# (Semi-)leptonic D decays at BESIII

Bai-Cian Ke
ZhengZhou University
On behalf of the BESIII Collaboration

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# Outline

- Introduction
  - $D^0$, $D^+$,and $D_s$ Dataset
- Pure leptonic decays of $\boldsymbol{D^0}$
- Semi-leptonic decays of $\boldsymbol{D^{0(+)}}$
- (Semi-) leptonic decays of $\boldsymbol{D}_s$
- Summary

# BESIII Data Taken near DD$^{bar}$ Threshold

- BEPCII $e^+e^-$ collider
- 2.9 fb$^{-1}$ dataset at $\psi(3770) \to$ DD$^{bar}$ resonance

**Not even enough energy for one additional pion**

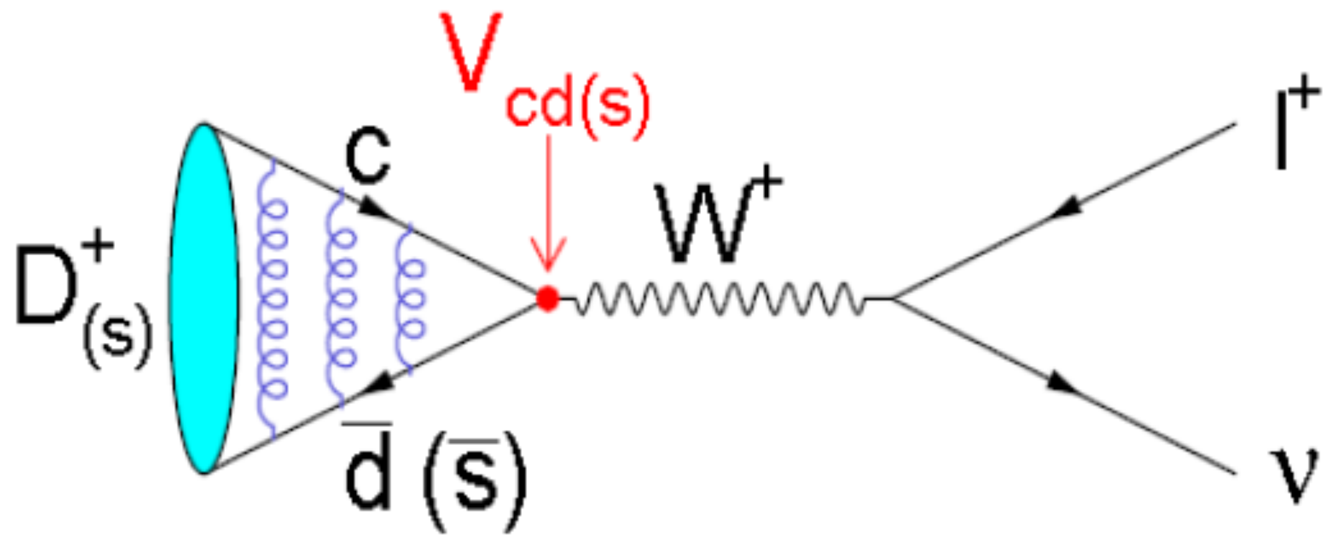
- 3.19 fb$^{-1}$ dataset at $E_{cm}$ 4.178GeV
  - $D_s$ are produced via $e^+e^- \to D_sD_s^*$
- XYZ dataset at $E_{cm}$ 4.19 - 4.23 GeV (about .8x of 4180 data)
- Advantages:

**Clean** **Tagging**

**Access to absolute branching fraction**

**Many systematic uncertainties cancel**

# Pure leptonic D decay




$$\Gamma\left(D^+_{(s)} \to l^+\nu\right) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} \left|V_{cd(s)}\right|^2 m_l^2 m_{D^+_{(s)}} \left(1 - \frac{m_l^2}{m^2_{D^+_{(s)}}}\right)^2$$

Decay constant $f_{D^+_{(s)}}$:

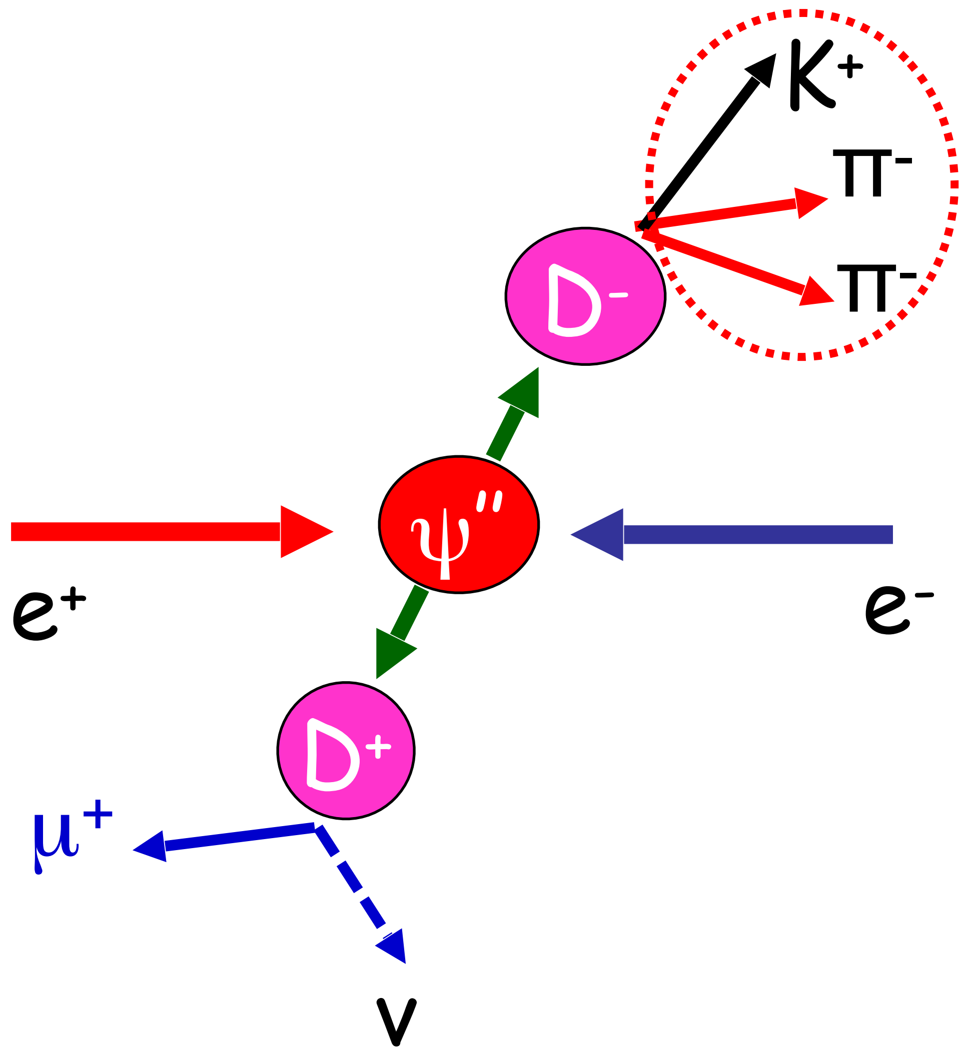
Calibrate Lattice QCD

CKM matrix element $|Vcd(s)|$:

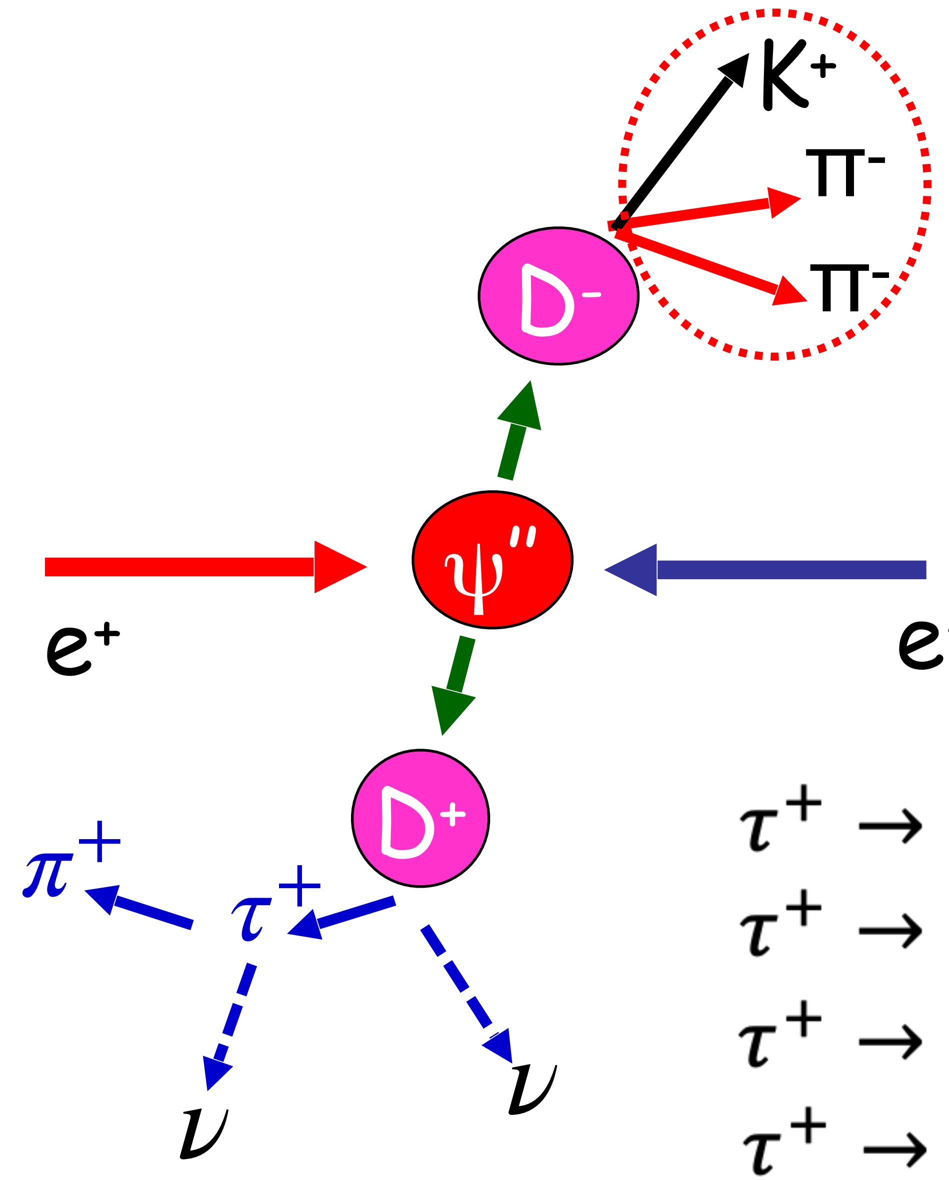
Test the unitarity of CKM matrix

Lepton flavor universality

| | $e^+\nu_e$ | $\mu^+\nu_\mu$ | $\tau^+\nu_\tau$ |
|---|---|---|---|
| $D^+$ $10^{-5}$ | : | 1 | : 2.67 |
| $D_s^+$ $10^{-5}$ | : | 1 | : 9.75 |




One neutrino missing in an muonic event



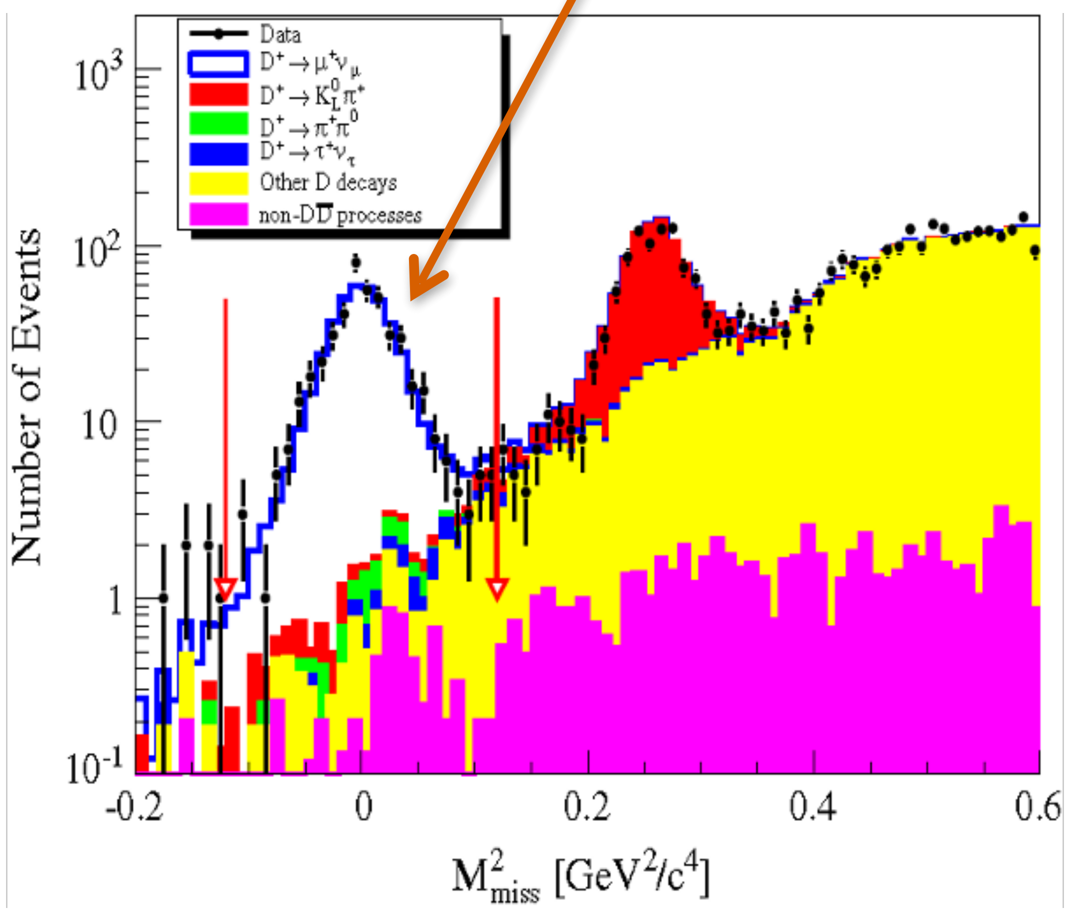

$$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$$
$$\tau^+ \to \pi^+ \bar{\nu}_\tau$$
$$\tau^+ \to \rho^+ \bar{\nu}_\tau$$
$$\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$$

