Leptonic D/D_s decays and decay constants

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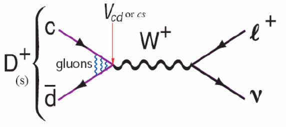
Heavy Quarks and Leptons 2010

Introduction

- Leptonic decays: $D^+_{(s)} \to \ell^+\nu$, $\ell = e, \mu, \tau$
- In SM these decays proceed via tree diagram:



- Decay rate:

$$\Gamma(D^+_{(s)} \to \ell^+\nu) = \frac{G_F^2}{8\pi} f^2_{D^+_{(s)}} m_\ell^2 M_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{M^2_{D^+_{(s)}}}\right)^2 |V_{cd(cs)}|^2$$

- SM branching fraction ratio:

$$e : \mu : \tau = 2.35\times10^{-5} : 1 : 2.65\ (9.76)$$

- $f_{D^+_{(s)}}$(decay constant): overlap of heavy and light-quark wave-functions
- Aim of measurements: precision test of non-pert. QCD techniques

Recent measurements

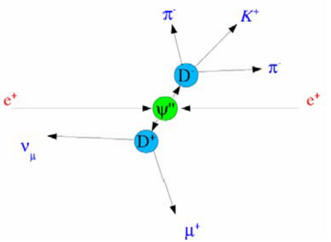
- CLEO-c
  - $D^+ \to \mu^+\nu$ PRD 78, 052003 (2008)
  - $D_s^+ \to \mu^+\nu$ PRD 79, 052001 (2009)
  - $D_s^+ \to \tau^+\nu$, $\tau^+ \to \pi^+\nu$ PRD 79, 052001 (2009)
  - $D_s^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$ PRD 79, 052002 (2009)
  - $D_s^+ \to \tau^+\nu$, $\tau^+ \to \rho^+\nu$ PRD 80, 112004 (2009)
- Belle
  - $D_s^+ \to \mu^+\nu$ PRL 100, 241801 (2008)
- BaBar
  - $D_s^+ \to \mu^+\nu$ arXiv:1008.4080 (2010)
  - $D_s^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$ arXiv:1008.4080 (2010)
  - $D_s^+ \to \tau^+\nu$, $\tau^+ \to \mu^+\nu\nu$ arXiv:1008.4080 (2010)

Measurement techniques

- CLEO-c: use $e^+e^- \to D^+D^-$ at $\psi(3770)$
  or $e^+e^- \to D_s D_s^*$ at 4170 MeV
- Belle & BaBar: $e^+e^- \to c\bar{c}$ at $\Upsilon(4S)$

Common to all analyzes:

- Fully reconstruct one D as “the tag”
- then analyze decay of second D to extract exclusive or inclusive properties
- high tagging efficiency $\sim 20\%$

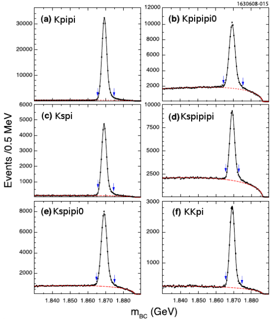


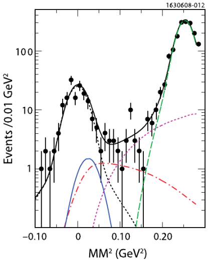
CLEO-c: $D^+ \to \mu^+\nu$ (818 pb^{-1})

PRD 78, 052003 (2008)

Measurement:

- Use $e^+e^- \to D^+D^-$ at $\psi(3770)$
- Pure DD, no additional particles
- Tag side:
  - reconstructed in six decay modes
  - tagging efficiency 22%
  - in total 460 000 signal tags
- Signal side:
  - single extra track of opposite charge to the tag and with $E_{\rm cal} < 300$ MeV (minimum ionizing)
  - missing mass near zero (neutrino)
  - find 149.7 ± 12.0 $\mu\nu$ signal events (fixed τ/μ) or 153.9 ± 13.5 $\mu\nu$ and 13.5 ± 15.3 $\tau\nu$
  - backgrounds: $\tau^+\nu$, $\pi^0\pi^+$, $\overline{K}^0\pi^+$, other





