# Charm physics at BESIII

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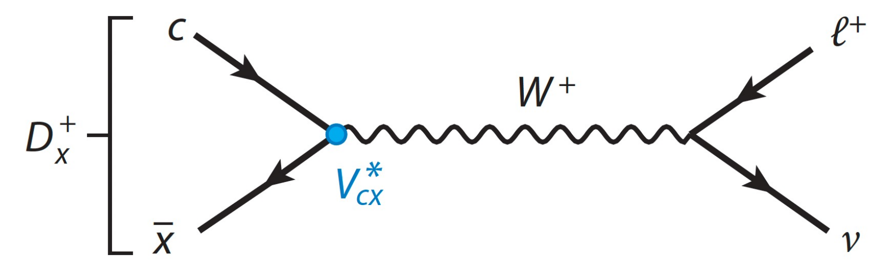
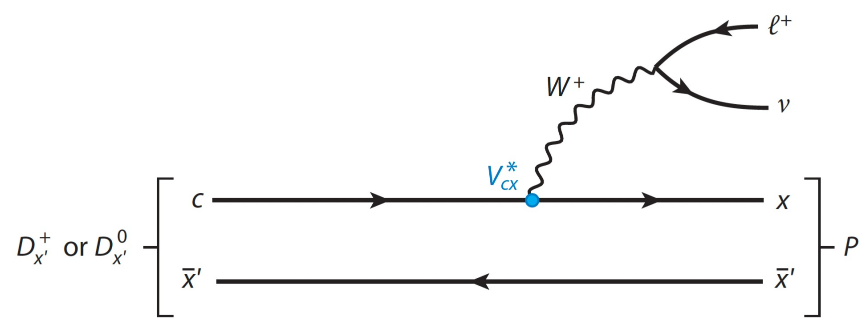
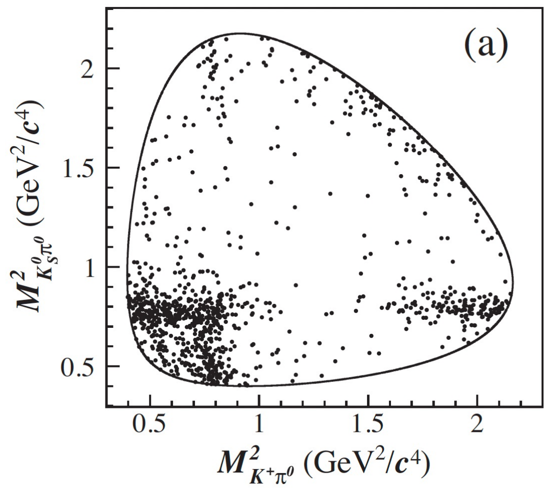
# Outline

- BESIII dataset
- Charmed meson ($D^0$, $D^+$, $D_s^+$)
  - pure leptonic decays
  - semi-leptonic decays
  - hadronic decays
  - quantum correlation
- Charmed baryon ($\Lambda_c^+$)
  - semi-leptonic decays
  - hadronic decays
- Prospect



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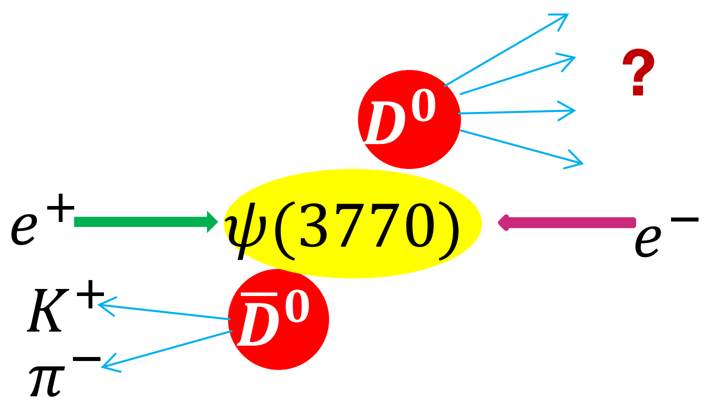
- Summary

# BESIII Data Taken near Threshold

- 7.9 fb$^{-1}$ at E$_{cm}$ 3.773 GeV: $e^+e^- \to \psi(3770) \to D\bar{D}$
- 7.3fb$^{-1}$ at E$_{cm}$ 4.128 - 4.226 GeV: $e^+e^- \to D_s D_s^*$
- 4.5 fb$^{-1}$ at Ecm = 4.600-4.699 GeV: $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$

**Production of charm hadron pair**




**Tag one side to study another side**

**Fully reconstruction** → **Clean sample** → **Hadronic decays**

**Recoil four-momentum** → **missing particle (neutrino)** → **(Semi)-leptonic decays**

**Absolute branching fraction**

**Amplitude analysis**

**etc.**

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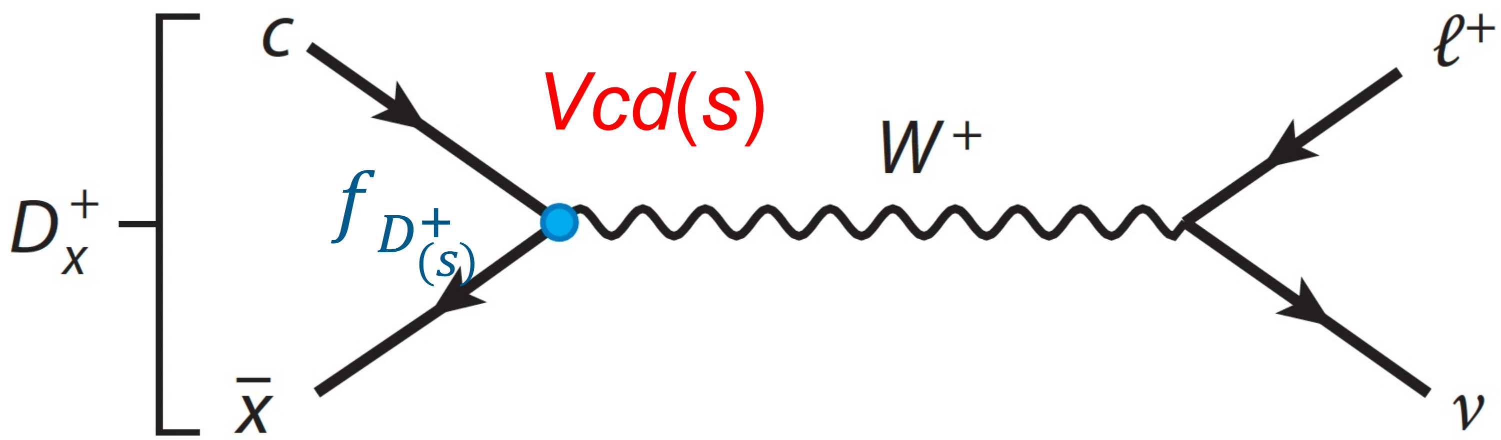
# Pure leptonic D decay




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

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

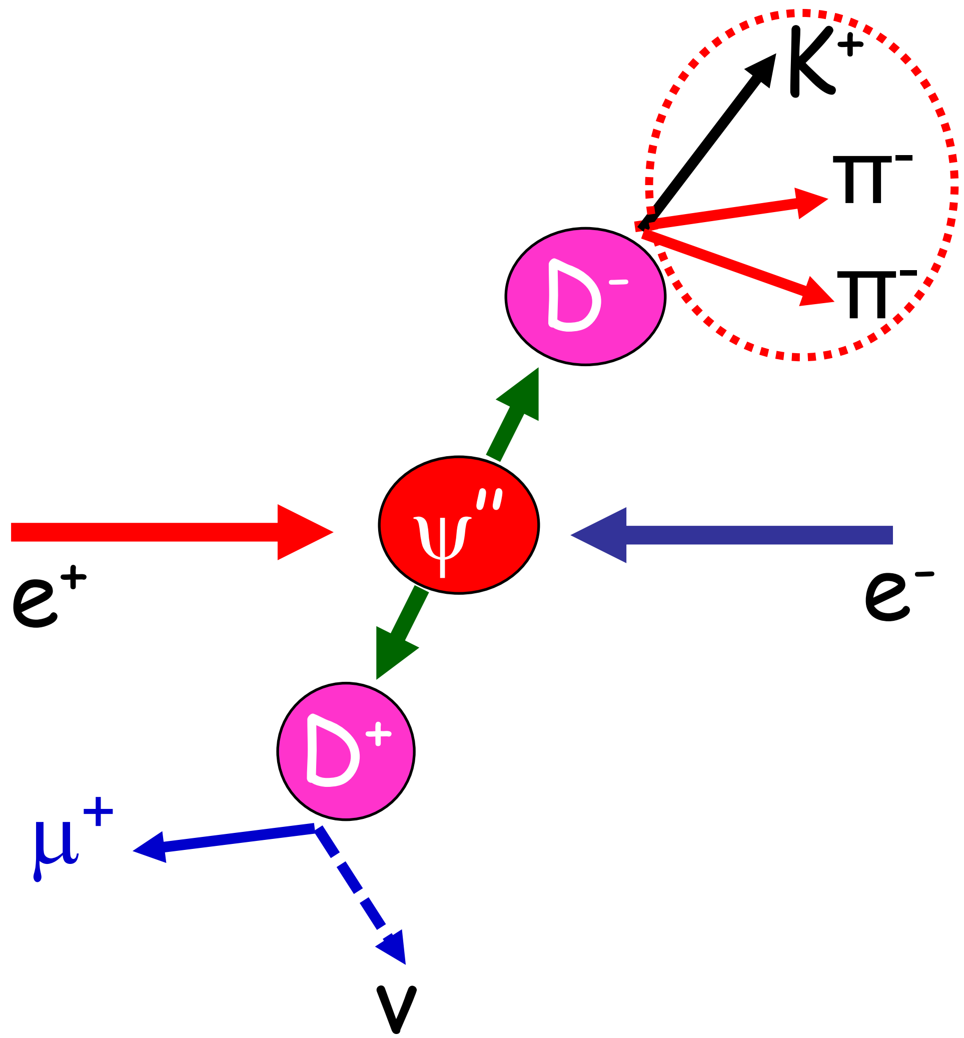
Calibrate Lattice QCD

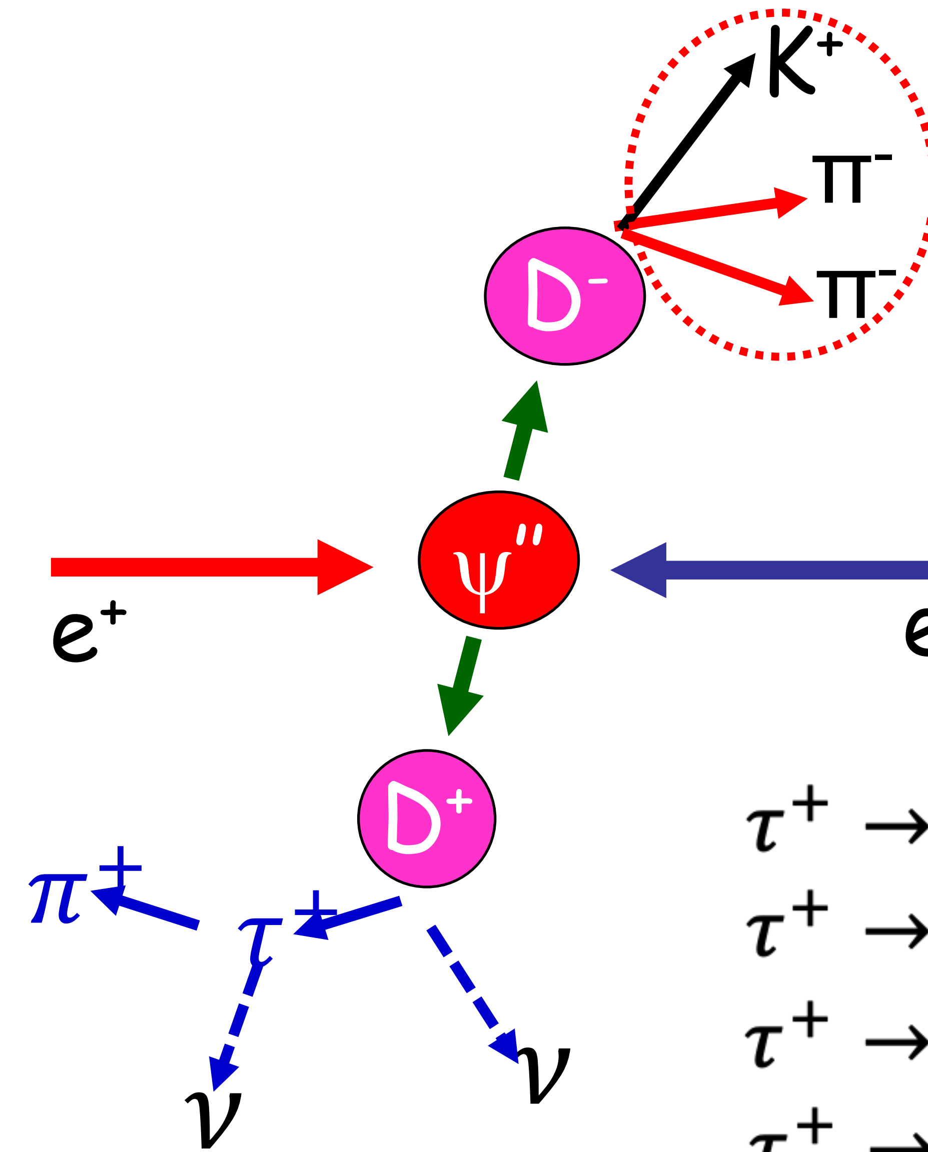
CKM matrix element $|V_{cd(s)}|$ :

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 |




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

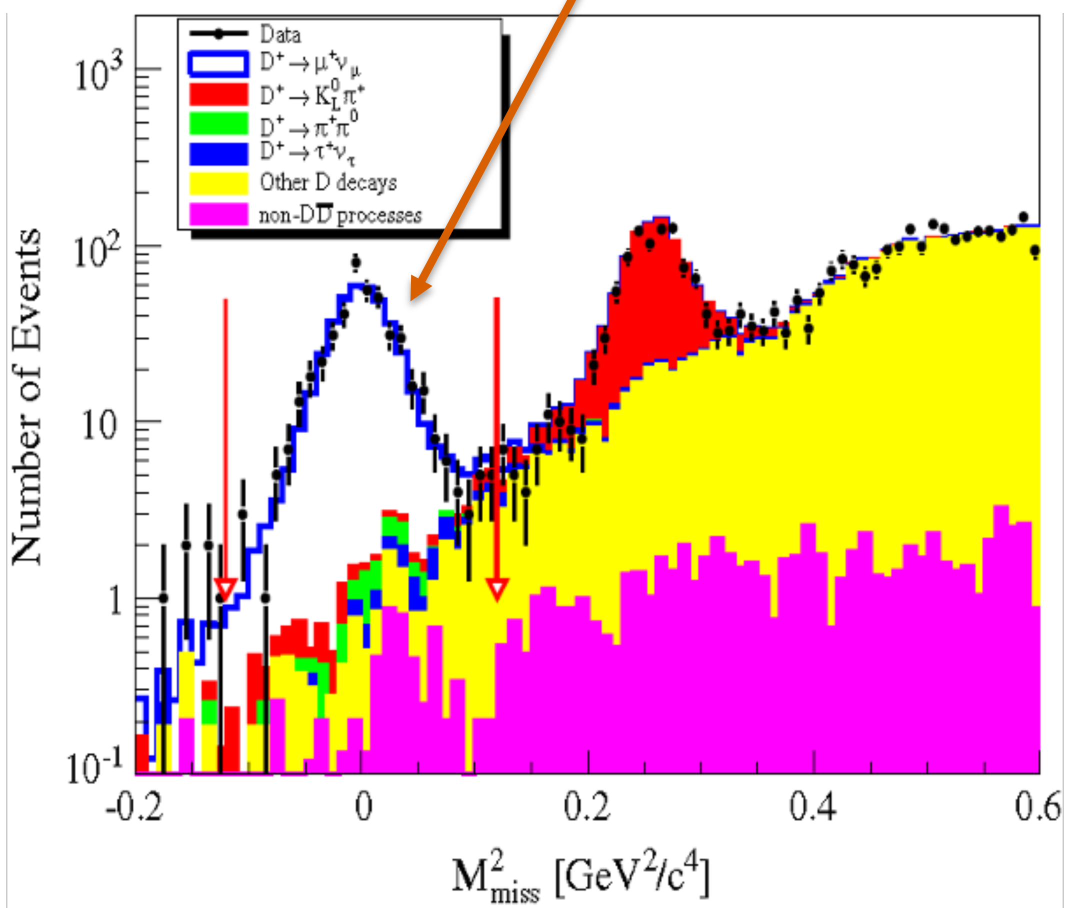
One neutrino missing in an muonic event

Two or three neutrinos missing in an tau event

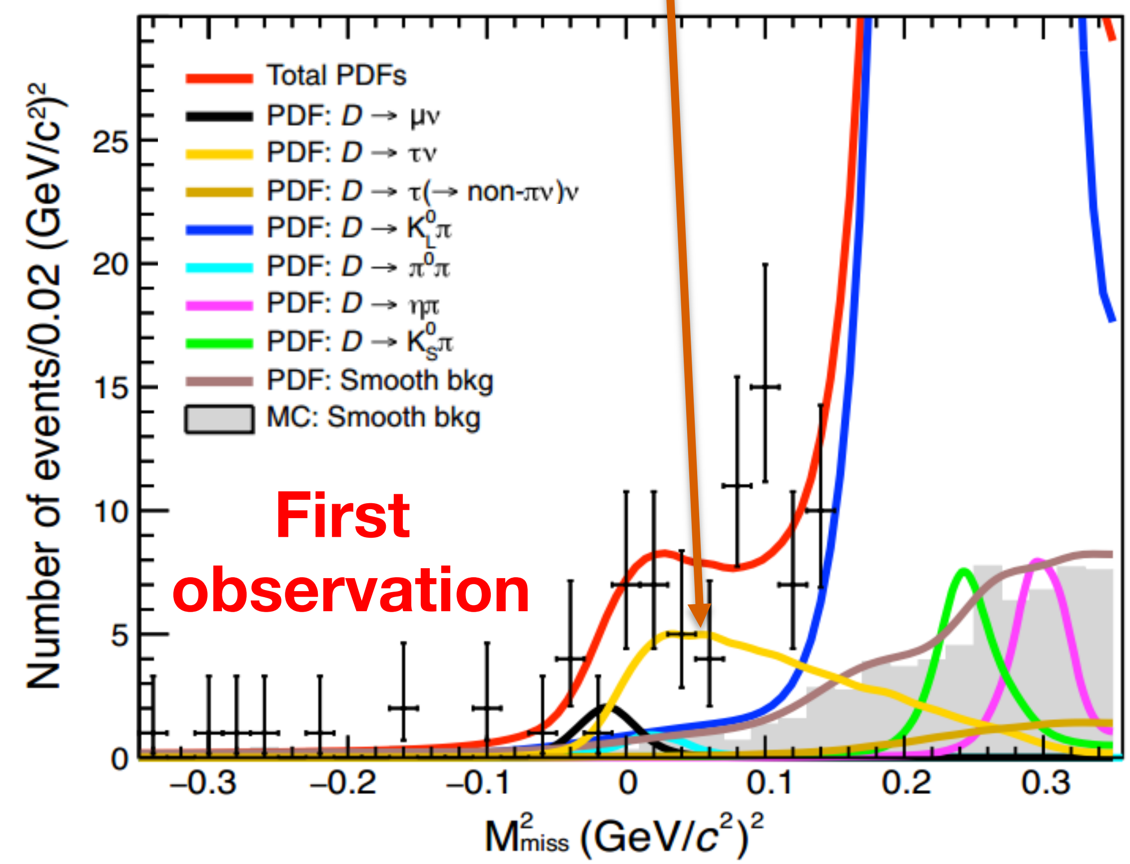
$$U_{\mathrm{miss}} = E_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|$$
$$M^2_{\mathrm{miss}} = E^2_{\mathrm{miss}} - |\vec{p}^{\,2}_{\mathrm{miss}}|$$

