Results for exclusive $D$ semileptonic decays from CLEO-c
Overview of an exclusive $B \rightarrow \pi/\rho \ l \ \nu$ analysis
The CLEO detector and data samples

The CLEO detector was developed for $B$ physics at the $Y(4S)$ at the Cornell Electron Storage Ring (CESR):

- **B-field**: 1.5 T
- **Gas (drift chamber)**: He and $C_3H_8$
- **Tracking**: 93% of $4\pi$, $\delta P/P \approx 0.6\%$ for a 1.0 GeV track
- **Hadron particle ID**: RICH (80% of $4\pi$) and $dE/dx$
- **E/M crystal calorimeter**: 93% of $4\pi$, $\delta E/E \approx 2\%(4\%)$ for a 1.0 GeV (100 MeV) photon
- **Muon Chambers**: Proportional chambers at 3, 5 and 7 $\lambda_I$.

Transitions from CLEO III to CLEO-c:

- **B-field**: 1.5 T $\rightarrow$ 1.0 T
- **Silicon vtx detector** $\rightarrow$ low mass stereo drift chamber

CESR is a symmetric $e^+e^-$ collider operating in the region of the $Y$ resonances. Transition from CESR to CESR-c:

- **12 wigglers were installed**

~16 fb$^{-1}$ at the $Y(4S)$

Over 20 years of data taking at $Y(4S)$

Pilot run starting in the fall of 2003

~56 pb$^{-1}$ at the $\psi(3770)$ in fall-03/winter-04 (now have 280 pb$^{-1}$)

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Exclusive Semileptonic D and B decays from CLEO
Semileptonic decays

- Semileptonic decays are a principal process for measuring the CKM matrix elements:
- Strong interaction effects reside in the hadronic current only and are parameterized by form factors (assuming charged lepton mass is zero):
  - for $P$ to $P$ transitions:
    \[ H^\mu = f_+(q^2)(p_i + p_f)^\mu \]
  - for $P$ to $V$ transitions three form factors are needed:
    \[ H^\mu = \frac{2ie^{\mu\nu\alpha\beta}}{M_D + m_V} e^\nu p_f p_i p_\beta V(q^2) - (M_D + m_V) e^\mu A_1(q^2) + \frac{e^\mu e^\nu}{M + m_V} (p_i + p_f)^\mu A_2(q^2) \]
  
- The theory must predict the absolute normalization of form factors for the CKM matrix element measurements:
  \[ \Gamma(D^0 \rightarrow \pi^- e^+\nu) = \frac{B(D^0 \rightarrow \pi^- e^+\nu)}{\tau(D^0)} = \gamma \left| V_{cd} \right|^2 \Rightarrow \delta V_{cd}^2 = \frac{\delta\Gamma}{2\Gamma} + \frac{\delta\gamma}{2\gamma} \]

- In charm semileptonic decays $|V_{cs}|$ and $|V_{cd}|$ are tightly constrained by the unitarity of the CKM matrix. Therefore measurements of charm semileptonic decay rates and form factors rigorously test the theory (e.g., LQCD and LCSR).

- Testing theoretical predictions for semileptonic form factors is an important task of the CLEO-c program underway at CESR (Ref.: CLNS 01/1742).
The $\psi(3770)$ is about 40 MeV above the $DD$ pair production threshold and decay predominantly to $DD$ pairs ($P_D = -P_{\bar{D}}$).

One of the two $D$'s is reconstructed in a hadronic decay channel. It is called a tag. Two key variables in the tag reconstruction:

- $M_{bc} = \sqrt{E_{\text{beam}}^2 - P_{\text{candidate}}^2}$
- $\Delta E = E_{\text{beam}} - E_{\text{candidate}}$

From the remaining tracks and showers the semileptonic decay is reconstructed.

$U \equiv E_{\text{miss}} - |P_{\text{miss}}|$ is used to separate signal from background, where $E_{\text{miss}}$ and $P_{\text{miss}}$ are the missing energy and momentum approximating the neutrino $E$ and $P$. The signal peaks at zero in $U$.