CLEO-c: $D^+ \to \mu^+\nu$ (818 pb^{-1})

Results:

- Assuming the SM ratio for $\tau^+\nu/\mu^+\nu$:

$$\mathcal{B}(D^+ \to \mu^+\nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$$

$$f_{D^+} = (205.8 \pm 8.5 \pm 2.5)\mathrm{MeV}$$

- Floating $\tau^+\nu/\mu^+\nu$ ratio:

$$\mathcal{B}(D^+ \to \mu^+\nu) = (3.93 \pm 0.35 \pm 0.09) \times 10^{-4}$$

$$f_{D^+} = (207.6 \pm 9.3 \pm 2.5)\mathrm{MeV}$$

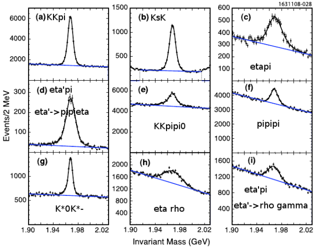
- Unquenched Lattice QCD calculations in good agreement:
  - $f_{D^+} = (207 \pm 4)\mathrm{MeV}$ E. Follana et al., PRL 100, 062002 (2008)
  - $f_{D^+} = (207 \pm 11)\mathrm{MeV}$ C. Aubin et al., PRL 95, 122002 (2005)

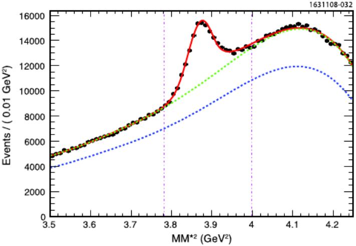
CLEO-c: $D_s^+ \to \mu^+\nu$ & $D_s^+ \to \tau^+\nu(\to \pi^+\nu\nu)$ (600 pb^{-1})

PRD 79, 052001 (2009)

Measurement:

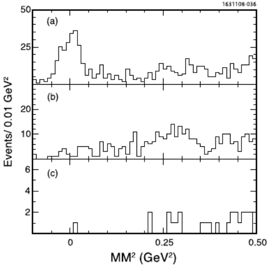
- Use $e^+e^- \to D_s^+ D_s^{*-}$, $D_s^{*-} \to \gamma D_s^-$ at 4170 MeV
- Tag side:
  - Fully reconstruct $D_s\gamma$ to look for another D_s
  - D_s reconstructed in nine decay modes
  - tags selected in missing mass recoiling against $D_s\gamma$
    $\longrightarrow$ for $D_s D_s^*$ events this always peaks at M_{D_s}
  - in total 44 000 signal tags found in missing mass spectrum

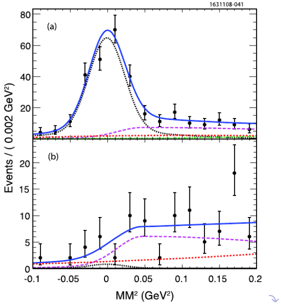




CLEO-c: $D_s^+ \to \mu^+\nu$ & $D_s^+ \to \tau^+\nu(\to \pi^+\nu\nu)$ (600 pb^{-1})

- Signal side:
  - single extra track with opposite charge to tag, not being identified as electron or kaon, with
    (a) $E_{\rm cal} < 300$ MeV (99% μ, 55% π) or
    (b) $E_{\rm cal} > 300$ MeV (1% μ, 45% π)
  - 2D fit to D_s-tag mass and missing mass to extract signal yields
  - cases (a) and (b) fitted simultaneously
  - find 235.5 ± 13.8 $\mu\nu$ events
    and 125.6 ± 15.7 $\tau\nu(\tau \to \pi\nu)$ events
  - backgrounds: about 10 events in total
    $\tau^+ \to \pi^+\pi^0\nu, \mu^+\nu\nu,$
    $D_s^+ \to \pi^+\pi^0\pi^0, K^0\pi^+, \eta\pi^+,$





CLEO-c: $D_s^+ \to \mu^+\nu$ & $D_s^+ \to \tau^+\nu(\to \pi^+\nu\nu)$ (600 pb^{-1})

