Semileptonic decays of D mesons at CLEO

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Content of the talk

• Report on two recent measurements with the CLEO-c detector:
  – Improved measurements of D meson semileptonic decays to $\pi$ and K mesons [arXiv:0906.2983]
  – Study of semileptonic decay $D_s \rightarrow f_0(980)e^+\nu$ and implications for $B_s \rightarrow J/\psi f_0$ [preliminary].

• Data collected at charm threshold:
  – $e^+e^- \rightarrow \psi(3770) \rightarrow D\overline{D}$
  – $e^+e^- \rightarrow D_s^*\overline{D}_s$ at 4170 MeV

• CLEO-c detector:
  – Charged particle detection (1T): $\sigma_p/p=0.6\%$ at 1 GeV
  – Photon detection: $\sigma_E/E=4.8\%$ at 100 MeV, 2.2\% at 1 GeV
  – Hadron ID: dE/dX+RICH (fake rates at a few \% level)
Motivation for $D \rightarrow K/\pi \, e^+\nu$ Measurements

- Direct determination of $|V_{cs\, (cd)}|$.
- Theoretical (Lattice QCD) errors on the form-factor predictions dominate.
- Taking $|V_{cs\, (cd)}| = |V_{ud\, (us)}|$ can turn data into form-factor measurements (normalization and $q^2$ dependence) to test/develop LQCD.
- Potentially, leads to improved predictions for the form-factors in semileptonic $b$ decays and improved determination of $|V_{ub}|$.
- Only one form-factor in decays to pseudoscalar mesons – easiest to deal with theoretically.
Tagging technique

• **Very effective at threshold:** $e^+e^- \rightarrow D\bar{D}$:
  - No fragmentation particles produced

• **Reconstruct one D (tag) in several clean hadronic decay modes:**
  - Cut on $\Delta E = E_D - E_{\text{beam}}$
  - Fit $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_D^2}$ to determine $N_{\text{tag}}$
  - The tag determines momentum of the other D:
    \[ p_{D\text{ signal}} = - p_{D\text{ tag}} \]

• **Find subsample in which the rest of reconstructed particles consists of an electron (e) and desired hadron (h) from semileptonic D-decay.**
  - Calculate missing (i.e. neutrino) energy
    \[ E_{\text{miss}} = E_{\text{beam}} - E_e - E_h \]
    and momentum \( p_{\text{miss}} = - p_{D\text{ tag}} - p_e - p_h \).
    Fit \( U_{\text{miss}} = E_{\text{miss}} - |p_{\text{miss}}| \) to extract $N_{\text{signal}}$.
  - $\text{BR} = \left( \frac{N_{\text{signal}}}{\varepsilon_{\text{signal}}} \right) / \left( \frac{N_{\text{tag}}}{\varepsilon_{\text{tag}}} \right)$
  - Also determine differential rates in
    \[ q^2 = (E_{\text{beam}} - E_h)^2 - (-p_{D\text{ tag}} - p_h)^2 \]
Tag

- CLEO-c reconstructs a tag in about \(\sim 20\%\) of all \(D\bar{D}\) events
- Compared to \(\sim 0.1\%\) tagging efficiency for \(Y(4S) \to BB\)
**Signal – π, K (tagged)**

- Cabibbo suppressed
  - $D^0 \rightarrow \pi^- e^+ \nu$
  - $D^0 \rightarrow \rho^- e^+ \nu$
  - $D^0 \rightarrow K^- e^+ \nu$

- Cabibbo favored
  - $D^0 \rightarrow K^- e^+ \nu$
  - $D^+ \rightarrow \pi^0 e^+ \nu$
  - $D^+ \rightarrow K^0 e^+ \nu$
  - $D^+ \rightarrow K^0 e^+ \nu$

<table>
<thead>
<tr>
<th>Cabibbo Suppressed</th>
<th>Cabibbo Favored</th>
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<tbody>
<tr>
<td>~1,400 events</td>
<td>~14,000 events</td>
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<tr>
<td>BR=(2.88±0.008±0.003) $10^{-3}$</td>
<td>BR=(3.50±0.03±0.04) $10^{-2}$</td>
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- $U_{\text{miss}} = E_{\text{mis}} - |p_{\text{mis}}|$ (GeV)

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<tr>
<th>Signal</th>
<th>BR</th>
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<tr>
<td>$D^0 \rightarrow \pi^- e^+ \nu$</td>
<td>(4.05±0.016±0.009) $10^{-3}$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^- e^+ \nu$</td>
<td>(8.83±0.01±0.02) $10^{-3}$</td>
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- Excellent background suppression. Small feed-across due to threshold kinematics.
Branching Ratio Results - Comparison

• Significant improvement in precision by recent BaBar/Belle/CLEO-c measurements (CLEO-c most precise).
Form factors

- Form factors are related to probability of forming final state hadron at given $q^2$.
- Theoretical predictions for form factors needed to turn the measured rates into $V_{cs (cd)}$ determinations.
- Theory often calculates this probability at fixed $q^2$ and uses parameterizations to extrapolate to full $q^2$ range.
- Theoretical approaches include phenomenological models, QCD sum rules, LQCD.
- Only the latter is systematically improvable.

\[ H^\mu = f_+(q^2)(P_D + P_h)^\mu \quad \text{(for } m_l=0) \]

\[ H^\mu = \frac{2i \epsilon^{\mu \nu \alpha \beta}}{m_D + m_h} e_\nu^* P_{h\alpha} P_{D\beta} (V(q^2)) - (m_D + m_h) e^{\mu*} A_1(q^2) + \frac{e^{*\alpha} q_\alpha}{m_D + m_h} (P_D + P_h)^\mu A_2(q^2) \]

