Branching Fractions for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, and a Search for CP Violation in D^0 Decays *

Fermilab E791 Collaboration

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Using the large hadroproduced charm sample collected in experiment E791 at Fermilab, we have measured ratios of branching fractions for the two-body singly-Cabibbo-suppressed charged decays of the D^0: $\dfrac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)} = 0.109 \pm 0.003 \pm 0.003$, $\dfrac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = 0.040 \pm 0.002 \pm 0.003$, and $\dfrac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)} = 2.75 \pm 0.15 \pm 0.16$. We have looked for differences in the decay rates of D^0 and $\overline{D}^0$ to the CP eigenstates K^+K^- and $\pi^+\pi^-$, and have measured the CP asymmetry parameters $A_{CP}(K^+K^-) = -0.010 \pm 0.049 \pm 0.012$ and $A_{CP}(\pi^+\pi^-) = -0.049 \pm 0.078 \pm 0.030$, both consistent with zero.

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The measured world average for the ratio of the branching fractions of the two-body singly-Cabibbo-suppressed (SCS) charged decays of the D^0 meson is $\dfrac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)} = 2.86 \pm 0.28$ [1]. Models including final state interactions [2–4], penguin diagrams [5], QCD sum rules [6], and non-perturbative algebraic approaches [7] have been proposed to explain the experimental value observed for this ratio. Precise measurements of this ratio can help to differentiate among models, and can also aid in our understanding of the Standard Model predictions for D^0–$\overline{D}^0$ mixing via long-range mechanisms, which require $SU(3)$ symmetry-breaking to be non-zero [8–10].

To date CP violation has been observed only in the neutral kaon system. In

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the Standard Model this violation is a consequence of a complex amplitude in the Cabibbo-Kobayashi-Maskawa matrix. In this model, strange quarks couple to the top quark in diagrams with internal loops, leading to observable CP violation. The comparable diagrams in the charm sector have bottom quarks in the internal loops, resulting in very small Standard Model contributions to CP violation. Thus the charm sector may be uniquely sensitive to physics outside the Standard Model, at the 10^{-3} level [11]. Currently, the measured limits for charged and neutral D's are at the level of (5–10)% from experiments E687 [12,13] and E791 [14] at Fermilab, and CLEO [15,16].

In this paper, we first report measurements of the branching fractions for the SCS decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ relative to the Cabibbo-favored decay $D^0 \to K^-\pi^+$, based on a total sample of about 42,000 fully reconstructed two-body D^0 decays. Second, we present a search for CP violation in the SCS decay of the D^0 using a sample of 14,225 D^0's tagged through the decay $D^{*+} \to D^0\pi^+$. Throughout this paper, the CP-conjugate states are implicitly included unless otherwise noted. At the level of sensitivity of this experiment, any direct CP violation would indicate physics outside the Standard Model.

The current results are based on data accumulated by experiment E791 in a 500 GeV π^- beam during the 1991/92 Fermilab fixed-target run. E791 was the fourth in a series of charm experiments performed in the Fermilab Tagged Photon Laboratory. The E791 spectrometer [17] was an open geometry detector with 23 planes of silicon microstrip detectors (6 upstream and 17 downstream of the target), 35 drift chamber planes, 10 proportional wire chambers (8 upstream and 2 downstream of the target), two magnets for momentum analysis, two large multicell threshold Čerenkov counters for charged particle identification, electromagnetic and hadronic calorimeters for electron/hadron separation as well as for online triggering, and a fast data acquisition system that allowed us to collect data at a rate of 30 Mbyte/s with a 50 μs/event deadtime. The target consisted of a 0.6-mm thick platinum foil followed by four 1.5-mm diamond foils. Each target center was separated from the next by about 1.5 cm, allowing observation of charmed-particle decays in air without background from secondary interactions. The very open transverse-energy trigger was based on the energy deposited in the calorimeters and was highly efficient for charm events. Over 2×10^{10} events were recorded during a six-month period.

The two-body decay sample was selected based upon several criteria. A decay track candidate must have made a large contribution to the χ^2 of the event production vertex fit when included in that fit. The significance of the measured separation (in the beam direction) of the candidate decay vertex from the production vertex had to be $> 8\sigma$, where σ is the error on the measured separation of the two points. The momentum component of the D^0 candidate transverse to the line connecting the production and decay vertices had to be less than 0.40 GeV/c. The sum of p_t^2 of the decay tracks, with p_t measured relative to the direction of the D^0 candidate, was required to be greater than 0.52 (GeV/c)^2. Finally, the decay vertex had to be located well outside the target foils.

