Experimental status of $|V_{cs}|$ and $|V_{cd}|$ at BESIII

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IHEP

(On behalf of the BESIII Collaboration)

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Outline

1 Motivation

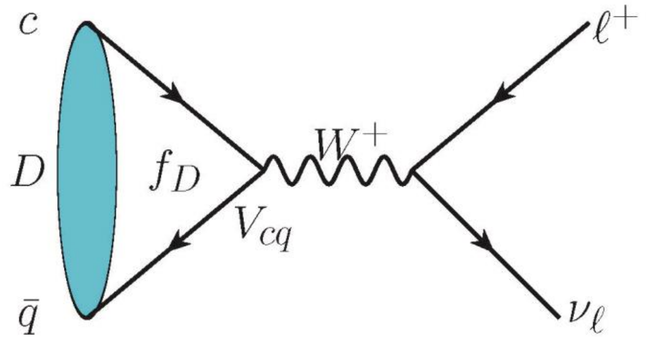
$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

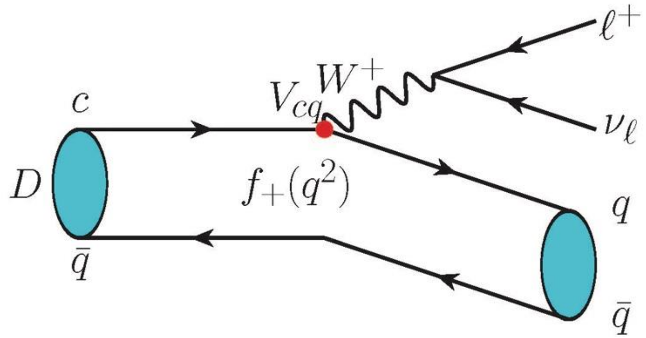
What is the importance of the CKM Matrix?

- **Standard Model**
  - explains how quarks of different flavors can transform into one another during weak interactions — **Quark Flavor Mixing**
- **CP Violation**
  - essential for explaining the matter-antimatter asymmetry in the universe
- **New Physics**
  - Precision measurements of its elements can reveal deviations from the Standard Model, hinting at new physics beyond it

1 Motivation

How to determine the elements $|V_{cs}|$ and $|V_{cd}|$ of the CKM Matrix?





- **Obtained from the experiment with Leptonic and Semi-Leptonic Decays of charm hadrons**
  - **Leptonic:** $\Gamma(c \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{cq}|^2|f_D|^2 m_\ell^2 m_D\left(1-\frac{m_\ell^2}{m_D^2}\right)^2$
  - **Semi-Leptonic:** $\frac{d\Gamma}{dq^2} = X\frac{G_F^2}{24\pi^3}|V_{cq}|^2|f_+(q^2)|^2|\vec{p}_P|^3$
- **Uncertainties of CKM :**
  - **Contributed by $|V_{cs}|(\sigma = 0.6\%)$ and $|V_{cd}|(\sigma = 1.8\%)$**
- **$|V_{cq}|$ Measurement ⇒ Test CKM matrix unitarity**

1 Motivation

What else can be determined with Leptonic and Semi-Leptonic Decays?

- Latest LQCD predicts the decay constant f_D and form factors $f_+(q^2)$
  - $f_{D^+} = 212.1(07)\mathrm{MeV}$ $(\sigma = 0.3\%)$
  - $f_{D_s^+} = 249.9(05)\mathrm{MeV}$ $(\sigma = 0.2\%)$
  - $f_+^{D\to K}(q^2) = 0.7452(31)(\sigma = 0.4\%)$
  - $f_+^{D\to\pi}(q^2) = 0.6300(51)(\sigma = 0.8\%)$

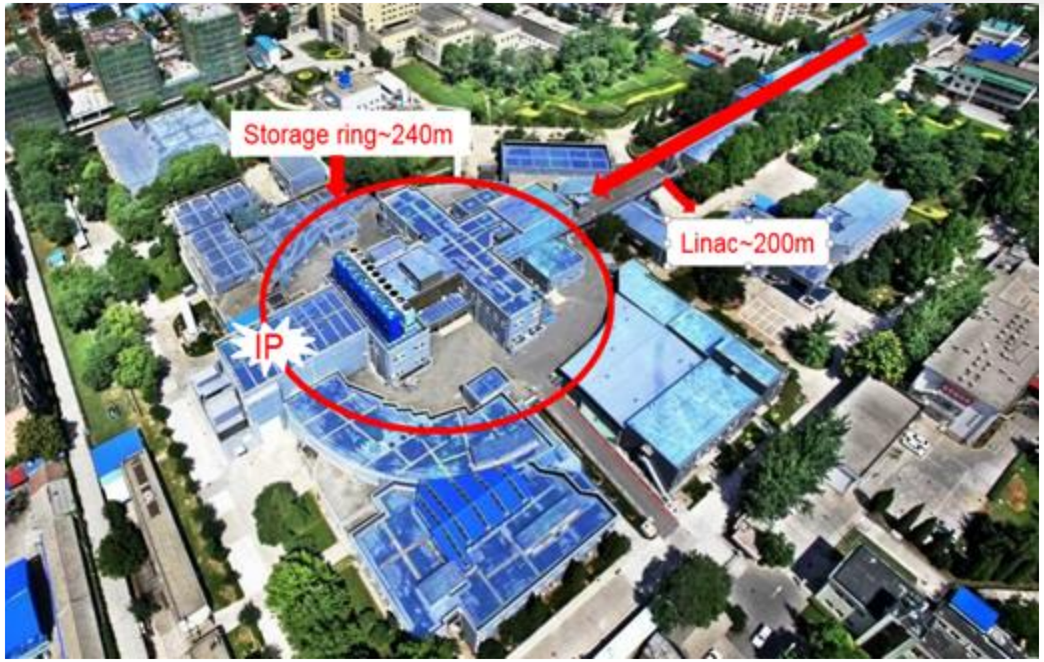
Need experimental Measurements to calibrate LQCD calculations

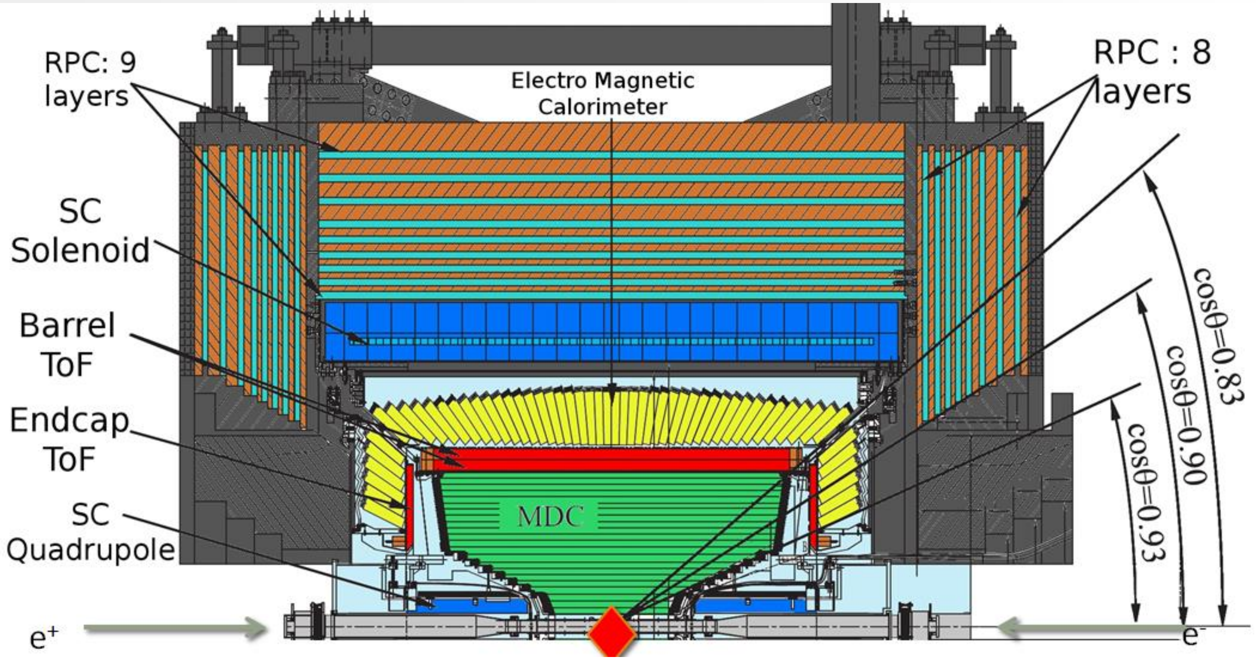
- Measurement the branching fraction

Test lepton flavor universality (LFU)

2 BESIII experiment

BEPCII and BESIII

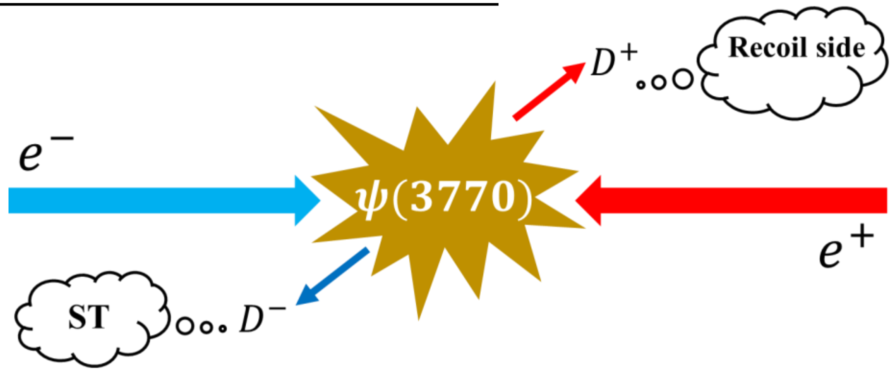




- $\sqrt{s} = (1.84 - 4.95)$ GeV
- Designed luminosity (L): $1.00 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @ 3.773 GeV
- In 2022, peak L reached 1.1 times of the designed L
- MDC: $\sigma_p/p = 0.5\%$@ 1 GeV, $\sigma_{dE/dx} = 6\%$
- TOF: $\sigma_T = 68(110)$ ps for barrel (edncap); end cap TOF was upgraded in 2015→ 60 ps
- EMC: $\sigma_E/E = 2.5\%(5\%)$ ps for barrel (edncap)

