D Leptonic and Semi-leptonic Decays

Hailong Ma (IHEP)
For BESIII Collaboration

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  - $D^+ \rightarrow K^-\pi^+ e^+\nu$
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- Summary

See Fenfen’s talk on May 21st for more details
D leptonic and semi-leptonic decays are ideal window to probe for weak and strong effects

- Precision measurements of decay constants $f_{D^+}$, $f_{D_s^+}$, form factors $f_{+}^{D \rightarrow K(\pi)(q^2)}$ of semi-leptonic decays of D mesons will calibrate LQCD calculations at higher accuracy. Once they pass experimental tests, the precise LQCD calculations of $f_D/f_B$, $f_{D_s}/f_{B_s}$ and form factors will be helpful for measurement in B decay.

- Recent LQCD calculations on $f_{D(s)}^{[0.5(0.5)]\%}$, $f_{+}^{D \rightarrow K(\pi)(0)}^{[1.7(4.4)]\%}$ provide good chance to precisely measure the CKM matrix element $|V_{cs(d)}|$, which are important for the unitarity test of the CKM matrix and search for NP beyond the SM.
Data Sample

Designed luminosity is $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$ at $\psi(3770)$

Highest luminosity reached $0.85 \times 10^{33}$ cm$^{-2}$s$^{-1}$ at $\psi(3770)$ in 2014

Highest luminosity reached $0.85 \times 10^{33}$ cm$^{-2}$s$^{-1}$ at $\psi(3770)$ in 2014

The parameters of each sub-detectors can be found in previous talks

2.92 fb$^{-1}$ at $\psi(3770)$

3.6 x CLEOc
Singly Tagged $\bar{D}^0$ and $D^-$ Mesons

$D^0\bar{D}^0$ and $D^+D^-$ are produced in pair at $\psi(3770)$

Singly tagged $\bar{D}^0$ and $D^-$ mesons are reconstructed by hadronic decays with large branching fraction and less combinatorial backgrounds.

- $D^+\rightarrow K_L e^+\nu$
- $D^+\rightarrow K^-\pi^+ e^+\nu$
- $D^+\rightarrow \omega/\phi e^+\nu$

At the recoil side of singly tagged $\bar{D}^0$ and $D^-$ mesons, leptonic and semi-leptonic decays can be studied.
\textbf{D}^+ \text{ Leptonic Decays}

\begin{align*}
\Gamma(D_{(s)}^{+} \rightarrow \ell^+ \nu_\ell) &= \frac{G_F^2 f_{D(s)}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}^{+}} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^{+}}^2}\right)^2 \\
\end{align*}

\text{In the SM:}

\text{Bridge to precisely measure}

- Decay constants $f_{D(s)^+}$ with input $|V_{cd(s)}|^\text{CKMfitter}$
- CKM matrix element $|V_{cd(s)}|$ with input $f_{LQCD}^{D(s)^+}$
Measurement of $B[D^+ \to \mu^+ \nu]$, $f_{D^+}$ and $|V_{cd}|$

$e^+e^- \to \psi(3770) \to D^+D^-$

$N_{D_{\ell\bar{\ell}}^0} = (170.31 \pm 0.34) \times 10^4$

$B[D^+ \to \mu^+ \nu] = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$

$f_{D^+} = (203.2 \pm 5.3 \pm 1.8) \text{ MeV}$

$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$

2.92 fb$^{-1}$ data@ 3.773 GeV

PRD89(2014)051104R

Input $t_{D^+}$, $m_{D^+}$, $m_{\mu^+}$ on PDG and $|V_{cd}|$ of CKM-Fitter

Input $t_{D^s}$, $m_{D^s}$, $m_{\mu^+}$ on PDG and LQCD calculated $f_{D^s} = 207 \pm 4$ MeV [PRL100(2008)062002]
Comparisons of $B[D^+ \rightarrow \mu^+ \nu_\mu]$ and $f_{D^+}$

- $(0.0393 \pm 0.0035 \pm 0.0009)\%$ CLEO-c
- $(0.0371 \pm 0.0019 \pm 0.0006)\%$ BESIII
- $(0.0382 \pm 0.0033)\%$ PDG2014

$B[D^+ \rightarrow \mu^+ \nu]$ versus $f_{D^+}$ [MeV]

- $209.0 \pm 9.3 \pm 2.6$ CLEO-c
- $203.2 \pm 5.3 \pm 1.8$ BESIII
  
  PRD89 (2014) 051104 (R)

