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Measurement of the Semileptonic Branching Fractions of the D^0 Meson

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Abstract

Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have measured the semileptonic branching ratios of the D^0 meson to be $Br(D^0 \to e^+\nu_e X) = (6.9 \pm 0.3 \pm 0.5)\,\%$ and $Br(D^0 \to \mu^+\nu_\mu X) = (6.0 \pm 0.7 \pm 1.2)\,\%$, and the semileptonic branching ratio of the charmed hadron mixture from e^+e^- annihilation around 10 GeV to be $Br(c \to e^+\nu_e X) = (9.6 \pm 0.4 \pm 1.1)\,\%$.

The semileptonic decays of heavy mesons are the clearest source of information about heavy quarks. The difference in D^0 and D^+ lifetimes is not quantitatively understood but is expected to be due to a difference in hadronic decays. To prove this conjecture accurate measurements of the semileptonic branching ratios of the D^0 and D^+ mesons are required. Only two Cabbibo-allowed exclusive semileptonic D^0 decays to electrons have been observed so far: $D^0 \to e^+\nu_e K^-$ and $D^0 \to e^+\nu_e K^{*-}$ [1] with branching ratios of $(3.80 \pm 0.22)\,\%$ and $(2.0 \pm 0.4)\,\%$, respectively [1]. A comparison of the sum of these branching ratios with the inclusive D^0 semileptonic branching ratio $Br(D^0 \to e^+\nu_e X)$ of $(7.7 \pm 1.2)\,\%$ [1] suggests that up to 25 % of the semileptonic D^0 decays proceed through higher resonance states. These decays have been searched for but were not found, the upper limits obtained being quite low (see Table 1) [1]. One possible reason for this discrepancy could be an overestimation of the inclusive semileptonic branching ratio which is dominated by a single measurement by MARK III of $(7.5 \pm 1.1 \pm 0.4)\,\%$

[1] References to a specific particle state imply also the charge-conjugate state.

Table 1: Upper limits on the branching ratios for semileptonic D^0 decays which could proceed through higher kaon resonances [1].

Experiment	D^0 decay mode	Branching ratio at 90 % CL
E653 [2]	$(\overline{K^*}\pi)^-\mu^+\nu_\mu$	$< 0.14\,\%$
E653 [2]	$K^-\pi^+\pi^-\mu^+\nu_\mu$	$< 0.12\,\%$
CLEO [3]	$\overline{K^{*0}}\pi^- e^+\nu_e$	$< 1.3\,\%$

[4]. Another measurement of this branching ratio would contribute much to the understanding of the discrepancy.

In this paper the semileptonic branching ratios of the D^0 meson and of the charmed hadron mixture from nonresonant e^+e^- annihilation around 10 GeV are measured. The total number of D^0 mesons produced in the $D^{*+} \to D^0\pi^+$ channel is determined using a partial reconstruction technique similar to the one used in our previous analysis [5]. The determination of the number of $D^{*+} \to D^0\pi^+$, $D^0 \to l^+\nu_l X$ decay chains and $c \to l^+\nu_l X$ decays requires in addition the presence of a lepton of appropriate charge and direction with respect to the pion in the event. Given the ratio of these numbers the semileptonic branching ratio of the D^0 meson and of the charmed hadron mixture can be calculated.

The data sample used for the analysis corresponds to an integrated luminosity of 355 pb^{-1} obtained with the ARGUS detector at the DORIS II storage ring while running on the $\Upsilon(4S)$ resonance and in the nearby continuum. The ARGUS detector is a 4π spectrometer described in detail elsewhere [6]. For the identification of charged hadrons the measured specific ionization in the main drift chamber and the measured time-of-flight were coherently combined into a likelihood ratio for each of the particle species π, K and p. A mass hypothesis was accepted if its likelihood ratio exceeded 1 %. For electrons also the energy deposition as well as the size and lateral spread of the associated cluster in the electromagnetic calorimeter was used in constructing the likelihood ratio. For muons, the quality of the match between the projected particle track and the associated hit in the muon chambers, located outside the magnet return yoke, was also used in forming the likelihood ratio. Electron and muon candidates were required to have a likelihood ratio > 0.7, to lie in a polar angle range satisfying $|\cos\Theta| < 0.9$, and to have an electron (muon) momentum greater than 0.4 GeV/c (1.4 GeV/c). Energy clusters in the calorimeter of more than 80 MeV were considered to be photons provided they were not associated with a charged track. K^0_S mesons were reconstructed from $\pi^+\ \pi^-$ pairs forming a secondary vertex [6].