Two or three neutrinos missing in an tau event

$$U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$
$$M^2_{\text{miss}} = E^2_{\text{miss}} - |\vec{p}^{\,2}_{\text{miss}}|$$

# $D^+ \to l^+\nu_l$

## $D^+ \to \mu^+\nu_\mu$

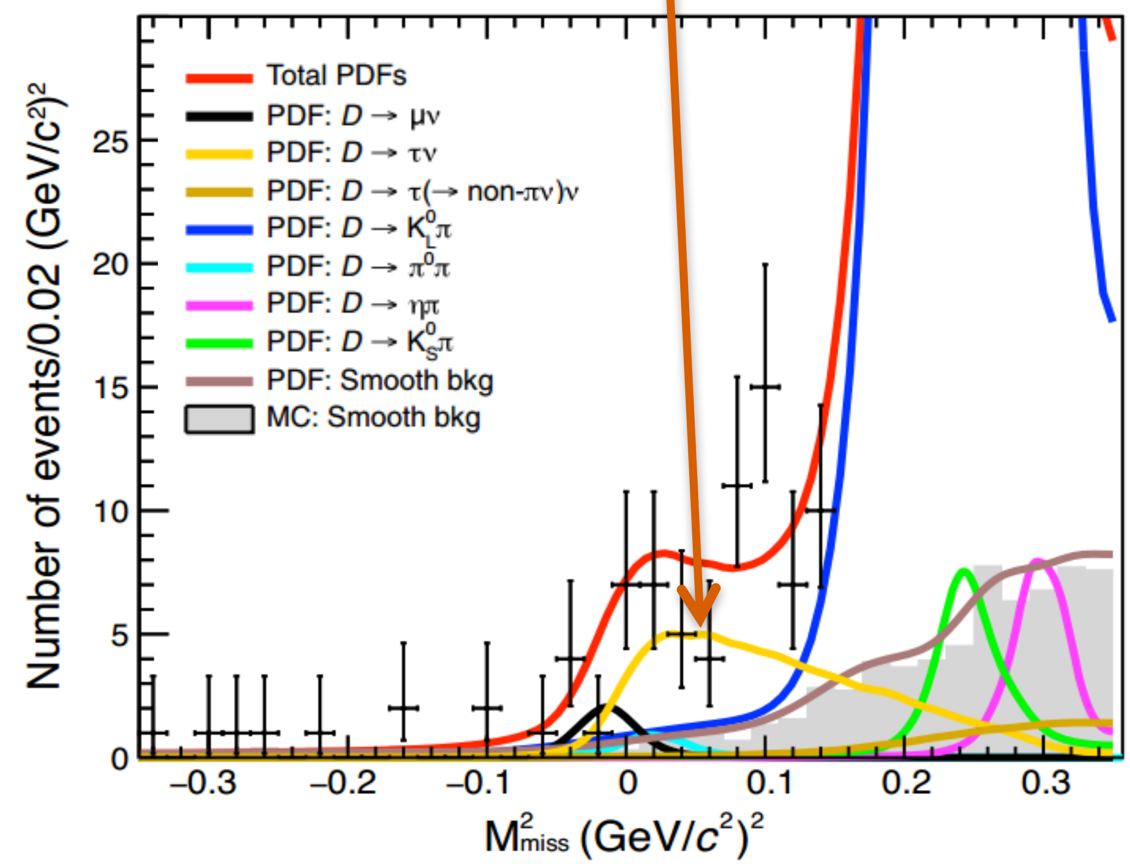



$\mathscr{B}(D^+ \to \mu^+\nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$

$f_{D^+}|V_{cd}| = 46.7 \pm 1.2 \pm 0.4$ MeV

*Phys. Rev. D 89, 051104 (2014)*

## $D^+ \to \tau^+\nu_\tau$




**$\tau^+$ is reconstructed via $\tau^+ \to \pi^+\nu_\tau$**

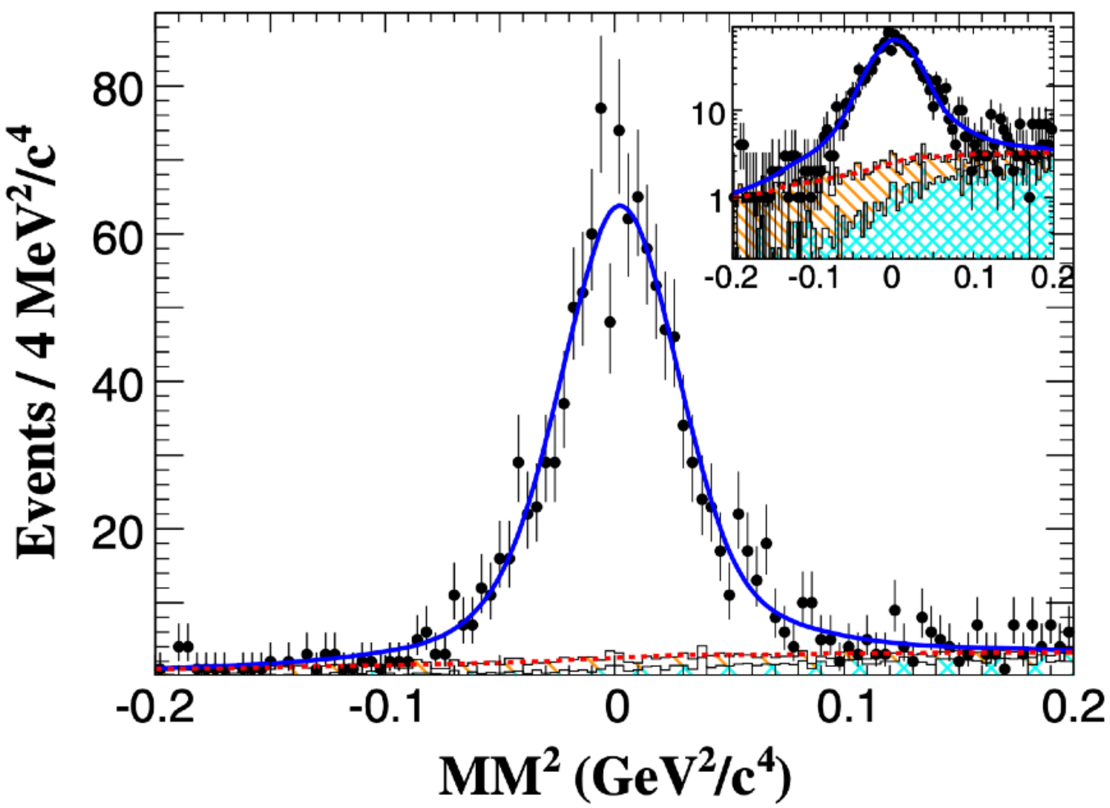
$\mathscr{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$

$f_{D^+}|V_{cd}| = 50.4 \pm 5.0 \pm 2.5$ MeV

*Phys. Rev. Lett. 123, 211802 (2019)*

# $D_s^+ \to l^+\nu$

$D_s^+ \to \mu^+\nu$
3.19fb-1 @ 4.18 GeV

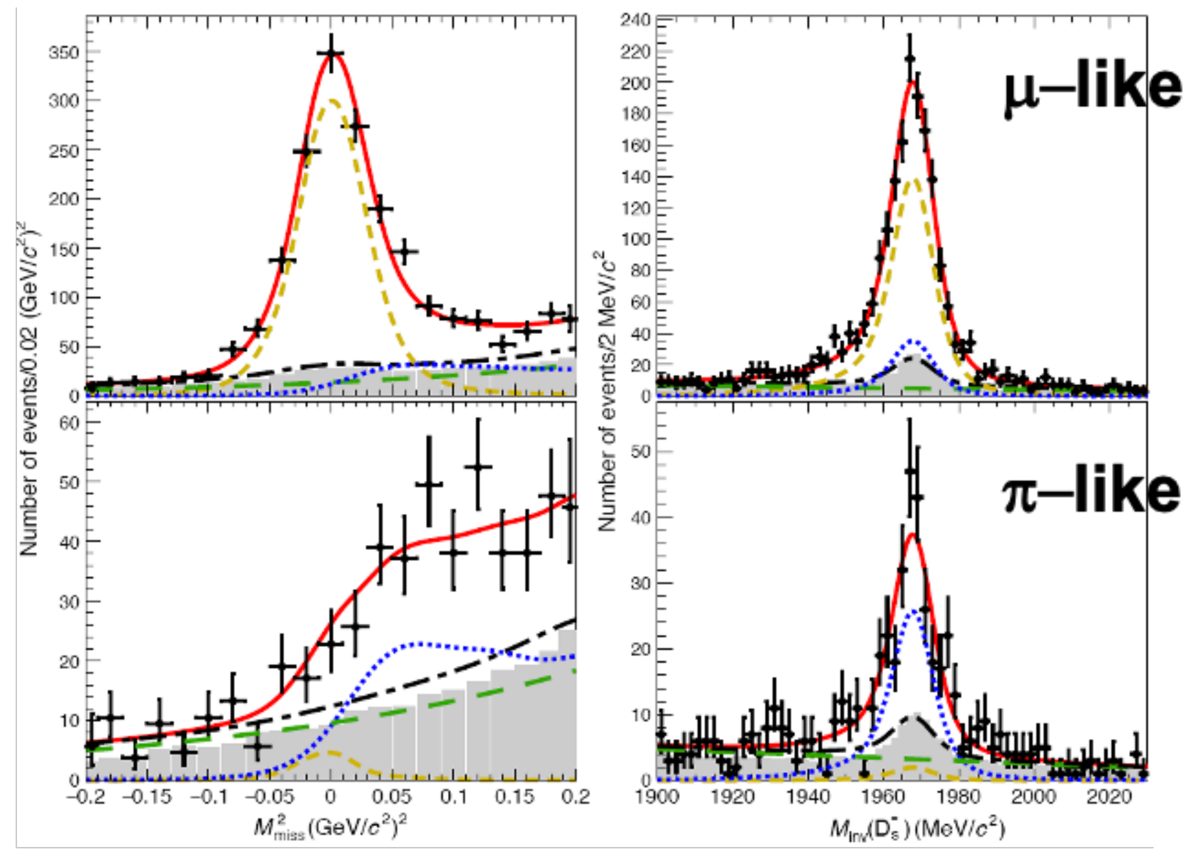



$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$

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

*Phys. Rev. Lett. 122, 071802 (2019)*

$D_s^+ \to \mu^+\nu + \tau^+(\pi^+\nu)\nu$
6.3 fb-1 @ 4.18-4.23 GeV




$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.35 \pm 0.13 \pm 0.16) \times 10^{-3}$

$f_{D_s^+}|V_{cs}| = 243.1 \pm 3.0 \pm 3.7$ MeV$[\mu]$

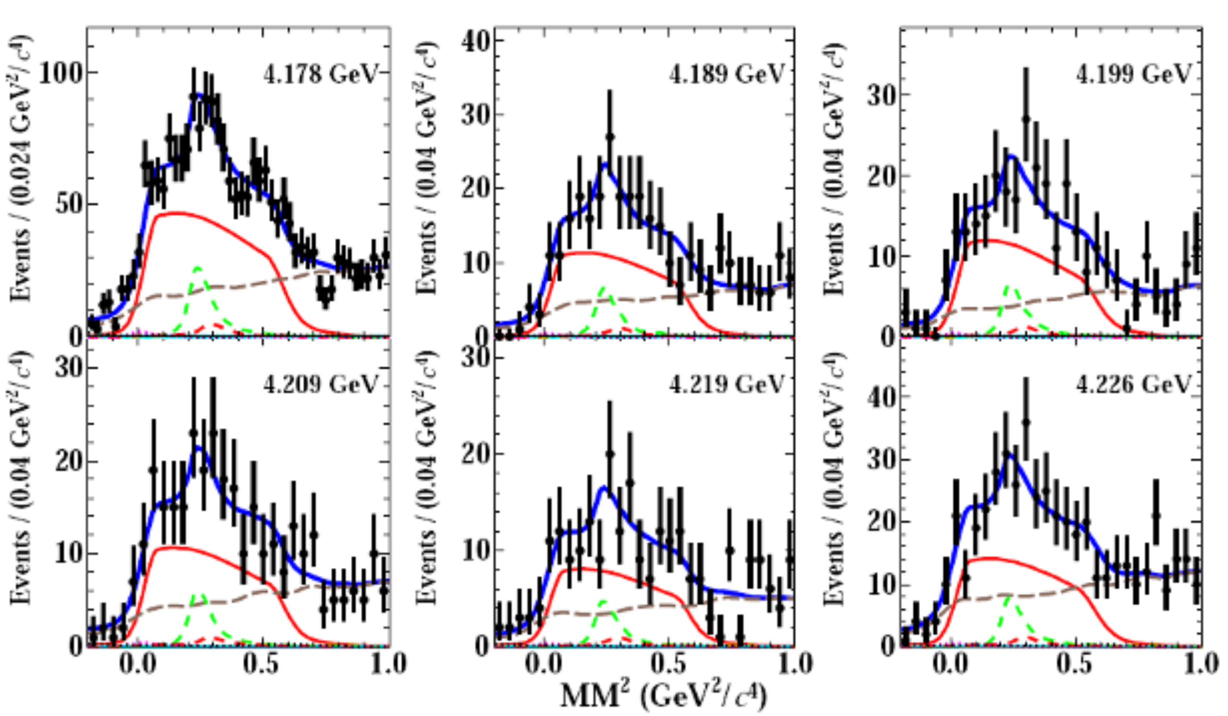
$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.22 \pm 0.25 \pm 0.17)\,\%$

