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Observation of D^0 - \bar{D}^0 Mixing Using the CDF II Detector

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We measure the time dependence of the ratio of decay rates for $D^0 \rightarrow K^+ \pi^-$ to the Cabibbo-favored decay $D^0 \rightarrow K^- \pi^+$. The charge conjugate decays are included. A signal of 3.3×10^4 $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^+ \pi^-$ decays is obtained with D^0 proper decay times between 0.75 and 10 mean D^0 lifetimes. The data were recorded with the CDF II detector at the Fermilab Tevatron and correspond to an integrated luminosity of 9.6 fb^{-1} for $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. Assuming CP conservation, we search for D^0 - \bar{D}^0 mixing and measure the mixing parameters to be $R_D = (3.51 \pm 0.35) \times 10^{-3}$, $y' = (4.3 \pm 4.3) \times 10^{-3}$, and $x'^2 = (0.08 \pm 0.18) \times 10^{-3}$. We report Bayesian probability intervals in the x'^2 - y' plane and find that the significance of excluding the no-mixing hypothesis is equivalent to 6.1 Gaussian standard deviations, providing the second observation of D^0 - \bar{D}^0 mixing from a single experiment.

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A neutral meson that is a superposition of weakly decaying mass eigenstates can spontaneously change into its antiparticle. This process is referred to as mixing and is well established for K^0 , B^0 , and B_s^0 mesons [1]. The mixing of these mesons is understood within the framework of the standard model with the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. Substantial evidence exists for D^0 - \bar{D}^0 mixing [2–6], and the process was recently observed in the $K\pi$ channel by the LHCb experiment [7]. In the standard model, D^0 - \bar{D}^0 mixing is a weak-interaction process that occurs primarily through long-range virtual intermediate states that consist of common decay channels for the particle and antiparticle, such as $\pi^+ \pi^-$. The prediction of the mixing rate has significant uncertainty because it requires a strong-interaction model. A direct calculation from quantum chromodynamics is not currently possible [8,9]. Mixing could also result from exotic particles that appear as virtual states in a short-range box diagram. Such a process could provide indirect evidence for physics beyond the standard model [10,11]. It is of great interest to verify independently the observation of D^0 - \bar{D}^0 mixing in a single experiment and to improve the measurement of the mixing parameters. We report a measurement using the decay $D^0 \rightarrow K^+ \pi^-$ and its charge conjugate.

The decay $D^0 \rightarrow K^+ \pi^-$ can arise from mixing of a D^0 state to a \bar{D}^0 state, followed by a Cabibbo-favored (CF) decay, or from a doubly Cabibbo-suppressed (DCS) decay

of a D^0 . (In this Letter, reference to a specific decay chain implicitly includes the charge-conjugate decay.) The mixing measurement is based on the ratio R of $D^0 \rightarrow K^+ \pi^-$ to $D^0 \rightarrow K^- \pi^+$ decay rates. This ratio can be approximated [12,13] as a quadratic function of t/τ , where t is the proper decay time and τ is the mean D^0 lifetime:

$$R(t/\tau) = R_D + \sqrt{R_D} y' (t/\tau) + \frac{x'^2 + y'^2}{4} (t/\tau)^2. \quad (1)$$

This form is valid under the assumption of CP conservation and small values for the parameters $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where Δm is the mass difference between the mass eigenstates, $\Delta\Gamma$ is the decay-width difference, and Γ is the mean decay width of the eigenstates. The parameter R_D is the squared modulus of the ratio of DCS to CF amplitudes. The parameters x' and y' are linear combinations of x and y according to the relations

$$x' = x \cos \delta + y \sin \delta \quad \text{and} \quad y' = -x \sin \delta + y \cos \delta,$$

where δ is the strong-interaction phase difference between the DCS and CF amplitudes. In the absence of mixing, $x' = y' = 0$ and $R(t/\tau) = R_D$.

