Charm physics at BESIII

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Abstract. By analyzing data samples taken at the center-of-mass energies $\sqrt{s} = 3.773$ GeV and $\sqrt{s} = 4.009$ GeV with the Beijing Spectrometer (BESIII) detector at the Beijing Electron Positron Collider (BEPCII), we determined the $D^+_s$ decay constants, the form factors of semileptonic decays of $D$ meson, the CKM matrix elements $|V_{cs(d)}|$, the $D^+_s$ hadronic decays, and we search for charm rare decays. In this article we briefly report the results.

1. Introduction
The leptonic and semileptonic charm decays provide an ideal window to explore the strong and weak interactions. The Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{cs(d)}|$ could be well determined via precision measurements of these decays, which can test the CKM matrix unitary. On the other hand with precision measurements of the decay constants $f_{D^+_s}$ and form factor, we are able to calibrate the Lattice QCD calculations. Hadronic decays of charmed mesons provide important information on flavor mixing, CP violation, and strong-interaction effects. Precision measurements of the hadronic decay rates also strengthen the understanding of U-spin and SU(3)-flavor symmetry breaking effects in $D$ meson decays. In addition, the search for charm rare decays can provide plentiful information for the new physics (NP).

In this paper, the samples for the recent studies of the leptonic, semileptonic, hadronic and rare charm decays described in the following were recorded with the BESIII detector at the $D^0\bar{D}^0/D^+D^−$ threshold ($\sqrt{s} = 3.773$ GeV) and at the $D^+_sD^−_s$ threshold ($\sqrt{s} = 4.009$ GeV) with integrated luminosities of 2.93 fb$^{-1}$ and 482 pb$^{-1}$, respectively. Throughout the proceeding, charge conjugate is implied.

2. BESIII and data analysis method
The BESIII is a general purpose magnetic detector working at a double-ring $e^+e^−$ collider operating in center-of-mass energy between 2.0 GeV and 4.6 GeV, located at the Institute of High Energy Physics (IHEP), Beijing. The maximum luminosity of the BEPCII at 3.773 GeV is $1^{33} cm^{-2} s^{-1}$. In data analysis, taking $D^+_s$ meson as an example, at $\sqrt{s} = 4.009$ GeV, the $D^+_s$ and $D^-_s$ mesons are produced in $e^+e^−$ annihilation. We first selected the $D^-_s$ meson sample from its hadronic decay modes, which is called singly tagged $D^-_s$ meson or single $D^-_s$ tag, and then selected the leptonic or semileptonic $D^+_s$ decays in the system recoiling against the singly tagged $D^-_s$ mesons. To select the leptonic and semileptonic $D^+_s$ decays with missing neutrino, we calculated $U_{\text{miss}} \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}|$ or $M^2_{\text{miss}} \equiv E^2_{\text{miss}} - |\vec{p}^2_{\text{miss}}|$, where $E_{\text{miss}}$ and $\vec{p}_{\text{miss}}$ are the missing energy and missing momentum of the event, respectively. From the $U_{\text{miss}}$ or $M^2_{\text{miss}}$...
distributions we can get the number of signal candidates for the leptonic or semileptonic $D_s^+$ decays, and then measure their decay branching fractions (BFs).

### 3. Pure leptonic $D_{(s)}$ decays

The pure leptonic decay of charged $D_{(s)}^+$ mesons proceeds via the annihilation of the $c$ quark and the anti-$d$ (anti-$s$) quark to a virtual $W^\pm$ boson and its decay to $\ell^\pm \nu_\ell$. The decay rate can be parametrized as:

$$
\Gamma(D_{(s)}^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} f_{D_{(s)}}^2 m_{\ell} m_{D_{(s)}} (1 - \frac{m_\ell^2}{m_{D_{(s)}}^2})^2 |V_{cd(s)}|^2,
$$

where $G_F$ is the Fermi coupling constant, $m_\ell$ and $m_{D_{(s)}}$ are the masses of the lepton and the $D_{(s)}$ meson in the final state, respectively. Hence the leptonic decays of the charmed meson provide us an opportunity to measure the decay constants $f_{D_{(s)}}$ and the magnitudes of CKM element $|V_{cd(s)}|$.