2 Dataset and method

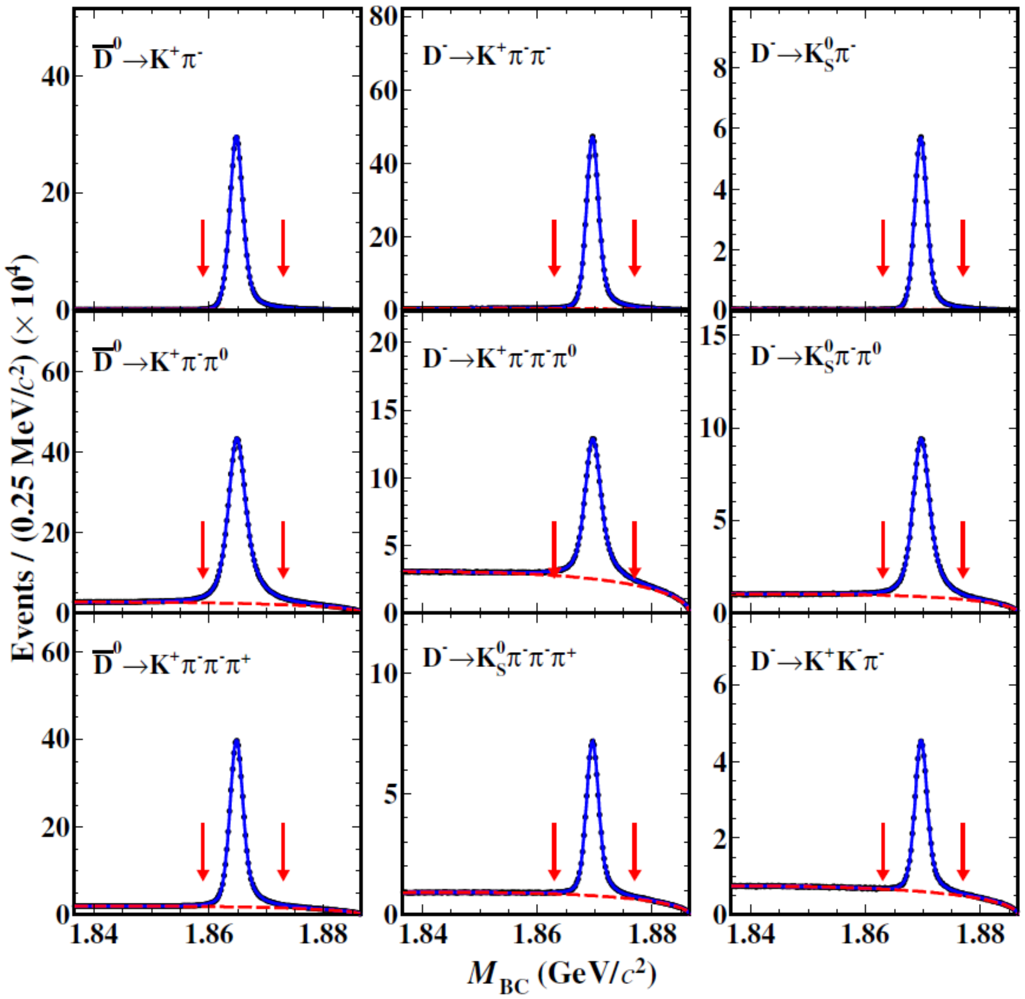
Data sample	E_{cm}(GeV)	$\mathcal{L}_{int}(fb^{-1})$
$e^+e^- \to \psi(3770) \to D\bar{D}$	3.773	20.3
$e^+e^- \to D_s^{\pm} D_s^{*\mp}$	4.128-4.226	7.33
$e^+e^- \to D_s^{*+} D_s^{*-}$	4.237-4.669	10.64
$e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$	4.600-4.669	4.5



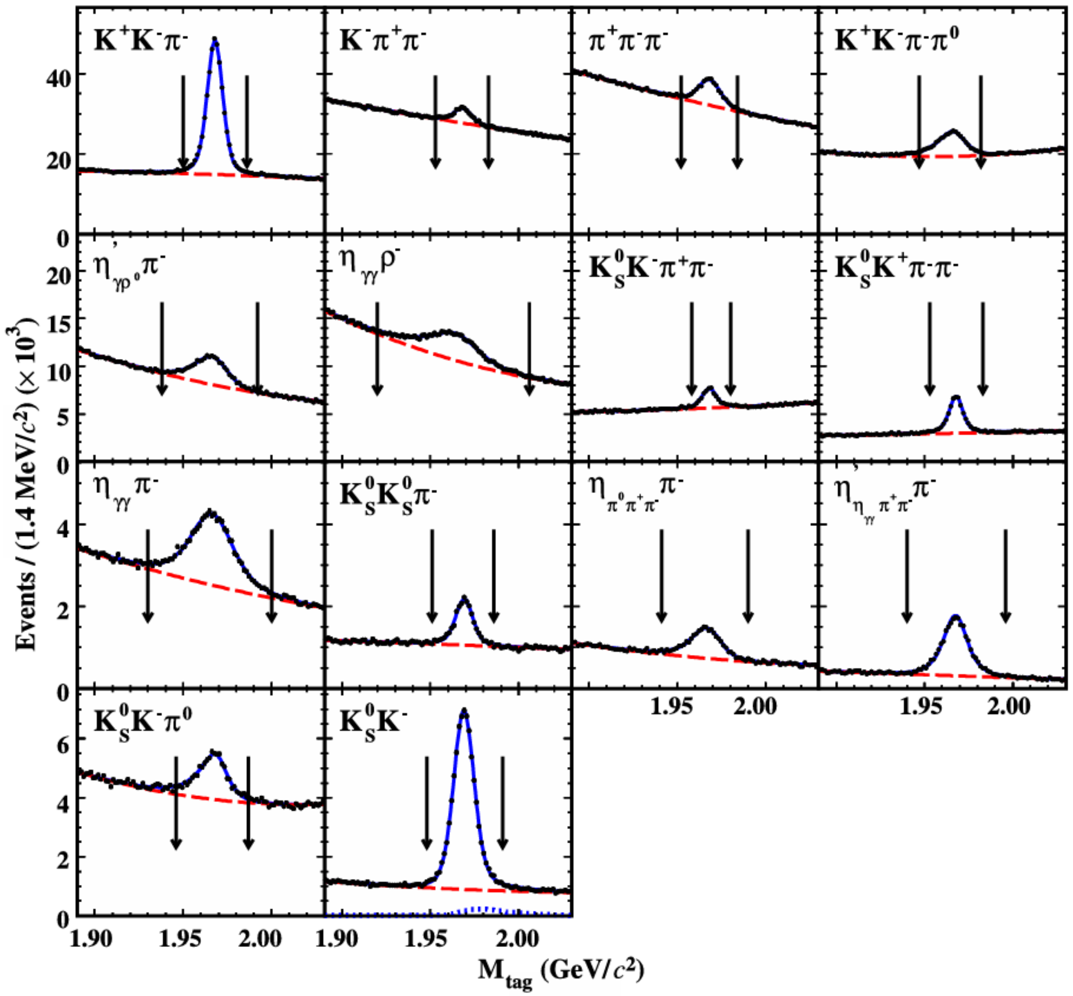
- e^+e^- annihilations data near threshold
  - Double-tag method
  - Clean environment
- Undetectable neutrinos
  - extract the (semi-)leptonic signals
  - $U_{miss} = E_{miss} - |p_{miss}|$ and $M^2_{miss} = E^2_{miss} - |p^2_{miss}|$
- Measurement of the branching fraction with double-tag method:
  - $\mathcal{B}_{sig} = \frac{N_{tag,sig}}{N_{tag}\frac{\varepsilon_{tag,sig}}{\varepsilon_{tag}}}$ Systematic uncertainties from the ST mostly canceled

2 Single Tag Yield

- $e^+e^- \to \psi(3770) \to D\bar{D}$
  - $\bar{D}^0 \sim 16.9 \times 10^6$
  - $D^- \sim 11.0 \times 10^6$

