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CHARM SEMILEPTONIC DECAYS AT e^+e^- MACHINES*

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Abstract

Recent results from the CLEO and ARGUS collaborations on charm semileptonic decays are presented.

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1 Introduction

Interest in charm semileptonic decays is motivated by the simplicity of the decay. For example, in the decay $D^0 \to K^- e^+ \overline{\nu}$ the electron and anti-neutrino are unaffected by the strong interaction and all strong interaction effects can be absorbed in a form factor. This form factor can be thought of as the probability that the meson K will be formed as a function of the momentum transfer in the decay, $q^2 = M_W^2$. We write the differential decay rate for $D^0 \to K^- e^+ \overline{\nu}$ as:

$$d\Gamma/dq^2 = (1/24\pi^3) G_F^2 |V_{cs}|^2 f_+(q^2) P_K^3 \tag{1}$$

where G_F is the fermi constant and $|V_{cs}|$ is Cabibbo-Kobayashi-Maskawa (CKM) matrix element governing the $c \to s$ transition of the charm quark. The $c \to d$ transition is also allowed for the charm quark, such decays are called Cabibbo suppressed since the CKM matrix element for these decays, $|V_{cd}|$ is much smaller than $|V_{cs}|$. The form factor in Equation 1 is denoted as $f_+(q^2)$. The P_K^3 factor is the phase space term for a spin one half particle decaying into a vector and pseudo-scalar. Since the CKM matrix elements, V_{cs} and V_{cd} are known to within $\pm 1\%$ due to the unitarity constraint [1], measurements of charm semileptonic decay rates provide information on the form factors involved. These measurements are then to be compared with predictions obtained from quark models, QCD sum rules and lattice gauge calculations.

Charm analysis at e^+e^- machines operating in the $\Upsilon(4s)$ resonance region uses charm events produced in continuum reactions, $e^+e^- \to c\overline{c}$. The c and $\overline{c}$ quark fragment into a spectrum of charmed hadrons. The momentum distribution of charm hadrons from continuum production is much harder than that of charm hadrons from B decays. This fact is utilized by placing momentum cuts to reduce the combinatoric background and obtain clean signals.

There are two active experiments, ARGUS which completed data taking in 1991 and CLEO II which started taking data in 1990 and continues to take data. The ARGUS experiment recorded $0.33 fb^{-1}$ of data and the CLEO II experiment has recorded $2.6 fb^{-1}$, with $1.8 fb^{-1}$ analyzed. Due to the large luminosity recorded by CLEO II their results dominate this paper.

The results are presented as follows, first I present the recent results on the Cabibbo favored channels of the D^0 and D^+ mesons, including a measurement of the q^2 dependence of the form factor $f_+(q^2)$ in $D^0 \to K^- l^+ \overline{\nu}$ decays. Followed by the observation Cabibbo suppressed decay $D^+ \to \pi^0 l^+ \overline{\nu}$. New results on the decay $\Lambda_c \to \Lambda l \overline{\nu}$ and measurement of the decay asymmetry are presented. The last measurement discussed will be the observation of the purely leptonic decay $D_s^+ \to \mu^+ \overline{\nu}$. For a more complete and thorough review of charm semileptonic decay results see references [2, 3].

2 The D^0 and D^+ semileptonic decays

The D^0 and D^+ mesons are the most scrutinized charm hadrons. The measurements of the semileptonic exclusive rates are becoming precise enough for detailed comparisons with the model predictions. Both CLEO [4] and ARGUS [5] rely on the initial $D^{*+} \to \pi_s^+ D^0$ decay to reduce backgrounds. CLEO also exploits their exceptional calorimeter to utilize the initial $D^{*+} \to \pi_s^0 D^+$ decay to gain access to the D^+ channels. This technique utilizes the fact that although the momentum of the neutrino is lost, the mass difference, $\delta m = m_{\overline{K}^{(*)} l^+ \pi_s^+} - m_{\overline{K}^{(*)} l^+}$ still peaks at the nominal value. As the mass of the $\overline{K}^{(*)} l$ system increases the momentum carried away by the neutrino decreases and the δm distribution becomes more sharply peaked as shown in Figure 1 for Monte Carlo $D^{*+} \to \pi^+ D^0$, $D^0 \to K^- l^+ \overline{\nu}$ events.

