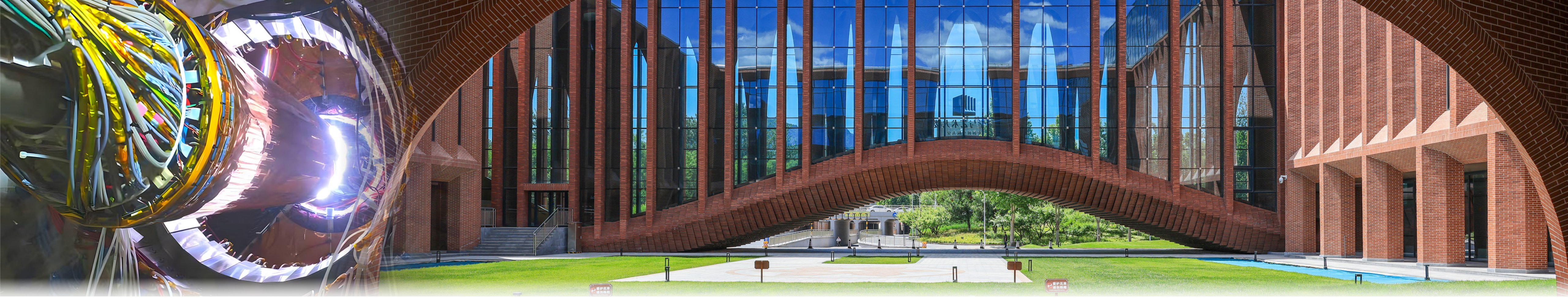


The semi-leptonic decays of charmed hadrons at BESIII

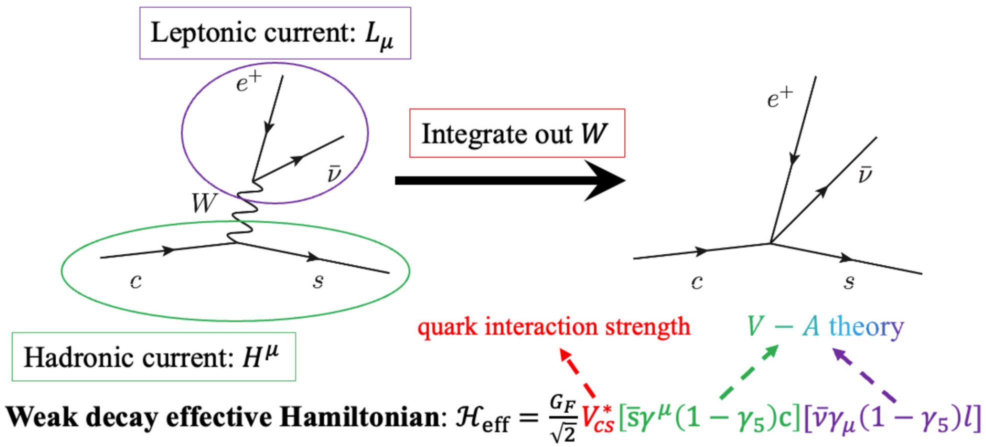
Yangu Li on behalf of the BESIII Collaboration
University of Chinese Academy of Sciences

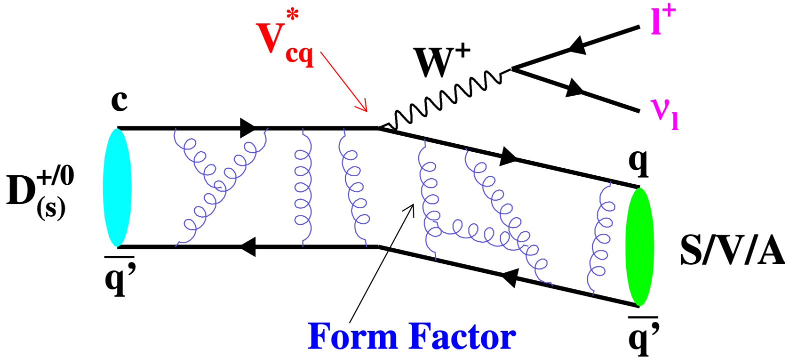
HQL 2025, Beijing, China
September 18, 2025

Introduction (I)

- **Semi-leptonic decays of charmed hadron provide ideal probes to study weak & strong interactions**
  - Weak interaction determines quark flavor change
  - Strong interaction isolated in initial-final hadron transition

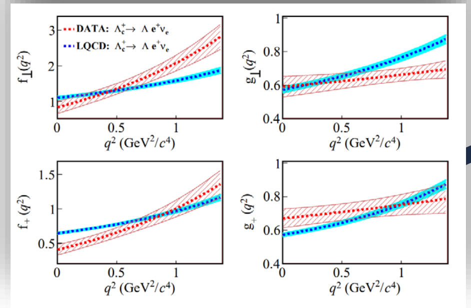
- **Formalism in a nutshell**
  - Helicity amplitude as a product of leptonic current L_μ and hadronic current H^μ
    - L_μ is well understood, H^μ is hard to calculate due to non-perturbative QCD effect
  - H^μ can be parameterized by form factors (FFs)
    - Functions of momentum transfer q^2





Introduction (II)

- **Test of SM from various aspects**

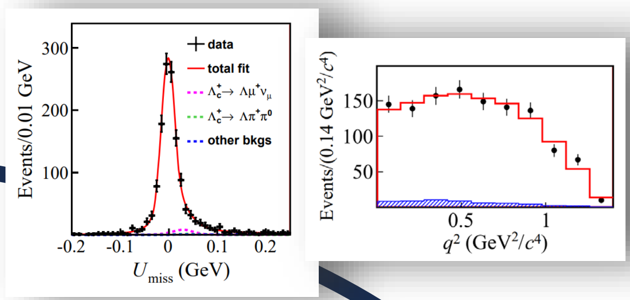


Form factors

Calculated by LQCD, HQET, quark models, sum rules, SU(3)...

Physics observables

BF, differential decay width, etc.



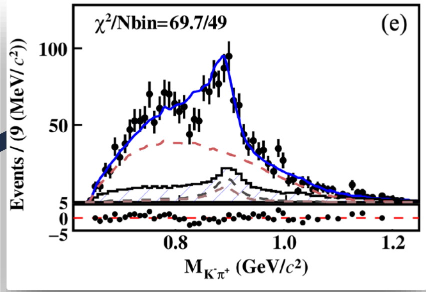
Formalism

$$\int \frac{d\Gamma}{dq^2} dq^2 = \frac{\mathcal{B}(\Lambda_c^+ \to h e^+ \nu_e)}{\tau_{\Lambda_c^+}},$$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cq}|^2}{192\pi^3 M_{\Lambda_c}^2} \times P q^2 \times \left[\left|H_{\frac{1}{2}1}\right|^2 + \left|H_{-\frac{1}{2}-1}\right|^2 + \left|H_{\frac{1}{2}0}\right|^2 + \left|H_{-\frac{1}{2}0}\right|^2 \right]$$