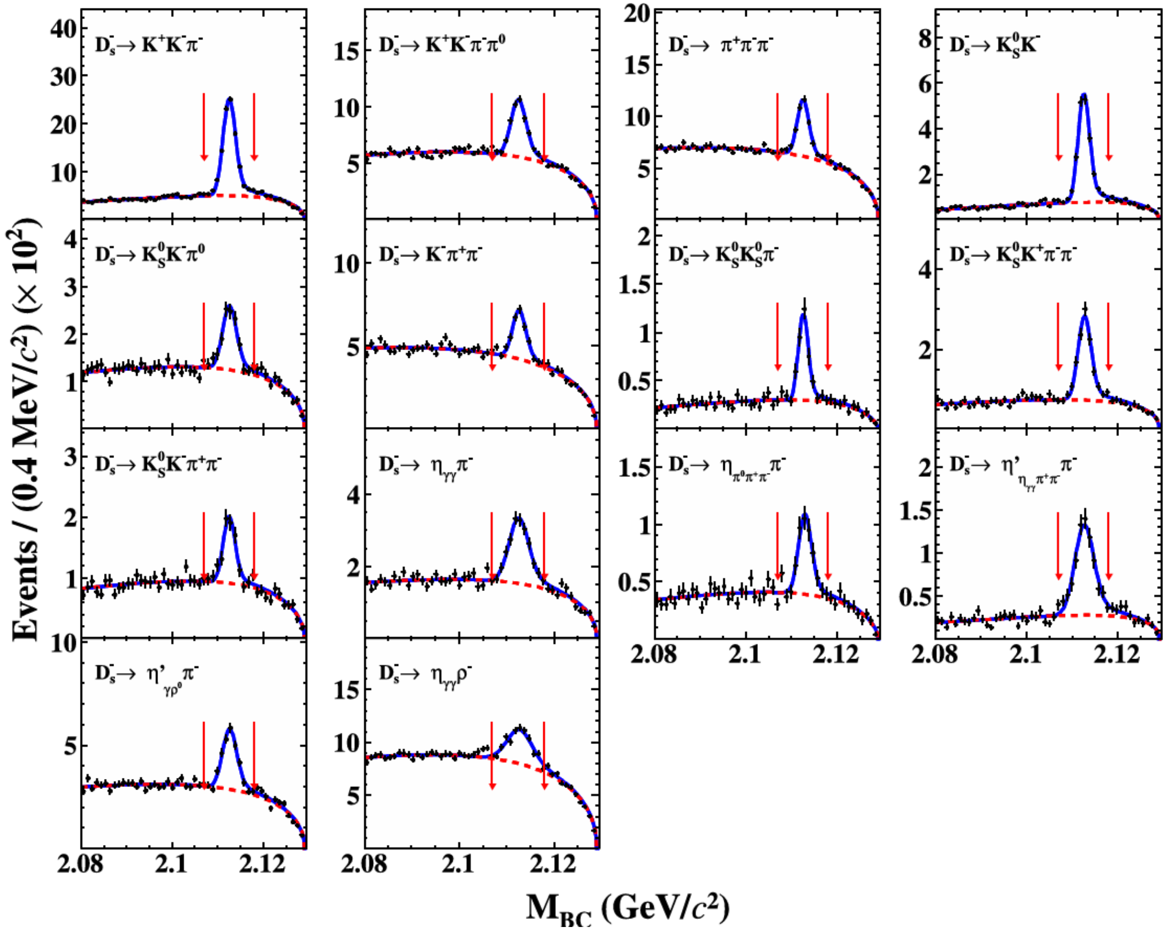


- $e^+e^- \to D_s^{\pm} D_s^{*\mp}$
  - $D_s^- \sim 0.8 \times 10^6$

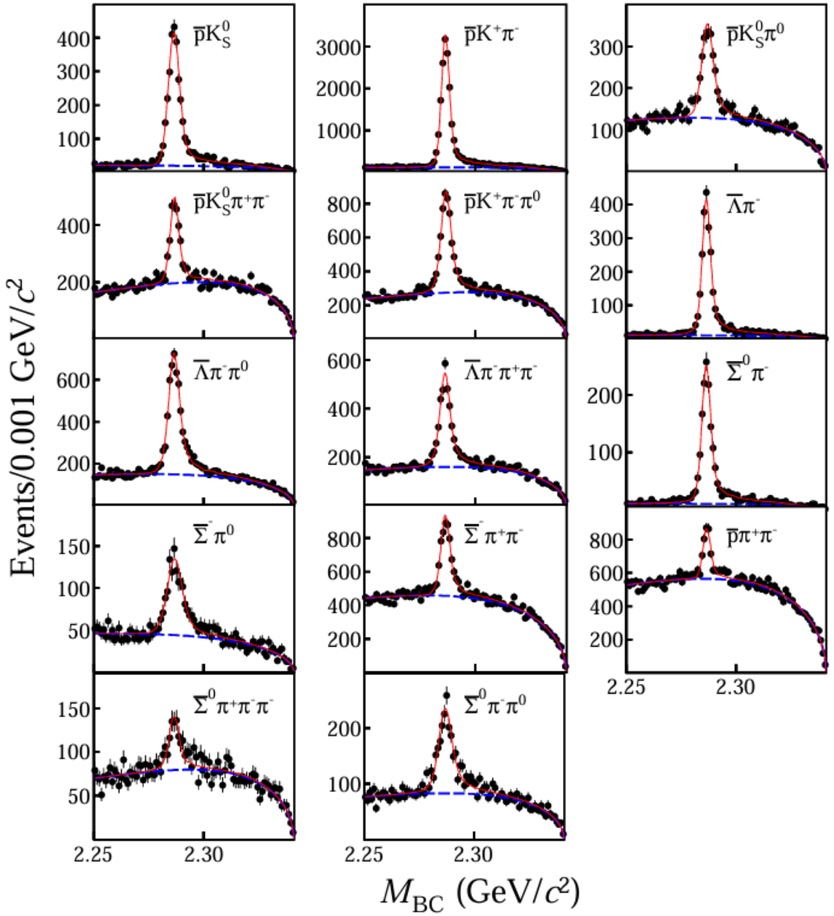


2 Single Tag Yield

- $e^+e^- \to D_s^{*+}D_s^{*-}$
  - $D_s^- \sim 0.12 \times 10^6$



- $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$
  - $\bar{\Lambda}_c^- \sim 0.12 \times 10^6$



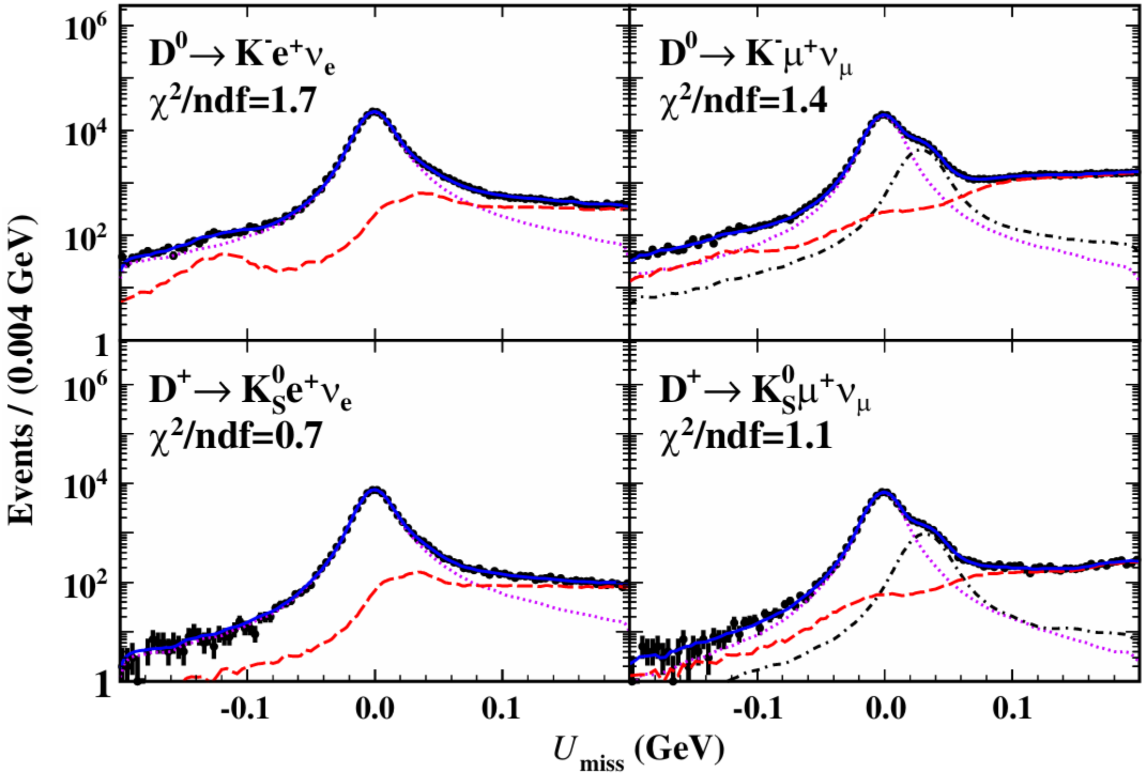
$D \to \bar{K}\ell^+\nu_\ell(\ell = e,\mu)$

- 7.93 fb^{-1}@3.773 GeV
- Phys. Rev. D **110**, 112006 (2024)

- **Branching fractions:**
  - $\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.521 \pm 0.009 \pm 0.016)\%$
  - $\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu) = (3.419 \pm 0.011 \pm 0.016)\%$
  - $\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.864 \pm 0.039 \pm 0.082)\%$
  - $\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu) = (8.665 \pm 0.046 \pm 0.084)\%$

- **LFU test:**
  - $\frac{\mathcal{B}(D^0\to K^-\mu^+\nu_\mu)}{\mathcal{B}(D^0\to K^-e^+\nu_e)} = 0.971 \pm 0.004 \pm 0.006$
  - $\frac{\mathcal{B}(D^+\to \bar{K}^0\mu^+\nu_\mu)}{\mathcal{B}(D^+\to \bar{K}^0e^+\nu_e)} = 0.978 \pm 0.007 \pm 0.013$

consistent with SM: 0.975±0.001

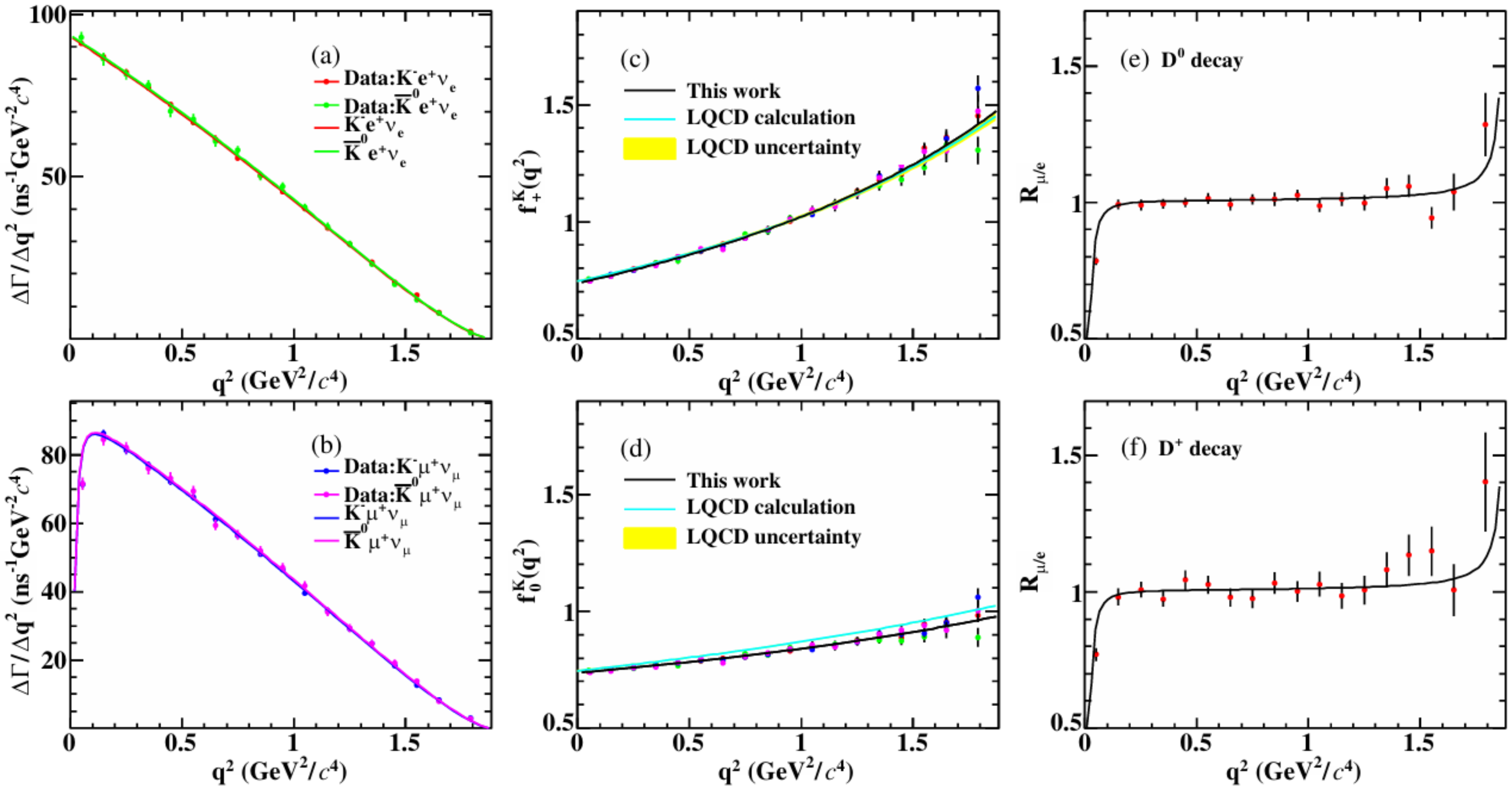


$D \to \bar{K}\ell^+\nu_\ell$ ($\ell = e, \mu$)

➢ **Simultaneous fit to $\frac{d\Gamma}{dq^2}$ to all four channels:**

Phys. Rev. D **110**, 112006 (2024)

