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Leptonic and semileptonic D meson decays

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Herein, we report recently improved measurements of the decay constants $f_{D^+_{(s)}}$, the form factors $f_+^{K(\pi)}(0)$, and the CKM matrix element $|V_{cs(d)}|$, which are made based on analysis of $D^+_{(s)} \to \ell^+ \nu_\ell$ and $D^0 \to K(\pi)^- e^+ \nu_e$ at BABAR, BELLE and BESIII. These provide important information to better validate the LQCD calculations of $f_{D^+_{(s)}}$ and $f_+^{K(\pi)}(0)$, and to better test the unitarity of the CKM matrix.

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1. Introduction

In the Standard Model, the $D^+_{(s)}$ mesons decay into $\ell\nu_\ell$ via a virtual W^+ boson. The decay rate of the leptonic decays $D^+_{(s)} \to \ell^+\nu_\ell$ can be parameterized by the $D^+_{(s)}$ decay constant $f_{D^+_{(s)}}$ via

$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{\rm cd(s)}|^2 f_{D^+_{(s)}} m_\ell^2 m_{D^+_{(s)}} (1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}), \tag{1.1}$$

where G_F is the Fermi coupling constant, $|V_{\rm cd(s)}|$ is the CKM matrix element between the two quarks $c\bar{d}(\bar{s})$, m_ℓ and $m_{D^+_{(s)}}$ are the masses of the lepton and $D^+_{(s)}$.

On the other hand, the semileptonic decays $D^0 \to K(\pi)^- e^+\nu_e$ can be well interpreted because the effects of the weak and strong interaction can be well separated in theory. Their differential decay rates can be simply written as

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{\rm cs(d)}|^2 p^3_{K(\pi)} |f_+^{K(\pi)}(q^2)|^2, \tag{1.2}$$

where G_F is the Fermi coupling constant, $|V_{\rm cs(d)}|$ is the CKM matrix element between the two quarks $c\bar{s}(\bar{d})$, $p_{K(\pi)}$ is the momentum of the kaon(pion) in the rest frame of D^0 meson, $f_+^{K(\pi)}(q^2)$ is the form factor of hadronic weak current depending on the square of the four momentum transfer $q = p_D - p_{K(\pi)}$.

The world largest e^+e^- annihilation data set taken at $\psi(3770)$ with the BESIII detector, as well as the huge e^+e^- annihilation data sets taken at $\Upsilon(4S)$ with the BABAR and BELLE detectors provide good opportunities to better study the leptonic decays $D^+_{(s)} \to \ell^+\nu_\ell$ and the semileptonic decays $D^0 \to K(\pi)^- e^+\nu_e$. Based on these, the decay constants of $D^+_{(s)}$, the form factors $f_+^{K(\pi)}(q^2)$ or the CKM matrix elements $|V_{\rm cd(s)}|$ can be accurately extracted, thus precisely validating the LQCD calculations on $f_{D^+_{(s)}}$ and $f_+^{K(\pi)}(0)$ and/or precisely testing the unitarity of the CKM matrix. Also, these are helpful to improve the measurement accuracies in the experimental studies of the leptonic and semileptonic decays of B mesons indirectly.

Herein, some recent results on the leptonic decay $D^+ \to \mu^+\nu_\mu$ and the semileptonic decays $D^0 \to K(\pi)^- e^+\nu_e$ at the BESIII, as well as the leptonic decay $D_s^+ \to \ell^+\nu_\ell(\ell = \mu,\ \tau)$ and the semileptonic decays $D^0 \to K(\pi)^- e^+\nu_e$ at the BABAR and BELLE are reported. Throughout the proceeding, the charge conjugate is implied.

