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Recent Experimental Results on Semileptonic D Decays and Determination of $|V_{cd(s)}|$

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Semileptonic D decays provide a window on both the weak and strong interactions. The magnitudes of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix elements $|V_{cd}|$ and $|V_{cs}|$ can be determined from measurements of the semileptonic D decays supplemented by theoretical calculations for corresponding hadronic form factors. On the other hand, the hadronic form factors can be determined from decay rates in conjunction with the $|V_{cd(s)}|$ obtained from the CKM unitarity. These determined $|V_{cd}|$ and $|V_{cs}|$ can be used to check the unitarity of the CKM matrix in the Standard Model (SM) of particle physics and search for New Physics (NP) beyond the SM, while the precisely determined form factors can be used to validate the lattice quantum chromodynamics (LQCD) calculations of these form factors and then to improve determinations of other CKM matrix elements, as well as improve determination of unitarity trangle of the CKM matrix. These could help more precisely test the SM and search for NP beyond the SM. In this paper, we first briefly review some recent experimental results of semileptonic D decays and measurements of the form factors from the BABAR, Belle, BESIII and CLEO-c experiments. We then present some determinations of the $|V_{cd}|$ and $|V_{cs}|$ from these experiments and some updated determinations of these $|V_{cd}|$ and $|V_{cs}|$ extracted from all available measurements of semileptonic D decays as well as leptonic $D^+_{(s)}$ decays measured at all experiments in the last thirty years.

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1. Introduction

Semileptonic decays of D mesons play an important role in understanding of both the weak and strong interactions. The amplitude of the semileptonic D decay is proportional to a product of a leptonic and a hadronic weak-currents, where the hadronic weak-current describes the nonperturbative strong interaction of binding quarks into hadrons. These nonperturbative strong interaction effects can be parameterized by one or more form factors which can be calculated in lattice quantum chromodynamics (LQCD). As the weak and strong interactions can be well separated, the semileptonic D decays provide an excellent means not only to investigate the decay dynamics, but also to extract the quark mixing parameters $|V_{cd}|$ and $|V_{cs}|$, which are two of the nine weak-current quark coupling elements of the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) matrix [1].

In the standard model (SM) of particle physics the CKM matrix is unitary. This unitarity can be checked with the first, second and third column/row unitarity. In addition, the unitarity also gives rise to unitarity triangle (UT) relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$. To check for this column/row unitarity and the UT relation, many experimental measurements and theoretical efforts have been made in flavor physics for many years. If any of these consistency checks significantly deviate from unitarity, it may indicate some evidence for New Physics (NP) effects beyond the SM involved in these related meson decays. In addition, the unitarity of the CKM matrix implies that the $|V_{cd}|$ coincides with the $|V_{us}|$. Comparing a more precisely extracted value of $|V_{cd}|$ from experimental measurements with the value of $|V_{cd}|$ obtained by imposing unitarity of the CKM matrix would also represent an indication of presence or absence of NP in these related meson decays. On the other hand, combined measurements of semileptonic D decay rates and the $|V_{cd(s)}|$ from the unitarity, the form factors can be determined. These determined form factors can be used to validate LQCD calculations of the form factors, and then improve determinations of other CKM matrix elements as well as further reduce uncertainty in the determined UT in flavor physics [2].

In recent years, many experimental studies of semileptonic D decays were performed at τ-Charm experiments and B factories. In this paper, we first briefly review some recent experimental results on $D \to Ve^+\nu_e$ and $D \to Pe^+\nu_e$ decays (V and P denote vector and pseudoscalar meson, respectively), and measurements of the form factors performed at the BABAR, Belle, BESIII and CLEO-c experiments, then we present some determinations of the $|V_{cd}|$ and $|V_{cs}|$ from these experiments and some updated determinations of $|V_{cd}|$ and $|V_{cs}|$ which were extracted from all available measurements of both semileptonic D decays and leptonic $D^+_{(s)}$ decays measured at all experiments in the last thirty years. After these we present an updated check of the unitarity of the CKM matrix with these more precisely determined $|V_{cd}|$ and $|V_{cs}|$.