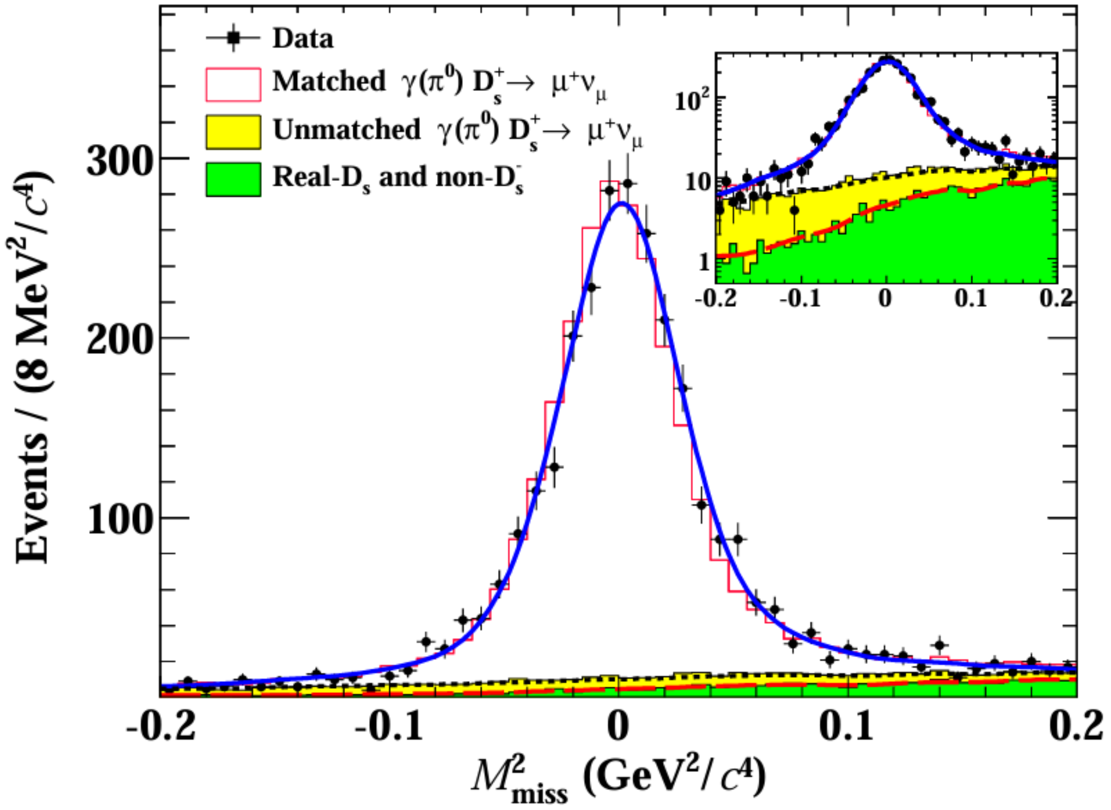
- $f_+^K(0) = 0.7366 \pm 0.0011_{\text{stat.}} \pm 0.0013_{\text{syst.}}$ $(\sigma_{\text{exp.}} = 0.23\%)$
- $|V_{cs}| = 0.9623 \pm 0.0015_{\text{stat.}} \pm 0.0017_{\text{syst.}} \pm 0.0040_{\text{LQCD}}$ $(\sigma_{\text{exp.}} = 0.18\% \& \sigma_{\text{LQCD.}} = 0.45\%)$



Results of 20.3 fb^{-1} on going
The precision will be improved by 1.5 times.

$D_s^+ \to \mu^+ \nu_\mu$

- 7.33 fb^{-1}@4.128-4.226 GeV
- Phys. Rev. D **108**, 112001(2023)

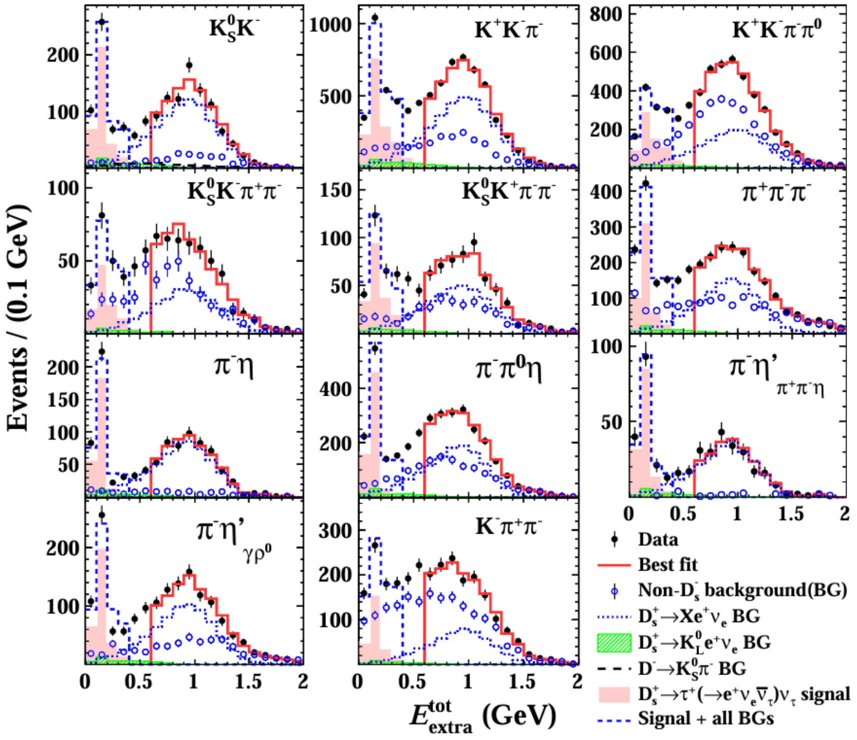


- $\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu) = (5.294 \pm 0.108 \pm 0.085) \times 10^{-3}$
- $f_{D_s^+} = (248.4 \pm 2.5_{\text{stat.}} \pm 2.2_{\text{syst.}})$;$(\sigma_{\text{exp.}} = 1.4\%)$
- $|V_{cs}| = 0.968 \pm 0.010_{\text{stat.}} \pm 0.009_{\text{syst.}}$;$(\sigma_{\text{exp.}} = 1.4\%)$

3 Status of $|V_{cs}|$

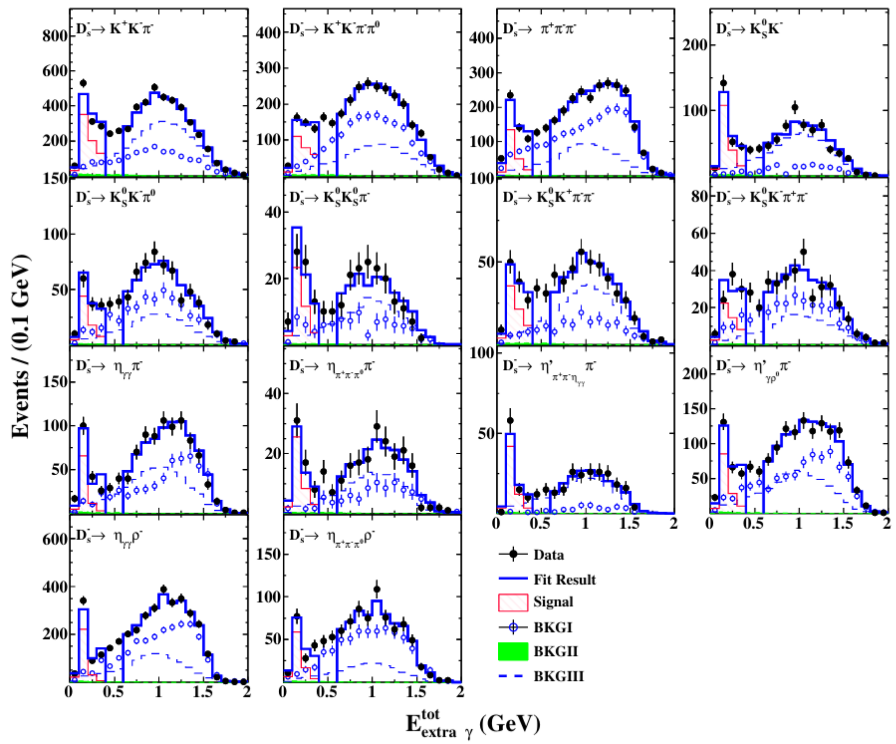
$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau (\ell = e, \mu)$

- 6.32 fb^{-1}@4.178-4.226 GeV
- Phys. Rev. Lett. **127**, 171801 (2021)



- $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$
  - $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.27 \pm 0.10 \pm 0.12)\%$
  - $f_{D_s^+} = (251.1 \pm 2.4_{\text{stat.}} \pm 3.0_{syst.})$;($\sigma_{\text{exp.}} = 1.5\%$)
  - $|V_{cs}| = 0.978 \pm 0.009_{\text{stat.}} \pm 0.012_{\text{syst.}}$;($\sigma_{\text{exp.}} = 1.5\%$)

- 7.33 fb^{-1}@4.128-4.226 GeV
- JHEP 09, 124 (2023)

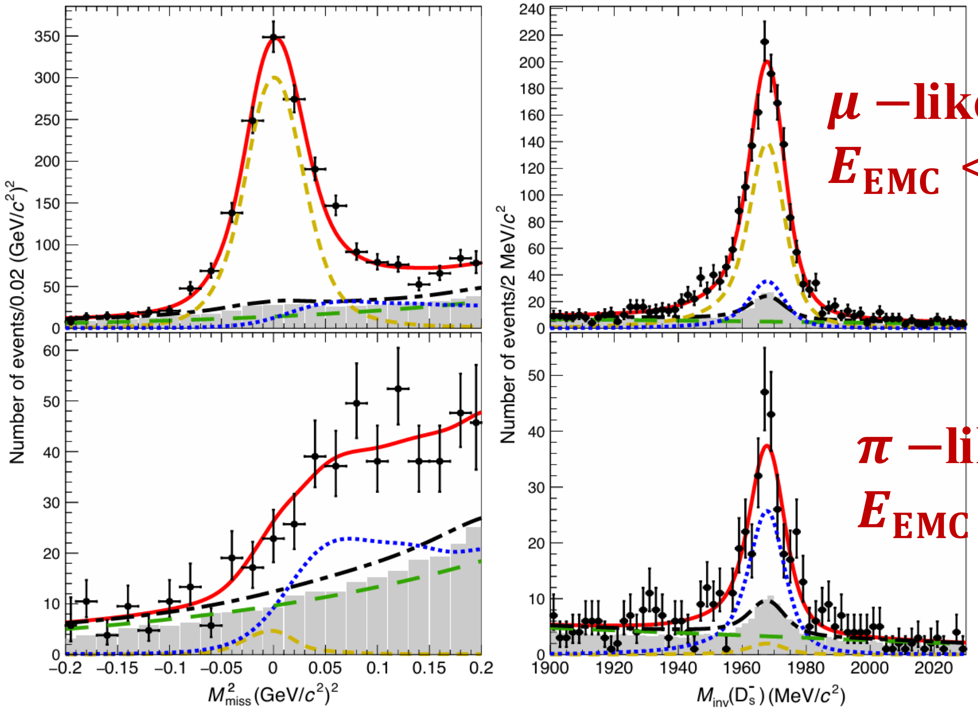


- $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$
  - $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.37 \pm 0.17 \pm 0.15)\%$
  - $f_{D_s^+} = (253.4 \pm 4.0_{\text{stat.}} \pm 3.7_{syst.})$;($\sigma_{\text{exp.}} = 2.2\%$)
  - $|V_{cs}| = 0.987 \pm 0.016_{\text{stat.}} \pm 0.014_{\text{syst.}}$;($\sigma_{\text{exp.}} = 2.2\%$)

