Open Charm Physics at CLEO-c

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Recent CLEO-c results on open charm physics at the \( \psi(3770) \) are presented. Measurements of hadronic and semileptonic branching fractions of the \( D^0 \) and \( D^+ \) mesons are discussed as well as the leptonic decay \( D^+ \to \mu^+ \nu_\mu \) and determination of the \( D \) meson decay constant.

1 Introduction

The CLEO-c experiment at the Cornell Electron Positron Storage Ring has recorded 281 pb\(^{-1} \) at the \( \psi(3770) \). This sample provides a very clean environment for studying decays of \( D \) mesons. The \( \psi(3770) \) produced in the \( e^+e^- \) annihilation decays to pairs of \( D \) mesons, either \( D^+D^- \) or \( D^0\bar{D}^0 \). In particular, the produced \( D \) mesons can not be accompanied by any additional pions.

The analyses presented here all have in common that they use a tagging technique. This technique was used by the MARK III collaboration\(^{11} \). In these analyses one of the \( D \) mesons is fully reconstructed in a hadronic final state. From energy and momentum conservation we can predict the four-momentum of the other \( D \) meson in the event.

We report here on measurements of the absolute hadronic branching fractions of \( D^0 \) and \( D^+ \) mesons, measurements of semileptonic branching fractions and the measurement of the branching fraction for the leptonic decay \( D^+ \to \mu^+ \nu_\mu \) and the determination of the \( D \) meson decay constant \( f_D \).

2 Absolute \( D \) hadronic branching fractions

Determination of the absolute hadronic branching fractions for \( D \) mesons is important as they provide the normalization for practically all \( B \) decays, and as such impact for example the determination of \( |V_{cb}| \) using exclusive \( B \to D^*\ell\nu \). The branching fractions for \( D^0 \) decays have been measured to about 3% prior to CLEO-c while \( D^+ \) meson branching fractions were only known to about 6%. The results presented here on 56 pb\(^{-1} \) represent significant improvements to the \( D^+ \) branching fractions\(^{2} \).

This analysis makes use of a 'double tag' technique in which we determine the number of single tags, separately for \( D \) and \( \bar{D} \) decays, \( N_i = \epsilon_i B_i N_{DD} \) and \( \bar{N}_j = \bar{\epsilon}_j B_j N_{DD} \) where \( \epsilon_i \) and \( B_i \) are the efficiencies and branching fractions for mode \( i \). Similarly we reconstruct double tags where both \( D \) mesons are found. The number of double tags found is given by \( N_{ij} = \epsilon_{ij} B_i B_j N_{DD} \) where \( i \) and \( j \) label the \( D \) and \( \bar{D} \) mode used to reconstruct the event and \( \epsilon_{ij} \) is the efficiency for
reconstructing the final state. Combining the two equations above we can solve for $N_{DD}$ as

$$N_{DD} = \frac{N_i \bar{N}_j}{N_{ij} \epsilon_i \epsilon_j}.$$ 

In this analysis we make use of three $D^0$ decays and six $D^+$ modes as shown in Fig. 1. We have a total of 2,484 ± 51 neutral double tags and 1,650 ± 42 charged double tags. The scale of the statistical error on the branching fractions are set by the number of double tags, ≈ 2.0% and ≈ 2.5% for the neutral and charged modes respectively. The branching fractions obtained are summarized in Table 1.

### Table 1: Fitted branching fractions and $D\bar{D}$ pair yields. Uncertainties are statistical and systematic, respectively.

