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# CHARM PHYSICS IN THE LHCB EXPERIMENT, FIRST EVIDENCE FOR CP VIOLATION IN CHARM DECAYS*

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A search for the time integrated CP violation in the $D^0 \to h^- h^+$ ($h = K, \pi$) decays is presented using 0.62 fb$^{-1}$ of data collected by the LHCb experiment in 2011. The flavour of the charm meson is determined by the charge of the slow pion in the $D^{*+} \to D^0\pi^+$ and the $D^{*-} \to \bar{D}^0\pi^-$ decays chain. The difference in CP asymmetry between the $D^0 \to K^-K^+$ and the $D^0 \to \pi^-\pi^+$, $\Delta A_{\rm CP} \equiv A_{\rm CP}(K^-K^+) - A_{\rm CP}(\pi^-\pi^+)$, is measured to be $[-0.82 \pm 0.21({\rm stat}) \pm 0.11({\rm syst})]\%$. This differs from the hypothesis of CP conservation by 3.5 standard deviations. An additional search for the time integrated CP violation in the Cabibbo suppressed decay $D^+ \to K^-K^+\pi^+$ is also presented. Here no evidence for CP asymmetry is found using a model independent method. The data used here was collected by the LHCb experiment in 2010 and corresponds to an integrated luminosity of 35 pb$^{-1}$. The normalized Dalitz plot distributions for the $D^+$ and the $D^-$ are compared using two different binning schemes that are sensitive to different manifestations of CP violation.

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## 1. Introduction

To date CP violation (CPV) has been observed only in decays of neutral $K$ and $B$ mesons. All observations are consistent with CP violation being generated by the phase in the Cabibbo–Kobayashi–Maskawa (CKM) matrix of the Standard Model (SM). The charm sector is a promising place to probe for the effects of physics beyond the SM. There has been a resurgence of interest in the past few years since evidence for the $D^0$ mixing was first seen

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[1,2,3]. No evidence for CPV in charm decays has yet been found. LHCb [4] is a precision heavy flavour experiment which exploits the abundance of the charm particles produced in LHC collisions to acquire large samples of the $D$ decays.

Methods of CPV measurements can be grouped into two types, as the time dependent and the time integrated measurements. The time dependent measurements provide information about CP violation in mixing and in interference. Such measurements were done in LHCb and they are not presented in this paper [5]. The time integrated measurements provide information about CPV in decays and in mixing. This contribution focuses on the study of the time integrated CP asymmetry in the decays of $D^0 \to h^-h^+$, where $h = K, \pi$ and the $D^+ \to K^-K^+\pi^+$ recorded in LHCb detector. The measurements are discussed in Secs. 2 and 3, respectively.

## 2. Evidence for CPV in $D^0 \to h^-h^+$ decays

In this section, a measurement of the difference in the time integrated CP asymmetries between the $D^0 \to K^-K^+$ and the $D^0 \to \pi^-\pi^+$ is presented. This measurement is performed with 0.62 fb$^{-1}$ of data collected in LHCb between March and June 2011.

The time integrated CP asymmetry has two contributions: an indirect and a direct components. An indirect component is universal for CP eigenstates in the SM and it is expected to be small. A direct component is in general different for different final states. In the SM direct CPV in the $D^0 \to K^-K^+$ and the $D^0 \to \pi^-\pi^+$ decays is expected to be $10^{-3}$ or less [6]. However, in the presence of the New Physics, the rate of CPV could be enhanced. Although values of 1% or more in these final states are now excluded experimentally an observation of larger then expected asymmetry would be a hint of the New Physics.

