Measurement of Partial Widths and Search for Direct CP Violation in D^0 Meson Decays to K^-K^+ and $\pi^-\pi^+$

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We present a measurement of relative partial widths and decay rate CP asymmetries in K^-K^+ and $\pi^-\pi^+$ decays of D^0 mesons produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$. We use a sample of 2×10^5 $D^{*+}\to D^0\pi^+$ (and charge conjugate) decays with the D^0 decaying to $K^-\pi^+$, K^-K^+, and $\pi^-\pi^+$, corresponding to $123\,\text{pb}^{-1}$ of data collected by the CDF II experiment at the Fermilab Tevatron collider. No significant direct CP violation is observed, we measure $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to K^-\pi^+) = 0.0992 \pm 0.0011 \pm 0.0012$, $\Gamma(D^0 \to \pi^-\pi^+)/\Gamma(D^0 \to K^-\pi^+) = 0.03594 \pm 0.00054 \pm 0.00040$, $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to \pi^-\pi^+) = 2.760 \pm 0.040 \pm 0.034$, $A_{CP}(K^-K^+) = (2.0 \pm 1.2 \pm 0.6)\,\%$, and $A_{CP}(\pi^-\pi^+) = (1.0 \pm 1.3 \pm 0.6)\,\%$, where, in all cases, the first uncertainty is statistical and the second is systematic.

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The Cabibbo suppressed decays $D^0\to K^-K^+, \pi^-\pi^+$ have been used to study D^0 mixing and CP violation in the charm sector. Direct CP violation in decay rates requires the interference of two amplitudes with different weak and strong phases. In $D^0\to K^-K^+, \pi^-\pi^+$, the spectator and penguin amplitudes have different weak phases, and different strong phases are expected to be generated by rescattering in final state interactions (FSI). The predicted rates of CP violation are of the order of the imaginary part of the V_{cs} element of the CKM matrix, $O(0.1\%)$. New physics, providing additional phases, can enhance these predictions up to $O(1\%)$ [1]. At present there is no experimental evidence of direct CP violation in these decays; a combination of previous measurements [2] yields, for the direct CP asymmetries (A_{CP}), $A_{CP}(K^-K^+) = 0.005 \pm 0.016$, and $A_{CP}(\pi^-\pi^+) = 0.021 \pm 0.026$.

In the limit of exact SU(3) flavor symmetry [3] $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to \pi^-\pi^+) \sim 1$. Including the effects of phase space, the difference of the kaon and pion decay constants and other SU(3) breaking effects may increase this ratio up to 1.4 [4]. The world average value is 2.826 ± 0.097 [2], well above the expectations. Large FSI and contributions from penguin diagrams have been proposed to explain this discrepancy [5]. Phenomenological analyses [6], using available data on D^0 and D^+ branching ratios, derive the magnitudes and phase shifts of the relevant amplitudes, including FSI, that reproduce the above world-average measured ratio. The same phenomenological analyses predict CP asymmetries as high as 0.1% for certain Cabbibo-suppressed decays and somewhat lower asymmetries for the K^-K^+ and $\pi^-\pi^+$ channels. A significant asymmetry at the level of 1%, not yet excluded experimentally, would be an interesting indication for non-standard model sources of CP violation in the charm sector.

We present measurements of the ratios $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to K^-\pi^+)$, $\Gamma(D^0 \to \pi^-\pi^+)/\Gamma(D^0 \to K^-\pi^+)$, and $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to \pi^-\pi^+)$, and results of the search for direct CP violation in the Cabibbo-suppressed $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays based on $123 \pm 7\ \mathrm{pb}^{-1}$ of data recorded by the CDF II experiment at the Tevatron collider at $\sqrt{s} = 1.96$ TeV. The sample contains 2×10^5 $D^{*+} \to D^0\pi^+$ events, with D^0 decaying to the three modes under study (charge conjugate states are implied throughout this paper, unless otherwise stated). The D^0 flavor is unambiguously determined from the charge of the pion in the strong decay $D^{*+} \to D^0\pi^+$.

