(Semi-)leptonic charmed meson decays at BESIII

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BESIII has collected the electron-positron collision data sample corresponding to an integrated luminosity of 2.93 fb^{-1} and 6.32 fb^{-1} taken at the center-of-mass energy of 3.773 GeV and 4.180-4.226 GeV, repectively. We report the recent measurements of the leptonic and semi-leptonic D decays at BESIII which contribute the precise experimental measurements of CKM matrix elements $|V_{cd(s)}|$, the decay constant $f_{D_{(s)}}$ and the form factors of D semi-leptonic decay $f_+(0)$. These measruements are important for the stretching test on the unitary of the CKM metrices and allow us calibrate the theoretical calculations of $f_{D_{(s)}}$ and $f_+(0)$. They also provide important tests in the lepton flavour universality (LFU) with (semi-) leptonic $D_{(s)}$ decays.

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1. Introduction

Experimental investigations of charm (semi-)leptonic decays can greatly aid our understanding of strong and weak interactions [1–3]. For example, via the purely leptonic $D_{(s)}$ decays $D_{(s)} \to \ell\nu_\ell$ ($\ell = e, \mu$), we could perform accurate measurements of the $f_{D_{(s)}}|V_{cd(s)}|$, which is the basis for the extraction of the decay constant and Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{cd(s)}|$, as one of the elements is the essential input to constrain the other. These precise measurements are essential to calibrate the theoretical calculations like Lattice quantum chromodynamics (LQCD) and to test the unitarity of the CKM matrix. Besides, in the standard model (SM), the lepton flavor universality (LFU) constrains the ratio of decay widths for the purely leptonic decays deponding only on the masses of leptons and mesons. It's also expected that the semi-leptonic charmed meson decays with same hadronic final states but different leptons have the same branching fractions (BFs). However, since the first observation of the hints of LFU violation in the semi-leptonic B decays [4], it will be of great interest to search for LFU in the purely leptonic and semi-leptonic D decays with high precision, which can provide important information for the search for new physics.

The $D\bar{D}$ and $D_s\bar{D}_s$ pairs are produced in e^+e^- annihilations at $\sqrt{s} = 3.773$ GeV and $\sqrt{s} = 4.178-4.226$ GeV, respectively. These processes offer a clean environment to measure the branching fractions of the (semi-) leptonic $D_{(s)}$ decays with the double-tag (DT) method [5]. A DT signal is the purely leptonic or semi-leptonic signal $D_{(s)}$ candidate accompanied by a fully reconstruction of the other $D_{(s)}$ meson. Throughout this paper, charge conjugate processes are always implied, unless otherwise stated.

2. Purely leptonic D_s^+ decays

2.1 $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \nu_e\bar{\nu}_\tau$

To effectively discriminate signal from background, the variable $E_{\rm extra}^{\rm tot}$ is used to demonstrate the signal D^{s+} candidate in the decay of $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \nu_e\bar{\nu}_\tau$ [6], which is defined as the total energy of the good electromagnetic calorimeter (EMC) shower excluding those associated with the fully reconstucted D^{s-} candidates and those associated with the final state radiation within 5° from the positron tracks. The DT signal yields in the signal region of $E_{\rm extra}^{\rm tot} < 0.4$ GeV is obtained after subtacting the number of background extrapolated from the individual fit of $E_{\rm extra}^{\rm tot}$ in the high side region of $E_{\rm extra}^{\rm tot} > 0.6$ GeV. The BFs for $D_s^+ \to \tau^+\nu_\tau$ is then determined to be $\mathcal{B}_{D_s^+\to\tau^+\nu_\tau} = (5.27 \pm 0.10_{\rm stat.} \pm 0.12_{\rm syst.})\%$, which is the most precise measurement to date.

2.2 $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$

To obtain the signal yields of the decay $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$, we perform a simultaneous fit to the missing mass square (MM^2) distribution of different data samples at $\sqrt{s} = 4.178 - 4.226$ GeV [7], which are constrained to have a common leptonic BF. Here, the variable MM^2 is often used to obtain the DT signal yields due to the undetectable neutrino in the final state. After the simultaneous fit, the signal events is retained to be (1745 ± 84) and the BF is measureed to be $\mathcal{B}_{D_s^+\to\tau^+\nu_\tau} = (5.29 \pm 0.25_{\rm stat.} \pm 0.20_{\rm syst.})\%$.

