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Measurements of the q^2 dependence of the $D^0 \to K^-\mu^+\nu$ and $D^0 \to \pi^-\mu^+\nu$ form factors

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Abstract

Using a large sample of $D^0 \to K^-\mu^+\nu$ and $D^0 \to \pi^-\mu^+\nu$ decays collected by the FOCUS photoproduction experiment at Fermilab, we present new measurements of the q^2 dependence for the $f_+(q^2)$ form factor. These measured $f_+(q^2)$ form factors are fit to common parameterizations such as the pole dominance form. We find $m_{\text{pole}} = 1.93 \pm 0.05 \pm 0.03$ GeV/c^2 for $D^0 \to K^-\mu^+\nu$ and $m_{\text{pole}} = 1.91^{+0.30}_{-0.15} \pm 0.07$ GeV/c^2 for $D^0 \to \pi^-\mu^+\nu$ and $f_-^{(K)}(0)/f_+^{(K)}(0) = -1.7^{+1.5}_{-1.4} \pm 0.3$.

1 Introduction

In this paper, we provide a new non-parametric measurement of the q^2 evolution for the $f_+(q^2)$ form factor describing pseudoscalar decay $D^0 \to K^-\mu^+\nu$. The measurement is presented in a form that is convenient for parametric and non-parametric comparisons to other experiments and theoretical predictions. Our q^2 evolution is compared to the lattice gauge representation in [1], and we show that fits to the q^2 evolution agree with traditional parametric analyses of the data and results from other experiments.

Two form factors describe the matrix element for such decays according to Eq. 1

$$M = G_F V_{cs} \left[f_+(q^2)\ (P_D + P_K)_\sigma + f_-(q^2)\ (P_D - P_K)_\sigma \right]\ \bar{u}_\mu \gamma^\sigma (1 - \gamma_5) u_\nu \tag{1}$$

These lead to a differential width of the form given by Eq. 2 where P_K is the kaon momentum in the D^0 rest frame and all $f_-(q^2)$ contributions are multiplied by the square of the muon mass. [1]

$$\begin{aligned} \frac{d\Gamma}{dq^2} = \frac{G_F^2}{8\pi^3\, m_D} |V_{cs}|^2 \left|f_+(q^2)\right|^2 P_K \left(\frac{W_0 - E_K}{F_0}\right)^2 \Bigg[\frac{1}{3} m_D P_K^2 + \frac{m_\mu^2}{8 m_D}(m_D^2 + m_K^2 + 2 m_D E_K) \\ + \frac{1}{3} m_\mu^2 \frac{P_K^2}{F_0} + \frac{1}{4} m_\mu^2 \frac{m_D^2 - m_K^2}{m_D} Re\left(\frac{f_-(q^2)}{f_+(q^2)}\right) + \frac{1}{4} m_\mu^2 F_0 \left|\frac{f_-(q^2)}{f_+(q^2)}\right|^2 \Bigg] \end{aligned} \tag{2}$$

In Eq. 2, $W_0 = \left(m_D^2 + m_K^2 - m_\mu^2\right)/(2m_D)$, $F_0 = W_0 - E_K + m_\mu^2/(2m_D)$ and P_K , E_K are the momenta and energy of the kaon in the D^0 rest frame. Assuming $f_-(q^2)/f_+(q^2)$ is on the order of unity as expected, the corrections due to $f_-(q^2)$ are fairly small and, apart from the low q^2 region, $d\Gamma/dq^2 = G_F^2\ |V_{cs}|^2\ P_K^3\ |f_+(q^2)|^2/(24\pi^3)$ is an excellent approximation.