The measurement uses the full data set collected by the CDF II detector at the Fermilab Tevatron collider, from February 2002 to September 2011, corresponding to an integrated luminosity of 9.6 fb^{-1} for $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. We previously reported evidence for D^0 - \bar{D}^0 mixing [5] based on a subset of the data corresponding to

an integrated luminosity of 1.5 fb^{-1} . The multipurpose CDF II detector [14] is a magnetic spectrometer surrounded by a calorimeter and a muon detector. The detector components pertinent to this analysis are the silicon microstrip vertex detector, the multiwire drift chamber, and the 1.4 T magnet, which together measure the trajectories and momenta of charged particles. The drift chamber measures ionization energy loss for charged particles, which is used for particle identification. Events are selected in real time with a trigger system developed for a broad class of heavy-flavor decays. The trigger [15] selects events with a pair of oppositely charged particles originating from a decay point separated by at least $200 \mu\text{m}$ from the beam line in the transverse plane.

We identify the CF decay $D^0 \rightarrow K^- \pi^+$ through the right-sign (RS) decay chain $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^- \pi^+$. The decay $D^0 \rightarrow K^+ \pi^-$ is identified through the wrong-sign (WS) decay chain $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^+ \pi^-$. The relative charges of the pions determine whether the decay chain is RS (same charge) or WS (opposite charge). The RS and WS D^* decays have the same kinematic distributions, and may differ only in decay time distributions. To reduce systematic uncertainties, we use the same selection criteria (cuts) for both the RS and WS decay modes. Analysis cuts were optimized before the WS candidates were revealed, and were chosen to maximize the expected WS signal significance.

The D^0 candidate reconstruction starts with a pair of tracks from oppositely charged particles that satisfy the trigger requirements. The tracks are considered with both $K^- \pi^+$ and $\pi^- K^+$ interpretations. A third track, required to have transverse momentum in the range $[0.4, 2.0] \text{ GeV}/c$ (see [16]), is used to form a D^* candidate when considered as a pion and combined with the D^0 candidate.

We use a method primarily based on D^0 decay kinematics to reduce the background to the WS signal from RS decays where the D^0 decay tracks are misidentified because the kaon and pion assignments are mistakenly interchanged. As determined from data for RS D^{*+} 's, 96% of D^0 decays with correct mass assignments are reconstructed with invariant masses within $20 \text{ MeV}/c^2$ of the D^0 mass. The invariant mass distribution for misidentified D^0 decays is much broader, and has only 23% of the events within the same mass range. We remove WS candidates that have a RS mass within that range. To further reject D^* candidates with misidentified decay tracks, we impose a cut based on particle identification, described in Ref. [15], that is used to choose between $K^- \pi^+$ and $\pi^- K^+$ assignments for the D^0 decay tracks.

We use a series of cuts based on the decay topology of signal events in which the D^* is produced at the collision point and the D^0 travels a measurable distance before it decays. The topological cuts reduce background from combinations involving one or more tracks that do not originate from the D^* decay chain of interest. We require

the significance of the transverse decay length to satisfy $L_{xy}/\sigma_{xy} > 4$, where L_{xy} is the distance between the collision point (measured on an event-by-event basis) and the reconstructed D^0 decay point in the plane transverse to the beam line, and σ_{xy} is the uncertainty on L_{xy} . The transverse impact parameter d_0 is the distance of closest approach in the transverse plane between a track (or reconstructed particle) and the collision point. The D^* -decay pion must have $d_0 < 600 \mu\text{m}$, and it must also have a distance of closest approach to the collision point less than 1.5 cm along the beam line. To reduce the contribution of nonprompt D^* 's produced in beauty-particle decays, we require $d_0 < 60 \mu\text{m}$ for the inferred track of the D^0 candidate. The remaining contribution of nonprompt D^* mesons is taken into account in the analysis of the time dependence of the WS/RS ratio, as discussed later.

The ratio t/τ is determined for each D^0 candidate by $t/\tau = M_{D^0} L_{xy}/(p_T \tau)$, where $M_{D^0} = 1.8648 \text{ GeV}/c^2$ and $\tau = 410.1 \text{ fs}$ are the world-average values for the D^0 mass and lifetime, respectively [1]. To study $R(t/\tau)$, we divide the data into 20 bins of t/τ ranging from 0.75 to 10.0, choosing bins of increasing size from 0.25 to 2.0 to reduce statistical uncertainty per bin at larger times. The bin sizes are larger than the typical t/τ resolution of 0.16.