The components of the CDF II detector pertinent to this analysis are described briefly below; a more complete description can be found elsewhere [7]. For this measurement we use only tracks reconstructed by both the Central Outer Tracker (COT) and the silicon microstrip detector (SVX II) in the pseudorapidity range $|\eta| \lesssim 1$ [8]. The SVX II detector consists of double-sided silicon strip sensors arranged in five cylindrical shells with radii between 2.5 and 10.6 cm [9]. Surrounding the SVX II is the COT [10], an open-cell drift chamber that has an inner (outer) radius of 40 (137) cm. The COT has 96 layers, organized in 8 superlayers with alternating superlayers of axial and $\pm 2^\circ$ stereo readout. The D^0 decays used in this analysis are selected with a three-level trigger system. At Level 1, charged tracks are reconstructed in the COT axial superlayers by a hardware processor (eXtremely Fast Tracker) [11]. The trigger requires two oppositely charged tracks with transverse momenta $p_T \geq 2\,\mathrm{GeV}/c$ and the scalar sum $p_{T1} + p_{T2} \geq 5.5\,\mathrm{GeV}/c$. At Level 2, the Silicon Vertex Tracker (SVT) [12] associates SVX II r-ϕ position measurements with XFT tracks, providing a precise measurement of the track impact parameter (d_0), defined as the distance of closest approach, in the transverse plane, of the trajectory of the track to the beam axis. The resolution of this impact parameter measurement is $50\,\mu$m, which includes a $\approx 30\,\mu$m contribution from the transverse beam size. Hadronic decays of heavy flavor particles are selected by requiring two-tracks (trigger tracks) with $120\,\mu\mathrm{m} \leq d_0 \leq 1.0\,\mathrm{mm}$. The two trigger tracks must have an opening angle in the transverse plane satisfying $2^\circ \leq |\Delta\phi| \leq 90^\circ$ and must satisfy the requirement $L_{\mathrm{xy}} > 200\,\mu$m, where the two-dimensional decay length, L_{xy}, is calculated as the transverse distance from the beam line to the two-track vertex projected along the total transverse momentum of the track pair. At Level 3, a complete event reconstruction is performed, and the Level 1 and Level 2 requirements are confirmed.

The reconstruction of D^{*+} candidates starts from the selection of pairs of oppositely charged tracks that satisfy the trigger requirements. We form one $D^0 \to K^-\pi^+$, K^-K^+, and $\pi^-\pi^+$ candidate for each trigger pair. For the $K^-\pi^+$ mode we also form a second D^0 candidate with the mass assignments interchanged. No K or π particle identification is used in this analysis. D^0 candidates whose invariant mass is within $\pm 100\,\mathrm{MeV}/c^2$ of the mean reconstructed D^0 mass are combined with a third track with $p_T \geq 0.4\,\mathrm{GeV}/c$ to form a $D^{*+} \to D^0\pi^+$ candidate. In the reconstruction of $D^0 \to K^-\pi^+$ decays, the charge of the pion from the D^0 decay is required to be the same as the charge of the pion from the D^{*+} decay. To reduce combinatorial background and background from partially reconstructed D^0 decays, we require the measured mass difference, ΔM, between the D^{*+} and D^0 mesons to be within three standard deviations in experimental resolution of the expected value: $143.5\,\mathrm{MeV}/c^2 < \Delta M < 147.2\,\mathrm{MeV}/c^2$. Finally, to reduce the potential systematic uncertainty induced by the different acceptance ratios of D^{*+} produced in B-hadron decays, the contribution ($\sim$12%) [13] of non-prompt D^{*+} is reduced by requiring the impact parameter of the D^0 meson to satisfy $d_0(D^0) \leq 100\,\mu$m.

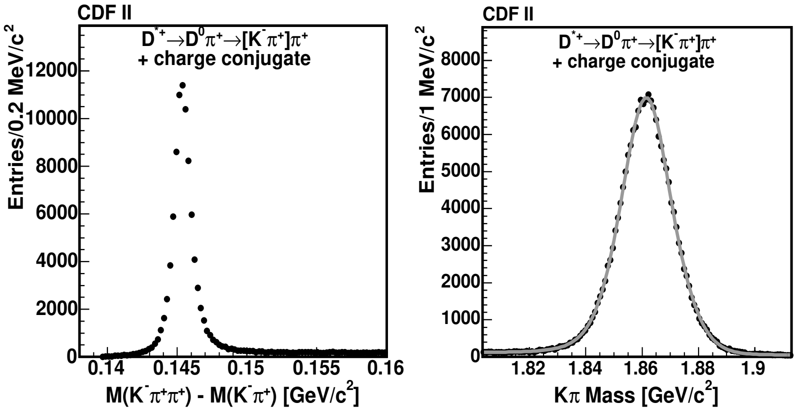

FIG. 1: The $\Delta M = M(K^-\pi^+\pi^+) - M(K^-\pi^+)$ distribution (left) for the $D^0 \to K^-\pi^+$ candidates. The $K^-\pi^+$ invariant mass distribution (right) after all selection criteria have been applied. The curve is the sum of the fits performed separately for the D^0 and $\overline{D^0}$ mesons.