### *2.1. Formalism*

The analysed $D^0$ decays are reconstructed as a part of a $D^{*+} \to D^0\pi^+$ decay chain. To first order the raw time integrated asymmetry may be written as a sum of various components, coming from both physics and detector effects

$$A_{\rm RAW}(f) = A_{\rm CP}(f) + A_D(f) + A_D\left(\pi_{\rm s}^+\right) + A_{\rm P}\left(D^{*+}\right) .$$

Here $A_{\rm CP}(f)$ is the intrinsic physics CP asymmetry, $A_D(f)$ is the asymmetry for selecting the $D^0$ decay into the final state $f$, $A_D(\pi_{\rm s}^+)$ is the asymmetry for selecting a slow pion from the $D^{*+}$ decay chain, and $A_{\rm P}(D^{*+})$ is the production asymmetry for the $D^{*+}$ mesons. All asymmetries $A_{\mathrm{CP}}$, $A_D$ and $A_{\mathrm{P}}$ are defined in the same fashion as $A_{\mathrm{RAW}}$, such that, for example

$$A_{\mathrm{P}}\left(D^0\right) = \frac{N_P\left(D^0\right) - N_P\left(\bar{D}^0\right)}{N_P\left(D^0\right) + N_P\left(\bar{D}^0\right)},$$

where $N_P(D^0/\bar{D}^0)$ is the number of observed $D^0/\bar{D}^0$ decays.

For a two body decays of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ , the final states are symmetric and there can be no $D^0$ detection asymmetries, *i.e.* $A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$. The asymmetries $A_D(\pi_{\mathrm{s}}^+)$ and $A_{\mathrm{P}}(D^{*+})$ are independent of $f$ and thus in the first order those terms cancel in the difference $A_{\mathrm{RAW}}(K^-K^+) - A_{\mathrm{RAW}}(\pi^-\pi^+)$, leaving a quantity, defined as $\Delta A_{\mathrm{CP}}$, which equals to the difference in physics CP asymmetries

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{RAW}}\left(K^-K^+\right) - A_{\mathrm{RAW}}\left(\pi^-\pi^+\right) = A_{\mathrm{CP}}\left(K^-K^+\right) - A_{\mathrm{CP}}\left(\pi^-\pi^+\right).$$

The quantity $\Delta A_{\mathrm{CP}}$ allows 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 subtraction. To check that there are no second order effects, the analysis is performed in bins of the relevant kinematic variables.

### *2.2. Data set and selection*

The flavour of the initial state (the $D^0$ and the $\bar{D}^0$) is tagged by requiring a $D^{*+} \to D^0\pi_{\mathrm{s}}^+$ decay, with the flavour determined by the charge of the slow pion ($\pi_{\mathrm{s}}^+$). So the selections are applied to provide samples of a $D^{*+} \to D^0\pi_{\mathrm{s}}^+$ candidates with the $D^0 \to K^-K^+$ or the $D^0 \to \pi^-\pi^+$. The selections impose a variety of requirements on kinematics and decay time to isolate the decays of interest, including requirements on the track quality, on the vertex fit quality, on the transverse momentum, on the angle between the $D^0$ momentum in the lab frame and its daughters' momenta in the rest frame. The selection is described in details in [7].

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 the $K^-K^+$ and 11.2 MeV$/c^2$ for the $\pi^-\pi^+$. The mass difference spectra of selected candidates, $\delta m \equiv m(h^-h^+\pi_{\mathrm{s}}^+) - m(h^-h^+) - m(\pi^+)$ for $h = K, \pi$, are shown in Fig. 2. The candidates are required to lie inside a wide $\delta m$ window of 0–15 MeV$/c^2$ and a mass signal window of 1844–1884 MeV$/c^2$. The $D^{*+}$ signal yields are approximately $1.44 \times 10^6$ in the $K^-K^+$ sample and $0.38 \times 10^6$ in the $\pi^-\pi^+$ sample.