$f_{D_s^+}|V_{cs}| = 243.0 \pm 5.8 \pm 4.0$ MeV$[\tau]$

*Phys. Rev. D 104, 052009 (2021)*

# $D_s^+ \to l^+\nu$

$D_s^+ \to \tau^+(\rho^+\nu)\nu$
6.3 fb-1 @ 4.18-4.23 GeV

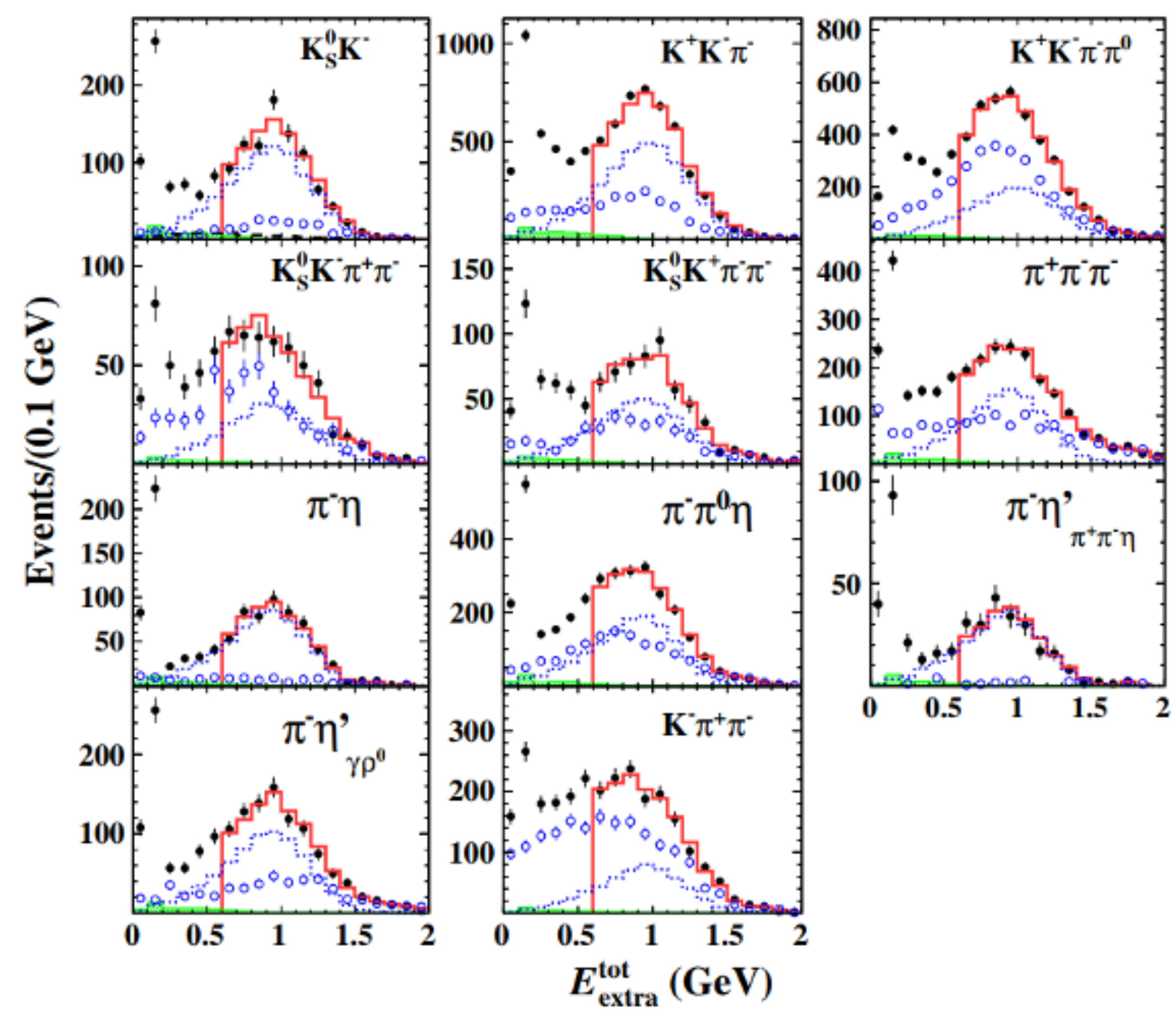



$\mathscr{B}(D_s^+ \to \tau^+\nu_\tau) = (5.29 \pm 0.25 \pm 0.20)\,\%$

$f_{D_s^+}|V_{cs}| = 244.8 \pm 5.8 \pm 4.8$ MeV

*Phys. Rev. D 104, 032001 (2021)*

$D_s^+ \to \tau^+(e^+\nu\nu)\nu$
6.3 fb-1 @ 4.18-4.23 GeV



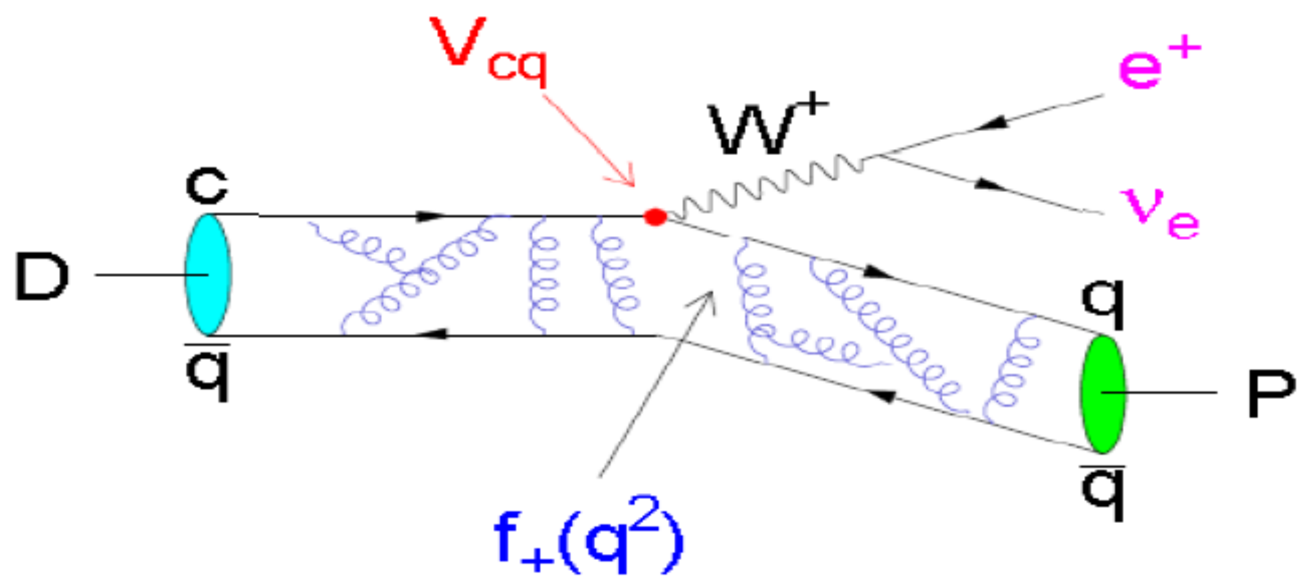

Using extra photon energy

$\mathscr{B}(D_s^+ \to \tau^+\nu_\tau) = (5.27 \pm 0.10 \pm 0.12)\,\%$

$f_{D_s^+}|V_{cs}| = 244.4 \pm 2.3 \pm 2.9$ MeV

*Phys. Rev. Lett. 127, 171801 (2021)*

# Semi-leptonic $D \to P e^+ \nu$




$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2 p^3}{24\pi^3} \left| f_+(q^2) \right|^2 \left| V_{cd(s)} \right|^2 (X = 1\ for\ K^-,\ \pi^-,\ \bar{K}^0, \eta^{(\prime)}; X = \frac{1}{2}\ for\ \pi^0)$$

– **Single pole form**

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M_{pole}^2}$$

– **Modified pole model**

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M_{pole}^2}\right)\left(1 - \alpha \frac{q^2}{M_{pole}^2}\right)}$$

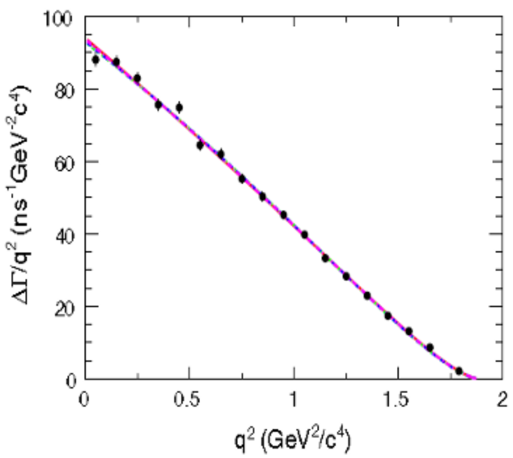
– **ISGW2 model**

$$f_+(q^2) = f_+(q_{max}^2)\left(1 + \frac{r^2}{12}(q_{max}^2 - q^2)\right)^{-2}$$

– **Series expansion model**

$$f_+(t) = \frac{1}{P(t)\Phi(t,\ t_0)} a_0(t_0)(1 + \sum_{k=1}^{\infty} r_k(t_0)\left[z(t, t_0)\right]^k)$$

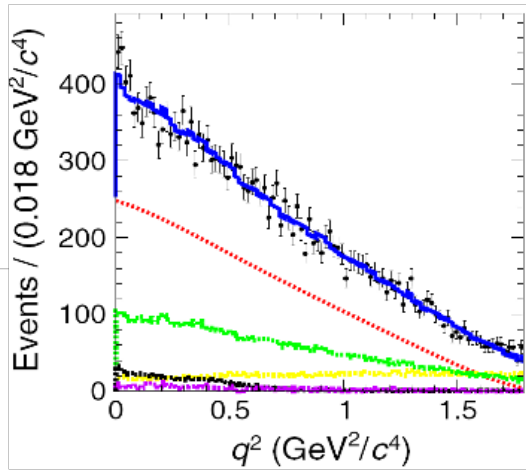
# $c \to s l^+ \nu$




$D^0 \to K^- e^+ \nu$

$f_+^{D\to K}(0)|V_{cs}| = 0.717(03)(04)$

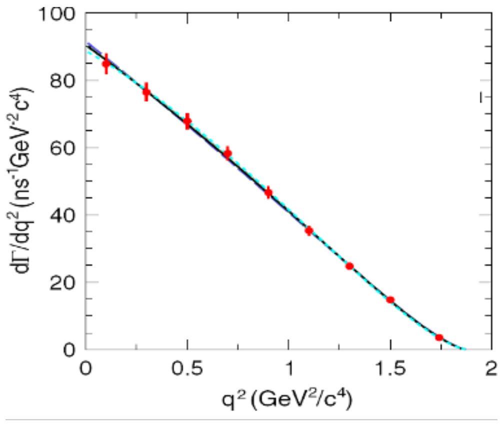
*Phys. Rev. D 92, 072012 (2015)*




$D^+ \to K_L e^+ \nu$

$f_+^{D\to K}(0)|V_{cs}| = 0.728(06)(11)$

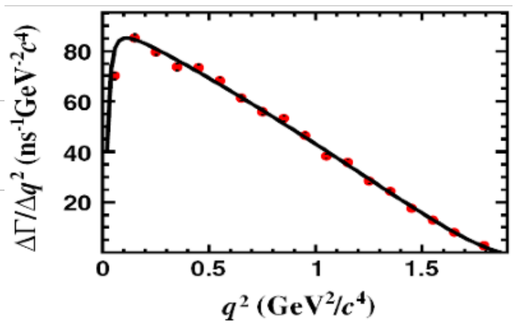
*Phys. Rev. D 92, 112008 (2015)*




$D^+ \to \bar{K}^0 e^+ \nu$

$f_+^{D\to K}(0)|V_{cs}| = 0.705(04)(11)$

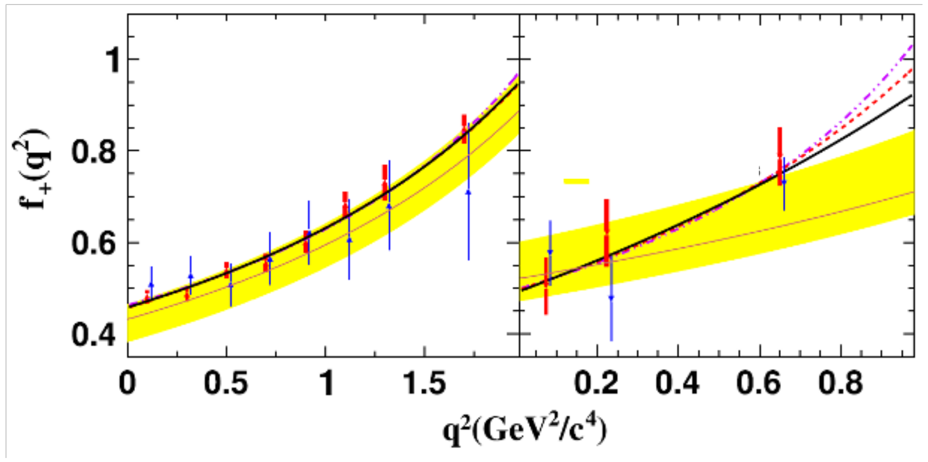
*Phys. Rev. D 96, 012002 (2017)*




$D^0 \to K^- \mu^+ \nu$

$f_+^{D\to K}(0)|V_{cs}| = 0.7148(38)(29)$

*Phys. Rev. Lett. 122, 011804 (2019)*



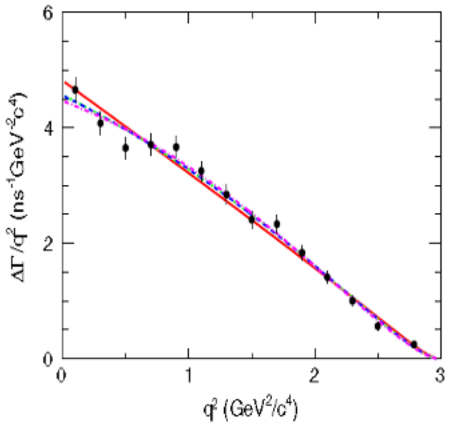

$D_s^+ \to \eta^{(\prime)} e^+ \nu$

$f_+^{D_s\to\eta}(0)|V_{cs}| = 0.446(05)(04)$

$f_+^{D_s\to\eta'}(0)|V_{cs}| = 0.477(49)(11)$

*Phys. Rev. Lett. 123, 121801 (2019)*

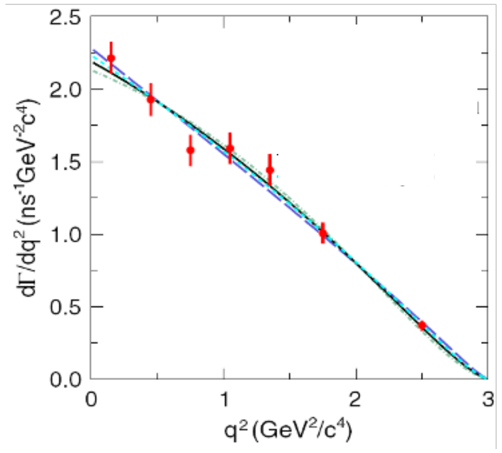
# $c \to d l^+ \nu$



$D^0 \to \pi^- e^+ \nu$

$f_+^{D\to\pi}(0)|V_{cd}| = 0.144(02)(01)$

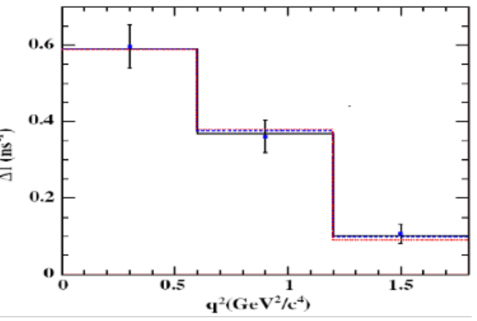
Phys. Rev. D 92, 072012 (2015)



