The Purely Leptonic Decays $D^+ \to \mu^+\nu$ and $D_s^+ \to \ell^+\nu$ at CLEO

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We update our previous results by increasing the luminosity, the efficiency, and for the D_s^+ the number of tags. We determine $f_{D^+} = (205.8 \pm 8.5 \pm 2.5)$ MeV, and an interim preliminary value of $f_{D_s^+} = (267.9 \pm 8.2 \pm 3.9)$ MeV, where both results are radiatively corrected. We agree with the recent most precise unquenched Lattice-QCD calculation for the D^+, but are in disagreement for the D_s^+. Several consequences are discussed, including the possibility of physics beyond the Standard Model.

1. Introduction

Purely leptonic decays of heavy mesons proceed in the Standard Model (SM) via a W^+ annihilation diagram shown specifically for $D^+ \to \ell^+\nu$ in Fig. 1. The strong interaction effects are parameterized in terms of the "decay constant" for the D^+ meson f_{D^+}. The decay width is given by

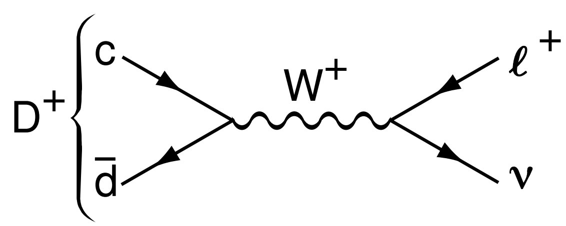

Figure 1: The decay diagram for $D^+ \to \ell^+\nu$.

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

where G_F is the Fermi constant, M_{D^+} is the D^+ mass, m_ℓ the final state charged-lepton mass, and V_{cd} is a CKM matrix element, taken equal to V_{us}. Thus, in the SM measurement of purely leptonic decays allow a determination the decay constant, f_{D^+} of the D^+ meson and similarly f_{D_s} of the D_s^+ meson.

Meson decay constants in the B system are used to translate measurements of $B\bar{B}$ mixing to CKM matrix elements. Currently, it is not possible to determine f_B accurately from leptonic B decays, so theoretical calculations of f_B must be used. Since the B_s^0 meson does not have $\ell^+\nu$ decays, it will never be possible to determine f_{B_s} experimentally, so again theory must be relied upon. If calculations disagree on 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 effects SM based predictions of the B decay constants. Decay constants can be calculated using Lattice-QCD techniques. Recently, Follana *et al.* using an unquenched lattice technique predicted $f_{D^+} = (207 \pm 4)$ MeV and $f_{D_s} = (241 \pm 3)$ MeV. [1]

In these analyses we exploit the reactions $e^+e^- \to D^-D^+$, and $e^+e^- \to D_s^{*-}D_s^+$ or $D_s^-D_s^{*+}$. The D^+ is studied at 3770 MeV using 818 pb^{-1}. D_s^+ is studied at 4170 MeV, using 400 pb^{-1} for the $\mu^+\nu$, and $\tau^+\nu$, $\tau^+ \to \pi^+\overline{\nu}$ final states, and 300 pb^{-1} for $\tau^+ \to e^+\nu\overline{\nu}$. (Eventually CLEO will present results using 600 pb^{-1}.)

2. $D^+ \to \ell^+\nu$

We use a "double tag" technique where one $D^\pm$ is fully reconstructed and the oppositely charged D can then be found even if there is a missing neutrino in the final state [2]. For notational convenance, the D^- is referred to for the fully reconstructed tag, although D^+ states are also used. To reconstruct D^- tags we require that the tag candidates have a measured energy consistent with the beam energy, and have a "beam constrained mass," m_{BC}, consistent with the D^- mass, where $m_{\rm BC} = \sqrt{E_{\rm beam}^2 - (\sum_i \mathbf{p}_i)^2}$, $E_{\rm beam}$ is the beam energy and i runs over all the final state particles three-momenta. Fig. 2 shows the m_{BC} distribution summed over all the decay modes we use for tagging. Selecting events in the mass peak we count 460,055±787 signal events over a background of 89,472 events.

To search for signal events we look for events with one additional track with opposite sign of charge to the tag. The track must have an angle >25.8° with the beam line. We separate these events into two categories. Case (i): those which deposit < 300 MeV of energy in the calorimeter, characteristic of 99% of muons, and case (ii) those which deposit > 300 MeV, characteristic of 45% of the pions, those that happen to interact in the calorimeter.

