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## Measurement of Partial Widths and Search for Direct CP Violation

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Collider Detector at Fermilab Collaboration

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## 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  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV. We use a sample of  $2 \times 10^5$   $D^{*+} \rightarrow D^0\pi^+$  (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 Collider Detector at Fermilab II experiment at the Fermilab Tevatron collider. No significant direct  $CP$  violation is observed. We measure  $\Gamma(D^0 \rightarrow K^-K^+)/\Gamma(D^0 \rightarrow K^-\pi^+) = 0.0992 \pm 0.0011 \pm 0.0012$ ,  $\Gamma(D^0 \rightarrow \pi^-\pi^+)/\Gamma(D^0 \rightarrow K^-\pi^+) = 0.03594 \pm 0.00054 \pm 0.00040$ ,  $A_{CP}(K^-K^+) = (2.0 \pm 1.2 \pm 0.6)\%$ , 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  $D^0 \rightarrow K^-K^+$ ,  $\pi^-\pi^+$  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  $D^0 \rightarrow K^-K^+$ ,  $\pi^-\pi^+$ , 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 Cabibbo-Kobayashi-Maskawa 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 mea-

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]  $\Gamma(D^0 \rightarrow K^-K^+)/\Gamma(D^0 \rightarrow \pi^-\pi^+) \sim 1$ . 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  $2.826 \pm 0.097$  [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 Cabibbo-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  $\Gamma(D^0 \rightarrow K^-K^+)/\Gamma(D^0 \rightarrow K^-\pi^+)$ , and  $\Gamma(D^0 \rightarrow \pi^-\pi^+)/\Gamma(D^0 \rightarrow K^-\pi^+)$  and results of the search for direct  $CP$  violation in the Cabibbo-suppressed  $D^0 \rightarrow K^-K^+$  and  $D^0 \rightarrow \pi^-\pi^+$  decays. The sample contains  $2 \times 10^5$   $D^{*+} \rightarrow D^0\pi^+$  events, with  $D^0$  decaying to the three modes under study (charge conjugate states are implied throughout this Letter, unless otherwise stated). The  $D^0$  flavor is unambiguously determined from the charge of the pion in the strong decay  $D^{*+} \rightarrow D^0\pi^+$ .

The components of the Collider Detector at Fermilab (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) [8] and the silicon microstrip detector (SVX II) [9] in the pseudorapidity range  $|\eta| \leq 1$  [10]. 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 transverse plane by a hardware processor [Extremely Fast Tracker (XFT)] [11]. The trigger requires two oppositely charged tracks with transverse momenta  $p_T \geq 2$  GeV/ $c$  and the scalar sum  $p_{T1} + p_{T2} \geq 5.5$  GeV/ $c$ . At level 2, the Silicon Vertex Tracker (SVT) [12] associates SVX II  $r$ - $\phi$  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  $\mu\text{m}$ , which includes a  $\approx 30$   $\mu\text{m}$  contribution from the transverse beam size. Hadronic decays of heavy flavor particles are selected by requiring two tracks (trigger tracks) with  $120 \mu\text{m} \leq d_0 \leq 1.0$  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  $L_{xy} > 200 \mu\text{m}$ , 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  $D^0 \rightarrow K^-\pi^+$ ,  $K^-K^+$ , 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  $\pi$  particle identification is used in this analysis.  $D^0$  candidates whose invariant mass is within  $\pm 100$  MeV/ $c^2$  of the mean reconstructed  $D^0$  mass are combined with a third track with  $p_T \geq 0.4$  GeV/ $c$  to form a  $D^{*+} \rightarrow D^0\pi^+$  candidate. In the reconstruction of  $D^0 \rightarrow K^-\pi^+$  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,  $\Delta M$ , between the  $D^{*+}$  and  $D^0$  mesons to be within 3 standard deviations in experimental resolution of the expected value:  $143.5 \text{ MeV}/c^2 < \Delta M < 147.2 \text{ MeV}/c^2$ . 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 nonprompt  $D^{*+}$  is reduced by requiring the impact parameter of the  $D^0$  meson to satisfy  $d_0(D^0) \leq 100 \mu\text{m}$ .

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  $K^-\pi^+$  misidentification peaks in the  $K^-K^+$  and  $\pi^-\pi^+$  modes and the background from partially reconstructed  $D^0 \rightarrow K^-\pi^+\pi^0$  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 Figs. 1 and 2. The number of signal events from the fits to the invariant mass distributions are reported in Table I.

