(Semi-)leptonic D decays at BESIII

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粒子物理天问论坛
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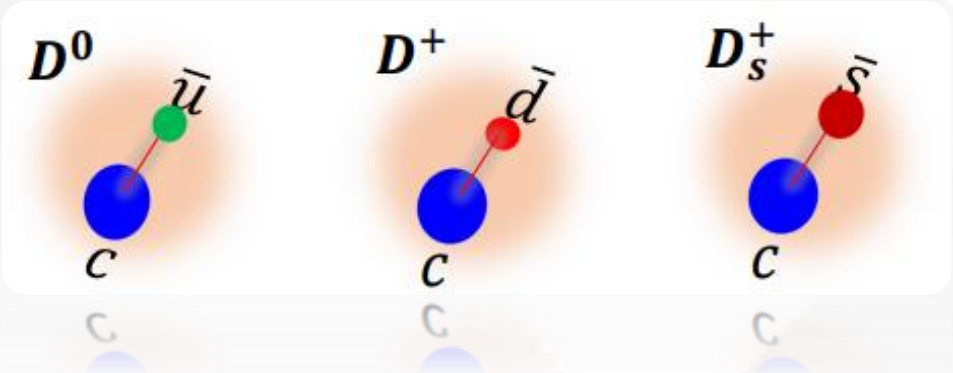
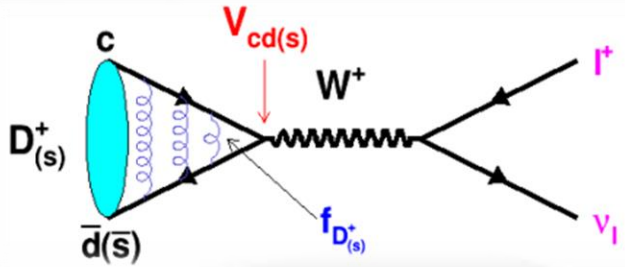
Outline

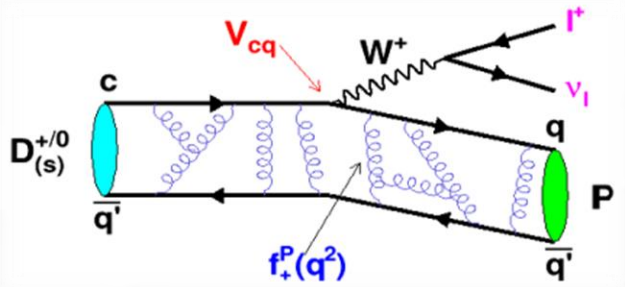
- Motivation
- BESIII experiment
- Pure leptonic decays of *D*
- Semi-leptonic decays of *D*
- Summary and prospect



Motivation

- Measure decay constant and semi-leptonic decay form factor → Test and Calibrate Lattice QCD
- Measure CKM matrix element($|V_{cs}|$、$|V_{cd}|$) → Test the unitarity of CKM matrix
- $\frac{\mathcal{B}(D_{(s)} \to \tau^+ \nu_\tau)}{\mathcal{B}(D_{(s)} \to \mu^+ \nu_\mu)}$ and $\frac{\mathcal{B}(D_{(s)} \to X\, \mu^+ \nu_\mu)}{\mathcal{B}(D_{(s)} \to X\, e^+ \nu_e)}$ → Check the lepton flavor universality



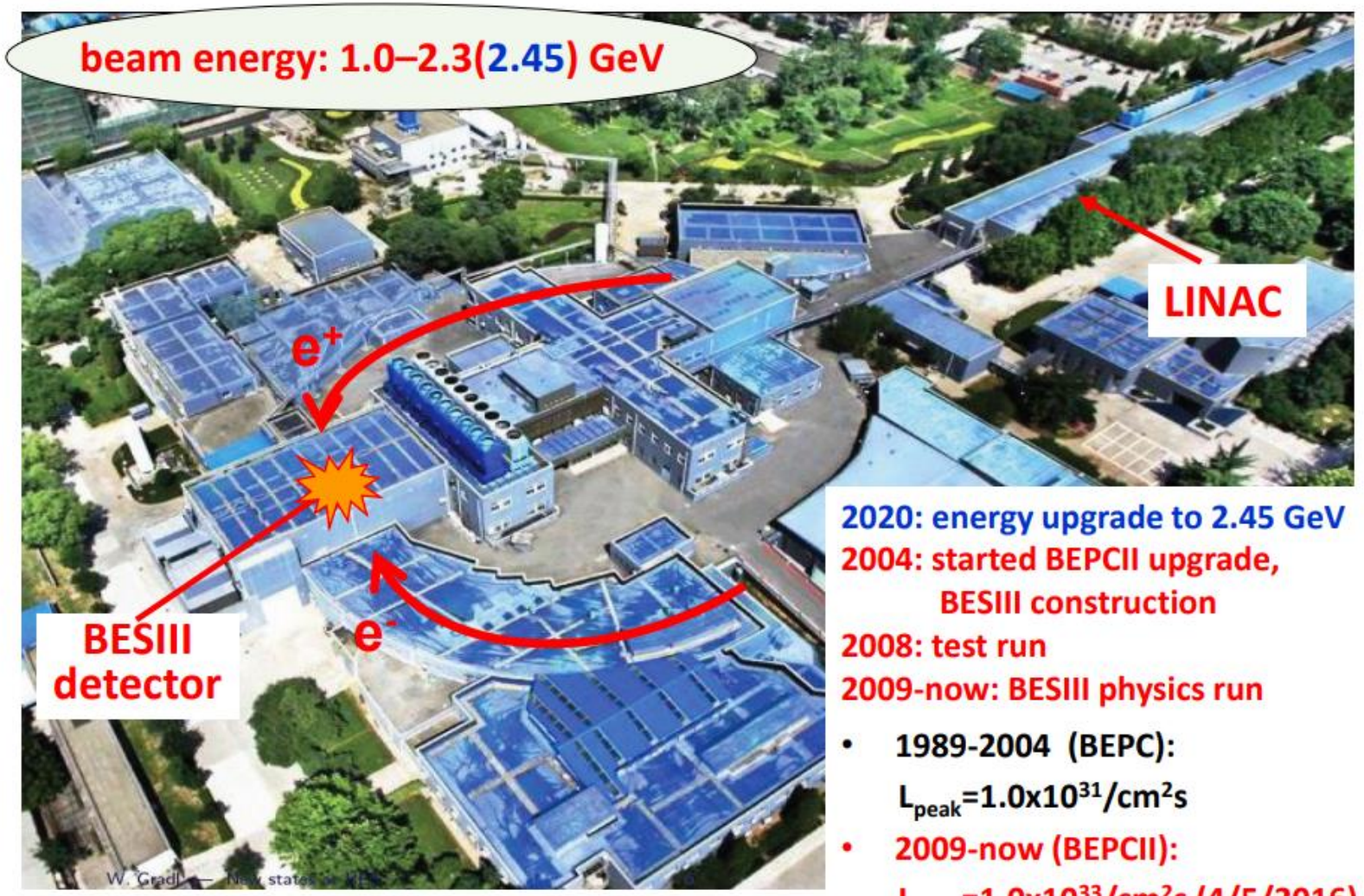


$$\Gamma\left(D_{(s)}^{+} \to \ell^{+}\nu_{\ell}\right) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}^+} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2$$

$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2 |V_{cd(s)}|^2}{24\pi^3} p^3 |f_+(q^2)|^2$$

$$(X = 1\ for\ K^-, \pi^-, \bar{K}^0, \eta^{(\prime)}; X = \frac{1}{2}\ for\ \pi^0)$$

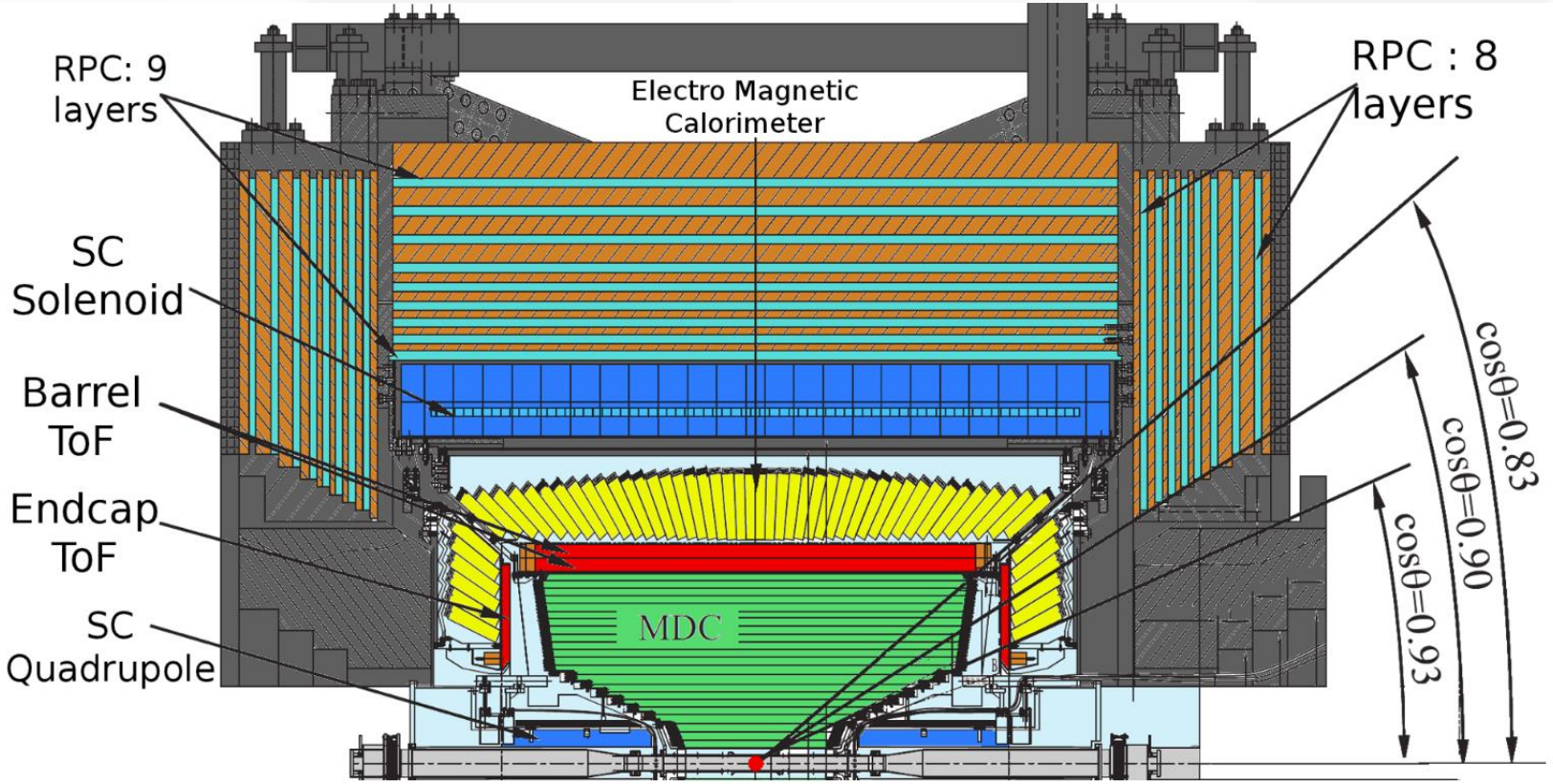
Beijing Electron Positron Collider (BEPCII)



2020: energy upgrade to 2.45 GeV
2004: started BEPCII upgrade,
BESIII construction
2008: test run
2009-now: BESIII physics run

- 1989-2004 (BEPC):
  $L_{peak}=1.0\times10^{31}/cm^2s$
- 2009-now (BEPCII):
  $L_{peak}=1.0\times10^{33}/cm^2s$ (4/5/2016)