The RS and WS candidates in each t/τ bin are further divided into 60 bins of mass difference $\Delta M \equiv M_{K^+ \pi^- \pi^+} - M_{K^+ \pi^-} - M_{\pi^+}$ for WS candidates, and analogously for RS candidates. For each of the 1200 WS and 1200 RS ΔM bins, the D^0 signal yield is determined from a fit to the corresponding distribution of $M_{K\pi}$, which has 60 bins in the range of $1.80\text{--}1.92 \text{ GeV}/c^2$. For the $M_{K\pi}$ fit, the signal shape is modeled by a double-Gaussian form with a low-mass tail, and the combinatorial background is modeled by an exponential. For the WS $M_{K\pi}$ fit, a Gaussian term models the RS misidentified background, with mean and width determined from the data. The D^* signal yield for each time bin is determined from a χ^2 fit of the D^0 signal yield versus ΔM . The signal shape is modeled by a double Gaussian and an asymmetric tail. The background shape is modeled by the product of a power law and an exponential function. The WS signal shape parameters for both the $M_{K\pi}$ and ΔM distributions are fixed to the RS parameters. For each $M_{K\pi}$ and ΔM distribution, the parameters for the background shape are allowed to float. The amplitudes of the signal and background are determined independently for all $M_{K\pi}$ and ΔM fits. The RS distributions have similar absolute amounts of background as the WS distributions, but the RS signal is about 230 times larger. A detailed description of the functional forms for the signal and background shapes is presented in Ref. [16]. The $M_{K\pi}$ distributions from a subset of the data, which are characteristic of the full data set, are reported in [5,15]. The 2400 $M_{K\pi}$ histograms are well fit by the functional forms used with 57 degrees of freedom. The distribution of χ^2/dof has a mean of 1.2 and a standard deviation of 0.4. The

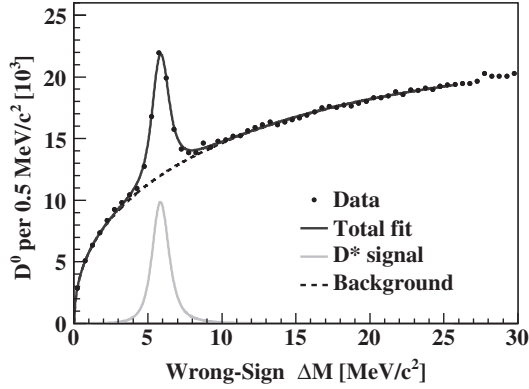


FIG. 1. Time-integrated distribution for wrong-sign $D^0 \rightarrow K^+ \pi^-$ signal yield as a function of ΔM . The signal yield for each bin of ΔM is determined from a fit to the corresponding $M_{K\pi}$ distribution. The result of a χ^2 fit to the ΔM distribution is shown.

time-integrated WS ΔM distribution is shown in Fig. 1. The time-integrated signal yields are $(3.27 \pm 0.04) \times 10^4$ (WS) and $(7.604 \pm 0.005) \times 10^6$ (RS).

The measured ratio R_m of WS to RS signal for each of the 20 t/τ bins is shown in Fig. 2. The data point for each bin is located at the mean value of t/τ for the RS signal in that bin. Each error bar is determined from the fit uncertainties of the WS and RS signal yields. The large uncertainty in the smallest t/τ bin is due to the small event yield caused by the trigger turn-on. After the trigger turn-on, the uncertainties increase with t/τ because of the exponential falloff in the number of decays.

