Test lepton flavor universality with (semi)leptonic D decays at BESIII

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Abstract

Using 2.93 fb^{-1} data taken at $\sqrt{s} = 3.773$ GeV, 0.482 fb^{-1} data taken at $\sqrt{s} = 4.009$ GeV and 3.19 fb^{-1} data taken at $\sqrt{s} = 4.178$ GeV with the BESIII detector, precision measurements of the branching fractions of $D^0 \to K^-\mu^+\nu_\mu$, $D^+ \to \bar{K}^0\mu^+\nu_\mu$, $D^0 \to \pi^-\mu^+\nu_\mu$, $D^+ \to \pi^0\mu^+\nu_\mu$, $D^+ \to \ell^+\nu_\ell$ and $D_s^+ \to \ell^+\nu_\ell$ are performed. Combining the known branching fractions of $D \to \bar{K}e^+\nu_e$, $D \to \pi e^+\nu_e$ and $D_s^+ \to \tau^+\nu_\tau$, we have tested the lepton flavor universality with $D \to \bar{K}\ell^+\nu_\ell$, $D \to \pi\ell^+\nu_\ell$, $D^+ \to \ell^+\nu_\ell$ and $D_s^+ \to \ell^+\nu_\ell$ decays. We have also tested lepton flavor universality in different $q^2_{\ell\nu_\ell}$ intervals for $D \to \bar{K}\ell^+\nu_\ell$ ($\ell = e$ or μ). Besides, hadronic form factor $f_+^K(0)$, D meson decay constant $f_{D_s^+}$ and f_{D^+}, and quark mixing matrix element $|V_{cs}|$ and $|V_{cd}|$ are also extracted with the most precise accuracies to date.

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1 Introduction

In the standard model (SM), the strong and weak interactions in leptonic and semileptonic D decays can be well separated, as shown in Fig. 1. The decay amplitude is described as the vector product of the hadronic current and the leptonic current. As a result, we have [1]

$$\Gamma(D \to \ell\nu_\ell) = \frac{G_F^2}{8\pi}(|V_{cs(d)}|f_D)^2 m_\ell^2 m_D \left(1 - \frac{m_\ell^2}{m_{D_s^+}^2}\right)^2 \tag{1}$$

for pure leptonic decays, and

$$\frac{d\Gamma(D \to P\ell\nu_\ell)}{dq^2} = \frac{G_F^2}{24\pi^3}(|V_{cs(d)}|f_+(q^2))^2|\vec{p}_P|^3 + O(m_\ell^2) \tag{2}$$

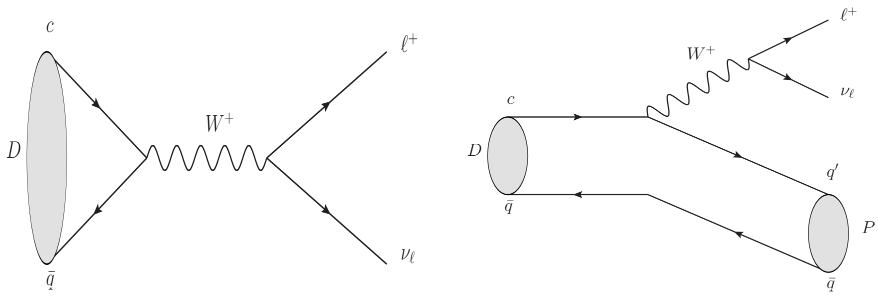

Figure 1: Feynman diagrams for leptonic D decays (left) and semileptonic D decays to pseudoscalar mesons (right).

for semileptonic decays to pseudoscalar mesons, where f_D and $f_+(q^2)$ are the D meson decay constant and hadronic from factor parametrizing the hadronic current, $V_{cs(d)}$ is the Cabbibo-Kobayashi-Maskawa (CKM) matrix element describing the mixing between quark weak eigenstates and flavor eigenstates, G_F is the Fermi coupling constant, m_D and m_ℓ are the masses of D meson and lepton [2], and p_P is the momentum of the pseudoscalar meson.

Thus, if we calculate the ratio of the decay rates of (semi)leptonic decays involving different generations of leptons, the hadronic currents which are not well calculated in theory are almost canceled out. This gives a very strict constraint on the SM, which can be used to test the lepton flavor universality (LFU).