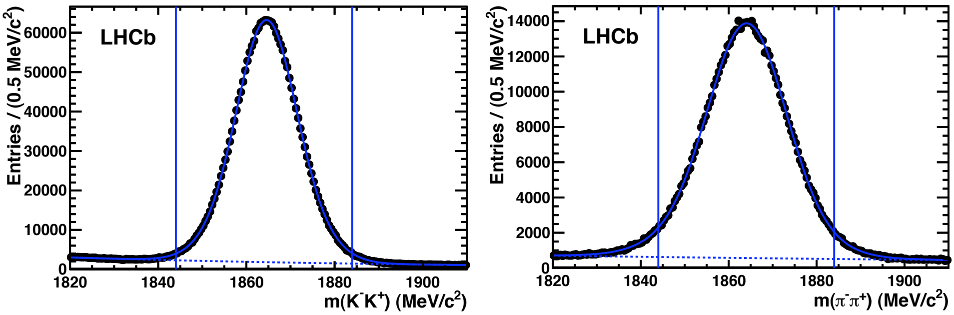


Fig. 1. Fits to the $m(K^-K^+)$ (left) and the $m(\pi^-\pi^+)$ (right) spectra of $D^{*+}$ candidates passing the selection and satisfying $0 < \delta m < 15$ MeV$/c^2$, where $\delta m \equiv m(h^-h^+\pi_{\rm s}^+) - m(h^-h^+) - m(\pi^+)$ for $h = K, \pi$. The dashed line corresponds to the background component in the fit and the vertical lines indicate the signal window of 1844–1884 MeV$/c^2$.

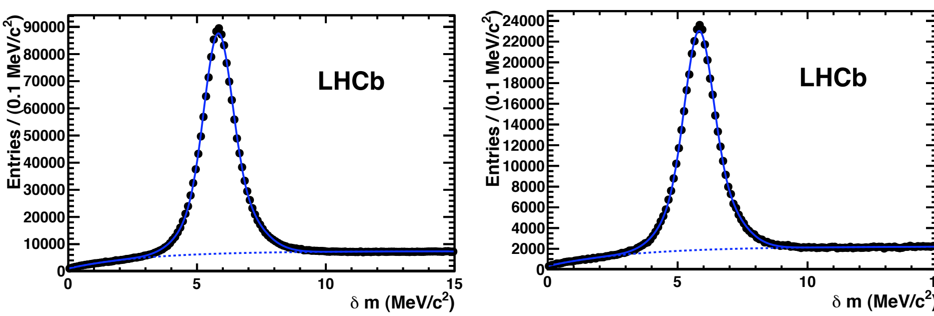


Fig. 2. Fits to the mass difference spectra, $\delta m \equiv m(h^-h^+\pi_{\rm s}^+) - m(h^-h^+) - m(\pi^+)$ for $h = K, \pi$, where the $D^0$ is reconstructed in the final states $K^-K^+$ (left) and $\pi^-\pi^+$ (right), with a $D^0$ mass lying in the window 1844–1884 MeV$/c^2$.

### *2.3. Results and systematic uncertainties*

The value of $\Delta A_{\rm CP}$ is determined using the results for $A_{\rm RAW}(K^-K^+)$ and $A_{\rm RAW}(\pi^-\pi^+)$, which are taken from the fits to the mass difference spectra of selected $K^-K^+$ and $\pi^-\pi^+$ pairs. The production and the detection asymmetries can vary with $p_{\rm T}$ and pseudorapidity, $\eta$, and so can the detection efficiency of the two different $D^0$ decays. For this reason the analysis is performed in 54 kinematic bins, divided by the $p_{\rm T}$ and the $\eta$ of the $D^{*+}$ candidates, the momentum of the slow pion, and whether the initial trajectory of the slow pion is in the left or right direction. Further the events are separately processed for the two dipole magnet polarities and for 60% of data from the remainder with the division aligned with a break in data taking due to an LHC technical stop. In total, there are 216 statistically independent measurements for each decay mode. In each bin, one dimensional unbinned maximum likelihood fits to the $\delta m$ spectra are performed. The $D^{*+}$ and the $D^{*-}$ samples in a given bin are fitted simultaneously and share all shape parameters. The raw asymmetry in the signal yield is extracted directly from this simultaneous fit. No fit parameters are shared between the 216 subsamples of data, nor between a $K^-K^+$ and a $\pi^-\pi^+$ final states. A value of $\Delta A_{\rm CP}$ is determined in each measured bin as the difference between $A_{\rm RAW}(K^-K^+)$ and $A_{\rm RAW}(\pi^-\pi^+)$. The value of $\Delta A_{\rm CP}$ is found to be consistent in all bins and in all cases good stability is observed. No systematic dependence of $\Delta A_{\rm CP}$ is observed with respect to the kinematic variables. A weighted average is performed to yield the result