BESIII detector



MDC
$\frac{\delta p}{p} < 0.5\%$ @1 GeV
$\frac{\delta(dE/dx)}{dE/dx} < 6\%$

TOF
δt 80 ps Barrel
δt 110 ps Endcap

EMC
$\frac{\delta E}{E} < 2.5\%$ @1 GeV
$\delta z = 0.6/\sqrt{E}$

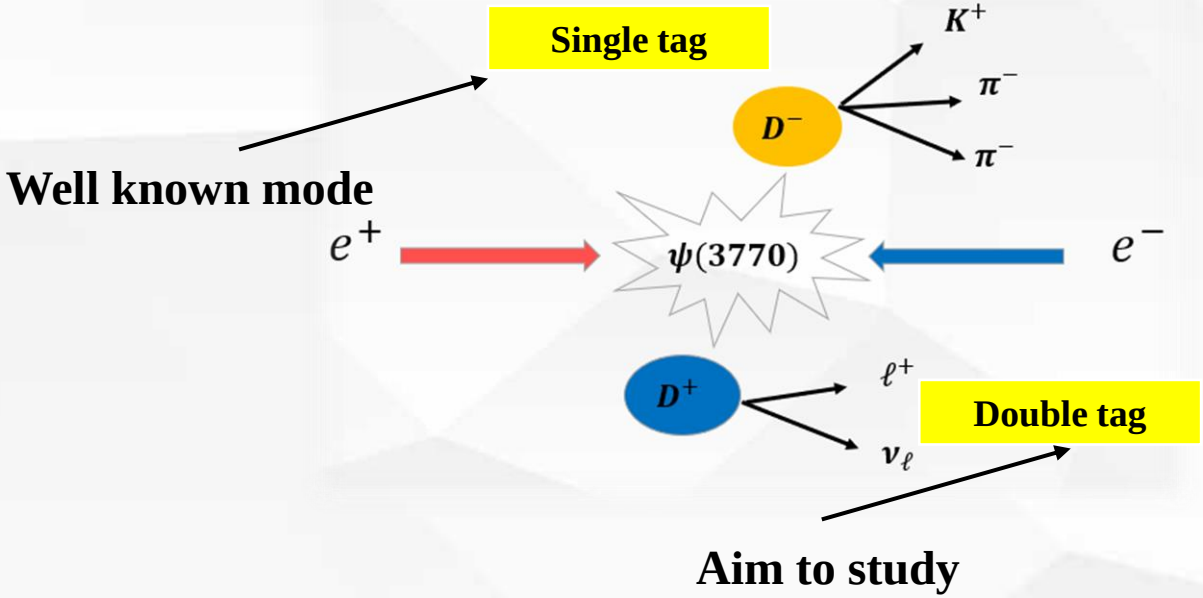
MUC
$\delta(xy)$ <2 cm

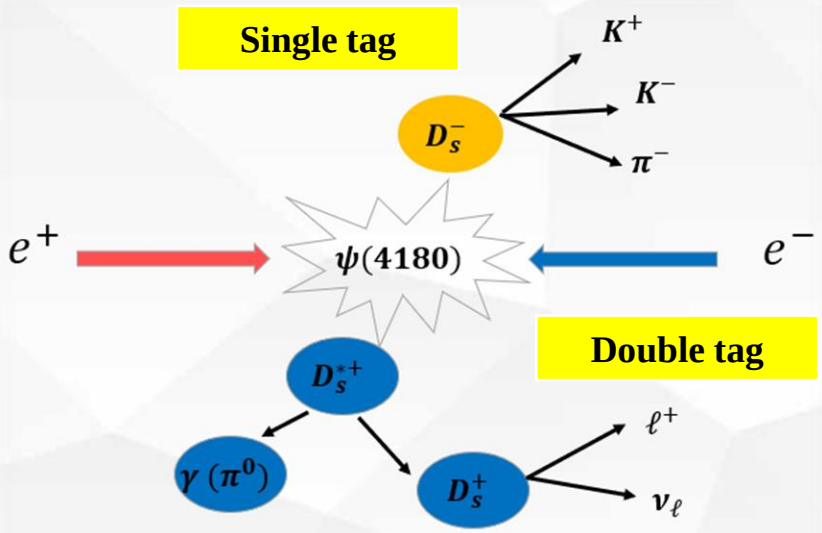
Data samples at BESIII

TECN	Luminosity (fb^{-1})	E_{cm} (GeV)	Year
BESIII	$D^{+(0)}$: 2.93 (8) D_s^+ : 7.33	3.773 4.128-4.223	2010-2011(+2022) 2013-2019
CLEO-c	$D^{+(0)}$: 0.82 D_s^+ : 0.6	3.770 4.170	— 2008

2023—2024 : 8 → 20 fb^{-1} $\psi(3770)$ (for $D^{+(0)}$) at BESIII.

Pure leptonic D decay





- Single tag(ST)

$$N_{tag}^{ST} = 2N_{D^+D^-}\mathcal{B}_{tag}\epsilon_{tag}$$

- Double tag(DT)

$$N_{tag,sig}^{DT} = 2N_{D^+D^-}\mathcal{B}_{tag}\mathcal{B}_{sig}\epsilon_{tag,sig}$$

$$\mathcal{B}_{sig} = \frac{N_{tag,sig}^{DT}}{N_{tag}^{ST}}\frac{\epsilon_{tag}}{\epsilon_{tag,sig}}$$

$$U_{miss} = E_{miss} - |\vec{p}_{miss}|$$

$$M_{miss}^2 = E_{miss}^2 - |\vec{p}_{miss}|^2$$

Studies of $D^+ \to \ell^+ \nu_\ell$

$2.9\ \mathrm{fb}^{-1}$ @3.773 GeV

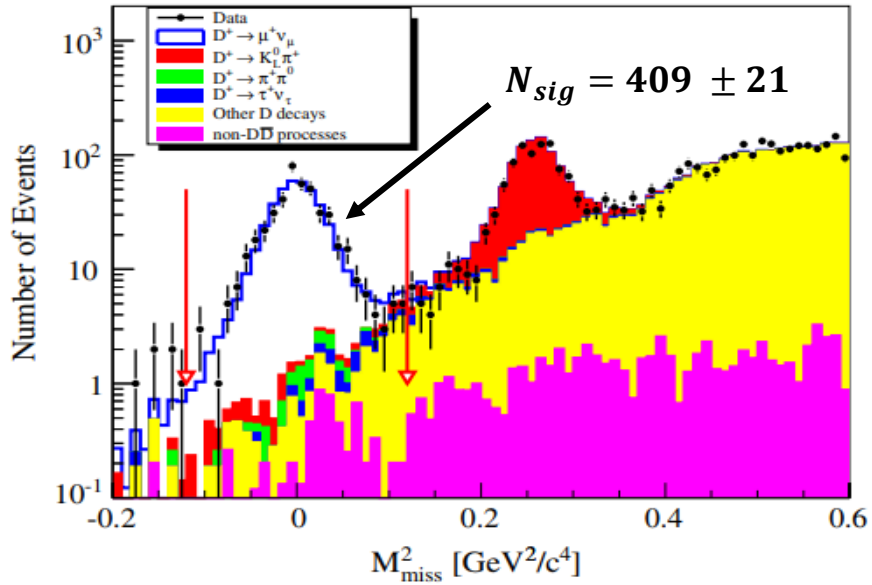
$D^+ \to \mu^+ \nu_\mu$

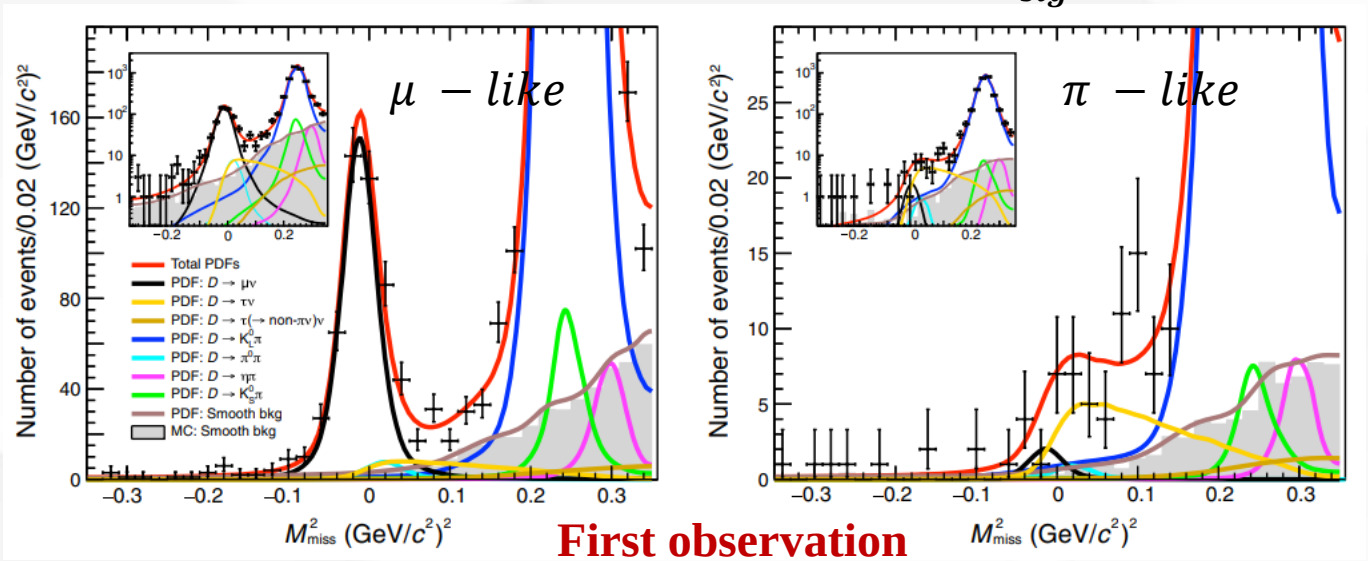
$\mu - like$: $E_{ECM} \leq 300$ MeV

$\pi - like$: $E_{ECM} > 300$ MeV

$D^+ \to \tau^+(\pi^+ \bar{\nu}_\tau)\, \nu_\tau$

$N_{sig} = 137 \pm 27$





First observation

The most accurate measurement

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

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

Phys. Rev. D 89, 051104 (2014)

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

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

$$R_D = \frac{\mathcal{B}(D^+ \to \tau^+ \nu_\tau)}{\mathcal{B}(D^+ \to \mu^+ \nu_\mu)_{PDG}} = 3.21 \pm 0.64 \pm 0.43$$

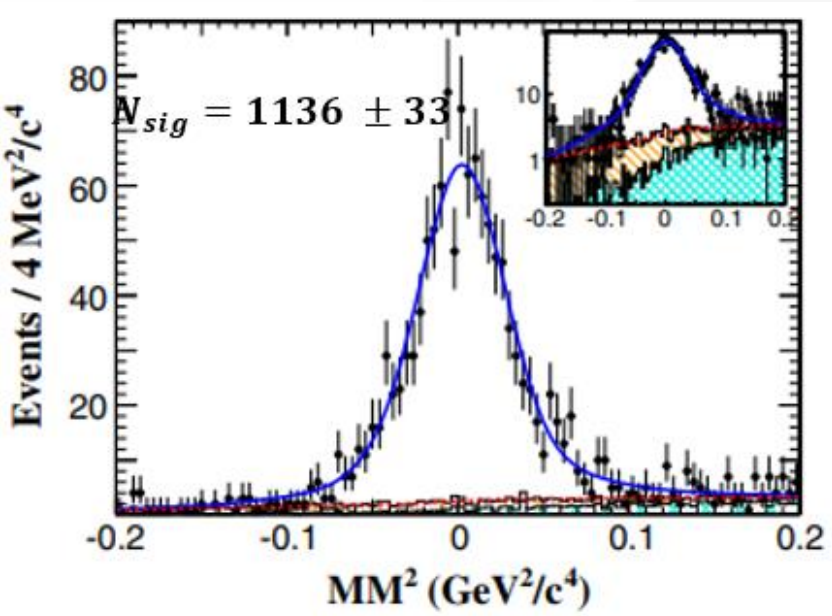
Phys. Rev. Lett. 123, 211802 (2019)

