Charm Physics at BESIII

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Abstract. Recently, BESIII has performed many analyses with the largest \( e^+ e^- \) annihilation data set taken on the mass-thresholds. Those works focus on the measurements of the CKM matrix elements \(|V_{cd}(s)|\), the transition form factors \( f_{D^0} \), tests of lepton flavor universality, precise measurements of branching fraction, studies of interesting intermediate states in the multiple-body decays, and searches for the new physics. Among those, we present the results with three categories, the (semi-) leptonic decays, hadronic decays, and the rare decays.

1 Introduction

The \( \psi(3770) \) lies below the \( D\bar{D}^* \) threshold and decays predominately into \( D\bar{D} \) pairs, making it an ideal ”\( D \)-meson factory”. For now, the BESIII has collected the largest coherent \( D\bar{D} \) pair data set in the world at \( \sqrt{s} = 3.773 \) GeV with an integrated luminosity of \( 2.93 \) fb\(^{-1}\) and \( \sqrt{s} = 4.178 \) GeV with an integrated luminosity of \( 3.19 \) fb\(^{-1}\), respectively, offering unique opportunities to study the charm decays. Since a \( D\bar{D} \) pair is produced, the constraint kinematics offer events with a low background level and allow the prediction of missing tracks, e.g., neutrinos, making it an ideal place to study (semi-)leptonic decays. In the case of neutral charm mesons, the correlated production allows to determine quantum numbers (e.g. \( CP \) or flavour) of one hadron and interfere with the corresponding quantum numbers of the other hadron. If such a “tag” is reconstructed additionally to the signal decay, we refer to a tagged analysis, otherwise to an untagged analysis.

2 Measurement of decay constants, form factors and CKM matrix elements

The leptonic decay rate usually taken as form

\[
\Gamma(D^+_c \rightarrow l^+\nu_l) = \frac{G_F^2 f_{D^+_c}^2 |V_{cd}(s)|^2 m_l^2 m_{D^+_c}}{8\pi} \left( 1 - \frac{m_l^2}{m_{D^+_c}^2} \right)^2,
\]

where \( G_F \) is the Fermi constant, \( m_l \) the mass of lepton \( l \), \( m_{D^+_c} \) the mass of \( D^+ \) (\( D^+_c \)) meson, \( f_{D^+_c} \) the decay constants of \( D^+_c \) meson. With the measured partial width of the leptonic \( D^+ \) decays channel, the \( f_{D^+_c} \) can be determined. With the input of \( |V_{cd}(s)| \), the decay constants

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$f_{D_s^+}$ could be determined, so as to $|V_{cs}|$. For the semi-leptonic decay, such as $D \rightarrow P l^+ \nu_l$, the $q^2$ dependent width usually takes as

$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2 p^3}{24\pi}|f_+(q^2)|^2 |V_{cd(s)}|^2,$$

(2)

where $X$ is a multiplicative factor to isospin, which equals to 1 for modes $D^0 \rightarrow K^- l^+ \nu_l, D^0 \rightarrow \pi^- l^+ \nu_l$ and 1/2 for mode $D^+ \rightarrow \pi^0 l^+ \nu_l$, $p$ the momentum of the pseudoscalar meson $P$ in the rest frame of the $D$ meson, $q^2$ is the squared four-momentum transfer, $f_+(q^2)$ is the form factor.

The decay constant can be calculated by LQCD and the comparison with experimental results is crucial. Study of leptonic $D$ decays also help to test the lepton flavor universality. The most recent measurements at BESIII are presented below.

### 2.1 Semi-leptonic decay

#### 2.1.1 $D_s^+ \rightarrow \mu^+ \nu_\mu$

The analysis of the pure-leptonic decay $D_s^+ \rightarrow \mu^+ \nu_\mu$ yields a signal of $1135.9 \pm 33.1$ tagged events from a sample of $3.19 \text{ fb}^{-1}$ recorded at the $D_s D_s^*$ threshold. With partial decay width and the masses of $D_s^+$ and $\mu^+$, the product of $V_{cs}$ and $f_{Ds}$ is determined to be

$$f_{Ds} |V_{cs}| = 246.2 \pm 3.6\text{(stat)} \pm 3.5\text{(sys)} \text{ MeV.}$$

(3)

Using external measurements [1–3] we determine

$$f_{Ds} = 252.9 \pm 3.7\text{(stat)} \pm 3.6\text{(sys)} \text{ MeV}$$

(4)

and

$$|V_{cs}| = 0.985 \pm 0.014\text{(stat)} \pm 0.014\text{(sys)}. \quad (5)$$

Results are published in [4].