Results:

- Fix $\tau\nu/\mu\nu$ ratio at SM prediction :

$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.591 \pm 0.037 \pm 0.018)\%$$

- Float $\tau\nu/\mu\nu$ ratio:

$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.565 \pm 0.045 \pm 0.017)\%$$

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (6.42 \pm 0.81 \pm 0.18)\%$$

- Ratio is consistent with SM prediction of 9.76:

$$R \equiv \frac{\Gamma(D_s^+ \to \tau^+\nu)}{\Gamma(D_s^+ \to \mu^+\nu)} = 11.4 \pm 1.7 \pm 0.2$$

- Decay constant:

$$f_{D_s^+} = (257.6 \pm 10.3 \pm 4.3)\mathrm{MeV} \qquad (\mu^+\nu)$$

$$f_{D_s^+} = (278.0 \pm 17.5 \pm 4.4)\mathrm{MeV} \qquad (\tau^+\nu)$$

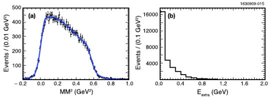
CLEO-c: $D_s^+ \to \tau^+\nu$, $\tau^+ \to \rho^+\nu$ (600 pb^{-1})

PRD 80, 112004 (2009)

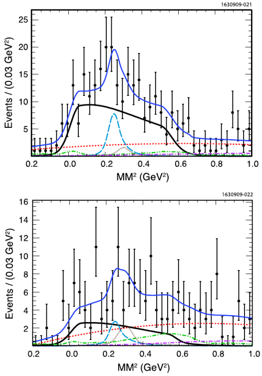
Measurement:

- $e^+e^- \to D_s^+ D_s^{*-}$, $D_s^{*-} \to \gamma D_s^-$ at 4170 MeV
- Tag side: same as for $D_s^+ \to \mu^+\nu$
- Signal side:
    - event with exactly one charged pion forming $\rho^+ \to \pi^+\pi^0$
    - use missing mass (not peaking at zero!) and extra energy in the calorimeter ($E_{\rm extra}$)
    - subtract combinatorial bkg. using D_s-tag sidebands; use known branching fractions and MC shapes to model other backgrounds
    - fit MM^2 distribution in the first two $E_{\rm extra}$ bins
    - signal yields:
      155.2 ± 16.5, $E_{\rm extra} < 0.1$ GeV
      43.7 ± 11.3, $0.1 < E_{\rm extra} < 0.2$ GeV

signal MC



data



CLEO-c: $D_s^+ \to \tau^+\nu$, $\tau^+ \to \rho^+\nu$ (600 pb^{-1})

Results:

- Branching fraction:

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.52 \pm 0.57 \pm 0.21)\%$$

- Consistent with their measurement in $\tau^+ \to \pi^+\nu$ mode
  $(\mathcal{B}(D_s^+ \to \tau^+\nu) = (6.42 \pm 0.81 \pm 0.18)\%)$
- Decay constant:

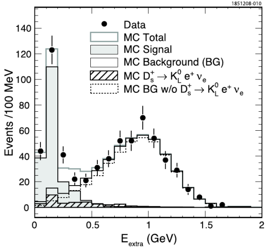
$$f_{D_s^+} = (257.8 \pm 13.3 \pm 5.2)\mathrm{MeV}$$

CLEO-c: $D_s^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$ (600 pb^{-1})

Measurement:

PRD 79, 052002 (2009)

- $e^+e^- \to D_s^+ D_s^{*-}$, $D_s^{*-} \to \gamma D_s^-$ at 4170 MeV
- Tag side:
  - similar to $D_s^+ \to \mu^+\nu$
  - only cleanest modes used ($D_s^- \to \phi\pi^-$, $D_s^- \to K^-K^{*0}$, $D_s^- \to K^-K_s^0$)
- Signal side:
  - event with exactly one electron
  - use $E_{\mathrm{extra}} < 400$ MeV
  - subtract combinatorial bkg. using D_s-tag sdb.
  - estimate $D_s^+ \to K_L^0 e^+\nu$ peaking bkg. from MC
  - E_{extra} sideband to estim. D_s semileptonic bgk.
  - signal yield: 180.6 ± 15.9



