CDF note 11117

Measurement of indirect 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 CP-violating asymmetry (A_Γ) between effective lifetimes of anticharm and charm mesons reconstructed in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. We use the full data set of proton-antiproton collisions collected by the Collider Detector at Fermilab experiment and corresponding to 9.7 fb^{-1} of integrated luminosity. The strong decay $D^{*+} \to D^0\pi^+$ is used to identify the meson at production as D^0 or $\overline{D}^0$. Mesons originated in b-hadron decays are subtracted from the sample and fits to signal yields as functions of the observed decay-time distributions are used to measure the asymmetries. We measure $A_\Gamma(K^+K^-) = \big(-1.9 \pm 1.5\ (\text{stat}) \pm 0.4\ (\text{syst})\big) \times 10^{-3}$ and $A_\Gamma(\pi^+\pi^-) = \big(-0.1 \pm 1.8\ (\text{stat}) \pm 0.3\ (\text{syst})\big) \times 10^{-3}$. The results are consistent with CP symmetry and their combination yields $A_\Gamma = \big(-1.2 \pm 1.2\big) \times 10^{-3}$.

Decay-time-dependent rate asymmetries of decays into CP eigenstates, such as $D \to h^+h^-$, where D indicates a D^0 or $\overline{D}^0$ meson, and h a K or π meson, are among the most sensitive probes for CP violation [4]. Such asymmetries,

$$\mathcal{A}_{CP}(t) = \frac{d\Gamma(D^0 \to h^+h^-)/dt - d\Gamma(\overline{D}^0 \to h^+h^-)/dt}{d\Gamma(D^0 \to h^+h^-)/dt + d\Gamma(\overline{D}^0 \to h^+h^-)/dt}, \tag{1}$$

probe non-SM physics contributions in the *oscillation* and *penguin* transition amplitudes. Oscillations indicates D^0–$\overline{D}^0$ 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. Either amplitude may be affected by the exchange of non-SM particles, which could enhance the magnitude of the observed CP violation with respect to the SM expectation. The asymmetry $\mathcal{A}_{CP}(t)$ thus receives contributions from any difference between D^0 and $\overline{D}^0$ decay amplitudes (direct CP violation) and from either the difference in oscillation probabilities between charm and anticharm mesons and the interference between decays that follow, or not, an oscillation (indirect CP violation). Due to the slow oscillation rate of charm mesons [1], Eq. (1) is approximated to first order as [5],

$$\mathcal{A}_{CP}(t) \approx \mathcal{A}_{CP}^{\rm dir}(h^+h^-) - \frac{\langle t \rangle}{\tau}\, A_\Gamma(h^+h^-), \tag{2}$$

where $\langle t \rangle$ is the sample mean of decay time and τ is the CP-averaged D lifetime [6]. The first term arises from direct CP violation and depends on the decay mode; the second term is proportional to the asymmetry between the *effective* lifetimes $\hat{\tau}$ of anticharm and charm mesons,

$$A_\Gamma = \frac{\hat{\tau}(\overline{D}^0 \to h^+h^-) - \hat{\tau}(D^0 \to h^+h^-)}{\hat{\tau}(\overline{D}^0 \to h^+h^-) + \hat{\tau}(D^0 \to h^+h^-)}, \tag{3}$$

and is mostly due to indirect CP violation [7]. Effective lifetimes are those resulting from a single-exponential fit of the time evolution of neutral meson decays that may undergo oscillations. In the SM, A_Γ is universal for all final states with same CP-parity [8], such as K^+K^- and $\pi^+\pi^-$; contributions from non-SM processes may introduce channel-specific differences. Measurements have been reported from electron-positron collisions at the $\Upsilon(4S)$ resonance [9] and from high-energy proton-proton collisions [10]. All results are consistent with CP symmetry with $\mathcal{O}(10^{-3})$ uncertainties. Any independent measurement of comparable precision further constrains the phenomenological bounds and may improve the knowledge of CP violation in the charm sector. Decays $D \to h^+h^-$ are well suited for pursuing a measurement of A_Γ at the Collider Detector at Fermilab (CDF) experiment. Fully reconstructed final states provide a precise determination of the decay time and large signal-yields with moderate backgrounds allow for reduced systematic uncertainties.