If there is a new physics (NP) mechanism that couples with different generations of leptons with different strengths, such as NP models involving a charged Higgs boson, or a NP mechanism that allows the lepton to change its flavor, such as the leptoquark mechanism, then the LFU in the SM may be violated [3–8]. Evidence of LFU violation has been found in B meson decays in the measurements of $R_{D^{(*)}} = \frac{\Gamma(B\to D^{(*)}\tau^+\nu_\tau)}{\Gamma(B\to D^{(*)}\mu^+\nu_\mu)}$ and $R_{K^{(*)}} = \frac{\Gamma(B^+\to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^+\to K^{(*)+}e^+e^-)}$ [9–13]. While in the charm sector, no significant deviation from the SM prediction has been found [14]. With the world's largest $D\bar{D}$ samples near threshold, test of the LFU using (semi)leptonic D decays with better precision at BESIII provides a chance to further test the SM and understand the anamolies in B meson decays.

Besides, study of (semi)leptonic D decays allow us to measure the corresponding D meson decay constants, hadronic from factors, and the CKM matrix elements. These measurements can help to validate the theoretical calculations and test the unitarity of the CKM matrix.

2 The BESIII detector and the analysis method

2.1 The BESIII detector

The BESIII detector is a magnetic spectrometer [15] located at the Beijing Electron Positron Collider [16]. The cylindrical core of the BESIII detector consists of a helium-based multilayer drift chamber, a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The acceptance of charged particles and photons is 93% over 4π solid angle. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for the electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution of the TOF barrel part is 68 ps, while that of the end cap part is 110 ps. The end cap TOF system is upgraded in 2015 with multi-gap resistive plate chamber technology, providing a time resolution of 60 ps [17, 18].

2.2 The analysis method

For data taken at the center mass energy near $D\bar{D}$ threshold in e^+e^- collider, the D mesons are produced in pair. If we fully reconstruct a D meson via hadronic decays (called the single tagged D meson), the other D meson is guaranteed to exist. By searching for the (semi)leptonic decay in the recoiling system of the single tagged D meson, we can then measure its branching fraction (BF) via

$$\mathcal{B} = \frac{N_{\rm sig}}{N_{\rm ST}\varepsilon_{\rm sig}},$$

where $N_{\rm ST}$ and $N_{\rm sig}$ are the number of single tagged D mesons and the number of reconstructed (semi)leptonic events, respectively. $\varepsilon_{\rm sig}$ is the efficiency of reconstructing the (semi)leptonic decay in the present of the single tagged D meson. Here the number of reconstructed (semi)leptonic events is determined by examining the kinematic variables of the missing neutrio

$$U_{\rm miss} = E_{\rm miss} - |\vec{p}_{\rm miss}|,$$
$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2,$$

where $E_{\rm miss}$ and $p_{\rm miss}$ are the missing energy and missing momentum of the system. For correctly reconstructed (semi)leptonic decays, these variables should peak at zero.

3 Recent results at BESIII

3.1 Leptonic D_s^+ decays

In 2014, BESIII collected 482 pb^{-1} data at the center mass energy of 4.009 GeV (near $D_s^+D_s^-$ threshold). Using this data sample, the BFs of leptonic D_s^+ decays are measured with a total number of 15127 ± 321 single tagged D_s mesons reconstructed [19]. By constraining the ratio of the decay rates of $D_s^+ \to \tau^+\nu_\tau$ and $D_s^+ \to \mu^+\nu_\mu$ to the SM prediction 9.74, the BFs of these two decays are determined to be (See Fig. 2)

$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.495 \pm 0.067 \pm 0.026)\%,$$

$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (4.83 \pm 0.65 \pm 0.26)\%.$$

With the input of $m_{D_s^+}$ and m_ℓ from PDG, we have

$$f_{D_s^+}|V_{cs}| = 234.8 \pm 15.9 \pm 6.4 \text{ MeV}.$$

The BFs are also determined without the SM constraint to be

$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.517 \pm 0.075 \pm 0.021)\%,$$

$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (3.28 \pm 1.83 \pm 0.37)\%.$$

In 2016, BESIII collected another 3.19 fb^{-1} data at the center mass energy of 4.178 GeV. Taking advantage of the much higher $e^+e^- \to D_s^+D_s^{*-}$ cross section here, more precise measurements are perfromed with a total number of about 3.9×10^5 single tagged D_s mesons reconstructed [20]. The BF of $D_s^+ \to \mu^+\nu_\mu$ is measured to be (See Fig. 3)