- $208.3 \pm 3.4$ HPQCD
  
  PRD86(2012)054510

- $212.6 \pm 0.4^{+1.0}_{-1.2}$ Fermilab Lattice+MILC
  
  PRD90(2014)074509
Comparisons of $f_{D^+}$, $f_{Ds^+}$ and $f_{D^+}:f_{Ds^+}$

Taken from Gang Rong’s talk at CKM2014

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Femilab Lattice+MILC (2014)</th>
<th>HPQCD (2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Averaged</td>
<td>Expected</td>
</tr>
<tr>
<td>$f_{D^+}(\text{MeV})$</td>
<td>203.9±4.7</td>
<td>212.6±0.4^{+1.0}_{-1.2}</td>
</tr>
<tr>
<td>$f_{Ds^+}(\text{MeV})$</td>
<td>256.9±4.4</td>
<td>249.0±0.3^{+1.1}_{-1.5}</td>
</tr>
<tr>
<td>$f_{D^+} : f_{Ds^+}$</td>
<td>1.260±0.036</td>
<td>1.1712±0.0010^{+0.0029}_{-0.0032}</td>
</tr>
</tbody>
</table>

- Precisions of the LQCD calculations of $f_{D^+}$, $f_{Ds^+}$, $f_{D^+} : f_{Ds^+}$ reach 0.5%, 0.5% and 0.3%, which are challenging the experiments.

- The experimentally measured and the theoretically expected $f_{D^+}$, $f_{Ds^+}$, $f_{D^+} : f_{Ds^+}$ differ by about 2σ.

- Improving measurement with larger data sample is expected at BESIII!
D Semi-leptonic Decays

Differential rates:
\[ \frac{d\Gamma}{dq^2} = \chi \frac{G_F^2 |V_{cd(s)}|^2}{24\pi^3} p^3 |f_+(q^2)|^2 \]

Bridge to precisely measure:

- Form factors $f^{D\rightarrow K(\pi)^+}(q^2)$ with input $|V_{cd(s)}|^{CKMfitter}$
  - Single pole form
    \[ f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{pole}^2}} \]
  - ISGW2 model
    \[ f_+(q^2) = f_+(q_{\text{max}}) \left( 1 + \frac{r^{\text{ISGW2}}}{12} (q_{\text{max}}^2 - q^2) \right)^{-2} \]
  - Modified pole model
    \[ f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{M_{pole}^2})(1 - \alpha \frac{q^2}{M_{pole}^2})} \]
  - Series expansion model
    \[ f_+(t) = \frac{1}{P(t)\Phi(t,t_0)} a_0(t_0) \left( 1 + \sum_{k=1}^{\infty} r_k(t_0)[z(t,t_0)]^k \right) \]

- CKM matrix element $|V_{cs(d)}|$ with input $f^{LQCD,D\rightarrow K(\pi)^+}(0)$
Measurement of $B[D^0 \rightarrow K(\pi^-e^+\nu)]$

$e^+e^- \rightarrow \psi(3770) \rightarrow D^0\overline{D^0}$

$N_{D^0_{\text{tag}}} = (279.33 \pm 0.37) \times 10^4$

$B_{D^0 \rightarrow K^-e^+\nu} = (3.505 \pm 0.014 \pm 0.033)\%$

$B_{D^0 \rightarrow \pi^-e^+\nu} = (0.2950 \pm 0.0041 \pm 0.0026)\%$
Comparison of $B[D^0 \rightarrow K(\pi)^- e^+ \nu]$
Extracted Parameters of Form Factors

