

# Semi-leptonic and Leptonic Charm Decays at BESIII

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BESIII

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# Outline

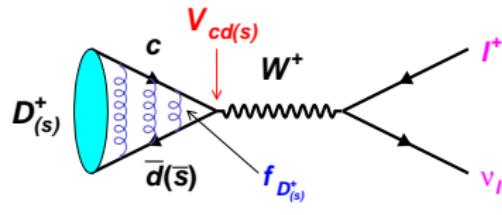
1 Introduction

2 Leptonic Decays of  $D^+$  and  $D_s^+$

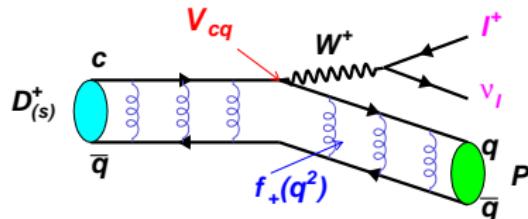
3 Semileptonic Decays of  $D^0$ ,  $D^+$  and  $D_s^+$

4 Conclusions

# Introduction



$$\Gamma(D_{(s)}^+ \rightarrow l^+ \nu_l) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} |V_{cd(s)}|^2 m_l^2 m_{D_{(s)}^+} (1 - \frac{m_l^2}{m_{D_{(s)}^+}^2})^2$$



$$\frac{d\Gamma(D_{(s)}^+ \rightarrow Pl\nu_l)}{dq} = \frac{G_F^2 p^3}{24\pi^3} |f_+(q^2)|^2 |V_{cq}|^2$$

- Precise measurements of decay constants  $f_{D_{(s)}^+}$ , form factors  $f_+^{D_{(s)}^+ \rightarrow P}(q^2)$  of  $D_{(s)}$  decays can **calibrate theoretical calculations with higher accuracy**.
- Precise measurements of CKM matrix elements  $|V_{cd(s)}|$  can **test unitarity of CKM martix and search for NP beyond SM**.
- Test on lepton flavor universality in charm sector.

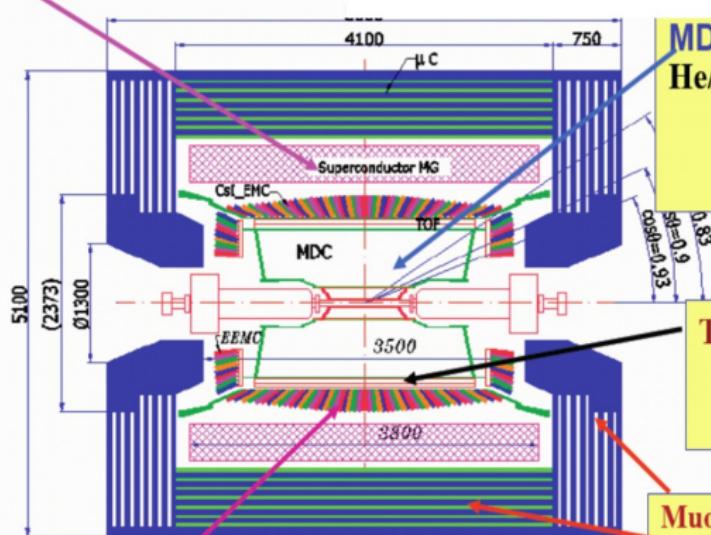
# BEPCII



# BESIII detector

Nucl. Instr. Meth. A614, 345 (2010)

Magnet: 1 T Super conducting



EMC: CsI crystal, 28 cm  
 $\Delta E/E = 2.5\% @ 1 \text{ GeV}$   
 $\sigma_z = 0.6 \text{ cm}/\sqrt{E}$

Data Acquisition:  
Event rate = 4 kHz  
Total data volume  $\sim 50 \text{ MB/s}$

MDC: small cell & Gas:  
 $\text{He/C}_3\text{H}_8 (60/40)$ , 43 layers  
 $\sigma_{xy} = 130 \mu\text{m}$   
 $\sigma_p/p = 0.5\% @ 1\text{GeV}$   
 $dE/dx = 6\%$

TOF:  
 $\sigma_T = 100 \text{ ps}$  Barrel  
 $110 \text{ ps}$  Endcap

Muon ID: 9 layers RPC  
8 layers for endcap

60 ps for ETOF after  
upgraded in 2015

# Method and data samples at BESIII

## Double Tag (DT) Method

The yields of each tag modes can be written as

$$N_{\text{tag}} = 2 \cdot N_{D\bar{D}} \cdot \mathcal{B}_{\text{tag}} \cdot \varepsilon_{\text{ST}} \quad (1)$$

The yields of signal can be written as

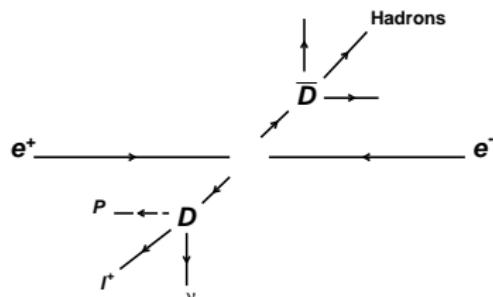
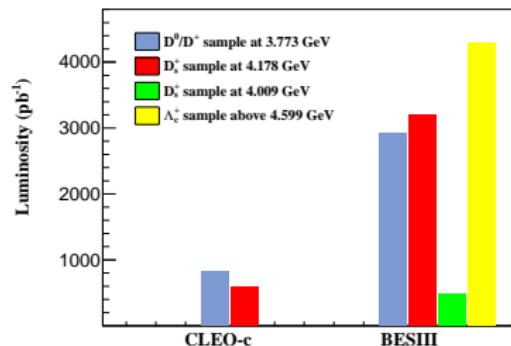
$$N_{\text{sig}} = 2 \cdot N_{D\bar{D}} \cdot \mathcal{B}_{\text{tag}} \cdot \mathcal{B}_{\text{sig}} \cdot \varepsilon_{\text{DT}} \quad (2)$$

