Measurement of $\mathcal{B}(D^0 \to K^- \pi^+)$ Using Partial Reconstruction of $\overline{B} \to D^{*+} X \ell^- \bar{\nu}$

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We present a measurement of the absolute branching fraction for $D^0 \to K^-\pi^+$ using the reconstruction of the decay chain $\overline{B} \to D^{*+}X\ell^-\overline{\nu}$, $D^{*+} \to D^0\pi^+$ where only the lepton and the low-momentum pion from the D^{*+} are detected. With data collected by the CLEO II detector at the Cornell Electron Storage Ring, we have determined $\mathcal{B}(D^0 \to K^-\pi^+) = [3.81 \pm 0.15(\mathrm{stat}) \pm 0.16(\mathrm{syst})]\%$. [S0031-9007(98)05813-X]

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As most of the published branching fractions of D^0, D^+, and D_s^+ mesons are normalized to the $D^0 \to K^-\pi^+$ [1] decay mode, then the value of $\mathcal{B}(D^0 \to K^-\pi^+)$ directly affects many topics in heavy flavor physics.

In order to measure the absolute branching fraction for $D^0 \to K^-\pi^+$ decay, one needs to find the number of D^0's without reconstructing a particular D^0 decay mode. In this Letter we present a measurement of the absolute $D^0 \to K^-\pi^+$ branching fraction, developing the method first used by the ARGUS Collaboration [2]. The inclusive number of D^0's is determined by partial reconstruction of the decay chain $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$, $D^{*+} \to D^0\pi^+$, where only the lepton and the slow pion from the D^{*+}, hereafter denoted as π_s, are detected. The systematic errors involved are largely different from those of other recent measurements [3–5], where slow pions within jets were used to tag the decay $D^{*+} \to D^0\pi^+$.

We have used 3.1 fb^{-1} of data collected on the $\Upsilon(4S)$ resonance by the CLEO II detector [6]. The data set corresponds to 3.3×10^6 $B\overline{B}$ events. In order to suppress non-$B\overline{B}$ (continuum) background we required the ratio of the Fox-Wolfram moments H_2/H_0 [7] to be less than 0.4. The remaining contribution from continuum events was estimated using 1.6 fb^{-1} of data collected just below the $B\overline{B}$ threshold.

We required lepton candidates to have a momentum between 1.4 and 2.5 GeV/c. The π_s candidate must have the opposite charge with respect to the lepton and have a momentum lower than 190 MeV/c.

The partial reconstruction of the decay $\overline{B} \to D^{*+}X\ell^-\overline{\nu}$ exploits the extremely low energy release in the decay $D^{*+} \to D^0\pi_s^+$. The pion is almost at rest in the D^{*+} frame, and its velocity vector in the lab frame is approximately equal to that of the D^{*+}. Our main signal mode is $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$, for which the missing mass squared is calculated as

$$MM^2 = (E_B - E_\ell - E_{D^{*+}})^2 - |\vec{P}_B - \vec{P}_\ell - \vec{P}_{D^{*+}}|^2. \tag{1}$$

The energy of the B meson is precisely the beam energy. We do not know the direction of motion of the B, but the B momentum is sufficiently small ($\approx$300 MeV/c) compared to the typical values of $|\vec{P}_\ell|$ and $|\vec{P}_{D^{*+}}|$ that we can set $\vec{P}_B = 0$. We approximated the direction of motion of the D^{*+} by the direction of motion of the π_s. We used a parametrization obtained from Monte Carlo simulations to estimate $E_{D^{*+}}$ as a function the π_s momentum [8].

