Experimental review of (semi-)leptonic charm decays

Hailong Ma (IHEP&BESIII)

2nd International Workshop on Physics at Future High Intensity Collider @ 2-7GeV in China, March 19-21 2018

UCAS, Beijing, China
Contents

- Introduction
- Data sample
- $D_{(s)} \rightarrow l^+ v$
- $D \rightarrow K(\pi)e^+ v$
- Other topics ($D, D_s, \Lambda_c$) at threshold
- Summary
Studies of (semi-)leptonic charm decays are important to explore weak and strong effects in charm decays.

\[ \Gamma(D^+_{(s)} \to \ell^+ \nu_\ell) = \frac{G_F^2 f_{D(s)}^2}{8\pi} |V_{cd(s)}|^2 m_{D(s)}^2 \left(1 - \frac{m_\ell^2}{m_{D(s)}^2}\right)^2 \]

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

- Precise measurements of decay constants \( f_{D^+}, f_{Ds^+}, \) form factors \( f_+^{D(s)\to P(q^2)} \) of semi-leptonic (SL) \( D_{(s)} \) decays will calibrate LQCD calculations at higher accuracy. Once they pass experimental tests, the precisely LQCD calculated \( f_D/f_B, f_{Ds}/f_{Bs} \) and \( f_+^{D\to P(0)}/f_+^{B\to P(0)} \) will be helpful for measurements in B decays.

- Improved LQCD calculations on \( f_{D(s)^+}[0.5(0.5)\%], f_+^{D\to K(\pi)(0)}[2.4(4.4)\%] \) help to precisely measure the CKM matrix element \( |V_{cs(d)}| \), which are important for the CKM matrix unitarity test and search for NP beyond SM.

- Test on lepton flavor universality in charm sector.
### Recent $D^{0(+)}$, $D_s^+$ and $\Lambda_c^+$ samples

Taking from Longke Li’s talk at joint workshop of BESIII/Belle/LHCb at Nankai

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Machine</th>
<th>C.M</th>
<th>Lumin.</th>
<th>N($D$)</th>
<th>efficiency</th>
<th>advantage/disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>CESR ($e^+e^-$)</td>
<td>3.77 GeV</td>
<td>0.8 fb$^{-1}$</td>
<td>$2.9 \times 10^6$</td>
<td>$2.3 \times 10^6$ (D$^\pm$)</td>
<td>~10-30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.17 GeV</td>
<td>0.6 fb$^{-1}$</td>
<td>$0.6 \times 10^6$</td>
<td></td>
<td>☑️ extremely clean enviroment ☑️ pure D-beam, almost no bkg ☑️ quantum coherence ☑️ no CM boost, no T-dep analyses</td>
</tr>
<tr>
<td>BESIII</td>
<td>BEPC-II ($e^+e^-$)</td>
<td>3.77 GeV</td>
<td>2.92 fb$^{-1}$</td>
<td>$10.5 \times 10^6$</td>
<td>$8.4 \times 10^6$ D$^{0(+)}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.18 GeV</td>
<td>3 fb$^{-1}$</td>
<td>$3 \times 10^9$</td>
<td>$3 \times 10^9$ D$^{0(+)}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.6 GeV</td>
<td>0.567 fb$^{-1}$</td>
<td>D$^+_s$</td>
<td>☄️</td>
<td>★★★</td>
</tr>
<tr>
<td>BELLE</td>
<td>KEKB ($e^+e^-$)</td>
<td>10.58 GeV</td>
<td>1 ab$^{-1}$</td>
<td>$1.3 \times 10^9$</td>
<td></td>
<td>☑️ clear event environment ☑️ high trigger efficiency ☑️ high-efficiency detection of neutrals ☑️ many high-statistics control samples ☑️ time-dependent analysis ☑️ smaller cross-section than pp colliders</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEP-II</td>
<td>10.58 GeV</td>
<td>0.5 ab$^{-1}$</td>
<td>$6.5 \times 10^8$</td>
<td></td>
<td>~5-10%</td>
<td>☑️ large production cross-section ☑️ large boost: excellent time resolution ☑️ dedicated trigger required ☑️ hard to do neutrals and neutrinos</td>
</tr>
<tr>
<td></td>
<td>4.6 GeV</td>
<td>0.567 fb$^{-1}$</td>
<td>D$^{0(+)}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>Tevatron ($p\bar{p}$)</td>
<td>1.96 TeV</td>
<td>9.6 fb$^{-1}$</td>
<td>$1.3 \times 10^{11}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LHC ($pp$)</td>
<td>7 TeV</td>
<td>1.0 fb$^{-1}$</td>
<td>$5.0 \times 10^{12}$</td>
<td>~&lt;0.5%</td>
<td>☑️</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 TeV</td>
<td>2.0 fb$^{-1}$</td>
<td></td>
<td></td>
<td>☑️</td>
</tr>
</tbody>
</table>

