(Semi-)leptonic D decays at BESIII

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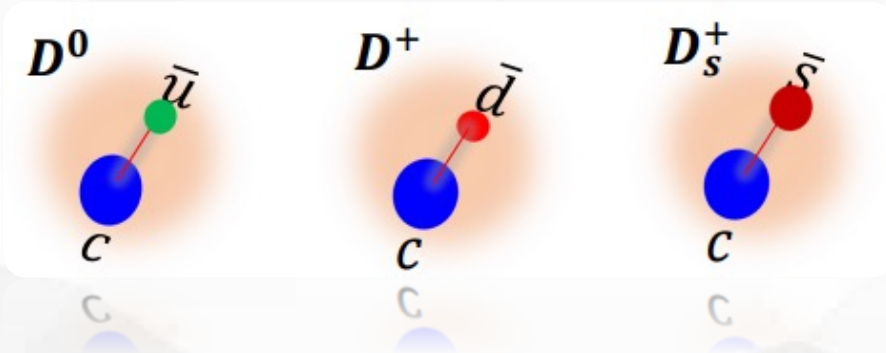
On behalf of the BESIII Collaboration

中国物理学会高能物理分会第十一届全国委员代表大会暨学术年会（线上）

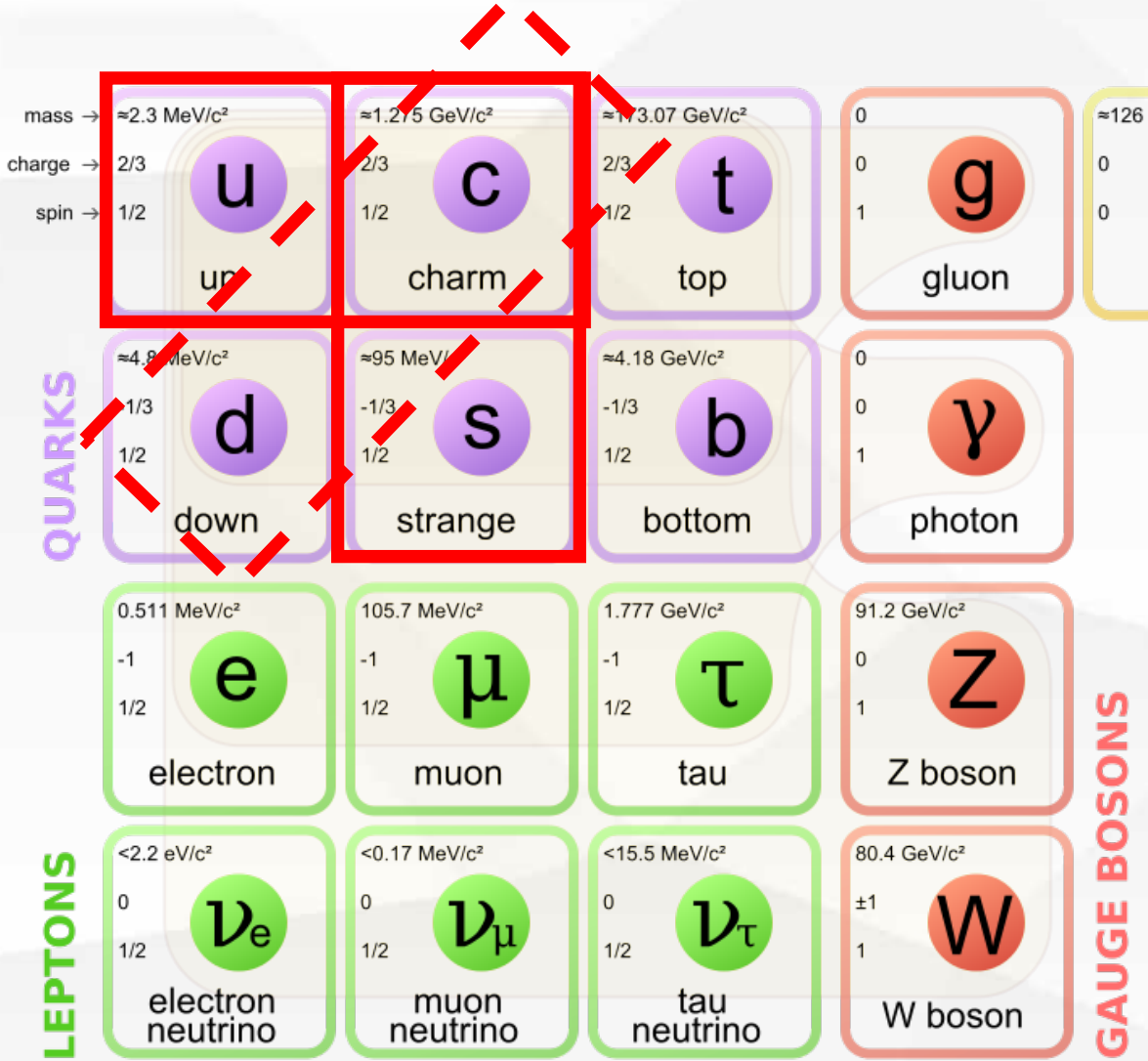
2022年8月10日 大连

Outline

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



Motivation



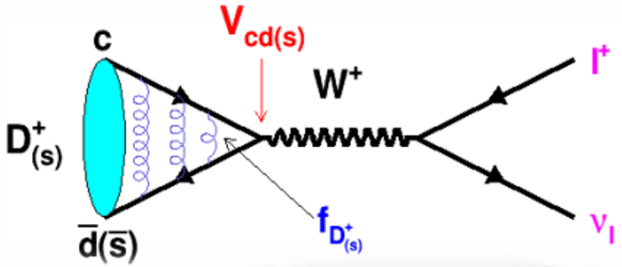
Charm physics

- **SM :** High precision frontier -> **NP**
- **QCD :** Nonperturbative physics

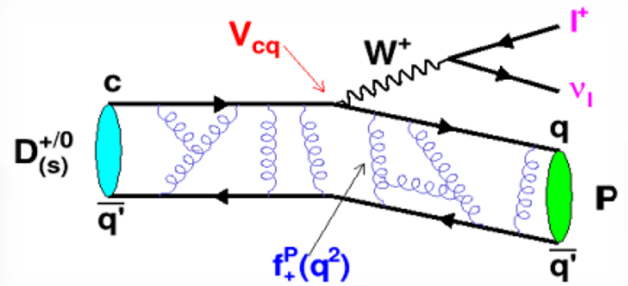
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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 $\frac{\mathcal{B}(D_{(s)} \to X\, \mu^+ \nu_\mu)}{\mathcal{B}(D_{(s)} \to X\, e^+ \nu_e)}$ → Test the lepton flavor universality



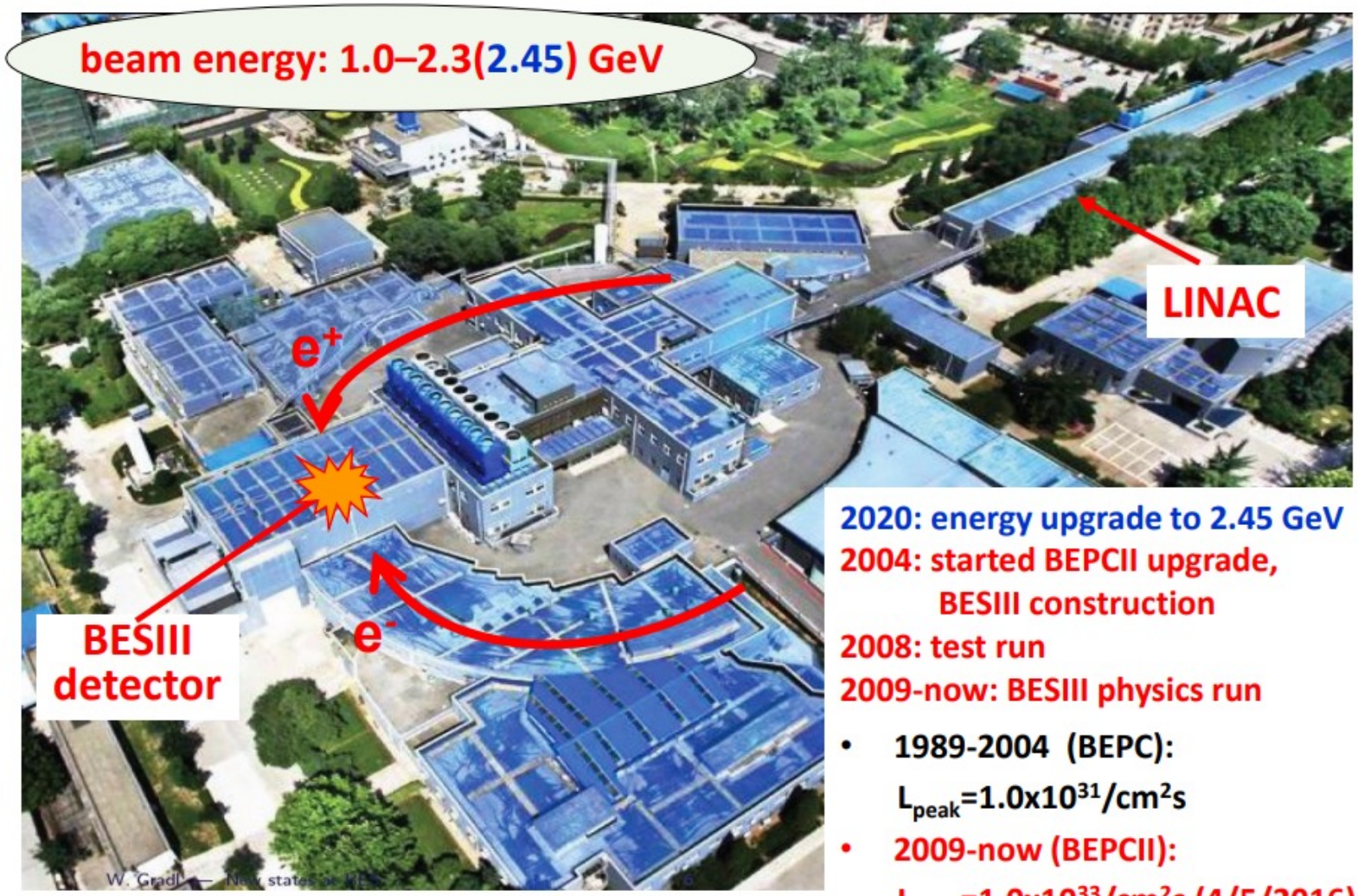
$$\Gamma(D_{(s)}^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}^+} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2$$