| Parameter | Fitted Value | PDG |
|-----------|--------------|-----|
| $N_{D^0\bar{D}^0}$ | $(2.01 \pm 0.04 \pm 0.02) \times 10^9$ | — |
| $B(D^{0} \rightarrow K_{s}^{-} \pi^{+})$ | $(3.91 \pm 0.08 \pm 0.09)$% | $3.18 \pm 0.09$% |
| $B(D^{0} \rightarrow K_{s}^{-} \pi^{+} \pi^{0})$ | $(14.9 \pm 0.3 \pm 0.5)$% | $13.2 \pm 1.0$% |
| $B(D^{0} \rightarrow K^{-} \pi^{+} \pi^{+} \pi^{-})$ | $(8.3 \pm 0.2 \pm 0.3)$% | $7.48 \pm 0.30$% |
| $N_{D^+\bar{D}^-}$ | $(1.56 \pm 0.04 \pm 0.01) \times 10^9$ | — |
| $B(D^{+} \rightarrow K_{s}^{-} \pi^{+} \pi^{+})$ | $(9.5 \pm 0.2 \pm 0.3)$% | $9.2 \pm 0.6$% |
| $B(D^{+} \rightarrow K_{s}^{-} \pi^{+} \pi^{+} \pi^{0})$ | $(6.0 \pm 0.2 \pm 0.2)$% | $6.5 \pm 1.1$% |
| $B(D^{+} \rightarrow K_{s}^{0} \pi_{s}^{+})$ | $(1.55 \pm 0.05 \pm 0.06)$% | $1.42 \pm 0.09$% |
| $B(D^{+} \rightarrow K_{s}^{0} \pi_{s}^{+} \pi^{0})$ | $(7.2 \pm 0.2 \pm 0.4)$% | $5.4 \pm 1.5$% |
| $B(D^{+} \rightarrow K_{s}^{0} \pi_{s}^{+} \pi^{+} \pi^{-})$ | $(3.2 \pm 0.1 \pm 0.2)$% | $3.6 \pm 0.5$% |
| $B(D^{+} \rightarrow K^{+} K^{-} \pi^{+})$ | $(0.97 \pm 0.04 \pm 0.04)$% | $0.89 \pm 0.08$% |

### 3 Semileptonic $D$ decays

Semileptonic branching fractions have been studied for several Cabibbo favored and suppressed modes in a sample of 56 pb$^{-1}$. In this analysis we reconstruct one $D$ meson and look at the recoil $D$ to identify the signal. The signal is identified by requiring that one electron is found and the hadronic final state is reconstructed. This means that all particles except the neutrino...
is reconstructed. Using four-momentum conservation we can infer the energy and momentum of the neutrino. To extract the signal we form a quantity known as $E-U = |P|$. Using four-momentum conservation we can infer the energy and momentum of the neutrino. For signal events this quantity should peak at zero.

Figure 2 shows the semileptonic yields for $D^0$ and $D^+$ decays. The extracted branching fractions are summarized in Table 2.

| Mode | $B(\%)$ CLEOc | $B(\%)$ PDG |
|------|----------------|-------------|
| $D^0 \rightarrow \pi^- e^+\nu_e$ | $0.26 \pm 0.03 \pm 0.01$ | $0.36 \pm 0.06$ |
| $D^0 \rightarrow K^- e^+\nu_e$ | $3.44 \pm 0.10 \pm 0.10$ | $3.58 \pm 0.18$ |
| $D^0 \rightarrow K^{*-}(K^-\pi^0)e^+\nu_e$ | $2.11 \pm 0.23 \pm 0.10$ | $2.15 \pm 0.35$ |
| $D^0 \rightarrow K^{*-}(K^0\pi^-)e^+\nu_e$ | $2.19 \pm 0.20 \pm 0.11$ | $2.15 \pm 0.35$ |
| $D^0 \rightarrow \rho^- e^+\nu_e$ | $0.19 \pm 0.03 \pm 0.04$ | — |
| $D^+ \rightarrow \pi^0 e^+\nu_e$ | $0.44 \pm 0.06 \pm 0.03$ | $0.31 \pm 0.15$ |
| $D^+ \rightarrow K^0 e^+\nu_e$ | $8.71 \pm 0.38 \pm 0.37$ | $6.7 \pm 0.9$ |
| $D^+ \rightarrow K^{*0} e^+\nu_e$ | $5.56 \pm 0.27 \pm 0.23$ | $5.5 \pm 0.7$ |
| $D^0 \rightarrow \rho^0 e^+\nu_e$ | $0.21 \pm 0.04 \pm 0.01$ | $0.25 \pm 0.10$ |
| $D^0 \rightarrow \omega^0 e^+\nu_e$ | $0.16^{+0.07}_{-0.06} \pm 0.01$ | — |