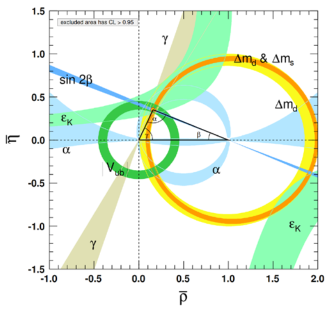
Light hadron spectrum

In multi-body hadronic final states



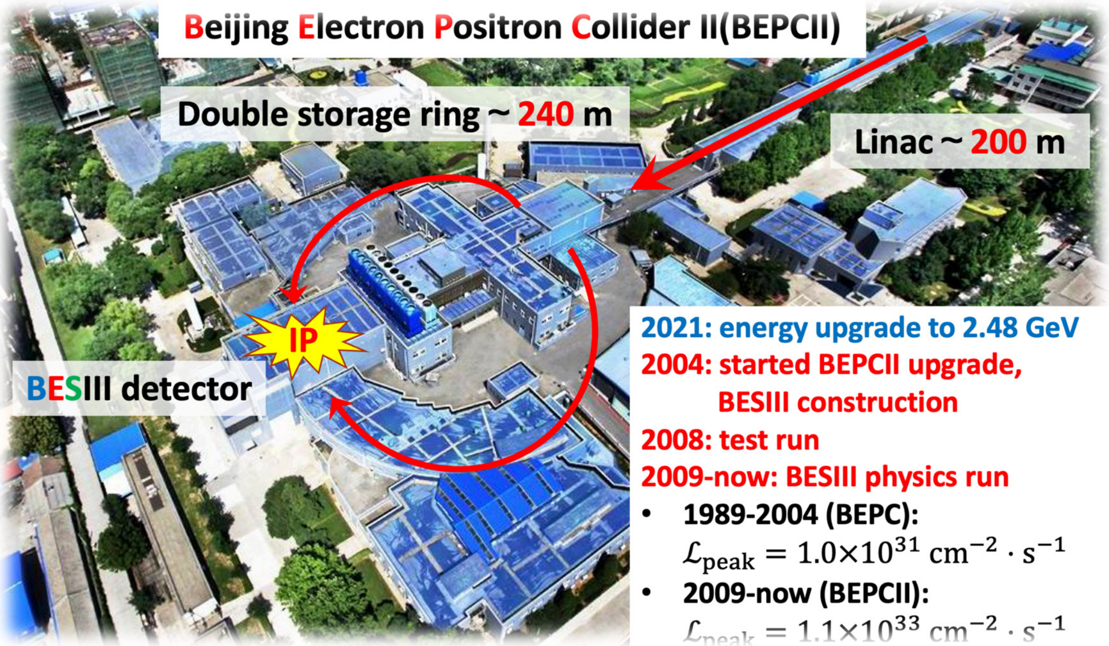
CKM unitarity

Access to $|V_{cs}|$ & $|V_{cd}|$, test LFU & CPV



BESIII experiment

- **Beijing Electron-Positron Collider II (BEPCII)**



2021: energy upgrade to 2.48 GeV

2004: started BEPCII upgrade, BESIII construction

2008: test run

2009-now: BESIII physics run

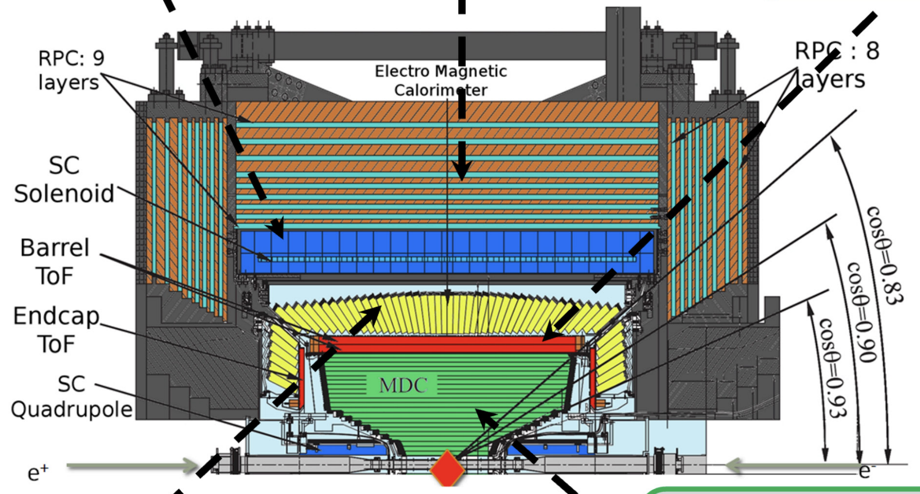
- **1989-2004 (BEPC):** $\mathcal{L}_{\text{peak}} = 1.0\times10^{31}\ \text{cm}^{-2}\cdot\text{s}^{-1}$
- **2009-now (BEPCII):** $\mathcal{L}_{\text{peak}} = 1.1\times10^{33}\ \text{cm}^{-2}\cdot\text{s}^{-1}$

- **Beijing Spectrometer III (BESIII)**

Superconducting solenoid
- **1.0 T**

Muon Counter (MUC)
- 9 layers (barrel) + 8 layers (end-cap)

Time Of Flight (TOF)
- σ_t = 90 ps (barrel)
- σ_t = 65 ps (end cap)



Electromagnetic Calorimeter(EMC)
- $\Delta E/E$ = 2.5% @ 1.0 GeV
- $\sigma_{\phi z}$ = 0.6 cm @ 1.0 GeV

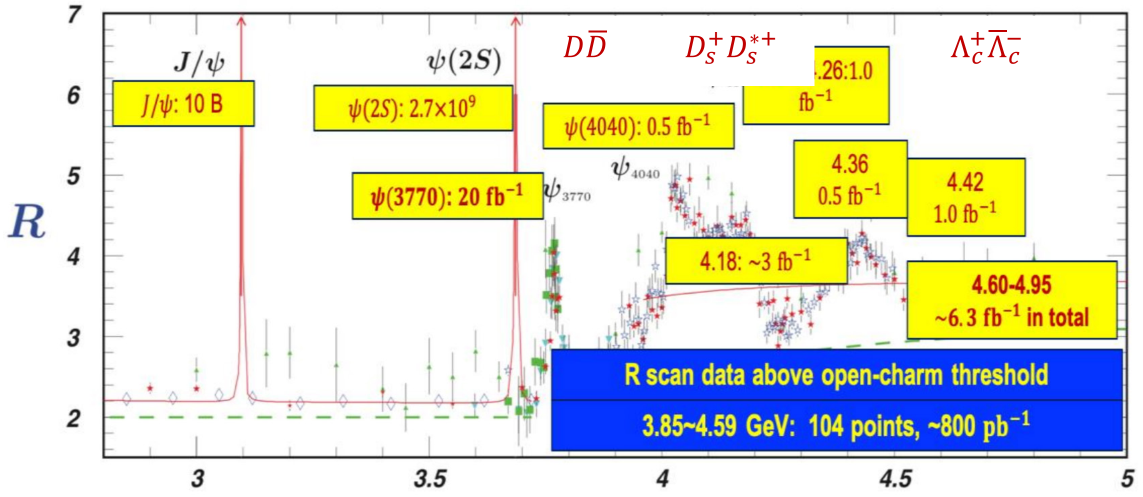
Main Drift Chamber (MDC)
- σ_{xy} = 130 μm
- $\Delta P/P$ = 0.5% @ 1.0 GeV
- $\sigma_{dE/dx} = 6 - 7\%$

Data samples

- $\boldsymbol{D^{0/+}}$ **study:** $20.3\ \mathrm{fb}^{-1}$ collected at $\sqrt{s} = 3.773\ \mathrm{GeV}$
  - Produced via $\psi(3770) \to D\bar{D}$
  - Single-tag yields 16.9M D^0 & 11.0M D^+ events

- $\boldsymbol{D_s^+}$ **study:** $7.33\ \mathrm{fb}^{-1}$ collected at $\sqrt{s} = 4.13 - 4.23\ \mathrm{GeV}$
  - Mainly produced via $e^+e^- \to D_s^{*+}D_s^-$ due to larger cross-section
  - Can be also accessed from $e^+e^- \to D_s^{*+}D_s^{*-}$
  - Single-tag yields 0.8M D_s^+ events

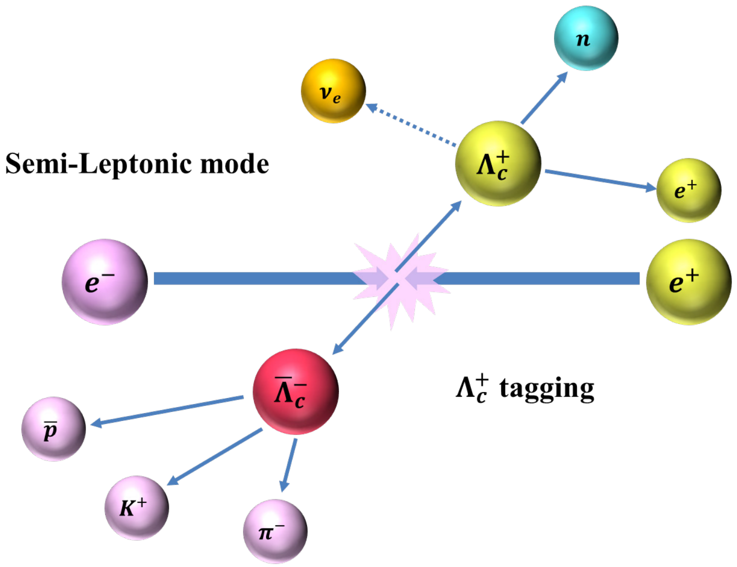
- $\boldsymbol{\Lambda_c^+}$ **study:** $4.5\ \mathrm{fb}^{-1}$ collected at $\sqrt{s} = 4.6 - 4.7\ \mathrm{GeV}$
  - Produced via $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$
  - Single-tag yields 0.1M Λ_c^+ events



Unique abilities (I)

- **Near-threshold pair production**
  - Without accompanying hadrons
  - Clean backgrounds and well constrained kinematics

- **Double-tag method**
  - Reconstruct $h \to$ signal & $\bar{h} \to$ hadronic tag modes sequentially
  - Allow to:
    - Measure absolute BF
    - Suppress hadronic background
    - Recoil missing neutrino
    - Cancel systematics



$$\mathcal{B}_{\rm sig} = \frac{\sum_{i,j} N^{i,j}_{\rm DT}}{\sum_{i,j}\left(\frac{N^{i,j}_{\rm ST}}{\epsilon^{i,j}_{\rm ST}}\cdot\epsilon^{i,j}_{\rm DT}\right)} = \frac{N_{\rm DT}}{\sum_{i,j}\left(\frac{N^{i,j}_{\rm ST}}{\epsilon^{i,j}_{\rm ST}}\cdot\epsilon^{i,j}_{\rm DT}\right)} = \frac{N_{\rm DT}}{N_{\rm ST}\cdot\epsilon^{\rm sig}},$$