2. $D \to Ve^+\nu_e$ Decays

2.1 Differential decay rate and form factors of $D^+ \to K^-\pi^+e^+\nu_e$ decay

For the decay process $D \to Ve^+\nu_e$, where $V \to P_1P_2$ (P_1 and P_2 are pseudoscalar mesons), the differential decay rate can be expressed in terms of five kinematic variables: (1) m^2, the mass squared of the P_1P_2 system; (2) q^2, the mass squared of the $e^+\nu_e$ system; (3) θ_V, the angle between the P_1 and the D direction in the P_1P_2 rest frame, (4) θ_e, the angle between the ν_e and the D direction in the $e^+\nu_e$ rest frame, (5) χ, the acoplanarity angle between the two decay planes. The differential decay rate of this D decay is given by [3, 4]

$$\frac{d\Gamma(D\to Ve^+\nu_e)}{dm^2dq^2d\cos\theta_V d\cos\theta_e d\chi}=\frac{G_F^2|V_{cq'}|^2}{(4\pi)^6m_D^2}X\beta I(m^2,q^2,\theta_V,\theta_e,\chi), \tag{2.1}$$

where $X=p_{P_1P_2}m_D$, $p_{P_1P_2}$ is the momentum of the P_1P_2 system in the D rest frame, m_D is the mass of the D meson, $\beta=2p^*/m$, p^* is the breakup momentum of the P_1P_2 system in the D rest frame, $V_{cq'}$ ($q'=d$, s) is the CKM matrix element for $c\to q'$, and I can be expressed in terms of helicity amplitudes $H_{0,\pm}$:

$$H_0(q^2)=\frac{1}{2mq}[(m_D^2-m^2-q^2)(m_D+m)A_1(q^2)-4\frac{m_D^2p_{P_1P_2}^2}{m_D+m}A_2(q^2)]$$

and

$$H_\pm(q^2)=(m_D+m)A_1(q^2)\mp\frac{2m_Dp_{P_1P_2}}{m_D+m}V(q^2)].$$

In these three helicity amplitudes, $A_1(q^2)$ and $A_2(q^2)$ are two axial-vector form factors, and $V(q^2)$ is the vector form factor. Under assumption of the single pole dominance, these form factors are given by

$$A_1(q^2)=\frac{A_1(0)}{1-q^2/m_A^2},\quad A_2(q^2)=\frac{A_2(0)}{1-q^2/m_A^2}\quad\text{and}\quad V(q^2)=\frac{V(0)}{1-q^2/m_V^2},$$

where m_A and m_V are the axial-vector and vector pole masses, respectively. These form factors and pole masses can be experimentally measured with $D\to Ve^+\nu_e$ decays. Experiments often measured below two ratios of these three from factors

$$r_V=\frac{V(0)}{A_1(0)}\quad\text{and}\quad r_2=\frac{A_2(0)}{A_1(0)}.$$

2.2 Results from $D^+\to K^-\pi^+e^+\nu_e$ decay

In 2011, the BABAR Collaboration studied the semileptonic decay $D^+\to K^-\pi^+e^+\nu_e$ using 347.5 fb^{-1} data collected with the BABAR detector at the PEP-II e^+e^- collider. By analyzing the five-dimensional differential decay rates as shown in Eq. (2.1) or the five-dimensional distributions of these kinematic variables for this decay, the BABAR Collaboration measured the mass and width of $K^*(892)^0$ to be $m_{K^*(892)^0}=(895.4\pm0.2\pm0.2)$ MeV/c^2, $\Gamma_{K^*(892)^0}=(46.5\pm0.3\pm0.2)$ MeV, and measured the branching fraction to be $\mathscr{B}(D^+\to K^-\pi^+e^+\nu_e)=(4.00\pm0.03\pm0.04\pm0.09)\%$, $\mathscr{B}(D^+\to K^-\pi^+e^+\nu_e)_{K^*(892)^0}=(3.77\pm0.04\pm0.05\pm0.09)\%$, and $\mathscr{B}(D^+\to K^-\pi^+e^+\nu_e)_{S-\mathrm{wave}}=(0.232\pm0.007\pm0.007\pm0.005)\%$. The BABAR measured the form factor ratios of $r_V=1.463\pm0.017\pm0.031$ and $r_2=0.801\pm0.020\pm0.020$, and measured axial-vector pole mass of $m_A=(2.63\pm0.10\pm0.13)$ GeV/c^2.

Similarly, the BESIII Collaboration recently performed an analysis of the semileptonic $D^+\to K^-\pi^+e^+\nu_e$ decays using a 2.92 fb^{-1} data sample taken with the BESIII detector at 3.773 GeV. From analysis of five-dimensional distributions of these kinematic variables [see Eq. (2.1)] for this decay, they measured $m_{K^*(892)^0}=(894.60\pm0.25\pm0.08)$ MeV/c^2, $\Gamma_{K^*(892)^0}=(46.42\pm0.56\pm0.15)$ MeV and obtained fractions of the signal components to be $f(D^+\to(K^-\pi^+)_{K^*(892)^0}e^+\nu_e)=$

$(93.93 \pm 0.22 \pm 0.18)\%$, and $f(D^+ \to (K^-\pi^+)_{S-\mathrm{wave}} e^+ \nu_e) = (6.05 \pm 0.22 \pm 0.18)\%$. In addition, they measured the form factor ratios of $r_V = 1.411 \pm 0.058 \pm 0.007$ and $r_2 = 0.788 \pm 0.042 \pm 0.008$, and measured the vector and axial-vector pole masses of $m_V = (1.81^{+0.25}_{-0.17} \pm 0.02)$ GeV/c^2 and $m_A = (2.61^{+0.22}_{-0.17} \pm 0.03)$ GeV/c^2 [5].

