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E687

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Studies of the decay $D^0 \to K^- \mu^+ \nu_\mu$ are reported by Fermilab photoproduction experiment E687. The ratio $BR(D^0 \to K^- \mu^+ \nu_\mu)/BR(D^0 \to K^- \pi^+)$ is determined to be 0.852 ± 0.034 (statistical) $\pm\, 0.028$ (systematic). Using this result and an isospin argument we infer the ratio $BR(D^0 \to K^{*-} \mu^+ \nu_\mu)/BR(D^0 \to K^- \mu^+ \nu_\mu) = 0.62 \pm 0.07 \pm 0.09$. The pole mass from the single pole form factor is measured to be $M_{pole} = 1.87^{+0.11+0.07}_{-0.08-0.06}\, GeV/c^2$. Using M_{pole} and $BR(D^0 \to K^- \mu^+ \nu_\mu)/BR(D^0 \to K^- \pi^+)$, we calculate $|f_+(0)| = 0.71 \pm 0.03 \pm 0.03$. We also measure the ratio $f_-(0)/f_+(0) = -1.3^{+3.6}_{-3.4} \pm 0.6$.

The pseudoscalar to pseudoscalar meson semileptonic decay process is the easiest semileptonic decay process to understand. The expression for the matrix element separates into a well understood weak current and a less understood strong current which is constructed of two form factors. These form factors depend on the invariant mass of the virtual W exchanged during the decay. In most formalisms one form factor (f_+) dominates as the other (f_-) is suppressed by the mass of lepton in the final state. We parameterize[1] the form factors ($f_\pm$) for the decay $D^0 \to K^- \mu^+ \nu_\mu$ with a simple[2] pole form[1]:

$$f_\pm(q^2) = f_\pm(0)/(1 - q^2/M_{pole}^2), \quad q^2 = (P_D - P_{kaon})^2 = M_{W-virtual}^2.$$

Experimentally, we determine the yield of $D^0 \to K^- \mu^+ \nu_\mu$ events and the distribution of these events with respect to q^2 and E_μ ($E_\mu = P_D \cdot P_\mu / M_D$). Hence, we are able to measure the pole mass (M_{pole}) and the ratio of form factors ($f_-(0)/f_+(0)$) and, from our measurement of the yield, to calculate the decay rate and $f_+(0)$.

In this paper we report on the analysis of 1897 ± 62 events in the decay mode $D^0 \to K^- \mu^+ \nu_\mu$. The data were collected in the photoproduction experiment E687, conducted in the Fermilab Wide-band Photon beam during the 1990 and 1991 fixed–target runs. The E687 detector is described elsewhere[3, 4].

Potential events containing charm semileptonic decays are selected by requiring evidence of detached vertices in the event. Specifically, tracks reconstructed in both the microvertex detector and the multiwire proportional chambers are used to find all two–track vertices in an event. If any two of these vertices are separated by more than 4.5 standard deviations in the z, or beam, direction, the event is retained.

The $D^0 \to K^- \mu^+ \nu_\mu$ candidates are selected by first choosing a track that the Čerenkov system identifies as either a definite kaon or a kaon/proton ambiguous particle. This kaon is combined with

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[1] Informational notes on both kaon and D meson semileptonic decays and analyses can be found in reference [2]. Note that when we extend the vector propagator scheme used for kaon decays, M_{pole} is expected to be $M_{D_s^{*+}}$ and that we have assumed, via time reversal invariance, that the ratio f_-/f_+ is real.

[2] Over the q^2 range that we measure, the pole dominance form factor adequately describes our data.

an oppositely charged track that the muon system identifies as a muon[3] and that the Čerenkov system identifies as a pion/electron ambiguous particle. The kaon and muon tracks must form a (secondary) vertex with a confidence level of 5% or better. The remaining tracks in the event are used to construct a set of candidate primary vertices with confidence level greater than 1%. The highest multiplicity primary vertex candidate with the highest separation from the secondary vertex, in units of error (l/σ_l), of 4.5 or greater is retained.

To reduce backgrounds from secondary vertices containing more than two tracks, a fit is performed that uses microvertex tracks not already assigned to either the primary or the secondary vertex. We require the highest confidence level that any of these unassigned tracks is consistent with the secondary vertex to be $< 1\%$.

To reduce contamination from $D^0 \to K^-\pi^+$ the $K\mu$ invariant mass is required to be less than 1.855 GeV/c^2. To reduce backgrounds from muon misidentification and higher multiplicity D decay states containing a muon, we demand that the $K\mu$ invariant mass be larger than 0.95 GeV/c^2, the $K\mu$ momentum be greater than 35 GeV/c and the muon momentum be greater than 15 GeV/c.

To estimate the D^0 momentum, following references [5, 6], we assume the D^0 travels from the primary vertex to the secondary vertex; we then boost the Kμ candidate to a reference frame where the total visible momentum ($\vec{P}_\mu + \vec{P}_{kaon}$) is transverse to the reconstructed D^0 direction ($\hat{l}$), i.e. $(\vec{P}_\mu + \vec{P}_{kaon}) \cdot \hat{l} = 0$, and determine the amount of momentum parallel to the D^0 carried by the missing neutrino.

Due to resolution, $\sim 40\%$ of the $D^0 \to K^-\mu^+\nu_\mu$ events are reconstructed outside physical limits. We recover $\sim 80\%$ of these events without significantly degrading the resolution in q^2 by requiring that in the boosted frame $E_\nu > 0$ and $(\vec{P}_\nu \cdot \hat{l})^2 = (E_\nu^2 - P_{K\mu}^2) > -0.7 \ \ (GeV/c^2)^2$; for those events with $-0.7 < (E_\nu^2 - P_{K\mu}^2) < 0$ we set $(E_\nu^2 - P_{K\mu}^2) = 0$.

