Search for CP violation in $D^0 \rightarrow h^+h^-$ decays at CDF

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I report on a measurement of CP-violating asymmetries ($A_T$) between effective lifetimes of $D^0$ or $\bar{D}^0$ in fully reconstructed $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays collected in $p\bar{p}$ collisions by the Collider Detector at Fermilab experiment. The full CDF data set corresponding to 9.7 fb$^{-1}$ of integrated luminosity is used. The flavor of the charm meson at production is determined by exploiting the strong-interaction decay $D^{*+} \rightarrow D^0\pi^+$, while the contamination from mesons originated in $b$-hadron decays is evaluated and subtracted from the sample. Signal yields as functions of the observed decay-time distributions are extracted from maximum likelihood fits and used to measure the asymmetries. The results, $A_T(K^+K^-) = (-1.9 \pm 1.5 \text{ (stat)} \pm 0.4 \text{ (syst)}) \times 10^{-3}$ and $A_T(\pi^+\pi^-) = (-0.1 \pm 1.8 \text{ (stat)} \pm 0.3 \text{ (syst)}) \times 10^{-3}$, and their combination, $A_T = (-1.2 \pm 1.2) \times 10^{-3}$, are consistent with the SM predictions and other experimental determinations.

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1 Introduction

In charm transitions, the standard model (SM) predicts CP-violating effects not exceeding $O(10^{-2})$ \cite{1}. Indeed, no CP-violating effects have been firmly established yet in charm dynamics \cite{2}.

The decay-time-dependent rate asymmetries of charm mesons two body hadron decays ($D \to h^+h^-$, $h = K, \pi$),

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

probe non-SM physics contributions in the oscillation and penguin transition amplitudes which could be affected by non-SM contributions that enhance the magnitude of the observed CP violation w.r.t. SM expectation. The asymmetry $\mathcal{A}_{CP}(t)$ includes both direct and indirect CP violation effects. The slow oscillations rate \cite{2} of charm mesons allows approximating Eq. (1) as \cite{3},

$$\mathcal{A}_{CP}(t) \approx \mathcal{A}_{CP}^{\text{dir}}(h^+h^-) - \langle t \rangle \tau A_{\Gamma}(h^+h^-)$$

with

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

where $\langle t \rangle$ is the sample mean of decay time, $\tau$ is the CP-averaged $D$ lifetime \cite{2}, $\mathcal{A}_{CP}^{\text{dir}}$ is related to direct CP violation, and $A_{\Gamma}$ is the asymmetry between the effective lifetimes $\hat{\tau}$ of $D^0$ and $D^0$ and is mostly due to indirect CP violation. Recent measurements of $A_{\Gamma}$ \cite{4} showed consistency with CP symmetry with $O(10^{-3})$ uncertainties. However, additional determinations with comparable precision may improve the knowledge of CP violation in the charm sector. In this note I report a measurement of $A_{\Gamma}$ using fully reconstructed $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays collected in $p\bar{p}$ collisions by the Collider Detector at Fermilab experiment. The full CDF data set corresponding to $9.7 \text{ fb}^{-1}$ of integrated luminosity is used.

2 Selection and reconstruction

Online data selection is based on pairs of charged particles displaced from the $p\bar{p}$ collision point. Offline, a $D$ candidate is reconstructed using two oppositely charged tracks fit to a common decay vertex. A charged particle with $p_T > 400 \text{ MeV}/c$ is associated with each $D$ candidate to form $D^{*\pm}$ candidates. Constraining the $D^{*\pm}$ decay vertex to lie on the beam-line results in a 25% improvement in $D^{*\pm}$ mass resolution w.r.t Ref. \cite{3}. Ref. \cite{3} details the offline selection. The $h^+h^-$ mass of selected candidates is required to be within about $24 \text{ MeV}/c^2$ of the known $D^0$ mass, $m_{D^0}$ \cite{2}, to separate $D \to K^+K^-$ and $D \to \pi^+\pi^-$ samples. Final selected samples contain $6.1 \times 10^5 D^0 \to K^+K^-$, $6.3 \times 10^5 \bar{D}^0 \to K^+K^-$, $2.9 \times 10^5 D^0 \to \pi^+\pi^-$,
and $3.0 \times 10^5 \overline{D}^0 \rightarrow \pi^+\pi^-$ signal events. The main backgrounds are real $D^0$ decays associated with random pions or random combinations of three tracks (combinatorics) for the $\pi^+\pi^-$ sample, while the $K^+K^-$ sample is also polluted by misreconstructed multibody charm meson decays (i.e. $D^0 \rightarrow h^-\pi^+\pi^0$ and $D^0 \rightarrow h^-\ell^+\nu_\ell$, where $\ell$ is a muon or an electron), Figure (1).