In this note we report a measurement of the CP-violating effective-lifetime asymmetry of anticharm and charm mesons reconstructed in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. We use the full data set of 1.96 TeV proton-antiproton collisions collected by the CDF online event-selection system (trigger) on charged particles displaced from the primary collision and corresponding to 9.7 fb^{-1} of integrated luminosity. The analysis uses D candidates 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 $\overline{D}^0$ meson. Flavor conservation in the strong-interaction processes $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$ allows identification of the initial flavor through the charge of the low-momentum π meson (soft pion, π_s). Each sample is divided into subsamples according to production flavor and decay time. In each subsample, a fit to the $D\pi_s^\pm$ mass distribution is used to determine the relative proportions of signal and background. These proportions are used to construct a background-subtracted distribution of D impact parameter, the minimum distance from the beam of the D trajectory. This distribution is fit to identify $D^{*\pm}$ mesons from b-hadron decays (*secondary*), whose decay-time distribution is biased by the additional decay length of the b-hadron, and to determine the yields of charm (N_{D^0}) and anticharm ($N_{\overline{D}^0}$) mesons directly produced in the $p\bar{p}$ collision (*primary*). The yields are combined into the asymmetry $A = (N_{D^0} - N_{\overline{D}^0})/(N_{D^0} + N_{\overline{D}^0})$, which is fit with the linear function in Eq. (2). The slope of the function yields A_Γ; the intercept determines the asymmetry at $t = 0$, $A(0)$, which receives contributions from direct CP violation and possible instrumental asymmetries. We check that the latter are constant in decay time using a high-yield, low-background control sample of $D \to K^\mp\pi^\pm$ decays Sample selection, studies of background composition, and fit model are inherited from previous measurements of CP-violating asymmetries from the same samples [11].

The CDF II detector is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors. The detector components relevant for this analysis are outlined as follows; a detailed description is in Ref. [12]. 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 position measurement with up to 15 (70) μm resolution in the ϕ (z) direction [13]. The drift chamber has 96 measurement layers, between 40 and 137 cm in radius, organized into alternating axial and $\pm 2^\circ$ stereo superlayers [14]. The component of a charged particle's momentum transverse to the beam (p_T) is determined with a resolution of $\sigma_{p_T}/p_T^2 \approx 0.07\%$ (GeV/c)$^{-1}$, 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 trigger. At level 1, tracks are reconstructed in the transverse plane. Two oppositely-charged particles are required, with reconstructed transverse momenta $p_T > 2$ GeV/c, scalar sum $\sum p_T >$ 5.5 GeV/c, typically, and azimuthal opening angle $\Delta\phi < 90^\circ$ [15]. At level 2, tracks are combined with silicon hits and their impact parameter (transverse distance of closest approach to the beam line) is determined with 45 μm resolution (including the beam spread) and typically required to be between 0.12 and 1.0 mm [16]. A more stringent opening-angle requirement of $2^\circ < \Delta\phi < 90^\circ$ is also applied. Each track pair is then used to form a 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 reapplied on events that are fully reconstructed by an array of processors.

Offline, the reconstruction of signal candidates is solely based on tracking information, with no use of particle identification. Two tracks from oppositely-charged particles compatible with having fired the trigger are fit, with pion or kaon assignment, to a common decay vertex to form a D candidate. A charged particle with $p_T > 400$ MeV/c is associated with each D candidate to form $D^{*\pm}$ candidates. We improve the reconstruction with respect to Ref. [11] by using the position of the beam as a constraint in the fit of the $D^{*\pm}$ decay and retain only candidates with good fit quality. Since the beam position is determined more accurately than the trajectory of the soft pion, this provides a 25% improvement in $D^{*\pm}$ mass resolution. Other offline selection requirements are based on a more accurate determination of the same quantities used in the trigger and are detailed in Ref. [11]. The $D \to K^+K^-$ and $D \to \pi^+\pi^-$ samples are separated by requiring the selected candidates to have the relevant h^+h^- mass within about 24 MeV/c^2 of the known D^0 mass, m_{D^0} [6]. We reconstruct 6.1×10^5 $D^0 \to K^+K^-$, 6.3×10^5 $\overline{D}^0 \to K^+K^-$, 2.9×10^5 $D^0 \to \pi^+\pi^-$, and 3.0×10^5 $\overline{D}^0 \to \pi^+\pi^-$ signal decays (Fig. 1). The composition of the $\pi^+\pi^-$ sample is dominated by the signal of D^*-tagged D^0 decays and a background of real D^0 decays associated with random pions or random combinations of three tracks (combinatorics). 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.

Each sample is divided in charm and anticharm subsamples and in 30 bins of decay time between 0.15τ and 20τ chosen so that each contains approximately the same number of candidates. The D^0 decay time is determined as $t = L_{xy} m_{D^0}/p_T$, with approximately 0.2τ resolution independent of decay time. In each bin, the average decay-time $\langle t\rangle$ is determined from a sample of about 13×10^6 $D^{*\pm} \to D(\to K^\mp\pi^\pm)\pi_s^\pm$ signal decays. The observed decay-time distribution is biased by the trigger. The effect of the bias is assumed to be independent of the D^0 flavor and is accounted for when determining the value of $\langle t\rangle$. Bin-by-bin sample-specific differences in trigger bias are negligible.