$D^+ \to \pi^0 e^+ \nu$

$f_+^{D\to\pi}(0)|V_{cd}| = 0.140(03)(01)$

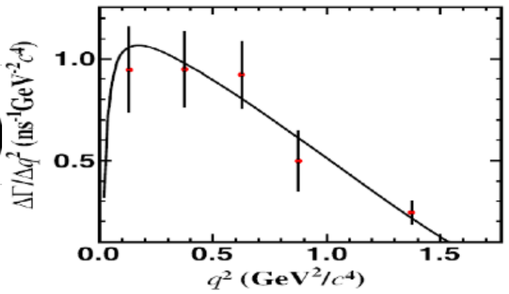
Phys. Rev. D 96, 012002 (2017)



$D^+ \to \eta e^+ \nu$

$f_+^{D\to\eta}(0)|V_{cd}| = 0.079(06)(02)$

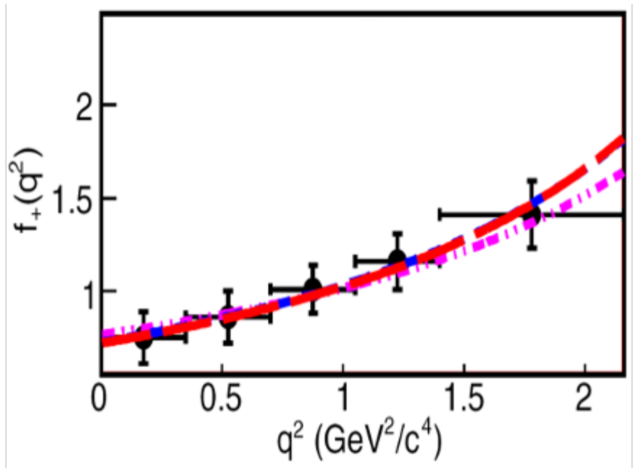
Phys. Rev. D 97, 092009 (2018)



$D^+ \to \eta \mu^+ \nu$

$f_+^{D\to\eta}(0)|V_{cd}| = 0.087(08)(02)$

Phys. Rev. Lett. 124, 231801 (2020)

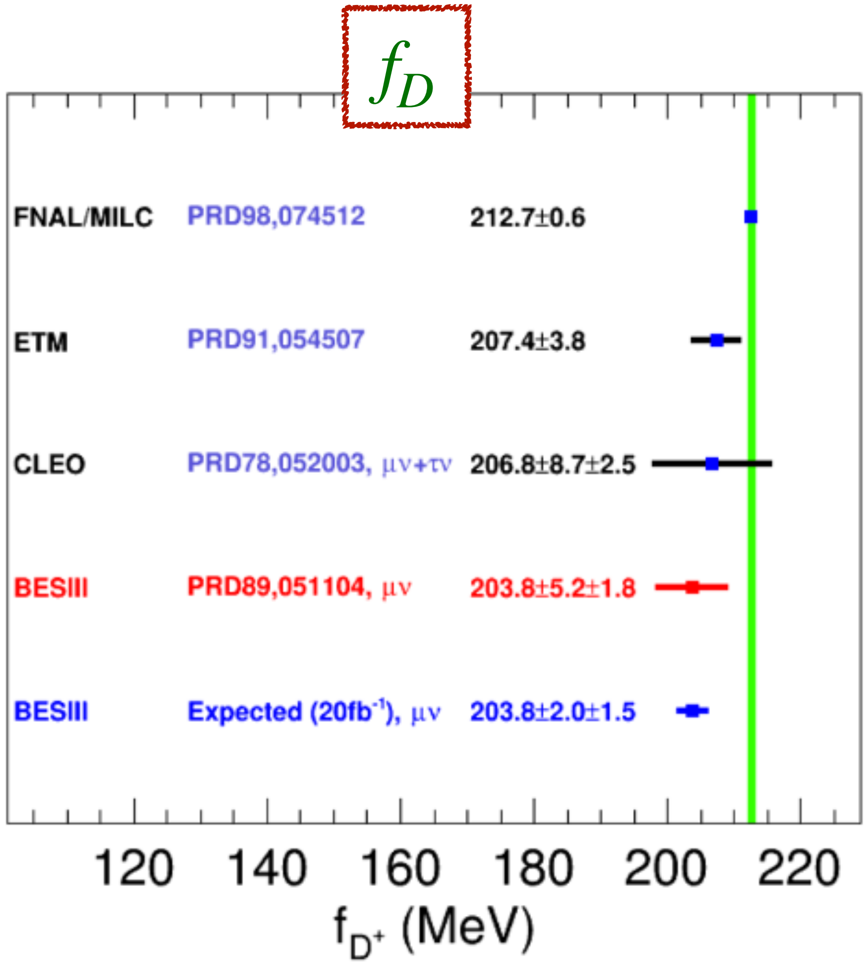


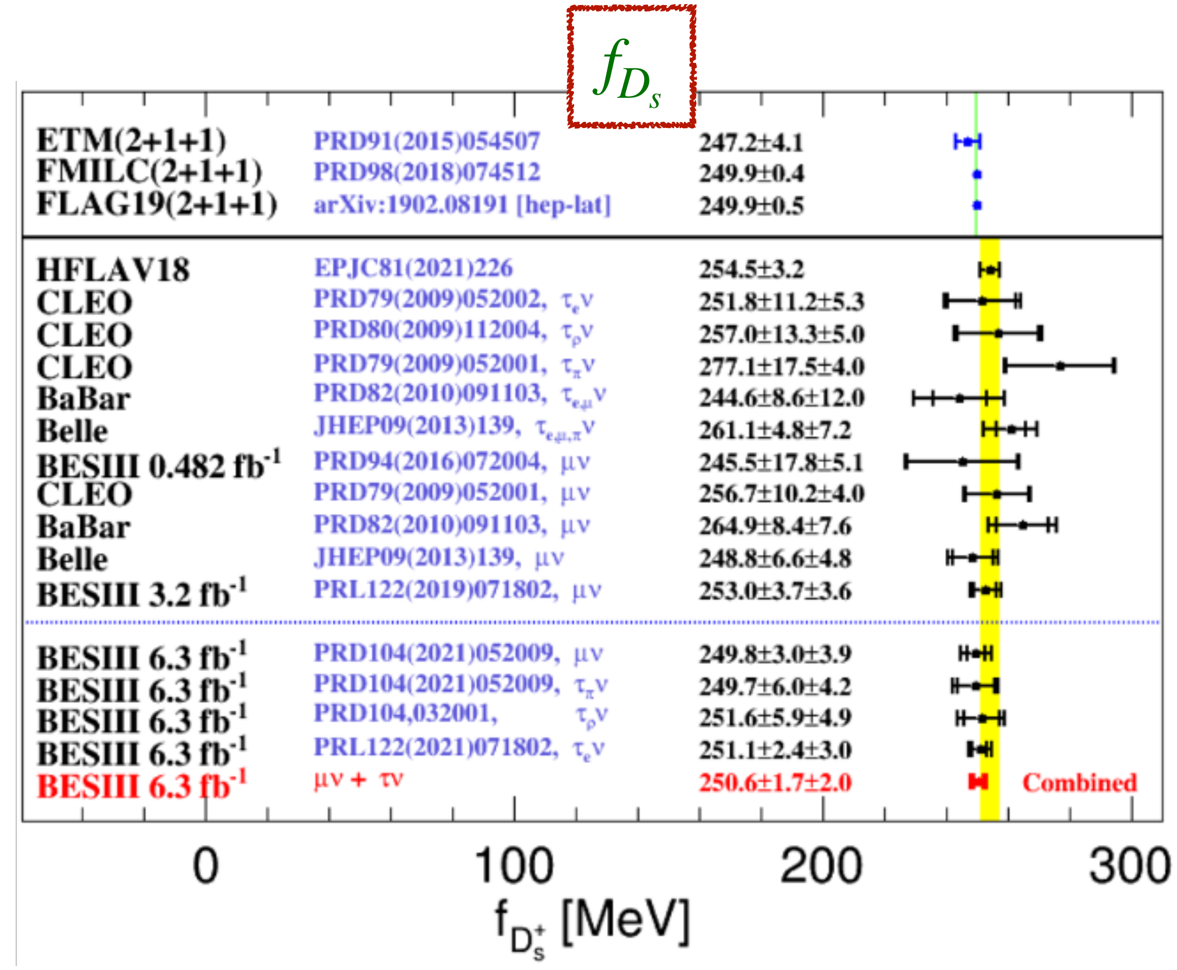
$D_s^+ \to K^0 e^+ \nu$

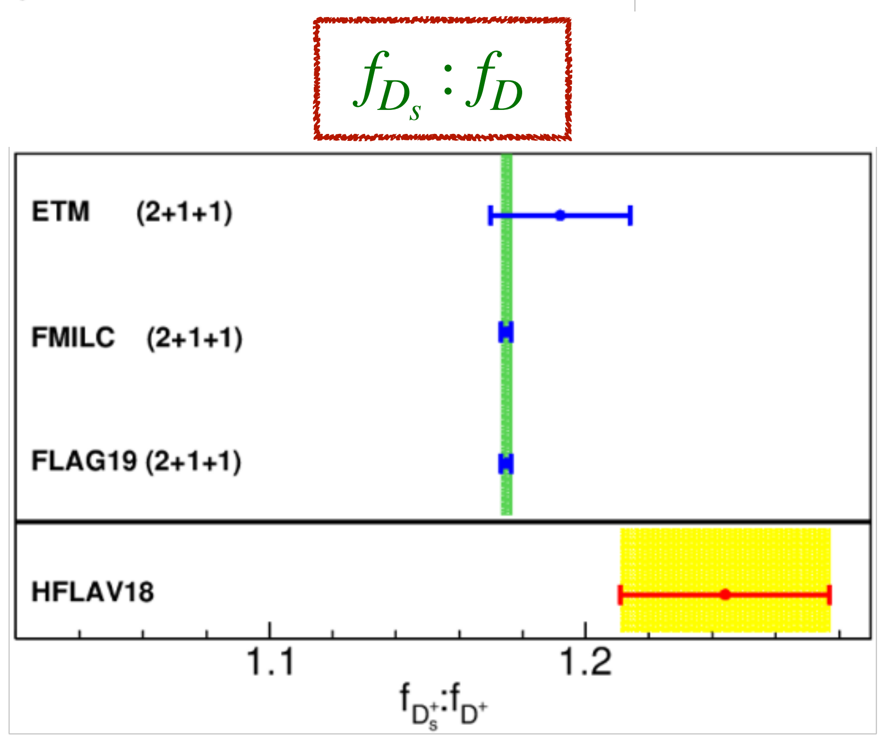
$f_+^{D_s\to K}(0)|V_{cd}| = 0.162(19)(03)$

Phys. Rev. Lett. 122, 061801 (2019)