Simplicity favors pseudoscalar decay modes.
Pseudoscalar Form Factors

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

- Much of the visible variation is due to the phase-space factor \((P^3)\).
Comparison to LQCD

Modified Pole Model
fit to FNAL-MILC lattice calculations

\[
f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{pole}^2}} - \frac{1}{1 - \alpha \frac{q^2}{M_{pole}^2}}
\]

Assuming \( V_{cs} = 0.9734 \)
Assuming \( V_{cd} = 0.2256 \)

- Good agreement between the data and LQCD on \( f_+(0) \)
- Shape of \( q^2 \) dependence also consistent, though data prefer lower \( \alpha \).
- Lattice calculation errors (10%) much bigger than the experimental errors (2.9%, 1.2%)
CKM results

Combine measured $|V_{cx}|f_+(0)$ values (fit of Hill&Becher f.f. parameterization) with FNAL-MILC calculations for $f_+(0)$

- Improvements in LQCD calculations are needed
Motivation for $D_s \to f_0 \, e^+\nu$ Measurement

- CP violating phase of $B_s - \overline{B_s}$ oscillations ($\phi_s$) is very small in SM. Sensitive to NP contributions.
- Present approach (CDF+D0) is to use $B_s \to J/\psi \, \phi$:
  - Simultaneous fit of CP asymmetry to time and angular distributions (to disentangle CP-odd and -even amplitudes)
  - CDF+D0 results $\sim 2.2\sigma$ away from the SM prediction!
- Stone&Zhang [PRD79,074024] suggested $B_s \to J/\psi \, f_0$ as useful alternative:
  - CP-eigenstate. No angular analysis is needed.
  - BR not know at present. Can be predicted from $D_s \to f_0 \, e^+\nu$ rate at $q^2=0$.

$$\frac{\Gamma(B_s \to J/\psi \, f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\psi \, \phi, \phi \to K^+K^-)} \approx \frac{\Gamma(D_s \to e^+\nu \, f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(D_s \to e^+\nu \, \phi, \phi \to K^+K^-)} \bigg|_{q^2=0}$$

- Can study properties of $f_0$ (poorly known!) in clean environment.
• Additional step needed due to presence of photon from $D_s^* \rightarrow \gamma D_s$

$$MM^{*2} = (E_{CM} - E_{D_s} - E_{\gamma})^2 - (\vec{p}_{CM} - \vec{p}_{D_s} - \vec{p}_{\gamma})^2$$
Signal events

\[ D_s \rightarrow \pi^+\pi^-e^+\nu \]

\[ D_s \rightarrow \eta'e^+\nu \]

\[ \text{43±7 signal events} \]

\[ \text{107±10 signal events} \]

\[ MM^2 = \left( E_{CM} - E_{D_s} - E_\gamma - E_e - E_{\pi^+} - E_{\pi^-} \right)^2 \]
\[ - \left( p_{CM} - p_{D_s} - p_\gamma - p_e - p_{\pi^+} - p_{\pi^-} \right)^2 \]

\[ f_0 \]

\[ M_{f_0} = (977^{+11}_{-9} \pm 1) \text{ MeV} \]

\[ \Gamma_0 = (91^{+30}_{-22} \pm 3) \text{ MeV} \]
Form factors and BR

- Fit $M(h^+h^-)$ in $q^2$ bins

$$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{pole}^2}}$$

Single Pole Model

From the sum of efficiency corrected yield in all $q^2$ bins:

$$BR(D_s \to f_0(980)e^+\nu, f_0 \to \pi^+\pi^-) = (0.20 \pm 0.03 \pm 0.01)\%$$

$$BR(D_s \to \phi e^+\nu) = (2.36 \pm 0.23 \pm 0.13)\%$$
From fits of $f_+(0)$

$$R_{f/\phi} = \frac{\Gamma(D_s \rightarrow e^+\nu f_0(980), f_0 \rightarrow \pi^+\pi^-)}{\Gamma(D_s \rightarrow e^+\nu \phi, \phi \rightarrow K^+K^-)} \bigg|_{q^2=0} = (42 \pm 11)\%$$

• Assuming

$$R_{f/\phi} = \frac{\Gamma(B_s \rightarrow J/\psi f_0(980), f_0 \rightarrow \pi^+\pi^-)}{\Gamma(B_s \rightarrow J/\psi \phi, \phi \rightarrow K^+K^-)}$$

• Since no angular analysis needed expect $B_s \rightarrow J/\psi f_0$ to provide a complementary way to $B_s \rightarrow J/\psi \phi$ of measuring CP-violating phase $\phi_s$

• Need explicit measurement of BR for $B_s \rightarrow J/\psi f_0$ to confirm
Summary

• Our knowledge of semileptonic D-decays and related parameters has been significantly improved thanks to high luminosities at B-factories (BaBar, Belle) and data taken at the charm threshold (CLEO-c). CLEO-c most precise.
  - \( \text{BR}(D \to K e \nu) \) 6% error → 1.4%
  - combined with LQCD calculations (10% errors) leads to best direct determination of \( V_{cs} \)
  - \( \text{BR}(D \to \pi e \nu) \) 45% error → 3%
  - Potential for best direct determination of \( V_{cd} \) if LQCD errors are improved

• From preliminary result

\[
R_{f/\phi} = \left. \frac{\Gamma(D_s \to e^+\nu f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(D_s \to e^+\nu \phi, \phi \to K^+K^-)} \right|_{q^2=0} = (42\pm11)\%
\]

predict \( B_s \to J/\psi f_0 \) can provide a complementary way to \( B_s \to J/\psi \phi \) of measuring CP-violating phase \( \phi_s \)