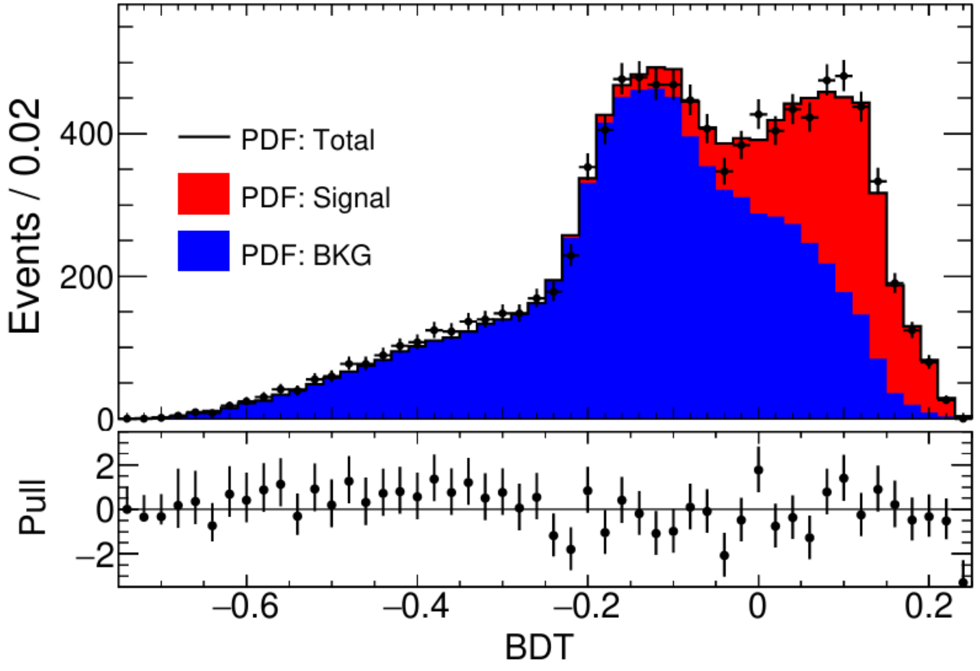
3 Status of $|V_{cs}|$

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$

- 6.32 fb^{-1}@4.178-4.226 GeV
- Phys. Rev. D **104**, 052009 (2021)



- 7.33 fb^{-1}@4.128-4.226 GeV
- Phys. Rev. D **108**, 092014 (2023)



- $\tau^+ \to \pi^+\bar{\nu}_\tau$
  - $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.21 \pm 0.25 \pm 0.17)\%$
  - $f_{D_s^+} = (249.7 \pm 6.0_{\text{stat.}} \pm 4.2_{syst.})$;($\sigma_{\text{exp.}} = 2.9\%$)
  - $|V_{cs}| = 0.972 \pm 0.023_{\text{stat.}} \pm 0.016_{\text{syst.}}$;($\sigma_{\text{exp.}} = 2.9\%$)

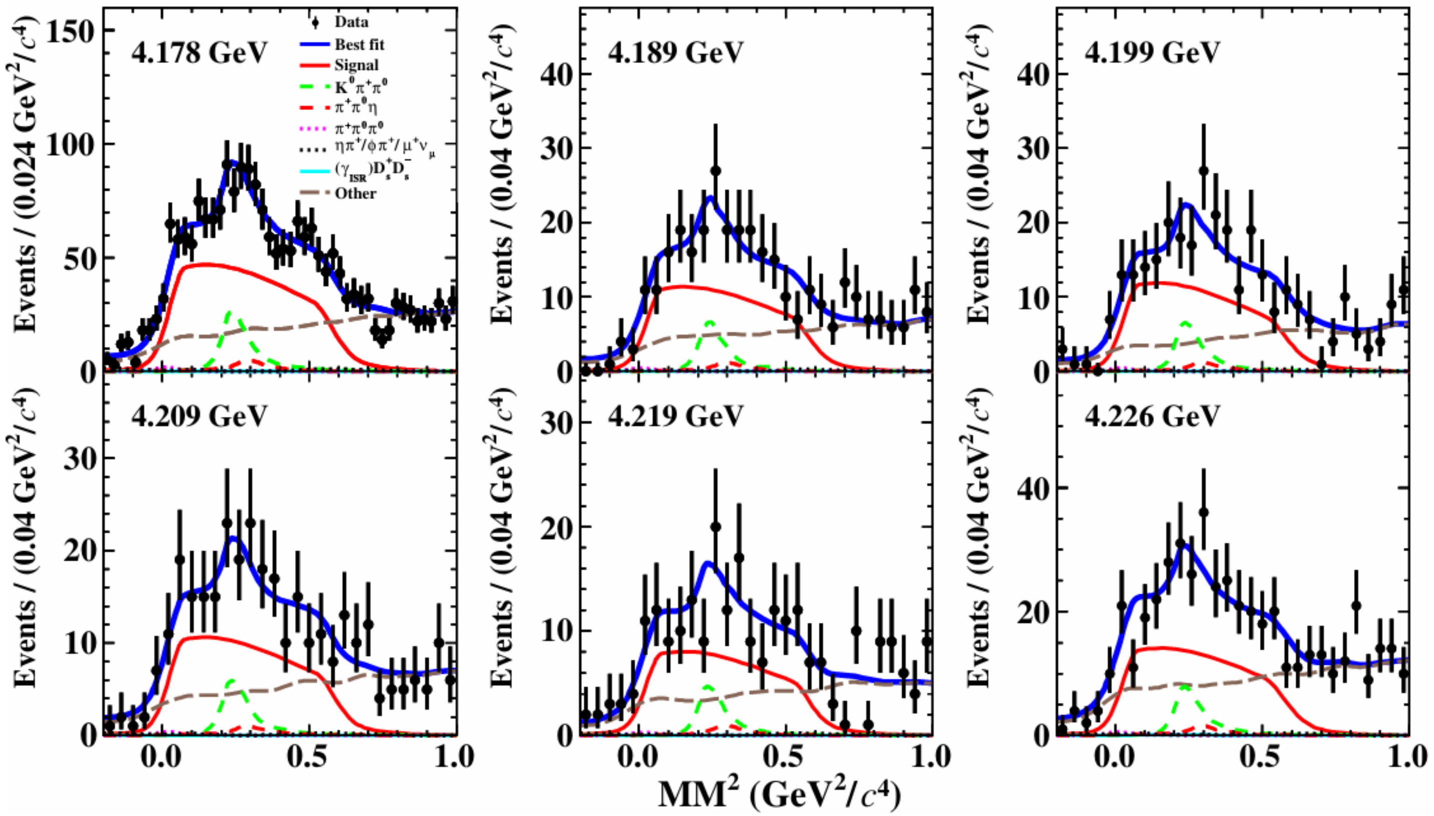
- $\tau^+ \to \pi^+\bar{\nu}_\tau$ with BDT
  - $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.44 \pm 0.17 \pm 0.13)\%$
  - $f_{D_s^+} = (255.0 \pm 4.0_{\text{stat.}} \pm 3.4_{syst.})$;($\sigma_{\text{exp.}} = 2.1\%$)
  - $|V_{cs}| = 0.993 \pm 0.015_{\text{stat.}} \pm 0.013_{\text{syst.}}$;($\sigma_{\text{exp.}} = 2.0\%$)

Status of $|V_{cs}|$

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$

- 6.32 fb^{-1}@4.178-4.226 GeV
- Phys. Rev. D **104**, 032001 (2021)

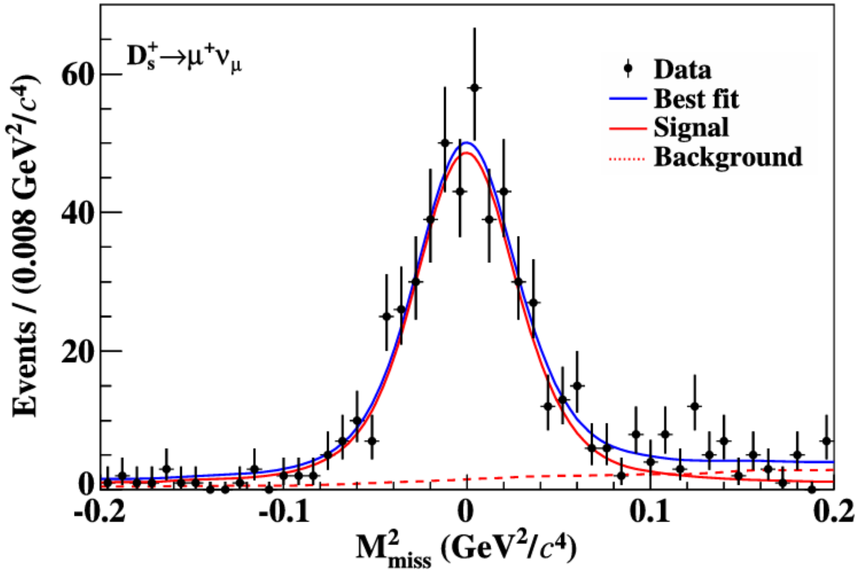
Simultaneous fit to M^2_{miss} at various energy points



