Leptonic Decays of *D* Mesons & Measurement of Pseudoscalar Form Factors

Sadia Khalil, Syracuse University, Syracuse, NY (On behalf of CLEO Collaboration).

Abstract

Using the CLEO-c detector at the CESR collider, we measure the branching ratio of the purely leptonic decay of D^+ and D^+_s mesons to be $\mathcal{B}(D^+\to\mu^+\nu) = (3.82 \pm 0.32 \pm 0.09)\times 10^{-4}$, $\mathcal{B}(D_s^+\to\mu^+\nu) = (0.591 \pm 0.037 \pm 0.018)\%$ and $\mathcal{B}(D_s^+\to\tau^+\nu) = (0.591 \pm 0.037 \pm 0.018)\%$, using 818 pb^{-1} and 600 pb^{-1} of data taken on the $\psi(3770)$ and $\psi(4170)$, respectively. Furthermore, we find $\mathcal{B}_{eff}(D^+_s\to\mu^+\nu) = (0.565 \pm 0.045 \pm 0.017)\%$ when we average results for $\tau^+\to\pi^+\nu$, and $\tau^+\to e^+\nu_e\nu_\tau$. We obtain the decay constants f_{D^+} and $f_{D_s^+}$, using these results, combined with precise measurement of D^+ and D_s^+ lifetimes and assumptions that $|V_{cd}| = |V_{us}|$ and $|V_{cs}| = |V_{ud}|$. We find $f_{D^+} = (207.6 \pm 9.3 \pm 2.5)$ MeV, $f_{D_s^+} = (259.5 \pm 6.6 \pm 3.1)$ MeV and $f_{D_s^+}/f_{D^+} = 1.26 \pm 0.06 \pm 0.02$. The value of $f_{D_s^+}$ is obtained by combining the results of a simultaneous Standard-Model fit to the two D_s^+ channels, $\mu^+\nu$ and $\tau^+\nu$, $\tau^+\to\pi^+\nu$, with an independent measurement of $D^+_s\to\tau^+\nu$, $\tau^+\to e^+\nu_e\nu_\tau$ decays. No evidence is found for a CP asymmetry between $\Gamma(D^-\to\mu^+\nu)$, $\Gamma(D_s^+\to\mu^+\nu)$ and $\Gamma(D_s^+\to\tau^+\nu)$, specifically the fractional difference in rates is measured to be 0.08±0.08 (4.8±6.1%) for D^+ (D_s^+) mesons. We also set 90% confidence level upper limits on $\mathcal{B}(D^+\to\tau^+\nu) < 1.2\times 10^{-3}$, $\mathcal{B}(D^+\to e^+\nu) < 8.8\times 10^{-6}$ and $\mathcal{B}(D_s^+\to e^+\nu) < 1.2\times 10^{-4}$.

1-Introduction

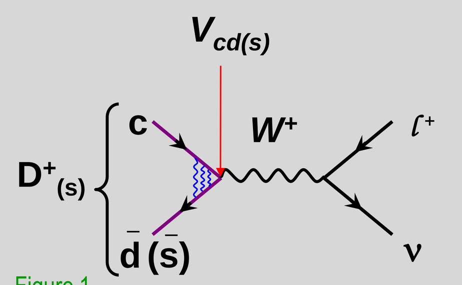

Figure 1

Purely leptonic decays of heavy mesons involve both weak and strong interactions. The weak part is easy to describe as the annihilation of the quark antiquark pair via the Standard Model (SM) W^+ boson. The strong interactions arise due to gluon exchanges between the charm (strange) quark and the light anti-quark. These are parameterized in terms of the "*decay constants*" for the D^+ and D_s^+ mesons as f_{D^+} and $f_{D_s^+}$. The decay rates are given by

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

and we use $|V_{cd}| = |V_{us}| = 0.2256$ and $|V_{cs}| = |V_{ud}| = 0.97418(26)$. The SM decay rates are predicted using Lattice QCD (LQCD) theoretical calculations of the decay constants. Meson decay constants in the *B* system are used to translate measurements of $B\bar B$ mixing to CKM matrix elements. If LQCD calculations disagree with the measured values of the decay constants for *D* mesons, they may be questionable on *B* mesons. If, on the other hand new physics is present, it is imperative to understand how it affects SM-based predictions of the *B* decay constants.