Note: The table above lists recent D$^{0(+)}, D_s^+$ and $\Lambda_c^+$ samples from various experiments. The efficiency values are provided alongside the N($D$) values, and the advantage/disadvantages are listed for each experiment.
Charm samples (pb$^{-1}$) at threshold

- **D$^{0(+)}$ samples**

- **D$^{s+}$/D$^{s^+}$/$\Lambda_c^+$ samples**

\[
N_{ST}^i = 2 \times N_{DD} \times B_{ST}^i \times \varepsilon_{ST}^i
\]

\[
N_{DT}^i = 2 \times N_{DD} \times B_{ST}^i \times B_{sig} \times \varepsilon_{ST vs. sig}^i
\]

\[
B_{sig} = \frac{N_{DT}^{tot}}{N_{ST}^{tot} \times \varepsilon_{sig}^{tot}}
\]

\[
\varepsilon_{sig} = \frac{\sum_{i=1}^{N} (N_{ST}^i \times \varepsilon_{ST vs. sig}^i / \varepsilon_{ST}^i)}{\sum_{i=1}^{N} N_{ST}^i}
\]
Earlier searches or measurements of $f_{D^+}$

- **MARKIII, 9.6 pb$^{-1}$ at $\psi''$**
  
  No $D^+\rightarrow\mu^+\nu$ signal found

  PRL60(1988)1375

  $f_{D^+} < 290$ MeV @ 90% C.L.

- **BESI, 22.3 pb$^{-1}$ at 4.03 GeV**

  1st signal of $D^+\rightarrow\mu^+\nu$

  PLB429(1998)188

  $f_{D^+} = (300^{+180+80}_{-150-40})$ MeV

- **BESII, 33 pb$^{-1}$ data at $\psi''$**

  2.7 signals of $D^+\rightarrow\mu^+\nu$

  PLB610(2005)183

  $f_{D^+} = (371^{+129}_{-119} \pm 25)$ MeV

- **2004-2008, CLEO-c, 818 pb$^{-1}$ at $\psi''$**

  150 signals of $D^+\rightarrow l^+\nu$

  PRD78(2008)052003

  $f_{D^+} = 205.8 \pm 7.5 \pm 2.5$ MeV
Results on $B[D^+ \to l^+\nu]$, $f_{D^+}|V_{cd}|$

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

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

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

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

20 fb$^{-1}$ data can reduce the statistical error of $f_{D^+}$ to 1%

$B[\tau \to \tau \nu] = (1.20 \pm 0.24_{\text{stat}}) \times 10^{-3}$

$R = \frac{\Gamma(D^+ \to \tau^+\nu)}{\Gamma(D^+ \to \mu^+\nu)} = \frac{m_{\tau^+}^2 \left( 1 - \frac{m_{\mu^+}^2}{M_{D^+}^2} \right)^2}{m_{\mu^+}^2 \left( 1 - \frac{m_{\mu^+}^2}{M_{D^+}^2} \right)^2}$

