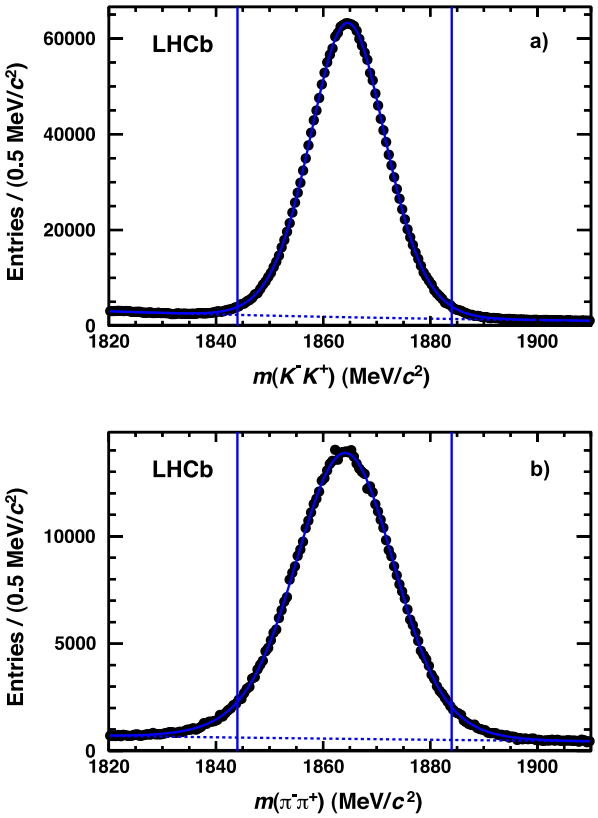

FIG. 1 (color online). Fits to the (a) $m(K^-K^+)$ and (b) $m(\pi^-\pi^+)$ spectra of D^{*+} candidates passing the selection and satisfying $0 < \delta m < 15$ MeV/c^2. The dashed line corresponds to the background component in the fit, and the vertical lines indicate the signal window of 1844–1884 MeV/c^2.

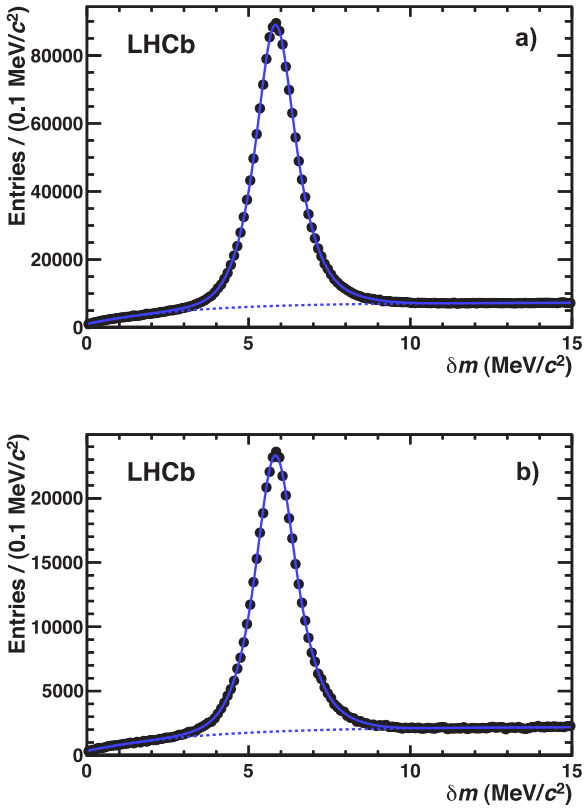

FIG. 2 (color online). Fits to the δm spectra, where the D^0 is reconstructed in the final states (a) K^-K^+ and (b) $\pi^-\pi^+$, with mass lying in the window of 1844–1884 MeV/c^2. The dashed line corresponds to the background component in the fit.

Systematic uncertainties on this quantity are assigned for the uncertainty on the world average D^0 lifetime τ (0.04%), charm from b-hadron decays (0.18%), and the background-subtraction procedure (0.04%). Combining the systematic uncertainties in quadrature, we obtain $\Delta\langle t\rangle/\tau = [9.83 \pm 0.22(\text{stat}) \pm 0.19(\text{syst})]\%$. The $\pi^-\pi^+$ and K^-K^+ average decay time is $\langle t\rangle = (0.8539 \pm 0.0005)$ ps, where the error is statistical only.