<table>
<thead>
<tr>
<th></th>
<th>$D^0 \rightarrow K^- e^+ \nu$</th>
<th>$D^0 \rightarrow \pi^- e^+ \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simple Pole</strong></td>
<td>$f_K^+(0)</td>
<td>V_{cs}</td>
</tr>
<tr>
<td></td>
<td>$M_{pole} = 1.9207^{+0.0193}_{-0.0069}$</td>
<td>$M_{pole} = 1.9114^{+0.0118}_{-0.0038}$</td>
</tr>
<tr>
<td><strong>Modified Pole</strong></td>
<td>$f_K^+(0)</td>
<td>V_{cs}</td>
</tr>
<tr>
<td></td>
<td>$\alpha = 0.3088^{+0.0195}_{-0.0129}$</td>
<td>$\alpha = 0.2794^{+0.0345}_{-0.0113}$</td>
</tr>
<tr>
<td><strong>ISGW2</strong></td>
<td>$f_K^+(0)</td>
<td>V_{cs}</td>
</tr>
<tr>
<td></td>
<td>$r_{ISGW2} = 1.6000^{+0.0141}_{-0.0091}$</td>
<td>$r_{ISGW2} = 2.0688^{+0.0394}_{-0.0124}$</td>
</tr>
<tr>
<td><strong>Series.2.Par</strong></td>
<td>$f_K^+(0)</td>
<td>V_{cs}</td>
</tr>
<tr>
<td></td>
<td>$r_1 = -2.2278^{+0.0864}_{-0.0575}$</td>
<td>$r_1 = -2.0365^{+0.0807}_{-0.0260}$</td>
</tr>
<tr>
<td><strong>Series.3.Par</strong></td>
<td>$f_K^+(0)</td>
<td>V_{cs}</td>
</tr>
<tr>
<td></td>
<td>$r_1 = -2.3331^{+0.1587}_{-0.0804}$</td>
<td>$r_1 = -1.8434^{+0.2212}_{-0.0690}$</td>
</tr>
<tr>
<td></td>
<td>$r_2 = 3.4223^{+3.9090}_{-2.4092}$</td>
<td>$r_2 = -1.3871^{+1.4615}_{-0.4677}$</td>
</tr>
</tbody>
</table>
Measurement of $f_{+}^{K(\pi)}(q^2)$

Experimental data calibrate LQCD calculation

Fermilab Lattice, MILC and HPQCD, PRL 94 (2005) 011601
Fermilab Lattice and MILC, PRD 80 (2009) 034026

Solid lines represent LQCD fits to the BK model, PLB 478 (2000) 417

$D^0 \rightarrow K^- e^+ \nu$

$D^0 \rightarrow \pi^- e^+ \nu$

BESIII Preliminary
### Measurement of $f_+^{K(\pi)(0)}$

**Input $|V_{cs(d)}|$ of CKM-Fitter**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BES-II</td>
<td>$0.78\pm0.04\pm0.03$</td>
<td>PLB597, 39</td>
</tr>
<tr>
<td>CLEO-c</td>
<td>$0.739\pm0.007\pm0.005$</td>
<td>PRD80, 032005, 3.Par.Ser.</td>
</tr>
<tr>
<td>BELLE</td>
<td>$0.695\pm0.007\pm0.022$</td>
<td>PRL97, 061804, Mod.Pole</td>
</tr>
<tr>
<td>BABAR</td>
<td>$0.727\pm0.007\pm0.005$</td>
<td>PRD76, 052005, ISGW2</td>
</tr>
<tr>
<td>BESIII</td>
<td>Preliminary</td>
<td></td>
</tr>
<tr>
<td>HPQCD</td>
<td>$0.747\pm0.011\pm0.015$</td>
<td>PRD82 (2010) 114506</td>
</tr>
</tbody>
</table>

**Output $f_+^{K(\pi)(0)}$**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BES-II</td>
<td>$0.73\pm0.14\pm0.06$</td>
<td>PLB597, 39</td>
</tr>
<tr>
<td>CLEO-c</td>
<td>$0.666\pm0.019\pm0.005$</td>
<td>PRD80, 032005, 3.Par.Ser.</td>
</tr>
<tr>
<td>BELLE</td>
<td>$0.624\pm0.020\pm0.007$</td>
<td>PRL97, 061804, Mod.Pole</td>
</tr>
<tr>
<td>Babar</td>
<td>$0.610\pm0.017\pm0.011$</td>
<td>PRD91 (2015) 052022 Babar, 3-Par.Ser.</td>
</tr>
<tr>
<td>BESIII</td>
<td>Preliminary</td>
<td></td>
</tr>
<tr>
<td>HPQCD</td>
<td>$0.666\pm0.020\pm0.021$</td>
<td>PRD84 (2011) 114505</td>
</tr>
</tbody>
</table>
Measurement of $|V_{cs(d)}|$