SM prediction: 2.66

BESIII: 3.21 \pm 0.64
Earlier measurements of $f_{D_s^+}$

- **WA75, Fixed target experiment**
  - $9.1 \pm 3.8 \, D_s^+ \rightarrow \mu^+ \nu$ signals
  - PTP89(1993)131
  - $f_{D_s^+} = 232 \pm 45 \pm 20 \pm 48 \text{ MeV}$

- **E653, Fermilab fixed target experiment**
  - $32 \, D_s^+ \rightarrow \mu^+ \nu$ signals
  - PLB382(1996)299
  - $f_{D_s^+} = 194 \pm 35 \pm 20 \pm 14 \text{ MeV}$

- **CLEOII, 2.13 fb$^{-1}$ at 10.6 GeV**
  - $38 \pm 10 \, D_s^+ \rightarrow \mu^+ \nu$ signals
  - PRD49(1994)5690
  - $f_{D_s^+} = 344 \pm 37 \pm 52 \pm 42 \text{ MeV}$

- **BESI, 22.3 pb$^{-1}$ at 4.03 GeV**
  - $3 \, D_s^+ \rightarrow \mu^+ \nu$ signals, PRL74(1995)4599
  - $f_{D_s^+} = 430^{+150}_{-130} \pm 40 \text{ MeV}$

First absolute measurement
Earlier measurements of $f_{D_s^+}$

- L3, $Z\rightarrow q\bar{q}$, 49.6 pb$^{-1}$ at 91.2 GeV
  - $15.6\pm6.0$ $D_s^+\rightarrow \mu^+\nu$ signals
  - $f_{D_s^+}=309\pm58\pm33\pm38$ MeV
- OPAL, $3.9\times10^6 e^+e^-\rightarrow q\bar{q}$
  - $22.5\pm6.9$ $D_s^+\rightarrow \tau^+\nu$ signals
  - $f_{D_s^+}=286\pm44\pm41$ MeV
- ALPHA, $3.97\times10^6$ Z hadronic decay
  - $306\pm62$ $D_s^+\rightarrow \tau^+\nu$ signals
  - $f_{D_s^+}=285\pm19\pm40$ MeV
  - $575\pm84$ $D_s^+\rightarrow \mu^+\nu$ signals

Results of $f_{D_{s}^{+}}$ at CLEO/Belle/BaBar

- $D_{s}^{*+}D_{s}^{-}$, 600 pb$^{-1}$ at 4.17 GeV [697 l$^{+}$v]

- Belle, 913 fb$^{-1}$ at 10.58 GeV [2698 l$^{+}$v]

- Babar, 521 fb$^{-1}$ at 10.58 GeV [1023 l$^{+}$v]

\[ e^{+}e^{-} \rightarrow DKXD_{s}^{*+} \]

**$f_{D_{s}^{+}}$ Results**

- $f_{D_{s}^{+}} = 263.3 \pm 8.2 \pm 1.9$ MeV
- $f_{D_{s}^{+}} = 252.2 \pm 11.1 \pm 5.2$ MeV
- $f_{D_{s}^{+}} = 257.8 \pm 13.3 \pm 5.2$ MeV

\[ f_{D_{s}^{+}} = 255.5 \pm 4.2 \pm 5.1 $ MeV

\[ f_{D_{s}^{+}} = 258.6 \pm 6.4 \pm 7.5 $ MeV

**References**

- PRD79(2009)052001
- JHEP1309(2013)129
- PRD80(2009)112004
- PRD82(2010)091103
Results on $B[D_{s}^{+}\rightarrow\mu^{+}\nu]$, $f_{D_{s}^{+}}|V_{cs}|$ at BESIII

0.48 fb$^{-1}$ data@4.01 GeV

3.19 fb$^{-1}$ data@4.178 GeV

PRD94(2016)072004

Use $\mu$ counter to suppress background

$$N[D_{s}^{+}\rightarrow\mu^{+}\nu]=1135.0\pm33.1$$

$$f_{D_{s}^{+}}=(241.0\pm16.3\pm6.6)\text{ MeV}$$

$$f_{D_{s}^{+}}|V_{cs}|=242.5\pm3.5\pm3.7\text{ MeV}$$

Precision on $f_{D_{s}^{+}}$ reach 2%. Combining $\tau^{+}\nu$ can reduce it to 1.5%
In the past 30 years, studies of $D \rightarrow K(\pi) l^+ v$ were made by MARKIII, E691, CLEO, CLEOII, BESII, FOCUS, BELLE, Babar and CLEO-c