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

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

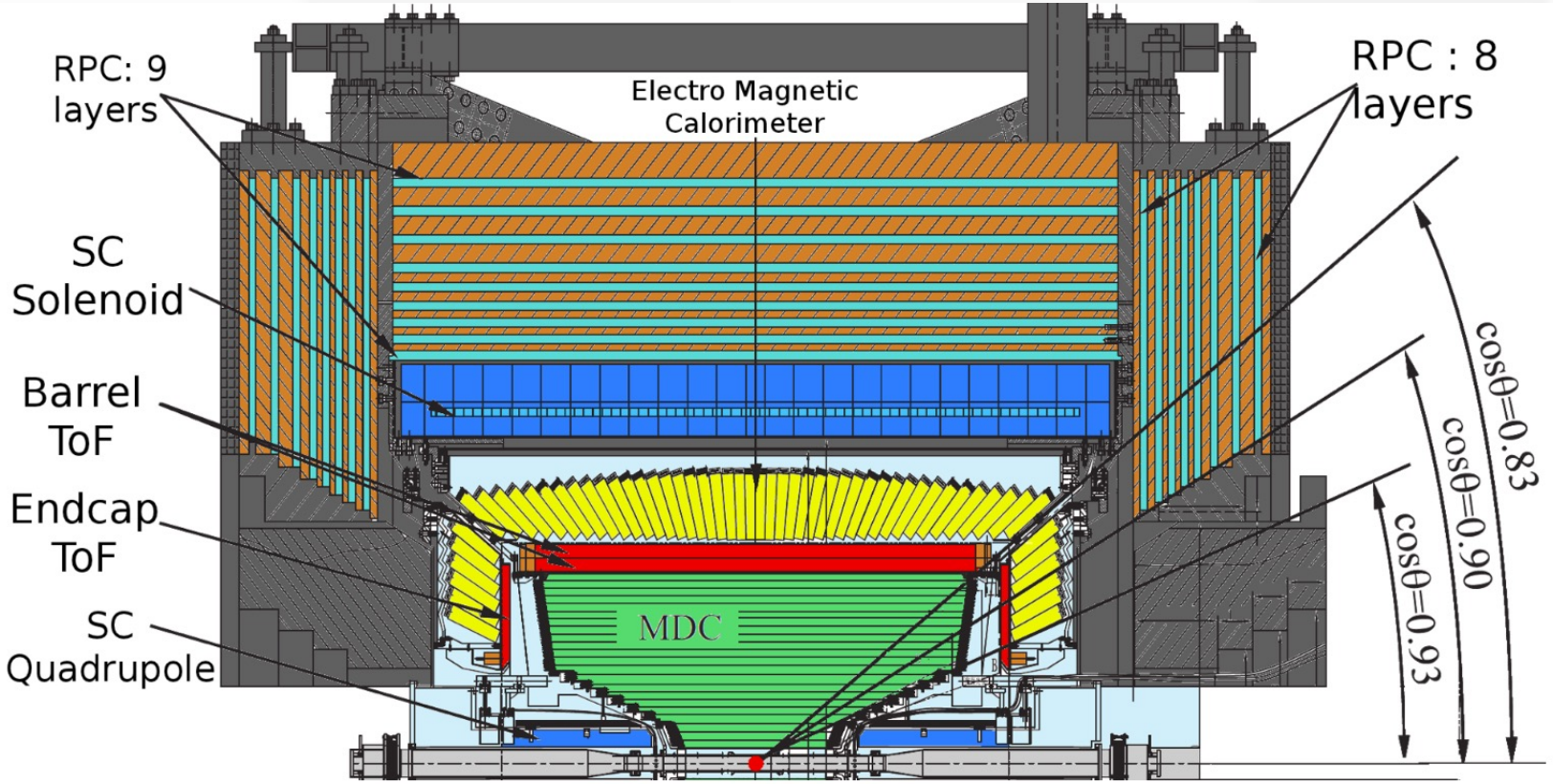
Beijing Electron Positron Collider (BEPCII)



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

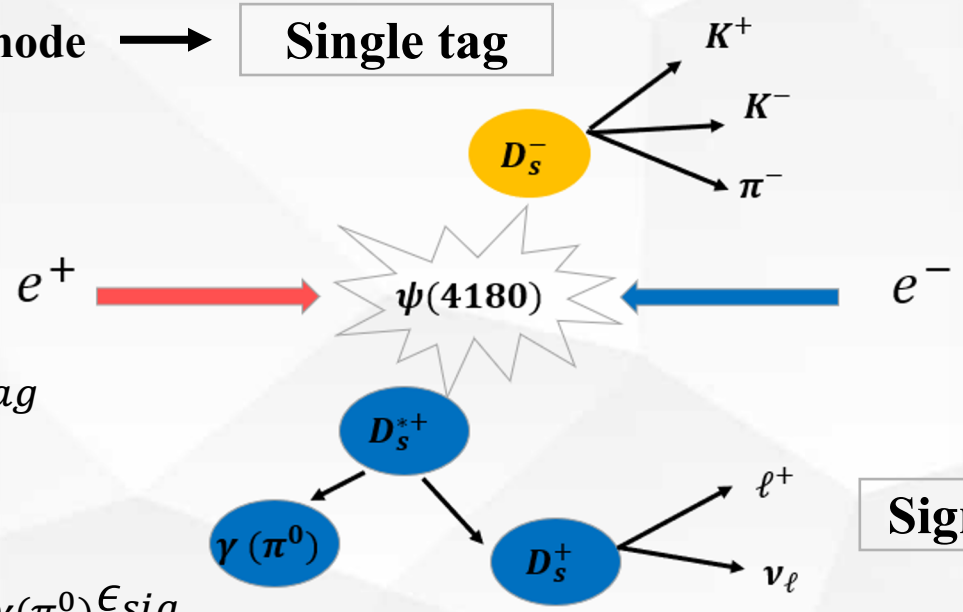
Data samples at BESIII

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

Well known mode → Single tag



Signal side ← Aim to study

- Single tag (ST)

$$N_{tag}^{ST} = 2N_{D_s^* D_s}\mathcal{B}_{tag}\,\epsilon_{tag}$$

- Double tag (DT)

$$N_{tag,sig}^{DT} = 2N_{D_s^* D_s}\mathcal{B}_{tag}\mathcal{B}_{sig}\mathcal{B}_{\gamma(\pi^0)}\epsilon_{sig}$$

$$\mathcal{B}_{sig} = \frac{N_{tag,sig}^{DT}}{\mathcal{B}_{\gamma(\pi^0)}\sum_\alpha N_{tag}^{ST,\alpha}\epsilon_{sig}^{\alpha}/\epsilon_{tag}^{\alpha}}$$

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

- $\mathcal{B}_{\gamma(\pi^0)} = \mathcal{B}(D_s^* \to \gamma(\pi^0)D_s)$

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

Phys. Rev. D 104, 032001 (2021)

