SEMILEPTONIC CHARM MESON DECAY RESULTS FROM CLEO-II

HIRO TAJIMA
Physics Department, University of California
Santa Barbara, California 93106, USA
(Representing the CLEO collaboration)

ABSTRACT

Using a sample of over 2 million $e^+e^- \to c\overline{c}$ continuum events collected by the CLEO-II detector at the Cornell Electron Storage Ring, we have measured branching fractions and form factors for semileptonic charm meson decays. We report a new measurement of $\mathcal{B}(D^0 \to Xe^+\nu) = (6.97 \pm 0.18 \pm 0.30)\%$. We present a first measurement of ratios $\mathcal{B}(D_s^+ \to \eta e^+\nu)/\mathcal{B}(D_s^+ \to \phi e^+\nu) = 1.74 \pm 0.34 \pm 0.24$ and $\mathcal{B}(D_s^+ \to \eta' e^+\nu)/\mathcal{B}(D_s^+ \to \phi e^+\nu) = 0.71 \pm 0.19 \pm 0.09$. Using these results, we estimate the absolute branching fraction for $D_s^+ \to \phi e^+\nu$ and $D_s^+ \to \phi\pi^+$ to be $(2.06 \pm 0.33)\%$ and $(3.82 \pm 0.74)\%$, respectively. Also presented is a new measurement of form factor ratios for $D_s^+ \to \phi e^+\nu$ decay, $R_2 = 1.4 \pm 0.5 \pm 0.3$ and $R_V = 0.9 \pm 0.6 \pm 0.3$.

1. Introduction

In B semileptonic decays, we measure $|V_{cb}|$ and $|V_{ub}|$ using the theoretical predictions on form factors. It is important to test and improve those theoretical predictions. In charm semileptonic decays, the absolute scale of form factors can be measured, since Cabibbo-Kobayashi-Masukawa (CKM) matrix elements, $|V_{cs}|$ and $|V_{cd}|$ are well known. In particular, theoretical predictions for $b \to u\ell^-\overline{\nu}$ must be improved in order to determine $|V_{ub}|$ and studies of charm semileptonic decay will provide theoretical information.

One of the outstanding problems in charm semileptonic decay is disagreement on vector-to-pseudoscalar (V/P) ratio, $\mathcal{B}(D \to \overline{K^*}e^+\nu)/\mathcal{B}(D \to \overline{K}e^+\nu)$.[1] The world average is 0.56 ± 0.06, while theory predicts $0.8 - 1.2$. While D^0 and D^+ semileptonic form factors have been studied in detail, in the D_s^+ sector only the $D_s^+ \to \phi\ell^+\nu$ has been studied. Fermilab experiment E653 has also seen evidence for $D_s^+ \to (\eta + \eta')\mu^+\nu$.[2]

In this report, we present a new measurement of $\mathcal{B}(D^0 \to Xe^+\nu)$ and a first measurement of the ratios $\mathcal{B}(D_s^+ \to \eta e^+\nu)/\mathcal{B}(D_s^+ \to \phi e^+\nu)$ and $\mathcal{B}(D_s^+ \to \eta' e^+\nu)/\mathcal{B}(D_s^+ \to \phi e^+\nu)$. Using these results, we estimate the absolute branching fraction for $D_s^+ \to \phi e^+\nu$. We also report a new measurement of the form factor ratios in $D_s^+ \to \phi e^+\nu$.

These analyses are based on a data sample of over 2 million $e^+e^- \to c\overline{c}$ continuum events at $\sqrt{s} \sim 10.6$ GeV collected by the CLEO-II detector[3] at the Cornell Electron Storage Ring.