SM prediction: 2.67

Studies of $D_s^+ \to \ell^+ \nu_\ell$

湖南大学 HUNAN UNIVERSITY

$D_s^+ \to \mu^+ \nu_\mu$ 3.19 fb^{-1} @4.18 GeV

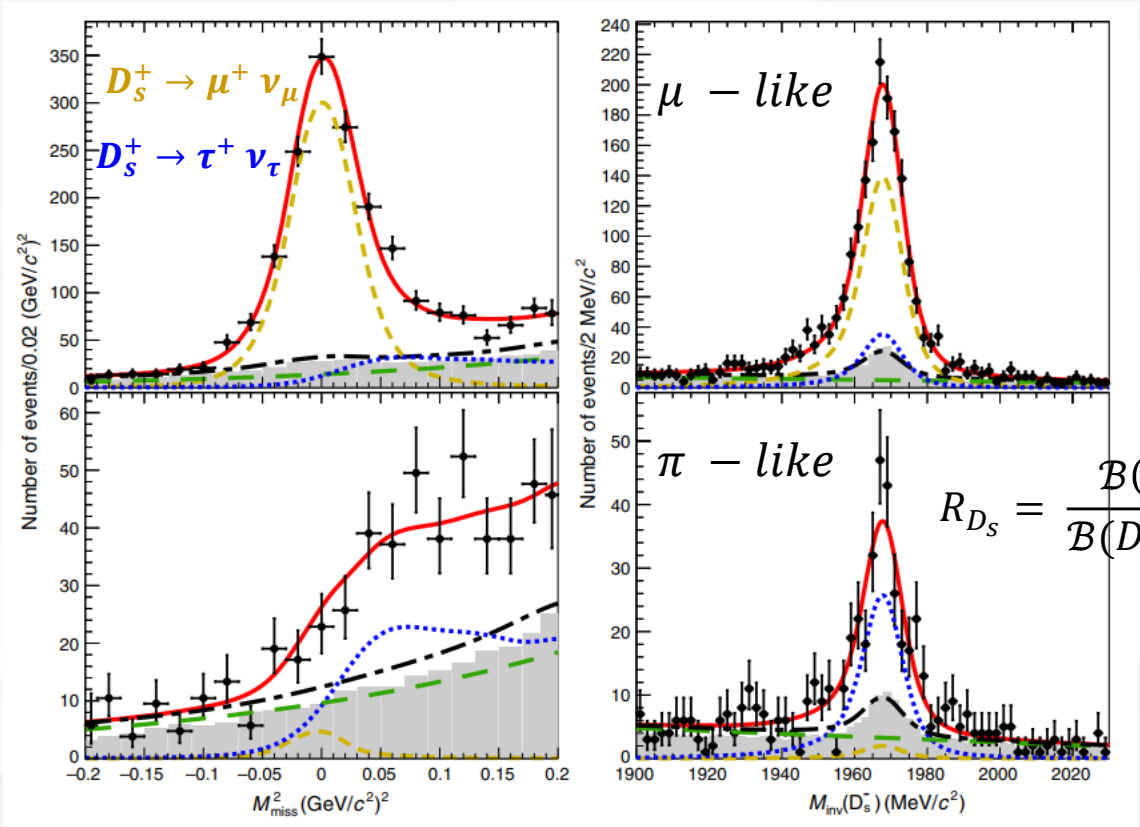


$\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$

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

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

$D_s^+ \to \mu^+ \nu_\mu$ and $\tau^+(\pi^+ \bar{\nu}_\tau)\nu_\tau$ 6.3 fb^{-1} @4.18 – 4.23 GeV



$N_{sig} = 2198 \pm 55$

$N_{sig} = 946 \pm 46$

$$R_{D_s} = \frac{\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu)_{PDG}} = 9.72 \pm 0.37$$

SM prediction: 9.75

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

$\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (5.21 \pm 0.25 \pm 0.17)\%$

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

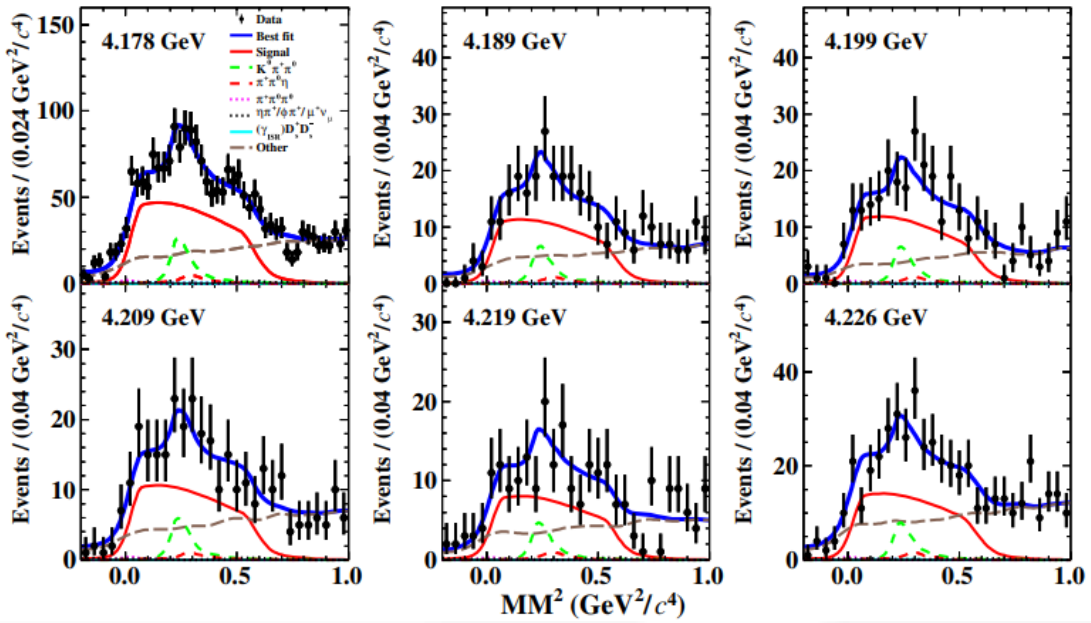
$f_{D_s^+}|V_{cs}| = 243.0 \pm 5.8 \pm 4.0$ MeV[τ]

Phys. Rev. D 104, 052009 (2021)

Studies of $D_s^+ \to \ell^+ \nu_\ell$

$6.3\ \mathrm{fb}^{-1}$ @4.18 – 4.23 GeV

$D_s^+ \to \tau^+(\rho^+\bar{\nu}_\tau)\nu_\tau$ $N_{sig} = 1745 \pm 84$



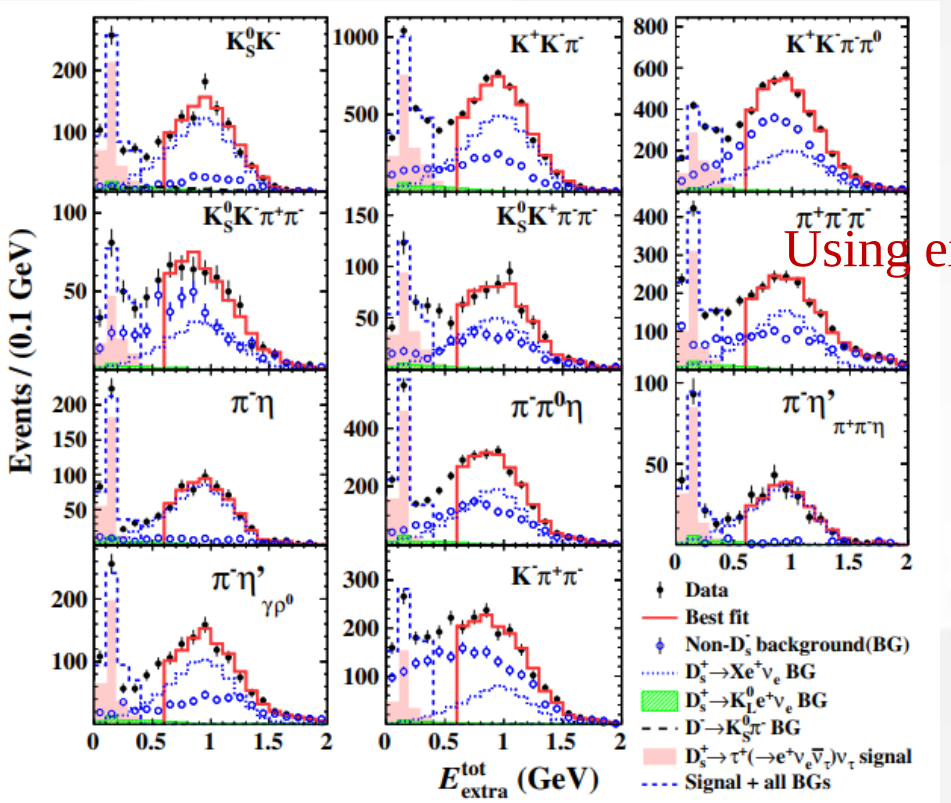
$\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (5.29 \pm 0.25 \pm 0.20)\%$

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

$R_{D_s} = \dfrac{\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu)_{BESIII}} = 9.89 \pm 0.71$

Phys. Rev. D 104, 032001 (2021)

$D_s^+ \to \tau^+(e^+\nu_e\bar{\nu}_\tau)\nu_\tau$ $N_{sig} = 4940 \pm 97$



Using extra photon energy

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

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

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

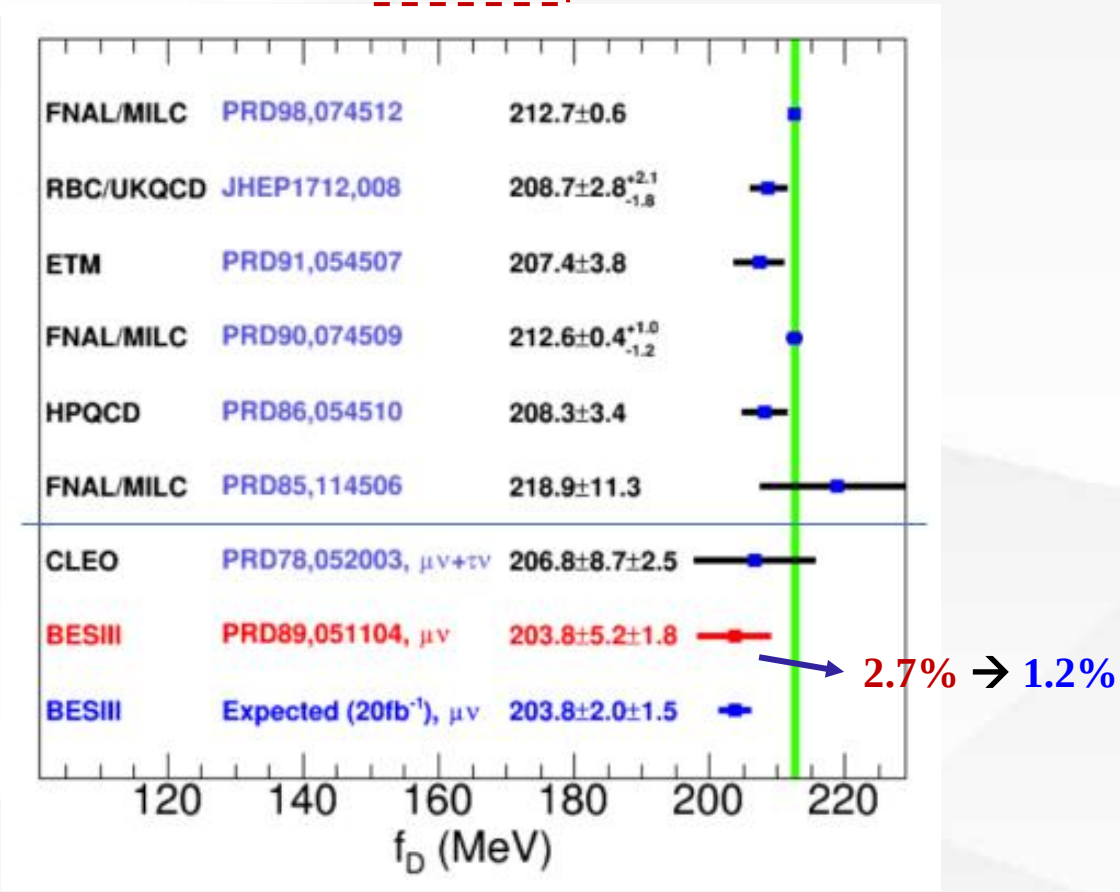
Combined results: **SM prediction: 9.75**

