Precision measurement of CP Violation in $D^0 \rightarrow \pi^+\pi^-$

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Abstract. We report a measurement of the CP violating asymmetry in $D^0 \rightarrow \pi^+\pi^-$ decays using approximately 215,000 decays reconstructed in about 5.94 fb$^{-1}$ of CDF data. We use the strong $D^\star + \rightarrow D^0 \pi^+$ decay ("$D^\star$ tag") to identify the flavor of the charmed meson at production time and exploit CP-conserving strong $c\bar{c}$ pair-production in $p\bar{p}$ collisions. Higher statistic samples of Cabibbo-favored $D^0 \rightarrow K^\pm\pi^\mp$ decays with and without $D^\star$ tag are used to highly suppress systematic uncertainties due to detector effects. The result is the world’s most precise measurement to date and it is fully consistent with no CP violation.

1. Introduction and motivation

Time integrated CP-violating asymmetries of singly-Cabibbo suppressed transitions as $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ are powerful probes of new physics (NP). Contribution to these decays from “penguin” amplitudes are negligible in the Standard Model (SM), but presence of NP particles could enhance the size of CP-violation with respect to the SM expectation. Any asymmetry significantly larger than few 0.1%, as expected in the CKM hierarchy, may unambiguously indicate new physics contributions [1]. We present a measurement of time-integrated CP violating asymmetry in the Cabibbo-suppressed $D^0 \rightarrow \pi^+\pi^-$ decay:

$$A_{CP}(\pi^+\pi^-) = \frac{\Gamma(D^0 \rightarrow \pi^+\pi^-) - \Gamma(D^0 \rightarrow \pi^-\pi^+)}{\Gamma(D^0 \rightarrow \pi^+\pi^-) + \Gamma(D^0 \rightarrow \pi^-\pi^+)}.$$  \hspace{1cm} (1)

Both direct and mixing-induced CP violation contribute to the asymmetry. The latter source produces a time-dependent asymmetry, whose expression when neutral charmed mesons decay into CP eigenstates is [1]

$$A_{CP}(t) \approx \frac{\eta_{CP}}{2} \frac{t}{\tau} \left[ y \left( \frac{|p|}{q} - \frac{|q|}{p} \right) \cos(\varphi) + x \left( \frac{|p|}{q} + \frac{|q|}{p} \right) \sin(\varphi) \right],$$  \hspace{1cm} (2)

that persists when integrated over time. In eq. (2) $\eta_{CP}$ is the CP-parity of the decay final state (+1 for $\pi^+\pi^-$), $x$, $y$, $p$ and $q$ are the usual parameters used to describe flavored mesons mixing, $\varphi$ is the weak CP violating phase and $t/\tau$ the proper decay time in unit of $D^0$ lifetime ($\tau \approx 0.5$ ps). The measured integrated asymmetry, owing to the slow mixing rate of charm mesons, reduces at first order to a sum of two terms:

$$A_{CP}(\pi^+\pi^-) = a^{\text{dir}}_{CP} + \int_0^\infty A_{CP}(t)D(t)dt \approx a^{\text{dir}}_{CP} + \frac{(t)}{\tau} a^{\text{ind}}_{CP}.$$  \hspace{1cm} (3)
The first term arises from direct and the second one from mixing-induced CP violation. The integration in eq. (3) is performed over the observed distribution of proper decay time, $D(t)$. Since the value of $\langle t \rangle$ depends strongly on $D(t)$, different values of $A_{CP}$ could be observed in different experimental environments because of different sensitivities to $a_{CP}^{dir}$ or $a_{CP}^{ind}$. Since the trigger used in this analysis imposes requirements on minimum impact parameters of the $D^0$ decay particles, our sample is enriched of higher-valued proper decay time candidates with respect to B-factory experiments. This makes this analysis more sensitive to mixing-induced CP violation.

The measurement, described with further details in [2], has been performed on about 5,94 fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the CDF II detector at Fermilab’s Tevatron collider.

2. Detector and trigger
The CDF II detector [3] is a magnetic spectrometer surrounded by calorimeters and muon detectors. It provides a determination of the decay point of particles with 15 $\mu$m resolution in the transverse plane using six layers of double-sided silicon-microstrip sensors at radii between 2.5 and 22 cm from the beam. A 96-layer drift chamber extending radially from 40 to 140 cm from the beam provides excellent momentum resolution, yielding approximately 8 MeV/$c^2$ mass resolution for two body charm decays. A three-level trigger system selects events enriched in decays of long-lived particles by exploiting the presence of displaced tracks in the event and measuring their impact parameter with offline-like 30 $\mu$m resolution. The trigger requires presence of two charged particles with transverse momenta greater than 2 GeV/$c$, impact parameters greater than 100 microns and basic cuts on azimuthal separation and scalar sum of momenta.