We compute $(\vec{P}_\nu \cdot \hat{l}) = \pm\sqrt{E_\nu^2 - P_{K\mu}^2} = \pm\vec{P}_D$, and both solutions are boosted to the lab frame to estimate the D^0 momentum. We choose the lower D^0 momentum solution ($-\vec{P}_D$ in the boosted

[3]Approximately 1.0% of all pions or kaons are identified as muons due to either pattern recognition failures, the decay of the pion, or the decay of the kaon. This probability, which depends on the momentum of the incident particle and the transverse track position of the particle determined at the front of the muon system, is measured using high statistics ϕ and K_s^0 decays.

frame) since it has the best E_k (or q^2) resolution in the region of highest M_{pole} sensitivity[4] and use the higher D^0 momentum solution as a check. When the two D^0 momentum solutions are the same, such as when $-0.7 < (E_\nu^2 - P_{K\mu}^2) < 0$, the solution is considered to be both a high D^0 momentum solution and a low D^0 momentum solution.

Because of the undetected neutrino, we cannot fully reconstruct the D^0 invariant mass. Therefore, we have contamination from other partially reconstructed charm decays which include a kaon and a particle misidentified as a muon. We determine both the overall level (roughly 20%) and kinematic shape of this background directly from our data by selecting events which satisfy the same vertex and kinematic cuts used for $K\mu$ candidates but fail the muon identification cut. Combinations that end up in this final sample are then weighted based on the probability that this non–muon candidate is misidentified as a muon.

There is also contamination from charm semileptonic decays where (expressions in parentheses are given as examples) there is a missing neutral ($D^0 \rightarrow K^{*-}(K^{*-} \rightarrow K^-\pi^0)\mu^+\nu_\mu$); we fail to reconstruct a charged particle ($D^+ \rightarrow \overline{K}^{*0}(\overline{K}^{*0} \rightarrow K^-\pi^+)\mu^+\nu_\mu$); a charged particle is misidentified by the Čerenkov algorithm ($D^0 \rightarrow \pi^-\mu^+\nu_\mu$); there is a missing neutral and a charged particle misidentified by the Čerenkov algorithm ($D^0 \rightarrow K^{*-}(K^{*-} \rightarrow \overline{K}^0\pi^-)\mu^+\nu_\mu$); or the muon from a semileptonic decay forms a vertex with a charged particle from either the primary interaction or the other charmed particle produced in the event.

We determine this semileptonic contamination by using the actual number of events reconstructed from the data in a particular mode, branching ratios and reconstruction efficiencies for the decays (quantities in parentheses are the contribution to the final signal) $D^0 \rightarrow K^{*-}\mu^+\nu_\mu$ ($\sim$ 8%), $D^+ \rightarrow \overline{K}^{*0}\mu^+\nu_\mu$ ($\sim$ 7%) and $D_s^+ \rightarrow \phi\mu^+\nu_\mu$ ($\sim$ 1%). The remainder of the background which is primarily due to Cabibbo suppressed, Čerenkov misidentified semileptonic decays and events where the muon and the kaon do not originate from the same decay vertex is simulated using events from the data where the K and the μ have the same charge. We find that this same sign background is approximately 2% of the signal as determined from the fit (explained below).

In order to include the effects of q^2 and E_μ smearing in the fitted intensity and to avoid

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[4]Our criteria for choice of solution is supported by our finding that the systematic error is almost a factor of 2 larger for the M_{pole} measurement which uses the high D momentum solution.

parameterizing the distributions of background events, we fit the data with a binned variant of the method first employed by E691[7, 8]. We form a histogram in bins of q^2 and E_μ and construct a likelihood function,

$$\mathcal{L} = \prod_{i}^{\text{bins}} \frac{n_i^{s_i} e^{-n_i}}{s_i!} \prod_{k}^{C's} e^{-0.5\left((C_k - C_k^0)/\sigma_{C_k^0}\right)^2}$$

where

$$s_i = \text{number of events in bin}_i$$

and

$$\begin{aligned} n_i =& \mathrm{Y} \times \Big(\frac{(D^0 \to K^- \mu^+ \nu_\mu)_i}{(D^0 \to K^- \mu^+ \nu_\mu)_{tot}} + C_1 \times \frac{(D^0 \to K^{*-} \mu^+ \nu_\mu)_i}{(D^0 \to K^- \mu^+ \nu_\mu)_{tot}} + \\ & C_1 C_2 \left(\frac{\tau_{D^+}}{\tau_{D^0}}\right) \times \frac{(D^+ \to \overline{K}^{*0} \mu^+ \nu_\mu)_i}{(D^0 \to K^- \mu^+ \nu_\mu)_{tot}} + C_1 C_2 \left(\frac{\tau_{D^+}}{\tau_{D^0}}\right) C_3 \times \frac{(D_s^+ \to \phi \mu^+ \nu_\mu)_i}{(D^0 \to K^- \mu^+ \nu_\mu)_{tot}} \Big) \\ & + C_4 \times (\text{muon misidentification})_i \\ & + \mathrm{B} \times (\text{background (from same sign data)})_i . \end{aligned}$$

The quantities in parentheses with subscript i represent the number of simulated events reconstructed[5] in bin_i for the $(D \to X)$'s and the normalized shapes from data for the representations of misidentification and additional backgrounds. The C_k's fit parameters represent the ratio[6] of vector to pseudoscalar decays $\left(\frac{D^0 \to K^{*-} \mu^+ \nu_\mu}{D^0 \to K^- \mu^+ \nu_\mu}\right)$ (C_1), the production[7] of D^+ relative to D^0 (C_2), the production[8] of $D_s^+ \to \phi \mu^+ \nu_\mu$ relative to $D^+ \to \overline{K}^{*0} \mu^+ \nu_\mu$ (C_3) and the total number of events

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[5]The same number of events are generated for each sample and reconstructed in the same way as the data. Proper reductions, such as those due to isospin considerations, are accounted for.

