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Observation of direct CP violation in D^0 meson decays at LHCb

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Summary. — A search for charge-parity (CP) violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is reported, using pp collision data corresponding to an integrated luminosity of 5.9 fb^{-1} collected at a center-of-mass energy of 13 TeV with the LHCb detector. The flavor of the D^0 meson is determined from the charge of the pion in $D^*(2010)^+ \to D^0\pi^+$ decays or from the charge of the muon in $\overline{B} \to D^0\mu^-\bar{\nu}_\mu X$ decays. The difference between the CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is measured to be $\Delta A_{CP} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$ for π-tagged and $\Delta A_{CP} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$ for μ-tagged D^0 mesons. The combination with previous LHCb results leads to $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$, where the uncertainty includes both statistical and systematic contributions. The measured value differs from zero by more than five standard deviations, corresponding to the first observation of CP violation in the decay of charm hadrons.

1. – Introduction

A necessary condition for the generation of the baryon asymmetry of the universe is the noninvariance of fundamental interactions under the combined action of charge conjugation (C) and parity (P) transformations [1]. Even if CP violation is envisaged by the Standard Model (SM) of particle physics through an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [2,3], its size is too small to account for the observed matter-antimatter asymmetry [4,5], suggesting the existence of sources of CP violation in some new physics processes.

While the presence of CP violation has been experimentally established, and well interpreted within the CKM formalism, in weak decays of the K- and B-meson systems [6-14], the observation of CP violation in the charm sector has not yet been achieved. Due to the presence of low-energy strong-interaction effects, theoretical predictions of CP asymmetries in charm decays are difficult to compute, and they are expected to have magnitude of the order of 10^{-4}–10^{-3} [15-33]. CP asymmetries have been measured to be consistent with zero within a few per mille precision in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$

decays([1]) by the BaBar [34], Belle [35], CDF [36, 37] and LHCb [38-42] Collaborations. This document reports a measurement of the difference of the time-integrated *CP* asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, performed using $p\,p$ collision data collected with the LHCb detector between 2015 and 2018 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $5.9\,\mathrm{fb}^{-1}$.

The time-integrated *CP* asymmetry, $A_{CP}(f)$, between states produced as D^0 or $\overline{D}^0$ mesons decaying to a *CP* eigenstate f is defined as

$$A_{CP}(f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}, \tag{1}$$

where Γ denotes the time-dependent rate of a given decay. The difference between *CP* asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+). \tag{2}$$

The flavor at production of D^0 mesons considered in this analysis is obtained from the charge of the accompanying pion (π-tagged) in the strong $D^*(2010)^+ \to D^0\pi^+$ decay([2]), with the D^{*+} produced at a $p\,p$ collision point (primary vertex, PV), or from the charge of the accompanying muon (μ-tagged) in semileptonic $\overline{B} \to D^0\mu^-\bar{\nu}_\mu X$ decays. The raw asymmetries measured for π-tagged and μ-tagged D^0 decays are defined as

$$\begin{aligned} A_{\text{raw}}^{\pi\text{-tagged}}(f) &\equiv \frac{N\left(D^{*+} \to D^0(f)\pi^+\right) - N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)}{N\left(D^{*+} \to D^0(f)\pi^+\right) + N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)}, \\ A_{\text{raw}}^{\mu\text{-tagged}}(f) &\equiv \frac{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) - N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)}{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) + N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)}, \end{aligned} \tag{3}$$

where N is the measured signal yield for each given decay. These can be approximated as

$$\begin{aligned} A_{\text{raw}}^{\pi\text{-tagged}}(f) &\approx A_{CP}(f) + A_{\mathrm{D}}(\pi) + A_{\mathrm{P}}(D^*), \\ A_{\text{raw}}^{\mu\text{-tagged}}(f) &\approx A_{CP}(f) + A_{\mathrm{D}}(\mu) + A_{\mathrm{P}}(B), \end{aligned} \tag{4}$$

where $A_{\mathrm{P}}(D^*)$ and $A_{\mathrm{P}}(B)$ are the production asymmetries of D^* mesons and b hadrons due to hadronization of charm and beauty quarks in $p\,p$ collisions, whereas $A_{\mathrm{D}}(\pi)$ and $A_{\mathrm{D}}(\mu)$ are detection asymmetries due to different reconstruction efficiencies between positive and negative tagging particles. The approximations in eqs. (4) are valid up to corrections of $\mathcal{O}(10^{-6})$, because the involved terms, averaged over phase space for selected events, are $\mathcal{O}(10^{-2})$ or less [43-46]. Since the values of the detection and production asymmetries are independent of the final state f, they cancel in the difference if the kinematic distributions of the two channels are equal, resulting in

$$\Delta A_{CP} = A_{\text{raw}}(K^-K^+) - A_{\text{raw}}(\pi^-\pi^+). \tag{5}$$

([1]) Charge-conjugate decay modes are implied throughout except in asymmetry definitions.
([2]) Hereafter $D^*(2010)^+$ is referred to as D^{*+}.

