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

CLEO Collaboration

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Abstract

The decay mode $D^0 \to K^-\pi^+$ is commonly used for normalizing other decay modes of D^0, D^+ and D_s^+. A precise measurement of $Br(D^0 \to K^-\pi^+)$ is thus essential for calibrating charm yields in a variety of environments such as the decays of B mesons or Z^0. Using data collected with the CLEO II detector, we have made an absolute measurement of $Br(D^0 \to K^-\pi^+)$ using the reconstruction of the decay chain $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$, $D^{*+} \to D^0\pi^+$, where only the lepton and the low-momentum pion from the D^{*+} are detected. The subsequent reconstruction of the decay $D^0 \to K^-\pi^+$ allows a measurement of the absolute $D^0 \to K^-\pi^+$ branching fraction. We find $Br(D^0 \to K^-\pi^+) = (3.81 \pm 0.15 \pm 0.17)\%$, where the first error is statistical and the second is systematic. The systematic errors involved are largely different from those of recent measurements where slow pions within jets are used to tag the decay $D^{*+} \to D^0\pi^+$.

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I. INTRODUCTION

At present, most of the branching fractions of D^0, D^+ and D_s^+ are normalized to the $D^0 \to K^-\pi^+$ [1] decay mode. Thus, the absolute value of $Br(D^0 \to K^-\pi^+)$ not only directly affects the branching fractions of those charmed mesons, but is also critical whenever the decays of D^0, D^+ and D_s^+ are used to determine other physical quantities. Some examples are charm counting in B meson decays where about 90% of the total charm yield is calibrated by $Br(D^0 \to K^-\pi^+)$ [1], the determination of $Br(Z^0 \to c\bar{c})$, and the investigation of any exclusive decay mode of the B meson which contains D^0, D^+ or D_s^+.

In order to measure the absolute value of $Br(D^0 \to K^-\pi^+)$, one needs to find the number of D^0's without reconstructing the explicit decay mode of the D^0. One way is to fully reconstruct one D^0 in $e^+e^- \to \psi(3770) \to D^0\overline{D}^0$ and look at the other side for the decay $D^0 \to K^-\pi^+$ [2]. However, the current world average value for $Br(D^0 \to K^-\pi^+)$ is dominated by recent ALEPH [3], CLEO [4], and ARGUS [5] measurements, all of which used the method first introduced by HRS Collaboration [6]. This method exploits $D^{*+} \to D^0\pi^+$ decays in jets in $e^+e^- \to c\bar{c}$ events. The decays $D^{*+} \to D^0\pi^+$ produce the excess of pions at low transverse momentum with respect to the jet axis. These measurements may share common systematic uncertainties, and thus it is desirable to measure $Br(D^0 \to K^-\pi^+)$ using some other method. In this paper we present a measurement of the absolute $D^0 \to K^-\pi^+$ branching fraction, developing the idea first used by the ARGUS Collaboration [7]. In this technique the inclusive number of D^0's is determined by partial reconstruction of the decay chain $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$, $D^{*+} \to D^0\pi^+$, where only the lepton and the low-momentum pion from the D^{*+} are detected.

Experiment	$Br(D^0 \to K^-\pi^+)$ (%)	Technique used to obtain the inclusive number of D^0's
ALEPH ('96) [3]	$3.90 \pm 0.09 \pm 0.12$	Tag $D^{*+} \to D^0\pi^+$ decays in jets by the excess of the π^+'s at low p_t with respect to the jet axis
CLEO ('93) [4]	$3.91 \pm 0.08 \pm 0.17$	
ARGUS ('94) [5]	$3.41 \pm 0.12 \pm 0.23$	
HRS ('88) [6]	$4.2 \pm 0.4 \pm 0.4$	
MARK-III ('88) [2]	$4.5 \pm 0.8 \pm 0.5$	Full reconstruction of one D^0 in $e^+e^- \to \psi(3770) \to D^0\overline{D}^0$
ARGUS ('94) [7]	$4.5 \pm 0.6 \pm 0.4$	Partial reconstruction of $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$, $D^{*+} \to D^0\pi^+$

[1] Charge conjugate modes are implied throughout this paper unless otherwise stated.

