Charmed meson decays at BESIII

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Summary. — Charm meson decays remain an exciting field for particle physics investigations. In this article, we summarize the results on charm meson decays that have been obtained in the BESIII experiment.

1. – Overview

The BESIII detector records symmetric e^+e^- collisions provided by the BEPCII storage ring, which operates with a peak luminosity of 1×10^{33} cm^{-2}s^{-1} in the center-of-mass energy range from 2.0 to 4.95 GeV [1]. The charmed meson pairs $D\bar{D}$ ($D_s\bar{D}_s^*$) are produced near the threshold energy of pair production, 3.773 GeV (4.128 – 4.226 GeV), with an integrated luminosity of 2.93 fb^{-1} (7.33 fb^{-1}). The double tag (DT) method is used for most analyses, where the hadron pair is fully reconstructed [2]. Throughout this paper, charge-conjugate modes are implicitly assumed.

2. – D_s (semi-)leptonic decays

The (semi-)leptonic decays offer a theoretically clean platform for the study of both strong and weak interactions. The Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, which describe the weak interaction, as well as the form factors and decay constants describing the strong interaction, can be extracted through the investigation of leptonic and semileptonic decays. This aids in testing the unitarity of the CKM matrix and calibrating lattice quantum chromodynamics (LQCD) calculations. Furthermore, it provides an opportunity to test lepton flavor universality.

2˙1. $D_s^+ \to \tau^+\nu_\tau$. – The measurements of the branching fraction of $D_s^+ \to \tau^+\nu_\tau$ are made with the decay modes $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ [3] and $\tau^+ \to \pi^+\bar{\nu}_\tau$ [4].

Using $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$, Ref. [3] extracts the signal on the variable $E_{\rm extra}^{\rm tot}$, which is the sum of isolated showers' energies deposited in the calorimeter that have not been used by the tag side reconstruction. The signal yield is obtained in the region $E_{\rm extra}^{\rm tot} < 0.4\,{\rm GeV}$

subtracting the background yield extrapolated from the region $E_{\rm extra}^{\rm tot} > 0.6\,{\rm GeV}$. The measured branching fraction is $(5.34 \pm 0.16_{\rm stat.} \pm 0.10_{\rm syst.})\%$. The product of the D_s^+ decay constant and the $c \to s$ CKM matrix element is determined to be $f_{D_s^+}|V_{cs}| = (246.2 \pm 3.7_{\rm stat.} \pm 2.5_{\rm syst.})\,{\rm MeV}$. Since the time of the conference an updated result has been published, where $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.37 \pm 0.17_{\rm stat.} \pm 0.15_{\rm syst.})\%$, $f_{D_s^+}|V_{cs}| = (246.7 \pm 3.9_{\rm stat.} \pm 3.6_{\rm syst.})\,{\rm MeV}$

The improved measurement of $D_s^+ \to \tau^+\nu_\tau$ through $\tau^+ \to \pi^+\bar{\nu}_\tau$ uses a boosted decision trees (BDT) method. This method is validated by the control samples $D_s^+ \to \eta\pi^+$, $D_s^+ \to \mu^+\nu_\mu$, $e^+e^- \to \tau^+\tau^-/q\bar{q}$ and other τ^+ decays. A fit is performed on the BDT output to extract the signal yield. The branching fraction of $D_s^+ \to \tau^+\nu_\tau$ is measured to be $(5.41 \pm 0.17_{\rm stat.} \pm 0.13_{\rm syst.})\%$, which leads to the product of $f_{D_s^+}|V_{cs}| = (247.6 \pm 3.9_{\rm stat.} \pm 3.2_{\rm syst.})\,{\rm MeV}$. Since the time of the conference an updated result has been published ,where $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.44 \pm 0.17_{\rm stat.} \pm 0.13_{\rm syst.})\%$, $f_{D_s^+}|V_{cs}| = (248.3 \pm 3.9_{\rm stat.} \pm 3.1_{\rm syst.} \pm 1.0_{\rm input})\,{\rm MeV}$. Here, the third uncertainty is due to the input parameters, mainly the lifetime of D_s^+. The comparisons of various measurements of $f_{D_s^+}$ and $|V_{cs}|$ are shown in Fig. 1.

