$D^+$ Leptonic and $D^0$ Semileptonic Decays
First Results from BESIII

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Leptonic Decay

\[
(D^+ \rightarrow \ell^+ \nu) = f_D^2 |V_{cd}|^2 \frac{G_F^2}{8} m_D m_\ell^2 \left(1 - \frac{m_\ell^2}{m_D^2}\right) \frac{m_D^2}{m_\ell^2}
\]

- Decay constant \( f_D \) incorporates the strong interaction effects (wave function at the origin)
- Use charm leptonic decays to validate theory (LQCD) and apply to \( B \) mixing, which requires \( f_B \)
- Multiple tests with charm: \( f_D, f_{Ds} \) (esp. ratios)
- Sensitivity to New Physics
**Window on Weak and Strong Physics**

**Semileptonic Decay**

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

- Use Strong Interaction theory (LQCD) for form factor, extract CKM
- Use other measurements and unitarity for CKM and test theory
- Theoretical uncertainties can be reduced in determinations of \(|V_{ub}|\) if FF calculations can be validated with charm
- Multiple tests available, semileptonic \(D\) decays to pseudoscalar mesons are cleanest

5 July 2012
Ron Poling - ICHEP 2012
• Widths of mixing and $|V_{ub}|$ bands will be reduced as charm validates LQCD
• Long-term goal: Over-constrain CKM and search for New Physics
Charm Physics at Threshold

- At $\psi(3770)$ charm production is $D^0\bar{D}^0$ and $D^+D$
- Fully reconstruct about 15% of $D$ decays

$E = E_D + E_{\text{Beam}}$

$M_{BC} = \sqrt{E_{\text{Beam}}^2 - p_D^2}$

- Hadronic tag on one side gives “beam” of $D^0$ or $D^+$ on the other side for leptonic/semileptonic studies. Neutrino is reconstructed from missing energy and momentum
BESIII at BEPCII

• Comparable capabilities to CLEO-c, plus muon ID
• The big advantage: BEPCII is a two-ring machine designed for charm
  – Design (achieved) luminosity at $\psi(3770)$: $1 \times 10^{33}$
BESIII Data

- World’s largest $\psi(3770)$ sample

- Tools/techniques for precision charm physics still under development – all results are PRELIMINARY

- $D^+ \rightarrow K^0(0)e^+$ analysis is “partially blind” – 0.92 fb$^{-1}$ analyzed so far. Full 2.9 fb$^{-1}$ later for final results
\[ D^+ \rightarrow + - \text{ Tag Selection} \]

- Nine \( D^- \) tag modes

\[
\begin{array}{cccccc}
K^+ & K^0 & K^0 K & K^+ K & K^+ & K^0 \\
+ & K^0 & 0 & K^+ & + & K^0
\end{array}
\]

\[
N_{D}^{\text{tag}} = (1.566 \pm 0.002) \times 10^6 \text{ in } 2.9 \text{ fb}^{-1}
\]

BESIII Preliminary
\[ D^+ \rightarrow + - \] Signal Selection

- Exactly one track in addition to tag, with the right charge
- Positive muon identification
- No extra photon
- Select on consistency with leptonic decay:

\[ M_{\text{miss}}^2 = (E_{\text{Beam}} - E)^2 \left( \vec{p}_{\text{tag}} \cdot \vec{p} \right)^2 = 0 \]

425 signal candidates:
small BG, mom. dist.
consistent with \( D^+ \rightarrow + \)
Positive muon ID requirement reduces background at the expense of a ~20% efficiency loss.
$D^+ \rightarrow +$ - Backgrounds

BESIII Preliminary

**Numbers of background events from $D\bar{D}$ decays**

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_{MC}^{bg}$</th>
<th>Scale factor $f$</th>
<th>$N_{data}^{bg} = \frac{N_{MC}^{bg}}{f} \times N_{MC}^{data}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K_L^0\pi^+$</td>
<td>111</td>
<td>10.8</td>
<td>7.9 ± 0.8 ± 0.3</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^+\pi^0$</td>
<td>53</td>
<td>10.8</td>
<td>3.8 ± 0.5 ± 0.3</td>
</tr>
<tr>
<td>$D^+ \rightarrow \tau^+\nu$</td>
<td>96</td>
<td>10.8</td>
<td>6.9 ± 0.7 ± 0.3</td>
</tr>
<tr>
<td>Other $D$ decays</td>
<td>250</td>
<td>10.8</td>
<td>17.9 ± 1.1 ± 0.5</td>
</tr>
<tr>
<td>Sum</td>
<td>510</td>
<td>10.8</td>
<td>36.4 ± 1.6 ± 0.7</td>
</tr>
</tbody>
</table>