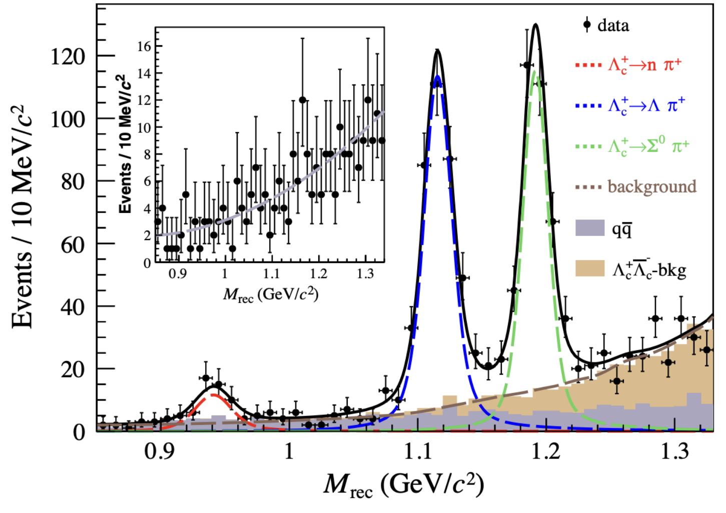
$$N^{i,j}_{\rm ST} = 2N^{j}_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}^{i}_{\rm tag}\epsilon^{i,j}_{\rm ST}, \qquad \epsilon^{\rm sig} = \sum_{i,j}\left(\frac{N^{i,j}_{\rm ST}}{\epsilon^{i,j}_{\rm ST}}\cdot\epsilon^{i,j}_{\rm DT}\right)\Big/\sum_{i,j}N^{i,j}_{\rm ST},$$

$$N^{i,j}_{\rm DT} = 2N^{j}_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}^{i}_{\rm tag}\mathcal{B}_{\rm sig}\epsilon^{i,j}_{\rm DT}, \qquad N_{\rm ST} = \sum_{i,j}N^{i,j}_{\rm ST}$$

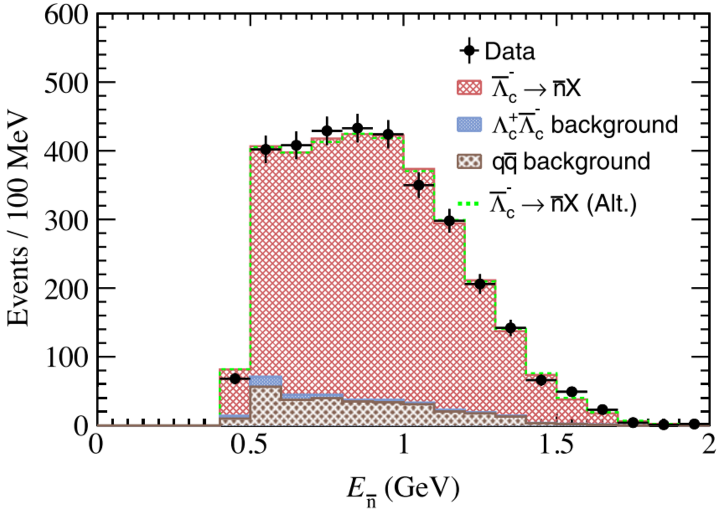
Unique abilities (II)

- **Neutral particle detection**
  - BESIII has high acceptance & performance EMC
  - Reconstruction for γ & π^0 is effective and precise
  - Reconstruction for n & K_L^0 is challenging yet possible
    - Deep learning methods are being explored

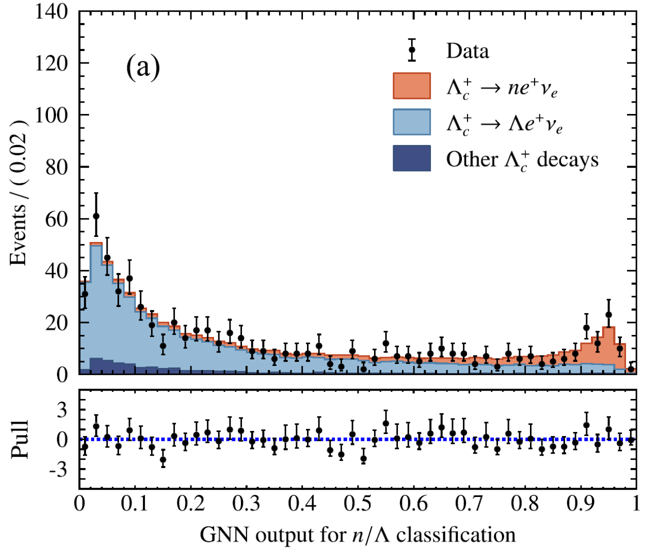
$\Lambda_c^+ \to n\pi^+$, PRL **128**, 142001 (2022)



$\bar{\Lambda}_c^- \to \bar{n} + X$, PRD **108**, L031101 (2023)



$\Lambda_c^+ \to ne^+\nu_e$, NatComm **16**, 681 (2025)



Recent physics results

Charmed meson → scalar decays

- $D^+ \to f_0(500) l^+ \nu_l$ — PRD **110**, 092008 (2024)
- $D^0 \to a_0(980) e^+ \nu_e$ — PRD **111**, L091501 (2025)
- $D_s^+ \to f_0(980) e^+ \nu_e$ — PRL **132**, 141901 (2024)

Charmed meson → vector decays

- $D^+ \to \bar{K}^0 \pi^0 e^+ \nu_e$ — JHEP **10**, 199 (2024)
- $D^+ \to \bar{K}^0 \pi^0 \mu^+ \nu_\mu$ — arXiv: 2506.05761
- $D^0 \to K^- \pi^0 \mu^+ \nu_\mu$ — PRL **134**, 011803 (2025)
- $D^0 \to \bar{K}^0 \pi^- e^+ \nu_e$ — JHEP **03**, 197 (2025)
- $D^0 \to \bar{K}^0 \pi^- \mu^+ \nu_\mu$ — arXiv: 2504.10867
- $D^0 \to \pi^0 \pi^- e^+ \nu_e$ — PRD **110**, 112018 (2024)
- $D_s^+ \to \phi e^+ \nu_e$ — PRD **110**, 072017 (2024)
- $D_s^+ \to \phi \mu^+ \nu_\mu$ — JHEP **12**, 072 (2023)

Charmed meson → axion vector decays

- $D \to b_1(1235) e^+ \nu_e$ — arXiv: 2407.20551
- $D \to K_1(1270) e^+ \nu_e$ — PRL **135**, 091801 (2025)
- $D \to K_1(1270) \mu^+ \nu_\mu$ — PRD **111**, L071101 (2025)

Charmed baryon decays

- $\Lambda_c^+ \to \Lambda e^+ \nu_e$ — PRL **129**, 231803 (2022)
- $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$ — PRD **108**, L031105 (2023)
- $\Lambda_c^+ \to p K^- e^+ \nu_e$ — PRD **106**, 112010 (2022)
- $\Lambda_c^+ \to n e^+ \nu_e$ — NatComm **16**, 681 (2025)
- $\Lambda_c^+ \to X e^+ \nu_e$ — PRD **107**, 052005 (2023)

* For charmed meson → pseudo scalar decays,
please refer to Chao Chen's talk on Sep 16

Charmed meson → scalar decays

$D \to S l \nu$

$D^+ \to f_0(500)[\to \pi^+\pi^-]l^+\nu_l$

PRD **110**, 092008 (2024)

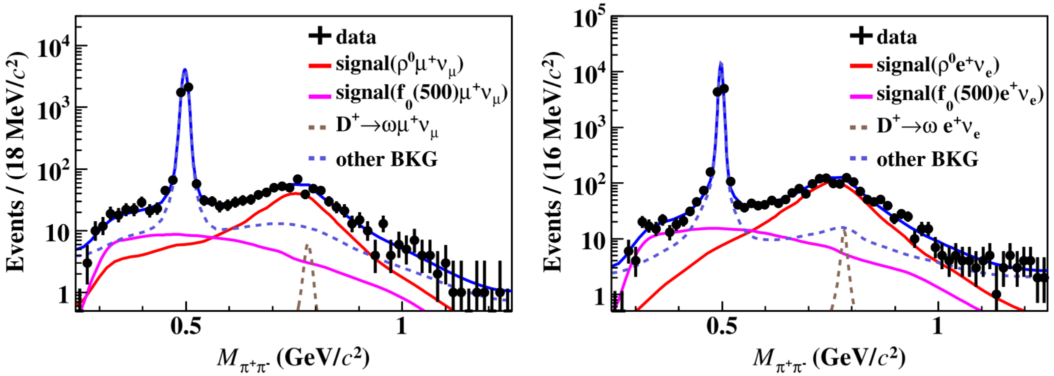
2.93 fb^{-1} data
0.4k (e) / 0.2k (μ) signal

First BF measurement

- $\mathcal{B}(D^+ \to f_0(500)\mu^+\nu_\mu) \times \mathcal{B}(f_0(500) \to \pi^+\pi^-) = (0.72 \pm 0.13 \pm 0.08) \times 10^{-3}$
- $\mathcal{B}(D^+ \to \rho^0\mu^+\nu_\mu) = (1.64 \pm 0.13 \pm 0.10) \times 10^{-3}$

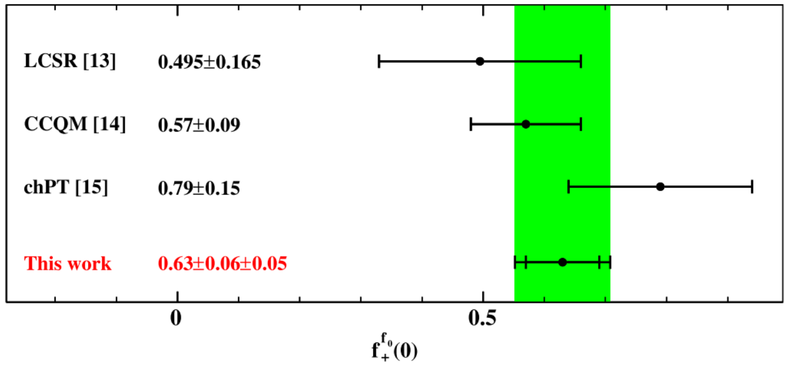
LFU test

- $\frac{\mathcal{B}(D^+\to f_0(500)\mu^+\nu_\mu)}{\mathcal{B}(D^+\to f_0(500)e^+\nu_e)} = 1.14 \pm 0.26$
- $\frac{\mathcal{B}(D^+\to \rho^0\mu^+\nu_\mu)}{\mathcal{B}(D^+\to \rho^0 e^+\nu_e)} = 0.88 \pm 0.10$