the branching fractions of semi-lepton decays can be determined by

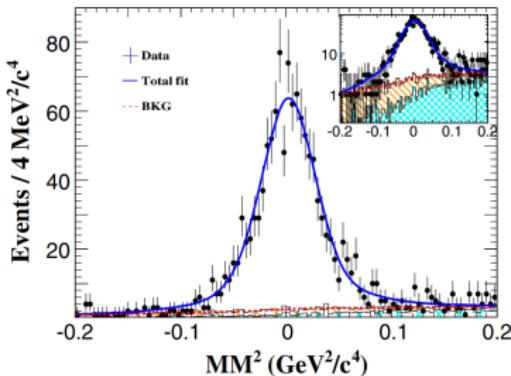
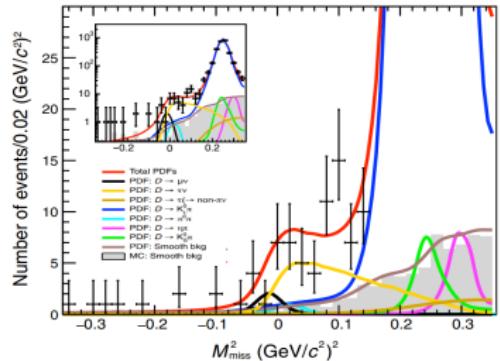
$$\mathcal{B}_{\text{sig}} = \frac{N_{\text{sig}} / (\varepsilon_{\text{DT}} / \varepsilon_{\text{ST}})}{N_{\text{tag}}} \quad (3)$$

Note that  $N_{\text{sig}}$  is determined by fitting the kinematic variables of the missing neutrino

$$U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}| \\ M_{\text{miss}}^2 = E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}^2| \quad (4)$$



$D^+ \rightarrow \tau^+ \nu_\tau$  and  $D_s^+ \rightarrow \mu^+ \nu_\mu$



Phys. Rev. Lett. 123 211802 (2019)

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

First observation with a significance of  $5.1\sigma$

$$\mathcal{B}(D^+ \rightarrow \tau^+ \nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$

$$R_D \equiv \frac{\Gamma(D^+ \rightarrow \tau^+ \nu_\tau)}{\Gamma(D^+ \rightarrow \mu^+ \nu_\mu)} = 3.21 \pm 0.77 \text{ (SM: 2.67)}$$

$$f_{D^+} = (224.5 \pm 22.8 \pm 11.3 \pm 0.9) \text{ MeV}$$

$$|V_{cd}| = (0.237 \pm 0.024 \pm 0.012 \pm 0.001)$$

Phys. Rev. Lett. 122 071802 (2019)

$$D_s^+ \rightarrow \mu^+ \nu_\mu \text{ at } 4.178 \text{ GeV}$$

$$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$

$$f_{D_s^+} |V_{cs}| = (246.2 \pm 3.6 \pm 3.5) \text{ MeV}$$

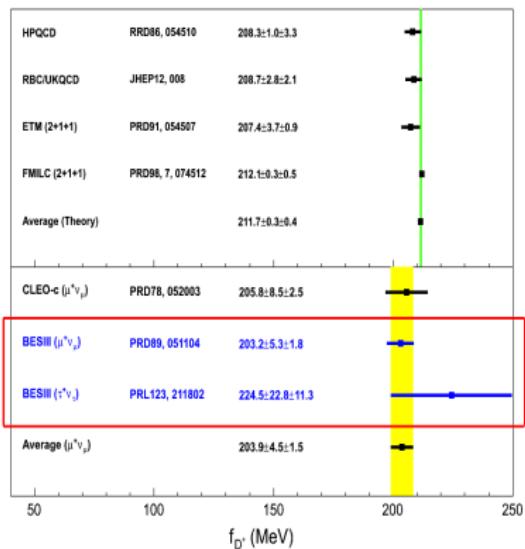
$$f_{D_s^+} = (252.9 \pm 3.7 \pm 3.6) \text{ MeV}$$

$$R_{D_s} \equiv \frac{\Gamma(D_s^+ \rightarrow \tau^+ \nu_\tau)}{\Gamma(D_s^+ \rightarrow \mu^+ \nu_\mu)} = 9.98 \pm 0.52 \text{ (SM: 9.74)}$$

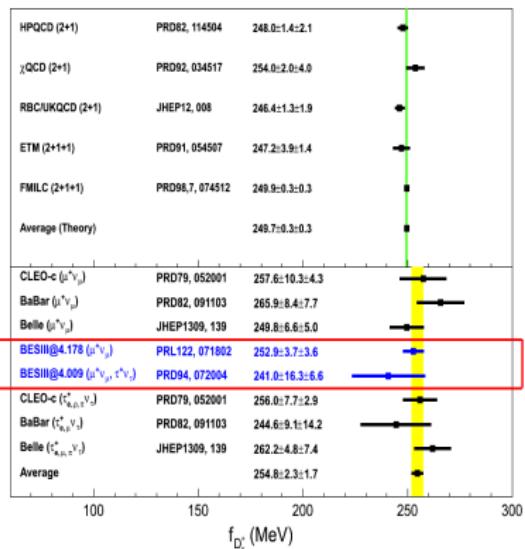
# Comparison of $f_{D^+}$ and $f_{D_s^+}$