This paper provides new measurements of the $f_+(q^2)$ form factors for $D^0 \to K^-\mu^+\nu$ and $D^0 \to \pi^-\mu^+\nu$ and of the ratio $f_-(0)/f_+(0)$ for $D^0 \to K^-\mu^+\nu$. [2] Our emphasis in this paper is on the *shape* of the q^2 dependence rather than on its absolute normalization. As a means of comparing our result to different parameterizations commonly used in the literature, we will fit our measurements of $f_+(q^2)$ to two different parameterizations in use: the pole form given by Eq. 3 and the *modified* pole form given by Eq. 4. [3]

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[1] This form was obtained using the basic formulae in [2].
[2] Throughout this paper, we will assume that $f_-(q^2)/f_+(q^2)$ is essentially independent of q^2.
[3] In this form, the parameter α gives the deviation of $f_+(q^2)$ from spectroscopic pole dominance where $m_{D^*} = m_{D_s^*} = 2.112$ GeV/c^2 for $D^0 \to K^-\mu^+\nu$ and $m_{D^*} = m_{D^{+*}} = 2.010$ GeV/c^2 for $D^0 \to \pi^-\mu^+\nu$

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/m^2_{\rm pole}} \tag{3}$$

$$f_+(q^2) = \frac{f_+(0)}{(1 - q^2/m^2_{D^*})\,(1 - \alpha\; q^2/m^2_{D^*})} \tag{4}$$

Throughout this paper, unless explicitly stated otherwise, the charge conjugate is also implied when a decay mode of a specific charge is stated.

2 Experimental and analysis details

The data for this paper were collected in the photoproduction experiment FOCUS during the Fermilab 1996–1997 fixed-target run. In FOCUS, a forward multi-particle spectrometer is used to measure the interactions of high energy photons on a segmented BeO target. The FOCUS detector is a large aperture, fixed-target spectrometer with excellent vertexing and particle identification. Most of the FOCUS experiment and analysis techniques have been described previously [3–5].

The non-parametric part of this analysis is based on a sample of $\approx 13,000$ decays of the form $D^{*+} \to D^0\pi^+$, where $D^0 \to K^-\mu^+\nu$. To isolate the $D^0 \to K^-\mu^+\nu$ topology, we required that the muon, and kaon tracks appeared in a secondary vertex with a confidence level exceeding 1%. In order to suppress backgrounds from higher multiplicity charm decays, we isolated the $K^-\mu^+$ vertex from other tracks (not including tracks from the primary vertex) by requiring that the maximum confidence level for another track to form a vertex with the candidate be less than 1%. The D^* decay pion was required to lie in the primary vertex.

The muon track, when extrapolated to the shielded muon arrays, was required to match muon hits with a confidence level exceeding 1% and all other tracks were required to have confidence level less than 1%. The muon candidate was allowed to have at most one missing hit in the 6 planes comprising our inner muon system and a momentum exceeding 10 GeV$/c$. In order to suppress muons from pions and kaons decaying within our apparatus, we required that each muon candidate had a confidence level exceeding 1% to the hypothesis that it had a consistent trajectory through our two analysis magnets. The kaon was required to have a Čerenkov light pattern more consistent with that of a kaon than that of a pion by 1 unit of log likelihood [5]. Non-charm and random combinatoric backgrounds were reduced by requiring a detachment between the vertex containing the $D^0 \to K^-\mu^+\nu$ and the primary production vertex of at least 5 standard deviations.

Possible background from $D^0 \to K^-\pi^+$, where a pion is misidentified as a muon, was reduced by requiring the reconstructed $K^-\mu^+$ mass be less than 1.812 GeV/c^2. Finally we put a cut on the confidence level ($\mathrm{CL_{closure}}$) that the event was consistent with the hypothesis $D^0 \to K^-\mu^+\nu$ that will be described below.

The $\delta m \equiv m(K^-\mu^+\nu \;\; \pi^+) - m(K^-\mu^+\nu)$ distribution for our tagged $D^0 \to K^-\mu^+\nu$ candidates is shown in Figure 1. The data of Figure 1 is "wrong sign subtracted" meaning that combinations where the D^* decay pion have the same charge as the kaon are subtracted from those where the decay pion and kaon have the opposite charge. Figure 1 was created using our *standard* [6] line-of-flight neutrino closure technique. Briefly, the standard neutrino closure method assumes the reconstructed D momentum vector points along the displacement between the secondary and primary vertex. This leaves a two-fold ambiguity on the neutrino momentum. For Figure 1, we use the neutrino momentum that resulted in the lower δm.