2-Data Sample and CLEO-c detector

In these studies we use 818 pb^{-1} and 600 pb^{-1} of CLEO-c data collected from e^+e^- collisions at the $\psi(3770)$ and $\psi(4170)$ resonances respectively. The CLEO-c detector is equipped to measure the momenta and directions of charged particles, identify charged hadrons, detect photons, and determine their directions and energies with good precision.

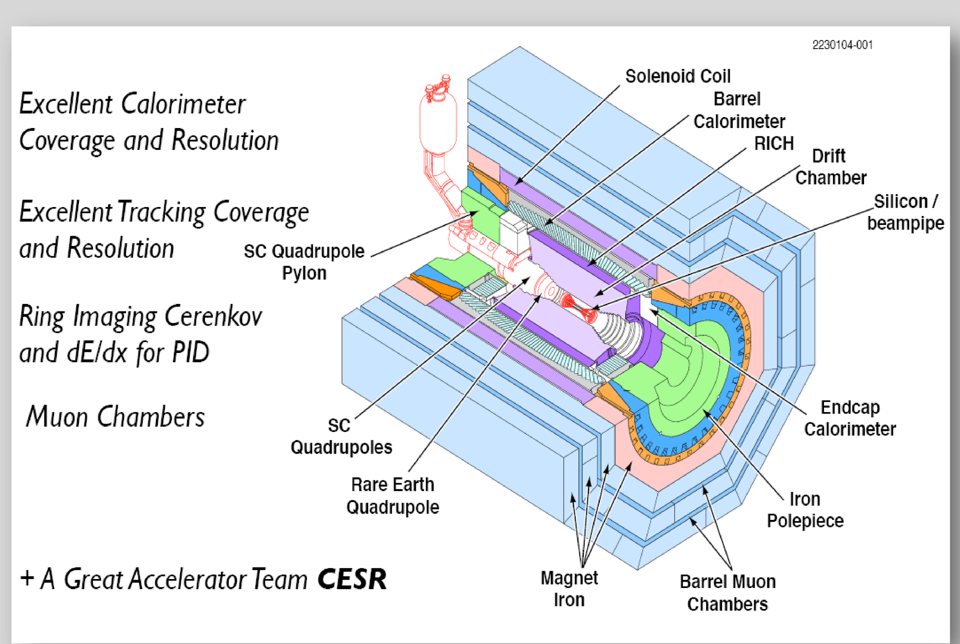

Figure 2

At the $\psi(3770)$ resonance, only $D\bar D$ pairs are produced, where *D* represents D^0 or D^+. At the $\psi(4170)$ resonance, $D\bar D^*$, $D^*\bar D^*$, $D\bar D$ are produced, where *D* is D^0 or D^+ or D_s. The largest D_s channel is $D_s\bar D_s^*$ which we use to study D_s leptonic decays.

3-Analysis techniques for $D^+\to\mu^+\nu$

We tag one D^- decay and search for our signal in the other D^+ decay. Tagging modes are fully reconstructed by first evaluating ΔE, the difference in the energy of the decay products and the beam energy.

For the selected events we then view the reconstructed D^- beam-constrained mass defined as

$$m_{BC} = \sqrt{E^2_{beam} - (\sum_i \vec p_i)^2}$$

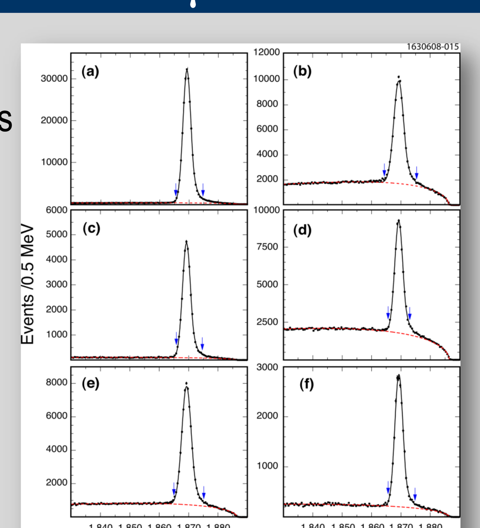
Figure 3

This sample includes 460,055 ± 787 ± 2,760 signal events and 89,472 background events.

