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# Leptonic Charm Decays at CLEO-c

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CLEO-c has measured the form factors $f_{D^+}$ and $f_{D_s}$ with unprecedented precision. In these proceedings, we summarise these results and put them into context with other recent measurements, and theoretical predictions.

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## 1. Introduction

The decay rate of charm mesons to purely leptonic states $\mathrm{D}^+_{(\mathrm{s})} \to \ell^+\nu_\ell$, where $\ell$ is either $e, \mu$, or $\tau$ is given by:

$$\Gamma\left(D^+_{(s)} \to \ell^+\nu_\ell\right) = f^2_{D^+_{(s)}} \left|V_{c(d,s)}\right|^2 \; \frac{G_F^2}{8\pi} m_\ell^2 M_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{M^2_{D^+_{(s)}}}\right)^2 \tag{1.1}$$

The charge conjugate mode is implied throughout. The entire QCD contribution is given by one single parameter, $f_{D^+}$ for $\mathrm{D}^+$ decays and $f_{D_s}$ for $\mathrm{D}^+_\mathrm{s}$ decays. All other factors are well-known Standard Model parameters. In particular (and in contrast to leptonic $\mathrm{B}^+$ decays), the CKM factor $\left|V_{c(d,s)}\right|$ is well-known from from the unitarity of the CKM matrix. Leptonic D decays therefore provide one of the cleanest windows onto QCD. Due to its particular running conditions at the charm threshold, and a suitable detector, CLEO-c has been able to make measurements of $f_{D^+}$ and $f_{D_s}$ with unprecedented precision [1–4]. In these proceedings, we summarise these results and put them into context with other measurements, and theoretical predictions, in particular the recent, very precise unquenched Lattice QCD calculations by the HPQCD+UKQCD collaboration [5].

## 2. CLEO-c and CESR

The CLEO-c experiment is located at the CESR $e^+e^-$ collider. The CLEO-c detector is described elsewhere [6–8]. The results for $f_{D^+}$ presented here are from $818\,\mathrm{pb}^{-1}$ of data at $\sqrt{s} = 3770\,\mathrm{MeV}$, with $e^+e^- \to \psi(3770) \to D\bar{D}$, corresponding to $3.0\,\mathrm{M}$ $\mathrm{D}^0\bar{\mathrm{D}}^0$ events and $2.4\,\mathrm{M}$ $\mathrm{D}^+\mathrm{D}^-$ events. The $f_{D_s}$ results are obtained with $600\,\mathrm{pb}^{-1}$ of data at $\sqrt{s} = 4170\,\mathrm{MeV}$, corresponding to $600\,\mathrm{k}$ $\mathrm{D}^\pm_\mathrm{s}\mathrm{D}^{\mp *}_\mathrm{s}$ events. Crucial to all analyses is:

- The D-mesons are produced in pairs, so that one D meson (the "tag") can be used to provide an normalisation for the decay rate of the other ("signal") D meson.
- The events are very clean. For signal events, there is no underlying event, the beam energy is fully converted into the $\mathrm{D}\bar{\mathrm{D}}$ or $\mathrm{D}^\pm_\mathrm{s}\mathrm{D}^{\mp *}_\mathrm{s}$ pair. Kinematic constraints allow the reconstruction of the $\nu$.

These two features allow CLEO-c to make by far the world's most precise $f_{D_{(s)}}$ measurements, despite having a data sample with only about 0.3% of the D mesons produced at the B factories.

The relative decay rates in the Standard Model to $\tau^+\nu$, $\mu^+\nu$ and $e^+\nu$ respectively are for $\mathrm{D}^+$: $2.65 : 1 : 2.3 \cdot 10^{-5}$, and for $\mathrm{D}^+_\mathrm{s}$: $9.76 : 1 : 2.3 \cdot 10^{-5}$. Due to helicity suppression, the decay to the heaviest lepton has the largest branching fraction - unfortunately, this is also the most difficult decay to reconstruct, as the final state contains at least two neutrinos. The main difference in decay rates between $\mathrm{D}^+$ and $\mathrm{D}^+_\mathrm{s}$ is due to the CKM factor $|V_{c(s,d)}|^2$, which is about 20 times larger for $\mathrm{D}^+_\mathrm{s}$ decays than for $\mathrm{D}^+$. For decays to $\tau^+\nu$, the extra phase space available to the $\mathrm{D}^+_\mathrm{s}$ provides an additional factor of 3.7. In the following we will briefly describe CLEO-c's measurements of $f_{D^+}$ from $\mathrm{D}^+ \to \mu^+\nu_\mu$ [1], and the measurement of $f_{D_s}$ from $\mathrm{D}^+_\mathrm{s} \to \mu^+\nu_\mu$ [2], $\mathrm{D}^+_\mathrm{s} \to \tau^+(\pi^+\bar{\nu}_\tau)\nu_\tau$ [2], $\mathrm{D}^+_\mathrm{s} \to \tau^+(\mathrm{e}^+\nu_\mathrm{e}\bar{\nu}_\tau)\nu_\tau$ [3], and $\mathrm{D}^+_\mathrm{s} \to \tau^+(\rho^+\bar{\nu}_\tau)\nu_\tau$ [4].