First extraction of FF

- $f_+^{f_0}(0) = 0.63 \pm 0.06 \pm 0.05$
- $r_1 = -5.8 \pm 2.4 \pm 0.5$ under z-series expansion



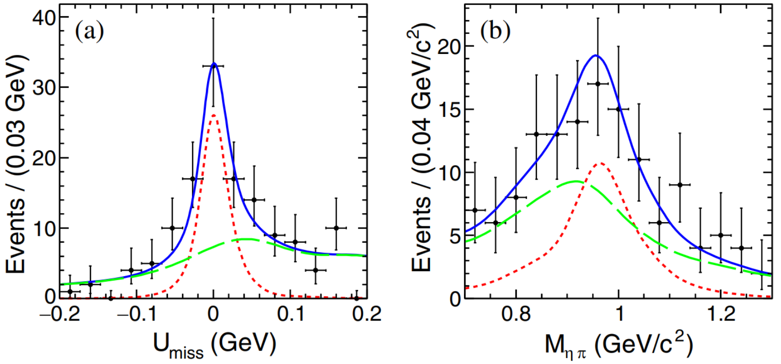
$D^0 \to a_0(980)^-[\to \eta\pi^-]e^+\nu_e$

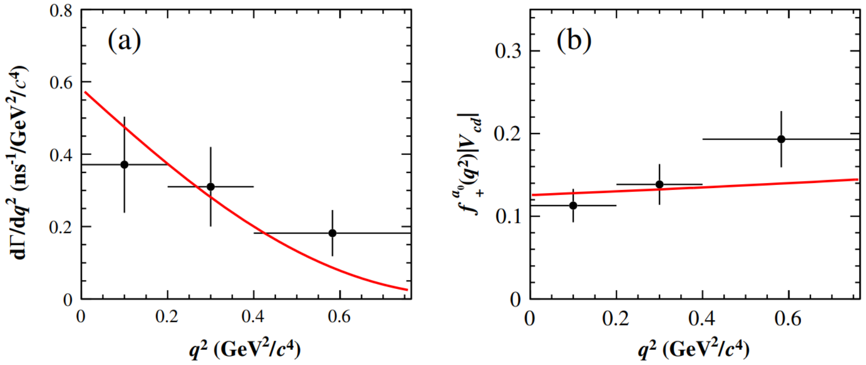
PRD **111**, L091501 (2025)

7.93 fb^{-1} data
~50 signal

Updated BF measurement

- $\mathcal{B}\left(D^0 \to a_0(980)^- e^+\nu_e\right) \times \mathcal{B}(a_0(980)^- \to \eta\pi^-) = (0.86 \pm 0.17 \pm 0.05) \times 10^{-4}$
- $a_0(980)^-$ parameterized with Flatte, $\eta\pi^-$ NR found to be negligible
- 1.2 times more precise than previous measurement





First extraction of FF

- $f_+^{a_0}(0) = 0.559 \pm 0.056 \pm 0.013$
- Favor four-quark picture of $a_0(980)$ over two-quark scenarios

Theory or experiment	$f_+^{a_0}(0)$	$\mathcal{B}(D^0 \to a_0(980)^- e^+\nu_e, a_0(980)^- \to \eta\pi^-)$ $(\times 10^{-4})$
CCQM [25]	$0.55^{+0.02}_{-0.02}$	1.43 ± 0.13^{a}
Ads/QCD [26]	0.72 ± 0.09	2.08 ± 0.26^{a}
LCSR 2017 [27]	$1.75^{+0.26}_{-0.27}$	$3.48^{+1.17a}_{-1.04}$
LCSR 2021 [28]	$0.85^{+0.10}_{-0.11}$	1.15
LCSR 2023 [29]	$1.058^{+0.068}_{-0.035}$	$1.330^{+0.216}_{-0.134}$
SU(3) flavor symmetry [20]	0.46 ± 0.06	...
BESIII 2018 [24]	...	$1.33^{+0.33}_{-0.29\,\text{stat}} \pm 0.09_{\text{syst}}$
This work	$0.559 \pm 0.056_{\text{stat}} \pm 0.013_{\text{syst}}$	$0.86 \pm 0.17_{\text{stat}} \pm 0.05_{\text{syst}}$

[a]The narrow width approximation is further applied to estimate the $\mathcal{B}\ l$ for uncomputed cases (denoted by the superscript *).

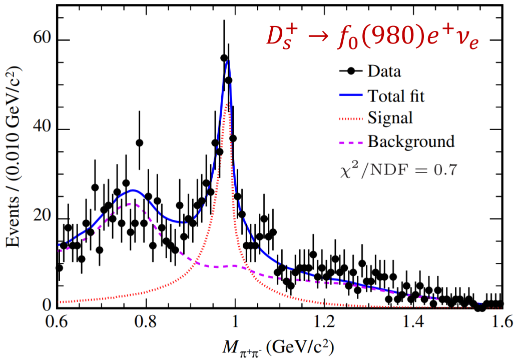
$D_s^+ \to f_0(980)[\to \pi^+\pi^-]e^+\nu_e$

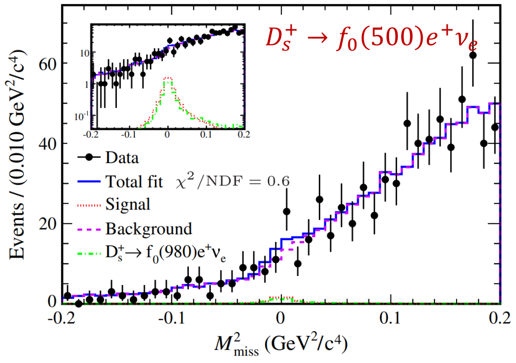
PRL **132**, 141901 (2024)

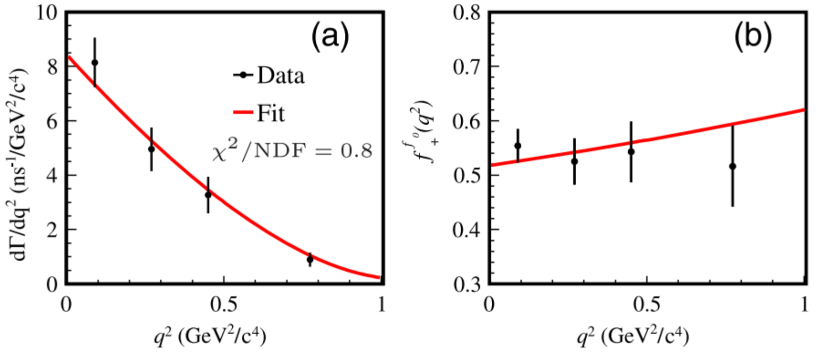
7.33 fb^{-1} data
0.4k signal

Updated BF measurement

- $\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e) \times \mathcal{B}(f_0(980) \to \pi^+\pi^-) = (1.72 \pm 0.13 \pm 0.10) \times 10^{-3}$
  - 2.6 times more precise than previous measurement
  - Extract mixing angle $\phi = (19.7 \pm 12.8)^\circ$
- $\mathcal{B}(D_s^+ \to f_0(500)e^+\nu_e) \times \mathcal{B}(f_0(500) \to \pi^+\pi^-) < 3.3 \times 10^{-4}$ @ 90% C. L.
- Favor the tetraquark composition of $f_0(980)$ & $f_0(500)$



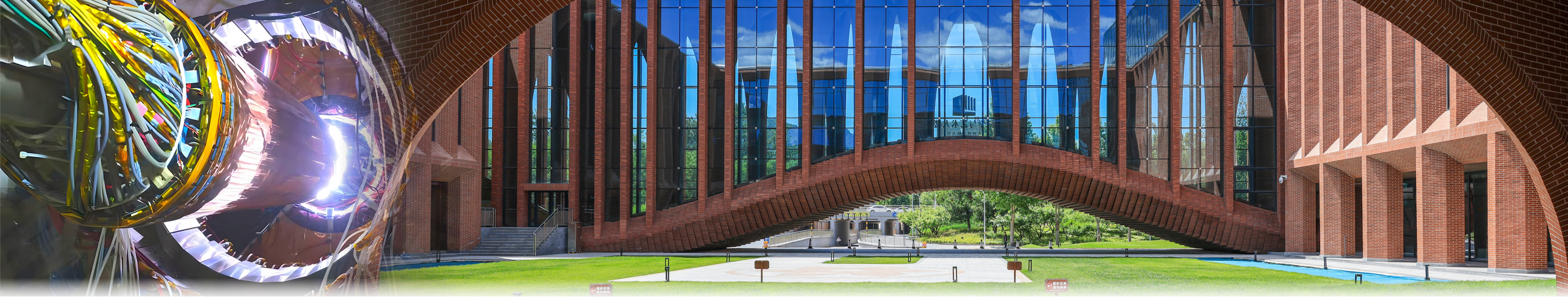




First extraction of FF

- $f_+^{f_0}(0) = 0.518 \pm 0.018 \pm 0.036$
- Theoretical predictions suffer from large ϕ uncertainty

