Measurement of the D^0-$\bar{D}^0$ mixing at CDF

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Abstract. We report on the observation of D^0–$\bar{D}^0$ oscillations by measuring the time-dependent ratio of yields for the rare decay $D^0 \rightarrow K^+\pi^-$ to the favored decay $D^0 \rightarrow K^-\pi^+$ at the Collider Detector at Fermilab (CDF). Using 9.6 fb^{-1} of integrated luminosity of $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions recorded in the full CDF Run II, the signals of 7.6×10^6 $D^0 \rightarrow K^-\pi^+$ and 33×10^3 $D^0 \rightarrow K^+\pi^-$ decays are reconstructed in D^*-tagged events, with proper decay times between 0.75 and 10 mean D^0 lifetimes. We measure the mixing parameters $x'^2 = (0.08 \pm 0.18) \times 10^{-3}$, $y' = (4.3 \pm 4.3) \times 10^{-3}$, and $R_D = (3.51 \pm 0.35) \times 10^{-3}$. Our results are consistent with standard model expectations and similar results from proton-proton collisions and exclude the no-mixing hypothesis with a significance equivalent to 6.1 standard deviations.

1 Introduction

Neutral mesons can oscillate into their antiparticles because they are produced in flavor eigenstates which are different from eigenstates with defined mass and lifetime. This quantum-mechanical oscillation is referred as mixing and can be characterized by the parameters $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where Δm is the mass difference, $\Delta\Gamma$ is the decay width difference, and Γ is the mean decay width of the mass eigenstates. The process is well established for K^0, B^0, and B^0_s mesons [1] and its study provides important information about electroweak interactions and the Cabibbo-Kobayashi-Maskawa (CKM) matrix, as well as the virtual particles that are exchanged in the mixing process itself. Evidence of D^0–$\bar{D}^0$ mixing was reported in recent years by the experiments Belle [2], Babar [3, 4] and CDF [5] and it was observed only in 2012 by LHCb [6]. Even if standard model (SM) calculations of the D^0–$\bar{D}^0$ mixing rate are affected by significant theoretical uncertainties, this process is expected to be much slower (i.e. $|x|, |y| \leq 10^{-3}$) than the B and K oscillations. However NP particles could enhance the mixing rate, thus providing indirect evidence for physics beyond the SM [7, 8]. Then, it is of great interest to establish conclusively D^0–$\bar{D}^0$ mixing in a specific decay channel and improve the precision of the measurement of the mixing parameters.

Charm mixing can be searched by measuring the time dependence of the rate of the rare $D^0 \rightarrow K^+\pi^-$ decay (including its charge-conjugate). This decay can arise from the oscillation of a D^0 state to a $\bar{D}^0$ state, followed by a Cabibbo-favored (CF) $D^0 \rightarrow K^-\pi^+$ decay, or from a doubly-Cabibbo suppressed (DCS) D^0 decay. Under the assumption that CP is conserved and the mixing parameters are small ($|x|, |y| \ll 1$), the ratio R of $D^0 \rightarrow K^+\pi^-$ to

$D^0 \rightarrow K^-\pi^+$ decay rates can be approximated by [1]

$$R(t) = R_D + \sqrt{R_D}\, y'\, t + \frac{x'^2 + y'^2}{4}\, t^2 \tag{1}$$

where t is the proper decay time expressed in units of mean D^0 lifetime. R_D is the DCS decay rate relative to the CF rate, while the parameters x' and y' are linear combinations of x and y according to the relations $x' = y \sin\delta_{K\pi} + x \cos\delta_{K\pi}$ and $y' = y \cos\delta_{K\pi} - x \sin\delta_{K\pi}$, where $\delta_{K\pi}$ is the strong interaction phase difference between the DCS and CF amplitudes. In the absence of mixing, $x' = y' = 0$ and $R(t) = R_D$.

The experimental method to identify the flavor of the charmed meson at production exploits the strong-interaction decays $D^{*+} \rightarrow \pi^+D^0$, $D^{*-} \rightarrow \pi^-\bar{D}^0$. The relative charges of the soft (low-momentum) tagging pion from D^* decay and the pion from D^0 decay determine whether the decay chain is right-sign (RS, like charge) or wrong-sign (WS, opposite charge). RS processes include mainly CF decays, while DCS and mixing decays contribute to WS processes.