$D_s^+ \to \tau^+(\rho^+\overline{\nu}_\tau)\nu_\tau$

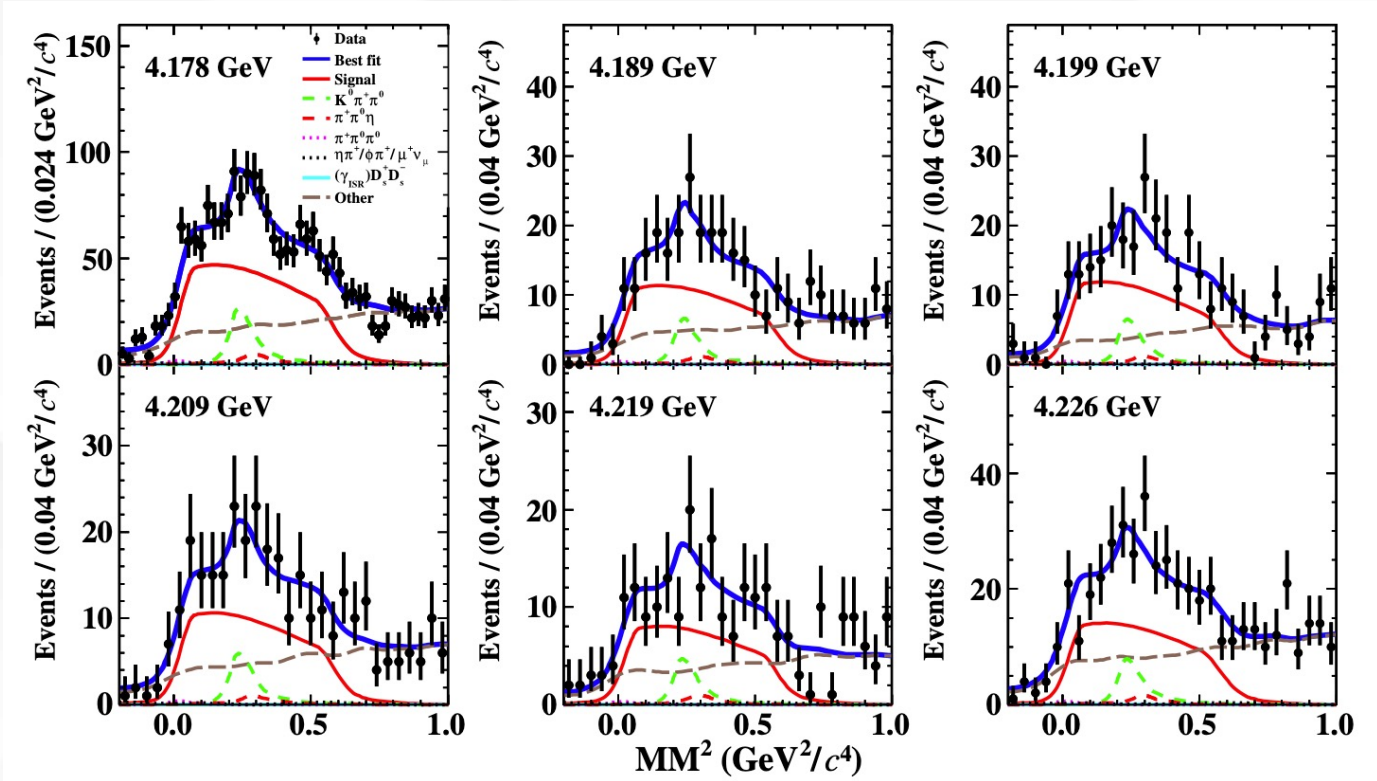
- **Data:** 6.3 fb^{-1} @4.18 $-$ 4.23 GeV
- $N_{sig} = 1745 \pm 84$
- $\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (5.29 \pm 0.25 \pm 0.20)\%$

$f_{D_s^+}|V_{cs}| = (244.8 \pm 5.8 \pm 4.8)$ MeV **精度~3.1%**

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

SM prediction: 9.75 ± 0.01

BESIII: Phys. Rev. D 104, 052009 (2021)



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

Phys. Rev. D 104, 052009 (2021)

$D_s^+ \to \mu^+ \nu_\mu$ and $D_s^+ \to \tau^+(\pi^+\bar{\nu}_\tau)\nu_\tau$

- **Data:** 6.3 fb^{-1} @4.18 − 4.23 GeV
- $N_{sig} = 2198 \pm 55$, $N_{sig} = 946 \pm 46$
- $\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu) = (5.35 \pm 0.13 \pm 0.16)\times 10^{-3}$

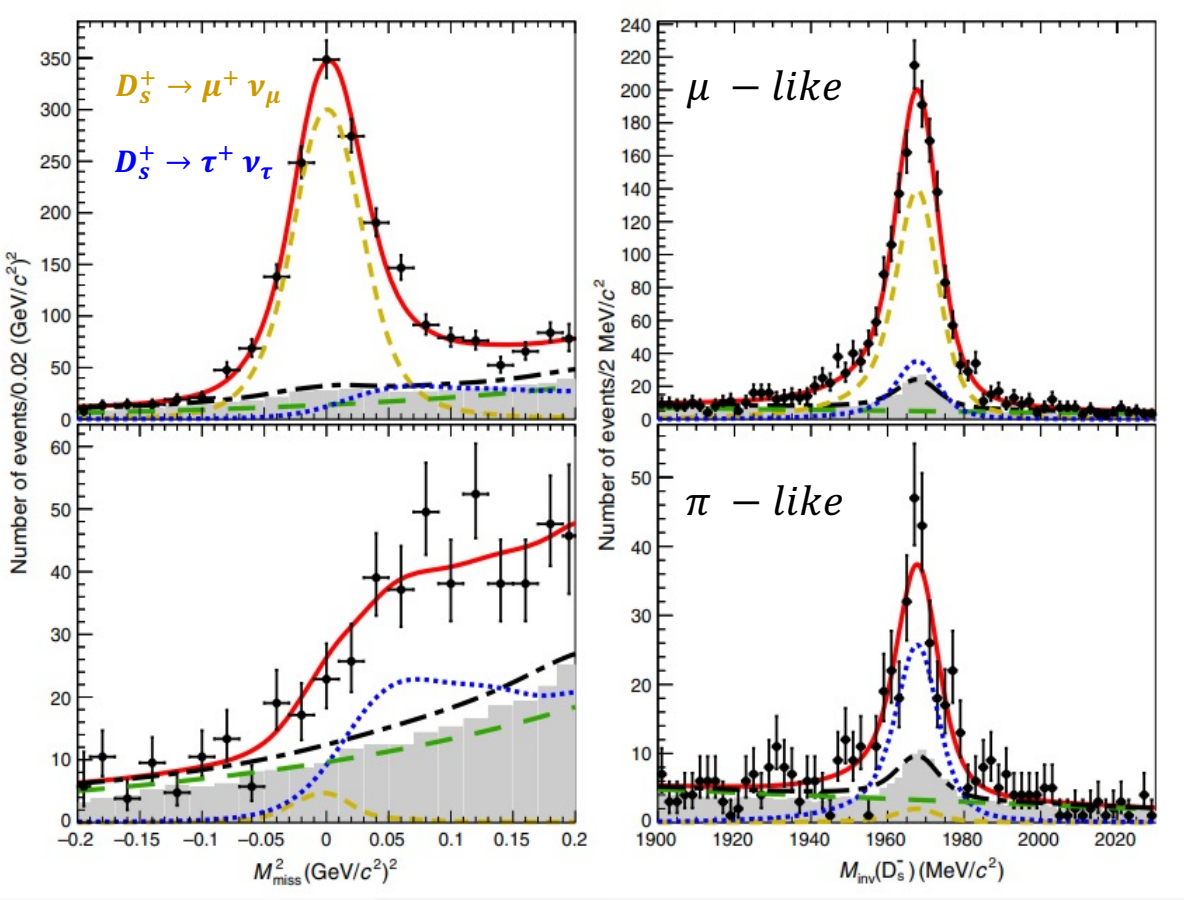
$f_{D_s^+}|V_{cs}| = (243.1 \pm 3.0 \pm 3.7)$ MeV $[\mu]$ **精度~2.0%**

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

$f_{D_s^+}|V_{cs}| = (243.0 \pm 5.8 \pm 4.0)$MeV $[\tau]$ **精度~2.9%**

$$R = \frac{\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu)_{PDG}} = 9.73^{+0.61}_{-0.58} \pm 0.37$$

SM prediction: 9.75 ± 0.01



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

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

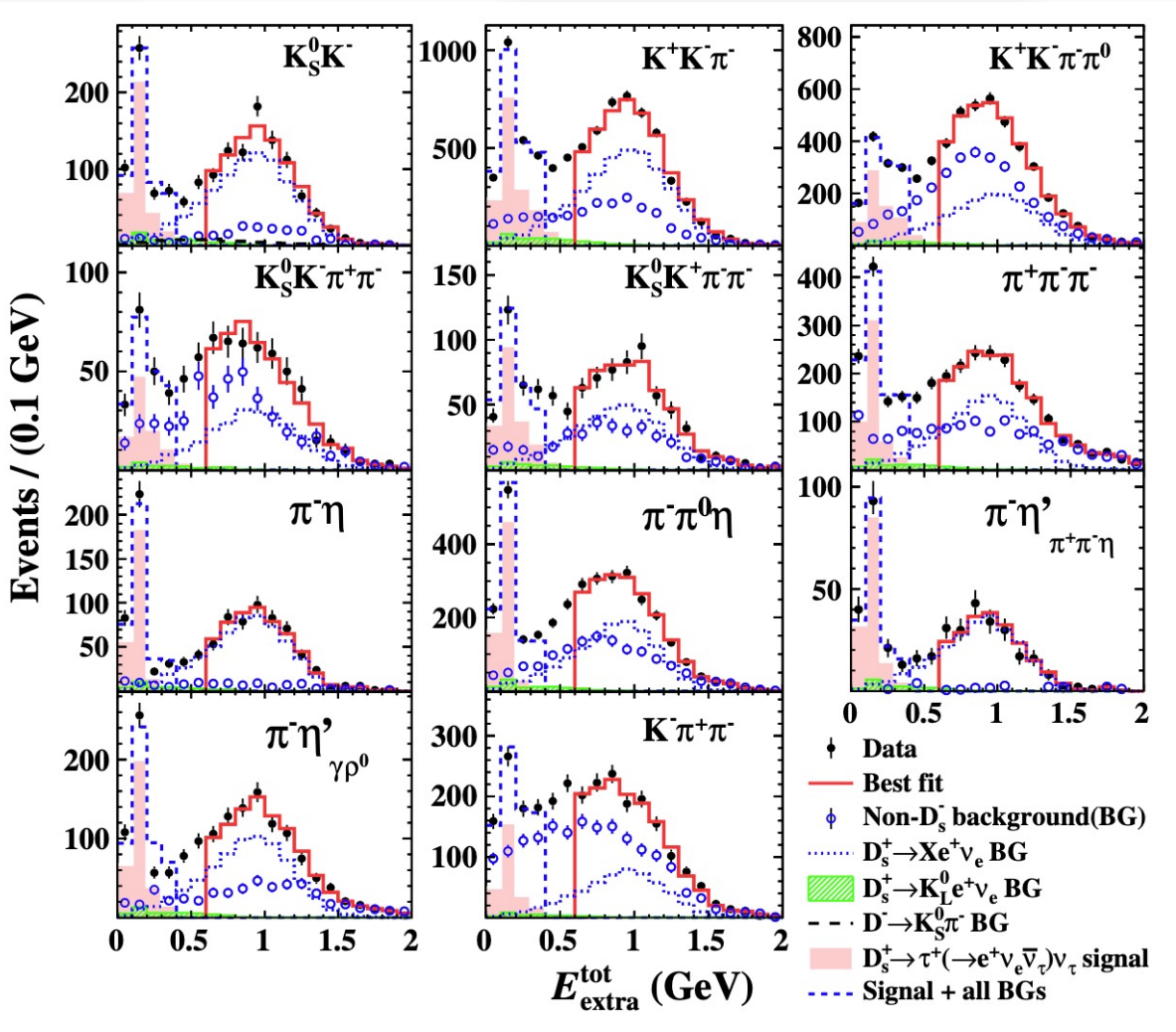
$D_s^+ \to \tau^+(e^+\nu_e\bar{\nu}_\tau)\nu_\tau$

