

Measurements of $|V_{cd(s)}|$, decay constants, and form factors in (semi-)leptonic $D_{(s)}$ decays at BESIII

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Abstract. The BESIII experiment accumulated the world's largest charm-meson samples. This proceeding presents recent measurements of decay constants, transition form factors, and CKM matrix elements from (semi-)leptonic D^+ and D_s^+ decays based on these datasets.

1 Introduction

Precision measurements of leptonic and semileptonic charm decays are essential for constraining the CKM matrix, which governs quark flavor and generation mixing under the weak interaction. These measurements allow extraction of decay constants and form factors parameterizing strong interaction effects. Charm physics provides fundamental information about non-perturbative QCD from decay constant and form factor measurements, and enables tests of the Standard Model (SM) via Cabibbo-Kobayashi-Maskawa (CKM) unitarity and lepton universality studies [1–3]

The BESIII detector [4] has accumulated e^+e^- collision data with integrated luminosities of 20.3 fb^{-1} at $\sqrt{s} = 3.773 \text{ GeV}$ and 7.33 fb^{-1} in the $\sqrt{s} = 4.128\text{--}4.226 \text{ GeV}$ energy region. At BESIII, experimental studies of various decays of D^0 , D^+ , D_s^+ and their excited states are reviewed in Ref. [5], while a comprehensive overview of the amplitude-analysis methodology for charm meson decays is presented in Ref. [6]. This proceeding mainly highlights the latest measurements of leptonic and semileptonic $D^{0(+)}$ and D_s^+ decays obtained using these two datasets. Such studies enable precision determinations of the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$, the decay constants f_{D^+} and $f_{D_s^+}$, and transition form factors.

Benefiting from the clean experimental environment and low background levels inherent to e^+e^- annihilation data near threshold, the double-tag (DT) method [7] is employed. Undetectable neutrinos are inferred using the variables $U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$ and $M_{\text{miss}}^2 = E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}|^2$ to identify (semi-)leptonic signals. The branching fraction is calculated via

$$\mathcal{B} = \frac{N_{\text{DT}}}{N_{\text{ST}} \epsilon_{\text{DT}} / \epsilon_{\text{ST}}} \quad (1)$$

where systematic uncertainties associated with the single-tag (ST) selection largely cancel out.

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2 Leptonic decays

2.1 Decay of $D^+ \rightarrow \mu^+ \nu_\mu$

With the 20.3 fb^{-1} data collected at $\sqrt{s} = 3.773 \text{ GeV}$, the BESIII Collaboration [8] measured the branching fraction (BF) of $D^+ \rightarrow \mu^+ \nu_\mu$ to be $(4.034 \pm 0.08_{\text{stat}} \pm 0.04_{\text{syst}}) \times 10^{-4}$. Interpreting this measurement with knowledge of the Fermi coupling constant G_F , the masses of D^+ and μ^+ as well as the life time of the D^+ meson [9], the product of the decay constant and the CKM matrix element is determined to be

$$f_{D^+} |V_{cd}| = (48.02 \pm 0.48_{\text{stat}} \pm 0.24_{\text{syst}} \pm 0.12_{\text{input}} \pm 0.15_{\text{EM}}) \text{ MeV}. \quad (2)$$

Using the value of the magnitude of the CKM matrix element V_{cd} given by the global standard model fit [9], the D^+ decay constant is extracted

$$f_{D^+} = (213.5 \pm 2.1_{\text{stat}} \pm 1.1_{\text{syst}} \pm 0.8_{\text{input}} \pm 0.7_{\text{EM}}) \text{ MeV} \quad (3)$$

Alternatively, taking the value of f_{D^+} from a precise LQCD calculation [10], the CKM matrix element is extracted

$$V_{cd} = 0.2265 \pm 0.0023_{\text{stat}} \pm 0.0011_{\text{syst}} \pm 0.0009_{\text{input}} \pm 0.0007_{\text{EM}}. \quad (4)$$

These are the most precise measurements. The precision is improved by a factor of 2.3 compared to the previous best measurement [11].