A comparison of the experimental measurements to some theoretical expectations for these form factor ratios and pole masses is shown in Fig. 1. The average of these form factor ratios measured at the two experiments are $\bar{r}_V = 1.449 \pm 0.030$ and $\bar{r}_2 = 0.797 \pm 0.024$.

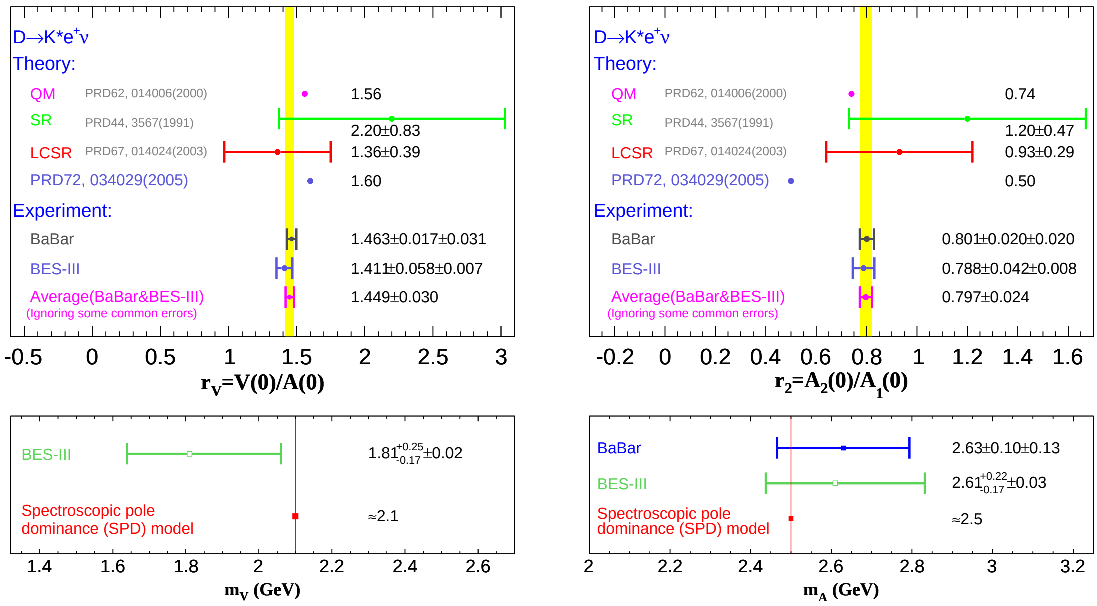

Figure 1: Comparison of some theoretical predictions and the measurements of the form factor ratios $r_V \equiv \frac{V(0)}{A_1(0)}$ and $r_2 \equiv \frac{A_2(0)}{A_1(0)}$, and the vector pole mass m_V as well as axial-vector pole mass m_A for $D^+ \to K^-\pi^+ e^+ \nu_e$ decay, where the measurements were performed at the *BABAR* and BESIII experiments.

2.3 Results from $D^0 \to \rho^- l^+ \nu_l$ and $D^+ \to \rho^0 l^+ \nu_l$ decays

The CLEO Collaboration made measurements of $D^0 \to \rho^- l^+ \nu_l$ and $D^+ \to \rho^0 l^+ \nu_l$ ($l = e$ or μ) decays based on 0.82 fb^{-1} data taken at the peak of the $\psi(3770)$ resonance in 2013. Using double tag technique the CLEO Collaboration made an analysis of four-dimensional distributions of these kinematic variables [6], and measured the branching fractions $\mathcal{B}(D^0 \to \rho^- l^+ \nu_l) = (1.77 \pm 0.12 \pm 0.10)\%$ and $\mathcal{B}(D^+ \to \rho^0 l^+ \nu_l) = (2.17 \pm 0.12^{+0.12}_{-0.22})\%$. They also measured $\frac{\Gamma(D^0 \to \rho^- l^+ \nu_l)}{2\Gamma(D^+ \to \rho^0 l^+ \nu_l)} = 1.03 \pm 0.09^{+0.08}_{-0.02}$, indicating that the isospin conservation is held in these decays. In addition, they measured $r_V = 1.48 \pm 0.15 \pm 0.05$ and $r_2 = 0.83 \pm 0.11 \pm 0.04$ [6].

The upper two figures in Fig. 2 shows comparison of some theoretical predictions for the form factor ratios and that measured at the CLEO-c experiment.