$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.549 \pm 0.016 \pm 0.015)\%,$$

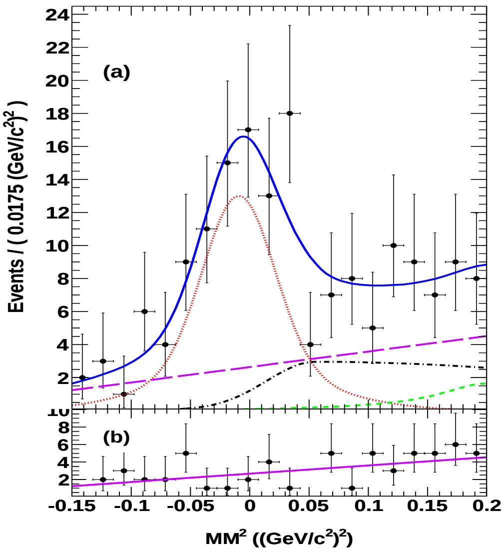

Figure 2: Projections of the simultaneous fit to the M^2_{miss} distributions of events in (a) signal and (b) sideband region of the single tagged D_s mesons. The red dotted curve shows the $\mu^+\nu_\mu$ signal and the black dot-dashed curve shows the $\tau^+\nu_\tau$ signal.

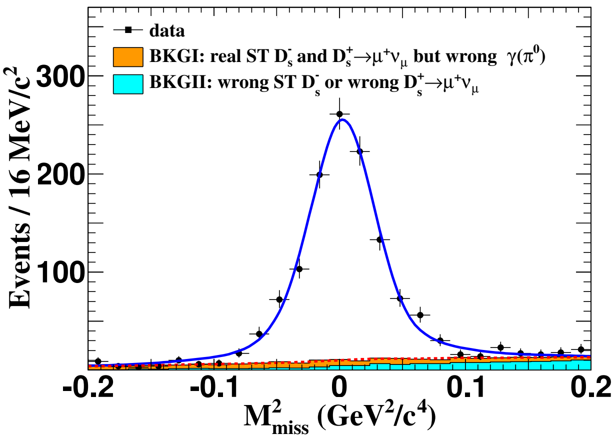

Figure 3: The fit to the M^2_{miss} distribution of $D_s^+\to\mu^+\nu_\mu$ candidates.

which gives

$$f_{D_s^+}|V_{cs}| = 246.2 \pm 3.6 \pm 3.5 \text{ MeV}.$$

Combining with the BF of $D_s^+\to\tau^+\nu_\tau$ in PDG, we have

$$R_{D_s^+} = \frac{\Gamma(D_s^+\to\tau^+\nu_\tau)}{\Gamma(D_s^+\to\mu^+\nu_\mu)} = 9.98 \pm 0.52\,,$$

which is consistent with the SM prediction. The measurement of the BF of $D_s^+\to\tau^+\nu_\tau$ using this larger data sample is also ongoing.

3.2 Leptonic D^+ decays

Measurements of the BFs of leptonic D^+ decays are perfromed using 2.93 fb^{-1} data at the center mass energy of 3.773 GeV collected in 2010 and 2011. With a total number of about

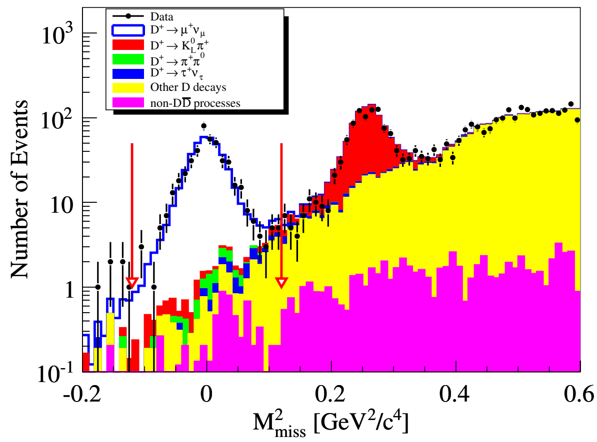

Figure 4: The fit to the M^2_{miss} distribution of $D^+ \to \mu^+\nu_\mu$ candidates.