The relative branching fractions are extracted using the formula

$$\frac{\Gamma(D^0 \rightarrow h^-h^+)}{\Gamma(D^0 \rightarrow K^-\pi^+)} = \frac{N_{h^-h^+}}{N_{K\pi}} \frac{\epsilon_{K\pi}}{\epsilon_{h^-h^+}} = \frac{N_{h^-h^+}}{N_{K\pi}} R_{h^-h^+}, \quad (1)$$

where  $h = K$  or  $\pi$ ,  $N_{h^-h^+}$  is the total number of  $D^0$  mesons

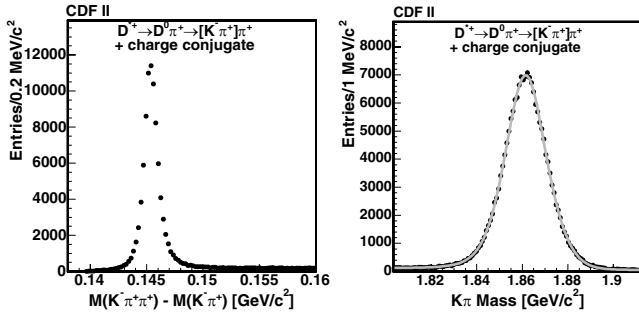


FIG. 1. The  $\Delta M = M(K^- \pi^+ \pi^+) - M(K^- \pi^+)$  distribution (left) for the  $D^0 \rightarrow K^- \pi^+$  candidates. The  $K^- \pi^+$  invariant mass distribution (right) after all selection criteria have been applied. The curve is the sum of the fits performed separately for the  $D^0$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

decaying in the appropriate mode from Table I, and  $\epsilon_{h^- h^+}$  is the average  $D^0$  and  $\bar{D}^0$  acceptance for each of the decays, including trigger and reconstruction efficiency. The quantity  $R_{h^- h^+}$  is the efficiency ratio of the  $D^0 \rightarrow K^- \pi^+$  to  $D^0 \rightarrow h^- h^+$  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  $\pi^+$ ,  $\pi^-$ ,  $K^+$ , 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]. 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.

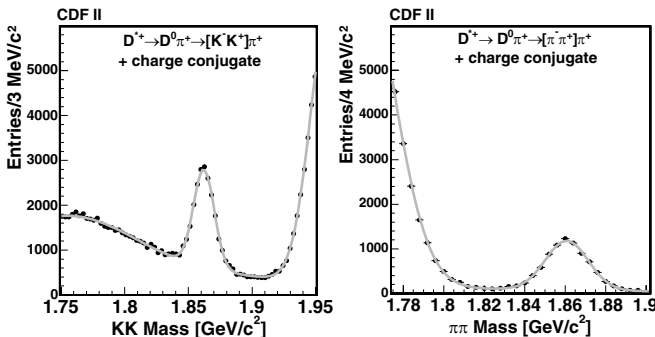


FIG. 2. The  $K^- K^+$  (left) and  $\pi^- \pi^+$  (right) invariant mass distributions after all selection criteria have been applied.

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

| Mode     | $D^0$             | $\bar{D}^0$       | Total              |
|----------|-------------------|-------------------|--------------------|
| $K\pi$   | $88\,310 \pm 330$ | $92\,600 \pm 340$ | $180\,910 \pm 480$ |
| $KK$     | $8190 \pm 140$    | $8030 \pm 140$    | $16\,220 \pm 200$  |
| $\pi\pi$ | $3660 \pm 69$     | $3674 \pm 68$     | $7334 \pm 97$      |

For the relative  $D^0 \rightarrow K^- K^+$  to  $D^0 \rightarrow \pi^- \pi^+$  efficiencies we obtain  $1.2488 \pm 0.0078$ .

The systematic uncertainty on the ratios of 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  $p_T(D^0)$ . This systematic uncertainty is listed in the first row of Table II. We have evaluated the systematic uncertainty in the determination of the relative efficiencies from the following sources: Monte Carlo statistic, 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 derive  $\Gamma(D^0 \rightarrow K^- K^+)/\Gamma(D^0 \rightarrow \pi^- \pi^+) = 2.760 \pm 0.040(\text{stat}) \pm 0.034(\text{syst})$ .