We assume that the WS/RS ratio of decay rates $R(t/\tau)$, given by Eq. (1), is the same for D^0 's produced in beauty-particle decays as for promptly produced D^0 's, but with decay time measured from the beauty-particle decay point. The predicted value of R_m for a given t/τ bin can be expressed in terms of contributions from prompt and non-prompt production according to

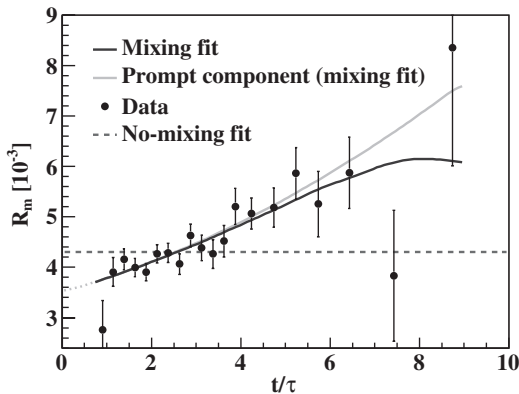


FIG. 2. Measured ratio R_m of wrong-sign to right-sign D^* decays as a function of normalized proper decay time. The results of a least-squares fit are shown for R_m^{pred} (mixing fit) and the prompt component R . A fit assuming no mixing is clearly incompatible with the data.

$$R_m^{\text{pred}} = R(t/\tau)[1 - f_B(t/\tau)] + R_B(t/\tau)f_B(t/\tau), \quad (2)$$

where $f_B(t/\tau)$ is the fraction of nonprompt RS D^* decays and $R_B(t/\tau)$ is the WS/RS ratio of nonprompt D^* decays. For nonprompt decays, the measured decay time is due to the combination of the decay times for the beauty-particle parent and its D^0 daughter. The function $f_B(t/\tau)$ is determined from data, and $R_B(t/\tau)$ is determined from a full detector simulation.

The function $f_B(t)$ is determined from the d_0 distribution of D^0 's from RS D^* decays, as illustrated in Fig. 3. For each bin of t/τ , the d_0 distribution is obtained by selecting RS events with $4 < \Delta M < 8 \text{ MeV}/c^2$ and $1.848 < M_{K\pi} < 1.880 \text{ GeV}/c^2$ ($\pm 2\sigma$) and subtracting background determined from the $M_{K\pi}$ sidebands (low-mass $1.808\text{--}1.824 \text{ GeV}/c^2$, high-mass $1.904\text{--}1.920 \text{ GeV}/c^2$). The peak at small d_0 is due to the prompt component. The broad distribution extending to large d_0 is due to the nonprompt component. The prompt and nonprompt components are each modeled with the sum of two Gaussians. The fraction f_B is determined in each time bin for the region $d_0 < 60 \mu\text{m}$, which is dominated by the prompt component. The time dependence of f_B is characterized by a five-parameter polynomial fit to the values from each time bin. The value of f_B is $(1.5 \pm 0.4)\%$ at $t/\tau = 1.4$ and increases with t/τ due to the faster decay rate of D^0 mesons compared to beauty particles. At $t/\tau = 6.4$, $f_B = (24 \pm 1)\%$. The function $R_B(t/\tau)$ can be expressed in terms of a function $H(t/\tau, t'/\tau)$ which gives the distribution of nonprompt D^0 decays versus t/τ for a given t'/τ , where t'/τ is measured from the decay point of the beauty particle. The function H is determined from a full detector simulation of beauty particle to D^* decays for the 20 bins of t/τ , and 100 bins of t'/τ . The function $R_B(t/\tau)$ is given by

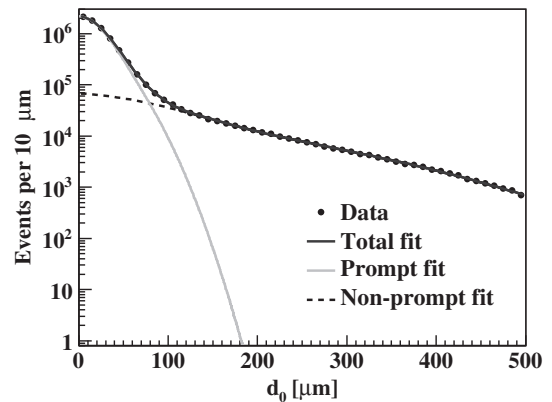


FIG. 3. Distribution of transverse impact parameter d_0 for right-sign D^0 candidates from all t/τ bins. The narrow peak is due to promptly produced D^0 mesons and the broad distribution is due to nonprompt D^0 mesons from beauty-particle decay. For candidates with $d_0 < 60 \mu\text{m}$, 95% are produced promptly at the collision point and 5% are nonprompt.