2.2 Decay of $D_s^+ \rightarrow \mu^+ \nu_\mu$

Using the data with the integrated luminosity of 7.33 fb^{-1} collected at center-of-mass energies between 4.128 and 4.226 GeV, the BESIII Collaboration measured the BF of the leptonic decay for $D_s^+ \rightarrow \mu^+ \nu_\mu$ [12]

$$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (0.5294 \pm 0.0108_{\text{stat}} \pm 0.0085_{\text{syst}})\% \quad (5)$$

Combining the measured BF with the world average values of G_F , m_μ , $m_{D_s^+}$ and the D_s^+ life time [9], the product of the D_s^+ decay constant $f_{D_s^+}$ and the magnitude of the $c \rightarrow s$ quark mixing matrix element V_{cs} is determined

$$f_{D_s^+} |V_{cs}| = 241.8 \pm 2.5_{\text{stat}} \pm 2.2_{\text{syst}} \text{ MeV}. \quad (6)$$

Using the value of V_{cs} given by the global SM fit [9] or the averaged decay constant from recent LQCD calculation [13, 14] as input, the decay constant $f_{D_s^+}$ and the CKM matrix element $|V_{cs}|$ are extracted to be $f_{D_s^+} = 248.4 \pm 2.5_{\text{stat}} \pm 2.2_{\text{syst}} \text{ MeV}$ and $|V_{cs}| = 0.968 \pm 0.010_{\text{stat}} \pm 0.009_{\text{syst}}$.

Figure 1 and Figure 2 summarize, respectively, the experimental measurements and theoretical predictions for the decay constants f_{D^+} and $f_{D_s^+}$, and the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$. The BESIII measurements yield the most precise determinations to date.

3 Semileptonic Decays

3.1 Measurements for $D^{0(+)} \rightarrow P^{-(0)} \ell^+ \nu_\ell$

With the integrated luminosity of 20.3 fb^{-1} D data sample, the BESIII experiment performed the precise measurements of the semileptonic decays [15] $D^0 \rightarrow K^- e^+ \nu_e$, $D^0 \rightarrow$

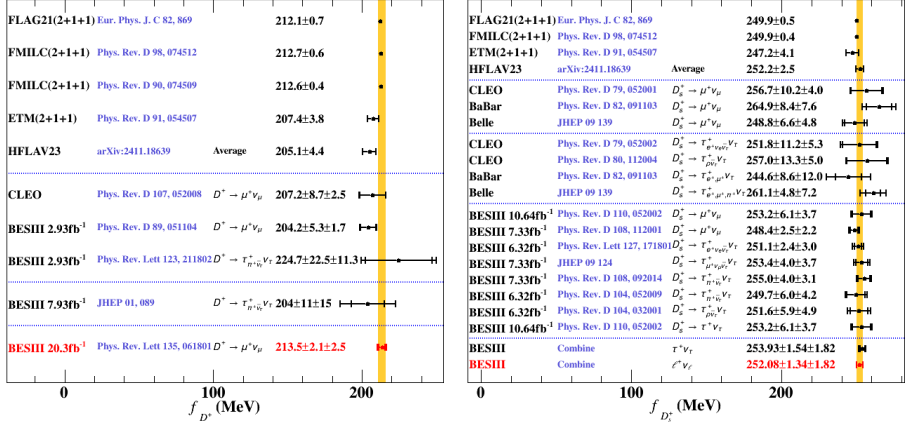


Figure 1. Comparisons of the decay constants f_{D^+} (left) and $f_{D_s^+}$ (right) to various experimental measurements and theoretical determinations

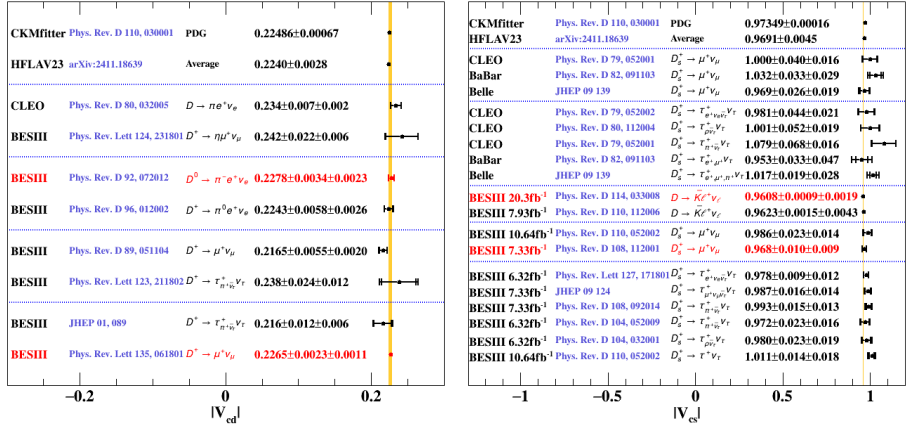


Figure 2. Comparisons of the CKM matrix elements $|V_{cd}|$ (left) and $|V_{cs}|$ (right) to various experimental measurements and theoretical determinations