2. Leptonic decays $D^+_{(s)} \to \ell^+\nu_\ell$

2.1 $D^+ \to \mu^+\nu_\mu$ at the BESIII [3]

In 2010 and 2011, the BESIII [1] accumulated 2.92 fb^{-1} data at $\sqrt{s}$ = 3.773 GeV [2], where $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ (D^+D^-) is produced predominantly, thus providing ideal place to study the decays of D^0 and D^+ mesons. To investigate $D^+ \to \mu^+\nu_\mu$, BESIII reconstructs singly tagged D^- mesons by using 9 hadronic decays. Figure 1 (left side) shows the fits to the beam-energy-constrained mass spectra of the (a) $K^+\pi^-\pi^-$, (b) $K^0_S\pi^-$, (c) $K^0_S K^-$, (d) $K^+K^-\pi^-$, (e) $K^+\pi^-\pi^-\pi^0$, (f) $\pi^-\pi^-\pi^+$, (g) $K^0_S\pi^-\pi^0$, (h) $K^+\pi^-\pi^-\pi^-\pi^+$ and (i) $K^0_S\pi^-\pi^-\pi^+$ combinations, which yield $(170.31 \pm 0.34) \times 10^4$ singly tagged D^- mesons.

Figure 1 (right side) shows the $M^2_{\rm miss}$ distribution of the candidates for $D^+ \to \mu^+\nu_\mu$, which are selected in the systems against the singly tagged D^- mesons. BESIII obtains 409 ± 21 signal events of $D^+ \to \mu^+\nu_\mu$, which yields the branching fraction for $D^+ \to \mu^+\nu_\mu$

$$B(D^+ \to \mu^+\nu_\mu) = (3.71 \pm 0.19_{\rm stat.} \pm 0.06_{\rm sys.}) \times 10^{-4}.$$

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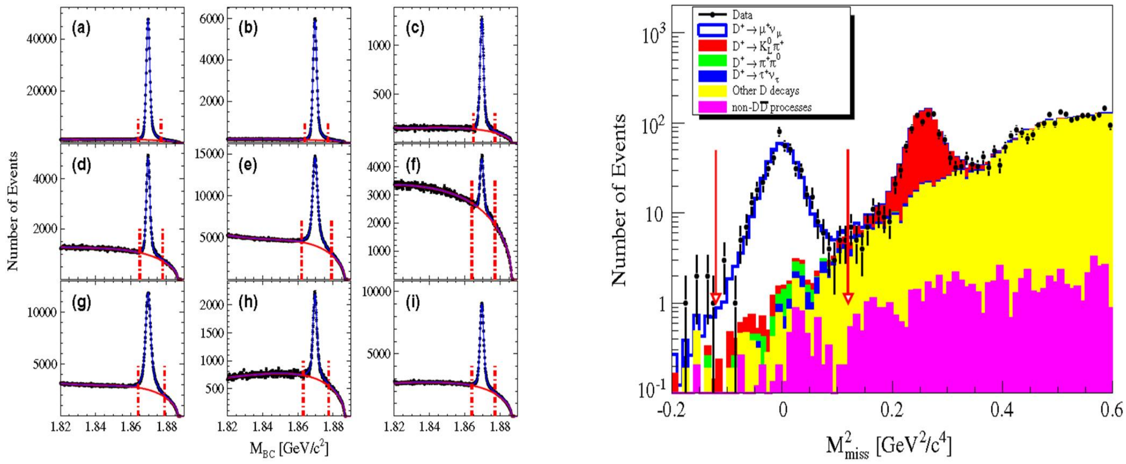

Figure 1: (left side) The fits to the beam-energy-constrained mass spectra for singly tagged D^- modes (the signal region is marked by the pair of arrows in each sub-figure). (right side) The $M^2_{\rm miss}$ distribution for $D^+ \to \mu^+\nu_\mu$ candidates.

Using the measured $B(D^+ \to \mu^+\nu_\mu)$ and the CKM matrix element $|V_{\rm cd}|$ value determined from a global Standard Model fit [4], BESIII determines the decay constant of D^+ to be

$$f_{D^+} = 203.2 \pm 5.3_{\rm stat.} \pm 1.8_{\rm sys.}\ \mathrm{MeV}.$$

The $B(D^+ \to \mu^+\nu_\mu)$ and f_{D^+} measured at BESIII are consistent within errors with those measured at the BESI [5], BESII [6]and CLEO-c [7] experiments, but with the best precision.