	This work	CLFD [6]	DR [6]	QCDSR [7]	QCDSR [8]	LCSR [9]	LFQM [11]	CCQM [12]
$f_+^{f_0}(0)$	$0.518 \pm 0.018_{\mathrm{stat}} \pm 0.036_{\mathrm{syst}}$	0.45	0.46	0.50 ± 0.13	0.48 ± 0.23	0.30 ± 0.03	0.24 ± 0.05	0.36 ± 0.02
Difference (σ)	···	1.7	1.4	0.1	0.2	4.3	4.3	2.8
ϕ in theory	···	$(32 \pm 4.8)^\circ$	$(41.3 \pm 5.5)^\circ$	35°	$(8^{+21}_{-8})^\circ$	···	$(56 \pm 7)^\circ$	31°



Charmed meson → vector decays

$D \to V l \nu$

$D^+ \to \bar{K}^*(892)^0[\to \bar{K}^0\pi^0]l^+\nu_l$ (I)

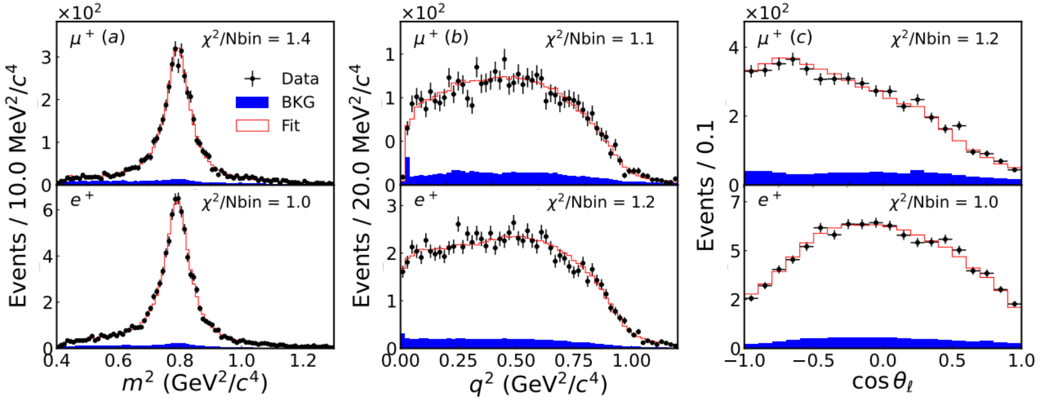
JHEP **10**, 199 (2024)
arXiv: 2506.05761

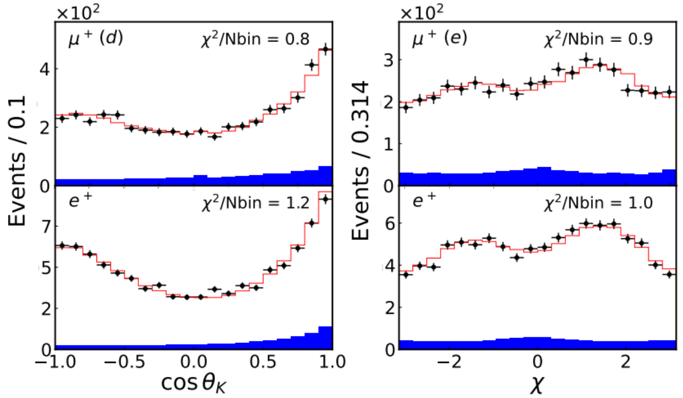
20.3 fb^{-1} data
11.1k (e) / 6.8k (μ) signal

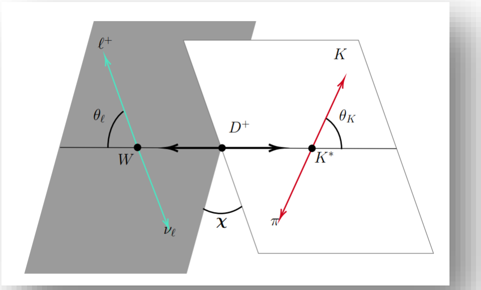
- **BF measurements**
  - $\mathcal{B}(D^+ \to K_S^0\pi^0 e^+\nu_e) = (0.943 \pm 0.012 \pm 0.010)\%$
  - $\mathcal{B}(D^+ \to K_S^0\pi^0 \mu^+\nu_\mu) = (0.896 \pm 0.017 \pm 0.008)\%$
  - $\mathcal{B}(D^+ \to \bar{K}^*(892)^0 e^+\nu_e) = (5.29 \pm 0.07 \pm 0.06)\%$
  - $\mathcal{B}(D^+ \to \bar{K}^*(892)^0 \mu^+\nu_\mu) = (4.99 \pm 0.10 \pm 0.05)\%$

- **Study of $K\pi$ amplitude structure & $D^+ \to \bar{K}^*$ FF**
  - Calculated via 5-D fits from full angular analysis

Variable	$D^+ \to K_S^0\pi^0 e^+\nu_e$	$D^+ \to K_S^0\pi^0 \mu^+\nu_\mu$
$m_{\bar{K}^{*0}}$ (MeV/c^2)	894.76 ± 0.29	
$\Gamma_{\bar{K}^{*0}}$ (MeV/c^2)	$45.24 \pm 0.62 \pm 0.45$	
r_V	$1.42 \pm 0.03 \pm 0.02$	
r_2	$0.75 \pm 0.03 \pm 0.01$	
$a_{S,\mathrm{BG}}^{1/2}$ (GeV/c)$^{-1}$	$2.32 \pm 0.11 \pm 0.25$	$1.47 \pm 0.25 \pm 0.22$
r_S (GeV)$^{-1}$	$-8.44 \pm 0.13 \pm 0.37$	$-9.59 \pm 0.46 \pm 0.58$
$f_{S\text{-wave}}$	$6.39 \pm 0.17 \pm 0.14$	$7.10 \pm 0.68 \pm 0.41$
$f_{\bar{K}^{*0}}$	$93.50 \pm 0.18 \pm 0.28$	$92.81 \pm 0.67 \pm 0.47$





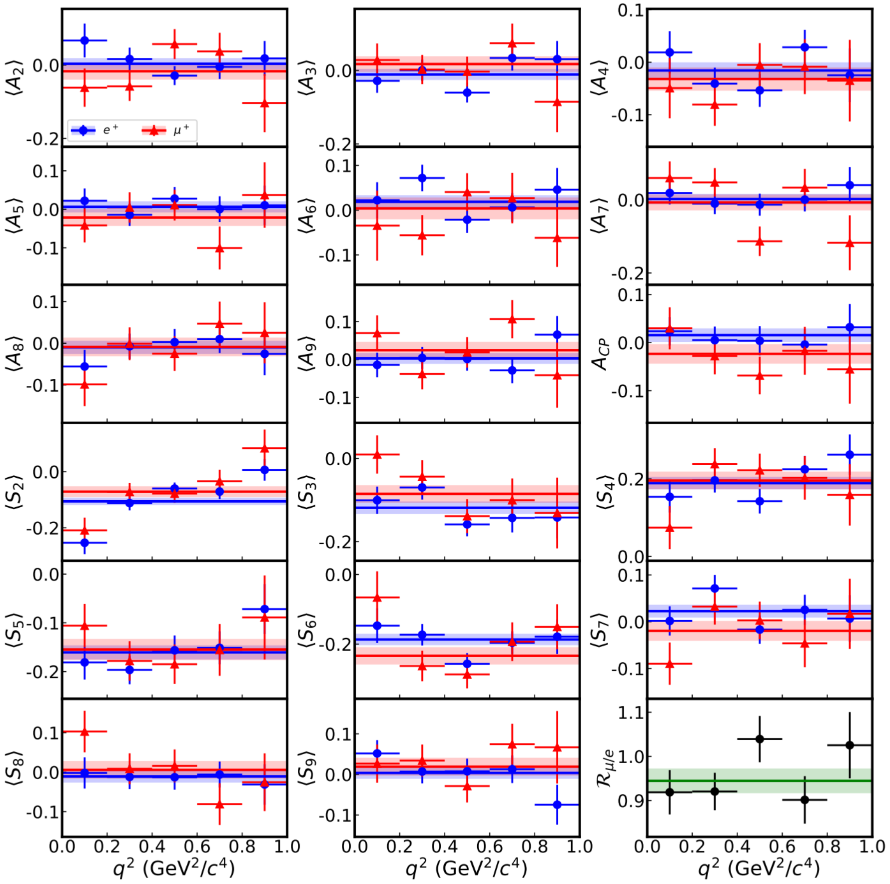


$D^+ \to \bar{K}^*(892)^0[\to \bar{K}^0\pi^0]l^+\nu_l$ (II)

JHEP **10**, 199 (2024)
arXiv: 2506.05761

- **CPV, LFU & angular observables**
  - Measured in different q^2 regions of $K^*(892)$
  - All consistent with SM predictions