$\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (5.34 \pm 0.13)\%$

$R_{D_s} = \dfrac{\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu)_{PDG}} = 9.72 \pm 0.37$

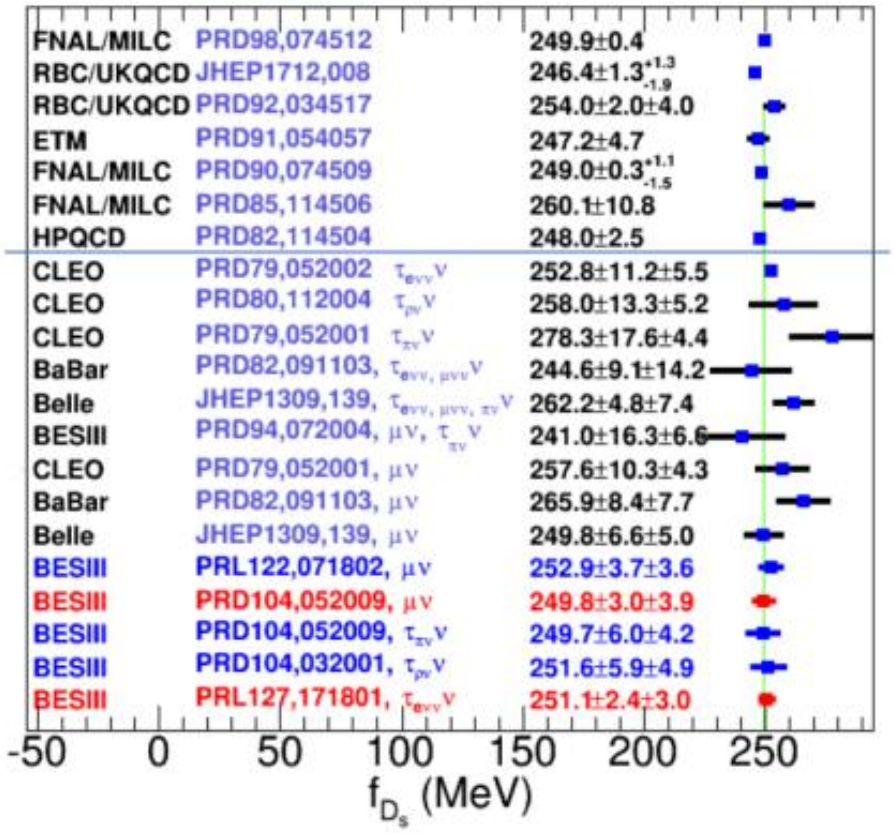
Comparisons of f_{D^+} and $f_{D_s^+}$

f_{D^+}

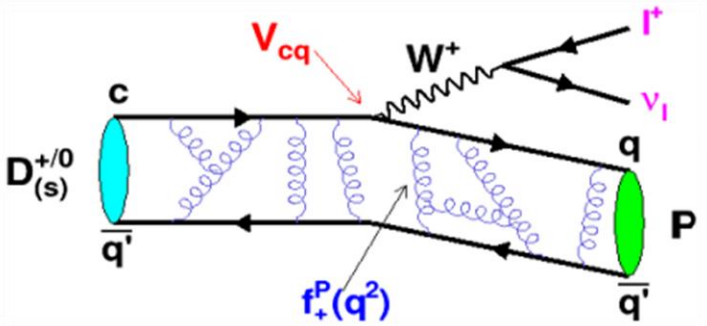


2.7% → 1.2%

$f_{D_s^+}$



Semi-leptonic $D \rightarrow P\, e^+\, \nu_e$



$$\frac{d\Gamma}{dq^2} = X\,\frac{G_F^2\,|V_{cd(s)}|^2}{24\pi^3}\,p^3|f_+(q^2)|^2$$

$$(X = 1\ for\ K^-, \pi^-, \bar{K}^0, \eta^{(\prime)}; X = \frac{1}{2}\ for\ \pi^0)$$

Dynamics study → $f_+^{D\rightarrow P}(0)\,|V_{cd(s)}|$

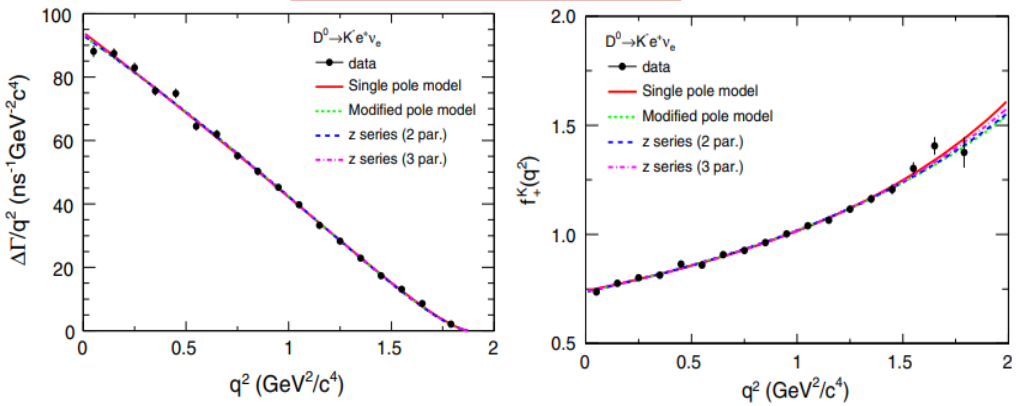
Parametric form of form factor:

- **Single pole form** $f_+(q^2) = \frac{f_+(0)}{1-q^2/M_{pole}^2}$
- **Modified pole model** $f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{M_{pole}^2})(1-\alpha\frac{q^2}{M_{pole}^2})}$
- **ISGW2 model** $f_+(q^2) = f_+(q_{max}^2)(1+\frac{r^2}{12}(q_{max}^2-q^2))^2$
- **Series expansion mode** $f_+(t) = \frac{1}{P(t)\Phi(t,t_0)}\,a_0(t_0)(1+\sum_{i=1}^{\infty} r_k(t_0)\,[z(t,t_0)]^k)$

Studies of $c \to s\,\ell^+\,\nu_\ell$ semi-leptonic decays

$2.9\ \mathrm{fb}^{-1}$ @3.773 GeV

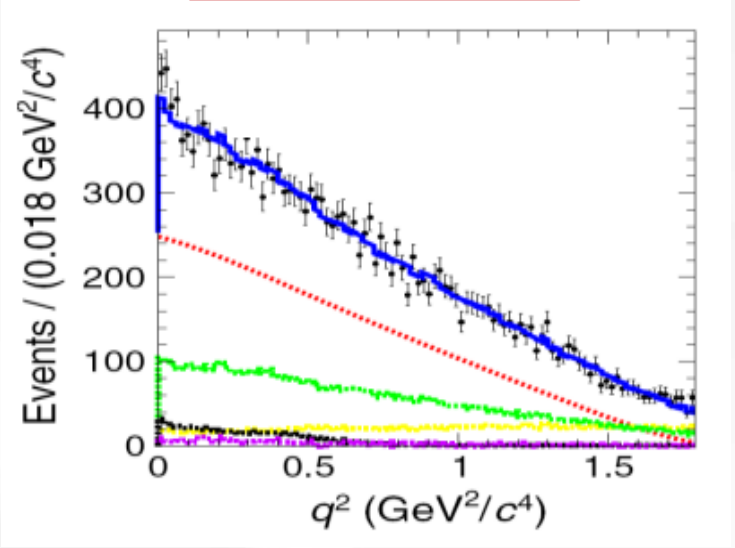
$D^0 \to K^- e^+ \nu_e$



$f_+^{D\to K}(0)|V_{cs}| = 0.717 \pm 0.003 \pm 0.004$

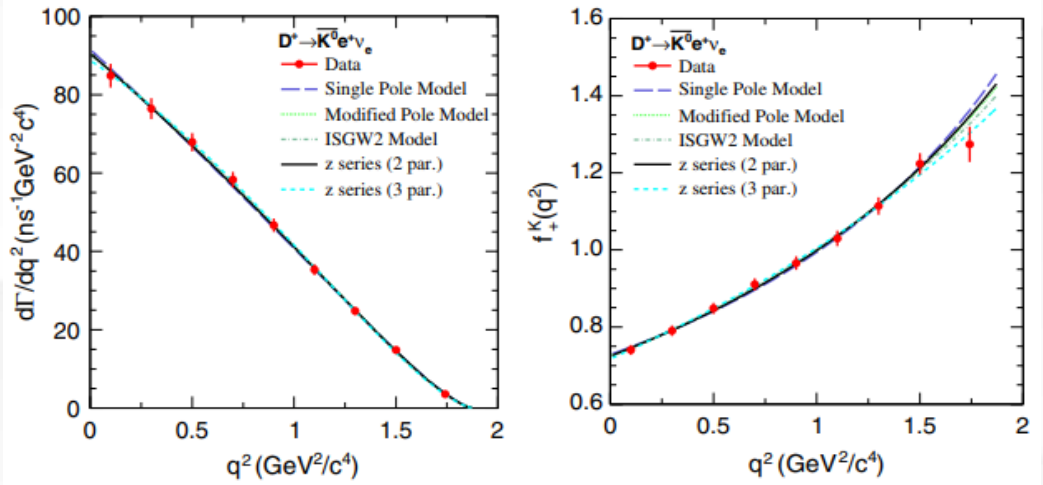
Phys. Rev. D 92, 072012 (2015)

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



$f_+^{D\to K}(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$

Phys. Rev. D 92, 112008 (2015)



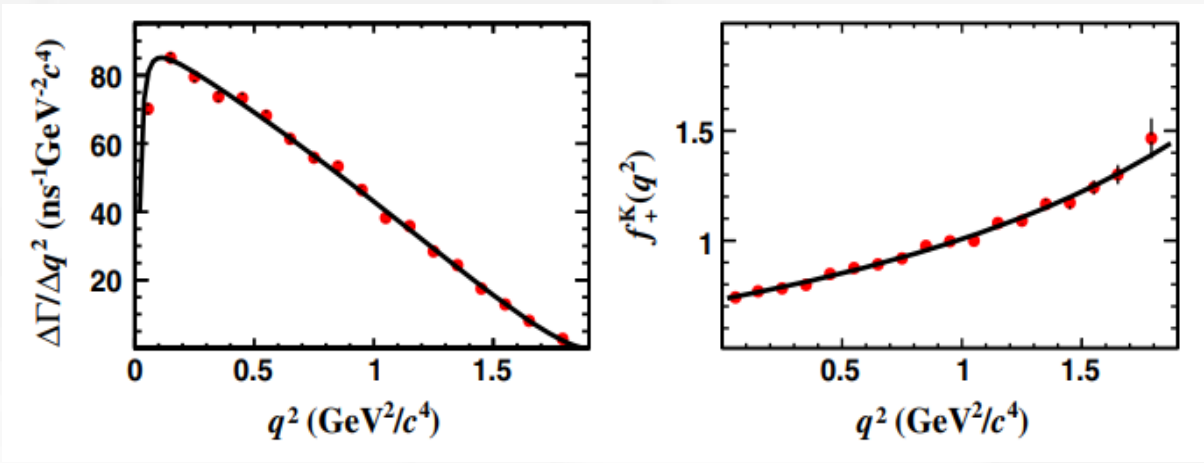
$D^+ \to \bar{K}^0 e^+ \nu_e$

$f_+^{D\to K}(0)|V_{cs}| = 0.705 \pm 0.004 \pm 0.011$

Phys. Rev. D 96, 012002 (2017)