#### 3.1. $D^+ \to \mu^+ \nu_\mu$

By analyzing the data sample at $\sqrt{s} = 3.773$ GeV, we studied the $D^+ \to \mu^+ \nu_\mu$ decay. Nine hadronic $D^-$ decay modes are used to accumulate the single tagged $D^-$. The $D^+ \to \mu^+ \nu_\mu$

![Figure 1. The $M_{\text{miss}}^2$ distributions of the $D^+ \to \mu^+ \nu_\mu$ candidates, where dots with error bars indicate the data, the opened histogram is for Monte Carlo simulated signal events of $D^+ \to \mu^+ \nu_\mu$ decays, and the hatched histograms are for the simulated backgrounds from $D^+ \to K^0_s\pi^+$ (red), $D^+ \to \pi^0\pi^+$ (green), $D^+ \to \tau^+\nu_\tau$ (blue), all other $D$-meson decays (yellow), and non-$D\bar{D}$ processes (pink).](image)

decay is selected in the recoil side of the single tagged $D^-$. Figure 1 shows the distribution of $M_{\text{miss}}^2$. After subtracting the backgrounds originating from various $D^+$ decay channels, $409.0 \pm 21.2$ signal events are retained and the BF is measured to be $\mathcal{B}(D^+ \to \mu^+ \nu_\mu) = (3.71 \pm 0.19_{\text{stat}} \pm 0.06_{\text{syst}}) \times 10^{-4}$, which is the most precise measurement to date. Combining this BF measurement and the Particle Data Group (PDG) values of $D^+$ lifetime, $m_{D^+}$, $m_\mu$ and magnitude of $|V_{cd}|$ determined from the global Standard Model (SM) fit, the decay constant is determined to be $f_{D^+} = (203.2 \pm 5.3_{\text{stat}} \pm 1.8_{\text{syst}})$ MeV. Alternately, the magnitude of CKM matrix element $V_{cd}$ is extracted to be $V_{cd} = 0.2210 \pm 0.0058_{\text{stat}} \pm 0.0047_{\text{syst}}$ [1].

#### 3.2. $D_s^+ \to \mu^+ \nu_\mu$ and $D_s^+ \to \tau^+ \nu_\tau$

By analyzing the data taken at 4.009 GeV, we also studied the leptonic $D^+_s$ decays. From nine $D_s^-$ hadronic decay modes, $15127 \pm 321$ singly tagged $D_s^-$ mesons were accumulated. In the system recoiling against the single tagged $D_s^-$, the signal events of $D_s^+ \to \ell^+ \nu_\ell$ ($\ell = \mu$, or $\tau$) were selected. The distribution of $M_{\text{miss}}^2$ is shown in Fig. 2, we obtained $69.3 \pm 9.3$ $D_s^+ \to \mu^+ \nu_\mu$ and $32.5 \pm 4.3$ $D_s^+ \to \tau^+ \nu_\tau$ events. The results of the BF are determined to be $\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu) = (0.495 \pm 0.067_{\text{stat}} \pm 0.026_{\text{syst}})\%$, $\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (4.83 \pm 0.65_{\text{stat}} \pm 0.26_{\text{syst}})\%$, and the decay constant $f_{D_s} = (241.0 \pm 16.3_{\text{stat}} \pm 6.6_{\text{syst}})$ MeV [2].
the magnitudes of CKM matrix elements and validate the lattice QCD calculations by measuring the form factors at $q$ and $1/2$ for mode $D$ measured to be $B$ the most precise at present [4]. Similarly, the BFs for $D(0)$ are given by $B(D^+ \rightarrow \gamma e^+ \nu_e) = (3.505 \pm 0.014_{\text{stat}} \pm 0.033_{\text{syst}})\%$ and $B(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.004_{\text{stat}} \pm 0.003_{\text{syst}})\%$, which are consistent with the previous measurements and are the most precise at present [4]. Similarly, the BFs for $D^+ \rightarrow K^0 e^+ \nu_e$ and $D^+ \rightarrow \pi^0 e^+ \nu_e$ are measured to be $B(D^+ \rightarrow K^0 e^+ \nu_e) = (8.60 \pm 0.06_{\text{stat}} \pm 0.15_{\text{syst}})\%$ and $B(D^+ \rightarrow \pi^0 e^+ \nu_e) = 0.35_{\text{stat}} \pm 0.09_{\text{syst}}).$
(0.363 ± 0.008_{\text{stat}} ± 0.005_{\text{syst}})\% , which are consistent within errors with previous measurements but with better precisions [5]. We also studied the differential decay rates of these two processes. We first divided the semileptonic events into several $q^2$ bins and measure the partial decay rates in each $q^2$ bin, then we fit these partial decay rates using different form factor models. Single pole model, modified pole model and series expansion are tried. Figures 3 and 4 show the fit results.

From the fits, we extract the product $f_{\pi}(0)|V_{cs}(d)|$ and other form factor parameters. Using the values for $f_{\pi}(0)|V_{cs}(d)|$ from the two-parameter $z$-series expansion fits and with $f_{\pi}(0) = 0.747 ± 0.011 ± 0.015$ [6] and $f_{K(\pi)}(0) = 0.666 ± 0.020 ± 0.021$ [7] calculated in LQCD, $|V_{cs}|$ is obtained to be $0.9601±0.0033±0.0047±0.0239$ ($|V_{cd}| = 0.2155±0.0027±0.0014±0.0094$), where the first uncertainties are statistical, the second ones systematic, and the third ones are due to the theoretical uncertainties in the form factor calculations. The BESIII results are in good agreement with the previous measurements, and with the best precision to date.