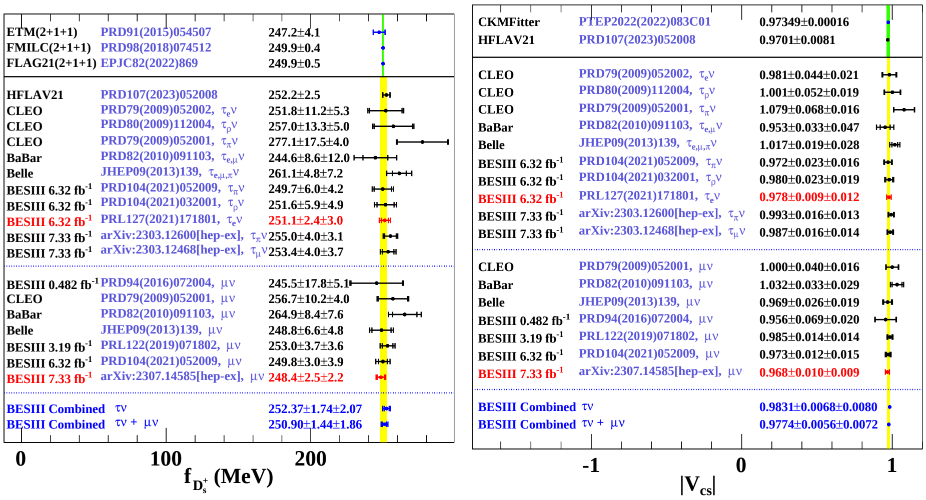

Fig. 1. – Comparison of the results for $f_{D_s^+}$ and $|V_{cs}|$, measured by the BESIII, Belle, BaBar, and CLEO experiments. The green bands present the LQCD uncertainties. Values marked in black circle denote LQCD calculations, values marked in blue square denotes average experimental results at BESIII. Figure provided by Hai-Long Ma.

2$\cdot$2. $D_s^{*+} \to e^+\nu_e$. – BESIII also investigates the purely leptonic decay $D_s^{*+} \to e^+\nu_e$ [7]. A signal is observed with a statistical significance of 2.9σ. The branching fraction is determined to be $(2.1^{+1.2}_{-0.9\,{\rm stat.}} \pm 0.2_{\rm syst.}) \times 10^{-5}$, corresponding to an upper limit of 4.0×10^{-5} at the 90% confidence level. In the standard model (SM), the decay width of $D_s^{*+} \to e^+\nu_e$ can be written as [8]

$$(1)\qquad \Gamma(D_s^{*+} \to \ell^+\nu_\ell) = \frac{G_F^2}{12\pi}|V_{cs}|^2 f_{D_s^{*+}}^2 m_{D_s^{*+}}^3 \left(1 - \frac{m_{\ell^+}^2}{m_{D_s^{*+}}^2}\right)^2 \left(1 + \frac{m_{\ell^+}^2}{2m_{D_s^{*+}}^2}\right),$$

where G_F is the Fermi coupling constant, $|V_{cs}|$ is the $c \to s$ CKM matrix element, m_{ℓ^+} is the lepton mass, and $m_{D_s^{*+}}$ is the D_s^{*+} mass.

Using the total width of the D_s^* meson, predicted as (0.070 ± 0.028) keV by LQCD as input, we determine the decay constant of the D_s^* to be $f_{D_s^*} = (213.6^{+61.0}_{-45.8}{}_{\text{stat.}} \pm 43.9_{\text{syst.}})$ MeV. This corresponds to an upper limit of 353.8 MeV at the 90% confidence level.

The total width of the D_s^{*+} is estimated to be $\Gamma^{\text{total}}_{D_s^{*+}} = (121.9^{+69.6}_{-52.2} \pm 11.8)\,\text{eV}$, by combining the world average values of $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$, the lifetime of the D_s^+, m_e, $m_{D_s^{*+}}$, m_μ, and $m_{D_s^+}$ [9], $\frac{f_{D_s^{*+}}}{f_{D_s^+}} = 1.12 \pm 0.01$ averaged from the LQCD calculations [8, 12, 13, 14, 15, 16] and $\mathcal{B}(D_s^{*+} \to e^+\nu_e)$ obtained in this work.

This is the first experimental study of the purely leptonic decay $D_s^{*+} \to e^+\nu_e$. This result indirectly constrains the upper limit on $\Gamma^{\text{total}}_{D_s^{*+}}$ from MeV [9] to keV level. The obtained $f_{D_s^{*+}}$ offers the first experimental test on various theoretical calculations. This analysis opens an avenue to study the weak decays of charmed vector mesons in experiments.