Several cuts were applied to suppress QED background events and to reject electron candidates resulting from photon conversion or $\pi^0 \to e^+e^-\gamma$ decays. The total multiplicity $N_{tot} = N_{ch} + N_\gamma/2$ had to be greater than or equal to 6, where N_{ch} is the charged multiplicity and N_γ is the neutral multiplicity. This cut also

suppresses background contributions from τ pair events. Events in which all particle momenta were collinear, characteristic of QED processes, were removed from the sample using a cut on the thrust T [7] of the event, $T \leq 0.998$, calculated using both charged and neutral particles. e^+e^- pairs forming a secondary vertex or coming from the main vertex and having an invariant mass of less than 100 MeV/c^2 were considered to be converted photons and were excluded from the analysis.

D^{*+} mesons produced in the fragmentation of charmed quarks in the continuum process $e^+e^- \rightarrow c\overline{c}$ have a hard momentum spectrum and therefore their direction is close to the jet axis. The available energy in the $D^{*+} \rightarrow D^0\pi^+$ decay is only 6 MeV. Therefore the angle between the D^* flight direction, or jet axis, and the pion momentum vector is small. The jet axis was defined to be the thrust axis of the particles in the hemisphere opposite to the pion direction [5] in order to eliminate the influence of specific D^0 decay channels on its determination. The distribution of the angle Θ_π between the pion direction and the thrust axis was then studied. For the analysis we used pions in the momentum range $0.2 < p_\pi < 0.3\, GeV/c$. The upper bound is near the kinematic limit for pions from D^* decays. Pions with $p_\pi < 0.2\ GeV/c$ were excluded from the analysis in order to suppress the contribution from the decay chain $B \rightarrow D^{*+}X$, $D^{*+} \rightarrow \pi^+D^0$. The obtained $|\cos\Theta_\pi|$ distribution is shown in Figure 1. The peak at unity

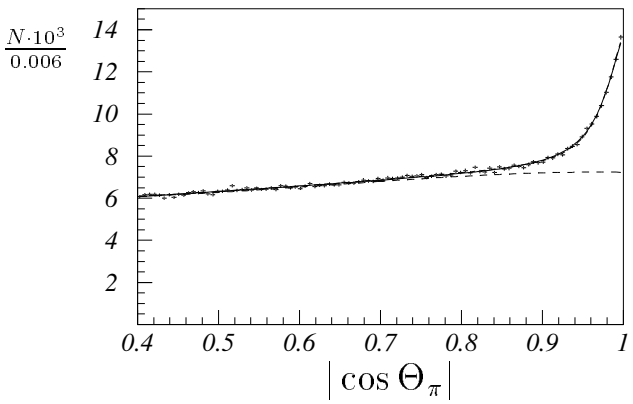

Figure 1: Distribution of $|\cos\Theta_\pi|$. The dashed line represents the background parametrization including the Σ_c contribution.

corresponds to $D^{*+} \to \pi^+ D^0$ decays. To extract the number of $D^{*+} \to D^0\pi^+$ decays the $|\cos\Theta_\pi|$ distribution was fitted with a third order inverse polynomial to parametrize the background and a signal term obtained from data using completely reconstructed D^{*+} mesons in the decay channel $D^{*+} \to D^0\pi^+$ followed by decays $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, or $\overline{K^0}\pi^+\pi^-$. This procedure is described in detail in [5]. Background contribution may come from the decays of the charmed particles, which in contrast to the particles produced in light quark fragmentation have a small opening angle with respect to the thrust direction. The energy release in such decays must be small enough in order to have a small angle between a daughter pion momentum and the direction of the decayed particle [5]. The only known decay which gives a considerable contribution and has a peak at $|\cos\Theta_\pi| = 1$ is $\Sigma_c \to \pi\Lambda_c$. The absolute value of this contribution was determined using our measurement of the Σ_c yield [8] and was fixed in the fit. The fit yielded $48500 \pm 640 \pm 374$ D^0 mesons from D^{*+} decays, where the systematic error is due to the uncertainty in the background shape and in the Σ_c contribution.