3. Analysis overview
We measure the asymmetry using $D^0 \rightarrow \pi^+\pi^-$ decays from charged $D^*$ mesons through fits of the $D^0\pi$ mass distributions. The observed asymmetry includes a possible contribution from actual CP violation, diluted in much larger effects from instrumental charge-asymmetries. We exploit a fully data-driven method that uses higher statistic samples of $D^*$-tagged (indicated with an asterisk) and untagged Cabibbo-favored $D^0 \rightarrow K^-\pi^+$ decays to correct for all detector effects thus suppressing systematic uncertainties to below the statistical ones. We define “raw” asymmetries the observed asymmetries in signal yields, $A_{CP}^{raw}(D^0 \rightarrow f) = \frac{N_{\text{obs}}(D^0 \rightarrow f) - N_{\text{obs}}(\bar{D}^0 \rightarrow \bar{f})}{N_{\text{obs}}(D^0 \rightarrow f) + N_{\text{obs}}(\bar{D}^0 \rightarrow \bar{f})}$, before any correction for instrumental effects has been applied. Then the uncorrected “raw” asymmetries in the three samples can be written as a sum of several contributions:

$$ A_{CP}^{raw}(\pi\pi) = A_{CP}(\pi\pi) + \delta(\pi_s)_{\pi\pi}^* $$

$$ A_{CP}^{raw}(K\pi) = A_{CP}(K\pi) + \delta(\pi_s)_{K\pi}^* + \delta(K\pi)_{K\pi}^* $$

$$ A_{CP}^{raw}(K\pi) = A_{CP}(K\pi) + \delta(K\pi)_{K\pi}^* $$
where

- $A_{\text{CP}}(\pi\pi)$ and $A_{\text{CP}}(K\pi)$ are the actual physical asymmetries;
- $\delta(\pi_0)_{\pi\pi}$ and $\delta(\pi_0)_{K\pi}$ are the instrumental asymmetries in reconstructing a positive or negative soft pion associated to a $\pi^+\pi^-$ and a $K^+\pi^-$ or $K^-\pi^+$ charm decay. This is mainly induced by charge-asymmetric track-reconstruction efficiency at low transverse momentum.
- $\delta(K\pi)_{K\pi}$ and $\delta(K\pi)_{\pi\pi}$ are the instrumental asymmetries in reconstructing a $K^+\pi^-$ or a $K^-\pi^+$ charm decay respectively for the untagged and the $D^*$-tagged case. These are mainly due to the difference in interaction cross-section with matter between positive and negative kaons. Smaller effect are due to charge-curvature asymmetries in track triggering and reconstruction.

The physical asymmetry is extracted by subtracting the instrumental effects through the combination

$$A_{\text{CP}}(\pi\pi) = A_{\text{CP}}^{\text{raw}}(\pi\pi) - A_{\text{CP}}^{\text{raw}}(K\pi) + A_{\text{CP}}^{\text{raw}}(K\pi),$$

(4)

that is valid if kinematics distributions are equal across samples. Any instrumental effect can vary as a function of a number of kinematic variables or environmental conditions in the detector, but if the kinematic distributions of soft pions are consistent in $K\pi^*$ and $\pi\pi^*$ samples, and the distributions of $D^0$ decay products are consistent in $K\pi^*$ and $K\pi$ samples, then $\delta(\pi_0)_{\pi\pi} \approx \delta(\pi_0)_{K\pi}$ and $\delta(K\pi)_{\pi\pi} \approx \delta(K\pi)_{K\pi}$. This condition was verified in the analysis by inspecting a large set of kinematic distributions and applying small corrections (reweight) when needed.

4. Measurement

The trigger selects pair of tracks from oppositely charged particles that are consistent with originating from a secondary decay vertex separated from the beamline, requiring an impact parameter greater than 100 $\mu$m. Using these tracks we reconstruct signals consistent with the desired two-body decays ($\pi^+\pi^-$ or $K^-\pi^+$ or $K^+\pi^-$) of a neutral charmed meson ($D^0$ or $\bar{D}^0$). To remove most part of non-promptly produced charmed mesons we also require the impact parameter of the $D^0$ candidate not to exceed 100 $\mu$m. Then we associate a low-momentum charged particle to the meson candidate to construct a $D^{*+}$ (or $D^{*-}$) candidate. The flavor of the charmed meson is determined from the charge of the pion in the strong $D^{*+} \rightarrow D^0\pi^+$ (or $D^{*-} \rightarrow \bar{D}^0\pi^-$) decay. Sample-specific mass requirements are used for the two tagged samples: we ask the two-body invariant mass ($M(K\pi)$ for the $D^0 \rightarrow K\pi$ case and $M(\pi\pi)$, for the $D^0 \rightarrow \pi\pi$ case) to lie within 24 MeV/$c^2$ of the nominal $D^0$ mass.

