Open Charm Physics at BESIII

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Abstract. The study of mesons and baryons containing at least one c quark is denoted as open charm physics. BESIII has collected large data samples at charm related thresholds which provide unique opportunities to study charm decays. BESIII has published many results in the past years. Among those we present the measurement of the CKM matrix elements $|V_{cd(s)}|^2$ and the form factors $f_{\mathrm{D}(s)}$ using the (semi-)leptonic decays $\mathrm{D_s} \rightarrow \mu^+\nu_\mu$ and $\mathrm{D}^0 \rightarrow \mathrm{K}^-\mu^+\nu_\mu$, a test for lepton flavour violation in the process $\mathrm{D} \rightarrow \mathrm{K}\pi\mathrm{e}^+\mathrm{e}^+$ and the study of intermediate states in the decays $\mathrm{D} \rightarrow \pi\pi\mathrm{e}^+\nu$ and $\mathrm{D}^+ \rightarrow \mathrm{K_S^0}\pi^-\pi^-\pi^+$.

1 Introduction

The study of open charm decays at-thresholds offers unique opportunities. As illustrated in figure 1 a meson anti-meson, or, baryon anti-baryon 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 ideal to study (semi-)leptonic decays. In the case of neutral hadrons the correlated production allows to determine quantum numbers (e. g. *CP* or flavour) of one hadron and interfere 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 and to an untagged analysis otherwise.

The theoretical motivation for the study of charm decays and BESIII results on $\Lambda_c^+\Lambda_c^-$ decays were presented at the same conference [1, 2]. An overview of the measurements related to D^0 mixing and prospects of measurements of the strong phase can be found elsewhere [3, 4]. For the sake of brevity those aspects are omitted in the following.

2 Measurement of Decay Constants, Form Factors and CKM Matrix Elements

The decay rate of leptonic and semi-leptonic D decays depend on the CKM matrix element $|V_{cd(s)}|^2$ and QCD effects which are parametrised by a decay constant in case of pure leptonic decays and a q^2 depended form factor in case of semi-leptonic decays. The decay constant and the form factor at $q^2 = 0$ can be calculated by lattice QCD (LQCD) and the comparison with experimental results is crucial.

From the measurement of the (partial) decay width and external input from LQCD for the decay constant or form factor, $|V_{cd(s)}|$ can be inferred. Vice-versa with external input from a global fit of $|V_{cd(s)}|$, decay constant or form factor can be derived. The most recent measurements at BESIII are presented below.

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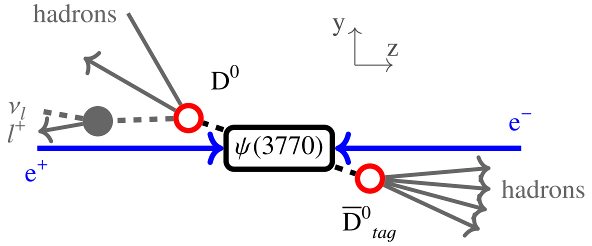


Figure 1: Decay topology in the $\psi(3770)$ rest frame. An undetected particle track can be reconstructed using the constrained kinematics of the decay.

2.1 $D_s \rightarrow \mu^+\nu_\mu$

The analysis of the pure-leptonic decay $D_s \rightarrow \mu^+\nu_\mu$ yields a signal of 1136 ± 331 tagged events from a sample of $3.19\,\text{fb}^{-1}$ recorded at the $D_sD_s^*$ threshold. Its decay width can be parametrised as

$$\Gamma_{D_s^+\rightarrow\mu^+\nu} = \frac{G_F^2}{8\pi}|V_{cd(s)}|^2 f_{D_s}^2 m_\mu^2 m_D^2 \left(1 - \frac{m_\mu^2}{m_D^2}\right), \tag{1}$$

with the decay constant f_{D_s} and the masses of D_s (m_D) and μ^- (m_μ). We measure the total branching fraction and calculate:

$$|V_{cs}|f_{D_s} = (246.2 \pm 3.6_{(\text{stat})} \pm 3.5_{(\text{stat})})\text{MeV}. \tag{2}$$

Using external measurements [5–7] we interfere

$$f_{D_s} = (252.9 \pm 3.7_{(\text{stat})} \pm 3.6_{(\text{sys})})\text{MeV} \tag{3}$$

and

$$|V_{cs}| = 0.985 \pm 0.014_{(\text{stat})} \pm 0.014_{(\text{sys})}. \tag{4}$$

Results are published in [8].