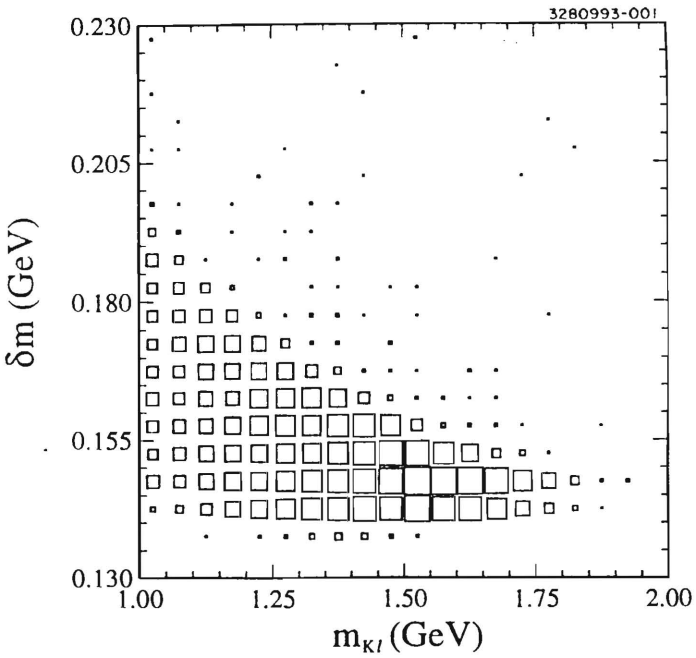

Figure 1: The mass difference, $\delta m = m_{K^-l^+\pi_s^+} - m_{K^-l^+}$, versus $m_{K^-l^+}$ for $D^{*+} \to \pi_s^+$, $D^0 \to K^-l^+\overline{\nu}$ Monte Carlo events.

2.1 Measurement of the $D \to \overline{K}^{(*)}e^+\overline{\nu}$ branching ratios

The CLEO collaboration has measured yields in all four Cabibbo favored decay modes of the D^0 and D^+, $D^0 \to K^-l^+\overline{\nu}$, $D^+ \to \overline{K}^0 l^+\overline{\nu}$, $D^0 \to K^{*-}l^+\nu$ and $D^+ \to \overline{K}^{*0}l^+\overline{\nu}$. The $\overline{K}^*$ channels are reconstructed through the following decay chains, $K^{*-} \to K_s^0\pi^-$, $K_s^0 \to \pi^+\pi^-$ and $\overline{K}^{*0} \to K^-\pi^+$. The data is split into two mass regions, low $\overline{K}^{(*)}l^+$ mass ($1.2 \leq m_{\overline{K}^{(*)}l^+} < 1.4$ GeV/c^2) and high $\overline{K}^{(*)}l^+$ mass ($1.4 \leq m_{\overline{K}^{(*)}l^+} < 1.8$ GeV/c^2) to take advantage of the correlation in Figure 1. For the $D \to \overline{K}^*l^+\overline{\nu}$ modes a fit was performed to the $M_{K\pi}$ distributions for each bin in δm. The data is shown in Figure 2. CLEO combines the electronic and muonic yields, corrects for the phase space difference due to the different lepton masses [6], and quotes a value for the semi-electronic branching ratio. The yields are normalized to hadronic decay modes of the D that resemble in topology the semileptonic decay. Table 1 lists the four ratios obtained by CLEO compared with previous measurements, also included is a recent result from the ARGUS collaboration on $D^0 \to K^{*-}e^+\overline{\nu}$. For those ratios where a common normalizing mode has been used among the experiments, the agreement is quite good.

2.2 Measurement of the q^2 of the $f_+(q^2)$ form factor

With the large sample of $D^0 \to K^-l^+\overline{\nu}$ decays, 1510 ± 60 events, CLEO has extracted the q^2 distribution and performed a fit to two functional forms of the form factor $f_+(q^2)$. The most common form is the pole form, $f(q^2) = f_+(0)/(1 - q^2/M_{pole}^2)$, where one extracts the value of the M_{pole}. There also exists an exponential parameterization due to Isgur *et al.* (ISGW) of the form $f_+(q^2) = f_+(0)e^{\alpha q^2}$ [7].