The resulting MM^2 distribution is shown in Fig. 1(a). The events with the lepton and slow pion coming from $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$, $D^{*+} \to D^0\pi_s^+$ produce a prominent peak at $MM^2 \approx 0$. However, the decays $\overline{B} \to D^{*+}X\ell^-\overline{\nu}$, $D^{*+} \to D^0\pi_s^+$ also contribute to this peak. We have considered these decay modes to be signal because they produce true $D^{*+} \to D^0\pi_s^+$. More specifically, we allowed the D^{*+} to come from $\overline{B} \to D^{*+}n\pi\ell^-\overline{\nu}$ decays, where $D^{*+}n\pi$ may or may not form a resonance. We also allowed the lepton to come from τ in the decays $\overline{B} \to D^{*+}\tau^-\overline{\nu}$ or from $\overline{D}$ in the decays $\overline{B} \to D^{*+}\overline{D}X$, where $\overline{D}$ represents $\overline{D}^0$, D^- or D_s^-. Our analysis is therefore not dependent on the branching fractions assumed in the Monte Carlo simulation for the poorly measured $\overline{B} \to D^{*+}n\pi\ell^-\overline{\nu}$ and $\overline{B} \to D^{*+}\overline{D}X$ decays, because these decays were considered to be signal. The requirement for the lepton to have a momentum greater than 1.4 GeV/c suppresses the signal decay modes other than $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$. According to our Monte Carlo simulation, the decays $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ compose $\approx$84% of the signal yield, the decays $\overline{B} \to D^{*+}n\pi\ell^-\overline{\nu}$ contribute $\approx$15%, and $\overline{B} \to D^{*+}\overline{D}X$ together with $\overline{B} \to D^{*+}\tau^-\overline{\nu}$ decays contribute less than 1%.

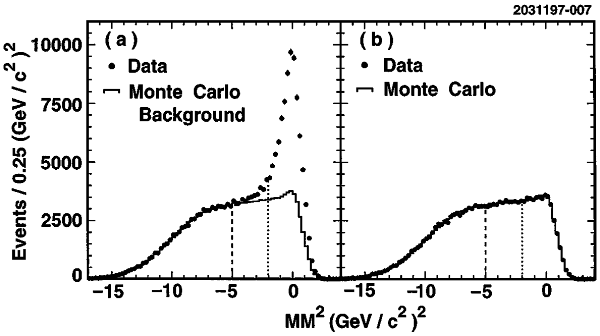

FIG. 1. The missing mass squared (MM^2) distribution for the right-sign (a) and wrong-sign (b) $\ell\pi_s$ pairs. The estimated contribution from non-$B\overline{B}$ (continuum) events has been subtracted. The Monte Carlo background shape has been normalized to the data distribution in the sideband region indicated by the dashed line ($MM^2 < -5$ GeV$^2/c^4$). The lower limit for the signal region is indicated by the dotted line.

A Monte Carlo simulation of the $B\overline{B}$ events was used to determine the background shape. For the background study we used the same selection criteria as for the data analysis, but we removed the $\ell^- \pi_s^+$ pairs coming from the signal decay modes which were defined in the previous paragraph. We normalized the background shape to the data distribution in the sideband region ($MM^2 < -5\ \mathrm{GeV}^2/c^4$). After the background subtraction, the number of events in the signal region (defined as $MM^2 > -2\ \mathrm{GeV}^2/c^4$) was found to be $N^{\mathrm{incl}} = 44\,504 \pm 360$ (stat). In this way we have extracted the number of $\overline{B} \to D^{*+} X \ell^- \overline{\nu}$ events in which $D^{*+} \to D^0 \pi_s^+$.

We have thus obtained a sample of $D^{*+} \to D^0 \pi^+$ decays without reconstructing a particular D^0 decay mode. Next we need to determine how many D^0's from these $D^{*+} \to D^0 \pi^+$ events decay to $K^- \pi^+$. For every $\ell^- \pi_s^+$ pair for which the value of MM^2 was within the signal region we searched for a $K^- \pi^+$ pair, assigning the kaon mass to the track of the opposite charge with respect to π_s, and requiring $|M(K^- \pi^+) - M(D^0)| < 35\ \mathrm{MeV}/c^2$ (the D^0 mass resolution is $\sigma(M(K\pi)) \simeq 10\ \mathrm{MeV}/c^2$). The $K^- \pi^+$ pair was combined with the π_s^+ and the mass difference $\Delta M \equiv M(K^- \pi^+ \pi_s^+) - M(K^- \pi^+)$ was formed. The resulting ΔM distribution is shown in Fig. 2. The prominent peak at $\Delta M \approx 145.4\ \mathrm{MeV}/c^2$ is produced by $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ decays. We normalized the background shape obtained from the Monte Carlo simulation to the data distribution in the sideband region ($155 < \Delta M < 180\ \mathrm{MeV}/c^2$). True $D^{*+} \to D^0 \pi_s^+$, $D^0 \to K^- \pi^+$ decays where the D^{*+} does not come from a signal decay chain were considered to be background.

