Charm Physics at BESIII
(Leptonic and semi-leptonic D decays)

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Contents

■ Introduction
■ Data Sample
■ $D^+ \rightarrow \mu^+ \nu$
■ $D^0 \rightarrow K(\pi)^- e^+ \nu$
■ Summary

➢ What happen in the past 26 years?
➢ Precision measurements at BESIII
➢ Opportunity in the next 20 years?

I would like to thank Prof. Steve Olsen for his helpful suggestions to improve my slides!
Why they are important?

Leptonic and semi-leptonic D decays are ideal window to probe for weak and strong effects

- Precision measurements of decay constants $f_{D^+}$, $f_{D_s^+}$, form factors $f_{+}^{D \rightarrow K(\pi)}(0)$ of semi-leptonic decays of $D_{(s)}$ mesons will calibrate LQCD calculations at higher accuracy. Once they pass experimental tests, the precisely LQCD calculated $f_{D}/f_{B}$, $f_{D_s}/f_{B_s}$ and $f_{+}^{D \rightarrow K(\pi)}(0)/f_{+}^{B \rightarrow K(\pi)}(0)$ will be helpful for measurements in B decays.

- Recently improved LQCD calculations on $f_{D(s)+}[0.5(0.5)\%]$, $f_{+}^{D \rightarrow K(\pi)}(0) [2.4(4.4)\%]$ 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

2.92 fb$^{-1}$ data were taken around 3.773 GeV
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 hadron decays with large branching fraction and less combinatorial backgrounds.

At the recoil side of singly tagged $\bar{D}^0$ and $D^-$ mesons, leptonic and semi-leptonic decays can be studied.
In the SM:

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

Bridge to precisely measure:

- Decay constant $f_{D(s)^+}$ with input $|V_{cd(s)}|_{\text{CKMfitter}}$
- CKM matrix element $|V_{cd(s)}|$ with input $f_{\text{LQCD}}^{D(s)^+}$
Progress of Measuring $f_{D^+}$ in past 26 years

- **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
  
  $f_{D^+} = (300^{+180}_{-150} \pm 40)$ 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 $D^+ \rightarrow \pi^+\nu$
  
  PRD78(2008)052003
  
  $f_{D^+} = 205.8 \pm 7.5 \pm 2.5$ MeV
Progress of Measuring $f_{D_s^+}$ in past 21 years