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

The analysis of the semi-leptonic decay $D^0 \rightarrow K^-\mu^+\nu_\mu$ is performed using a data sample of $2.93\,\text{fb}^{-1}$ at the $D\overline{D}$ threshold. We find 447100 ± 259 tagged events and the differential decay rate is given by

$$\left(\frac{d\Gamma}{dq^2}\right)_{D^0\rightarrow K^-\mu^+\nu} = \frac{G_F^2}{5\pi^3 m_D}|V_{cs}|^2\,|f_+^K(q^2)|^2\,|\vec{p}_K|\,X(q^2). \tag{5}$$

The q^2 dependent form factor is denoted by $|f_+^K(q^2)|^2$. The term $X(q^2)$ is almost constant. Extrapolating the differential decay width to $q^2 = 0$ we obtain

$$|V_{cs}|f_+^K(0) = (246.2 \pm 3.6_{(\text{stat})} \pm 3.5_{(\text{stat})})\text{MeV} \tag{6}$$

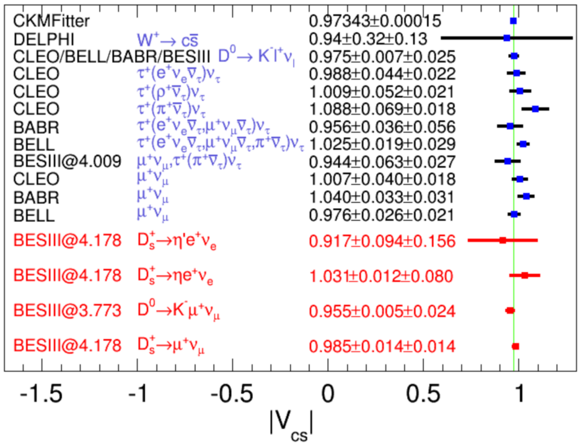


Figure 2: Comparison of experimental results for $|V_{cs}|$. The BESIII measurements are published in [8, 10, 11].

and interfere using [5, 9]

$$f_+^K(0) = (0.7327 \pm 0.0039_{(\text{stat})} \pm 0.0030_{(\text{sys})})\text{MeV} \tag{7}$$

and

$$|V_{cs}| = 0.955 \pm 0.005_{(\text{stat})} \pm 0.004_{(\text{sys})} \pm 0.024_{(\text{LQCD})}. \tag{8}$$

Results are published in [10]. The comparison with results from other experiments in figure 2 shows the high accuracy of the BESIII results.

3 Test for Lepton Flavour Violation

We search for the lepton flavour violating process $\text{D} \to \text{K}\pi\text{e}^+\text{e}^+$. Such a process could be enhanced over the vanishing Standard Model prediction by the existence of a Majorana neutrino ν_N, as illustrated in figure 3a.

We perform an untagged measurement using a sample of 2.93 fb^{-1} recorded at the $\text{D}\bar{\text{D}}$ threshold. No significant signal is observed and we obtain the upper limits at 90 % confidence level of $\mathcal{B}(\text{D}^0 \to \text{K}^-\pi^-\text{e}^+\text{e}^+) < 2.7 \times 10^{-6}$, $\mathcal{B}(\text{D}^+ \to \text{K}_S^0\pi^-\text{e}^+\text{e}^+) < 3.3 \times 10^{-6}$ and $\mathcal{B}(\text{D}^+ \to \text{K}^-\pi^0\text{e}^+\text{e}^+) < 8.5 \times 10^{-6}$.

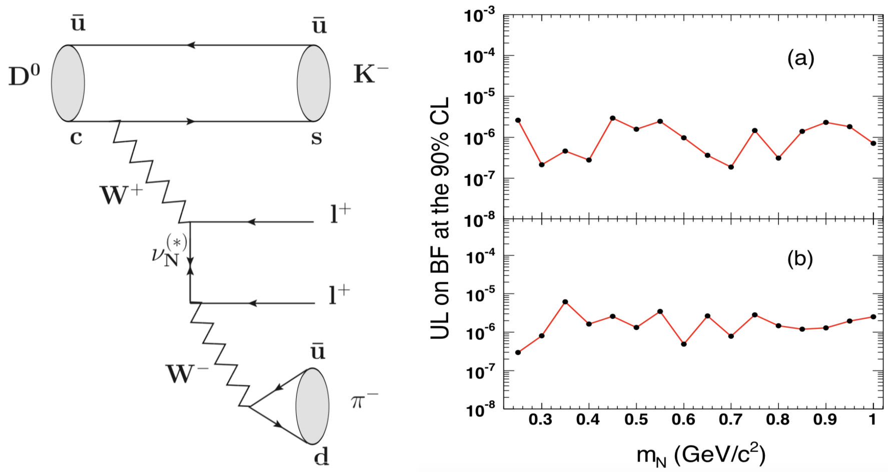
Furthermore, we determine upper limits with respect to the mass of a hypothetical intermediate state, i. e. a Majorana neutrino. The result is shown in figure 3b.

