Exclusive $D^0$ Semileptonic Decays and Determinations of $V_{cd}$ and $V_{cs}$

Abstract

Based on a data sample of 60 pb$^{-1}$ collected at the $\psi(3770)$ resonance, we have improved measurements of absolute branching ratios for $D^0$ semileptonic decays into $K^-$ $e^+\nu$, $\pi^-$ $e^+\nu$, $K^{*-}e^+\nu$ and $\rho^-e^+\nu$. The expected sensitivity for measurements of semileptonic decay form factors and the CKM matrix elements will be reviewed.

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1 Introduction

In the Standard Model of electroweak interactions, the weak eigenstates are not the same as the quark mass eigenstates. The weak eigenstates are the mixing of the charge \(-e/3\) quark mass eigenstates \(d, s, b\), conventionally expressed in term of a \(3 \times 3\) unitary matrix \(V\), named as Cabibbo-Kobayashi-Maskawa (CKM) matrix:

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{td} & V_{ts} & V_{tb} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td'} & V_{ts'} & V_{tb'}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix} 
\]

(1)

\(CP\) symmetry violation is an expected consequence of the Standard Model with three quark generations which incorporates a complex phase in the CKM quark-mixing matrix. Besides the \(CP\) violation observed in neutral \(K\) decays, the Standard Model predicts a multitude of \(CP\)-violating effects in \(B\) decays which have been observed at \(B\) factories BABAR and BELLE. To test the predictions of the Standard Model, we need to measure the CKM elements as precisely as possible.

In principle, the values of the CKM matrix elements can be determined from weak decays of the relevant quarks. The current precision for \(V_{cs}\) and \(V_{cd}\) is 13\% and 7\% respectively [1]. At CLEO-c, D meson semileptonic decays can be used to determine two CKM elements \(V_{cs}\) and \(V_{cd}\) more precisely.

Charm meson leptonic and semileptonic decays are depicted in Fig. 1. In the Standard Model, the semileptonic charm meson decay matrix element can be expressed as

\[
\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{cd} \bar{u}(q_e) \gamma^\mu (1 - \gamma_5) u(q_\ell) J^\mu, 
\]

(2)

where \(G_F\) is the Fermi coupling constant, \(V_{cd}\) is a Cabibbo-Kobayashi-Maskawa matrix element; \(q_e\) and \(q_\ell\) are the four-momenta of the neutrino and the lepton, respectively; \(J^\mu \equiv \langle\text{hadrons}|V^\mu - A^\mu|0\rangle\) is the hadronic current, and \(V^\mu\) and \(A^\mu\) are the vector and axial vector quark currents.

The differential decay rate for \(D \to P \ell \nu\) with the electron mass effects neglected (\(P\) stands for a pseudoscalar meson) can be expressed as [2]:

\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cd}|^2 p_\ell^3 \left| f_+(q^2) \right|^2, 
\]

(3)
Figure 1: Charm meson leptonic (a) and semileptonic decays.

where $q^2$ is the four-momentum transfer squared between the parent $D$ meson and the final state meson, $p_P$ is the momentum of the pseudoscalar meson in the $D$ rest frame, and $V_{cd}$ is the relevant CKM matrix element, either $V_{cs}$ or $V_{cd}$. $f_+(q^2)$ is the form factor which measures the probability that the flavor changed quark ($q'$, see Fig. 1b) and the spectator quark ($\bar{q}$) will form a meson in the final state. The corresponding branching fractions can be obtained from

$$B(D \to P \ell \nu) = \frac{\tau_D}{\tau} \int dq^2 \frac{d\Gamma}{dq^2}. \quad (4)$$

From the measurements of the branching fractions, we can extract the CKM elements $V_{cs}$ and $V_{cd}$. To determine an individual matrix element, theory must provide the absolute normalization of the form factor describing the decay at some fixed $q^2$ point, usually at $q^2 = 0$. Since theory also provides the $q^2$ dependence of the form factor, we can check the theory by measuring the form factor shape. At CLEO-c, the gold-plated modes for the determinations of $V_{cs}$ and $V_{cd}$ are the decays $D^0 \to K^- e^+ \nu$ and $D^0 \to \pi^- e^+ \nu$, respectively.

Rewrite Eq. (3), we obtain

$$\frac{d\Gamma}{p_P^2 dq^2} = \frac{G_F^2}{16\pi} |V_{cq}|^2 |f_+(q^2)|^2. \quad (5)$$

From Eq. 5, we can measure the form factor shape.

In the $D$ rest frame, momentum-energy conservation gives

$$p_h = \sqrt{\frac{(m_D^2 + m_h^2 - q^2)^2}{4m_D^2} - m_h^2}. \quad (6)$$

Here $p_h$ stands for the momentum of the final state hadronic system, either a pseudoscalar or a vector meson to be discussed in the $D$ meson rest frame. Alternatively, we have

$$q^2 = (p_\ell^2 + p_\nu^2) - (P_P^2 - p_h^2) = m_D^2 + m_h^2 - 2M_D E_h. \quad (7)$$

Since $(p_\ell^2 + p_\nu^2) \geq m_i^2$ and $E_h \geq m_h$, and we have

$$m_i^2 \leq q^2 \leq m_D^2 + m_h^2 - 2m_D m_h = (m_D - m_h)^2. \quad (8)$$
$D$ meson leptonic decays can provide measurements of their decay constants

$$B(D_q \to \ell^+\bar{v}) = \frac{G_F^2}{8\pi} |V_{cq}|^2 f_{D_q}^2 M_{D_q} m_{\ell}^2 \left(1 - \frac{m_{\ell}^2}{M_{D_q}^2}\right)^2 \tau_{D_q}. \quad (9)$$

Precision measurements of the CKM elements $V_{cs}$ and $V_{cd}$ are essential for us to measure these decay constants precisely.

$$ \theta_e \quad \theta_K \quad \chi \quad W^+ \quad D^0 \quad K^0 \quad K^* $$

Figure 2: Decay angles for $D$ meson semileptonic decays to vector final states. The example given is $D^0 \to K^{*-}e^+\nu$ where $\theta_e$ is the decay angle of lepton in the virtual $W$ rest frame, $\theta_K$ the decay angle of kaon in the $K^{*-}$ rest frame, $\chi$ the angle between the two decay planes defined by $e, \nu_e$, and $K^-, \pi^0$.

$D$ meson semileptonic decays to vector final states (such as $D^0 \to K^{*-}/\rho^- e^+\nu$) with the vector meson to two pseudoscalars ($V \to P_1P_2$) can also provide measurements of the CKM elements $V_{cs}$ and $V_{cd}$, but with much more hadronic complexity. The decays are usually characterized by three decay angles $\theta_\ell$, $\theta_V$ and $\chi$ of the lepton and one heavier pseudoscalar, and the relative orientation of the decay planes as illustrated in Fig. 2; as well as three helicity amplitudes, $H_+(q^2)$, $H_-(q^2)$ and $H_0(q^2)$ which themselves are functions of the vector and axial vector form factors. These characterize the probabilities that the the flavor changed quark ($q'$) and the spectator quark ($\bar{q}$) will form a vector meson in the final state. The differential decay rate with the electron mass effects neglected can be expressed as [3]:

$$ \frac{d\Gamma}{dq^2 d \cos \theta_V d \cos \theta_\ell d \chi} = \frac{3G_F^2}{8(4\pi)^4} |V_{cq}|^2 \frac{p_V q^2}{M_D^2} B(V \to P_1P_2) \times \left[ (1 + \cos \theta_\ell)^2 \sin^2 \theta_V |H_+(q^2)|^2 + (1 - \cos \theta_\ell)^2 \sin^2 \theta_V |H_-(q^2)|^2 \right. $$

$$ + 4 \sin^2 \theta_\ell \cos^2 \theta_V |H_0(q^2)|^2 $$

$$ + 4 \sin \theta_\ell (1 + \cos \theta_\ell) \sin^2 \theta_V \cos \theta_V \cos \chi H_+(q^2)H_0(q^2) $$

$$ - 4 \sin \theta_\ell (1 - \cos \theta_\ell) \sin^2 \theta_V \cos \theta_V \cos \chi H_-(q^2)H_0(q^2) $$

$$ - 2 \sin^2 \theta_\ell \sin^2 \theta_V \cos 2\chi H_+(q^2)H_-(q^2) \right]. \quad (10) $$
The helicity amplitudes can be expressed explicitly by

\begin{align}
H_{\pm}(q^2) &= (M_D + M_V)A_1(q^2) + \frac{2M_D p_V}{M_D + M_V}V(q^2), \\
H_0(q^2) &= \frac{1}{2M_V \sqrt{q^2}} \left[ (M_D^2 - M_V^2 - q^2)(M_D + M_V)A_1(q^2) - 4\frac{M_D^2 p_V^2}{M_D + M_V}A_2(q^2) \right].
\end{align}