We reconstruct approximately 215,000 $D^*$-tagged $D^0 \rightarrow \pi^+\pi^-$ decays, 5 million $D^*$-tagged $D^0 \rightarrow \pi^+K^-$ decays and 29 million $D^0 \rightarrow \pi^+K^-$ decays where no tag was required. The much larger statistics of $D^0 \rightarrow \pi^+K^-$ channels, with respect to the signal sample, is used for correction of instrumental asymmetries and ensures smaller systematic uncertainties than statistical ones on the final result.

We extract independent signal yields for $D^0$ and $\bar{D}^0$ candidates without using particle identification in the analysis. In the two $D^*$-tagged samples this is done using the charge of the soft pion. In the untagged $D^0 \rightarrow K^-\pi^+$ sample we randomly divided the sample in two independent subsamples similar in size. In each subsample we calculate the mass of each candidate with a specific mass assignments: $K^-\pi^+$ in the first subsample and $K^+\pi^-$ in the second one. In one sample the $D^0 \rightarrow K^-\pi^+$ signal is correctly reconstructed and appears as a narrow peak (about 8 MeV/$c^2$ wide), overlapping a $\sim 10$ times broader peak of the misreconstructed $\bar{D}^0 \rightarrow K^+\pi^-$ component (red and green curves in figs. 1 (e)-(f)). The viceversa applies the other sample. The yield asymmetry is extracted by fitting the number of candidates populating the two narrow peaks.
Figure 1. Projections of the combined fit on data for tagged $D^0 \rightarrow \pi^+\pi^-$ (a)-(b), tagged $D^0 \rightarrow K^-\pi^+$ (c)-(d) and untagged $D^0 \rightarrow K^-\pi^+$ (e)-(f) decays.
We determine the yields by performing a binned $\chi^2$ fit to the $D^0\pi_\pm$-mass ($K\pi$-mass) distribution combining positive and negative decays of both tagged (untagged) samples. The fits projections are shown in fig. 1, the resulting raw asymmetries are: $A_{CP}^{raw}(\pi\pi^*) = (-1.86 \pm 0.23)\%$, $A_{CP}^{raw}(K\pi^*) = (-2.91 \pm 0.05)\%$, $A_{CP}^{raw}(K\pi) = (-0.83 \pm 0.03)\%$.

5. Systematic uncertainties
The analysis technique has been extensively tested on Monte Carlo simulation using samples simulated with a wide range of physical and detector asymmetries to verify that the cancellation works regardless of the specific configuration. These studies confirm the validity of our approach and provide a quantitative estimate of possible asymmetries induced by higher order detector effect that may not get fully cancelled or effects of not factorization of $K\pi$ and $\pi_\pm$ reconstruction efficiencies. This upper limit is used as systematic uncertainty and amount to 0.009%.

We evaluate all other systematic uncertainties from data. In most cases, this implied varying slightly the shape of the functional forms used in fits, repeating the fit on data, and using the difference between the results of these and the central fit as a systematic uncertainty. This overestimates the size of the systematic effects because it introduces an additional statistical source of fluctuation in the results. But we can comfortably afford that given the large event samples size involved.

Small differences between $D^0\pi_\pm$-mass distributions of positive and negative $D^*$ candidates selected in their $D^0(\to K\pi)\pi$ decay are present. This may be due to possible small differences in tracking resolutions between positive and negative tracks at low momentum. These effects impact at first order the observed asymmetry. Insignificant differences are observed in the $K\pi$-mass distributions of the untagged $D^0 \to K\pi$ sample. To evaluate an associated systematic uncertainty we repeated the fits after fixing signal shapes to be the same and/or leaving background shapes to vary independently for positive and negative $D^*$ candidates. The maximum observed variations (0.088% for the tagged case and 0.044% for the untagged one) are used as systematic uncertainties.

A contamination by charm mesons produced in $b$–hadron decays could affect the asymmetry measurement in case CP–violating asymmetries in $B$ decays induce an asymmetric source of charm and anti-charm mesons. These effect may be sizable for a single exclusive mode, but are expected to average to very small values for inclusive $B \to D^0/D^*X$ decays. In the analysis we exclude the majority of non-primary charm contributions by applying an upper threshold on the $D^0$ candidate impact parameter. However, a fit to the impact parameter distribution determines a residual 16.6% fraction of charm from $B$ in our sample. To assess the effect of these events we repeat the measurement using only charm mesons with large impact parameters, enriched in $b$–hadron decays. The observed asymmetry is

$$A_{CP}(B \to D^0/D^*X) = (-0.21 \pm 0.20)\%.$$  

The uncertainty on this number, and the fraction of the non-prompt contribution that survives the $D^0$ impact parameter cut, is used to assess a conservative estimate of the systematic uncertainty caused by the non-prompt contamination in our samples.