20.3 fb^{-1} data
11.1k (e) / 6.8k (μ) signal



$D^0 \to \bar{K}^*(892)^-[\to K^-\pi^0]\mu^+\nu_\mu$

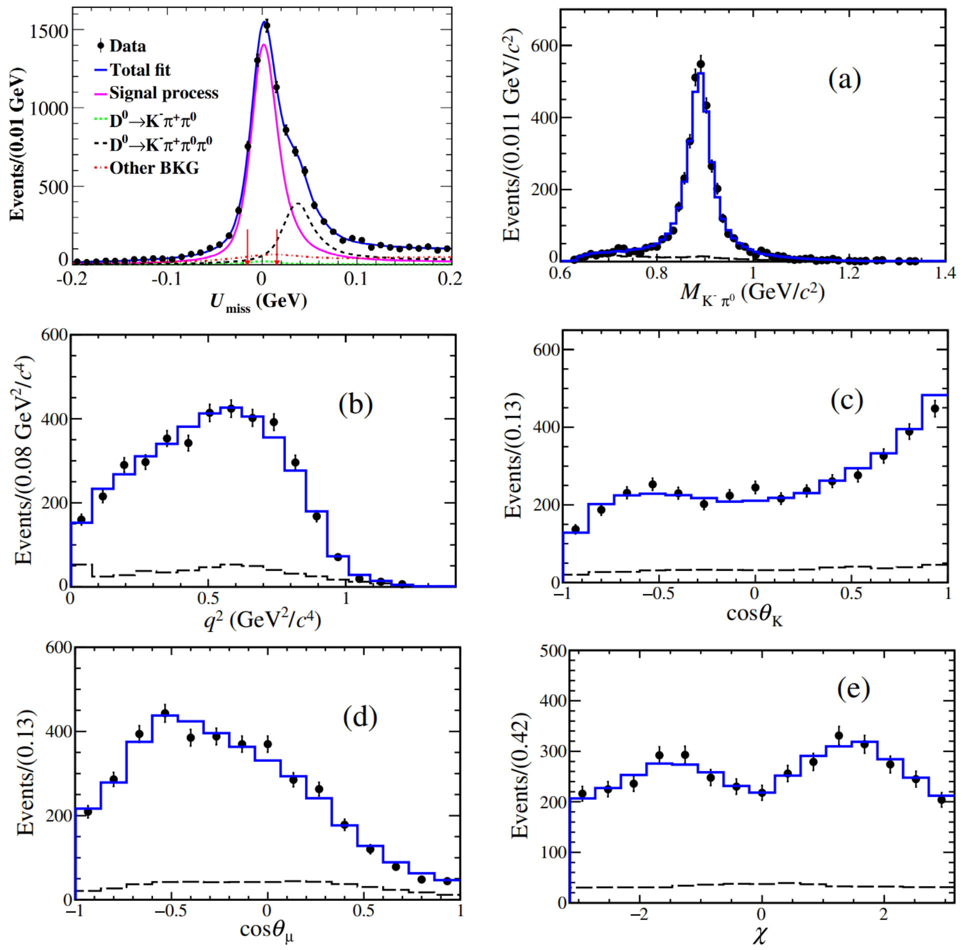
PRL **134**, 011803 (2025)

- **BF measurements**
  - $\mathcal{B}\left(D^0 \to K^*(892)^-\mu^+\nu_\mu\right) = (2.073 \pm 0.039 \pm 0.032)\%$
  - $\mathcal{B}\left(D^0 \to (K^-\pi^0)_{S-\mathrm{wave}}\mu^+\nu_\mu\right) = (4.223 \pm 0.268 \pm 0.222) \times 10^{-4}$

7.93 fb^{-1} data
6.4k signal

- **Study of $K\pi$ amplitude structure & $D^0 \to \bar{K}^*$ FF**
  - Calculated via 5-D fits from full angular analysis

Theory	$\mathcal{B}$ (%)	r_V	r_2
LCSR [7,16]	$2.01^{+0.09}_{-0.08}$	1.39	0.60
χUA [17]	1.98	...	...
CCQM [6]	2.80	1.22 ± 0.24	0.92 ± 0.18
CQM [8,18]	3.09	1.56	0.74
LFQM [9]	...	1.36	0.83
HM$_\chi$T [10]	...	1.60	0.50
Experiments	$\mathcal{B}$ (%)	r_V	r_2
BESIII [39]	...	$1.46 \pm 0.07 \pm 0.02$	$0.67 \pm 0.06 \pm 0.01$
FOCUS [11]	1.89 ± 0.24	$1.71 \pm 0.68 \pm 0.34$	$0.91 \pm 0.37 \pm 0.10$
This Letter	$2.073 \pm 0.039 \pm 0.032$	$1.37 \pm 0.09 \pm 0.03$	$0.76 \pm 0.06 \pm 0.02$



$D^0 \to \bar{K}^*(892)^-[\to \bar{K}^0\pi^-]l^+\nu_l$

JHEP **03**, 197 (2025)
arXiv: 2504.10867

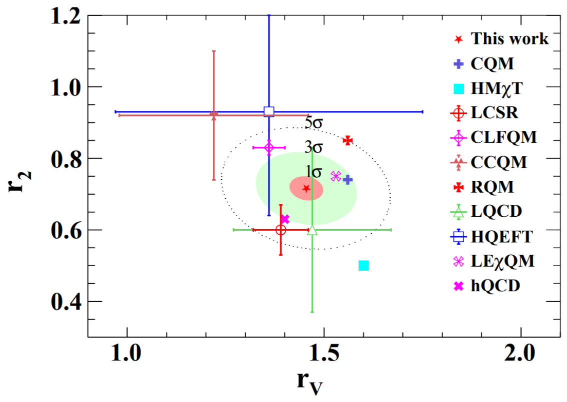
7.93 fb^{-1} data
8.8k (e) / 6.8k (μ) signal

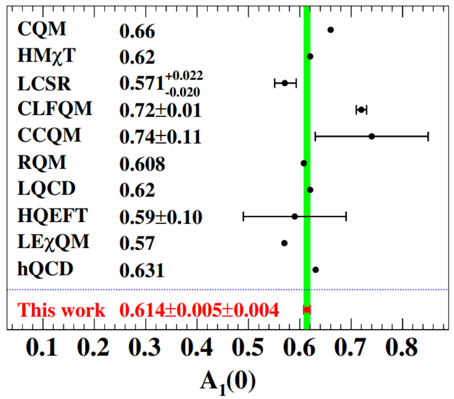
BF measurements

- $\mathcal{B}(D^0 \to \bar{K}^0\pi^0 e^+\nu_e) = (1.444 \pm 0.022 \pm 0.024)\%$
- $\mathcal{B}(D^0 \to \bar{K}^0\pi^0 \mu^+\nu_\mu) = (1.373 \pm 0.020 \pm 0.023)\%$
- $\mathcal{B}(D^0 \to \bar{K}^*(892)^- e^+\nu_e) = (2.039 \pm 0.032 \pm 0.034)\%$
- $\mathcal{B}(D^0 \to \bar{K}^*(892)^- \mu^+\nu_\mu) = (1.948 \pm 0.033 \pm 0.036)\%$

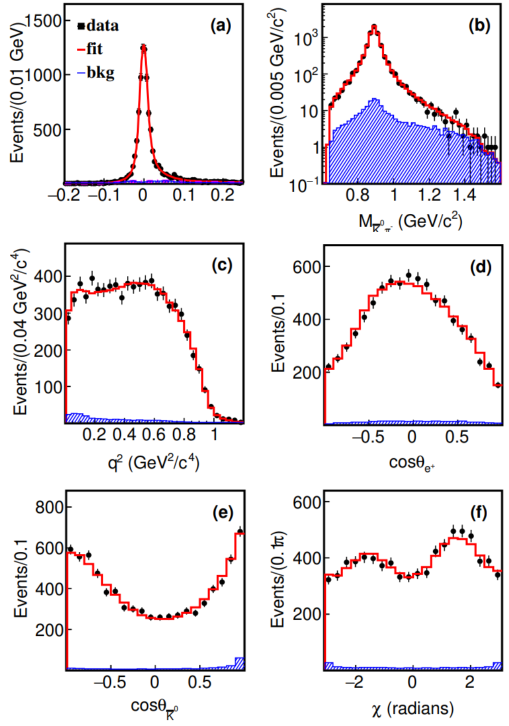
Study of $K\pi$ amplitude structure & $D^0 \to \bar{K}^*$ FF

- $r_V = 1.456 \pm 0.040 \pm 0.016$
- $r_2 = 0.715 \pm 0.031 \pm 0.014$
- $A_1(0) = 0.614 \pm 0.005 \pm 0.004$

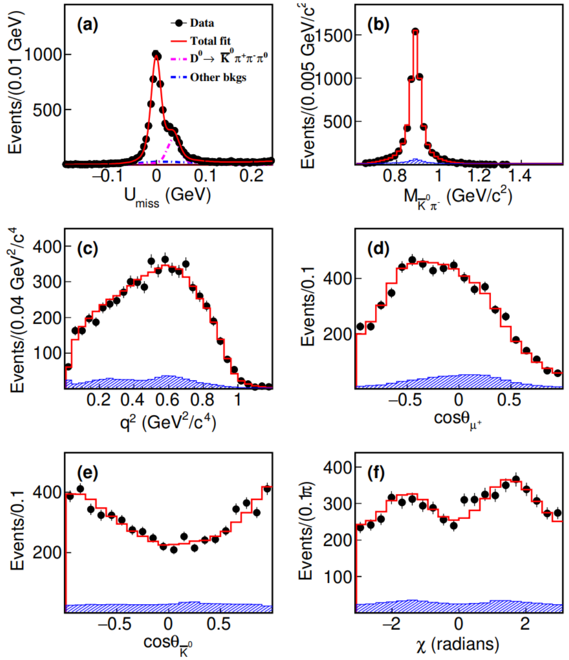




$D^0 \to \bar{K}^0\pi^- e^+\nu_e$



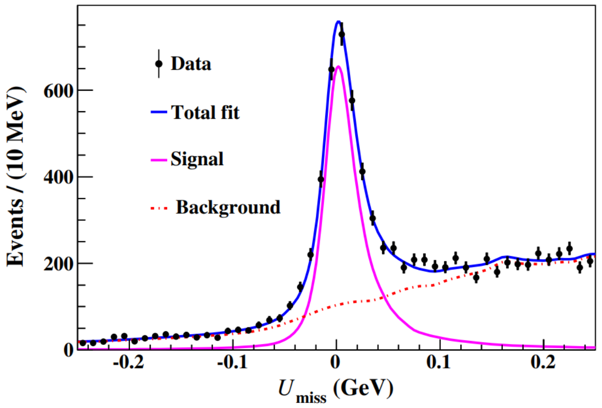
$D^0 \to \bar{K}^0\pi^- \mu^+\nu_\mu$



$D^0 \to \rho(770)^-[\to \pi^-\pi^0]e^+\nu_e$

PRD **110**, 112018 (2024)