[6]We average the results from references[9, 6, 10] to find $C_1^0 = 0.60$ and $\sigma_{C_1^0} = \pm 0.06$

[7]We estimate a D^+/D^0 production ratio with our 1988 data of $C_2^0 = 0.42$ and $\sigma_{C_2^0} = \pm 0.05$[11]. We also use the isospin argument $\Gamma(D^+ \to \overline{K}^{*0} \mu^+ \nu) = \Gamma(D^0 \to K^{*-} \mu^+ \nu)$ in calculating the expected number of $D^+ \to \overline{K}^{*0} \mu^+ \nu_\mu$ decays.

[8]We estimate a $D_s^+ \to \phi(\phi \to K^+ K^-) \mu^+ \nu_\mu / D^+ \to \overline{K}^{*0} (\overline{K}^{*0} \to K^- \pi^+) \mu^+ \nu_\mu$ production ratio of $C_3^0 = 0.11$ and $\sigma_{C_3^0} = \pm 0.03$ using the efficiency corrected and background subtracted yield ratio for $D_s^+ \to \phi(\phi \to K^+ K^-) \mu^+ \nu_\mu$ and $D^+ \to \overline{K}^{*0} (\overline{K}^{*0} \to K^- \pi^+) \mu^+ \nu_\mu$ decays observed[4, 12, 13] in E687.

expected from muon misidentification (C_4). Our likelihood expression ties each C_k fit parameter to its previously estimated value (C_k^0) within each C_k^0's combined, in quadrature, statistical and systematic error ($\sigma_{C_k^0}$). In this way the fit error is a natural combination of the data statistics and the inherent variation present in the C_k^0 fit parameters. The quantity $(D^0 \to K^-\mu^+\nu_\mu)_{tot}$ represents the summation of $(D^0 \to K^-\mu^+\nu_\mu)_i$ and is the total number of $D^0 \to K^-\mu^+\nu_\mu$ events reconstructed from the simulation. We use our measured lifetimes[14] for the D^0 (τ_{D^0}) and the D^+ (τ_{D^+}). The $D^0 \to K^-\mu^+\nu_\mu$ yield (Y), background level (B), pole mass (M_{pole}) and all the C_k's are allowed to vary freely in the fit. Due to the level of the background present, including $f_-(0)/f_+(0)$ as a fit parameter introduces large correlations between the fit parameters and increases the level of systematic error in the final results. We choose to set $f_-(0)/f_+(0) = 0$ for the fit to the number of events and the pole mass, which we use to calculate the relative branching ratios, $f_+(0)$ and the decay rate. A separate fit of $f_-(0)/f_+(0)$ using a cleaner data sample is described later in the text.

During the fitting process, the shape of the $D^0 \to K^-\mu^+\nu_\mu$ signal reconstructed from the simulation changes, and there is a slight ($\sim 0.5\%$) correction to the number of $D^0 \to K^-\mu^+\nu_\mu$ events reconstructed from the simulation. These changes come from varying M_{pole} in the expression for the rate. In order to compute the predicted number of events falling in each bin of reconstructed (q^2, E_μ) for the decay $D^0 \to K^-\mu^+\nu_\mu$, we begin with a Monte Carlo generated with a nominal pole mass of 2.11 GeV/c^2. The predicted population for each reconstructed bin is then obtained by summing the weights for events falling in the bin where the weight is given by the ratio of the intensity function[9] with the new pole mass over the original intensity.

Due to a change in the muon system[10] between the 1990 and 1991 runs, we analyze the 1990 and 1991 runs separately. The C_k's representing the ratio of vector to pseudoscalar decays, the production of D^0 relative to D^+ and the production of $D_s^+ \to \phi(\phi \to K^+K^-)\mu^+\nu_\mu$ relative to $D^+ \to \overline{K}^{*0}(\overline{K}^{*0} \to K^-\pi^+)\mu^+\nu_\mu$ are shared in the simultaneous fit of both data sets, while the other parameters, C_4, Y, B and M_{pole}, are represented for each run separately.

From this fit we obtain a pole mass of $1.87^{+0.11\ (fit)+0.07\ (systematic)}_{-0.08\ (fit)-0.06\ (systematic)}$ GeV/c^2 averaged over

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[9]The (normalized) intensity for a given event is calculated using $\frac{d\Gamma(q^2,E_\mu)}{dq^2 dE_\mu}$ and the given pole mass.

[10]Counters were removed to accommodate another experiment. This change reduced muon identification efficiency by $\sim 40\%$.

both runs. We obtain 797 ± 38 $D^0 \to K^- \mu^+ \nu_\mu$ events for 1990 data with a fitted pole mass of $1.96^{+0.25}_{-0.15}$ GeV/c^2; while in 1991 we obtain 1100 ± 49 $D^0 \to K^- \mu^+ \nu_\mu$ events with a fitted pole mass of $1.82^{+0.13}_{-0.09}$ GeV/c^2.

In Figures 1a–d we show the distributions from the data used in the fit. Both 1990 and 1991 signals are shown with the fit overlaid as a dashed line and the estimated background contribution to the signal overlaid as a hatched area. The plots shown are projections of the 2–dimensional histogram for the quantities q^2 and E_μ.

The $K^- \pi^+$ signal used for the branching ratio normalization is isolated using the same initial selection requirements, vertexing scheme and acceptance cuts with one exception. Due to the constraints already imposed on the $K^- \pi^+$ total momentum, the intrinsic momentum selection present in the Čerenkov requirement for the pion and the fact that $D^0 \to K^- \pi^+$ is a 2–body decay, we find that signal to noise is increased significantly when we exclude $K^- \pi^+$ events that have a kaon with momentum less than 10 GeV/c.

The resulting signal is shown in Figure 2. We find 1720 ± 58 events for 1990 data and 3822 ± 86 events for 1991 data.

