Precision Charm Meson Decays
Leptonic, Semileptonic, Hadronic

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(+ CLEO & BESIII)

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Why Charm?

Previous “wisdom”: charm is a bit boring for flavor physics

Cabibbo-allowed decays dominate: hard to see rare processes

D Mixing is suppressed in SM & hard to estimate
CP violation suppressed

Light enough to make theory difficult (tough for HQET, etc.)
and lots of strong-interaction physics obscuring the weak

Better wisdom:
Charm is a gift!

B physics very productive... but limited by theory in many cases.
✦ Lattice QCD can help & charm can test it ✦
Today’s Topics

Leptonic Decays $D(s) \rightarrow \mu\nu$

to extract decay constants

$D \rightarrow Kl\nu$, $\pi l\nu$

to measure form factors

$D^0 \rightarrow K\pi$  $D^+ \rightarrow K\pi\pi$  $D_s \rightarrow KK\pi$

normalization from golden-mode branching rations

NOTE:
Precision lifetimes (dominated by FOCUS) are also useful!

Current Leaders

CLEO-c: Tagging with D pairs  very clean

Belle/BaBar: Continuum charm  large statistics

Sometimes using “continuum tagging”

Key issue:
Agreement with latest unquenched Lattice QCD?
Techniques

**CLEO-c uses Tagging:**
\[ e^+e^- \rightarrow \psi(3770) \rightarrow D^0D^0, D^+D^- \]
\[ e^+e^- @ 4170 \text{ MeV}: D_s^+D_s^- \text{ & } \text{c.c.} \]
creates ONLY D pairs

**Fully reconstruct one \( D_{(s)} \)**
- Can then infer neutrinos  
  (constrained kinematics)
- or get absolute hadronic BFs

**Typical tag rate per \( D \):**
15% / 10% / 5%
\( D^0 / D^+ / D_s \)

**Belle:**
Has used a similar technique, with exclusive final states from continuum at 10 GeV
Decay Constants: Pre-FPCP2008

\[ D^+ : \text{Consistent with LQCD, but tests limited by experimental precision} \]

\[ D_s : \text{Disagreement with latest Lattice result} \]
D Decay Constant Status

Previous CLEO & Belle results average to give \( f_{Ds} = 274 \pm 10 \text{ MeV} \)

( see Rosner & Stone arXiv:0802.1043 )

Best 2+1 unquenched lattice QCD obtains \( 241 \pm 3 \text{ MeV} \)

( Follana et.al, PRL 100, 062002 (2008) )

Dobrescu & Kronfeld argue that this could be the effect of NP, either charged Higgs (their own model) or leptoquarks

( see arXiv:0803.0512 )

Kundu & Nandi suggest R-parity violating SUSY to explain large \( f_{Ds} \) and \( B_s \) mixing phase

( see arXiv:0803.1898 )

Modest update from CLEO-c at FPCP2008 recapped here, along with 2007 Belle result.

Next, recall the previous CLEO \( f_{D^+} \) result: \( f_D = 223 \pm 17 \text{ MeV} \)

Imprecise, compared to Follana et al., lattice: \( 207 \pm 4 \text{ MeV} \)

Significant update from CLEO-c at FPCP2008 recapped here.
$D^+ \rightarrow \mu^+\nu$ Update

Neutrino from 4-momentum balance can plot (missing mass)$^2$: $MM^2$

Clean, isolated signal peak: Power of D-tagging:
Recall that the signal is one track + neutrino!

Fit (log scale)
$D^+ \rightarrow \mu^+\nu$ Results

**Fix $\tau\nu/\mu\nu$ at SM ratio of 2.65:**

$\mathcal{B}(D^+ \rightarrow \mu^+\nu) = (3.86 \pm 0.32 \pm 0.09) \times 10^{-4}$

$f_{D^+} = (206.7 \pm 8.5 \pm 2.5) \text{ MeV}$

Best number in context of SM

**Float $\tau\nu/\mu\nu$:**

$\mathcal{B}(D^+ \rightarrow \mu^+\nu) = (3.96 \pm 0.35 \pm 0.10) \times 10^{-4}$

$f_{D^+} = (208.5 \pm 9.3 \pm 2.5) \text{ MeV}$

Best number for use with Non-SM models
$D_s \rightarrow \mu^+\nu \ & \ \tau^+\nu$

($w/ \ \tau^+ \rightarrow \pi \nu$)

Have published:

PRL99, 071802
PRD76, 072002
(2007) 314 pb$^{-1}$

PRELIMINARY
FPCP2008
~400 pb$^{-1}$
(& 200 more soon)
Use only cleanest tags (for now)

Always have \( >1 \) neutrino!
Abandon use of \( MM^2 \)
Semileptonic events tend to have hadronic Energy in CsI (but careful re: \( K_L \) !)