II. DATA SAMPLE AND EVENT SELECTION

The data were taken with CLEO II detector [8] at the Cornell Electron Storage Ring. We use 3.1 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance and we also use 1.6 fb^{-1} of data collected just below the $\Upsilon(4S)$ to estimate the contribution from continuum events. For the analysis we select hadronic events with at least one lepton candidate. We also require at least one additional track with momentum below 190 MeV/c, which is slightly below the upper kinematic limit for pions coming from $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$, $D^{*+} \to D^0\pi^+$. In order to suppress the contribution from continuum production of $q\bar{q}$ pairs, we require the ratio of the Fox-Wolfram moments H_2/H_0 [9] to be less than 0.4. The remaining contribution from continuum events is subtracted using appropriately scaled data taken at an energy just below the $\Upsilon(4S)$. In the following the continuum subtraction is implicit.

We require lepton candidates to have a momentum between 1.4 GeV/c and 2.5 GeV/c and to be in the barrel region of the detector. Muon candidates are required to penetrate an iron absorber to the depth of at least five nuclear interaction lengths. Electrons are identified through a comparison of the energy deposited in the calorimeter with the momentum measured in the tracking chambers and the specific ionization energy loss (dE/dx) of the particle within the drift chamber.

III. ANALYSIS PROCEDURE

The partial reconstruction of the decay $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$ exploits the extremely low energy release in the decay $D^{*+} \to D^0\pi^+$, where $Q \equiv M_{D^{*+}} - M_{D^0} - M_{\pi^+} = 6$ MeV. The slow pion, π_s, from the decay $D^{*+} \to D^0\pi_s^+$ is almost at rest in the D^* frame, and its velocity vector is approximately equal to that of the D^{*+}.

The missing mass squared in the decay $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$ 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 is precisely the beam energy. We do not know the direction of motion of the B, but the B momentum is small enough ($|\vec{P}_B|$ $\approx$300 MeV/c) that we can set $\vec{P}_B = 0$. We approximate the direction of motion of the D^{*+} by the direction of motion of the π_s^+. If the π_s were exactly at rest in the D^* frame, the D^* energy would be given by $E_{D^*}^{lab} = \frac{E_\pi^{lab}}{E_\pi^{CM}} M_{D^*}$. In order to correct for the non-zero momentum of the π_s in the D^* frame, we use a parameterization obtained from Monte Carlo to estimate $E_{D^{*+}}$ as a function of the momentum of π_s. Thus, only information about the lepton from the B and the slow pion from the D^* is used to calculate MM^2 in the decay $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$. The resulting MM^2 distribution is shown in Figure 1. The events with the lepton and slow pion coming from $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$, $D^{*+} \to D^0\pi_s^+$ produce a prominent peak at $MM^2 \approx 0$. However, the decays $\overline{B} \to D^{*+}X\ell^-\bar{\nu}$, $D^{*+} \to D^0\pi_s^+$ [2] also contribute to the peak at $MM^2 \approx 0$. Because these decays have true $D^{*+} \to D^0\pi_s^+$, we consider these modes as signal. Namely, we allow

[2] $\overline{B}$ can be either $\overline{B}^0$ or B^-.

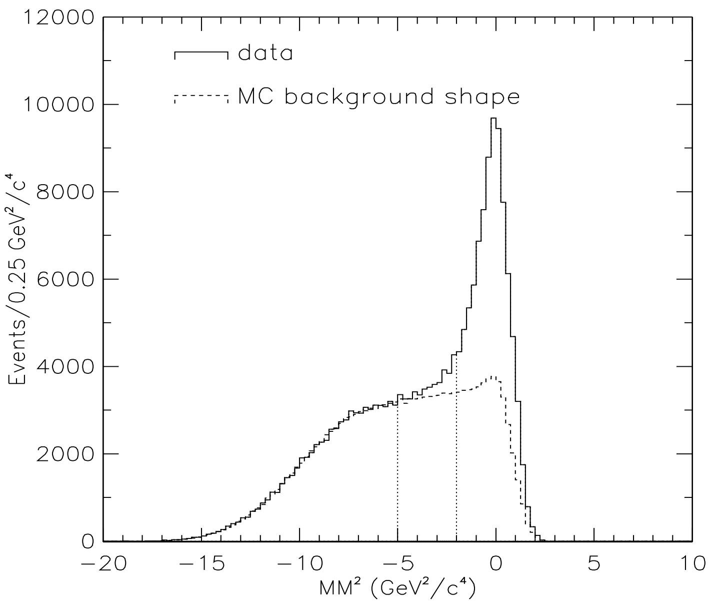

FIG. 1. MM^2 distribution for data with the Monte Carlo background shape fit in the sideband region. The sideband region ($MM^2 < -5\ GeV^2/c^4$) and signal region ($MM^2 > -2\ GeV^2/c^4$) are indicated by dotted lines.

