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(Semi-) leptonic $D_{(s)}$ decays at BESIII

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BESIII has collected 2.93 fb^{-1} and 6.32 fb^{-1} of e^+e^- collision data samples at the center-of-mass energies 3.773 and 4.178-4.226 GeV, respectively. We report recent measurements of the (semi-) leptonic decays $D_s \to \ell^+\nu_\ell$ ($\ell = \mu, \tau$) and $D_{(s)} \to X\ell^+\nu_\ell$ [$X = \eta, K_1(1270), \rho$ or denotes generic decays, and $\ell = e, \mu$]. The decay constant $f_{D_s^+}$, the semileptonic form factor $f_+^\eta(0)$ and the CKM matrix elements $|V_{cd(s)}|$ are determined precisely. These results are important to verify the theoretical calculations of $f_{D_s^+}$ and $f_+^\eta(0)$, and the unitarity of the CKM matrix. Precision tests of lepton-flavor universality with (semi-) leptonic $D_{(s)}$ decays are also performed.

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The leptonic and semileptonic charm decays provide an ideal window to explore the strong and weak interactions. In the standard model (SM), due to lepton flavor universality (LFU), the ratio of decay widths [1] for the pure leptonic decays of a charmed meson with different generation leptons should only depend on the masses of the leptons and the charmed meson, and it is expected to have the same branching fraction (BF) for the charmed meson decaying to the same hadronic final states and different generation leptons in the limit that the lepton masses are negligible. However, the hints of LFU violation have been observed in the semi-leptonic B decays recently [2]. Thus, it will be of great interest to search for LFU in the pure leptonic and semi-leptonic D decays with high precision. Besides, measurements of these decays will also provide the accurate basis for deducing the decay constant $f_{D_s^+}$ or form factor $f_+(0)$, and Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{cd(s)}|$, respectively.

Benefiting from the $D\bar{D}$ and $D_s^{*\pm}D_s^{\mp}$ pairs produced in e^+e^- collision at center-of-mass energies of $\sqrt{s}$ = 3.773 GeV and $\sqrt{s}$ = 4.178 − 4.226 GeV [3], a double-tag (DT) technique pioneered by the Mark III experiments [4] can be employed to measure the absolute BF of $D_{(s)}$ decays in BESIII experiment [5]. A DT signal is the pure leptonic or semi-leptonic signal $D_{(s)}$ candidate accompanied by a fully reconstruction of the other $D_{(s)}$ meson. Throughout the text, charge-conjugate modes are implicitly assumed, unless otherwise stated.

1. Pure leptonic D_s^+ decays

1.1 $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$

Using a data set of 6.32 fb^{-1} of e^+e^- annihilation data collected with the BESIII detector at the center-of-mass energies between 4.178 and 4.226 GeV, we have measured the absolute BF of the leptonic decay $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$. Since the massless neutrinos are undetected, the variable of $E^{\rm tot}_{\rm extra}$, as shown in Fig. 1, has been adopted to analyze the signal $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ [6], where $E^{\rm tot}_{\rm extra}$ denotes the total energy of the good electromagnetic calorimeter (EMC) showers excluding those associated with the fully reconstructed D_s^- candidate and those within 5° of the initial direction of the positron. The signal yields are determined in the region $E^{\rm tot}_{\rm extra} < 0.4$ GeV by statistically subtracting the backgrounds extrapolated from the fits to $E^{\rm tot}_{\rm extra}$ in $E^{\rm tot}_{\rm extra} > 0.6$ GeV. The BF of $D_s^+ \to \tau^+\nu_\tau$ is 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 result to date.

1.2 $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$

In order to obtain the signal yield in the analysis of $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$ [7], a simultaneous fit to the missing mass square (MM^2) is performed for the data samples taken at the center-of-mass energies between 4.178-4.226 GeV, sharing with a common $\mathcal{B}_{D_s^+\to\tau^+\nu_\tau}$, which is shown in Fig. 2. Here, the missing means the information of the undetected neutrinos. The signal yield is estimated to be (1745 ± 84), and the measured BF of $D_s^+ \to \tau^+\nu_\tau$ is to be $\mathcal{B}_{D_s^+\to\tau^+\nu_\tau} = (5.29 \pm 0.25_{\rm stat.} \pm 0.20_{\rm syst.})\%$.