### 3 Determination of the asymmetry

The flavor-conserving strong-interaction processes $D^{*+} \rightarrow D^0\pi^+$ and $D^{*-} \rightarrow \overline{D}^0\pi^-$ allow identification of the initial flavor through the charge of the low-momentum $\pi$ meson (soft pion, $\pi_s$). $D^0$ or $\overline{D}^0$ subsamples are thus divided in equally populated 30 bins of decay time between $0.15\tau$ and $20\tau$. In each bin, the average decay-time $\langle t \rangle$ is determined from a sample of about $13 \times 10^6 \; D^{*\pm} \rightarrow D(\rightarrow K^{\mp}\pi^{\pm})\pi_s^{\pm}$ signal decays. Signal and background yields in the signal region are determined in each decay-time bin, and for each flavor, through $\chi^2$ fits of the $D\pi_s^\pm$ mass distribution. The functional form of the signal shapes is determined from simulation [3], with parameters tuned in the sample of $D \rightarrow K^{\mp}\pi^\pm$ decays, independently for each $D$ flavor and decay-time bin. The resulting signal-to-background proportions are used to construct signal-only distributions of the $D$ impact parameter (IP). In each bin and for each flavor background-subtracted IP distributions are formed by subtracting IP distributions of background candidates, sampled in the $2.015 < M(D\pi^\pm) < 2.020$ GeV/c$^2$
region for the $\pi^+\pi^-$ sample, from IP distributions of signal candidates which have 
$M(D\pi^\pm)$ within 2.4 MeV/c$^2$ of the known $D^+$ mass [2]. Contamination from 
multi-body decays in the $K^+\bar{K}^-$ sample is taken into account using as background can-
didates in the sideband $m_{D^0} - 64$ MeV/c$^2 < M(K^+\bar{K}^-) < m_{D^0} - 40$ MeV/c$^2$ and 
with $M(D\pi^\pm)$ within 2.4 MeV/c$^2$ of the known $D^*\pm$ mass. A $\chi^2$ fit of these signal-
only IP distributions identifies $D^{*\pm}$ mesons from $b$-hadron decays (secondary) and 
determines the yields of charm ($N_{D^0}$) and anticharm ($N_{\overline{D}^0}$) mesons directly pro-
duced in the $p\bar{p}$ collision (primary). Double-Gaussian models are used for both 
the primary and secondary components. The parameters of the primary compo-
nent are derived from a fit of candidates in the first decay-time bin ($t/\tau < 1.18$), 
where any bias from the $O(\%)$ secondary contamination is negligible, and fixed in 
all fits. The parameters of the secondary component are determined by the fit in-
dependently for each decay-time bin, Figure 1. The yields are then 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, which yields $A_{\Gamma}$, is extracted using a $\chi^2$ fit. 
The fit is shown in Fig. 2 and yields $A_{\Gamma}(K^+\bar{K}^-) = (-1.9 \pm 1.5 \text{ (stat)}) \times 10^{-3}$ and 
$A_{\Gamma}(\pi^+\pi^-) = (-0.1 \pm 1.8 \text{ (stat)}) \times 10^{-3}$. In both samples, we observe a few percent 
value for $A(0)$, due to the known detector-induced asymmetry in the soft-pion recon-
struction efficiency [3]. The independence of instrumental asymmetries from decay 
time is demonstrated by the analysis of $D \rightarrow K^+\pi\pm$ decays, where no indirect CP 
violation occurs and instrumental asymmetries are larger; an asymmetry compatible 
with zero is found, $(-0.5 \pm 0.3) \times 10^{-3}$.

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 $K^+\bar{K}^-$ sample this effect only contributes 0.013%. The choice of the background 
sideband has a dominant effect in the $K^+\bar{K}^-$ analysis (0.038%) and a minor impact 
(0.010%) on the $\pi^+\pi^-$ result.

4 Conclusions

A measurement of the difference in effective lifetime between anticharm and charm 
mesons reconstructed in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays using the full CDF 
data set is reported. The final results,

\begin{align*}
A_{\Gamma}(\pi^+\pi^-) &= (-0.1 \pm 1.8 \text{ (stat)} \pm 0.3 \text{ (syst)}) \times 10^{-3}, \\
A_{\Gamma}(K^+\bar{K}^-) &= (-1.9 \pm 1.5 \text{ (stat)} \pm 0.4 \text{ (syst)}) \times 10^{-3},
\end{align*}

are consistent with CP symmetry and combined to yield $A_{\Gamma} = (-1.2 \pm 1.2) \times 10^{-3}$ [5]. 
The results are also consistent with the current best results [4], have the second best 
precisions, and contribute to improve the global constraints on indirect CP violation 
in charm meson dynamics.
Figure 2: Effective lifetime asymmetries as functions of decay time for the (a) $D \rightarrow K^+K^-$ and (b) $D \rightarrow \pi^+\pi^-$ samples. Results of fits not allowing for (red dotted line) and allowing for (blue solid line) $CP$ violation are overlaid.

References

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