$K^-\mu^+\nu_\mu$, $D^+ \rightarrow \bar{K}^0\mu^+\nu_e$ and $D^+ \rightarrow \bar{K}^0\mu^+\nu_\mu$, and the absolute BFs measured to be $(3.548 \pm 0.006_{\text{stat}} \pm 0.017_{\text{syst}})\%$, $(3.445 \pm 0.007_{\text{stat}} \pm 0.017_{\text{syst}})\%$, $(8.928 \pm 0.025_{\text{stat}} \pm 0.050_{\text{syst}})\%$, and $(8.770 \pm 0.029_{\text{stat}} \pm 0.053_{\text{syst}})\%$, respectively. The ratios of the BFs between semimuonic and semielectronic D decays are determined to be $R_{\mu/e}^{D^0} = 0.971 \pm 0.003_{\text{stat}} \pm 0.004_{\text{syst}}$ and $R_{\mu/e}^{D^+} = 0.982 \pm 0.004_{\text{stat}} \pm 0.002_{\text{syst}}$ which exhibit a slight difference with the LFU prediction of 0.975 ± 0.001 [16] up to 1.5σ . The first measurement of the forward-backward asymmetries as well as the precise measurements of the partial decay rates of $D^{0(+)} \rightarrow \bar{K}l^+\nu_l(l = \mu, e)$

are reported [17]. A simultaneous fit to these kinematic variables gives the first experimental constraint on the scalar current contribution in the $D^{0(+)} \rightarrow \bar{K}l^+\nu_l$ transition. The complex Wilson coefficient is determined to be $Re(c_s^\mu) = 0.017 \pm 0.008_{\text{stat}} \pm 0.006_{\text{syst}}$ and $Im(c_s^\mu) = 0.077 \pm 0.011_{\text{stat}} \pm 0.009_{\text{syst}}$, which deviates from the SM by 2.3σ . Besides, the improved measurements of the BFs and tests of the lepton-flavor universality (LFU), the hadronic transition FFs $f_+(0)$, as well as the CKM matrix element $|V_{cs}|$, which are in the highest precision to date, were also presented.

Using the same dataset, the first observation of the semileptonic decay $D^+ \rightarrow \eta'\mu^+\nu_\mu$ with a significance of 8.6σ and an improved measurement of $D^+ \rightarrow \eta'e^+\nu_e$ are reported [18]. The BFs of $D^+ \rightarrow \eta'\mu^+\nu_\mu$ and $D^+ \rightarrow \eta'e^+\nu_e$ are determined to be $(1.92 \pm 0.28_{\text{stat}} \pm 0.08_{\text{syst}}) \times 10^{-4}$ and $(1.79 \pm 0.19_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-4}$, respectively. The ratio of the two BFs is determined to be $R_{\mu/e} = 1.07 \pm 0.19_{\text{stat}} \pm 0.03_{\text{syst}}$, which agrees with the theoretical expectation of lepton flavor universality within the SM. From an analysis of the $D^+ \rightarrow \eta'\ell^+\nu_l$ decay dynamics, the product of the hadronic form factor (FF) $f_+^{\eta'}(0)$ and the CKM matrix element $|V_{cd}|$ is measured for the first time, giving $f_+^{\eta'}(0)|V_{cd}| = (5.92 \pm 0.56_{\text{stat}} \pm 0.13_{\text{syst}}) \times 10^{-2}$. Combining with the BFs of $D^+ \rightarrow \eta\ell^+\nu_\ell$ [9] and $D_s^+ \rightarrow \eta^{(\prime)}\ell^+\nu_\ell$ [19, 20], the η - η' mixing angle in the quark flavor basis is determined to be $\phi_P = (39.8 \pm 0.8_{\text{stat}} \pm 0.3_{\text{syst}})^\circ$, which provides complementary data to constrain the gluon component in the η' meson.