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

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




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




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

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

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

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

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

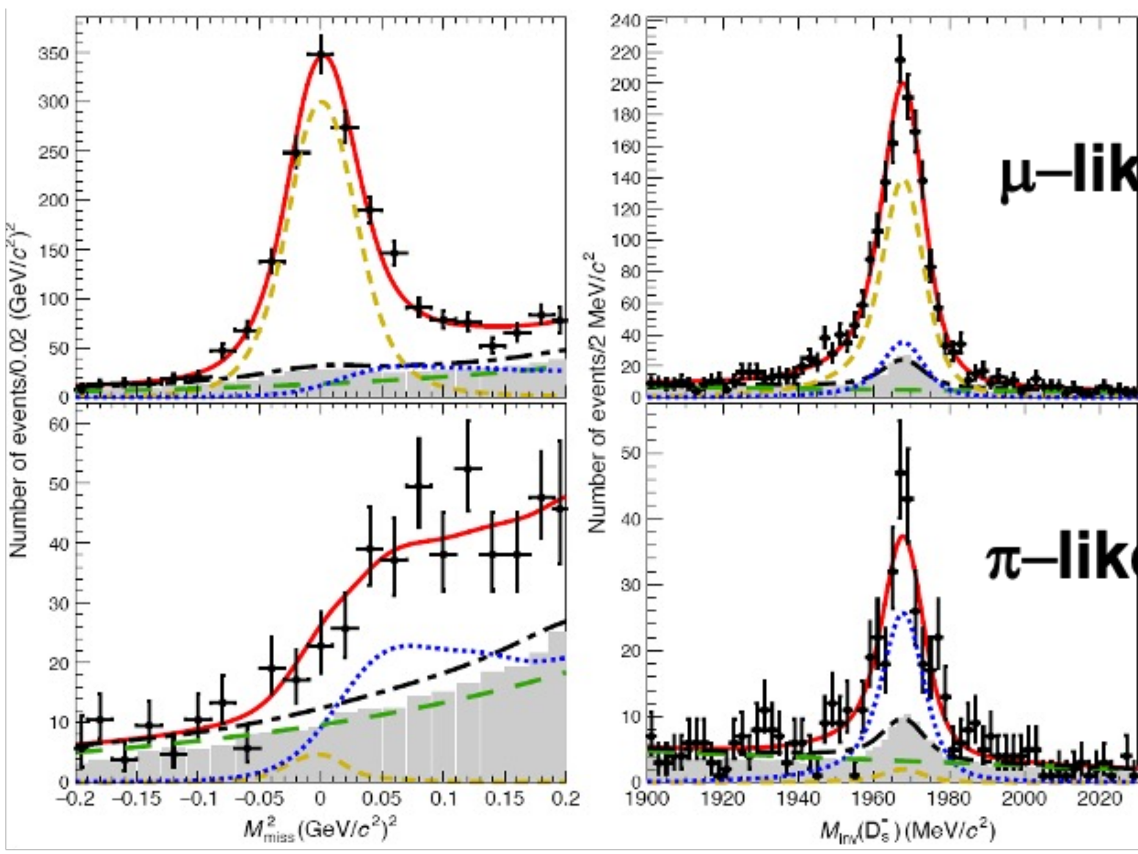
$f_{D^+}|V_{cd}| = 50.4 \pm 5.0 \pm 2.5$ MeV

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

Unfortunately $D^+ \to \tau^+\nu_\tau$ can't contribute to $D^+$ decay constant measurement

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

## $D_s^+ \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$




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

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

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

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

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

## $D_s^+ \to \tau^+(\rho^+\nu)\nu$

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

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

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

## $D_s^+ \to \tau^+(e^+\nu\nu)\nu$ most precise

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

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

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

## $D_s^+ \to \tau^+(\mu^+\nu\nu)\nu$

$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.34 \pm 0.16 \pm 0.10)\%$

$f_{D_s^+}|V_{cs}| = (246.2 \pm 3.7_{\rm stat} \pm 2.5_{\rm syst})$ MeV.

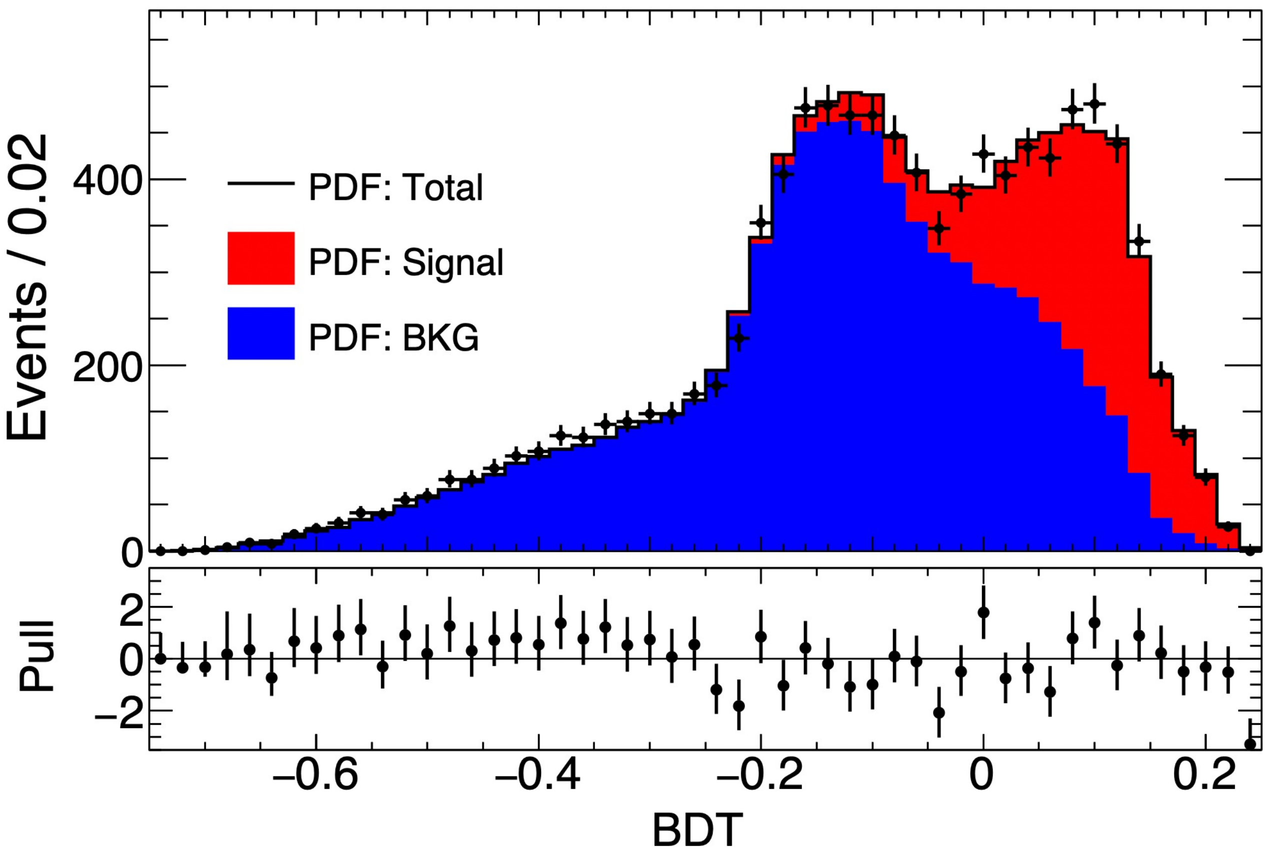
*arXiv: 2303.12468*

$D^+ \to \tau^+\nu_\tau$ can contribute comparable statistics to $\mu^+\nu$

## Remeasure $D_s^+ \to \tau^+(\pi^+\nu)\nu$ with BDT method New

arXiv: 2303.12600

**Fit to BDT score on signal channel**



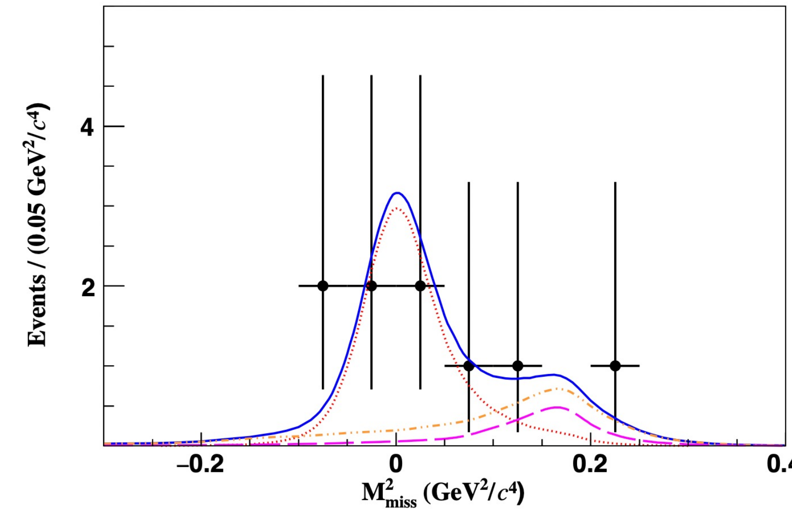

$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.41 \pm 0.17 \pm 0.13)\%$$

$$f_{D_s^+}|V_{cs}| = (247.6 \pm 3.9 \pm 3.2)\ \mathrm{MeV}$$

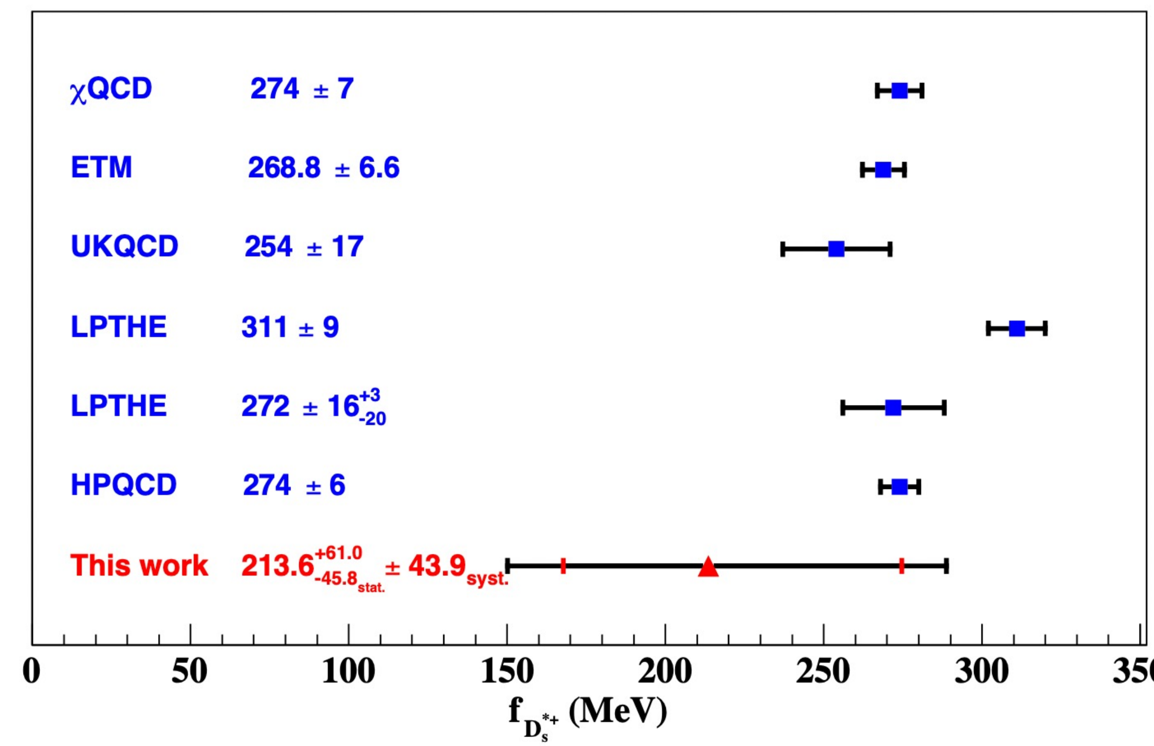
**Statistical precision is improved by a factor of 1.5**

## First experimental study of $D_s^{*+} \to e^+\nu$ New

Phys. Rev. Lett. 131, 14180(2023)




**First experimental result on $f_{D_s^{*+}}$**




$$\mathcal{B}(D_s^{*+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9} \pm 0.2)\text{x}10^{-5}$$

with significance $2.9\sigma$

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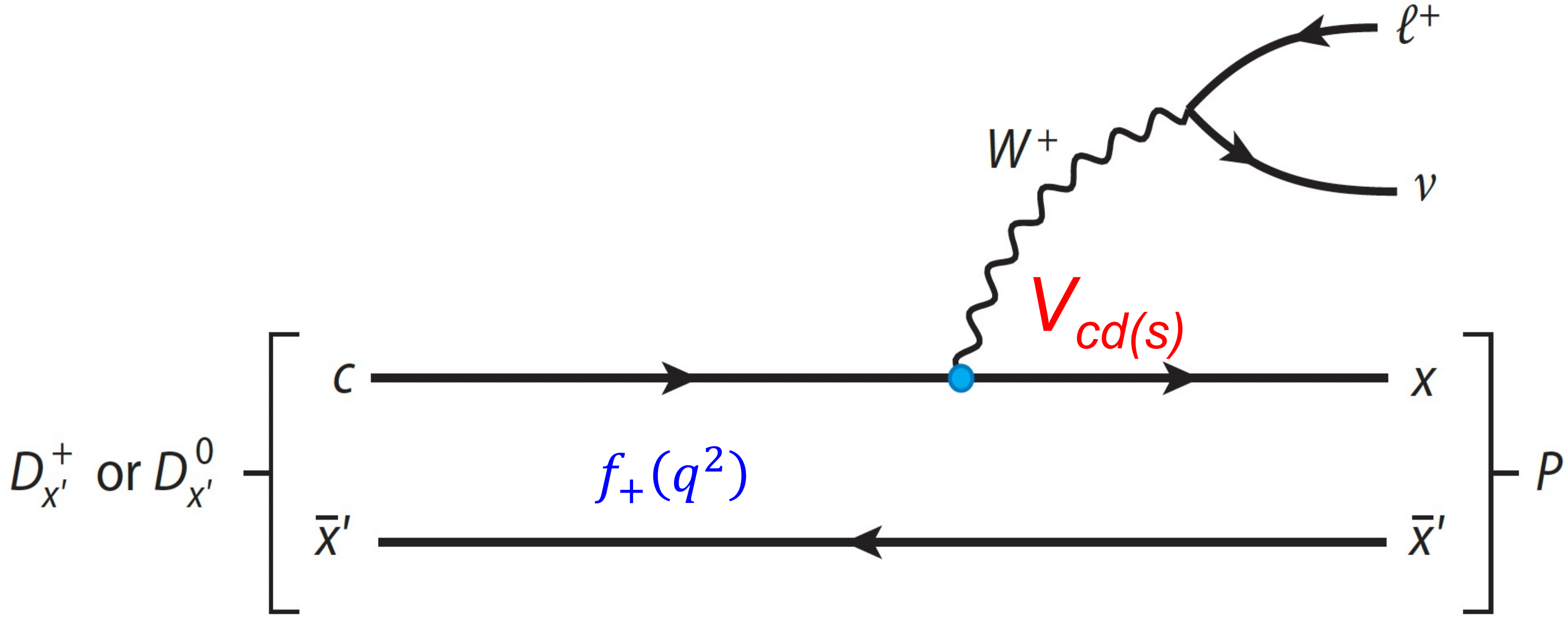
# Semi-leptonic $D \to Pe^+\nu$



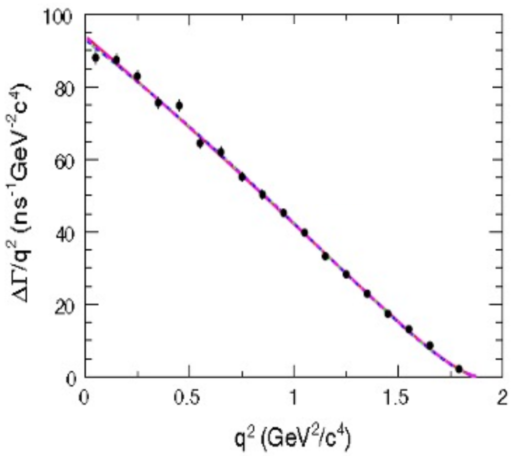

$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2 p^3}{24\pi^3}|f_+(q^2)|^2\left|V_{cd(s)}\right|^2$$