- **Data: $6.3\ \mathrm{fb}^{-1}$ @$4.18 - 4.23$ GeV**
- $N_{sig} = 4940 \pm 97$
- $\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (5.27 \pm 0.10 \pm 0.12)\%$

$f_{D_s^+}|V_{cs}| = (244.4 \pm 2.3 \pm 2.9)$MeV **精度~1.5%**

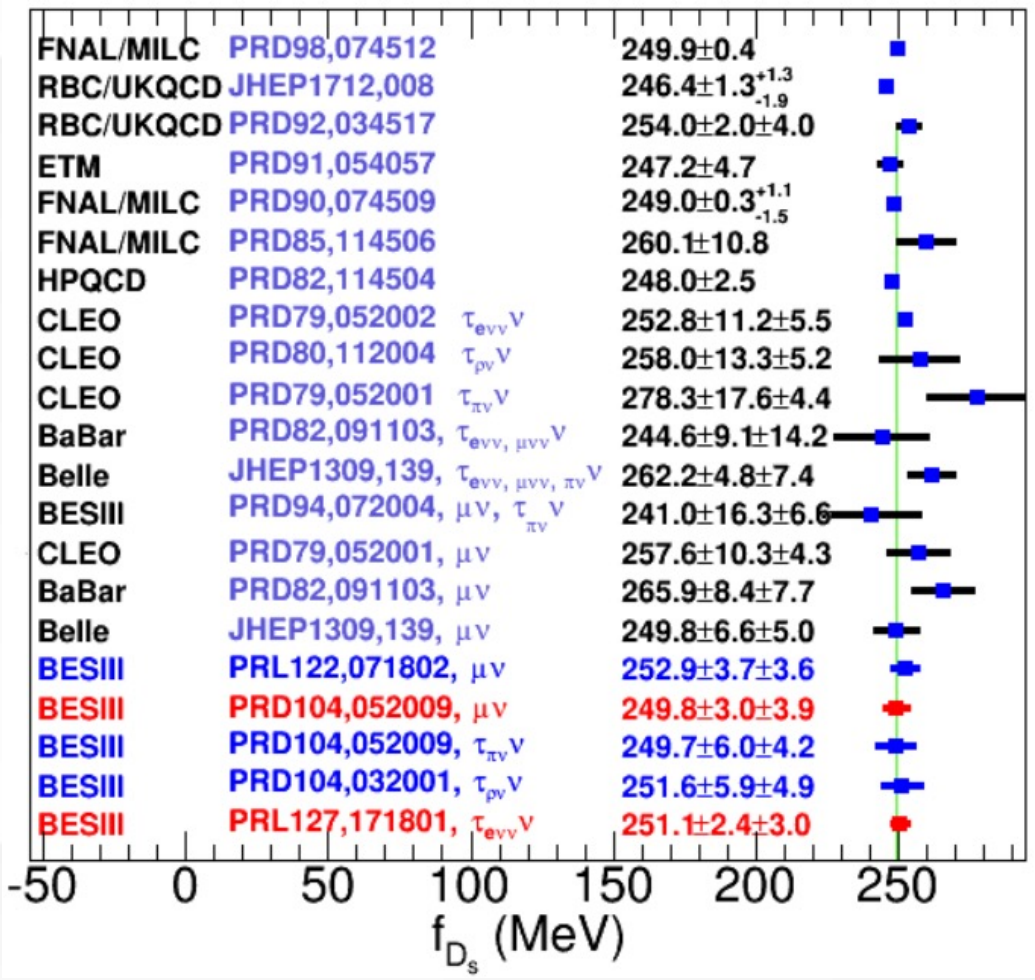
$$R = \frac{\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu)_{PDG}} = 9.72 \pm 0.37$$

SM prediction: 9.75 ± 0.01

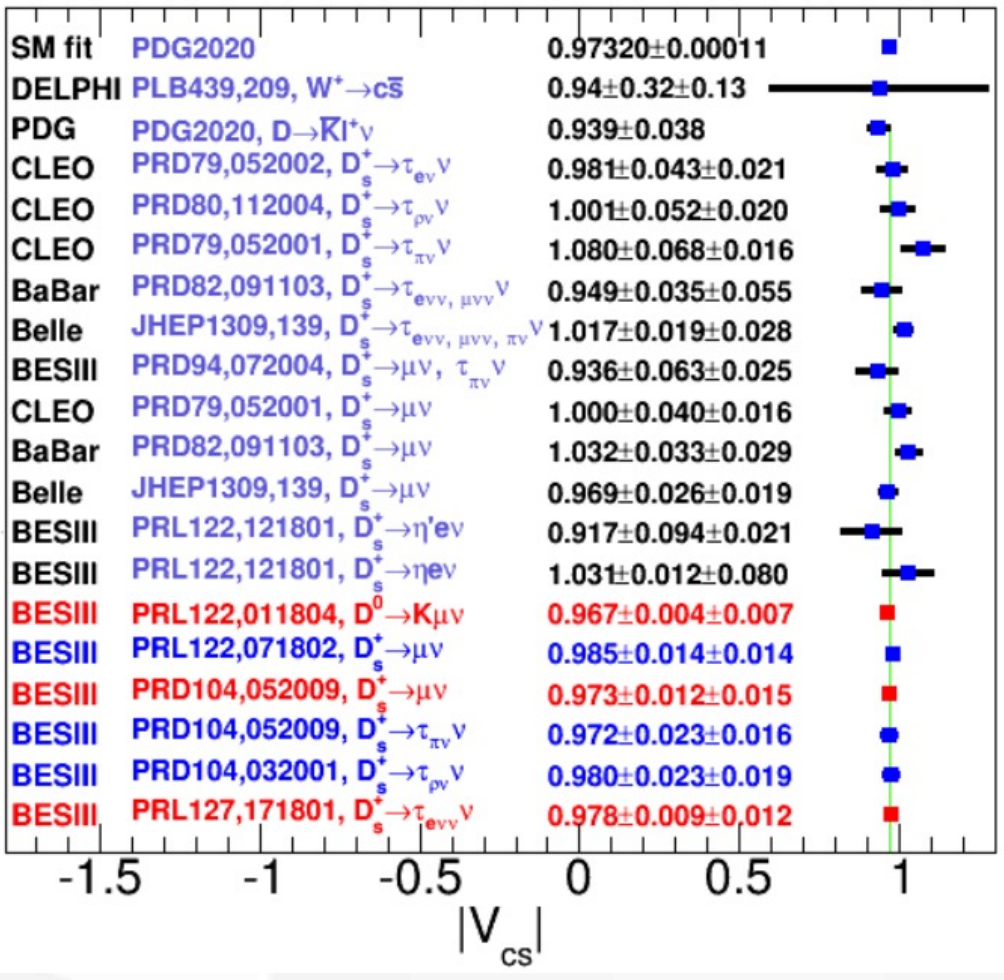


Comparisons of $f_{D_s^+}$ and $|V_{cs}|$

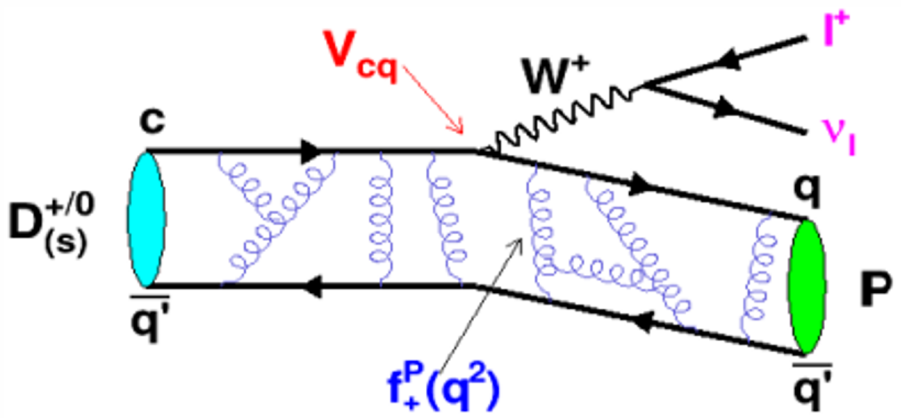
$f_{D_s^+}$



$|V_{cs}|$



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



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

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

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

★ Very helpful for us to study:

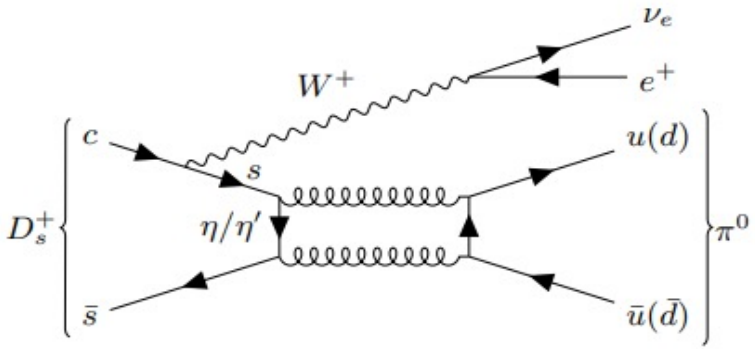
- light meson spectrum
- Nonperturbative QCD by measuring the form factor

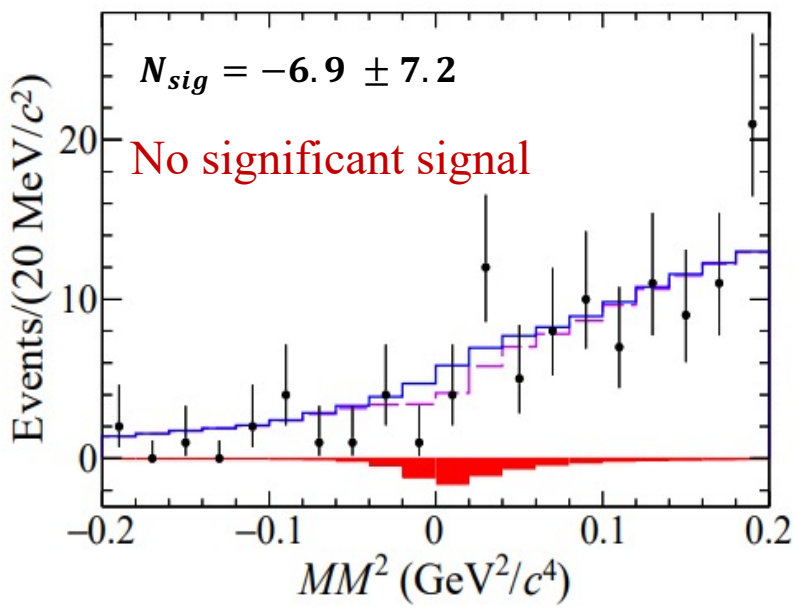
Parametric form of form factor:

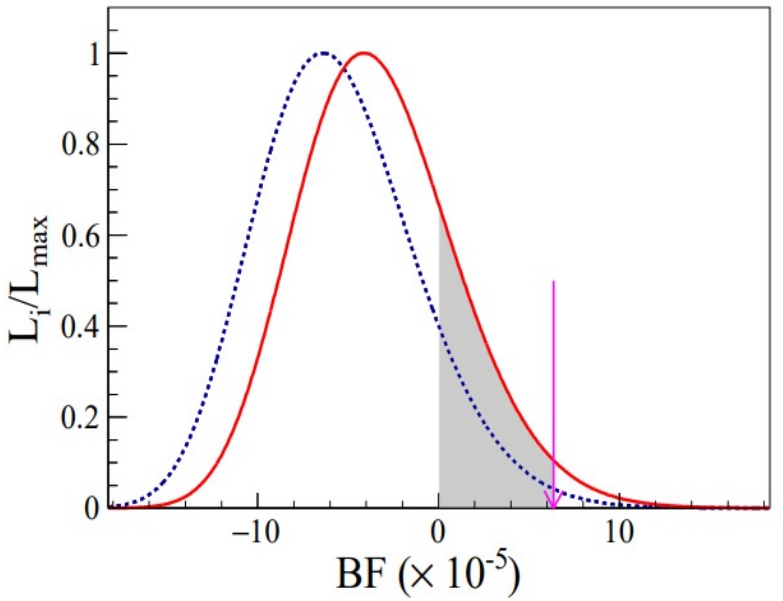
(1) Single pole form (2) Modified pole model (3) ISGW2 model (4) Series expansion mode

Study of $D_s^+ \to \pi^0 e^+ \nu_e$

arXiv:2206.13870(2022)







To study $\pi^0 - \eta$ mixing effect

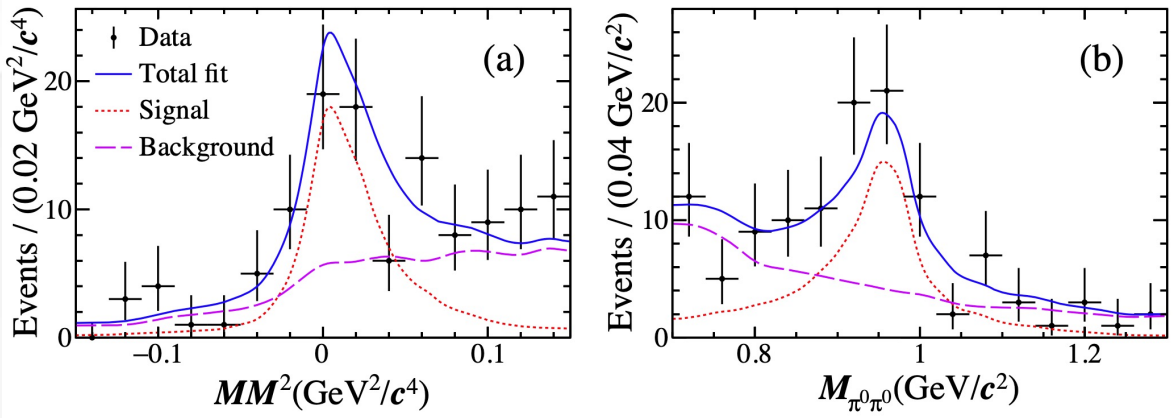
- **Data**: 6.3 fb^{-1} @4.18 − 4.23 GeV
- $\mathcal{B}(D_s^+ \to \pi^0 e^+ \nu_e) < 6.4 \times 10^{-5}$@90%CL

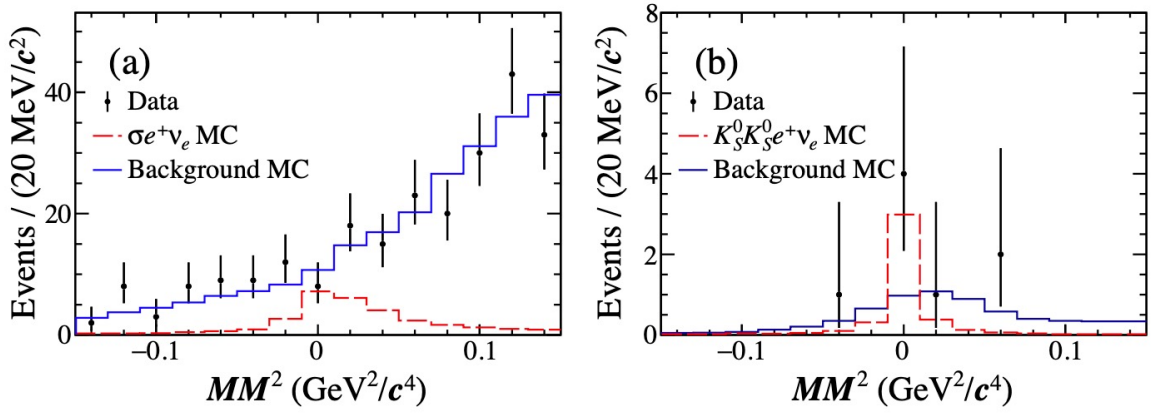
No significant signal

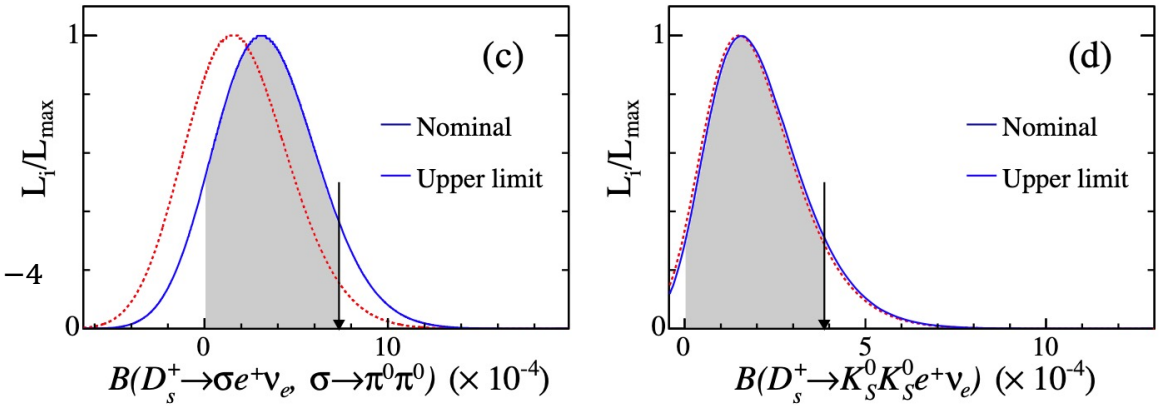
Theory: $(2.65 \pm 0.38) \times 10^{-5}$ [PLB811,135879(2020)]