To improve the statistical significance of the ratio $\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)}$, we required the daughter tracks to have K or π signatures in the threshold Čerenkov counters. However, the efficiency of our identification depends on particle momentum. We have studied these particle identification efficiencies for the data sample $D^0 \to K^-\pi^+$ as a function of momentum, transverse momentum with respect to the beam direction, charge, and particle type. Based on this study, we required the particle momenta to be in the range 6 to 80 GeV/c. We then corrected for the particle identification efficiency by weighting each D^0 candidate by the inverse of the product of the two particle identification efficiencies. Using this procedure we have weighted each track according to its p and p_t, rather than applying one global factor to the final results. We calculated the statistical errors in the weighted signals by scaling the statistical errors of the unweighted signals by the ratios of the weighted to unweighted sample sizes. Figure 1 shows the Čerenkov-weighted invariant mass distributions for our data. The peaks to the right of the signal region in the K^+K^- distribution and to the left of the signal region in the $\pi^+\pi^-$ distribution are due to misidentified $K\pi$ events, whereas the peak to the left of the signal region in the K^+K^- distribution is due to misidentified $K\pi\pi^0$ events. A binned maximum-likelihood fit was performed for each distribution with the signal function assumed to be Gaussian. The backgrounds were fit to the following functions: $K^-\pi^+$ – a third-order polynomial (Figure 1 left); K^+K^- – a linear term plus a Breit-Wigner function for misidentified $K\pi\pi^0$ and a half-Gaussian-half-Breit-Wigner function for misidentified $K\pi$ (Figure 1 middle); $\pi^+\pi^-$ – an exponential term plus a half-Breit-Wigner-half-Gaussian for misidentified $K\pi$ (Figure 1 right). Cross-hatched areas are the estimated backgrounds under the signals.

We have used a Pythia-based Monte Carlo (MC) [18] which incorporates a full detector simulation to correct for detector acceptance effects other than Čerenkov identification. The efficiencies determined from the Monte Carlo simulation and the number of signal events extracted from both the unweighted and weighted mass distributions are given in Table 1.

We calculate the ratios of branching fractions from the numbers in the last two rows of Table 1 and present them together with previous measurements in Table 2. The quoted systematic errors are the quadrature sums of systematic uncertainties from the following sources: relative efficiencies for the selection criteria, fitting functions, MC production models, and the Čerenkov particle identification weighting procedure. Table 3 presents the contribution of each