Plot \( E_{\text{extra}} \) in Calorimeter (Extra: not tag or \( e \))

Peaks away from zero:
\( E_{\text{extra}} \) can include \( \gamma \) from \( D_s^* \) decay
**CLEO-c $D_s$ Summary**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{B}$ (%)</th>
<th>$f_{D_s}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) $\mu\nu+\tau\nu$</td>
<td>$\mathcal{B}_{\text{eff}}(D_s \rightarrow \mu\nu) =$</td>
<td>$268.2 \pm 9.6 \pm 4.4$</td>
</tr>
<tr>
<td>(fix SM ratio)</td>
<td>$(0.613 \pm 0.044 \pm 0.020)$</td>
<td></td>
</tr>
<tr>
<td>(2) $\mu\nu$ only</td>
<td>$\mathcal{B}(D_s \rightarrow \mu\nu) =$</td>
<td>$265.4 \pm 11.9 \pm 4.4$</td>
</tr>
<tr>
<td></td>
<td>$(0.600 \pm 0.054 \pm 0.020)$</td>
<td></td>
</tr>
<tr>
<td>(3) $\tau\nu$, $\tau \rightarrow \pi\nu$</td>
<td>$\mathcal{B}(D_s \rightarrow \tau\nu) =$</td>
<td>$271 \pm 20 \pm 4$</td>
</tr>
<tr>
<td></td>
<td>$(6.1 \pm 0.9 \pm 0.2)$</td>
<td></td>
</tr>
<tr>
<td>(4) $\tau\nu$, $\tau \rightarrow e\nu\nu$</td>
<td>$\mathcal{B}(D_s \rightarrow \tau\nu) =$</td>
<td>$273 \pm 16 \pm 8$</td>
</tr>
<tr>
<td></td>
<td>$(6.17 \pm 0.71 \pm 0.36)$</td>
<td></td>
</tr>
<tr>
<td>CLEO Average</td>
<td></td>
<td>$269.4 \pm 8.2 \pm 3.9$</td>
</tr>
<tr>
<td>of (1) &amp; (4)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CLEO-c updated both $D$ and $D_s$ at FPCP2008:**
- Due to time, I can't do justice to the many nice cross-checks...
- Please see S. Stone's FPCP talk for more details.
**Belle: \( D_s \rightarrow \mu^+\nu \)**

Use “Continuum tagging”:
\[
e^+e^- \rightarrow D^{\pm,0} K^{\pm,0} \times D_s^*,
\]
\( X = n\pi \) - or - \( n\pi \gamma \) (fragmentation)
about 25% of \( D \) BF used

Use recoil mass:
against \( DKX\gamma \) counts total \( D_s \)
against \( DKX\gamma\mu \) counts \( D_s \rightarrow \mu^+\nu \)

\[
\mathcal{B}(D_s^+ \rightarrow \mu^+\nu) = (0.644 \pm 0.076 \pm 0.057)\% 
\]

\( f_{D_s} = 275 \pm 16 \pm 12 \text{ MeV} \)
**Decay Constant Summary**

Weighted Ave. CLEO+Belle:  \( f_{Ds} = 270.4 \pm 7.3 \pm 3.7 \) MeV  
( systematic errors are uncorrelated )

Using \( f_{D^+} = (206.7 \pm 8.5 \pm 2.5) \) MeV  
\( f_{Ds}/f_{D^+} = 1.31 \pm 0.06 \pm 0.02 \) larger than predicted

\( \Gamma(D_S^+ \rightarrow \tau^+\nu) / \Gamma(D_S^+ \rightarrow \mu^+\nu) = 10.3 \pm 1.1, \quad SM = 9.72 \)

Consistent with lepton universality

Note: BaBar \( f_{Ds} \) PRL 98, 141801 (2007) & others depending on “B(D_s \rightarrow \phi\pi)” are omitted here...
Semileptonic Decays

Concentrate on Form Factors
  o Pseudoscalar modes for Lattice QCD tests
    Key: \(D \rightarrow \pi l\nu\) as test of \(B \rightarrow \pi l\nu\) (needed for \(V_{ub}\))
  o \(D_s \rightarrow K\bar{\ell}\nu\): newest precision result