Study of $D_s^+ \to f_0 e^+ \nu_e$

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







- **Data:** 6.3 fb^{-1} @4.18 $-$ 4.23 GeV
- $N_{sig} = 54.8 \pm 10.1$ **(significance: 7.8σ)**
- $\mathcal{B}(D_s^+ \to f_0(980) e^+ \nu_e, f_0(980) \to \pi^0\pi^0) = (7.9 \pm 1.4 \pm 0.4) \times 10^{-4}$
- $\mathcal{B}(D_s^+ \to f_0(500) e^+ \nu_e, f_0(500) \to \pi^0\pi^0) < 7.3 \times 10^{-4}$ @90%CL
- $\mathcal{B}(D_s^+ \to K_S^0 K_S^0 e^+ \nu_e) < 3.8 \times 10^{-4}$ @90%CL

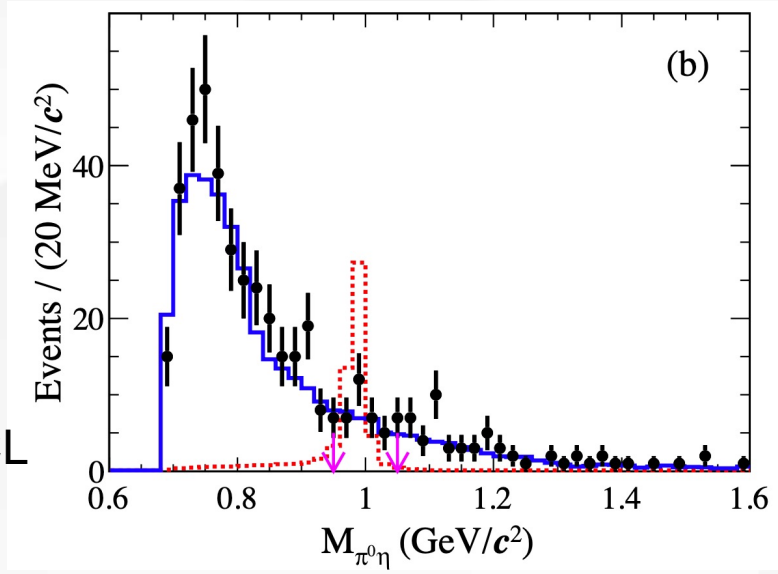
No significant signal

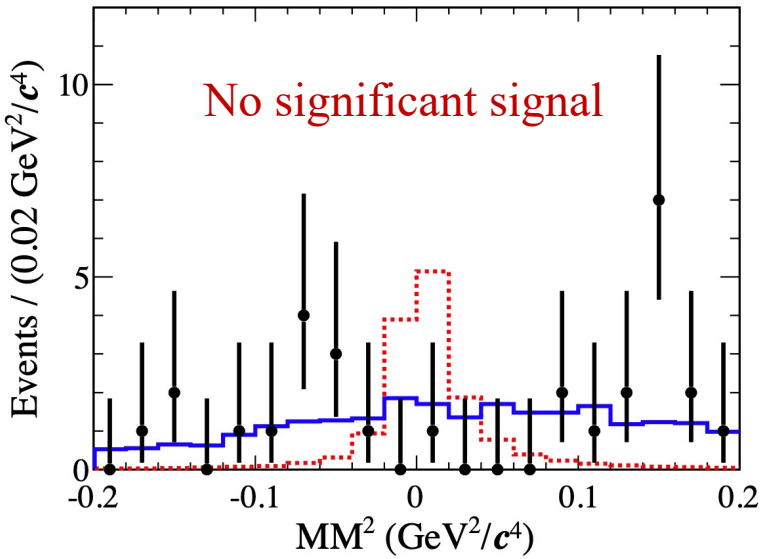
Study of $D_s^+ \to a_0(980)^0 e^+ \nu_e$

Phys. Rev. D 103, 092004 (2021)

To study $a_0(980)^0 - f_0(980)$ mixing effect

- **Data**: 6.3 fb^{-1} @4.18 $-$ 4.23 GeV
- $\mathcal{B}(D_s^+ \to a_0(980)^0 e^+ \nu_e, a_0(980)^0 \to \pi^0\eta) < 1.2\times10^{-4}$@90%CL





- ✓ First study of $a_0(980)^0 - f_0(980)$ mixing in the charm sector
- ✓ No conflict with the previous $a_0(980)^0 - f_0(980)$ mixing measurement at BESIII [PRL121,022001(2018)]

Inclusive D_s semi-leptonic decay

Phys. Rev. D 104, 012003 (2021)

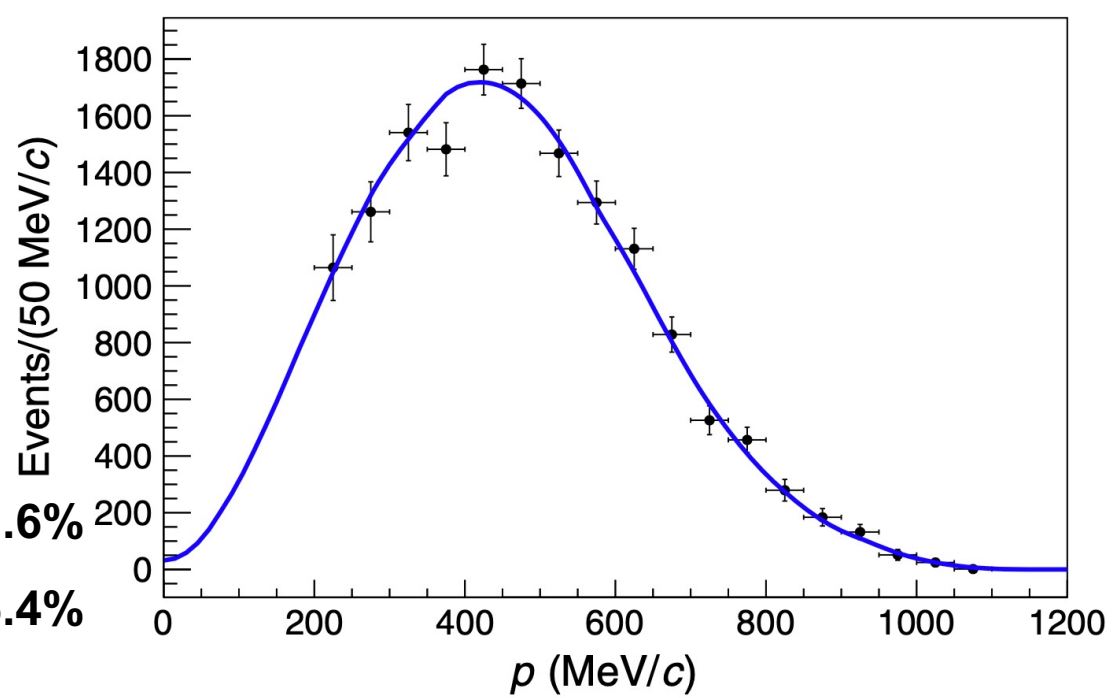
- **Data**: 6.3 fb^{-1} @4.18 $-$ 4.23 GeV
- $N_{tag}(D_s^- \to K^+K^-\pi^-)$ = **262660±1137**
- $N_{sig} = \mathbf{16648 \pm 326}$

$\mathcal{B}(D_s^+ \to Xe^+\nu_e) = (6.30 \pm 0.13 \pm 0.09 \pm 0.04)\%$ **精度~2.6%**

$\mathcal{B}(D_s^+ \to Xe^+\nu_e)_{CLEO} = (6.52 \pm 0.39 \pm 0.15)\%$ **精度~6.4%**

$$\mathcal{B}(D_s^+ \to Xe^+\nu_e) - \sum_i \mathcal{B}(D_s^+ \to X_i e^+\nu_e)$$
$$= (-0.04 \pm 0.13 \pm 0.09 \pm 0.17)\%$$

No evidence for unobserved exclusive semi-electronic modes



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

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

Phys. Rev. D 104, 052008 (2021)

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

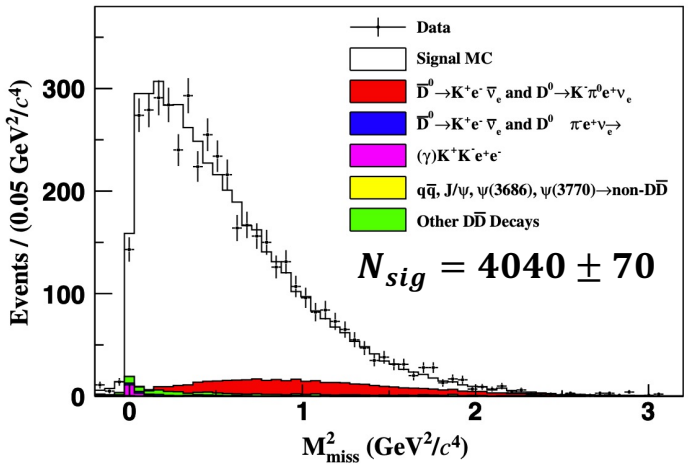
$D^+ \rightarrow \bar{K}^0 e^+ \nu_e$

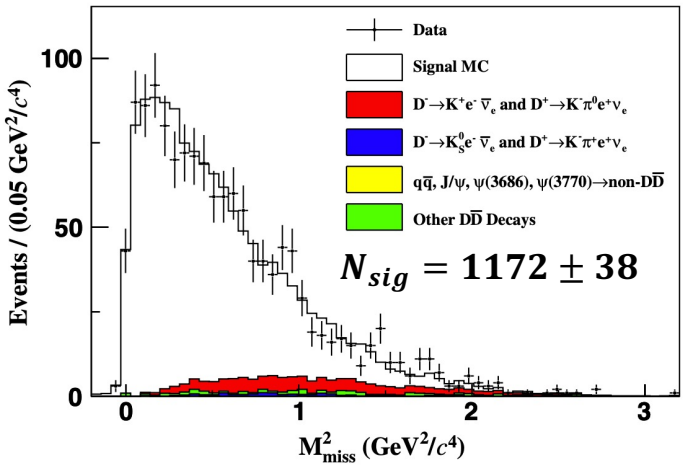
Independent sample of previous measurement with hadronic tags

