Measurement of the Difference in CP-Violating Asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ Decays at CDF

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We report a measurement of the difference (ΔA_{CP}) between time-integrated CP-violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays reconstructed in the full data set of proton-antiproton collisions collected by the Collider Detector at Fermilab, corresponding to 9.7 fb^{-1} of integrated luminosity. The strong decay $D^{*+} \to D^0\pi^+$ is used to identify the charm meson at production as D^0 or $\bar{D}^0$. We measure $\Delta A_{CP} = [-0.62 \pm 0.21(\text{stat}) \pm 0.10(\text{syst})]\%$, which differs from zero by 2.7 Gaussian standard deviations. This result supports similar evidence for CP violation in charm-quark decays obtained in proton-proton collisions.

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The noninvariance of the laws of physics under the simultaneous transformations of parity and charge conjugation (CP violation) is accommodated in the standard model (SM) through the presence of a single irreducible complex phase in the weak couplings of quarks. Generic extensions of the SM are expected to introduce additional sources of CP violation, which, if observed, could provide indirect signs of new particles or interactions. To date, CP violation has been established in transitions of strange and bottom hadrons, with effects consistent with the SM interpretation [1–3]. Studies of CP violation in charm decays provide a unique probe for non-SM physics. The neutral D system is complementary to the B and K sectors in that up-type quarks (electric charge $+2/3$) are involved in the initial state. Therefore, CP-violating effects probe the presence of down-type (charge $-1/3$) new physics through charged-current couplings [4–7]. However, CP-violating effects are expected not to exceed $\mathcal{O}(10^{-2})$ in the SM [4], because charm transitions are well described by the physics of the first two quark generations. Indeed, no CP-violating effects have been firmly established yet in charm dynamics.

Time-integrated CP-violating asymmetries of decays into CP eigenstates such as $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ probe non-SM physics contributions in the *oscillation* and *penguin* transition amplitudes. Oscillation indicates D^0-$\bar{D}^0$ transitions governed by the exchange of virtual heavy particles occurring before the D meson decay. Penguin decays are second-order transitions mediated by an internal loop. Both amplitudes may be affected by the exchange of non-SM particles, which could enhance the size of the observed CP violation with respect to the SM expectation. In 2011, CDF reported CP-violating asymmetries compatible with zero within a few 10^{-3} uncertainty in these decays, along with a measurement of the difference ΔA of CP-violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, also consistent with zero [8]. Shortly after, LHCb reported a more precise determination of the difference, which is 3.5σ different from zero [9]. If established, this result provides the first evidence for CP violation in charm dynamics, with a size larger than most SM expectations [10]. Among the quantities sensitive to CP violation in charm mesons, ΔA_{CP} can be measured with good accuracy because many common systematic uncertainties cancel. In addition, ΔA_{CP} could be maximally sensitive to CP violation since the individual asymmetries are expected to have opposite signs, if the invariance of the dynamics under interchange of d with s quarks is approximately valid [4].

In this Letter, we report a measurement of the difference of CP-violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays reconstructed in the full data set of 1.96 TeV proton-antiproton collisions collected by the Collider Detector at Fermilab, corresponding to 9.7 fb^{-1} of integrated luminosity. In addition to the increase in the size of the data set with respect to the previous measurement [8], we optimize the selection for a measurement of the difference of asymmetries, reaching a sensitivity competitive with the LHCb result [9].

For each decay mode, the CP-violating time-integrated asymmetry between decays of states produced as D^0 and $\bar{D}^0$ is defined as

$$\frac{N(D^0 \to h^+h^-;t) - N(\bar{D}^0 \to h^+h^-;t)}{N(D^0 \to h^+h^-;t) + N(\bar{D}^0 \to h^+h^-;t)}, \quad (1)$$

where h identifies a charged kaon or pion. The asymmetry can receive contributions from any difference in partial decay widths between D^0 and $\bar{D}^0$ mesons (direct CP violation) and both the difference in mixing probabilities between D^0 and $\bar{D}^0$ mesons and the interference between mixed and unmixed decays (indirect CP violation). Because of the slow mixing rate of charm mesons, the asymmetry is approximated to first order as the sum of two terms [8],

$$A_{CP}(h^+h^-) = A_{CP}^{\rm dir}(h^+h^-) + \frac{\langle t\rangle}{\tau} A_{CP}^{\rm ind}(h^+h^-). \quad (2)$$