4 Study of Intermediate States

4.1 $\text{D} \to \pi\pi\text{e}^+\nu$

Semi-leptonic decays offer a clean production process to study light scalar mesons of which the nature of several states is still unclear. In particular, the nature of the scalar mesons $f_0(500)$, $f_0(980)$ and $a_0(980)$ are not clear yet. Is has been proposed [12] that the ratio

$$R = \frac{\mathcal{B}(\text{D}^+ \to f_0(980)\text{e}^+\nu_\text{e}) + \mathcal{B}(\text{D}^+ \to f_0(500)\text{e}^+\nu_\text{e})}{\mathcal{B}(\text{D}^+ \to a_0(980)\text{e}^+\nu_\text{e})} \tag{9}$$



(a) (b)

Figure 3: (a) Feynman diagram of the Cabibbo-favoured process and (b) upper limits on the branching fraction w.r.t the mass m_N of a hypothetical Majorana neutrino ν_N.

Table 1: Result of the partial-wave analysis of the decay $\mathrm{D} \to \pi\pi \mathrm{e}^+\nu$. Uncertainties are statistical followed by systematical uncertainty.

Process	Branching fraction $[10^{-3}]$
$\mathrm{D}^0 \to \pi^-\pi^0\mathrm{e}^+\nu_\mathrm{e}$	$1.445 \pm 0.058 \pm 0.0039$
$\mathrm{D}^0 \to \rho^-\mathrm{e}^+\nu_\mathrm{e}$	$1.445 \pm 0.058 \pm 0.0039$
$\mathrm{D}^+ \to \pi^-\pi^+\mathrm{e}^+\nu_\mathrm{e}$	$2.449 \pm 0.074 \pm 0.073$
$\mathrm{D}^+ \to \rho^0\mathrm{e}^+\nu_\mathrm{e}$	$1.860 \pm 0.070 \pm 0.061$
$\mathrm{D}^+ \to \omega\mathrm{e}^+\nu_\mathrm{e}$	$2.05 \pm 0.66 \pm 0.30$
$\mathrm{D}^+ \to f_0(500)\mathrm{e}^+\nu_\mathrm{e} \to \pi^-\pi^+\mathrm{e}^+\nu$	$0.630 \pm 0.043 \pm 0.032$
$\mathrm{D}^+ \to f_0(980)\mathrm{e}^+\nu_\mathrm{e} \to \pi^-\pi^+\mathrm{e}^+\nu$	< 0.028

could distinguish between a two-quark description ($R = 1.0 \pm 0.3$) and a SU(3) tetra-quark model ($R = 3.0 \pm 0.9$).

We analyse the neutral and charged D modes using $2.91\,\mathrm{fb}^{-1}$ of data recorded at the $\mathrm{D\overline{D}}$ threshold. A partial-wave analysis in the 5-dim phase space using 1667 ± 50 tagged decays is performed. Projections on the fit variables of the data sample and the amplitude model of the D^+ mode is shown in figure 4 and the branching fractions of the intermediate states are listed in table 1. We observe the $f_0(500)$ with a significance larger than $10\,\sigma$ and determine an upper limit the contribution of the $f_0(980)$. The combination with a previous BESIII measurement of $\mathcal{B}(\mathrm{D}^+ \to a_0(980)\mathrm{e}^+\nu_\mathrm{e})$[13] gives an upper limit of $R > 2.7$ (90 % C.L.). Thus, our result favours a tetra-quark description. Results are published in [14].

4.2 $\mathrm{D}^+ \to \mathrm{K}^0_\mathrm{S}\pi^-\pi^-\pi^+$

Charmed meson decays offer a laboratory to study strong dynamics at low energy and final state interactions. We analyse the decay $\mathrm{D}^+ \to \mathrm{K}^0_\mathrm{S}\pi^-\pi^-\pi^+$ using using $2.91\,\mathrm{fb}^{-1}$ of data