Combining the results of the $K^- \mu^+$ and the $K^- \pi^+$ data analyses and using the efficiencies for each mode (from our simulation and fit), we determine:

$$\frac{BR(D^0 \to K^- \mu^+ \nu_\mu)}{BR(D^0 \to K^- \pi^+)} = 0.852 \pm 0.034\ (fit) \pm 0.028\ (systematic).$$

The systematic error in these analyses can come from uncertainty in known quantities which cannot be included in the fit as parameters (C_k), unanticipated variations between the data and the simulation, variations due to the fit, and the analysis technique.

There is systematic error due to the uncertainty in the parameters of the matrix element used to generate the $D \to \overline{K}^* \mu \nu$ background contributions, the theoretical variation in $f_-(0)/f_+(0)$ estimates, and uncertainty in the simulation of the muon system. To estimate the contributions from the muon efficiency and the parameters used in the vector matrix element, we vary each of these quantities separately by their 1σ uncertainties and refit the signal. The uncertainty from the $f_-(0)/f_+(0)$ estimates is determined by refitting[11] the signal with $f_-(0)/f_+(0) = -1$. The difference

[11] Our intention is to roughly cover the range of theoretical values from references [20–27] as well as provide a measurement that assumes no $f_-(0)/f_+(0)$ value.

between the returned result and the original result is then the estimate of the systematic error due to the quantity varied. We add these three separate uncertainties in quadrature to determine a systematic error of ± 0.025 for the relative branching ratio and $\pm 0.01\ GeV/c^2$ for the pole mass due to these additional sources. Note that we have assumed that these additional sources of error are uncorrelated.

To investigate quantitative variations between the data and the simulation we divide the data that survived our full selection process into subsamples based on the momenta of the decay products, the cuts used to improve the signal quality and an additional check on higher multiplicity contamination. For each physical quantity varied, the data is split into four roughly equivalent statistically separate samples using the following criteria: 1990 signal, 1991 signal, the signal below the cut used to split the data and the signal above the cut used to split the data.

There are 6 physical quantities varied to check statistical consistency: l/σ_l, $M(K\mu)$, confidence level of the fit to the $K\mu$ vertex, momentum of the kaon, momentum of the muon (or pion) and a more stringent exclusion cut[12]. The tighter exclusion cut serves as a further check on any higher multiplicity states contaminating the signal as well. In addition, we check the relative branching ratio measurement using the other (high) D momentum solution since our *a priori* bias is to maximize the precision of our M_{pole} measurement.

We find no evidence for additional variations beyond the statistical variations already returned by the fit and the variation assessed due to uncertainty in the parameters of the matrix element used to generate the $D \rightarrow \overline{K}^{*} \mu\nu$ background contributions, our choice of $f_-(0)/f_+(0)$, and the uncertainty in the simulation of the muon system.

To determine the variation due to the fit we compute a sample variance using the high D momentum and low D momentum solutions, the results from a separate analysis (explained shortly) and the average result from each of the 6 separate tests described previously. We find an additional error of

$$\sigma_{fit}\left(\frac{BR(D^0 \rightarrow K^-\mu^+\nu_\mu)}{BR(D^0 \rightarrow K^-\pi^+)}\right) = \pm 0.013 \text{ and } \sigma_{fit}(M_{pole}) =^{+0.07}_{-0.05}\ GeV/c^2$$

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[12]We take *all* microvertex tracks not in the $K\mu$ vertex, even tracks assigned to the primary vertex, and determine the highest confidence level that any of these tracks are consistent with being in the $K\mu$ vertex.

for the results using this test.

As a check on the analysis technique which we include in the sample variance estimate, we analyze the data for the case where the D^0 is consistent with the hypothesis that it was produced from a D^{*+} ($D^{*+} \to D^0\pi^+$). This analysis process is similar to the previous analysis but with some notable differences.

We relax several cuts in the D^{*+} analysis since the signal to noise in this analysis is higher. Using the two D momenta solutions and the momenta measured for the soft pion, we arbitrate our initial candidate choice on the basis of the reconstructed D^{*+} mass. This allows us to choose the one candidate per event that has the lowest $D^{*+} - D^0$ mass solution.

After we choose our sample, we boost each event to the $K\mu$ center of mass frame where the neutrino and the D momentum are equal and form a cone of possible directions about the soft pion. By comparing solutions for the D momentum on the cone to the decay direction measured with the primary and secondary vertices, we choose the solution most consistent with our measured decay direction and eliminate events inconsistent with the D^{*+} hypothesis. Thus, we eliminate the need to choose a D momentum solution, and the returned D momentum is always physical. Additionally, there is a small reduction in background and a marginal improvement in resolution.

To measure the yield and pole mass it is sufficient to measure only the q^2 distribution because discrimination from other background is not as important for the D^{*+} analysis (see Figure 3). From this fit we obtain a pole mass of $2.01^{+0.32}_{-0.18}\ GeV/c^2$ averaged over both runs. For 1990 data we find 195 ± 16 events for the $K^-\mu^+$ analysis, 446 ± 21 events for the $K^-\pi^+$ analysis and a pole mass of $2.09^{+0.66}_{-0.29}\ GeV/c^2$. For 1991 data we find 232 ± 22 events for the $K^-\mu^+$ analysis, 972 ± 34 events for the $K^-\pi^+$ analysis and a pole mass of $1.97^{+0.43}_{-0.22}\ GeV/c^2$. Combining the $K^-\mu^+$ and $K^-\pi^+$ analyses we determine:

$$\left(\frac{BR(D^0 \to K^-\mu^+\nu_\mu)}{BR(D^0 \to K^-\pi^+)}\right)_{D^{*+}} = 0.85 \pm 0.06\ (fit).$$

There are additional contributions to the uncertainty in this result as well, but our intention is to show that the two analyses are completely consistent. We include the information from this D^{*+} analysis in the computation of the sample variance used to estimate the variation due to the fit.