The first term arises from direct CP violation and depends on the decay mode, the second from indirect CP violation and is nearly independent of the decay mode [11]. The average decay time of the sample used in the measurement $\langle t\rangle$ depends on the detector acceptance as a function of decay time and τ is the D^0 lifetime. To measure each individual asymmetry, we determine the number of detected decays of D^0 and $\bar{D}^0$ and use the fact that primary charm and anticharm mesons are produced in equal numbers by the CP-conserving strong $p\bar{p}$ interactions. We require the D candidate to be produced in the decay of an identified D^{*+} or D^{*-} meson to determine whether the decaying state was initially produced as a D^0 or a $\bar{D}^0$ meson. Flavor conservation in the strong-interaction decay of the $D^{*\pm}$ meson, $D^{*+} \to D^0(\to h^+h^-)\pi_s^+$ and $D^{*-} \to \bar{D}^0(\to h^+h^-)\pi_s^-$, allows identification of the initial charm flavor through the sign of the charge of the low-momentum π meson (soft pion, π_s). The observed asymmetry, $A(h^+h^-) = N_{\rm obs}(D^0 \to h^+h^-) - N_{\rm obs}(\bar{D}^0 \to h^+h^-)/[\text{sum}]$, is the combination of the contributions from CP violation and from the detection asymmetry between D^{*+} and D^{*-} mesons, due to different reconstruction efficiency for positive and negative soft pions. The combination is linear for small asymmetries, $A(h^+h^-) = A_{CP}(h^+h^-) + \delta(\pi_s)^{h^+h^-}$. The instrumental asymmetry is due to differences in interaction cross sections with matter between positive and negative low-momentum pions and the geometry of the CDF tracking system (see below). The combined effect of a few percent cancels in the difference of asymmetries between K^+K^- and $\pi^+\pi^-$ decays,

$$\begin{aligned}\Delta A_{CP} &= A(K^+K^-) - A(\pi^+\pi^-)\\ &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)\\ &= \Delta A_{CP}^{\rm dir} + A_{CP}^{\rm ind}\Delta\langle t\rangle/\tau.\end{aligned}$$

Kinematic differences between the K^+K^- and $\pi^+\pi^-$ decays result in a fractional 10% difference in average decay time of the sample, $\Delta\langle t\rangle/\tau = 0.27 \pm 0.01$, measured through a fit to the decay time distribution of background-subtracted signal candidates [8]. Therefore, most of the indirect CP-violating asymmetry cancels in the subtraction and ΔA_{CP} approximates the difference in direct CP-violating asymmetries of the two decays.

The CDF II detector is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors. The detector components relevant for this analysis are briefly outlined below; a more detailed description is in Ref. [8]. A silicon microstrip vertex detector and a cylindrical drift chamber immersed in a 1.4 T axial magnetic field allow reconstruction of charged-particle trajectories (tracks) in the pseudorapidity range $|\eta| < 1.0$. The vertex detector contains seven concentric layers of single- and double-sided silicon sensors at radii between 1.5 and 22 cm, each providing a measurement with up to 15 (70) μm resolution in the ϕ (z) direction [12]. The drift chamber has 96 measurement layers, between 40 and 137 cm in radius, organized into alternating axial and $\pm 2°$ stereo superlayers [13]. A 35° tilt angle between the drift chamber cell orientation and the radial direction facilitates track finding, but induces charge-dependent detection asymmetries of up to a few percent for low-momentum charged particles [8,14]. The component of a charged particle's momentum transverse to the beam (p_T) is determined with a resolution of $\sigma_{p_T}/p_T^2 \approx 0.07\%$ (p_T in GeV/c), corresponding to a typical mass resolution of 8 MeV/c^2 for a two-body charm-meson decay.