2. – Selection

The LHCb detector is a single-arm forward spectrometer designed for the study of particles containing b or c quarks [47, 48]. The LHCb tracking system uses a dipole magnet whose magnetic-field polarity is reversed periodically during data taking.

The online event selection is performed by a trigger, consisting of a hardware stage based on information from the calorimeter and muon systems, and two software stages. D^0 candidates are fully reconstructed in the second software stage using topological, kinematic and particle-identification (PID) criteria. The π-tagged D^0 and pion candidates are combined to form D^{*+} candidates by requiring a good fit quality of the D^{*+} vertex, constrained to coincide with the nearest PV. In the μ-tagged sample, D^0 candidates are combined with muons to form B candidates, under the requirement that they are consistent with originating from a common vertex. A veto in the invariant mass of the $\mu^{\mp}\pi^{\pm}$ ($\mu^{\mp}K^{\pm}$) pair, where the pion (kaon) is given the muon mass hypothesis, is applied to suppress background from b-hadron decays to $c\bar{c}\pi^{\pm}X$ ($c\bar{c}K^{\pm}X$), where the $c\bar{c}$ resonance decays to a pair of muons.

In certain kinematic regions of the tagging particles, very large raw asymmetries, up to 100%, occur because, for a given magnet polarity, low-momentum particles of one charge may be deflected out of the detector or into the LHC beam pipe, while particles with the other charge are more likely to remain within the acceptance. For this reason, in the offline selection, fiducial requirements are imposed to exclude those kinematic regions.

The detection and production asymmetries are expected to depend on the kinematics of the reconstructed particles, and an incomplete cancellation in the difference in eq. (5) may be therefore induced by possible differences between the kinematic distributions of reconstructed D^{*+} or B candidates and of the tagging pions or muons in the K^-K^+ and $\pi^-\pi^+$ decay modes. For this reason, a small correction to the K^-K^+ sample is applied by means of a weighting procedure: candidate-by-candidate weights are calculated from the ratio between the three-dimensional background-subtracted distributions of pseudorapidity, transverse momentum and azimuthal angle of the D^{*+} (D^0) meson in the K^-K^+ and $\pi^-\pi^+$ modes for the π-tagged (μ-tagged) sample. It is then checked *a posteriori* that the distributions of the same variables for tagging pions and muons are also equalized by the weighting.

3. – Measurement of the asymmetries

For each decay mode, simultaneous least-square fits to the binned mass distributions of D^{*+} and D^{*-} (D^0 and $\overline{D}^0$) candidates for the π-tagged (μ-tagged) sample are performed to obtain the raw asymmetries of signal and background components, which are free parameters of the fits.

In the analysis of the π-tagged sample the fits are performed to the $m(D^0\pi^+)$ and $m(\overline{D}^0\pi^-)$ distributions, that are defined using the known value of the D^0 mass [36]. The signal mass model consists of the sum of a Johnson S_U function [49] and three Gaussian functions, while the combinatorial background is described by an empirical function of the form $[m(D^0\pi^+) - m(D^0) - m(\pi^+)]^{\alpha} e^{\beta\, m(D^0\pi^+)}$. In the analysis of the μ-tagged sample, the fits are performed to the $m(D^0)$ distributions. The signal is described by the sum of two Gaussian functions convolved with a truncated power-law function describing final-state photon radiation effects, whereas an exponential function is used to model the combinatorial background. A small contribution from $D^0 \to K^-\pi^+$ decays with a