**Numbers of background events from non – $D\bar{D}$ decays**

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_{MC}^{bg}$</th>
<th>Scale factor $f$</th>
<th>$N_{data}^{bg} = \frac{N_{MC}^{bg}}{f} \times N_{MC}^{data}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow (\gamma)\psi(3686)$</td>
<td>2</td>
<td>6.3</td>
<td>0.2 ± 0.2 ± 0.0</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow (\gamma)J/\psi$</td>
<td>0</td>
<td>5.7</td>
<td>0.0 ± 0.0 ± 0.0</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow Light Hadron$</td>
<td>33</td>
<td>3.1</td>
<td>8.2 ± 1.4 ± 0.3</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tau^+\tau^-$</td>
<td>15</td>
<td>6.0</td>
<td>1.9 ± 0.5 ± 0.4</td>
</tr>
<tr>
<td>$\psi(3770) \rightarrow non – D\bar{D}$</td>
<td>7</td>
<td>5.8</td>
<td>0.9 ± 0.4 ± 0.9</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>11.3 ± 1.6 ± 1.0</td>
</tr>
<tr>
<td><strong>Total (D decay and non – D decay)</strong></td>
<td></td>
<td></td>
<td>47.7 ± 2.3 ± 1.3</td>
</tr>
</tbody>
</table>

**Event type**

| Number | ...
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>425</td>
<td>$N(D^+ \rightarrow \mu^+\nu_\mu)$_\text{candidate}</td>
</tr>
<tr>
<td>47.7 ± 2.3 ± 1.3</td>
<td>$N_b$</td>
</tr>
<tr>
<td>377.3 ± 20.6 ± 2.6</td>
<td>$N(D^+ \rightarrow \mu^+\nu_\mu)$</td>
</tr>
</tbody>
</table>
\( D^+ \rightarrow + \) - Results

**BESIII Preliminary**

\[
N(D^+ \rightarrow +) = 377.3 \pm 20.6
\]

\[
\mathcal{B}(D^+ \rightarrow \mu^+\nu) = (0.0374 \pm 0.0021\pm 0.0006)\%
\]

\[
f_{D^+} = (203.9 \pm 5.7 \pm 2.0) \text{ MeV}
\]

- Excellent agreement with CLEO-c
- Still statistics limited – need more data!
$D^+ \rightarrow \mu^+ \nu$ - Comparisons (from G. Rong)

$LQCD (HPQCD 2012) (208.3^{+1.0}_{-1.1} \pm 3.3) \text{ MeV}$

$LQCD (FNAL/MILC 2012) (219^{+11}_{-10}) \text{ MeV}$

$B(E665) (206.6^{+1.3}_{-1.2} \pm 2.2) \text{ MeV}$

$QL (QCDSF) (235^{+8}_{-16}) \text{ MeV}$

$QL (Taiwan) (210^{+10}_{-10}) \text{ MeV}$

$QL (UKQCD) (211^{+14}_{-13}) \text{ MeV}$

$QL$ (from G. Rong)

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$QL$ (from G. Rong)
$D^0 \rightarrow K \left( \begin{array}{c} e^+ \\ e^- \end{array} \right)$ - Tag Selection

- Four $D^0$ tag modes

$N_{D^0}^{\text{tag}} = (0.774 \pm 0.001) \times 10^6$ in 0.92 fb$^{-1}$
$D^0 \rightarrow K \ (\ ) e^+ e^- - $ Signal Selection

- Tag plus exactly two oppositely-charged tracks
- Kaon/pion/electron ID
- Electron has right charge
- No extra neutral energy
- Select on consistency with semileptonic decay

\[
U = \begin{vmatrix} E_{\text{miss}} & \vec{P}_{\text{miss}} \end{vmatrix} \begin{vmatrix} 0 
\end{vmatrix}
\]

- Fit $U$ distribution to extract yield

BESIII Preliminary

$N_{\text{sig}} = 18460 \pm 143$

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

BESIII Preliminary

$N_{\text{sig}} = 1677 \pm 45$

$D^0 \rightarrow e^+ e^- $
• Systematic uncertainties are preliminary

• Good consistency with CLEO-c, statistical precision is comparable with only 1/3 data analyzed
$D^0 \rightarrow K \left( e^+ e^- \right)$ - $q^2$ distribution

- Partition $D^0$ semileptonic candidates in bins of $q^2 = (E + E_e)^2 \left| \vec{p} + \vec{p}_e \right|^2$ with $E = E_{\text{miss}}$ and $\left| \vec{p} \right| = E_{\text{miss}}$

- Fit $U$ distribution in each $q^2$ bin

\[ q^2 = (E + E_e)^2 \left| \vec{p} + \vec{p}_e \right|^2 \quad \text{with} \quad E = E_{\text{miss}} \quad \left| \vec{p} \right| = E_{\text{miss}} \]
$D^0 \rightarrow K (\quad ) e^+ e^-$ - Project $f(q^2)$

- Points are data with statistical errors only
- Curves are Fermilab/MILC (arXiv:1111.5471) with $\pm 1\sigma$ (statistical) bands
\[ D^0 \rightarrow K \left( \begin{array}{c} \text{l} \\ \text{e}^+ \end{array} \right) e^- \ - \ FF \ Parameterizations \]

Simple Pole Model

\[ f_+(q^2) = \left( \frac{f_+(0)}{1 - \frac{q^2}{m_{H^*}^2}} \right) \]