The total systematic error is determined by adding in quadrature the results of the sample variance test, the variation assessed due to uncertainty in the parameters of the matrix element used to generate the $D \to \overline{K}^* \mu\nu$ background contributions, our choice of $f_-(0)/f_+(0)$, and the uncertainty in the simulation of the muon system. The total systematic uncertainity is determined to be ± 0.028 for the relative branching ratio and $^{+0.07}_{-0.06}$ GeV/c^2 for the pole mass measurement. We find that the systematic error for the relative branching ratio is dominated by uncertainty in the simulation of the muon system and variation in the choice of $f_-(0)/f_+(0)$, and the systematic error for the pole mass measurement comes dominantly from our estimate of the pole mass sample variance.

We use the result from the relative branching ratio measurement and combine it with our measurements of $\frac{\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}$[4], τ_{D^0} and τ_{D^+}[14], the CLEO[13] results for $BR(D^0 \to K^-\pi^+)$[15] and $BR(D^+ \to K^-\pi^+\pi^+)$[16], and the isospin argument

$$\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu) = \Gamma(D^0 \to K^{*-}\mu^+\nu)$$

to calculate the ratio $\frac{BR(D^0 \to K^{*-}\mu^+\nu_\mu)}{BR(D^0 \to K^-\mu^+\nu_\mu)}$. We calculate:

$$\frac{BR(D^0 \to K^{*-}\mu^+\nu_\mu)}{BR(D^0 \to K^-\mu^+\nu_\mu)} = 0.62 \pm 0.07 \pm 0.09,$$

where statistical (systematic) errors for quantities used in the calculation have been added in quadrature to determine the total statistical (systematic) error. We find that the statistical and systematic error for this calculation are dominated by our previous $\frac{\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}$[4] measurement and the CLEO $BR(D^+ \to K^-\pi^+\pi^+)$[16] measurement.

To measure $f_-(0)/f_+(0)$ we include $f_-(0)/f_+(0)$ as an additional fit parameter in a two dimensional (q^2, E_μ) fit to the very clean D^{*+} data (see Figure 3). The estimates of $\left(\frac{BR(D^0 \to K^-\mu^+\nu_\mu)}{BR(D^0 \to K^-\pi^+)}\right)_{D^{*+}}$ and M_{pole} using this technique are completely consistent with our previous estimates using only the q^2 distribution of the D^{*+} sample. We perform nearly identical systematic studies, as described previously, and find[14] that $f_-(0)/f_+(0) = -1.3^{+3.6}_{-3.4} \pm 0.6$ (see Figure 4). Our systematic error for the estimate of $f_-(0)/f_+(0)$ is primarily due to the sample variance.

In Table I we compare our results to those from other experiments[15]. Our $f_+(0)$ measurement

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[13]We have emphasized results from CLEO to allow a more direct comparison of our results to those of reference[9].

[14]We have assumed symmetric errors throughout the estimate of the systematic error in the $f_-(0)/f_+(0)$ measurement.

[15]Note that the CLEO[9, 17] results are combined electron and muon(e, μ) measurements except

includes the uncertainty in the relative branching ratio, the uncertainty in the pole mass, the uncertainty from $BR(D^0 \to K^-\pi^+)$[15], the uncertainty in V_{cs} from unitarity constraints[18] and the uncertainty between $f_-(0)/f_+(0) = 0$ and $f_-(0)/f_+(0) = -1$ in the integral for the total rate. Our measurement of $\Gamma(D^0 \to K^-\mu^+\nu_\mu)$ includes the uncertainty in the ratio of branching ratios and the uncertainty from $BR(D^0 \to K^-\pi^+)$[15]. Our results are consistent with previous measurements[16].

In Table II we compare theoretical estimates of $f_-(0)/f_+(0)$ to our measurement. Our result is consistent with the theoretical estimates.

The results we have presented for the semimuonic decay mode $D^0 \to K^-\mu^+\nu_\mu$ represent a significant improvement over past semimuonic measurements[6, 17, 28, 29]. We have measured the ratio $f_-(0)/f_+(0)$ for the first time for this decay, and the result, though lacking statistical power, is consistent with theoretical estimates. Our measurements of other quantities are consistent with previous measurements, and our errors are equivalent to the best measurement of the semielectronic mode. Our results confirm the trend seen by other recent experiments that $\frac{BR(D^0 \to K^{*-}l^+\nu_l)}{BR(D^0 \to K^-l^+\nu_l)}$ is closer to 0.5 than to 1.0, that $BR(D^0 \to K^-\mu^+\nu_\mu) < BR(D^0 \to K^-e^+\nu_e)$ and that $M_{pole} < M_{D_s^{*+}}$.

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where noted, that the results in references [17] and [5, 10](electron only) use older measurements of $BR(D^0 \to K^-\pi^+)$ and $BR(D^+ \to K^-\pi^+\pi^+)$, and that the CLEO[9] result is dominantly in the electron mode. Note also that the vector to pseudoscalar ratios are a combination of D^0 and D^+ either through the isospin argument or through direct measurement.

[16] For comparison purposes note it is expected that $\Gamma(D^0 \to K^-\mu^+\nu_\mu) = 0.97\Gamma(D^0 \to K^-e^+\nu_e)$[19].

