PROCEEDINGS OF SCIENCE

(Semi-)leptonic decays of $D_{(s)}$ Mesons at BESIII

Y.H. Yang for the BESIII Collaboration[*]
School of Physics, Nanjing University, Gulou district, Nanjing, Jiangsu Province 210093, China
E-mail: `yangyh@ihep.ac.cn`

Leptonic and semi-leptonic D decays at BESIII contribute the most precise experimental measurement of $|V_{cs(d)}|$ and decay constants $f_{D_{(s)}}$ in the world based on 2.93 fb^{-1} and 3.19 fb^{-1} data taken at center-of-mass energies $\sqrt{s} = 3.773$ GeV and 4.178 GeV, respectively. The largest samples at the mass threshold of the charmed hadrons $D_{(s)}$ also provide chances to extract form factors of some semi-electronic decays for the first time and together with the semi-muonic decays we could understand lepton flavour universality better.

ALPS 2019 An Alpine LHC Physics Summit
April 22 - 27, 2019
Obergurg, Austria

---

[*] Speaker.

`https://pos.sissa.it/`

1. Introduction

The ground-states of charmed hadrons, e.g., $D^{0(+)}$ [1–13], D_s^+ [14–19] and Λ_c^+ [20, 21], can only decay weakly. Precision measurements of charm (semi-)leptonic decays provide rich information to better understand strong and weak effects as shown in Fig. 1. BESIII produces these charmed hadrons near their mass thresholds; this allows exclusive reconstruction of their decay products with well-determined kinematics. For example, using $D \to \ell\nu_\ell$ ($\ell = e, \mu$), we perform the most accurate measurements of $f_{D_{(s)}}|V_{cd(s)}|$, which the extraction of Cabibbo-Kabayshi-Maskawa (CKM) matrix elements $|V_{cd(s)}|$ are essential inputs to constrain the unitarity of the CKM matrix and some first measurements of form factor $f_+^{D\to M}(0)$ by studying semi-leptonic decay $D_{(s)} \to M\ell\nu_\ell$, where M is a meson. They are essential measurements for the heavy quark decays to calibrate the theoretical calculation [22–40] like Lattice QCD, QCD sum rule, *etc*. The ratio of semi-muonic and -electronic decays provide an important test in the lepton flavour universality (LFU).

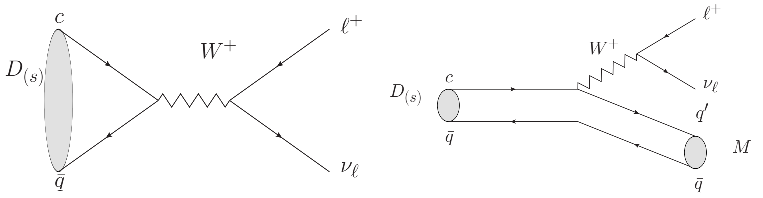

Figure 1: Feynman diagrams for leptonic D decays (left) and semileptonic D decays to mesons (right).

2. Leptonic decays

In the Standard Model, D mesons decay into $\ell\nu_\ell$ via a virtual W^+ boson. The decay rate of the leptonic decays $D^+_{(s)} \to \ell^+\nu_\ell$ can be parameterized by the $D^+_{(s)}$ decay constant $f_{D^+_{(s)}}$ via [41]

$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{cd(s)}|^2 f^2_{D^+_{(s)}} m_\ell^2 m_{D^+_{(s)}} (1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}), \tag{2.1}$$

where G_F is the Fermi coupling constant, $|V_{cs}|$ is the quark mixing matrix element, m_ℓ and $m_{D^+_{(s)}}$ are the lepton and D^+ masses, respectively. Using the measured branching fractions (BF) of these decays, one can determine the product of $f_{D^+_{(s)}}|V_{cd(s)}|$. By taking the $f_{D^+_{(s)}}$, calculated in LQCD, or $V_{cd(s)}$, obtained from a global fit to other CKM matrix elements that assumes unitarity, the $|V_{cd(s)}|$ or $f_{D^+_{(s)}}$ can be obtained.