We look for $D^+ \to \mu^+\nu$ by computing the square of the missing mass

$$\mathrm{MM}^2 = \left(E_{\rm beam} - E_{\mu^+}\right)^2 - \left(-\mathbf{p}_{D^-} - \mathbf{p}_{\mu^+}\right)^2 , \quad (2)$$

where $\mathbf{p}_{D^-}$ is the three-momentum of the fully reconstructed D^-, and $E_{\mu^+}(\mathbf{p}_{\mu^+})$ is the energy (momentum) of the μ^+ candidate. The signal peaks at zero for $\mu^+\nu$ and is smeared toward more positive values for $\tau^+\nu$, $\tau^+ \to \pi^+\overline{\nu}$.

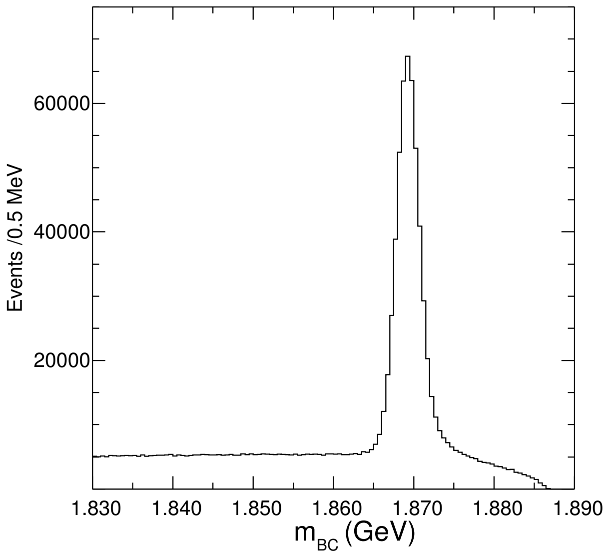

Figure 2: The beam-constrained mass distributions summed over D^- decay candidates in the final states: $K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S\pi^-$, $K_S\pi^-\pi^-\pi^+$, $K_S\pi^-\pi^0$ and $K^+K^-\pi^-$.

The fit to the case (i) MM^2 distribution is shown in Fig. 3 contains separate shapes for signal, $\pi^+\pi^0$, $\overline{K}^0\pi^+$, $\tau^+\nu$ ($\tau^+ \to \pi^+\bar{\nu}$), and a background shape describing three-body decays. Here we assume the SM ratio of 2.65 for the ratio of the $\tau^+\nu/\mu^+\nu$ component and constrain the area ratio of these components to the product of 2.65 with $\mathcal{B}(\tau^+ \to \pi^+\bar{\nu})$=(10.90±0.07)% [5] and the 55% probability that the pion deposits <300 MeV in the calorimeter. We veto events with an extra neutral energy cluster > 250 MeV. This removes most $\pi^+\pi^0$ events; the residual background is fixed at 9.2 events. The normalizations of the signal, $\overline{K}^0\pi^+$, and 3-body background shapes are allowed to float.

The fit yields 149.7±12.0 $\mu^+\nu$ signal events and 25.8 $\tau^+\nu$, $\tau^+ \to \pi^+\bar{\nu}$ events (for the entire MM^2 range). We also perform the fit allowing the $\tau^+\nu$, $\tau^+ \to \pi^+\bar{\nu}$ component to float. Then we find 153.9±13.5 $\mu^+\nu$ events and 13.5±15.3 $\tau^+\nu$, $\tau^+ \to \pi^+\bar{\nu}$ events, compared with the 25.8 we expect in the SM. Performing the fit in this manner gives a result that is independent of the SM expectation of the $D^+ \to \tau^+\nu$ rate. To extract a branching fraction, in either case, we subtract off 2.4±1.0 events found from simulations and other studies to be additional backgrounds, not taken into account by the fit.

We find $\mathcal{B}(D^+ \to \mu^+\nu) = (3.82\pm0.32\pm0.09)\times10^{-4}$. The decay constant f_{D^+} is then obtained from Eq. (1) using 1040±7 fs as the D^+ lifetime [5] and 0.2256 as $|V_{cd}|$. Our final result, including radiative corrections is