Omitting:
  o Many other branching ratios
    esp. \(D \rightarrow \rho/\omega/\eta/K_1 \epsilon \nu\) (CLEO)
  o Non-Parametric FF analysis (CLEO)
  o Untagged \(D \rightarrow Kl\nu\) (BaBar)
$D^0 \rightarrow \pi e^+\nu$, $K e^+\nu$ (tagged)

**Cabibbo suppressed**

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

699$\pm$28 events

$BR=(3.1\pm0.1\pm0.1) \times 10^{-3}$

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

$D^0 \rightarrow K^\pi^\pi^0$

$D^0 \rightarrow \rho e^\nu$

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

295$\pm$20 events

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

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

2910$\pm$55 events

**Cabibbo favored**

$U_{\text{miss}} = E_{\text{mis}} - |p_{\text{mis}}| \ (\text{GeV})$

Excellent background suppression

Small $K^-\pi$ feed-across due to threshold kinematics

Past results: $K^-\pi$ signals overlapped completely!
**D^0 \rightarrow \pi l\nu, K l\nu**

Use "Continuum tagging" again: \( e^+e^- \rightarrow D^{(*)}_{\text{tag}} D^{(*)}_{\text{signal}} X \).

Reconstruct all particles (except for neutrino)

Tagging provides absolute normalization \( \sim 56,000 \) tagged \( D^0 \)

**Cabibbo suppressed**

\[
D^0 \rightarrow \pi^- e^+ \nu \\
126 \pm 12 \text{ events}
\]

\[
D^0 \rightarrow \pi^- \mu^+ \nu \\
106 \pm 12 \text{ events}
\]

\[
m_{\text{miss}}^2 = E_{\text{miss}}^2 - p_{\text{miss}}^2 \quad \text{(GeV)}
\]

**Cabibbo favored**

\[
D^0 \rightarrow K^- e^+ \nu \\
1318 \pm 37 \text{ events}
\]

\[
D^0 \rightarrow K^- \mu^+ \nu \\
1249 \pm 37 \text{ events}
\]

\[
m_{\text{miss}}^2 = E_{\text{miss}}^2 - p_{\text{miss}}^2 \quad \text{(GeV)}
\]

Impressive results in difficult production environment

Both \( e \) and \( m \) measured, but only \( D^0 \)

vs. CLEO-c: 1000x lumi, but \( \sim 3x \) less signal events & \( \sim 10x \) worse signal/noise
$D^{0+} \rightarrow \pi^+ e^- \nu_e$, Keν (untagged)

Compared to the tagged analysis:
- Factor $\sim 2$ increase in the signal statistics.

Use global 4-momentum balance
Infer neutrino 4-vector w/o explicit tag
Can then use familiar beam-constrained mass
**Branching Ratios**

Cabibbo suppressed

<table>
<thead>
<tr>
<th>PDG (2004)</th>
<th>BES II</th>
<th>Belle (tag, 282 fb⁻¹)</th>
<th>Preliminary</th>
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</thead>
<tbody>
<tr>
<td>CLEO-c (tag, 281 pb⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLEO-c (no tag, 281 pb⁻¹)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Cabibbo favored

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<th>BES II</th>
<th>Belle (tag, 282 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR (no tag, 75 fb⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLEO-c (tag, 281 pb⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLEO-c (no tag, 281 pb⁻¹)</td>
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<td></td>
</tr>
</tbody>
</table>

Significant improvement in precision by recent BaBar/Belle/CLEO-c measurements

(CLEO-c best, especially for πeν)
Much of the visible variation is due to the phase-space factor ($P^3$).
Single Pole Model describes data reasonably well, but not with spectroscopic $D_s^*$ mass

(from Ian Shipsey's talk at LQCD workshop, FNAL, Dec 2007 – see for more extensive discussion of form factor results)
D → K e⁺ νₑ Form Factor vs. LQCD

Assuming $V_{cs} = 0.9745$

Fit of Modified Pole Model to LQCD simulation points

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

FNAL-MILC-HPQCD Curve – courtesy of Andreas Kronfeld

LQCD mean
LQCD Statistical
LQCD Systematic
CLEO-c (tag)
CLEO-c (no tag)
BELLE
BaBar
**D → π eν Form Factor vs. LQCD**

![Graph showing D → π eν form factor vs. LQCD](image)

Assuming $V_{cd}=0.2238$

**Careful re: comparisons on next page:**

If paremetrization wrong, comparisons can be misleading!