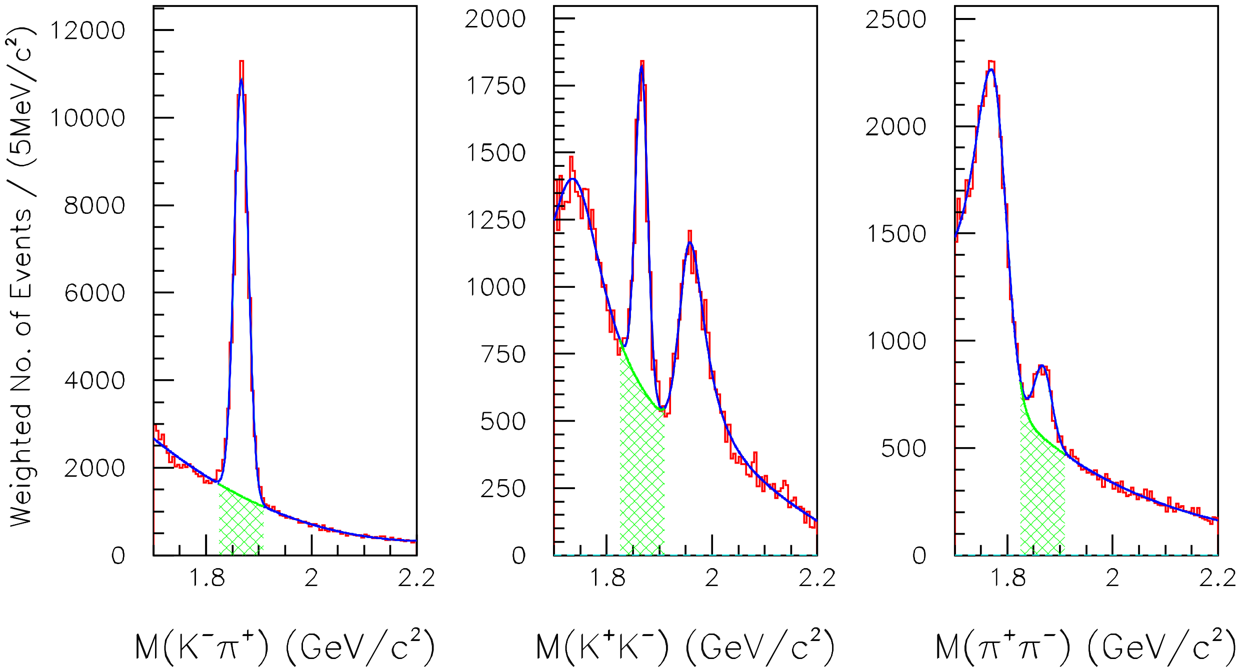

Fig. 1. Invariant mass of Čerenkov-weighted candidates. The solid lines correspond to a binned maximum-likelihood fit to a signal given by a Gaussian distribution plus different background functions given by: $D^0 \to K^-\pi^+$ – a third-order polynomial (left); $D^0 \to K^+K^-$ – a linear term plus a Breit-Wigner function for misidentified $K\pi\pi^0$ and a half-Gaussian-half-Breit-Wigner function for misidentified $K\pi$ (middle); and $D^0 \to \pi^+\pi^-$ – an exponential term plus a half-Breit-Wigner-half-Gaussian function for misidentified $K\pi$ (right). Cross-hatched areas are our estimates of backgrounds below the signals.

Table 1
Sample sizes and average geometric acceptances for three decay modes of the D^0.

	$D^0 \to K^-\pi^+$	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$
Unweighted Sample	36955 ± 217	3317 ± 84	2043 ± 95
Weighted Sample	63177 ± 371	6845 ± 172	2521 ± 117
Average Acceptance	3.21%	3.18%	3.22%

of these to the total systematic uncertainty, expressed as a percentage of the statistical uncertainty. The "Selection Criteria" entry reflects uncertainties in the details of the MC modeling of the experimental acceptance. The "Fitting Functions" uncertainty corresponds to various estimates of the background, especially for $\pi\pi$. We note that $K\pi$ reflections do not contribute directly in the KK or $\pi\pi$ signal regions. The shapes of the $K\pi$ and $K\pi\pi^0$ reflections have been studied in detail, and the same fitting function yields good fits to both MC and data. Uncertainties resulting from the MC production model were investigated by changing PYTHIA default parameters to agree with a study of $D^{\pm}$ production in E791[19].

Table 2
$D^0 \to K^+K^-$ and $\pi^+\pi^-$ relative branching ratio measurements compared with previous experiments.

Year	Group	$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)}$	$\frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}$	$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)}$
1997	E791	$0.109 \pm 0.003 \pm 0.003$	$0.040 \pm 0.002 \pm 0.003$	$2.75 \pm 0.15 \pm 0.16$
1979	Mark II [21]	0.113 ± 0.030	0.033 ± 0.015	3.4 ± 1.8
1984	Mark III [22]	$0.122 \pm 0.018 \pm 0.012$	$0.033 \pm 0.010 \pm 0.006$	3.7 ± 1.3
1989	ARGUS [23]	$0.10 \pm 0.02 \pm 0.01$	$0.040 \pm 0.007 \pm 0.006$	2.5 ± 0.7
1990	CLEO [15]	$0.117 \pm 0.010 \pm 0.007$	$0.050 \pm 0.007 \pm 0.005$	$2.35 \pm 0.37 \pm 0.28$
1991	E691 [24]	$0.107 \pm 0.010 \pm 0.009$	$0.055 \pm 0.008 \pm 0.005$	$1.95 \pm 0.34 \pm 0.22$
1992	WA82 [25]	$0.107 \pm 0.029 \pm 0.015$	$0.048 \pm 0.013 \pm 0.008$	$2.23 \pm 0.81 \pm 0.46$
1993	CLEO [16]		$0.0348 \pm 0.0030 \pm 0.0023$	
1994	E687 [12]	$0.109 \pm 0.007 \pm 0.009$	$0.043 \pm 0.007 \pm 0.003$	$2.53 \pm 0.46 \pm 0.19$
1996	PDG [1]	0.113 ± 0.006	0.0396 ± 0.0027	2.86 ± 0.28

Table 3
Contributions to the systematic uncertainty for each of the measured branching ratios. The systematic uncertainties are expressed as a percentage of the statistical uncertainty for the corresponding branching ratio.