2.4 Results from $D^+ \to \omega e^+ \nu_e$ and $D^+ \to \phi e^+ \nu_e$ decays

From 0.82 fb^{-1} data taken at the peak of the $\psi(3770)$ resonance, the CLEO measured the branching fraction for $D^+ \to \omega l^+ \nu_l$ decay to be $\mathcal{B}(D^+ \to \omega l^+ \nu_l) = (1.82 \pm 0.18 \pm 0.07)\%$ [6].

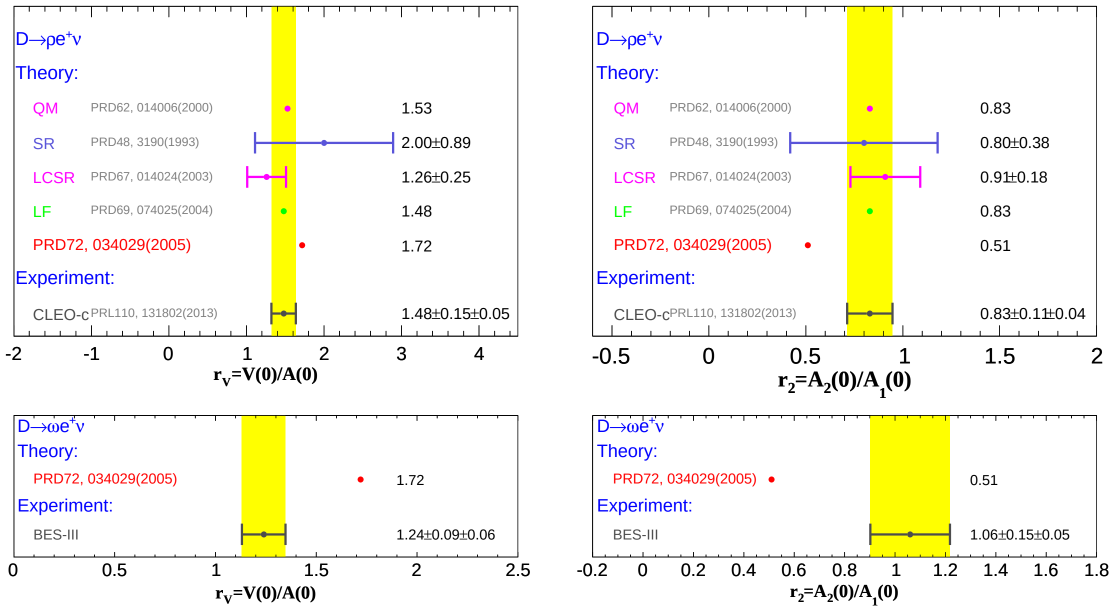

Figure 2: Comparison of theoretical predictions for form factor ratios and measurements of these ratios, the upper two figures are for the decay $D \to \rho l^+ \nu_l$ measured at the CLEO-c experiment, while the bottom two figures are for the decay $D^+ \to \omega l^+ \nu_l$ measured at the BESIII experiment.

Using a similar way as the one for analysis of $D^+ \to K^- \pi^+ e^+ \nu_e$ decay, the BESIII Collaboration recently studied the $D^+ \to \omega e^+ \nu_e$ decay, where $\omega \to \pi^+ \pi^- \pi^0$. By analyzing multi-dimensional distributions of kinematic variables selected from 2.92 fb^{-1} data sample taken at 3.773 GeV, the BESIII Collaboration made an improved measurement of the branching fraction for $D^+ \to \omega e^+ \nu_e$ decay to be $\mathscr{B}(D^+ \to \omega e^+ \nu_e) = (0.163 \pm 0.011 \pm 0.008)\%$ [5]. In addition, they measured the form factor ratios of $r_V = 1.24 \pm 0.09 \pm 0.06$ and $r_2 = 1.06 \pm 0.15 \pm 0.05$. The comparison of the measured form factor ratios and some theoretical expectations for these ratios are illustrated in the two bottom figures in Fig. 2.

From this data sample the BESIII searched for the $D^+ \to \phi e^+ \nu_e$ decay. But, they did not observe any significant event for this decay. They set an upper limit of the decay branching fraction to be $\mathscr{B}(D^+ \to \phi e^+ \nu_e) < 1.3 \times 10^{-5}$ at 90% CL.

