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Search for a Lifetime Difference in D^0 Decays

The *BABAR* Collaboration

Abstract

The D^0 mixing parameter $y = \Delta\Gamma/2\Gamma$ was determined by measuring the D^0 lifetime separately for the $K^-\pi^+$ decay mode and the K^-K^+ decay mode with $12.4\,\mathrm{fb}^{-1}$ of data collected by the *BABAR* experiment in 2001. Backgrounds were suppressed with the $D^* \to D^0\pi^+$ decay and particle identification. The following preliminary result was obtained:

$$y = (-1.0 \pm 2.2(\mathrm{stat}) \pm 1.7(\mathrm{syst}))\ \%\,.$$

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1 Introduction

If *CP* conservation holds in the D^0 system, the *CP*-even and *CP*-odd eigenstates are mass eigenstates with widths Γ_+ and Γ_-, respectively. The mixing parameter $y = (\Gamma_+ - \Gamma_-)/(\Gamma_+ + \Gamma_-)$ is a measure of the difference of these lifetimes and is expected to be small (10^{-3}) within the Standard Model [1]. If the observed value of y is much larger than this expectation, it could be difficult to reconcile with theory. Otherwise, a small value of y would be useful in constraining the size of the other mixing parameter $x = 2(M_+ - M_-)/(\Gamma_+ + \Gamma_-)$ in direct measurements of D^0 mixing, where $M_\pm$ are the masses of the *CP* eigenstates.

A value of y may be determined by measuring the lifetime for D^0 mesons[1] that decay into final states of specific *CP* symmetry [2]. One such final state that is an equal mixture of *CP*-even and *CP*-odd is produced by the Cabibbo-favored decay $D^0 \to K^-\pi^+$. If y is small, the lifetime distribution of D^0 mesons decaying into this final state can be approximated as an exponential with lifetime $\tau_{K\pi} = 1/\Gamma$ where $\Gamma = (\Gamma_+ + \Gamma_-)/2$.

The $K^-\pi^+$ final state may be compared to K^-K^+ which is *CP*-even and is produced by the Cabibbo-suppressed decay $D^0 \to K^-K^+$. The lifetime distribution of D^0 mesons that decay into K^-K^+ is exponential with lifetime $\tau_{KK} = 1/\Gamma_+$. This lifetime can be compared to $\tau_{K\pi}$ to obtain y:

$$y = \frac{\tau_{K\pi}}{\tau_{KK}} - 1 \; . \tag{1}$$

Since the $K^-\pi^+$ and K^-K^+ final states have similar topology, many systematic uncertainties in the D^0 lifetimes cancel in their ratio, making Eq. 1 a particularly sensitive measurement.

Presented in this paper is a preliminary measurement of y based on data collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- collider. The results were obtained from a sample of $12.4\,\mathrm{fb}^{-1}$ of 2001 data that were reconstructed with the latest tracking alignment parameters and reconstruction algorithms. Data taken on and off the $\Upsilon(4S)$ resonance were used at a center-of-mass that corresponds to a nominal Lorentz boost of $\beta\gamma = 0.56$ along the beam axis. The size of the interaction point (IP) transverse to the beam direction was typically 6 μm in the vertical direction and 120 μm in the horizontal direction.

2 The *BABAR* Detector

The *BABAR* detector, a general purpose, solenoidal, magnetic spectrometer, is described in more detail elsewhere [4]. Those detector components employed in this analysis are briefly discussed here. Charged particles were detected and their momenta measured by a combination of a 40-layer drift chamber (DCH) and a five-layer, double-sided, silicon vertex tracker (SVT), both operating within a 1.5 T solenoidal magnetic field. D^0 decay vertices were typically reconstructed with a resolution along the D^0 direction of 75 μm for two-prong decays. A ring-imaging Cherenkov detector (DIRC) was used for charged particle identification.

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[1] In this paper, statements involving the D^0 meson and its decay modes are intended to apply in addition to their charged conjugates.