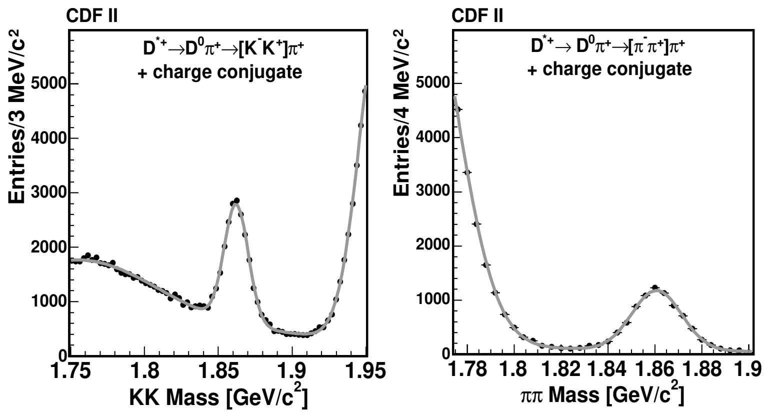

FIG. 2: The K^-K^+ (left) and $\pi^-\pi^+$ (right) invariant mass distributions after all selection criteria have been applied. The superimposed curves represent the sum of the individual fits for the D^0 and $\overline{D^0}$ distributions described in the text. The $D^0 \to \pi^-\pi^+$ and $D^0 \to K^-K^+$ peaks are well separated from the mis-identification peak due to the $K^-\pi^+$ mode.

The D^0 yields are obtained from binned maximum likelihood fits to the D^0 invariant mass distributions. For the $K^-\pi^+$ mode, the signal is modeled with a single Gaussian function plus a convolution of an exponential function with an error function to model the low mass tail of the observed distribution; a second-degree polynomial is used to model the combinatorial background. For the K^-K^+ and $\pi^-\pi^+$ modes, due to the limited event statistics, we use a single Gaussian as a model for the signal. We use Gaussian functions to describe both the $K^-\pi^+$ mis-identification peaks in the K^-K^+ and $\pi^-\pi^+$ modes and the background from partially reconstructed $D^0 \to K^-\pi^+\pi^0$ decays in the K^-K^+ mode, and we verified, in simulated samples of inclusive D^0 decays, that this model adequately describes both sources of background. The invariant mass distributions for the $K^-\pi^+$, K^-K^+, and $\pi^-\pi^+$ modes are shown in Fig. 1 and Fig. 2. The number of signal events from the fits to the invariant mass distributions are reported in Table I.

TABLE I: The D^0 and $\overline{D^0}$ signals determined from the fits to the invariant mass distributions. The errors are the statistical uncertainties from the fits.

Mode	D^0	$\overline{D^0}$	Total
$K\pi$	$88,310 \pm 330$	$92,600 \pm 340$	$180,910 \pm 480$
KK	$8,190 \pm 140$	$8,030 \pm 140$	$16,220 \pm 200$
$\pi\pi$	$3,660 \pm 69$	$3,674 \pm 68$	$7,334 \pm 97$

The systematic uncertainty on the signal yields due to the fitting procedure has been estimated by varying the model used for the combinatorial background (using a third-degree polynomial instead of a second-degree polynomial), using two Gaussian functions with different means and widths to describe D^0 signals, and performing the fits in different ranges of $p_T(D^0)$.

The relative branching fractions are extracted using the formula

$$\frac{\Gamma\left(D^0 \to h^-h^+\right)}{\Gamma\left(D^0 \to K^-\pi^+\right)} = \frac{N_{h^-h^+}}{N_{K\pi}} \cdot \frac{\epsilon_{K\pi}}{\epsilon_{h^-h^+}} = \frac{N_{h^-h^+}}{N_{K\pi}} \cdot R_{h^-h^+}, \tag{1}$$

where $h = K$ or π, $N_{h^-h^+}$ is the total number of D^0 mesons decaying in the appropriate mode from Table I, and $\epsilon_{h^-h^+}$ is the average D^0 and $\overline{D^0}$ acceptance for each of the decays, including trigger and reconstruction efficiency. The quantity $R_{h^-h^+}$ is the efficiency ratio of the $D^0 \to K^-\pi^+$ to $D^0 \to h^-h^+$ mode.