# Comparison of decay constant



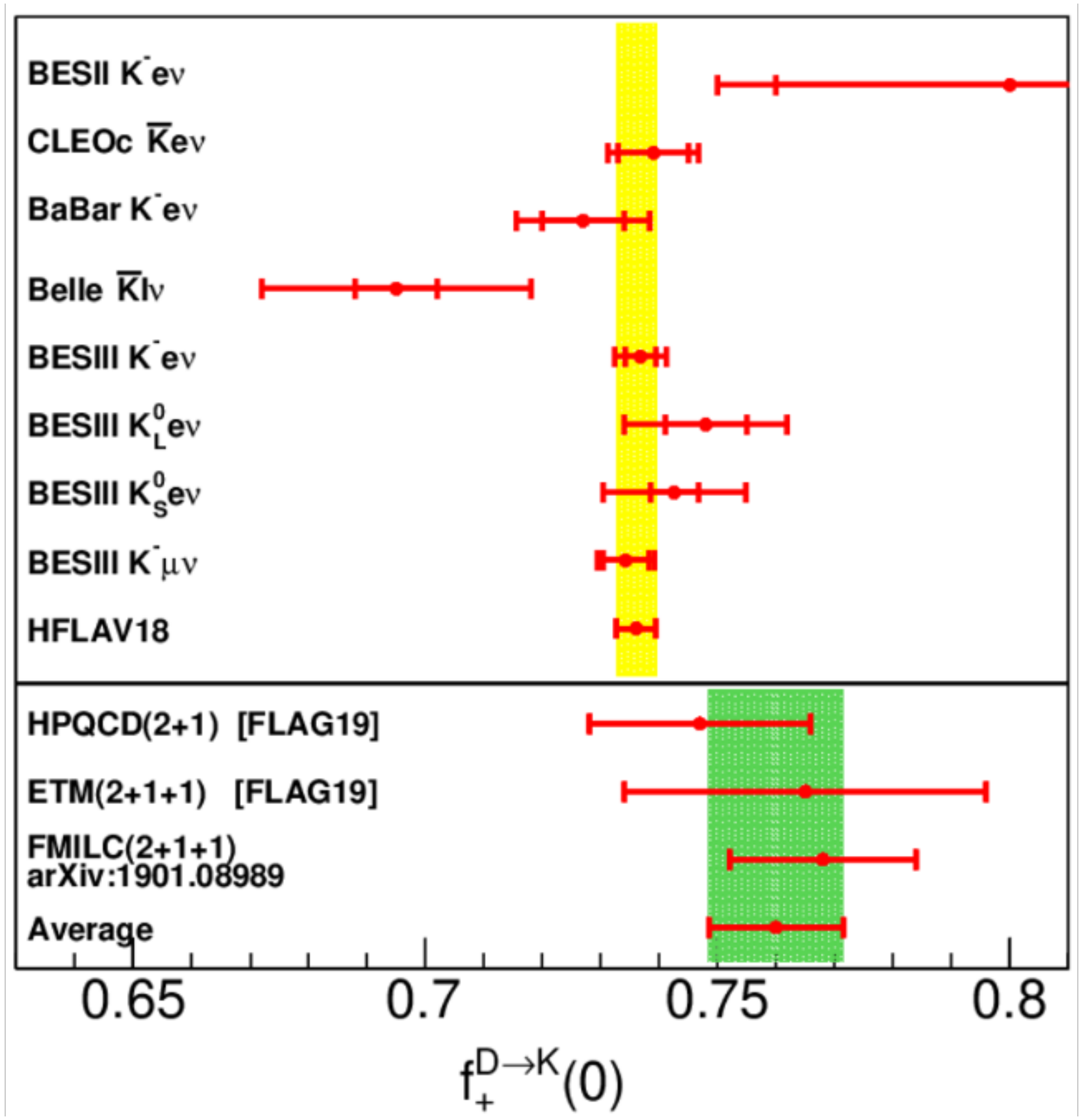



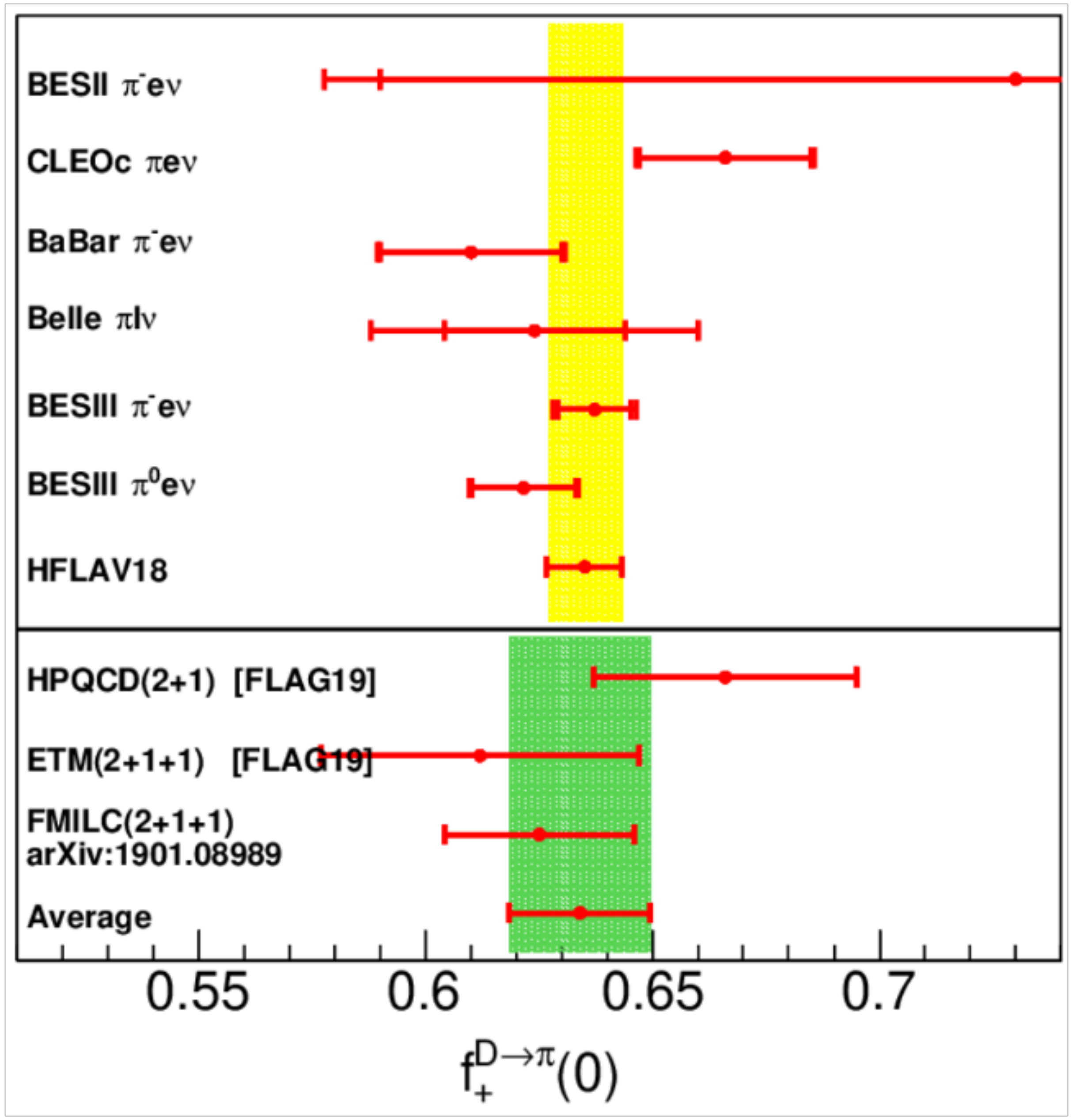

**2σ difference**

# Comparison of form factor

$D \to K$

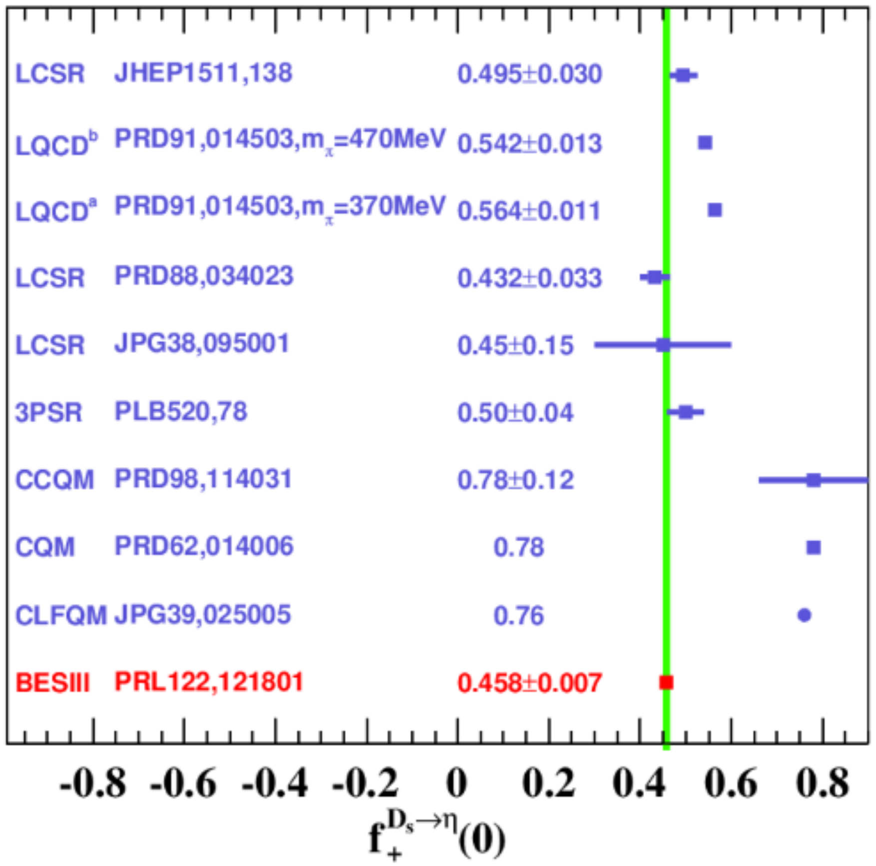



$D \to \pi$

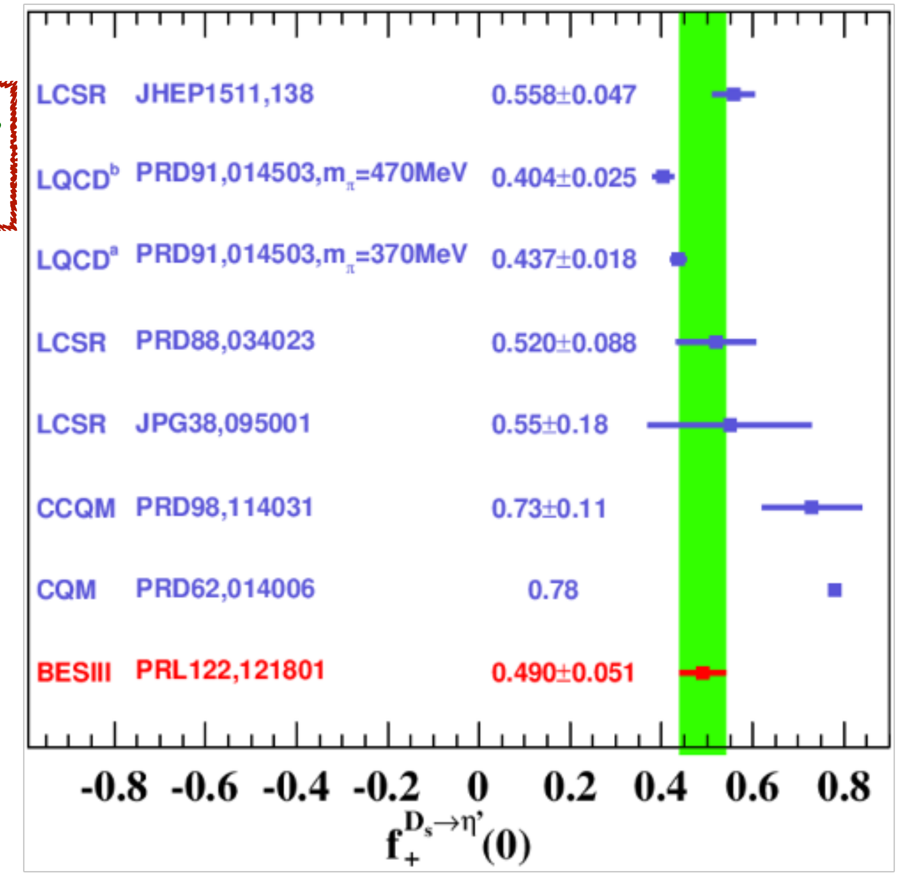


# Comparison of form factor

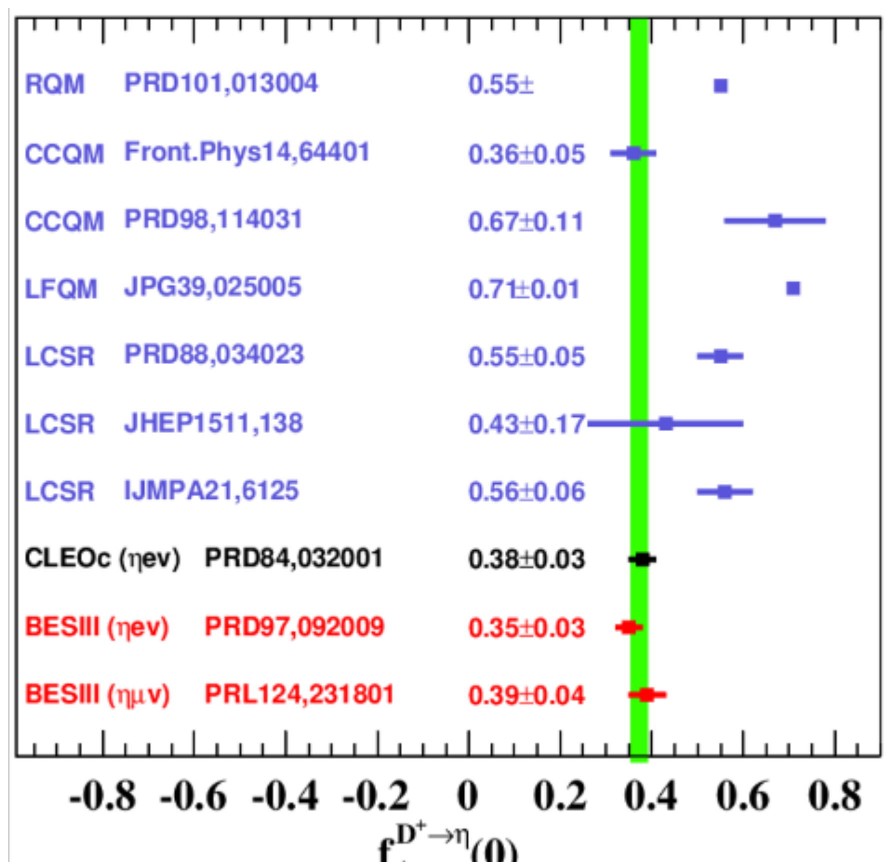
$D_s \to \eta$




$D_s \to \eta'$

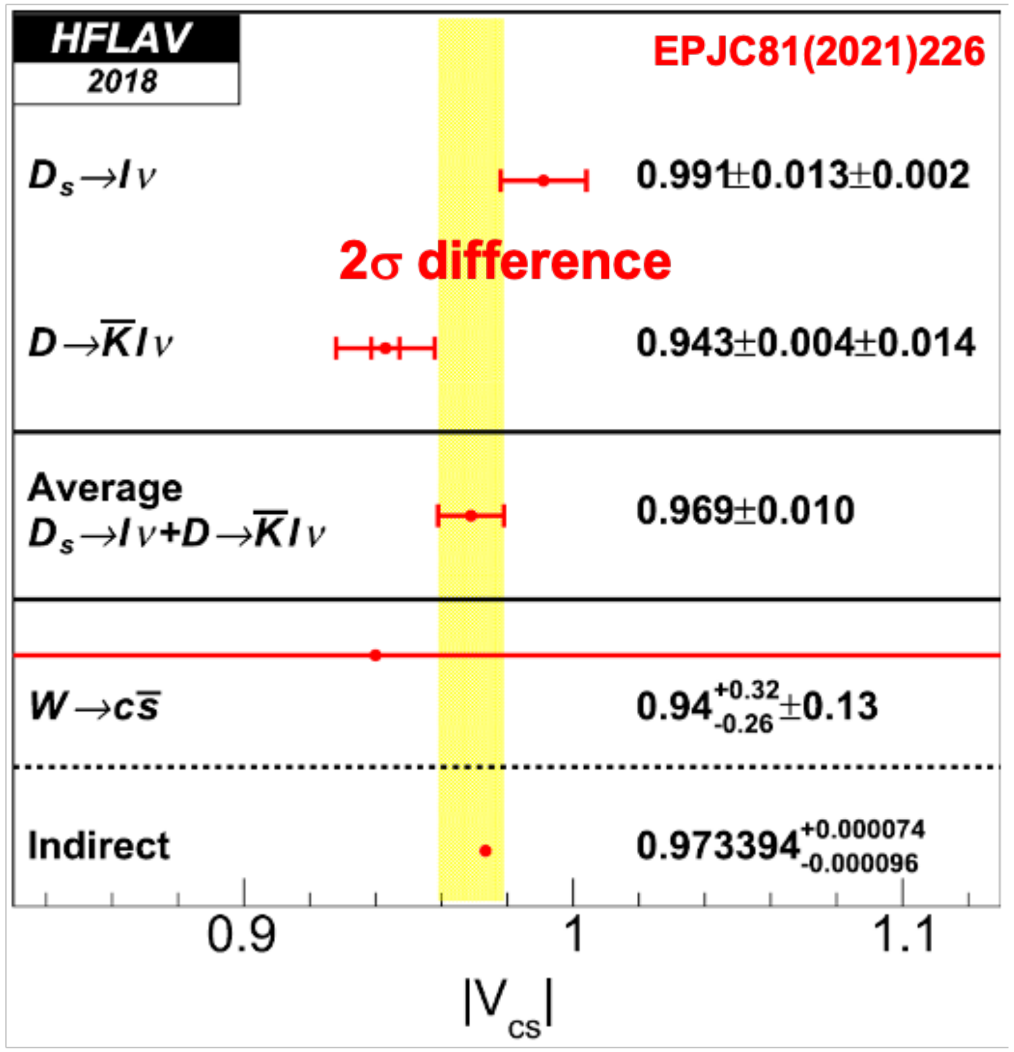