Tab. 1 summarizes the set of all systematic uncertainties considered in the measurement. Assuming they are independent and summing in quadrature we obtain a total systematic uncertainty on our final $A_{CP}(\pi\pi)$ measurement of 0.11%, approximately half of the statistical uncertainty.

6. Final result and conclusions
We report the measurement of the CP asymmetry in the decay $D^0 \to \pi^+\pi^-$ using 5.94 fb$^{-1}$ of data collected by the CDF displaced track trigger. The final result is

$$A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24 \ (stat.) \pm 0.11 \ (syst.)] \%,$$
Table 1. Summary of systematic uncertainties.

| Source of systematic uncertainty                          | Variation on $A_{\text{CP}}(\pi\pi)$ |
|-----------------------------------------------------------|--------------------------------------|
| Approximations in the method                              | 0.009%                               |
| Beam drag effects                                         | 0.004%                               |
| Contamination of non-prompt $D^0$s                        | 0.034%                               |
| Templates used in fits                                    | 0.010%                               |
| Templates charge differences                              | 0.098%                               |
| Asymmetries from non-subtracted backgrounds               | 0.018%                               |
| Imperfect sample reweighing                               | 0.0005%                              |
| Sum in quadrature                                         | 0.105%                               |

Figure 2. (a) Fit to the proper decay time (in units of $D^0$ lifetime) distribution of sideband-subtracted tagged $D^0 \rightarrow \pi\pi$ data. (b) Comparison of our measurement with current best results from B-factories in the parameter space $(a_{\text{ind}}^{\text{CP}}, a_{\text{dir}}^{\text{CP}})$. which is consistent with CP conservation and also with the SM predictions.

To disentangle the independent contributions of direct and indirect CP violation in $D^0 \rightarrow \pi^+\pi^-$ decays, an analysis where the time evolution of charm decays is studied is needed. Nevertheless some interesting conclusions could be derived either comparing our result with B-factories measurements or making some theoretical assumptions.

The observed asymmetry is at first order the linear combination of a direct, $a_{\text{dir}}^{\text{CP}}$, and an indirect, $a_{\text{ind}}^{\text{CP}}$, CP violating asymmetry through a coefficient that is the mean proper decay time of $D^0$ candidates in the data sample (see eq. (3)). Fig. 2 (a) shows a fit to the mean proper decay time distribution of our tagged $D^0 \rightarrow \pi^+\pi^-$ sample, the resulting mean value is $2.40 \pm 0.03$ (stat. + syst.) times the $D^0$ lifetime. Our measurement therefore describes a straight band in the plane $(a_{\text{ind}}^{\text{CP}}, a_{\text{dir}}^{\text{CP}})$ with angular coefficient $-2.4$. The same holds for B-factories’ measurements, with angular coefficient $-1$ [4], due to their unbiased acceptance in charm decay time. The three measurements in the plane $(a_{\text{ind}}^{\text{CP}}, a_{\text{dir}}^{\text{CP}})$ are shown in fig. 2 (b), where the bands are $1\sigma$ wide and the red curves represent the 68% and 95% CL limits of the combined result assuming Gaussian uncertainties.
If we assume no direct CP violation in the charm sector eq. (3) simplifies to

\[ A_{CP}(\pi^+\pi^-) \approx \frac{\langle t \rangle}{\tau} a^{\text{ind}}_{CP} \]

so this measurement implies

\[ a^{\text{ind}}_{CP} = [+0.09 \pm 0.10 \ (\text{stat.}) \pm 0.05 \ (\text{syst.})] \% , \]

that means the range \([-0.124, 0.307]\)% covers \(a^{\text{ind}}_{CP}\) at the 95% CL. Note that, since \(\langle t \rangle/\tau\) in our sample is greater than in B-factories ones, this range is more than five times tighter than the ones obtained using B-factories measurements, as shown in fig. 3 (a).

Conversely, assuming \(a^{\text{ind}}_{CP} = 0\), our number is directly comparable to other measurements in different experimental configurations. In this case, fig. 3 (b), our statistical uncertainties are half those from the best B-factories measurements, and also systematic uncertainties are smaller.

We have measured the CP asymmetry in the \(D^0 \rightarrow \pi^+\pi^-\) decay with unprecedented precision, and find a result compatible with zero. A new measurement is expected from the channel \(D^0 \rightarrow K^+K^-\), which is more abundant, although the higher level of background requires additional care in the analysis. It is expected that these high precision measurements will allow to put tight constraints on NP in the up-quark sector.

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