## Inputs from CKMFitter

- Input:  $|V_{cd}| = 0.22438 \pm 0.00044$

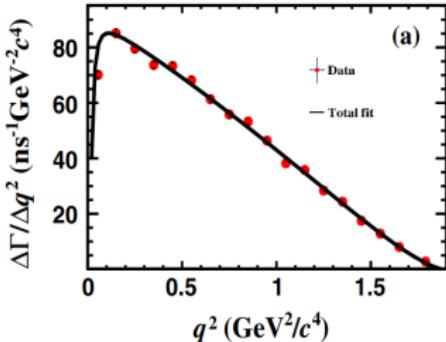
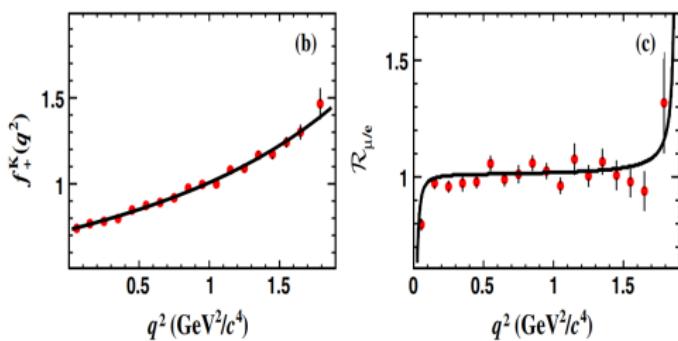
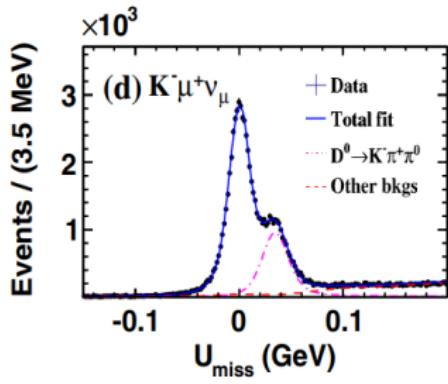


- Input:  $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$



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

PRL122 011804 (2019)



$D^0 \rightarrow K^- \mu^+ \nu_\mu$  at 3.773 GeV

$$\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_\mu) = (3.413 \pm 0.0019 \pm 0.035)\%$$

$$f_+^K(0)|V_{cs}| = (0.7133 \pm 0.0038 \pm 0.0030)$$

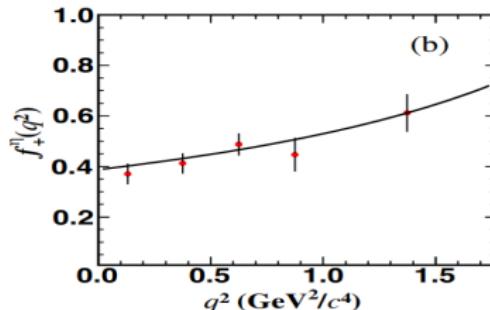
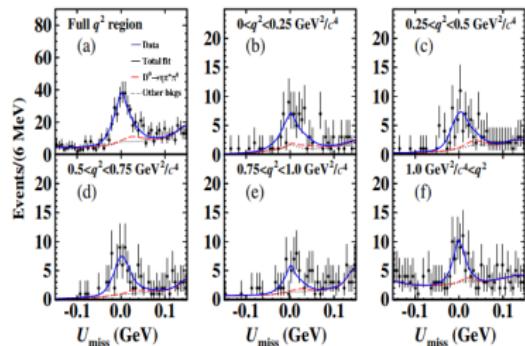
$$f_+^K(0) = (0.7327 \pm 0.0039 \pm 0.0030)$$

$$|V_{cs}| = (0.955 \pm 0.005 \pm 0.004 \pm 0.024)$$

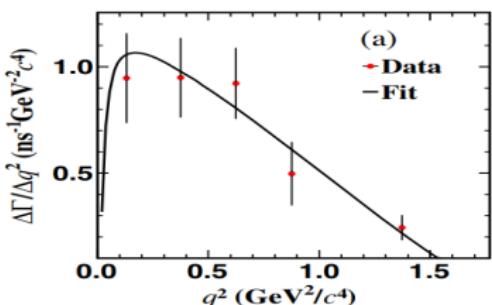
$$\frac{\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e)} = (0.974 \pm 0.007 \pm 0.012) (0.975)$$

$$D^+ \rightarrow \eta \mu^+ \nu_\mu$$

PRL124 231801 (2020)



Experimental confirmation for the first time since it was predicted in 1989. (PRD39, 799)



$$\mathcal{B}(D^+ \rightarrow \eta \mu^+ \nu_\mu) = (10.4 \pm 1.0 \pm 0.5) \times 10^{-4}$$