2.1 $D^+ \to \mu^+\nu_\mu$ and $D^+ \to \tau^+\nu_\tau$

This analysis is based on the 2.93 fb^{-1} data sample taken at the center-of-mass energy of $\sqrt{s} = 3.773$ GeV. With a total number of about 1.7×10^6 single tagged D mesons reconstructed. We obtain 409 ± 21 signals for $D^+ \to \mu^+\nu_\mu$ decay shown in Fig. 2. The BF of $D^+ \to \mu^+\nu_\mu$ is $\mathscr{B}_{D^+\to\mu^+\nu_\mu} = [3.71 \pm 0.19 \pm 0.06] \times 10^{-4}$, where the first uncertainties are statistical and the second are systematic, and in conjunction with the Cabibbo-Kobayashi-maskawa matrix element $|V_{\rm cd}|$ determined from a global Standard Model fit, it implies a value for the weak decay constant $f_{D^+} = 203.2 \pm 5.3 \pm 1.8$ MeV [15].

BESIII also searches for the leptonic decay $D^+ \to \tau^+\nu_\tau$. The preliminary result of BF is $\mathscr{B}_{D^+\to\tau^+\nu_\tau} = 1.20 \pm 0.24 \times 10^{-3}$, where only statistical uncertainty is given. Combing $\mathscr{B}_{D^+\to\mu^+\nu_\mu}$, we obtain $R = \frac{\mathscr{B}_{D^+\to\tau^+\nu_\tau}}{\mathscr{B}_{D^+\to\mu^+\nu_\mu}} = 3.21 \pm 0.64$, which is consistent with the leptonic flavor universality in the SM prediction.

2.2 $D_s^+ \to \mu^+\nu_\mu$

The analysis of $D_s^+ \to \mu^+\nu_\mu$ [14] is based on the 3.19 fb^{-1} data sample taken at $\sqrt{s} = 4.178$ GeV. A signal yield of 1135.9 ± 33.1 is obtained by fitting the $M^2_{\rm miss}$ as shown in Fig. 3, leading to the most precision measurement of $\mathscr{B}_{D_s^+\to\mu^+\nu_\mu} = [5.49 \pm 0.16 \pm 0.15]\%$ and $f_{D_s^+} = 252.9 \pm 3.7 \pm 3.6$ MeV.

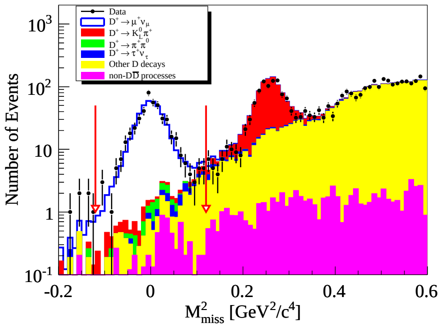

Figure 2: The $M^2_{\rm miss}$ distributions of the accepted candidates of $D^+ \to \mu^+\nu_\mu$. Description of each background can be found on the legend.

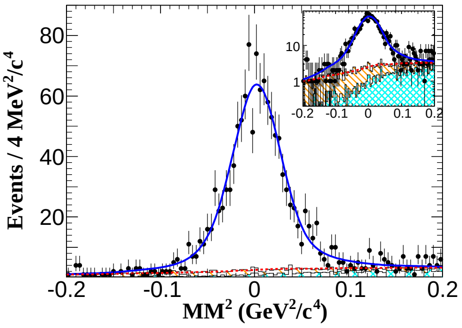

Figure 3: Fit to the accepted $D_s^+ \to \mu^+\nu_\mu$candidate events. The dots with error bars are data. The blue solid curve is the fit result. The red dotted curve is the fitted background.