Relative proportions between signal and background yields in the signal region are determined in each decay-time bin, and for each flavor, through χ^2 fits of the $D\pi_s^\pm$ mass distribution. The $D\pi_s^\pm$ mass is calculated using the vector

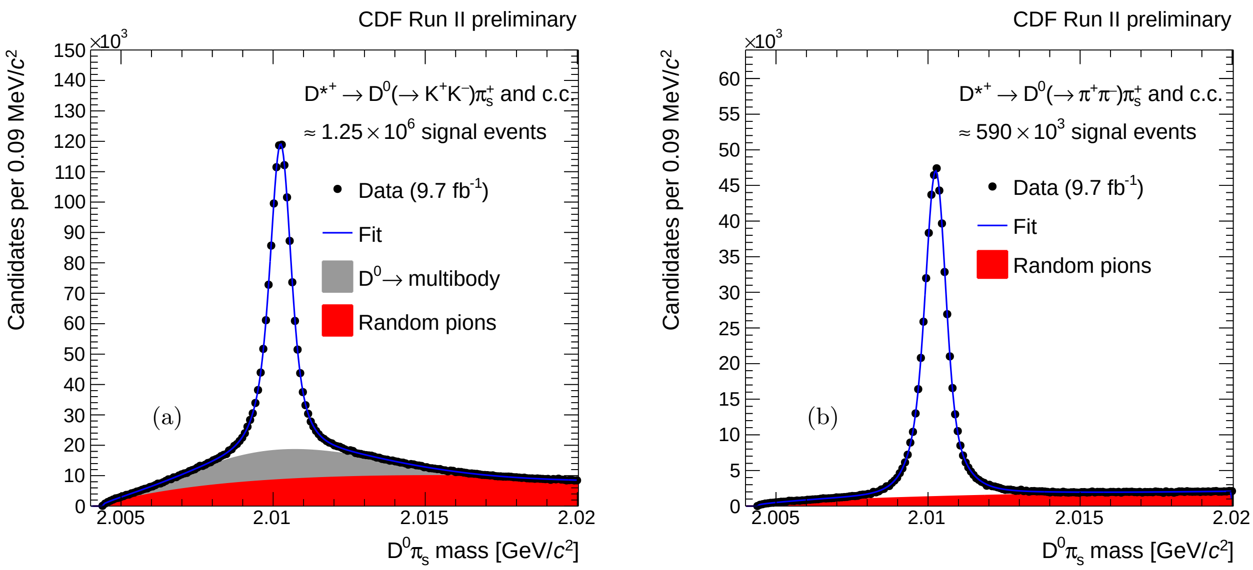

FIG. 1: Distributions of $D\pi^\pm$ mass with fit results overlaid for (a) the $D \to K^+K^-$ sample and (b) the $D \to \pi^+\pi^-$ sample.

sum of the momenta of the three particles to determine the $D^{*\pm}$ momentum and the known D^0 and charged π meson masses [6]. The functional form of the signal shapes is determined from simulation [5], with parameters tuned in the sample of $D \to K^{\mp}\pi^{\pm}$ decays, independently for each D flavor and decay-time bin. The parameters of the mass shapes of random pion and multibody background components [5] are determined by the fit, independently for each flavor and decay-time bin. The fit allows for asymmetries between combinatorial and misreconstructed background events yields, respectively, in the D^{*+} and D^{*-} samples. The resulting shapes and background proportions are used to derive signal-only distributions of the D impact parameter in each bin and for each flavor.