3 Event Selection

The widths Γ and Γ_+ were determined by fitting the decay time distributions of independent samples of $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$ decays. The D^0 candidates of each sample were identified from the charged particles belonging to their final state. The decay $D^{*+} \to D^0\pi^+$ and $K^\pm$ particle identification were used to suppress backgrounds.

D^0 candidates were selected by searching for pairs of tracks of opposite charge and combined invariant mass near the D^0 mass m_D. Each track was required to contain a minimum number of SVT and DCH hits in order to ensure their quality. The two D^0-candidate daughter tracks were fit to a common vertex. The χ^2 probability of this vertex fit was required to be better than 1%.

Each D^0 daughter track that corresponds to a $K^\pm$ particle was required to pass a likelihood-based particle identification algorithm. This algorithm was based on the measurement of the Cherenkov angle from the DIRC for momenta $p \gtrsim 0.6\,\mathrm{GeV}/c$ and on the energy loss (dE/dx) measured with the SVT and DCH for momenta $p \lesssim 0.6\,\mathrm{GeV}/c$. The charged $K^\pm$ identification efficiency was approximately 80% on average for tracks within the DIRC acceptance with a $\pi^\pm$ misidentification probability of about 2%.

The decay $D^{*+} \to D^0\pi^+$ is distinguished by a π^+ of low momentum, commonly referred to as the slow pion (π_s). To increase acceptance, π_s candidate tracks were not required to contain DCH hits. To improve resolution, a vertex fit was used to constrain each π_s candidate track to pass through the intersection of the D^0 trajectory and the IP. If the χ^2 probability of this vertex fit was less than 1%, the D^* candidate was discarded.

The D^* candidates peak at a value of $\delta m \approx 145.4\,\mathrm{MeV}/c^2$, where δm is the difference in the reconstructed D^* and D^0 masses. Backgrounds were rejected by discarding events with a value of δm that deviated more than a given margin from the peak. The size of this margin corresponded to approximately three standard deviations and varied between 1 and $2.5\,\mathrm{MeV}/c^2$ depending on the quality of the π_s track.

To remove background from B meson decays, each D^* candidate was required to have a momentum p^* in the center-of-mass greater than $2.6\,\mathrm{GeV}/c$. This requirement was also effective at removing combinatorial background that tended to accumulate at lower momenta.

The D^0 mass and δm distribution of the selected events are shown in Fig. 1. The relative size of the background was about 2% and 5% for the $K^-\pi^+$ and K^-K^+ samples, respectively, when measured inside a $\pm 20\,\mathrm{MeV}/c^2$ window. According to Monte Carlo simulations, of the background in the $K^-\pi^+$ (K^+K^-) sample, 1/2 (1/3) were combinatorial background, 1/3 (1/6) were produced by incorrectly identified π_s tracks, and about 1/6 (1/2) originated from other D^0 decays.

4 Lifetime Determination

The flight length and its measurement error for each D^0 candidate were determined by a global, three dimensional, multiple vertex fit that included the D^0 daughter tracks, the π_s track, and the IP envelope. This fit did not include explicit constraints on the D^* or D^0 masses. The value listed by the Particle Data Group (PDG) for the D^0 mass ($m_D = 1.8654\ \mathrm{GeV}/c^2$ [3]) and the momentum of the D^0 obtained with the vertex fit were used to calculate the boost of the D^0 and obtain the proper decay time.

An unbinned maximum likelihood fit was used to extract the lifetime from the D^0 samples. The likelihood function was divided into a decay time distribution function for the signal and a decay time distribution function for the background. The signal function was composed of a convolution