3. $D \to P e^+ \nu_e$ Deacys

3.1 Differential decay rate of $D \to P e^+ \nu_e$ decay

In the SM, the differential decay rate of $D \to P e^+ \nu_e$ $(P = \pi, K)$ decay relates to a product of decay form factor $f_+^P(q^2)$ and the CKM matrix element $V_{cq'}$ by

$$\frac{d\Gamma(D \to P e^+ \nu_e)}{dq^2} = Y \frac{G_F^2}{24\pi^3} |\vec{p}|^3 |f_+^P(q^2)|^2 |V_{cq'}|^2, \tag{3.1}$$

where q^2 is square of the four-momenta transfer, $\vec{p}$ is the three-momentum of the P meson in the rest frame of the D meson, and Y is a factor due to isospin, which equals to 1 for $P = \pi^-, K^-, \bar{K}^0$, and equals to $1/2$ for $P = \pi^0$. From the differential decay rates of this semileptonic D decay the product $|f_+^P(q^2)|\ |V_{cq'}|$ can be directly measured. Then the $f_+^P(q^2)$ ($|V_{cq'}|$) can be determined in conjunction with the value of $|V_{cq'}|$ ($f_+^P(q^2)$) from the CKM unitarity (calculated in the LQCD). The determined $|V_{cq'}|$ can be used to test the CKM unitarity, while the determined $f_+^P(q^2)$ can be used to validate LQCD calculations of the form factor which can help improve determinations of other CKM matrix elements, and help in precision test of the SM and search for NP.

3.2 Recent results of $D \to Pe^+\nu_e$ decays

In 2006, the Belle Collaboration made measurements of $D^0 \to \pi^- l^+ \nu_l$ and $D^0 \to K^- l^+ \nu_l$ decays. In analysis of 282 fb^{-1} data taken at 10.58 GeV they measured decay branching fractions $\mathcal{B}(D^0 \to K^- l^+ \nu_l) = (3.45 \pm 0.07 \pm 0.20)\%$ and $\mathcal{B}(D^0 \to \pi^- l^+ \nu_l) = (0.255 \pm 0.019 \pm 0.016)\%$, extracted the form factors $f_+^\pi(q^2)$ and $f_+^K(q^2)$ from these decays, and determined $f_+^\pi(0) = 0.624 \pm 0.020 \pm 0.030$ as well as $f_+^K(0) = 0.695 \pm 0.007 \pm 0.022$ [7].

The BABAR Collaboration recently reported a measurement of $D^0 \to \pi^- e^+ \nu_e$ decays. In a 347.2 fb^{-1} data sample taken near 10.6 GeV, they observed 5300 $D^0 \to \pi^- e^+ \nu_e$ events and measured a relative branching ratio $R_B = \mathcal{B}(D^0 \to \pi^- e^+ \nu_e)/\mathcal{B}(D^0 \to K^- \pi^+) = 0.0702 \pm 0.0017 \pm 0.0023$ and determined $\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = (0.2770 \pm 0.0068 \pm 0.0092 \pm 0.0037)\%$. They also measured $f_+^\pi(0)|V_{cd}| = 0.1374 \pm 0.0038 \pm 0.0022 \pm 0.0009$ [8]. By analyzing 75 fb^{-1} data sample taken near 10.6 GeV, the BABAR determined branching fraction $\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.522 \pm 0.027 \pm 0.065)\%$ and obtained $f_+^K(0) = 0.727 \pm 0.007 \pm 0.005 \pm 0.007$ [9]. Multiplying this $f_+^K(0) = 0.727 \pm 0.007 \pm 0.005 \pm 0.007$ by $|V_{cs}| = 0.9729 \pm 0.0003$ used in their paper yields $f_+^K(0)|V_{cs}| = 0.707 \pm 0.007 \pm 0.005 \pm 0.007$.

In 2009, the CLEO Collaboration studied the semileptonic decays of $D^0 \to \pi^- e^+ \nu_e$, $D^0 \to K^- e^+ \nu_e$, $D^+ \to \pi^0 e^+ \nu_e$ and $D^+ \to \bar{K}^0 e^+ \nu_e$ by analyzing 0.82 fb^{-1} data taken at 3.773 GeV. The CLEO Collaboration measured these decay branching fractions to be $\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = (0.288 \pm 0.008 \pm 0.003)\%$, $\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.50 \pm 0.03 \pm 0.04)\%$, $\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e) = (0.405 \pm 0.016 \pm 0.009)\%$ and $\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.83 \pm 0.10 \pm 0.20)\%$. By analyzing q^2 spectra of these decays in combining these neutral and charged D decay modes together, they obtained $f_+^\pi(0)|V_{cd}| = 0.150 \pm 0.004 \pm 0.001$ and $f_+^K(0)|V_{cs}| = 0.719 \pm 0.006 \pm 0.005$ [10], where the first errors are statistical and the second systematic.