- **WA75, Fixed target experiment**
  
  $9.1 \pm 3.8$ D$_s^+ \rightarrow \mu^+\nu$ signals
  
  PTP89(1993)131

  $f_{D_s^+} = 232 \pm 45 \pm 20 \pm 48$ MeV

- **E653, Fermilab fixed target experiment**

  $32$ D$_s^+ \rightarrow \mu^+\nu$ signals

  PLB382(1996)299

  $f_{D_s^+} = 194 \pm 35 \pm 20 \pm 14$ MeV

- **CLEOII, 2.13 fb$^{-1}$ at 10.6 GeV**

  $38 \pm 10$ D$_s^+ \rightarrow \mu^+\nu$ signals

  PRD49(1994)5690

  $f_{D_s^+} = 344 \pm 37 \pm 52 \pm 42$ MeV

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

  $3$ D$_s^+ \rightarrow \mu^+\nu$ signals, PRL74(1995)4599

  $f_{D_s^+} = (430^{+150+40}_{-130-40})$ MeV

  First absolute measurement
Progress of Measuring $f_{D_s^+}$ in past 21 years

- L3, $Z \to q\bar{q}$, 49.6 pb$^{-1}$ at 91.2 GeV

  $15.6 \pm 6.0 \ D_s^+ \to \mu^+ \nu$ signals

  PLB396(1997)327

  $f_{D_s^+} = 309 \pm 58 \pm 33 \pm 38 \text{ MeV}$

- OPAL, $3.9 \times 10^6 \ e^+e^- \to q\bar{q}$

  $22.5 \pm 6.9 \ D_s^+ \to \tau^+ \nu$ signals

  PLB516(2001)236

  $f_{D_s^+} = 286 \pm 44 \pm 41 \text{ MeV}$

- ALPHA, $3.97 \times 10^6 \ Z$ hadronic decay

  $306 \pm 62 \ D_s^+ \to \tau^+ \nu$ signals

  PLB528(2002)1

  $575 \pm 84 \ D_s^+ \to \mu^+ \nu$ signals

  $f_{D_s^+} = 285 \pm 19 \pm 40 \text{ MeV}$
Progress of Measuring $f_{D_{s}^{+}}$ in past 21 years

- **CLEO-c, 600 pb$^{-1}$ at 4.17 GeV**

**Absolute measurement**

- $235 \pm 14 \text{ D}_{s}^{+} \rightarrow \mu^{+}\nu +\tau^{+}\nu \text{ signals}$
- $126 \pm 16 \text{ D}_{s}^{+} \rightarrow \tau^{+}\nu \text{ signals}$

**Improved statistical and systematic errors**

- $f_{D_{s}^{+}} = 263.3 \pm 8.2 \pm 1.9 \text{ MeV}$
- $f_{D_{s}^{+}} = 257.8 \pm 13.3 \pm 5.2 \text{ MeV}$
Progress of Measuring $f_{D_s^+}$ in past 21 years

- Belle, 913 fb$^{-1}$ at 10.58 GeV
- Babar, 521 fb$^{-1}$ at 10.58 GeV

Absolute measurements

$$e^+e^- \rightarrow c\bar{c} \rightarrow D_{\text{tag}}K_{\text{frag}}X_{\text{frag}}D_s^{*-}$$

- $N_{D_s^+ \rightarrow \mu^+\nu^+} = 492 \pm 26$
- $N_{D_s^+ \rightarrow e^+\nu^+\nu^\prime} = 952 \pm 59$
- $N_{D_s^+ \rightarrow e^+\nu^+\nu^\prime} = 758 \pm 48$
- $N_{D_s^+ \rightarrow e^+\nu^+\nu^\prime} = 496 \pm 35$

$$e^+e^- \rightarrow D_KX_{\mu^+\nu^+}$$

- $N_{D_s^+ \rightarrow \mu^+\nu^+} = 275 \pm 17$
- $N_{D_s^+ \rightarrow e^+\nu^+\nu^\prime} = 408 \pm 42$
- $N_{D_s^+ \rightarrow e^+\nu^+\nu^\prime} = 340 \pm 32$

$f_{D_s^+} = 255.5 \pm 4.2 \pm 5.1$ MeV
2698 signals, JHEP1309(2013)129

$f_{D_s^+} = 258.6 \pm 6.4 \pm 7.5$ MeV
1023 signals, PRD82(2010)091103

Better statistical but worse systematic errors at B factory
Improved $B[D^+ \rightarrow \mu^+\nu]$, $f_{D^+}$ and $|V_{cd}|$ at BESIII

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

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

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

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

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

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

Input $t_{D^+}$, $m_{D^+}$, $m_{\mu^+}$ on PDG and LQCD calculated $f_{D^+} = 207 \pm 4$ 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

- $209.0 \pm 9.3 \pm 2.6$ 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

$B[D^+ \rightarrow \mu^+\nu]$

$f_{D^+}$ [MeV]
Comparisons of Existing $f_{D+}$, $f_{Ds+}$ and $f_{D+:f_{Ds+}}$

Taken from Gang Rong’s talk at CKM2014

- 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 calculated $f_{D+}$, $f_{Ds+}$, $f_{D+:f_{Ds+}}$ differ by about $2\sigma$

- Improving measurement with larger data sample is necessary!