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

Form factor $f_+(0)$: Calibrate Lattice QCD

CKM matrix element $|V_{cd(s)}|$: Test the unitarity of CKM matrix

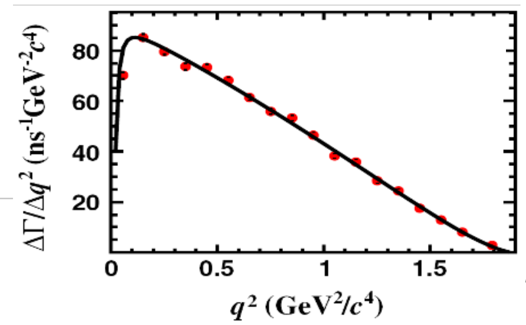
Test $\mathrm{e} - \mu$ Lepton flavor universality




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

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

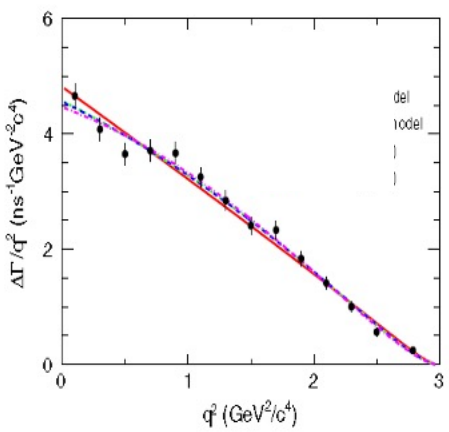
*Phys. Rev. D 92, 072012 (2015)*




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

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

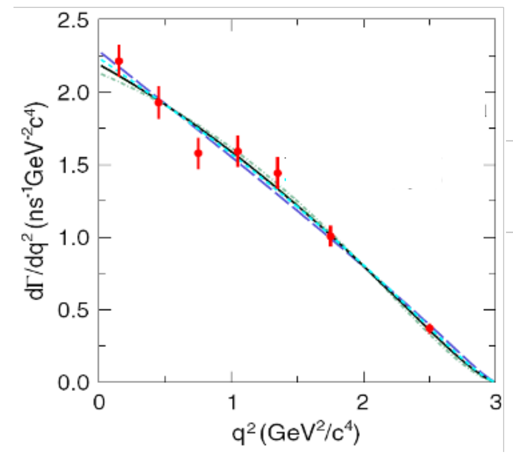
*Phys. Rev. Lett. 122, 011804 (2019)*




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

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

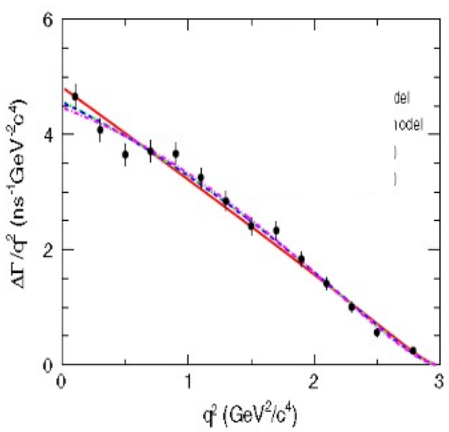
*Phys. Rev. D 92, 072012 (2015)*




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

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

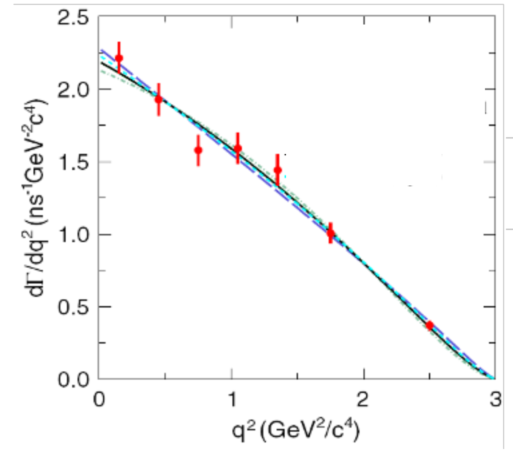
*Phys. Rev. D 96, 012002 (2017)*




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

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

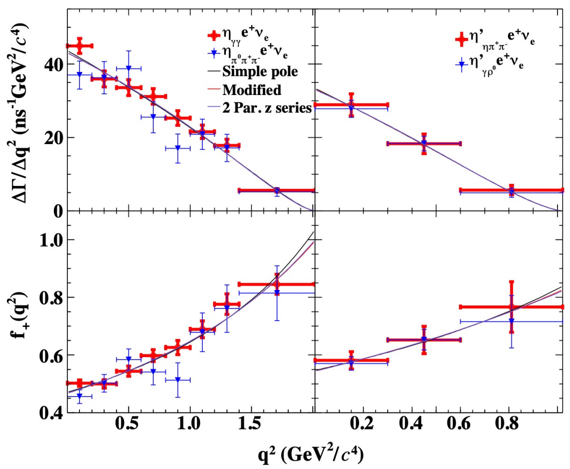
*Phys. Rev. D 92, 072012 (2015)*




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

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

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




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

$f_+^{\eta}(0)|V_{cs}| = 0.4553 \pm 0.0071_{\rm stat} \pm 0.0061_{\rm syst}$

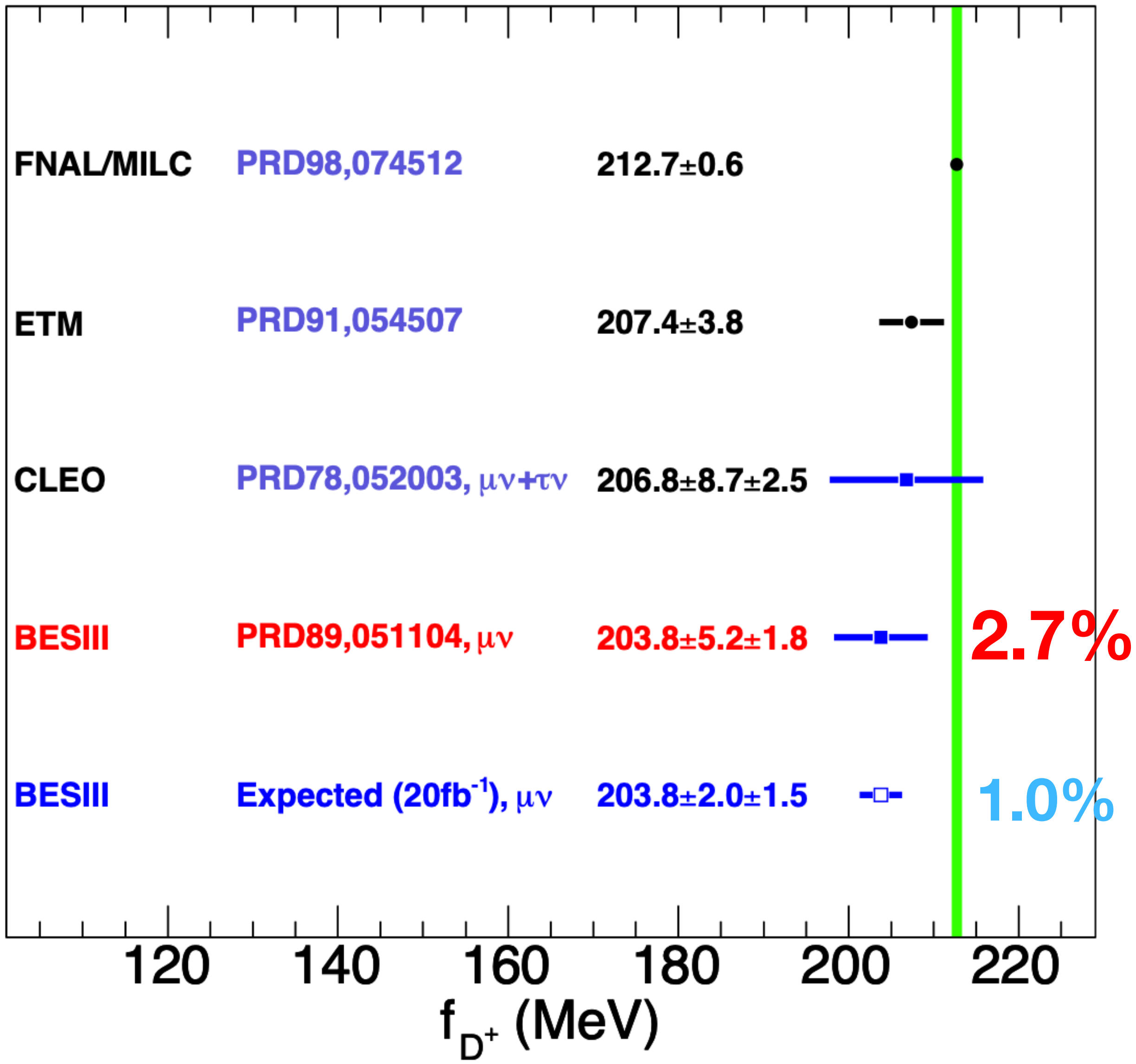
$f_+^{\eta'}(0)|V_{cs}| = 0.529 \pm 0.024_{\rm stat} \pm 0.008_{\rm syst}$