(11)

Where \(A_1(q^2)\) and \(A_2(q^2)\) are axial vector form factors and \(V(q^2)\) is the vector form factor, and \(p_V\) is the momentum of the vector meson in the \(D\) rest frame. After integrating over the three decay angles, we have

\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2}{96\pi^3} |V_{\text{ct}}|^2 \frac{p_V q^2}{M_D^2} B(V \rightarrow P_1 P_2) \left( |H_+(q^2)|^2 + |H_-(q^2)|^2 + |H_0(q^2)|^2 \right).
\]

(12)

As the range of \(q^2\) in the decays is small, the decay rate distribution is determined by the three parameters \(A_1(0), A_2(0)\) and \(V(0)\). The shape of the form factors can be measured by comparing the angular and \(q^2\) distributions of the data to the differential decay rate given by Eq. 10. Conventionally, we measure the ratios \(R_V = V(0)/A_1(0)\), \(R_2 = A_2(0)/A_1(0)\) and \(A_1(0)\) instead of \(A_1(0), A_2(0)\) and \(V(0)\) from the angular distributions of the data.

The available data sample of 60 pb\(^{-1}\) taken at the \(\psi(3770)\) during the initial cleo-c running is not enough for the study of the angular distributions. But we will take the form factors from the study of \(D^+ \rightarrow V \ell\nu\) as inputs for systematics study.

Form factors in charm semileptonic decays play an important role in testing lattice QCD and testing other theories of heavy quark decays. The form factors in charm semileptonic decays are related to those in \(B\) decays by Heavy Quark Symmetry and so aid the determination of \(V_{\text{ub}}\) which is hard to be determined precisely at \(B\) factories due to the small branching fractions for \(b \rightarrow u\) transitions and huge backgrounds from \(b \rightarrow c\) transitions.

The shape of the form factors governing semileptonic decays have not been well-measured. At CLEO-c, the kinematics of the threshold production allow for the isolation of the background free samples of semileptonic decays. This in turn allows measurements of the form factors with much better signal to background ratios.

Compared to leptonic decays, semileptonic decays have two distinct advantages. First, they have substantially larger branching fractions and cleaner signatures; and second, they offer more observables, overall rate and form factors, while leptonic decays manifest rate only. Taking advantage of the latter feature, one can use inclusive semileptonic decays to test the heavy quark expansion theory, HQET, and exclusive semileptonic decays to test Lattice QCD.
2 Analysis Technique for $D$ Semileptonic Decays

2.1 Analysis Technique

We fully reconstruct one $D$ meson of the $D \bar{D}$ pairs in the events produced at the $\psi(3770)$ resonance which helps determine the charge and flavor of the semileptonic decay of the other $D$ meson if available, resulting in great suppression of the backgrounds. The fully reconstructed $D$ meson serves as a tag. We identify an electron and a set of hadrons recoiling against the tag, reconstructing the missing momentum and missing energy. The excellent particle identification of the CLEO-c detector are well-suited for this purpose. The unique kinematics of threshold production provide additional and very powerful means to reject background from misidentified and missing particles. The difference between the missing energy and missing momentum in an event $U = E_{\text{miss}} - p_{\text{miss}}$ will peak at zero if the event is correctly reconstructed due to the undetected neutrino.

To determine $V_{cs}$ and $V_{cd}$, we need to study the $q^2$-dependent differential decay rate. In practice, the value of $q^2$ is determined by energy-momentum conservation in the laboratory frame

\begin{align*}
E_W &= E_{\text{beam}} - E_h, \\
\vec{p}_W &= -\vec{p}_{\text{tag}} - \vec{p}_h, \\
q^2 &= E_W^2 - |p_W|^2.
\end{align*}

Here $E_{\text{beam}}$ is the beam energy, $E_W, \vec{p}_W$ are the energy and momentum vector of $\ell\nu$ system or virtual $W$, $\vec{p}_{\text{tag}}$ and $\vec{p}_h$ the momentum vectors of the tagging $D$ meson and the hadronic system from the other $D$ semileptonic decays.

2.2 Absolute Branching Fraction Measurements

To measure the absolute $D$ semileptonic decay branching fractions $\mathcal{B}$, we use $D$ meson hadronic decays $D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^0\pi^0, K^-\pi^+\pi^-\pi^-, K_S\pi^0, K_S\pi^+\pi^-\pi^0, K^-\pi^+\pi^-\pi^0, K^+\pi^0, K^-\pi^+\pi^-\pi^0, K_S\pi^+\pi^-\pi^0, K^-\pi^+\pi^-\pi^0, K^-K^+$ to tag the other $D^0$ semileptonic decays. The number of tag yield and signal yield for semileptonic decays are given by:

\begin{align*}
N_{\text{tag}} &= 2N_{D\bar{D}}\epsilon_{\text{tag}}\mathcal{B}_{\text{tag}}, \\
N_{\text{signal}} &= 2N_{D\bar{D}}\epsilon_{\text{signal}}\mathcal{B}_{\text{tag}}.
\end{align*}

Here $N_{D\bar{D}}$ is the number of $D\bar{D}$ pairs produced at the $\psi(3770)$ resonance, $N_{\text{signal}}$ and $N_{\text{tag}}$ are the number of the signal and tag events observed, $\epsilon_{\text{signal}}$ and $\epsilon_{\text{tag}}$ are the efficiencies for the signal and tag events. The efficiency for the signal events $\epsilon_{\text{signal}}$ is obtained for fully constructed tag $D$ and the other $\bar{D}$ semileptonic decays, ie, it includes the tag side. The branching fraction can be obtained:

\begin{equation}
\mathcal{B} = \frac{N_{\text{signal}}}{N_{\text{tag}}\epsilon_{\text{tag}}}.
\end{equation}
Given the tag side and the semileptonic side are independent, or their correlation are weak, we have

$$\epsilon_{signal} = \epsilon_{tag} \times \epsilon_{h\nu}$$

(16)

In this case, the branching fraction can be obtained in an alternative way:

$$\mathcal{B} = \frac{N_{signal}/\epsilon_{h\nu}}{N_{tag}}$$

(17)

Where $\epsilon_{h\nu}$ is the efficiency only for the semileptonic decay side, it does not include the tag side. In principle, these two procedures are equivalent.

3 Data Sample and MC Samples

The official Dskim of 60 pb$^{-1}$ released for ICHEP for data31-33 is used for this analysis. Here are MC samples:

- $q\bar{q}$: 5404997 with $D\bar{D}$ excluded; $D^0\bar{D}^0$: 2035186; $D^+D^-$: 1525822; radiative return $\psi'$: 1277665; no $\tau^+\tau^-$; $^2$

For the normalization of these samples, the following cross sections are used:

- $\sigma_{D^0\bar{D}^0} = 3.56 \pm 0.13$ nb, $\sigma_{D^+D^-} = 2.70 \pm 0.14$ nb (see W. Sun’s talk, July’04),
  $\sigma_{q\bar{q}}$ = 14.04 nb (extracted from BES R measurements, see also Tomasz, CBX-03-34 ($\sigma_{q\bar{q}}$ = 14.0 nb )).