The data are collected by a three-level online selection (trigger) system. At level 1, tracks are reconstructed in the transverse plane. Two oppositely charged particles are required, with reconstructed transverse momenta p_{T1}, $p_{T2} > 2$ GeV/c, the scalar sum $p_{T1} + p_{T2} > 5.5$ GeV/c

typically, and an azimuthal opening angle $\Delta\phi < 90°$ [15]. At level 2, tracks are combined with silicon hits and their impact parameter d (transverse distance of closest approach to the beam line) is determined with 45 μm resolution (including the beam spread) and typically required to be $0.12 < d < 1.0$ mm [16]. A slightly tighter opening-angle requirement of $2° < \Delta\phi < 90°$ is also applied. Each track pair is then used to form a neutral D candidate, whose flight distance in the transverse plane projected onto the transverse momentum L_{xy} is required to exceed 200 μm. At level 3, the selection is confirmed on events that are fully reconstructed by an array of processors.

The offline selection is based on a more accurate determination of the same quantities used in the trigger and is detailed in Refs. [8,14]. Here we only describe the improvements specifically aimed at enhancing the sensitivity to ΔA_{CP}. By exploiting the highly accurate cancellation of instrumental effects in ΔA_{CP}, the selection of Ref. [8] is loosened to significantly increase signal efficiency. Requirements on the minimum number of measurement points for reconstructing tracks are loosened, and the transverse momentum threshold for D decay products is lowered from 2.2 to 2.0 GeV/c, nearly doubling the D^0 yield. Asymmetries from charm mesons produced in B meson decays (secondary charm) may introduce a common bias in the individual CP-violating asymmetries, which cancels in the difference of asymmetries. Secondary charm decays are therefore not excluded from the analysis, providing a 12% additional signal. An additional 10% of events is contributed by secondary trigger selections that were not used in Ref. [8]. Finally, the additional integrated luminosity contributes approximately 20% more events. As a result, the expected average resolution on the difference of asymmetries is improved by approximately 50% with respect to Ref. [8].

The reconstruction of signal candidates is entirely based on tracking information, with no use of particle identification. Two tracks from oppositely charged particles, with pion or kaon assignment, are fit to a common decay vertex to form a neutral D candidate. A low-momentum ($p_T >$ 400 MeV/c) charged particle is associated with each D candidate to form the charged D^* candidates. This allows identification of the charm meson at production as a D^0 or a $\bar{D}^0$ and strongly rejects background, albeit with an 85% reduction in signal yield. In the few percent of cases in which multiple candidates per event are reconstructed, one is randomly chosen for further analysis. The resulting sample contains approximately 591 000 $D^0 \to K^+K^-$ candidates, 619 000 $\bar{D}^0 \to K^+K^-$ candidates, 270 000 $D^0 \to \pi^+\pi^-$ candidates, and 279 000 $\bar{D}^0 \to \pi^+\pi^-$ candidates. Many kinematic distributions are compared for the K^+K^- and $\pi^+\pi^-$ samples. Small differences are observed in the distributions of the soft pion's impact parameter, transverse momentum, and pseudorapidity. The final candidates are reweighted to make these distributions equal, by using as a weight a smooth function extracted from a fit to the ratio of K^+K^- and $\pi^+\pi^-$ distributions. The data show that the weight function factorizes into the product of three one-dimensional functions and typically does not exceed 10%. The reweighting ensures that any kinematics-dependent instrumental asymmetry cancels in the difference of observed asymmetries.

The observed asymmetry in each sample is determined from a simultaneous χ^2 fit of the $D^0\pi^+$ and $\bar{D}^0\pi^-$ binned mass distributions of candidates restricted to the signal D region, defined as those with mass within 24 MeV/c^2 (3σ) of the known D^0 mass. The $D^0\pi$ mass is calculated using the vector sum of the momenta of the three particles to determine the D^* momentum and the known D^0 mass. This quantity has the same resolution advantages of the more customary $M(h^+h^-\pi) - M(h^+h^-)$ mass difference, but it is independent of the mass assigned to the D^0 decay products.