1.3 $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$ and $D_s^+ \to \mu^+\nu_\mu$

Due to the similar masses between pion and muon, the analyses of $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$ and $D_s^+ \to \mu^+\nu_\mu$ are studied together [3]. The sample in the signal D_s^+ side is split into two parts

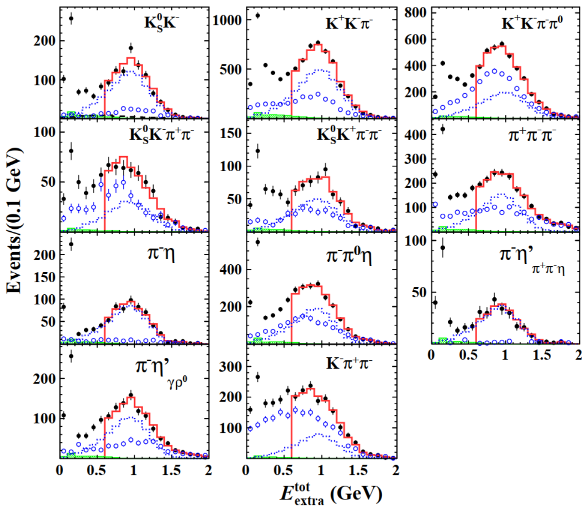

Figure 1: The $E_{\rm extra}^{\rm tot}$ distributions of the DT candidates in the combined data sample (black points with error bars), along with results of fits to $E_{\rm extra}^{\rm tot}$ > 0.6 GeV (solid red) and background estimates for non-D_s^- (circles with error bars), $D_s^+ \to K_L^0 e^+\nu_e$ (hatched green), $D_s^+ \to K_L^0 e^+\nu_e$ (dotted blue), and $D^- \to K_S^0\pi^-$ (dashed black, only for $D_s^- \to K_S^0 K^-$).

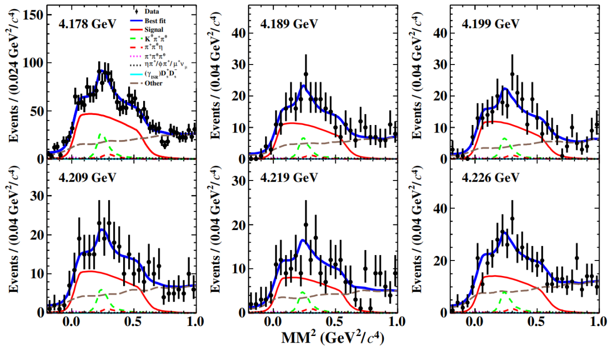

Figure 2: Simultaneous fit to the MM^2 distributions of the accepted $D_s^+ \to \tau^+\nu_\tau$ candidates from the data samples at various energy points. Points with error bars are data. Solid blue curves are the fit results. Red solid lines show the signals. Green dashed, red dashed, pink dotted, black dotted, cyan solid, and brown dashed curves are the backgrounds.

based on the energy-deposit ($E_{\rm EMC}$) properties of muons and pions in the EMC. Candidates with $E_{\rm EMC} \leq 300$ MeV are classified as μ-like sample and the remainder as π-like sample. An unbinned simultaneous maximum likelihood fit to the two dimensional (2D) distributions are performed for the two kinds of samples, where the 2D distributions are the invariant mass of the fully reconstructed D_s^- and the MM^2 as shown in Fig.3. The signal yields are obtained to be (946^{+46}_{-45}) for $D_s^+ \to \tau^+\nu_\tau$, and (2198 ± 55) for $D_s^+ \to \mu^+\nu_\mu$, where the uncertainty are statistical only. The measured BFs are $\mathcal{B}_{D_s^+\to\tau^+\nu_\tau} = (5.21 \pm 0.25_{\rm stat.} \pm 0.17_{\rm syst.}) \times 10^{-2}$, 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 [8], the ratio of the $\mathcal{B}_{D_s^+\to\tau^+\nu_\tau}$ over $\mathcal{B}_{D_s^+\to\mu^+\nu_\mu}$ is estimated to be 9.67 ± 0.34, which is consistent with the SM prediction of 9.75 ± 0.01. Taking the CKM matrix element $|V_{cs}| = 0.97320 \pm 0.00011$ from the global SM fit [8], or the averaged decay constant $f_{D_s^+} = 249.9 \pm 0.5$ MeV of LQCD calculations [9]

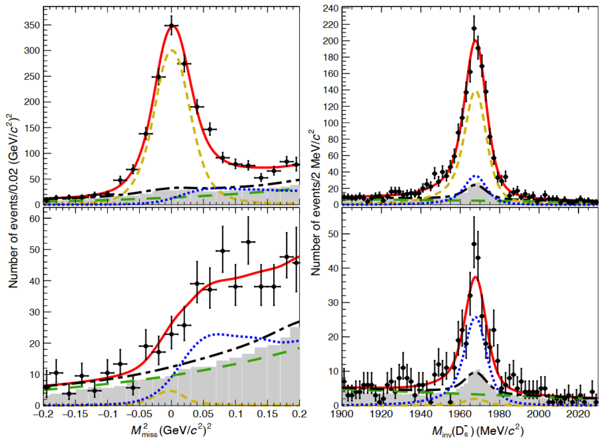

Figure 3: Projections onto the $M^2_{\rm miss}$ (left) and $M_{\rm inv}(D_s^-)$ (right) axes of the two-dimensional fit to 4180 data for the μ-like (top) and the π-like (bottom) samples. The black points are data, the shaded histograms correspond to the 40× MC sample scaled to the integrated luminosity of data, and the lines represent the fitted signal and background shapes. The red-solid, orange-dashed, and blue dotted lines represent the total, $D_s^+ \to \mu^+\nu_\mu$, and $D_s^+ \to \tau^+\nu_\tau$, while black-dot-dashed and green-long-dashed lines correspond to the total background and the case when both tag and signal sides are misreconstructed, respectively.