4 Event Selection

4.1 Event Selection for the Tagging $D$’s

The suggested criteria for hadrons from the tagging $D$ decays are used.

- Hadrons from Tagging $D$’s:
  - Good track:
    - $|d_0| < 0.005$ m, $|z_0| < 0.05$ m, $|\cos \theta| < 0.93$, $0.05 < p < 2$ GeV;
    - hitfraction $> 0.5$;
  - Lepton veto: only for the events with two tracks and no showers with $E_\gamma > 50$ MeV on the other side (DTagUtilities) which help to reject some cosmic backgrounds;

$^2$Since $\tau$ background is negligible (see my talk at CLEO meetings), it is not included this time.
Hadron ID:

- $3|\sigma| \frac{dE}{dx}$ for kaons and pions;
  - for $p > 0.55$ GeV, $L_{L_1} - L_{L_2} + \sigma^2_\pi - \sigma^2_K > (\leq 0)$ and $N_{\gamma} > 2$ for $K(\pi)$ within
  $|\cos \theta| \leq 0.8$ if RICH available; otherwise, $3|\sigma| \frac{dE}{dx}$ kaons and pions;

- $\pi^0$ and showers:
  - Good showers: noTrackMatch(), !hot(), $E_\gamma > 30$ MeV;
  - $\pi^0$: two good showers (default $E_9/E25$ cut) within $(-3.0, 3.0)\sigma$ and constrained to the
    $\pi^0$ mass $m_{\pi^0}$;

- $K^0_S$:
  - within 12 MeV of its nominal mass;

To avoid double counting, we use minimum $|\Delta E|$ to select one entry per tag mode. In case of
cross feeds among different tags, we have no way to justify which one should be chosen, so we
keep all. The cross feeds among different tags will cancel in the branching fractions. Currently,
DTagProd could not deal with mode-dependent cuts, we use $|\Delta E| < 35$ MeV for all tag modes
for convinience. In Fig. 3 and 4, we present the fits to the selected $D^0$ beam constrained masses
in the data with a Gaussian and a bifurcated Gaussian to account for the initial state radiation
(ISR) for signal plus Argus function for backgrounds. Similarly, we fit the $D^0$ beam constrained
masses in the MC samples to obtain the tagging efficiencies with the cross-feed decays excluded,
for example, $D^0 \rightarrow K_S \pi^0 \rightarrow \pi^+ \pi^- \pi^0$ and $D^0 \rightarrow \pi^\pm \pi^\mp \pi^0$, $D^0 \rightarrow \pi^+\pi^-\pi^0$ and $D^0 \rightarrow
K_S \pi^+ \pi^- \rightarrow \pi^+ \pi^- \pi^0$ and $D^0 \rightarrow \pi^+\pi^-\pi^0$, and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^0 \rightarrow K^- \pi^+ \pi^- \pi^0$.
Since charged track finding in the
data is 3% more efficient than that in our MC, the efficiencies from MC are corrected by
a factor of $1.03^N$, where $N$ is the number of the charged tracks. All the efficiencies given
throughout this note have been corrected (for detail, see W. Sun’s talk, July 29’04). While in
the data, the cross-feeds cancel in the branching ratios (see Eq. 15) since it appears in both $N_{signal}$
and $N_{tag}$. The tag yields and tag efficiencies will be given in Table 1. For the $D^0$ semileptonic
decays, the selection criteria for the tag side will be the same throughout this analysis.
Figure 3: Fits to the beam constrained masses for different tags with a Gaussian and a bifurcated Gaussian to account for the initial state radiation for signals plus Argus function for backgrounds.
Figure 4: Fits to the beam constrained masses for different tags with a Gaussian and a bifurcated Gaussian to account for the initial state radiation for signals plus Argus function for backgrounds.
4.2 Event Selection for $D^0$ Semileptonic Decays

One advantage of the threshold production is that kinematics provide very powerful means to reject background from misidentified and missing particles. In Fig. 5, based on signal MC, we present kaon momentum versus $U = E_{\text{miss}} - p_{\text{miss}}$ for $D^0 \rightarrow K^- e^+ \nu$ and the background from $D^0 \rightarrow \pi^- e^+ \nu$ reconstructed as $D^0 \rightarrow K^- e^+ \nu$ without kaon identification. It clear that the signal ($D^0 \rightarrow K^- e^+ \nu$) and background ($D^0 \rightarrow \pi^- e^+ \nu$) are well-separated even without kaon identification. As the kaon momentum increases, the separation decreases. For the decay $D^0 \rightarrow K^- e^+ \nu$, there is considerable background from $D^0 \rightarrow K^*- e^+ \nu$ decay due to a missing $\pi^0$, we will present the detailed background study later.

![Figure 5: Kaon momentum (from $D^0 \rightarrow K^- e^+ \nu$) vs. $U = E_{\text{miss}} - p_{\text{miss}}$ based on MC, the background from $D^0 \rightarrow \pi^- e^+ \nu$ reconstructed as $D^0 \rightarrow K^- e^+ \nu$ is overlaid and normalized by $\frac{\text{BR}(D^0 \rightarrow \pi^- e^+ \nu)}{\text{BR}(D^0 \rightarrow K^- e^+ \nu)} = 0.1$ from the PDG’02. the right plot shows the projection onto the $U$ axis in linear and log scales.](image)

Similarly, in Fig. 6, we present pion momentum versus $U = E_{\text{miss}} - p_{\text{miss}}$ for $D^0 \rightarrow \pi^- e^+ \nu$ and the background from $D^0 \rightarrow K^- e^+ \nu$ reconstructed as $D^0 \rightarrow \pi^- e^+ \nu$ without hadron identification. It is clear that the signal and the dominant background are well-separated. So we do not need tight hadron identification for the signal side.

We further check the hadron separation capability using $D^0 \rightarrow K^- \pi^+$ with tighter kinematic cuts $|M_{bc} - 1.8645| < 5$ MeV and $|\Delta E| < 20$ MeV (without particle identification). In Fig. 7, we present the likelihood differences for the kaon and pion candidates from $D^0 \rightarrow K^- \pi^+$, you will see that $LL_K - LL_\pi > 0$ for pion, $LL_K - LL_\pi < 0$ for kaon without cuts on $N_{K(\pi)}$ reject the dominant swap background.
Figure 6: pion momentum (from $D^0 \rightarrow \pi^- e^+ \nu$) vs. $U = E_{miss} - p_{miss}$ based on MC, the background from $D^0 \rightarrow K^- e^+ \nu$ reconstructed as $D^0 \rightarrow \pi^- e^+ \nu$ is overlaid and normalized by $\frac{B(D^0 \rightarrow \pi^- e^+ \nu)}{B(D^0 \rightarrow K^- e^+ \nu)} = 0.1$ from the PDG’02. the right plot shows the projection onto the $U$ axis in linear and log scales.

Figure 7: The loglikelihood differences $LL_K - LL_\pi$ (RICH only) for the kaon and pion candidates without PID from $D^0 \rightarrow K^- \pi^+$ in MC (left, with MC tag) and data (right). The $\pi\pi$ and $KK$ backgrounds (clusters indicated in the left plot) are attributed to the random combinations.
We have also found that there is clear discrepancy between the number of photons for kaons and pions from $D^0 \rightarrow K^-\pi^+$ in the data and MC, it is shown in Fig. 8. So we don’t cut on the number of photons for the time being, otherwise, it will yield larger systematics when the cut applies.

![Diagram](image)

Figure 8: Comparison of number of photons for kaon and pion candidates from $D^0 \rightarrow K^-\pi^+$ in our data and MC.

From the above discussions, we don’t need tight hadron identification from the $D^0$ semileptonic decays. Besides the track quality requirements which are the same as those for tag D’s, the following criteria apply to the $D^0$ semileptonic decays.