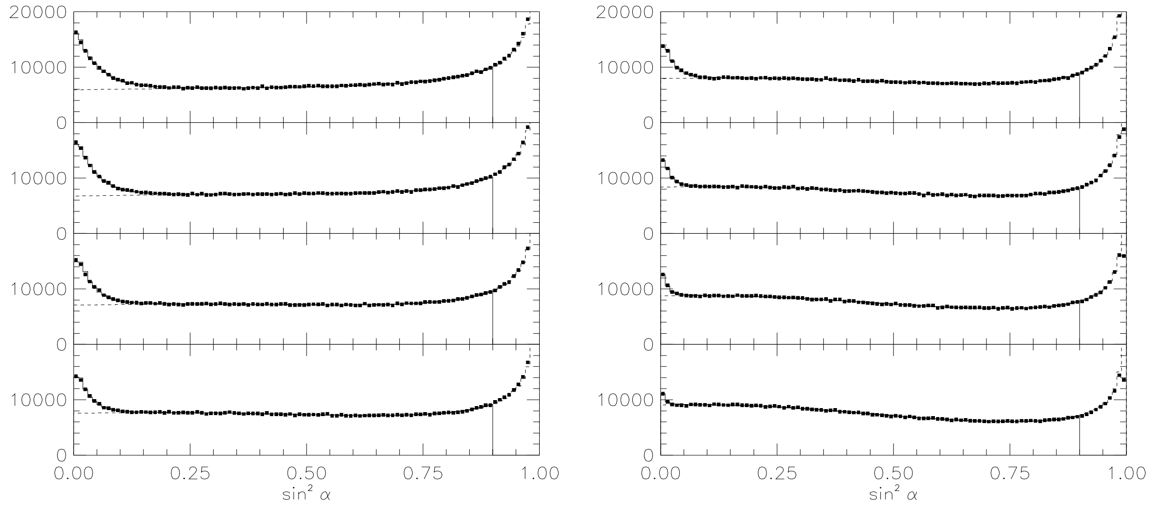

Fig. 1. The $\sin^2\alpha$ distribution for the pions accompanied by the right sign electron for the eight 25 MeV/c momentum slices. The solid histogram is the result of a fit which includes signal and background functions. The dashed histogram shows the background contribution.

2. Measurement of $\mathcal{B}(D^0 \to Xe^+\nu)$

In order to measure an absolute branching fraction for D^0 decay, we must first determine the number of D^0 mesons in the data sample. We use the decay $D^{*+} \to D^0\pi^+$ to achieve this. We exploit the fact that transverse momentum (p_T) of π^+ relative to D^{*+} direction is very small, less than 40 MeV/c, due to the small Q-value of the decay. This low transverse momentum provides the $D^{*+} \to D^0\pi^+$ signature. The D^0 is not reconstructed, so the D^{*+} direction is not measured. It is well approximated, however, by the thrust axis of the event. The resolution on the D^{*+} direction using this technique has been measured with data to be 0.08 *rad* FWHM. We use the $\sin^2\alpha = (p_T/p_\pi)^2$ distribution in eight 25 MeV/c slices in p_π to determine the total number of $D^{*+} \to D^0\pi^+$, $N(D^{*+} \to D^0\pi^+)$, where α is the angle between the pion and the thrust axis. This is the technique used to obtain the absolute branching fraction for $D^0 \to K^-\pi^+$.[4] We then require an electron with the same charge as the tagged pion in the same jet (right-sign combination) to obtain the total number of $D^{*+} \to D^0\pi^+$, $D^0 \to Xe^+\nu$, $N(D^{*+} \to D^0\pi^+, D^0 \to Xe^+\nu)$. The wrong-sign combination is used to model the background shape in the right-sign combination. Figure 1 shows the $\sin^2\alpha$ distributions for the pions accompanied by a right-sign electron in eight momentum slices from 225 to 425 MeV/c. A clear peak from $D^{*+} \to D^0\pi^+$ decays is observed near $\sin^2\alpha = 0$. The histogram is the result of a fit to a signal shape obtained from a Monte Carlo simulation and a background shape obtained from the wrong sign combination.

Dividing $N(D^{*+} \to D^0\pi^+, D^0 \to Xe^+\nu)$ by $N(D^{*+} \to D^0\pi^+)$, we obtain $\mathcal{B}(D^0 \to Xe^+\nu) = (6.97 \pm 0.18 \pm 0.30)\%$, where the first error is statistical and the second error is systematic. The dominant source of the systematic error is the uncertainty in the electron identification efficiency (3%).