2·3. $D_s^+ \to \pi^+\pi^- e^+\nu_e$. – The semileptonic decays offer a good platform to study the inner structure of the hadrons in the final states because they only interact weakly with the other final states leptons. BESIII reports the study of $D_s^+ \to f_0(980)e^+\nu_e$ with $f_0(980) \to \pi^+\pi^-$ [17], which can probe the nature of the light scalar meson $f_0(980)$. The branching fraction of $D_s^+ \to f_0(980)e^+\nu_e$ with $f_0(980) \to \pi^+\pi^-$ is measured to be $(1.72 \pm 0.13_{\text{stat.}} \pm 0.10_{\text{syst.}}) \times 10^{-3}$, which is 2.6 times more accurate than the previous measurement [10]. This indicates that the $s\bar{s}$ component is dominant according to the relation between the branching fraction and the mixing angle ϕ involved in the $q\bar{q}$ mixture picture for $f_0(980)$ as $\sin\phi\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) + \cos\phi(s\bar{s})$. By studying the differential decay rate of $D_s^+ \to f_0(980)e^+\nu_e$, the form factor of $f_+^{f_0}(q^2 = 0)$ is determined for the first time. The product of the form factor $f_+^{f_0}(0)$ and $|V_{cs}|$ is determined to be $f_+^{f_0}(0)|V_{cs}| = 0.504 \pm 0.017_{\text{stat.}} \pm 0.035_{\text{syst.}}$. The obtained form factor is important to constrain the angle ϕ and helps distinguish between different theoretical models.

3. – $D_{(s)}$ hadronic decays

Precise measurements of hadronic charm decay branching fractions offer crucial insights into non-perturbative QCD, enable tests of various phenomenological models, and provide a window into the intricate dynamics of $SU(3)$ flavor symmetry and its breaking.

The BESIII experiment, renowned for its quantum-correlated $D^0\bar{D}^0$ dataset [11], offers a unique opportunity for investigation. The interference term in the decay amplitude of a DT event is exceptionally sensitive to variations in strong-phase components. Accurate measurements of these phases play a pivotal role in elevating the precision of γ/ϕ_3 determinations, thereby advancing our efforts to test the predictions of the SM concerning CP violation and explore potential new physics.

3˙1. $D_s^+ \to K_S^0 K^+ \pi^0$. – The first amplitude analysis of the $D_s^+ \to K_S^0 K^+ \pi^0$ decay has been performed [22], based on a dataset comprising 1050 DT events with a signal purity of 94.7%. In this study, the branching fraction for $D_s^+ \to K_S^0 K^+ \pi^0$ is determined to be $(1.46 \pm 0.06_{\rm stat} \pm 0.05_{\rm syst})$%. Furthermore, an intriguing resonance—an a_0-like state identified as $a_0(1817)^+$ has been observed with a statistical significance exceeding 10σ. This resonance exhibits a mass of $(1.817 \pm 0.008_{\rm stat} \pm 0.020_{\rm syst})$ GeV/c^2 and a width of $(0.097 \pm 0.022_{\rm stat} \pm 0.015_{\rm syst})$ GeV. However, the enigmatic nature of $a_0(1817)^+$ remains a subject of intrigue. Although it seems to be a candidate for the isovector partner of $f_0(1710)$, its mass deviates from expectations by approximately 100 MeV/c^2. This discrepancy suggests the possibility that $a_0(1817)^+$ may instead represent the isovector partner of $X(1817)$. To clarify this matter, a simultaneous amplitude analysis of both $D_s^+ \to K_S^0 K^+ \pi^0$ and $D_s^+ \to K_S^0 K_S^0 \pi^+$ decays is imperative. Furthermore, the study determines the branching fraction ratio for $a_0(980)^+ \to K^0 \bar{K}^+$ and $a_0(980)^+ \to \pi^+ \eta$ to be $(13.7 \pm 3.6_{\rm stat} \pm 4.2_{\rm syst})$%. This ratio serves as a linchpin for determining the coupling constants of $a_0(980)^+$, providing valuable insights into its quark composition.

3˙2. *Measurement of inclusive and exclusive branching fractions*. – Benefiting from the dataset collected at the $D\bar{D}$ threshold, we are able to do absolute branching fraction measurements with low backgrounds. Recently, the branching fractions of $D^+ \to K_S^0 X$ and $D^0 \to K_S^0 X$ were measured to be $(32.78 \pm 0.13_{\rm stat.} \pm 0.27_{\rm syst.})$% and $(20.54 \pm 0.12_{\rm stat.} \pm 0.18_{\rm syst.})$%, respectively [20]. Compared with the average values from the PDG, the precision of the branching fractions of $D^+ \to K_S^0 X$ and $D^0 \to K_S^0 X$ has improved by factors of 9.0 and 8.1, respectively. When summing over the branching fractions of the known $D^{+(0)}$ decay modes containing K_S^0, the differences between inclusive and exclusive decay branching fractions are (1.10 ± 0.41)% and (2.38 ± 0.75)% for D^+ and D^0 decays, respectively.