- Hadron ID for hadrons from $D$ semileptonic decays

  ◦ for $p < 0.6$ GeV: $3|\sigma| \frac{dE}{dx}$ for kaons and pions;
  ◦ for $p > 0.6$ GeV, $LL_\pi - LL_K + \sigma^2_\pi - \sigma^2_K > (\leq)0$ for K ($\pi$) within $|\cos \theta| < 0.8$ if RICH available (without cut on $N^\gamma_{K(\pi)}$); otherwise, $3|\sigma| \frac{dE}{dx}$ for kaons and pions;
• Electron ID: the electron ID package, based on $E/p$, $dE/dx$ and RICH PDF, by Rochester group is used. The following cut applies

\[ F_{with\ -\ rich} > 0.8 \] with $p_e > 0.2$ GeV/c (see Chulsu’s writeup);

• $\pi^0$ and showers:

  ◦ Good showers: noTrackMatch(), !hot(), $E_\gamma > 30(50)$ MeV if in the good barrel (end-cap), SplitOff info. used;

  ◦ $\pi^0$: two good showers (default $E_9/E_{25}$ cut), at least one in the good barrel within ($-3.5, 3.0$)$\sigma$ and constrained to the $\pi^0$ mass $m_{\pi^0}$;

• Bremsstrahlung recovery: we recover the radiative photons from the electron candidate which satisfy the following criteria:

  ◦ good showers with $E_\gamma > 10$ MeV and the angle $\theta_{e,\gamma}$ between the electron and showers less than $5^0$ ($\theta_{e,\gamma} < 5^0$). It helps recover about 5% efficiency within $3\sigma_U$, see my January’s talk.

• Veto on extra track and shower: we used double D-tag to study the extra track in a double-D tagged events and found that the extra track is well-modeled in MC, while the extra shower is not. A direct check with the selected $D^0 \rightarrow K^- e^+\nu$ sample is presented in Fig. 9. So we don’t allow any extra good track. We don’t apply any cut on extra shower.

![Figure 9: Comparison of the extra good track, the number of extra good showers and the maximum energy of the extra shower in a event between the data and MC.](image)

• For the semileptonic $D$ decays, besides its direction constrained by $\vec{p}_{semi} = -\vec{p}_{tag}$, we further constrain its energy and momentum to be $E_{cm}/2.0$ and $\sqrt{(E_{cm}/2)^2 - 1.8645^2}$ in the $\psi(3770)$ rest frame to improve the resolution of $U$. For the tag $D$’s, we require $|\Delta E| < 35$ MeV and the beam constrained masses $M_{bc} \in [1.858, 1.874]$ GeV.
5 Results for $D^0 \to K^- e^+ \nu$

In Fig. 10, we present the comparison of the distributions of $U = E_{\text{miss}} - p_{\text{miss}}$ for the selected $D^0 \to K^- e^+ \nu$ events between the data and MC using different tag modes. The comparison shows good agreement between the data and MC.

![Comparison of $U = E_{\text{miss}} - p_{\text{miss}}$ for $D^0 \to K^- e^+ \nu$ between the data and MC.](image)

Figure 10: Comparison of $U = E_{\text{miss}} - p_{\text{miss}}$ for $D^0 \to K^- e^+ \nu$ between the data and MC.

In Fig. 11, we present the missing mass squared for the selected $D^0 \to K^- e^+ \nu$ events, it peaks at zero due to the undetected neutrino. It means we do have neutrinos in the selected events.

In Fig. 12, we decompose different components using MC tags. For $D^0 \to K^- e^+ \nu$, there is
considerable background from $D^0 \rightarrow K^* e^+ \nu$ although its contribution is not significant. The fit to the backgrounds is presented.

In Figs. 13 and 14, we present the fits to the $U$ distributions for the selected $D^0 \rightarrow K^- e^+ \nu$ events with a Gaussian and a modified Crystal Ball function [4] for the signals to account for the tails due to the final state radiation of electron and backgrounds fixed at the MC level. In case of low statistical tags, we fix parameter $n$ and/or $\alpha$ at the determined value(s) from the fit to the data with all tags combined. Our comparison (see Fig. 10) shows that the background is well-modeled in MC although we will consider its contribution to systematics later. The yields are given in Table 1. The efficiencies and branching fractions are also listed in Table 1 for different tag modes. The inclusions of the tails in the fits help increase about 5% efficiencies.

In Fig. 15, we further check the momentum spectrum and angular distribution of lepton for the selected $D^0 \rightarrow K^- e^+ \nu$ events. The comparison shows good agreement between our data and MC.
Figure 12: Background for $D^0 \to K^-e^+\nu$ (left two plots), the dominant background comes from $D^0 \to K^-e^+\nu$ due to the missing $\pi^0$. The fit to the background with a modified hyperbolic tanh(x) function (right plot).

Table 1: The tag yields, efficiencies, and signal yields and efficiencies for $D^0 \to K^-e^+\nu$.

<table>
<thead>
<tr>
<th>Tags: $D^0 \to K^-e^+\nu$</th>
<th>tag yields</th>
<th>$\epsilon_{tag}$</th>
<th>signal yields</th>
<th>$\epsilon_{signal}$</th>
<th>$\mathcal{B}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-\pi^+$</td>
<td>10183±112</td>
<td>0.6535±0.0012</td>
<td>245.7±15.3</td>
<td>0.4269±0.0021</td>
<td>3.694±0.234</td>
</tr>
<tr>
<td>$K^-\pi^+\pi^0$</td>
<td>17208±160</td>
<td>0.3353±0.0007</td>
<td>407.7±20.4</td>
<td>0.2207±0.0018</td>
<td>3.599±0.183</td>
</tr>
<tr>
<td>$K^-\pi^+\pi^0\pi^0$</td>
<td>4475±208</td>
<td>0.1610±0.0006</td>
<td>106.6±10.6</td>
<td>0.1086±0.0013</td>
<td>3.532±0.388</td>
</tr>
<tr>
<td>$K^-\pi^+\pi^+$</td>
<td>14515±162</td>
<td>0.4693±0.0009</td>
<td>310.3±18.0</td>
<td>0.2980±0.0020</td>
<td>3.367±0.199</td>
</tr>
<tr>
<td>$K_S\pi^+\pi^-$</td>
<td>4629±101</td>
<td>0.3705±0.0015</td>
<td>100.0±10.2</td>
<td>0.2425±0.0019</td>
<td>3.301±0.344</td>
</tr>
<tr>
<td>$K_S\pi^+\pi^-\pi^0$</td>
<td>4403±240</td>
<td>0.1851±0.0009</td>
<td>119.2±10.6</td>
<td>0.1283±0.0019</td>
<td>3.906±0.407</td>
</tr>
<tr>
<td>$K_S\pi^0$</td>
<td>1502±43</td>
<td>0.2792±0.0022</td>
<td>26.6±5.3</td>
<td>0.1919±0.0017</td>
<td>2.577±0.519</td>
</tr>
<tr>
<td>$\pi^-\pi^+\pi^0$</td>
<td>2533±176</td>
<td>0.3991±0.0019</td>
<td>63.3±8.0</td>
<td>0.2667±0.0019</td>
<td>3.740±0.539</td>
</tr>
<tr>
<td>$K^-K^+$</td>
<td>928±35</td>
<td>0.5608±0.0038</td>
<td>22.4±4.9</td>
<td>0.3704±0.0021</td>
<td>3.655±0.811</td>
</tr>
<tr>
<td>all tags</td>
<td>1405.1±38.5</td>
<td>0.5608±0.0038</td>
<td>22.4±4.9</td>
<td>0.3704±0.0021</td>
<td>3.655±0.811</td>
</tr>
</tbody>
</table>
Figure 13: Fits to the $U$ distributions using different tag modes with a modified Crystal Ball function and a Gaussian for signals and backgrounds fixed at the MC level.
Figure 14: Fits to the $U$ distributions using different tag modes with a modified Crystal Ball function and a Gaussian for signals and backgrounds fixed at the MC level.
Figure 15: Comparison of electron momentum spectrum and angular distribution between the data and MC for the selected $D^0 \rightarrow K^- e^+ \nu$ events.