*arXiv:2306.05194*

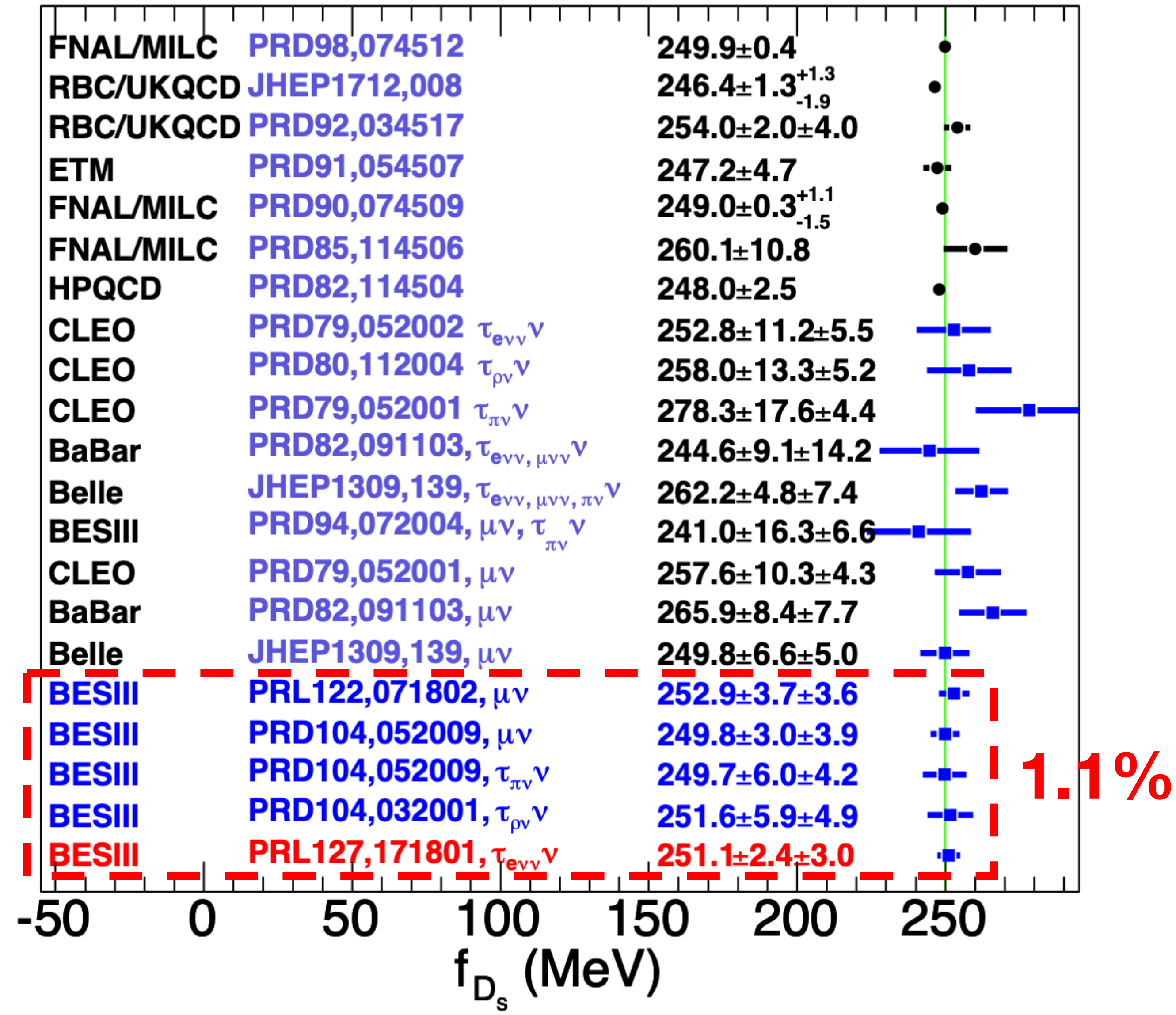
*Phys. Rev. Lett. 123, 121801 (2019)*

# Comparison of decay constant

$f_{D^+}$



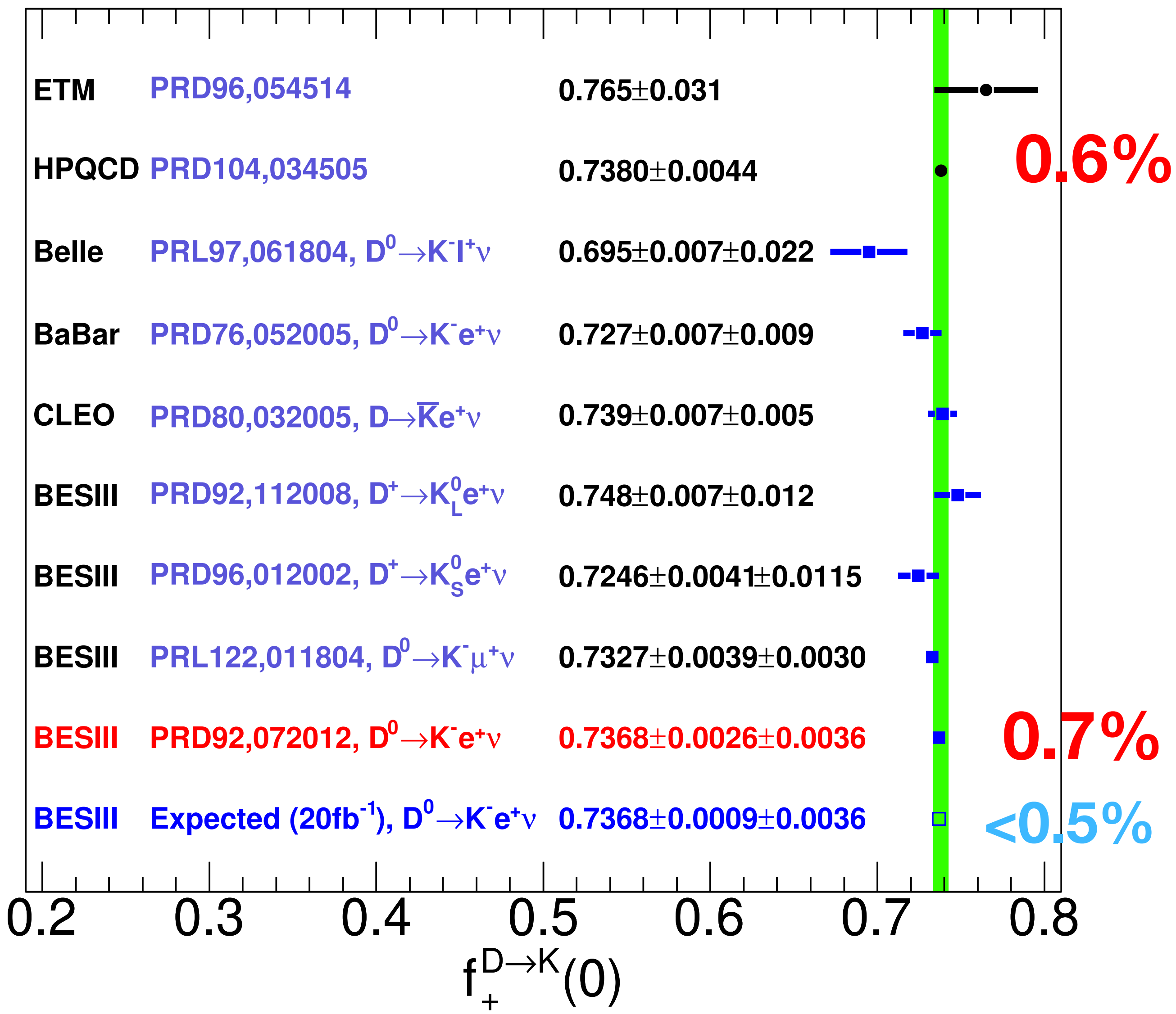

$f_{D_s^+}$



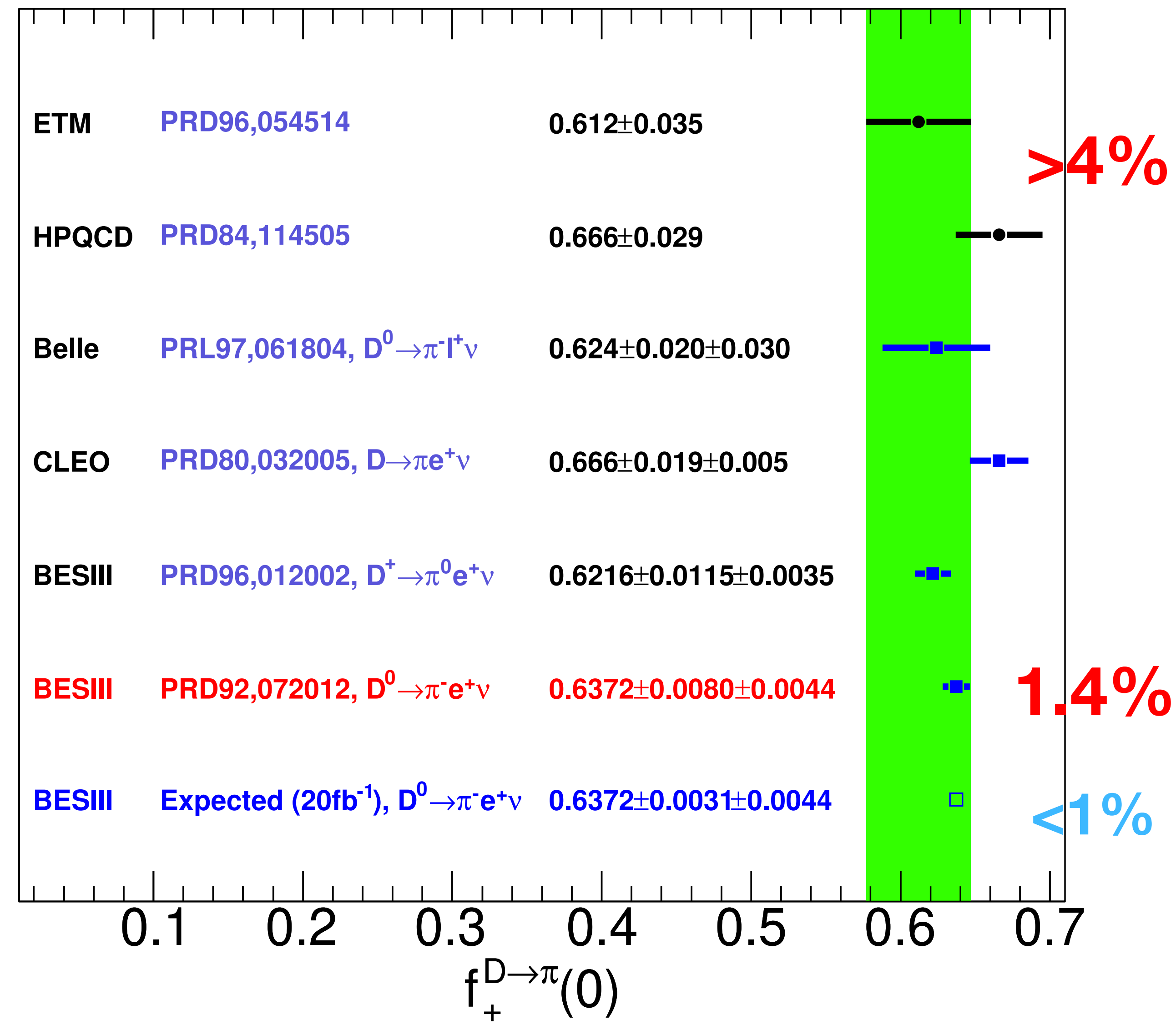

**Dominated by statistical uncertainty**

# Comparison of form factor

$D \to K$



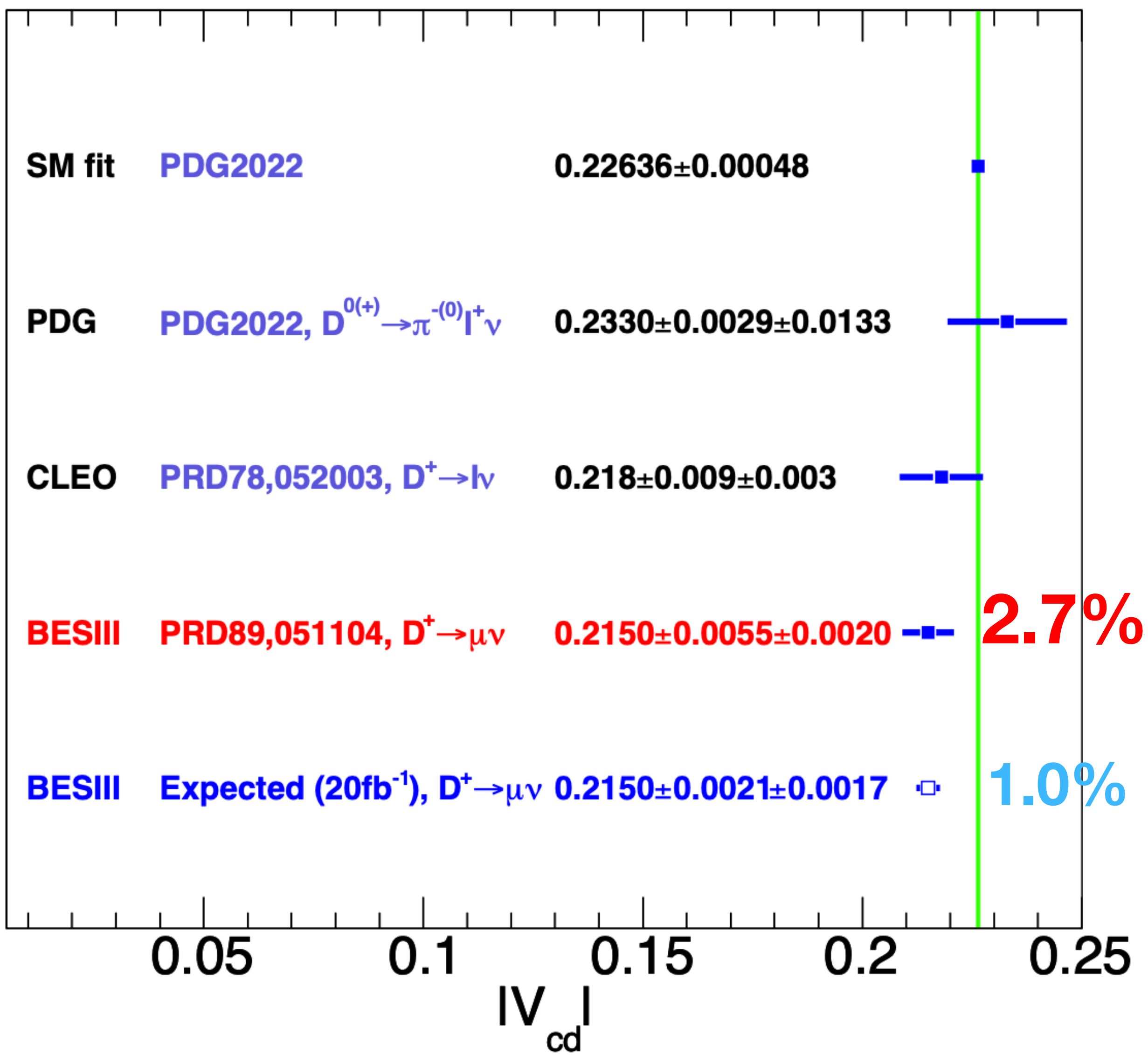

$D \to \pi$



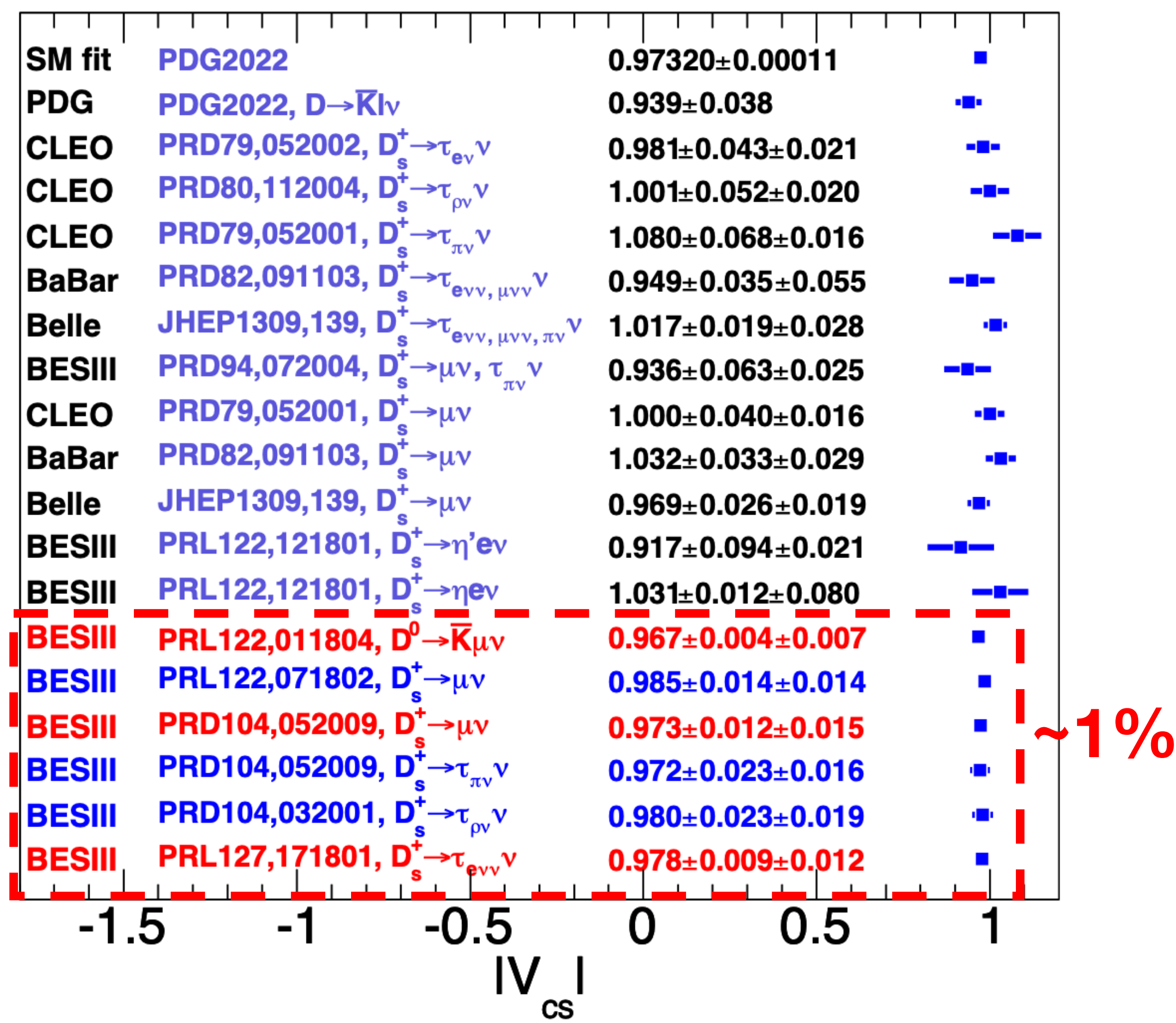

**Experimental precision is comparable to the latest QCD result**

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

$|V_{cd}|$




$|V_{cs}|$




**Both pure- and semi-leptonic decays contribute**

# We have also study…

$D \to Sl\nu$

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

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

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

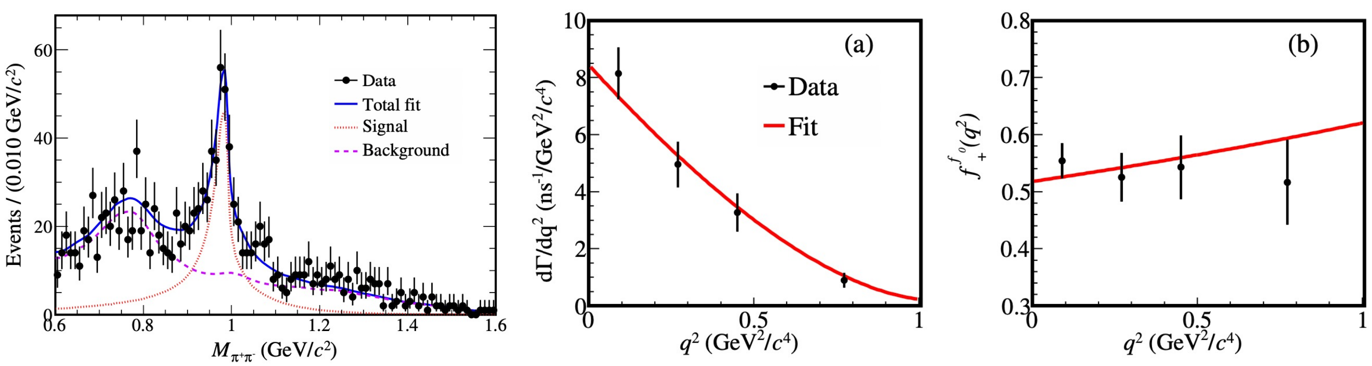
Study $f_0(980)$ in $D_s^+ \to \pi^+\pi^- e^+\nu_e$

$\mathcal{B} = (1.72 \pm 0.13 \pm 0.10)\times 10^{-3}$

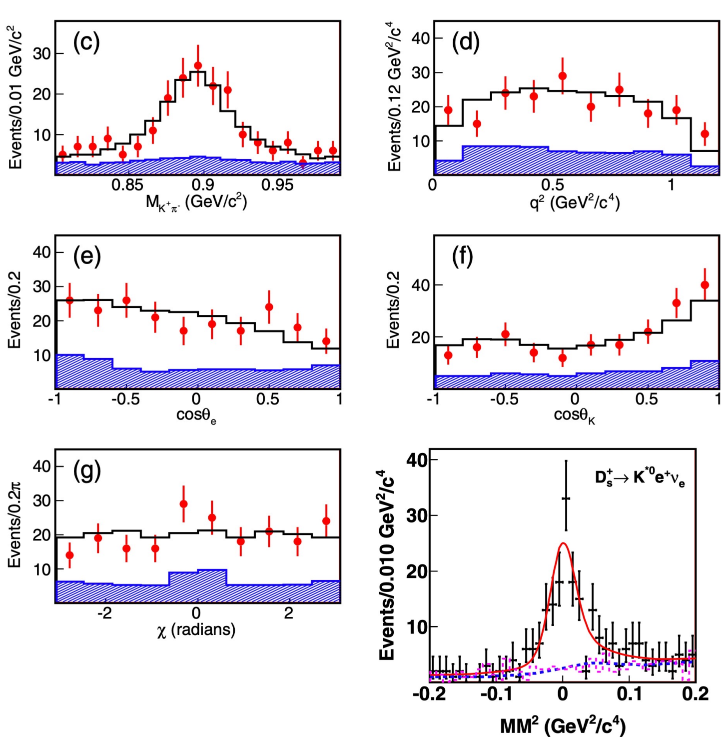
$f_+^{f_0}(0)|V_{cs}| = 0.504 \pm 0.017 \pm 0.035$