- **BELLE, 282 fb$^{-1}$ at 10.58 GeV**

![Graph showing $D^0 \rightarrow K^+ \nu$](PRL97(2006)061804)

- **2004-2009, CLEO-c, 818 pb$^{-1}$ at $\psi''$**

![Graph showing $D^0 \rightarrow \pi^+ e^+ v$](PRD80(2009)032005)

- **Babar, 75 fb$^{-1}$ at 10.58 GeV**

![Graph showing $D^0 \rightarrow K^+ e^+ v$](PRD76(2007)052005)

- **Babar, 347.2 fb$^{-1}$ at 10.58 GeV**

![Graph showing $D^0 \rightarrow \pi^+ e^+ v$](PRD91(2015)052022)

Before 2010, the LQCD calculated $f_+^{D \rightarrow K(\pi) (0)}$ precision is at 10% level, thus limiting $|V_{cs(d)}|$ measurement.
Impact of $f^{D\rightarrow K(\pi)(q^2)}$ on LQCD

BESIII, PRD92(2015)072012


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

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

$\Delta\Gamma/q^2$ (ns$^{-1}$ GeV$^{-2}$c$^{-4}$)

$\Delta\Gamma/q^2$ (ns$^{-1}$ GeV$^{-2}$c$^{-4}$)
Comparisons of $f^D \rightarrow K(\pi)(0)$ with LQCD

BESIII, PRD96(2017)012002
Comparisons of the measured $|V_{cs(d)}|$:

- **Method 1**
  \[ f_{D(s)} |V_{cd(s)}| \]

- **Method 2**
  \[ f^{D \rightarrow K(\pi)^+}_{+}(0) |V_{cs(d)}| \]

- **Method 3**
  \[ f^{D(s) \rightarrow \eta^+}_{+}(0) |V_{cd(s)}| \]

**Limited by both statistics and LQCD input**

Further improved LQCD calculations on $f^{D(s) \rightarrow P}_{+}(0)$ will improve the measurement of $|V_{cs(d)}|$ with much improved precision.
Evidence of violation of LFU at 4σ in

\[ R(D^{(*)}) = \frac{B(B \rightarrow D^{(*)}\tau\nu)}{B(B \rightarrow D^{(*)}\ell\nu)} \]

\[ \Delta \chi^2 = 1.0 \] contours

Other

Evidence at 2.6σ in FCNC decays \( B^+ \rightarrow K^+\mu^+\mu^-/K^+e^+e^- \)

\[ R_K = \frac{\Gamma(B \rightarrow \bar{K}\mu^+\mu^-)}{\Gamma(B \rightarrow \bar{K}e^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \]

BESIII, arXiv:1802.05492

Evidence of violation of LFU at 4σ in

\[ R_{LU}^{0(+)} = \frac{B(D^{0(+) \rightarrow \pi^-(0)\mu^+\nu})}{B(D^{0(+) \rightarrow \pi^-(0)e^+\nu})} \approx 0.97 \]

\[ B^{PDG16}: \quad R_{LU}^{0} = 0.82 \pm 0.08 \ (\sim 2.0\sigma) \]

\[ B(D^0 \rightarrow \pi^-\mu^+) = (0.237 \pm 0.024)\% \]

\[ B(D^0 \rightarrow \pi^\pm\mu^\mp e^\pm\nu) = (0.267 \pm 0.007 \pm 0.007)\% \]

\[ B(D^+ \rightarrow \pi^0\mu^+) = (0.342 \pm 0.011 \pm 0.010)\% \]