CLEO-II has measured three exclusive modes, $\mathcal{B}(D \to \overline{K}e^+\nu) = (3.77 \pm 0.28)\%$,

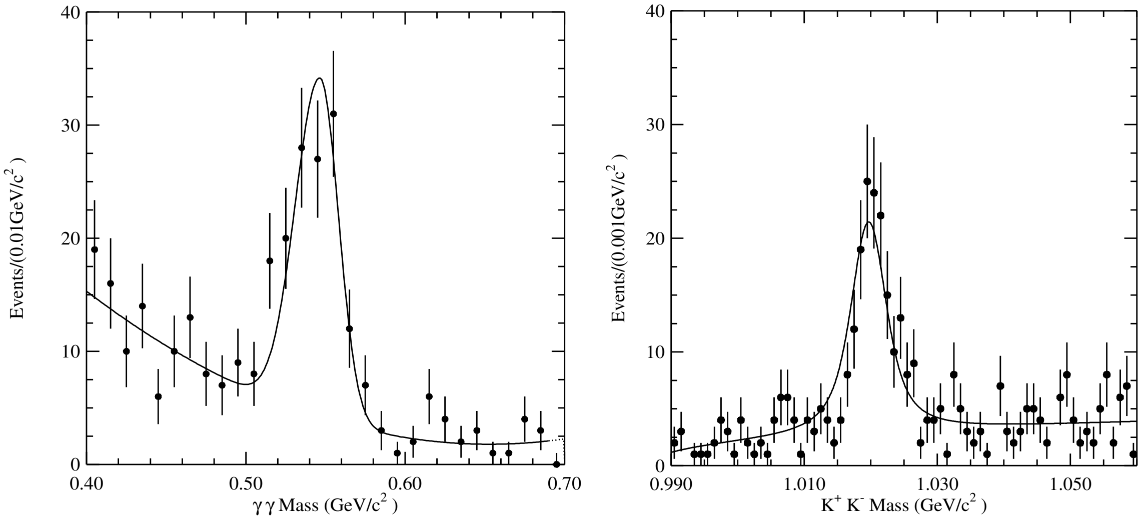

Fig. 2. The $\gamma\gamma$ and K^+K^- invariant-mass distributions for $D_s^+ \to \eta\ell^+\nu$ and $D_s^+ \to \phi\ell^+\nu$ candidates. The curve is the fit to the invariant-mass distribution.

$\mathcal{B}(D \to \overline{K^*}e^+\nu) = (2.36 \pm 0.29)\%$,[7] and $\mathcal{B}(D \to \pi e^+\nu) = (0.64 \pm 0.22)\%$.[8] The sum of those exclusive modes is $(6.77 \pm 0.45)\%$, which is consistent with expected small contributions from unobserved modes.

3. Study of $D_s^+ \to \phi\ell^+\nu$ and $D_s^+ \to \eta\ell^+\nu$ and $D_s^+ \to \eta'\ell^+\nu$

3.1. $D_s^+ \to \eta\ell^+\nu$ analysis

Due to the undetected neutrino, we cannot fully reconstruct $D_s^+ \to X_{s\bar{s}}\ell^+\nu$ ($X_{s\bar{s}} = \phi, \eta, \eta'$) decays. However, there are few processes which produce both a ϕ, η or η' meson and a lepton contained in the same jet. Consequently, this correlation can be used to extract a clean $D_s^+ \to X_{s\bar{s}}\ell^+\nu$ signal. The backgrounds due to misidentified leptons and from random $X_{s\bar{s}}\ell^+$ combinations can be reliably estimated, and the possible contamination from other decay modes can be shown to be small. We extract the yields of $D_s^+ \to X_{s\bar{s}}\ell^+\nu$ using a D_s^{*+} tag in order to reduce the random $X_{s\bar{s}}\ell^+$ background and normalize $D_s^+ \to \eta\ell^+\nu$ yield to $D_s^+ \to \phi\ell^+\nu$ yield. A detailed description of this analysis can be found elsewhere.[5]

We identify ϕ and η candidates by using the decay modes $\phi \to K^+K^-$ and $\eta \to \gamma\gamma$. After selecting $X_{s\bar{s}}\ell^+$ candidates which pass certain criteria, we then combine them with a photon which lies in the same hemisphere. To select $X_{s\bar{s}}\ell^+\gamma$ candidates which come from the $D_s^{*+} \to D_s^+\gamma$, $D_s^+ \to X_{s\bar{s}}\ell^+\nu$ decay chain, we require that $\Delta M \equiv M_{X_{s\bar{s}}\ell\gamma} - M_{X_{s\bar{s}}\ell}$ be between 0.1 and 0.2 GeV/c^2.

Figure 2 shows the $\gamma\gamma$ and K^+K^- invariant-mass distributions for all $\eta\ell^+\gamma$ and $\phi\ell^+\gamma$ combinations which pass our selection criteria. The fits yield 103.0 ± 11.9 $D_s^+ \to \eta\ell^+\nu$ candidates and 167.9 ± 15.8 $D_s^+ \to \phi\ell^+\nu$ candidates.