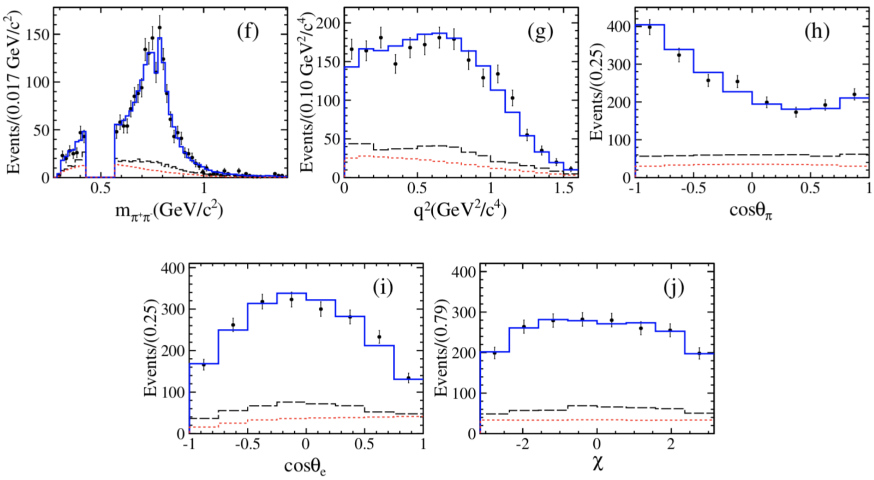


Figure 4: Projections of data sample (black dots) and amplitude model (blue line) on phase space variables.

recorded at the $D\overline{D}$ threshold. The internal structure of the decay is expected be dominated by axial-vector particles. Only few results exist [15–17] for the decay of D to axial-vector particles.

The dynamics of the decay involve the $(K_S^0\pi)$ S-wave which we describe by a effective range parametrisation [18], the ρ^0 (GS parametrization[19, 20]) and several other resonant states for which a relativistic Breit-Wigner is used. The angular distributions are modeled using the covariant tensor formalism. The partial-wave analysis is performed using 4559 tagged signal decays at a purity of 97.5 %.

The results of the branching fractions of the sub-modes are listed in table 2. Branching fractions are normalised to the total branching fraction $\mathcal{B}(D^+ \to K_S^0\pi^+\pi^+\pi^-)$. We are able to improve the precision of many decay modes. Compared to the neutral D decay[16, 17] we find that most decay modes agree, except $D^+ \to \bar{K}_1(1400)^0\pi^+$ which is significantly larger for the charged mode.

The analysis is available at [21] and was submitted to Physical Review D.

5 Outlook

Using high statistics data samples at charm related thresholds, BESIII is able to study various aspects of open charm decays. We presented 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 future.

In the long term perspective it is planned to increase the statistics at $D\overline{D}$, $D_s^+D_s^-$ and $\Lambda_c^+\Lambda_c^-$ thresholds significantly to 20 fb^{-1}, 6 fb^{-1} and 5 fb^{-1}. For the study of (semi-)leptonic decays those sample would yield a precision of 1 % and 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 $\overline{D}^0$ would be possible with a precision better than 0.4°.

Table 2: Results from the partial-wave analysis of the decay $D^+ \to K^0_S\pi^+\pi^+\pi^-$. Uncertainties are statistical and systematical uncertainties and the uncertainty related to $\mathcal{B}(D^+ \to K^0_S\pi^+\pi^+\pi^-)$.

Process	Branching fraction [%]
$D^+ \to K^0_S a_1(1260)^+(\rho^0\pi^+)$	$1.197 \pm 0.062 \pm 0.086 \pm 0.044$
$D^+ \to K^0_S a_1(1260)^+(f_0(500)\pi^+)$	$0.163 \pm 0.021 \pm 0.005 \pm 0.006$
$D^+ \to \bar{K}_1(1400)^0(K^{*-}\pi^+)\pi^+$	$0.642 \pm 0.036 \pm 0.033 \pm 0.024$
$D^+ \to \bar{K}_1(1270)^0(K^0_S\rho^0)\pi^+$	$0.071 \pm 0.009 \pm 0.021 \pm 0.003$
$D^+ \to \bar{K}(1460)^0(K^{*-}\pi^+)\pi^+$	$0.202 \pm 0.018 \pm 0.006 \pm 0.007$
$D^+ \to \bar{K}(1460)^0(K^0_S\rho^0)\pi^+$	$0.024 \pm 0.006 \pm 0.015 \pm 0.009$
$D^+ \to \bar{K}(1650)^0(K^{*-}\pi^+)\pi^+$	$0.048 \pm 0.012 \pm 0.027 \pm 0.002$
$D^+ \to K^0_S\pi^+\rho^0$	$0.190 \pm 0.021 \pm 0.089 \pm 0.007$
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	$0.241 \pm 0.018 \pm 0.018 \pm 0.009$

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