the D^{*+} to come from D^{**} in $\overline{B} \to D^{**}\ell^-\bar{\nu}$ decays or from $\overline{B} \to (D^{*+}n\pi)_{non-resonant}\ell^-\bar{\nu}$ decays, and we also allow the lepton to come from τ in the decays $\overline{B} \to D^{*+}\tau^-\bar{\nu}$ or from $\overline{D}^{(*)}_{(s)}$ in the decays $\overline{B} \to D^{*+}\overline{D}^{(*)}_{(s)}X$. Whenever we refer to the partial reconstruction of $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$, the other signal modes are also implied. We use Monte Carlo to simulate background under MM^2 peak. The background under the peak is estimated by fitting the Monte Carlo background shape to the data distribution in the sideband region ($MM^2 < -5\ GeV^2/c^4$). After the background subtraction we simply count the number of events in the signal region, which is defined as $MM^2 > -2\ GeV^2/c^4$. In this way we extract the number of $\overline{B}^0 \to D^{*+}(X)\ell^-\bar{\nu}$ events in which $D^{*+} \to D^0\pi^+$ and therefore we obtain the number of $D^{*+} \to D^0\pi^+$ decays, N^{incl}, without reconstructing a particular D^0 decay mode. We find $N^{incl} = 44,504 \pm 360\,[stat]$. Because of the way the signal yield is extracted our analysis is not dependent on the accurate Monte Carlo prediction for contributions from poorly known (or not yet implemented in Monte Carlo) $\overline{B} \to D^{**}\ell^-\bar{\nu}$, $\overline{B} \to (D^{*+}n\pi)_{non-resonant}\ell^-\bar{\nu}$ and $\overline{B} \to D^{*+}\overline{D}X$ decays.

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 that gives $MM^2 > -2\ GeV^2/c^4$ we look for a $K^-\pi^+$ pair, assigning the kaon mass to the track of the opposite charge with respect to π_s and assigning the pion mass to the other track. We require $|M(K^-\pi^+) - M(D^0)| < 35\ MeV/c^2$ (Figure 2). We then combine the $K^-\pi^+$ pair with the π_s^+ and form a mass difference $M_{D^{*+}} - M_{D^0} \equiv M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$ (Figure 3). We use Monte Carlo to simulate background under $M_{D^{*+}} - M_{D^0}$ peak. To obtain the scaling factor for background subtraction in the $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$ distribution, we fit the Monte Carlo background shape to data in the sideband region, which is defined as $155\ MeV/c^2 < M(K^-\pi^+\pi_s^+) - M(K^-\pi^+) < 180\ MeV/c^2$ (Figure 3). After the background subtraction we count the number of events in

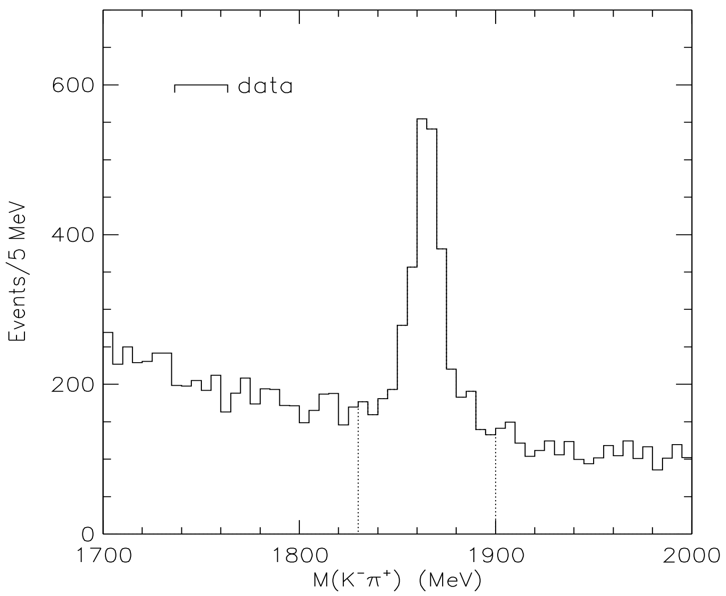

FIG. 2. $M(K^{-}\pi^{+})$ distribution for data. The signal region (1830 $MeV/c^2 < M(K^{-}\pi^{+}) <$1900 MeV/c^2) is indicated by the dotted lines.