arXiv:2303.12927

First measurement




$D \to Vl\nu$




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

$\mathcal{B} = (2.37 \pm 0.26 \pm 0.20)\times 10^{-3}$

$r_V = 1.67 \pm 0.34 \pm 0.16$

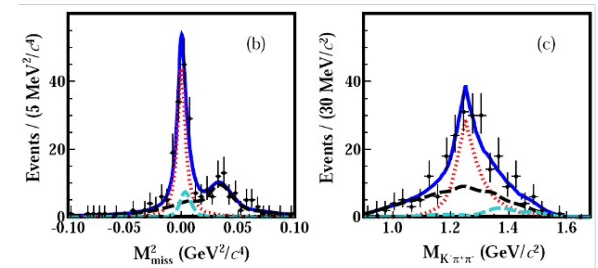
$r_2 = 0.77 \pm 0.28 \pm 0.07$

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

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

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

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

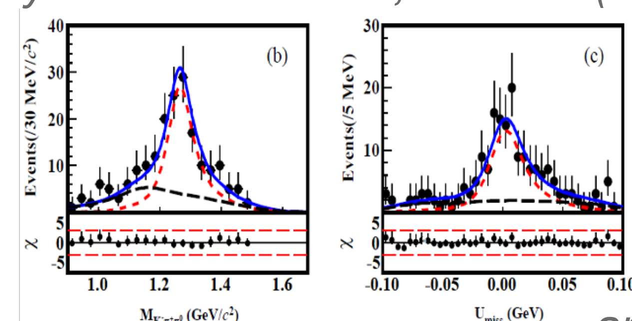



$D \to Al\nu$

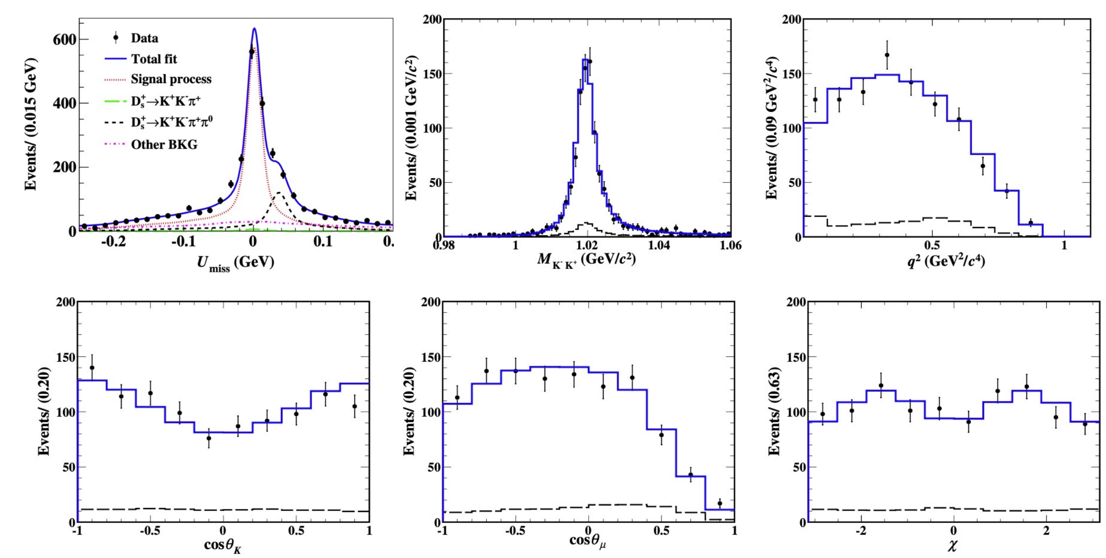
$D^+ \to K_1(1270)^0 e^+\nu$

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

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




arxiv: 2307.03024




$D_s^+ \to \phi\mu^+\nu_e$

$\mathcal{B} = (2.25 \pm 0.09 \pm 0.07)\times 10^{-2}$

$r_V = 1.58 \pm 0.17 \pm 0.02$

$r_2 = 0.77 \pm 0.28 \pm 0.07$

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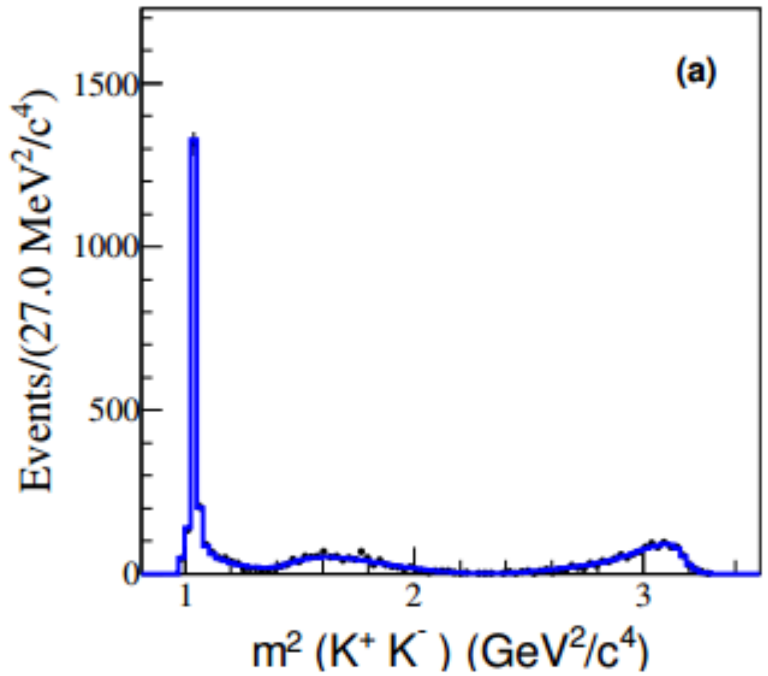
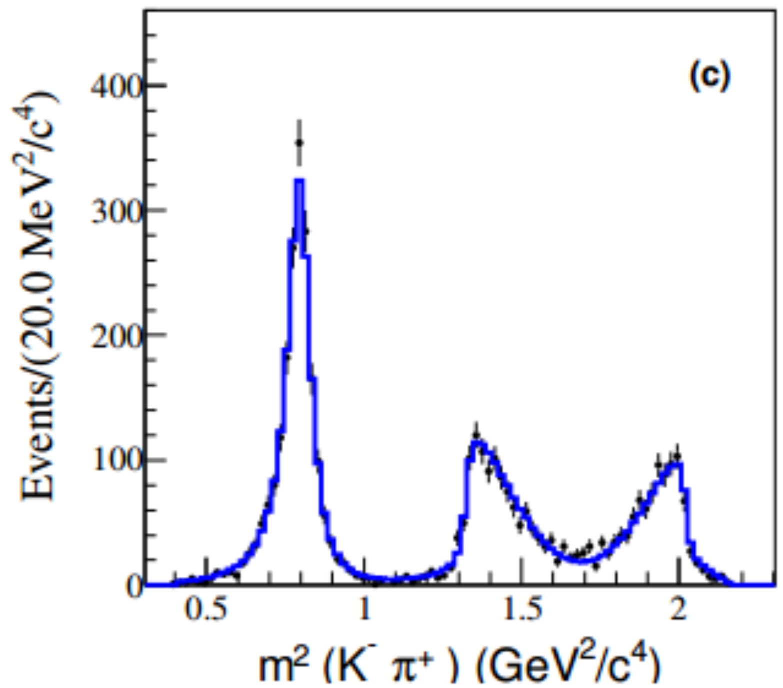
# Amplitude analysis of $D_s^+ \to K^+K^-\pi^+$

**Dalitz plot projections:**




**Considering interference of $D_s \to \phi\pi$ and other processes, such as $D_s \to K^*K$**

**The best precision at present**

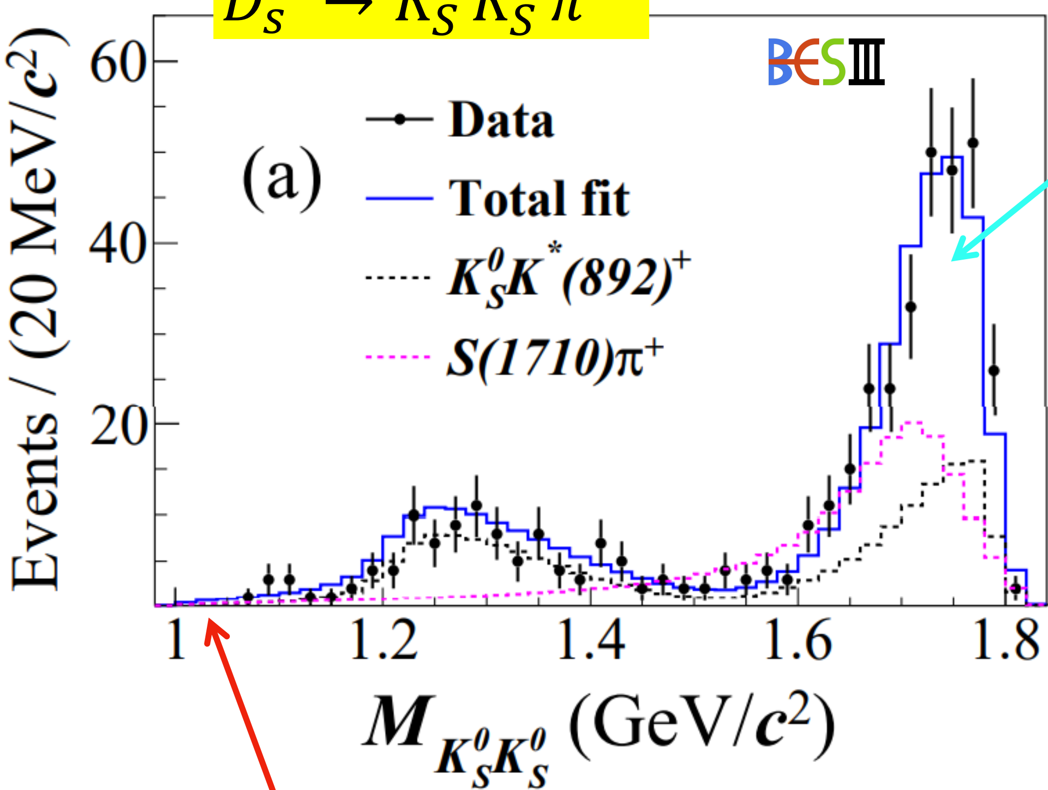
$$\mathcal{B}(D_s^+ \to K^+K^-\pi^+) = (5.47 \pm 0.08_{stat.} \pm 0.13_{syst.})\%$$

| Process | BF (%) | |
|---|---|---|
| | BESIII (this analysis) | PDG |
| $D_s^+ \to \bar{K}^*(892)^0K^+$, $\bar{K}^*(892)^0 \to K^-\pi^+$ | $2.64 \pm 0.06_{\rm stat} \pm 0.07_{\rm sys}$ | $2.58 \pm 0.08$ |
| $D_s^+ \to \phi(1020)\pi^+$, $\phi(1020) \to K^+K^-$ | $2.21 \pm 0.05_{\rm stat} \pm 0.07_{\rm sys}$ | $2.24 \pm 0.08$ |
| $D_s^+ \to S(980)\pi^+$, $S(980) \to K^+K^-$ | $1.05 \pm 0.04_{\rm stat} \pm 0.06_{\rm sys}$ | $1.14 \pm 0.31$ |
| $D_s^+ \to \bar{K}_0^*(1430)^0K^+$, $\bar{K}_0^*(1430)^0 \to K^-\pi^+$ | $0.16 \pm 0.03_{\rm stat} \pm 0.03_{\rm sys}$ | $0.18 \pm 0.04$ |
| $D_s^+ \to f_0(1710)\pi^+$, $f_0(1710) \to K^+K^-$ | $0.10 \pm 0.02_{\rm stat} \pm 0.03_{\rm sys}$ | $0.07 \pm 0.03$ |
| $D_s^+ \to f_0(1370)\pi^+$, $f_0(1370) \to K^+K^-$ | $0.07 \pm 0.02_{\rm stat} \pm 0.01_{\rm sys}$ | $0.07 \pm 0.05$ |
| $D_s^+ \to K^+K^-\pi^+$ total BF | $5.47 \pm 0.08_{\rm stat} \pm 0.13_{\rm sys}$ | $5.39 \pm 0.15$ |

# Observation of $a_0(1817)$ in $D_s$ decays

$D_s^+ \to K_S^0 K_S^0 \pi^+$

PRD 105, L051103 (2022)



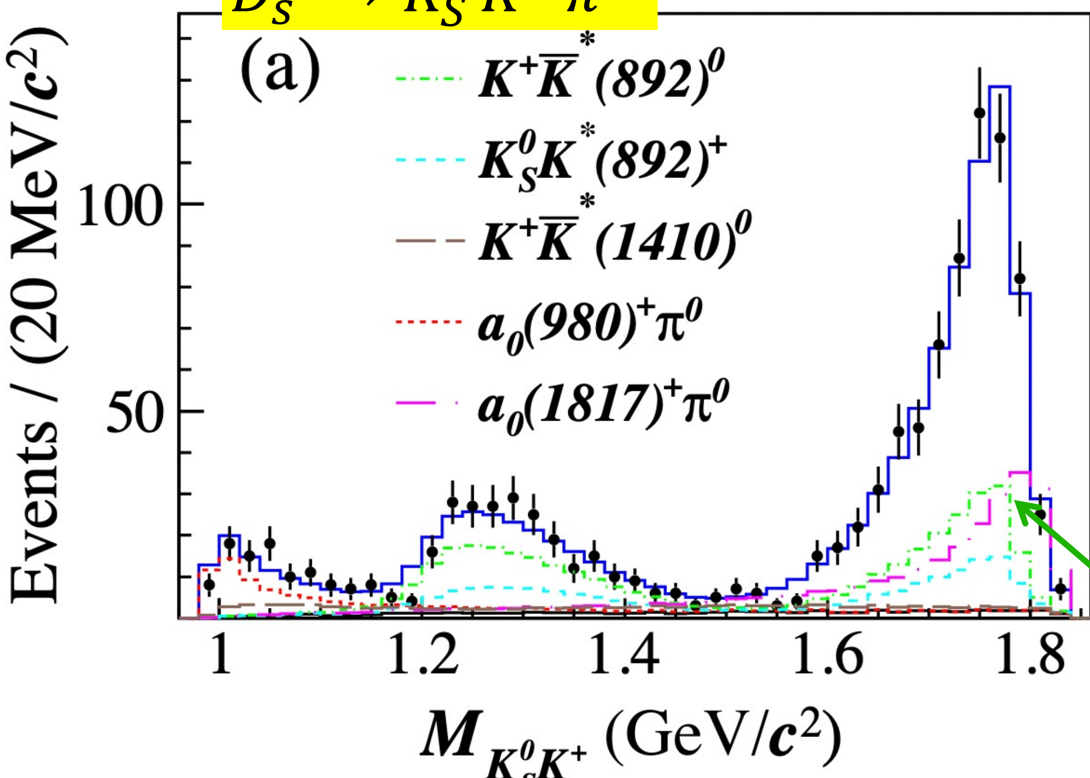

**constructive interference: $a_0(1817)$ and $f_0(1710)$**

**destructive interference: $a_0(980)$ and $f_0(980)$**

- **The isovector partner of $f_0(1710)$ or $X(1812)$?**
- **Same resonance observed in $\eta_c$ to $\pi\pi\eta$ by BaBar?** PRD 104, 072002 (2021)

$D_s^+ \to K_S^0 K^+ \pi^0$

PRL 129, 182001




- $M = 1.817 \pm 0.008 \pm 0.020$ GeV/$c^2$
- $\Gamma = 0.097 \pm 0.022 \pm 0.015$ GeV/$c^2$
- $\mathcal{B}(D_s^+ \to a_0(1817)^+\pi^0) = (3.44 \pm 0.52 \pm 0.32) \times 10^{-3}$
- **Significance $> 10\sigma$**

**$a_0(1817)^+$ in $K_S^0 K^+$ mass spectrum**

# Amplitudes analyses of $D_s$ decays

| | |
|---|---|
| $D_S^+ \to \pi^+\pi^0\eta$ | **Phys. Rev. Lett. 123, 112001 (2019)** |
| $D_s^+ \to K^+K^-\pi^+$ | **Phys. Rev. D 104, 112016 (2019)** |
| $D_s^+ \to K^+K^-\pi^+\pi^0$ | **Phys. Rev. D 104, 032011** (2021) |
| $D_s^+ \to K_s^0K^-\pi^+\pi^+$ | **Phys. Rev. D 103 , 092006 (2021)** |
| $D_s^+ \to \pi^+\pi^-\pi^+\eta$ | **Phys. Rev. D 104, L071101 (2021)** |
| $D_s^+ \to K_S^0\pi^+\pi^0$ | **JHEP 06, 181 (2021)** |
| $D_s^+ \to K_S^0K^+\pi^0$ | **Phys. Rev. Lett 129, 182001 (2022)** |
| $D_s^+ \to K_S^0K_S^0\pi^+$, | **Phys. Rev. D 105, L051103 (2022)** |
| $D_s^+ \to \pi^+\pi^0\eta'$ | **JHEP 04, 058 (2022)** |
| $D_s^+ \to \pi^+\pi^-\pi^+$ | **Phys. Rev. D 106, 112006 (2022)** |
| $D_s^+ \to \pi^+\pi^0\pi^0$ | **JHEP 01, 052 (2022)** |
| $D_s^+ \to K^+\pi^+\pi^-$ | **JHEP 08, 196 (2022)** |
| $D_S^+ \to K^+K^-\pi^+\pi^+\pi^-$ | **JHEP 07, 051 (2022)** |
| $D_S^+ \to K^+\pi^+\pi^-\pi^0$ | **JHEP 09(2022) 242** |
| $D_S^+ \to K^+\pi^+\pi^-$ | **JHEP 08(2022) 196** |

**We have finished amplitude analyses of most three and four body decays of Ds**

# Observation of the DCSD $D^+ \to K^+\pi^+\pi^-\pi^0$

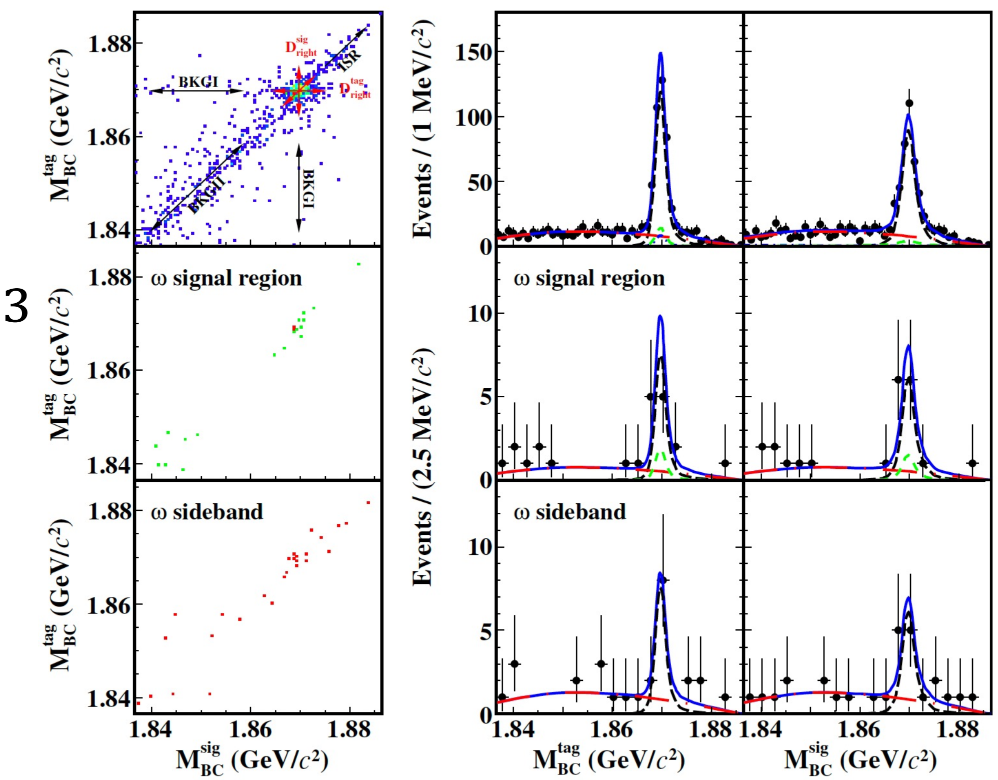
Use hadronic tags. 350 signal events

$$\mathcal{B}(D^+ \to K^+\pi^+\pi^-\pi^0) = (1.13 \pm 0.08 \pm 0.03)\times 10^{-3}$$

$$\frac{\mathcal{B}(D^+ \to K^+\pi^+\pi^-\pi^0)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)} = (1.81 \pm 0.15)\%$$

Corresponding to $(6.28 \pm 0.52)\, tan^4\theta_C$

One order larger than normal

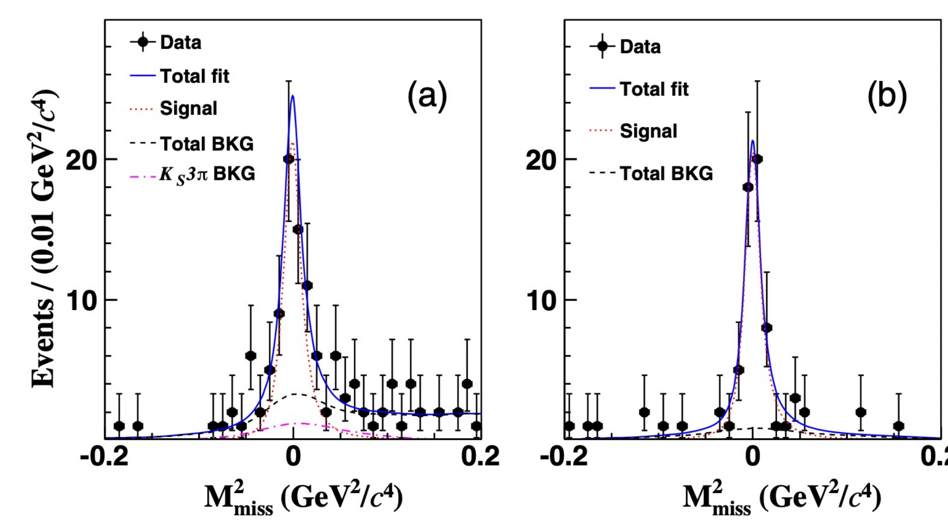



PRL 125, 141802 (2020)