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<tr>
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<td>Averaged</td>
<td>Expected</td>
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<tr>
<td>$f_{D+}$(MeV)</td>
<td>203.9±4.7</td>
<td>$212.6±0.4^{+1.0}_{-1.2}$</td>
</tr>
<tr>
<td>$f_{Ds+}$(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>
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Semi-leptonic Decay $D^0 \rightarrow K(\pi^-)e^+\nu$

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** $f_+^{D \rightarrow K(\pi)(0)}$ with input $|V_{cd(s)}|^{\text{CKMfitter}}$
  
  - Single pole form
  \[
f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{\text{pole}}^2}}
  \]

  - ISGW2 model
  \[
f_+(q^2) = f_+(q_{\text{max}}^2) \left(1 + \frac{r_{\text{ISGW2}}^2}{12} (q_{\text{max}}^2 - q^2)^2 \right)^{-2}
  \]

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

  - 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 $f_+^{LQCD,D \rightarrow K(\pi)(0)}$
During the past 26 years, studies of $D \rightarrow K(\pi) l^+ v$ are made by MARKIII, E691, CLEO, CLEOII, BESII, FOCUS, BELLE, Babar and CLEO-c

- **BELLE**, 282 fb$^{-1}$ at 10.58 GeV
  
  - 2004-2009, CLEO-c, 818 pb$^{-1}$ at $\psi''$

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

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


Before 2010, the LQCD calculated $f^+_D \rightarrow K(\pi) (0)$ precision is at 10% level, thus limiting $|V_{cs(d)}|$ measurement.
Improved $B[D^0 \rightarrow K(\pi)^- e^+ \nu]$ at BESIII

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

$U_{\text{miss}} = E_{\text{miss}} - P_{\text{miss}}$

$N_{D^+ \rightarrow K^- e^+ \nu} = 70727 \pm 278$

$N_{D^+ \rightarrow K^- e^+ \nu} = 6297 \pm 87$

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

$B_{D^0 \rightarrow \pi^- e^+ \nu} = (0.2950 \pm 0.0041 \pm 0.0026)\%$

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

$2.92 \text{ fb}^{-1} \text{ data@ 3.773 GeV}$
Comparisons of $B[D^0 \to K(\pi)^- e^+ \nu]$
### Extracted Parameters of Form Factors

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

| Simple Pole | $f_K^+(0)|V_{cs}|$ | $0.7209 \pm 0.0022 \pm 0.0033$ | $f_\pi^+(0)|V_{cd}|$ | $0.1475 \pm 0.0014 \pm 0.0005$ |
|-------------|-------------------|-----------------|-----------------|-----------------|
|             | $M_{pole}$        | $1.9207 \pm 0.0103 \pm 0.0069$ | $M_{pole}$       | $1.9114 \pm 0.0118 \pm 0.0038$ |

**Mod. Pole**

| $f_K^+(0)|V_{cs}|$ | $0.7163 \pm 0.0024 \pm 0.0034$ | $f_\pi^+(0)|V_{cd}|$ | $0.1437 \pm 0.0017 \pm 0.0008$ |
|-------------------|-----------------|-----------------|-----------------|
| $\alpha$          | $0.3088 \pm 0.0195 \pm 0.0129$ | $\alpha$        | $0.2794 \pm 0.0345 \pm 0.0113$ |

**ISGW2**

| $f_K^+(0)|V_{cs}|$ | $0.7139 \pm 0.0023 \pm 0.0034$ | $f_\pi^+(0)|V_{cd}|$ | $0.1415 \pm 0.0016 \pm 0.0006$ |
|-------------------|-----------------|-----------------|-----------------|
| $r_{ISGW2}$       | $1.6000 \pm 0.0141 \pm 0.0091$ | $r_{ISGW2}$     | $2.0688 \pm 0.0394 \pm 0.0124$ |