6 Results for $D^0 \rightarrow \pi^- e^+ \nu$

In Fig. 16a, we present the $U = E_{\text{miss}} - p_{\text{miss}}$ distribution for the selected $D^0 \rightarrow \pi^- e^+ \nu$ events with all tag modes combined due to limited statistics. The comparison shows that there is a clear excess in the signal region (near zero) in MC. While the background is well-modeled in MC. The backgrounds are decomposed in Fig. 16b. The fit to the background with a Gaussian (dominant background from $D^0 \rightarrow K^- e^+ \nu$) plus a 2nd order polynomials is shown in Fig. 17a. We fit the $U$ distribution with double Gaussians (signal, near zero) and a Gaussian (the dominant $D^0 \rightarrow K^- e^+ \nu$ background) plus a 2nd order polynomials. The 2nd order polynomials is fixed at the MC level, while all Gaussians are let to float when fitting. We observe $109.1 \pm 10.9$ events. The signal efficiencies and branching fraction will be given in Table 2.
Figure 16: $U = E_{\text{miss}} - p_{\text{miss}}$ for the selected $D^0 \rightarrow \pi^- e^+ \nu$ events (a), and the background components (b).

Figure 17: Fit to the backgrounds with a Gaussian plus a 2nd order polynomials (left). Fit to the $U$ distribution with double Gaussians (signal near zero) and a Gaussian (background) floating plus a 2nd order polynomial fixed at the MC level.
7 \( D^0 \rightarrow K^*^-e^+\nu \) and \( D^0 \rightarrow \rho^-e^+\nu \)

- \( K^{*-} (\rightarrow K^0\pi^0) \) and \( \rho^- (\rightarrow \pi^-\pi^0) \) selection:
  
  ◦ the criteria for charged kaon and pion are the same as those from \( D^0 \rightarrow K^-e^+\nu \) and \( D^0 \rightarrow \pi^-e^+\nu \), \( \pi^0 \) selection is described in Sect. 4.2;
  
  ◦ \( K^{*-} \): we require the \( K^{*-} \) candidate to be within 100 MeV of its nominal mass, the best \( K^{*-} \) candidate close to its nominal mass is selected in case of multiple \( K^{*-} \) candidates.
  
  ◦ \( \rho^- \): we require the \( \rho^- \) candidate to be within 150 MeV of its nominal mass, the best \( \rho^- \) candidate is selected in case of multiple candidates.

7.1 Results for \( D^0 \rightarrow K^*^-e^+\nu \)

In Fig. 18a, we present the comparison for \( D^0 \rightarrow K^*^-e^+\nu \) between the data and MC. Fig. 18b shows the components of the backgrounds. Fig. 19a shows the fit to the backgrounds with a 2nd order polynomials. Fig. 19b shows the fit to the \( U \) distribution for the selected \( D^0 \rightarrow K^*^-e^+\nu \) events with a Gaussian and a 2nd order polynomials fixed at the MC level. The yields and efficiencies are given in Table 2.

![Figure 18](image_url)

Figure 18: \( U \) distribution for the selected \( D^0 \rightarrow K^*^-e^+\nu \) events (left) and the components of backgrounds for \( D^0 \rightarrow K^*^-e^+\nu \).
Figure 19: Fit to the backgrounds with a 2nd order polynomials (left) and Fit to the $U$ distribution for $D^0 \rightarrow K^+ e^+ \nu$ with a Gaussian plus a 2nd order polynomials fixed at the MC level.
7.2 Results for $D^0 \rightarrow \rho^- e^+ \nu$

The comparison of $U$ distribution between the data and MC for $D^0 \rightarrow \rho^- e^+ \nu$ is shown in Fig. 20a. The components of backgrounds are shown in Fig. 20b. The fit to the backgrounds with a 2nd order polynomial is depicted in Fig. 21a. We fit the $U$ distribution for the selected $D^0 \rightarrow \rho^- e^+ \nu$ events with a Gaussian (signal) and a Gaussian (background) plus a 2nd order polynomials fixed at MC level, see Fig. 21b. The yield and efficiencies are given in Table 2.

Figure 20: $U$ distribution for the selected $D^0 \rightarrow \rho^- e^+ \nu$ events (left) and the decomposition of backgrounds.

8 $q^2$ Distributions

In Fig. 22, we present the comparison of the $q^2$ distributions for $D^0 \rightarrow K^- e^+ \nu$, $D^0 \rightarrow \pi^- e^+ \nu$ and $D^0 \rightarrow K^*^- e^+ \nu$ for the selected events. The $q^2$ distribution for $D^0 \rightarrow \rho^- e^+ \nu$ is not presented due to limited statistics. The comparison show that the agreement between the data and MC is reasonably good for $D^0 \rightarrow K^- e^+ \nu$ and $D^0 \rightarrow \pi^- e^+ \nu$ within current statistics, and not good for $D^0 \rightarrow K^*^- e^+ \nu$.

9 Systematics

We have considered the following sources of systematics which may affect the results: charged track and $\pi^0$ finding systematics, veto on the extra track, background normalization and shape, MC statistics, no initial state radiation (ISR) in generic MC, model-dependent form factors, hadron identification, electron identification. Their contributions to systematics are discussed as follows.
Figure 21: Fit to the backgrounds for $D^0 \to \rho^- e^+ \nu$ with a 2nd order polynomials plus a Gaussian (left) and fit to the $U$ distribution for the selected events with a Gaussian (signal) and a Gaussian plus a 2nd order polynomials fixed at the MC level.

Figure 22: $Q^2$ distributions for $D^0 \to K^- e^+ \nu$ (left), $D^0 \to \pi^- e^+ \nu$ (middle) and $D^0 \to K^*^- e^+ \nu$ (right). The comparison between the data and MC rescaled to the new measured branching fractions are presented.
Table 2: Efficiencies and yields for $D^0 \rightarrow \pi^- e^+ \nu$, $D^0 \rightarrow K^*^- e^+ \nu$ and $D^0 \rightarrow \rho^- e^+ \nu$ using different tag modes.

<table>
<thead>
<tr>
<th>Signal Modes</th>
<th>$D^0 \rightarrow \pi^- e^+ \nu$</th>
<th>$D^0 \rightarrow K^*^- e^+ \nu$</th>
<th>$D^0 \rightarrow \rho^- e^+ \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^- \pi^+$</td>
<td>$0.4806 \pm 0.0030$</td>
<td>$0.1434 \pm 0.0021$</td>
<td>$0.1813 \pm 0.0022$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^- \pi^+ \pi^0$</td>
<td>$0.2493 \pm 0.0026$</td>
<td>$0.0697 \pm 0.0015$</td>
<td>$0.0890 \pm 0.0016$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^- \pi^+ \pi^0 \pi^0$</td>
<td>$0.1247 \pm 0.0020$</td>
<td>$0.0351 \pm 0.0011$</td>
<td>$0.0452 \pm 0.0012$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^- \pi^+ \pi^- \pi^-$</td>
<td>$0.3328 \pm 0.0029$</td>
<td>$0.0961 \pm 0.0017$</td>
<td>$0.1162 \pm 0.0019$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_S \pi^+ \pi^-$</td>
<td>$0.2577 \pm 0.0027$</td>
<td>$0.0799 \pm 0.0016$</td>
<td>$0.0945 \pm 0.0017$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_S \pi^+ \pi^- \pi^0$</td>
<td>$0.1418 \pm 0.0015$</td>
<td>$0.0395 \pm 0.0011$</td>
<td>$0.0494 \pm 0.0013$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_S \pi^0$</td>
<td>$0.2145 \pm 0.0025$</td>
<td>$0.0628 \pm 0.0014$</td>
<td>$0.0739 \pm 0.0015$</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^- \pi^+ \pi^0$</td>
<td>$0.2898 \pm 0.0027$</td>
<td>$0.0883 \pm 0.0017$</td>
<td>$0.1064 \pm 0.0018$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^- K^+$</td>
<td>$0.4014 \pm 0.0029$</td>
<td>$0.1233 \pm 0.0019$</td>
<td>$0.1514 \pm 0.0021$</td>
</tr>
</tbody>
</table>

yields

| $109.1 \pm 10.9$ | $88.0 \pm 9.7$ | $30.1 \pm 5.8$ |

$\mathcal{B}(\times 10^{-3})$

| $(2.46 \pm 0.25)$ | $20.69 \pm 2.28$ | $1.89 \pm 0.36$ |

Systematics for track finding efficiency is 3% per charged track and 4.4% per $\pi^0$ by $D$ hadron group. MC statistics varies from 1% to 3%, depending on the tag modes, see Table 1 and 2.