Method 1

$B[D(s)^+ \rightarrow l^+\nu]$ 

Input $t_{D^+}$, $m_{D^+}$, $m_{\mu^+}$ on PDG and LQCD calculated $f_{D(s)^+}$

Input $f^{D\rightarrow K(\pi)_+(0)}$ of LQCD

Method 2

$f^{D\rightarrow K(\pi)_+(0)}|V_{cs(d)}|$ 

Method 2 suffers larger theoretical uncertainty in $f^{D\rightarrow K(\pi)_+(0)}$ [1.7(4.4)%]

Method: $D^+_s \rightarrow \mu^+\nu$

- $1.009\pm0.040\pm0.020$ CLEO-c
- $0.978\pm0.026\pm0.022$ BaBar
- $1.041\pm0.033\pm0.032$ Belle

Method: $D^+_s \rightarrow l^+\nu$

- $1.015\pm0.030\pm0.018$ CLEO-c
- $0.960\pm0.034\pm0.049$ BaBar
- $1.025\pm0.019\pm0.031$ Belle

Average ($D^+_s \rightarrow l^+\nu$)

- $0.961\pm0.011\pm0.024$ HPQCD
- $0.962\pm0.011\pm0.024$ HPQCD
- $0.962\pm0.012\pm0.024$ HPQCD

Method: $D \rightarrow K\mu^+\nu$

- $0.230\pm0.011$ PDG2014 ($\nu\nu$)
- $0.223\pm0.010\pm0.004$ HPQCD Calculation
- $0.225\pm0.006\pm0.010$ HPQCD Calculation
- $0.221\pm0.005\pm0.004$ BESIII ($D^+ \rightarrow \mu^+\nu$)
- $0.206\pm0.007\pm0.009$ BESIII Preliminary ($D^0 \rightarrow \pi^+\mu^+\nu$)

Method: $D \rightarrow K\pi\mu^+\nu$

- $0.230\pm0.011$ PDG2014 ($\nu\nu$)
- $0.223\pm0.010\pm0.004$ HPQCD Calculation
- $0.225\pm0.006\pm0.010$ HPQCD Calculation
- $0.221\pm0.005\pm0.004$ BESIII ($D^+ \rightarrow \mu^+\nu$)
- $0.206\pm0.007\pm0.009$ BESIII Preliminary ($D^0 \rightarrow \pi^+\mu^+\nu$)
Study of $D^+ \rightarrow K_L e^+ \nu$

- Regardless of long flight distance, $K_L$ interact with EMC and deposit part of energy, thus giving position information
- After reconstructing all other particles, $K_L$ can be inferred with position information and constraint $U_{miss} \rightarrow 0$.

First measurements

Simultaneous fit to event density $I(q^2)$ with 2-par. series Form Factor

\[
B(D^+ \rightarrow K_L e^+ \nu) = (4.482 \pm 0.027 \pm 0.103)\% 
\]

\[
A_{CP}^{D+ \rightarrow K_L e^+ \nu} = (-0.59 \pm 0.60 \pm 1.50)\% 
\]

$\frac{f^K_+(0)|V_{es}|}{r_1/a_1/a_0} = 0.728 \pm 0.006 \pm 0.011$

See Fenfen An’s talk for more detail
Study of $D^+ \rightarrow K^-\pi^+e^+\nu$

- Fractions with $>5\sigma$ significance
  
  \[ f(D^+ \rightarrow (K^-\pi^+)^{S_{\text{wave}}} e^+\nu_e) = (93.93 \pm 0.22 \pm 0.18)\% \]
  
  \[ f(D^+ \rightarrow (K^-\pi^+)^P e^+\nu_e) = (6.05 \pm 0.22 \pm 0.18)\% \]

- Measured parameters of $\bar{K}^*(892)$
  
  \[ m_{\bar{K}^*(892)} = (894.60 \pm 0.25 \pm 0.03) \text{ MeV}/c^2 \]
  
  \[ \Gamma_{\bar{K}^*(892)} = (46.42 \pm 0.56 \pm 0.15) \text{ MeV}/c^2 \]
  
  \[ \tau_{BW} = (3.07 \pm 0.26 \pm 0.11) (\text{GeV}/c)^{-1} \]

- Comparison of data and fit with S+P in $D^+ \rightarrow K^-\pi^+e^+\nu$

Form factors of $D^+ \rightarrow \bar{K}^*(892)e^+\nu$ by SPD model

\[ V(q^2) = \frac{V(0)}{1-q^2/m_V^2}, \quad A_{1,2}(q^2) = \frac{A_{1,2}(0)}{1-q^2/m_A^2} \]