$$f_{D^+} = (205.8 \pm 8.5 \pm 2.5)\ \mathrm{MeV}\ . \tag{3}$$

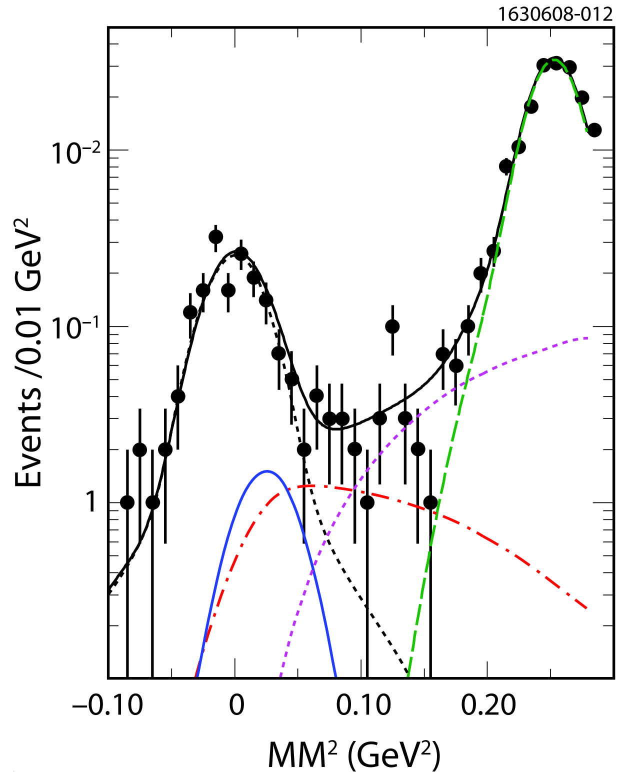

Figure 3: Fit to the MM^2 for case (i). The points with error bars show the data. The black (dashed) curve centered at zero shows the signal $\mu^+\nu$ events. The dot-dashed (red) curve that peaks around 0.05 GeV^2 shows the $D^+ \to \tau^+\nu$, $\tau^+ \to \pi^+\bar{\nu}$ component. The solid (blue) Gaussian shaped curve centered on the pion-mass squared shows the residual $\pi^+\pi^0$ component. The dashed (purple) curve that falls to zero around 0.03 GeV^2 is the sum of all the other background components, except the $\overline{K}^0\pi^+$ tail which is shown by the long-dashed (green) curve that peaks up at 0.25 GeV^2. The solid (black) curve is the sum of all the components.

3. $D_s^+ \to \ell^+\nu$

In the D_s case we have to take into account the additional photon from $D_s^* \to \gamma D_s$, since we use $e^+e^- \to D_s^* D_s$ events. We first examine the invariant masses (see Fig. 4). Then to select the appropriate D_s^- tag and γ candidate, we compute the square of the missing mass opposite the selected tag and candidate γ's, which peaks at the D_s^+ mass for correct combinations, where

$$\mathrm{MM}^{*2} = (E_{\mathrm{CM}} - E_{D_s} - E_\gamma)^2 - (\mathbf{p}_{\mathrm{CM}} - \mathbf{p}_{D_s} - \mathbf{p}_\gamma)^2 , \tag{4}$$

here E_{CM} ($\mathbf{p}_{\mathrm{CM}}$) is the center-of-mass energy (momentum), E_{D_s} ($\mathbf{p}_{D_s}$) is the energy (momentum) of the fully reconstructed D_s^- tag, and E_γ ($\mathbf{p}_\gamma$) is the energy (momentum) of the additional photon. In performing this calculation we use a kinematic fit that constrains the decay products of the D_s^- to the known D_s mass and conserves overall momentum and energy.

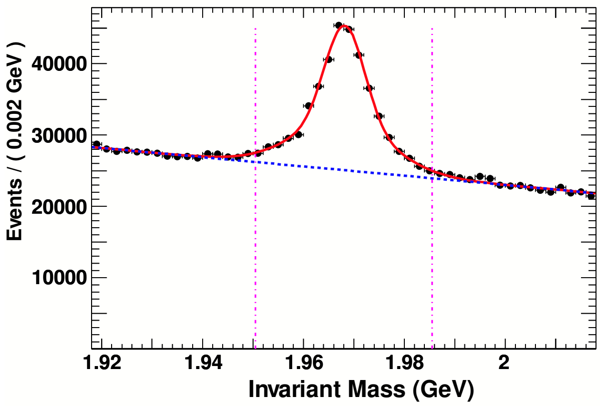

Figure 4: The invariant mass distributions summed over D_s^- decay candidates in the final states: $K^+K^-\pi^-$, K_SK^-, $\eta\pi^-$; $\eta\to\gamma\gamma$, $\eta'\pi^-$; $\eta'\to\pi^+\pi^-\eta$, $\eta\to\gamma\gamma$, $\phi\rho^-$; $\phi\to K^+K^-$, $\rho^-\to\pi^-\pi^0$, $\pi^+\pi^-\pi^-$, $K^{*-}K^{*0}$; $K^{*-}\to K_S^0\pi^-$, $K^{*0}\to K^+\pi^-$, $\eta\rho^-$; $\eta\to\gamma\gamma$, $\rho^-\to\pi^-\pi^0$, and $\eta'\pi^-$; $\eta'\to\pi^+\pi^-\gamma$. The curves represent signal and background.

The MM^{*2} distributions from the selected D_s^- event sample are shown in Fig. 5. We fit these distributions to determine the number of tag events.