There are three main sources of background in the sample: $X_{s\bar{s}}$'s accompanied by fake leptons, random $X_{s\bar{s}}\ell^+$ combinations, and random photon combinations with true $X_{s\bar{s}}\ell^+$. The background due to fake leptons is estimated by using the data. The

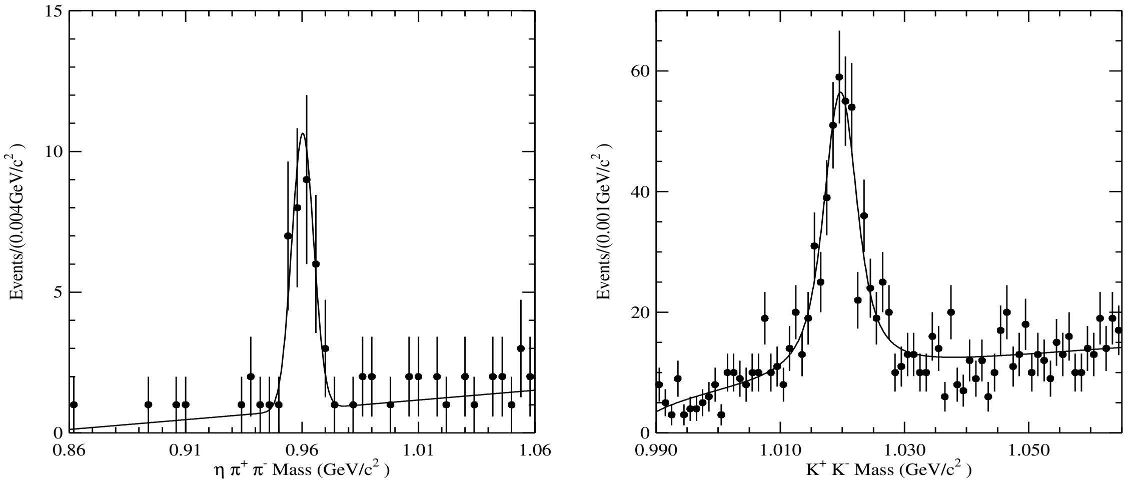

Fig. 3. The $\eta\pi^+\pi^-$ and K^+K^- invariant-mass distributions for $D_s^+ \to \eta'\ell^+\nu$ and $D_s^+ \to \phi\ell^+\nu$ candidates. The curve is the fit to the invariant-mass distribution.

backgrounds from random $X_{s\bar{s}}\ell^+$ combinations and random photon combinations are estimated using the Monte Carlo simulation. We scale the Monte Carlo prediction to account for the $X_{s\bar{s}}$ and γ production rate observed in the data.

We estimate 1.2 ± 0.4 background events for $D_s^+ \to \eta\ell^+\nu$ from $D_s^+ \to \eta'\ell^+\nu$ feed down. The contamination from the decays $D^+ \to \eta\ell^+\nu$ and $D^+ \to \eta'\ell^+\nu$ is negligible since these decay modes are Cabibbo suppressed and $\mathcal{B}(D^{*+} \to D^+\gamma)$ is small.

After subtracting all backgrounds, we find 60.9 ± 9.7 $D_s^+ \to \eta\ell^+\nu$ events and 105.3 ± 11.8 $D_s^+ \to \phi\ell^+\nu$ events. After correcting for the detection efficiency and for the $\eta \to \gamma\gamma$ and $\phi \to K^+K^-$ branching fractions,[6] the efficiency-corrected yields for $D_s^+ \to \eta\ell^+\nu$ and $D_s^+ \to \phi\ell^+\nu$ are 8320 ± 1320 and 4770 ± 530 events, respectively.

The ratio of branching fractions is

$$R_\eta = \frac{\mathcal{B}(D_s^+ \to \eta e^+\nu)}{\mathcal{B}(D_s^+ \to \phi e^+\nu)} = \frac{8320 \pm 1320}{4770 \pm 530} = 1.74 \pm 0.34 \pm 0.24, \qquad (1)$$

where the first error is statistical, and the second is an estimate of systematic effects. The dominant systematic error is the uncertainty in the level of continuum charm background (8.2%). Note that systematics associated with the rate of fake leptons and the scaling of the random photo background mostly cancel since they are correlated in both analyses.