4-$D^+\to\mu^+\nu$ Selection Criteria and Fits to the Data

Using our sample of D^- event candidates we search for events with a single additional charged track presumed to be a μ^+. Then we infer the existence of the neutrino by requiring a measured value of the missing mass (MM^2) near zero (the neutrino mass), where

$$MM^2 = (E_{D^+} - E_{\ell^+})^2 - (\vec p_{D^+} - \vec p_{\ell^+})^2,$$

Here $\vec P_{D^+}$ is the three-momentum of the fully reconstructed D^+, and E_{l+} is the energy (momentum) of the candidate μ^+.
As muons deposit less than 300 MeV of energy in the calorimeter 98.8% of the time, we define two cases, where
- case (i) refers to muon candidate tracks that deposit < 300 MeV (muons deposit less than 300 MeV, while hadrons often interact and deposit significantly more energy) and
- case (ii) is for candidates depositing > 300 MeV., which we use to check the background estimation.

We evaluate backgrounds comprising of $\bar K^0\pi^+$ peak in MM^2 spectrum near 0.25 GeV^2, $\pi^+\pi^0$ laying within the $\mu^+\nu$ signal region, $\tau^+\nu$, where $\tau^+\to\pi^+\nu$ and other τ^+ decay modes as $\rho^+\bar\nu$, $\mu^+\nu\bar\nu$, $\rho^+\pi^0$ and $\pi^0\mu^+\nu$ forming a cocktail. We obtain the line shape of $K^0\pi^+$ fit from $D^0\to K^-\pi^+$ and rest from MC. We also evaluate backgrounds from D^0 modes and continuum, which sums to 2.4 ± 1.0 events. Then we fit the data to obtain signal events, first by keeping the $\tau^+\nu/\mu^+\nu$ ratio fixed to SM ratio and then floated.

Case (i)

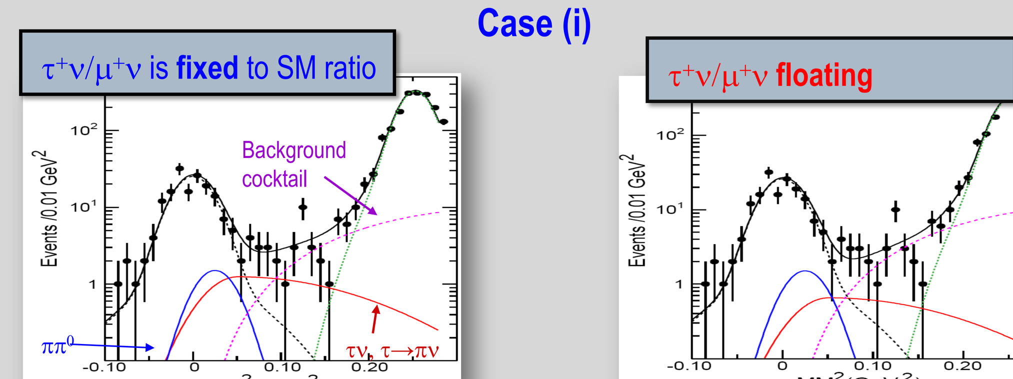

Figure 4

Fixed	Floating
149.7±12.0 $\mu^+\nu$ events	153.9±13.5 $\mu^+\nu$ events
25.8 $\tau^+\nu$ events	13.5±15.3 $\tau^+\nu$ events

5-Branching fraction and decay constant

The branching fraction determined by *fixing* the $\tau^+\nu$ contribution relative to the $\mu^+\nu$ contribution to the SM ratio is $\mathcal{B}(D^+\to\mu^+\nu) = (3.82\pm0.32\pm0.09)\times10^{-4}$.
The decay constant f_{D^+} is then obtained using 1040±7 fs as the D^+ lifetime and 0.2256 as $|V_{cd}|$. Our final result is $f_{D^+} = (205.8\pm8.5\pm2.5)$ MeV.