Use semileptonic tags. 112 signal events

$$\mathcal{B}(D^+ \to K^+\pi^+\pi^-\pi^0) = (1.03 \pm 0.12 \pm 0.06)\times 10^{-3}$$

First try of semileptonic tag at BESIII




PRD 104, 072005 (2021)

# $D^+ \to K^+\pi^0\pi^0$ and $D^+ \to K^+\pi^0\eta$

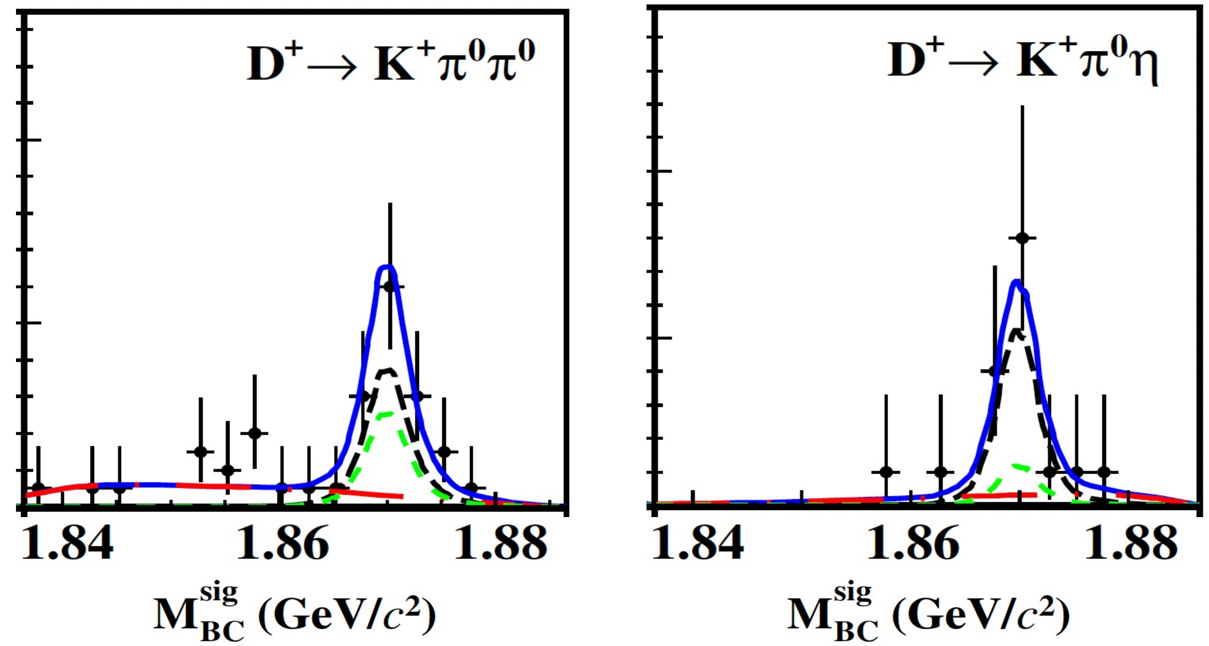
$\mathcal{B}(D^+ \to K^+\pi^0\pi^0) = (\mathbf{2.1 \pm 0.4 \pm 0.1}) \times 10^{-4}$

$$\frac{\mathcal{B}(D^+ \to K^+\pi^0\pi^0)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (2.24 \pm 0.40)\times 10^{-3}$$

$(0.77 \pm 0.14)\ tan^4\theta_C$

$$\frac{\mathcal{B}(D^+ \to K^+\pi^0\eta)}{\mathcal{B}(D^+ \to \overline{K^0}\pi^+\eta)} = (8.01 \pm 1.97)\times 10^{-3}$$

$(2.64 \pm 0.68)\ tan^4\theta_C$




JHEP 09 (2022) 107

# $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^0\pi^0$

Can not distinguish $D^0$ and $\bar{D}^0$ in DCSD measurements with hadronic tag

$\mathcal{B}(D^0 \to K^+\pi^-\pi^0 = (3.13^{+0.60}_{-0.56} \pm 0.09)\times 10^{-4}$

$\mathcal{B}(D^0 \to K^+\pi^-\pi^0\pi^0) < 3.6\times 10^{-4}$

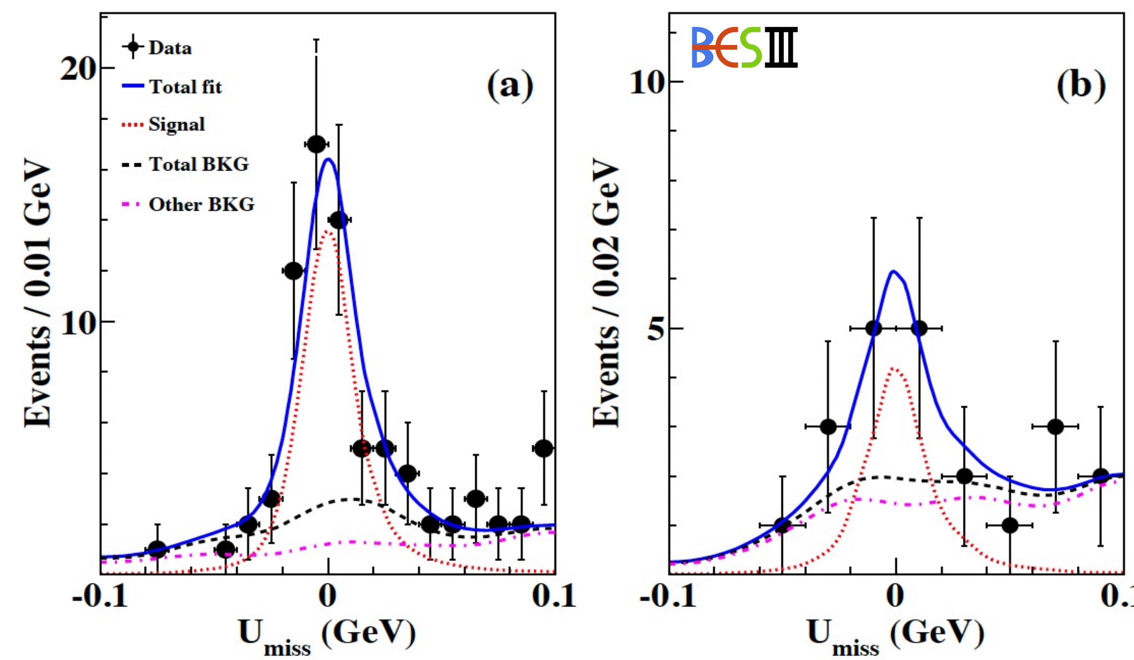
at the 90% C.L.

$$\frac{\mathcal{B}(D^0\to K^+\pi^-\pi^0)}{\mathcal{B}(D^0\to K^-\pi^+\pi^0)} = (\mathbf{0.22 \pm 0.44})\%$$

$(0.75 \pm 0.14) tan^4\theta_C$

$$\frac{\mathcal{B}(D^0\to K^+\pi^-\pi^0\pi^0)}{\mathcal{B}(D^0\to K^-\pi^+\pi^0\pi^0)} < \mathbf{0.40\%}$$

$< 1.37\times tan^4\theta_C$




PRD105, 112001 (2022)

- BESIII dataset
- Charmed meson ($D^0$, $D^+$, $D_s^+$)
  - pure leptonic decays
  - semi-leptonic decays
  - hadronic decays
  - quantum correlation
- Charmed baryon ($\Lambda_c^+$)
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- Prospect

# Quantum Correlation

**Quantum correlated data: $e^+e^- \rightarrow$ ψ(3770)$\rightarrow D^0\bar{D}^0$**

**Best laboratory to measure strong-phase parameters**

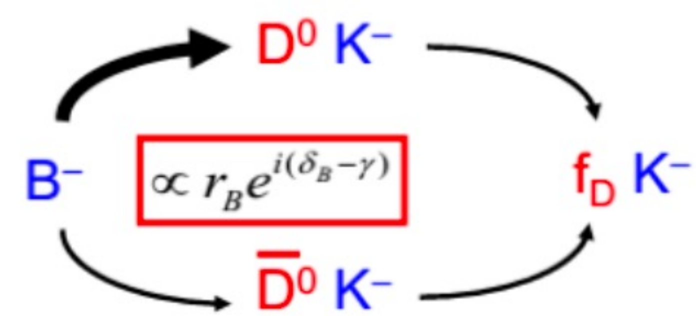
**CP-odd: ψ(3770)** $= \left(D^0\bar{D}^0 - D^0\,\bar{D}^0\right) = (D_+D_- - D_-D_+)$

$J^{PC} = 1^{--}$

CP-even eigenstate

CP-odd eigenstate

- **Inputs for CPV studies at B experiments**




- **The CKM angle γ/$\phi_3$:**

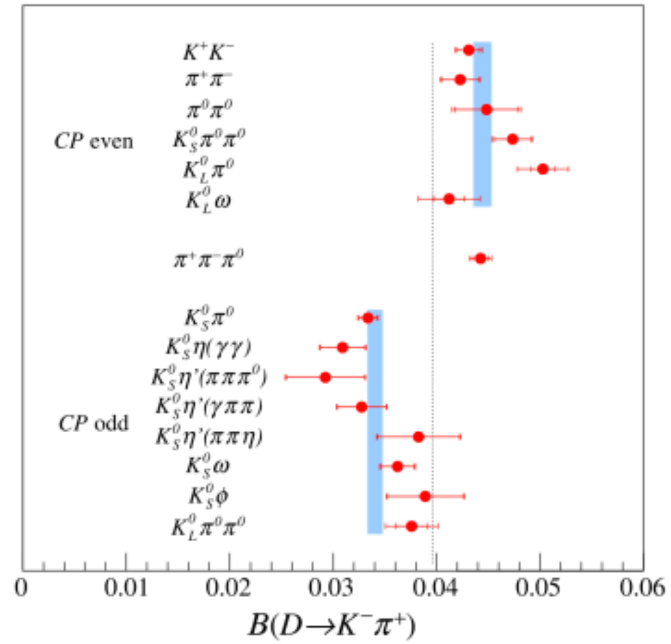
**self-conjugated decay: CP fraction $F_+$ → GLW/GGSZ method;**

**strong phase $ci$(') and $si$(') → GGSZ method**

**non-self-conjugated decay: the coherence factor R and averaged strong phase difference $\delta$ → ADS method**

# Determination of $\delta_D^{K\pi}$

- **An update measurement of the asymmetry between CP-odd and CP-even eigenstate decays into $K^-\pi^+$**



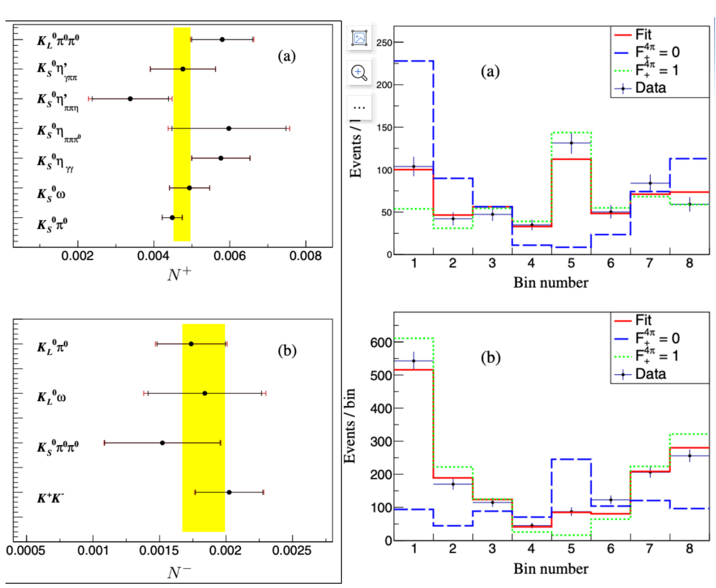

30% more precise !

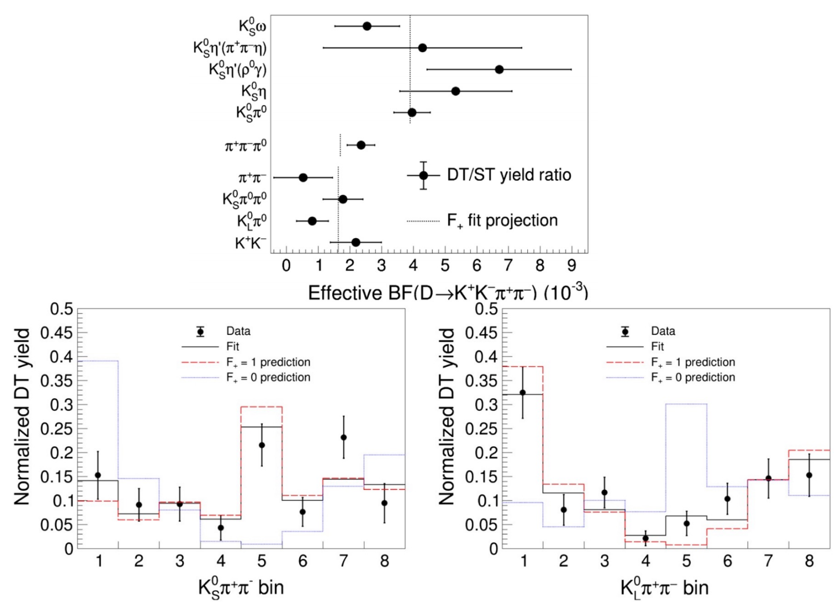
$$\mathcal{A}_{K\pi} \equiv \frac{\mathcal{B}(D_- \to K^-\pi^+) - \mathcal{B}(D_+ \to K^-\pi^+)}{\mathcal{B}(D_- \to K^-\pi^+) + \mathcal{B}(D_+ \to K^-\pi^+)} = \frac{-2r_D^{K\pi}\cos\delta_D^{K\pi} + y}{1 + \left(r_D^{K\pi}\right)^2} = 0.132 \pm 0.011 \pm 0.007$$

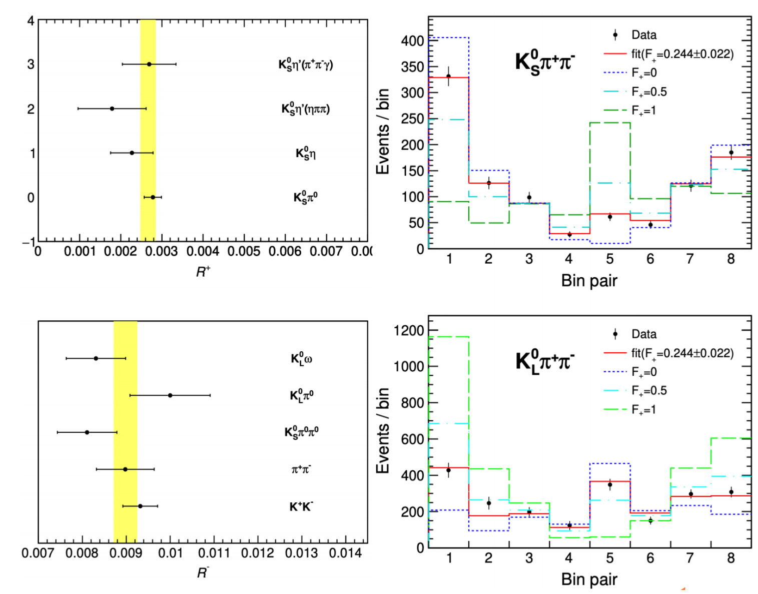
- $\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})$

EPJC 82, 1009 (2022)

# Determination of CP fraction




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

$F_+ = 0.735 \pm 0.015 \pm 0.005$

PRD 106, 092004(2022)

$D^0 \to K^+K^-\pi^+\pi^-$

$F_+ = 0.730 \pm 0.037 \pm 0.021$

PRD 107, 032009(2023)

$D^0 \to K_S^0\pi^-\pi^+\pi^0$

$F_+ = 0.235 \pm 0.010 \pm 0.002$

arxiv:2305.03975

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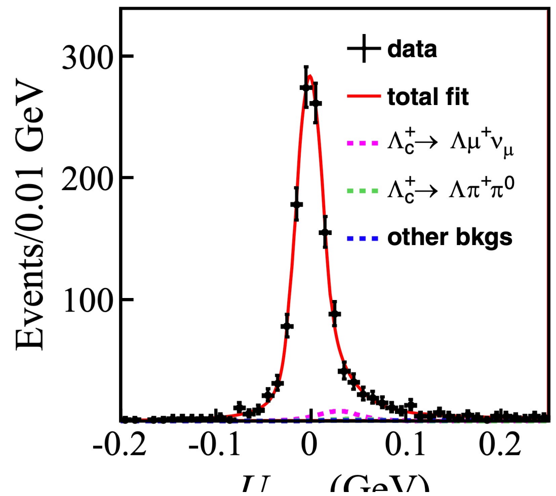
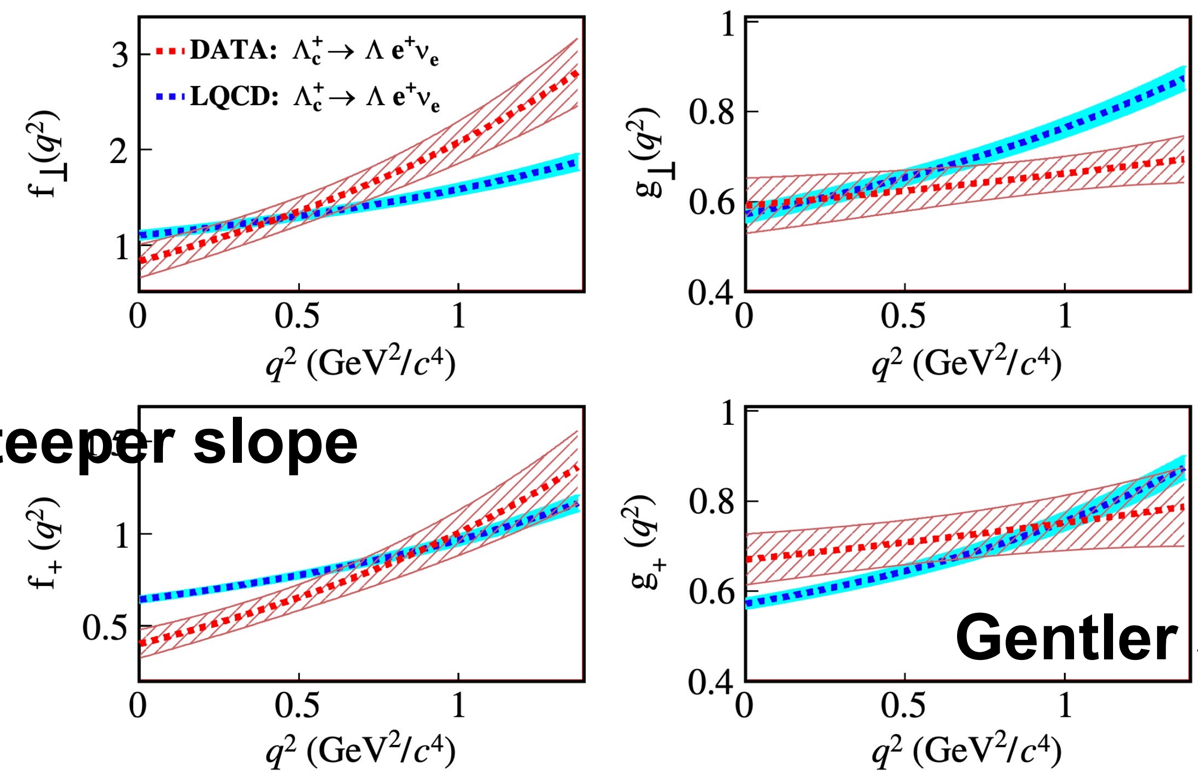
# Study of $\Lambda_c^+ \to \Lambda e^+ \nu$