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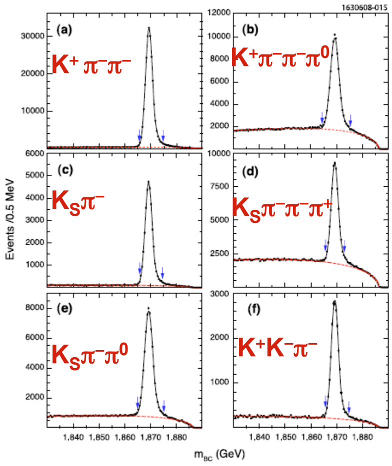


**Figure 1:** Beam constrained mass for the tag-modes used in CLEO-c's $f_{D^+}$ analysis [1]; in total this corresponds to 460k signal tags and 90k background events.

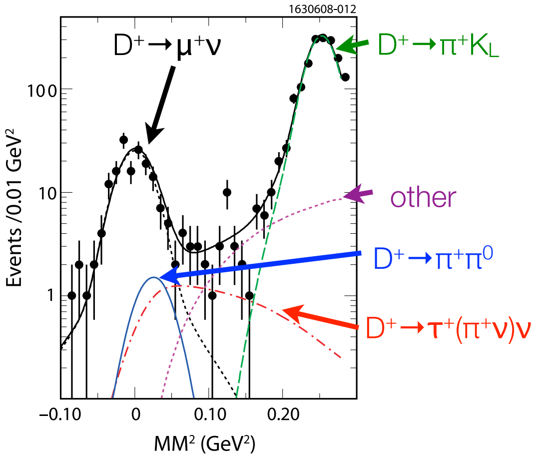


**Figure 2:** Missing mass-squared distribution of tagged $D^+ \to \mu^+\nu$ candidates (log-scale). The points represent the data. The black solid line represents the fit with all components, the other lines various fit components as indicated.

## 3. Measuring $f_{D^+}$ with $D^+ \to \mu^+\nu$

The first step in the analysis is to identify a sample of fully reconstructed "tag" $D^-$. These provide the normalisation. The second step is to find amongst this tag sample the signal $D^+ \to \mu^+\nu$ decay. Here we will usually call the tag a $D^-$ and the signal a $D^+$, but the charge conjugate states are also used. Figure 1 shows the reconstructed beam-constrained mass of all tag candidates reconstructed in $818\,\mathrm{pb}^{-1}$, corresponding to 460k signal tag events and 90k background events. To select the $D^+ \to \mu^+\nu$ signal, events are required to have one $\mu^+$ candidate in addition to the tracks associated to the tag, and no other charged tracks, or photon-candidates with $E > 250\,\mathrm{GeV}$. A $\mu^+$ candidate is a charged track with RICH and dE/dx information consistent with a muon. At the $D\bar{D}$ threshold, muons do not have enough energy to reach the detector's muon chambers that were designed for higher collision energies. For the events selected in this way, the missing mass-squared ($MM^2$) is calculated from the 4-momenta of the tag $p_{\mathrm{tag}}$, the $\mu^+$ candidate $p_\mu$, and the beam $p_{\mathrm{beam}}$:

$$MM^2 \equiv \left(p_{\mathrm{beam}} - p_{\mathrm{tag}} - p_\mu\right)^2 \qquad (3.1)$$

This should be 0 if the only missing particle is a neutrino. The $MM^2$ distribution is shown in Fig. 2. It shows a clear signal peak at $MM^2 = 0$. The decay $D^+ \to \tau^+(\pi^+\nu)\nu$ produces a broader $MM^2$ peak. Two fits are performed. One where the ratio of the $\tau\nu$ and $\mu\nu$ rate is fixed to its SM value of $10.9\% \pm 0.07\%$ [9] and another fit where this ratio is floated. Both give consistent results (given below). The default fit, shown in Fig. 2, is for the fixed ratio.