**Series.2.Par**

| $f_K^+(0)|V_{cs}|$ | $0.7172 \pm 0.0025 \pm 0.0035$ | $f_\pi^+(0)|V_{cd}|$ | $0.1435 \pm 0.0018 \pm 0.0009$ |
|-------------------|-----------------|-----------------|-----------------|
| $r_1$             | $-2.2278 \pm 0.0864 \pm 0.0575$ | $r_1$           | $-2.0365 \pm 0.0807 \pm 0.0260$ |

**Series.3.Par**

| $f_K^+(0)|V_{cs}|$ | $0.7196 \pm 0.0035 \pm 0.0041$ | $f_\pi^+(0)|V_{cd}|$ | $0.1420 \pm 0.0024 \pm 0.0010$ |
|-------------------|-----------------|-----------------|-----------------|
| $r_1$             | $-2.3331 \pm 0.1587 \pm 0.0804$ | $r_1$           | $-1.8434 \pm 0.2212 \pm 0.0690$ |
| $r_2$             | $3.4223 \pm 3.9090 \pm 2.4092$ | $r_2$           | $-1.3871 \pm 1.4615 \pm 0.4677$ |
Improved Form factor $f^{D\to K(\pi)}_{+}(0)$ at BESIII

\[ f^{D\to K(\pi)}_{+}(0) |V_{cs(d)}| \]

\[ f^{D\to K(\pi)}_{+}(0) \]

\[ f^{D\to K(\pi)}_{+}(0) |V_{cs(d)}| \] of CKM-Fitter

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

- **BES-II**
  - PLB597, 39: $0.78\pm0.04\pm0.03$
  - CLEO-c PRD80, 032005, 3. Par. Ser.: $0.739\pm0.007\pm0.005$
  - BELLE PRL97, 061804, Mod. Pole: $0.695\pm0.007\pm0.022$
  - BESIII Preliminary: $0.727\pm0.007\pm0.005$
  - HPQCD PRD82 (2010) 114506: $0.747\pm0.011\pm0.015$

- **CLEO-c PRD80, 032005, 3. Par. Ser.**
  - BELLE PRL97, 061804, Mod. Pole: $0.624\pm0.020\pm0.007$
  - BESIII Preliminary: $0.666\pm0.020\pm0.021$
  - HPQCD PRD84 (2011) 114505: $0.666\pm0.019\pm0.005$
Improved $|V_{cs(d)}|$ at BESIII

- Method 1

\[ B[D(s)_+ \to l^+\nu] \]

- Method 2

\[ f_+^{D \to K(\pi)(0)} |V_{cs(d)}| \]

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

Input $f^{D \to K_{(s)\pi}(0)}$ of LQCD

Method 2 suffers larger theoretical uncertainty in $f_+^{D \to K(\pi)(0)} [2.4(4.4)\%]$
Summary of BESIII results

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

- We provide improved measurement of decay constant \(f_{D^+}\) and form factor \(f^\pm_{D \rightarrow K(\pi)(q^2)}\), which are important to test and calibrate LQCD calculations accurately.

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

- BESIII will take 3 fb\(^{-1}\) data at 4.17 GeV in 2016, improved measurement of \(f_{Ds^+}\) and \(|V_{cs}|\) by \(D_s^+ \rightarrow l^+\nu\) is expected in the near future.
Why HIEPA is expected?

Leptonic decay $D(s)^+ \rightarrow l^+\nu$

- Measurement of $f_{D(s)^+}$ and $|V_{cd(s)}|$ is limited by data size
- More precise $f_{D^+}$, $f_{D_{s}^+}$, $f_{D^+}:f_{D_s}$ is expected

1. Challenge from LQCD calculation with 0.5%, 0.5% and 0.3% precisions
2. $\sim 2\sigma$ difference between experiment and theoretical calculation

Semi-leptonic decay $D^0 \rightarrow K(\pi)^-e^+\nu$

- Measurement of $f_{D \rightarrow \pi}(0)$ is limited by data size
- Measurement of $|V_{cs(d)}|$ is limited by $f_{LQCD,D \rightarrow K(\pi)}(0)$

Improving $|V_{cs(d)}|$, $f_{D(s)^+}$, $f_{D \rightarrow K(\pi)}(0)$ statistical precisions by an order of magnitude at HIEPA?
Prospects at HIEPA?