So far, the CKM matrix element $|V_{\rm cd}|$ has been measured though experimental studies of the semileptonic decay $D \to \pi\ell^+\nu_\ell$ or measurement of charm production cross section of $\nu\bar{\nu}$ interaction, among which the best measurement precision is 4.8% [4]. By using the measured $B(D^+ \to \mu^+\nu_\mu)$ and the Lattice QCD calculation on f_{D^+} [8], BESIII determines the CKM matrix element $|V_{\rm cd}|$ to be

$$|V_{\rm cd}| = 0.2210 \pm 0.058_{\rm stat.} \pm 0.047_{\rm sys.},$$

which has the best precision in the world to date.

2.2 $D_s^+ \to \ell^+\nu_\ell$ at the BABAR and BELLE

In 2010, the BABAR Collaboration investigated $D_s^+ \to \ell^+\nu_\ell$ by analyzing 521 fb^{-1} data taken at $\sqrt{s} = 10.58$ GeV [9]. They accumulated $(67.2 \pm 1.5) \times 10^3$ inclusive D_s^+ mesons by the decay chain $e^+e^- \to c\bar{c} \to DKXD_s^{*-}$. From the inclusive D_s^+ sample, they obtained 275 ± 17, 408 ± 42 and 340 ± 32 signals for $D_s^+ \to \mu^+\nu_\mu$, $D_s^+ \to \tau^+\nu_\tau$ with $\tau^+ \to e^+\nu\bar{\nu}$ and $D_s^+ \to \tau^+\nu_\tau$ with $\tau^+ \to \mu^+\nu\bar{\nu}$. Based on these, they measured the branching fraction for $D_s^+ \to \ell^+\nu_\ell$ to be

$$B(D_s^+ \to \mu^+\nu_\mu) = (0.602 \pm 0.038_{\rm stat.} \pm 0.034_{\rm sys.})\%$$

and

$$B(D_s^+ \to \tau^+\nu_\tau) = (5.00 \pm 0.35_{\rm stat.} \pm 0.49_{\rm sys.})\%.$$

Further, they determined the decay constant of D_s^+ to be

$$f_{D_s^+} = 258.6 \pm 6.4_{\rm stat.} \pm 7.5_{\rm sys.}\ \mathrm{MeV}.$$

In 2013, the BELLE Collaboration investigated $D_s^+ \to \ell^+\nu_\ell$ by analyzing 913 fb^{-1} data taken at $\sqrt{s} = 10.58$ GeV [10]. They accumulated $94360 \pm 1310_{\rm stat.} \pm 1450_{\rm sys.}$ inclusive D_s^+ mesons

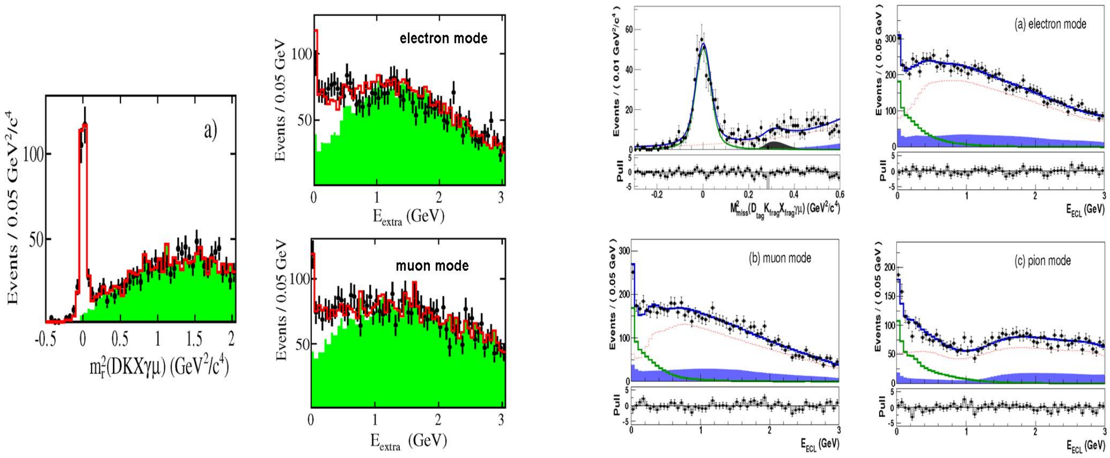

Figure 2: The distributions of the missing mass squares of the candidates for $D_s^+ \to \mu^+\nu_\mu$ and the extra energies of the candidates for $D_s^+ \to \ell^+\nu_\ell$ at the BABAR (left side) and the BELLE (right side).