Most aspects of the background fit are determined from data. The $\pi^+\pi^0$ component is particularly challenging as it peaks underneath the signal peak. Here, the shape and the branching fraction is obtained from CLEO-c data [10], while the efficiency with which it is reconstructed as $D^+ \to \mu^+\nu$ is obtained from Monte Carlo simulation. The full details of background analysis with its various cross checks are discussed [1].

The fit with fixed $\tau^+\nu$ to $\mu^+\nu$ ratio yields $149.7 \pm 12.0$ $D^+ \to \mu^+\nu$ events and 25.8 $D^+ \to \tau^+\nu$ events (this includes, as throughout the text, the charge-conjugate mode). Letting the ratio float gives $153.9 \pm 13.5$ $D^+ \to \mu^+\nu$ events and $13.5 \pm 15.3$ $D^+ \to \tau^+\nu$ events. Using the first number, the Branching Fraction is $\mathscr{B}(D^+ \to \mu^+\nu) = (3.82 \pm 0.32 \pm 0.09) \cdot 10^{-4}$. This number includes a 1% radiative correction taking into account the possible contribution from $D^+ \to D^{*+} \to \mu^+\nu\gamma$ with a soft photon (where the $D^{*+}$ is virtual) [11, 12]. The decay constant is calculated from the branching fraction using the $D^+$ lifetime of $(1.040 \pm 0.007)$ ps and assuming $|V_{cd}| = |V_{us}| = 0.2255 \pm 0.19$, (value for $|V_{us}|$ from [13]):

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

## 4. Measuring $f_{D_s}$

At a centre of mass energy of 4170 MeV, the $D_s$ pairs are produced as $D_s^{+*}D_s^-$ or $D_s^+D_s^{-*}$, both resulting in $D_s^+D_s^-\gamma$. The additional photon complicates the process of the tag selection. The tag $D_s^-$ is now selected based on the invariant mass rather than the beam-constrained mass as the latter is smeared out because of the additional photon in the event. The 4-momentum of the tag $D_s^-$, $p_{\text{tag}}$, is combined with with that of the photon $p_\gamma$ to calculate $\text{MM}^{*2} \equiv (p_{beam} - p_{tag} - p_\gamma)^2$, which peaks at the $D_s^+$ mass-squared for signal events. The final step in the reconstruction of the signal $D_s^+$ depends on the decay mode considered. In all cases, exactly one additional charged track, which must have the opposite charge of the tag-$D_s^-$, is required in the event. Events with additional charged tracks or with neutral energy clusters with $E > 300$ GeV, are rejected. For $D_s^+ \to \mu^+\nu$, $D_s^+ \to \tau^+(\pi^+\bar{\nu})\nu$, $D_s^+ \to \tau^+(\rho + \bar{\nu})\nu$, the selection is based on the same missing-mass variable defined in the previous section, which is obtained by subtracting the 4-momenta of $D_s^-$, all visible decay products of the signal $D_s^+$, and the photon, from the beam momentum. For $D_s^+ \to \mu^+\nu$, this should peak sharply at $\text{MM}^2 = 0$, for the other decay modes considered it is smeared out towards larger $\text{MM}^2$ values.

The decay $D_s^+ \to \tau^+(e^+\bar{\nu}\nu)\nu$, which has three neutrinos, is particularly challenging. Only the three cleanest tag modes are used, $D_s^- \to \phi\pi^-$, $D_s^- \to K^-K^{*0}$ and $D_s^- \to K^-K_S^0$. With three neutrinos in the final state, the $\text{MM}^2$ distribution is too broad to be useful. The main discriminating variable in the final selection is $E_{\text{extra}}$: the total energy measured in all calorimeter clusters that cannot be matched to reconstructed tracks. This peaks at the energy of the photon from the $D^*$ decay for those events where all the neutral particles apart from the photon are neutrinos, and is larger for other, such such as $D^\pm \to e^+\nu\eta$. The most difficult background is from $D_s \to K_L e\nu$ as it peaks underneath the signal - detailed Monte Carlo studies are used to estimate this contribution. $E_{\text{extra}}$ is also used to reduce background in the $D_s^+ \to \tau^+(\rho^+\bar{\nu})\nu$ mode.