The number of D^{*+} mesons obtained in this analysis is smaller than in [5] because of the cut against converted photons used in the present analysis. Electrons from conversion have a very small angle with respect to the original photon direction, which for energetic photons ($p_\gamma > 1\ GeV$) is strongly correlated with the thrust direction. Since there is no reliable e-π separation in the momentum region from 0.2 to 0.3 GeV/c, these electrons from conversion give a fake peak in the $\cos\Theta_\pi$ distribution. The cut we apply against converted electrons suppresses this background and contributes negligibly to the systematic error. The efficiency of this cut for signal pions was found to be 97 % from Monte Carlo study. Thus, our published D^0 branching ratios [5] are underestimated by approximately 2.5 %.

To study semileptonic D^0 decays we analyzed the $|\cos\Theta_\pi|$ distributions from events having a lepton in the pion hemisphere ($\cos(\vec{p_l}, \vec{t}) \cdot \cos(\vec{p_\pi}, \vec{t}) > 0$, where the vector $\vec{t}$ denotes the thrust axis of all charged and neutral particles in the event). The distributions for like-sign ($l^+\pi^+$) and unlike-sign ($l^-\pi^+$) combinations are shown in Figure 2. The peaks at unity are mainly due to $D^{*+} \to \pi^+ D^0$ decays. However, there are two additional sources of background leptons peaking at $|\cos\Theta_\pi| = 1$. The first arises from events in which an electron from photon conversion or $\pi^0 \to \gamma e^+ e^-$ decay goes undetected and therefore disables