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

Systematic uncertainties are assigned by loosening the selection criteria, repeating the analysis with the asymmetry extracted through the sideband subtraction in a $\delta m$ 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.

Combining statistical and systematic uncertainties in quadrature, the result is consistent at the $1\sigma$ level with the current HFAG world average [8]. Dividing the central value by the sum in quadrature of the statistical and systematic uncertainties, the significance of the measured deviation from zero is $3.5\sigma$. This is the first evidence for CPV in the charm sector.

### *2.4. Result interpretation*

The physics asymmetry of each final state, $A_{\rm CP}(f)$, 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. The time integrated asymmetry measured by an experiment, $A_{\rm CP}(f)$, depends upon the time acceptance of its detector. It can be written to first order as [9]

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

where $a_{\rm CP}^{\rm dir}(f)$ is direct CPV for the decay, $\langle t\rangle$ is average proper time in the reconstructed sample, $\tau$ is a $D^0$ lifetime, and $a_{\rm CP}^{\rm ind}$ is an indirect CPV coming from the mixing and/or the interference between mixing and decay.

Denoting by $\Delta$ the difference between quantities for the $D^0 \to K^-K^+$ and the $D^0 \to \pi^-\pi^+$, it is then possible to write

$$\begin{aligned} \Delta A_{\rm CP} &\equiv A_{\rm CP}\left(K^-K^+\right) - A_{\rm CP}\left(\pi^-\pi^+\right) \\ &= \left[a_{\rm CP}^{\rm dir}\left(K^-K^+\right) - a_{\rm CP}^{\rm dir}\left(\pi^-\pi^+\right)\right] + \frac{\Delta\langle t\rangle}{\tau} a_{\rm CP}^{\rm ind} , \end{aligned}$$

where $\Delta\langle t\rangle$ is the difference in average proper time of the $D^0$ mesons in the $K^-K^+$ and the $\pi^-\pi^+$ samples. In the limit that $\Delta\langle t\rangle$ vanishes, $\Delta A_{\rm CP}$ probes the difference in direct CPV between the two decays.

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 as $\Delta\langle t\rangle/\tau = [9.83 \pm 0.22({\rm stat}) \pm 0.19({\rm syst})]\%$. The $\pi^-\pi^+$ and the $K^-K^+$ average decay time is $\langle t\rangle = (0.8539 \pm 0.0005)$ ps, where the error is statistical only.

Given the dependence of $\Delta A_{\rm CP}$ on direct and indirect CP asymmetries, the contribution from an indirect CPV is suppressed here in one order of magnitude and $\Delta A_{\rm CP}$ is primarily sensitive to a direct CPV.

## 3. Search for CPV in $D^+ \to K^-K^+\pi^+$ decays

In decays of hadrons, CPV can be observed when two different amplitudes with non-zero relative weak and strong phases contribute coherently to a final state. Three body decays are dominated by an intermediate resonant states. The interference between resonances in the two dimensional phase space can lead to observable asymmetries which vary across the Dalitz plot for the Cabibbo suppressed decay $D^+ \to K^-K^+\pi^+$ which is treated as a signal decay because in these decays CPV is expected to be measured. In contrast, such asymmetries are investigated in the two control channels, the $D_s^+ \to K^-K^+\pi^+$ and the $D^+ \to K^-\pi^+\pi^+$, where the differences between the $D^+$ and the $D^-$ caused by CPV are not expected.