The results for CLEO-c's $f_{D_s}$ measurements [2–4] are summarised in Tab. 1, which is, including the averages, taken from CLEO-c's latest $f_{D_s}$ publication [4]. As in the case of $f_{D^+}$, the results from the $\mu^+\nu$ final state include a 1% radiative correction [11, 12] (such a correction is not necessary for decays to $\tau^+\nu$). As can be seen from the table, the results from the various decay modes are consistentwith each other. The dominant errors are statistical. Combining these results gives [2–4]:

$$f_{D_s}^{CLEO} = (259.0 \pm 6.2 \pm 3.0)\text{ MeV}$$

**Table 1:** Recent absolute measurements of $f_{D_s}$ from CLEO-c, reproduced from [4].

| Experiment | Mode | $\mathscr{B}$ (%) | $f_{D_s}$ (MeV) |
|---|---|---|---|
| CLEO-c [4] | $\tau^+\nu$ $(\rho^+\overline{\nu})$ | $(5.52 \pm 0.57 \pm 0.21)$ | $257.8 \pm 13.3 \pm 5.2$ |
| CLEO-c [2] | $\tau^+\nu$, $(\pi^+\overline{\nu})$ | $(6.42 \pm 0.81 \pm 0.18)$ | $278.0 \pm 17.5 \pm 4.4$ |
| CLEO-c [3] | $\tau^+\nu$ $(e^+\nu\overline{\nu})$ | $(5.30 \pm 0.47 \pm 0.22)$ | $252.6 \pm 11.2 \pm 5.6$ |
| Average | $\tau^+\nu$ | $(5.58 \pm 0.33 \pm 0.13)$ | $259.7 \pm 7.8 \pm 3.4$ |
| CLEO-c [2] | $\mu^+\nu$ | $(0.565 \pm 0.045 \pm 0.017)$ | $257.6 \pm 10.3 \pm 4.3$ |
| Average | $\tau^+\nu$+$\mu^+\nu$ | | $259.0 \pm 6.2 \pm 3.0$ |

**Table 2:** Experimental results of $f_{D_s^+}$, $f_{D^+}$ (with statistical and systematic errors added in quadrature) and predictions from unquenched LQCD. In line with PDG practise [18, 19], the averages (by [4]) include only results from absolute branching fraction measurements. All results include a 1% radiative correction to the measured $\mu\nu$ branching fraction [11, 12] and have been adjusted to correspond to $M_{D_s^+} = 1.96849(34)$ GeV, $\tau_{D_s^+} = 0.500(7)$ ps, $M_{\tau^+} = 1.77684(17)$ GeV [13], $|V_{cs}| = 0.97338(26)$, as discussed in [4].

| | $f_{D_s^+}$ (MeV) | $f_{D^+}$ (MeV) |
|---|---|---|
| CLEO-c [1–4] | $259.0 \pm 6.9$ | $205.8 \pm 8.9$ |
| average(CLEO-c & BELLE [14]) | $260.7 \pm 6.5$ | $205.8 \pm 8.9$ |
| Lattice (HPQCD+UKQCD) [5] | $241 \pm 3$ | $208 \pm 4$ |
| Lattice (FNAL+MILC+HPQCD) [20, 21] | $260 \pm 10$ | $217 \pm 10$ |