Recently, the BESIII Collaboration reported preliminary results on measurements of $D^0 \to \pi^- e^+ \nu_e$ and $D^0 \to K^- e^+ \nu_e$ decays. From 2.92 fb^{-1} data taken at 3.773 GeV, the BESIII Collaboration accumulated $(279.3 \pm 0.4) \times 10^4$ $\bar{D}^0$ tags with five hadronic decay modes. In this sample of $\bar{D}^0$ tags, they observed 6297 ± 87 and 70727 ± 278 signal events for $D^0 \to \pi^- e^+ \nu_e$ and $D^0 \to K^- e^+ \nu_e$ decays, respectively, and measured the branching fractions $\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = (0.2950 \pm 0.0041 \pm 0.0026)\%$ and $\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033)\%$ [11]. By analyzing differential decay rates [see Eq. (3.1)] of these two decays, they directly measured $f_+^\pi(0)|V_{cd}| = 0.1420 \pm 0.0024 \pm 0.0010$ and $f_+^K(0)|V_{cs}| = 0.7196 \pm 0.0035 \pm 0.0041$ [11], where the first errors are statistical and the second systematic.

After adopting a technique of partial reconstructing K_L^0 meson, the BESIII Collaboration studied the semileptonic $D^+ \to K_L^0 e^+ \nu_e$ decay [5] and measured the decay branching fraction $\mathcal{B}(D^+ \to K_L^0 e^+ \nu_e) = (4.482 \pm 0.027 \pm 0.103)\%$. In addition, they measured CP asymmetry to

Table 1: Comparison of $|V_{cd}|$ and $|V_{cs}|$ measurements.

Experiment	$\lvert V_{cd}\rvert$	$\lvert V_{cs}\rvert$
BABAR [8]	$0.206 \pm 0.007 \pm 0.009$	N/A
BESIII [11]	$0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094$	$0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239$
CLEO-c [10]	$0.234 \pm 0.007 \pm 0.002 \pm 0.025$	$0.985 \pm 0.009 \pm 0.006 \pm 0.103$

be $\mathscr{A}_{CP}^{D^+ \to K_L^0 e^+ \nu_e} = (-0.59 \pm 0.60 \pm 1.48)\%$ in this decay, which is consistent with no significant *CP* violation signal observed in this decay. From q^2 spectra [see Eq. (3.1)] of this decay the BESIII Collabration directly measured $f_+^K(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$.

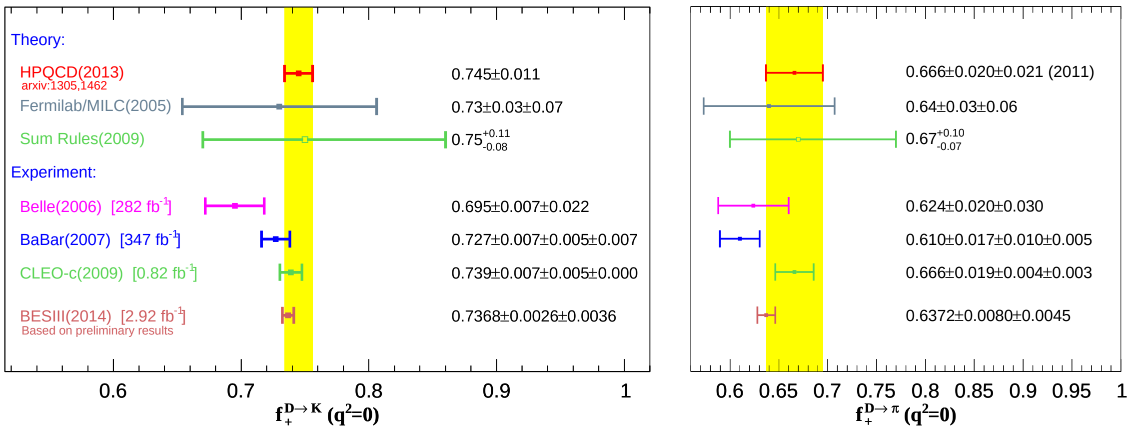

Figure 3: Comparison of measurements and theoretical predictions for $f_+^K(0)$ and $f_+^\pi(0)$, where the number in square brackets is the luminosity of the data sample used in the measurement.

Combining the directly measured $f_+^{\pi(K)}(0)|V_{cd(s)}|$ together with the $|V_{cd(s)}|$ from the CKM unitarity, the *BABAR* , BESIII and CLEO Collaborations obtained the form factors $f_+^\pi(0)$ and $f_+^K(0)$. These $f_+^\pi(0)$ and $f_+^K(0)$ from the *BABAR*, Belle, BESIII and CLEO-c experiments and some theoretical predictions for the form factors are compared in Fig. 3. These experimentally determined values of the form factors are in good agreement with the values of the form factors calculated in LQCD and QCD sum rules. Averaging these values of the form factors determined at the four experiments yields

$$f_+^\pi(0) = 0.637 \pm 0.008 \qquad \text{and} \qquad f_+^K(0) = 0.735 \pm 0.004,$$

which are almost a factor of 4 and 3 more precisions than that calculated in LQCD, respectively.