To calculate q^2 for the event, CLEO II uses $q^2 = M_l^2 + 2[E_l E_{\overline{\nu}} - P_l P_{\overline{\nu}} \cos\theta_{l\overline{\nu}}]$ where in the Kl rest frame only $\cos\theta_{l\overline{\nu}}$ is unknown. The range of $\cos\theta_{l\overline{\nu}}$ can be restricted to reside within the two values given by $\cos\theta_{l\overline{\nu}} = \cos\theta_{\pi\overline{\nu}}\cos\theta_{\pi l} \pm \sin\theta_{\pi\overline{\nu}}\sin\theta_{\pi l}$ where $\theta_{\pi\overline{\nu}}$ is determined from δm and m_{Kl}. The value of q^2 within the allowed range that is the most probable solution based on

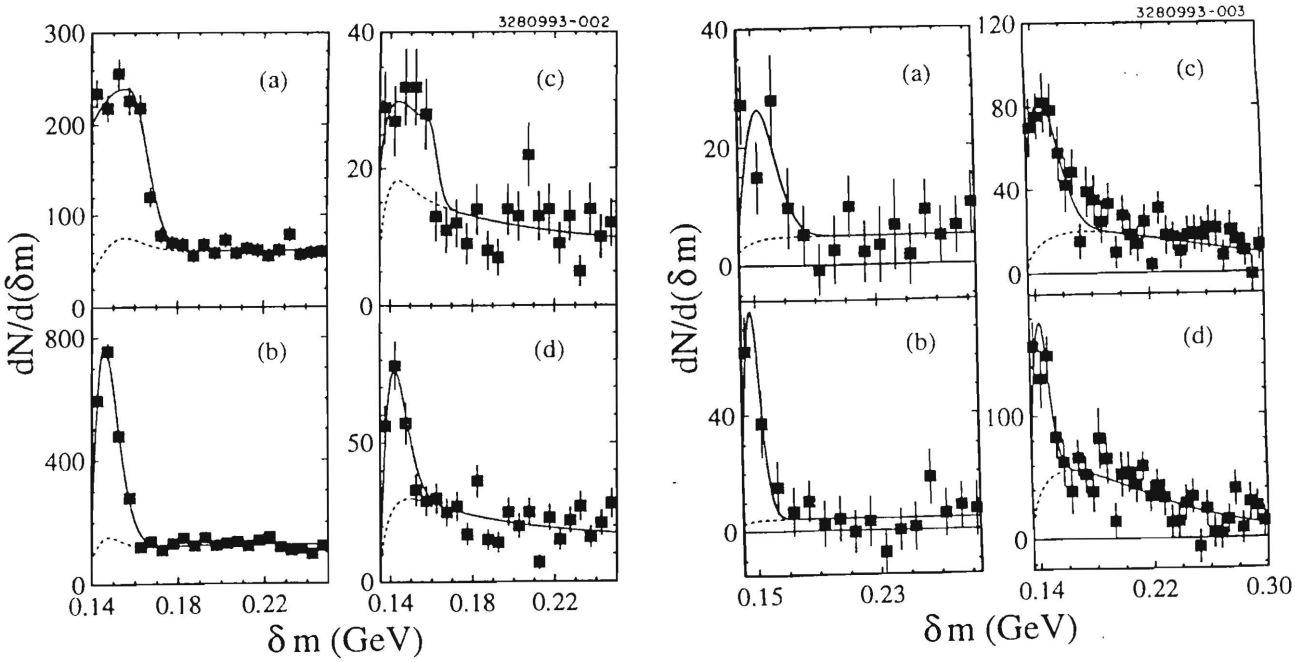

Figure 2: Fits to the δm distributions for $D^0 \to K^- l^+ \overline{\nu}$ in the left most column, $D^+ \to \overline{K}^0 l^+ \overline{\nu}$ in the next column, $D^0 \to K^{*-} l^+ \overline{\nu}$ in the next to last column and $D^+ \to \overline{K}^{*0} l^+ \overline{\nu}$ in the right most column. The top row represents the low $\overline{K}l$ mass sample and the bottom row represents the high $\overline{K}l$ mass sample. The dashed lines indicate the sum of all backgrounds.