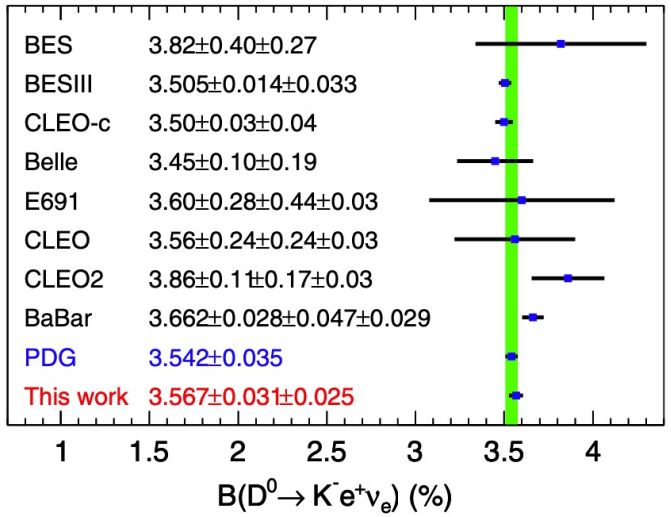
- **Data**: 2.93 fb^{-1} @3.773 GeV
- $\mathcal{B}_{SL} = \sqrt{N_{DT}/(N_{D\bar{D}} \cdot \epsilon_{DT})}$

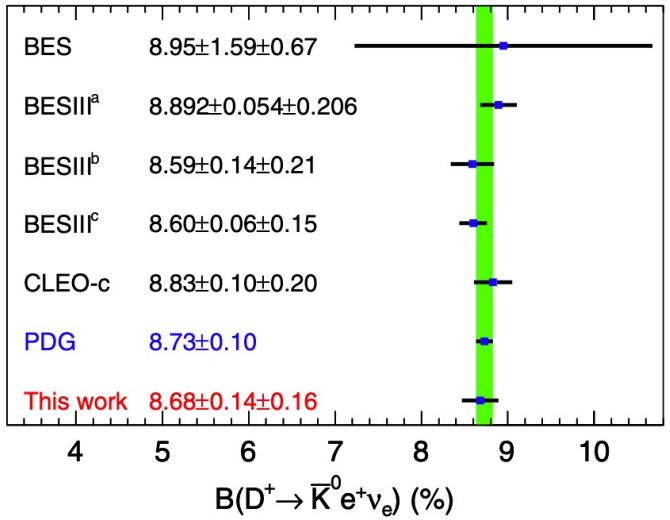
$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.567 \pm 0.031 \pm 0.025)\%$$

$$\mathcal{B}(D^+ \rightarrow \bar{K}^0 e^+ \nu_e) = (8.68 \pm 0.14 \pm 0.16)\%$$









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 $D_s^+ \to \pi^0 e^+ \nu_e$, $D_s^+ \to f_0(980)/f_0(500)[\pi^0\pi^0]e^+\nu_e$, $D_s^+ \to f_0(980)[K_S^0 K_S^0]e^+\nu_e$, $D_s^+ \to a_0(980)^0[\pi^0\eta]e^+\nu_e$ and inclusive D_s semi-leptonic decay.

(1) We have also reported the new method for $D \to K\ e\ \nu_e$

➢ 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 statistical uncertainty of f_{D^+} and $|V_{cd}|$ from about 2.6% to about 1% 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