5.2. $D_{s}^{+} \rightarrow \eta(\eta')e^{+}\nu_{e}$

By analyzing the data taken at 4.009 GeV, BESIII studied the semileptonic $D_{s}^{+} \rightarrow \eta(\eta')e^{+}\nu_{e}$ decays [8]. The 13157 ± 240 singly tagged $D_{s}^{-}$ mesons are reconstructed in ten hadronic decay modes. The information of the signal candidate is inferred from the variable $U_{\text{miss}}$. Figure 5 shows the distributions of $U_{\text{miss}}$. After subtracting the backgrounds, the BFs are determined to be $B(D_{s}^{+} \rightarrow \eta e^{+}\nu_{e}) = (2.30 ± 0.31_{\text{stat}} ± 0.08_{\text{syst}})\%$ and $B(D_{s}^{+} \rightarrow \eta' e^{+}\nu_{e}) = (0.93 ± 0.30_{\text{stat}} ± 0.05_{\text{syst}})\%$, which are consistent with previous measurements within uncertainties. Combining the BF measurements, we obtain the ratio $B(D_{s}^{+} \rightarrow \eta e^{+}\nu_{e}) / B(D_{s}^{+} \rightarrow \eta' e^{+}\nu_{e}) = 2.53 ± 0.30_{\text{stat}} ± 0.10_{\text{syst}})$.

Figure 3. Fits to partial decay widths of $D^{+} \rightarrow \bar{K}^{0}e^{+}\nu_{e}$ (left) and $D^{+} \rightarrow \pi^{0}e^{+}\nu_{e}$ (right).

Figure 4. Fits to partial decay widths of $D^{+} \rightarrow \bar{K}^{0}e^{+}\nu_{e}$ (left) and $D^{+} \rightarrow \pi^{0}e^{+}\nu_{e}$ (right).
Figure 5. The $U_{\text{miss}}$ distributions of the (a) $D^+ \rightarrow \mu^+ \nu_\mu$, (b) $D_s^+ \rightarrow \eta'(\eta \pi^+\pi^-)e^+\nu_e$ and (c) $D_s^+ \rightarrow \eta'(\gamma\rho^0)e^+\nu_e$ candidates, where arrows denote the signal regions.

$0.40^{+0.14}_{-0.14}\text{stat}^{+0.02}_{0.02}\text{syst}$, which provides complementary information to understand $\eta-\eta'$ mixing [8].

6. Handronic $D$ decays

An amplitude analysis of the decay $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ has been performed with the data at $\sqrt{s} = 3.773$ GeV. With a nearly background free sample of about 16000 events, we investigate the substructure of the decay and determine the relative fractions and the phases among the different intermediate processes. Our amplitude model includes the two-body decays $D^0 \rightarrow \bar{K}^*\rho^0$, $D^0 \rightarrow K^-a_1^+(1260)$ and $D^0 \rightarrow K^-_1(1270)\pi^+$, the three-body decays $D^0 \rightarrow \bar{K}^*0\pi^+\pi^-$, $D^0 \rightarrow K^-\pi^+\rho^0$, as well as the four-body nonresonant decay $D^0 \rightarrow K^-\pi^+\pi^-\pi^-$. The dominant intermediate process is $D^0 \rightarrow K^-a_1^+(1260)$, accounting for a fit fraction of 54.6%. By using the inclusive BF $B(D^0 \rightarrow K^-\pi^+\pi^-\pi^-) = (8.07 \pm 0.23)\%$, taken from the PDG and the fit fraction for the different components $FF(n)$ obtained in this analysis, we calculate the exclusive absolute BFs for the individual components with $B(n) = B(D^0 \rightarrow K^-\pi^+\pi^-\pi^-) \times FF(n)$ [9].

7. Summary

By analysing 2.93 and 0.482 fb$^{-1}$ data taken at $\sqrt{s} = 3.773$ and 4.009 GeV with the BESIII detector, we present a selection of recent BESIII charm results. From the leptonic $D^+_s$ and semileptonic $D^{+0}$ decays we determined the most precise values for the decay constant $f_D$, the hadronic form factors $f_K^+(q^2)$, and the form factor shape $f_K^+(q^2)$, which provide important test to LQCD calculations, CKM matrix unitary. The study of charmed meson hadronic decays is given with significant improved precision. BESIII have taken more than 3 fb$^{-1}$ $D_sD_s^*$ data at $\sqrt{s} = 4.180$ GeV, many more results are expected.

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