We have used a Monte Carlo simulation, based on GEANT [14], of the CDF II detector and trigger to determine the ratios of the relative trigger, and reconstruction efficiencies for the three decay modes. The trigger efficiency varies among the three modes due to the different nuclear interaction and decay-in-flight probabilities for π^+, π^-, K^+, and K^-; the differences in the kinematics of the decay (*e.g.*, opening angle distributions), induced by the masses of the final state particles, and the different XFT efficiency as a function of the track p_T caused by the different specific ionization in the COT for $\pi^\pm$ and $K^\pm$. The simulated signals have been generated using as input the momentum and rapidity distributions of the D^{*+} mesons as measured by CDF II [13]. We generated four to ten times the signal statistics in the data sample, depending on the mode. The simulation of the CDF II detector includes the time variation of the beam position and of the hardware configuration in the SVX II and SVT. The trigger efficiencies have been studied in detail using calibration samples of real data. For the ratio of efficiencies we obtain $R_{KK} = 1.1073 \pm 0.0074$ and $R_{\pi\pi} = 0.8867 \pm 0.0056$, where the uncertainties are due to Monte Carlo statistics. For the relative $D^0 \to K^-K^+$ to $D^0 \to \pi^-\pi^+$ efficiencies we obtain 1.2488 ± 0.0078.

The following are sources of uncertainty in the determination of the relative efficiencies: the simulation of the XFT and SVT triggers, the time-dependent variations of the beam spot size in z, the simulation of nuclear interactions in the CDF II detector, the effect on the trigger efficiency due to a possible lifetime difference between the CP-even and CP-mixed D^0 decays, the input p_T spectra for D^{*+} mesons and the different ratios of efficiencies for D^{*+} produced in B-hadron decays. The contribution of each source listed above to the total relative systematic error on the ratio of branching fraction measurements is reported in Table II.

Using Eq. 1 we derive the relative branching ratios reported in Table III. In addition, we obtain $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to \pi^-\pi^+) = 2.760 \pm 0.040\,(stat) \pm 0.034\,(syst)$.

We extract the CP decay rate asymmetries, using the same samples of D^0 decays described above, by measuring

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

where f represents either the K^-K^+ or $\pi^-\pi^+$ final state. The direct production of charm mesons in $p\overline{p}$ collisions is assumed to be CP invariant. The measured CP asymmetry must be corrected

TABLE II: The sources of systematic uncertainty on the ratios of branching fractions and their contributions to the total fractional systematic uncertainty. Listed in the final row is the sum in quadrature of the individual entries.

Systematic source	$(\frac{KK}{K\pi})[\%]$	$(\frac{\pi\pi}{K\pi})[\%]$	$(\frac{KK}{\pi\pi})[\%]$
Fit Model	0.64	0.54	0.67
Monte Carlo statistics	0.67	0.63	0.62
Trigger simulation	0.34	0.31	0.37
Beam spot size	0.35	0.24	0.35
Material in GEANT	0.28	0.30	0.59
Lifetime difference	0.55	0.55	
Input spectra	0.05	< 0.01	< 0.01
Non prompt D^*	0.16	0.08	0.24
Total relative error:	1.2	1.1	1.2

for different detector efficiencies (detector charge asymmetry) for positive and negative charged pions in the D^* decay, which produce a different detection efficiency for D^{*+} and D^{*-} mesons.

The detector charge asymmetry is produced by the interactions of particles with the detector material and by effects related to the cell geometry of the COT. We measure this asymmetry in order to correct the number of observed $D^{*+} \to D^0\pi^+$ decays relative to the number of observed $D^{*-} \to \overline{D^0}\pi^-$ decays for the difference in detection efficiencies of π^+ and π^-. For the detector charge asymmetry measurement, we compare the numbers of reconstructed positive and negative tracks as a function of track p_T in a high statistics data sample collected with the same trigger used to collect the signal sample. We avoid a bias in the charge asymmetry due to interactions of the beam with material in the detector near the interaction region by selecting tracks which originate from the primary $p\overline{p}$ collision point, requiring the track impact parameter to be $d_0 \leq 100\,\mu$m. The detector charge asymmetry, defined as $(N^+ - N^-)/(N^+ + N^-)$, where N^+ (N^-) is the number of positive (negative) tracks in the sample, is shown as a function of