Account for the background in the signal region of $U$. Account for systematic uncertainties.
$D^0$ and $D^+$ tag yields in 56 pb$^{-1}$ of DATA

<table>
<thead>
<tr>
<th>$D^0$ Decay Mode</th>
<th>$B$ (%) PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^-\pi^+$</td>
<td>$(3.80 \pm 0.09)$</td>
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<tr>
<td>$D^0 \rightarrow K^-\pi^+\pi^0$</td>
<td>$(13.1 \pm 0.9)$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^-\pi^+\pi^-\pi^0$</td>
<td>$(7.46 \pm 0.31)$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^0\pi^0$</td>
<td>$(2.28 \pm 0.22)$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^0\pi^+\pi^-$</td>
<td>$(5.92 \pm 0.35)$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^0\pi^+\pi^-\pi^0$</td>
<td>$(10.8 \pm 1.3)$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+K^-$</td>
<td>$(0.41 \pm 0.01)$</td>
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<table>
<thead>
<tr>
<th>$D^+$ Decay Mode</th>
<th>$B$ (%) PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K^0\pi^+$</td>
<td>$(2.77 \pm 0.18)$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^-\pi^+\pi^0$</td>
<td>$(9.1 \pm 0.6)$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^0\pi^+\pi^0$</td>
<td>$(9.7 \pm 3.0)$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+\pi^+\pi^-\pi^0$</td>
<td>$(6.4 \pm 1.1)$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+\pi^-\pi^+\pi^0$</td>
<td>$(7.0 \pm 0.9)$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+K^-\pi^+$</td>
<td>$(0.9 \pm 0.1)$</td>
</tr>
</tbody>
</table>

Examples of Mbc for tag modes in the data

- $D^0 \rightarrow K^-\pi^+$ ~10K events
- $D^0 \rightarrow K^-\pi^+\pi^0$ ~19K events
- $D^+ \rightarrow K^-\pi^+\pi^0$ ~15K events
- $D^0 \rightarrow K^+\pi^+\pi^0\pi^0$ ~4.5K events
- $D^+ \rightarrow K^-\pi^+\pi^0\pi^0$ ~5.0K events
- $D^+ \rightarrow K^-\pi^+\pi^0\pi^0$ ~3.5K events

Tagging creates a single beam of $D$ mesons with known momentum

$\sim$30% tagging efficiency
$\sim$20% tagging efficiency

July, 2005 Exclusive Semileptonic D and B decays from CLEO
Reconstruction of semileptonic decays

- Semileptonic modes listed in the table are reconstructed
- Electron identification (muons are not used):
  - Likelihood function built from E/P, dE/dx and RICH information (~95% efficient above 300 MeV with fake rates below ~0.2%)
  - Bremsstrahlung photons for electrons are recovered
- Hadron identification is based on dE/dx (all momenta) and RICH (above 700 MeV)
- $K^*$, $\rho$, and $\omega$ have 100, 150 and 20 MeV mass window cuts respectively
- Events with extra tracks are vetoed
- The crossing angle is accounted for and the 4-moment of the signal $D$ is approximated by $(E_{\text{beam}}, -\sqrt{E_{\text{beam}}^2 - m_D^2 \hat{p}_{D_{\text{tag}}}})$
- One entry per $U$ plot per $D$ tag mode is chosen based on $K^*/\rho/\omega$ and/or $\pi^0$ masses
- Again, semileptonic decays peak at zero in $U \equiv E_{\text{miss}} - |P_{\text{miss}}|$
- Semileptonic branching fractions are obtained as $B(D^0 \rightarrow \pi^- e^+ \nu) = \frac{N(\pi^- e^+ \nu)}{\varepsilon(\pi^- e^+ \nu)N(D_{\text{tag}}^0)}$ (independent of the luminosity)

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Semileptonic modes listed in the table are reconstructed

<table>
<thead>
<tr>
<th>Decay Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $D^0 \rightarrow K^- e^+ \nu$</td>
</tr>
<tr>
<td>2. $D^0 \rightarrow K^- e^+ \nu$</td>
</tr>
<tr>
<td>3. $D^0 \rightarrow K^0 (K^- \pi^0) e^+ \nu$</td>
</tr>
<tr>
<td>4. $D^0 \rightarrow K^0 (K^0 \pi^-) e^+ \nu$</td>
</tr>
<tr>
<td>5. $D^0 \rightarrow \rho^0 e^+ \nu$</td>
</tr>
<tr>
<td>6. $D^+ \rightarrow \pi^0 e^+ \nu$</td>
</tr>
<tr>
<td>7. $D^+ \rightarrow K^0 e^+ \nu$</td>
</tr>
<tr>
<td>8. $D^+ \rightarrow K^{*0} (K^- \pi^+) e^+ \nu$</td>
</tr>
<tr>
<td>9. $D^+ \rightarrow \rho^0 (\pi^+ \pi^-) e^+ \nu$</td>
</tr>
<tr>
<td>10. $D^+ \rightarrow \omega (\pi^+ \pi^- \pi^0) e^+ \nu$</td>
</tr>
</tbody>
</table>