4. Extraction of $|V_{cd}|$ and $|V_{cs}|$

Based on directly measured product $f_+^{\pi(K)}(0)|V_{cd(s)}|$, the *BABAR*, BESIII and CLEO Collaborations determined $|V_{cd}|$ and $|V_{cs}|$, which are summarized in Table 1. In addition to these, there are several determinations of these $|V_{cd}|$ and $|V_{cs}|$ based on measured branching fractions of D decays from these four experiments or from other experiments [12].

In order to more precisely determine $|V_{cd}|$ and $|V_{cs}|$, several authors [13, 14] globally analyzed all available measurements of branching fractions and/or rates of $D \to \pi e^+ \nu_e$ and $D \to K e^+ \nu_e$ decays to extract product $f_+^{\pi(K)}(q^2)|V_{cd(s)}|$ in this year. Figure 4 shows the product $f_+^{\pi(K)}(q^2)|V_{cd(s)}|$ which were translated from various measurements of these two semileptonic decays, where the blue curves represent the best fits to the data. The fits yield the products $f_+^{\pi}(0)|V_{cd}| = 0.1428 \pm 0.0019^{+0.0019}_{-0.0011}$ and $f_+^K(0)|V_{cs}| = 0.717 \pm 0.004$. With the LQCD results of $f_+^{\pi}(0) = 0.666 \pm 0.029$ [15] and $f_+^K(0) = 0.745 \pm 0.011$ [16] as inputs, the magnitudes of these two CKM matrix elements are determined to be

$$|V_{cd}| = 0.2144^{+0.0040}_{-0.0033} \pm 0.0093 \qquad \text{(from } D \to \pi l^+ \nu_l \text{ decays)}$$

and

$$|V_{cs}| = 0.962 \pm 0.005 \pm 0.014 \qquad \text{(from } D \to K l^+ \nu_l \text{ decays)},$$

which are the most precise determinations of $|V_{cd}|$ and $|V_{cs}|$ from semileptonic D decays up to date [13, 14].

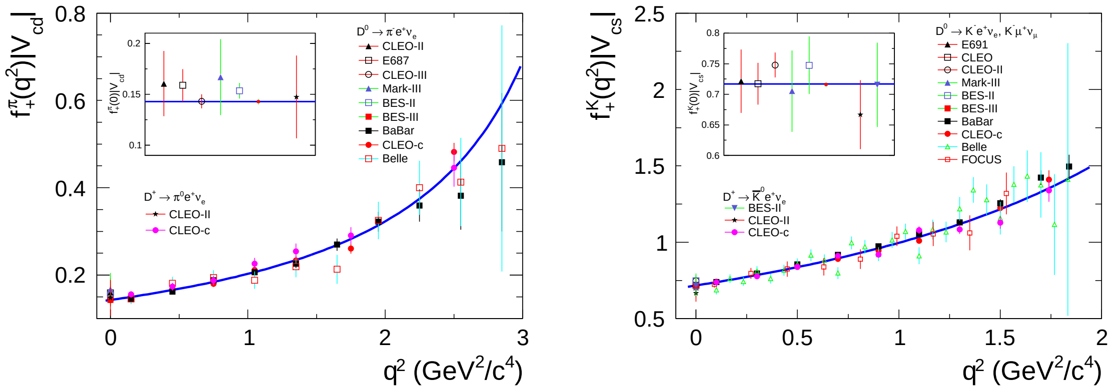

Figure 4: The product $f_+(q^2)|V_{cq'}|$ as a function of q^2, which are obtained by globally analyzing all available measurements of semileptonic D decays.

Combining the measurements of semileptonic D decays and leptonic $D^+_{(s)}$ decays together with the latest LQCD calculations of the corresponding decay form factors and decay constants, these authors found [13, 14]

$$|V_{cd}| = 0.2157 \pm 0.0045$$

and

$$|V_{cs}| = 0.983 \pm 0.011,$$

which are the most precise determination of $|V_{cd}|$ and $|V_{cs}|$ up to date. Figure 5 shows the comparisons of the values of $|V_{cd}|$ and $|V_{cs}|$ extracted by various groups with various approaches.