The impact parameter distributions of the sum of signal and background components are formed by restricting the analysis to candidates with $M(D\pi_s^{\pm})$ within 2.4 MeV/c^2 of the known D^{*+} mass [6]. From these, we subtract the impact parameter distribution of the background, sampled in the $2.015 < M(D\pi^{\pm}) < 2.020$ GeV/c^2 region for the $\pi^+\pi^-$ sample. The additional contamination from multibody decays in the K^+K^- sample requires choosing a suited sideband that contains the same admixture of combinatorial and misreconstructed backgrounds as that expected in the signal region. We select as background the candidates with $m_{D^0} - 64$ MeV/$c^2 < M(K^+K^-) < m_{D^0} - 60$ MeV/c^2 and with $M(D\pi_s^{\pm})$ within 2.4 MeV/c^2 of the known $D^{*\pm}$ mass. Checks on data show that the final results are robust against variations of this choice. We perform a χ^2 fit of the background-subtracted D impact parameter distributions in each subsample of decay-time and flavor using double-Gaussian models for both the primary and secondary components. The parameters of the primary component are fixed in all fits. They are derived from a fit of candidates in the first decay-time bin ($t/\tau < 1.18$), where any bias from the $\mathcal{O}(\%)$ secondary contamination is negligible, as supported by repeating the fit using an alternative model derived from the second bin and observing no difference in the results. The parameters of the secondary component are determined by the fit independently for each decay-time bin. As we determine impact parameters using information associated with the D decay only, the impact-parameter distributions of D^0 and $\overline{D}^0$ mesons are consistent. Example impact parameters fits are shown in Fig. 2. All mass and impact parameter fits show good agreement with data. Extreme variations of model parameters yield large variations in fit χ^2 but negligible changes of the results.

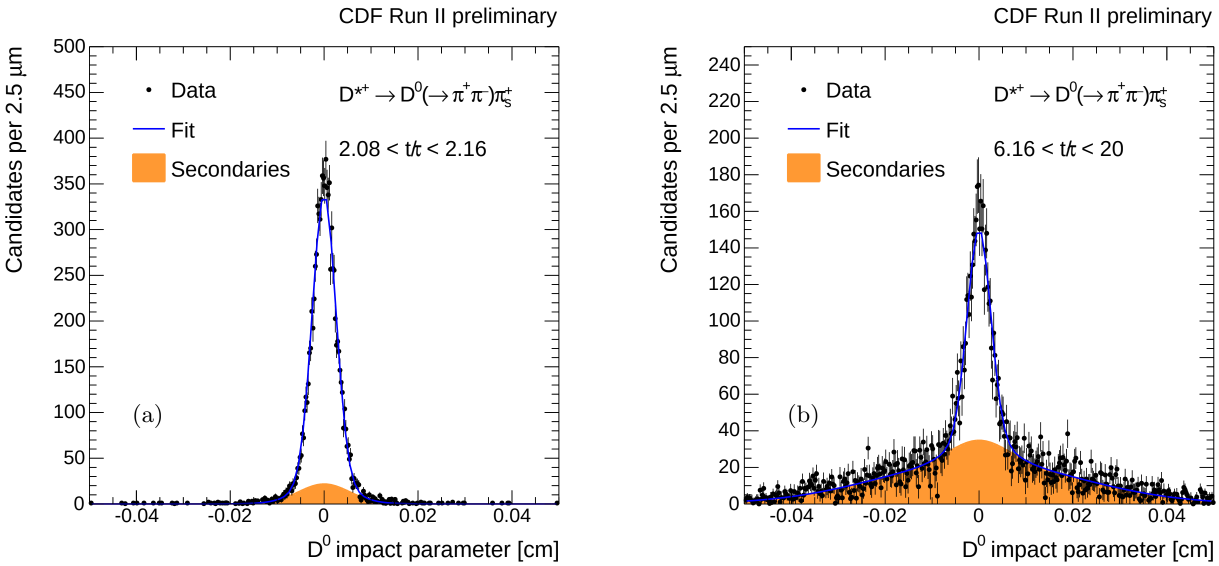

FIG. 2: Distributions of D^0 impact parameter with fit results overlaid for background-subtracted $D^{*+} \to D^0(\to \pi^+\pi^-)\pi_s^+$ decays restricted to (a) the decay-time bin $2.08 < t/\tau < 2.16$ and (b) the decay-time bin $6.16 < t/\tau < 20$.

A final χ^2 fit of the asymmetry between the resulting yields of primary charm and anticharm decays as a function of decay time is used to determine the values of A_Γ in the two samples. The fit is shown in Fig. 3 and yields $A_\Gamma(K^+K^-) = \big(-1.9 \pm 1.5 \text{ (stat)}\big) \times 10^{-3}$ and $A_\Gamma(\pi^+\pi^-) = \big(-0.1 \pm 1.8 \text{ (stat)}\big) \times 10^{-3}$. In both samples, we observe a few percent value for $A(0)$, due to the known detector-induced asymmetry in the soft-pion reconstruction efficiency [5]. The independence of instrumental asymmetries from decay time is checked for by performing the analysis on $D \to K^{\mp}\pi^{\pm}$ decays, where no indirect CP violation occurs and instrumental asymmetries are larger due to the additional effect from the difference in interaction probability with matter of opposite-charge kaons; an asymmetry compatible with zero is found, $(-0.5 \pm 0.3) \times 10^{-3}$. The width of the impact-parameter distribution of primary D mesons increases as a function of decay time, as observed in simulation. This has no significant effect on A_Γ, as verified by repeating the measurement with a floating decay-time-dependent width.