3. Semi-leptonic decays $D \to M\ell^+\nu_\ell$

In the SM, the weak and strong effects in SL D decays can also be well separated. Their differential decay rate can be simply written as

$$\frac{d\Gamma}{dq^2} = \frac{\mathscr{B}_{D\to M\ell^+\nu_\ell}}{\tau_{D_{(s)}}} = X\frac{G_F^2}{24\pi^3}|V_{cs(d)}|^2 p_M^3 |f_+^M(q^2)|^2, \tag{3.1}$$

where X is a multiplicative factor due to isospin, which equals to $1/2$ for the decay $D^+ \to \pi^0 e^+\nu_e$ and 1 for the other decays, G_F is the Fermi coupling constant, p_M is the meson momentum in the D rest frame, $f_+^M(q^2)$ is the form factor of hadronic weak current depending on the square of the transferred four-momentum $q = p_D - p_M$. Based on analyzing the dynamics of SL decays, one can obtain the product of $f_+^M(0)$ and $|V_{cd(s)}|$. The form factor $f_+^M(0)|V_{cs(d)}|$ can be extracted from a fit to the measured partial decay rates in separated q^2 intervals.

3.1 $D \to \bar{K}(\pi)e^+\nu_e$

Using the same data as that of the measurement of $D^+ \to \mu^+\nu_\mu$, BESIII has measured the BF of $D \to K(\pi)e^+\nu_e$ [2, 3, 7], $\mathscr{B}_{D^+\to K^0_S e^+\nu_e} = [8.604 \pm 0.056 \pm 0.151]\%$, $\mathscr{B}_{D^+\to\pi^0 e^+\nu_e} = [0.363 \pm 0.008 \pm 0.005]\%$, $\mathscr{B}_{D^0\to K^- e^+\nu_e} = [3.505 \pm 0.014 \pm 0.033]\%$, $\mathscr{B}_{D^0\to\pi^- e^+\nu_e} = [0.295 \pm 0.004 \pm 0.003]\%$, and form factors [2, 3, 7] of $D \to K(\pi)e^+\nu_e$ $f_+^K(0)[D^+ \to K^0_S e^+\nu_e] = 0.7248 \pm 0.0041 \pm 0.0115$, $f_+^K(0)[D^0 \to K^- e^+\nu_e] = 0.7368 \pm 0.0026 \pm 0.0036$, $f_+^\pi(0)[D^+ \to \pi^0 e^+\nu_e] = 0.6216 \pm 0.0115 \pm 0.0035$, $f_+^\pi(0)[D^+ \to \pi^0 e^+\nu_e] = 0.6372 \pm 0.0080 \pm 0.0044$,

Figures 4 and 5 show the projections of form factor on the fit to partial decay rates of $D \to K(\pi)e^+\nu_e$.

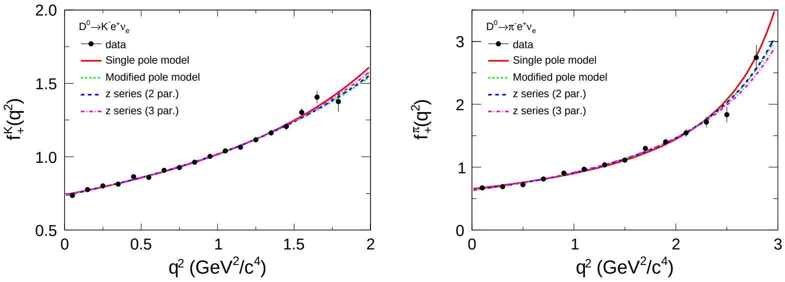

Figure 4: Projection on $f_+(q^2)$ for $D^0 \to K^- e^+\nu_e$ and $D^0 \to \pi^- e^+\nu_e$.

