Review of Charm Semileptonic Decays and QCD*

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In this paper, we review recent progress in the field of semileptonic decays of charm mesons, including topics on the relative branching ratio and the form factors. The comparison between the experimental form factor measurements and the Lattice QCD calculations is emphasized.

PACS numbers: 13.20.Fc,12.38.Gc

1. Charm semileptonic decays as tests of Lattice QCD

The semileptonic decays of charm mesons provide an ideal environment to refine the QCD physics. The decay rates are computed from the first principles using Cabbibo-Kobayashi-Maskawa quark-mixing matrix elements. The hadronic complications are contained in the form factors, which are calculable via non-perturbative Lattice QCD, HQET or quark models. With the rapid advance in the computer technology, the lattice community is generating visible improvements in major QCD topics. By comparing the experimental measurements on the charm semileptonic decays with the lattice QCD calculations, we can establish a high quality lattice calibration and reduce systematic errors in the Unitary triangle. The QCD techniques validated in the charm decays can be applied to the similar physics topics in the beauty decays, which will definitely improve the precision analysis tools to deal with the excellent data sets generated in the current and future B experiments.

The field of the semileptonic charm physics is quite active. Various new results have been reported recently and several more papers are expected to be published in near future. In the following sessions, some of the results and the corresponding theories are summarized. The charge conjugate modes are implicitly included in all the decay channels mentioned in the paper.

* Presented at XXXIV International Symposium on Multiparticle Dynamics, July 2004, Sonoma County, California, USA

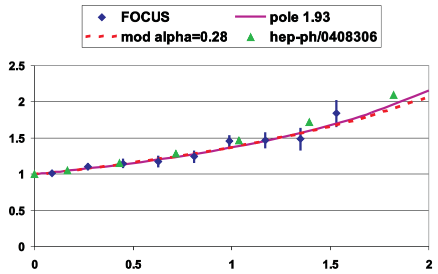

Fig. 1. The overlay of the unquenched LQCD calculation of the form factor $f_+(q^2)$[1] over the preliminary FOCUS preliminary result. The solid line represents a pole form fit to the FOCUS data while the dotted line represents a modified pole form fit. All the data points and the fitted lines are normalized to have $f_+(0) = 1$.

2. The pseudoscalar channel, $D \to Pl\nu$

2.1. The form factors and their parameterization

When a charm meson decays into a single pseudoscalar meson, a lepton and a neutrino, its decay rate can be described by a simple equation of q^2 with an easy-to-extract form factor f_+ as follows,

$$\frac{d\Gamma(D \to Pl\nu)}{dq^2} = \frac{G_F^2 |V_{cq}|^2 P_p^3}{24\pi^3} (|f_+(q^2)|^2 + O(m_l^2)) \tag{1}$$

In the Lattice QCD, the $f_+(q^2)$ distribution is easiest to calculate when $q^2 = q^2_{max}$, since the pseudoscalar meson is at rest in the parent charm meson center of mass frame, which makes the wavelength of the the child quark larger than the lattice size. But the decay rate of the charm meson is smallest at $q^2 = q^2_{max}$, which suppresses the sensitivity to the f_+ measurement. Vice versa, the decay rate of the charm meson is highest when q^2 is smallest, i.e, where the theoretical calculation is least certain. The lattice community is actively working to overcome this problem and reported a remarkably precise result (See Figure 2.1.) [1].

In the past, one used parameterization to describe the $f_+(q^2)$ distribution, since the statistics of the experimental data was not large enough. There are several parameterization forms in current use: The more traditional pole form ($\sim 1/(q^2 - \mathrm{M(pole)}^2)$), the ISGW1 form ($\sim \exp(\alpha q^2)$) and its revision ISGW2 form.[1] The basis of the pole form is as follows: When a charm quark decays into a lighter quark, the parent and the child quark

[1] A recent addition is the modified pole form, which incorporates a second pole effect.

make a spin one resonance during the process, which subsequently annihilates into a W boson. The character of the spin one resonance manifests itself as the pole mass.

Two decay modes have been studied in the pseudoscalar channel, $D^0 \to K^- l^+ \nu$ and $D^0 \to \pi^- l^+ \nu$. The $D^0 \to K^- l^+ \nu$ decay has the merit of larger branching fraction while the $D^0 \to \pi^- l^+ \nu$ decay has a broader q^2 range, which gives it a more discerning power among several parameterization models.