EXPT	$\frac{\mathcal{B}(D^0 \to K^- e^+ \overline{\nu})}{\mathcal{B}(D^0 \to K^- \pi^+)}$	$\frac{\mathcal{B}(D^+ \to \overline{K}^0 e^+ \overline{\nu})}{\mathcal{B}(D^+ \to \overline{K}^0 \pi^+)}$	$\frac{\mathcal{B}(D^0 \to K^{*-} e^+ \overline{\nu})}{\mathcal{B}(D^0 \to \overline{K}^0 \pi^+ \pi^-)}$	$\frac{\mathcal{B}(D^+ \to \overline{K}^{*0} e^+ \overline{\nu})}{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}$
CLEO II [4]	$0.978 \pm 0.027 \pm 0.044$	$2.60 \pm 0.35 \pm 0.26$	$0.38 \pm 0.06 \pm 0.03$	$0.67 \pm 0.09 \pm 0.07$
			$\frac{\mathcal{B}(D^0 \to K^{*-} e^+ \overline{\nu})}{\mathcal{B}(D^0 \to K^{*-} \pi^+ \pi^-)}$	
ARGUS [5, 15]			$0.40 \pm 0.07 \pm 0.07$	$0.55 \pm 0.08 \pm 0.10$
			$\frac{\mathcal{B}(D^0 \to K^{*-} e^+ \overline{\nu})}{\mathcal{B}(D^0 \to K^- e^+ \overline{\nu})}$	
CLEO1.5 [16]	0.87 ± 0.07		$0.51 \pm 0.18 \pm 0.06$	
		$\frac{\mathcal{B}(D^+ \to \overline{K}^0 e^+ \overline{\nu})}{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}$		
E691 [17]	$0.91 \pm 0.07 \pm 0.11$	$0.66 \pm 0.09 \pm 0.14$		$0.49 \pm 0.04 \pm 0.05$
E687 [18]	$0.87 \pm 0.08 \pm 0.06$			$0.56 \pm 0.04 \pm 0.06$
WA82 [19]				$0.62 \pm 0.15 \pm 0.09$
	$\frac{\mathcal{B}(D^0 \to K^- e^+ \overline{\nu})}{\mathcal{B}(D^0 \to e^+ X)}$			
E653 [20]	$0.32 \pm 0.05 \pm 0.05$			$0.46 \pm 0.07 \pm 0.08$
	$\mathcal{B}(D^0 \to K^- e^+ \overline{\nu})$	$\mathcal{B}(D^+ \to \overline{K}^0 e^+ \overline{\nu})$	$\mathcal{B}(D^0 \to K^{*-} e^+ \overline{\nu})$	$\mathcal{B}(D^+ \to \overline{K}^{*0} e^+ \overline{\nu})$
MARK III [21]	$3.4 \pm 0.5 \pm 0.4\%$	$6.0^{+2.2}_{-1.3} \pm 0.7\%$	$5.4^{+1.9}_{-1.1} \pm 0.6\%$	$4.4^{+1.9}_{-1.0} \pm 0.7\%$

Table 1: Summary of $D \to K^{(*)} l^+ \overline{\nu}$ branching ratio measurements. The use of different normalizing modes makes comparisons difficult for the $D^+ \to \overline{K}^0 l^+ \overline{\nu}$ and $D^0 \to K^{*-} l^+ \overline{\nu}$ channel.

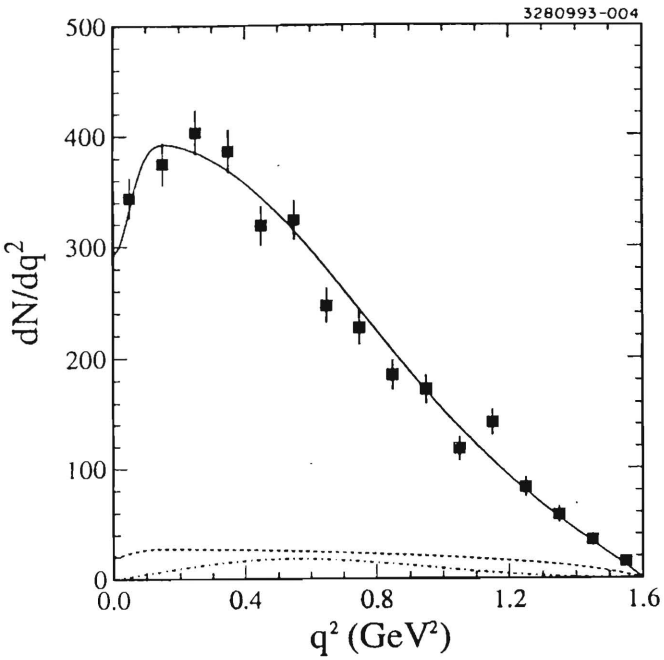

Figure 3: The q^2 distribution for the $D^0 \to K^- l^+ \overline{\nu}$ sample. The solid curve is the result of the fit. The dashed line represents the combinatorial background and the dotted line is the contribution from $K^* l\nu$ decays.

the known decay angular distributions is then chosen. This gives a resolution in q^2 of 0.24 GeV^2 (RMS). The data and fit are shown in Figure 3. The result of the fit is $M_{pole} = 2.00 \pm 0.12 \pm 0.18$ GeV or $\alpha = 0.29 \pm 0.04 \pm 0.06$ GeV^{-2}. The pole mass agrees with the expected value of the D_s^* mass, and the value of α corresponds to $\kappa = 0.57 \pm 0.07$ which agrees with the value of $\kappa = 0.7$ used by ISGW.