A somewhat less precise value is obtained by *floating* the $\tau^+\nu$ to $\mu^+\nu$ ratio. That fit gives $\mathcal{B}(D^+\to\mu^+\nu) = (3.93\pm0.35\pm0.10)\times10^{-4}$
The corresponding value of the decay constant is
$f_{D^+} = (207.6\pm9.3\pm2.5)$ MeV [radiatively corrected]

6-Search for $D^+\to\tau^+\nu$ and $D^+\to e^+\nu$

We fit both case(i) & case(ii) constraining the relative $\tau^+\nu$ yield to the pion acceptance in calorimeter = 55/45. The fit yields a sum of 27.8 ± 16.4 $\tau^+\nu$, $\tau^+\to\pi^+\bar\nu$ event. We find that
$\mathcal{B}(D^+\to\tau^+\nu) < 1.2\times10^{-3}$, @ 90% c.l.,

The SM ratio of $\tau^+\nu$ to $\mu^+\nu$ is 2.65. We find
$\mathcal{B}(D^+\to\tau^+\nu)/2.65\mathcal{B}(D^+\to\mu^+\nu) < 1.2$ @ 90% c. l.

For $e^+\nu$, we do not find any candidates allowing us to set an limit
$\mathcal{B}(D^+\to e^+\nu) < 8.8\times10^{-6}$, @ 90% c.l.

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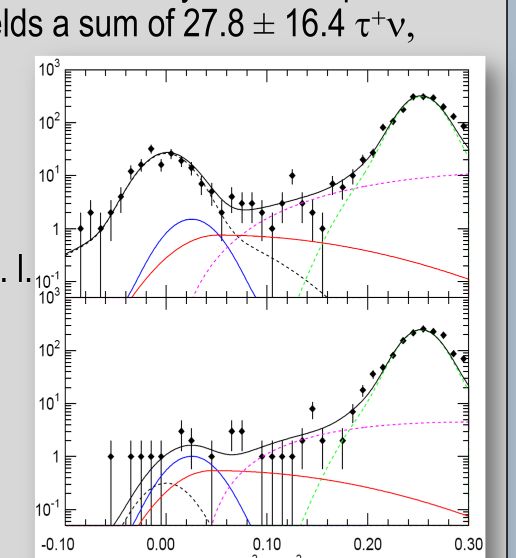


Figure 5

7- Analysis Technique for $D^+_s\to\ell^+\nu$ ($\ell^+ = \mu^+, \tau^+(\tau^+\to\pi^+\bar\nu)$)

We tag D_s^- decay either produced directly or from $D_s^{*-}\to\gamma D_s^-$ and search for the signal in the other D_s^+. Tagging modes are fully reconstructed by first constraining 2.015 < m_{BC} < 2.067 GeV and then examining invariant mass (M_{D_s}). In order to detect the photon from D_s^*, we look for MM^{*2}, defined as

$$MM^{*2} = (E_{CM} - E_{D_s} - E_\gamma)^2 - (\vec p_{CM} - \vec p_{D_s} - \vec p_\gamma)^2,$$

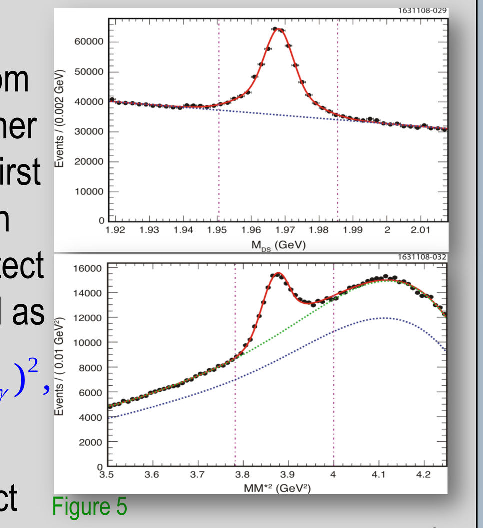


Figure 5

recoiling against the photon and the D_s^- tag should peak at the D_s^+ mass-squared. To extract tags, we perform a two-dimensional binned maximum likelihood fit of the MM^{*2} and M_{D_s} distributions in the intervals of 3.5 < MM^{*2} < 4.25 GeV^2 and ± 60 MeV from M_{D_s} respectively. We find a total of 43859±936 tag events within the intervals 3.872 < MM^{*2} < 4.0 GeV^2 and ±17.5 MeV from M_{D_s}.