Using the most precise values of $|V_{cd}|$ and $|V_{cs}|$ and the values of other CKM matrix elements given by PDG [17], the unitarity of the CKM matrix are checked for the first column, second column and the second row. The unitarity test results are shown in Fig. 6 together with the PDG2014 [17] values of these. It is found that $|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 - 1 = -0.004 \pm 0.002$ deviates from the unitarity by 2 standard deviation. If we directly compare the value of $|V_{cd}| = 0.2157 \pm$

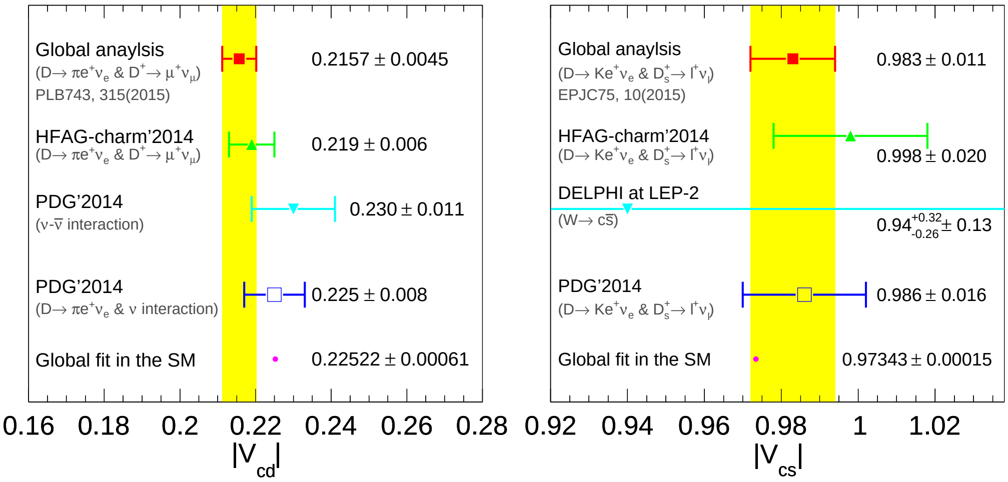

Figure 5: Comparison of $|V_{cd}|$ and $|V_{cs}|$.

0.0045 extracted from experimental measurements with $|V_{cd}|_{\rm GFSM} = 0.22522 \pm 0.00062$ [17] from the global fit in the SM, we find that $|V_{cd}| = 0.2157 \pm 0.0045$ (see left figure in Fig. 5) deviates from the SM prediction by 2.1 standard deviation. These may indicate some evidence for NP effects involved in related meson decays.

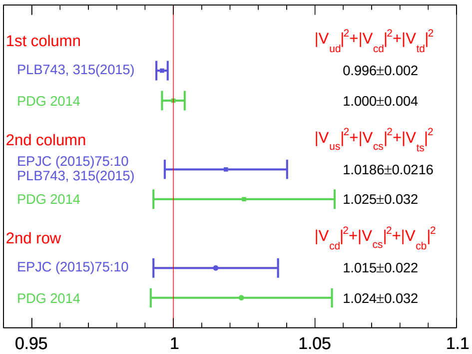

Figure 6: Unitarity checks for the first column, second column and second row of the CKM matrix.

5. Summary

In the last few years, many precise measurements of semileptonic decays of D mesons were performed at e^+e^- experiments with high statistics. These precise measurements of semileptonic D decays lead more precise determinations of both the decay form factors and the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$. The uncertainties of the averages of the form factor ratios $\Delta r_V/r_V$ and $\Delta r_2/r_2$ measured at the *BABAR*, BESIII and CLEO-c experiments achieved to 2.1% and 3.0% already. The average of the measured form factors $f_+^{\pi(K)}(0)$ from the *BABAR*, Belle, BESIII and CLEO-c experiments are consistent within error with those calculated in LQCD, but with a factor of 4 (3) more precisions than that calculated in LQCD. By analyzing all available measurements of semileptonic D decays and leptonic $D^+_{(s)}$ decays together, in conjunction with the recent LQCD calculations for these form factors and decay constants, ones find $|V_{cd}| = 0.2157 \pm 0.0045$ and $|V_{cs}| = 0.983 \pm 0.011$, which are the most precise determinations of $|V_{cd}|$ and $|V_{cs}|$ up to date. At present, the uncertainties of the extracted $|V_{cd}|$ and $|V_{cs}|$ are still dominated by the errors of $f_+^{\pi(K)}(0)$ calculated in LQCD. If these errors of $f_+^{\pi(K)}(0)$ calculated in LQCD could be negligible, the relative accuracy of $|V_{cd}|$ and $|V_{cs}|$ from semileptonic D decays could reach to $\Delta|V_{cd}|/|V_{cd}| \sim 1.2\%$ and $\Delta|V_{cs}|/|V_{cs}| \sim 0.5\%$. With the more precisely determined $|V_{cd}|$ together with the $|V_{ud}|$ and $|V_{td}|$ given in PDG2014 [17], an updated unitarity check shows $|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 - 1 = -0.004 \pm 0.002$ deviating from the unitarity by 2 standard deviation, which may indicate some evidence for NP effects involved in related meson decays. At present the uncertainty of the unitarity check is still large. This uncertainty could be reduced when the precision of the value of $f_+^{\pi}(0)$ calculated in LQCD increase to the comparable precision of the value of $f_+^{\pi}(0)$ determined at the experiments in the future.

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