by the decay chain $e^+e^- \to c\bar{c} \to DKXD_s^{*-}$. From the inclusive D_s^+ sample, they found 492 ± 26, 952 ± 59, 758 ± 48 and 496 ± 35 signals for $D_s^+ \to \mu^+\nu_\mu$, $D_s^+ \to \tau^+\nu_\tau$ with $\tau^+ \to e^+\nu\bar{\nu}$, $D_s^+ \to \tau^+\nu_\tau$ with $\tau^+ \to \mu^+\nu\bar{\nu}$ and $D_s^+ \to \tau^+\nu_\tau$ with $\tau^+ \to \pi^+\nu$. Based on these, they measured the branching fraction for $D_s^+ \to \ell^+\nu_\ell$ to be

$$B(D_s^+ \to \mu^+\nu_\mu) = (0.531 \pm 0.028_{\rm stat.} \pm 0.020_{\rm sys.})\%$$

and

$$B(D_s^+ \to \tau^+\nu_\tau) = (5.70 \pm 0.21_{\rm stat.} \pm 0.31_{\rm sys.})\%.$$

Further, they determined the decay constant of D_s^+ to be

$$f_{D_s^+} = 255.5 \pm 4.2_{\rm stat.} \pm 5.1_{\rm sys.}\ {\rm MeV}.$$

2.3 Comparison of the extracted $f_{D^+_{(s)}}$

Figure 3 compares the measured f_{D^+} at the BESIII and the measured $f_{D_s^+}$ at the BABAR and BELLE with the ones from other experiments or theory calculation.

3. Semileptonic decays $D^0 \to K(\pi)^-e^+\nu_e$

3.1 Previous or preliminary results at the BABAR and BELLE

In 2006, the BELLE Collaboration investigated $D^0 \to K(\pi)^-e^+\nu_e$ by analyzing 282 fb^{-1} data taken at $\sqrt{s} = 10.58$ GeV [11]. They determined the branching fractions for $D^0 \to K(\pi)^-e^+\nu_e$ which are $B(D^0 \to K^-e^+\nu_e) = (3.45 \pm 0.10_{\rm stat.} \pm 0.19_{\rm sys.})\%$ and $B(D^0 \to \pi^-e^+\nu_e) = (0.279 \pm 0.027_{\rm stat.} \pm 0.016_{\rm sys.})\%$. By fitting the decay widths for $D^0 \to K(\pi)^-\ell^+\nu_\ell$ ($\ell = e,\ \mu$), they extracted the form factors $f_+^K(0) = 0.695 \pm 0.007 \pm 0.022$ and $f_+^\pi(0) = 0.624 \pm 0.020 \pm 0.030$.

In 2007, by analyzing 75 fb^{-1} data taken at $\sqrt{s} = 10.58$ GeV, the BABAR Collaboration studied $D^0 \to K^-e^+\nu_e$ [12]. Using a similar analysis, they determined the branching fraction to be $B(D^0 \to K^-e^+\nu_e) = (3.522 \pm 0.027_{\rm stat.} \pm 0.079_{\rm sys.})\%$, and extracted the form factor to be $f_+^K(0) = 0.727 \pm 0.007 \pm 0.086$. At ICHEP2014, the BABAR Collaboration reported preliminary results on $D^0 \to \pi^-e^+\nu_e$ based on a similar analysis of 347.2 fb^{-1} data taken at $\sqrt{s} = 10.58$ GeV [13]. They determined $B(D^0 \to \pi^-e^+\nu_e) = (2.770 \pm 0.068_{\rm stat.} \pm 0.099_{\rm sys.}) \times 10^{-3}$, and extracted the form factor to be $f_+^\pi(0) = 0.610 \pm 0.017 \pm 0.011$ or the CKM matrix element $|V_{\rm cd}|$ to be $|V_{\rm cd}| = 0.206 \pm 0.007 \pm 0.009_{\rm LQCD}$.