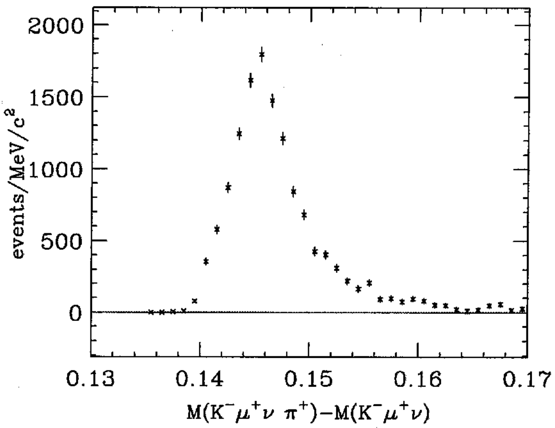

Fig. 1. The $D^* - D$ mass difference distribution for events satisfying our signal selection cuts. The muon and the kaon are required to have the opposite charge. There is an excess of 12,840 opposite charge combinations over same charge combinations where the $D^* - D$ mass difference was less than 0.160 GeV/c^2.

To improve the q^2 resolution beyond this point, we developed an alternative neutrino closure technique that we will call D^* *cone closure*. We require that the $K^-\mu^+\nu$ reconstructs to the mass of a D^0 and the $K^-\mu^+\nu\;\pi^+$ reconstructs to the mass of D^{*+}. When viewed in the $K^-\mu^+$ rest frame, these constraints place the neutrino momentum vector on a cone about the D^* decay pion where both the neutrino energy and cone half-angle are determined from the mass constraints and the well measured K^-, μ^+, and π^+ momentum vectors. We then sample all azimuths for the neutrino in this cone, reconstruct the lab frame D^0 momentum vector, and choose the azimuth where the D^0 is most consistent with pointing to the primary vertex based on minimizing a χ^2 variable. In order to further reduce backgrounds, we required $\mathrm{CL_{closure}} > 1\%$ where $\mathrm{CL_{closure}}$ is a confidence level based this minimal χ^2.

Averaged over all detected $D^0 \to K^-\mu^+\nu$ events, the Monte Carlo predicted a rather non-Gaussian q^2 resolution with an r.m.s. width of 0.22 GeV^2/c^2 using the D^* cone closure technique.

It was important to test the fidelity of the simulation with respect to the reproducibility of the q^2 resolution. To do this, we studied tagged, fully-reconstructed $D^0 \rightarrow K^-\pi^+\pi^+\pi^+$ decays from $D^{*+} \rightarrow D^0\pi^+$ where, as a test, one of the D^0 decay pions was reconstructed using our neutrino cone closure technique. We then reconstructed the q^2 using the neutrino closure and compared it to a precisely reconstructed q^2 obtained obtained from the magnetically reconstructed "neutrino" pion. The difference between these two q^2 values provided a resolution distribution obtained from data that could then be compared to the same resolution distribution obtained using tagged $D^0 \rightarrow K^-\pi^+\pi^+\pi^+$ in our Monte Carlo. The Monte Carlo resolution distribution was a good match to the observed resolution distribution.

We next describe the method used to correct for the effects of acceptance and q^2 resolution. We will call this our *deconvolution* technique. The goal of the deconvolution is to produce a set of $f_+^2(q_i^2)$ that represents measured $f_+(q^2)$ values - each averaged over the (narrow) width of the q_i^2 *reporting* bins. Under the assumption that $f_-(q^2)/f_+(q^2)$ is on the order of unity, Eq. 2 implies that the number of events expected in a given q^2 bin is proportional to $|f_+(q^2)|^2$. Our Monte Carlo is used to determine the fraction of events reconstructed in a given q^2 bin that were generated in another q^2 bin. This information, along with the $f_+(q^2)$ distribution used in the original generation[4] of the $D^0 \rightarrow K^-\mu^+\nu$ Monte Carlo sample, was combined to form a matrix that linearly relates a vector of the predicted number of events reconstructed in each q^2 bin to a vector of assumed $f_+^2(q_i^2)$ values. The "deconvolved" $f_+^2(q_i^2)$ is then given by the inverse of this matrix times a vector consisting of the observed number of events reconstructed in each q^2 bin. We will call the inverse of this matrix, the *deconvolution* matrix.