\[ \mathcal{R}_{LU}^{0} = 0.905 \pm 0.027_{\text{stat.}} \pm 0.023_{\text{syst.}} \]

\[ \mathcal{R}_{LU}^{+} = 0.942 \pm 0.037_{\text{stat.}} \pm 0.027_{\text{syst.}} \]
BFs help to constrain gluon component

\[
\begin{pmatrix}
\eta \\
\eta' \\
G
\end{pmatrix} =
\begin{pmatrix}
\cos \phi' & -\sin \phi' & 0 \\
\sin \phi' \cos \phi_G & \cos \phi' \cos \phi_G & \sin \phi_G \\
-\sin \phi' \sin \phi_G & -\cos \phi' \sin \phi_G & \cos \phi_G
\end{pmatrix}
\begin{pmatrix}
\eta \\
\eta' \\
G
\end{pmatrix}
\]

Combing CLEO’s BFs and taking input value by EPJC69,133 and NPPS162, 312, the $\eta-\eta'$ mixing angle is determined to be $\phi_F = (40 \pm 3_{\text{experiment}} \pm 3_{\text{theory}}) \degree$
Other topics: $D \rightarrow Ve^+\nu$ at BESIII

BESIII, PRD94(2016)032001

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

BESIII, PRD92(2015)071101(RC)

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

Model independent form factors

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

$r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$
Observation of $D \to Se^+ \nu$ at BESIII

- Explore the nontrivial internal structure of light hadron mesons, traditional $q\bar{q}$ states, tetra quark system.

- With chiral unitarity approach in the coupled channels, BF is predicted to be order of $5(6) \times 10^{-5}$ for $D^{0(+) \to \eta \pi}$ decays.

- Improve understanding of classification of light scalar mesons

\[
R \equiv \frac{B(D^+ \to f_0 l^+ \nu) + B(D^+ \to \sigma l^+ \nu)}{B(D^+ \to a_0 l^+ \nu)}
\]

$R=1(3)$ if traditional $q\bar{q}$ (tetra quark) system.

\[
B(D^+ \to a_0(980)^0 e^+ \nu_e) \times B(a_0(980)^0 \to \eta \pi^0) = (1.66^{+0.81}_{-0.66} \pm 0.11) \times 10^{-4}, \quad < 3.0 \times 10^{-4} \text{ at the } 90\% \text{ C.L.}
\]

\[
B(D^0 \to a_0(980)^- e^+ \nu_e) \times B(a_0(980)^- \to \eta \pi^-) = (1.33^{+0.33}_{-0.29} \pm 0.09) \times 10^{-4}
\]

\[
\frac{\Gamma(D^0 \to a_0(980)^- e^+ \nu_e)}{\Gamma(D^+ \to a_0(980)^0 e^+ \nu_e)} = 2.03 \pm 0.95 \pm 0.06
\]
Evidence of $D \rightarrow A e^+ v$ at CLEO

CLEO, PRL(2007)191801

with 281 pb$^{-1}$ data@3.773 GeV

$\mathcal{B}(D^0 \rightarrow K^- \pi^+ \pi^- e^+ \nu_e) = [2.8^{+1.4}_{-1.1} \text{ (stat)} \pm 0.3 \text{ (syst)}] \times 10^{-4}$

$\mathcal{B}(D^0 \rightarrow \bar{K}_1^-(1270)e^+ \nu_e) \times \mathcal{B}(K_1^- (1270) \rightarrow \bar{K}^- \pi^+ \pi^-) = [2.5^{+1.3}_{-1.0} \text{ (stat)} \pm 0.2 \text{ (syst)}] \times 10^{-4}$

Using $\mathcal{B}(K_1^- (1270) \rightarrow \bar{K}^- \pi^+ \pi^-) = (33 \pm 3)\%$