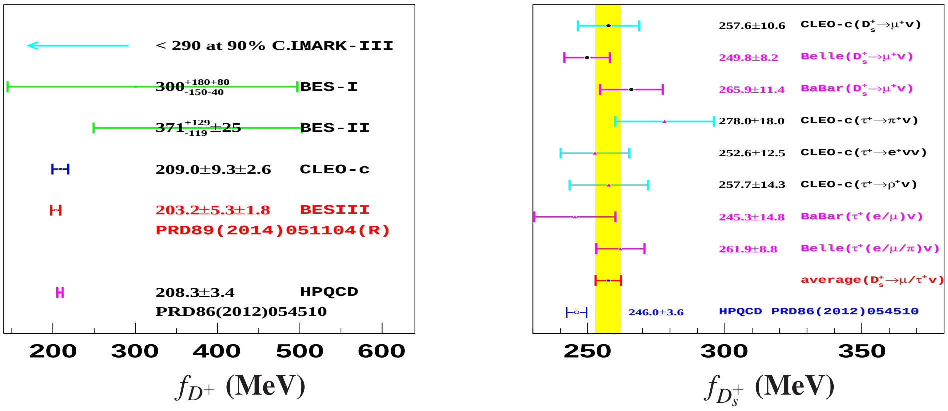

Figure 3: Comparison of the extracted decay constants.

3.2 Preliminary results at the BESIII

To investigate $D^0 \to K(\pi)^- e^+ \nu_e$, BESIII reconstructs singly tagged $\bar{D}^0$ mesons by using 5 hadronic decays. Figure 4 (left side) shows the fits to the beam-energy-constrained mass spectra of (a) $K^+\pi^-$, (b) $K^+\pi^-\pi^0$, (c) $K^+\pi^-\pi^-\pi^+$, (d) $K^+\pi^-\pi^-\pi^+\pi^0$ and (e) $K^+\pi^-\pi^0\pi^0$ combinations from 2.92 fb^{-1} data taken at $\sqrt{s} = 3.773$ GeV. From the fits, BESIII obtains $(279.33 \pm 0.37) \times 10^4$ singly tagged $\bar{D}^0$ mesons in the $\bar{D}^0$ signal region.

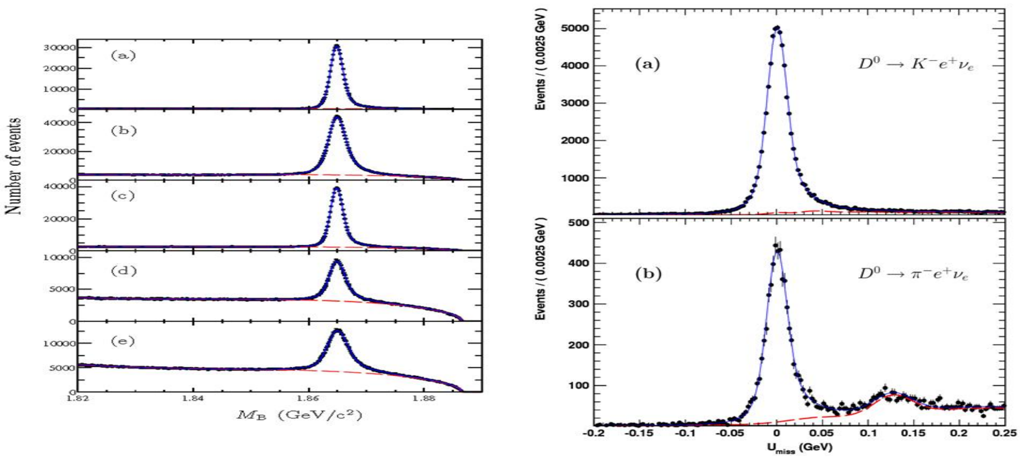

Figure 4: (left side) The fits to the beam-energy-constrained mass spectra for singly tagged $\bar{D}^0$ modes. (right side) The U_{miss} fits for $D^0 \to K^- e^+ \nu_e$ and $D^0 \to \pi^- e^+ \nu_e$ candidates.