3.2 Measurements for $D^+ \rightarrow V\ell^+\nu_\ell$

The BESIII experiment reported the first measurement of full set of CP asymmetries and averaged angular observables with A_{CP} in the decays $D^+ \rightarrow \bar{K}^{*0}\ell^+\nu_\ell$ via $\bar{K}^{*0} \rightarrow K_S^0\pi^0$ [21]. In addition, the absolute BF of $D^+ \rightarrow K_S^0\pi^0\mu^+\nu_\mu$ is measured to be $(0.943 \pm 0.012_{\text{stat}} \pm 0.010_{\text{syst}})\%$ for the first time, and the absolute BF of $D^+ \rightarrow K_S^0\pi^0e^+\nu_e$ is measured with improved precision. By analyzing the $D^+ \rightarrow K_S^0\pi^0\ell^+\nu_\ell$ decay dynamics, the fraction of the P-wave component and the hadronic FF ratios of $D^+ \rightarrow \bar{K}^{*0}$ were presented. The LFU was tested, and no evidence for violation of $\mu - e$ LFU was observed in either the full range or the five chosen bins of momentum-transfer squared.

3.3 Measurements for $D_s^+ \rightarrow S\ell^+\nu_\ell$

Based on the D_s data sample of 7.33 fb^{-1} , an analysis of the decay $D_s^+ \rightarrow \pi^+\pi^-e^+\nu_e$ via the intermediate resonant state $f_0(980) \rightarrow \pi^+\pi^-$ has been performed [22]. The BF of the $D_s^+ \rightarrow f_0(980)e^+\nu_e$ decay with the subsequent decay $f_0(980) \rightarrow \pi^+\pi^-$ is measured to be $(1.72 \pm 0.13 \pm 0.10) \times 10^{-3}$. By investigating the decay dynamics with a simple pole parameterization for the FF and the Flatté formula to characterize the $f_0(980)$ contribution in the differential decay rate, the product of the hadronic FF $f_+^{D_s \rightarrow f_0(980)}(0)$ and the $c \rightarrow s$ CKM matrix element $|V_{cs}|$ is determined for the first time, yielding $f_+^{D_s \rightarrow f_0(980)}(0)|V_{cs}| = 0.504 \pm 0.017_{\text{stat}} \pm 0.035_{\text{syst}}$. Furthermore, the decay $D_s^+ \rightarrow f_0(500)e^+\nu_e$ is searched for the first time but no signal is found. The upper limit on the BF of $D_s^+ \rightarrow f_0(500)e^+\nu_e$, $f_0(500) \rightarrow \pi^+\pi^-$ decay is set to be 3.3×10^{-4} at 90% confidence level.

3.4 Measurements for $D_s^+ \rightarrow A\ell^+\nu_\ell$

Using 7.33 fb^{-1} of data at 4.128–4.226 GeV, the semileptonic decays $D_s^+ \rightarrow K_1(1270)^0e^+\nu_e$ and $D_s^+ \rightarrow b_1(1235)^0e^+\nu_e$ [23] as well as $D_s^+ \rightarrow f_1(1420)e^+\nu_e$ and $D_s^+ \rightarrow f_1(1285)e^+\nu_e$ [24] are also searched for the first time. The first evidence for the decay $D_s^+ \rightarrow f_1(1420)e^+\nu_e$ is found with a statistical significance of 3.4σ , and its product branching fraction $\mathcal{B}[D_s^+ \rightarrow$

$f_1(1420)e^+\nu_e]$. $\mathcal{B}[f_1(1420) \rightarrow K^+K^-\pi^0]$ is determined to be $(4.5^{+2.0}_{-1.7}) \times 10^{-4}$. No significant signals of $D_s^+ \rightarrow K_1(1270)^0e^+\nu_e$ and $D_s^+ \rightarrow b_1(1235)^0e^+\nu_e$, and $D_s^+ \rightarrow f_1(1285)e^+\nu_e$ are observed and the upper limit on their product BF at the 90% confidence level are set to be $\mathcal{B}[D_s^+ \rightarrow K_1(1270)^0e^+\nu_e] < 4.1 \times 10^{-4}$, $\mathcal{B}[D_s^+ \rightarrow b_1(1235)^0e^+\nu_e] \cdot \mathcal{B}[b_1(1235)^0 \rightarrow \omega\pi^0] < 6.4 \times 10^{-4}$, and $\mathcal{B}[D_s^+ \rightarrow f_1(1285)e^+\nu_e] \cdot \mathcal{B}[f_1(1285) \rightarrow \pi^+\pi^-\eta] < 1.7 \times 10^{-4}$, respectively.