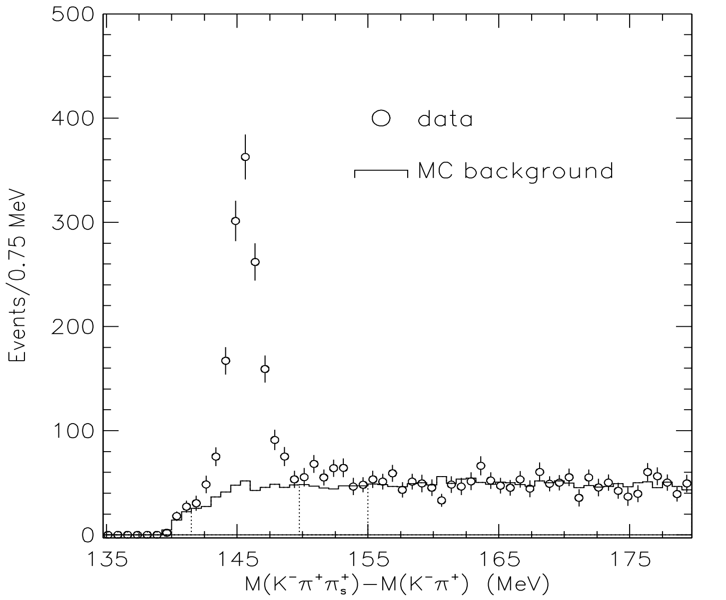

FIG. 3. $M(K^{-}\pi^{+}\pi_s^{+}) - M(K^{-}\pi^{+})$ distribution for data with the Monte Carlo background shape fit to data in the sideband region.
The sideband region (155 $MeV/c^2 < M(K^{-}\pi^{+}\pi_s^{+}) - M(K^{-}\pi^{+}) <$180 MeV/c^2) and signal region (141.5 $MeV/c^2 < M(K^{-}\pi^{+}\pi_s^{+}) - M(K^{-}\pi^{+}) < 149.75$ MeV/c^2) are indicated by the dotted lines.

the signal region, defined as 141.5 $MeV/c^2 < M(K^-\pi^+\pi_s^+) - M(K^-\pi^+) < 149.75\ MeV/c^2$. We find the number of decays $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$, denoted as N^{excl}, to be 1165 ± 45 $[stat]$.

To extract $Br(D^0 \to K^-\pi^+)$ we need to correct for the track reconstruction and acceptance efficiencies :

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

We obtain ϵ using a full Monte Carlo simulation of the CLEO II detector. To a good approximation the lepton and slow pion reconstruction efficiencies cancel out. Therefore ϵ includes only K^- and π^+ track selection efficiencies and acceptance efficiencies that correspond to the chosen signal regions for the $M(K^-\pi^+)$ and $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$ distributions. However, the cancellation of the lepton and slow pion reconstruction efficiencies is not exact because the average charged multiplicity of the 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 high multiplicity environment than in a low one. This effect changes ϵ by $\approx 3.7\%$ of itself. In order to take this effect into account, we select signal events from generic $B\overline{B}$ Monte Carlo and extract ϵ by equating the value of $Br(D^0 \to K^-\pi^+)$ obtained to the value of 3.91% which is input to the Monte Carlo:

$$Br(D^0 \to K^-\pi^+)_{MC} = \frac{N^{excl}_{MC}(M_{D^{*+}} - M_{D^0}\ peak)}{N^{incl}_{MC}(MM^2\ peak)} \cdot \frac{1}{\epsilon} \equiv 3.91\%. \tag{3}$$

We obtain $\epsilon = 68.6\%$. Note that in this procedure $N^{incl}_{MC}(MM^2\ peak)$ corresponds to the number of $D^{*+} \to D^0\pi^+$ events where D^0's are allowed to decay generically, not forced to decay into $K^-\pi^+$.