$$R_B(t_i/\tau) = \frac{\sum_{j=1}^{100} H(t_i/\tau, t'_j/\tau) R(t'_j/\tau)}{\sum_{j=1}^{100} H(t_i/\tau, t'_j/\tau)}, \quad (3)$$

where i and j denote the bins in t and t' . Note that R_B depends directly on the prompt D^* WS/RS ratio R defined in Eq. (1).

To fit for the mixing parameters, we define

$$\chi^2 = \sum_{i=1}^{20} \left[\frac{R_m(t_i/\tau) - R_m^{\text{pred}}(t_i/\tau)}{\sigma_i} \right]^2 + C_B + C_H, \quad (4)$$

where σ_i is the uncertainty on $R_m(t_i/\tau)$. The terms C_B are Gaussian constraints on the five fitted parameters describing $f_B(t/\tau)$, and C_H are Gaussian constraints on the values of $H(t_i/\tau, t'_j/\tau)$. The statistical uncertainties on the $H(t_i/\tau, t'_j/\tau)$ are due to the number of events in the simulation. The mixing parameters R_D , y' , and x'^2 , and the Gaussian-constrained parameters for f_B and H are found by minimizing the χ^2 defined in Eq. (4).

To verify the self-consistency of the analysis procedure, we simulate distributions of $M_{K\pi}$ and ΔM for different assumed values of the mixing parameters R_D , y' , and x'^2 . We generate 400 samples for each of four different sets of mixing parameters. For each parameter set, the distributions of fitted parameters have mean values consistent with the input parameters.

We examine various sources of systematic uncertainty in the analysis procedure. The effect on the WS signal yields due to the uncertainty in the signal shapes used to fit the $M_{K\pi}$ and ΔM distributions is studied by independently varying the shape parameters by $\pm 1\sigma$. For each parameter, the resulting variation of the signal yield is negligible compared to the statistical uncertainty. We check the sensitivity of the WS and RS signals to the assumed shape of the $M_{K\pi}$ background by using simulations with alternative forms for the background shape. The alternative forms include explicit shapes for backgrounds due to $D^+ \rightarrow K^- \pi^+ \pi^+$ decays, determined from data, and partially reconstructed charm-particle decays, based on a full detector simulation. In both simulation studies, the mixing parameters are found to be consistent with those generated. To determine the sensitivity of R_m to R_B , we fit the d_0 distributions with an alternative shape function, leading to

an alternate form for R_B with larger values at small t/τ . The resulting change in R_m is negligible, which can be understood from the small fraction of nonprompt D^{*+} s at small t/τ . To check the sensitivity of R_m to $H(t/\tau, t'/\tau)$, we scale t/τ and t'/τ by $\pm 10\%$. The resulting changes in R_m are negligible compared to statistical uncertainties.

The results for the mixing parameters are given in Table I. The parameter values are highly correlated with correlation coefficients of -0.97 for the (R_D, y') term, 0.90 for (R_D, x'^2) and -0.98 for (y', x'^2) . The resulting functions $R_m^{\text{pred}}(t/\tau)$ and $R(t/\tau)$, describing the prompt component, are shown in Fig. 2. The two functions differ at large t/τ due to the effect of nonprompt D^* production. As shown in Table I, our results for the mixing parameters are consistent with previous measurements and our measurement of x'^2 is comparable in precision to that from LHCb.