We actually perform the matrix multiplication using a weighting technique. Each $f_+^2(q_i^2)$ is a sum of weights over all events where the event weight is the deconvolution matrix element whose row is given by the number of the q^2 *reporting* bin and whose column is given by the number of the reconstructed q^2 bin for that event.[5] The covariance between two q^2 reporting bins is then given by the sum of the product of event weights for the two reporting bins.

Because our signal is based on the $D*-D$ mass difference, non-charm backgrounds are negligible. Our charm background correction is based on a Monte Carlo, which incorporates all known charm decays and charm decay mecha-

[4] The sample was generated assuming $f_-(q^2)/f_+(q^2) = -0.7$

[5] We also create a WS subtraction by multiplying the deconvolution matrix element by +1 if the kaon of the event had the opposite sign of the D^* decay pion and -1 otherwise. We also did a background subtraction by subtracting these weights for the background events predicted by our charm Monte Carlo.

nisms. The charm background was normalized to the same number of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ events observed in the data. Figure 2 compares the $f_+(q_i^2)$ values obtained with and without the background subtraction.[6] Figure 2 shows that most of the charm background is expected in the high q^2 region, and once the background is subtracted the data is an excellent fit to the pole form. In the range $\delta m < 0.16$ GeV/c^2, the expected, wrong-sign subtracted background yield from our Monte Carlo was found to be 12.6 % of the total number of events in this δm range when using our baseline cuts.

The deconvolution was obtained by summing the weights of all events with $\delta m < 0.16$ GeV/c^2. A ten bin deconvolution matrix was used, with the overflow bin dropped. Given that our bin width, 0.18 GeV^2/c^2, is comparable to our r.m.s. q^2 resolution, adjacent $f_+(q_i^2)$ values have a strong, negative correlation (typically - 65%) and the error bars are thus significantly inflated over naive counting statistics errors.

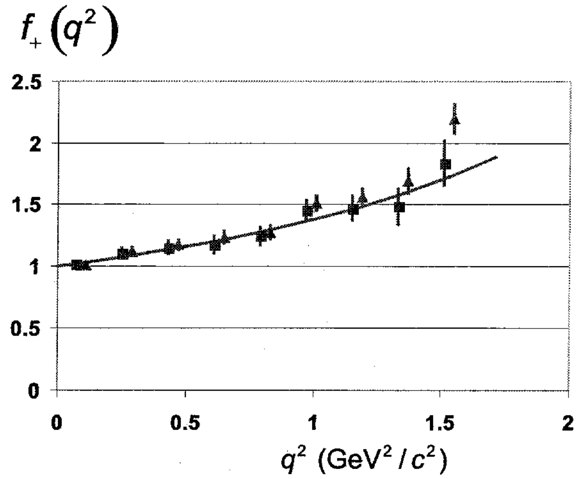

Fig. 2. The deconvolved $f_+(q^2)$ for $D^0 \to K^-\mu^+\nu$ events using nine, 0.18 GeV^2/c^2 bins. The triangular points are prior to subtraction of known charm backgrounds. The square points are after subtraction for known charm backgrounds. The line shows the pole form with $m_{\text{pole}} = 1.91$ GeV/c^2 – the value obtained from a fit to the displayed $f_+(q^2)$ points. After background subtraction, the confidence level of the fit to the pole form is 87%. A fit to the modified pole form produced an α parameter of 0.32 with a confidence level of 82%.

[6] We take the square root of the $f_+^2(q_i^2)$ returned by the fit and make the appropriate adjustment to the variances obtained from the diagonal elements of the covariance matrix.