2.2. The new results from $D^0 \to K^- l^+ \nu / \pi^- l^+ \nu$ decays

The CLEO experiment reported preliminary results on the $D^0 \to K^- l^+ \nu$ and the $D^0 \to \pi^- l^+ \nu$ decays [2], based on the $7fp^{-1}$ of data collected with the CLEO III detector. From the pole form fit to the data, they obtained $\mathrm{M(pole)}^{D \to K} = 1.89 \pm 0.05^{+0.04}_{-0.03}\, GeV$ and $\mathrm{M(pole)}^{D \to \pi} = 1.86^{+0.10+0.07}_{-0.06-0.03}\, GeV$. The ISGW2 form fit to the $D^0 \to K^- l^+ \nu$ channel was found to be disfavored by 4.2σ. The relative branching ratio between $D^0 \to \pi^- l^+ \nu$ and $D^0 \to K^- l^+ \nu$ was obtained as $0.082 \pm 0.006 \pm 0.005$ and subsequently,

$$\frac{|f_+^\pi(0)|^2 |V_{cd}|^2}{|f_+^K(0)|^2 |V_{cs}|^2} = 0.038^{+0.006+0.005}_{-0.007-0.003}, \tag{2}$$

where the first error is the statistical and the second error is systematic. If the average numbers for the CKM element the Particle Data Group (PDG) are applied, we get $|f_+^\pi(0)|/|f_+^K(0)| = 0.86 \pm 0.07 \pm 0.05 \pm 0.01$, which confirms the SU(3) symmetry breaking in the charm meson sector.

At the recent DAFNE04 conference, the BELLE experiment reported a preliminary study on the $D^0 \to K^- l^+ \nu$ and $D^0 \to \pi^- l^+ \nu$ decays, based on the $152fp^{-1}$ of data[3]. To obtain a better q^2 resolution, they required the candidate events consist of a prompt D^*, a prompt $\overline{D^*}$ and lighter mesons generated from the primary interaction point. They concluded that it's possible to get a very high precision measurement on the q^2 using the BELLE data set, comparable to the one achievable at a threshold charm factory such as the CLEO-c.

The FOCUS experiment is also analyzing these decays. They reconstructed about 12,000 events in the $D^0 \to K^- \mu^+ \nu$ decay and obtained a non-parametric distribution of the f_+ form factor (See Figure 2.1.).

Figure 2.2 shows the new world average of the $\mathrm{M(pole)}^{D \to K}$ including the preliminary results from the CLEO and the FOCUS, obtained as 1.91 ± 0.03.

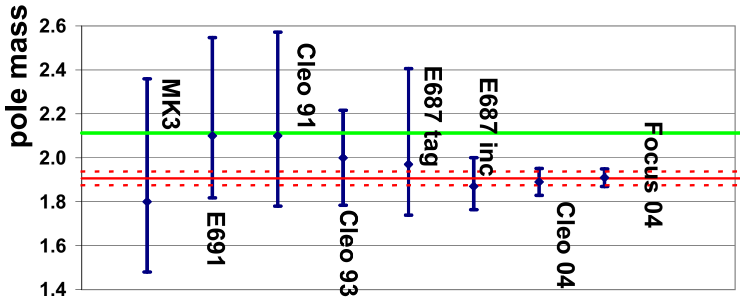

Fig. 2. The compilation of the M(pole)$^{D\to K}$ including the preliminary CLEO and FOCUS results. The new world average is calculated as 1.91 ± 0.03, shown as the lower solid line and two dotted lines in the figure. The upper solid line represents the mass of D_s^*, the pole mass from a naive pole form model.

3. The vector channel, $D \to Vl\nu$

3.1. Kinematics of the vector decays

Several decay modes are available for the study of a charm meson decaying into a vector meson, a lepton and a neutrino. The Cabbibo allowed $D^+ \to \overline{K^{*0}}l^+\nu$ decay is an excellent mode to study, which has the statistical advantage over others. Since the child $\overline{K^{*0}}$ promptly decays into a K^- and a π^+, the kinematics of the $D^+ \to \overline{K^{*0}}l^+\nu$ channel becomes 4-body and is described by two invariant masses and three decay angles. The decay amplitude is written by using these five kinematical variables and three helicity-based form factors: $H_0(q^2)$, $H_+(q^2)$, and $H_-(q^2)$, which can be computed by the lattice QCD. The helicity form factors are combinations of one vector and two axial-vector form factors, which are parameterized in general as,

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2}, \quad V_i(q^2) = \frac{V_i(0)}{1 - q^2/M_V^2}. \tag{3}$$

Traditionally, three observables are used to describe the vector channel: The branching fraction and the form factor ratios r_V and r_2, which are defined as $V(0)/A_1(0)$ and $A_2(0)/A_1(0)$, respectively.

3.2. The s-wave interference in the $D^+ \to K^-\pi^+\mu^+\nu$ decay

In 2002, the FOCUS experiment published a series of paper based on the $D^+ \to K^-\pi^+\mu^+\nu$ decay. A sample of 31,000 $D^+ \to K^-\pi^+\mu^+\nu$ events was reconstructed, providing one of the largest K^{*0} samples in the world. They updated the branching ratio and the form factor measurements with an excellent precision, and they discovered a surprising s-wave component in the decay, which was never seen before in the charm semileptonic decays[4].

When the distribution of the decay angle of K^- in the $K^-\pi^+$ system was analyzed, a huge forward-backward asymmetry was found, with its amplitude depending on the invariant mass of the $K^-\pi^+$. One possible explanation was a quantum interference between the K^{*0} and a s-wave component. They assumed a simple toy s-wave model with a constant amplitude and a phase, and fitted the asymmetry. The amplitude was measured about 7% of the K^{*0} Breit-Wigner amplitude and the relative phase between the s-wave and the K^{*0} was measured at 45 degrees. Remarkably, the relative phase of the new s-wave component were comparable to the one measured from a t-channel $K-\pi$ scattering experiment by the LASS Collaboration[5]. This compatibility is not unexpected, since the semileptonic decays do not involve final state interactions.