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

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

TABLE II. The sources of systematic uncertainty on the ratios of branching fractions and their contributions to the total fractional systematic uncertainty.

| Systematic source      | $(\frac{KK}{K\pi})$ (%) | $(\frac{\pi\pi}{K\pi})$ (%) | $(\frac{KK}{\pi\pi})$ (%) |
|------------------------|-------------------------|-----------------------------|---------------------------|
| Signal yields          | 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                     |
| Nonprompt $D^*$        | 0.16                    | 0.08                        | 0.24                      |
| Total relative error:  | 1.2                     | 1.1                         | 1.2                       |

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

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

where  $f$  represents either the  $K^- K^+$  or  $\pi^- \pi^+$  final state. The direct production of charm mesons in  $p\bar{p}$  collisions is assumed to be  $CP$  invariant. The measured  $CP$  asymmetry must be corrected 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  $D^{*+} \rightarrow D^0 \pi^+$  decays relative to the number of observed  $D^{*-} \rightarrow \bar{D}^0 \pi^-$  decays for the difference in detection efficiencies of  $\pi^+$  and  $\pi^-$ . 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  $p\bar{p}$  collision point, requiring the track impact parameter to be  $d_0 \leq 100 \mu\text{m}$ . 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 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.

To evaluate the systematic uncertainty associated with the charge asymmetry corrections we apply the corrections to the sample of  $D^{*+} \rightarrow D^0 \pi^+ \rightarrow [K^- \pi^+] \pi^+$  decays,

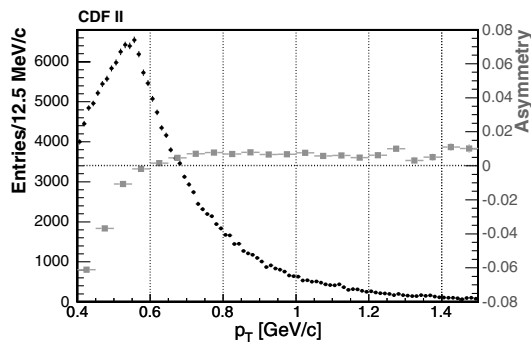


FIG. 3. The  $D^{*+}$  decay pion  $p_T$  distribution (black dots) and the detector charge asymmetry (gray squares) as a function of track  $p_T$ .

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 calculation described above. A residual asymmetry of  $(0.35 \pm 0.53)\%$  is found, where the error is the statistical uncertainty due to the data and Monte Carlo statistics. In addition, we check the possible dependence of the charge asymmetry corrections on the event environment by deriving the corrections using track samples selected by different triggers and using a sample of  $K_S^0 \rightarrow \pi^- \pi^+$  decays instead of generic tracks. We also check for charge dependent effects on the observables used in the analysis ( $\Delta M$  and  $D^0$  invariant mass) and in the signal shapes. In all cases we find negligible effects. Finally we test the quality of the charge asymmetry corrections by performing the  $CP$  asymmetry measurements dividing the signal samples into two ranges of  $D^{*+}$  pion transverse momentum ( $p_T > 0.6 \text{ GeV}/c$  and  $p_T \leq 0.6 \text{ GeV}/c$ ). 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. An additional systematic uncertainty of  $\pm 0.2\%$ , due to the yield determination of  $D^0$  and  $\bar{D}^0$ , 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  $\Gamma(D^0 \rightarrow K^- K^+)/\Gamma(D^0 \rightarrow K^- \pi^+) = 0.0992 \pm 0.0011(\text{stat}) \pm 0.0012(\text{syst})$ ,  $\Gamma(D^0 \rightarrow \pi^- \pi^+)/\Gamma(D^0 \rightarrow K^- \pi^+) = 0.03594 \pm 0.00054(\text{stat}) \pm 0.00040(\text{syst})$ . These measurements agree with, and are an improvement in precision over, the world averages  $\Gamma(D^0 \rightarrow K^- K^+)/\Gamma(D^0 \rightarrow K^- \pi^+) = 0.1023_{-0.0027}^{+0.0022}$ ,  $\Gamma(D^0 \rightarrow \pi^- \pi^+)/\Gamma(D^0 \rightarrow K^- \pi^+) = 0.0362 \pm 0.0010$  [2]. We have made the most precise measurement to date of the direct  $CP$  asymmetries  $A_{CP}(K^- K^+) = [2.0 \pm 1.2(\text{stat}) \pm 0.6(\text{syst})]\%$  and  $A_{CP}(\pi^- \pi^+) = [1.0 \pm 1.3(\text{stat}) \pm 0.6(\text{syst})]\%$ . In agreement with the world averages  $A_{CP}(K^- K^+) = (0.5 \pm 1.6)\%$  and  $A_{CP}(\pi^- \pi^+) = (2.1 \pm 2.6)\%$  [2]. At present there is no evidence for direct  $CP$  violation in Cabibbo-suppressed  $D^0$  decays.

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