Studies of $c \to s\,\ell^+\,\nu_\ell$ semi-leptonic decays

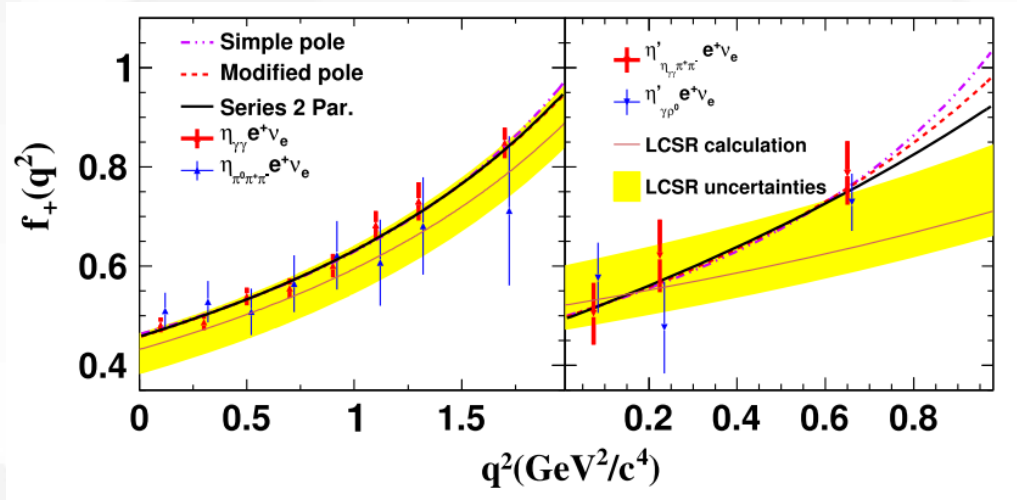
$D^0 \to K^-\mu^+\nu_\mu$ 2.9 fb^{-1} @3.773 GeV



$$f_+^{D\to K}(0)|V_{cs}| = 0.713 \pm 0.004 \pm 0.003$$
$$R_{\mu/e} = 0.974 \pm 0.007 \pm 0.012$$

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

$D_s^+ \to \eta^{(\prime)}e^+\nu_e$ 3.19 fb^{-1} @4.18 GeV



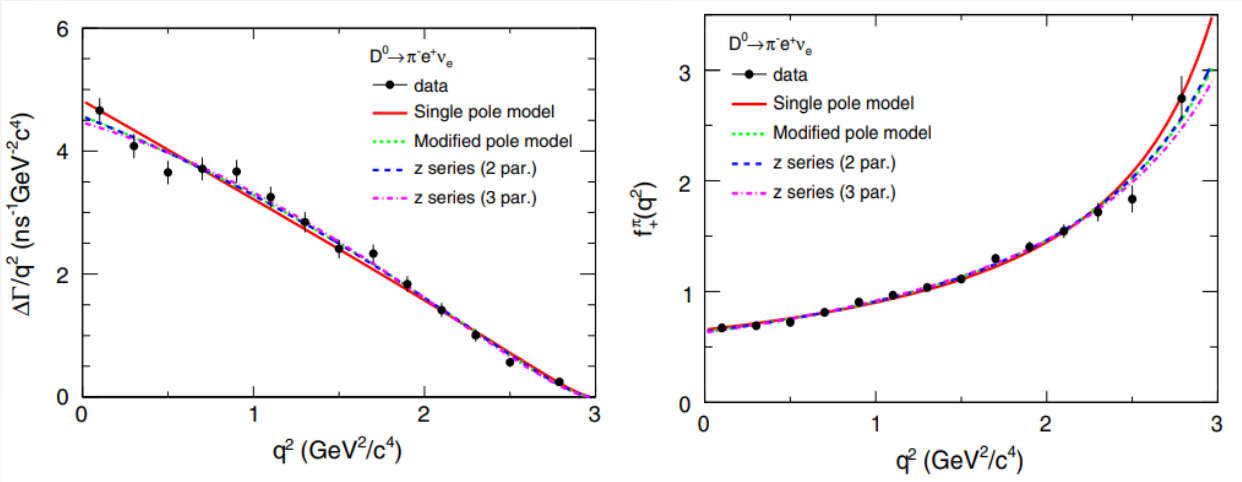
$$f_+^{D\to\eta}(0)|V_{cs}| = 0.446 \pm 0.005 \pm 0.004$$
$$f_+^{D\to\eta'}(0)|V_{cs}| = 0.477 \pm 0.049 \pm 0.011$$

Phys. Rev. Lett. 122, 121801 (2019)

Studies of $c \to d\,\ell^+\,\nu_\ell$ semi-leptonic decays

$2.9\ \mathrm{fb}^{-1}$ @3.773 GeV

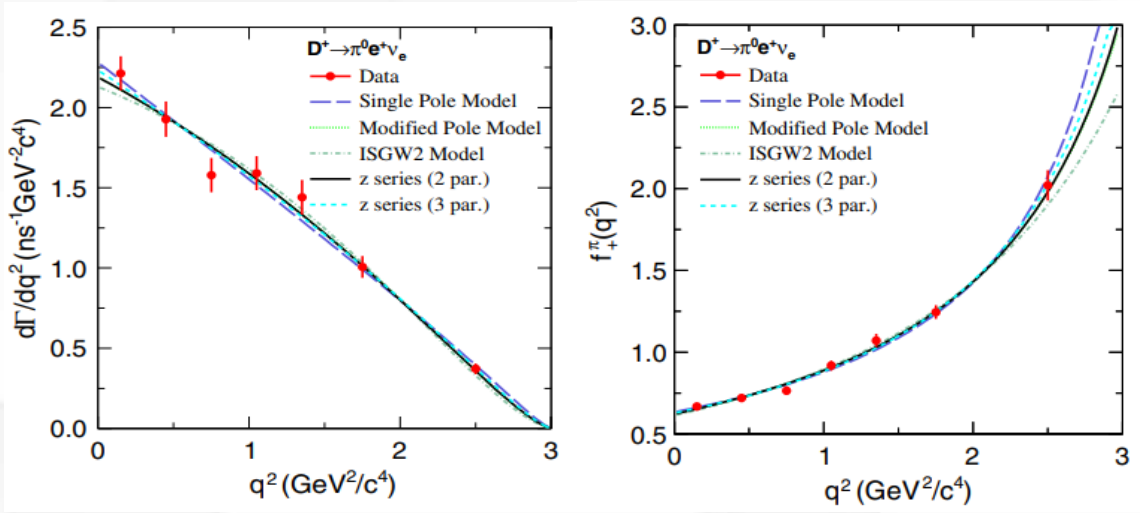
$D^0 \to \pi^- e^+ \nu_e$



$$f_+^{D\to\pi}(0)|V_{cd}| = 0.144 \pm 0.002 \pm 0.001$$

Phys. Rev. D 92, 072012 (2015)

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

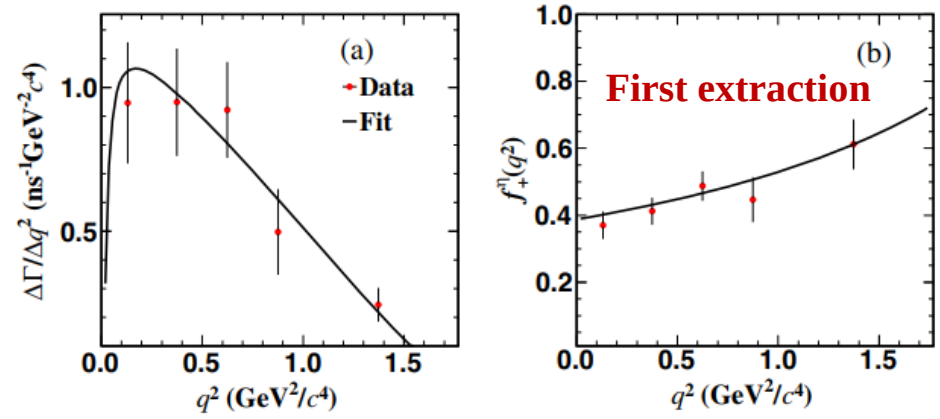


$$f_+^{D\to\pi}(0)|V_{cd}| = 0.140 \pm 0.003 \pm 0.001$$

Phys. Rev. D 96, 012002 (2017)

Studies of $c \to d\,\ell^+\,\nu_\ell$ semi-leptonic decays

$D^+ \to \eta\mu^+\nu_\mu$ 2.9 fb^{-1} @3.773 GeV

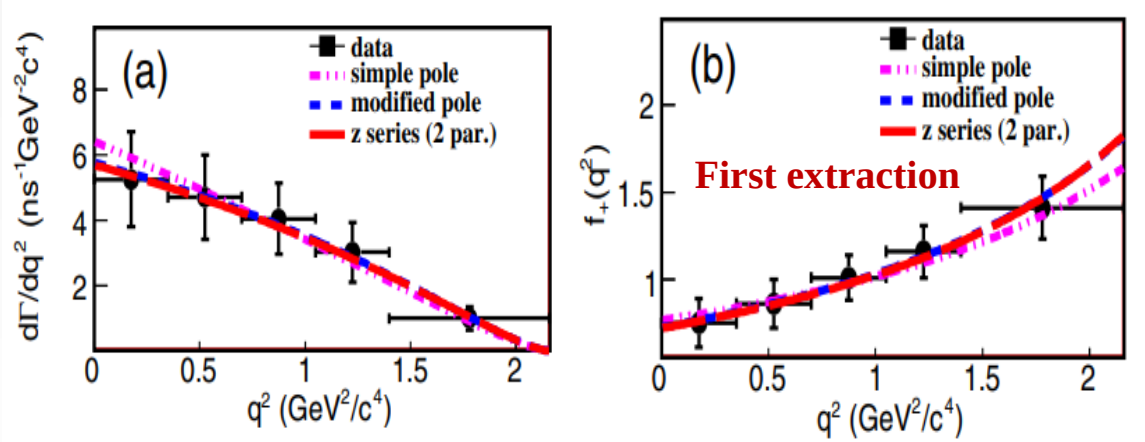


$f_+^{D\to\eta}(0)|V_{cd}| = 0.087 \pm 0.008 \pm 0.002$

$R_{\mu/e} = 0.91 \pm 0.13$

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

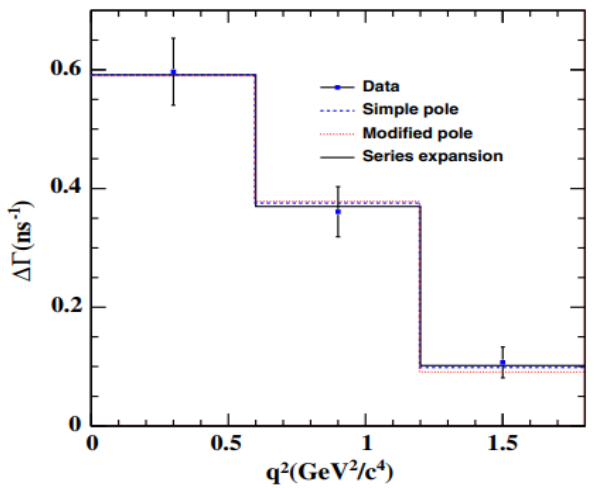
$D_s^+ \to K^0 e^+ \nu_e$ 3.19 fb^{-1} @4.18 GeV