Opportunity: If we have 300 fb\(^{-1}\) data at 3.773 GeV and 300 fb\(^{-1}\) data at 4.17/4.03 GeV, what precisions we can reach?

Roughly estimate based on BESIII and CLEO-c experiments

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<th>Systematic error</th>
<th>Statistical error</th>
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<tr>
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<td>~3 fb(^{-1})</td>
<td>12 fb(^{-1})</td>
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<tr>
<td>(\Delta f_{D^{+}}/f_{D^{+}})</td>
<td>~0.9%(\text{BESIII})</td>
<td>2.6%</td>
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<tr>
<td>(\Delta f_{Ds^{+}}/f_{Ds^{+}})</td>
<td>~1.5%(\text{CLEO-c})</td>
<td>1.1%/2.0%</td>
</tr>
<tr>
<td>(\Delta f_{D^{0}\rightarrow K}/f_{D^{0}\rightarrow K})</td>
<td>~0.5%(\text{BESIII})</td>
<td>0.35%</td>
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<tr>
<td>(\Delta f_{D^{0}\rightarrow \pi}/f_{D^{0}\rightarrow \pi})</td>
<td>~0.7%(\text{BESIII})</td>
<td>1.26%</td>
</tr>
<tr>
<td>(</td>
<td>V_{csl}</td>
<td>_{Ds^{0}\rightarrow l^{+}v})</td>
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<td>(</td>
<td>V_{csl}</td>
<td>_{D^{0}\rightarrow K-e+v})</td>
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<tr>
<td>(</td>
<td>V_{cdl}</td>
<td>_{D^{+}\rightarrow \mu^{+}v})</td>
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<tr>
<td>(</td>
<td>V_{cdl}</td>
<td>_{D^{0}\rightarrow \pi^{-}e+v})</td>
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Challenges:
- Measuring \(|V_{csl(d)}|\) by \(D^{0}\rightarrow K(\pi)e^{+}v\) will be limited by LQCD calculation precision of \(f_{+}^{D^{0}\rightarrow K(\pi)(0)}\), whether it can reach 0.5\% level?
- Measuring \(f_{Ds^{+}}\) and \(|V_{csl}|\) will be limited by systematic error of selecting \(D_{s^{+}}\rightarrow l^{+}v\), whether it can reach 1.0\% level?
Thank you!
Back-up slides
Comparisons of $B[D^+ \rightarrow \mu^+ \nu]$ and $f_{D^+}$
Comparisons of $B[D_{(s)}^{+} \rightarrow l^{+}\nu]$ 

Taking from Gang Rong's talk at CHARM2012
Comparisons of $B[D_{(s)}^+ \rightarrow l^+\nu]$ and $f_{D_s}$

Taking from Gang Rong’s talk at CHARM2012

Based on the measured branching fractions of $D_s^+$ leptonic decays (after radiative correction), and with inputs of $D_s^+$ mass, lepton mass, $D_s^+$ lifetime and $|V_{cs}|=0.97345$ from CKMfitter, we calculate the $f_{D_s}$. 

![Diagram showing $D_s^+ \rightarrow \mu^+\nu_\mu$ and $D_s^+ \rightarrow \tau^+\nu_\tau$ distributions with data points from various experiments.](image)
Comparisons of existing $B[D_s^{+} \rightarrow \mu(\tau)^{+}\nu]$
Projections on Form Factors $f^{K(\pi)}_+(q^2)$

\[ D^0 \rightarrow K^- e^+ \nu \]

\[ D^0 \rightarrow \pi^- e^+ \nu \]
Comparisons of Form Factors

Experimental data calibrate LQCD calculation

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

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

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

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

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

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

- 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