$$f_+^\eta(0)|V_{cd}| = 0.087 \pm 0.008 \pm 0.002$$

$$f_+^\eta(0) = 0.39 \pm 0.04 \pm 0.01$$

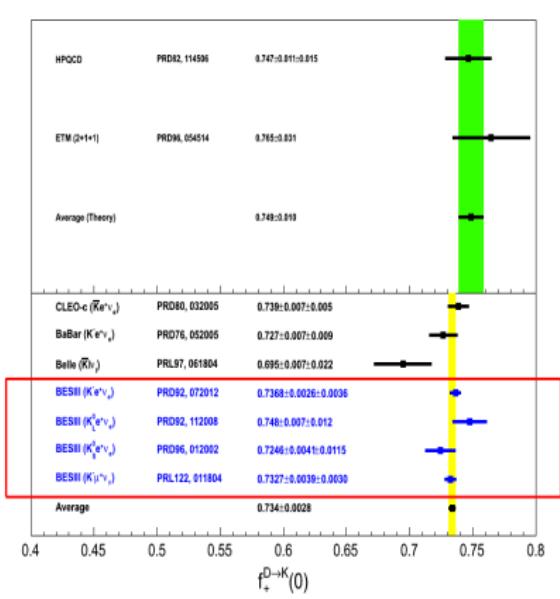
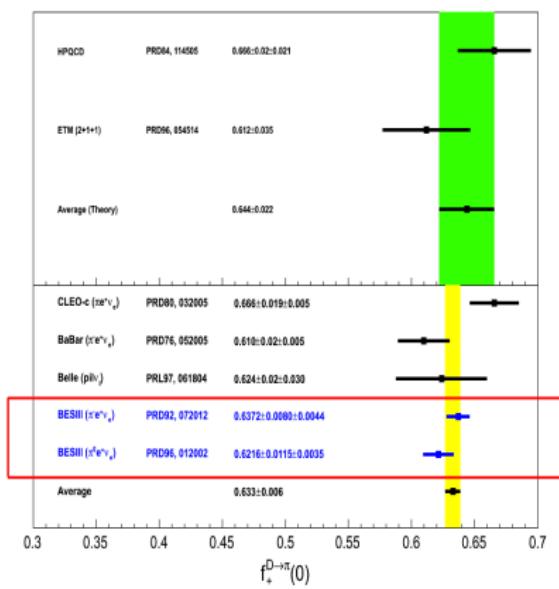
$$|V_{cd}| = 0.242 \pm 0.022 \pm 0.006 \pm 0.033$$

$$R = \frac{\mathcal{B}(D^+ \rightarrow \eta \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \rightarrow \eta e^+ \nu_e)_{\text{PDG}}} = 0.91 \pm 0.13$$

# Comparison of $f_+^{D \rightarrow \pi}(0)$ and $f_+^{D \rightarrow K}(0)$

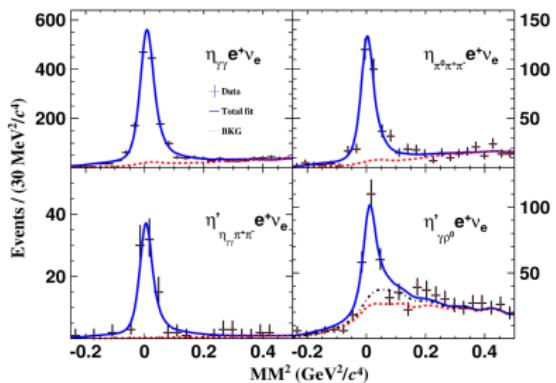
## Inputs from CKMFitter

- Input:  $|V_{cd}| = 0.22438 \pm 0.00044$
- Input:  $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$



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

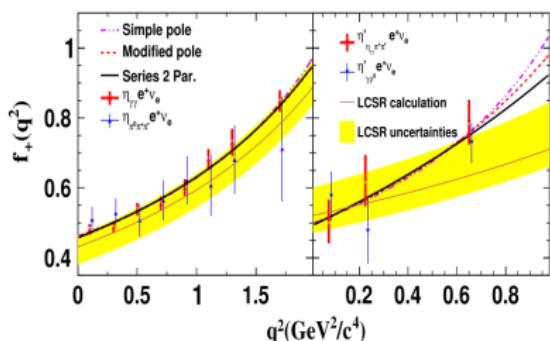
PRL122 121801 (2019)



$$\mathcal{B}(D_s^+ \rightarrow \eta e^+ \nu_e) = (2.323 \pm 0.063 \pm 0.063)\%$$

$$\mathcal{B}(D_s^+ \rightarrow \eta' e^+ \nu_e) = (0.824 \pm 0.073 \pm 0.027)\%$$

Precision improved  $\times 2$  over PDG



Input:

$$|V_{cs}| = 0.97343 \pm 0.00015 \text{ (PRD98, 030001)}$$

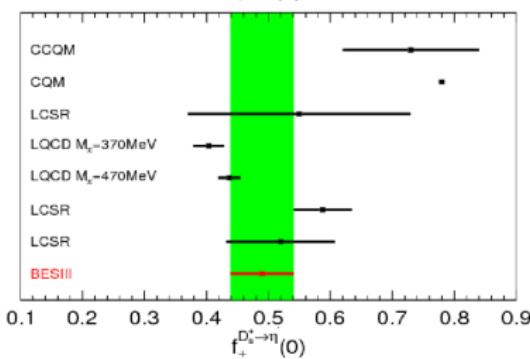
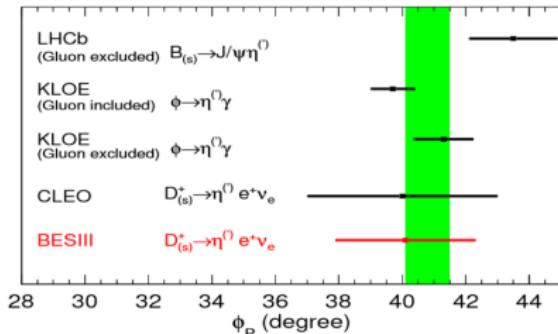
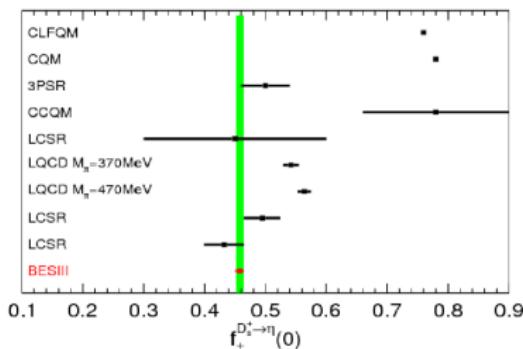
$$f_+^{D_s \rightarrow \eta}(0) = (0.4576 \pm 0.0054 \pm 0.0045)$$

$$f_+^{D_s \rightarrow \eta'}(0) = (0.490 \pm 0.050 \pm 0.011)$$

First FF measurement

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

PRL122 121801 (2019)