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Exclusive Semileptonic D and B decays from CLEO
Background is small and peaks outside the signal region (kinematic separation)

Most background comes from cross-feed among $D$ semileptonic decays

In other experimental configurations the momentum of the parent $D$ meson is unmeasured because of the neutrino, which leads to poorer separation between signal and background

For example, in a CLEO III analysis using Y(4S) data (PRL 94, 011802 (2005)) to reduce background $D^0 \rightarrow \pi^+ e^+ \nu$ is tagged with $\pi_{slow}: D^{*+} \rightarrow D^0 \pi_{slow}$. Fits are made to $\Delta M \equiv M(D^{*+}) - M(D^0)$ in bins of $q^2$
**U distributions for \( P \rightarrow P \) decays in 56 pb\(^{-1}\) of data**

Cabibbo favored modes

- \( D^0 \rightarrow K^- e^+ \nu \) 
  - \( \sim 1300 \) events

- \( D^0 \rightarrow \pi^- e^+ \nu \) 
  - \( \sim 110 \) events

Cabibbo suppressed modes

- \( D^+ \rightarrow K_S^0 e^+ \nu \) 
  - \( \sim 550 \) events

- \( D^+ \rightarrow \pi^0 e^+ \nu \) 
  - \( \sim 65 \) events
$U$ distributions for $P \to V$ decays in 56 pb$^{-1}$ of data

Cabibbo favored modes

$D^0 \to K^−(K^0\pi^0)e^+\nu$

$\sim 90$ events

$D^0 \to K^* K^0_s\pi^-e^+\nu$

$\sim 120$ events

$D^+ \to K^{*0}(K^-\pi^+)e^+\nu$

$\sim 420$ events

Cabibbo suppressed modes

$D^0 \to \rho^-e^+\nu$

$\sim 30$ events

First Observation

$D^+ \to \rho^0e^+\nu$

$\sim 30$ events

First Observation

$D^+ \to \omega e^+\nu$

8 events
Absolute branching fractions for $D$ semileptonic decays

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B$ (%)</th>
<th>$B$ (%) (PDG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to \pi^- e^+ \nu_e$</td>
<td>$0.26 \pm 0.03 \pm 0.01$</td>
<td>$0.36 \pm 0.06$</td>
</tr>
<tr>
<td>$D^0 \to K^- e^+ \nu_e$</td>
<td>$3.44 \pm 0.10 \pm 0.10$</td>
<td>$3.58 \pm 0.18$</td>
</tr>
<tr>
<td>$D^0 \to K^-(K^-\pi^0)e^+ \nu_e$</td>
<td>$2.11 \pm 0.23 \pm 0.10$</td>
<td>$2.15 \pm 0.35$</td>
</tr>
<tr>
<td>$D^0 \to K^-(K^0\pi^-)e^+ \nu_e$</td>
<td>$2.19 \pm 0.20 \pm 0.11$</td>
<td>$2.15 \pm 0.35$</td>
</tr>
<tr>
<td>$D^0 \to \rho^- e^+ \nu_e$</td>
<td>$0.19 \pm 0.04 \pm 0.01$ —</td>
<td></td>
</tr>
<tr>
<td>$D^+ \to \pi^0 e^+ \nu_e$</td>
<td>$0.44 \pm 0.06 \pm 0.03$</td>
<td>$0.31 \pm 0.15$</td>
</tr>
<tr>
<td>$D^+ \to K^0 e^+ \nu_e$</td>
<td>$8.71 \pm 0.38 \pm 0.37$</td>
<td>$6.7 \pm 0.9$</td>
</tr>
<tr>
<td>$D^+ \to \bar{K}^0 e^+ \nu_e$</td>
<td>$5.56 \pm 0.27 \pm 0.23$</td>
<td>$5.5 \pm 0.7$</td>
</tr>
<tr>
<td>$D^+ \to \rho^0 e^+ \nu_e$</td>
<td>$0.21 \pm 0.04 \pm 0.01$</td>
<td>$0.25 \pm 0.10$</td>
</tr>
<tr>
<td>$D^+ \to \omega e^+ \nu_e$</td>
<td>$0.16^{+0.07}_{-0.06} \pm 0.01$ —</td>
<td></td>
</tr>
</tbody>
</table>