$D \to \eta$

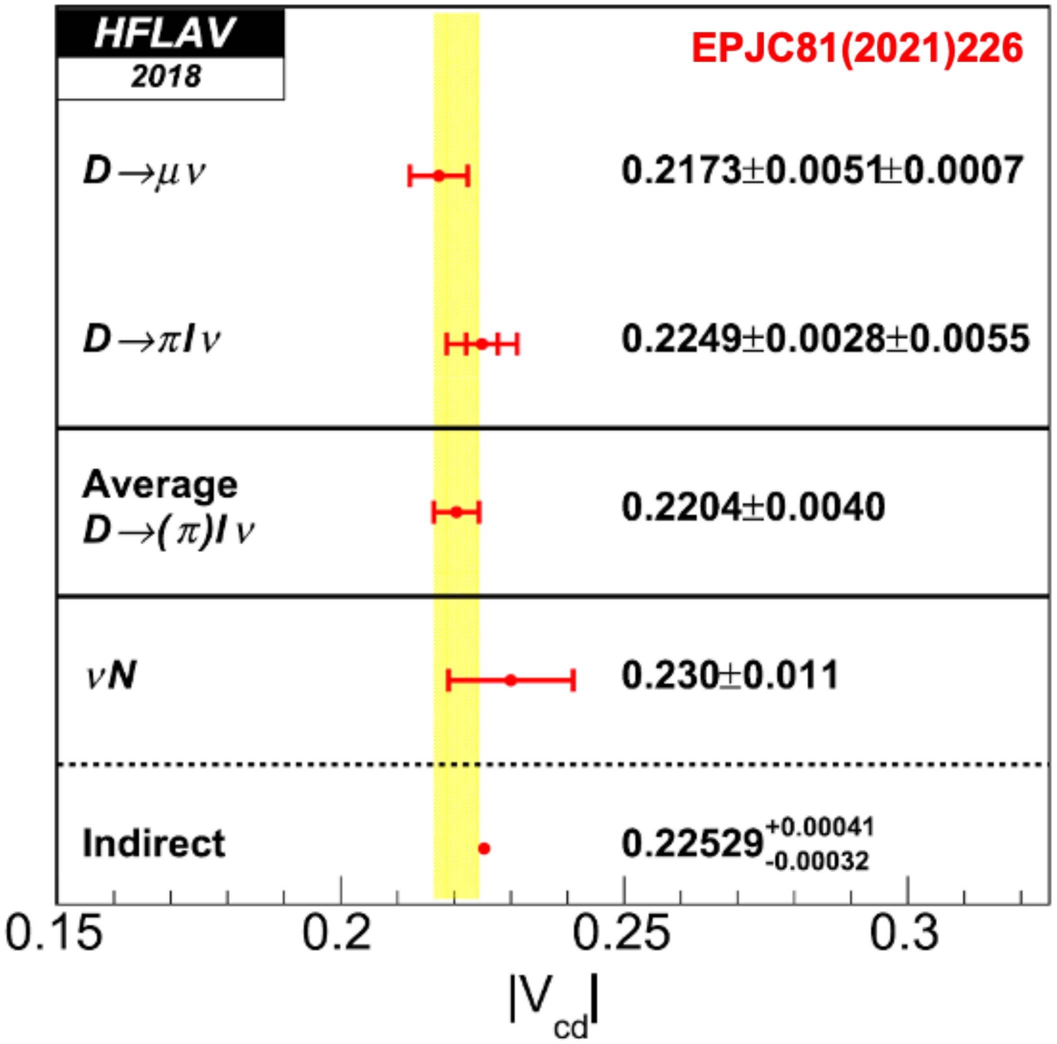


# Comparison of $|V_{cd(s)}|$

$|V_{cs}|$




$|V_{cd}|$



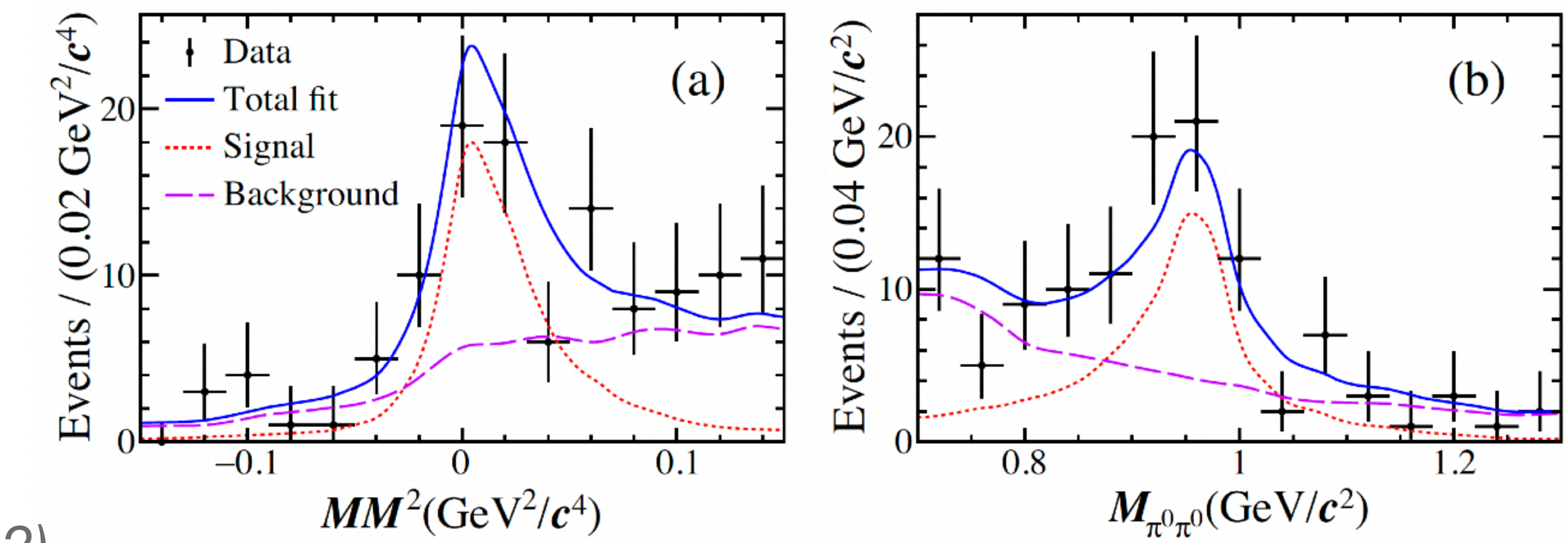
# Scalar particle in $D$ semileptonic decay

Observe $f_0(980)$ in $D_s^+ \to \pi^0\pi^0 e^+\nu$

$\mathscr{B} = (7.9 \pm 1.4 \pm 0.4) \times 10^{-4}$

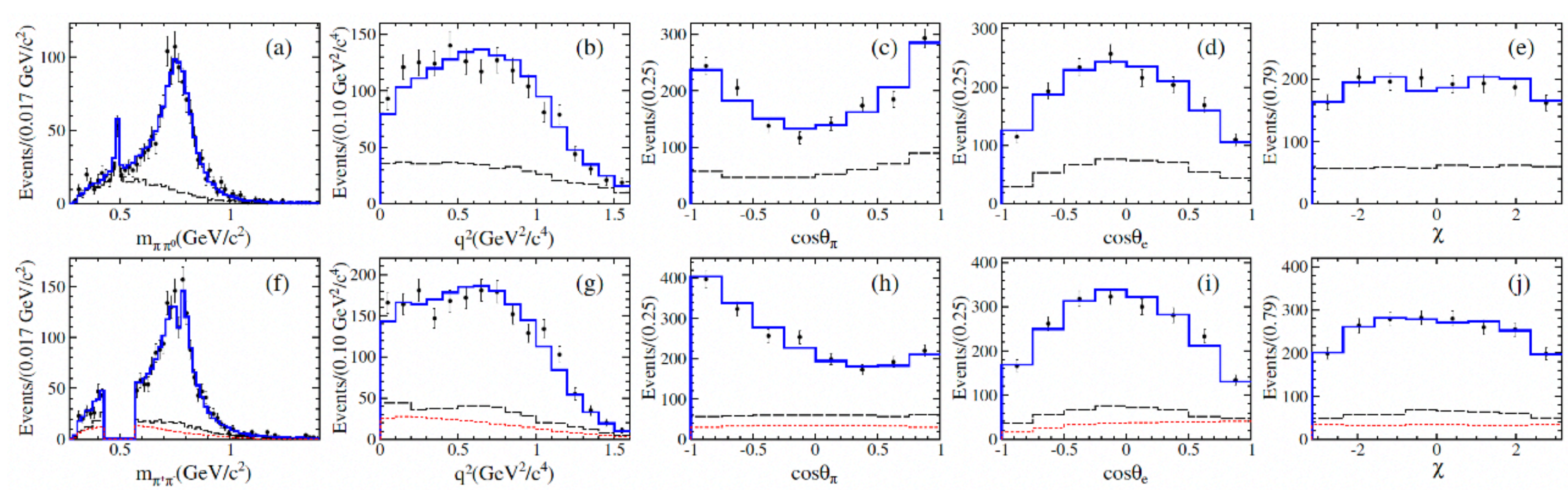
No significant $f_0(500)e^+\nu$ and $K_S^0 K_S^0 e^+\nu$