$\eta - \eta'$  mixing angle  $\phi_P$  can be determined

$$\cot^4 \phi_P = \frac{\Gamma(D_s^+ \rightarrow \eta' e^+ \nu_e) / \Gamma(D_s^+ \rightarrow \eta e^+ \nu_e)}{\Gamma(D^+ \rightarrow \eta' e^+ \nu_e) / \Gamma(D^+ \rightarrow \eta e^+ \nu_e)}$$

Input previous BESIII results (PRD97, 092009):

$$\mathcal{B}(D^+ \rightarrow \eta e^+ \nu_e) = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$$

$$\mathcal{B}(D^+ \rightarrow \eta' e^+ \nu_e) = (1.91 \pm 0.51 \pm 0.13) \times 10^{-4}$$

$$\phi_P = (40.1 \pm 2.1 \pm 0.7)^\circ$$

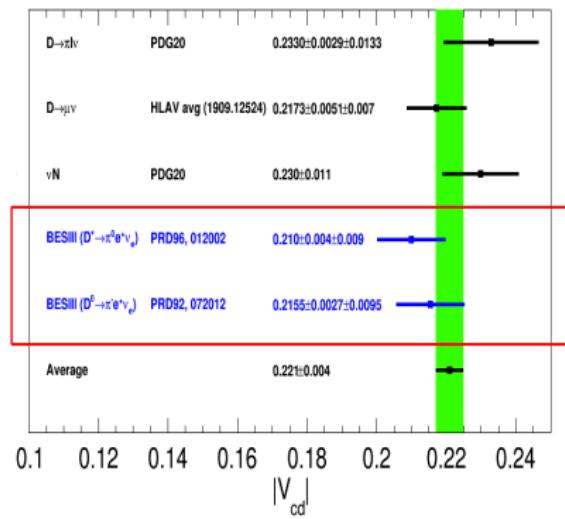
## Comparison of $|V_{cd}|$ and $|V_{cs}|$

## Inputs from FLAG (EPJC80, 2, 113)

**Input:**

$$f_+^{D \rightarrow \pi}(0) = 0.612 \pm 0.035$$

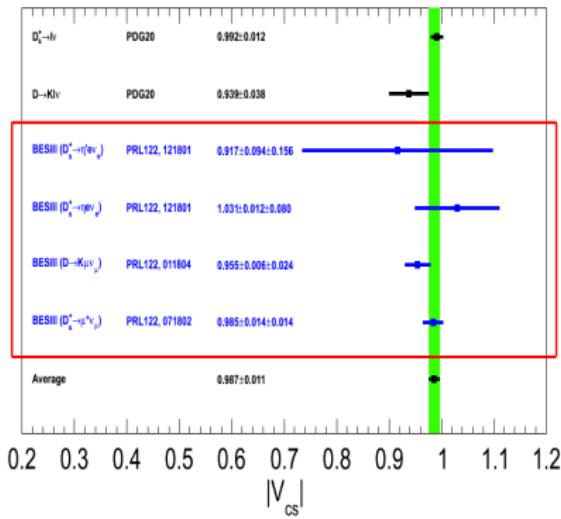
$$f_D = 212.0 \pm 0.7 \text{ MeV}$$



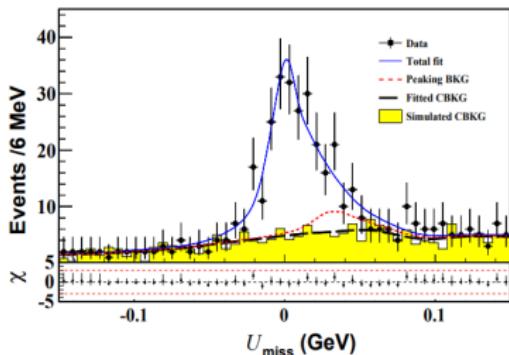
**Input:**

$$f_+^{D \rightarrow K}(0) = 0.765 \pm 0.031$$

$$f_{D_s} = 249.9 \pm 0.5 \text{ MeV}$$



$D^+ \rightarrow \omega\mu^+\nu_\mu$  and  $D_s^+ \rightarrow \phi e^+\nu_e$



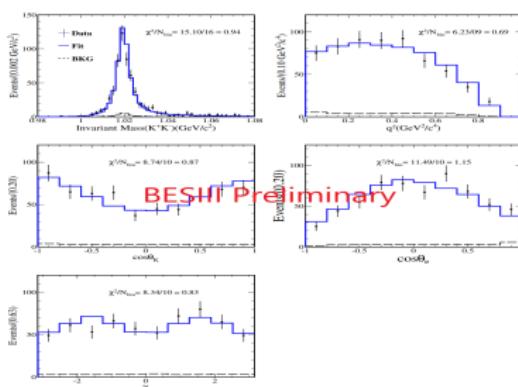
Phys. Rev. D101 072005 (2020)

$$D^+ \rightarrow \omega\mu^+\nu_\mu$$

Experimental confirmation for the first time since it was predicted in 1989. (PRD39, 799)

$$\mathcal{B}(D^+ \rightarrow \omega\mu^+\nu_\mu) = (17.7 \pm 1.8 \pm 1.1) \times 10^{-4}$$

$$R = \frac{\mathcal{B}(D^+ \rightarrow \omega\mu^+\nu_\mu)}{\mathcal{B}(D^+ \rightarrow \omega e^+\nu_e)^{\text{PDG}}} = 1.05 \pm 0.14$$



## BESIII preliminary result

PWA is performed to the final state  $D_s^+ \rightarrow K^+ K^- e^+\nu_e$  with 604 events