Figure 2: Left: Yields of $D^0$ semileptonic decays to a) $K^- e^+\nu_e$, b) $\pi^- e^+\nu_e$, c) $K^{*-}(K^-\pi^0)e^+\nu_e$, d) $K^{*-}(K^0\pi^-)e^+\nu_e$, and e) $\rho^- e^+\nu_e$. Right: Yields of $D^+$ semileptonic decays to a) $K^0 e^+\nu_e$, b) $K^{*0} e^+\nu_e$, c) $\pi^0 e^+\nu_e$, d) $\rho^0 e^+\nu_e$, and e) $\omega^+$.

4 Leptonic $D^+$ decays and $f_D$

The decay $D^+ \rightarrow \mu^+\nu_\mu$ provides a direct measurement of the $D$ meson decay constant, $f_D$. The partial width for $D^+ \rightarrow \ell^+\nu_\ell$ is given by

$$\Gamma(D^+ \rightarrow \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} f_D^2 m_D m_\ell \left[ 1 - \frac{m_\ell^2}{m_D^2} \right] |V_{cd}|^2$$

where all factors are known except for the decay constant. A measurement of the branching fraction combined with the well known $D^+$ lifetime allows us to determine the decay constant. Precise measurements of the decay constant in $D$ and $D_s$ decays allow for precise tests of Lattice QCD.
This analysis reconstructs charged $D$ mesons in six modes, a total 158, 354 ± 496 tags were reconstructed in the 281 pb$^{-1}$ sample. We look for one, and only one additional track from the interaction point in the event. We require this track to be consistent with being a muon by its energy deposit in the electromagnetic calorimeter (EMC), we require less than 350 MeV to be deposited. In addition, we veto events from $D^+ \rightarrow \pi^+\pi^0$, we require that there were no extra, unmatched, showers in the EMC with an energy of over 250 MeV.

For events that satisfy these requirements we calculate the missing mass square, $M_{\text{miss}}^2$. This is the mass that the tag $D$ and muon candidate is recoiling against. For signal events this will peak at $M_{\text{miss}}^2 = m_{\nu}^2 = 0$. Figure 3 shows the observed missing mass square distribution. The signal region contains 50 events. An evaluations of the backgrounds gives an estimate of $2.81 \pm 0.30 \pm 0.27$ background events in the signal region. Combining the signal yield of $47.2 \pm 7.1^{+0.3}_{-0.8}$ events with the number of tags and the signal detection efficiency we find

$$B(D^+ \rightarrow \mu^+\nu_\mu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}$$

and the decay constant $f_D = (222.6 \pm 16.7^{+2.8}_{-3.4})$ MeV. This measurement is in good agreement with theoretical predictions. In particular, a recent unquenched lattice calculation by the Fermilab-MILC-HPQCD collaboration gives $f_D = (201 \pm 3 \pm 17)$ MeV.

5 Summary

The CLEO-c experiment has recorded 281 pb$^{-1}$ of $e^+e^-$ annihilation data at the $\psi(3770)$. Here results for hadronic branching fractions and semileptonic decays were presented on 56 pb$^{-1}$ and the leptonic decay was based on the full 281 pb$^{-1}$ sample. CLEO-c will run until March 31, 2008 and we plan to record a total of about 750 pb$^{-1}$ at the $\psi(3770)$. We have also recorded a sample of about 200 pb$^{-1}$ at $E_{\text{CM}} \approx 4170$ MeV. The goal is to recored a sample of 750 pb$^{-1}$ at this energy for $D_s$ studies.

Acknowledgments

This work was supported by the National Science Foundation grant PHY-0202078 and by the Alfred P. Sloan fundation.

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