Fits are performed on the samples in order to determine $A_{\text{raw}}(K^-K^+)$ and $A_{\text{raw}}(\pi^-\pi^+)$. The production and detection asymmetries can vary with p_T and pseudorapidity η, and so can the detection efficiency of the two different D^0 decays, in particular, through the effects of the particle identification requirements. The analysis is performed in 54 kinematic bins defined by the p_T and η of the D^{*+} candidates, the momentum of the slow pion, and the sign of p_x of the slow pion at the D^{*+} vertex. The events are further partitioned in two ways. First, the data are divided between the two dipole magnet polarities. Second, the first 60% of data are processed separately from the remainder, with the division aligned with a break in data taking due to an LHC technical stop. In total, 216 statistically independent measurements are considered for each decay mode.

In each bin, one-dimensional unbinned maximum likelihood fits to the δm spectra are performed. The signal is described as the sum of two Gaussian functions with a common mean μ but different widths σ_i, convolved with a function $B(\delta m; s) = \Theta(\delta m)\delta m^s$ taking account of the asymmetric shape of the measured δm distribution. Here, $s \simeq -0.975$ is a shape parameter fixed to the value determined from the global fits shown in Fig. 2, Θ is the Heaviside step function, and the convolution runs over δm. The background is described by an empirical function of the form $1 - e^{-(\delta m - \delta m_0)/\alpha}$, where δm_0 and α are free parameters describing the threshold and shape of the function, respectively. The D^{*+} and D^{*-} samples in a given bin are fitted simultaneously and share all shape parameters, except for a charge-dependent offset in the central value μ and an overall scale factor in the mass resolution. The raw asymmetry in the signal yields is extracted directly from this simultaneous fit. No fit parameters are shared between the 216 subsamples of data, nor between the K^-K^+ and $\pi^-\pi^+$ final states.

The fits do not distinguish between the signal and backgrounds that peak in δm. Such backgrounds can arise from D^{*+} decays in which the correct slow pion is found but the

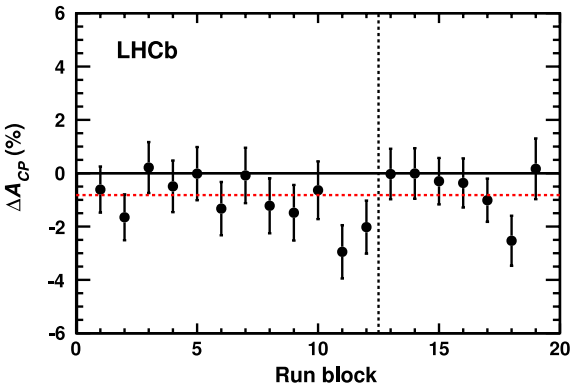

FIG. 3 (color online). Time dependence of the measurement. The data are divided into 19 disjoint, contiguous, time-ordered blocks and the value of ΔA_{CP} measured in each block. The horizontal red dashed line shows the result for the combined sample. The vertical dashed line indicates the technical stop referred to in Table I.

D^0 is partially misreconstructed. These backgrounds are suppressed by the use of tight particle identification requirements and a narrow D^0 mass window. From studies of the D^0 mass sidebands (1820–1840 and 1890–1910 MeV/c^2), this contamination is found to be approximately 1% of the signal yield and to have small raw asymmetry (consistent with zero asymmetry difference between the K^-K^+ and $\pi^-\pi^+$ final states). Its effect on the measurement is estimated in an ensemble of simulated experiments and found to be negligible; a systematic uncertainty is assigned below based on the statistical precision of the estimate.

A value of ΔA_{CP} is determined in each measurement bin as the difference between $A_{\rm raw}(K^-K^+)$ and $A_{\rm raw}(\pi^-\pi^+)$. Testing these 216 measurements for mutual consistency, we obtain $\chi^2/{\rm ndf} = 211/215$ (χ^2 probability of 56%). A weighted average is performed to yield the result $\Delta A_{CP} = (-0.82 \pm 0.21)\%$, where the uncertainty is statistical only.