## 5. Comparison Experiment/Theory

Experimental results and recent unquenched LQCD calculations for $f_{D^+}$ and $f_{D_s}$ are summarised in Tab. 2. For the purpose of the comparison presented here, we use the result by the HPQCD+UKQCD collaboration [5] who quote the smallest error, acknowledging that an independent confirmation of this result with similar precision would be desirable. The LQCD result for $f_{D^+}$ is in in excellent agreement with CLEO-c's determination $f_{D^+}^{CLEO} = (205.8 \pm 8.9)$ MeV [1]. On the other hand, $f_{D_s}^{LQCD}$ is 2.4 standard deviations lower than the combined CLEO-c measurement $f_{D_s}^{CLEO} = (259.0 \pm 6.9)$ MeV. BELLE also published a result based on absolute branching fractions [14]: $f_{D_s}^{BELLE} = (275 \pm 16 \pm 12)$ MeV. Combining the results gives $f_{D_s} = (260.7 \pm 6.5)$ MeV [4], which is $2.8\sigma$ higher than the HPQCD+UKQCD prediction. Another recent $f_{D_s}$ measurement is by BaBar [15], $f_{D_s}^{BaBar} = (283 \pm 17 \pm 7 \pm 14)$ MeV. In contrast to the results shown so far, this is not based on an absolute branching fraction measurement, but relies on $D^+ \to \phi\pi^+$ as normalisation mode; the last error in the result given above is due to the normalisation. The reliance on this normalisation mode is problematic [16, 17], for this reason the result has been omitted from the average by [4] reproduced in Tab. 2. Ignoring these concerns for a moment and including the BaBar result anyway, we find (the author's own average) $f_{D_s} = (262.5 \pm 6.3)$ MeV, which is $3.1\sigma$ higher than the LQCD calculation by HPQCD+UKQCD predicts.

The discrepancies between experiment and LQCD could be due to a large statistical fluctuation, unknown systematic uncertainties either in LQCD calculations or in the measurements, or physics beyond the Standard Model. To decide between these possibilities will require BES III's data [22], and an independent confirmation of HPQCD+UKQCD's calculations with comparable precision. If the discrepancies are due to BSM physics, theories to explain them must provide a mechanism that increases $f_{D_s}$ while leaving $f_{D^+}$, as well as the ratio of the branching fractions $\frac{\mathscr{B}(\mathrm{D_s^+}\to\tau^+\nu)}{\mathscr{B}(\mathrm{D_s^+}\to\mu^+\nu)}$ largely unaffected. The latter is naturally accommodated in charged Higgs-mediated decays, as the mass-dependent Higgs coupling mimics the helicity suppression in $\mathrm{W}^{\pm}$-mediated decays. However, as pointed out by Akeroyd, Chen and Mahmoudi [23, 24], charged Higgs contributions in 2-Higgs-Doublet models would, through destructive interference, reduce the observed decay rate, rather than increase it. Several models have been proposed that lead to an increased $f_{D_s}$. These include leptoquark models (Dobrescu and Kronfeld [11]), and R-parity violating SUSY models by Akeroyd and Recksiegel [25], and Kundu and Nandi [26] who relate the discrepancy in $f_{D_s}$ to hints of a non-SM CP-violating phase $\phi_s$ in $\mathrm{B_s}-\bar{\mathrm{B}}_\mathrm{s}$ mixing [27]. Dorsner *et. al* show that scalar leptoquarks in R-parity violating SUSY models would affect $\mathrm{D_s^+}\to\tau^+\nu$ and $\mathrm{D_s^+}\to\mu^+\nu$ differently [28] and conclude that they can therefore not naturally explain the observed data. Gninenko and Gorbunov [29] argue that sterile neutrinos could explain both the enhanced leptonic $\mathrm{D_s^+}$ rates and the excess of low energy electron-like events observed at MiniBooNE [30].

## 6. Conclusion

CLEO-c has been able to measure $f_{D^+}$ and $f_{D_s}$ with unprecedented precision [1–4]. Crucial to this precision is the ability to measure absolute branching fractions, and the ability to cleanly reconstruct missing $\nu$ momenta from beam constraints. This new level of experimental precision coincides with a remarkable increase in the precision of LQCD predictions for $f_{D^+}$ and $f_{D_s}$ [5]. Tables 1 and 2 summarise the experimental results and predictions from unquenched LQCD. While there is excellent agreement between CLEO-c's measurment and LQCD for $f_{D^+}$, CLEO-c finds a value for $f_{D_s}$ that is $2.4\sigma$ larger than predicted by the most precise unquenched LQCD calculation (HPQCD+UKQCD [5]). Combining CLEO-c's result with BELLE's recent measurement [14], that is also based on absolute branching fractions, the discrepancy increases to $2.8\sigma$. Several beyond-the-SM theories have been put forward to explain the observed effect. We look forward to a further increase in the experimental precision, in particular from BES III's data, that, in conjunction with further progress in LQCD (an independent confirmation of HPQCD+UKQCD's precise result would be desirable), should be able to answer the question whether the observed discrepancy is indeed caused by BSM physics.

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