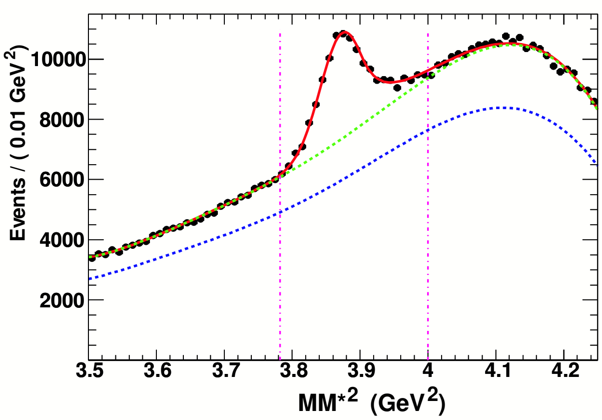

Figure 5: The MM^{*2} from a γ plus tag candidate. The curves represent signal and background components.

After selecting the tags we then find events with a single oppositely charged track to the tag and compute

$$\begin{aligned}\mathrm{MM}^2 \;=\; & (E_{\rm CM}-E_{D_s}-E_\gamma-E_\mu)^2 \\ & -(\mathbf{p}_{\rm CM}-\mathbf{p}_{D_s}-\mathbf{p}_\gamma-\mathbf{p}_\mu)^2 \;\;.\end{aligned} \quad (5)$$

We make use of a set of kinematical constraints and fit each event to two hypotheses one of which is that the D_s^- tag is the daughter of a D_s^{*-} and the other that the D_s^{*+} decays into γD_s^+, with the D_s^+ subsequently decaying into $\mu^+\nu$. The MM^2 distributions from data are shown in Fig. 6 where we have summed cases (i) and (ii). After fixing the ratio of $\tau^+\nu/\mu^+\nu$ to the SM value we find $f_{D_s^+}=(268.2\pm9.6\pm4.4)$ MeV.

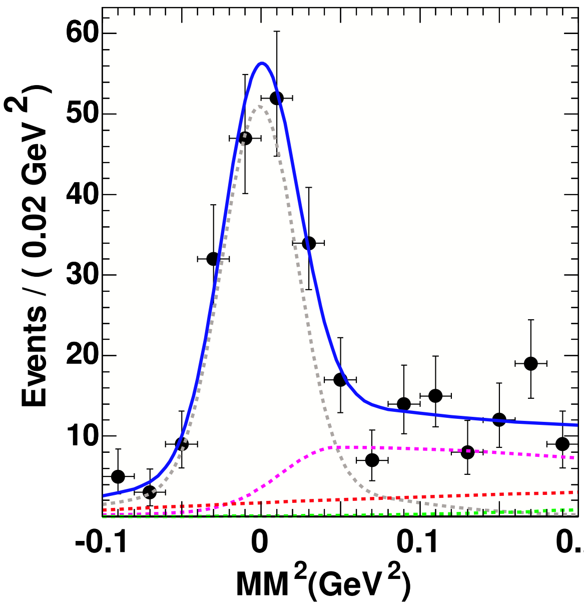

Figure 6: The MM^2 distribution. The dashed (grey) Gaussian shaped curve peaked near zero is the $\mu^+\nu$ component, while the dashed (purple) curve that rises sharply from zero and then flattens out shows the $\tau^+\nu$ component. The two lines are background components. The solid curve shows the sum.

We can also use the decay mode $\tau^+\to e^+\nu\overline{\nu}$. This result has already been published. [6] The technique here is to use only three tagging modes: $\phi\pi^-$, K^-K^{*0} and $K_S^0K^-$, to ensure that the tags are extremely clean. Then events with an identified e^+ and no other charged tracks are selected. Any energy not associated with the tag decay products is tabulated. Those events with small extra energy below 400 MeV are mostly pure $D_s^+\to\tau^+\nu$ events. After correcting for efficiencies and residual backgrounds we find $f_{D_s^+}=(273\pm16\pm8)$ MeV.

4. Conclusions

The preliminary CLEO average is $f_{D_s^+}=(267.9\pm8.2\pm3.9)$ MeV (radiatively corrected). Averaging in the Belle result [7] $f_{D_s^+}=(269.6\pm8.3)$ MeV, which differs from the Follana *et al.* calculation [1] by 3.2 standard deviations, while the result for $f_{D^+}=(205.8\pm8.5\pm2.5)$ MeV is in good agreement. This discrepancy can be explained either by New Physics [4] or casts suspicion on the theoretical prediction. As similar calculations are used for f_{B_s}/f_B, we need worry about them, or the effects of New Physics on this ratio.

Acknowledgments

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