2.3 $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$ and $D_s^+ \to \mu^+\nu_\mu$

As the pions and muons are charged particles with similar masses, the extra information in the EMC shower is applied as the criteria to discriminate muons from pions, where the deposited energies of pions tend to be larger due to the nuclear interactions. The signal candidates of D_s^+ are split into two parts based on the the charged tracks deposit energy in the EMC ($E_{\rm EMC}$). Candidates satisfying $E_{\rm EMC} \leq 300$ MeV are classified as μ-like and the rest as π-like [8]. An unbinned simultaneous maximum likelihood fit to two-dimensional (2D) distributions of the invariant mass of the fully reconstructed D_s^- vs. MM^2 are performed for two samples individually. The siganl yield for $D_s^+ \to \tau^+\nu_\tau$ and $D_s^+ \to \mu^+\nu_\mu$ are obtained to be (946^{+46}_{-45}) and (2198 ± 55), respectively, where the uncertainty are only statistical only. The BFs are measureed to be $\mathcal{B}_{D_s^+\to\tau^+\nu_\tau} = (5.21 \pm 0.25_{\rm stat.} \pm 0.17_{\rm syst.})\%$ and $\mathcal{B}_{D_s^+\to\mu^+\nu_\mu} = (5.35 \pm 0.13_{\rm stat.} \pm 0.16_{\rm syst.}) \times 10^{-3}$.

Combined the above results from BESIII measurements and the world average values [9], the ratio of decay widths of the $D_s^+ \to \tau^+\nu_\tau$ over $D_s^+ \to \mu^+\nu_\mu$ is obtained to be (9.67 ± 0.34), which is consistent with the SM prediction of (9.75 ± 0.01).

After inputting the CKM matrix element $|V_{cs}| = 0.97329 \pm 0.00011$ from the global SM fit [9] and the averaged decay constant $f_{D_s} = 249.90.5$ MeV from LQCD calculations [10] into the measureed product $f_{D_s}|V_{cs}|$, the f_{D_s} and $|V_{cs}|$ can be determined, respectively. Figure 1 shows a comparison of experimental measurements of $f_{D_s^+}$ and $|V_{cs}|$ including the BESIII and other collaborations' results.

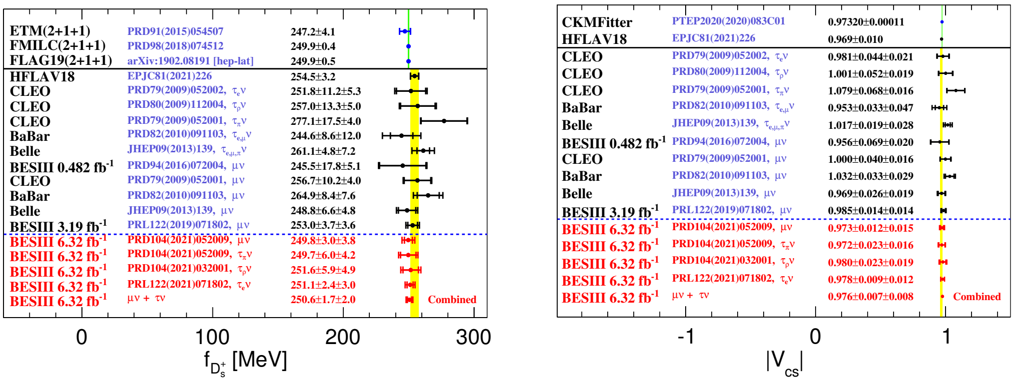

Figure 1: Comparisons of decay constant $f_{D_s^+}$ and CKM matrix element $|V_{cs}|$ including the BESIII and other collaborations' results.

3. Semi-leptonic D_s decays

3.1 $D^+ \to \eta\mu^+\nu_\mu$

To obtain the signal yields of the decay $D^+ \to \eta\mu^+\nu_\mu$, we perform an unbinned fit to the $U_{\rm miss}$ distribution [11]. A signal yield of (234 ± 22) is obtained after the fit, and the measured BF is determined to be $\mathcal{B}_{D^+\to\eta\mu^+\nu_\mu} = (10.4 \pm 1.0_{\rm stat.} \pm 0.5_{\rm syst.}) \times 10^{-4}$. Combined with the average value of $\mathcal{B}_{D^+\to\eta^+\nu}$ [9], the ratio of $\mathcal{B}_{D^+\to\eta\mu^+\nu_\mu}$ over $\mathcal{B}_{D^+\to\eta^+\nu}$ is obtained to be (0.91 ± 0.13), which is consistent with the SM prediction of (0.97-1.00). Besides, the BESIII has also reported the first measurement on dynamics of $D^+ \to \eta\mu^+\nu_\mu$ decay. The result of form factor for $D^+ \to \eta\mu^+\nu_\mu$ is $f_+^\eta(0) = (0.39 \pm 0.04_{\text{stat.}} \pm 0.01_{\text{syst.}})$, and the CKM matrix element is obtained to be $|V_{cd}| = (0.242 \pm 0.022_{\text{stat.}} \pm 0.006_{\text{syst.}} \pm 0.033_{\text{theory}})$.