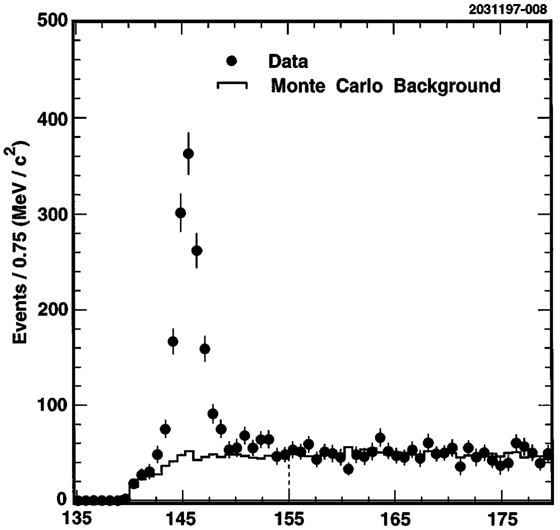

FIG. 2. $\Delta M \equiv M(K^- \pi^+ \pi_s^+) - M(K^- \pi^+)$ distribution for the continuum-subtracted data. The Monte Carlo background shape has been normalized to the data distribution in the sideband region. The lower limit for the sideband region is indicated by the dashed line.

After the background subtraction we counted the number of events in the signal region, defined as $141.50 < \Delta M < 149.75\ \mathrm{MeV}/c^2$. The number of decays $D^{*+} \to D^0 \pi^+$ with $D^0 \to K^- \pi^+$, denoted as N^{excl}, was found to be 1165 ± 45 (stat).

To extract $\mathcal{B}(D^0 \to K^- \pi^+)$ we need to correct the ratio $N^{\mathrm{excl}}/N^{\mathrm{incl}}$ for the track reconstruction and acceptance efficiencies:

$$\mathcal{B}(D^0 \to K^- \pi^+) = \frac{N^{\mathrm{excl}}}{N^{\mathrm{incl}}} \frac{1}{\epsilon}\,. \tag{2}$$

We obtained ϵ using a Monte Carlo simulation of the CLEO II detector. To a good approximation the lepton and slow pion reconstruction efficiencies cancel in the ratio when we calculate ϵ. Therefore ϵ mainly includes reconstruction and selection efficiencies for K^- and π^+ tracks and acceptance efficiencies for the $M(K\pi)$ and ΔM signal regions. However, the cancellation of the lepton and slow pion reconstruction efficiencies is not exact because the average charged track multiplicity for D^0 decays is higher than that for $D^0 \to K^- \pi^+$ mode and it is more difficult to reconstruct a track in a higher multiplicity environment. We found that this effect changes ϵ by 3.7% of itself. In order to take this into account, we calculated ϵ by selecting signal events from the Monte Carlo simulation of $B\overline{B}$ events, and comparing the value of $N_{\mathrm{MC}}^{\mathrm{excl}}/N_{\mathrm{MC}}^{\mathrm{incl}}$ to the branching ratio that was used in the Monte Carlo calculation. We obtained $\epsilon = [68.6 \pm 2.1(\mathrm{syst})]\%$, and using this value of ϵ together with Eq. (2), we found

$$\mathcal{B}(D^0 \to K^- \pi^+) = [3.81 \pm 0.15(\mathrm{stat}) \pm 0.16(\mathrm{syst})]\%\,.$$

The total systematic error was obtained by summing in quadrature the errors given in Table I. We will now discuss the systematic uncertainties dividing the possible sources into three categories: (i) determination of N^{incl} using the MM^2 distribution, (ii) determination of N^{excl} using the ΔM distribution, (iii) efficiency extraction from Monte Carlo.

(i) First, to see how well the Monte Carlo can simulate the background shape for the MM^2 distribution, we looked at the MM^2 distribution for the wrong-sign (i.e., same sign) $\ell \pi_s$ pairs [Fig. 1(b)]. We normalized the Monte Carlo shape to data distribution in the sideband region and compared the Monte Carlo prediction with data in the signal region. We found excellent agreement within the statistical precision of 0.8% of the signal region population. We include this 0.8% as a part of the systematic error. This result is encouraging, but different physics can contribute to the distributions for wrong-sign and right-sign background $\ell\ \pi_s$ pairs. Using Monte Carlo simulations, we performed a study comparing the MM^2 distributions for the various physical processes producing the wrong-sign or the right-sign background $\ell \pi_s$ pairs.