3.2 $D \to K^-(\pi)\mu^+\nu_\mu$

Muon channels also provide a chance to improve the precision of measurement on form factor $f_+^K(0)$, and more important, recent tension of LFU between τ^+ and μ^+ [42–44] need improved understanding in charm sector. Using

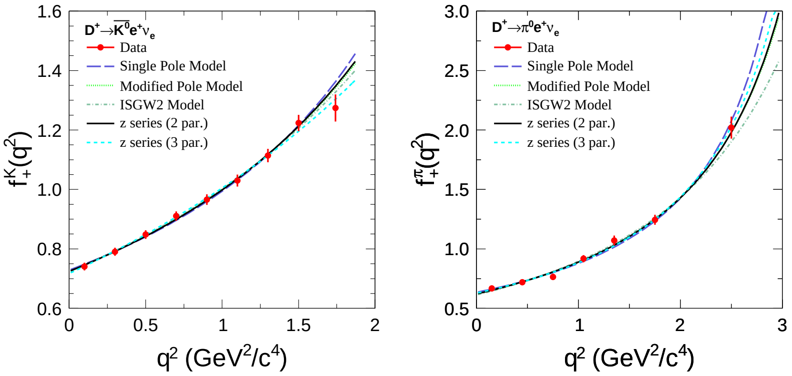

Figure 5: Projections on $f_+(q^2)$ for $D^+\to\bar{K}^0e^+\nu_e$ (left) and $D^+\to\pi^0e^+\nu_e$ (right) as function of q^2, where the dots with error bars show the data and the lines give the best fits to the data with different form factor parameterizations.

2.93 fb^{-1} data at $\sqrt{s}=3.773$ GeV, the BF of $D^0\to K^-\mu^+\nu_\mu$ is measured to be $[3.413\pm0.019\pm0.035]\%$. With the same data and fitting method as previous electron channel, we obtain $f_+^K(0)=0.7327\pm0.0039\pm0.0030$ [10]. Figure 6 shows the projection of form factor on the fit to partial decay rates. Combining with our previous measurement, LFU test is performed with

$$R_{K^-}=\frac{\Gamma(D^0\to K^-\mu^+\nu_\mu)}{\Gamma(D^0\to K^-e^+\nu_e)}=0.974\pm0.007\pm0.012. \tag{3.2}$$

There is no deviation lager than 2σ from 1 in q^2 interval (0.2, 1.5) GeV^2/c^4 as Fig 6 shows. For the pion channel, the BF of $D\to\pi\mu^+\nu_\mu$ [12] is measured to be $\mathscr{B}_{D^0\to\pi^-\mu^+\nu_\mu}=[0.272\pm0.008\pm0.006]\%$ and $\mathscr{B}_{D^+\to\pi^-\mu^+\nu_\mu}=[0.350\pm0.011\pm0.010]\%$. Using these results along with $\mathscr{B}_{D\to\pi e^+\nu_e}$, we have

$$R_{\pi^-}=\frac{\Gamma(D^0\to\pi^-\mu^+\nu_\mu)}{\Gamma(D^0\to\pi^-e^+\nu_e)}=0.922\pm0.030\pm0.022, \tag{3.3}$$

$$R_{\pi^0}=\frac{\Gamma(D^0\to\pi^0\mu^+\nu_\mu)}{\Gamma(D^0\to\pi^0e^+\nu_e)}=0.964\pm0.037\pm0.026. \tag{3.4}$$

These results show no significant deviations from the standard model predictions.

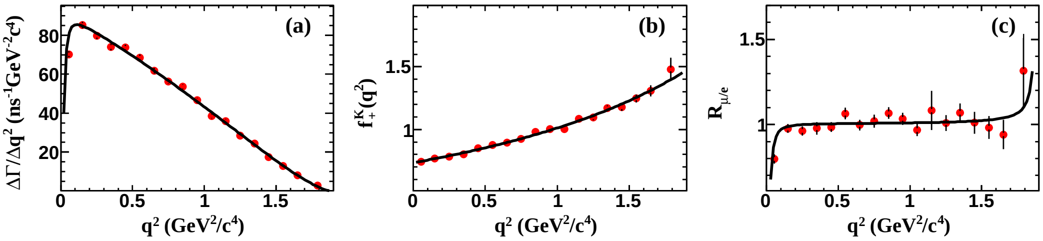

Figure 6: The fit to the partial decay rates of $D^0\to K^-\mu^+\nu_\mu$ (left), the projection to the hadronic form factor (middle) and LFU test in various q^2 intervals (right).