Our generic MC samples for $D\bar{D}$ are generated without the initial state radiation (ISR). To test the effect of ISR, we have generated signal MC with and without ISR, and have found the efficiencies vary within 1%, so we assign a 1% systematics due to the missing ISR in our generic $D\bar{D}$ MC.

As discussed before, the extra tracks in an event is well modeled in our MC. Using the selected $D^0 \rightarrow K^- e^+ \nu$ events, we find 0.51% events have extra tracks in our data, 0.41% events in our MC. The data and MC agrees very well. We assign a 0.5% systematics due to the veto on extra tracks.

To estimate the systematics from the backgrounds, we vary the background functions by $\pm 1 \sigma$, taking the correlation of parameters into account. We find the background normalization and shape contributes a systematics of 1.1%, 3.1%, 2.9% and 5.3% for $D^0 \rightarrow K^- e^+ \nu$, $D^0 \rightarrow \pi^- e^+ \nu$, $D^0 \rightarrow K^*^- e^+ \nu$ and $D^0 \rightarrow \rho^- e^+ \nu$, respectively.

In our procedure, we have fixed the backgrounds at the MC level when fitting the $U$ distributions. We also let the backgrounds float and find that the yield differences are $< 1\%$, $1.9\%$, $1\%$ and $2.7\%$ for $D^0 \rightarrow K^- e^+ \nu$, $D^0 \rightarrow \pi^- e^+ \nu$, $D^0 \rightarrow K^*^- e^+ \nu$ and $D^0 \rightarrow \rho^- e^+ \nu$, respectively. We assign the yield differences as systematics for the yield extractions. Direct countings of the number of events in the data and backgrounds in MC give consistent results.
9.1 Model Dependent Systematics

We obtain the detection efficiencies based on ISGW2 model for $D$ semileptonic decays. It is found that this model does not describe the data well. Our long term plan is that we will study the differential decay rate to extract the information of form factors. For the time being, we try to take advantage of our current knowledge of the form factors for $D$ semileptonic decays. To estimate the systematics due to the model, we use the form factors from the analysis of $D^0 \rightarrow K^- e^+ \nu$ and $D^0 \rightarrow \pi^- e^+ \nu$ at CLEO III [5]. The fit to the differential decay rate to extract the information of form factors is depicted in Fig. 23. We used the parameters given in Ref. [5] to generate signal MC and find the efficiencies vary less than 2% for $D^0 \rightarrow K^- e^+ \nu$ and $D^0 \rightarrow \pi^- e^+ \nu$.

For $D^0 \rightarrow K^*- e^+ \nu$ and $D^0 \rightarrow \rho^- e^+ \nu$, we use the parameterization of form factors from the study of $D^+ \rightarrow \bar{K}^* e^+ \nu$ at E791 [6] to generate signal MC. The E791 analysis is shown in Fig. 24. We find that the efficiencies vary less than 2% for $D^0 \rightarrow K^* e^+ \nu$ and 5.0% for $D^0 \rightarrow \rho^- e^+ \nu$.

Victor is working on incorporating different models to estimate the model-dependent systematics.

![Figure 23: Analysis of differential decay rate to extract form factors for $D^0 \rightarrow K^- e^+ \nu$ and $D^0 \rightarrow \pi^- e^+ \nu$ at CLEO III [5].](image)
9.2 Electron Identification Systematics

In Fig. 25, we present the comparison of the electron identification variable $F_{with rich}$ for the selected $D^0 \rightarrow K^- e^+ \nu$ events, a cut at $F_{with rich} = 0.8$ or 0.5 yields less than 0.5% efficiency difference between the data and MC. Tighter cut at 0.95 yields 3.2% efficiency difference, but we don’t use that tight cut. We assign a 1% systematics or 3.2% systematics if tighter cut applied.

9.3 Hadron Identification Systematics

Since the hadron momentum spectra from $D$ semileptonic decays cover up to 1.1 GeV/c, we combine $D^0 \rightarrow K^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ to study hadron identification efficiency in our data and MC. We require that the beam constrained masses for $D^0 \rightarrow K^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ candidates must be within 5 MeV of their nominal masses, and $|\Delta E| < 20$ MeV, the $\Delta E$ sidebands within (45,65) MeV and (-65,-45) MeV are used to subtract the residual random combinatorial backgrounds. Since kinematics of the threshold production provide powerful means to reject backgrounds from misidentified and missing particles as discussed in Sect. 4.2. We use the following loose hadron identification criteria to obtain higher efficiency as discussed in Sect. 4.2:

- for $p < 0.6$ GeV: $3|\sigma| \frac{dE}{dx}$ for kaons and pions;
- for $p > 0.6$ GeV, $LL_{\pi} - LL_K + \sigma^2_{\pi} - \sigma^2_K > (\leq) 0$ for K(π) within $|\cos \theta| < 0.8$ if RICH available (without cut on $N_{K(\pi)}^\gamma$); otherwise, $3|\sigma| \frac{dE}{dx}$ for kaons and pions.
Figure 25: Comparison of $\mathcal{F}_{\text{with } -r \text{ rich}}$ between the data and MC for the selected $D^0 \rightarrow K^- e^+ \nu$ events.

In Fig. 26, we present momentum dependent kaon and pion identification efficiencies with $3|\sigma|$ dE/dx requirements. The comparison shows good agreement between our data and MC, the overall efficiency difference is about 0.2%.

In Fig. 27, we present momentum dependent kaon and pion identification efficiencies with requirements of $LL_\pi - LL_K + \sigma_\pi^2 - \sigma_K^2 > (\leq)0$ for $K(\pi)$ within $|\cos \theta| < 0.8$ if RICH available (without cut on $N_{K(\pi)}^{\gamma}$); otherwise, $3|\sigma|$ dE/dx for kaons and pions. The comparison shows good agreements (less than 0.2% difference) between our data and MC for kaons and pions with $p < 0.7$ GeV/c. Above 0.7 GeV/c, our data is 1.5% more efficient than MC.

We further check that the difference is not attributed to the procedure we used. We use MC truth to tag the MC samples and compare the efficiencies from MC and MC truth. Fig. 28 shows the comparison, you will see the perfect agreement.

9.4 Systematics

In Table 3, we summarize the systematics discussed above. The systematics from MC statistics is weighted with tag yields. We add these sources in quadrature to obtain the total systematics for each decay mode. From the study of hadron identification, we find that our data is more efficient than MC. In our procedure to obtain the branching ratios (see Eq. (15) ), tag $D$’s appear in both the denominator and nominator for $N_{tag}$ and $N_{signal}$, and for $\epsilon_{tag}$ and $\epsilon_{signal}$, the systematics from tag $D$’s cancels. When calculating the ratios of branching fractions, some systematics cancel.
Figure 26: Comparison of kaon and pion identification efficiencies with $3|\sigma| \text{dE/dx}$ requirements in our data and MC from $D^+ \rightarrow K^-\pi^+\pi^+$. For kaons and pions with $p < 0.6$ GeV/c, we have requirements of $3|\sigma| \text{dE/dx}$. 
Figure 27: Comparison of kaon and pion identification efficiencies with $LL_\pi - LL_K + \sigma_\pi^2 - \sigma_K^2 > (\leq) 0$ for $K(\pi)$ within $|\cos \theta| < 0.8$ if RICH available (without cut on $N_{K(\pi)}^l$); otherwise, $3|\sigma| dE/dx$ for kaons and pions. These PID requirements only apply for kaons and pions with $p > 0.6$ GeV/c.
Figure 28: Comparison of kaon and pion identification efficiencies with RICH+dE/dx veto (see Fig. 27) from MC and MC tag (truth).
Table 3: Systematics for four $D^0$ semileptonic decays (in %).