2 Analysis

2.1 Data selection

Our measurement uses the full data set corresponding to an integrated luminosity of 9.6 fb^{-1} recorded by the CDF II detector at the Tevatron in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We reconstruct the WS $D^{*+} \rightarrow \pi^+D^0(\rightarrow K^+\pi^-)$, and the RS $D^{*+} \rightarrow \pi^+D^0(\rightarrow K^-\pi^+)$ decay chains and measure the time dependence of their rates ratio. The components of the CDF II detector most relevant for this analysis are the multi-wire drift chamber (COT) and the silicon microstrip

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vertex detector located inside a solenoid, which provides a 1.4 T magnetic field [9].

The events for this analysis are selected online by a trigger system [10] which identifies pairs of oppositely charged particle tracks from a decay vertex detached by at least 200 μm from the beamline. In the off-line analysis, the tracks satisfying the trigger requirements are considered with both $K^-\pi^+$ and π^-K^+ interpretations in order to reconstruct D^0 candidates. Minimal requirements on the momenta and impact parameters of the tracks and the displacement of the reconstructed D^0 decay vertex are imposed. A low-momentum tagging pion track is combined with the D^0 candidate to form a D^* candidate. To reduce the contribution of D^* mesons produced from b-hadron decays, D^0 candidate are required to have an impact parameter $d_0 < 60$ μm. RS D^0 decays incorrectly reconstructed as WS decays, because the kaon and pion assignments are mistakenly interchanged, represent a large background to the WS signal. Two selection cuts have been applied to reduce this background. WS candidates with RS $K\pi$ invariant mass reconstructed within 20 MeV/c^2 of the known D^0 mass are removed. This cut retains 78% of the WS signal, and rejects 96.5% of the RS D^0 decays with incorrect mass assignment. A second cut exploits the K/π separation based on the measurements of the ionization energy loss in the COT [10]. The combination of these two cuts greatly reduces the mis-assigned RS background improving the WS signal over background ratio by a factor ~ 100.

2.2 Signal extraction

The reconstructed RS and WS condidates are classified into 20 intervals of proper decay time t which is determined (normalized to the mean D^0 lifetime $\tau = 410.1$ fs) as $t = m_{D^0}L_{xy}/(p_T\tau)$, where $m_{D^0} = 1.8648$ GeV/c^2 is the known D^0 mass [1], L_{xy} is the transverse D^0 decay length, and p_T its transverse momentum. D^0 candidates in each time bin are further divided into 60 bins of mass difference $\Delta M \equiv M(K\pi\pi) - M(K\pi) - M(\pi)$, with equal size 0.5 MeV/c^2. For each of the resulting 1200 WS and 1200 RS bins, the D^0 signal yield is determined by fitting the corresponding binned distribution of the Kπ invariant mass $M_{K\pi}$. The signal shape is modeled by the sum of two Gaussian functions with a low-mass tail, and the combinatoric background by an exponential function. A Gaussian term is included in the WS fit to model the residual background from misidentified RS decays, with shape determined from the data. The D^* signal 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 function, the background shape by the product of a power-law and an exponential function. The amplitudes of the signal and background and the background shape parameters are determined independently for all $M_{K\pi}$ and ΔM fits, while the signal shape is fixed to the RS time-integrated shape. The D^* fit procedure for the time-integrated ΔM distributions is shown in Fig. 1. The fitted RS and WS signal yields are about 7.6×10^6 and 33×10^3, respectively.
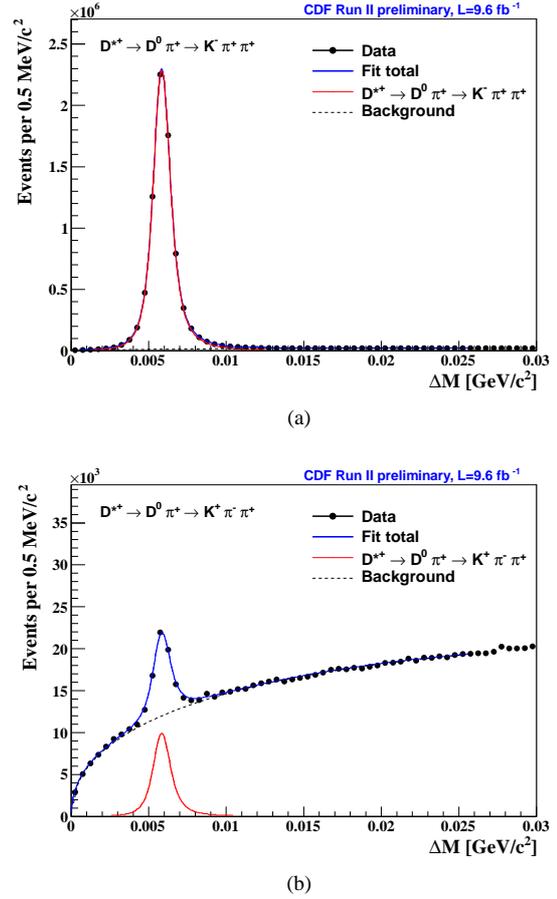

(a)

(b)

Figure 1. Time-integrated ΔM distribution for (a) RS and (b) WS decays, with fit curves superimposed.