Now integrating $f_+(q^2)$ over the q^2 range the value of $f_+(0)$ can be extracted. Using the CLEO II [8] measurement of $\mathcal{B}(D^0 \to K^-\pi^+)$ and the world average [1] for τ_{D^0}, CLEO finds $\Gamma(D^0 \to K^- e^+ \overline{\nu}) = (9.1 \pm 0.3 \pm 0.6) \times 10^{10} s^{-1}$ for the decay width. This width corresponds to $f_+(0) = 0.77 \pm 0.01 \pm 0.04$ in good agreement with the model predictions [6, 7, 9, 10, 11, 12, 13, 14]. CLEO also extracts the decay width for $D \to \overline{K}^* e^+ \overline{\nu}$ by averaging the two $D \to \overline{K}^* e^+ \overline{\nu}$ modes, they find $\Gamma(D \to \overline{K}^* e^+ \overline{\nu}) = (5.7 \pm 0.7) \times 10^{10} s^{-1}$.

2.3 Observation of the decay, $D^+ \to \pi^0 l \overline{\nu}$

CLEO [22] last year reported observation of the Cabibbo suppressed decay $D^+ \to \pi^0 l^+ \overline{\nu}$. The technique was similar to that just described for the Cabibbo favored channels except that tighter cuts were used. Figure 4 shows the δm distribution for the CLEO $D^+ \to \pi^0 l^+ \overline{\nu}$ candidates and the δm distribution for the normalizing mode $D^+ \to \overline{K}^0 l^+ \overline{\nu}$. The result obtained was $\mathcal{B}(D^+ \to \pi^0 l^+ \overline{\nu})/\mathcal{B}(D^+ \to \overline{K}^0 l^+ \overline{\nu}) = 8.5 \pm 2.7 \pm 1.4\%$. The ratio of the Cabibbo suppressed to the Cabibbo favored decay rate provides access to the ratio of form factors involved in the decay, $|\frac{f_+^\pi(0)}{f_+^K(0)}|^2 = |\frac{V_{cs}}{V_{cd}}|^2 \frac{2\mathcal{B}(D^+ \to \pi^0 l^+ \overline{\nu}) C_\pi(q^2)}{\mathcal{B}(D^+ \to \overline{K}^0 l^+ \overline{\nu}) C_K(q^2)}$. Here C_π and C_K are the results of integrating the phase space and q^2 dependence of the form factors over the allowed q^2 range. The factor of two accounts for the coupling of the $d\overline{d}$ quarks to the π^0. Using the PDG values for the CKM matrix elements CLEO finds $|f_+^\pi(0)/f_+^K(0)| = 1.29 \pm 0.21 \pm 0.11$ in agreement with expectations that this ratio is unity.

MARK III [23] has previously reported a measurement of $D^0 \to \pi^- e^+ \overline{\nu}$ based on 7 events

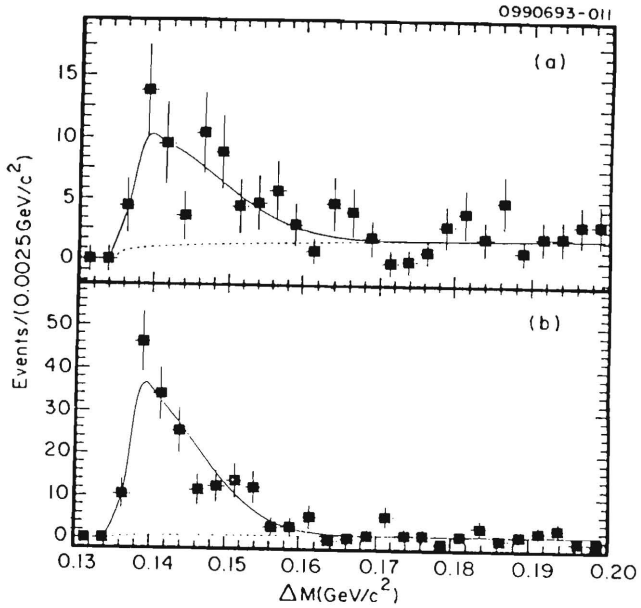

Figure 4: The δm distribution for a) $D^+ \to \pi^0 l^+ \nu$ candidates and for b) $D^+ \to \overline{K}^0 l^+ \nu$ candidates.