<table>
<thead>
<tr>
<th>sources</th>
<th>$D^0 \rightarrow K^-e^+\nu$</th>
<th>$D^0 \rightarrow \pi^-e^+\nu$</th>
<th>$D^0 \rightarrow K^{*-}e^+\nu$</th>
<th>$D^0 \rightarrow \rho^-e^+\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>tracking</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>$\pi^0$ finding</td>
<td>-</td>
<td>-</td>
<td>4.4</td>
<td>4.4</td>
</tr>
<tr>
<td>EID</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>PID</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>extra track</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>extra shower</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>No ISR</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MC statistics</td>
<td>&lt;1</td>
<td>1.1</td>
<td>2.2</td>
<td>1.9</td>
</tr>
<tr>
<td>backgrounds</td>
<td>1</td>
<td>3.1</td>
<td>2.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Form factors</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>5.0</td>
</tr>
<tr>
<td>yields</td>
<td>1</td>
<td>1.9</td>
<td>1</td>
<td>2.7</td>
</tr>
<tr>
<td>total</td>
<td>7.0</td>
<td>7.8</td>
<td>8.9</td>
<td>11.2</td>
</tr>
</tbody>
</table>

10 Results and Discussions

In summary, we have improved measurements of the $D^0$ semileptonic decay branching fractions. The branching fractions are listed in Table 4.

Table 4: Branching ratios for four $D^0$ semileptonic decays.

<table>
<thead>
<tr>
<th>Decays</th>
<th>$\mathcal{B}$</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^-e^+\nu$</td>
<td>$(3.517\pm0.098\pm0.246)%$</td>
<td>$(3.58\pm0.18)%$</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^-e^+\nu$</td>
<td>$(0.246\pm0.025\pm0.019)%$</td>
<td>$(0.36\pm0.06)%$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^{*-}e^+\nu$</td>
<td>$(2.069\pm0.228\pm0.184)%$</td>
<td>$(2.15\pm0.35)%$</td>
</tr>
<tr>
<td>$D^0 \rightarrow \rho^-e^+\nu$</td>
<td>$(0.189\pm0.036\pm0.021)%$</td>
<td>none</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0\rightarrow K^-e^+\nu)$</td>
<td>$(7.0\pm0.7\pm0.3)%$</td>
<td>$(10.1\pm1.8)%$</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0\rightarrow K^{*-}e^+\nu)$</td>
<td>$(9.2\pm2.0\pm0.8)%$</td>
<td>none</td>
</tr>
</tbody>
</table>

Our results for $D^0 \rightarrow K^-e^+\nu$ and $D^0 \rightarrow K^{*-}e^+\nu$ are consistent with those from the PDG. Our result $\mathcal{B}(D^0 \rightarrow \pi^-e^+\nu)$ is lower than that from the PDG. The ratio $\mathcal{B}(D^0 \rightarrow \pi^-e^+\nu)/\mathcal{B}(D^0 \rightarrow K^-e^+\nu)$ is close to the CLEO III result $(8.2\pm0.6\pm0.5)\%$, while lower than the PDG value. We have improved the measurements of these branching fractions.

From Eqs. 3 and 4, in order to extract the CKM matrix elements $V_{cs}$ and $V_{cd}$, we need to know both the absolute normalization and the shape of form factors. There are two convenient
parameterizations of the form factors. One is the simple pole approximation parameterized as following

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M_{\text{pole}}^2}. \quad (18)$$

Where $M_{\text{pole}}$ is assumed to be an effective pole mass which is nominally that of the lowest $D^*$ states. The other one is the modified pole model conveniently parameterized as

$$f_+(q^2) = \frac{f_+(0)}{(1 - q^2/M_{D^{(*)}}^2)(1 - \beta q^2/M_{D^{(*)}}^2)}. \quad (19)$$

Where the mass of the lowest pole is $M_{D^*}$ for $D^0 \to \pi^- e^+ \nu$ and $M_{D^{(*)}}$ for $D^0 \to K^- e^+ \nu$, $\beta$ is a parameter to correct the effects of higher resonance poles by assuming a second effective pole mass at $M_{D^{(*)}}/\sqrt{\beta}$. When $\beta = 0$, it simplifies as a simple pole model.

In Table 5, we list the parameterizations of the form factors for $D^0 \to K^- e^+ \nu$ and $D^0 \to \pi^- e^+ \nu$ from ISGW2 [7], light cone sum rule (LCSR) [8], quenched Lattice QCD [9] and unquenched Lattice QCD [10] and the results at CLEO III [5]. The parameterizations of form factors in ISGW2 model is more complicated, details can be found in Appendix C of Ref. [7]. The decay widths $i\Gamma_{\ell^-} \Gamma_{\ell^+}$ predicted by different models are given in Table 5, the errors are attributed to the uncertainties of parameters $\beta$ or pole mass if available. Using $\tau_{D^0} = (410.3 \pm 1.5) \times 10^{-15}$s, $V_{cs} = 0.996 \pm 0.013$ and $V_{cd} = 0.224 \pm 0.012$ [1], we present the branching fractions predicted by these models in Table 5. For the simple and modified pole models, the Lattice QCD results $f_+^K(0) = 0.73 \pm 0.03 \pm 0.07$ for $D^0 \to K^- e^+ \nu$ and $f_+^\pi(0) = 0.64 \pm 0.03 \pm 0.06$ for $D^0 \to \pi^- e^+ \nu$ are used. The last errors come from the uncertainties of $V_{cs}$ or $V_{cd}$ and $\tau_{D^0}$ [1], the others from the theoretic uncertainties of the model parameters. Alternatively, we extract the CKM matrix elements $V_{cs}$ and $V_{cd}$ using the measured branching fractions and the form factors predicted by these models which are presented in Table 5, where the last errors are due to the uncertainties of the measured branching fractions and $\tau_{D^0}$, the others are due to the uncertainties of the model parameters. It is clear that the uncertainties of these results are dominated by those from theory, so we need precise Lattice QCD results for both the absolute normalization and the shape of the form factors. In the near future at CLEO-c, with the study of $q^2$-dependent differential decay rate, we are expecting great improvement of our knowledge of form factors and precision measurements of CKM elements $V_{cs}$ and $V_{cd}$

**Acknowledgments**

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Table 5: Comparison of our results for $D^0 \rightarrow K^- e^+ \nu$ and $D^0 \rightarrow \pi^- e^+ \nu$ with different models. The branching fractions is obtained using $\tau_{D^0} = (410.3 \pm 1.5) \times 10^{-15}$s. The predicted widths are given in unit of $10^{11}$s$^{-1}$