**First direct comparisons to LQCD for $\Lambda_c^+ \to \Lambda$ decay form factor**

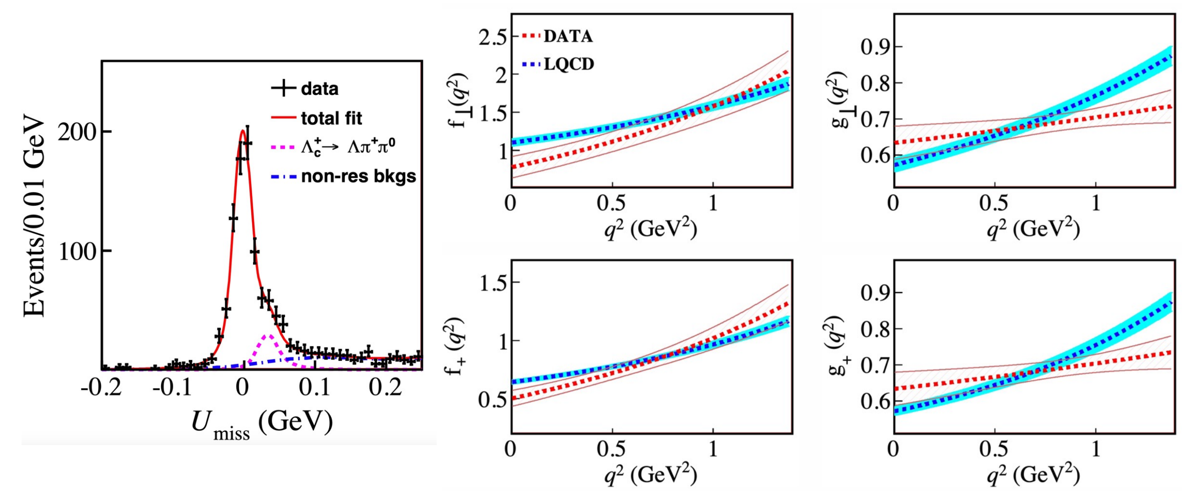
**Different kinematic behavior compared to LQCD**




**Steeper slope**

**Gentler slope**

## Study of $\Lambda_c^+ \to \Lambda \mu^+ \nu$




**Updated BF and first FF measurement:**

**~4% most precise**

$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu) = (3.56 \pm 0.11 \pm 0.07)\times 10^{-3}$$

$$|V_{cs}| = (0.936 \pm 0.017_{\mathcal{B}} \pm 0.024_{LQCD} \pm 0.0240.024_{\tau_{\Lambda_c^+}})\times 10^{-3}$$

PRL 129, 231803 (2022)

**Agree with PDG 2022**

$$\mathcal{B} = (3.48 \pm 0.14 \pm 0.10)\times 10^{-3}$$

$$R_{e/\mu} = 0.98 \pm 0.05 \pm 0.03$$

**vs SM: 0.97 --> No LFUV**

Arxiv:2306.02624 (2023)

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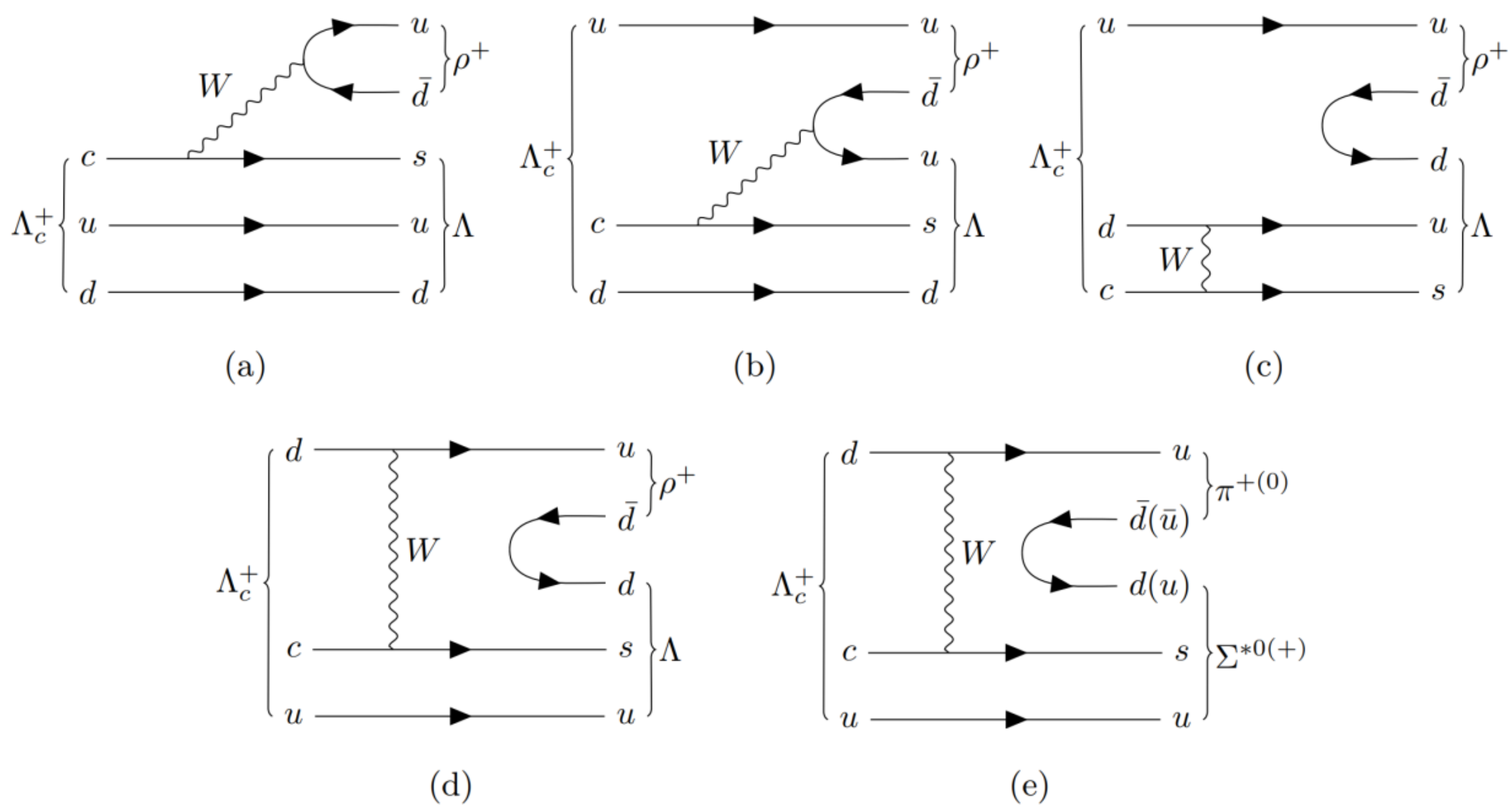
# Partial wave analysis of the charmed baryon hadronic decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$




**$\Lambda_c^+ \to \Lambda\rho^+$: both factorizable(a) and non-factorizable(b-d)**

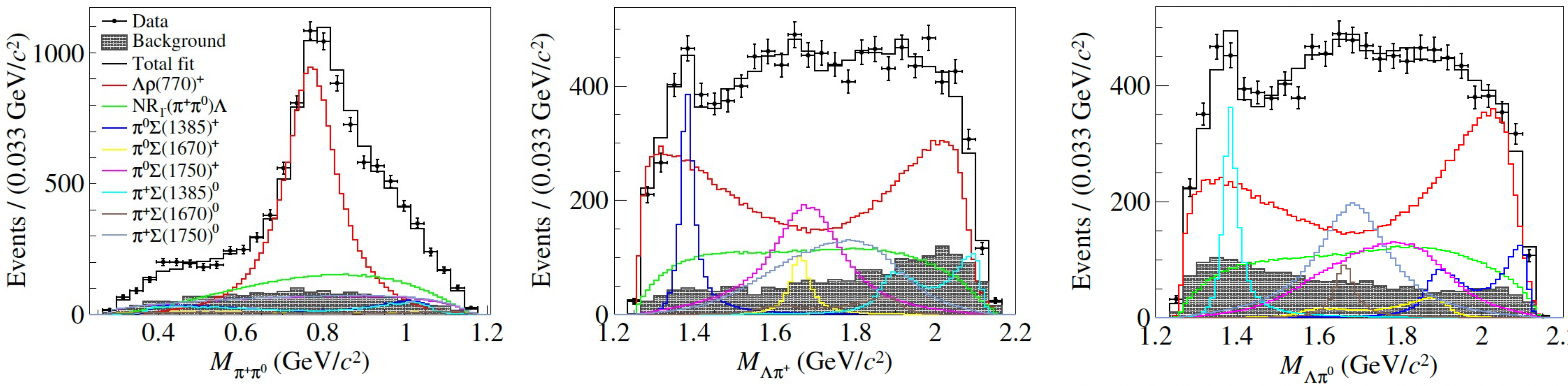
**$\Lambda_c^+ \to \Sigma(1385)\pi$: pure non-factorizable(e)**

**Provide important inputs to the theoretical calculations for non-factorizable**

**Use new-developed Tensor Flow based package TF-PWA*.**

**(*BESIII Preliminary: https://github.com/jiangyi15/tf-pwa)**

# Partial wave analysis of the charmed baryon hadronic decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$




## The first PWA of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

| | Theoretical calculation | | This work | PDG |
|---|---|---|---|---|
| $10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$ | $4.81 \pm 0.58$ [13] | $4.0$ [14, 15] | $4.06 \pm 0.52$ | $< 6$ |
| $10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$ | $2.8 \pm 0.4$ [16] | $2.2 \pm 0.4$ [17] | $5.86 \pm 0.80$ | — |
| $10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$ | $2.8 \pm 0.4$ [16] | $2.2 \pm 0.4$ [17] | $6.47 \pm 0.96$ | — |
| $\alpha_{\Lambda\rho(770)^+}$ | $-0.27 \pm 0.04$ [13] | $-0.32$ [14, 15] | $-0.763 \pm 0.070$ | — |
| $\alpha_{\Sigma(1385)^+\pi^0}$ | $-0.91^{+0.45}_{-0.10}$ [17] | | $-0.917 \pm 0.089$ | — |
| $\alpha_{\Sigma(1385)^0\pi^+}$ | $-0.91^{+0.45}_{-0.10}$ [17] | | $-0.79 \pm 0.11$ | — |

**The first measurement of the decay asymmetry parameters for the relevant resonance**


Ref. [13]: PRD 101 (2020) 053002.
Ref. [14,15]: PRD 46 (1992) 1042; PRD 55 (1997) 1697.
Ref. [16]: EPJC 80 (2020) 1067.
Ref. [17]: PRD 99 (2019) 114022

# Measurement of the absolute branching fraction of the singly Cabibbo suppressed decays of $\Lambda_c^+ \to n\pi^+$

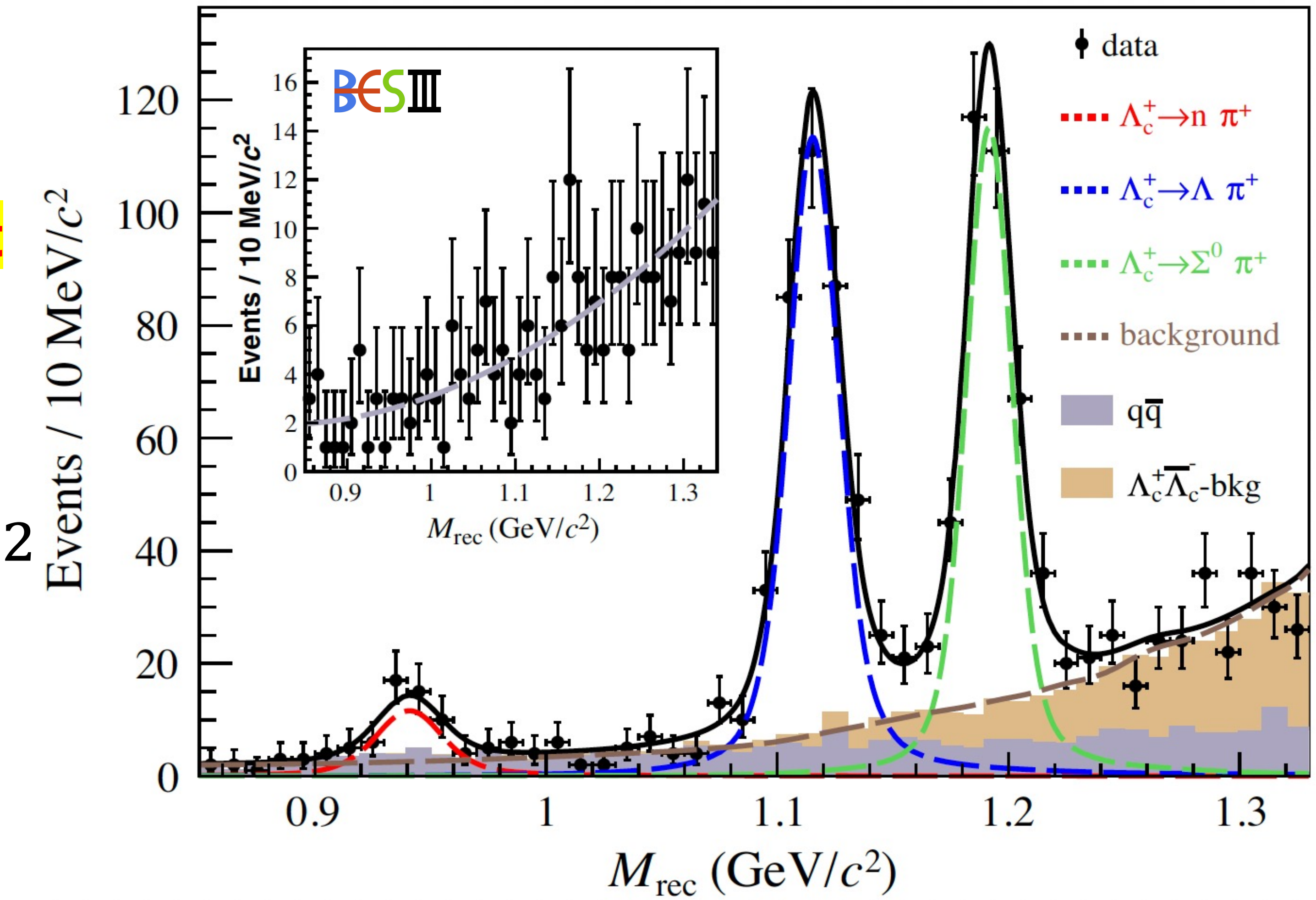
PRL 128, 142001 (2022)

$\mathcal{B}(\Lambda_c^+ \to n\pi^+)$ **First measurement**
$=(6.6 \pm 1.2 \pm 0.4)\times 10^{-4}$

$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)$
$=(1.31 \pm 0.08 \pm 0.05)\times 10^{-2}$

$\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)$
$=(1.22 \pm 0.08 \pm 0.07)\times 10^{-2}$

$\mathcal{B}(n\pi^+)/\mathcal{B}(p\pi^0) > 7.2$ at 90% C.L.