Mode	Source	Rate ($10^{10} s^{-1}$)
$D \to \overline{K} e \overline{\nu}$	CLEO II [4]	$9.1 \pm 0.3 \pm 0.6$
$D \to \overline{K}^* e \overline{\nu}$	CLEO II [4]	5.7 ± 0.7
$D \to \pi e \overline{\nu}$	CLEO II [22]/MARK III [23]	1.2 ± 0.3
Sum		16.0 ± 1.0
$D \to X e \overline{\nu}$	MARK III [24]	16.7 ± 1.5
Gap		0.7 ± 1.8

Table 2: Comparison of the sum of exclusive semileptonic channels of the D meson to the inclusive measurement.

in a double tagged sample. They find $\mathcal{B}(D^0 \to \pi^+ e^- \overline{\nu}) = 0.39^{+0.24}_{-0.11} \pm 0.04\%$. Using their yield in the $D^0 \to K^- e^+ \nu$ decay mode they find $|f_+^\pi(0)/f_+^K(0)| = 1.0^{+0.6}_{-0.3} \pm 0.1$ in agreement with the CLEO result. The average decay width for $D \to \pi e^+ \overline{\nu}$ is given in Table 2.

2.4 $\sum_i \Gamma(D \to X_i l \overline{\nu})$ versus $\Gamma(D \to X l \overline{\nu})$

It has been noted that the sum of the exclusive semileptonic decay widths does not saturate the inclusive $D \to X l \overline{\nu}$ measurements. Table 2 sums up the CLEO II measurement for the Cabibbo favored channels and the average of the CLEO II and MARK III measurements for $D \to \pi e^+ \overline{\nu}$. This sum is then compared with the average of the MARK III measurements of the inclusive rate. There is no gap evident. Other decay modes, Cabibbo suppressed and higher mass K^* resonances, do not account for much of the D semileptonic decay width.

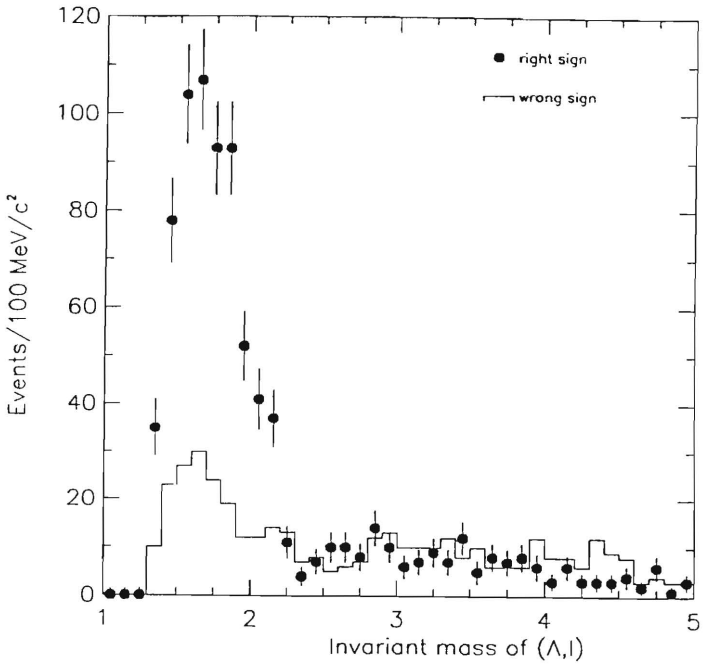

Figure 5: The $M_{\Lambda l}$ distribution for the CLEO data. The points are the right sign data and the histogram is the wrong sign data.

3 $\Lambda_c \to \Lambda l \overline{\nu}$

The semileptonic decay of the Λ_c provides an excellent laboratory to study weak decays of charmed baryons. Compared to charm meson semileptonic decays, the Λ_c semileptonic decay is simpler to interpret. This is due to the fact that the ud spectator quarks form an isospin zero and spin zero system that is unperturbed during the decay. Thus the two dominant decay channels are $\Lambda_c \to \Lambda l \overline{\nu}$ and $\Lambda_c \to \Lambda^* l \overline{\nu}$. Both ARGUS [25] and CLEO [26] extract the yield of $\Lambda_c \to X \Lambda l \overline{\nu}$ by studying Λl correlations in the data.