Previously, CPV using the Dalitz plot asymmetries in three body charm decays were investigated in BaBar [10], CLEO-c [11] and BELLE [12] experiments. To date CPV has not been observed in these $D$ meson decays.

### *3.1. Strategy of the analysis*

A direct comparison between the $D^+$ and the $D^-$ Dalitz plots is made on a bin-by-bin basis. For each bin in Dalitz plot, a local CP asymmetry variable is defined as [13]

$$S^i_{\rm CP} = \frac{N^i\left(D^+\right) - \alpha N^i\left(D^-\right)}{\sqrt{N^i\left(D^+\right) + \alpha^2 N^i\left(D^-\right)}}\,,$$

where $N^i(D^+)$ and $N^i(D^-)$ are the numbers of $D^+$ and $D^-$ candidates in the $i$th bin and $\alpha$ parameter is a ratio between the total reconstructed the $D^+$ and the $D^-$ candidates

$$\alpha = \frac{N_{\rm tot}\left(D^+\right)}{N_{\rm tot}\left(D^-\right)}\,.$$

The $\alpha$ parameter accounts for global asymmetries which is a constant across the Dalitz plot.

In the absence of the Dalitz plot dependent asymmetries, the $S^i_{\rm CP}$ values are distributed according to a Gaussian distribution with zero mean and unit with. The CPV signals are deviations from this behaviour. The numerical comparison between the $D^+$ and the $D^-$ is made with a $\chi^2$ test ($\chi^2 = \Sigma(S^i_{\rm CP})^2$), where a $p$-value is calculated.

The method depends on the number of bins in the Dalitz plot. In our search for localized asymmetries, two types of binning scheme are employed. The first type is simply an uniform grid of equally sized bins. The second type "adaptive binning" scheme uses smaller bins where the density of events is high, aiming for a uniform bin population. In each scheme, the different numbers of bins were taken into account.

### *3.2. Event selections*

In this study, the data sample used is approximately 35 pb$^{-1}$, collected in 2010 using the LHCb detector. The event selection is based on many cuts, as for example a cut on a relative log-likelihood for pion and kaon hypothesis, a cut on a fit quality for each particle reconstructed in the final state, a cut on a primary and a secondary vertex reconstruction and a cut on a flight distance variable. The full description of the selection can be found in [14].

The reconstructed invariant mass distributions of the $K^-\pi^+\pi^+$ and the $K^-K^+\pi^+$ are shown in Fig. 3. From the simultaneous fit to the invariant mass distributions of the $D^+$ and the $D^-$, the signal yields are extracted. A double Gaussian fit is used for the $K^-K^+\pi^+$ signal, whilst the background is described by a quadratic component and a single Gaussian for the small contamination from the $D^{*+} \to D^0(K^-K^+)\pi^+$ above the $D_s^+$ peak. A weighted mean of the widths of the two Gaussian contributions to the mass peak is used to determine the overall widths, $\sigma$, as 6.35 MeV$/c^2$ for the

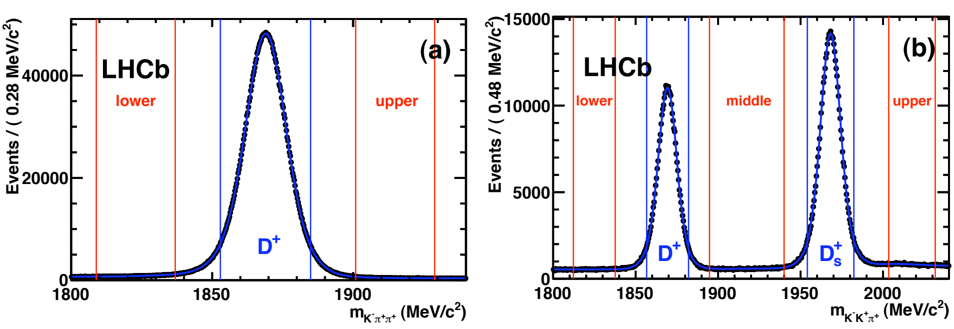


Fig. 3. Fitted mass spectra of (a) $K^-\pi^+\pi^+$ and (b) $K^-K^+\pi^+$ candidates. The signal mass windows and sidebands defined in the text are labelled.