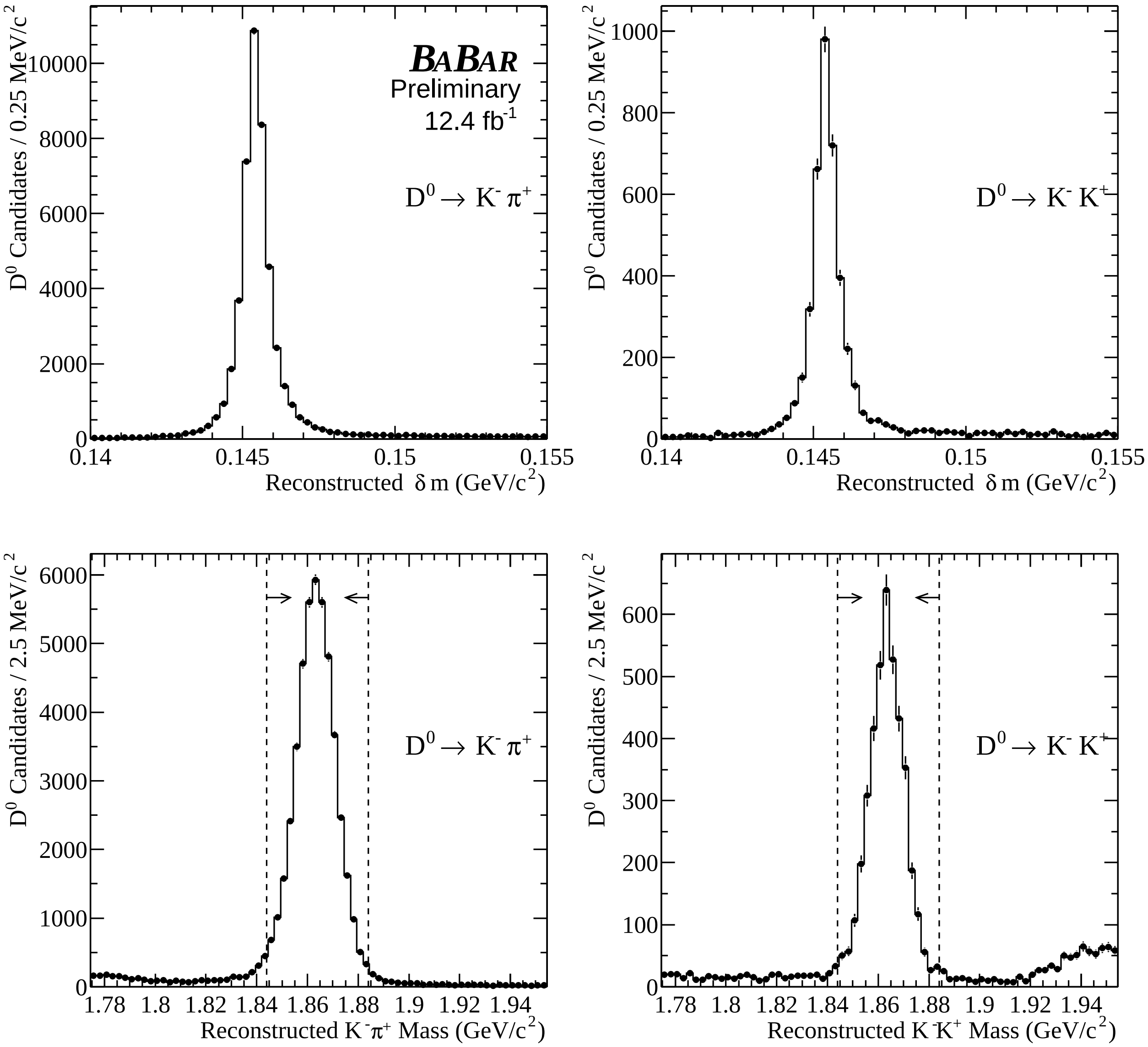

Figure 1: The reconstructed δm and D^0 mass distributions after event selection for the $K^-\pi^+$ and K^-K^+ decay modes. The δm plots include candidates both inside and outside the δm selection requirement but which fall within the m_D window indicated in the lower plots.

of an exponential and a resolution function. The resolution function was the sum of two Gaussian distributions with zero mean and with widths that were proportional to the measurement error (typically 180 fsec) of the decay time of each D^0 candidate. The parameters in the fit associated with the signal were the lifetime, the proportional widths of the two Gaussians, and the fraction of signal that was assigned to the second Gaussian.