TABLES

TABLE I. Final Results and Comparison to Other Experiments

Reference	$\frac{BR(D^0 \to K^- l^+ \nu_l)}{BR(D^0 \to K^- \pi^+)}$	Pole Mass M_{pole}	$\frac{BR(D \to K^* l \nu_l)}{BR(D \to K l \nu_l)}$
This Paper	$0.852 \pm 0.034 \pm 0.028$	$1.87^{+0.11+0.07}_{-0.08-0.06}$ (GeV/c^2)	$0.62 \pm 0.07 \pm 0.09$
[9](CLEO '93)	$0.978 \pm 0.027 \pm 0.044$	$2.00 \pm 0.12 \pm 0.18$	0.62 ± 0.08
[17](CLEO '91)	$0.79 \pm 0.08 \pm 0.09(\mu\ only)$	$2.0^{+0.4+0.3}_{-0.2-0.2}$	$0.51 \pm 0.18 \pm 0.06$
[5, 10](E691)	$0.91 \pm 0.07 \pm 0.11$	$2.1^{+0.4}_{-0.2} \pm 0.2$	0.55 ± 0.14

Reference	$\Gamma(D^0 \to K^- l^+ \nu_l)$	$f_+(0)$
This Paper	$(8.07 \pm 0.37 \pm 0.44)$ $\times 10^{10}/sec$	$0.71 \pm 0.03 \pm 0.03$
[9] (CLEO '93)	$(9.1 \pm 0.3 \pm 0.6)$	$0.77 \pm 0.01 \pm 0.04$
[17] (CLEO '91)		$0.81 \pm 0.03 \pm 0.06$
[5] (E691)	$(9.1 \pm 1.1 \pm 1.4)$	$0.79 \pm 0.05 \pm 0.06$

TABLE II. Comparison of $f_-(0)/f_+(0)$ to Theoretical Estimates

Reference	f_-/f_+
This Paper	$-1.3^{+3.6}_{-3.4} \pm 0.6$
[20] (BES)	-1.2 ± 0.5
[21] (BSW)	-0.46
[22–24] (GISW,AW)	-0.60
[25, 26] (KS)	-0.46
[27] (GBD)	$-0.36 \to -1.07$

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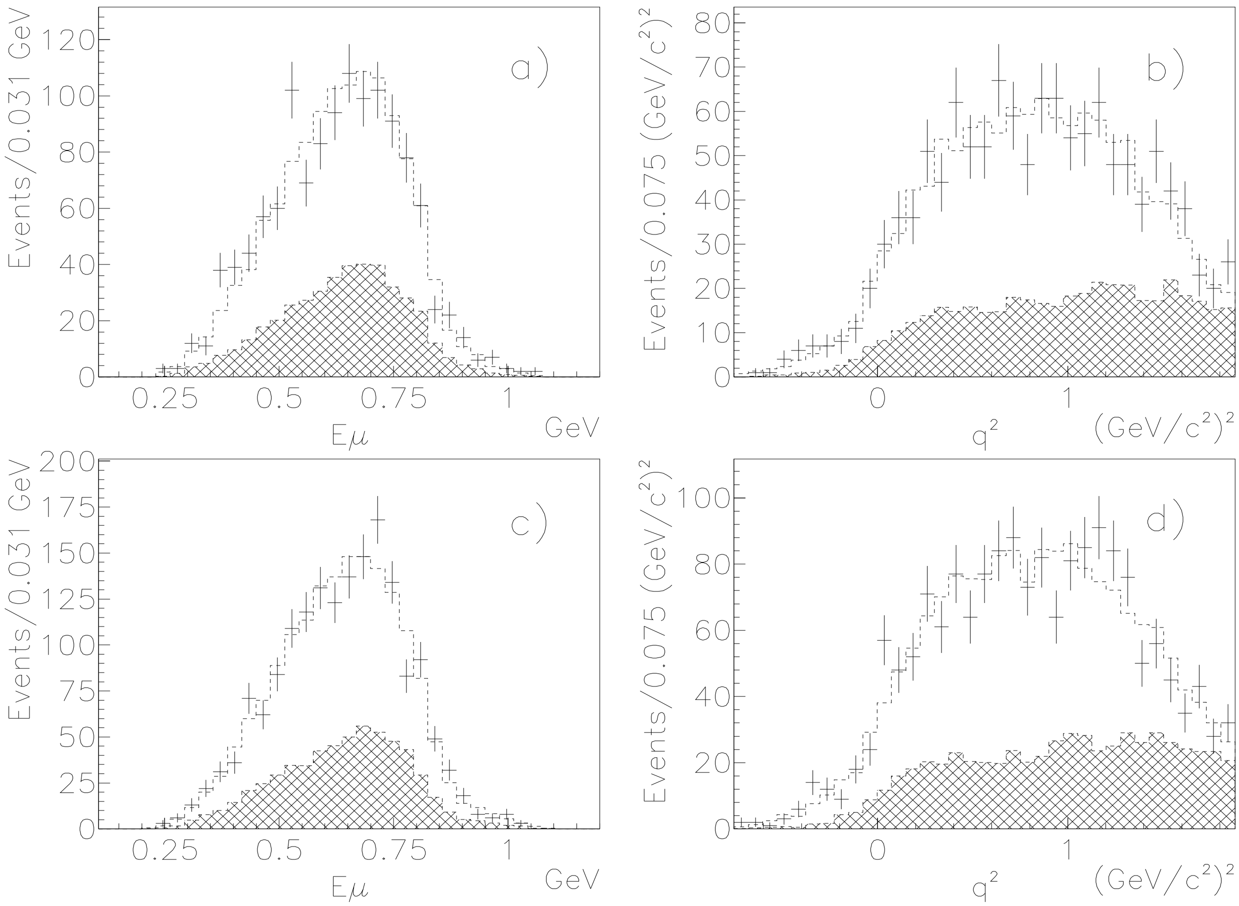
FIGURES