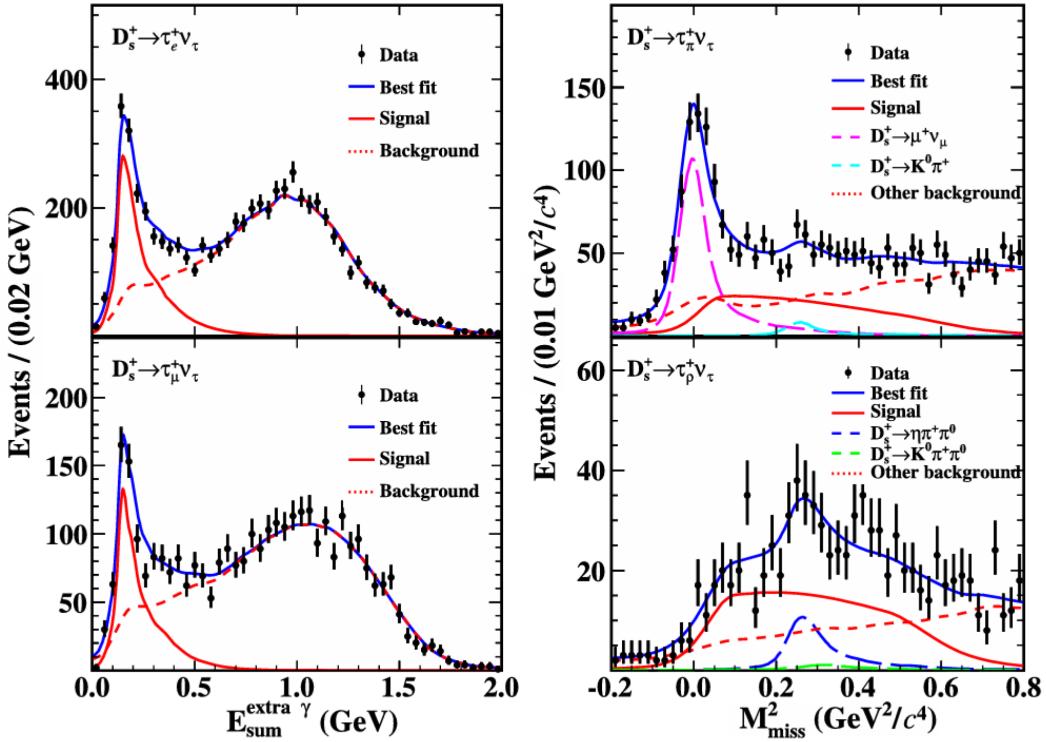
- $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.29 \pm 0.25 \pm 0.20)\%$
- $f_{D_s^+} = (251.6 \pm 5.9_{\text{stat.}} \pm 4.9_{syst.})$;($\sigma_{\text{exp.}} = 3.0\%$)
- $|V_{cs}| = 0.980 \pm 0.023_{\text{stat.}} \pm 0.019_{\text{syst.}}$;($\sigma_{\text{exp.}} = 3.0\%$)

$D_s^+ \to \ell^+\nu_\ell$ via $e^+e^- \to D_s^{*\pm}D_s^{*\mp}$

- 10.64 fb^{-1}@4.237-4.669 GeV
- Phys. Rev. D **110**, 052002 (2024)



$D_s^+ \to \tau^+\nu_\tau$ constrain the same BF

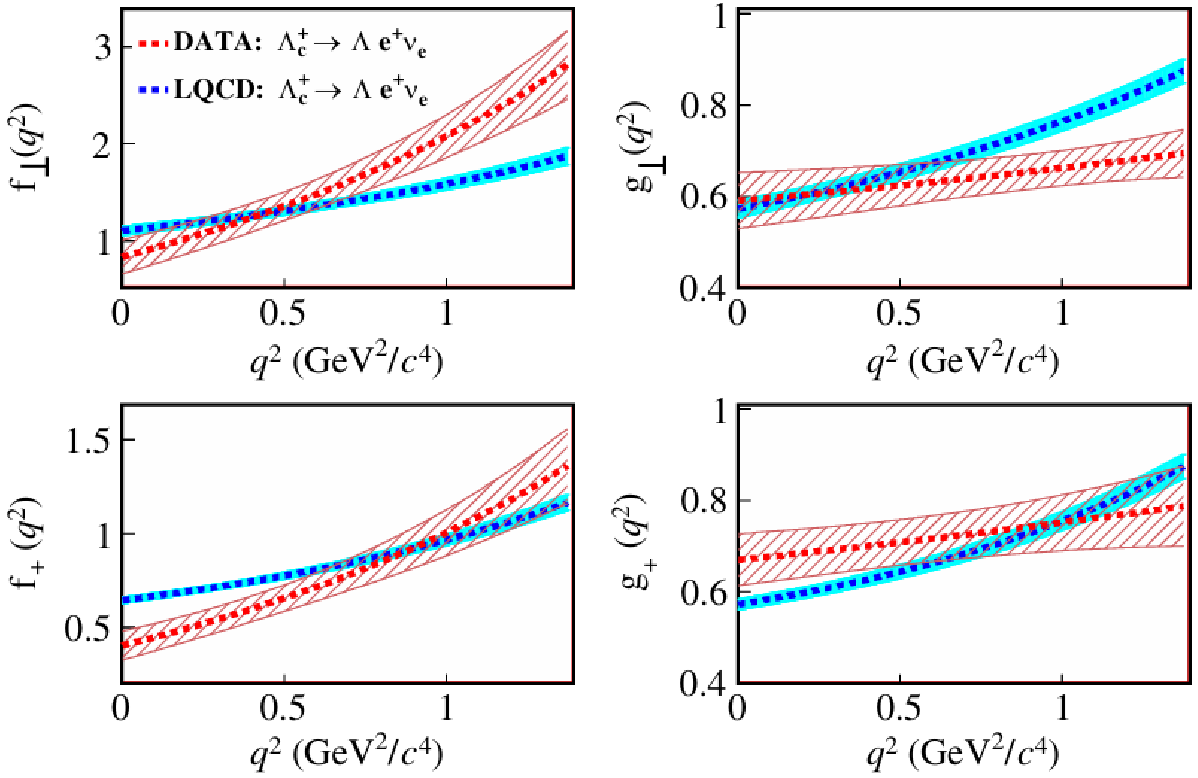


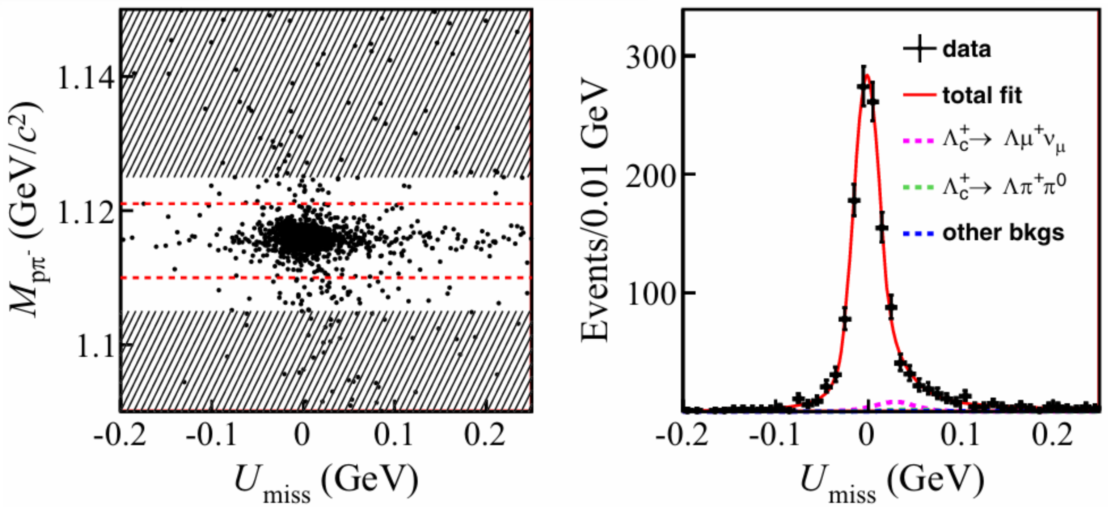
- $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.547 \pm 0.026 \pm 0.016)\%$
- $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.60 \pm 0.16 \pm 0.016)\%$
- $f_{D_s^+}|V_{cs}|_{\mu^+\nu_\mu} = (246.5 \pm 5.9_{\text{stat.}} \pm 3.6_{syst.})$;**($\sigma_{\text{exp.}} = 2.8\%$)**
- $f_{D_s^+}|V_{cs}|_{\tau^+\nu_\tau} = (252.7 \pm 3.6_{\text{stat.}} \pm 4.5_{syst.})$;**($\sigma_{\text{exp.}} = 2.3\%$)**
- $|V_{cs}|_{\mu^+\nu_\mu} = 0.986 \pm 0.023_{\text{stat.}} \pm 0.014_{\text{syst.}} \pm 0.003_{\text{input.}}$;**($\sigma_{\text{exp.}} = 2.8\%$)**
- $|V_{cs}|_{\tau^+\nu_\tau} = 1.011 \pm 0.014_{\text{stat.}} \pm 0.018_{\text{syst.}} \pm 0.003_{\text{input.}}$;**($\sigma_{\text{exp.}} = 2.3\%$)**

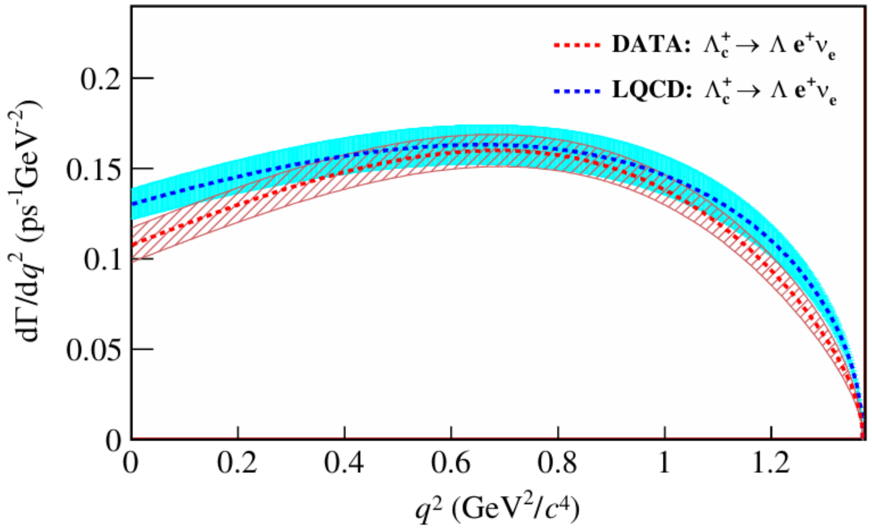
3 Status of $|V_{cs}|$

$\Lambda_c^+ \to \Lambda e^+ \nu_e$

- $4.5\ \mathrm{fb}^{-1}$@4.600-4.669 GeV
- Phys. Rev. Lett. **129**, 231803 (2022)