#### 2.1.2 $D^+ \rightarrow \tau^+ \nu_\tau$

With doubly tag (DT) method, we observe the leptonic decay containing $\tau$ lepton. The $\tau$ lepton is reconstructed via $\tau \rightarrow \pi^+ \bar{\nu}_\tau \nu_\tau$. The sample are divided into two parts according to the energy deposited ($E_{EMC}$) in the electromagnetic calorimeter(EMC), as shown in Fig. 1. The background of the sample with $E_{EMC}$ less than 300 MeV is mainly caused by $D^* \rightarrow \mu^+ \nu_{\mu}$, in which the $\mu^+$ lepton is misidentified as the pion meson. With total $137 \pm 27$ signal events, the preliminary branching fraction is determined to be $\mathcal{B}(D^+ \rightarrow \tau^+ \nu_\tau) = (1.20 \pm 0.24\text{(stat)}) \times 10^{-4}$, in which the systematic uncertainties are still under studying. Combining with the measurement of $D^+ \rightarrow \mu^+ \nu_\mu$, the ratio between branching fractions of those two lepton decays are determined to be

$$R = \frac{\Gamma(D^+ \rightarrow \tau^+ \nu_\tau)}{\Gamma(D^+ \rightarrow \mu^+ \nu_\mu)} = \frac{m_\tau^2}{m_\mu^2} \left(1 - \frac{m_\mu^2}{m_D^2}\right) = 2.67 \pm 0.01,$$

(6)

which is consistent with the SM prediction within 0.9 $\sigma$. 

2
2.2 $D^0 \rightarrow K^- \mu^+ \nu_\mu$

The absolute branching fraction is significantly improved and determined to be $\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_\mu) = (3.413 \pm 0.019({\text{stat}}) \pm 0.035({\text{sys}}))\%$. Combining with our previous measurement of branching fraction of $D^0 \rightarrow K^- e^+ \nu_e$ decay, the ratio of the two semi-leptonic decays is determined to be

$$\frac{\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e)} = 0.974 \pm 0.007({\text{stat}}) \pm 0.012({\text{sys}}),$$

which agrees with the theoretical expectation of lepton flavor universality within one sigma. $f_{\pi}^K(0)|V_{cs}|$ is determined to be $0.7133 \pm 0.0038({\text{stat}}) \pm 0.0029({\text{sys}})$ by fit to the $q^2$ dependent partial width. The result is published at [5].

2.3 First observation $D \rightarrow a_0(980)e^+\nu_e$ decay

The ratio between three semi-leptonic decays

$$R = \frac{\mathcal{B}(D^+ \rightarrow a_0(980)e^+\nu_e) + \mathcal{B}(D^0 \rightarrow a_0(980)e^+\nu_e)}{\mathcal{B}(D^+ \rightarrow a_0(980)e^+\nu_e)},$$

will help to determine the nature of $a_0(980)$, $f_0(500)$, and $f_0(980)$ [6]. With DT method, we first determine the absolute BF of $D \rightarrow a_0(980)e^+\nu_e$ by 2 dimensional fit to the invariant mass of $\pi\eta$ and missing mass. The absolute branching fractions are determined to be $\mathcal{B}(D^0 \rightarrow a_0(980)e^+\nu_e \times B(a_0(980) \rightarrow \eta\pi^-) = (1.33^{+0.11}_{-0.29})\% \pm 0.09({\text{sys}})) \times 10^{-4}$ and $\mathcal{B}(D^+ \rightarrow a_0(980)e^+\nu_e \times B(a_0(980) \rightarrow \pi^0\eta) = (1.66^{+0.11}_{-0.08})\% \pm 0.11({\text{sys}})) \times 10^{-4}$, with significances of 6.4$\sigma$ and 2.9$\sigma$, respectively. The result is published at [7].

3 Measurements of branching fraction and study of intermediate states

3.1 Observation of $D_s^+ \rightarrow p\bar{\eta}$ decay

The decay $D_s^+ \rightarrow p\bar{\eta}$ is the only kinematically allowed baryonic decay of the three ground-state charmed mesons $D^0$, $D^+$, and $D_s^+$. The yield of signal is determined by fit to the missing
mass square. The branching fraction is determined to be $(1.21 \pm 0.10 \pm 0.05) \times 10^{-3}$ [8], confirming the result of CLEOc [9].