$M_{V/A}$ is expected to $M_{D^*}(1^{++})$

\[ m_V = (1.81_{-0.15}^{+0.25} \pm 0.02) \text{ GeV}/c^2 \]

\[ m_A = (2.61_{-0.17}^{+0.22} \pm 0.03) \text{ GeV}/c^2 \]

\[ A_1(0) = 0.573 \pm 0.011 \pm 0.020 \]

\[ r_V = \frac{V(0)}{A_1(0)} = 1.411 \pm 0.058 \pm 0.007 \]

\[ r_2 = \frac{A_2(0)}{A_1(0)} = 0.788 \pm 0.042 \pm 0.008 \]

See Fenfen An’s talk for more detail
Study of $D^+ \rightarrow K^-\pi^+e^+\nu$

- Events located in the $K^{*0}(892)$ window [0.8, 1] GeV/c², are used to measure the form factors by a Projective Weighting Technique [citation: CLEO collaboration, Phys. Rev. D 81, 112001 (2010)].

- Signal is assumed to be composed of $K^{*0}(892)$ and a non-resonant S-wave.

- Helicity basis form factors include:
  - P-wave related: $H_{\pm 0}(q^2)$
  - S-wave related: $h_0(q^2)$

- Five weighted $q^2$ histograms are built. Weight is assigned to each event based on $(q^2, \cos \theta_K, \cos \theta_\theta)$.

- Form factors are independently computed in each $q^2$ bin.

- The model-independent measurements are generally consistent with CLEO’s report. And they are also consistent with the predicted trend based on the SPD model from amplitude analysis.

Model independent measurement of form factors in $D^+ \rightarrow \overline{K}^{*0}(892)e^+\nu$
Study of $D^+ \to \omega e^+\nu$ and Search for $D^+ \to \phi e^+\nu$

$B[D^+ \to \omega e^+\nu] = (1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$

$B[D^+ \to \phi e^+\nu] < 1.3 \times 10^{-5}$ at 90% C.L.

Amplitude analysis is performed

$r_\nu = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06$

$r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$

See Fenfen An’s talk for more detail
Summary

- With 2.92 fb\(^{-1}\) data taken at 3.773 GeV by BESIII, we study the leptonic decay \(D^+ \rightarrow \mu^+ \nu\), the semi-leptonic decays \(D^0 \rightarrow K(\pi)^- e^+ \nu\), as well as \(D^+ \rightarrow K_L e^+ \nu\), \(K^- \pi^+ e^+ \nu\) and \(\omega/\phi e^+ \nu\).

  - Improved decay constant \(f_{D^+}\), form factors \(f_{D^+}^{D \rightarrow K(\pi)}(q^2)\) in \(D \rightarrow K(\pi)e^+ \nu\), as well as form factors in \(D^+ \rightarrow V e^+ \nu\), which are important to test/calibrate LQCD calculations accurately.

  - Improved CKM matrix element \(|V_{cs(d)}|\), which is important for unitarity test of the CKM matrix.

  - Some other topics are ongoing.

- BESIII decide to take 3 fb\(^{-1}\) data at 4.17 GeV in 2016, improved \(f_{D_{s^+}}\) and \(|V_{cs}|\) by \(D_{s^+} \rightarrow l^+ \nu\) are expected in the near future.

- 10 fb\(^{-1}\) more data at 3.773 GeV will be more helpful for further improving decay constant, form factors, \(|V_{cs(d)}|\), as well as strong phases......
Thank you!
Back-up slides
Progress in LQCD Calculation

Taking from Aida X. El-Khadra’s talk at Beauty2014

errors (in %) comparison: **FLAG-2 averages** vs. **new results**

- $f_{D_s}/f_{D^+}$
- $f_{D_s}$
- $f_{D^+}$
- $f_{+K}^{DK}(0)$
- $f_{+\pi}^{D\pi}(0)$
- $\hat{B}_D$

small errors due to

- physical light quark masses
- improved charm-quark action (HISQ)
- PCAC (no renormalization)
- ensembles with small lattice spacings

work in progress by FNAL/MILC (Lattice 2014), ETM, HPQCD, ...

- First results for $D$ mixing bag parameters (all five) with local operators only by ETM (2013, 2014) $n_f = 2, 2+1+1$

- work in progress: FNAL/MILC (Lattice 2014)

review by C. Bouchard @ Lattice 2014