The $\pi^+\pi^-$ sample is dominated by the signal of D^*-tagged D^0 decays, a background of real D^0 decays associated with random pions or random combinations of three tracks (combinatorics), and a 0.93% contamination of the high-mass tail of the $D^0 \to K^-\pi^+$ signal misreconstructed as a $\pi^+\pi^-$ final state. In the K^+K^- sample, an additional background is contributed by misreconstructed multibody charm meson decays, dominated by the $D^0 \to h^-\pi^+\pi^0$ and the $D^0 \to h^-\ell^+\nu_\ell$ contributions, where ℓ is a muon or an electron. The functional form of the signal mass shapes is determined from simulation, with parameters tuned in a low-background sample of 12.5×10^6 D^*-tagged $D^0 \to K^-\pi^+$ decays [8]. The data indicate a small asymmetry between signal shapes of D^{*+} and D^{*-} decays, which can be attributed to differences in the tracking resolution for positive and negative soft pions. This asymmetry is included in our fit model [8]. The shape of the combinatorial component is obtained and fixed from data, by forming artificial D^* candidates where each D^0 candidate is associated with soft pions of all candidates found in different, randomly chosen events. The functional form of the misreconstructed decays is extracted from samples of simulated inclusive charm meson decays, and its parameters are fit together with the desired asymmetries [8]. The $K\pi$ tail is not included in the $\pi\pi$ fit, but is accounted for in the systematic uncertainties. In the $\pi^+\pi^-$ sample, the parameters determined by the fit are the asymmetry between D^{*+} and D^{*-} yields and the relative sizes between the signals and the combinatoric background components. In the K^+K^- sample, the fit also determines the relative sizes and values of the shape parameters of the misreconstructed component. The fit allows for asymmetries between the numbers of combinatorial and misreconstructed background events in the D^{*+} and D^{*-} samples. For each final state, we minimize the total χ^2 for the D^{*+} and D^{*-} samples and obtain the results shown in Fig. 1. The fits show agreement with data, and the observed asymmetries are