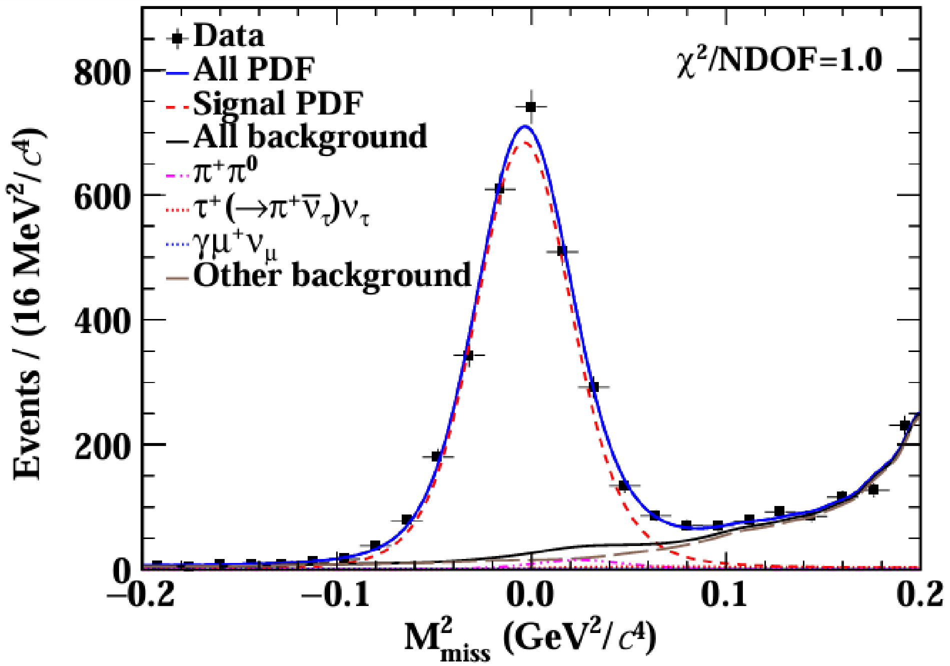


- $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$
- $|V_{cs}| = \left(0.936 \pm 0.017_{\mathcal{B}.} \pm 0.024_{\mathrm{LQCD.}} \pm 0.007_{\tau_{\Lambda_c}.}\right)$;$(\sigma_{\mathrm{exp.}} = 3.2\%)$

4 Status of $|V_{cd}|$

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

- 20.3 fb^{-1}@3.773 GeV
- Phys. Rev. Lett. **135**, 061801(2025)



- **Branching fractions:**
  - $\mathcal{B}(D^+ \to \mu^+ v_\mu) = (4.034 \pm 0.080 \pm 0.040) \times 10^{-4}$

- **Radiative correction:**
  - $\Gamma(D^+ \to \mu^+ v_\mu) = \Gamma(c \to \ell^+ \nu_\ell)\left[1 + \frac{\alpha}{\pi} C_p\right]$

1. Short-distance electroweak correction increases BF by 1.8% [PRD98,074512, NPB196,83]
2. Long-distance electroweak correction [inner bremsstrahlung and virtual photon] reduce BF by 2.5% with 0.6% uncertainty of unknown electromagnetic correction [PRD98,074512]

- $f_{D^+} = (213.5 \pm 2.1_{\text{stat.}} \pm 1.1_{\text{syst.}} \pm 0.8_{\text{input.}} \pm 0.7_{\text{EM.}})$;$(\sigma_{\text{exp.}} = 1.2\%\ \&\ \sigma_{\text{all.}} = 1.3\%)$
- $|V_{cd}| = 0.2265 \pm 0.0023_{\text{stat.}} \pm 0.0011_{\text{syst.}} \pm 0.0009_{\text{input.}} \pm 0.0007_{\text{EM.}}$;$(\sigma_{\text{exp.}} = 1.1\%\ \&\ \sigma_{\text{all.}} = 1.2\%)$

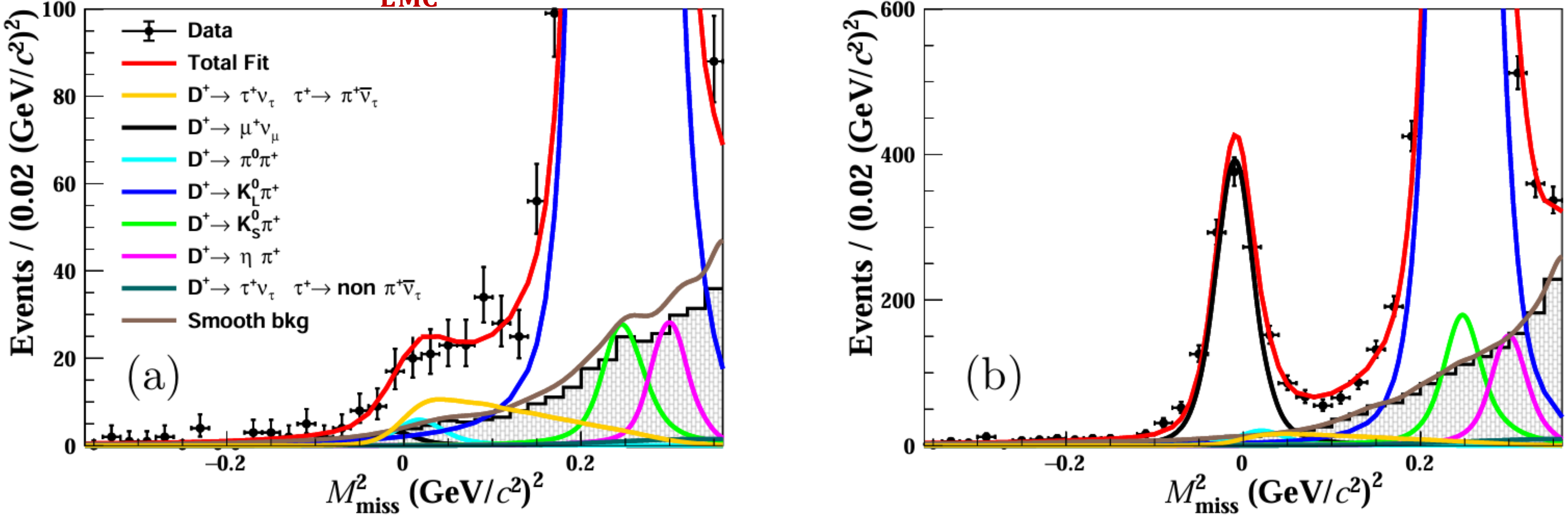
4 Status of $|V_{cd}|$

$D^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$

- 7.93 fb^{-1}@3.773 GeV
- JHEP 01 089 (2025)

π −like: $E_{\mathrm{EMC}} > 300\mathrm{MeV}$

μ −like: $E_{\mathrm{EMC}} < 300\mathrm{MeV}$



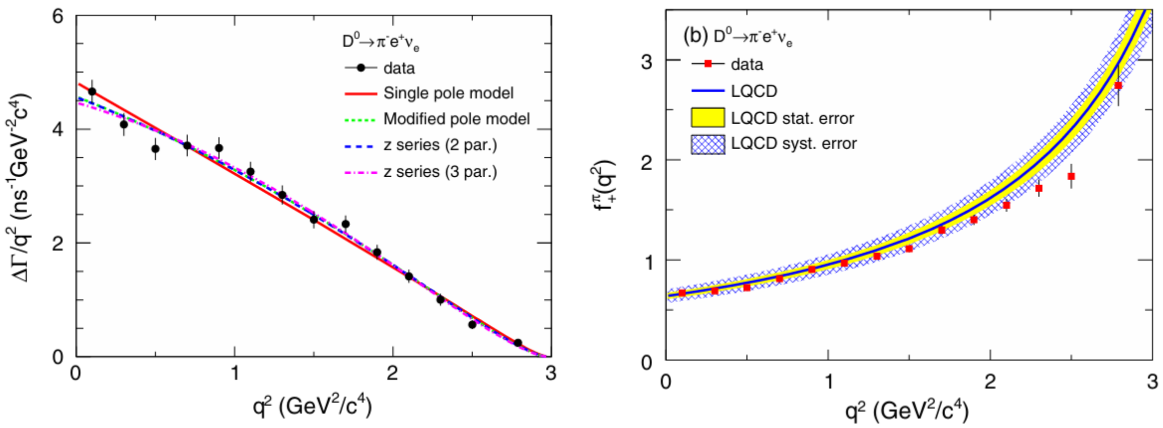
- $\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (9.9 \pm 1.1 \pm 0.5) \times 10^{-4}$; (Precision of BF is improved by 1.8)
- $f_{D^+} = (204 \pm 11_{\mathrm{stat.}} \pm 5_{\mathrm{syst.}} \pm 1_{\mathrm{input.}})$; $(\sigma_{\mathrm{exp.}} = 5.9\%)$
- $|V_{cd}| = 0.216 \pm 0.012_{\mathrm{stat.}} \pm 0.006_{\mathrm{syst.}} \pm 0.001_{\mathrm{input.}}$; $(\sigma_{\mathrm{exp.}} = 6.2\%)$

Status of $|V_{cd}|$

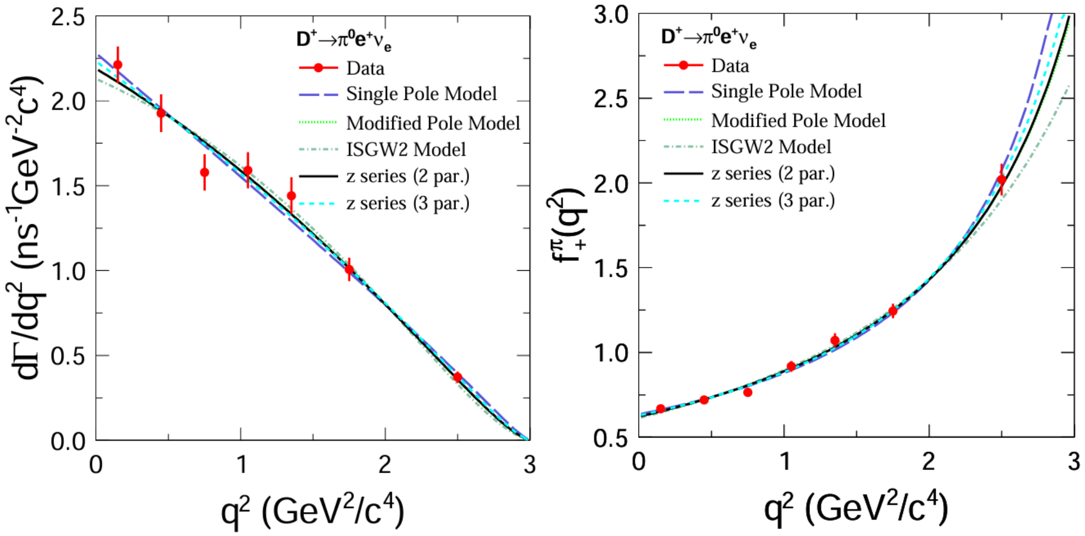
$D^{0(+)} \to \pi^{-(0)} e^+ \nu_e$

- **2.93 fb^{-1}@3.773 GeV**

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



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



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

- $f_+^\pi(0) = 0.6372 \pm 0.0080_{\text{stat.}} \pm 0.0044_{\text{syst.}}$ $(\sigma_{\text{exp.}} = 1.4\%)$
- $|V_{cs}| = 0.2155 \pm 0.0027_{\text{stat.}} \pm 0.0014_{\text{syst.}} \pm 0.0094_{\text{LQCD}}$ $(\sigma_{\text{exp.}} = 1.4\% \& \sigma_{\text{LQCD.}} = 4.6\%)$