3.3. The measurement of the form factors in the D^+ decay

The FOCUS experiment measured the form factors of the $D^+ \to \overline{K^{*0}}\mu^+\nu$ decays, including the effects of the s-wave. The r_V and r_2 were obtained as $1.504 \pm 0.057 \pm 0.039$ and $0.875 \pm 0.049 \pm 0.064$, respectively[6]. The FOCUS r_V value is 2.9σ away from the one measured by the E791 Collaboration, the previous world best[7]. The updated world averages of the form factor ratios are 1.62 ± 0.08 and 0.83 ± 0.05, respectively.

3.4. The measurement of the form factors in the D_s decay

According to the theoretical calculations, the form factors of the $D_s^+ \to \phi l^+\nu$ decay should be comparable to those of the $D^+ \to \overline{K^{*0}} l^+\nu$ decay within 10%. In the past, the r_V measurement was consistent between the D_s and the D^+ decays, but the r_2 of the D_s decay was found twice the size of that of the D^+ decay. Recently, the FOCUS experiment published a paper on the $D_s^+ \to \phi\mu^+\nu$ decay[8], where they measured the form factor ratios r_V and r_2 as $1.549 \pm 0.250 \pm 0.145$ and $0.713 \pm 0.202 \pm 0.266$, respectively. Both values are consistent with those for the $D^+ \to \overline{K^{*0}} l^+\nu$ decays.

4. The direct measurement of the $\Gamma(K^*\mu\nu)/\Gamma(K\mu\nu)$ ratio

In a naive model, the branching ratio of the vector charm semileptonic decays (via a K^*) over the pseudoscalar ones (via a K) is about one. During the 90's, both the theoretical calculations and the experimental measurements obtained smaller vector decay rate (See Figure 4.),

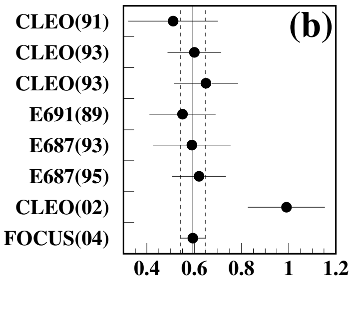

Fig. 3. (a) The compilation of the theoretical calculations on the relative branching ratio of $\Gamma(K^* l\nu)/\Gamma(Kl\nu)$. (b) The compilation of the experimental measurements, including both electron and muon channels. For both plots, the sold lines and the dashed lines represent the value and the error of the recent FOCUS measurement. The CLEO 2002 number was obtained by using the PDG 2002 $\Gamma(D^+ \to \overline{K^0} e^+ \nu)$ value. Courtesy of Prof. Will Johns of Vanderbilt University.

but a year 2002 analysis by the CLEO measured the ratio near unity, which fact generated an urgency to require further investigation. Recently, the FOCUS group measured the ratio directly using the $D^+ \to \overline{K^{*0}} \mu^+ \nu$ and $D^+ \to \overline{K^0} \mu^+ \nu$ decays and obtained $0.594 \pm 0.043 \pm 0.033$, confirming the measurements from 90's[9]. The CLEO 2002 measurement was obtained indirectly, by dividing the $\Gamma(D^+ \to \overline{K^{*0}} e^+ \nu)/\Gamma(D^+ \to K^- \pi^+ \pi^+)$ branching ratio with the average $\Gamma(D^+ \to \overline{K^0} e^+ \nu)$ from the PDG 2000. The discrepancy between the CLEO 2002 measurement and the other experimental measurements is partly due to the slightly higher value for the $\Gamma(D^+ \to \overline{K^{*0}} e^+ \nu)/\Gamma(D^+ \to K^- \pi^+ \pi^+)$ and partly due to the PDG $\Gamma(D^+ \to \overline{K^0} e^+ \nu)$ number, which is much lower than the new FOCUS measurement, $\Gamma(D^+ \to \overline{K^0} \mu^+ \nu) = 9.27 \pm 0.69 \pm 0.59 \pm 0.62$.

5. Summary

Various results from the recent analysis on the charm semileptonic decays were reviewed. In the pseudoscalar channel, the pole mass and the branching ratio measurements are being updated by several experiments. In the vector channel, a new s-wave interference phenomena was found in the D^+ decay, and the form factors were updated for both D^+ and D_s decays, found to be consistent between two decay modes. The vector to pseudoscalar decay ratio was updated with a consistent value to the 90's measurements.

The CLEO-c experiment started data taking, showing a promising future and other experiments are collecting high quality charm data sets. We expect to resolve the various problems in the semileptonic charm physics with excellent statistics in near future.

Acknowledgments

This work was supported by University of Illinois under contract DE-FG02-91ER-40677 with the U.S. Department of Energy.

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