**Use recoil mass to access neutron**

- **Disagrees with most predictions of phenomenological models**
- **Non-factorization contributions may be overestimated.**

# Other $\Lambda_c^+$ results

## ➢Semi-leptonic decays

- $\Lambda_c^+ \to pK^- e^+ \nu_e$ [PRD 106, 112010(2023)]
- $\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e$ *and* $pK_s\pi^- e^+\nu_e$ [PLB 843, 137993(2023)]
- $\Lambda_c^+ \to X e^+$ [PRD 107, 052005(2023)]

## ➢Hadronic decays

- $\Lambda_c^+ \to p\eta$ *and* $\Lambda_c^+ \to p\omega$ [arXiv:2307.09266]
- $\Lambda_c^+ \to \Sigma^+ h^+ h^- (\pi^0)$ [arXiv:2304.09405]
- $\Lambda_c^+ \to \bar{n}X$ [PRD 108, L031101(2023)]
- $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^-\pi^+$ *and* $nK^-\pi^+\pi^-$ [CPC 47, 023001(2023)]
- $\Lambda_c^+ \to \Lambda K^+$ [PRD 106, L111101(2023)]
- $\Lambda_c^+ \to \Sigma^0 K^+$ *and* $\Sigma^+ K_S^0$ [PRD 106, 052003(2022)]
- $\Lambda_c^+ \to p\eta'$ [PRD 106, 072002(2022)]

## ➢Rare decays

- $\Lambda_c^+ \to \Sigma^+\gamma$ [PRD 107, 052002(2023)]
- $\Lambda_c^+ \to p\gamma'$ [PRD 106, 072008(2022)]

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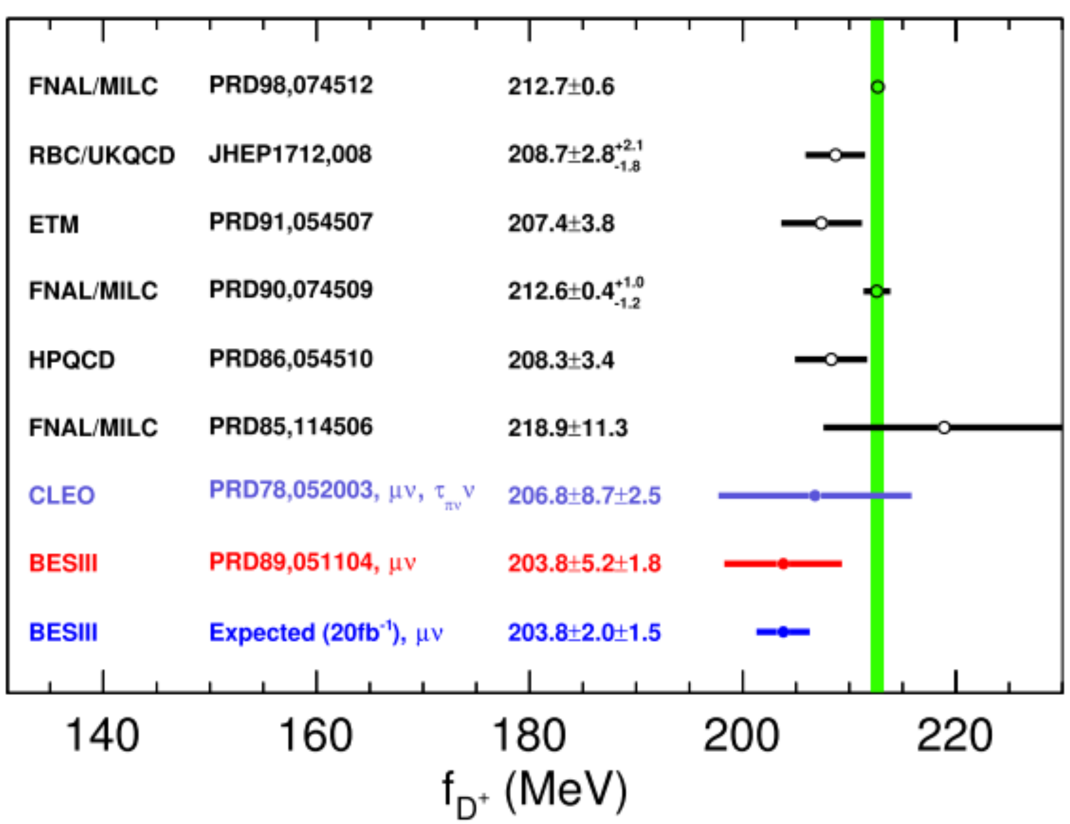
# Prospect

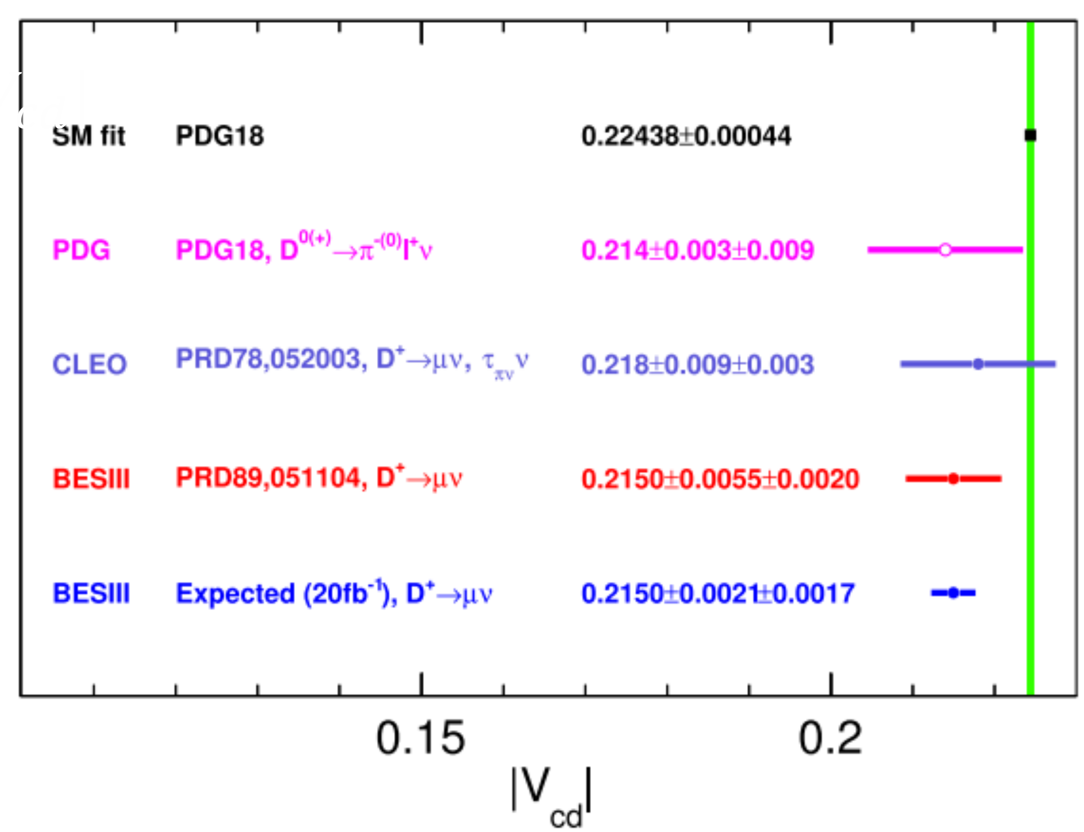
From White Paper (Chin. Phys. C 44, 040001 (2020))

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 $|V_{cd}|$ and test LFU in $D^+ \to l^+\nu_l$ decays.

# Prospect

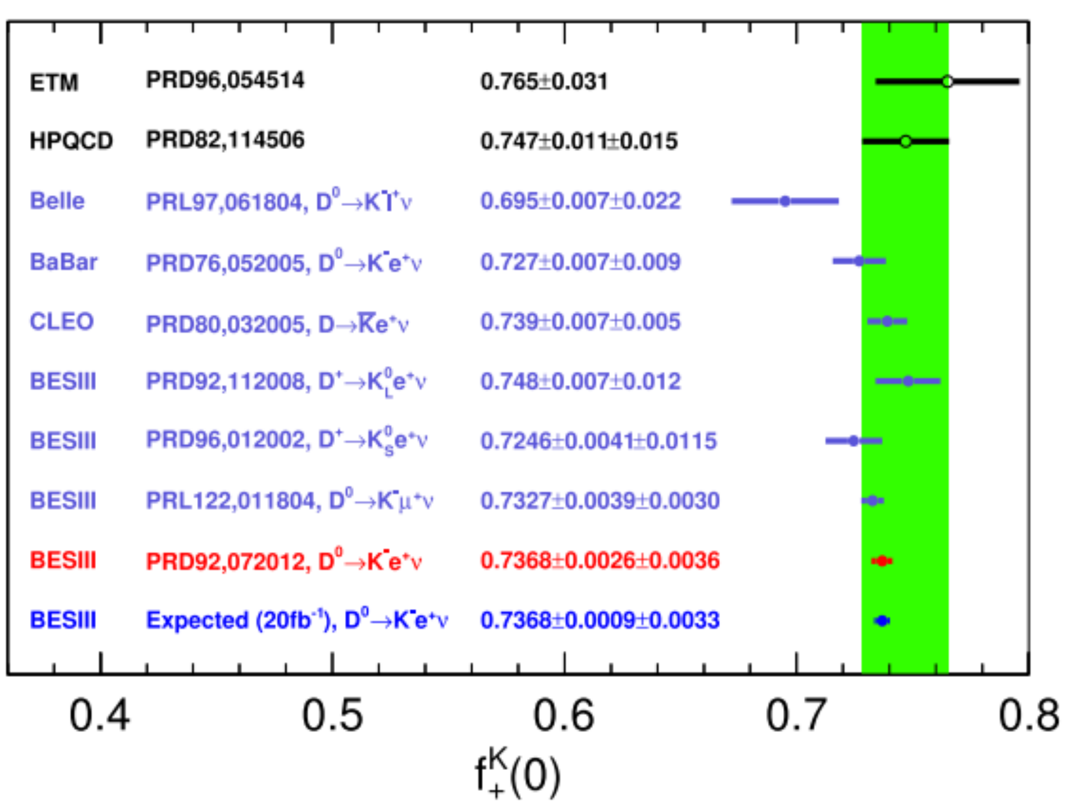
From White Paper (Chin. Phys. C 44, 040001 (2020))

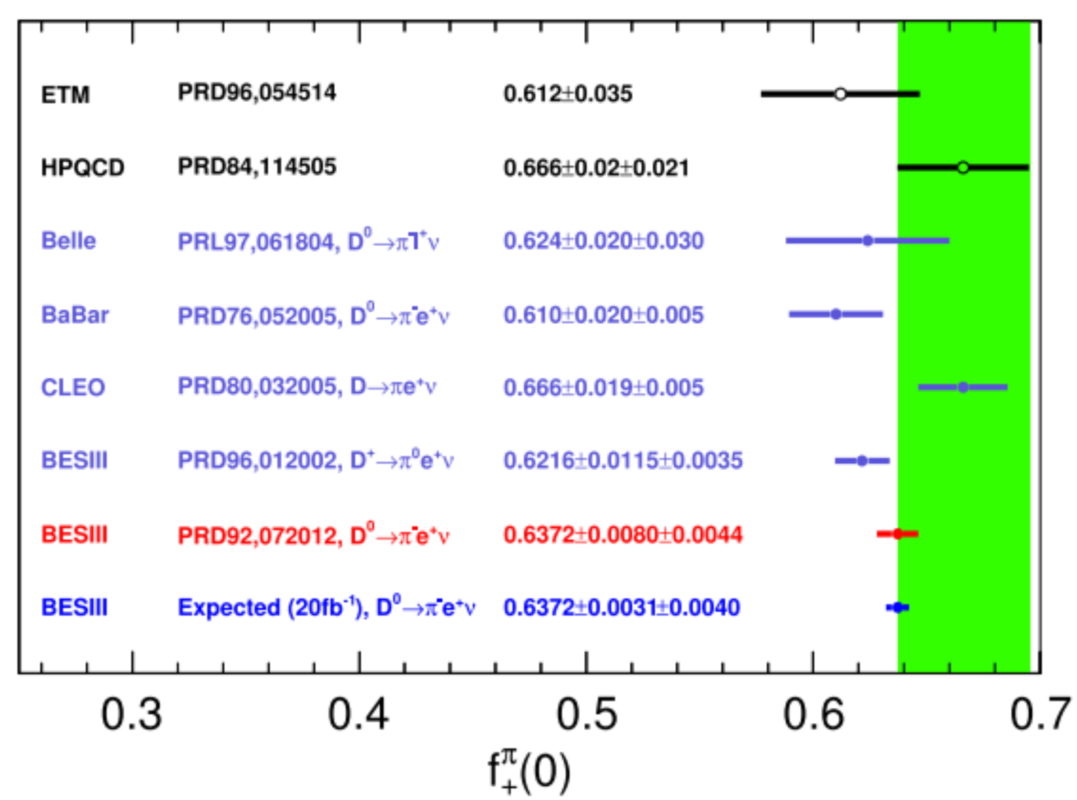
20 $fb^{-1}$ of data set at 3.773 GeV is on the way

**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% |



# Prospect

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

## Quantum correlation of neutral charmed meson pairs

| Decay mode | Quantities | Status ( 2.93 $\text{fb}^{-1}$ ) |
|---|---|---|
| $K_S^0\pi^+\pi^-$ | $c_i, s_i$ | Finished(2020) |
| $K_S^0K^+K^-$ | $c_i, s_i$ | Finished(2021) |
| $K^-\pi^+\pi^+\pi^-$ | $R, \delta$ | Finished(2020) |
| $K^+K^-\pi^+\pi^-$ | $F_+$ or $c_i, s_i$ | $F_+$ Finished(2022), $c_i, s_i$ on going |
| $\pi^+\pi^-\pi^+\pi^-$ | $F_+$ or $c_i, s_i$ | $F_+$ Finished(2022), $c_i, s_i$ on going |
| $K^-\pi^+\pi^0$ | $R, \delta$ | Finished(2021) |
| $K_S^0K^\pm\pi^\mp$ | $R, \delta$ | On going |
| $\pi^+\pi^-\pi^0$ | $F_+$ | On going |
| $K_S^0\pi^+\pi^-\pi^0$ | $F_+$ or $c_i, s_i$ | $F_+$ Finished(2023), $c_i, s_i$ on going |
| $K^+K^-\pi^0$ | $F_+$ | On going |
| $K^-\pi^+$ | $\delta$ | Updated Finished (2022) |

- Making progress in past few years.
- Many ongoing projects, eventually 20 $\text{fb}^{-1}$ $\psi(3770)$ data samples.

# Prospect

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

**Amplitude analyses and branching fraction measurement of charmed meson hadronic decays**

Precisely measuring the structure of golden modes, for example $D^+ \to K^-\pi^+\pi^+$

First amplitude analysis of Cabbibo-suppressed decays.

**Measuring the polarization of $\mathrm{D} \to \mathrm{VV}$ in $\mathrm{D} \to \mathrm{K3\pi}$ or $\mathrm{D} \to \mathrm{KK\pi\pi}$**

**Searching for new physics and rare decays**

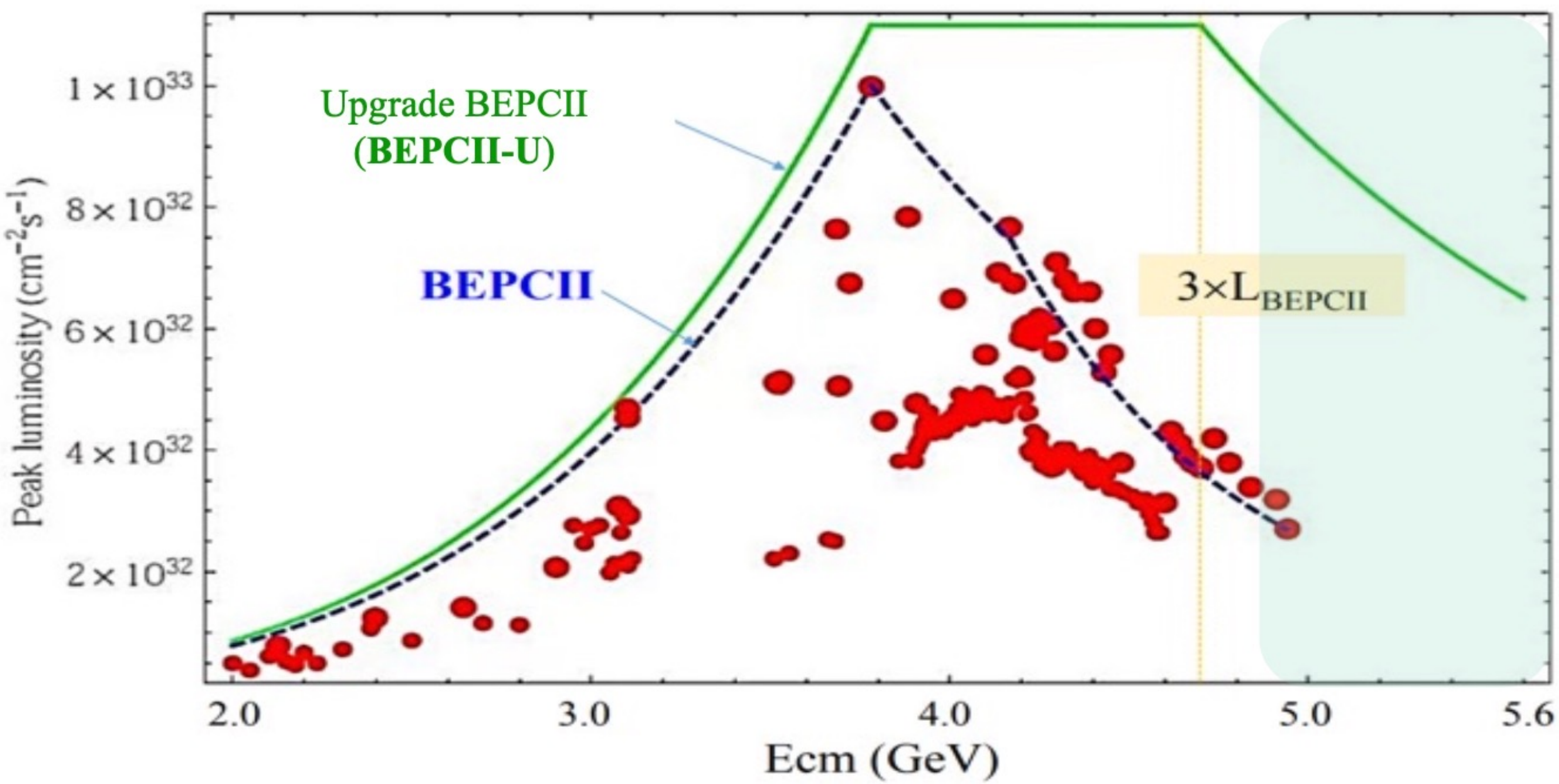
Flavor changing neutral currents (FCNC) $e^+e^-, \mu^+\mu^-$ etc.

Quantum number violation processes $e^+e^+, \mu^-\mu^-$ etc.

Radiative decays $\gamma\omega,\ \gamma K_1$ etc.

# Prospect

**Opportunities to study other charmed baryons in the BEPCII-U phase**




Energy thresholds

| | |
|---|---|
| $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ | 4.74 GeV |
| $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\ \pi$ | 4.88GeV |
| $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ | 4.91 GeV |
| $e^+e^- \to \Xi_c\bar{\Xi}_c$ | 4.94 GeV |
| $e^+e^- \to \Omega_c\bar{\Omega}_c$ | 5.40GeV |

Thanks for your attention