No signal is observed significantly from  $f_0(980)$  or phase-space  $S$ -wave

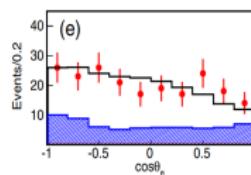
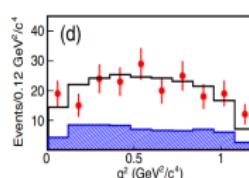
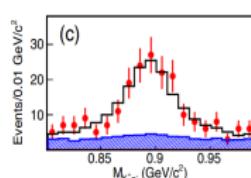
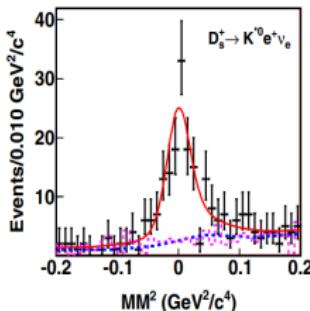
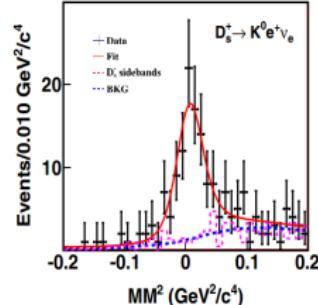
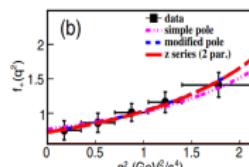
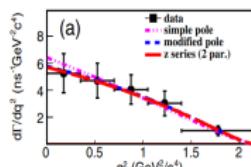
$$\mathcal{B}(D_s^+ \rightarrow \phi e^+\nu_e) = (2.35 \pm 0.10 \pm 0.10)\%$$

$$r_V = 1.79 \pm 0.19 \pm 0.06$$

$$r_2 = 0.77 \pm 0.15 \pm 0.07$$

$$D_s^+ \rightarrow \bar{K}^{0(*)} e^+ \nu_e$$

PRL122, 061801 (2019)



$$\mathcal{B}(D_s^+ \rightarrow \bar{K}^0 e^+ \nu_e) = (3.25 \pm 0.38 \pm 0.16) \times 10^{-3}$$

$$\mathcal{B}(D_s^+ \rightarrow \bar{K}^{*0} e^+ \nu_e) = (2.37 \pm 0.26 \pm 0.20) \times 10^{-3}$$

Precision improved  $\times 2$  over PDG

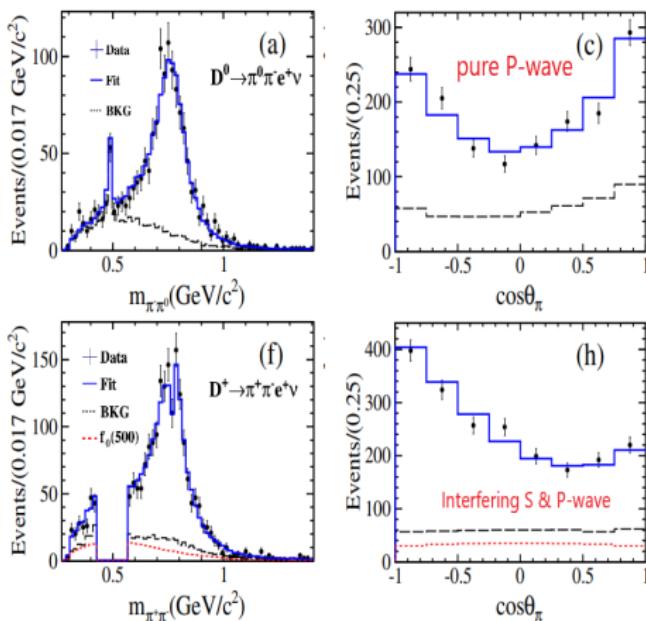
$$f_+^{D_s \rightarrow K^0}(0) = 0.720 \pm 0.084 \pm 0.013$$

$$r_v = 1.67 \pm 0.34 \pm 0.16, r_2 = 0.77 \pm 0.28 \pm 0.07$$

First FF measurements

# $D \rightarrow \pi\pi e^+ \nu_e$ (*S*-wave)

PRL122, 062001 (2019)



First observation for *S*-wave contribution

$$\frac{\mathcal{B}(D^+ \rightarrow (\pi^+ \pi^-)_{S\text{-wave}} e^+ \nu_e)}{\mathcal{B}(D^+ \rightarrow \pi^+ \pi^- e^+ \nu_e)} = (25.7 \pm 1.6 \pm 1.1)\%$$

$$\mathcal{B}(D^0 \rightarrow \pi^- \pi^0 e^+ \nu_e) = (1.445 \pm 0.058 \pm 0.039) \times 10^{-3}$$

$$\mathcal{B}(D^+ \rightarrow \pi^+ \pi^- e^+ \nu_e) = (1.860 \pm 0.070 \pm 0.061) \times 10^{-3}$$