3.2 $D^0 \to K_1(1270)^- e^+\nu_e$

An 2D unbinned extended maximum-likelihood simultaneous fits shared with the same value of $\mathcal{B}_{D^0\to K_1(1270)^- e^+\nu_e} \cdot \mathcal{B}_{K_1(1270)^-\to K^-\pi^+\pi^+}$ is performed to obtain the siganl yields of $D^0 \to K_1(1270)^- e^+\nu_e$ [12]. Here the 2D distribution is the invariant mass of $K^-\pi^+\pi^+$ vs. the MM^2. A signal yield of (109.0 ± 12.5) is obtained after the fit, and the measured BF is determined to be $\mathcal{B}_{D^0\to K_1(1270)^- e^+\nu_e} = (1.09 \pm 0.13^{+0.09}_{-0.13} \pm 0.12_{\text{ext}}) \times 10^{-3}$. Combined with the measured BF of $\mathcal{B}_{D^+\to \bar{K}_1(1270)^0 e^+\nu_e}$, the ratio of decay widths of $D^0 \to K_1(1270)^- e^+\nu_e$ over $D^+ \to \bar{K}_1(1270)^0 e^+\nu_e$ is determined to be $(1.20 \pm 0.02_{\text{stat.}} \pm 0.14_{\text{syst.}} \pm 0.04_{\text{ex}})$, which agrees with unity as predicted by isospin symmetry.

3.3 $D_s^+ \to X e^+\nu_e$

The BESIII has also reported the study of inclusive semi-electronic D_s^+ decay [13]. to obtain the siganl yields of the inclusive decay $D_s^+ \to X e^+\nu_e$, a fit to the momentum of the positron p_e is performed in the region of $p_e \geq 200\text{MeV/c}$. The signal yields with momentum below 200 is then determined by extrapolation of the fit. The total signal yields in the whole momentum region is then determined to be (16648 ± 326), and the BF of $D_s^+ \to X e^+\nu_e$ is measured to be $\mathcal{B}_{D_s^+\to X e^+\nu_e} = (6.30 \pm 0.13_{\text{stat.}} \pm 0.10_{\text{syst.}}\%)$. Combined with the D^0 case, the ratio of decay widths of $D_s^+ \to X e^+\nu_e$ over $D^0 \to X e^+\nu_e$ is measured to be $(0.790 \pm 0.016_{\text{stat.}} \pm 0.020_{\text{syst.}})$, which is consist with the theoretical prediction of 0.79.

3.4 $D^0 \to K^- e^+\nu_e$ and $D^+ \to \bar{K}^0 e^+\nu_e$

The signal $D^0 \to K^- e^+\nu_e$ and $D^+ \to \bar{K}^0 e^+\nu_e$ are analyzed through independent measurement with new method at BESIII called the double semi-leptonic tag method [15], which is develped to decrease the systematical error since both sides of the decay are semi-leptonic decays. The measured BFs are $\mathcal{B}_{D^0\to K^- e^+\nu_e} = (3.567 \pm 0.031_{\text{stat.}} \pm 0.021_{\text{syst.}}\%)$ and $\mathcal{B}_{D^+\to \bar{K}^0 e^+\nu_e} = (8.68 \pm 0.14_{\text{stat.}} \pm 0.16_{\text{syst.}}\%)$. The ratio of decay widths of $D^0 \to K^- e^+\nu_e$ over $D^+ \to \bar{K}^0 e^+\nu_e$ is then determined to be $(0.790 \pm 0.016_{\text{stat.}} \pm 0.020_{\text{syst.}})$, which support the isospin symmetry within 1.9σ.

3.5 $D^0 \to \rho^-\mu^+\nu_\mu$

The BESIII has reported the first measurement on the BF of $D^0 \to \rho^-\mu^+\nu_\mu$ [16]. In order to obtain the signal yield in the decay of $D^0 \to \rho^-\mu^+\nu_\mu$, an unbinned maximum likelihood fit to the MM^2 distribution is performed for the data sample at $\sqrt{s} = 3.773$ GeV. The signal yiled is measured to be (570 ± 40), and the BF of $D^0 \to \rho^-\mu^+\nu_\mu$ is determined to be $\mathcal{B}_{D^0\to\rho^-\mu^+\nu_\mu} = (1.35 \pm 0.09_{\text{stat.}} \pm 0.09_{\text{syst.}} \times 10^{-3})$. Combined with the world average value of $\mathcal{B}_{D^0\to\rho^{-+}\nu_e}$ [9], The ratio of BF $R_{\mu/e}$ is determined to be $R_{\mu/e} = (0.90 \pm 0.11)$, which agrees with the theoretical expectation of lepton flavor universality within the uncertainty.

4. Summary

With 2.93 fb^{-1} at $\sqrt{s}$ = 3.773 GeV and 6.32 fb^{-1} at $\sqrt{s}$ = 4.178 − 4.226 GeV, BESIII has reported the latest results with higher precision for purely leptonic and semi-electronic D_s^+ decays, the first measurement on dynamics of $D^+ \to \eta\mu^+\nu_\mu$, and the first observation of the semi-leptonic decays $D^0 \to K_1(1270)^- e^+\nu_e$ and $D^0 \to \rho^-\mu^+\nu_\mu$. In the near future, BESIII will collect 20 fb^{-1} at $\sqrt{s}$ = 3.773 GeV data sample, and another 3 fb^{-1} at $\sqrt{s}$ = 4.178 GeV data samples [1], which are essential to improve the signal precision on the measurements of the (semi-) leptonic $D_{(s)}$ decays.

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