We have found that the most dangerous source of background which peaks in the signal region of MM^2

TABLE I. Systematic error summary table.

Quantity	Possible source of systematic error	Estimate of error (% of final result)
N^{incl}	Background subtraction in MM^2 distribution	2.5%
	Slow pion momentum cut (affects MM^2 background shape)	1.0%
	Fitting and yield determination	0.6%
	Fake leptons	0.2%
N^{excl}	Background subtraction in ΔM distribution	1.1%
	Fitting and yield determination	0.3%
ϵ	$K^-\pi^+$ reconstruction efficiency	2.0%
	Choice of signal region in ΔM distribution	1.6%
	Nonexact cancellation of ℓ and π_s reconstruction efficiencies	1.1%
	Monte Carlo statistics	1.4%
	Continuum subtraction	0.1%
	Total	4.3%

distribution is the decay chain $\overline{B} \to DX\ell^-\overline{\nu}$, $D \to$ (something heavy) + π^+, where the π^+ is moving slowly in the D rest frame and mimics the pion from $D^{*+} \to D^0\pi_s^+$ decay. These decays do not contribute to the ΔM peak and thus can reduce the measured $D^0 \to K^-\pi^+$ branching fraction. To estimate the systematic error due to this background we identified such low Q-value decay modes in our Monte Carlo simulation: $D^+ \to \overline{K}^*(\omega \text{ or } \rho)\pi^+$. Monte Carlo predicts that the events with the pion coming from one of these modes account for 0.7% of the events under the MM^2 peak with respect to the number of events in the signal peak. We have exploited the difference in the MM^2 distribution shapes for this background and the signal and fitted the whole MM^2 data distribution with three histograms obtained from Monte Carlo simulation: signal, the contribution from the decay chain $\overline{B} \to D^+X\ell^-\overline{\nu}$ where $D^+ \to \overline{K}^*(\omega \text{ or } \rho)\pi^+$, and the rest of background. The fit showed that the contribution from these modes is consistent with the Monte Carlo prediction. However, we should keep in mind that the decay modes we are considering here are poorly measured and that there could be other similar low Q-value decays that have not yet been observed. In order to be conservative, we varied the contribution from $\overline{B} \to D^+X\ell^-\overline{\nu}$, $D^+ \to \overline{K}^*(\omega \text{ or } \rho)\pi^+$ in the Monte Carlo background shape by the fit error and obtained a 2.3% variation in final result, which we took as the systematic error due to this background.

Another source of background which peaks in the signal region of the MM^2 distribution results when the slow pion from a signal decay chain decays in flight to a muon, and we identify this muon as the slow pion. Monte Carlo simulations predict the magnitude of background from this source in the MM^2 peak region to be 2.5% of the signal. Even though this is the largest source of background which peaks in the signal region it does not significantly bias the $\mathcal{B}(D^0 \to K^-\pi^+)$ measurement because this background produces smeared peaks in the signal regions of both the MM^2 *and* the ΔM distributions. We varied the Monte Carlo prediction for this background by 30% of itself and obtained 0.3% variation in final result, which we took as the systematic error.

Another background which peaks in the MM^2 signal region results when we identify as a π_s^+ a positron from $\pi^0 \to \gamma e^+e^-$ or γ conversion in the decay chain $\overline{B} \to D^*X\ell^-\overline{\nu}$, $D^* \to D\pi^0$, $D\gamma$. Monte Carlo simulations predict the magnitude of background from this source in the MM^2 peak region to be 0.7% of the signal. We varied the Monte Carlo prediction for this background by 30% of itself and obtained 0.4% variation in final result, which we took as the systematic error.

Combining the errors described above in (i) we estimated the systematic error due to background subtraction in the MM^2 distribution to be 2.5%. Table I also includes the estimated systematic errors due to the cut on slow pion momentum, fitting and yield determination in MM^2 distribution, and fake leptons.