3.1 $\mathcal{B}(\Lambda_c \to pK\pi)/\mathcal{B}(\Lambda_c \to X\Lambda l\overline{\nu})$ and extraction of $B(\Lambda_c \to pK\pi)$

Figure 5 shows the Λl invariant mass distribution for the CLEO data. The solid histogram is the wrong sign background determined from data. A clear excess of $530 \pm 27 \pm 40$ events is observed. The yield of $\Lambda_c \to pK\pi$ is normalized to the semileptonic yield, CLEO finds, $R = \mathcal{B}(\Lambda_c \to pK\pi)/\mathcal{B}(\Lambda_c \to X\Lambda l\overline{\nu}) = 1.8 \pm 0.1 \pm 0.3$ and ARGUS with smaller statistics finds, $R = 2.7 \pm 0.8 \pm 0.6$. The average of the two results is $< R >= 1.9 \pm 0.3$

By noting that the inclusive semileptonic width for all charm decays should be equal, one can determine the inclusive branching fraction for $\mathcal{B}(\Lambda_c \to Xl) =< \Gamma(D \to Xl) > \tau_{\Lambda_c}$ [24, 1]. One further assumption is needed that being $f = \mathcal{B}(\Lambda_c \to X\Lambda l\overline{\nu})/\mathcal{B}(\Lambda_c \to Xl) = 0.8 \pm 0.2$. This is a *guess* based on the observed ratio in charm meson decay [4], $\Gamma(D \to (K^* + K)l\overline{\nu})/\Gamma(D \to Xl) = 0.89 \pm 0.10$. Combining we find $\mathcal{B}(\Lambda_c \to pK\pi) = f < R > \mathcal{B}(\Lambda_c \to Xl) = 5.2 \pm 1.7\%$.

3.2 Measurement of the decay asymmetry

The differential decay rate for $\Lambda_c \to \Lambda l \overline{\nu}$ can be written as,

$$\frac{d\Gamma}{dq^2 d\cos\theta_\Lambda} \propto 1 + \alpha_{\Lambda_c}\alpha_\Lambda \cos\theta_\Lambda. \tag{2}$$

Where θ_Λ is the angle between the proton in the Λ rest frame with respect to the Λ direction in the Λ_c rest frame. There are two asymmetry parameters; α_{Λ_c} and α_Λ. Using $\alpha_\Lambda = 0.64$ determined from $\Lambda \to p\pi$ decays one can extract α_{Λ_c}. CLEO finds $\alpha_{\Lambda_c} = -0.87^{+0.22}_{-0.13}$ and ARGUS finds $\alpha_{\Lambda_c} = -0.91 \pm 0.49$. The prediction that the asymmetry be maximal at $q^2 = 0$ and not to deviate far from that value is in agreement with these measurements [27].

4 Observation of $D_s \to \mu\overline{\nu}$ and extraction of f_{D_s}

The decay $D_s \to l\overline{\nu}$ proceeds through annihilation of the $c\overline{s}$ quarks and therefore provides access to the wave function overlap of the $c\overline{s}$ quarks at zero spatial separation. This overlap is known as the meson decay constant, f_{D_s}. The decay rate for $D_s \to l\overline{\nu}$ is written as

$$\Gamma(D_s \to l^+\overline{\nu}) = \frac{1}{8\pi} G_F^2 f_{D_s}^2 m_l^2 M_{D_s} (1 - \frac{m_l^2}{M_{D_s}^2})^2 |V_{cs}|^2, \tag{3}$$

where M_{D_s} is the mass of the D_s and m_l is the mass of the lepton. The relative branching ratios for the $e\overline{\nu}$, $\mu\overline{\nu}$ and $\tau\overline{\nu}$ decay modes are $2 \times 10^{-5} : 1 : 10$. Although the $\tau\overline{\nu}$ mode has the largest relative branching ratio it is experimentally hard to detect. The $\mu\overline{\nu}$ channel is the most promising channel and there are several efforts to observe this decay both at fixed target experiments and e^+e^- experiments.

4.1 Hermiticity and CLEO

The decay $D_s \to \mu\overline{\nu}$ is a two body decay and the neutrino carries away a large amount of momentum. CLEO [29] uses the visible energy and momentum in the event to *reconstruct* $p_{\overline{\nu}}$ and $E_{\overline{\nu}}$. With the momentum of the neutrino one can then form the mass difference, $\delta m = M_{D_s^*} - M_{D_s} = M_{\gamma\mu\overline{\nu}} - M_{\mu\overline{\nu}}$. To demonstrate that the technique works, $D^{*0} \to \gamma D^0$, $D^0 \to K^-\pi^+$ events in the data, were reconstructed without using the momentum information of the π^+. The resulting δm distribution is shown in Figure 6a. In Figure 6b is the δm distribution for $D^{*+} \to \pi^+ D^0$, $D^0 \to K^-\pi^+$ events where momentum information for the pions from both the D^{*+} decay and the D^0 decay are ignored. This plot represents the random photon background. A clear signal is observe is Figure 6a and there is no signal in Figure 6b.