$f_+^{D_s\to K}(0)|V_{cd}| = 0.162 \pm 0.019 \pm 0.003$

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

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



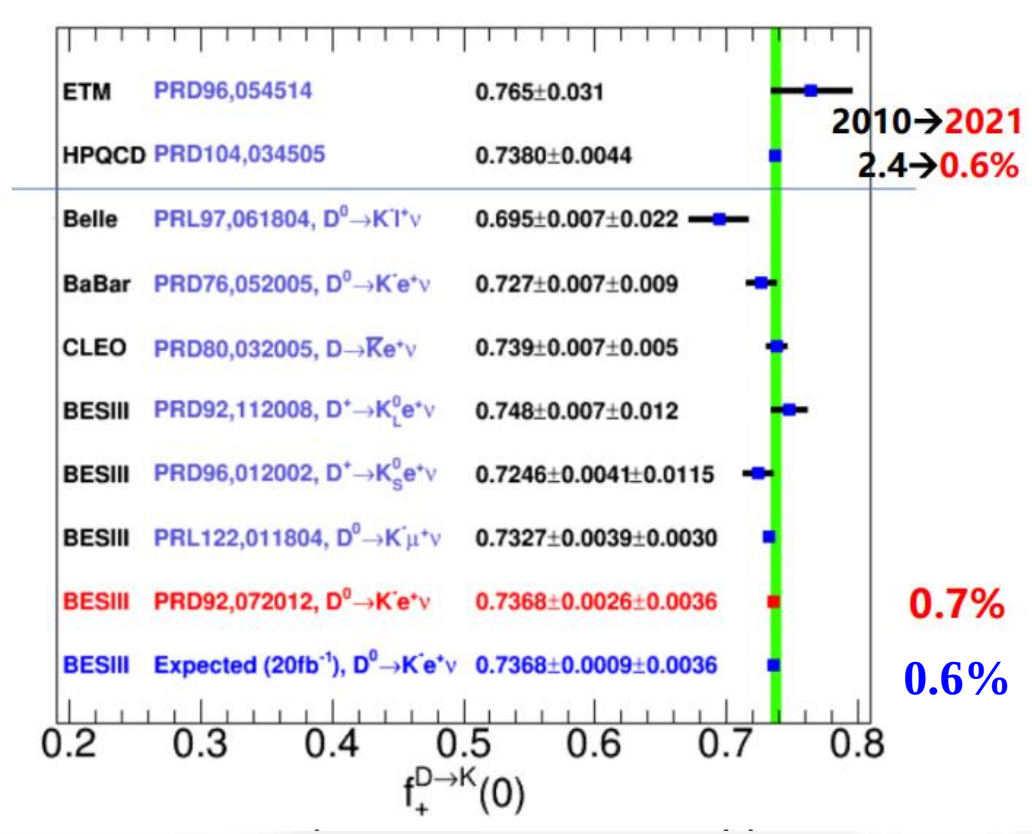
2.9 fb^{-1} @3.773 GeV

$f_+^{D\to\eta}(0)|V_{cd}| = 0.079 \pm 0.006 \pm 0.002$

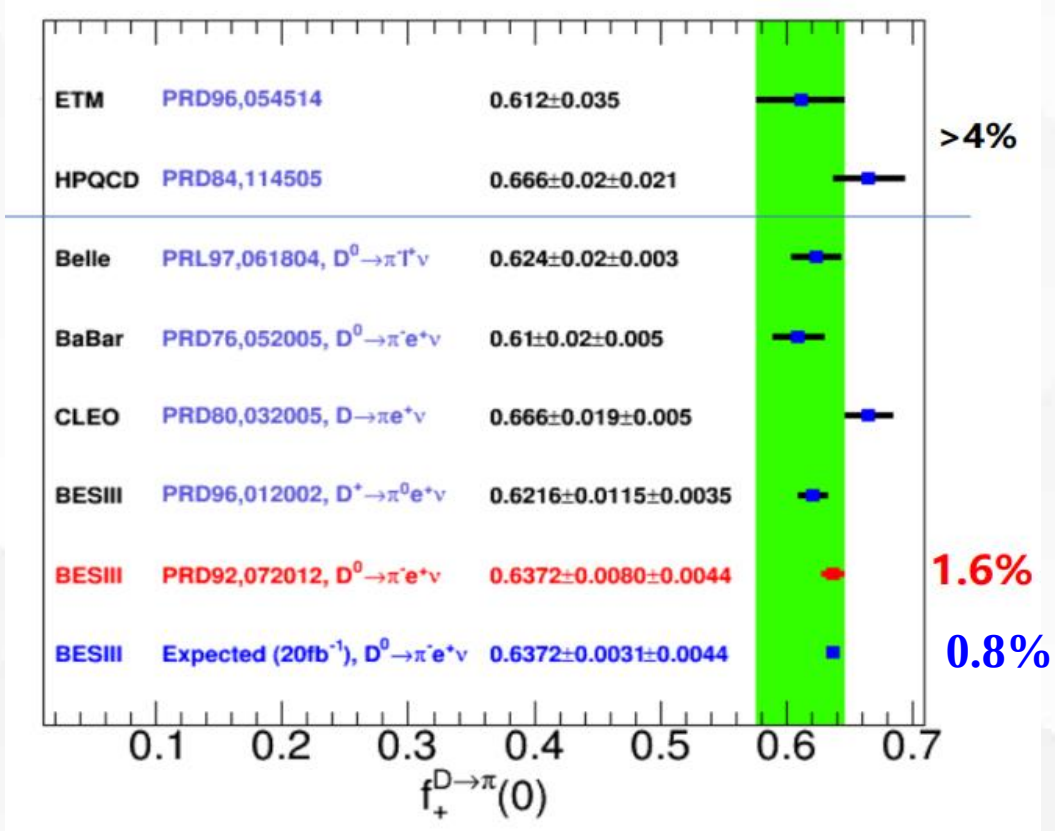
Phys. Rev. D 97, 092009 (2018)

Comparisons of $f_+^{D\to K}(0)$ and $f_+^{D\to\pi}(0)$

$D \to K$



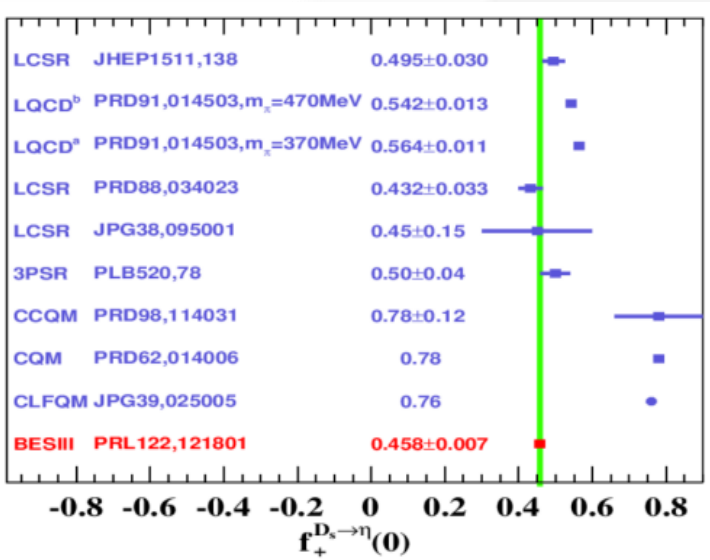
$D \to \pi$



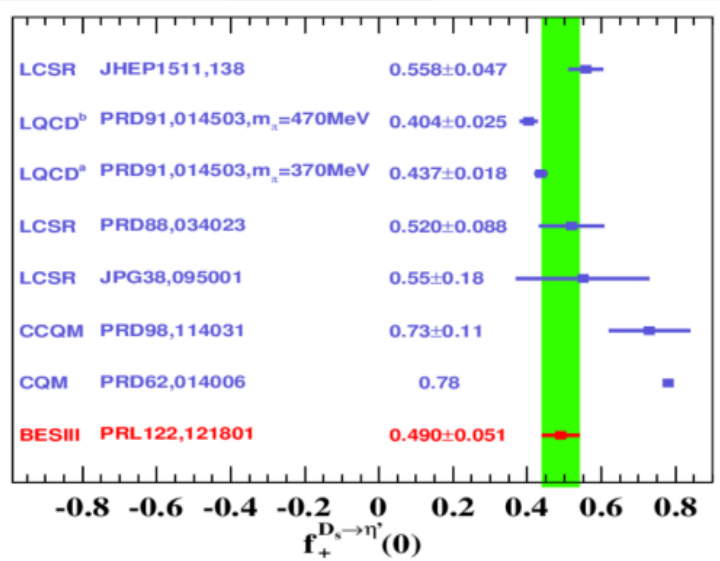
- Experimental precision is comparable to the latest LQCD result
- The measurements of the Cabibbo-suppressed decays are still dominated by statistical uncertainties