3 Parameterized $f_+(q^2)$ forms for $D^0 \to K^-\mu^+\nu$ and $D^0 \to \pi^-\mu^+\nu$

In this section we present values of the m_{pole} and α parameters for the pole form (Eq. 3) and modified pole form (Eq. 4) as well as the ratio $f_-^{(K)}(0)/f_+^{(K)}(0)$. For the case of $D^0 \to K^-\mu^+\nu$ we have done this directly from a χ^2 fit of the non-parametric $f_+(q^2)$ values illustrated in Figure 2 as well as from a 2 dimensonal binned likelihood fit to the q^2 and $\cos\theta_\ell$ scatterplot where θ_ℓ is the angle between the ν and the D direction in the $\mu\nu$ rest frame. Because of the much larger background contamination in the Cabibbo suppressed $D^0 \to \pi^-\mu^+\nu$, only the 2 dimensional binned likelihood fit was employed to extract $f_+(q^2)$ parameters for this mode. We begin with a discussion of the results from the two dimensional fit.

One of the principal motivations for the two dimensional fit analysis, was to compare the decay widths for $D^0 \to \pi^-\mu^+\nu$ and $D^0 \to K^-\mu^+\nu$ and extract the ratio $f_+^{(\pi)}(0)/f_+^{(K)}(0)$. As such, the analysis cuts used for the two dimensional analysis are somewhat different than those previously described for the deconvolution analysis in order to reduce systematic uncertainty on the ratio. Several additional cuts on the muon candidate were applied to remove contamination from electrons. The kaon, in $D^0 \to K^-\mu^+\nu$, was required to have a Čerenkov light pattern more consistent with that for a kaon than with that for a pion by 3 units of log likelihood. The pion track, in $D^0 \to \pi^-\mu^+\nu$, was required to have a Čerenkov light pattern more consistent with that of a pion than that of a kaon by 3 units of log likelihood. For both the pion from $D^0 \to \pi^-\mu^+\nu$ decay as well as the D^{*+} decay pion, we further required that no other hypothesis was favored over the pion hypothesis by more than 6 units of likelihood. The pion in $D^0 \to \pi^-\mu^+\nu$ was required to have a momentum greater than 14 GeV/c , and the D^* decay pion was required to have a momentum greater than 2.5 GeV/c. A $D^* - D$ mass difference cut of $\delta m < 0.154$ GeV/c^2 was applied. Finally the hadron-muon mass was required to exceed 1 GeV/c^2.

Information on parameterized $f_+(q^2)$ and $f_-^{(K)}(0)/f_+^{(K)}(0)$ is obtained by using a weighting technique that is similar to that described in [6]. We use a binned version of the fitting technique developed by the E691 collaboration [7] for fitting decay intensities where the kinematic variables that rely on reconstructed neutrino kinematics are poorly measured. The observed number of events in each q^2-$\cos\theta_\ell$ bin is compared to a prediction based on signal intensity as well as background contributions.

The signal component is constructed from a weighted Monte Carlo. The signal Monte Carlo was initially generated using nominal values for $f_-(0)/f_+(0)$ and m_{pole}. Both the generated as well as reconstructed kinematic variables were stored for each event. The signal prediction for a given fit iteration is then computed by weighting each event within a given reconstructed kinematic bin by the intensity evaluated using the generated kinematic variables for the current set of fit parameters divided by the generated intensity.

A variety of possible backgrounds were included for our two processes. These included general charm background based on our charm Monte Carlo as well as specific backgrounds that create peaks in the δm distribution. For the case of $D^0 \to \pi^-\mu^+\nu$, the specific backgrounds included $K^-\mu^+\nu$, $K^-\pi^0\mu^+\nu$, $\overline{K}^0\pi^-\mu^+\nu$ and $\rho^-\mu\nu$; while for $D^0 \to K^-\mu^+\nu$ this included $K^-\pi^0\mu^+\nu$. In all cases, the shape of the backgrounds were determined from our Monte Carlo that incorporated known decay intensities. The branching ratio of each specific background relative to the two signal processes were allowed to float, but a χ^2 (likelihood penalty term) was included to tie a given backgrounds branching ratio relative to the signal to the measured values within their known uncertainties. The yield of $D^0 \to K^-\mu^+\nu$ deduced from a fit to its q^2-$\cos\theta_\ell$ scatterplot served as an estimate of this important background in the fit to the q^2-$\cos\theta_\ell$ scatterplot for $D^0 \to \pi^-\mu^+\nu$. A more complete description of this fitting procedure will appear in a companion paper [8]. Figure 3 shows