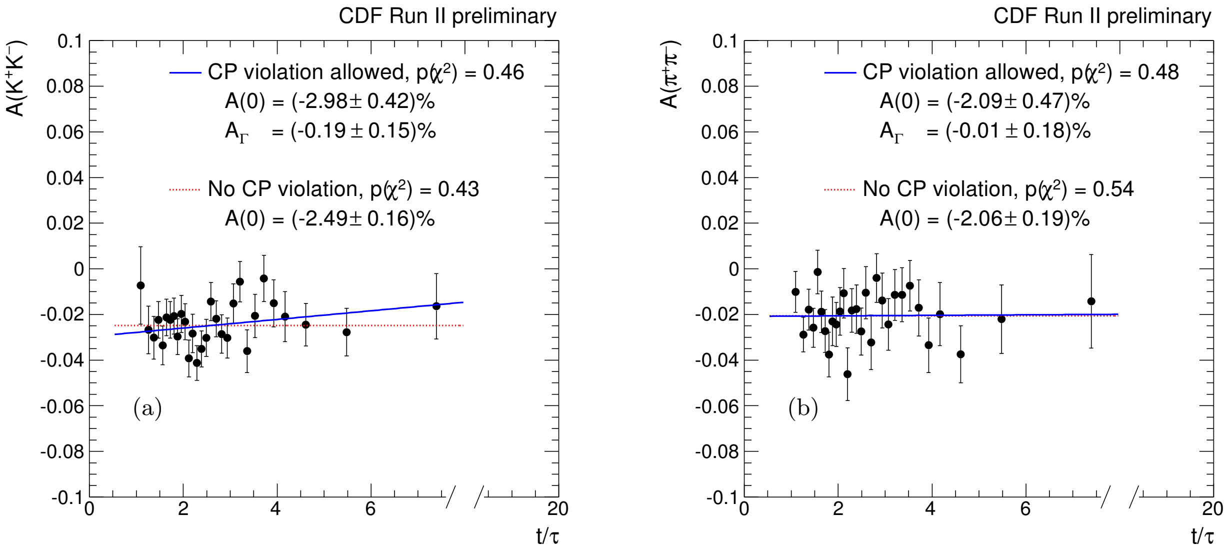

FIG. 3: Effective lifetime asymmetries as functions of decay time for the (a) $D \to K^+K^-$ and (b) $D \to \pi^+\pi^-$ samples. Results of fits not allowing for (red dotted line) and allowing for (blue solid line) *CP* violation are overlaid.

For the $\pi^+\pi^-$ analysis, the dominant systematic uncertainty of 0.028% arises from the choice of the impact-parameter shape of the secondary component whereas for the K^+K^- sample this effect only contributes 0.013%. The choice of the background sideband has a dominant effect in the K^+K^- analysis (0.038%) and a minor impact (0.010%) on the $\pi^+\pi^-$ result. Other minor effects are associated to the uncertainty on the vertex-detector length-scale (0.001%–0.002%); the neglected 0.93% contamination of misreconstructed $K^-\pi^+$ decays in the $\pi^+\pi^-$ sample ($< 0.001\%$); the neglected bin-by-bin migration due to the decay-time resolution ($< 0.001\%$); and any possible fit biases ($< 0.001\%$), probed by repeating the analysis on the $\pi^+\pi^-$ sample with random flavor assignment.

In summary, we measure the difference in effective lifetime between anticharm and charm mesons reconstructed in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays using the full CDF data set. The final results,

$$A_\Gamma(\pi^+\pi^-) = (-0.1 \pm 1.8\ (\text{stat}) \pm 0.3\ (\text{syst})) \times 10^{-3},$$
$$A_\Gamma(K^+K^-) = (-1.9 \pm 1.5\ (\text{stat}) \pm 0.4\ (\text{syst})) \times 10^{-3},$$

are consistent with *CP* symmetry. The final A_Γ results are also combined. We don't attempt at equalizing the value of $A(0)$ between the two channels, which would require kinematic reweighing and is verified to have a negligible effect on the combined result. All uncertainties are considered uncorrelated in the combination, which yields $A_\Gamma = \big(-1.2 \pm 1.2\big) \times 10^{-3}$. The results are also consistent with the current best results [9, 10], have precisions competitive with them, and contribute to improve the global constraints on indirect *CP* violation in charm meson dynamics.

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