A fit assuming no mixing, shown in Fig. 2, is clearly incompatible with the data. We quantify this incompatibility using both Bayesian and frequentist methods. We define a likelihood $\mathcal{L} = \exp(-\chi^2/2)$, normalized over the mixing parameter space, with χ^2 as defined in Eq. (4). We compute contours bounding a region with a given value of Bayesian posterior probability. A uniform prior is used for R_D , y' , and x'^2 , and R_D is treated as a nuisance parameter. The contours are shown in Fig. 4. The no-mixing point, $y' = x'^2 = 0$, lies on the contour corresponding to 6.1 Gaussian (1D) standard deviations. If the physical restriction $x'^2 > 0$ is imposed, there is no change in the no-mixing significance. Using alternative priors, uniform in x' or y'^2 , the no-mixing significance is 6.3σ . A frequentist test statistic $\Delta\chi^2$ is formed from the difference in χ^2 between a fit with $y' = x'^2 = 0$ and a fit with all three mixing parameters floating. For the data, $\Delta\chi^2 = 58.75 - 16.91 = 41.84$. A frequentist p value is obtained by simulating R_m distributions for the 20 time bins using $y' = x'^2 = 0$ and evaluating $\Delta\chi^2$ using the same procedure as for data. In 10^{10} samples, 6 are found with $\Delta\chi^2 > 41.8$, giving a p value corresponding to 6.1σ .

In summary, we measure the time dependence of the ratio of decay rates for $D^0 \rightarrow K^+ \pi^-$ to the Cabibbo-favored decay $D^0 \rightarrow K^- \pi^+$. A signal of $3.3 \times 10^4 D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^+ \pi^-$ decays is obtained with proper decay times between 0.75 and 10 mean D^0 lifetimes. The data sample recorded with the CDF II detector at the Fermilab

TABLE I. Mixing parameter results and comparison with previous measurements. All results use $D^0 \rightarrow K^+ \pi^-$ decays and fits assuming no CP violation. The uncertainties include statistical and systematic components. The significance for excluding the no-mixing hypothesis is given in terms of the equivalent number of Gaussian standard deviations σ .

| Experiment | $R_D(10^{-3})$ | $y'(10^{-3})$ | $x'^2(10^{-3})$ | σ (no mixing) |
|------------------|-----------------|---------------------|------------------------|----------------------|
| This measurement | 3.51 ± 0.35 | 4.3 ± 4.3 | 0.08 ± 0.18 | 6.1 |
| Belle [17] | 3.64 ± 0.17 | $0.6^{+4.0}_{-3.9}$ | $0.18^{+0.21}_{-0.23}$ | 2.0 |
| BABAR [3] | 3.03 ± 0.19 | 9.7 ± 5.4 | -0.22 ± 0.37 | 3.9 |
| CDF [5] | 3.04 ± 0.55 | 8.5 ± 7.6 | -0.12 ± 0.35 | 3.8 |
| LHCb [7] | 3.52 ± 0.15 | 7.2 ± 2.4 | -0.09 ± 0.13 | 9.1 |

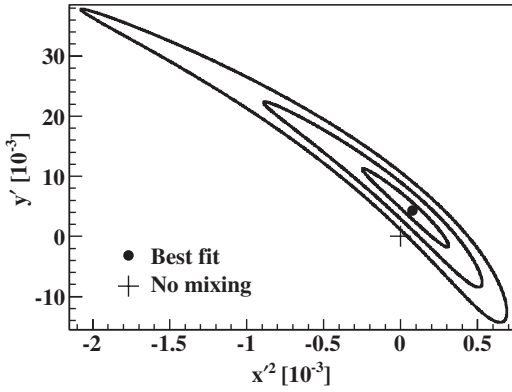


FIG. 4. Contours in x'^2 - y' parameter space bounding regions with Bayesian posterior probability corresponding to 1, 3, and 5 Gaussian standard deviations.

Tevatron corresponds to an integrated luminosity of 9.6 fb^{-1} for $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. Assuming CP conservation, we measure the D^0 - \bar{D}^0 mixing parameters to be $R_D = (3.51 \pm 0.35) \times 10^{-3}$, $y' = (4.3 \pm 4.3) \times 10^{-3}$, and $x'^2 = (0.08 \pm 0.18) \times 10^{-3}$, providing important accuracy for the world averages. We report contours in the x'^2 - y' plane which bound regions of a given Bayesian posterior probability; we find that the significance of excluding the no-mixing hypothesis is equivalent to 6.1 Gaussian standard deviations, thus confirming the observation of D^0 - \bar{D}^0 mixing.

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