8-Signal Reconstruction of $D^+_s\to\ell^+\nu$

Using the selected D_s^- sample from the MM^{*2} region, we search for events with a single additional charged track presumed to be a μ^+, requiring that it makes an angle >25.8° with the beam axis. We require no extra tracks or showers above 300 MeV. With kinematic constraints, we compute MM^2, defined as

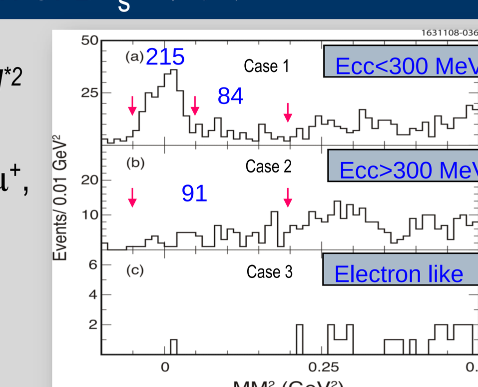
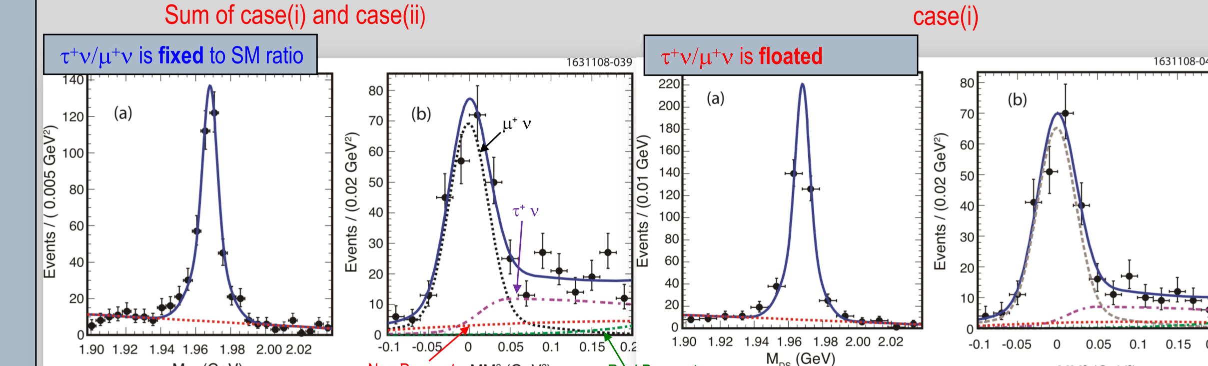


Figure 6

$$MM^2 = (E_{CM} - E_{D_s} - E_\gamma - E_\mu)^2 - (\vec p_{CM} - \vec p_{D_s} - \vec p_\gamma - \vec p_\mu)^2,$$

We perform a two-dimensional unbinned maximum likelihood fit to the sum of the MM^2 distributions for case (i) and case (ii). The other dimension in the fit is the invariant mass spectrum.

Sum of case(i) and case(ii) — case(i)



Fixed	Floated
235.5 ± 13.8 $\mu^+\nu$ events	221.8 ± 17.1 $\mu^+\nu$ events
113.4 $\tau^+\nu$ events	67.5 ± 12.6 $\tau^+\nu$ events

Simultaneous Fit
125.6 ± 15.7 $\tau^+\nu$ events
Fix $\mu\nu$ area in $\frac{\text{case(i)}}{\text{case(ii)}} = \frac{98.8}{1.2}$
Fix $\tau\nu$ area in $\frac{\text{case(i)}}{\text{case(ii)}} = \frac{55}{45}$