<table>
<thead>
<tr>
<th>Model</th>
<th>$\beta$</th>
<th>$M_{pole}$ GeV</th>
<th>$f_+(0)$</th>
<th>$V_{cd}/V_{cs}$</th>
<th>$B_{theory}$ (x10^-3)</th>
<th>$V_{exp}^{cd}$</th>
<th>$V_{exp}^{cs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^- e^+ \nu$</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>LQCD I [9]</td>
<td>0.27±0.11</td>
<td>2.112</td>
<td>0.66±0.04</td>
<td>$1.646^{+0.053}_{-0.049}$</td>
<td>$29.09^{+0.94}_{-0.87} \pm 3.53 \pm 0.77$</td>
<td>$1.095^{+0.017}_{-0.017} \pm 0.066 \pm 0.041$</td>
<td></td>
</tr>
<tr>
<td>LQCD II [9]</td>
<td>0.43±0.12</td>
<td>2.112</td>
<td>0.66±0.04</td>
<td>$1.719^{+0.065}_{-0.060}$</td>
<td>$30.47^{+1.15}_{-1.06} \pm 3.69 \pm 0.80$</td>
<td>$1.070^{+0.019}_{-0.020} \pm 0.065 \pm 0.040$</td>
<td></td>
</tr>
<tr>
<td>LCSR [8]</td>
<td>$0.07^{+0.15}_{-0.07}$</td>
<td>2.110</td>
<td>0.78±0.11</td>
<td>$1.499^{+0.059}_{-0.026}$</td>
<td>$37.12^{+1.47}_{-0.64} \pm 10.47 \pm 0.98$</td>
<td>$0.970^{+0.009}_{-0.019} \pm 0.137 \pm 0.037$</td>
<td></td>
</tr>
<tr>
<td>LQCD [10]</td>
<td>0.50±0.04</td>
<td>2.112</td>
<td>0.73±0.03</td>
<td>$0.73 \pm 0.07$</td>
<td>$1.756^{+0.022}_{-0.021}$</td>
<td>$38.09^{+0.48}_{-0.46} \pm 7.93 \pm 1.00$</td>
<td>$0.957^{+0.006}_{-0.006} \pm 0.100 \pm 0.036$</td>
</tr>
<tr>
<td>Mod. pole [5]</td>
<td>0.36±0.12</td>
<td>2.112</td>
<td>0.73±0.03</td>
<td>$0.73 \pm 0.07$</td>
<td>$1.683^{+0.062}_{-0.057}$</td>
<td>$36.52^{+1.34}_{-1.23} \pm 7.60 \pm 0.96$</td>
<td>$0.977^{+0.017}_{-0.017} \pm 0.102 \pm 0.037$</td>
</tr>
<tr>
<td>Simple pole</td>
<td>0.</td>
<td>2.112</td>
<td>0.73±0.03</td>
<td>$0.73 \pm 0.07$</td>
<td>$1.525$</td>
<td>$33.08 \pm 6.89 \pm 0.87$</td>
<td>$1.027 \pm 0.107 \pm 0.039$</td>
</tr>
<tr>
<td>Simple pole [5]</td>
<td>0.</td>
<td>1.89±0.06</td>
<td>0.73±0.03</td>
<td>$0.73 \pm 0.07$</td>
<td>$1.663^{+0.054}_{-0.045}$</td>
<td>$36.06^{+1.17}_{-0.98} \pm 7.51 \pm 0.95$</td>
<td>$0.984^{+0.014}_{-0.016} \pm 0.102 \pm 0.037$</td>
</tr>
<tr>
<td>ISGW2</td>
<td>0.05</td>
<td>0.85</td>
<td>1.418</td>
<td>41.74±1.10</td>
<td>$0.914 \pm 0.035$</td>
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</tr>
<tr>
<td>$D^0 \rightarrow \pi^- e^+ \nu$</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LQCD I [9]</td>
<td>0.27±0.14</td>
<td>2.01</td>
<td>0.57±0.06</td>
<td>$3.441^{+0.288}_{-0.241}$</td>
<td>$2.30^{+0.19}_{-0.16} \pm 0.48 \pm 0.25$</td>
<td>$0.232^{+0.009}_{-0.009} \pm 0.024 \pm 0.015$</td>
<td></td>
</tr>
<tr>
<td>LQCD II [9]</td>
<td>0.36±0.16</td>
<td>2.01</td>
<td>0.57±0.06</td>
<td>$3.620^{+0.378}_{-0.304}$</td>
<td>$2.42^{+0.25}_{-0.20} \pm 0.51 \pm 0.26$</td>
<td>$0.226^{+0.010}_{-0.011} \pm 0.024 \pm 0.014$</td>
<td></td>
</tr>
<tr>
<td>LCSR [8]</td>
<td>$0.01^{+0.11}_{-0.07}$</td>
<td>2.01</td>
<td>0.65±0.11</td>
<td>$3.022^{+0.094}_{-0.092}$</td>
<td>$2.63^{+0.14}_{-0.08} \pm 0.89 \pm 0.28$</td>
<td>$0.217^{+0.003}_{-0.006} \pm 0.037 \pm 0.014$</td>
<td></td>
</tr>
<tr>
<td>LQCD [10]</td>
<td>0.44±0.04</td>
<td>2.01</td>
<td>0.64±0.03</td>
<td>$0.64 \pm 0.06$</td>
<td>$3.798^{+0.097}_{-0.092}$</td>
<td>$3.20^{+0.08}_{-0.08} \pm 0.67 \pm 0.34$</td>
<td>$0.196^{+0.002}_{-0.002} \pm 0.021 \pm 0.013$</td>
</tr>
<tr>
<td>Mod. pole [5]</td>
<td>0.37±0.48</td>
<td>2.01</td>
<td>0.64±0.03</td>
<td>$0.64 \pm 0.06$</td>
<td>$3.641^{+1.555}_{-0.775}$</td>
<td>$3.07^{+1.31}_{-0.65} \pm 0.64 \pm 0.33$</td>
<td>$0.201^{+0.026}_{-0.033} \pm 0.021 \pm 0.013$</td>
</tr>
<tr>
<td>Simple pole</td>
<td>0.</td>
<td>2.01</td>
<td>0.64±0.03</td>
<td>$0.64 \pm 0.06$</td>
<td>$3.008$</td>
<td>$2.54 \pm 0.53 \pm 0.27$</td>
<td>$0.221 \pm 0.023 \pm 0.014$</td>
</tr>
<tr>
<td>Simple pole [5]</td>
<td>0.</td>
<td>1.86±0.12</td>
<td>0.64±0.03</td>
<td>$0.64 \pm 0.06$</td>
<td>$3.485^{+0.420}_{-0.405}$</td>
<td>$2.94^{+0.35}_{-0.34} \pm 0.62 \pm 0.32$</td>
<td>$0.205^{+0.013}_{-0.011} \pm 0.021 \pm 0.013$</td>
</tr>
<tr>
<td>ISGW2</td>
<td>0.06</td>
<td>2.680</td>
<td>1.97±0.21</td>
<td></td>
<td>$0.250 \pm 0.016$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
References


[4] Modified Crystal Ball line shape is used to model this Gaussian core with a power-law tail due to the final state electron radiation:

\[
    f(x) = \text{norm} \begin{cases} 
    e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} & \text{for } \frac{x-\bar{x}}{\sigma} > -|\alpha|, \\
    \left(\frac{\alpha}{|\alpha|}\right)^n e^{-\frac{\alpha^2}{2}} \left(\frac{x-\bar{x}}{\sigma} + \frac{n}{|\alpha|} - |\alpha|\right) & \text{for } \frac{x-\bar{x}}{\sigma} \leq -|\alpha|.
    \end{cases}
\]

where \(\alpha\) is the cross-over point from Gaussian to power-law in units of \(\sigma\), \(n\) is real. The lower numbers of \(n\) give longer tails. In Mn_fit, the function exists with \(\alpha > 0\) only. In that case, the power tail is below the Gaussian peak. In our case, the tail is above the Gaussian peak, so we extend \(\alpha < 0\), allowing it to account for the tail above the Gaussian peak. In the case of \(\alpha < 0\), \(x\) and \(\bar{x}\) swap, i.e. \(x \leftrightarrow \bar{x}\). We have also found that in Mn_fit, the Crystal Ball line shape function is normalized within \((-\infty, +\infty)\), it won’t give the correct yield if the function does not converge within the integral interval, see Fig. 29a. After we correct the normalization within \((x_{\text{min}}, x_{\text{max}})\), we obtain the correct yields, see Fig. 29b. Please keep in mind that the normalization for \(\alpha > 0\) and \(\alpha < 0\) is also different.


Figure 29: Fit to the distributions of random number generated according to Crystal Ball line shape function with $\alpha > 0$ (a) and $\alpha < 0$ (b). The fit in (a) gives the yield (287,582) greater than the entry (280,528) due to the incorrect normalization in Mn$_{\text{fit}}$. After the normalization corrected, the fit gives the right yield, see Figure (b).