Exclusive Semileptonic Decays of $D$ Mesons Produced at Threshold

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Abstract. Initial running of the CLEO-c detector has provided the world’s largest sample of $\psi(3770)$ decays. Using this data sample, we have reconstructed $D$ mesons decaying to hadronic final states and have used them to tag events with a charm-anti-charm pair. In this contribution, we present preliminary results from this data sample, which constitute a first step towards measurements of semileptonic decay form factors and the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $V_{cs}$ and $V_{cd}$ with the full CLEO-c data set to be collected in the near future.

1. Introduction
The matrix element of a semileptonic decay factorizes into a product of a leptonic and a hadronic current. For this reason semileptonic decays are the principal process for extracting the CKM matrix elements (the coupling at the vertex of the quark transition) and probing QCD effects of the hadron formation described by the hadronic current, which are usually parameterized by form factors.

In this contribution, preliminary results of a study of a number of $D_0^0$ ($D_0^0 \to \pi^- e^+ \nu$, $D_0^0 \to K^- e^+ \nu$, $D_0^0 \to K^*0$($K^-\pi^0)e^+\nu$ and $D_0^0 \to \rho^-(\pi^-\pi^0)e^+\nu$) and $D^+$ ($D^+ \to K^0(\pi^-\pi^+)e^+\nu$, $D^+ \to K^0(\pi^-\pi^+)e^+\nu$, $D^+ \to K^0(\pi^-\pi^+)e^+\nu$, $D^+ \to \rho^0(\pi^-\pi^+)e^+\nu$) semileptonic modes using the 57 pb$^{-1}$ data sample collected at the $\psi(3770)$ resonance in the fall (2003) – winter (2004) running period by the CLEO-c detector at the Cornell Electron Storage Ring (CESR) are presented. (The CLEO-c detector is a modified version of the CLEO III detector described in [1]). Among the modes listed above, the two modes of $D_0^0 \to \pi^- e^+ \nu$ and $D_0^0 \to K^- e^+ \nu$ are especially important as they are simplest for both theory (e.g., LQCD [2]) and the experiment, and therefore they will provide very stringent tests of the theory and most precise measurements of the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$ in the near future.

2. Analysis technique
The $\psi(3770)$ resonance decays to final states with two $D$ mesons and no extra particles. The analysis technique is to fully reconstruct one $D$ meson in a hadronic final state, which is referred to as the tag, and then to analyze the decay of the second $D$ meson in the event to extract its properties. In this analysis the absolute exclusive $D$ semileptonic branching ratios are determined. The technique is well illustrated by Figure 1, which shows a typical event in which the tag is reconstructed in a hadronic channel $D_0^0 \to K^+\pi^-$. Tagging creates a single $D$ beam of known momentum. From the remaining tracks and showers in the event a semileptonic decay is reconstructed (tracks $K^-$ and $e^+$ in the event shown for $D_0^0 \to K^- e^+ \nu$). To separate signal
from background, we define $U \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}|$, where $E_{\text{miss}}$ and $|\vec{p}_{\text{miss}}|$ are the missing energy and momentum of the $D$ decaying semileptonically. If only a massless particle is missing, $U$ peaks at zero. Due to the finite resolution of the detector, semileptonic decays are approximately Gaussian in $U$ and occupy a region centered at $U = 0$ that is approximately 10 MeV wide (this value varies by mode). Events in which there are missing particles or an incorrect assignment of particles populate the regions outside the signal region at zero allowing a smooth extrapolation into the signal region and extraction of the signal yields in fits to the $U$ distributions.

The semileptonic branching ratio for a $D$ meson, for example, for $D^0 \to K^−e^+\nu$, averaged over the charge conjugate states is measured using tag events in the following way:

$$B(D^0 \to K^−e^+\nu) = \frac{N_{\text{signal}}}{N_{\bar{D}^0}} \epsilon,$$

where $N_{\text{signal}}$ is the number of fully reconstructed signal events with semileptonic decays obtained from a fit to the $U$ distribution, $N_{\bar{D}^0}$ is the number of events tagged with $\bar{D}^0$ or $D^0$ meson, and $\epsilon$ is the reconstruction efficiency for the semileptonic decay in the presence of a $D$ tag. To good approximation, it is independent of the $D$ tag mode with which the semileptonic decay is reconstructed.

3. Event selection

Tags are reconstructed in the following modes: $K^{-}\pi^{+}$, $K^{-}\pi^{+}\pi^{0}$, $K^{-}\pi^{+}\nu\pi^{0}$, $K^{-}\pi^{+}\nu\pi^{-}$, $K_{S}^{0}\pi^{0}$, $K_{S}^{0}\pi^{+}\pi^{-}$, $K_{S}^{0}\pi^{+}\pi^{-}\pi^{0}$, $K^{-}K^{-}$, for neutral $D$ mesons, and the following modes: $K_{S}^{0}\pi^{+}$, $K^{-}\pi^{+}\pi^{+}$, $K_{S}^{0}\pi^{+}\pi^{0}$, $K^{-}\pi^{+}\pi^{0}$, $K_{S}^{0}\pi^{+}\pi^{-}$, $K^{-}\pi^{+}\pi^{-}$, for charged $D$ mesons. The selection of tags follows closely the procedure in [3]. In events with tags having $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - \vec{p}_{D}^2} \in [M_D - 6.5 \text{ MeV}/c^2; M_D + 9.5 \text{ MeV}/c^2]$, the reconstruction of the semileptonic side is attempted. Figure 2 shows the $M_{bc}$ distributions for a few $D$ tag modes, as an example. Below, only the selection criteria for the semileptonic side of the event are briefly described.