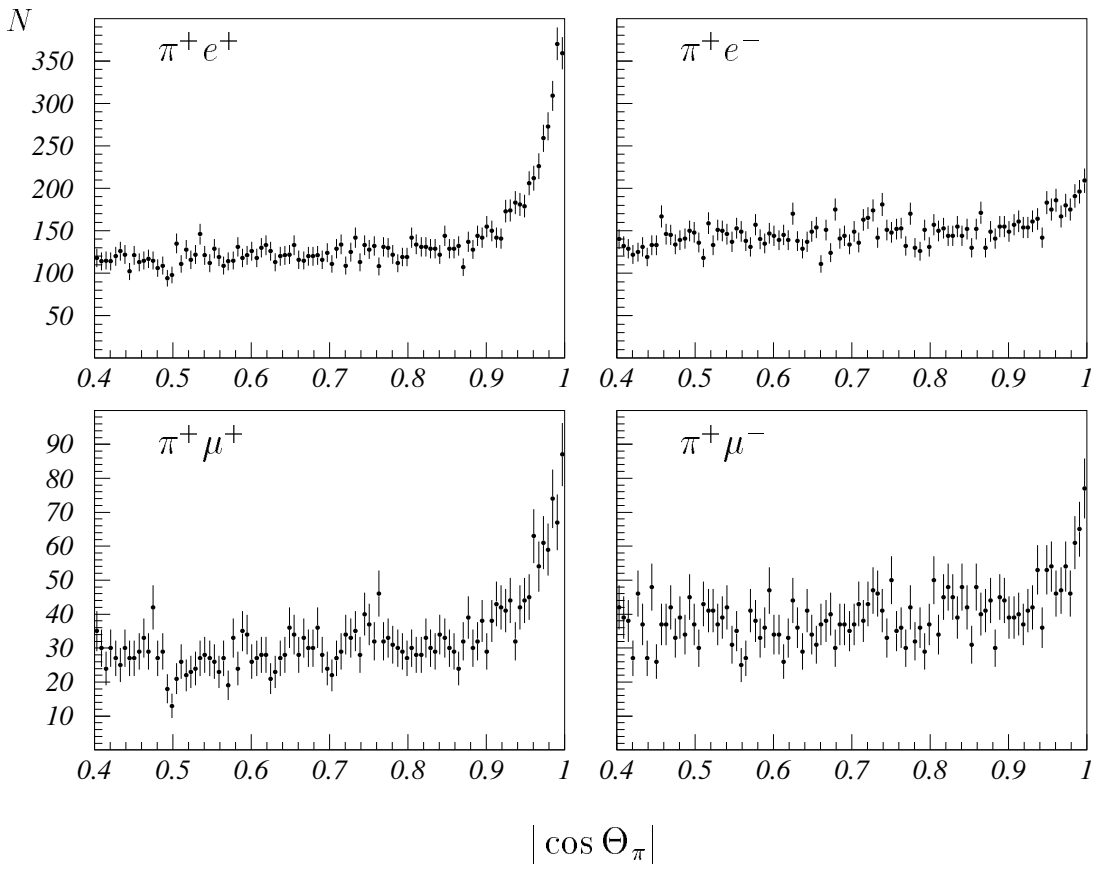

Figure 2: The $|\cos\Theta_\pi|$ distributions for events with a lepton in the pion hemisphere.

the anti-conversion cuts. The contribution from this background was estimated using a Monte Carlo simulation. The second source is hadron-lepton misidentification. To estimate its contribution the same distributions were obtained requiring hadrons instead of leptons and then multiplied by the rate of misidentifying hadrons as leptons which is $(0.5 \pm 0.1)\,\%$ [9] for electrons and $(1.7 \pm 0.4)\,\%$ for muons. The rate for misidentification of hadrons as muons was determined using a clean sample of pions and kaons from the $D^{*+} \to \pi^+ D^0$, $D^0 \to K^-\pi^+$ decay chain. A summary of background sources is given in Table 2. The $|\cos\Theta_\pi|$ distributions after bin by bin background subtraction are shown in Figure 3. There are peaks at $|\cos\Theta_\pi| = 1$ for like-sign combinations while the distributions are flat for unlike-sign combinations. According to the Monte Carlo simulation the

Table 2: Contributions of the backgrounds peaking at the signal region for events with a lepton in the pion hemisphere.

	$l^+\pi^+$	$l^-\pi^+$
hadrons misidentified as muons	127 ± 30	209 ± 48
hadrons misidentified as electrons	208 ± 42	270 ± 54
electrons from conversion	152 ± 22	198 ± 29

distribution shapes for $l^+\pi^-$ combinations well describe the background shapes for $l^+\pi^+$ combinations. The distributions for the like-sign combinations were fitted with a second order inverse polynomial with parameters fixed from the fit of the distributions for the unlike-sign combinations, except for the normalization, and the same signal term as in the inclusive analysis [5].

The fit yielded $1670 \pm 76 \pm 36$ ($310 \pm 35 \pm 51$) events for the electron (muon) sample. The uncertainty in the shape of the signal leads to a systematic error in the number of D^0 mesons of about 6 %. However, in the ratio of the number of D^0 mesons with and without subsequent D^0 semileptonic decay this uncertainty mainly cancels. In order to study the systematic error in this ratio, different signal parametrizations were used and the fit parameters of the signal function were varied within their errors. The resulting systematic errors for the D^0 semileptonic branching ratios are equal to 2 % for the $D^0 \to e^+\nu_e X$ channel and 3 % for the $D^0 \to \mu^+\nu_\mu X$ channel.

Fitting the $|\cos\Theta_\pi|$ distributions in bins of electron momentum we obtained the electron momentum spectrum for semileptonic D^0 decays. The efficiency corrected spectrum is shown in Figure 4. The solid line is the Monte Carlo prediction (normalized to the data) using the D^{*+} momentum spectrum from [10] and the BSW model [11] for the semileptonic D^0 decay. The Monte Carlo prediction describes the data reasonably well.