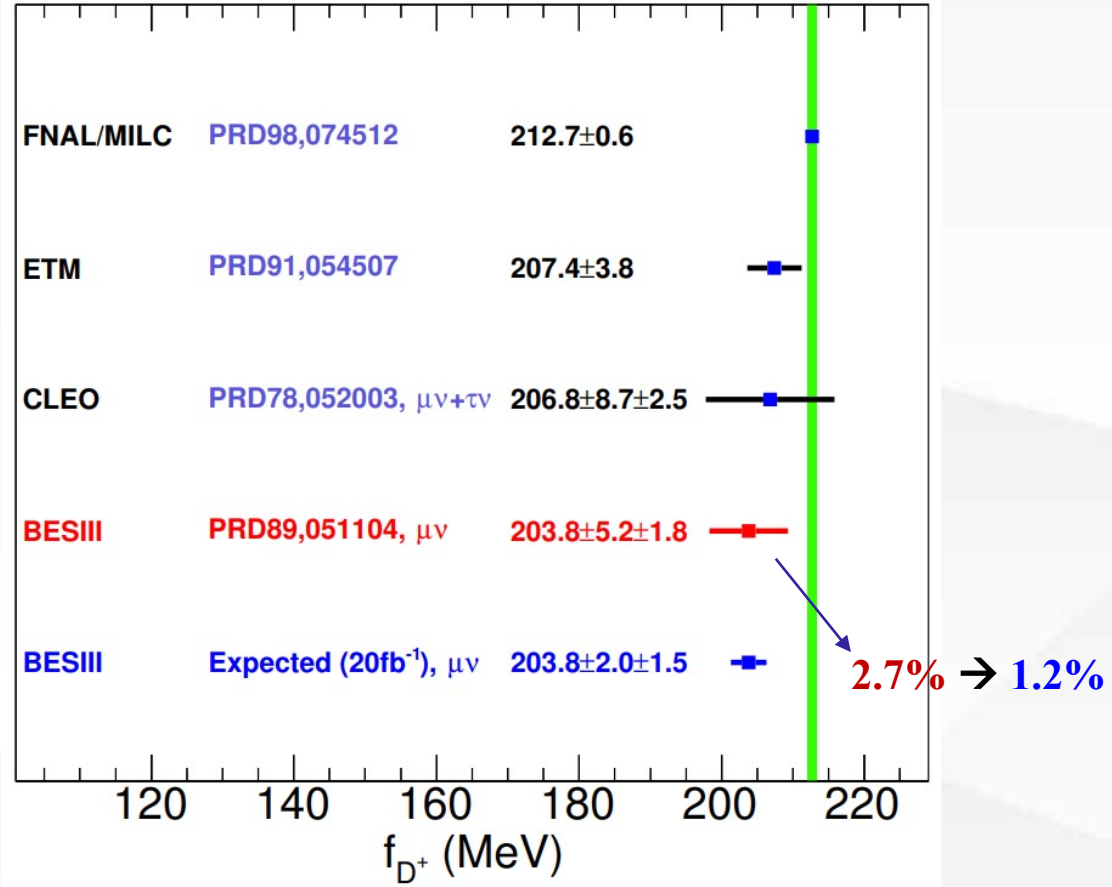
Backup

Other semi-leptonic D decays

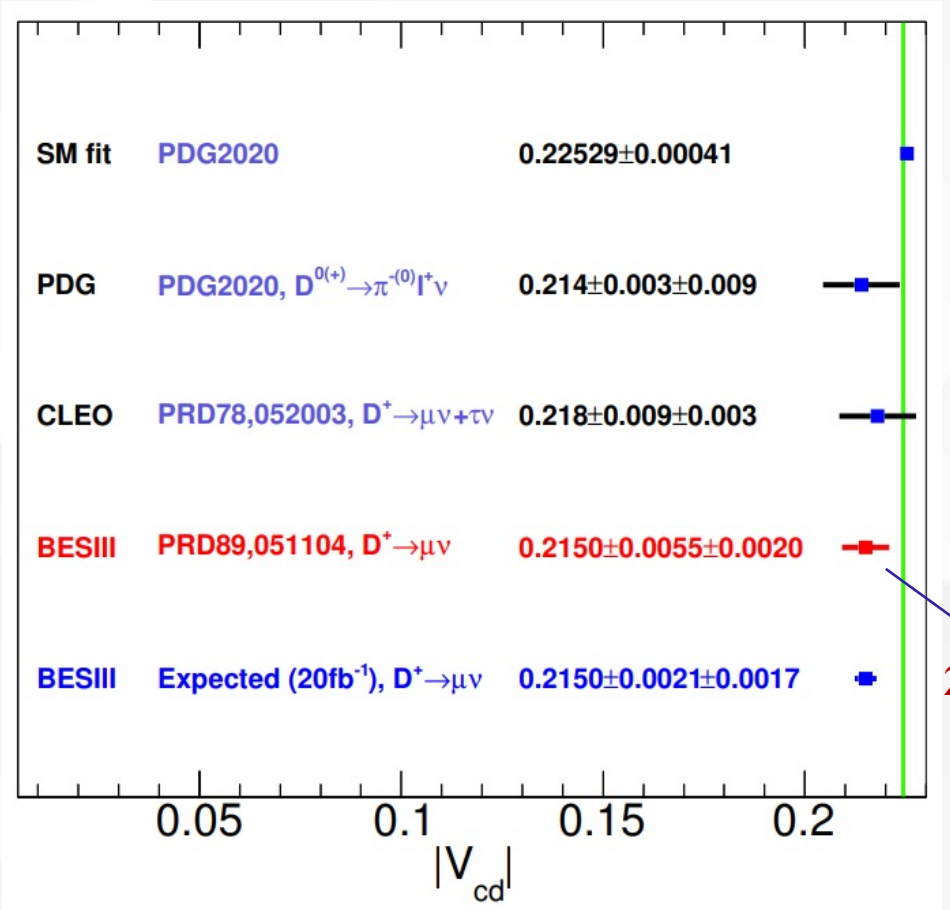
✓ $D^0 \to K_1(1270)^- e^+ \nu_e$	PRL127,131801(2021)
✓ $D^0 \to \rho\,(770)^- \mu^+ \nu_\mu$	PRD104,L091103(2021)
✓ $D^{0(+)} \to b_1(1235)^{-(0)} e^+ \nu_e$	PRD102,112005(2020)
✓ $D^+ \to \eta \mu^+ \nu_\mu$	PRL124,231801(2020)
✓ $D^+ \to \omega \mu^+ \nu_\mu$	PRD101,072005(2020)
✓ $D^+ \to K_1(1270)^0 e^+ \nu_e$	PRL123,231801(2019)
✓ $D^{0(+)} \to \pi^- \pi^{0(+)} e^+ \nu_e$	PRL122,062001(2019)
✓ $D_s^+ \to K^{(*)0} e^+ \nu$	PRL122,061801(2019)
✓ $D^0 \to \bar{K}^0 \pi^- e^+ \nu_e$	PRD99,011103R(2019)
✓ $D_s^+ \to p\bar{p} e^+ \nu_e$	PRD100,112008(2019)
✓ $D_s^+ \to \gamma e^+ \nu_e$	PRD99,072002(2019)
✓ $D^0 \to K^- \mu^+ \nu_\mu$	PRL122,011804(2019)
✓ $D^+ \to \tau^+ \nu_\tau$	PRL123,211802(2019)
✓ $D^{0(+)} \to a_0(980)^{-(0)} e^+ \nu$	PRL121,081802(2018)
✓ $D_s^+ \to \eta^{(')} \mu^+ \nu \; and \; \phi \mu^+ \nu$	PRD97,012006(2018)
✓ $D^+ \to \eta^{(')} e^+ \nu_e$	PRD97,092009(2018)
✓ $D^{0(+)} \to \pi^{-(0)} \mu^+ \nu_\mu$	PRL121,171803(2018)

Comparisons of f_{D^+} and $|V_{cd}|$

f_{D^+}

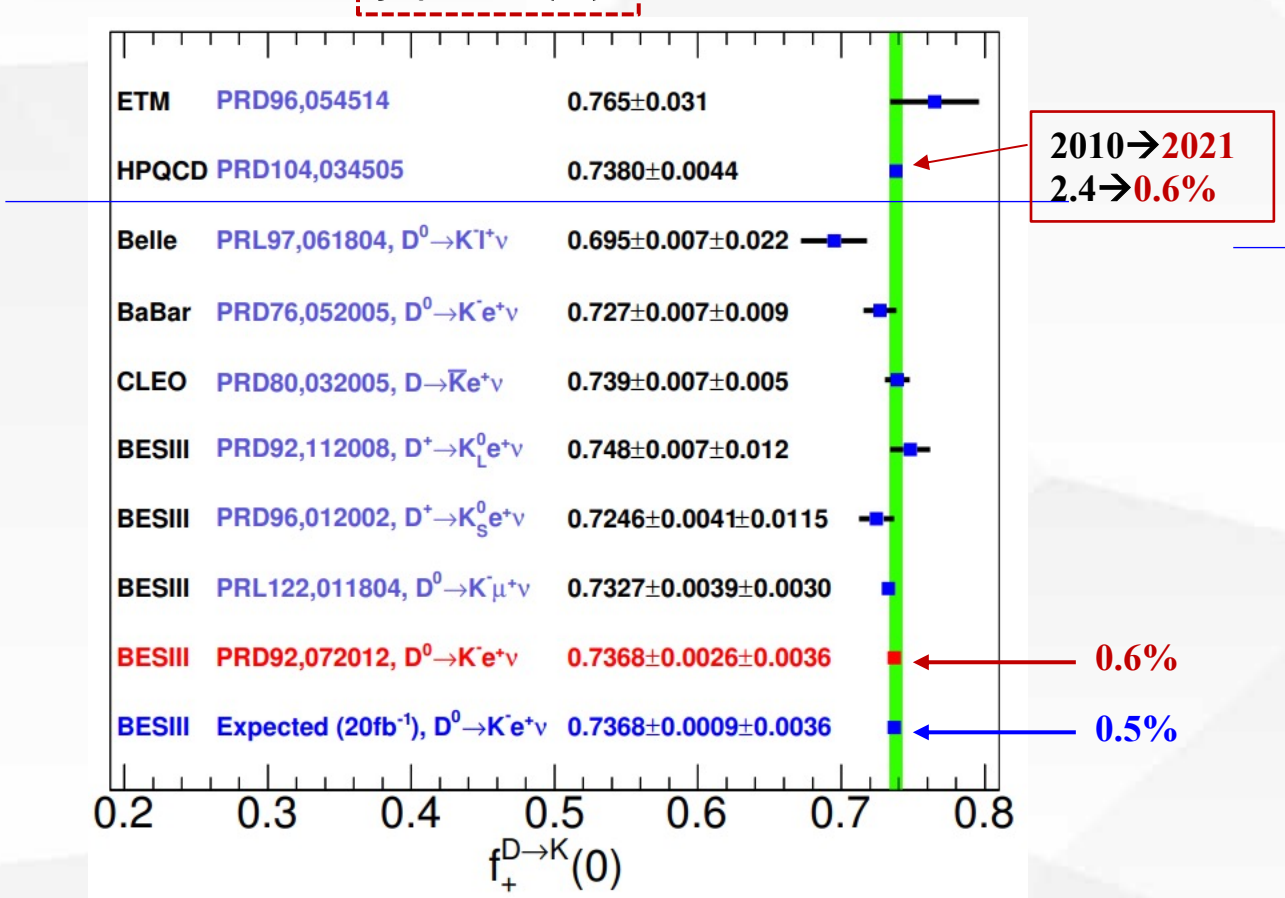


$|V_{cd}|$



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

$f_+^{D\to K}(0)$

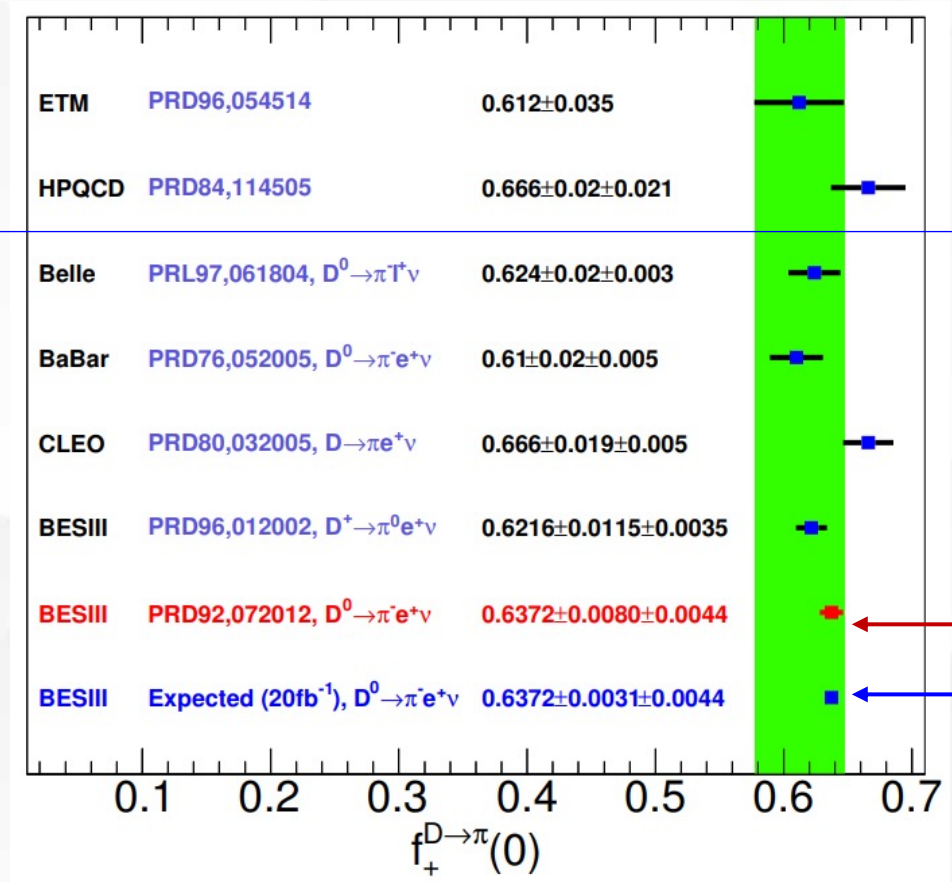


2010→2021
2.4→0.6%

0.6%

0.5%

$f_+^{D\to\pi}(0)$



>4%

1.6%

0.8%