$\mathcal{B}(D^0 \rightarrow K_1^- (1270)e^+ \nu_e) = [7.6^{+4.1}_{-3.0} \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 0.7] \times 10^{-4}$
\[ \phi e^+\nu \]
\[ \eta e^+\nu \]
\[ \eta' e^+\nu \]
\[ K^0 e^+\nu \]
\[ f e^+\nu \]

\[ \Gamma(D_s \to \eta' e\nu) = R_D \cot^2 \phi \]

\[ \frac{\Gamma(D_s \to \eta' e\nu)}{\Gamma(D_s \to \eta e\nu)} = \cot^4 \phi \]

 Erements/0.010 GeV^2

\[ \theta(\eta-\eta' \text{ mixing angle }) = (42 \pm 2 \pm 2)^0 \]
\[ \theta(f_0-ss \text{ mixing angle }) = (20^{+32}_{-20})^0 \]
First study of $D^+_s \rightarrow K^{(*)0}e^+\nu_e$ dynamics at BESIII

**BESIII preliminary**

$D^+_s \rightarrow K^0e^+\nu_e$  
$N_{\text{obs}} = 117.2 \pm 13.9$

$B[D_s^+ \rightarrow K^0 e^+\nu_e ] = (3.25 \pm 0.38_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-3}$

$(3.9 \pm 0.9) \times 10^{-3}$ [PDG17]

$B[D_s^+ \rightarrow K^*0 e^+\nu_e ] = (2.38 \pm 0.26_{\text{stat}} \pm 0.12_{\text{syst}}) \times 10^{-3}$

$(1.8 \pm 0.4) \times 10^{-3}$ [PDG17]

Four dimensional un-binned likelihood fit is performed. $K^*$ parameters are fixed

Taking $|V_{\text{CKMfitter}}|_{\text{cd}}$ as input

$r_V = 1.67 \pm 0.34 \pm 0.16$

$r_2 = 0.77 \pm 0.28 \pm 0.07$
First absolute BF of $\Lambda_c^+ \rightarrow \Lambda l^+ \nu$ at BESIII

- $\Lambda_c^+$ was observed in 1979
- All decays of $\Lambda_c^+$ were measured with high energy data and relative to $pK^-\pi^+$, which suffers an error of 25%. No absolute measurement using threshold $\Lambda_c^+$ data before BESIII
- Only about 60% decays are known

**Theory: (1.4-9.2)\%**

<table>
<thead>
<tr>
<th>Theoretical Models</th>
<th>Predicted Branching Fraction for $\Lambda_c^+ \rightarrow \Lambda e^+\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBM [1]</td>
<td>1.9%</td>
</tr>
<tr>
<td>NRQM [1]</td>
<td>3.6%</td>
</tr>
<tr>
<td>SU(4)-symmetry limit [2]</td>
<td>9.52%</td>
</tr>
<tr>
<td>NRQM [2]</td>
<td>4.4%</td>
</tr>
<tr>
<td>SQM [6]</td>
<td>5.62%</td>
</tr>
<tr>
<td>NRQM2 [6]</td>
<td>1.96%</td>
</tr>
<tr>
<td>NRQM3 [7]</td>
<td>1.45%</td>
</tr>
<tr>
<td>QCD SR1 [8]</td>
<td>$(3.6 \pm 0.4)%$</td>
</tr>
<tr>
<td>QCD SR2 [9]</td>
<td>$(2.6 \pm 0.4)%$</td>
</tr>
<tr>
<td>QCD SR3 [9]</td>
<td>$(5.8 \pm 1.5)%$</td>
</tr>
<tr>
<td>STSR. [10]</td>
<td>2.22% for $\Lambda_c^+ \rightarrow \Lambda \pi^+$</td>
</tr>
<tr>
<td>STNR. [10]</td>
<td>1.58% for $\Lambda_c^+ \rightarrow \Lambda \pi^+$</td>
</tr>
<tr>
<td>HSNR. [10]</td>
<td>4.72% for $\Lambda_c^+ \rightarrow \Lambda \pi^+$</td>
</tr>
<tr>
<td>HCNR. [10]</td>
<td>4.52% for $\Lambda_c^+ \rightarrow \Lambda \pi^+$</td>
</tr>
<tr>
<td>LCSR [11]</td>
<td>$(3.0 \pm 0.3)%$ for $\Lambda_c^+ \rightarrow \Lambda \pi^+$ (CZ-type)</td>
</tr>
<tr>
<td>PDG 2014 [14]</td>
<td>$(2.1 \pm 0.6)%$</td>
</tr>
<tr>
<td>BESIII</td>
<td>$(3.63 \pm 0.38 \pm 0.20)%$</td>
</tr>
</tbody>
</table>