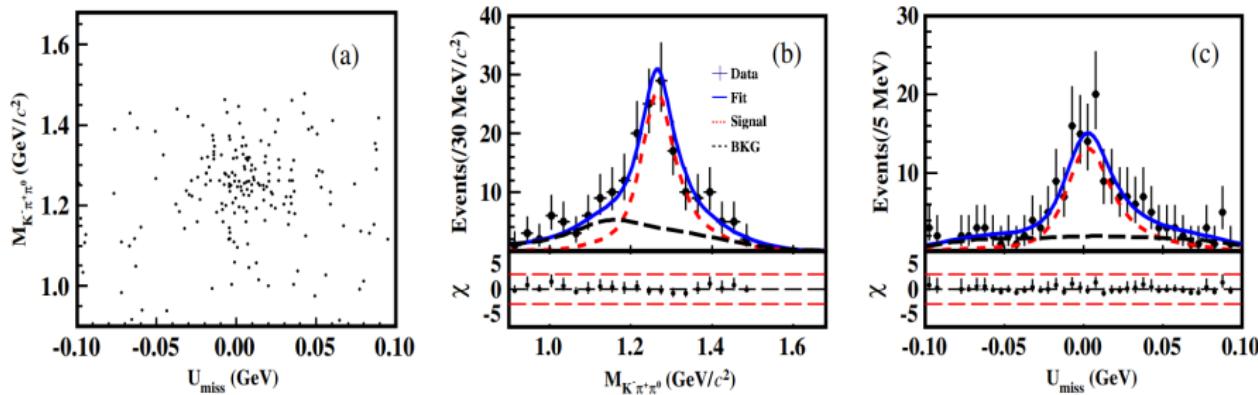
$$\mathcal{B}(D^+ \rightarrow f_0(500) e^+ \nu_e, f_0(500) \rightarrow \pi^+ \pi^-) = (6.30 \pm 0.043 \pm 0.032) \times 10^{-4}$$

$$R = \frac{\mathcal{B}(D^+ \rightarrow f_0(980) e^+ \nu_e) + \mathcal{B}(D^+ \rightarrow f_0(500) e^+ \nu_e)}{\mathcal{B}(D^+ \rightarrow a_0(980) e^+ \nu_e)} > 2.7$$

Tetraquark description favored

$$D^+ \rightarrow \bar{K}_1(1270)^0 e^+ \nu_e$$

PRL123, 231801 (2019)



$$\mathcal{B} = (D^+ \rightarrow \bar{K}_1(1270)^0 e^+ \nu_e) = (2.3 \pm 0.26^{+0.18}_{-0.21} \pm 0.25) \times 10^{-3} \quad (\text{Significance: } > 10\sigma)$$

Experimental confirmation for the first time since it was predicted in 1989. (PRD39, 799)

The predicted BFs are sensitive to  $\theta_{K_1}$  and its sign.

$\theta_{K_1}$  is  $K_1(1270)$  and  $K_1(1400)$  mixing angle.

Our results agrees with the CLFQM and LCSR predictions when  $\theta_{K_1} \approx 33^\circ$  or  $57^\circ$

# Conclusions

BESIII has studied leptonic and semi-leptonic decays with data taken at 3.773 and 4.178 GeV

- First evidences for:
  - $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$
- First observation for:
  - $D^+ \rightarrow \tau^+ \nu_\tau$
  - $D^+ \rightarrow \pi^0 \mu^+ \nu_\mu$
  - $D^0 \rightarrow a_0(980)^- e^+ \nu_e$
  - $D^+ \rightarrow f_0(500) e^+ \nu_e$
  - $D^+ \rightarrow \eta \mu^+ \nu_\mu$
  - $D^+ \rightarrow \omega \mu^+ \nu_\mu$
- First measurements the dynamics on:
  - $D_s^+ \rightarrow \eta(') e^+ \nu_e$
  - $D_s^+ \rightarrow K^0(*) e^+ \nu_e$
  - $D^0 \rightarrow \bar{K}^0 \pi^- e^+ \nu_e$

By using data at 4.19-4.23 GeV,  $D_s^+$  leptonic and semi-leptonic decays are being studied.  
 More  $\psi(3770)$  data (17/fb) will be collected in the next two years. More results from BESIII to be expected.

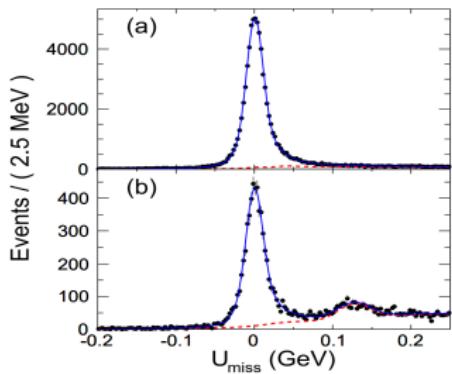
- Precisely measured:
  - Decay constant  $f_{D_{(s)}}$
  - FF  $f_+^K(0)$ ,  $f_+^\pi(0)$  and  $f_+^{\eta(')}(0)$
  - $|V_{cd}|$  and  $|V_{cs}|$
- Test the lepton universality:
  - No evidence for LFUV in charm at 1.5% precision
- Light Hadron Results
  - $\eta - \eta'$  mixing angle
  - Test on  $\theta_{K_1}$  and its sign
  - Tetraquark description favored for  $a_0(980)$ ,  $f_0(500)$  and  $f_0(980)$

Thank you

# Back up

$$D^0 \rightarrow K^-(\pi^-)e^+\nu_e$$

PRD92 072012 (2015)



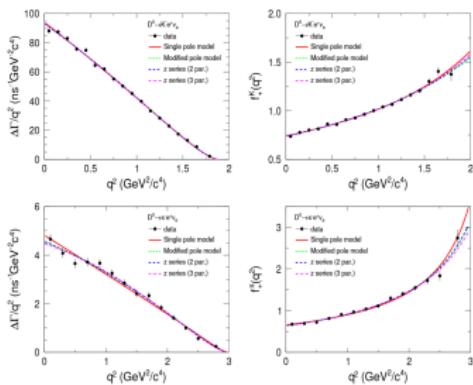
$D^0 \rightarrow K^- e^+ \nu_e$  at 3.773 GeV