Figure 4 (right side) shows the fits to the U_{miss} distributions of the candidates for $D^0 \to K^- e^+ \nu_e$ and $D^0 \to \pi^- e^+ \nu_e$, which are selected in the events containing singly tagged $\bar{D}^0$ mesons. From the fits, BESIII obtains 70727 ± 278 and 6297 ± 87 signal events of $D^0 \to K^- e^+ \nu_e$ and $D^0 \to \pi^- e^+ \nu_e$. Based on these, the branching fractions for $D^0 \to K^- e^+ \nu_e$ and $D^0 \to \pi^- e^+ \nu_e$ are determined to be

$$B(D^0 \to K^- e^+ \nu_e) = (3.505 \pm 0.014_{\text{stat.}} \pm 0.033_{\text{sys.}})\%$$

and

$$B(D^0 \to \pi^- e^+ \nu_e) = (0.2950 \pm 0.0041_{\text{stat.}} \pm 0.0026_{\text{sys.}})\%,$$

respectively. The measured $B(D^0 \to K^- e^+ \nu_e)$ and $B(D^0 \to \pi^- e^+ \nu_e)$ at the BESIII are consistent within errors with those measured at the BESII [14], CLEO-c [15], BELLE [11] and BABAR [12, 13] experiments, but with the best precision.

Figure 5 shows the fits to the partial widths and the projections on the form factors of $D^0 \to K^- e^+ \nu_e$ and $D^0 \to \pi^- e^+ \nu_e$ using the Simple Pole model [16], the Modified Pole model [16], the ISGW2 model [17], the two-parameter series expansion (Series.2.Par.) [18] and the three-parameter series expansion (Series.3.Par.) [18]. From the fits, BESIII obtains the extracted parameters of different models, which are summarized in Table 1.

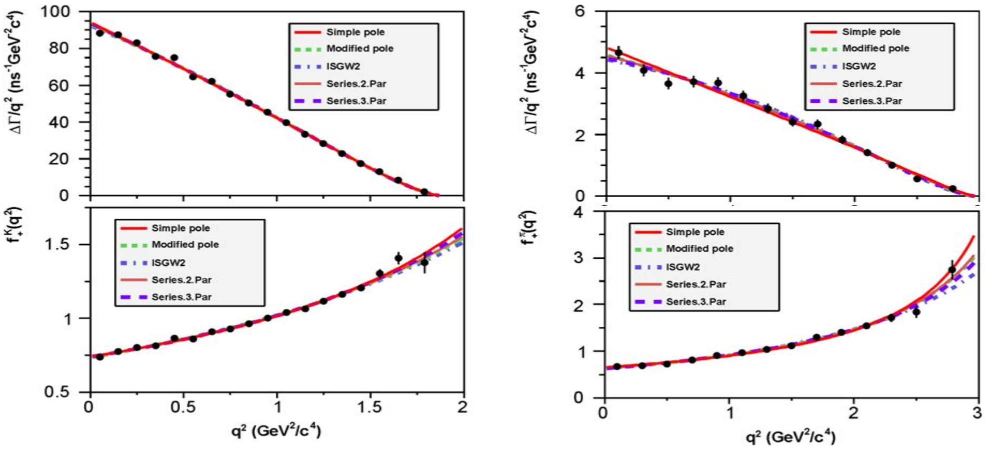

Figure 5: The fits to the partial widths and the projections on the form factors of $D^0 \to K^- e^+ \nu_e$ (left side) and $D^0 \to \pi^- e^+ \nu_e$ (right side).

Table 1: Summary of the extracted parameters from the fits to the partial widths.