Comparisons of other form factors

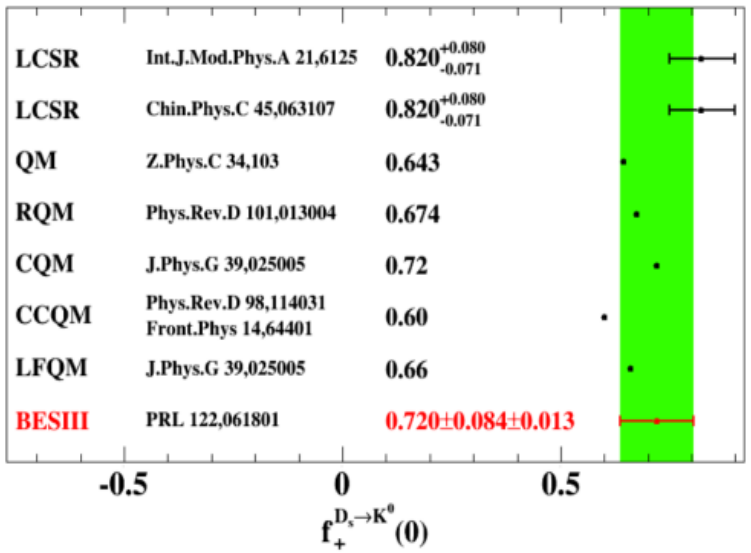
$D_s \to \eta$



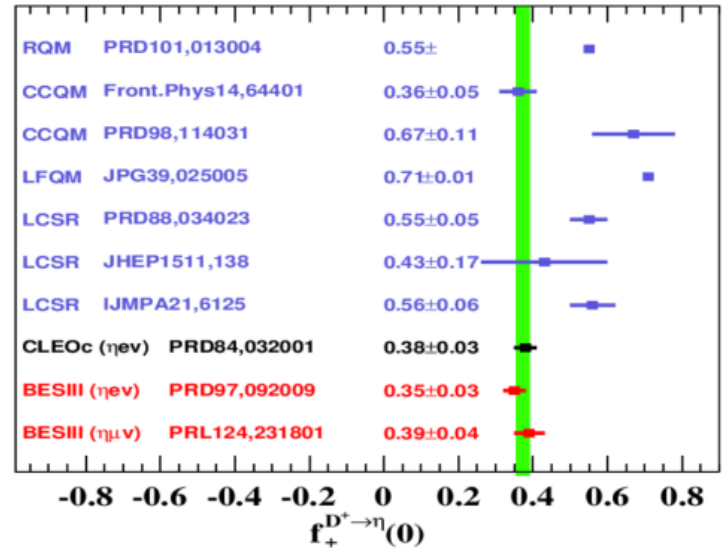
$D_s \to \eta'$



$D_s \to K^0$

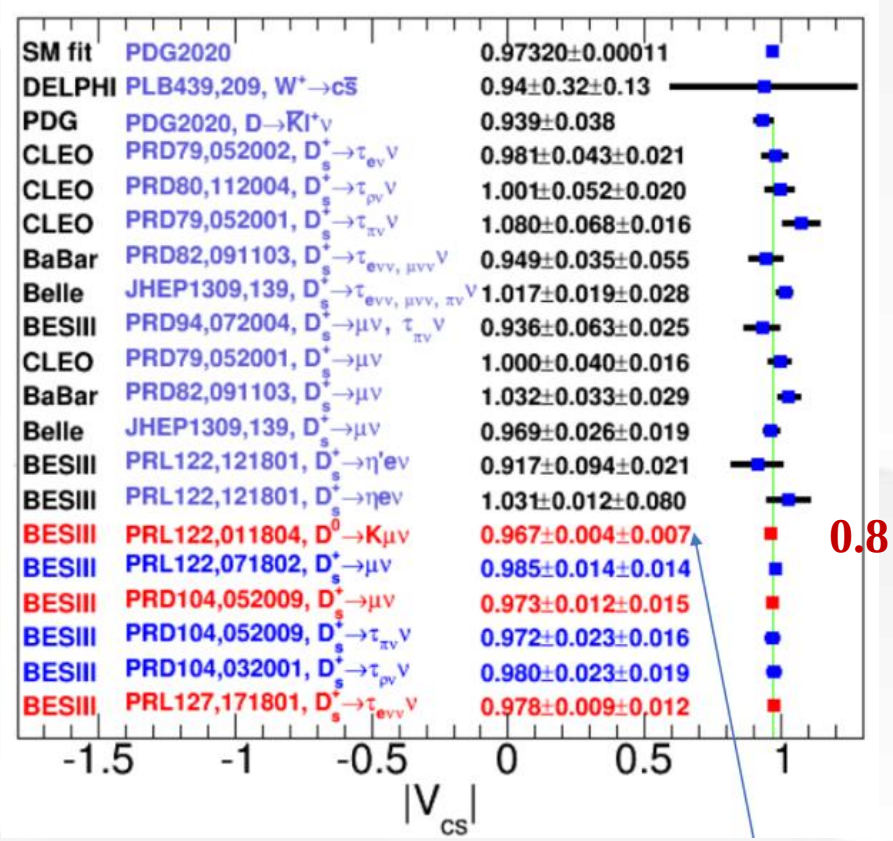


$D \to \eta$



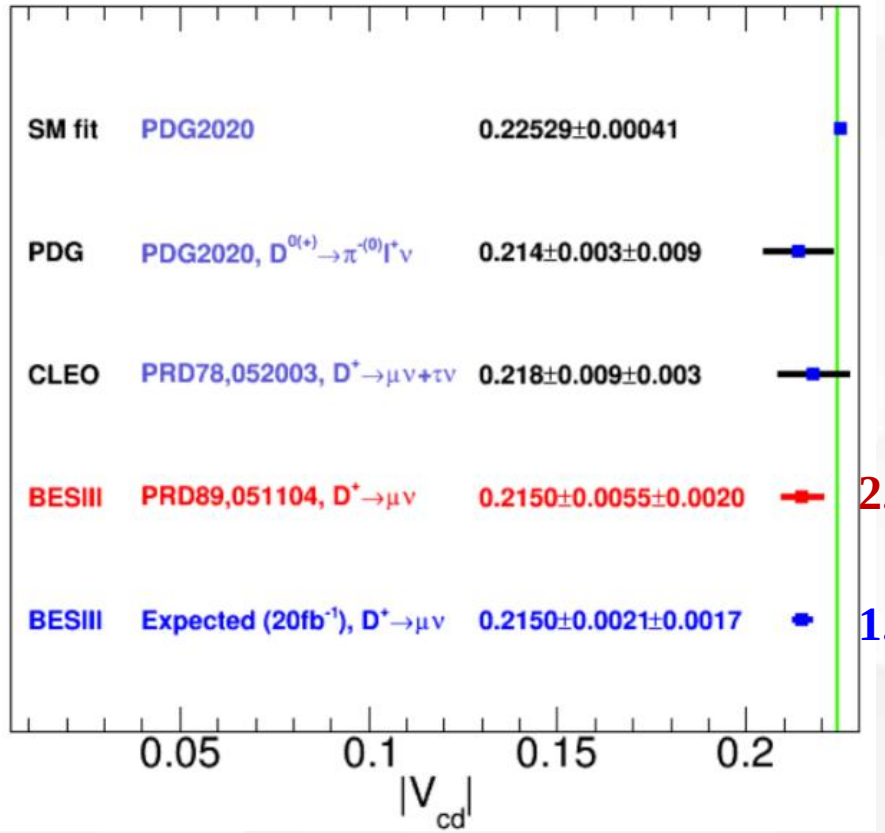
Comparisons of $|V_{cs}|$ and $|V_{cd}|$

$|V_{cs}|$



0.8%

$|V_{cd}|$



2.7%

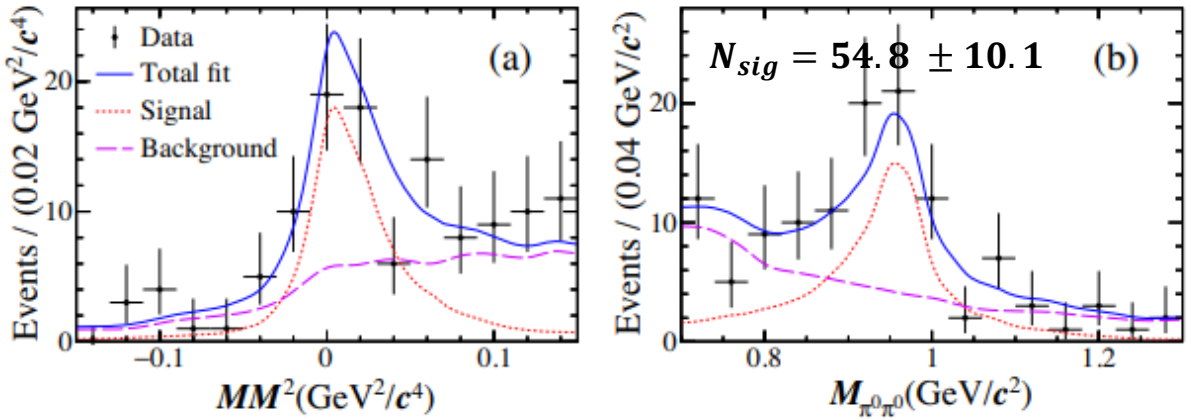
1.3%

$f_+^k(0)$ @HPQCD accuracy: 2.4%→0.6%

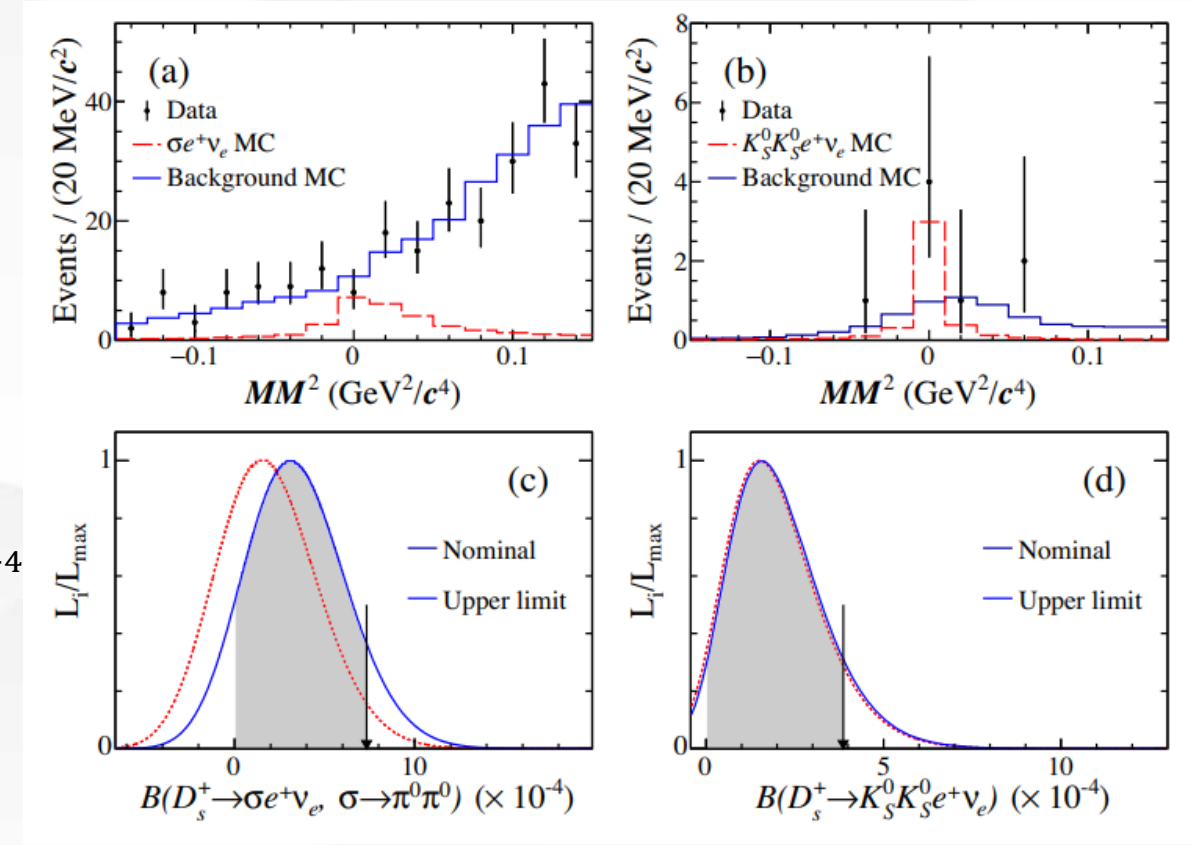
Scalar particle in D_s semi-leptonic decay

$6.3\ \mathrm{fb}^{-1}$ @4.18 – 4.23 GeV

$D_s^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^0\pi^0$



$D_s^+ \to f_0(500)e^+\nu_e(f_0(500) \to \pi^0\pi^0)$ and $K_S^0K_S^0e^+\nu_e$



$\mathcal{B}(D^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^0\pi^0) = (7.9 \pm 1.4 \pm 0.4) \times 10^{-4}$

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

$\mathcal{B}(D^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^0\pi^0) < 7.3 \times 10^{-4}$

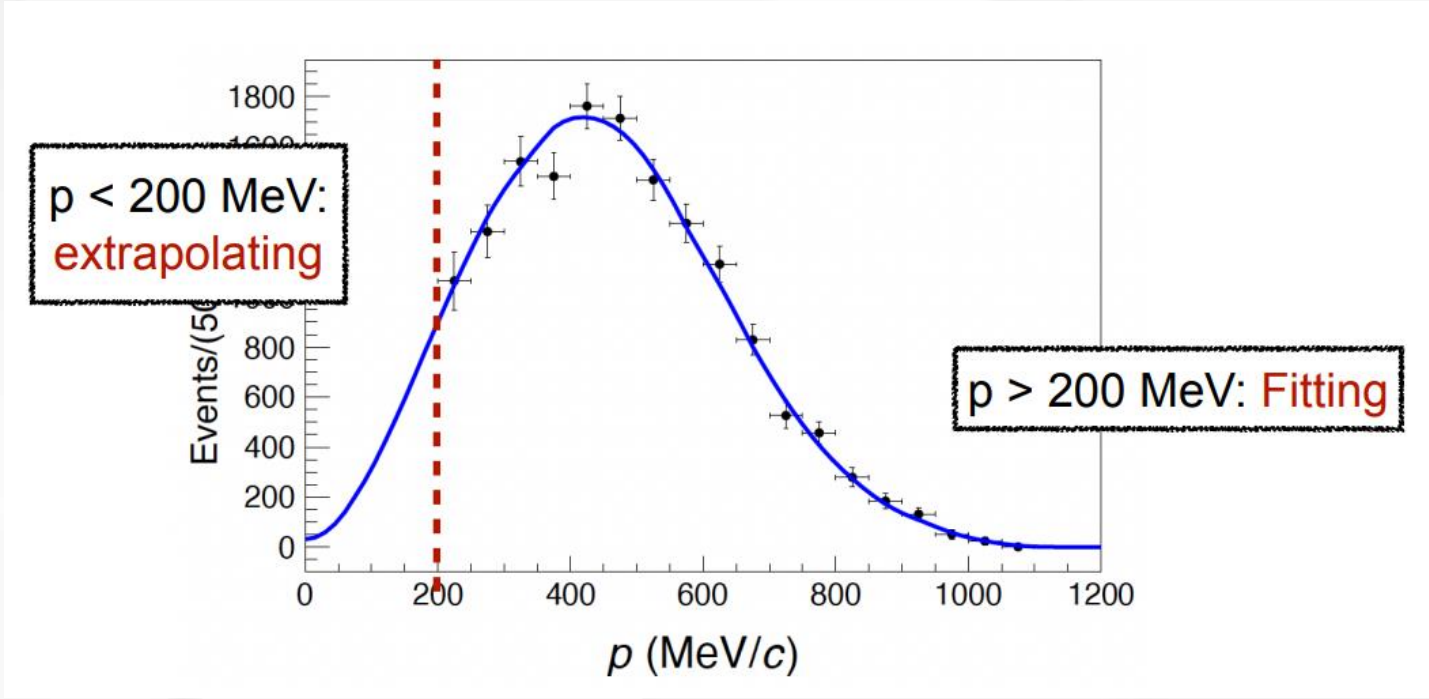
$\mathcal{B}(D^+ \to K_S^0K_S^0e^+\nu_e) < 3.8 \times 10^{-4}$