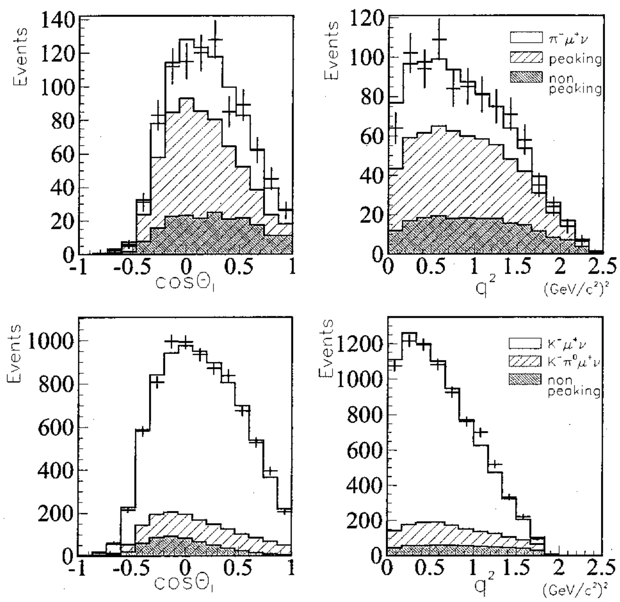

Fig. 3. The q^2 and $\cos\theta_\ell$ projections of the two-dimensional fit compared to the data histogram for both $D^0 \to \pi^-\mu^+\nu$ (upper row) and $D^0 \to K^-\mu^+\nu$ (lower row). For the case of $D^0 \to \pi^-\mu^+\nu$, the peaking backgrounds included the sum of $K^-\mu^+\nu$, $K^-\pi^0\mu^+\nu$, $\overline{K}^0\pi^-\mu^+\nu$ and $\rho^-\mu\nu$; while for $D^0 \to K^-\mu^+\nu$ they included $K^-\pi^0\mu^+\nu$.

how the q^2 and $\cos\theta_\ell$ projections predicted by the fit compare to the data as well as the various signal and background components of these projections. The results relevant to $D^0 \to K^-\mu^+\nu$ are $m_{\text{pole}} = 1.93 \pm 0.05 \pm 0.03$ GeV$/c^2$, $\alpha = 0.28 \pm 0.08 \pm 0.07$, and $f_-^{(K)}(0)/f_+^{(K)}(0) = -1.7^{+1.5}_{-1.4} \pm 0.3$.

The systematic error was determined by comparing results using different event selections, alternative fit methods, and looking at the consistency of results between split samples. We begin with some of the many alternative event selections that were investigated. A $f_+(q^2)$ and $f_-^{(K)}(0)/f_+^{(K)}(0)$ measurement was obtained from fits where each of these cuts was varied relative to our baseline: the detachment of the secondary vertex from the primary vertex was varied from 4 to 12 standard deviations, the secondary vertex was required to lie out of all target material, the momentum cut on the muon was raised from 10 to 25 GeV/c, the secondary isolation cut was tightened from $< 1\%$ to $< 0.1\%$ and the confidence level on the secondary vertex was raised from $> 1\%$ to $> 15\%$. The split sample compared the form factor information for particles to that for antiparticles. Various alternative fits were employed. For example, in some fits, the two pole masses were allowed to float while keeping $f_-^{(K)}(0)/f_+^{(K)}(0)$ fixed compared to our standard fit where all three parameters were free to float. In another fit variant, the fit was performed on the δm - q^2 scatter plot as opposed to the q^2 - $\cos\theta_\ell$ scatterplot.