4.2 Extraction of the yield and f_{D_s}

The estimate the physics backgrounds CLEO uses the electron sample reconstructed with the same cuts as the muon sample; as most physics backgrounds have the same rate for electrons and muons. Figure 7 shows the resulted δm distribution for the data with the background levels overlaid. CLEO finds 52 ± 14 events and normalizing to the $D_s \to \phi\pi$ yield they measure $\Gamma(D_s \to \mu\overline{\nu})/\Gamma(D_s \to \phi\pi) = 0.245 \pm 0.052 \pm 0.074$. Using $\mathcal{B}(D_s \to \phi\pi) = 3.7 \pm 0.9\%$, the decay constant f_{D_s} is measured to be $344 \pm 37 \pm 52 \pm 42$. The previous result of WA75 is consistent with this result [30].

5 Conclusions

The large dataset collected by the CLEO collaboration has enabled statistically rich measurements of the Cabibbo favored semileptonic channels and has provided sensitivity to suppressed processes. As CLEO continues to collect data the statistical significance of the signals observed

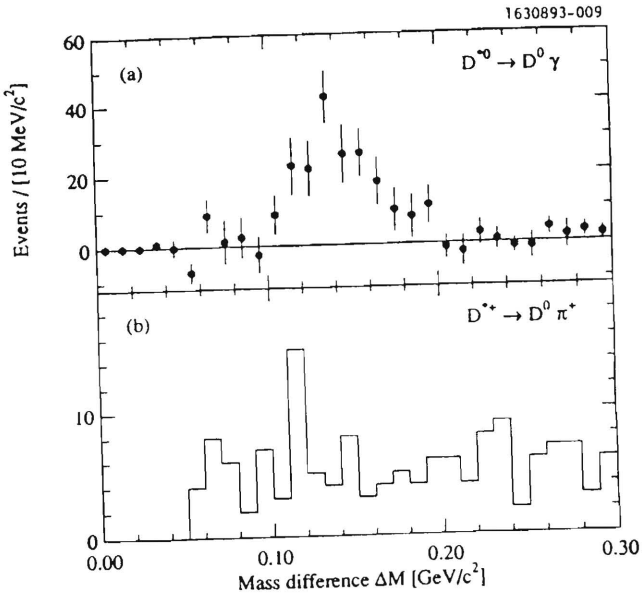

Figure 6: The δm distribution for a) the $D^{*0} \to \gamma D^0$, $D^0 \to K^-\pi^+$ events where the π information is ignored, and b)the $D^{*+} \to \pi^+ D^0$, $D^0 \to K^-\pi^+$ where information from both pions is ignored.

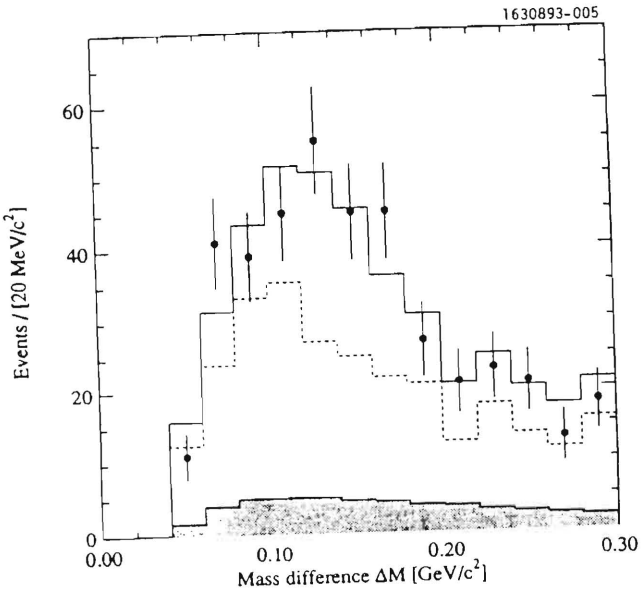

Figure 7: The δm distribution for $D_s \to \mu\bar{\nu}$ candidate events. The points are the muon data, the dashed histogram represents the electron data and the shaded region represents the fake muon contribution. The solid histogram is the result of the fit.

in the $D^+ \to \pi^0 l^+ \overline{\nu}$ and $D_s \to \mu\overline{\nu}$ decay channels should improve and the measurements of $f_+^\pi(0)/f_+^K(0)$ and f_{D_s} will become more precise.

6 Acknowledgements

Much of what has been presented here represents the tireless efforts of my colleagues on CLEO and I thank them for their efforts. I would also like to thank the ARGUS collaboration their results presented here.

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