2.3 WS/RS yield ratio

The measured ratio R_m of WS to RS signal yields in the 20 time intervarls is shown in Fig. 2. Since the measured yields include the contribution of D^* mesons produced from b-hadron decays, the time dependence of R_m is different from that of the WS/RS ratio of prompt decays R (Eq. 1). The expected value of R_m in a given time bin can be factorized as the product of R by a correction factor due to the non-prompt production

$$R_m^{pred}(t) = R(t)\left[1 + f_B(t)\left(\frac{R_B(t)}{R(t)} - 1\right)\right] \quad (2)$$

where $f_B(t)$ is the fraction of non-prompt RS D^* decays and $R_B(t)$ is the WS/RS ratio of non-prompt D^* decays with measured decay time t. For non-prompt decays, the measured decay time is the sum of the decay times of the beauty particle parent and the D^0 daughter. The function $R_B(t)$ is calculated by weighting $R(t)$ with the decay-time distributions of non-prompt D^0 decays obtained from a full detector simulation. The function $f_B(t)$ is determined from data by fitting the d_0 distributions of RS D^* decays in each time bin. These are characterized by a peak at small d_0 due to the prompt component, and a broad distribution extending to large d_0 due to the non-prompt component
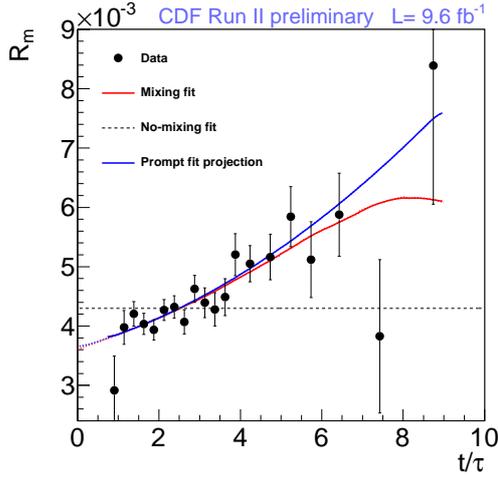
Figure 2. Measured ratio of WS to RS signal yields as a function of normalized proper decay time.

(a)

(b)

Figure 3. (a) Distribution of transverse impact parameter d_0 for RS D^0 candidates for all the time bins. (b) Fraction of non-prompt RS D^* decays as a function of proper decay time.

(Fig. 3(a)). Both the prompt and non-prompt components are modeled with the sum of two Gaussians. The time dependence of f_B in the region $d_0 < 60\,\mu m$ is parametrized by a 4-degree polynomial (Fig. 3(b)). The value of f_B is less than 1% in the first time bin and increases with time due to the faster exponential decay rate for D^0 mesons compared to beauty particles. In the last time bin, $f_B = (44 \pm 7)\%$.

The mixing parameters R_D, y', and x'^2 are found by minimizing the χ^2 function
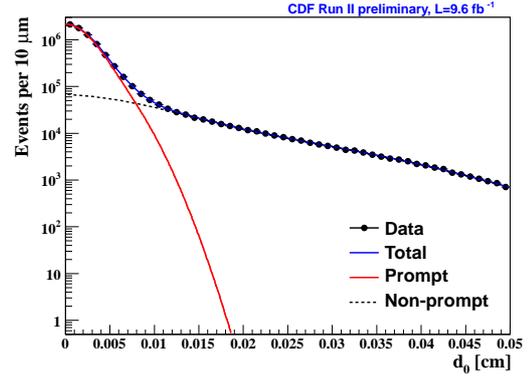
$$\chi^2 = \sum_{i=1}^{20} \left[\frac{R_m(t_i) - R_m^{pred}(t_i)}{\sigma_i} \right]^2 + C_B + C_H \qquad (3)$$