All tracks and showers are required to satisfy a set of standard quality criteria. Charged pions or kaons are identified using the specific ionization information ($dE/dx$) in the drift chamber and the information from the Ring Imaging Cherenkov Detector (RICH), if it is available. Identification of electrons for tracks above 200 MeV/$c$ is based on a likelihood function constructed from the ratio of the energy deposited in the calorimeter to the track momentum measured by the drift chambers, and the information from the $dE/dx$ and RICH systems. Bremsstrahlung photons from electrons are recovered using showers in the crystal calorimeter that are not matched to the electron track but that line up with the track momentum. Neutral pion candidates are formed from pairs of showers with the invariant mass within $[-3.5\sigma;+3.0\sigma]$ from the $\pi^0$ mass. $K_{S}^{0}$ candidates are built from pairs of oppositely charged pions constrained by
Figure 2. Examples of the $M_{bc}$ distributions for $D^0$ (first row) and $D^+$ (second row) tags. There are nine $D^0$ tag modes and six $D^+$ tag modes in the study. The last column shows the sum of all $D^0$ and $D^+$ tag modes. The arrows show the signal window for $D$ tags. Preliminary.

Figure 3 shows fits to $U$ distributions for $D^0$ and $D^+$ semileptonic decays. In these fits, a signal PDF function consisting of a crystal ball function and a Gaussian is used for the main results. Differences in the fit results to an alternative PDF function (double Gaussian) are reflected in the systematic uncertainties. Background PDF functions are determined from the generic Monte Carlo simulation; their normalizations are allowed to float in the fits.

We have considered the following sources of systematic uncertainty in the measurements of the branching fractions. The uncertainties associated with the track (3.0% per track), $\pi^0$ (4.4% per $\pi^0$) and $K_S^0$ (3.0% per $K_S^0$) finding efficiencies are estimated using missing mass techniques [4]. The uncertainty in electron identification efficiency is evaluated by embedding studies, in which the tracks in radiative Bhabha events were analyzed in isolation and after embedding in hadronic events; a 2.0% systematic uncertainty is assigned from this source. Uncertainties in the charged pion and kaon identification efficiencies are estimated using hadronic $D$ meson decays (1.0% per pion and 1.0% per kaon). Other smaller systematic uncertainties include uncertainties in the number of $D$ tags, the modeling of the background shapes in the fits to the $U$ distributions, the incomplete knowledge of the semileptonic form factors, the requirement that the number of tracks unused in the full event reconstruction be zero, and uncertainties in the simulation of the final-state radiation. In addition, there is systematic uncertainty due to the limited size of the Monte Carlo sample used for measuring the reconstruction efficiencies.

Table 1 show the preliminary results for the $D^0$ modes. These results were first reported in [5] and are currently being revised for publication. The results for the $D^+$ semileptonic branching fractions are forthcoming. The statistical uncertainties for the $D^0$ modes and the expected uncertainties for the $D^+$ modes in this contribution are all smaller than the total uncertainties in [6], and many systematic uncertainties above are already reduced. The mode $D^0 \rightarrow \rho^- e^+ \nu$ is observed for the first time. The set of $D$ semileptonic branching ratios of the modes in this contribution, when combined with the precisely determined $D$ meson lifetimes [6], allows a test of a variety of relations among the $D^0$ and $D^+$ semileptonic decay widths, on which we will report in a journal publication.
Figure 3. Fits to the $U$ distribution for $D^0$ (first row) and $D^+$ (second row) semileptonic decays. Preliminary.

| Decay Mode                  | $B$ (%) (here) | $B$ (%) (PDG-04) |
|-----------------------------|----------------|------------------|
| $D^0 \to \pi^- e^+ \nu$    | 0.25 ± 0.03 ± 0.02 | 0.36 ± 0.06 |
| $D^0 \to K^- e^+ \nu$      | 3.52 ± 0.10 ± 0.25 | 3.58 ± 0.18 |
| $D^0 \to K^{*-}(K^-\pi^0)e^+\nu$ | 2.07 ± 0.23 ± 0.18 | 2.15 ± 0.35 |
| $D^0 \to \rho^- e^+ \nu$  | 0.19 ± 0.04 ± 0.02 | — |

Table 1. Summary of preliminary results for $D^0$ semileptonic decays. In the second column, the first uncertainty is statistical and the second uncertainty is systematic. The results for $D^+$ semileptonic branching fractions are forthcoming.

4. Conclusion

Using 57 pb$^{-1}$ of data collected with the CLEO-c detector at the $\psi(3770)$ resonance in a pilot run, we have presented the preliminary results for $D$ semileptonic decays. These results are being revised for a journal publication. Among the modes considered in this contribution, the modes of $D^0 \to \pi^- e^+ \nu$ and $D^0 \to K^- e^+ \nu$ are especially important; they will provide a rigorous test of the theory and precise measurements of the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$ in the near future. With this modest in size data sample, we have measured $\Gamma(D^0\to\pi^-e^+\nu)/\Gamma(D^0\to K^-e^+\nu) = (7.0 \pm 0.7 \text{(stat)} \pm 0.3 \text{(sys)}) \times 10^{-2}$, which is consistent with the CLEO III result in [7], and we have observed $D^0 \to \rho^- e^+ \nu$ for the first time.

Reference

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