4 Summary and outlook

The BESIII experiment has achieved world-leading precision measurements for leptonic and semileptonic decays of D^+ and D_s^+ : the decay constants are measured to a precision of about 1%, and the CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$ are extracted to precisions of 0.5% and 1%, respectively. Looking ahead, many new and updated measurements are expected using the BESIII charm datasets.[25].

References

- [1] J. D. Richman and P. R. Burchat, Leptonic and semileptonic decays of charm and bottom hadrons, *Rev. Mod. Phys.* 67, 893-976 (1995). <https://journals.aps.org/rmp/pdf/10.1103/RevModPhys.67.893>
- [2] B.-C. Ke, J. Koponen, H.-B. Li and Y. Zheng, Recent progress in leptonic and semileptonic decays of charmed hadrons, *Annu. Rev. Nucl. Part. Sci.* 73, 285-314 (2023). <https://doi.org/10.1146/annurev-nucl-110222-044046>
- [3] H.-B. Li and X.-R. Lyu, Study of the standard model with weak decays of charmed hadrons at BESIII, *National Sci. Rev.* 8, nwab181 (2021). <https://doi.org/10.1093/nsr/nwab181>
- [4] BESIII Collaboration, M. Ablikim et al., Design and Construction of the BESIII Detector, *Nucl. Instrum. Meth. A* 614, 345(2010),0911.4960. <https://doi.org/10.1016/j.nima.2009.12.050>
- [5] Y.J. Zeng, X. Pan and H.L. Ma, Review of experimental studies of charmed meson decays at BESIII, arXiv:2604.20644v2. <https://doi.org/10.48550/arXiv.2604.20644>
- [6] H. Zhang, Z.X. Li, C.Y. Guan, Z.H. Lu, H. Li, L.P. Yang, Y.C. Yu, N. Zhang, M.G. Zhao, Y. Lu, B.-C. Ke and L.Y. Dong, Amplitude analysis for charmed meson decays at BESIII, *Chin. Phys. C* 50, 9, 093002 (2026). <https://iopscience.iop.org/article/10.1088/1674-1137/ae7962/pdf>
- [7] MARK-III Collaboration, J. Adler et al., Reanalysis of charmed- D meson branching fractions, *Phys. Rev. Lett.* 60, 89 (1988). <https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.60.89>
- [8] BESIII Collaboration, M. Ablikim et al., Precision measurement of the branching fraction of $D^+ \rightarrow \mu^+\nu_\mu$, *Phys. Rev. Lett.* 135, 061801 (2025). <https://doi.org/10.1103/gb8v-4rnh>
- [9] S. Navas et al. (Particle Data Group), *Phys. Rev. D* 110, 030001 (2024). <https://journals.aps.org/prd/abstract/10.1103/PhysRevD.110.030001>
- [10] Y. Aoki et al. (Flavour Lattice Averaging Group (FLAG) Collaboration), *Eur. Phys. J. C* 82, 869 (2022). <https://link.springer.com/article/10.1140/epjc/s10052-022-10536-1>
- [11] M. Ablikim et al. (BESIII Collaboration), Precision measurements of $\mathcal{B}(D^+ \rightarrow \mu^+\nu_\mu)$, the pseudoscalar decay constant f_{D^+} , and the quark mixing matrix element $|V_{cd}|$, *Phys. Rev. D* 89, 051104 (2014). <https://doi.org/10.1103/PhysRevD.89.051104>
- [12] M. Ablikim et al. (BESIII Collaboration), Improved measurement of the branching fraction of $D_s^+ \rightarrow \mu^+\nu_\mu$, *Phys. Rev. D* 108, 112001 (2023). <https://doi.org/10.1103/PhysRevD.108.112001>