as input, the $f_{D_s^+}$ and $|V_{cs}|$ can be determined, respectively.

2. Semi-leptonic $D_{(s)}$ decays

2.1 $D^+ \to \eta\mu^+\nu_\mu$

BESIII has reported the first measurement on dynamics of $D^+ \to \eta\mu^+\nu_\mu$ decay [10]. 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 world average value of $\mathcal{B}_{D^+\to\eta e^+\nu_e}$ [8], the ratio of $\mathcal{B}_{D^+\to\eta\mu^+\nu_\mu}$ over $\mathcal{B}_{D^+\to\eta e^+\nu_e}$ is estimated to be (0.91 ± 0.13), which is consistent with the SM prediction with a range of (0.97-1.00). Subsequently, the form factor $f_+^\eta(0)$ and the CKM matrix element $|V_{cd}|$ are determined to be $f_+^\eta(0) = 0.39\pm0.04_{\rm stat.}\pm0.01_{\rm syst.}$ and $|V_{cd}| = 0.242\pm0.022_{\rm stat.}\pm0.006_{\rm syst.}\pm0.033_{\rm theory}$, respectively.

2.2 $D^0 \to K_1(1270)^-e^+\nu_e$

The signal $D^0 \to K_1(1270)^-e^+\nu_e$ with $K_1(1270)^- \to K^-\pi^+\pi^-$ [11] is analyzed through an unbinned extended maximum likelihood simultaneous fit to the MM^2 and the invariant mass of $K^-\pi^+\pi^-$, sharing the same value of the product of $\mathcal{B}_{D^0\to K_1(1270)^-e^+\nu_e}$ and $\mathcal{B}_{K_1(1270)^-\to K^-\pi^+\pi^-}$. The signal yield is obtained to be (109.0 ± 12.5), and the measured BF is $\mathcal{B}_{D^0\to K_1(1270)^-e^+\nu_e} = (1.09 \pm 0.13^{+0.09}_{-0.16} \pm 0.12_{\rm ex}) \times 10^{-3}$.

2.3 $D_s^+ \to Xe^+\nu_e$

In order to study the inclusive semielectronic D_s^+ decays [12], a fit to the momentum of the positron (p_e) greater than 200 MeV/c is performed, and the signal yield in $p_e < 200$ MeV/c is extrapolated from the fit. The signal region in the whole region of p_e is estimated to be (16648 ± 326), and the measured BF is $\mathcal{B}_{D_s^+\to Xe^+\nu_e} = (6.30 \pm 0.13_{\rm stat.} \pm 0.10_{\rm syst.}) \times 10^{-2}$, showing no evidence for unobserved exclusive semielectronic modes.

2.4 $D^0 \to \rho^-\mu^+\nu_\mu$

The semileptonic decay $D^0 \to \rho^-\mu^+\nu_\mu$ has been observed for the first time [13]. The absolute BF of this decay is determined to be $\mathcal{B}_{D^0\to\rho^-\mu^+\nu_\mu} = (1.35 \pm 0.09_{\text{stat.}} \pm 0.09_{\text{syst.}}) \times 10^{-3}$. Using the world average value of $\mathcal{B}_{D^0\to\rho^-e^+\nu_e}$, we obtain the BF ratio $\mathcal{B}_{D^0\to\rho^-\mu^+\nu_\mu}/\mathcal{B}_{D^0\to\rho^-e^+\nu_e} = 0.90\pm0.11$, which agrees with the theoretical expectation of lepton flavor universality within the uncertainty.

3. Summary

Utilizing the data samples of 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 pure leptonic and inclusive semielectronic D_s^+ decays with higher precision, the first measurement on dynamics of $D^+ \to \eta\mu^+\nu_\mu$, and the first observations for $D^0 \to K_1(1270)^-e^+\nu_e$ and $D^0 \to \rho^-\mu^+\nu_\mu$ decays. In the near future, BESIII will collect another 17 fb^{-1} at $\sqrt{s}$ = 3.773 GeV and 3 fb^{-1} at $\sqrt{s}$ = 4.178 GeV data samples [14], which will help us to achieve a further improved precision on measurements of the pure leptonic and semi-leptonic $D_{(s)}$ decays.

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