3.3 $D_s^+\to\eta^{(\prime)}e^+\nu_e$

BESIII measure the absolute BFs for semi-leptonic $D_s^+\to\eta^{(\prime)}e^+\nu_e$ decays [19] with improved precision. The preliminary results are $\mathscr{B}_{D_s^+\to\eta e^+\nu_e}=[2.323\pm0.063\pm0.063]\%$ and $\mathscr{B}_{D_s^+\to\eta e^+\nu_e}=[0.824\pm0.073\pm0.027]\%$ by a simultaneous fits on $\eta\to\gamma\gamma$ and $\eta\to\pi^+\pi^-\pi^0$ for η mode and $\eta'\to\eta_{\gamma\gamma}\pi^+\pi^-$ and $\eta'\to\gamma\pi^+\pi^-$ for η' mode. Combing the our previous measurement on $\mathscr{B}_{D^+\to\eta^{(\prime)}e^+\nu_e}$ [11], the $\eta-\eta'$ mixing angle is determined to be $\phi_P=(40.1\pm2.1\pm0.7)^\circ$. And for the first time, the experimental measurement of the dynamics of $D_s^+\to\eta^{(\prime)}e^+\nu_e$ are performed, the products of the hadronic form factor $f_+^{\eta^{(\prime)}}(0)$ and $|V_{cs}|$ are extracted with different form factor parameterizations. Figure 7 shows the projection of form factor on the fit to partial decay rates, where the yellow band comes from light cone sum rule [45]. For the two parameter series expansion, the preliminary results are $f_+^{\eta}(0)|V_{cs}| = 0.4455 \pm 0.0053 \pm 0.0044$ and $f_+^{\eta'}(0)|V_{cs}| = 0.477 \pm 0.049 \pm 0.011$. Taking $|V_{cs}|$ from the CKMfitter as input, we determine preliminary $f_+^{\eta}(0) = 0.4576 \pm 0.0054 \pm 0.0045$ and $f_+^{\eta'}(0) = 0.490 \pm 0.050 \pm 0.011$. Alternatively, using the $f_+^{\eta^{(\prime)}}(0)$ calculated by light-cone sum rules leads to $|V_{cs}| = 1.032 \pm 0.012 \pm 0.009 \pm 0.079$ and $0.917 \pm 0.094 \pm 0.021 \pm 0.155$, respectively, where the last uncertainties is theoretical.

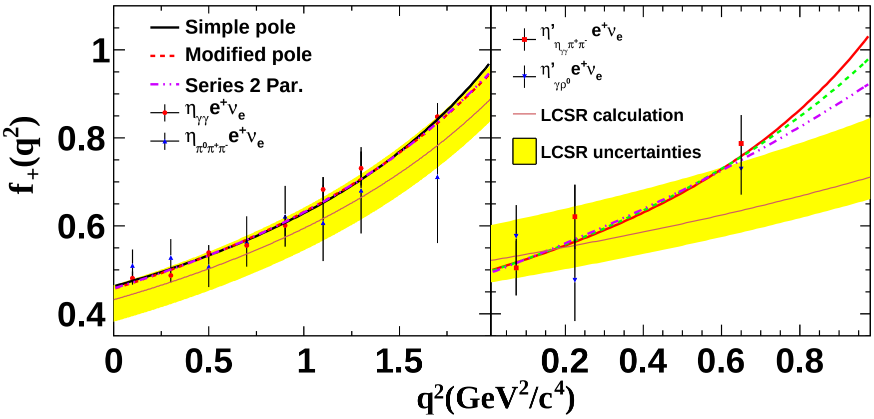

Figure 7: Projections of the fits to partial decay rate of $D_s^+ \to \eta^{(\prime)} e^+\nu_e$. Dots with error bars are data. Curves are the fits as described in text. Pink lines with yellow bands are the LCSR calculations with uncertainties.