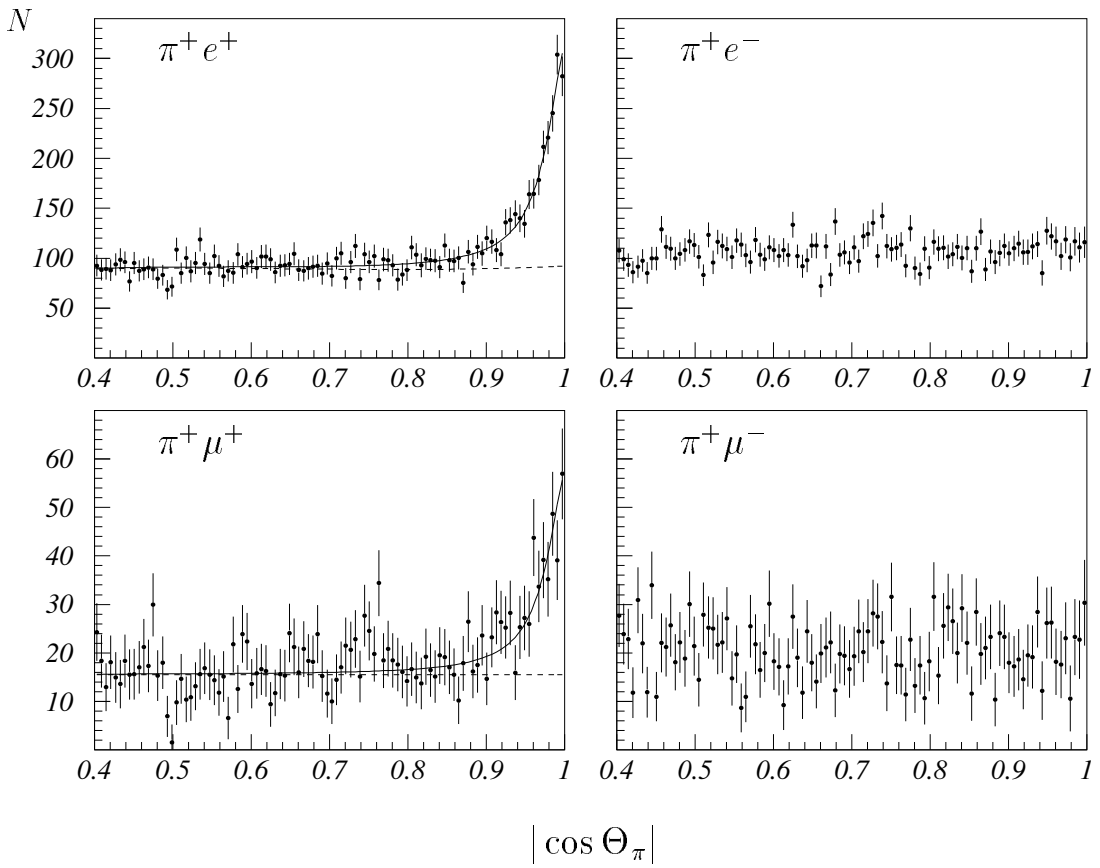

Figure 3: The $|\cos\Theta_\pi|$ distributions for events with a lepton in the pion hemisphere after background subtraction. Solid lines show the results of the fits described in the text. Dashed lines represent the background parametrizations of the fits.

A similar method can be used to determine the number of semileptonic decays of the second $\overline{c}$ quark in the hemisphere opposite to the pion from the D^{*+} decay. Thus we can calculate the inclusive semileptonic branching ratio of the mixture of charmed particles produced in e^+e^- annihilation around 10 GeV. We investigated the $|\cos\Theta_\pi|$ distributions from events having an electron in the hemisphere opposite to the pion ($\cos(\vec{p_e},\vec{t}) \cdot \cos(\vec{p_\pi},\vec{t}) < 0$). The sources of background for both like-sign and unlike-sign combinations of electron and pion are again hadron-electron misidentification and electrons from conversion. The study of the background contribution to the signal region is similar to the