Model	$D^0 \to K^- e^+ \nu_e$		$D^0 \to \pi^- e^+ \nu_e$	
Simple Pole	$f_+^K(0)\|V_{cs}\|$	$0.7209 \pm 0.0022 \pm 0.0033$	$f_+^\pi(0)\|V_{cs}\|$	$0.1475 \pm 0.0014 \pm 0.0005$
	$M_{\rm pole}$	$1.9207 \pm 0.0103 \pm 0.0069$	$M_{\rm pole}$	$1.9114 \pm 0.0118 \pm 0.0038$
Modified Pole	$f_+^K(0)\|V_{cs}\|$	$0.7163 \pm 0.0024 \pm 0.0034$	$f_+^\pi(0)\|V_{cs}\|$	$0.1437 \pm 0.0017 \pm 0.0008$
	α	$0.3088 \pm 0.0195 \pm 0.0129$	α	$0.2794 \pm 0.0345 \pm 0.0113$
ISGW2	$f_+^K(0)\|V_{cs}\|$	$0.7139 \pm 0.0023 \pm 0.0034$	$f_+^\pi(0)\|V_{cs}\|$	$0.1415 \pm 0.0016 \pm 0.0006$
	r_{ISGW2}	$1.6000 \pm 0.0141 \pm 0.0091$	r_{ISGW2}	$2.0688 \pm 0.0394 \pm 0.0124$
Series.2.Par.	$f_+^K(0)\|V_{cs}\|$	$0.7172 \pm 0.0025 \pm 0.0035$	$f_+^\pi(0)\|V_{cs}\|$	$0.1435 \pm 0.0018 \pm 0.0009$
	r_1	$-2.2278 \pm 0.0864 \pm 0.0575$	r_1	$-2.0365 \pm 0.0807 \pm 0.0260$
Series.3.Par.	$f_+^K(0)\|V_{cs}\|$	$0.7196 \pm 0.0035 \pm 0.0041$	$f_+^\pi(0)\|V_{cs}\|$	$0.1420 \pm 0.0024 \pm 0.0010$
	r_1	$-2.3331 \pm 0.1587 \pm 0.0804$	r_1	$-1.8434 \pm 0.2212 \pm 0.0690$
	r_2	$3.4223 \pm 3.9090 \pm 2.4092$	r_2	$-1.3871 \pm 1.4615 \pm 0.4677$

3.3 Comparison of $|f_+^{K(\pi)}(0)|$

With the measured $f_+^{K(\pi)}(0)|V_{cs(d)}|$ and the CKM matrix element $|V_{cs(d)}|$ values determined from a global Standard Model fit [4], one can calculate the form factors $|f_+^{K(\pi)}(0)|$. Figure 6 compares the calculated form factors $|f_+^{K(\pi)}(0)|$ based on the preliminary results of $f_+^{K(\pi)}(0)|V_{cs(d)}|$ at BESIII with the ones from other experiments or theory calculation.

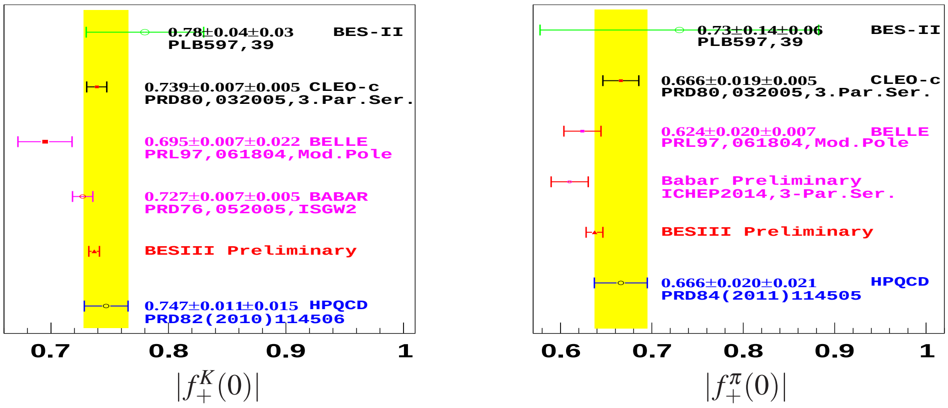

Figure 6: Comparison of the extracted form factors.

4. Summary

During the past several years, precision measurements on $D^+_{(s)} \to \ell^+\nu_\ell$ and $D^0 \to K(\pi)^- e^+\nu_e$ had been made by the CLEO-c, BABAR, BELLE and BESIII. These improved measurements provide important information to better validate the LQCD calculations of the decay constants $f_{D^+_{(s)}}$ and the form factors $f_+^{K(\pi)}(0)$, and to better test the unitarity of the CKM matrix. In the near future, BESIII plans to collect 3 fb^{-1} data at $\sqrt{s} = 4.17$ GeV. Also, more data are expected to be collected at $\sqrt{s} = 3.773$ GeV. These will provide new chances to further improve the measurements based on the leptonic decays $D^+_{(s)} \to \ell^+\nu_\ell$ and the semileptonic decays $D^0 \to K(\pi)^- e^+\nu_e$.

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