3.2. $D_s^+ \to \eta'\ell^+\nu$ *analysis*

We reconstruct η' with the decay chain $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$. We do not use the D_s^{*+} tag for the $D_s^+ \to \eta'\ell^+\nu$ analysis since the sensitivity for the η' decay chain is 1/5 of that for the $\eta \to \gamma\gamma$ decay. To compensate for the absence of the D_s^{*+} constraint, we apply tighter cuts than those used for $D_s^+ \to \eta\ell^+\nu$ analysis.

Figure 3 shows the $\eta\pi^+\pi^-$ and K^+K^- invariant-mass distributions for all $\eta'\ell^+$ and $\phi\ell^+$ combinations which pass the our selection criteria. The fits yield $29.1^{+6.2}_{-5.6}$ $D_s^+ \to \eta'\ell^+\nu$ candidates and 419 ± 24 $D_s^+ \to \phi\ell^+\nu$ candidates.

The backgrounds are estimated in the same manner as the $D_s^+ \to \eta\ell^+\nu$ analysis. After subtracting all backgrounds, the efficiency corrected yields for $D_s^+ \to \eta'\ell^+\nu$ and $D_s^+ \to \phi\ell^+\nu$ decays are 6100 ± 1600 and 8580 ± 600 events, respectively.

The ratio of branching fractions is

$$R_{\eta'} = \frac{\mathcal{B}(D_s^+ \to \eta' e^+\nu)}{\mathcal{B}(D_s^+ \to \phi e^+\nu)} = \frac{6100 \pm 1600}{8580 \pm 600} = 0.71 \pm 0.19 \pm 0.09, \tag{2}$$

3.3. Implication of $D_s^+ \to \eta\ell^+\nu$ and $D_s^+ \to \eta'\ell^+\nu$ results

The V/P ratio, $\mathcal{B}(D_s^+ \to \phi e^+\nu)/\mathcal{B}(D_s^+ \to (\eta + \eta')e^+\nu)$ is predicted to be 1.19 by a modified ISGW model.[9] This value is considerably higher than our measurement of $1/(R_\eta + R_{\eta'}) = 0.41 \pm 0.06 \pm 0.04$. Our result is consistent with E653 result of $0.26^{+1.7}_{-0.08}$.[2] Our result is also comparable with the V/P ratio for D^0 and D^+ decay, $\mathcal{B}(D \to \overline{K^*}e^+\nu)/\mathcal{B}(D \to \overline{K}e^+\nu) = 0.56 \pm 0.06$.

The factorization hypothesis implies $\mathcal{B}(D_s^+ \to \eta'\rho^+)/\mathcal{B}(D_s^+ \to \eta\rho^+) = \mathcal{B}(D_s^+ \to \eta' e^+\nu)/\mathcal{B}(D_s^+ \to \eta e^+\nu)$. CLEO-II has measured $\mathcal{B}(D_s^+ \to \eta'\rho^+)/\mathcal{B}(D_s^+ \to \eta\rho^+) = 1.20 \pm 0.33$, which is inconsistent with our measurement of $\mathcal{B}(D_s^+ \to \eta' e^+\nu)/\mathcal{B}(D_s^+ \to \eta e^+\nu) = 0.41 \pm 0.13 \pm 0.05$. This disagreement suggests that the factorization hypothesis doesn't hold for D_s^+ decay.

Having measured dominant modes of D_s^+ semileptonic decay, we calculate the absolute branching fraction for $D_s^+ \to \phi e^+\nu$ as,

$$\Gamma(D_s^+ \to \phi e^+\nu) = \frac{\Gamma(D_s^+ \to \phi e^+\nu)}{\Gamma(D_s^+ \to (\phi + \eta + \eta')e^+\nu)} \frac{\Gamma(D_s^+ \to (\phi + \eta + \eta')e^+\nu)}{\Gamma(D_s^+ \to X e^+\nu)} \Gamma(D_s^+ \to X e^+\nu) \tag{3}$$