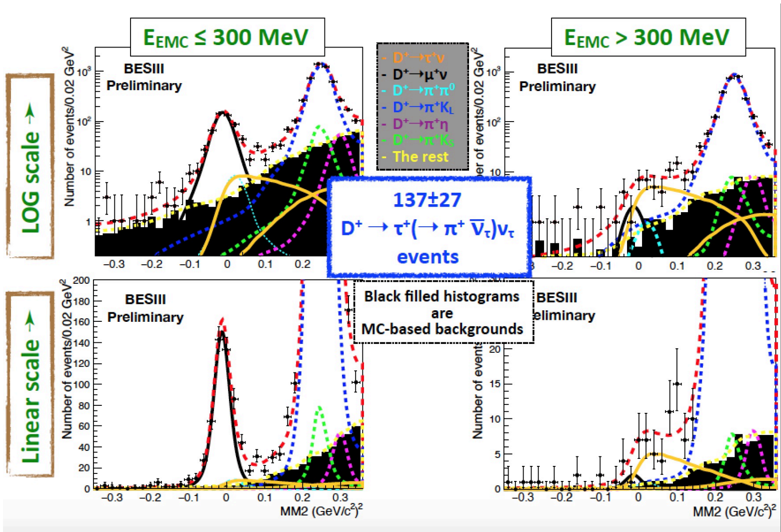

Figure 5: The simultaneous fit to the M^2_{miss} distributions of the muon-like sample (with deposited energy in the EMC less than 300 MeV) and the pion-like sample (with deposited energy in the EMC larger than 300 MeV).

1.7×10^6 single tagged D mesons reconstructed, the BF of $D^+ \to \mu^+\nu_\mu$ is measured to be $(3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$ (See Fig. 4) [21], which gives

$$f_{D^+}|V_{cd}| = 45.75 \pm 1.20 \pm 0.39 \text{ MeV}.$$

Meanwhile, preliminary result of the measurement of the BF of $D^+ \to \tau^+\nu_\tau$ finds the evidence of $D^+ \to \tau^+\nu_\tau$ signal for the first time with a statistical significance of 4 σ (See Fig. 5). The BF is measured to be $(1.20 \pm 0.24) \times 10^{-3}$. Combining these two measurements we have

$$R_{D^+} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64,$$

which is consistent with the SM prediction 2.66.

3.3 Semileptonic $D^{0(+)}$ decays

With the large $D\bar{D}$ sample at center mass energy of 3.773 GeV, BESIII has published the results of the BFs of $D \to \bar{K}e^+\nu_e$ and $D \to \pi e^+\nu_e$ with significantly improved precision [22–25]. How-

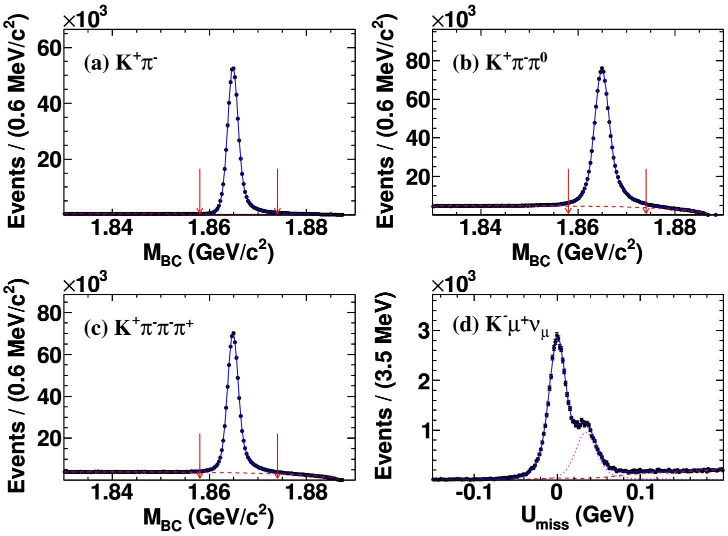

Figure 6: The fits to the mass distributions of single tagged D meons and to the U_{miss} distribution of $D^0 \to K^- \mu^+ \nu_\mu$ candidates.