$D^+ \to K^-K^+\pi^+$, 7.05 MeV$/c^2$ for the $D_s^+ \to K^-K^+\pi^+$ and 8.0 MeV$/c^2$ for the $D^+ \to K^-\pi^+\pi^+$. These values are used to define the signal mass windows of approximately $2\sigma$ in which the Dalitz plots are constructed. The total number of candidates (the signal and the background) in the signal windows are 403 894 for the $D^+ \to K^-K^+\pi^+$, 563 938 for the $D_s^+ \to K^-K^+\pi^+$ and 383 9868 for the $D^+ \to K^-\pi^+\pi^+$. Within $2\sigma$ $D^+ \to K^-K^+\pi^+$ mass window from 1856.7 to 1882.1 MeV$/c^2$, about 8.6% of events are the background and there are 200 336 and 203 558 the $D^+$ and the $D^-$ candidates. The purities vary from 90% to 98%. The Dalitz plot of data in the $D^+$ window is shown in Fig. 4.

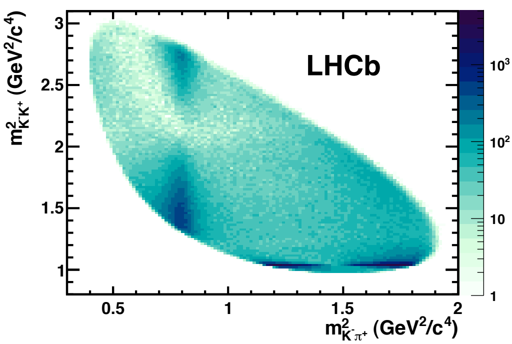


Fig. 4. Dalitz plot of the $D^+ \to K^-K^+\pi^+$ decay for selected candidates in the signal window. The vertical $\bar{K}^*(892)^0$ and horizontal $\phi(1020)$ contributions are clearly visible in the data.

### *3.3. Results*

It was checked that using the method in the control channels $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to K^-K^+\pi^+$ and in the sidebands of the $K^-K^+\pi^+$ mass spectrum the local asymmetries are not visible [14]. Thus the method can be used in the signal sample to search for localized asymmetries. The results for the signal decays of the $S^i_{\rm CP}$ distribution are shown in Fig. 5 for two binning schemes: different size and different bin numbers, 25 bins (Adaptive I) and 106 bins (Adaptive II) and different number of equal size bins, 200 bins (Uniform I) and 530 bins (Uniform II). For each of these binning choices, the significance $S^i_{\rm CP}$ of the differences in the $D^+$ and the $D^-$ population is computed for each bin $i$. The $\chi^2/\mathrm{ndf} = \Sigma(S^i_{\rm CP})^2/\mathrm{ndf}$ is calculated and the $p$-value is obtained. The distributions of $S^i_{\rm CP}$ are fitted to the Gaussian functions. The results are presented in Table I. The calculated $p$-values are above 10% and the fits are consistent with the Gaussian distributions, with the means and widths consistent with 0 and 1, respectively. The $p$-values and the fits obtained here indicate that there is no evidence for CPV in analysed sample of the $D^+ \to K^-K^+\pi^+$.