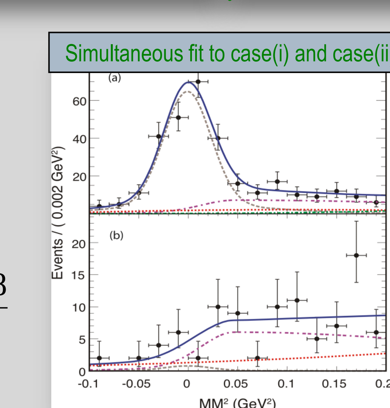


Figure 7

9-Branching fraction and decay constant

The branching fraction determined from the fit to sum of case 1 and case 2 by *fixing* the $\tau^+\nu$ contribution relative to the $\mu^+\nu$ is
$\mathcal{B}^{eff}(D^+_s\to\mu^+\nu) = (0.591 \pm 0.037 \pm 0.017)\%$ [1% radiatively corrected]
$f_{D_s^+} = (263.3 \pm 8.2 \pm 3.7)$ MeV

The branching fraction determined from *simultaneous fit* to case 1 and case 2 without SM assumption is
$\mathcal{B}(D_s\to\mu\nu) = (0.565 \pm 0.045 \pm 0.016)\%$ [radiatively corrected]
$f_{D_s^+} = (257.3\pm 10.3 \pm 3.6)$ MeV
$\mathcal{B}(D_s\to\tau\nu) = (6.42 \pm 0.81 \pm 0.18)\%$
$f_{D_s^+} = (278.7\pm 17.1 \pm 3.8)$ MeV
R = 11.4 ± 1.7 ± 0.2 [SM value 9.72]

The 90%C.L upper limit on the branching fraction of $D^+_s\to e^+\nu$ is
PRD 79, 052001 (2009) $\mathcal{B}(D^+_s\to e^+\nu) < 1.2\times10^{-4}$

10-Analysis Technique for $D^+_s\to\tau^+\nu$ ($\tau^+\to e^+\nu\bar\nu$)

We reconstruct one D_s to tag the events with a D_s single tag (ST). We identify a single tag (ST) by using the invariant mass (M_{Ds}) and recoil mass, $M_{recoil(Ds)}$ against the tag. The $M_{recoil(Ds)}$ is defined as

$$M_{recoil(D_s)} = \sqrt{(E_{ee} - E_{D_s})^2 - |\vec p_{ee} - \vec p_{D_s}|^2}$$

and is required to be within 55 MeV of the D^+_s mass. To estimate the tags and backgrounds due to the wrong tag combinations, we use the tag M_{Ds} sidebands. The signal and side band regions are defined as
−20 MeV < ΔM_{Ds} < +20 MeV and −55 MeV < ΔM_{Ds} < −35 MeV or +35 MeV < ΔM_{Ds} < +55 MeV, respectively, where $\Delta M_{Ds} \equiv M_{Ds} - m_{Ds}$. We find a scaled sideband subtracted yield equal to 26334 ± 213 STs.

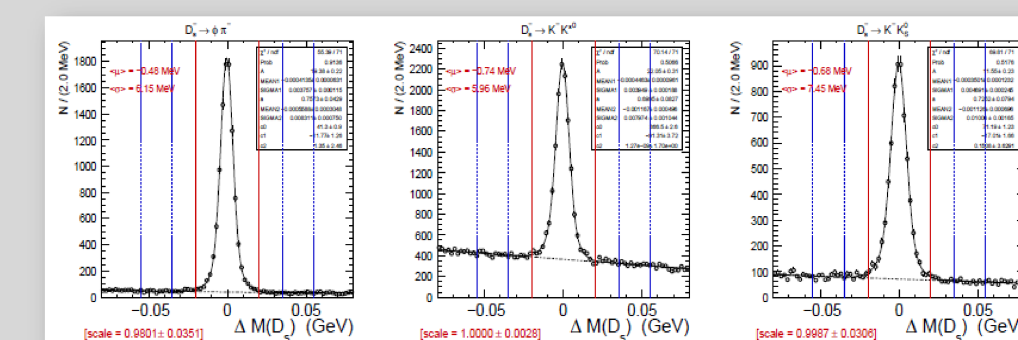


Figure 8

11-Signal Reconstruction of $D^+_s\to\tau^+\nu$

Using the ST sample, we search for events with a single additional charged track, presumed to be a e^+ with momentum of at least 200 MeV. We then find neutral clusters in the calorimeter that are not matched with the ST tracks or e^+ candidate and that are consistent with being photons above 30 MeV. We then study the total energy E_{extra} of these clusters and ΔM_{Ds} sideband regions. The signal and sideband regions are chosen to be E_{extra}< 400 MeV and 600 MeV < E_{extra} < 2 GeV respectively. The contributions of several backgrounds in these regions is estimated using Monte Carlo simulations. The signal region yields, 80.6±15.9 events after background subtraction.