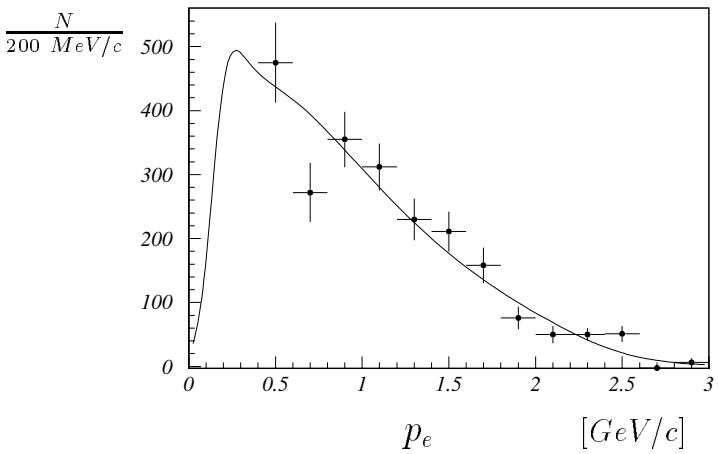

Figure 4: The efficiency corrected electron momentum spectrum for semileptonic D^0 decays. The solid line is a Monte Carlo prediction normalized to the data.

one for semileptonic D^0 decays. A summary of background sources is given in Table 3. The $|\cos\Theta_\pi|$ distributions after bin by bin background subtraction are

Table 3: Contributions of the backgrounds peaking in the signal region for events with an electron in the hemisphere opposite to the pion.

	$e^+\pi^+$	$e^-\pi^+$
hadrons misidentified as electrons	258 ± 51	313 ± 63
electrons from conversion	141 ± 20	181 ± 26

shown in Figure 5. The peak in the distribution for unlike-sign combinations is due to $\overline{c} \to e^-\overline{\nu_e}X$ decays. The shape of this peak differs from the shape of the peak for semileptonic D^0 decays since the requirement of an electron in the hemisphere used for the thrust calculation implies the presence of a neutrino distorting the thrust direction. Therefore the shape of the peak, parametrized

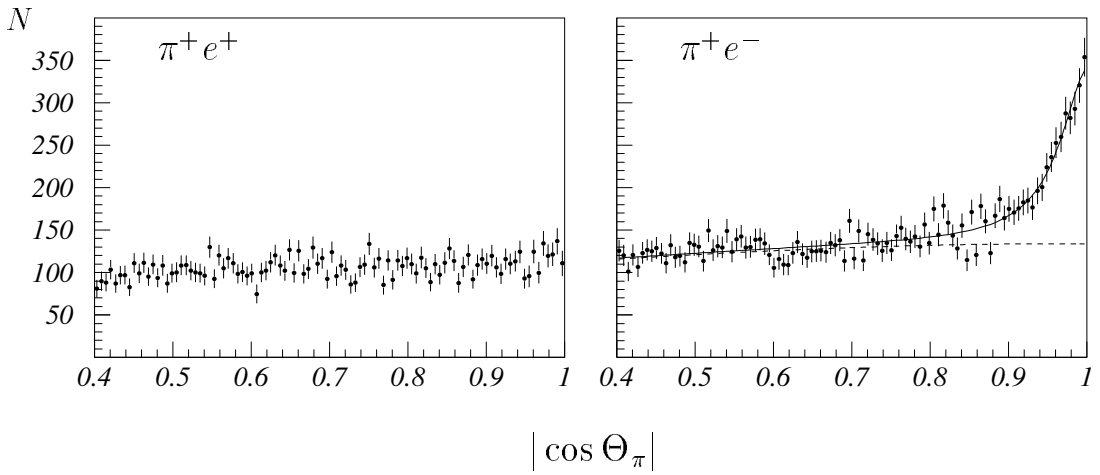

Figure 5: The $|\cos\Theta_\pi|$ distributions for events with an electron in the hemisphere opposite to the pion after background subtraction. The solid line shows the result of the fit described in the text. The dashed line represents the background parametrization.

by a third order inverse polynomial, was left unfixed in the fit. The background shape was fixed using the $|\cos\Theta_\pi|$ distribution for like-sign combinations. Monte Carlo simulation confirms that the background shapes are the same for like-sign and unlike-sign combinations. The fit yielded $2207 \pm 93 \pm 155$ $\overline{c} \to e^-\overline{\nu_e}X$ decays. Since the shape of the signal term is determined from the fit there is a large correlation between the numbers of signal and background events, and this is the main source of error in the number of semileptonic charm decays. An error of 6 % in the number of $D^{*+} \to D^0\pi^+$ decays due to the uncertainty in the $D^{*+} \to \pi^+D^0$ signal shape [5] is also included in the systematic error of the branching ratio.