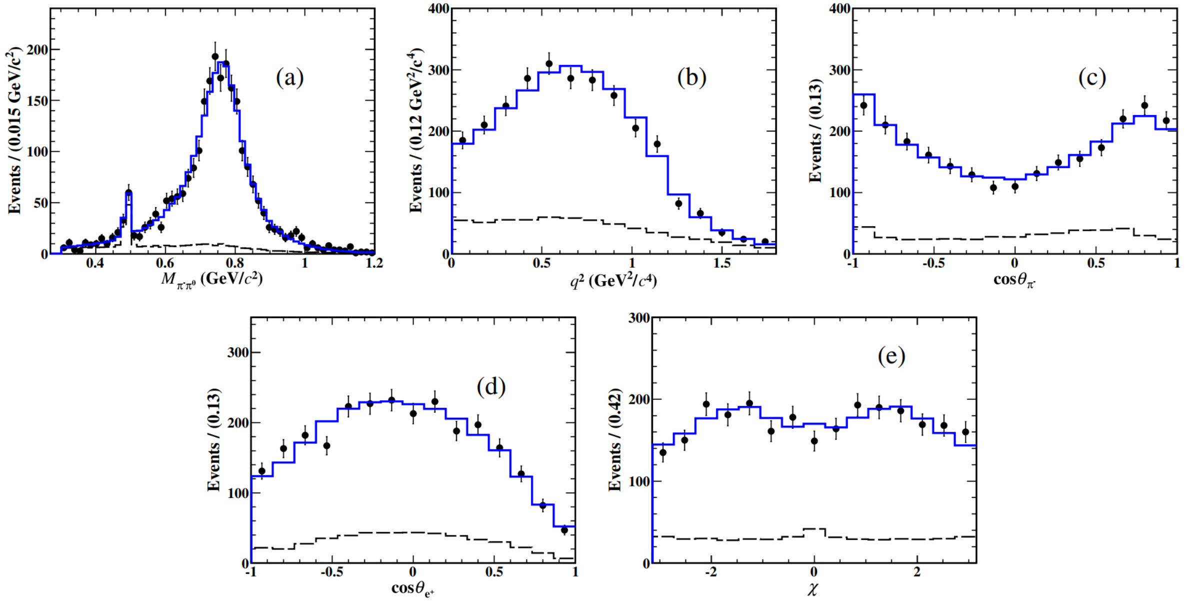
- **Updated BF measurement**
  - $\mathcal{B}\left(D^0 \to \rho(770)^- e^+\nu_e\right) = (1.439 \pm 0.033 \pm 0.027) \times 10^{-3}$
  - 1.6 times more precise than previous measurement



7.93 fb^{-1} data
3.3k signal

- **Extraction of FF**
  - $r_V = 1.548 \pm 0.079 \pm 0.041$
  - $r_2 = 0.823 \pm 0.056 \pm 0.026$

Experiments	r_V	r_2
This analysis	$1.548 \pm 0.079 \pm 0.041$	$0.823 \pm 0.056 \pm 0.026$
BESIII [39]	$1.695 \pm 0.083 \pm 0.051$	$0.845 \pm 0.056 \pm 0.039$
CLEO [40]	$1.48 \pm 0.15 \pm 0.05$	$0.83 \pm 0.11 \pm 0.04$



$D_s^+ \to \phi[\to K^+K^-]l^+\nu_l$

10.64 fb^{-1} (e) / 7.33 fb^{-1} (μ) data
0.4k (e) / 1.7k (μ) signal

BF measurements

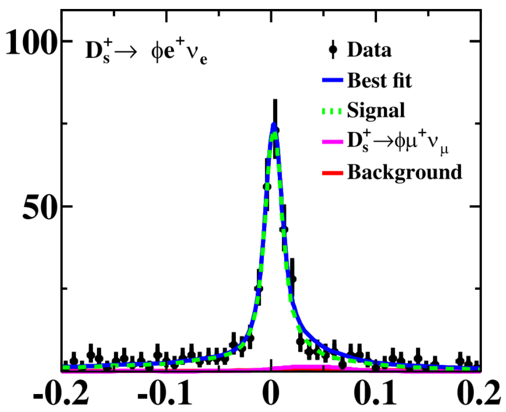
- $\mathcal{B}(D_s^+ \to \phi e^+\nu_e) = (2.21 \pm 0.16 \pm 0.10)\%$
- $\mathcal{B}(D_s^+ \to \phi \mu^+\nu_\mu) = (2.25 \pm 0.09 \pm 0.07)\%$
- $\mathcal{B}(D_s^+ \to f_0(980) e^+\nu_e) \times \mathcal{B}(f_0(980) \to K^+K^-) < 5.45 \times 10^{-4}$ @ 90% C. L.

Extraction of FF (from muonic mode)

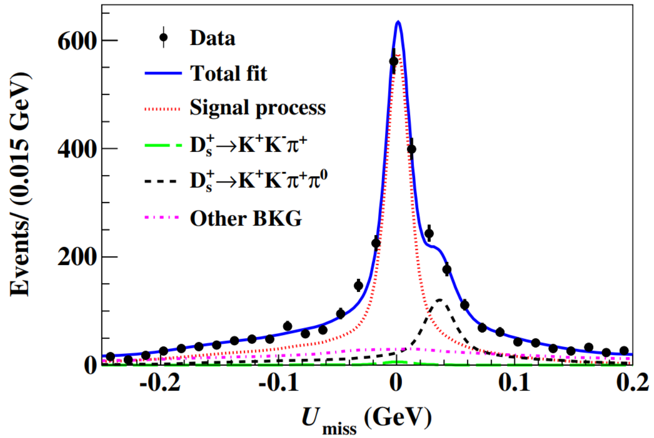
- $r_V = 1.68 \pm 0.17 \pm 0.02$
- $r_2 = 0.71 \pm 0.14 \pm 0.02$

Experiments	r_V	r_2
PDG [45]	1.80 ± 0.08	0.84 ± 0.11
This analysis	$1.58 \pm 0.17 \pm 0.02$	$0.71 \pm 0.14 \pm 0.02$
BABAR [26]	$1.807 \pm 0.046 \pm 0.065$	$0.816 \pm 0.036 \pm 0.030$
FOCUS [59]	$1.549 \pm 0.250 \pm 0.148$	$0.713 \pm 0.202 \pm 0.284$
Theory	r_V	r_2
CCQM [5]	1.34 ± 0.27	0.99 ± 0.20
CQM [6]	1.72	0.73
LFQM [7]	1.42	0.86
LQCD [3]	1.72 ± 0.21	0.74 ± 0.12
HMχT [8]	1.80	0.52

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



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



Charmed meson → axion vector decays

$D \to A l \nu$

$D \to b_1(1235)[\to \omega\pi]e^+\nu_e$

arXiv: 2407.20551

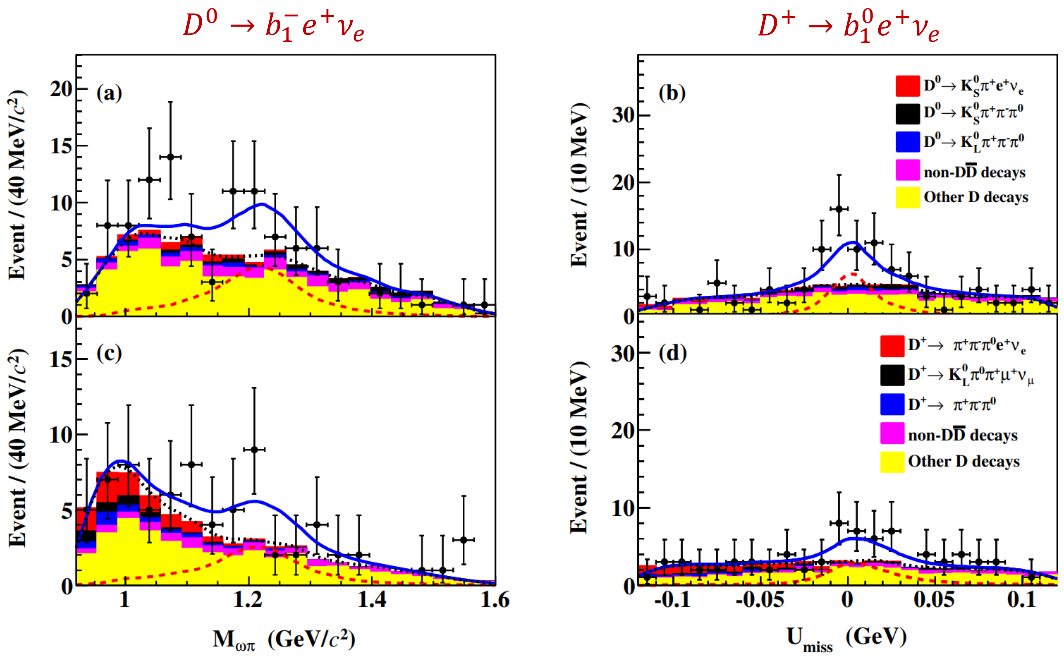
7.93 fb^{-1} data
~36 (D^0) / ~18 (D^+) signal