*Phys. Rev. D(L) 105, L031101 (2022)*




$D^0 \to \pi^-\pi^0 e^+\nu$

$D^+ \to \pi^+\pi^- e^+\nu$



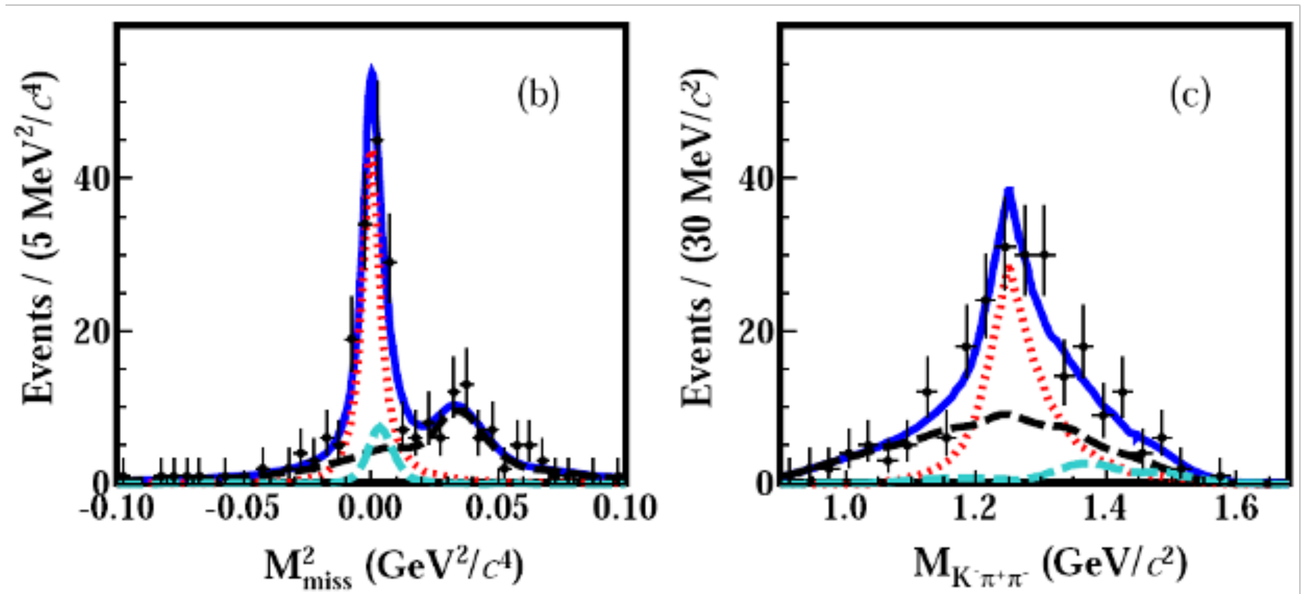

Observation of $D^+ \to f_0(500)e^+\nu_e$

$$r_V = \frac{V(0)}{A_1(0)} = 1.695 \pm 0.083 \pm 0.051$$

$$r_2 = \frac{A_2(0)}{A_1(0)} = 0.845 \pm 0.056 \pm 0.039$$

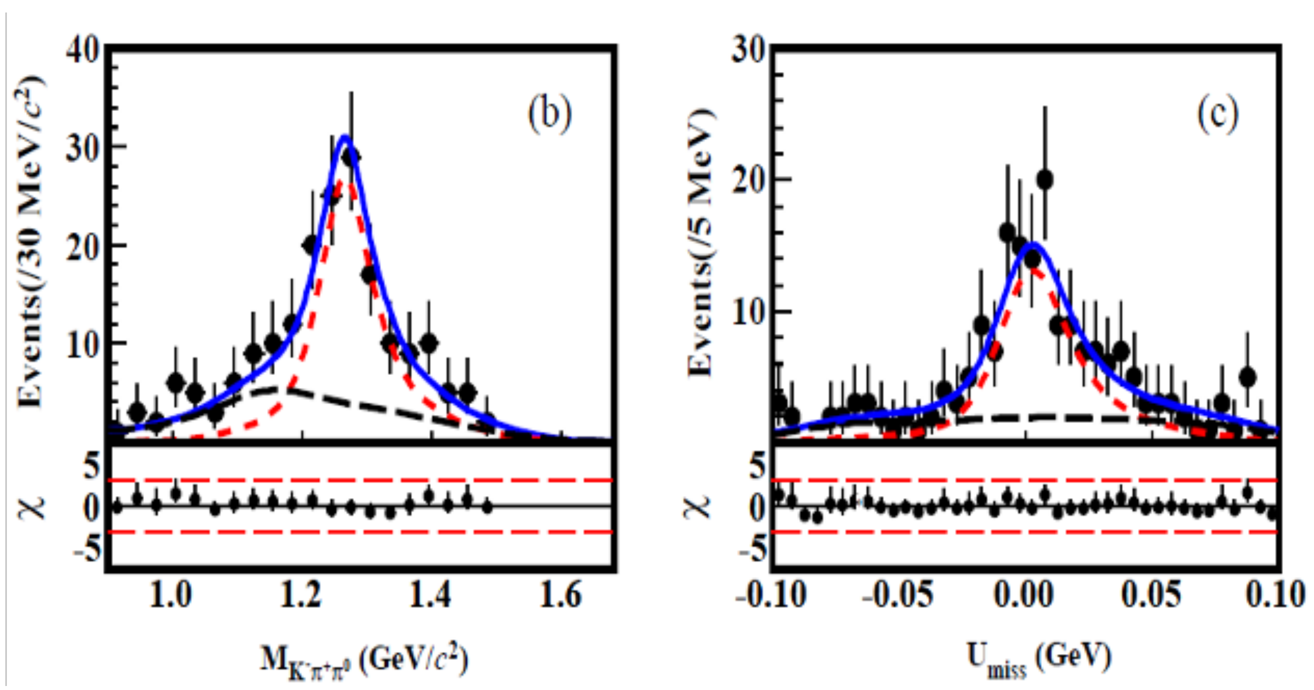
*Phys. Rev. Lett. 122, 062001 (2019)*

# Axial Vector particle in $D$ semileptonic decay




$$D^0 \to K_1(1270)^- e^+ \nu$$

$$\mathscr{B} = (1.9 \pm 0.13 \pm 0.13 \pm 0.12) \times 10^{-4}$$




$$D^+ \to K_1(1270)^0 e^+ \nu$$

$$\mathscr{B} = (2.30 \pm 0.26 \pm 0.18 \pm 0.25) \times 10^{-4}$$

$$\frac{\Gamma_{D^0 \to K_1(1270)^- e^+ \nu}}{\Gamma_{D^+ \to \bar{K}_1^0(1270) e^+ \nu}} = 1.20 \pm 0.20 \pm 0.15$$

*Phys. Rev. Lett. 127, 131801 (2021)*

*Phys. Rev. Lett. 123, 231801 (2019)*

# $\tau - \mu$ Lepton universality test in pure leptonic decays

$$R_D = \frac{B[D^+ \to \tau^+ v]}{B[D^+ \to \mu^+ v]} = 3.21 \pm 0.64 \pm 0.43$$

SM prediction: 2.67

$$R_{Ds} = \frac{B[D_S^+ \to \tau^+ v]}{B[D_S^+ \to \mu^+ v]} = 9.94 \pm 0.52$$

SM prediction: 9.75

# $e - \mu$ Lepton universality test in semileptonic decays

## $D \to \pi l \nu$

$$R_{D\pi} = \frac{\Gamma[D^0 \to \pi^- \mu^+ \nu]}{\Gamma[D^0 \to \pi^- e^+ \nu]} = 0.922 \pm 0.030 \pm 0.022$$

$$R_{D\pi} = \frac{\Gamma[D^+ \to \pi^0 \mu^+ \nu]}{\Gamma[D^+ \to \pi^0 e^+ \nu]} = 0.964 \pm 0.037 \pm 0.026$$

$1.7\sigma$

SM prediction: 0.985

## $D \to K l \nu$

$$R_{DK} = \frac{\Gamma[D^+ \to \overline{K}^0 \mu^+ \nu]}{\Gamma[D^+ \to \overline{K}^0 e^+ \nu]} = 1.00 \pm 0.03$$

$$R_{DK} = \frac{\Gamma[D^0 \to K^- \mu^+ \nu]}{\Gamma[D^0 \to K^- e^+ \nu]} = 0.978 \pm 0.007 \pm 0.012$$

SM prediction: 0.97

## $D \to \omega l \nu$

$$R_{D\omega} = \frac{\Gamma[D^+ \to \omega \mu^+ \nu]}{\Gamma[D^+ \to \omega e^+ \nu]} = 1.05 \pm 0.14$$

SM prediction: 0.93-0.96

*Phys. Rev. D 101, 072005 (2020)*

## $D \to \eta l \nu$

$$R_{D\eta} = \frac{\Gamma[D^+ \to \eta \mu^+ \nu]}{\Gamma[D^+ \to \eta e^+ \nu]} = 0.91 \pm 0.13$$

SM prediction: 0.93-0.96

*Phys. Rev. Lett. 124, 231801 (2020)*

## $D \to \rho l \nu$

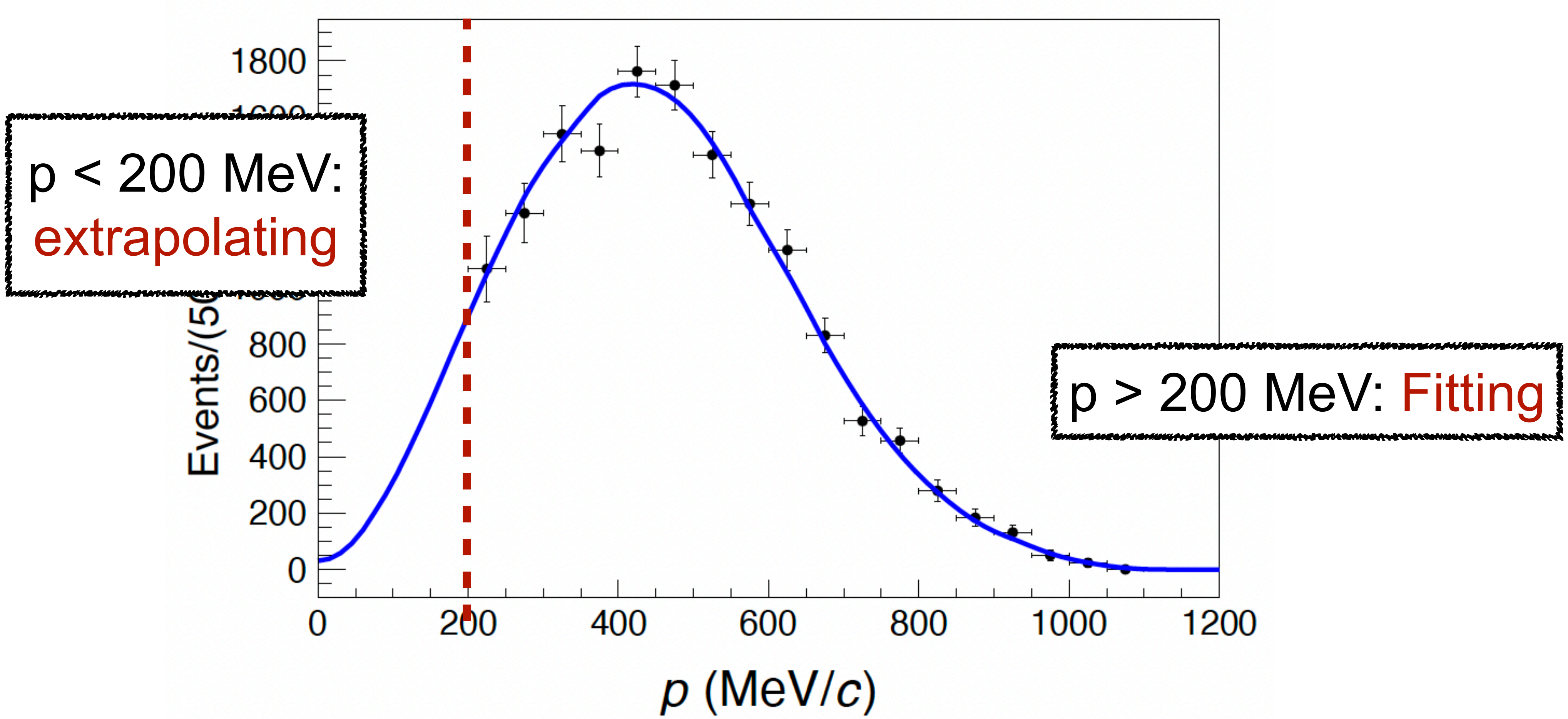
$$R_{D\eta} = \frac{\Gamma[D^0 \to \rho^- \mu^+ \nu]}{\Gamma[D^0 \to \rho^- e^+ \nu]} = 0.90 \pm 0.11$$