The efficiency for lepton reconstruction and identification and the extrapolation of the lepton momentum spectra below the experimental cut were determined using Monte Carlo. The detector response for leptons was obtained in bins of lepton momentum using a full detector simulation. For the $D^{*+} \to D^0\pi^+$, $D^0 \to l^+\nu_l X$ decay chain D^{*+} mesons were generated according to the momentum distribution previously obtained by ARGUS [10]. The pion momentum was required to be $0.2 < p_\pi < 0.3\ GeV/c$ as in the data analysis. For the $c \to e^+\nu_e X$ study a

mixture of D^0, D^+, and D_s mesons was generated with meson momentum spectra according to [10] and [12]. The BSW [11] and IGSW [13] models were used for the semileptonic decay description. The ratio of the exclusive decays $D^0 \to K^- l^+ \nu_l$ and $D^0 \to K^{*-} l^+ \nu_l$ was fixed from [1] and varied within errors. The influence of the K^* polarization on the shape of the lepton momentum spectra was studied by varying the parameters in the BSW [11] model. The derived uncertainties were included in the systematic error. The lepton momentum spectra were convoluted with the detector response. The resulting efficiencies were found to be 0.496 ± 0.036 (0.107 ± 0.011) for electrons (muons) for $D^0 \to l^+ \nu_l X$ decays and 0.474 ± 0.030 for $\overline{c} \to e^- \overline{\nu_e} X$ decays. The systematic errors are mainly due to the efficiency of lepton reconstruction and identification, and the model uncertainty in the shape of the lepton spectra.

Combining the number of $D^{*+} \to D^0 \pi^+$ decays with the number of $D^{*+} \to D^0 \pi^+$, $D^0 \to l \nu_l X$ decay chains and the number of $\overline{c} \to e^- \overline{\nu_e} X$ decays we obtain $Br(D^0 \to e^+ \nu_e X) = (6.9 \pm 0.3 \pm 0.5)\,\%$, $Br(D^0 \to \mu^+ \nu_\mu X) = (6.0 \pm 0.7 \pm 1.2)\,\%$, and $Br(c \to e^+ \nu_e X) = (9.6 \pm 0.4 \pm 1.1)\,\%$.

Our results for the D^0 semileptonic branching ratios are in better agreement with the sum of the exclusive semileptonic D^0 branching ratios than the previous measurement [4]. The ratio of the semileptonic branching ratios of D^+ and D^0 mesons $Br(D^+ \to e^+ \nu_e X)/Br(D^0 \to e^+ \nu_e X) = 2.49 \pm 0.35$ derived from our result and the PDG value of $Br(D^+ \to e^+ \nu_e X)$ [1] is in good agreement with the ratio of the well measured D^+ and D^0 lifetimes of 2.547 ± 0.051 [1]. The semileptonic branching ratio of the charmed hadron mixture agrees well with the previous ARGUS measurement of $Br(c \to e^+ \nu_e X) = (9.8 \pm 0.9 \pm^{0.6}_{0.5})\,\%$ [14].

In summary, we have measured the D^0 semileptonic branching ratios, $Br(D^0 \to e^+ \nu_e X) = (6.9 \pm 0.3 \pm 0.5)\,\%$ and $Br(D^0 \to \mu^+ \nu_\mu X) = (6.0 \pm 0.7 \pm 1.2)\,\%$, and the semileptonic branching ratio of the charmed hadron mixture from e^+e^- annihilation around 10 GeV, $Br(c \to e^+ \nu_e X) = (9.6 \pm 0.4 \pm 1.1)\,\%$, by tagging $D^{*+} \to D^0 \pi^-$ decays through the excess over background of low momentum pions correlated with the thrust direction. Our results for the D^0 semileptonic branching ratios are smaller than the world average values [1] though within 1 (electron channel) and 1.5 (muon channel) standard deviations.

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