3.4 $D_s^+ \to K^{0(*)} e^+\nu_e$

Using the data sample collected at $\sqrt{s} = 4.178$ GeV, BESIII measured $D_s^+ \to K^{0(*)} e^+\nu_e$ [18]. The preliminary results are $\mathscr{B}_{D_s^+ \to K^0 e^+\nu_e} = [3.25 \pm 0.38 \pm 0.16]\%$ and $\mathscr{B}_{D_s^+ \to K^{0*} e^+\nu_e} = [2.37 \pm 0.26 \pm 0.20]\%$. The first measurements of the hadronic form-factor parameters are obtained. The preliminary result for $D_s^+ \to K^0 e^+\nu_e$ is $f_+^K = 0.720 \pm 0.084 \pm 0.013$, and for $D_s^+ \to K^{0*} e^+\nu_e$, the preliminary form-factor ratios are $r_V = V(0)/A_1(0) = 1.67 \pm 0.34 \pm 0.016$ and $r_2 = A_2(0)/A_1(0) = 0.77 \pm 0.28 \pm 0.07$.

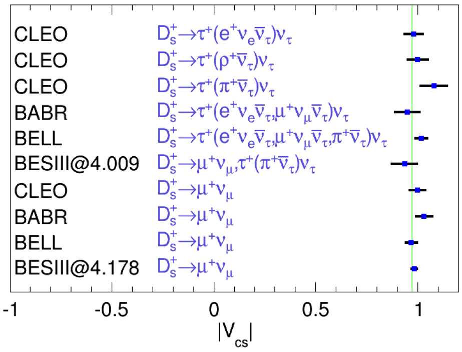

Figure 8: Comparison of $|V_{cs}|$ with different experiments.

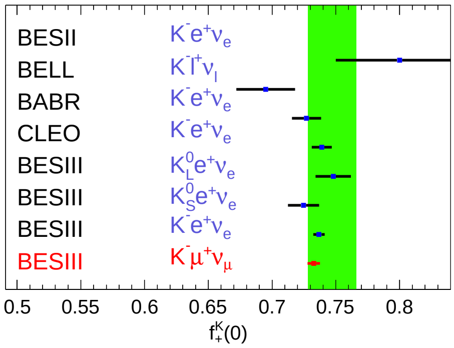

Figure 9: Comparison of $f_+^K(0)$ with different experiments.

4. Summary

In summary, with the word's largest $D\bar{D}$ samples near threshold, precision measurements of BFs of $D_{(s)}^+ \to \ell^+\nu_\ell$, $D \to \bar{K}(\pi)\ell^+\nu_\ell$, $D_{(s)0}^+ \to \eta' e^+\nu_e$ and $D_s^+ \to K^{0(*)} e^+\nu_e$ are performed at BESIII. In these decays, the form factors of

$f^{D_s\to\eta}$, $f^{D_s\to K^{0(*)}}$ are extracted for the first time. Besides, CKM absolute matrix $|V_{cs(d)}|$, D_s meson decay constant $f_{D_s^+}$ and hadronic from factor $f_+^{D\to K}(0)$ is also determined. Meanwhile, LFU test using (semi-)leptonic D decays is performed at BESIII, and no significant deviation from the SM prediction is found at current statistics.

Funding information

The author thanks for the support by Jonit Large-Scale Scientific Facility Funds of the National Natural Science Foundation of China and the Chinese Academy of Sciences under Contract No. U1532257.

References

[1] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **92**, 071101 (2015).

[2] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **92**, 112008 (2015).

[3] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **92**, 072012 (2015).

[4] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **94**, 032001 (2016).

[5] M. Ablikim *et al.* [BESIII Collaboration], Eur. Phys. J. C **76**, no. 7, 369 (2016).