Results:

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.30 \pm 0.47 \pm 0.22)\%, \qquad f_{D_s^+} = (252.5 \pm 11.1 \pm 5.2)\mathrm{MeV}$$

CLEO-c: summary

PRD 80, 112004 (2009)

TABLE IV: Recent absolute measurements of f_{D_s} from CLEO-c

Experiment	Mode	$\mathcal{B}$ (%)	f_{D_s} (MeV)
This result	$\tau^+\nu$ $(\rho^+\overline{\nu})$	$(5.52 \pm 0.57 \pm 0.21)$	$257.8 \pm 13.3 \pm 5.2$
CLEO-c [9]	$\tau^+\nu$, $(\pi^+\overline{\nu})$	$(6.42 \pm 0.81 \pm 0.18)$	$278.0 \pm 17.5 \pm 4.4$
CLEO-c [16]	$\tau^+\nu$ $(e^+\nu\overline{\nu})$	$(5.30 \pm 0.47 \pm 0.22)$	$252.6 \pm 11.2 \pm 5.6$
Average	$\tau^+\nu$	$(5.58 \pm 0.33 \pm 0.13)$	$259.7 \pm 7.8 \pm 3.4$
CLEO-c [9]	$\mu^+\nu$	$(0.565 \pm 0.045 \pm 0.017)$	$257.6 \pm 10.3 \pm 4.3$
Average	$\tau^+\nu$+$\mu^+\nu$		$259.0 \pm 6.2 \pm 3.0$

- CLEO-c average:

$$f_{D_s^+} = (259.0 \pm 6.2 \pm 3.0)\mathrm{MeV}$$

- Ratio consistent with lepton universality:

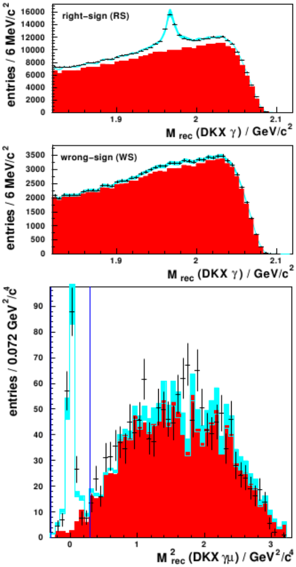
$$\frac{f_{D_s^+}(D_s^+ \to \tau^+\nu)}{f_{D_s^+}(D_s^+ \to \mu^+\nu)} = 1.01 \pm 0.05$$

Belle: $D_s^+ \to \mu^+\nu$ (548 fb^{-1})

PRL 100, 241801 (2008)

Measurement:

- $e^+e^- \to c\bar{c}$ at $\Upsilon(4S)$
  - use events of the type: $D^{\pm,0}K^{\pm,0}XD_s^{*+}$
  - $X = n\pi$ or $X = n\pi\ \gamma$ (fragmentation)
- Tag side:
  - consists of D and K
  - D reconstructed in $D \to Kn\pi,\ n = 1, 2, 3$ (total $\mathcal{B} \approx 25\%$)
- Signal side:
  - consists of $D_s^{*+} \to D_s^+\gamma$
- Use recoil mass:
  - against $DKX\gamma$ counts total D_s
  - against $DKX\gamma\mu$ counts $D_s \to \mu\nu$



Belle: $D_s^+ \to \mu^+\nu$ (548 fb^{-1})

Results:

- Branching fraction:

$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.644 \pm 0.076 \pm 0.057)\%$$

- Consistent with CLEO
- Decay constant:

$$f_{D_s^+} = (275 \pm 16 \pm 12)\mathrm{MeV}$$

BaBar: $D_s^+ \to \mu^+\nu$ & $D_s^+ \to \tau^+\nu$ (521 fb^{-1})

arXiv:1003.3063 (2010)

- Most recent measurement, not yet published
- Same method as Belle
- Measure also $D_s^+ \to \tau^+\nu$ in $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$
  - yields in this case extracted from $E_{\rm extra}$