(ii) We have studied the systematic error due to the background subtraction in the ΔM distribution. We included true $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$ decays where the D^{*+} does not come from a signal decay chain in the definition of background. The main source of this background is $D^{*+}\ell^-$ pairs for which the D^{*+} comes from one $\overline{B}^0$, and the lepton is the primary lepton from another $\overline{B}^0$. This background is suppressed because it occurs only due to $B^0 - \overline{B}^0$ mixing. A less significant source is $D^{*+}\ell^-$ pairs for which the D^{*+} comes from one $\overline{B}^0$ or B^- and the lepton is a secondary lepton from the $\overline{D}$ from the other B^0 or B^+. This background is suppressed by the lepton momentum requirement which predominantly selects primary leptons from B decays. Neither of these background components contribute to the peak at $MM^2 \approx 0$ because the lepton and slow pion come from different B's. We varied the Monte Carlo prediction for these backgrounds by 20% (based on the conservative estimate of the uncertainties in the inclusive

D^{*+} and lepton yields, the $B^0 - \overline{B}^0$ mixing parameter, and the dependence of MM^2 distribution shape on the D^{*+} momentum spectrum), and obtained 0.6% variation in the final result, which we took as the systematic error.

The rest of the background in the ΔM distribution is combinatoric. To estimate the systematic error due to the Monte Carlo simulation of this background we substituted the combinatoric part of the Monte Carlo background shape by an analytic threshold function [we used the form $f(x) = N(x - x_0)^{a_1} e^{[b_1(x-x_0)+b_2(x-x_0)^2]}$] and obtained the 0.9% shift in the final result, which we took as the systematic error.

Combining the errors described above in (ii) we estimated the systematic error due to background subtraction in the ΔM distribution to be 1.1%. Table I also includes the estimated systematic errors due to the fitting and yield determination in the ΔM distribution.

(iii) A study has been performed to estimate the systematic error due to the extraction of the reconstruction efficiency for K^- and π^+ tracks from Monte Carlo simulations. We assigned a 2% error to the final result (1% per track). As was mentioned earlier, the lepton and slow pion reconstruction efficiencies do not cancel out exactly due to the difference in charged multiplicity between the cases $D^0 \to K^-\pi^+$ and $D^0 \to$ all. To estimate the systematic error due to this effect we extracted the efficiency from Monte Carlo forcing $D^0 \to K^-\pi^+$ when we determine $N_{\mathrm{MC}}^{\mathrm{incl}}$. As a systematic error we took 30% of the shift in the efficiency obtained using this method and the method actually employed in the analysis. Table I also includes the estimated systematic errors due to the choice of the signal region in the ΔM distribution.

The systematic errors due to the limited Monte Carlo statistics and the continuum subtraction are also given in Table I.

In conclusion, we have measured the absolute branching fraction for $D^0 \to K^-\pi^+$ decay using a $\overline{B} \to D^{*+}X\ell^-\overline{\nu}$ tag. We have found $\mathcal{B}(D^0 \to K^-\pi^+) = [3.81 \pm 0.15(\mathrm{stat}) \pm 0.16(\mathrm{syst})]\%$ [9]. Our result is consistent with a recent measurement by ALEPH of $(3.82 \pm 0.09 \pm 0.11)\%$ [3] [we took the value before correction for the final state radiation from the K and π daughters in the D^0 decay], two measurements by ARGUS of $(3.41 \pm 0.12 \pm 0.28)\%$ [4] and of $(4.5 \pm 0.6 \pm 0.4)\%$ [2], and two measurements by CLEO of $(3.91 \pm 0.08 \pm 0.17)\%$ [5] and of $(3.69 \pm 0.11 \pm 0.16)\%$ [10]. Taking into account correlations, we combined our result with the other two CLEO measurements and found a new CLEO average value for $\mathcal{B}(D^0 \to K^-\pi^+)$ to be $[3.82 \pm 0.07(\mathrm{stat}) \pm 0.12(\mathrm{syst})]\%$.

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[1] Charge conjugate modes are implied throughout this Letter unless otherwise stated. $\overline{B}$ can be either $\overline{B}^0$ or B^-.

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[9] The K and π daughters in the D^0 decay can radiate photons in final state. This radiation results in a radiative tail of the $M(K\pi)$ distribution, which we did not include in the calculation of the efficiency. The requirement $|M(K^-\pi^+) - M(D^0)| < 35\ \mathrm{MeV}/c^2$ implies the effective cut on γ energy in the D^0 rest frame of $E_\gamma^* < 30$ MeV. Therefore our result corresponds to the value of $\mathcal{B}[D^0 \to K^-\pi^+(\gamma)]$ with the effective cut on γ energy in the D^0 rest frame of $E_\gamma^* < 30$ MeV. We compare our measurement with several other measurements which have the $M(K\pi)$ resolution comparable to ours.

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