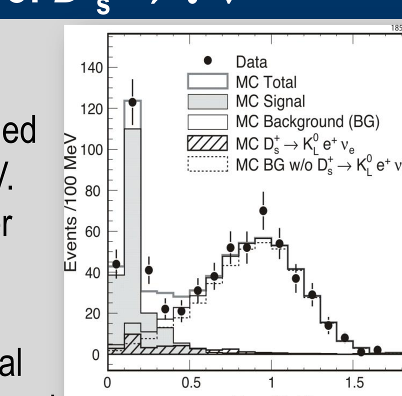


Figure 9

12-Branching fraction and decay constant

The branching fraction and decay constant are determined to be
$\mathcal{B}(D_s\to\tau\nu) = (5.30 \pm 0.47 \pm 0.22)\%$
$f_{D_s^+} = (252.5\pm 11.1 \pm 5.2)$ MeV

Combining this result of $f_{D_s^+}$ with our result for $f_{D_s^+}$ from the $\mu^+\nu$ plus $\tau^+\nu$ analysis with the SM constraint, we find
$\mathcal{B}(D_s\to\tau\nu) = (5.62 \pm 0.41 \pm 0.16)\%$
$f_{D_s^+} = (259.5\pm 6.6 \pm 3.1)$ MeV

Using the f_{D^+} calculation from $D^+\to\mu^+\nu$ analysis, we find
$f_{D_s^+}/f_{D^+} = 1.26\pm0.06\pm0.02$
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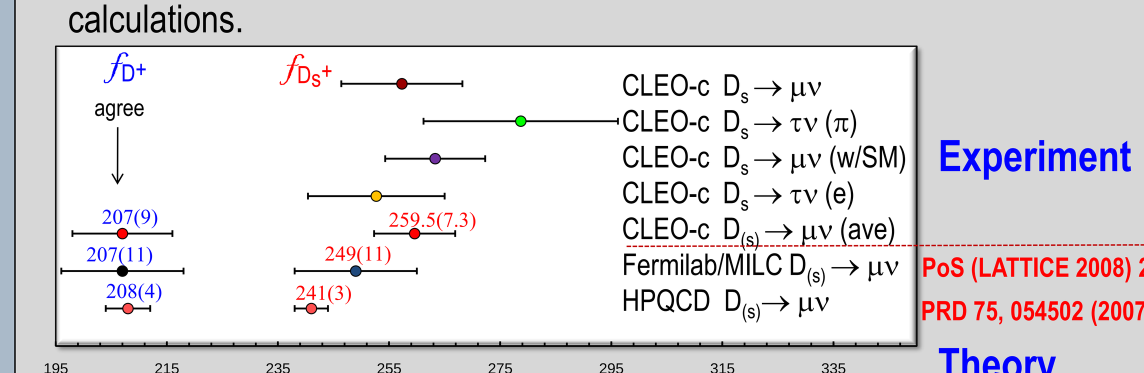
13-Conclusions

Our result of $f_{D^+} = 206(9)$ is in agreement with LQCD calculations of $f_{D^+} = 207(4)$ from the HPQCD & UKQCD and $f_{D^+} = 207(11)$ Fermilab/MILC collaborations. Our combined result of $f_{D_s^+} = 259(7)$ is 2.3σ and 0.7σ away from the results of $f_{D_s^+} = 241(3)$ and $f_{D_s^+} = 249(11)$ of the two LQCD groups, respectively. The difference in $f_{D_s^+}$ could be due to physics beyond SM, or statistical and systematic uncertainties in the experiment and LQCD calculations.



Experiment
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Theory