Using this value of ϵ together with Eqn. 2 we find

$$Br(D^0 \to K^-\pi^+) = (3.81 \pm 0.15 \pm 0.17)\%,$$

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

IV. SYSTEMATIC ERROR STUDY

The total systematic error was obtained by summing in quadrature the errors given in Table I. Some of the more important sources are discussed below.

We have used Monte Carlo to obtain the background shape under MM^2 and $M_{D^{*+}} - M_{D^0}$ peaks. To see how well the Monte Carlo can simulate the background shape for the MM^2 distribution we look at the distribution for the wrong-sign (i.e. same sign) $\ell - \pi_s$ pairs. We fit the Monte Carlo shape to data distribution in the sideband region ($MM^2 < -5\ GeV^2/c^4$), as we did for the right-sign $\ell - \pi_s$ pairs, and compare the Monte Carlo prediction with data in the signal region ($MM^2 > -2\ GeV^2/c^4$). We find excellent agreement within the statistical precision. 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, we performed a comprehensive study comparing the MM^2 distributions for the right-sign background and the wrong sign $\ell - \pi_s$ pairs. We found that the most dangerous source of background which peaks in the signal region of MM^2 distribution is the decay chain $\overline{B} \to D(X)\ell^-\bar{\nu}$, $D \to$ (something heavy) $+ \pi^+$, where the π^+ is moving slowly in the D rest frame, thus mimicking the pion from $D^{*+} \to D^0\pi_s^+$ decay. On the other hand these decays will not contribute to the $M_{D^{*+}} - M_{D^0}$ peak and can reduce the measured $D^0 \to K^-\pi^+$ branching fraction. In our Monte Carlo we identified three such modes: $D^+ \to \overline{K^{*0}}(892)\omega\pi^+$, $D^+ \to \overline{K^{*-}}\rho^+\pi^+$, and $D^+ \to \overline{K^{*0}}\rho^0\pi^+$. Only the branching fraction for the last mode has been experimentally measured. Energy release for these modes is typically 60 MeV, compared to 6 MeV for $D^{*+} \to D^0\pi_s^+$. To estimate the systematic error we exploit the difference in the MM^2 distribution shapes for this background and the signal (Figure 4). We fit the whole

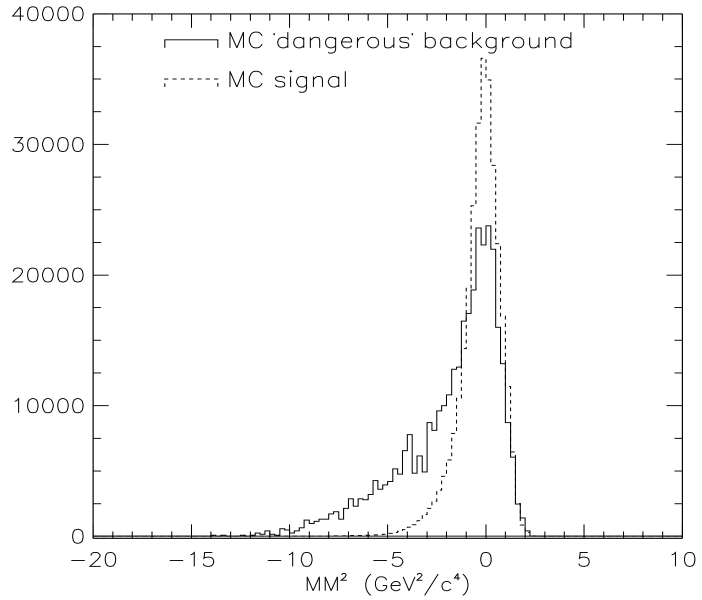

FIG. 4. The MM^2 distribution for Monte Carlo signal (dashed line) and the 'dangerous' background $\overline{B}^0 \to D^+(X)\ell^-\bar{\nu}$, $D^+ \to \overline{K^*}(\omega\, or\, \rho)\pi^+$ (solid line). The relative normalization is arbitrary.