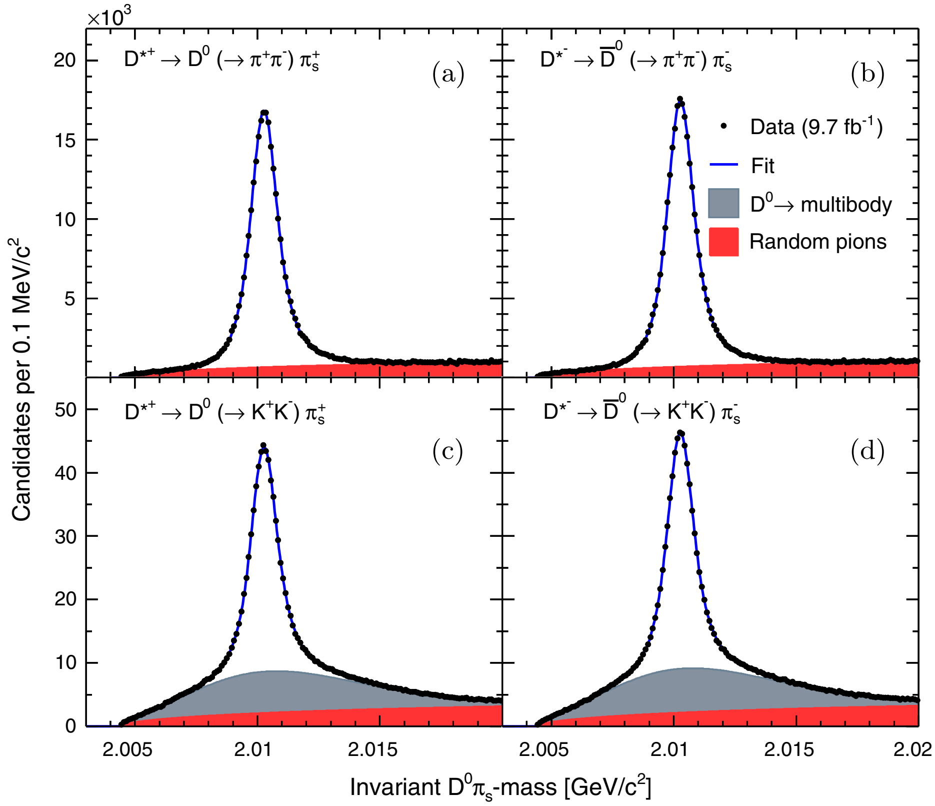

FIG. 1 (color online). Distributions of $D^0\pi^+$ mass with fit results overlaid for (a) $D^0 \to \pi^+\pi^-$ decays, (b) $\bar{D}^0 \to \pi^+\pi^-$ decays, (c) $D^0 \to K^+K^-$ decays, and (d) $\bar{D}^0 \to K^+K^-$ decays.

$$A(\pi^+\pi^-) = [-1.71 \pm 0.15(\text{stat})]\%, \qquad (3)$$

$$A(K^+K^-) = [-2.33 \pm 0.14(\text{stat})]\%. \qquad (4)$$

Both asymmetries are dominated by the detector-induced contribution. Fits including extreme variations of the signal and background models yield significantly larger values of reduced χ^2 with minimal variations in the observed asymmetries. As a consistency check, we compare the results of the measurement obtained in independent subsamples chosen according to the soft pion's direction in the four quadrants of the tracking volume, different data-taking periods (early and late data), or splitting the present sample in the subsample of events used in Ref. [8] and the complementary sample, in which we observe $\Delta A_{CP} = -0.74 \pm 0.27$. The results show a high level of consistency, with reduced χ^2 between observed asymmetry differences of 4.4/3, 0.38/1, and 0.46/1, respectively.

Most systematic effects cancel in the subtraction of asymmetries. Residual higher-order instrumental effects that do not cancel are estimated to contribute less than $\pm 0.009\%$ to ΔA_{CP}, based on simulations in which known instrumental asymmetries are varied as functions of the kinematic variables. The impact of possible residual mismodeling of the mass shapes used in fits is evaluated by repeating the measurement using extreme variations of the model, as derived from data, and contributes to ΔA_{CP} by less than $\pm 0.020\%$. A dominant systematic uncertainty of 0.1% arises from the possibility that signal and background shapes differ between the D^{*+} and D^{*-} samples. This effect is assessed by repeating the fit on data using various modifications of the fit shapes in which independent parameters are used for D^{*+} and D^{*-} samples. The effect of the $K\pi$ tail in the $\pi\pi$ signal induces a systematic uncertainty of 0.013% that is the product of the size of the contamination (0.93%) times the 3% observed asymmetry of the $D^0 \to K^-\pi^+$ decay. The impact of the statistical uncertainties associated with the kinematic reweighting is negligible.

The final result,

$$\Delta A_{CP} = [-0.62 \pm 0.21(\text{stat}) \pm 0.10(\text{syst})]\%, \qquad (5)$$

is consistent with and supersedes the previous CDF determination of $\Delta A_{CP} = [-0.46 \pm 0.31(\text{stat}) \pm 0.12]\%$ [8]. By adding in quadrature the uncertainties, assumed to be independent and Gaussian-distributed, the difference of asymmetries deviates from zero by 2.7 standard deviations, strongly indicating the presence of CP violation in the decays of D^0 mesons. This result is consistent with the LHCb measurement obtained in pp collisions, $\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\%$ [9], with comparable accuracy and less than 1σ difference in central value.

The combined results of the two experiments provide substantial evidence for *CP* violation in the charm sector with a size larger than most predictions [10], possibly suggesting the presence of non-SM dynamics. More precise determinations of the individual asymmetries in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays and extension of the precise experimental exploration to other charm decays may help in understanding whether the observed effect can be attributed to significant hadronic corrections to the SM weak amplitudes or to new, non-SM sources of *CP* violation [17].

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