Like the signal likelihood function, the background function was composed of a convolution of a resolution function and a lifetime distribution. The background lifetime distribution was the sum of an exponential distribution and a delta function at zero, the latter corresponding to those sources of background that originate at the IP. The resolution function consisted of the sum of three Gaussian distributions. The first two of these Gaussian distributions were chosen to match the resolution function of the signal. The third was given a width independent of the decay time error and accounted for outliers produced by long-lived particles or reconstruction errors. The additional fit parameters associated with the background included the fraction assigned to zero lifetime sources, the background lifetime, the width of the third Gaussian, and the fraction of background assigned to the third Gaussian.

To combine the signal and background likelihood functions, the reconstructed mass of each D^0 candidate was used to determine the likelihood that it was part of the signal. This calculation was based on a separate fit of the reconstructed D^0 mass distribution (Fig. 2). This fit included a resolution function composed of a Gaussian with an asymmetric tail and a linear portion to describe the background. The slope of the background was constrained with D^0 candidates in the δm sideband ($151 < \delta m < 159\,\mathrm{MeV}/c^2$).

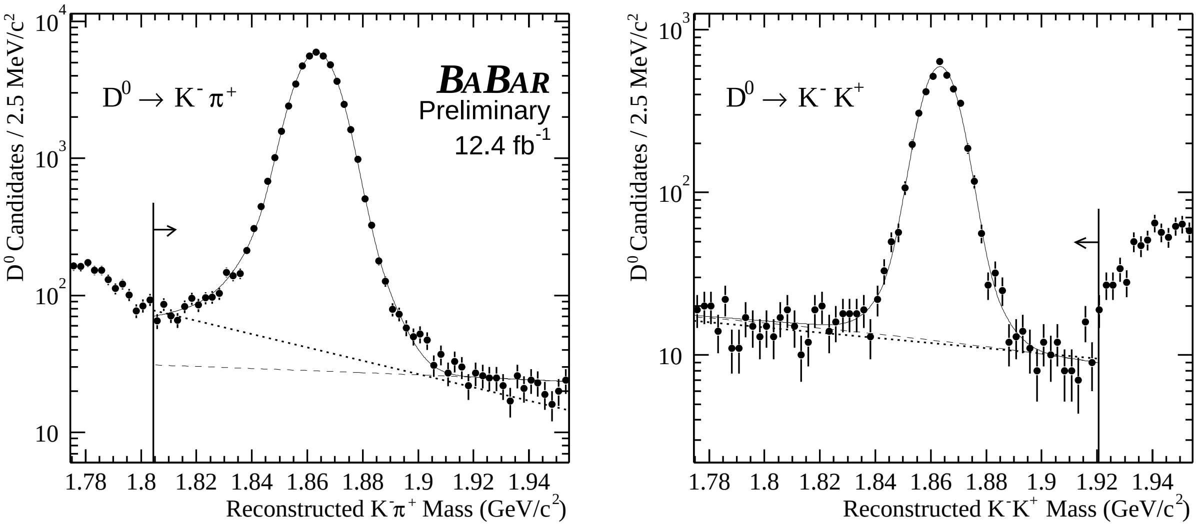

Figure 2: The fit to the reconstructed D^0 mass distribution used to determine the signal purity for the lifetime fits. The solid curve is the fit to the overall distribution and the dashed line is the portion assigned to the background. The dotted line is an alternative fit of the background level that is used as a systematic check.

The results of the lifetime fits are shown in Fig. 3. Typical values for the fit parameters were a background lifetime similar to the D^0 lifetime and a third Gaussian width that was several times larger than the typical decay time error. The proportionality factors associated with the two

Gaussians in the resolution function corresponded to a root-mean-square of approximately 1.2.

To ensure that the analysis was performed in an objective manner, the D^0 lifetime and y values were blinded. This blinding was performed by adding to each of the $\tau_{K\pi}$ and τ_{KK} fit results an offset chosen from a random Gaussian distribution of width 10 fsec. The values of the two offsets and the positive ($\tau_i > 0$) side of the lifetime distribution from the data and fit (Fig. 3) were concealed. The value of y was unblinded only after the analysis method and systematic uncertainties were finalized and the result was committed for public release.