MM^2 data distribution with three histograms obtained from Monte Carlo: signal + the contribution from $\overline{B} \to D^+(X)\ell^-\bar{\nu}$, $D^+ \to \overline{K^*}(\omega\ or\ \rho)\pi^+$ + the rest of background. The fit shows that the contribution from $\overline{B} \to D^+(X)\ell^-\bar{\nu}$, $D^+ \to \overline{K^*}(\omega\ or\ \rho)\pi^+$ should be enhanced by $(+124 \pm 217)\%$ of what is predicted by Monte Carlo. It is consistent with the hypothesis that nothing is wrong with the Monte Carlo prediction, but we should keep in mind that the decay modes we are considering here are poorly measured, and there could be other similar low Q-value decays that are not yet observed. In order to be conservative, in the Monte Carlo background shape we vary contribution from $\overline{B} \to D^+(X)\ell^-\bar{\nu}$, $D^+ \to \overline{K^*}(\omega\ or\ \rho)\pi^+$ by $\pm 220\%$ of itself and obtain $\pm 2.3\%$ variation in final result, which we take as the systematic error due to this background. This is the major single source of systematic uncertainty in the analysis.

The largest (but not the most dangerous) 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 muon, and we identify this muon as the slow pion. This background does not significantly bias the $Br(D^0 \to K^-\pi^+)$ measurement because it produces peaks in the signal regions of both the MM^2 *and* the $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$ distributions. We varied the

Monte Carlo prediction for this background by 30% of itself and assigned 0.3% error to the final result.

We will now discuss the systematics due to the background subtraction in the $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$ distribution. We have true $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$ decays where the D^{*+} does not come from a signal decay chain. The main source of this background is D^{*+}-ℓ^- pairs for which the D^{*+} comes from one $\overline{B}^0$, and the lepton is the primary lepton from another $\overline{B}^0$. This process occurs due to $B^0 - \overline{B}^0$ mixing. A less significant source is D^{*+}-ℓ^- pairs for which the D^{*+} comes from $\overline{B}^0$ or B^- and the lepton is a secondary lepton from the D from the other B^0 or B^+. This background is suppressed by the tight lepton momentum cut 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 25% of itself and assigned 0.7% error to the final result. The rest of the background in the $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$ distribution is simply combinatoric. To estimate the systematic error due to the Monte Carlo simulation of this background we substitute the combinatoric part of the Monte Carlo background shape by an analytic threshold function and obtain the 0.9% shift in the final result, which we take as the systematic error.

A careful study has been performed to estimate the systematic error due to our extraction of the reconstruction efficiency for K^- and π^+ tracks from Monte Carlo. We assign a 2% error to the final result (1% per track). As 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 extract N_{MC}^{incl}. As a systematic error we take 30% of the shift in the efficiency obtained using this method and the method actually employed in the analysis.

We have also studied possible systematic errors due to various cuts, our definitions of signal and sideband regions, fake leptons and continuum subtraction. The results are included in Table I.

Quantity	Possible source of systematic error	Systematic Error (% of final result)
N^{incl}	Background subtraction in MM^2 distribution	2.4%
	Slow pion momentum cut (affects MM^2 background shape)	1.0%
	Fitting and yield determination	0.6%
	Fake leptons	0.2%
	MC statistics	0.2%
N^{excl}	Background subtraction in $M(K\pi\pi_s) - M(K\pi)$ distribution	1.1%
	MC statistics	0.7%
	Fitting and yield determination	0.3%
	Continuum subtraction	0.1%
ϵ	Reconstruction efficiency for K^- and π^+ tracks	2.0%
	Choice of signal region in $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$ plot	1.6%
	MC statistics	1.3%
	Non-exact cancellation of ℓ and π_s reconstruction efficiencies	1.1%
	Choice of signal region in $M(K^-\pi^+)$ plot	0.9%
	Sum in quadrature	4.4%

TABLE I. Systematics summary table.

V. CONCLUSION

We have measured the absolute value of $Br(D^0 \to K^-\pi^+)$ using partial reconstruction of $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$. We find $Br(D^0 \to K^-\pi^+) = (3.81 \pm 0.15 \pm 0.17)\%$, where the first error is statistical and the second is systematic. Our result is consistent with recent ALEPH [3], CLEO [4], and ARGUS [5] measurements which utilize a different method and dominate the current world average value.

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