Much recent effort on systematic series expansions... but no time today


(previous work: Boyd, Grinstein, Lebed, Savage, Arnesen, Rothstein, Stewart...)

CLEO untagged paper uses these expansions along with older pole forms
More Tests of LQCD

Slope

Normalization

(assuming $|V_{cs\,(cd)}|=|V_{ud\,(us)}|$)

$D \rightarrow K\nu$

Normalization errors

<table>
<thead>
<tr>
<th>Channel</th>
<th>Experiments</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D \rightarrow K\nu$</td>
<td>2%</td>
<td>10%</td>
</tr>
<tr>
<td>$D \rightarrow \pi\nu$</td>
<td>4%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Theoretical errors larger than experimental
Untagged Analysis

Detailed form factor analysis  25K events (more complicated w/ a vector meson)

\[ D_s \rightarrow \phi e\nu \]

\[ D_s \rightarrow f_0 e\nu \]

(first evidence)
$D_s \rightarrow K^+K^-\nu$ FFs

3 form-factors for $\phi$
( fix $r_1 = 1.0$ )
1 form-factor for $f_0$
FIT:
Float ratios to $r_1$ at $q^2=0$
$M_V$ fixed; $M_A$ floats

$N_{sig} = 25,152 \pm 177 \pm 367$
$r_\nu = 1.868 \pm 0.061 \pm 0.079$
$r_2 = 0.763 \pm 0.072 \pm 0.062$
$r_0 = 15.3 \pm 2.6 \pm 1.0$
$m_A = 2.30^{+0.24}_{-0.18} \pm 0.21$ GeV

+ $BF(D_s \rightarrow KK\pi)$, $BF(\phi \rightarrow KK)$, $D_s$ lifetime, $V_{cs}$:
$A_1(q^2 = 0) = 0.605 \pm 0.012 \pm 0.018 \pm 0.018$

Agreement with Lattice, except $r_\nu$
(need better model?)

$Lattice$: UKQCD
Hep-lat/0109035

$A_1(q^2=0) = 0.63 \pm 0.02$

$r_\nu = 1.35 \pm 0.08$
$r_2 = 0.98 \pm 0.09$
Precision Hadronic Branching Fractions

Systematics:

tracking, PID efficiency
always present
BUT... some nice techniques to measure w/ tagging

Background issues:
better with threshold tagging...

Similar considerations for semileptonic, leptonic
but statistics still dominate there
( interested in Cabibbo-suppressed semileptonic,
or rare fully leptonic modes...)

Topics:
Hadronic modes and Golden-Mode BF\(s\): \(D^0, D^+, D_s\)
Quantum correlations \& \(K\pi\) Phase

Omitted
- In Backup slides: Interference \(D \rightarrow K_{L/S} \pi\)
- MANY other decay modes (Cabibbo-suppressed, ...)

Partial reconstruction of \( B^0 \rightarrow D^{*+} (X) l^- \nu_l \)
Slow pion used to estimate \( D^* \) momentum
Full recon of \( D^0 \rightarrow K^- \pi^+ \) within inclusive sample

\[
\text{BF} = (4.007 \pm 0.037 \pm 0.072)\% \\
\text{Systematics: } 1.8\% = 1.5\% \text{ exclusive effic. } \oplus 1.0\% \text{ inclusive}
\]
**D⁰ & D⁺ Comparisons**

NOTE: method cancels #DD pairs algebraically; & tag eff. almost cancels

"Golden Modes" are now systematics limited

**D⁰**

$K^−\pi^+$

**D⁺**

$K^−\pi^+\pi^+$

Use PDG04 since PDG06 included 56 pb⁻¹ CLEO-c

PRD 76, 112001 (2007) 281 pb⁻¹
Data @ $E_{cm} = 4170$ MeV

$\sim 1$ nb of $D_s^* D_s$

Projected $M(D_s^+) - M(D_s^-)$

$\sim 1000$ double tags

Sets scale of stat. error: $\sim 3.5\%$

( $\sim 1/2$ of total dataset )
**Ds Branching Ratios**

NEW key normalizing mode:

\[
B \left( D_s \rightarrow K^+ K^- \pi^+ \right) = (5.50 \pm 0.23 \pm 0.16) \%
\]

\( \phi \pi^+ \) "Branching fraction" ill-defined

Also quote \( B \left( D_s \rightarrow K^+ K^- \pi^+ \right) \) with various \( M(K^+ K^-) \) windows:

<table>
<thead>
<tr>
<th>Value</th>
<th>This result ( B ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_5 )</td>
<td>1.69 ± 0.08 ± 0.06</td>
</tr>
<tr>
<td>( B_{10} )</td>
<td>1.99 ± 0.10 ± 0.05</td>
</tr>
<tr>
<td>( B_{15} )</td>
<td>2.14 ± 0.10 ± 0.05</td>
</tr>
<tr>
<td>( B_{20} )</td>
<td>2.24 ± 0.11 ± 0.06</td>
</tr>
</tbody>
</table>

\( D_s \rightarrow K^+ K^- \pi^+ \)
Quantum Coherence & $K\pi$ phase

Correlated $D$ pairs are produced at the $\psi(3770)$:

Simultaneous fit to:
- hadronic & semilep modes + external mixing inputs:
  \[(x, y, x'^2, y', r^2)\]

Allows a measurement of strong $K\pi$ FSI phase, of great interest for $D$ mixing results!

\[
\cos\delta = 1.10 \pm 0.35 \pm 0.07
\]
\[
\delta = (22^{+11}_{-12}^{+9}_{-11})^\circ
\]
Not Covered…

Mixing, Dalitz, Spectroscopy: well-covered in other talks

Much other work:
  - CLEO: other hadronic & semileptonic modes (Cabibbo-suppressed, etc.)
  - BaBar: $D \rightarrow Kl\nu$ (2007, untagged)
  - Various: CPV searches, Rare decays
  - etc.

One “fun” new result:

$$B(D_s \rightarrow p \bar{n}) = (1.30 \pm 0.36 \pm 0.12 - 0.16) \times 10^{-3}$$
CLEO PRL 100, 181802 (2008)
Conclusions

Tests of Lattice QCD becoming precise
Intriguing disagreement for $f_{D_s}$?
Charm threshold best for experimental precision

Outlook

Lattice QCD marches onwards with CPU, techniques, ...
Much existing data left to mine at BaBar, Belle, CLEO
Very soon we will have data at BESIII & LHC-b, ...
Super-B, ... ???

Charm is alive & well
Acknowledgments

Thanks to CLEO collaborators I’ve borrowed from:
P. Onyisi, M. Shepherd, T. Skwarnicki, S. Stone, W. Sun, ...

& to my Charming BaBar & Belle colleagues:
(S. Prell, Y. Sakai, P. Chang)
Thanks for convenient web pages with results!

& to my new BESIII collaborators:
Thanks for providing me a future of continuing charm physics...

& finally to the HQL08 organizers:
Thanks for the opportunity to speak, and the great conference
BACKUP SLIDES
$f_{D_s}$: $D_s$ Mass Peaks

- $K^+ K^- \pi^-$
- $K_S K^-$
- $\eta \pi^-$
- $\eta' \pi^-$ $\eta' \rightarrow \pi^- \pi^+ \eta$
- $K^+ K^- \pi^- \pi^0$
- $\pi^- \pi^- \pi^+$
- $K^{*0} K^*$
- $\eta' \rho^-$
- $\eta' \pi^-$ $\eta' \rightarrow \rho \gamma$
$f_{D_s} : D_s \gamma$ (Missing Mass) $^2$
Systematics on BF

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

\[ D_s^- \rightarrow \mu^+ \nu \, \& \, \tau^+ \nu \quad (w/ \tau^+ \rightarrow \pi \nu) \]

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finding the ( \mu^+ ) track</td>
<td>0.7</td>
</tr>
<tr>
<td>Min. ionization of ( \mu^+ ) in EM cal</td>
<td>1.0</td>
</tr>
<tr>
<td>Particle identification of ( \mu^+ )</td>
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<tr>
<td>( MM^2 ) width</td>
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<tr>
<td>Extra showers in event &gt; 250 MeV</td>
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</tr>
<tr>
<td>Background</td>
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<td>Number of single tag ( D^+ )</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.2</strong></td>
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<tr>
<td>( MM^2 ) width</td>
<td>0.2</td>
</tr>
<tr>
<td>Extra showers with &gt; 300 MeV</td>
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</tr>
<tr>
<td>Background</td>
<td>0.5</td>
</tr>
<tr>
<td>Number of single tag ( D_s^- )</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.3</strong></td>
</tr>
</tbody>
</table>
**D⁰, D⁺ Branching Fractions**

Single Tags: \( N_j = N_{\text{DD}} \ \mathcal{B}_j \varepsilon_j \)