- [13] A. Bazavov et al., B - and D -meson leptonic decay constants from four-flavor lattice QCD, Phys. Rev. D 98, 074512 (2018). <https://doi.org/10.1103/PhysRevD.98.074512>
- [14] N. Carrasco et al., Leptonic decay constants f_K , f_D and f_{D_s} with $N_f = 2 + 1 + 1$ twisted-mass lattice QCD, Phys. Rev. D 91, 054507 (2015). <https://doi.org/10.1103/PhysRevD.91.054507>
- [15] M. Ablikim et al. (BESIII Collaboration), Precise measurements of $D^0 \rightarrow K^- \ell^+ \nu_\ell$ and $D^0 \rightarrow \bar{K}^0 \ell^+ \nu_\ell$ decays, Phys. Rev. D 114, 033008 (2026). <https://doi.org/10.1103/3fnf-x8k8>
- [16] L. Riggio, G. Salerno, and S. Simula, Extraction of $|V_{cd}|$ and $V_{cs}|$ from experimental decay rates using lattice QCD $D \rightarrow \pi(K) \ell \nu$, Eur. Phys. J. C 78, 501 (2018). <https://link.springer.com/article/10.1140/epjc/s10052-018-5943-5>
- [17] M. Ablikim et al. (BESIII Collaboration), First Experimental Constraint on the Scalar Current in the $D^{0(+)} \rightarrow \bar{K} \ell^+ \nu_\ell$ Transition, Phys. Rev. Lett. 137, 091803 (2026). <https://doi.org/10.1103/2ygw-n5b1>
- [18] M. Ablikim et al. (BESIII Collaboration), Observation of $D^+ \rightarrow \eta' \mu^+ \nu_\mu$ and First Experimental Study of $D^+ \rightarrow \eta' \ell^+ \nu_\ell$ Decay Dynamics, Phys. Rev. Lett. 134, 111801 (2025). <https://doi.org/10.1103/PhysRevLett.134.111801>
- [19] M. Ablikim et al. (BESIII Collaboration), Observation of $D_s^+ \rightarrow \eta' \mu^+ \nu_\mu$, Precision Test of Lepton Flavor Universality with $D_s^+ \rightarrow \eta^{(\prime)} \ell^+ \nu_\ell$, and First Measurements of $D_s^+ \rightarrow \eta^{(\prime)} \mu^+ \nu_\mu$ Decay Dynamics, Phys. Rev. Lett. 132, 091802 (2024). <https://doi.org/10.1103/PhysRevLett.132.091802>
- [20] M. Ablikim et al. (BESIII Collaboration), Precision measurements of $D_s^+ \rightarrow \eta e^+ \nu_e$ and $D_s^+ \rightarrow \eta' e^+ \nu_e$, Phys. Rev. D 108, 092003 (2023). <https://doi.org/10.1103/PhysRevD.108.092003>
- [21] M. Ablikim et al. (BESIII Collaboration), Observation of $D^+ \rightarrow K_S^0 \pi^0 \mu^+ \nu_\mu$, Test of Lepton Flavor Universality, and First Angular Analysis of $D^+ \rightarrow \bar{K}^*(892)^0 \ell^+ \nu_\ell$, Phys. Rev. Lett. 135, 171801 (2025). <https://doi.org/10.1103/w9vz-4fq9>
- [22] M. Ablikim et al. (BESIII Collaboration), Study of the $f_0(980)$ and $f_0(500)$ Scalar Mesons through the Decay $D_s^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$, Phys. Rev. Lett. 132, 141901 (2024). <https://doi.org/10.1103/PhysRevLett.132.141901>
- [23] M. Ablikim et al. (BESIII Collaboration), Search for the semileptonic decays $D_s^+ \rightarrow K_1(1270)^0 e^+ \nu_e$ and $D_s^+ \rightarrow b_1(1235)^0 e^+ \nu_e$, Phys. Rev. D 108, 112002 (2023) <https://doi.org/10.1103/PhysRevD.108.112002>
- [24] M. Ablikim et al. (BESIII Collaboration), First evidence for $D_s^+ \rightarrow f_1(1420) e^+ \nu_e$ and search for $D_s^+ \rightarrow f_1(1285) e^+ \nu_e$, arXiv:2601.16938. <https://doi.org/10.48550/arXiv.2601.16938>
- [25] M. Ablikim et al. (BESIII Collaboration), Future Physics Programme of BESIII, Chin. Phys. C 44, 040001 (2020). <https://iopscience.iop.org/article/10.1088/1674-1137/44/4/040001>