3 fb$^{-1}$ help to explore FF studies

$B[\Lambda_c^+ \rightarrow \Lambda e^+\nu_e]=(3.63\pm0.38\pm0.20)\%$  
$B[\Lambda_c^+ \rightarrow \Lambda \mu^+\nu_\mu]=(3.49\pm0.46\pm0.26)\%$  
$\Gamma[\Lambda_c^+ \rightarrow \Lambda \mu^+\nu_\mu]/\Gamma[\Lambda_c^+ \rightarrow \Lambda e^+\nu_e]=0.96 \pm 0.16 \pm 0.04$
With 2.9/3.2 fb\(^{-1}\) data taken at 3.773/4.178 GeV, BESIII has obtained the most precise measurements of \(D_{(s)}^{+} \rightarrow l^+\nu\), \(D \rightarrow P l^+\nu\) and other SL decays

**Improved measurements of** \(f_{D(s)^{+}}\) and \(f_{D^{+} \rightarrow K(\pi)(q^{2})}\), which are important to calibrate LQCD calculations

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

Other studies of D SL decays (form factor measurements, new decay modes) are ongoing and will be ready soon

With 0.567 fb\(^{-1}\) data taken at 4.6 GeV, BESIII reported the first absolute BFs of \(\Lambda_{c}^{+} \rightarrow \Lambda l^+\nu\)

In the near future, more 10 fb\(^{-1}\) data at 3.773 GeV and 3 fb\(^{-1}\) data at \(\sim 4.65\) GeV at BESIII will further benefit all measurements
If 300 fb\(^{-1}\) data can be collected at 3.773, 4.18 and 4.65 GeV, respectively.

<table>
<thead>
<tr>
<th></th>
<th>Systematic error</th>
<th>Statistical error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta f_{D+}/f_{D+})</td>
<td>~0.9%</td>
<td>2.6%</td>
</tr>
<tr>
<td>(\Delta f_{Ds+}/f_{Ds+})</td>
<td>~1.5%</td>
<td>1.1%</td>
</tr>
<tr>
<td>(\Delta f_{D\rightarrow K}/f_{D\rightarrow K})</td>
<td>~0.5%</td>
<td>0.35%</td>
</tr>
<tr>
<td>(\Delta f_{D\rightarrow \pi}/f_{D\rightarrow \pi})</td>
<td>~0.7%</td>
<td>1.26%</td>
</tr>
<tr>
<td>(</td>
<td>V_{cs}</td>
<td>D_{s}\rightarrow l^+v)</td>
</tr>
<tr>
<td>(</td>
<td>V_{cs}</td>
<td>D_{0}\rightarrow K^-e^+v)</td>
</tr>
<tr>
<td>(</td>
<td>V_{cd}</td>
<td>D_{+}\rightarrow \mu^+v)</td>
</tr>
<tr>
<td>(</td>
<td>V_{cd}</td>
<td>D_{0}\rightarrow \pi^-e^+v)</td>
</tr>
</tbody>
</table>

- LQCD calculation uncertainties in the FFs of \(D\rightarrow P l^+v\) are expected to reduce to (0.5-1.0)\% to better measure \(|V_{cs(d)}|\) using D SL decays.