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.0014 \pm 0.033)\%$$

$$f_+^K(0)|V_{cs}| = (0.7172 \pm 0.0025 \pm 0.0035)$$

$$f_+^K(0) = (0.7368 \pm 0.0026 \pm 0.0036)$$

$$|V_{cs}| = (0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239)$$



$D^0 \rightarrow \pi^- e^+ \nu_e$  at 3.773 GeV

$$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.004 \pm 0.003)\%$$

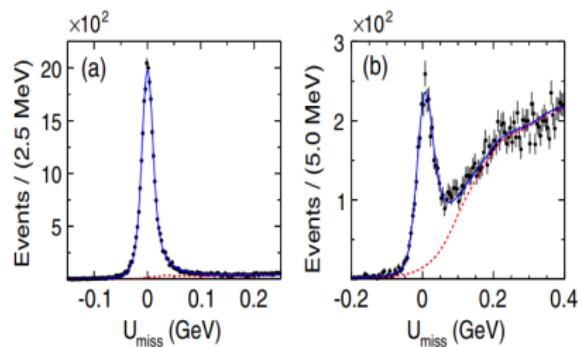
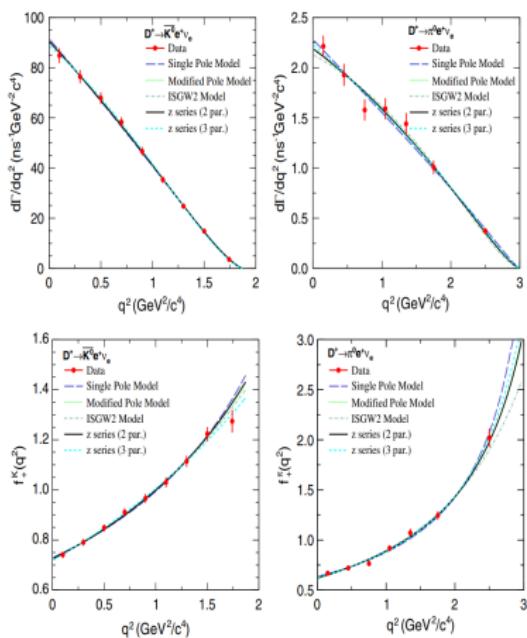
$$f_+^\pi(0)|V_{cs}| = (0.1435 \pm 0.0018 \pm 0.0009)$$

$$f_+^\pi(0) = (0.6372 \pm 0.0080 \pm 0.0044)$$

$$|V_{cd}| = (0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094)$$

$$D^+ \rightarrow \bar{K}^0(\pi^0)e^+\nu_e$$

PRD96 012002 (2017)



$$\mathcal{B}(D^+ \rightarrow \bar{K}e^+\nu_e) = (8.6 \pm 0.06 \pm 0.15)\%$$

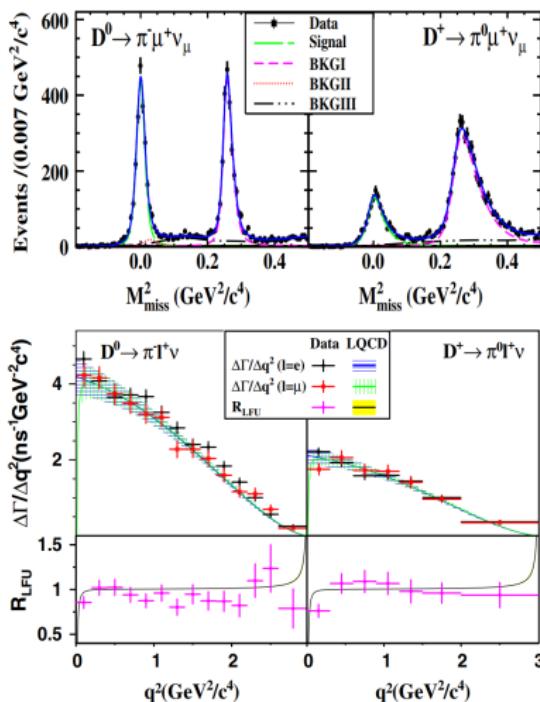
$$\mathcal{B}(D^+ \rightarrow \pi^0e^+\nu_e) = (0.363 \pm 0.008 \pm 0.005)\%$$

$$f_+^{D \rightarrow K}(0)|V_{cs}| = 0.7053 \pm 0.0040 \pm 0.0112$$

$$f_+^{D \rightarrow \pi}(0)|V_{cd}| = 0.1400 \pm 0.0026 \pm 0.0007$$

$$D^0(+) \rightarrow \pi^{-(0)} \mu^+ \nu_\mu$$

PRL121 171803 (2018)



$$\mathcal{B}(D^0 \rightarrow \pi^- \mu^+ \nu_\mu) = (2.72 \pm 0.08 \pm 0.06) \times 10^{-3}$$

$$\mathcal{B}(D^+ \rightarrow \pi^0 \mu^+ \nu_\mu) = (3.50 \pm 0.11 \pm 0.10) \times 10^{-3}$$

Input:

$$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (2.95 \pm 0.04 \pm 0.03) \times 10^{-3}$$

$$\mathcal{B}(D^0 \rightarrow \pi^0 e^+ \nu_e) = (3.63 \pm 0.08 \pm 0.05) \times 10^{-3}$$

$$\frac{\mathcal{B}(D^0 \rightarrow \pi^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e)} = (0.922 \pm 0.030 \pm 0.022)$$

$$\frac{\mathcal{B}(D^+ \rightarrow \pi^0 \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \rightarrow \pi^0 e^+ \nu_e)} = (0.964 \pm 0.037 \pm 0.026)$$

SM Prediction:

$$\frac{\mathcal{B}(D \rightarrow \pi \mu^+ \nu_\mu)}{\mathcal{B}(D \rightarrow \pi e^+ \nu_e)} = 0.985 \pm 0.002$$