Results:

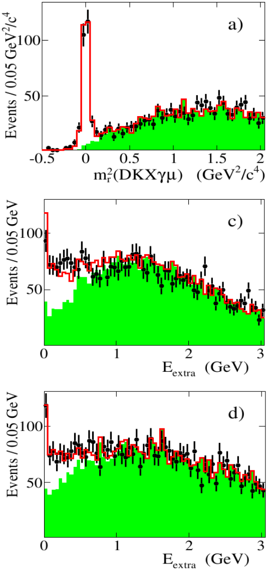
- Branching fractions:

$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.602 \pm 0.038 \pm 0.034)\%$$

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.07 \pm 0.52 \pm 0.68)\%$$

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (4.91 \pm 0.47 \pm 0.54)\%$$

- Consistent with CLEO and Belle



Results:

- Decay constant:

$$f_{D_s^+} = (265.7 \pm 8.4 \pm 7.7)\mathrm{MeV} \quad (\mu\nu)$$

$$f_{D_s^+} = (247 \pm 13 \pm 17)\mathrm{MeV} \quad (\tau_{e\nu\nu}\nu)$$

$$f_{D_s^+} = (243 \pm 12 \pm 14)\mathrm{MeV} \quad (\tau_{\mu\nu\nu}\nu)$$

- Error-weighted average:

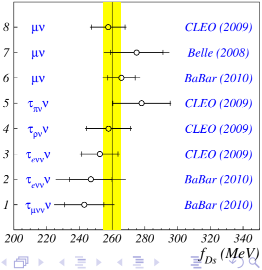
$$f_{D_s^+} = (258.6 \pm 6.4 \pm 7.5)\mathrm{MeV}$$

- CLEO-c average: $f_{D_s^+} = (259.0 \pm 6.2 \pm 3.0)\mathrm{MeV}$

Summary of $f_{D_s^+}$ measurements

mode	CLEO-c	Belle	BaBar
$\mu^+\nu$	$257.6 \pm 10.3 \pm 4.3$	$275 \pm 16 \pm 12$	$265.7 \pm 8.4 \pm 7.7$
$\tau^+_{\pi\nu}\nu$	$278.0 \pm 17.5 \pm 4.4$		
$\tau^+_{\rho\nu}\nu$	$257.8 \pm 13.3 \pm 5.2$		
$\tau^+_{e\nu\nu}\nu$	$252.6 \pm 11.2 \pm 5.6$		$247 \pm 13 \pm 17$
$\tau^+_{\mu\nu\nu}\nu$			$243 \pm 12 \pm 14$
average	$259.0 \pm 6.2 \pm 3.0$	$275 \pm 16 \pm 12$	$258.6 \pm 6.4 \pm 7.5$

- Naive average CLEO+Belle+BaBar: $f_{D_s^+} = (260.1 \pm 5.4)$ MeV
- HFAG average (for FPCP10 - latest BaBar results not included): $f_{D_s^+} = (254.6 \pm 5.9)$ MeV



Comparison with Lattice QCD

- Most precise unquenched Lattice QCD calculations (by HPQCD):
  - $f_{D_s^+} = 241 \pm 3$ MeV E. Follana et al., PRL 100, 062002 (2008)
  - $f_{D_s^+} = 248.0 \pm 2.5$ MeV C.T.H. Davies et al., arXiv:1008.4018 (2010)
- Measurements:
  - $f_{D_s^+} = 254.6 \pm 5.9$ MeV [HFAG average with old BaBar results]
  - $f_{D_s^+} = 260.1 \pm 5.4$ MeV [my naive average with new BaBar results]
- New HPQCD result in good agreement with recent HFAG average ($\sim 1\sigma$ away); the agreement with my naive average is at 2σ.

Conclusions

- LQCD/experiment discrepancy caused some excitement when first HPQCD result became available;
- since then several new measurements, experimental error significantly decreased;
- but also new value from HPQCD, higher than previous;
- at the moment no significant discrepancy;
- need further LQCD results to confirm the most precise determination up to date;
- need BES III results to improve the experimental precision.