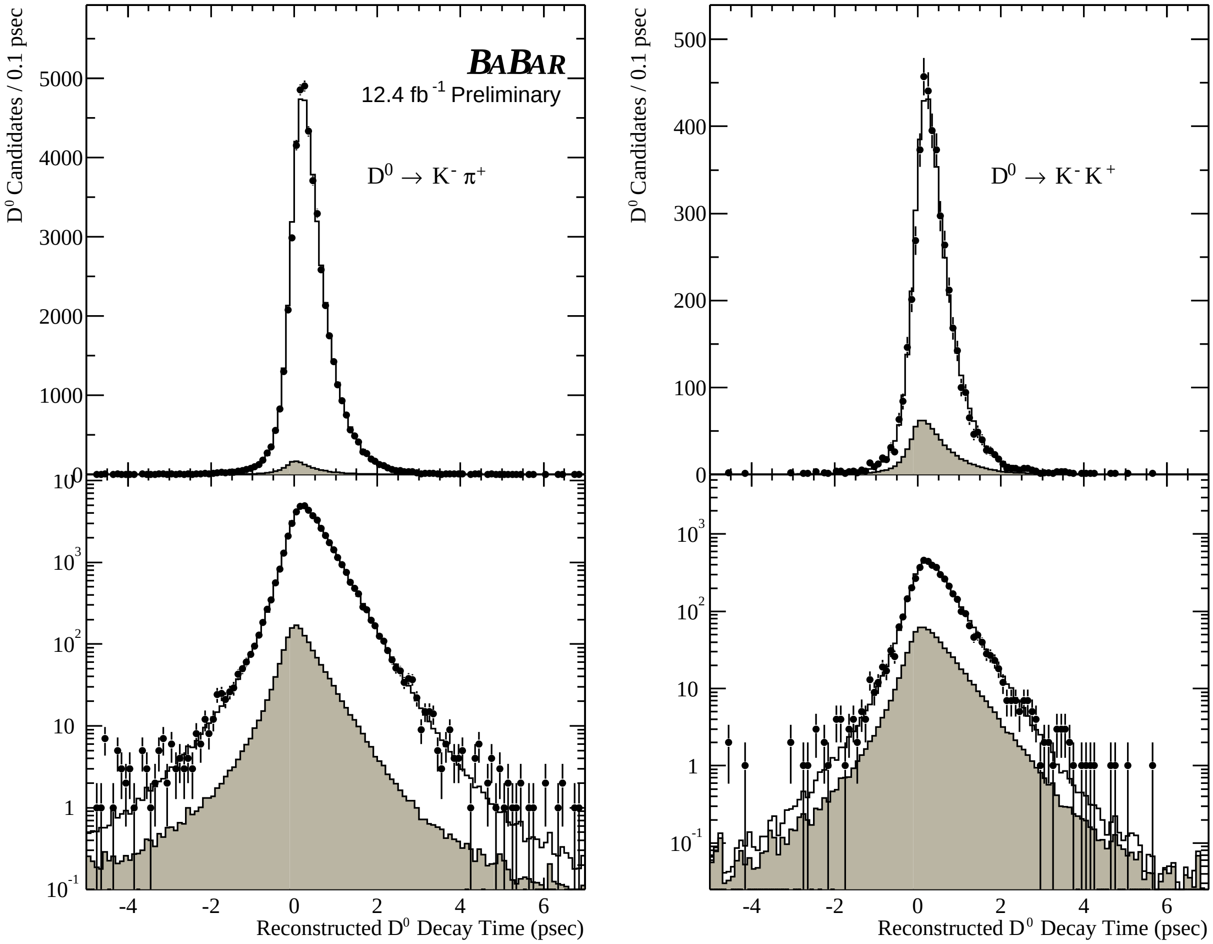

Figure 3: The fit to the reconstructed D^0 lifetime for the two D^0 decay modes for all events including the D^0 mass sidebands. The white histogram represents the result of the unbinned maximum likelihood fit described in the text. The gray histogram is the portion assigned to the background.