We assume that $\Gamma(D_s^+ \to (\phi + \eta + \eta')e^+\nu)/\Gamma(D_s^+ \to X e^+\nu) = 0.89 \pm 0.04$ and $\Gamma(D_s^+ \to X e^+\nu) = \Gamma(D \to X e^+\nu)$. Using our measurement of $\Gamma(D_s^+ \to \phi e^+\nu)/\Gamma(D_s^+ \to (\phi + \eta + \eta')e^+\nu) = 1/(1 + R_\eta + R_{\eta'}) = 0.292 \pm 0.040$ and $\Gamma(D^0 \to X e^+\nu) = (16.9 \pm 0.9) \times 10^{10}\ s^{-1}$, we obtain $\Gamma(D_s^+ \to \phi e^+\nu) = (4.35 \pm 0.66) \times 10^{10}\ s^{-1}$. Comparing this result with $\Gamma(D \to \overline{K^*}e^+\nu)$, we find $\Gamma(D_s^+ \to \phi e^+\nu)/\Gamma(D \to \overline{K^*}e^+\nu) = 0.91 \pm 0.16$, which is consistent with prediction of 1.02 by ISGW model.[9] We also find $\mathcal{B}(D_s^+ \to \phi e^+\nu) = (2.06 \pm 0.33)\%$, which is combined with our measurement of $\mathcal{B}(D_s^+ \to \phi e^+\nu)/\mathcal{B}(D_s^+ \to \phi\pi^+) = 0.54 \pm 0.05 \pm 0.04$[10] to obtain $\mathcal{B}(D_s^+ \to \phi\pi^+) = (3.82 \pm 0.74)\%$. The branching fraction for $D_s^+ \to \phi\pi^+$ sets the scale for all D_s^+ hadronic branching fractions.

4. Measurement of $D_s^+ \to \phi e^+\nu$ Form Factor Ratios

We measure $R_2 = A_2(0)/A_1(0)$ and $R_V = V(0)/A_1(0)$ by performing a two-parameter likelihood fit to the decay rate using the three kinematic variables, $|\cos\theta_V|$, $\cos\theta_e$ and q^2/q^2_{max}. A detailed description of this analysis can be found elsewhere.[11]

In order to perform the fit, the functional form for the form factors is assumed to be a single pole form, $F(q^2) = F(0)/(1 - q^2/M_p^2)$. Since the q^2 range in the decay is from 0 to 0.9 GeV/c^2, the results are rather insensitive to the particular parametrization chosen.

The fitting technique follows that developed by the E691 experiment for the determination of the $D^+ \to \overline{K^{*0}}e^+\nu$ form factor ratios.[12] The essence of the method is to determine the probability density function by using the population of appropriately weighted Monte Carlo events in the three-dimensional kinematic space.

Background is incorporated into the fit by constructing the probability $P = N_s p_s + N_b p_b$ where N_s is the number of signal events in the data sample, N_b is the number of background events in this sample, p_s and p_b are the probability densities for the signal and background distributions, respectively. Since the level of background in this analysis is greater than that for any previous analysis, the inclusion of background is studied using two other approaches. The difference in final result due to different approaches is taken into account as a systematic error.

The 474 events of the final data set are fit to the expression for the decay rate in terms of the three kinematic variables. We find: $R_2 = 1.4 \pm 0.5 \pm 0.3$ and $R_V = 0.9 \pm 0.6 \pm 0.3$. Our results are consistent with the previous measurements of the $D_s^+ \to \phi e^+ \nu$ form factor ratios.[13,14] Assuming $SU(3)$ symmetry, R_2 and R_V for the decays $D_s^+ \to \phi e^+ \nu_e$ and $D^+ \to \overline{K^{*0}} e^+ \nu$, should be approximately equal. Further, equality of the form factors for the two decays would imply equal partial widths. The latter point has been the basic assumption for determining the absolute branching ratio $D_s^+ \to \phi \pi^+$ from the ratio of branching ratios $\mathcal{B}(D_s^+ \to \phi e^+ \nu)/\mathcal{B}(D_s^+ \to \phi \pi^+)$. The new world averages including our results, $R_2 = 1.6 \pm 0.4$ and $R_V = 1.4 \pm 0.5$ are similar to those for $D \to \overline{K^*} e^+ \nu$, $R_2 = 0.73 \pm 0.15$ and $R_V = 1.89 \pm 0.25$.

5. Conclusions

In conclusion, we report a new measurement of $\mathcal{B}(D^0 \to X e^+ \nu) = (6.97 \pm 0.18 \pm 0.30)\%$. In D_s^+ sector we still see the disagreement on the V/P ratio between the experimental result and the theoretical prediction. We find similar characteristics for the V/P ratio and form factors between D_s^+ and D semileptonic decays. We obtain the absolute branching fraction of $D_s^+ \to \phi \pi^+$ decay to be $(3.82 \pm 0.74)\%$.

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