	$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)}$	$\frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}$	$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)}$
Selection Criteria	90%	100%	40%
Fitting Functions	60%	70%	90%
MC Production Model	30%	30%	20%
Particle ID Weighting	30%	30%	30%
Total	116%	129%	105%

We now present results of a search for CP violation in the SCS decays of the D^0 (or $\overline{D}^0$) beginning with the same data sample as above. Assuming CP conservation in the strong decay of the D^*, we identify the meson as either D^0 or $\overline{D}^0$ by tagging it using the charge of the slow π from $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$. We required the mass difference between D^* and D to be in the range 143 – 148 MeV/c^2 and the distance of closest approach of the bachelor pion to the primary vertex had to be < 120 μm. Because D^* tagging reduces background so strongly, we relaxed the requirement on the sum of p_t^2 of the D^0 decay tracks relative to the direction of the parent D^0 from 0.52 (GeV/c)^2 to 0.4 (GeV/c)^2. For this analysis, we used the same Čerenkov identification criteria as for the branching ratio measurements, but we did not weight the events.

The signal for CP violation is an absolute rate difference between decays of particle and antiparticle to charge-conjugate final states f and $\overline{f}$, where $f = K^+K^-$ or $\pi^+\pi^-$:

$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}. \tag{1}$$

In hadroproduction, D and $\overline{D}$ mesons are not produced equally. Therefore we normalized our signals to the Cabibbo-favored $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$ signals and measured

$$\frac{\dfrac{N(D^0 \to f)}{N(D^0 \to K^-\pi^+)} - \dfrac{N(\overline{D}^0 \to \overline{f})}{N(\overline{D}^0 \to K^+\pi^-)}}{\dfrac{N(D^0 \to f)}{N(D^0 \to K^-\pi^+)} + \dfrac{N(\overline{D}^0 \to \overline{f})}{N(\overline{D}^0 \to K^+\pi^-)}} \tag{2}$$

where, for each channel, $N = \epsilon n$ is the observed number of events, n is the produced number of events, and ϵ is the efficiency of our detector and analysis procedure. To the extent that

$$\frac{\epsilon(D^0 \to f)}{\epsilon(D^0 \to K^-\pi^+)} = \frac{\epsilon(\overline{D}^0 \to \overline{f})}{\epsilon(\overline{D}^0 \to K^+\pi^-)}, \tag{3}$$

the measured quantity (Eq. 2) is A_{CP}. We verified the validity of Eq. 3 for this analysis in two stages. First, we used real data to determine that the Čerenkov identification efficiencies for kaons and pions are independent of charge in any given momentum range from 6 to 80 GeV/c. Then, we used our Monte Carlo simulation of the experiment to determine that the geometric acceptances are independent of charge.

Note that any CP asymmetry from interference between mixing and tree-level diagrams will not cancel through the $D^0 \to K^-\pi^+$ normalization. Thus our normalized A_{CP} is not a direct CP asymmetry parameter, but rather a measure of combined direct and indirect CP asymmetries [20]. An implicit assumption in this analysis is that there is no measurable CP violation in the Cabibbo-favored decays of the D^0.

Figure 2 presents mass plots for the candidate D^0 and $\overline{D}^0$ decays to $K\pi$, KK, and $\pi\pi$, including our fits to the distributions. We used the same fixed central mass value and signal width for D^0 and $\overline{D}^0$ fits. The distributions fit the data well, and the integrals of the Gaussian fits to the signals were used to calculate the observed numbers of decays. Our asymmetry results are listed in Table 4 along with previous measurements. We see no evidence of CP violation.