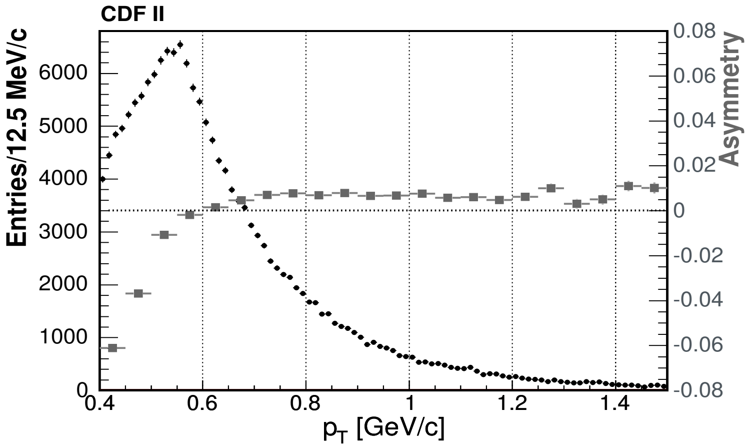

FIG. 3: The D^{*+} decay pion p_T distribution (black dots), and the detector charge asymmetry (gray squares) as a function of track transverse momentum measured from tracks reconstructed in a high statistics data sample collected with the same trigger used to collect the signal samples.

the track p_T in Fig. 3.

Using the event yields in Table I, and correcting for the detector charge asymmetry, we obtain the CP asymmetries reported in Table III.

TABLE III: Summary of results from this analysis. The first uncertainty is statistical, the second systematic.

	$D^0 \to K^- K^+$ [%]	$D^0 \to \pi^- \pi^+$ [%]
$\Gamma/\Gamma(K^-\pi^+)$	$9.92 \pm 0.11 \pm 0.12$	$3.594 \pm 0.054 \pm 0.040$
A_{CP}	$2.0 \pm 1.2 \pm 0.6$	$1.0 \pm 1.3 \pm 0.6$

To evaluate the systematic uncertainty associated with the charge asymmetry corrections we apply the corrections to the sample of $D^{*+} \to D^0\pi^+ \to [K^-\pi^+]\pi^+$ decays, where, in the standard model, we expect no CP violation. Unlike the analysis for the decays to CP eigenstates, in this case we must also apply an efficiency correction of 3% due to the different nuclear interaction rates of K^+ and K^-, derived from the Monte Carlo described above. A residual asymmetry of (0.35 ± 0.53)% is found, where the error is the statistical uncertainty due to the data and

Monte Carlo statistics. In addition, we check the analysis using charge asymmetry corrections determined with track samples selected by different triggers, by dividing the signal samples into two ranges of D^{*+} pion transverse momentum ($p_T > 0.6\,\mathrm{GeV}/c$ and $p_T \leq 0.6\,\mathrm{GeV}/c$) and by deriving the charge asymmetry correction using a sample of $K^0_S \to \pi^-\pi^+$ decays instead of generic tracks. These additional uncertainty estimates result in variations smaller than the uncertainty of $\pm 0.53\%$ on the asymmetry measurement described above, and this statistical uncertainty is adopted as a conservative estimate of our systematic error. The only additional systematic uncertainty is due to the yield determination of D^0 and $\overline{D^0}$, and is added in quadrature to the detector charge asymmetry correction uncertainty; other sources give negligible contributions and are ignored.

In summary, we have used the CDF II detector to measure the ratios of partial widths $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to K^-\pi^+) = 0.0992 \pm 0.0011\,(stat) \pm 0.0012\,(syst)$, $\Gamma(D^0 \to \pi^-\pi^+)/\Gamma(D^0 \to K^-\pi^+) = 0.03594 \pm 0.00054\,(stat) \pm 0.00040\,(syst)$, and $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to \pi^-\pi^+) = 2.760 \pm 0.040\,(stat) \pm 0.034\,(syst)$. These measurements agree with, and are an improvement in precision over, the best previously available measurements [2]. We have made the most precise measurement to date of the direct CP asymmetries $A_{CP}(K^-K^+) = (2.0 \pm 1.2\,(stat) \pm 0.6\,(syst))\%$, and $A_{CP}(\pi^-\pi^+) = (1.0 \pm 1.3\,(stat) \pm 0.6\,(syst))\%$. At present there is no evidence for direct CP violation in Cabibbo-suppressed D^0 decays.

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