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

Inclusive D_s semi-leptonic decay

$6.3\ \mathrm{fb}^{-1}$ @$4.18 - 4.23$ GeV

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



No evidence for unobserved exclusive semi-electronic modes

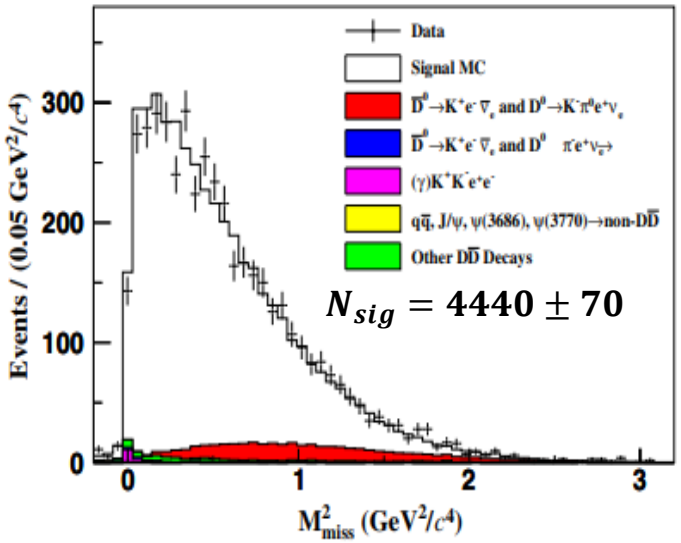
$$\mathcal{B}(D_s^+ \to Xe\nu_e) = (6.30 \pm 0.13 \pm 0.09)\%$$

Phys. Rev. D 104, 012003 (2021)

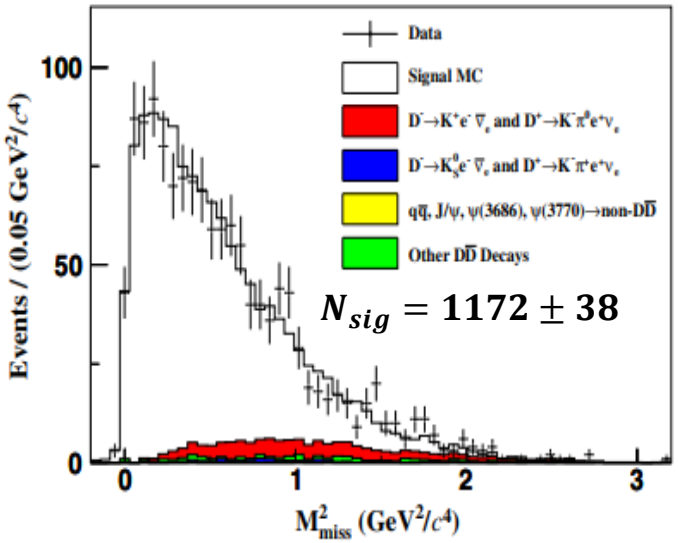
New method for $D \rightarrow K\, e\, \nu_e$

$2.9\ \mathrm{fb}^{-1}$ @3.773 GeV

$D^0 \rightarrow K^- e^+ \nu_e$



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



- Independent sample of previous measurement with hadronic tags(DT tag and ST tag method)
- $\mathcal{B}_{SL} = \sqrt{N_{DT}/(N_{D\bar{D}} \cdot \epsilon_{DT})}$

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.567 \pm 0.031 \pm 0.025)\%$$

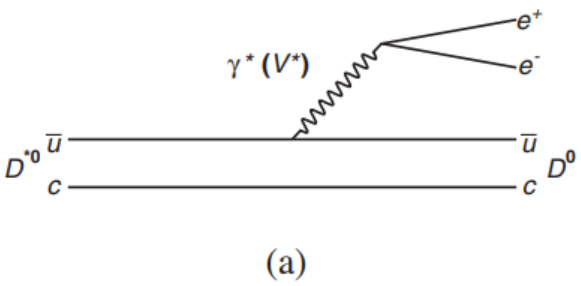
$$\mathcal{B}(D^+ \rightarrow \bar{K}^0 e^+ \nu_e) = (8.68 \pm 0.24 \pm 0.26)\%$$

larger statistical but smaller systematic uncertainties

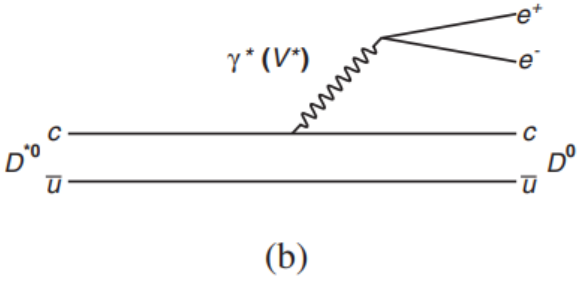
Phys. Rev. D 104, 052008 (2021)

New decay mode $D^{*0} \to D^0 e^+e^-$

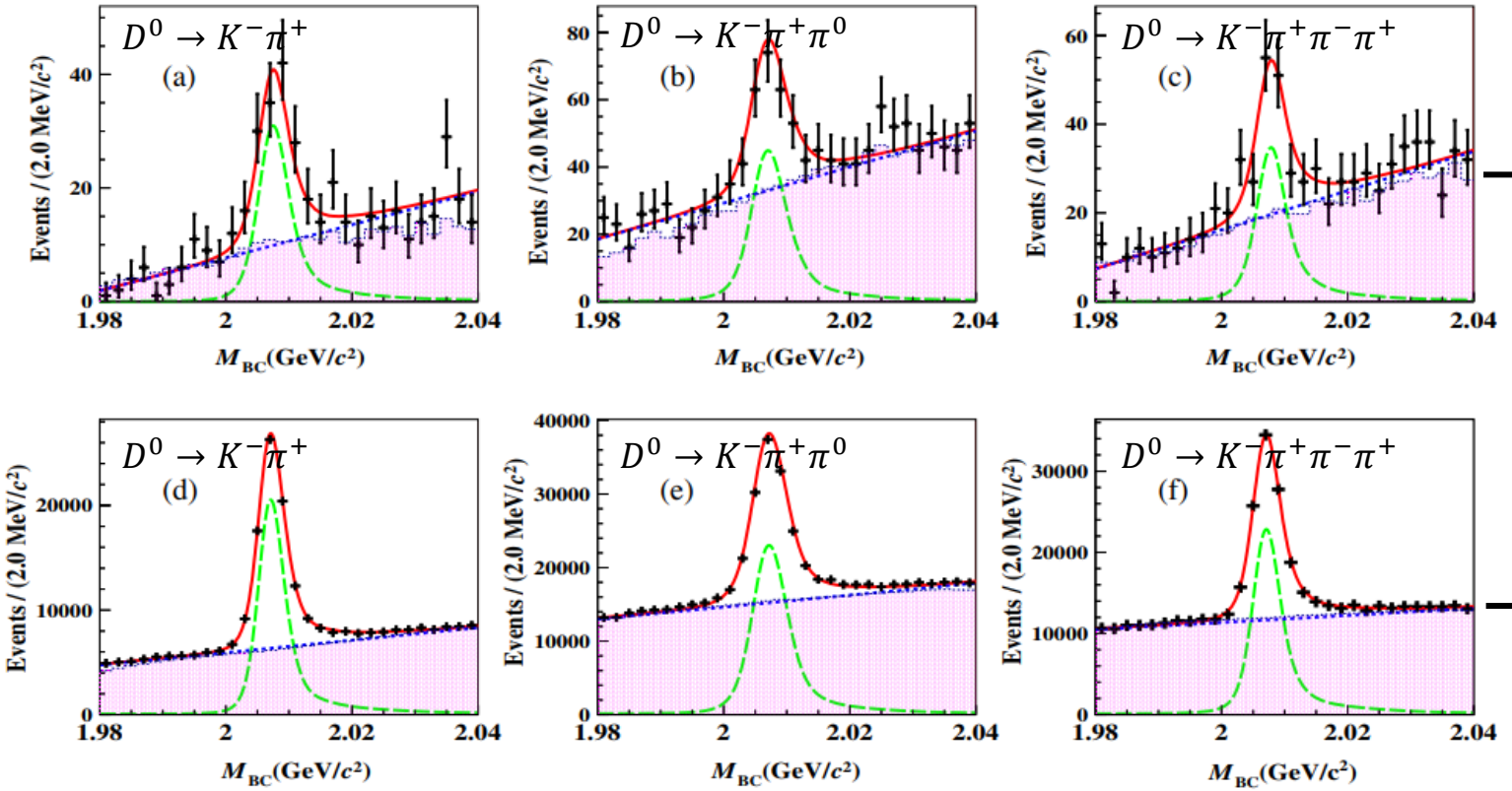
$3.19\ \mathrm{fb}^{-1}$ @4.18 GeV



(a)



(b)



$D^{*0} \to D^0 e^+e^-$

$D^{*0} \to D^0\gamma$

$$\mathcal{B}(D^{*0} \to D^0 e^+e^-) = \frac{N_{sig} \cdot \epsilon_{ref}}{N_{ref} \cdot \epsilon_{sig}} \cdot \mathcal{B}(D^{*0} \to D^0 \gamma)$$

$$\mathcal{B}(D^{*0} \to D^0 e^+e^-) = (3.91 \pm 0.27 \pm 0.17 \pm 0.10) \times 10^{-3}$$

From external input of the branching fraction for $D^{*0} \to D^0\gamma$

Phys. Rev. D 104, 112012(2021)

Summary and prospect

➢ Summary

(1) We have reported precision measurements of $f_{D_s^+}$, $|V_{cs}|$ and test of lepton flavor universality by studying the leptonic decays of $D_s^+ \to \tau^+ \nu_\tau$.

(2) We have reported the studies of $D_s^+ \to \pi^0\pi^0 e^+\nu_e$, $D_s^+ \to K_S^0 K_S^0 e^+\nu_e$ and inclusive Ds semi-leptonic decay.

(3) We have also reported the new method for $D \to K\, e\, \nu_e$ and the new decay mode $D^{*0} \to D^0\, e^+e^-$.

➢ Prospect @3.773 GeV --*From White Paper (Chin. Phys. C 44, 040001 (2020))*

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

(2) BESIII is expected to provide unique data to improve the knowledge of f_{D^+} and $|V_{cd}|$ and test LFU in $D^+ \to \ell^+ \nu_\ell$ decays.

(3) All form-factor measurements which are currently statistically limited will be improved by a factor of up to 2.6.

Thanks for your attention

Backup

Other semi-leptonic D decays

$D_s^+ \to \pi^0 e^+ \nu_e$	arXiv:2206.13870
$D^{0(+)} \to \bar{K} e^+ \nu_e$	PRD104(2021)052008
$D_s^+ \to a_0(980)^0 e^+ \nu$	PRD104(2021)092004
$D^0 \to b_1(1235)^- e^+ \nu$	PRD101(2020)112005
$D_s^+ \to p\bar{p} e^+ \nu_e$	PRD100(2019)112008
$D_s^+ \to \gamma e^+ \nu_e$	PRD99(2019)072002
$D_s^+ \to \eta^{(\prime)} \mu^+ \nu \; and \; \phi \mu^+ \nu$	PRD97(2018)012006
$D^+ \to \gamma e^+ \nu_e$	PRD95(2017)071102
$D^+ \to D^0 e^+ \nu_e$	PRD96(2016)092002
$D^+ \to \bar{K}^0 e^+ \nu_e \; via \; \bar{K}^0 \to \pi^0 \pi^0$	CPC40(2016)113001
$D_s^+ \to l^+ \nu_l @ 4.009 GeV$	PRD94(2016)072004
$D_s^+ \to \eta^{(\prime)} e^+ \nu_e @ 4.009 GeV$	PRD94(2016)112003