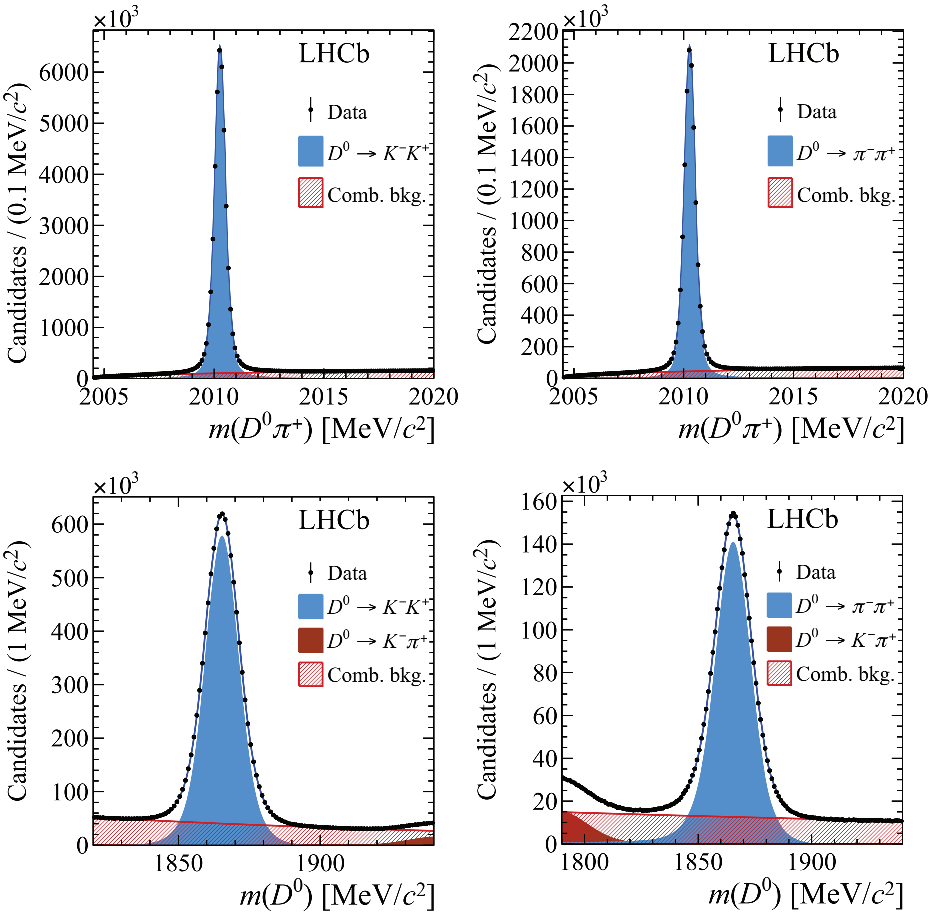

Fig. 1. – Mass distributions of selected (top) $\pi^\pm$-tagged and (bottom) $\mu^\pm$-tagged candidates for (left) $D^0 \to K^-K^+$ and (right) $D^0 \to \pi^-\pi^+$ decays, with fit projections overlaid.

misidentified kaon or pion is visible and is modeled as the tail of a Gaussian function. The π-tagged (μ-tagged) signal yields are approximately 44 (9) million $D^0 \to K^-K^+$ decays and 14 (3) million $D^0 \to \pi^-\pi^+$ decays. Figure 1 shows the $m(D^0\pi^+)$ and $m(D^0)$ distributions with fit projections overlaid.

4. – Systematic uncertainties

Several sources of systematic uncertainties are considered and studied independently for the π-tagged and μ-tagged samples. In the case of π-tagged decays, the dominant systematic uncertainty is related to the knowledge of the signal and background mass models. It is evaluated by generating pseudoexperiments according to the baseline fit model, then fitting both baseline and alternative models to those data and considering the difference between the resulting values of ΔA_{CP}. The largest observed variation, 0.6×10^{-4}, is assigned as a systematic uncertainty. A similar study with pseudoexperiments is also performed with the μ-tagged sample, resulting in a value of 2×10^{-4}. In the case of μ-tagged decays, the main systematic uncertainty is due to the possibility that misreconstruction leads to a wrong tag of the D^0 flavor. The probability of wrongly assigning the D^0 flavor (mistag), measured on a large sample of μ-tagged $D^0 \to K^-\pi^+$ decays by comparing the charges of kaon and muon candidates, is found to be at the percent level, and the corresponding systematic uncertainty is estimated to be 4×10^{-4}. Systematic uncertainties of 0.2×10^{-4} and 1×10^{-4} associated to the knowledge of the weights used in the kinematic weighting procedure are assessed for π-tagged and μ-tagged decays, respectively.

Other systematic uncertainties for the π-tagged analysis, accounting for the presence of a fraction of D^0 mesons from B decays still present in the sample and to the presence of background components peaking in $m(D^0\pi)$ and not in $m(D^0)$, are estimated to be 0.3×10^{-4} and 0.5×10^{-4}, respectively. In the case of μ-tagged decays, systematic uncertainties related to different fractions of reconstructed $\overline{B}$ decays and a different B reconstruction efficiency as a function of the decay time between the K^-K^+ and $\pi^-\pi^+$ decay modes are assigned, namely 1×10^{-4} and 2×10^{-4}, respectively.

The total systematic uncertainties on ΔA_{CP} are obtained by summing in quadrature all individual contributions, and are equal to 0.9×10^{-4} and 5×10^{-4} for the π-tagged and μ-tagged samples, respectively.

Numerous additional robustness checks are performed. For example, the measured value of ΔA_{CP} is studied as a function of several kinematic and geometrical variables. The total sample is also split into subsamples taken in different run periods, also distinguishing different magnet polarities and years of data taking. No evidence for unexpected dependences of ΔA_{CP} is found in any of these tests.

5. – Results

The measured differences of time-integrated CP asymmetries of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays are [50]

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4},$$

both in good agreement with previous LHCb results [41, 40] and world averages [51].

The full combination with previous LHCb measurements gives

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4},$$

where the uncertainty includes statistical and systematic contributions. The significance of the deviation from zero corresponds to 5.3 standard deviations, resulting in the first observation of CP violation in the decay of charm hadrons.

The result is consistent with, although in magnitude at the upper end of, SM expectations. Further measurements with charmed particles, along with possible theoretical improvements, will be needed in the next future to clarify the present physics picture, to establish whether this result is consistent with the SM or indicates the presence of new physics processes in the up-quark sector.

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