[6] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **95**, 071102 (2017).

[7] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **96**, 012002 (2017).

[8] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **96**, 092002 (2017).

[9] M. Ablikim *et al.*[BESIII Collaboration], Phys. Rev. D **97**, 012006 (2018).

[10] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **122**, 011804 (2019).

[11] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **97**, 092009 (2018).

[12] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **121**, 171803 (2018).

[13] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **121**, 081802 (2018).

[14] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **122**, 071802 (2019).

[15] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **89**, 051104 (2014).

[16] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **94**, 112003 (2016).

[17] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **94**, 072004 (2016).

[18] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **122**, 061801 (2019).

[19] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **122**, 121801 (2019)

[20] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **115**, 221805 (2015).

[21] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **121**, 251801 (2018).

[22] V. Lubicz *et al.* [ETM Collaboration], Phys. Rev. D **96**, 054514 (2017).

[23] L. Riggio, G. Salerno and S. Simula, Eur. Phys. J. C **78**, no. 6, 501 (2018).

[24] C. Aubin *et al.* [Fermilab Lattice and MILC and HPQCD Collaborations], Phys. Rev. Lett. **94**, 011601 (2005).

[25] P. Ball, V. M. Braun and H. G. Dosch, Phys. Rev. D **44**, 3567 (1991).

[26] H. Na, C. T. H. Davies, E. Follana, G. P. Lepage and J. Shigemitsu, Phys. Rev. D **82**, 114506 (2010).

[27] A. Bazavov *et al.*, Phys. Rev. D **98**, 074512 (2018).

[28] A. Bazavov *et al.* [Fermilab Lattice and MILC Collaborations], Phys. Rev. D **90**, 074509 (2014).

[29] P. A. Boyle, L. Del Debbio, A. Jüttner, A. Khamseh, F. Sanfilippo and J. T. Tsang, JHEP **1712**, 008 (2017).

[30] Y. B. Yang *et al.*, Phys. Rev. D **92**, 034517 (2015).

[31] A. Bazavov *et al.* [Fermilab Lattice and MILC Collaborations], Phys. Rev. D **85**, 114506 (2012).

[32] C. W. Hwang, Phys. Rev. D **81**, 054022 (2010).

[33] D. Becirevic, P. Boucaud, J. P. Leroy, V. Lubicz, G. Martinelli, F. Mescia and F. Rapuano, Phys. Rev. D **60**, 074501 (1999).

[34] H. Na, C. T. H. Davies, E. Follana, G. P. Lepage and J. Shigemitsu, Phys. Rev. D **86**, 054510 (2012).

[35] C. Aubin *et al.*, Phys. Rev. Lett. **95**, 122002 (2005).

[36] E. Follana *et al.* [HPQCD and UKQCD Collaborations], Phys. Rev. Lett. **100**, 062002 (2008).

[37] P. Dimopoulos *et al.* [ETM Collaboration], JHEP **1201**, 046 (2012).

[38] T. W. Chiu, T. H. Hsieh, J. Y. Lee, P. H. Liu and H. J. Chang, Phys. Lett. B **624**, 31 (2005).

[39] L. Lellouch *et al.* [UKQCD Collaboration], Phys. Rev. D **64**, 094501 (2001).

[40] A. M. Badalian, B. L. G. Bakker and Y. A. Simonov, Phys. Rev. D **75**, 116001 (2007).

[41] D. Silverman and H. Yao, Phys. Rev. D **38**, 214 (1988).

[42] J. P. Lees *et al.* [BaBar Collaboration], Phys. Rev. Lett. **109**, 101802 (2012).

[43] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115**, 111803 (2015) Erratum: [Phys. Rev. Lett. **115**, 159901 (2015)].

[44] S. Hirose *et al.* [Belle Collaboration], Phys. Rev. D **97**, 012004 (2018).

[45] N. Offen, F. A. Porkert and A. Schäfer, Phys. Rev. D **88**, 034023 (2013).