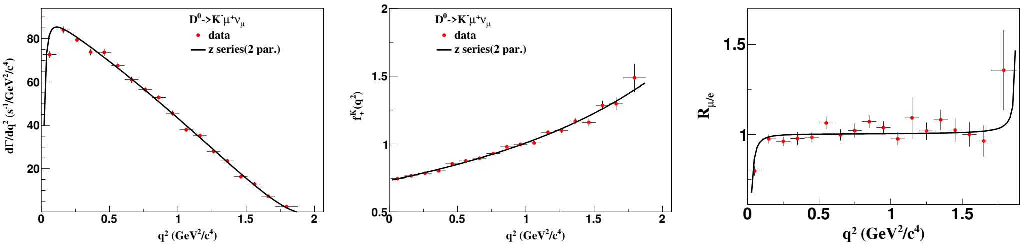

Figure 7: The fit to the partial decay rates of $D^0 \to K^- \mu^+ \nu_\mu$ (up left), the projection to the hadronic form factor (up right) and LFU test in various q^2 intervals (right).

ever, further study in semileptonic D decays concerning muon is still needed for more precise LFU test. In recent years, measurements of the BFs of these decays have been perfromed at BESIII. The BF $D^0 \to K^- \mu^+ \nu_\mu$ is measured to be $(3.413 \pm 0.019 \pm 0.035)\%$ (See Fig. 6) [26]. Combining with our previous measurement of $\mathcal{B}(D^0 \to K^- e^+ \nu_e)$, we have

$$R_{K^-} = \frac{\Gamma(D^0 \to K^- \mu^+ \nu_\mu)}{\Gamma(D^0 \to K^- e^+ \nu_e)} = 0.974 \pm 0.007 \pm 0.012.$$

With its largest statistics in semileptonic D decays, measurements of hadronic from factor $f_+^{D\to K}(0)$ and CKM matrix element $|V_{cs}|$ are perfromed by a fit to the measured partial decay rates in separated q^2 intervals, which yields

$$f_+^{D\to K}(0)|V_{cs}| = 0.7133 \pm 0.0038 \pm 0.0029.$$

Meanwhile, LFU test is perfromed in various q^2 intervals and no significant deviation from SM prediction is found (See Fig. 7).

The BF of $D^+ \to \bar{K}^0 \mu^+ \nu_\mu$ is measured to be $(8.72 \pm 0.07 \pm 0.18)\%$ [27]. Here, the $\bar{K}^0$ meson is reconstructed via both $K_S^0 \to \pi^+ \pi^-$ and $K_S^0 \to \pi^0 \pi^0$ decays and a simultaneous fit is perfromed for these two decays (See Fig. 8). Combining with our previous measurement, LFU test is perfromed with

$$R_{\bar{K}^0} = \frac{\Gamma(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)} = 0.988 \pm 0.033.$$

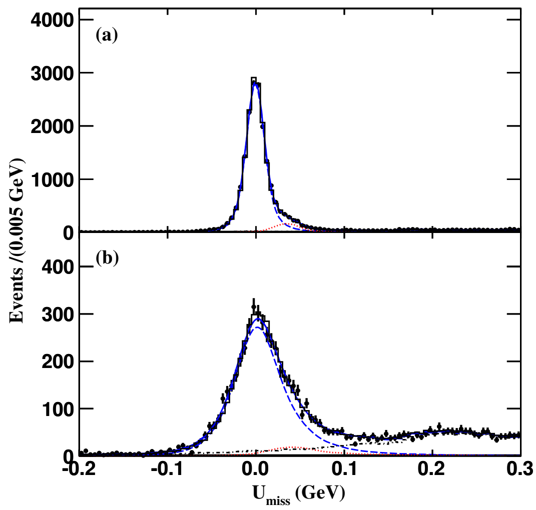

Figure 8: The simultaneous fit to the U_{miss} distributions of $D^+ \to \bar{K}^0\mu^+\nu_\mu$ candidates via (a) $K^0_S \to \pi^+\pi^-$ and (b) $K^0_S \to \pi^0\pi^0$.