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

- $f_+^\pi(0) = 0.622 \pm 0.012_{\text{stat.}} \pm 0.003_{\text{syst.}}$ $(\sigma_{\text{exp.}} = 2.0\%)$
- $|V_{cs}| = 0.210 \pm 0.004_{\text{stat.}} \pm 0.001_{\text{syst.}} \pm 0.009_{\text{LQCD}}$ $(\sigma_{\text{exp.}} = 2.0\% \& \sigma_{\text{LQCD.}} = 4.7\%)$

Results of 20.3 fb^{-1} on going, simultaneous fit to $\frac{d\Gamma}{dq^2}$ with four channels

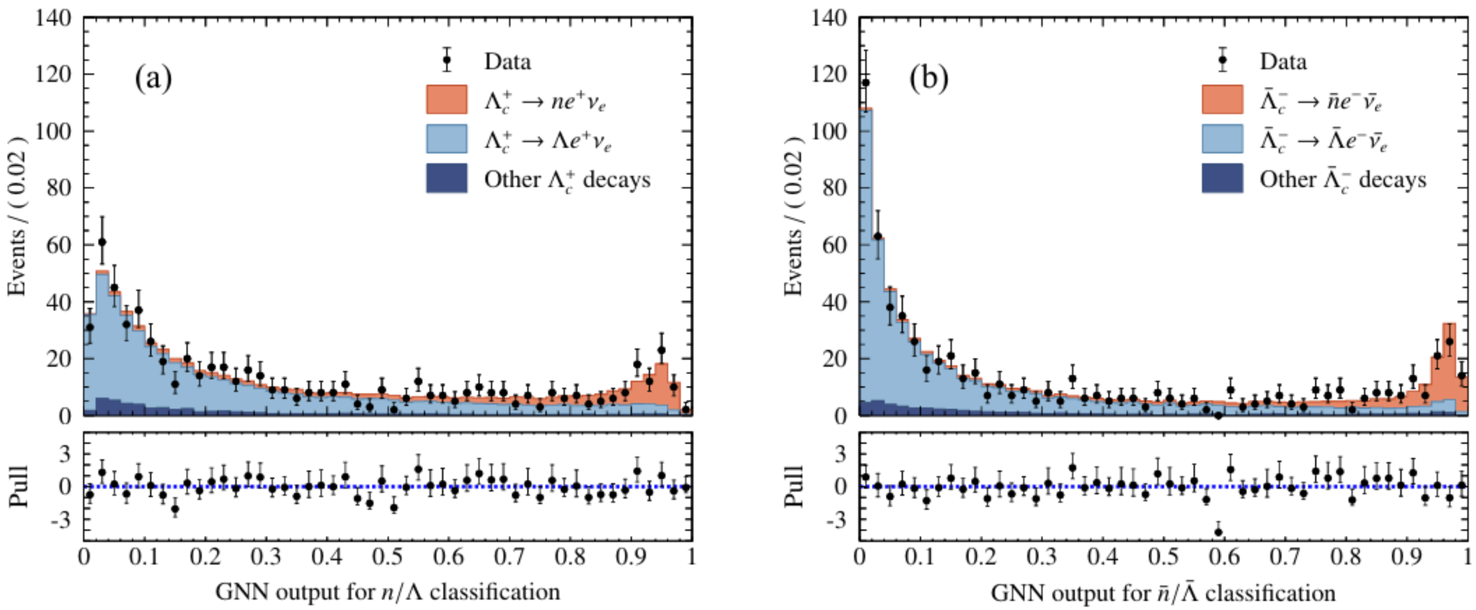
The precision will be improved by 2.5 times.

4 Status of $|V_{cd}|$

$\Lambda_c^+ \to n e^+ \nu_e$

- 4.5 fb^{-1}@4.600-4.669 GeV
- Nature Commun. **16**, 681 (2025)

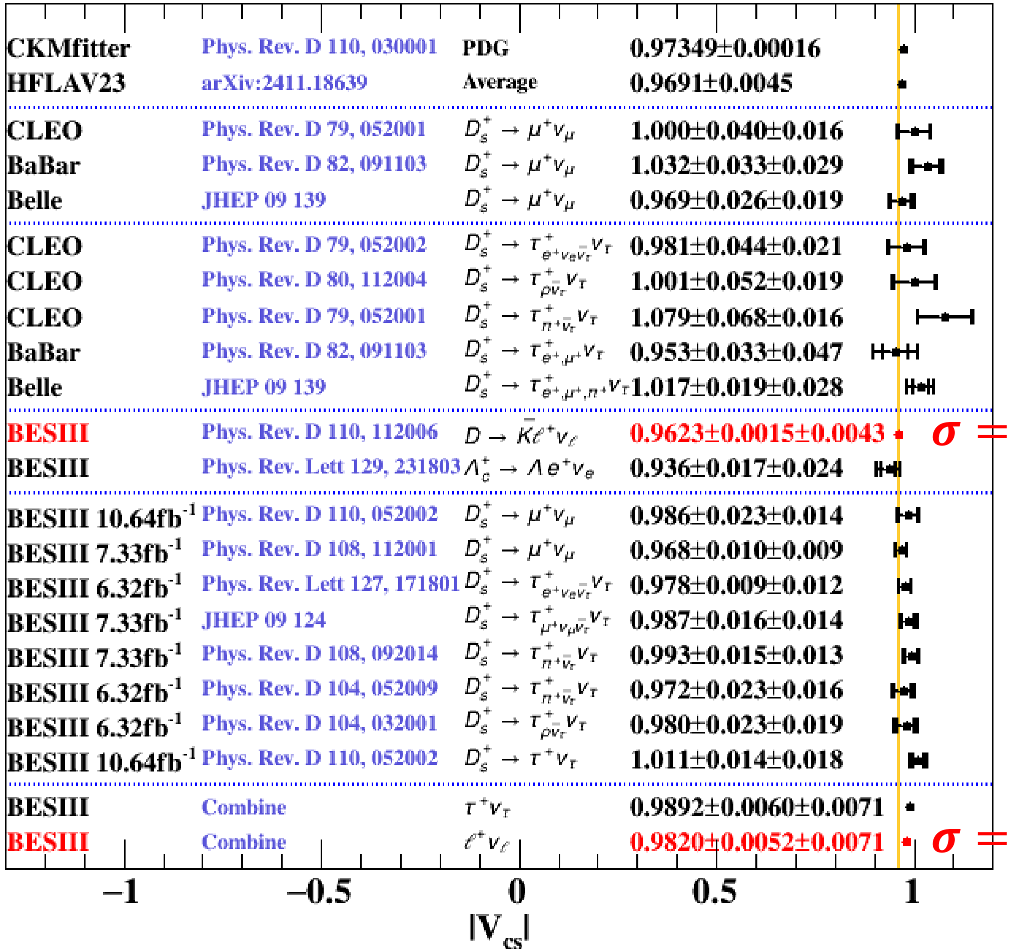
Graph Neural Network based technique effectively separates signals from dominant backgrounds



First determination of $|V_{cd}|$ from charmed baryon decays

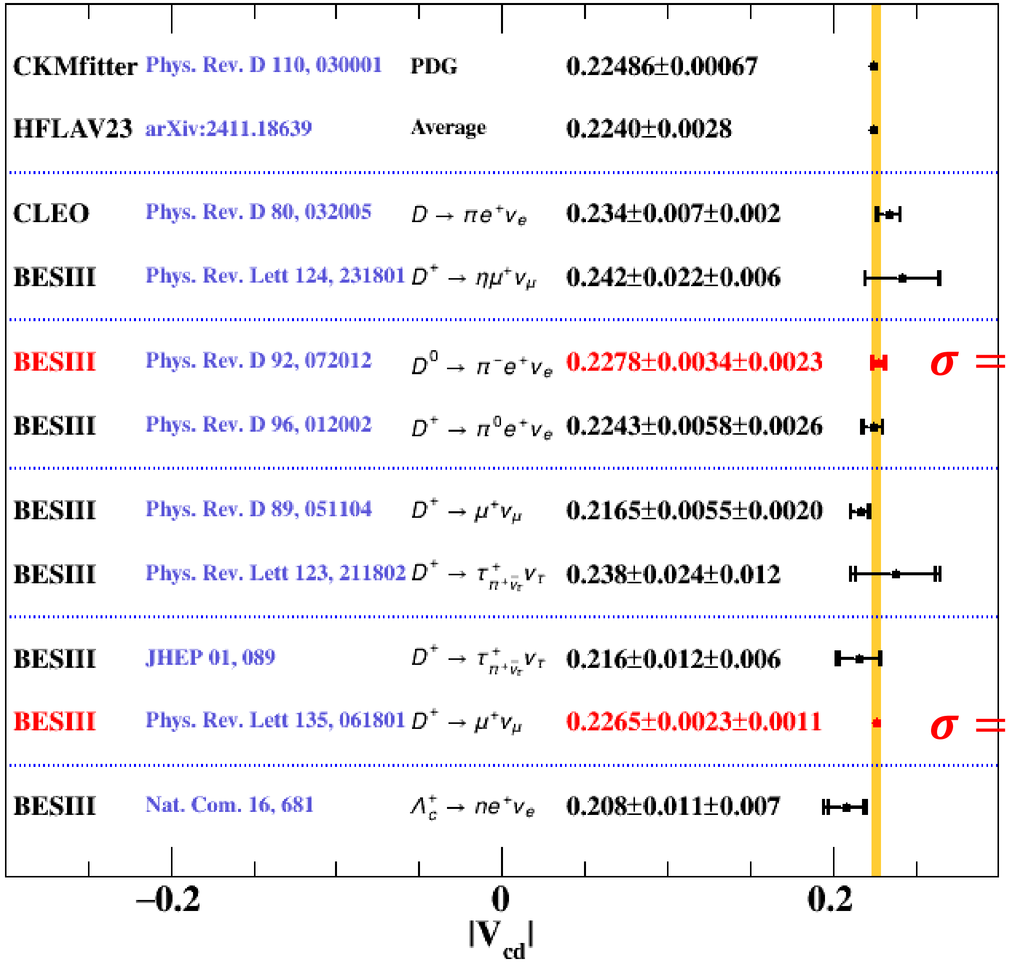
- $\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = (0.357 \pm 0.334 \pm 0.014)\%$
- $|V_{cd}| = 0.208 \pm 0.011_{\text{exp.}} \pm 0.007_{\text{LQCD.}} \pm 0.011_{\tau_{\Lambda_c}}$; $(\sigma_{\text{exp.}} = 8.2\%)$

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



$\sigma = 0.45\%$

$\sigma = 0.9\%$



$\sigma = 1.8\%$

$\sigma = 1.2\%$

5 Summary

* CPC 44, 040001 (2020)

- Purely leptonic and semi-leptonic decays of charm hadrons are important for determining CKM matrix elements, calibrating LQCD

- Precisions of $|V_{cs}|$ and $|V_{cd}|$ have been reduced to 0.6% and 1.2%, respectively

- 20.3 fb^{-1} data @3.773 GeV is ready at Jul. 2024, more precision measurements will be presented

- Additional 3 fb^{-1} data @4.178 GeV in future* will further improve the precisions in D_s sector

Thank you!

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