5 Systematic Errors and Results

Many systematic uncertainties cancel because y was measured from the ratio of lifetimes. The few uncertainties that do not were associated mostly with backgrounds. These were tested by varying each event selection requirement within its uncertainty and recording the subsequent change Δ_i in the measured value of y. The quadrature difference $(\delta\Delta_i)^2 = |\sigma_0^2 - \sigma_i^2|$ was used as an estimate of the statistical error $\delta\Delta_i$ in Δ_i, where σ_0 (σ_i) was the statistical error in y before (after) the ith systematic check. Each systematic check with $\Delta_i > \delta\Delta_i$ was included in the sum $\sum \Delta_i^2 - (\delta\Delta_i)^2$. The square root of this sum (1.7%) was used as the estimate for the systematic uncertainty from event selection and background.

Biases in tracking reconstruction were explored by studying Monte Carlo samples, which, within statistics, showed no reconstruction bias. In addition, the lifetimes were compared to measurements that employ a variety of vertexing techniques, including constraining the D^0 mass and using separate D^* and D^0 vertex fits. A systematic uncertainty of 0.4% was assigned as a result.

Detector misalignment was another potential source of bias. Systematic distortions of the SVT, even as small as a few microns, can produce significant variations in the apparent D^0 lifetime. Several studies were used to measure and characterize such distortions, and strategies were developed to correct them. One example was the study of proton tracks that were created by the interaction of off-energy beam particles and the beampipe. These tracks were used to measure the radius of the beampipe to a precision of a few microns, which limited the uncertainty in the radial scale of the SVT to three parts in one thousand.

Another example was a study of $e^+e^- \to \gamma\gamma \to 4\pi^\pm$ events in which the four charged tracks were known to originate from the IP. By selecting oppositely charged pairs of these tracks with opening angles similar to two-prong D^0 decays, it was possible to measure the apparent IP position as a function of D^0 trajectory and calculate a correction to the D^0 lifetime. For the data sample used in this analysis, this correction was determined to be +5 fsec, with negligible statistical error and a systematic uncertainty of ±5 fsec. This type of correction nearly cancels in the lifetime ratio and introduces little systematic uncertainty in y.

Table 1: Individual contributions to the systematic uncertainty in y.

Category	Uncertainty (%)
Event Selection and Background	1.7
Reconstruction and Vertexing	0.4
Alignment	0.3
Quadrature Sum	1.7

The systematic uncertainties in y are summarized in Table 1. When all systematic checks are added in quadrature, the preliminary result for y is:

$$y = (-1.0 \pm 2.2 \pm 1.7)\ \% ,$$

where the first error is statistical and the second, systematic.

The same set of systematic checks was applied to the D^0 lifetime. In this case, several of the systematic uncertainties, in particular those corresponding to detector alignment, do not cancel as they do for the lifetime ratio, and as a result, the total systematic uncertainty was dominated by different sources. Nevertheless, an important test of the y analysis was a D^0 lifetime that agreed with expectations. A corrected value of $\tau_{K\pi} = 412 \pm 2$ fsec was found with a systematic uncertainty of approximately 6 fsec, which is consistent with the PDG value of 412.6 ± 2.8 fsec [3].

6 Conclusion

The following preliminary value of y was measured using $12.4\,\mathrm{fb}^{-1}$ of data taken by the *BABAR* detector in 2001:

$$y = (-1.0 \pm 2.2 \pm 1.7)\ \% ,$$

where the first error is statistical and the second, systematic. This result is consistent with the Standard Model expectation of zero and consistent with published values from E791 [5] and FOCUS [6] and preliminary results from Belle [7] and CLEO [8].

The measurement reported in this paper is currently limited by statistics. As additional data are collected and as previous data are reprocessed with the latest alignment parameters, the statistical uncertainty is expected to decrease significantly.

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