BESIII reports the first observation of the double Cabibbo-suppressed (DCS) decays $D^+ \to K^+\pi^0\pi^0$ and $D^+ \to K^+\pi^0\eta$ [18]. Their branching fractions are measured to be $(2.1 \pm 0.4_{\rm stat.} \pm 0.1_{\rm syst.}) \times 10^{-4}$ and $(2.1 \pm 0.5_{\rm stat.} \pm 0.1_{\rm syst.}) \times 10^{-4}$, respectively. The branching fraction of the subprocess $D^+ \to K^*(892)^+\pi^0$ is determined to be $(4.4^{+1.8}_{-1.5}{}_{\rm stat.} \pm 0.1_{\rm syst.}) \times 10^{-4}$, with a significance of 3.2σ. BESIII also reports the branching fraction of $D^0 \to K^+\pi^-\pi^0$ and a search for $D^0 \to K^+\pi^-\pi^0\pi^0$ [21]. The branching fraction of $D^0 \to K^+\pi^-\pi^0$ is determined to be $(3.13^{+0.60}_{-0.56}{}_{\rm stat.} \pm 0.15_{\rm syst.}) \times 10^{-4}$. No signal is observed for $D^0 \to K^+\pi^-\pi^0\pi^0$, and an upper limit of 3.6×10^{-4} is set on the branching fraction at the 90% CL.

3˙3. *Strong phase measurements*. – The BESIII experiment has performed extensive investigations into charm meson decays, with a particular focus on the final states involving both Cabibbo-favored (CF) and DCS processes. These final states, including $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$, exhibit notable sensitivity to the determination of the CKM angle γ/ϕ_3, a crucial parameter in the study of *CP* violation. In a recent report by BESIII [19], a comprehensive study of $D \to K^-\pi^+$ has been presented, utilizing a dataset of quantum-correlated $D^0\bar{D}^0$ pairs. The asymmetry between *CP*-odd and *CP*-even eigenstate decays into $K^-\pi^+$, represented as $A_{K\pi}$, has been determined with high precision to be $0.132 \pm 0.011_{\rm stat.} \pm 0.007_{\rm syst.}$. Additionally, using predominantly *CP*-even tagged decays $D \to \pi^+\pi^-\pi^0$ and an ensemble of *CP*-odd eigenstate tags, the observable $A_{K\pi}^{\pi\pi\pi^0}$ has been measured as $0.130 \pm 0.012_{\rm stat.} \pm 0.008_{\rm syst.}$. These two asymmetries are particularly sensitive to the product $r_{K\pi}^D \cos\delta_{K\pi}^D$, where $r_{K\pi}^D$ and $\delta_{K\pi}^D$ represent the ratios of amplitudes and the phase difference, respectively, between DCS and CF decays.

Through an in-depth analysis of events containing $D \to K^-\pi^+$, tagged by $D \to K^0_{S,L}\pi^+\pi^-$ decays, the phase $\delta^D_{K\pi}$ is determined with precision to $(187.6^{+8.9+5.4}_{-9.7-6.4})^\circ$. This measurement is the most precise determination of $\delta^D_{K\pi}$ in quantum-correlated $D\bar{D}^0$ decays. Furthermore, the branching fractions for three K^0_L modes are determined to be $B(D^0 \to K^0_L\pi^0) = (0.97 \pm 0.03_{\text{stat.}} \pm 0.02_{\text{syst.}})\%$, $B(D^0 \to K^0_L\omega) = (1.09 \pm 0.06_{\text{stat.}} \pm 0.03_{\text{syst.}})\%$, and $B(D^0 \to K^0_L\pi^0\pi^0) = (1.26 \pm 0.05_{\text{stat.}} \pm 0.03_{\text{syst.}})\%$.

4. – Summary

The BESIII experiment has made substantial contributions to the field of charm physics. More onging investigations of charmed hadron decays will be coming soon. In the near future, BESIII is committed to achieving an impressive integrated luminosity milestone of 20 fb^{-1} at $\sqrt{s} = 3.773$ GeV [1]. This dataset is expected to provide more valuable insights into hadronic charm meson decays.

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