Numerous robustness checks are made. The value of ΔA_{CP} is studied as a function of the time at which the data were taken (Fig. 3) and found to be consistent with a constant value (χ^2 probability of 57%). The measurement is repeated with progressively more restrictive RICH particle identification requirements, finding values of $(-0.88 \pm 0.26)\%$ and $(-1.03 \pm 0.31)\%$; both of these values are consistent with the baseline result when correlations are taken into account. Table I lists ΔA_{CP} for eight disjoint subsamples of data split according to magnet polarity, the sign of p_x of the slow pion, and whether the data were taken before or after the technical stop. The χ^2 probability for consistency among the subsamples is 45%. The significances of the differences between data taken before and after the technical stop, between the magnet polarities, and between $p_x > 0$ and $p_x < 0$ are 0.4, 0.6, and 0.7 standard deviations, respectively. Other checks include applying electron and muon vetoes to the slow pion and to the D^0 daughters, use of different kinematic binnings, validation of the size of the statistical uncertainties with Monte Carlo pseudoexperiments, tightening of kinematic requirements, testing for variation of the result with the multiplicity of tracks and of primary vertices in the event, use of other signal and background parameterizations in the fit, and imposing a full set of common shape parameters between D^{*+} and D^{*-} candidates. Potential biases due to the inclusive hardware trigger selection are investigated with the subsample of data in which one of the signal final-state tracks is directly responsible for the hardware trigger decision. In all cases good stability is observed. For several of these checks, a reduced number of kinematic bins are used for simplicity. No systematic dependence of ΔA_{CP} is observed with respect to the kinematic variables.

Systematic uncertainties are assigned by loosening the fiducial requirement on the slow pion, assessing the effect of potential peaking backgrounds in Monte Carlo pseudoexperiments, repeating the analysis with the asymmetry extracted through sideband subtraction in δm instead of a fit, removing all candidates but one (chosen at random) in events with multiple candidates, and comparing with the result obtained without kinematic binning. In each case the

TABLE I. Values of ΔA_{CP} measured in subsamples of the data, and the $\chi^2/{\rm ndf}$ and corresponding χ^2 probabilities for internal consistency among the 27 bins in each subsample. The data are divided before and after a technical stop (TS), by magnet polarity (up, down), and by the sign of p_x for the slow pion (left, right). The consistency among the eight subsamples is $\chi^2/{\rm ndf} = 6.8/7$ (45%).

Subsample	ΔA_{CP}[%]	χ^2/ndf
Pre-TS, up, left	-1.22 ± 0.59	13/26(98%)
Pre-TS, up, right	-1.43 ± 0.59	27/26(39%)
Pre-TS, down, left	-0.59 ± 0.52	19/26(84%)
Pre-TS, down, right	-0.51 ± 0.52	29/26(30%)
Post-TS, up, left	-0.79 ± 0.90	26/26(44%)
Post-TS, up, right	$+0.42 \pm 0.93$	21/26(77%)
Post-TS, down, left	-0.24 ± 0.56	34/26(15%)
Post-TS, down, right	-1.59 ± 0.57	35/26(12%)
All data	-0.82 ± 0.21	211/215(56%)

TABLE II. Summary of absolute systematic uncertainties for ΔA_{CP}.

Source	Uncertainty
Fiducial requirement	0.01%
Peaking background asymmetry	0.04%
Fit procedure	0.08%
Multiple candidates	0.06%
Kinematic binning	0.02%
Total	0.11%

full value of the change in result is taken as the systematic uncertainty. These uncertainties are listed in Table II. The sum in quadrature is 0.11%. Combining statistical and systematic uncertainties in quadrature, this result is consistent at the 1σ level with the current HFAG world average [3].

In conclusion, the time-integrated difference in CP asymmetry between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays has been measured to be

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\%$$

with 0.62 fb^{-1} of 2011 data. Given the dependence of ΔA_{CP} on the direct and indirect CP asymmetries, shown in Eq. (4), and the measured value $\Delta\langle t\rangle/\tau = [9.83 \pm 0.22(\text{stat}) \pm 0.19(\text{syst})]\%$, the contribution from indirect CP violation is suppressed and ΔA_{CP} is primarily sensitive to direct CP violation. Dividing the central value by the sum in quadrature of the statistical and systematic uncertainties, the significance of the measured deviation from zero is 3.5σ. This is the first evidence for CP violation in the charm sector. To establish whether this result is consistent with the SM will require the analysis of more data, as well as improved theoretical understanding.

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