Finally a fit to m_{pole} was made directly from the non-parametric $f_+(q^2)$ results illustrated in Figure 2. This fit minimized a χ^2 given by given by Eq. 5.

$$\chi^2 = \sum_i \sum_j \left(f_+(q_i^2)^{(m)} - f_+(q_i^2)^{(p)}\right) C_{ij}^{-1} \left(f_+(q_j^2)^{(m)} - f_+(q_j^2)^{(p)}\right) + \left(\frac{b-1}{\sigma_b}\right)^2 \tag{5}$$

where the sum runs over all reporting bins, C^{-1} is the inverse of the covariance matrix, $f_+(q_i^2)^{(m)}$ are the measured $f_+(q^2)$ values, and $f_+(q_i^2)^{(p)}$ are the predicted $f_+(q^2)$ within the parameterization. The second term is a likelihood penalty term that parameterizes uncertainty in the level of the charm background. The parameter b is a background multiplier that multiplies the expected Monte Carlo background yield prior and σ_b is our estimate of its uncertainty. The parameterized $f_+(q_i^2)^{(p)}$ depends on a normalization parameter $f_+(0)$ and a shape parameter m_{pole}. This fit produced a pole mass of $m_{\text{pole}} = 1.91 \pm 0.04 \pm 0.05$ GeV/c^2 which is in remarkably good agreement with $m_{\text{pole}} = 1.93 \pm 0.05 \pm 0.03$ GeV/c^2. Again, the systematic error of the fit to the non-parametric $f_+(q^2)$ was obtained by checking its stability against a variety of different fit variants, cut variants, assumed background levels, and f_-/f_+ assumptions.

Finally, the m_{pole} result for $D^0 \to \pi^-\mu^+\nu$ is $m_{\text{pole}} = 1.91^{+0.30}_{-0.15} \pm 0.07$ GeV/c^2. The systematic error on this result included an additional important cut variant consisting of raising the log-likelihood difference between the kaon and pion Cerenkov hypothesis from 3 to 5 and in the process reducing the fraction of kaons misidentified as pions by about a factor of two.

Table 1
Measurements of $f_+(q^2)$ for $D^0 \to K^-\mu^+\nu$. The correlation matrix is available at http://web.hep.uiuc.edu/home/jew/fpluscorrelations.html.

q^2 bin GeV^2/c^2	$f_+(q^2)$
0.09	1.01 ± 0.03
0.27	1.11 ± 0.05
0.45	1.15 ± 0.07
0.63	1.17 ± 0.08
0.81	1.24 ± 0.09
0.99	1.45 ± 0.09
1.17	1.47 ± 0.11
1.35	1.48 ± 0.16
1.53	1.84 ± 0.19

4 Summary

Table 1 gives a summary of our non-parametric $f_+(q^2)$ measurements for $D^0 \to K^-\mu^+\nu$. They are normalized such that $f_+(0) = 1$.

Figure 4 compares our $f_+(q_i^2)$ measurements to a recent [1] Lattice QCD calculation[7] and our best fit values for m_{pole} in the pole mass parameterization (Eq. 3) and α in the modified pole mass parameterization (Eq. 4). We obtained a value of $f_-^{(K)}(0)/f_+^{(K)}(0) = -1.7^{+1.5}_{-1.4} \pm 0.3$ that also is consistent with the value that can be derived from information in [1].

Our fit to the m_{pole} parameter in pole mass parameterization was $m_{\text{pole}} = 1.93 \pm 0.05 \pm 0.03$ GeV/c^2. This is compared to previous published data in Figure 5. The most recent m_{pole} is from CLEO [9] who obtain $m_{\text{pole}} = 1.89 \pm 0.05 \pm 0.035$ GeV/c^2. All data are remarkably consistent.