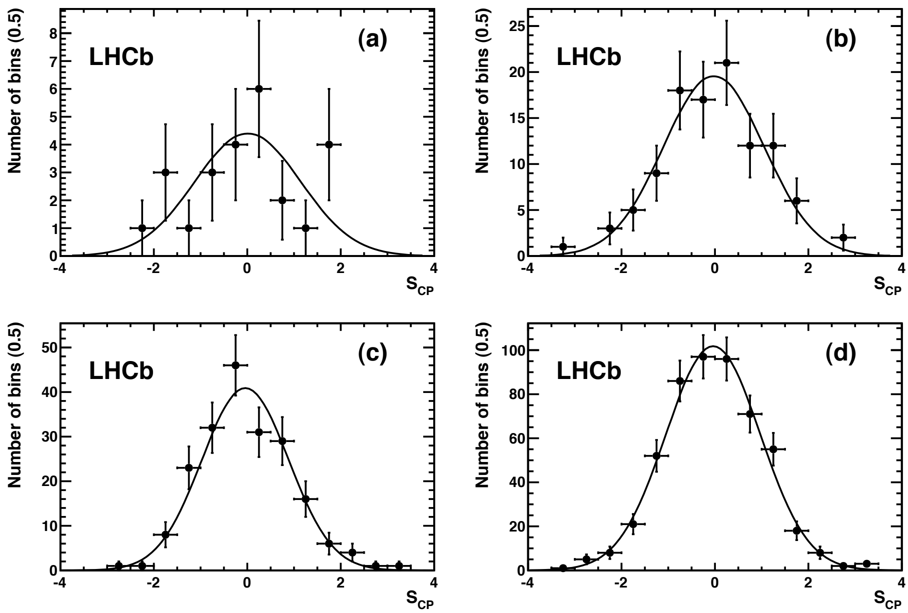


Fig. 5. Distribution of $S^i_{\mathrm{CP}}$ fitted to Gaussian functions for (a) Adaptive I, (b) Adaptive II, (c) Uniform I and (d) Uniform II.

TABLE I

Fitted means and widths, $\chi^2$/ndf and $p$-values for consistency with no CPV for the $D^+ \to K^-K^+\pi^+$ decay mode with four different binnings.

| Binning | Fitted mean | Fitted width | $\chi^2$/ndf | $p$-value (%) |
|---|---|---|---|---|
| Adaptive I | $0.01 \pm 0.23$ | $1.13 \pm 0.16$ | 32.0/24 | 12.7 |
| Adaptive II | $-0.024 \pm 0.010$ | $1.078 \pm 0.074$ | 123.4/105 | 10.6 |
| Uniform I | $-0.043 \pm 0.073$ | $0.929 \pm 0.051$ | 191.3/198 | 82.1 |
| Uniform II | $-0.039 \pm 0.045$ | $1.011 \pm 0.034$ | 519.5/529 | 60.5 |

## 4. Conclusion

LHCb has measured the time integrated difference in CP asymmetry between the $D^0 \to K^-K^+$ and the $D^0 \to \pi^-\pi^+$ decays

$$\Delta A_{\mathrm{CP}} = \left[a^{\mathrm{dir}}_{\mathrm{CP}}\left(K^-K^+\right) - a^{\mathrm{dir}}_{\mathrm{CP}}\left(\pi^-\pi^+\right)\right] + 0.10 a^{\mathrm{ind}}_{\mathrm{CP}}\,,$$

to be

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

The measured $\Delta A_{\rm CP}$ is mainly sensitive to the presence of a direct CPV and highly suppresses systematic uncertainties from the instrumental asymmetries. The measurement was performed with 0.62 fb$^{-1}$ of data collected in LHCb between March and June 2011. Dividing the central value by the sum in quadrature of the statistical and systematic uncertainties, the significance of the measured deviation from zero is $3.5\sigma$. This is the first evidence for CPV in the charm sector.

Using a model independent search for a direct CPV in the Cabibbo suppressed decay $D^+ \to K^- K^+ \pi^+$ with 35 pb$^{-1}$ of data no evidence for CPV is found.

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