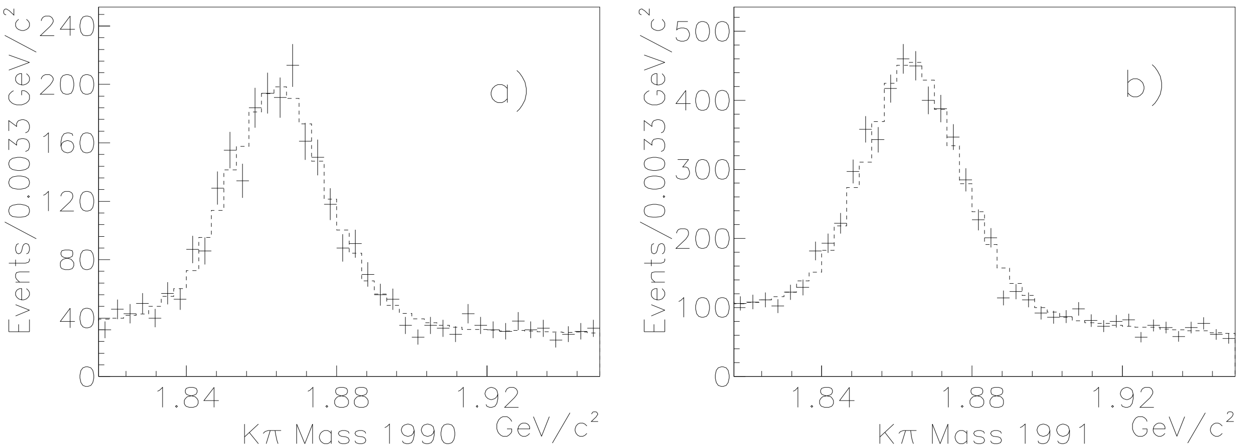
FIG. 1. (a) The E_μ projection for the 1990 data, (b) q^2 projection for the 1990 data, (c) E_μ projection for the 1991 data, and (d) q^2 projection for the 1991 data. The fits to the data are shown as dashed lines and the expected background is shown as a hatched area. Note the good agreement between the fit and the data and that the loss of $\sim 40\%$ of the acceptance of the muon system between the 1990 and 1991 runs has not dramatically altered the signal shape.

FIG. 2. (a) The 1990, and (b) 1991, $D^0 \rightarrow K^-\pi^+$ signals used in the ratio of branching ratios measurement. The fit is the dashed line. Events below 1.82 GeV/c^2 are eliminated from the fit to avoid parameterizing reflections from $D^0 \rightarrow K^-K^+$ decays.

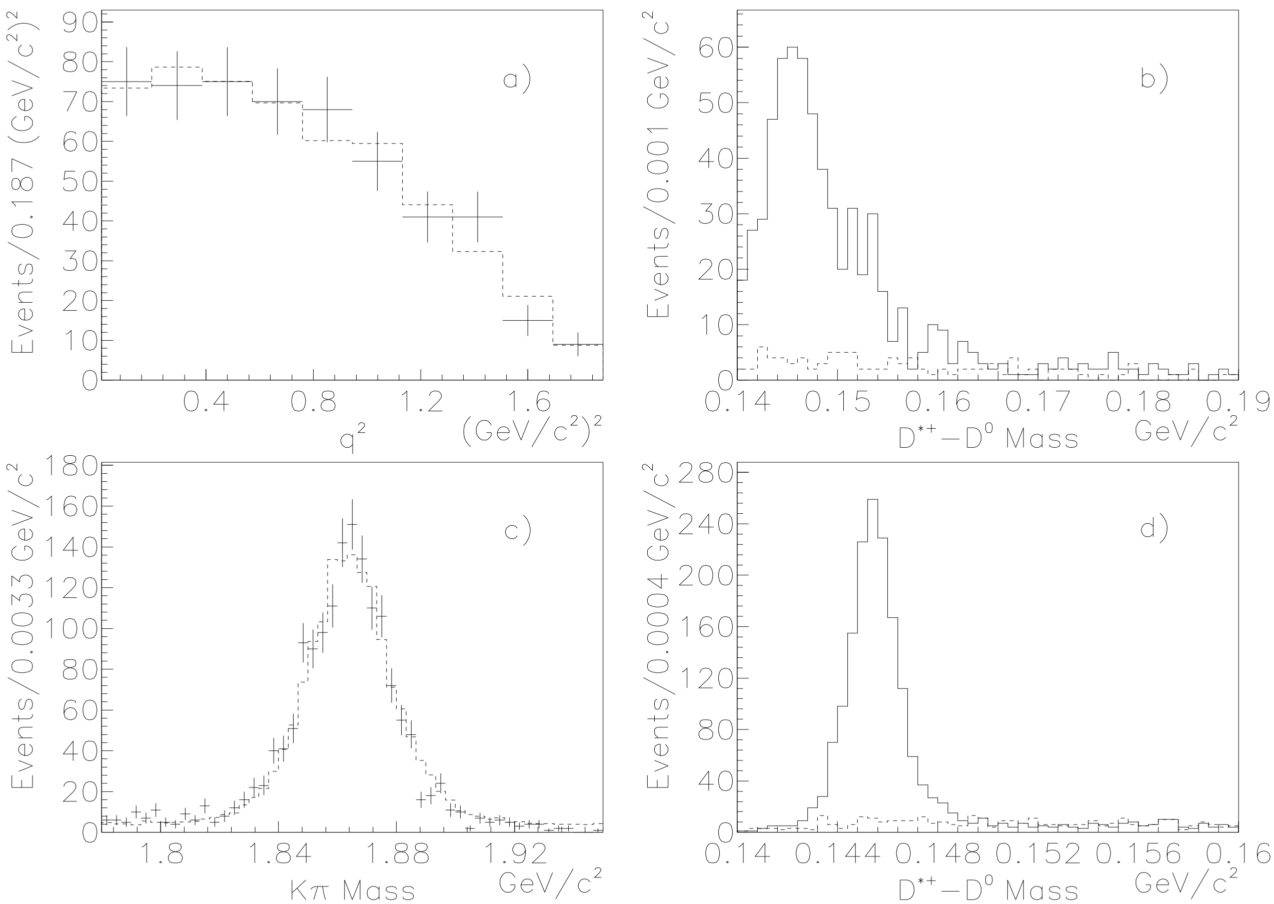
FIG. 3. (a) The q^2 distribution for $D^0 \rightarrow K^-\mu^+\nu_\mu$ events where a D^{*+} tag is present. (b) The mass difference $M(D^{*+} - D^0)$ for $D^0 \rightarrow K^-\mu^+\nu_\mu$. (c) The $D^0 \rightarrow K^-\pi^+$ signal used in the ratio of branching ratios measurement for events where a D^{*+} tag is present. (d) The mass difference $M(D^{*+} - D^0)$ for $D^0 \rightarrow K^-\pi^+$. In the plots (a) and (c), the results of the fit are overlaid on each plot as a dashed line. In (b) and (d), the background from events where the D^{*+} pion and the D^0 kaon are the same charge is overlaid on each plot as a dashed line.