- **BF** for $D^0 \to \pi^- e^+ \nu$ ($D^+ \to \bar{K}^0 e^+ \nu$) is measured to be somewhat lower (higher) than the PDG value.

- $B(D^0 \to \pi^- e^+ \nu) / B(D^0 \to K^- e^+ \nu) = (7.6\pm0.8 \pm 0.2) \times 10^{-2}$ compares favorably with the CLEO III result of $(8.2\pm0.6\pm0.5) \times 10^{-2}$ (CLEO, PRL 94, 011802 (2005)). The PDG-04 value for this ratio is 0.101\pm0.017.

- The following two modes $D^0 \to \rho^- e^+ \nu$ and $D^+ \to \omega e^+ \nu$ are observed for the first time.

- Most systematic uncertainties are measured in data and will be reduced with a larger data sample.

References:
- hep-ex/0506052 and hep-ex/0506053
  Both submitted to PRL
The widths of the isospin conjugate exclusive semileptonic decays are related due to the isospin invariance of the hadronic current. We find:

\[ \Gamma(D^0 \rightarrow K^- e^+ \nu) / \Gamma(D^+ \rightarrow K^0 e^+ \nu) = 1.00 \pm 0.05 \pm 0.04 \]
\[ \Gamma(D^0 \rightarrow \pi^- e^+ \nu) / [2 \cdot \Gamma(D^+ \rightarrow \pi^0 e^+ \nu)] = 0.75^{+0.14}_{-0.11} \pm 0.04 \]
\[ \Gamma(D^0 \rightarrow K^{*-} e^+ \nu) / \Gamma(D^+ \rightarrow \bar{K}^{*0} e^+ \nu) = 0.98 \pm 0.08 \pm 0.04 \]

Isospin averaged semileptonic decay widths:

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\Gamma (10^{-2} \cdot \text{ps}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D \rightarrow K e^+ \nu_e$</td>
<td>8.38 ± 0.20 ± 0.23</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^- e^+ \nu_e$</td>
<td>0.68 ± 0.05 ± 0.02</td>
</tr>
<tr>
<td>$D \rightarrow K^+ e^+ \nu_e$</td>
<td>5.32 ± 0.21 ± 0.20</td>
</tr>
<tr>
<td>$D^0 \rightarrow \rho^- e^+ \nu_e$</td>
<td>0.43 ± 0.06 ± 0.02</td>
</tr>
</tbody>
</table>

Summing up all exclusive semileptonic branching fractions measured in this analysis we find:

\[ \sum B(D^0_{\text{excl semil}}) = (6.1 \pm 0.2 \pm 0.2)\% \quad \text{and} \quad \sum B(D^+_{\text{excl semil}}) = (15.1 \pm 0.5 \pm 0.5)\% \]

These are consistent with the CLEO-c inclusive semileptonic branching fractions (Ref.: CLEO-CONF 05-3, LP2005-429):

\[ B(D^0_{\text{incl semil}}) = (6.5 \pm 0.2 \pm 0.2)\% \quad \text{and} \quad B(D^+_{\text{incl semil}}) = (16.2 \pm 0.2 \pm 0.4)\% \]

which excludes the possibility of additional $D$ semileptonic modes with large branching fractions.
CLEO is finishing studies of $B \to X_\mu l \nu$ with the complete CLEO II, II.V and III data sample of 15.4 million $BB$ events. Two analyses are ongoing:

- Weak annihilation in $B \to X_\mu l \nu$ (preliminary results are given in the talk by I.Shipsey in “Heavy Flavors” later today)
- An update for exclusive $B \to \pi/\rho l \nu$ and $|V_{ub}|$

The technique described in Phys.Rev. D 68 072003 (2003) is used for the latter analysis:

- Neutrino reconstruction: $(E_\nu, P_\nu) = (|P_{\text{miss}}|, P_{\text{miss}})$
- Rates are measured in $q^2$ bins (to minimize the uncertainty from form factors on the branching fractions)
- Simultaneous binned ML fit to all modes (to account for cross-feed among modes) using isospin or constituent quark model constraints for the branching fractions (results from 2003):

$$B(B^0 \to \pi^- l^+ \nu) = (1.33 \pm 0.18 \pm 0.11 \pm 0.01 \pm 0.07) \times 10^{-4};$$
$$B(B^0 \to \rho^- l^+ \nu) = (2.17 \pm 0.34 \pm 0.47 \pm 0.41 \pm 0.01) \times 10^{-4}$$

- $|V_{ub}|$ is extracted using LCSR for $q^2 \in [0;16]$ GeV$^2$ and LQCD for $q^2 \in [16; q_{\text{max}}^2]$ GeV$^2$. 
In the current $B \to \pi/\rho \ell \nu$ analysis, significant improvements in the systematic uncertainty related to the $B \to \rho \ell \nu$ modeling are expected:

- The lepton momentum cut is lowered to 1.0 GeV from 1.5 GeV
- The region $\cos(\theta_l) < 0.0$ is included in the fit

Changes to the $q^2$ binning are being considered

Recent unquenced lattice calculation for the $B \to \pi \ell \nu$ form factor is used (Shigemitsu, et al., hep-lat/0408019)

Final CLEO results on $|V_{ub}|$ using 15.4 million $BB$ pairs are forthcoming.
The analysis of absolute $D$ semileptonic branching fractions from the first $\sim 56 \text{ pb}^{-1}$ data sample collected at the $\psi(3770)$ by CLEO-c is completed. All measurements are most precise to date.

CLEO is finishing studies of $B \to X_u \ell \nu$ with the full $\Upsilon(4S)$ data set of 15.4 million $BB$ events.

Analyses of semileptonic form factors with 280 pb$^{-1}$ of new CLEO-c data are ongoing.

CLEO-c is going to collect a much larger data sample at the $\psi(3770)$ as well as data above the $D_s D_s$ threshold. This data sample will play an important role in particle physics as

- validation and calibration data for LQCD and other theories and models
- input data to the $B$ factories and other experiments increasing their potential in the search for new physics
Extra slides
The ~56 pb\(^{-1}\) data sample collected in fall-2003/winter-2004 by the CLEO-c detector already gives measurements of absolute branching fractions for all modes considered today with uncertainties smaller than the uncertainties in PDG-2004.

CLEO-c is going to collect a much larger data sample at the \(\psi(3770)\) and data at slightly higher energies for studies of \(D_s\) mesons.

An important aspect of the CLEO-c program is testing the LQCD predictions as well as predictions of models or other theories for semileptonic form factors:

- CLEO-c will measure form factors at a percent level in \(P \rightarrow P\) transitions and at a few percent level in \(P \rightarrow V\) transitions.
- Theory (e.g., LQCD) predictions for the absolute normalization of form factors (e.g., \(f_+(0)\)) can be tested if one assumes the unitarity of the CKM matrix (\(V_{cs}\) and \(V_{cd}\) become known to 0.1% and 1.0% respectively)
- Theory can be tested further without uncertainties associated with the CKM couplings or assumptions of the CKM unitarity using the following ratio of decay rates \(\Gamma(D^+ \rightarrow \pi^- \ell^+ \nu) / \Gamma(D^+ \rightarrow \ell^+ \nu)\)

Using future CLEO-c measurements of branching fractions for \(D \rightarrow \pi \ell\nu\) and \(D \rightarrow K \ell\nu\) (1.2% and 1.5% uncerts) and the world averages for \(D\) meson lifetimes, and assuming theory errors on \(\gamma_s\) and \(\gamma_d\) of 3%, the following uncertainties for \(V_{cs}\) and \(V_{cd}\) from \(D\) semileptonic decays at CLEO-c sample are possible:

\[\frac{\delta V_{cs}}{V_{cs}} \approx 1.6\% \quad \text{and} \quad \frac{\delta V_{cd}}{V_{cd}} \approx 1.7\%\]

First unquenched LQCD calculation for \(D \rightarrow \pi/Ke\nu\) (PRL 94, 011601 (2005))