Double Tags: \( N_{ij} = N_{\text{DD}} \ \mathcal{B}_i \mathcal{B}_j \varepsilon_{ij} \)

\[ \mathcal{B}_i = \frac{N_{ij} \varepsilon_j}{N_j \varepsilon_{ij}} \]

\[ N_{\text{DD}} = \frac{N_i N_j \varepsilon_{ij}}{N_{ij} \varepsilon_i \varepsilon_j} \]

**Key points:**

\( \mathcal{B} \) independent of \( N_{\text{DD}} \) (usual Achilles’ heel)

\( \varepsilon_j / \varepsilon_{ij} \sim \varepsilon_i \): \( \sim \) independent of tag \( j \)

**Systematics:**

-- *Study efficiencies with tag data*
CLEO-c semileptonic tagging analysis technique: big impact

1\textsuperscript{st} Observations:

- $D^0 \rightarrow \rho^- e^+ \nu_e$
- $D^+ \rightarrow \eta e^+ \nu_e$
- $D^+ \rightarrow \omega e^+ \nu_e$
- $D^0 \rightarrow K^- \pi^+ \pi^- e^+ \nu_e$
- $D^+ / D^0 \rightarrow X e^+ \nu_e$
- $D \rightarrow K^* e^+ \nu_e$

Form factors

- $D \rightarrow K / \pi e^+ \nu_e$

BFs 56/pb

References:
- PRL 95, 181801 (2005)
- PRL 95, 181802 (2005)
- PRL. 99, 191801 (2007)

Precision Measurements:

- $D^0 \rightarrow \pi^0 e^+ \nu$
- $D^0 \rightarrow K^- e^+ \nu$
- $D^0 \rightarrow K^- (K^0 \pi^0) e^+ \nu$
- $D^0 \rightarrow K^- (K_S^0 \pi^0) e^+ \nu$
- $D^0 \rightarrow \rho^- e^+ \nu$
- $D^0 \rightarrow K(1270)^- e^+ \nu$
- $D^0 \rightarrow X e^+ \nu$
- $D^+ \rightarrow \pi^0 e^+ \nu$
- $D^+ \rightarrow K^0 e^+ \nu$
- $D^+ \rightarrow K(1270)^- e^+ \nu$
- $D^+ \rightarrow X e^+ \nu$
- $D^+ \rightarrow \pi^0 e^+ \nu$
- $D^+ \rightarrow K^0 e^+ \nu$
- $D^+ \rightarrow \eta e^+ \nu$

Normalized to PDG

$D \rightarrow K / \pi e^+ \nu$ branching fractions are for 56/pb

CLEO’s measurements most precise for ALL modes; \textit{4 modes} observed for the first time
Neutrino “reconstruction” technique
Tagged with \( D^* \rightarrow D^0 p \pi^- \)

**Very large signal statistics.**

**Compared to CLEO-c results:**
- Factor \( \sim 300 \) more luminosity
- Factor \( \sim 5 \) more signal events
- Normalization to \( \text{BR}(D^0 \rightarrow K^- \pi^+) \) [determined by CLEO-c]
- Poor \( q^2 \) resolution (unfolding needed for form factor measurements)
- Much worse signal/noise (method not suitable for Cabibbo suppressed decays)
Interference in $K_L \pi, K_S \pi$

Decay diagrams source both $K^0$ and $K^0\bar{\text{b}}$ar
⇒ These interfere in physical $K_L$, $K_S$ final states: $K_S$, $K_L$ asymmetry

$$R(D) = \frac{B(D \Rightarrow K_S\pi) - B(D \Rightarrow K_L\pi)}{B(D \Rightarrow K_S\pi) + B(D \Rightarrow K_L\pi)}$$


$D^0$: expect BF asymmetry of: $R(D^0) = 2 \tan^2 \theta_C \sim 10$

$D^+:$ more diagrams to consider... $R(D^+)$ see next page...

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$$\bar{K}^0 = \frac{1}{\sqrt{2}} (K_S^0 - K_L^0)$$

$$K^0 = \frac{1}{\sqrt{2}} (K_S^0 + K_L^0)$$
Interference in $K_L \pi$, $K_S \pi$

**D^0:** $R_{D} = 0.108 \pm 0.025 \pm 0.024$
(consistent with $2 \tan^2 \theta_C$)

**D^+:** $R_{D} = 0.022 \pm 0.016 \pm 0.018$

Dao-Neng Gao predicts:
$R(D^+) = 0.035$ to $0.044$
( arXiv:hep-ph/0610389v2 )

J. Rosner, CHARM2007:
$R(D^+) = 0.067 \pm 0.007$