where σ_i is the uncertainty on $R_m(t_i)$ and C_B and C_H are Gaussian constraints to the parameters describing $f_B(t)$ and $R_B(t)$, respectively.
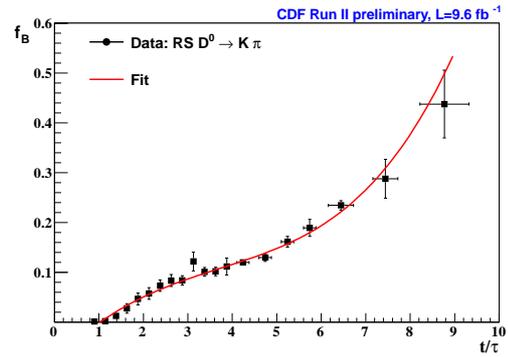
We investigated extensively systematic uncertainties due to a number of possible sources including: detector charged track asymmetries, uncertainties in the signal shapes used to fit $M_{K\pi}$ and ΔM distributions and in the shape of non-prompt component used to fit the d_0 distributions, background due to $D^+ \rightarrow K^- \pi^+ \pi^+$ and partially reconstructed charm decays, sensitivity of $R_B(t)$ on the simulated decay time distributions of non-prompt D^0. All these effects were found to be small compared to the mixing parameter errors derived from the fit.

2.4 Result

The fitted values of the mixing parameters are reported in Table 1. The function $R_m^{pred}(t)$ and the prompt component $R(t)$ as determined by the fit are shown in Fig. 2. They differ at large t due to the effect of non-prompt D^* production. A fit assuming no-mixing, i.e. $y' = x'^2 = 0$, is also shown and is clearly incompatible with the data. By calculating the Bayesian probability contours in the x'^2-y parameter space (Fig. 4(a)), we exclude the no-mixing hypothesis at

the level of 6.1 Gaussian standard deviations. Our results are consistent with SM calculations [7] and measurements from other experiments, as shown by comparing the 1σ x'^2-y contours in Fig. 4(b), and have similar precision to the recent LHCb observation [6].

3 Conclusion

We observe D^0–$\bar{D}^0$ mixing with a significance equivalent to 6.1σ, by measuring the decay-time-dependence of the ratio of yields for the suppressed $D^0 \rightarrow K^+ \pi^-$ to the favored $D^0 \rightarrow K^- \pi^+$ decays using the full CDF data set. We 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 $x'^2 = (0.08 \pm 0.18) \times 10^{-3}$. Our results are consistent with SM predictions and similar measurements from other experiments and substantially improve global knowledge of the charm mixing parameters.

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Fit type	χ^2/ndf	Parameter	Fitted values $\times 10^{-3}$	Correlation coefficient		
				R_D	y'	x'^2
Mixing	16.91/17	R_D	3.51 ± 0.35	1	-0.967	0.900
		y'	4.3 ± 4.3		1	-0.975
		x'^2	0.08 ± 0.18			1
No-mixing	58.75/19	R_D	4.30 ± 0.06			

Table 1. Mixing parameter results. The uncertainties include statistical and systematic components.

(a)

(b)

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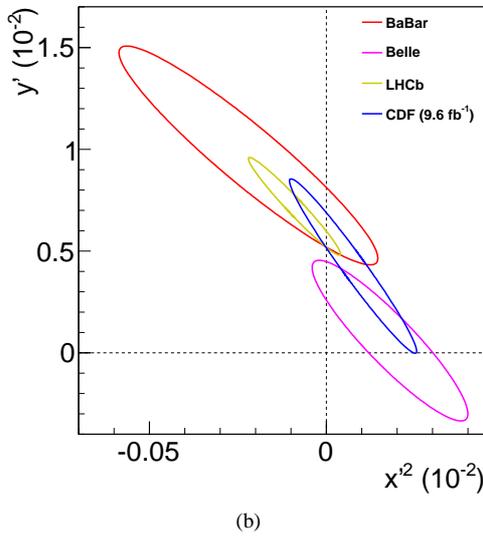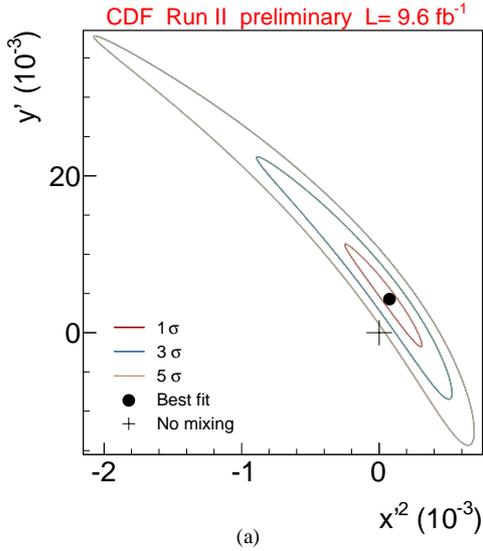[10] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **74**, 031109(R) (2006)

Figure 4. (a) Bayesian probability contours in $x'^2 - y'$ parameter space. (b) Comparison of 1σ contours between CDF (this work), Belle [2], Babar [3, 4] and LHCb [6].