SM prediction: 0.93-0.96

*Phys. Rev. D(L) 104, L091103 (2021)*

# Inclusive $D_s$ semileptonic decay

Extract $D_s^+ \to Xe^+\nu$ signal yields from $e^+$ momentum spectrum



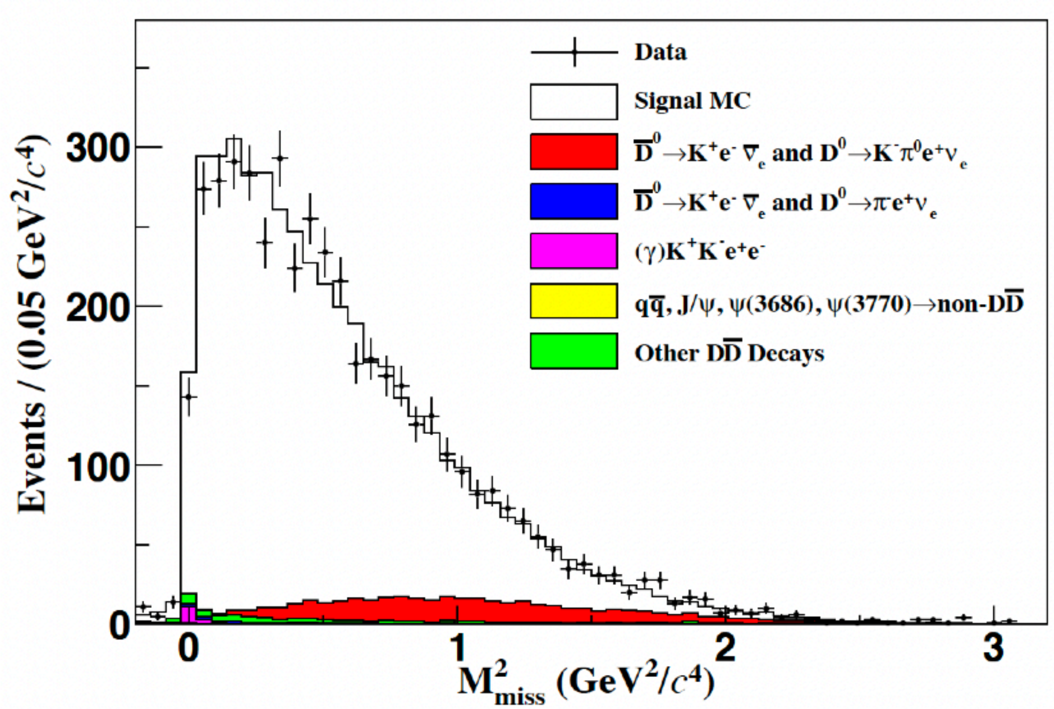

$\mathscr{B}(D_s^+ \to Xe^+\nu) = (6.30 \pm 0.13 \pm 0.10)\,\%$

No evidence for unobserved exclusive semielectronic modes

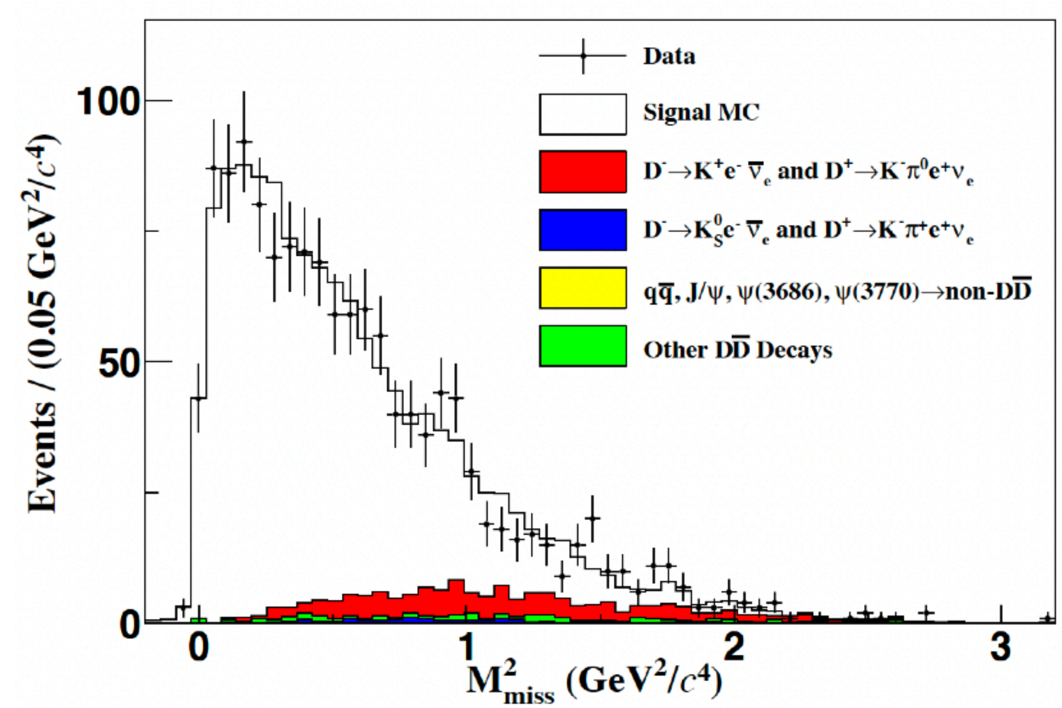
*Phys. Rev. D 104, 012003 (2021)*

# New method for $D \to Ke\nu$

$D^0 \to K^-e^+\nu$ vs. $\bar{D}^0 \to K^+e^-\nu$




$D^+ \to \bar{K}^0e^+\nu$ vs. $D^- \to K^0e^-\nu$




Independent sample of previous measurement with hadronic tags

$$\mathscr{B}(D^0 \to K^-e^+\nu) = (3.567 \pm 0.031 \pm 0.025)\,\%$$

$$\mathscr{B}(D^+ \to \bar{K}^0e^+\nu) = (8.68 \pm 0.14 \pm 0.16)\,\%$$

larger statistical but smaller systematic uncertainties

*Phys. Rev. D 104, 052008 (2021)*

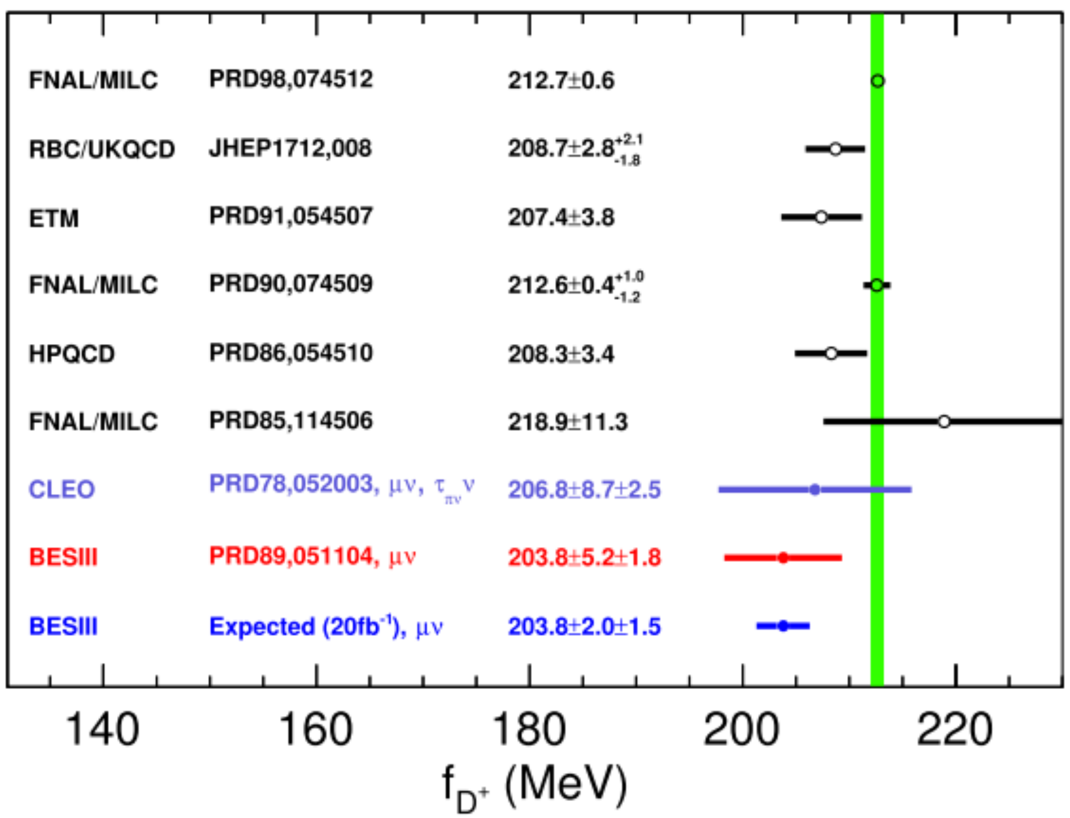
# Prospect

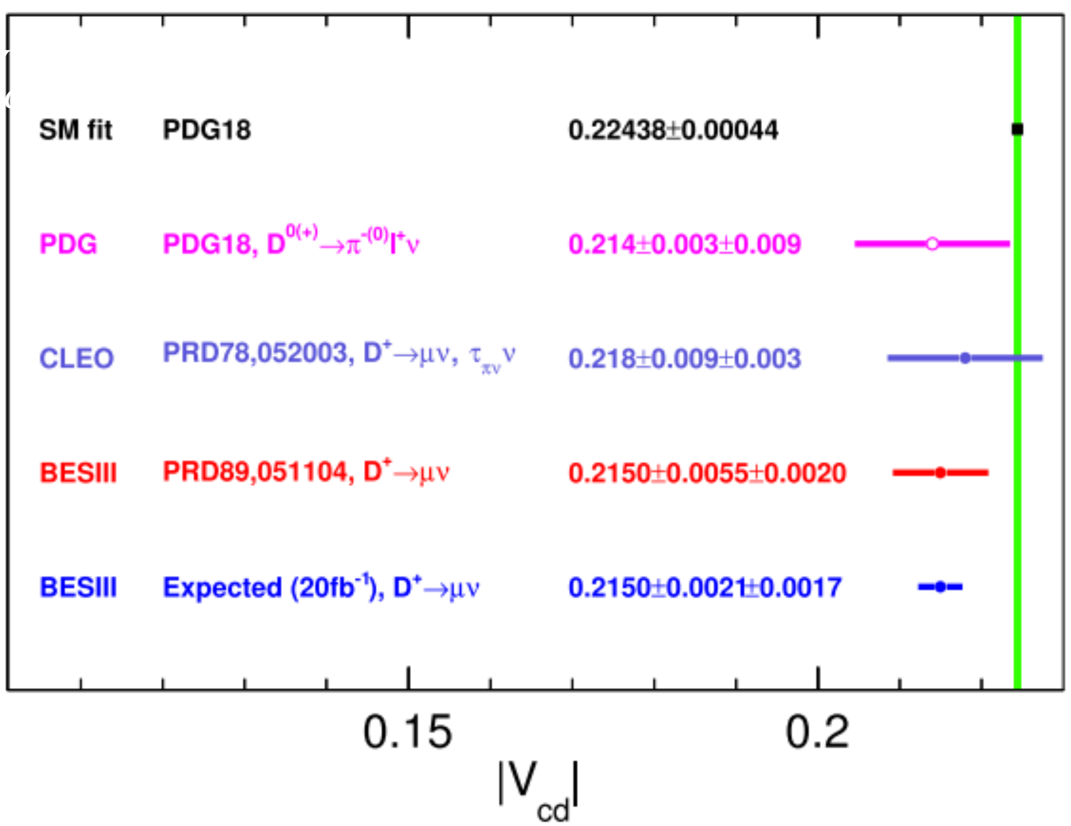
From White Paper (Chin. Phys. C 44, 040001 (2020))

20 $fb^{-1}$ of data set at 3.773 GeV is on the way

**Leptonic Decay**

| | 2.93 $fb^{-1}$ | 20 $fb^{-1}$ |
|---|---|---|
| $f_{D^+}$ | 2.6% | 1.0% |
| $\lvert V_{cd} \rvert$ | 2.5% | 1.0% |
| LFU | 19% | 8% |




BESIII is expected to provide unique data to improve the knowledge of $f_{D^+}$ and $\lvert V_{cd} \rvert$ and test LFU in $D^+ \to l^+ \nu_l$ decays.

# Prospect

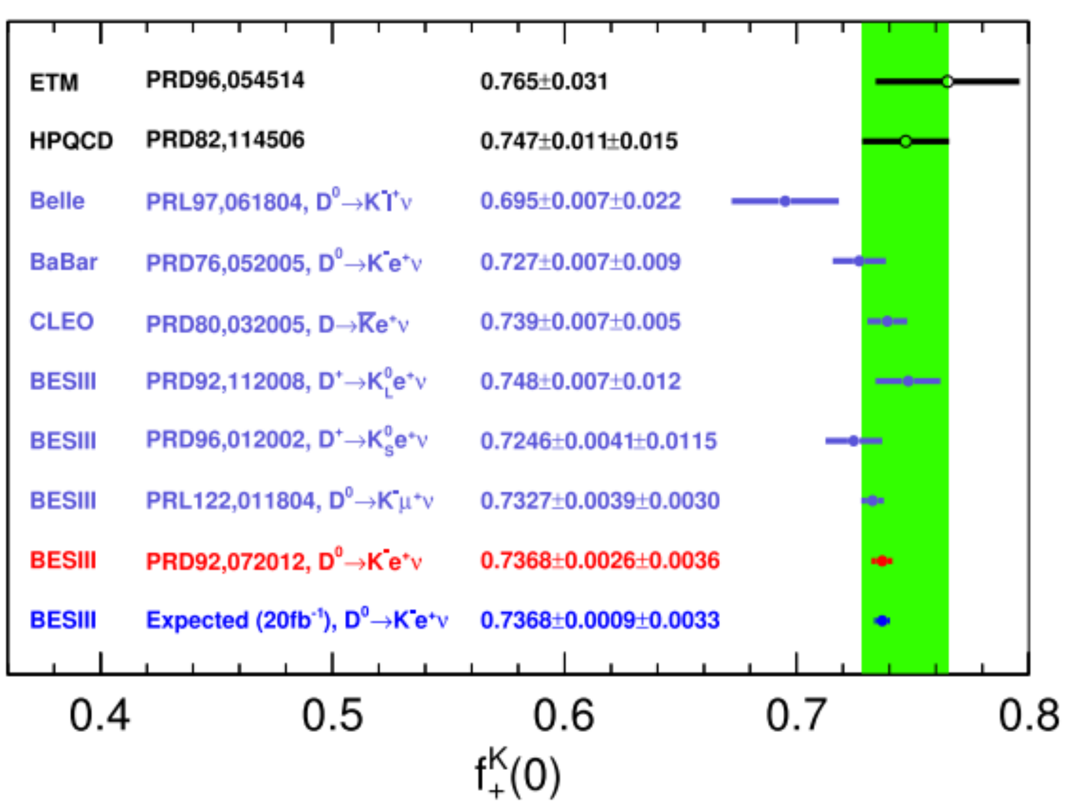
From White Paper (Chin. Phys. C 44, 040001 (2020))

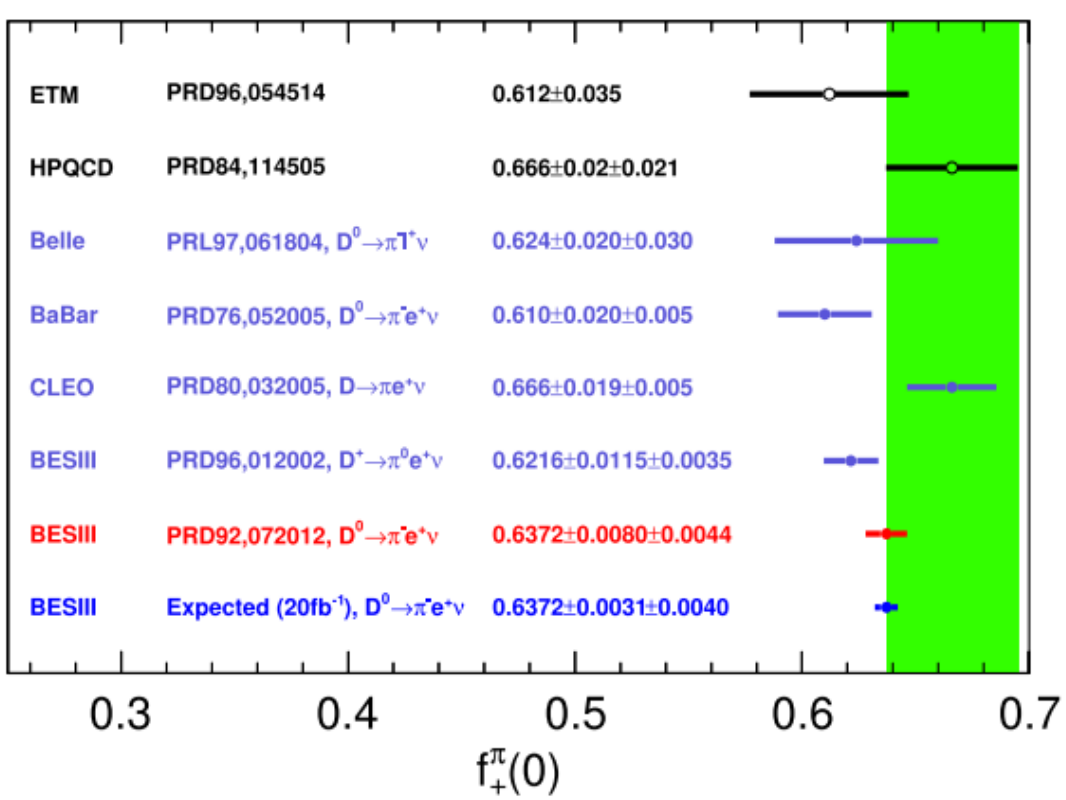
20 $fb^{-1}$ of data set at 3.773 GeV is on the way

**Semi-leptonic Decay**

- ➢ All form-factor measurements which are currently statistically limited will be improved by a factor of up to 2.6.
- ➢ Determine FF for the first time: $D^0 \to K(1270)^- \nu_e$, $D^+ \to \overline{K}_1(1270)^0 e^+ \nu_e$, $D^+ \to \eta' \mu^+ \nu_\mu$, $D^0 \to a_0(980)^- e^+ \nu_e$, $D^+ \to a_0(980)^0 e^+ \nu_e$
- ➢ $|V_{cd(s)}|$ with SL $D^{0(+)}$ decays in electron channels are expected to reach to 0.5%.

| | LQCD | Expected |
|---|---|---|
| $f_+^K(0)$ | 2.4% | 1.0% |
| $f_+^\pi(0)$ | 4.4% | 0.5% |



Thanks for your attention