- Precise FF studies, especially for \(D\rightarrow S/A e^+v\) and \(\Lambda_c^+\) SL decays, as well as other suppressed SL decays.
Thank you!
Simultaneous fit to event density $I(q^2)$ with 2-par. series Form Factor

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 $U_{\text{miss}} \to 0$

$B(D^+ \to K_L^0 e^+ \nu_e) = (4.482\pm 0.027\pm 0.103)\%$

$A_{CP}^{D^+ \to K_L^0 e^+ \nu_e} = -1.91\pm 0.33\pm 0.24$

$A_{CP}^{D^+ \to K_L^0 e^+ \nu_e} = (-0.59\pm 0.60 \pm 1.50)\%$

$D^+ \to K_L^0 e^+ \nu_e$ is measured for the first time

PRD92(2015)112008

With 6 dominant $D^-$ single tag

$f_{K^+}^{(0)} |V_{cs}| = 0.728\pm 0.006\pm 0.011$

$r_1 = a_1/a_0 = -1.91\pm 0.33\pm 0.24$
Taking $\tau_{D^+}$, $\tau_{D^0}$, $B[D^0 \rightarrow K^- e^+ v]$ and $B[D^+ \rightarrow K^0 e^+ v]$ from the PDG as input, the absolute BF for $D^+ \rightarrow K^0 e^+ v$ via $K^0 \rightarrow \pi^0 \pi^0$ agrees with isospin conservation within 1.2σ.
Simultaneous fits

With 6 dominant D⁻ single tag

(a) $\overline{K}^0 \rightarrow \pi^+\pi^-$

16516 ± 130

(b) $\overline{K}^0 \rightarrow \pi^0\pi^0$

4198 ± 33

Support isospin conservation in these two decays within errors

Taking $B[D^0 \rightarrow K^-\mu^+\nu]$ and $B[D^+ \rightarrow \overline{K}^0\mu^+\nu]$ from the PDG as input

\[
\frac{\Gamma[D^0 \rightarrow K^-\mu^+\nu]}{\Gamma[D^+ \rightarrow \overline{K}^0\mu^+\nu]} = 0.963 \pm 0.044
\]

Consistent with theory prediction 0.97 within error

BESIII, EPJC76(2016)369

(8.72 ± 0.07 ± 0.18)%
Our result

(9.20 ± 0.60)%
PDG2014

(9.27 ± 0.69 ± 0.59 ± 0.61)%
FOCUS

(10.30 ± 2.30 ± 0.80)%
BES-II
Benefit the understanding of the source of difference of inclusive decay rates of $D_0^{(+)}$ and $D_s^+$

Complementary information to understand $\eta - \eta'$ mixing

$482 \text{ pb}^{-1} \text{ data@4.009 GeV, PRD94(2016)112003}$

<table>
<thead>
<tr>
<th></th>
<th>BESIII</th>
<th>CLEOII 95</th>
<th>CLEOc09</th>
<th>CLEOc15</th>
<th>PDG [4]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(D_s^+ \to \eta e^+ \nu_e),[%]$</td>
<td>$2.30 \pm 0.31 \pm 0.08$</td>
<td>—</td>
<td>$2.48 \pm 0.29 \pm 0.13$</td>
<td>$2.28 \pm 0.14 \pm 0.20$</td>
<td>$2.67 \pm 0.29$</td>
</tr>
<tr>
<td>$B(D_s^+ \to \eta' e^+ \nu_e),[%]$</td>
<td>$0.93 \pm 0.30 \pm 0.05$</td>
<td>—</td>
<td>$0.91 \pm 0.33 \pm 0.05$</td>
<td>$0.68 \pm 0.15 \pm 0.06$</td>
<td>$0.99 \pm 0.23$</td>
</tr>
<tr>
<td>$B(D_s^+ \to \eta' e^+ \nu_e)$</td>
<td>$0.40 \pm 0.14 \pm 0.02$</td>
<td>$0.35 \pm 0.09 \pm 0.07$</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$B(D_s^+ \to \eta e^+ \nu_e)$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Much improved LQCD calculations

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

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

\[ f_{D_s}/f_{D^+} \]
\[ f_{D_s} \]
\[ f_{D^+} \]
\[ f_{D^+}^{DK}(0) \]
\[ f_{D^+}^{D\pi}(0) \]
\[ \hat{B}_{D}^i \]

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