Modified Pole Model

Becirevic and Kaidalov
PLB 478, 417 (‘00)

\[ f_+(q^2) = \left( \frac{f_+(0)}{1 - \frac{q^2}{m_{H^*}^2}} \right) \left( 1 - \frac{q^2}{m_{H^*}^2} \right) \]

Series Expansion

Becher and Hill
PLB 633, 61 (‘06)

\[ f_+(q^2) = \frac{1}{P(q^2)} \sum_{k=0}^{\infty} a_k(t_0) \left[ z(q^2, t_0) \right]^k \]

\[ z(q^2, t_0) = \frac{\sqrt{t_+} \frac{q^2}{\sqrt{t_+} + \sqrt{t_+}}}{\sqrt{t_+} q^2 + \sqrt{t_+} t_0} \quad t_\pm = \left( m_D \pm m_X \right)^2 \]
$D^0 \rightarrow K \left( \begin{array}{c} \varepsilon^+ \\ \varepsilon \end{array} \right) - FF Fits$

$D^0 \rightarrow K \ e^+_{\varepsilon}$

$D^0 \rightarrow \ e^+_{\varepsilon}$
\[ D^0 \rightarrow K \left( \begin{array}{c} \phi \end{array} \right) e^+ e^- \] - FF Results

| Simple Pole | \[ f_+(0)|V_{cd(s)}| \] | \[ m_{pole} \] |
|-------------|------------------|-----------------|
| \[ D^0 \rightarrow Ke\nu \] | 0.729±0.005±0.007 | 1.943±0.025±0.003 |
| \[ D^0 \rightarrow \pi e\nu \] | 0.142±0.003±0.001 | 1.876±0.023±0.004 |

| Modified Pole | \[ f_+(0)|V_{cd(s)}| \] | \[ \alpha \] |
|---------------|------------------|-----------------|
| \[ D^0 \rightarrow Ke\nu \] | 0.725±0.006±0.007 | 0.265±0.045±0.006 |
| \[ D^0 \rightarrow \pi e\nu \] | 0.140±0.003±0.002 | 0.315±0.071±0.012 |

| 2 par. series | \[ f_+(0)|V_{cd(s)}| \] | \[ r_1 \] |
|---------------|------------------|-----------------|
| \[ D^0 \rightarrow Ke\nu \] | 0.726±0.006±0.007 | -2.034±0.196±0.022 |
| \[ D^0 \rightarrow \pi e\nu \] | 0.140±0.004±0.002 | -2.117±0.163±0.027 |

| 3 par. series | \[ f_+(0)|V_{cd(s)}| \] | \[ r_1 \] | \[ r_2 \] |
|---------------|------------------|-----------------|-----------------|
| \[ D^0 \rightarrow Ke\nu \] | 0.729±0.008±0.007 | -2.179±0.355±0.053 | 4.539±8.927±1.103 |
| \[ D^0 \rightarrow \pi e\nu \] | 0.144±0.005±0.002 | -2.728±0.482±0.076 | 4.194±3.122±0.448 |

- Reasonable consistency with CLEO-c, comparable precision with 2/3 of data still to analyze

BESIII Preliminary
Future Charm Prospects at BESIII

- Finalize $D^+ \rightarrow ^+$ and $D^0 \rightarrow K \left( \begin{array}{c} \varepsilon^+ \\ \varepsilon \end{array} \right)$ on the 2.9 fb$^{-1}$ $\psi(3770)$ sample
- Extend to $D^+ \rightarrow K^0 \left( \begin{array}{c} 0 \\ \varepsilon^+ \varepsilon \end{array} \right)$ and other modes
- Highlights of coming data runs:
  
  **2012-2013** $E_{\text{CM}}=4260$ and 4360 MeV for “XYZ” studies (0.5 fb$^{-1}$ each)
  
  **2013-2014** $E_{\text{CM}}=4170$ MeV for $D_s$ ($\sim 2.4$ fb$^{-1}$)
  
  **TBD** Additional $\psi(3770)$ data
Summary and Conclusions

- First results from the BESIII experiment have been presented on
  
  \[ D^+ \text{ Leptonic Decays} \]

  \[ \mathcal{B}(D^+ \rightarrow \mu^+\nu) = (0.0374 \pm 0.0021 \pm 0.0006)\% \]

  \[ f_{D^+} = (203.9 \pm 5.7 \pm 2.0) \text{ MeV} \]

- \[ D^0 \text{ Semileptonic Decays} \]

  \[ \mathcal{B}(D^0 \rightarrow K^+\nu) = (3.542 \pm 0.030 \pm 0.067)\% \]

  \[ \mathcal{B}(D^0 \rightarrow \pi^+\nu) = (0.288 \pm 0.008 \pm 0.005)\% \]

  \[ \frac{\Delta \Gamma}{\Delta q^2} \text{ distributions } \rightarrow \text{ FF fits, parameters} \]

- BESIII has arrived for precision charm physics, with more data and more measurements to come