### 3.2 Measurements of absolute branching fraction of $D \to PP$ and First observation $D_s^+ \to K^+ \omega$ decay

The analysis of $D \to PP$ modes will provide materials for the study of $SU(3)$ break effect. Most of the $D$ decays have been studied by CLEOc in 2010, however, some of the branching fractions are not well established. With the largest $D\bar{D}$ sample taken by the BESIII detector, the results are improved significantly and published at [10]. As well as we firstly observe the decay $D_s^+ \to K^+ \omega$, the branching fraction is measured to be $(0.87 \pm 0.24(\text{stat}) \pm 0.07(\text{sys})) \times 10^{-3}$ [11].

### 3.3 $D^+ \to K^0\pi^-\pi^-\pi^+$

The amplitude analysis of multibody decays of $D$ meson helps to determine the absolute branching fraction, strong phase, benefit $\gamma/\phi_3$. Using 4559 tagged signal events with a purity of 97.5%, we analyse the decay $D^+ \to K^0\pi^-\pi^-\pi^+$ with amplitude analysis technique. The results of many decays are improved. The internal structure of the decay is expected be dominated by axial-vector particles. Compared to the neutral $D$ decay[12, 13], only $D^+ \to \bar{K}_1(1400)\pi^+$ is significantly larger for the charged mode, while other modes agree. The analysis is available at [14].

### 4 Search for the clue of New Physics

#### 4.1 Search for heavy Majorana neutrino via $D \to K\pi^+\pi^-$

We search for the Majorana neutrino ($\nu_m$) in the lepton number violating decays $D \to K\pi^+\pi^-$. No significant signal is observed, and the upper limits on the branching fraction at the 90% confidence level are set to be $\mathcal{B}(D^0 \to K^-\pi^+\pi^-) < 2.8 \times 10^{-6}$, $\mathcal{B}(D^+ \to K^0\pi^-\pi^+) < 3.3 \times 10^{-6}$ and $\mathcal{B}(D^+ \to K^-\pi^0\pi^+) < 8.5 \times 10^{-6}$. The results are published at [15].

#### 4.2 Search for $D \to h(h')\pi^+\pi^-$ decays

In the SM, the process $D \to h(h')\pi^+\pi^-$ accompanied via quark process $c \to u l^+\bar{\nu}_l$, which is known as a flavor changing neutral current (FCNC) process. FCNC happens only through a loop diagram. The long distance effects through (virtual) vector meson decays could enhance this decay rate, even above the level of $10^{-6}$ [16, 17]. We adopt the DT method to search for those rare decays and find no significant signal for all of them [18]. The upper limits on their branching fractions are set at 90% C.L shown in Table 1, highly improving the precision compared with the PDG results.

### 5 Outlook

Using high statistics data samples taken at charm related thresholds by BESIII, we are able to study various aspects of open charm decays. We present a selection of recent BESIII results with the aim to illustrate the variety of results published in the past years. Many analyses are ongoing and further interesting results can be expected in the near future.
Table 1. Results of the upper limits (UL) on the branching fractions for the investigated rare decays at the 90 % C.L.

| mode            | $\pi^+\pi^-e^+e^-$ | $K^+\pi^-e^+e^-$ | $K_S^0\pi^+e^+e^-$ | $K^+K^-e^+e^-$ | $\pi^+\pi^-e^+e^-$ |
|-----------------|---------------------|------------------|-------------------|----------------|-------------------|
| $UL (\times 10^{-5})$ | 1.4                | 1.5              | 2.6               | 1.1            | 1.1               |

| mode            | $K^+\pi^-e^+e^-$ | $\pi^0\pi^0e^+e^-$ | $\eta\pi^+e^-$ | $\omega\pi^-e^-$ | $K_S^0\pi^+e^-$ |
|-----------------|------------------|-------------------|----------------|-----------------|------------------|
| $UL (\times 10^{-5})$ | 4.1              | 0.4               | 0.3            | 0.6             | 1.2              |

In the long term perspective, it is planned to increase the statistics at $D\bar{D}$ and $D_s\bar{D}$ thresholds significantly to 20 fb$^{-1}$ and 6 fb$^{-1}$. For the studies of (semi-)leptonic decays those samples would yield a precision of 1 % or below for the product of CKM matrix element and decay constant (or form factor). Furthermore, the measurement of the strong phase difference between $D^0$ and $\bar{D}^0$ would be possible with a precision better than 0.4$^\circ$.

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