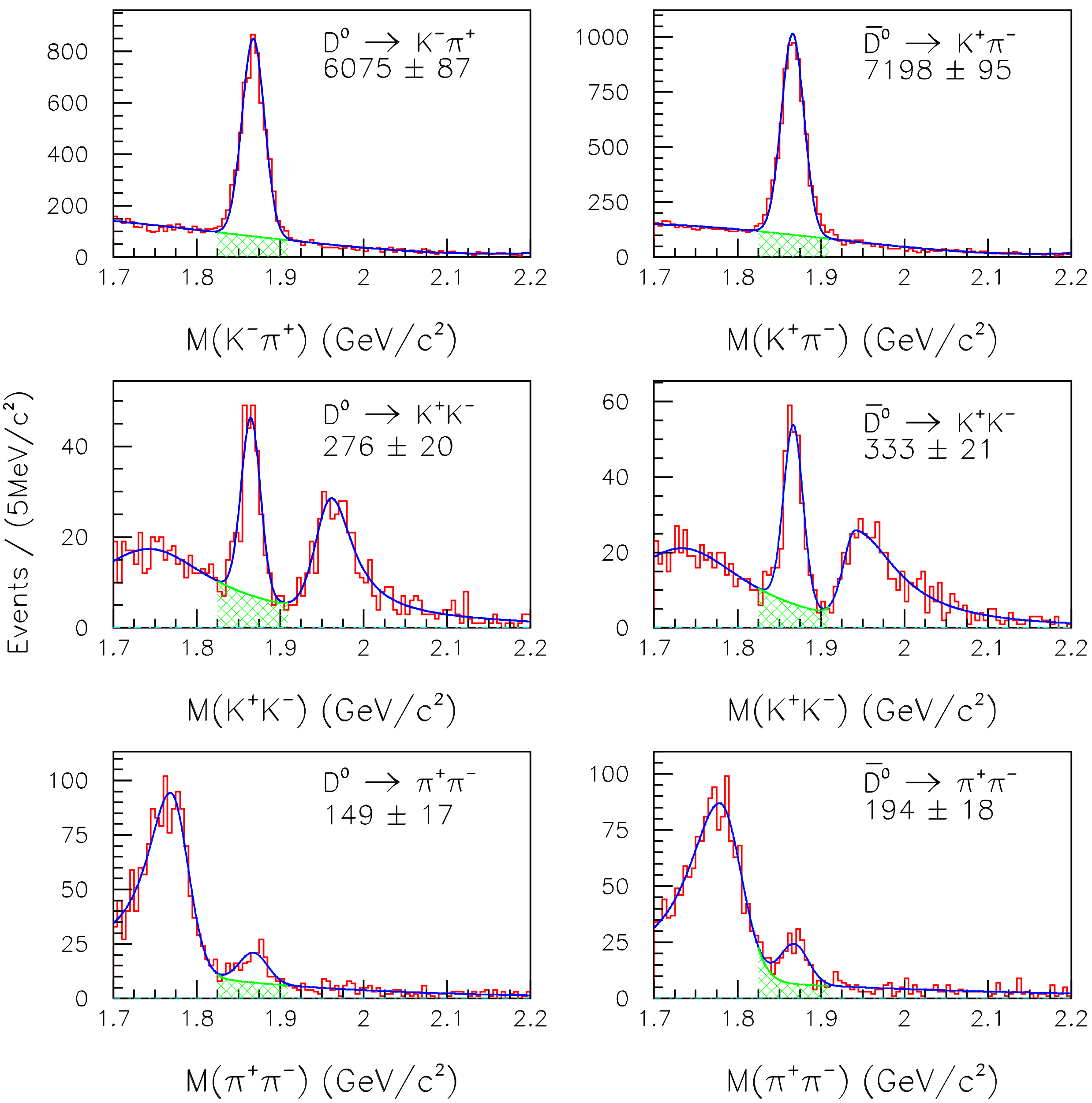

Fig. 2. Invariant mass of D^0 candidates (left column of figures) and $\overline{D}^0$ (right column of figures) tagged with the decay $D^* \to D^0\pi$, for the decay $D^0 \to K^-\pi^+$ (top), $D^0 \to K^+K^-$ (middle), and $D^0 \to \pi^+\pi^-$ (bottom). The numbers presented are the sample sizes as calculated from Gaussian fits to the signal regions, and the cross-hatched areas are our estimates of backgrounds below the signals.

In summary, we have measured the following ratios of branching fractions for the charged two-body decays of the D^0: $\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)} = 0.109 \pm 0.003 \pm 0.003$, $\frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = 0.040 \pm 0.002 \pm 0.003$, and $\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)} =$

Table 4
The measured asymmetry parameters A_{CP} for K^+K^- and $\pi^+\pi^-$ decay modes of the D^0 and their 90% confidence-level limits, compared with previous experiments.

Year	Group	A_{CP}	Limit at 90% confidence level
1997	E791	$-0.010 \pm 0.049 \pm 0.012$	$-9.3\% < A_{CP}(K^+K^-) < 7.3\%$
1997	E791	$-0.049 \pm 0.078 \pm 0.030$	$-18.6\% < A_{CP}(\pi^+\pi^-) < 8.8\%$
1991	E691 [24]	0.20 ± 0.15	$A_{CP}(K^+K^-) < 45\%$
1994	E687 [13]	0.024 ± 0.084	$-11\% < A_{CP}(K^+K^-) < 16\%$
1995	CLEO II [26]	0.080 ± 0.061	$-2.2\% < A_{CP}(K^+K^-) < 18\%$

$2.75 \pm 0.15 \pm 0.16$. We also find the 90% confidence-level intervals on the decay asymmetries of D^0 and $\overline{D}^0$ to the CP eigenstates K^+K^- and $\pi^+\pi^-$ to be $-9.3\% < A_{CP}(K^+K^-) < 7.3\%$ and $-18.6\% < A_{CP}(\pi^+\pi^-) < 8.8\%$. We find no evidence for CP violation in these decay modes. This is the first reported result of a search for CP violation in the decay mode $D^0 \to \pi^+\pi^-$.

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