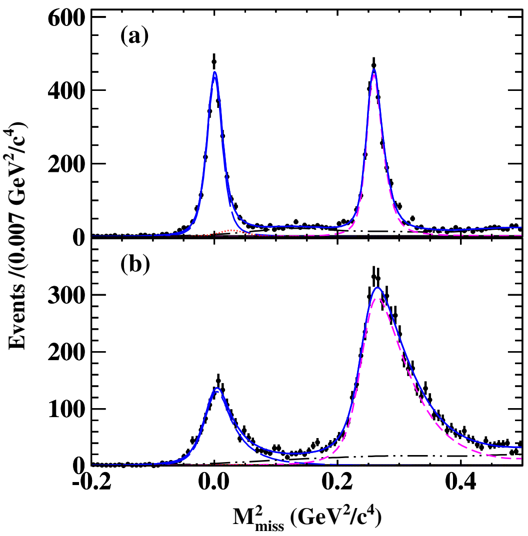

Figure 9: The fits to the M^2_{miss} distributions of (a) $D^0 \to \pi^-\mu^+\nu_\mu$ and (b) $D^+ \to \pi^0\mu^+\nu_\mu$ candidates.

Measurements of the BFs of the Cabbibo suppressed decays $D^0 \to \pi^-\mu^+\nu_\mu$ and $D^+ \to \pi^0\mu^+\nu_\mu$ are also perfromed at BESIII (See Fig. 9) [28]. Combining our measured BFs

$$\mathcal{B}(D^0 \to \pi^-\mu^+\nu_\mu) = (0.272 \pm 0.008 \pm 0.006)\%$$

and

$$\mathcal{B}(D^+ \to \pi^0\mu^+\nu_\mu) = (0.350 \pm 0.011 \pm 0.010)\%,$$

with our previous measurements yields

$$R_{\pi^-} = \frac{\Gamma(D^0 \to \pi^-\mu^+\nu_\mu)}{\Gamma(D^0 \to \pi^-e^+\nu_e)} = 0.922 \pm 0.030 \pm 0.022$$

and

$$R_{\pi^0} = \frac{\Gamma(D^+ \to \pi^0\mu^+\nu_\mu)}{\Gamma(D^+ \to \pi^0e^+\nu_e)} = 0.964 \pm 0.037 \pm 0.026.$$

4 Conclusion

In summary, with the world's largest $D\bar{D}$ samples near threshold, precision measurements of the BFs of $D^+_{(s)} \to \ell^+ \nu_\ell$, $D \to \bar{K}\mu^+\nu_\mu$ and $D \to \pi\mu^+\nu_\mu$ are performed at BESIII. Besides, and CKM matrix elements $|V_{cs(d)}|$, D meson decay constants $f_{D^+_{(s)}}$ and hadronic form factor $f_+^{D\to K}(0)$ are extracted. With the input of $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$ [2], $|V_{cd}| = 0.22438 \pm 0.00044$ [2], D^+_s lifetime $\tau_{D^+_s} = (5.04 \pm 0.04) \times 10^{-13}$ s [2], D^+ lifetime $\tau_{D^+} = (1040 \pm 7) \times 10^{-15}$ s [2], $f_{D^+_s} = 249.9 \pm 0.4$ MeV [29], $f_{D^+} = 212.7 \pm 0.6$ MeV [29] and $f_+^{D\to K} = 0.747 \pm 0.011 \pm 0.015$ [30], we obtain

$$f_{D^+_s} = 252.9 \pm 3.7 \pm 3.6 \text{ MeV}$$

and

$$|V_{cs}| = 0.985 \pm 0.014 \pm 0.014$$

using leptonic D^+_s decays,

$$f_{D^+} = 203.8 \pm 5.2 \pm 1.8 \text{ MeV}$$

and

$$|V_{cd}| = 0.2150 \pm 0.0055 \pm 0.0020$$

using leptonic D^+ decays,

$$f_+^{D\to K} = 0.7327 \pm 0.0039 \pm 0.0030$$

and

$$|V_{cs}| = 0.955 \pm 0.006 \pm 0.024$$

using $D^0 \to K^-\mu^+\nu_\mu$ decay.

Meanwhile, LFU test using (semi)leptonic D decays is perfromed at BESIII, and no significant deviation from the SM prediction is found at current statistics, as summarized in Table 1.

Table 1: LFU test at BESIII with (semi)leptonic D decays.

	$R(D^+_s)$	$R(D^+)$	$R(K^-)$	$R(\bar{K}^0)$	$R(\pi^-)$	$R(\pi^0)$
SM	9.74(1)	2.66(1)	0.975(1) [31]	0.975(1) [31]	0.985(2) [31]	0.985(2) [31]
BESIII	9.98(52)	3.21(64)	0.978(14)	0.988(33)	0.922(37)	0.964(45)

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