FIG. 4. Contours of constant likelihood for the parameters $f_{-}(0)/f_{+}(0)$ and M_{pole} obtained from the fit to the D^* sample. Note that the $f_{-}(0)/f_{+}(0)$ contours remain essentially symmetric well beyond the $-\Delta(\mathrm{Ln(L)}) = +0.5$ (1.0σ) contour where the systematic error was estimated (see text).

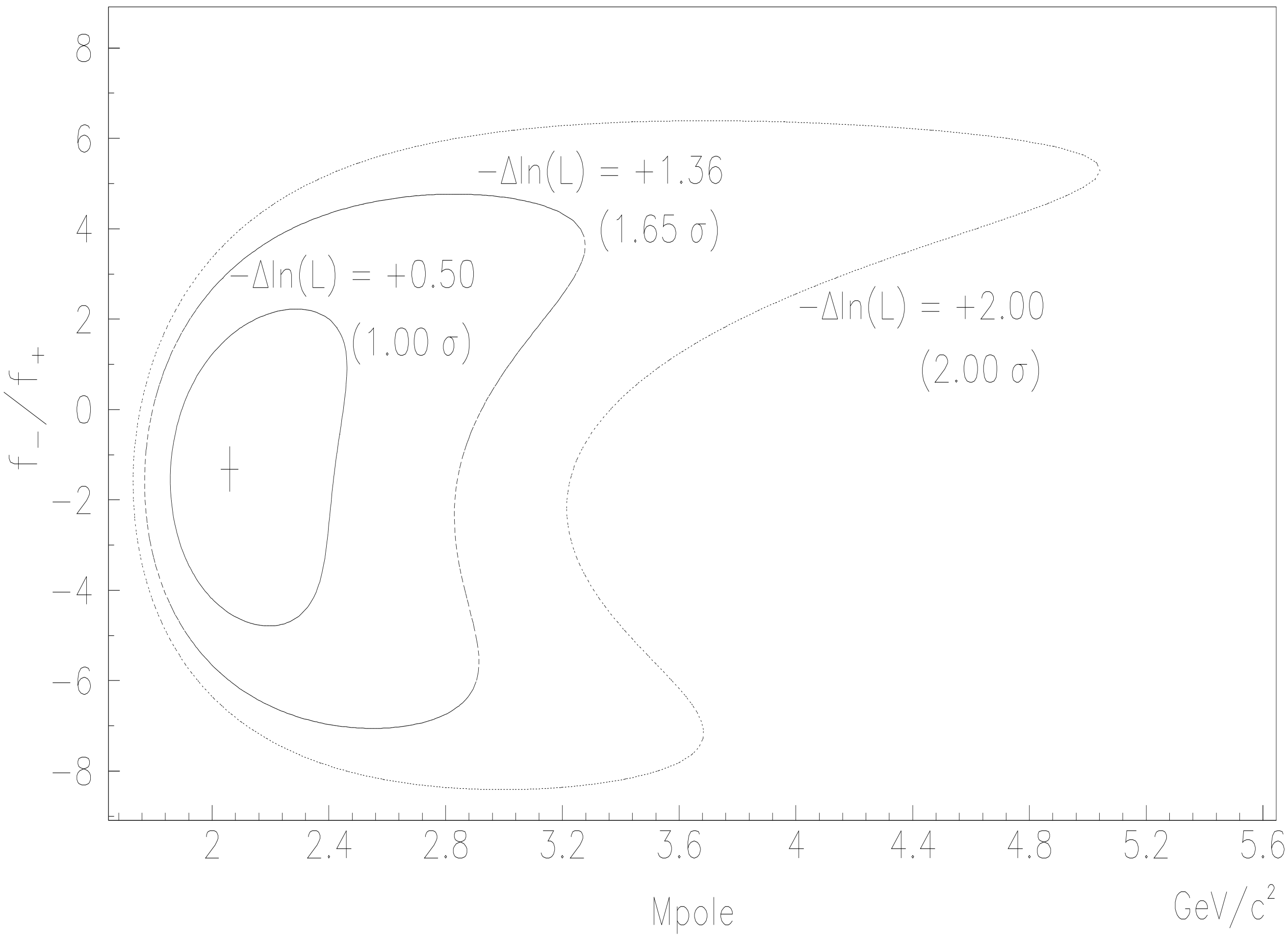

a)
b)
c)
d)
Events/0.031 GeV
Events/0.075 (GeV/c^2)^2
Eμ
GeV
q^2
(GeV/c^2)^2



Events/0.0033 GeV/c²
240
200
160
120
80
40
0
a)
1.84
1.88
1.92
Kπ Mass 1990
GeV/c²
Events/0.0033 GeV/c²
500
400
300
200
100
0
b)
1.84
1.88
1.92
Kπ Mass 1991
GeV/c²



a)
Events/0.187 (GeV/c²)²
q²
(GeV/c²)²
b)
Events/0.001 GeV/c²
D*+−D⁰ Mass
GeV/c²
c)
Events/0.0033 GeV/c²
Kπ Mass
GeV/c²
d)
Events/0.0004 GeV/c²
D*+−D⁰ Mass
GeV/c²



−Δln(L) = +1.36
(1.65 σ)
−Δln(L) = +0.50
(1.00 σ)
−Δln(L) = +2.00
(2.00 σ)
f−/f+
Mpole
GeV/c²
8
6
4
2
0
−2
−4
−6
−8
2
2.4
2.8
3.2
3.6
4
4.4
4.8
5.2
5.6