Our fit to the α parameter for the modified pole form is $\alpha = 0.28 \pm 0.08 \pm 0.07$ from the parameterized, two-dimensional fit. This is very consistent with 0.32 $\pm$ 0.09 $\pm$ 0.07 , the value obtained from our fits to non-parametric data shown in Figure 2. The most recent published measurement is from CLEO [9] who obtain $\alpha = 0.36 \pm 0.10^{+0.03}_{-0.07}$. Our value for the α parameter is 1.9 σ lower than the value quoted in [1] for $D^0 \to K^-\mu^+\nu$ although was extremely consistent with a preliminary version of that calculation [10].[8]

[7] We re-scaled their calculations to insure that $f_+(0) = 1$.
[8] We believe that only statistical errors on α are included in [1]

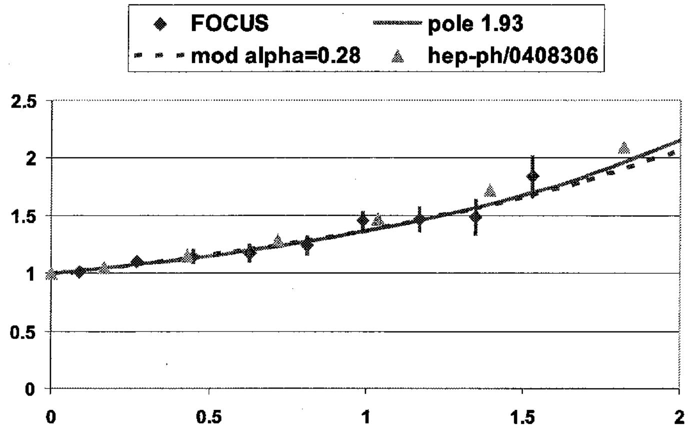

Fig. 4. The background subtracted $f_+(q^2)$ (diamonds with error bars) is compared to a pole form with $m_{\rm pole} = 1.93$ GeV/c^2 (solid curve) , a modified pole form with $\alpha = 0.28$ (dashed curve) , and the unquenched, Lattice QCD, calculations given in reference [1] (triangles with no error bars). This form factor is for the process $D^0 \to K^-\mu^+\nu$. The α and $m_{\rm pole}$ used for the plots are obtained using the two-dimensional, parameterized fit.

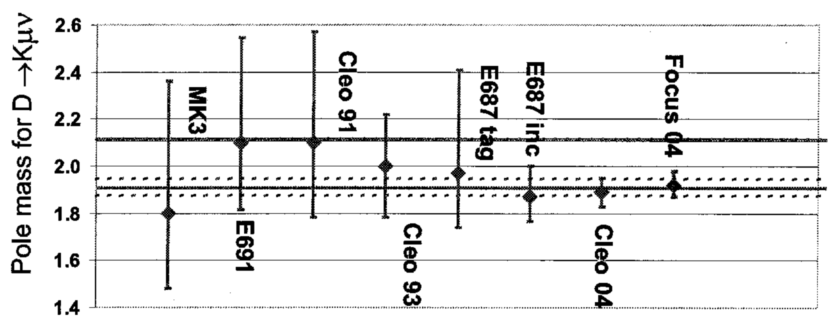

Fig. 5. Summary of $m_{\rm pole}$ measurements. All data are consistent with a weighted average pole mass of $m_{\rm pole} = 1.91 \pm 0.04$ GeV/c^2. The upper solid line shows the spectroscopic pole mass at $m_{D_s^*}$. The lower solid line and two dashed lines represent the weighted average and its error. Our weighted average of all data is 5.1 σ lower than this.

We also find that $m_{\rm pole}$ for $D^0 \to \pi^-\mu^+\nu$ is $m_{\rm pole} = 1.91^{+0.30}_{-0.15} \pm 0.07$ GeV/c^2. This value is compatible with our value for the pole mass for $D^0 \to K^-\mu^+\nu$. In the naive pole dominance model, the $m_{\rm pole}$ for $D^0 \to \pi^-\mu^+\nu$ would be at the mass of the D^{*+} and would therefore lie lower in mass than $m_{D_s^*}$ expected for $D^0 \to K^-\mu^+\nu$.

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