First observation & evidence

- $\mathcal{B}(D^0 \to b_1^- e^+\nu_e) \times \mathcal{B}(b_1^- \to \omega\pi^-) = (0.72 \pm 0.18^{+0.06}_{-0.08}) \times 10^{-4}$ with 5.2σ
- $\mathcal{B}(D^+ \to b_1^0 e^+\nu_e) \times \mathcal{B}(b_1^0 \to \omega\pi^0) = (1.16 \pm 0.44 \pm 0.16) \times 10^{-4}$ with 3.1σ
- Reinforce the assumption that $\omega\pi$ final state dominates b_1 decay

Ratio of particle decay width

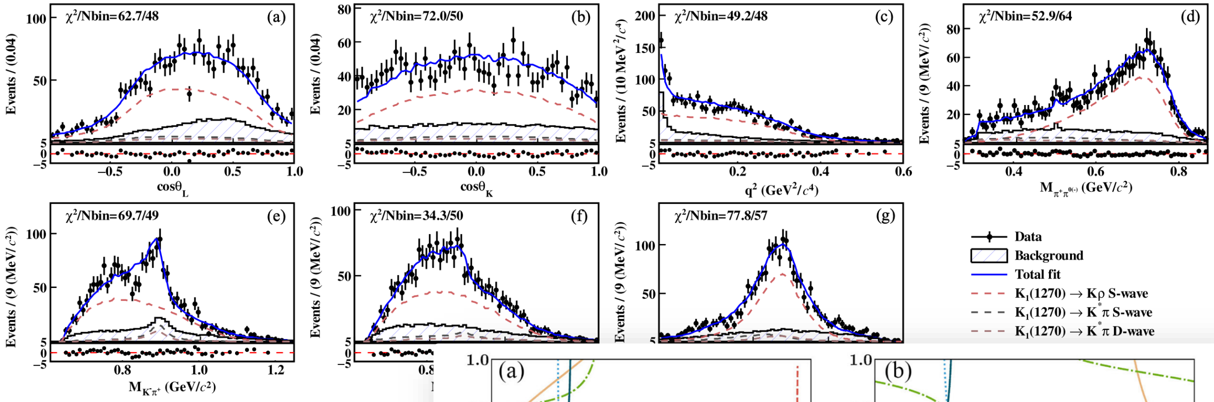
- $\frac{\Gamma(D^0 \to b_1^- e^+\nu_e)}{2\Gamma(D^+ \to b_1^0 e^+\nu_e)} = 0.78 \pm 0.19^{+0.04}_{-0.05}$
- Consistent with isospin conservation



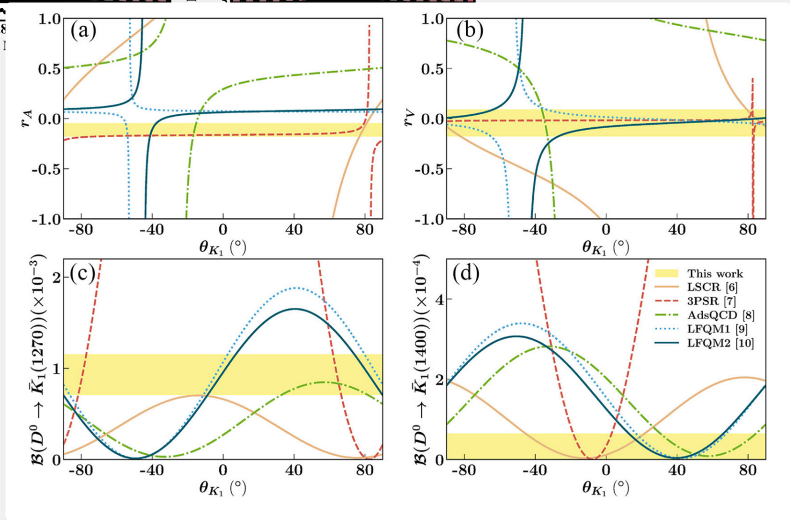
$D \to K_1(1270)[\to K\pi\pi]e^+\nu_e$

20.3 fb^{-1} data
1.3k (D^+) / 0.7k (D^0) signal

- **Updated BF measurements**
  - $\mathcal{B}\left(D^+ \to \overline{K_1}(1270)^0 e^+\nu_e\right) = (2.27 \pm 0.11 \pm 0.07 \pm 0.07) \times 10^{-3}$
  - $\mathcal{B}\left(D^0 \to K_1(1270)^- e^+\nu_e\right) = (1.02 \pm 0.06 \pm 0.06 \pm 0.03) \times 10^{-3}$
  - $\frac{\mathcal{B}(K_1(1270)\to K^*\pi)}{\mathcal{B}(K_1(1270)\to K\rho)} = (20.3 \pm 2.1 \pm 8.7)\%$



- **Study of K_1 structure & $D \to K_1$ FF**
  - Based on amplitudes analysis
  - $r_A = (-11.2 \pm 1.0 \pm 0.9) \times 10^{-2}$
  - $r_V = (-4.3 \pm 1.0 \pm 2.5) \times 10^{-2}$
  - Up-down asymmetry $\mathcal{A}'_{ud} = 0.01 \pm 0.11$
  - K_1 longitudinal polarization $F_L = 0.50 \pm 0.04$



Comparison with theoretical predictions in function of mixing angle θ_{K_1}

$D \to K_1(1270)[\to K\pi\pi]\mu^+\nu_\mu$

PRD **111**, L071101 (2025)

First BF measurements

- $\mathcal{B}(D^+ \to \overline{K_1}(1270)^0\mu^+\nu_\mu) = (2.36 \pm 0.20^{+0.18}_{-0.27} \pm 0.48) \times 10^{-3}$ with 12.5σ
- $\mathcal{B}(D^0 \to K_1(1270)^-\mu^+\nu_\mu) = (0.78 \pm 0.11^{+0.05}_{-0.09} \pm 0.15) \times 10^{-3}$ with 6.0σ

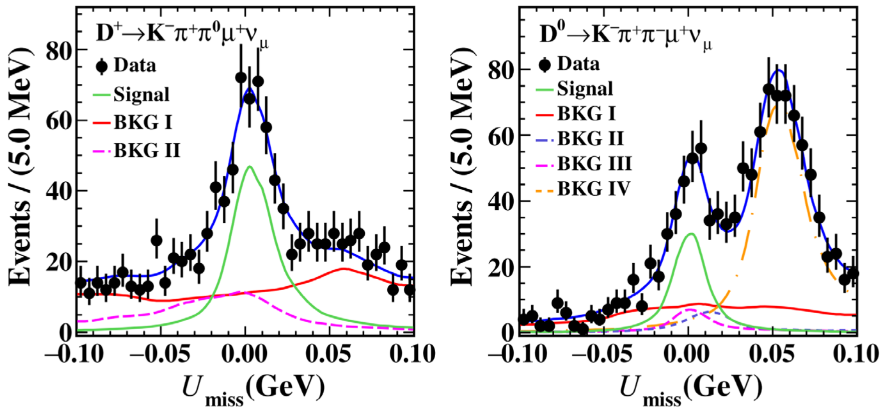
7.93 fb^{-1} data
0.4k (D^+) / 0.2k (D^0) signal

LFU test

- $\mathcal{R}^{D^+}_{\mu/e} = 1.03 \pm 0.14^{+0.11}_{-0.15}$
- $\mathcal{R}^{D^0}_{\mu/e} = 0.74 \pm 0.13^{+0.08}_{-0.13}$

Isospin test

- $\frac{\Gamma(D^+\to\overline{K_1}(1270)^0\mu^+\nu_\mu)}{\Gamma(D^0\to K_1(1270)^-\mu^+\nu_\mu)} = 1.22 \pm 0.10^{+0.06}_{-0.09}$



Decay		CLFQM [10]	3PSR [9]	LCSR [11]	LCSR [11]	LCSR [11]	CLFQM [12]	LFQM [12]	LCSR [12]	This work
	θ_{K1}	33°	37°		$-(34 \pm 13)°$			45°		⋯
$D^+ \to \bar{K}_1^0\mu^+\nu_\mu$	Predicted	2.60 ± 0.30	2.70 ± 0.25	18.59 ± 0.31	16.86 ± 0.27	19.73 ± 0.32	$5.9^{+0.47}_{-0.11}$	$3.7^{+0.00}_{-0.41}$	$1.4^{+0.15}_{-0.27}$	$2.36 \pm 0.20^{+0.18}_{-0.27} \pm 0.48$
	Deviation (σ)	0.4	0.6	27.3	25.2	29.0	6.8	2.6	1.8	
$D^0 \to K_1^-\mu^+\nu_\mu$	Predicted	⋯	1.03 ± 0.1	8.09 ± 0.15	6.78 ± 0.12	8.92 ± 0.16	$2.3^{+0.19}_{-0.44}$	$1.5^{+0.00}_{-0.16}$	$0.54^{+0.06}_{-0.11}$	$0.78 \pm 0.11^{+0.05}_{-0.09} \pm 0.15$
	Deviation (σ)	⋯	1.1	28.6	25.1	31.1	5.4	2.8	1.1	

Charmed baryon decays

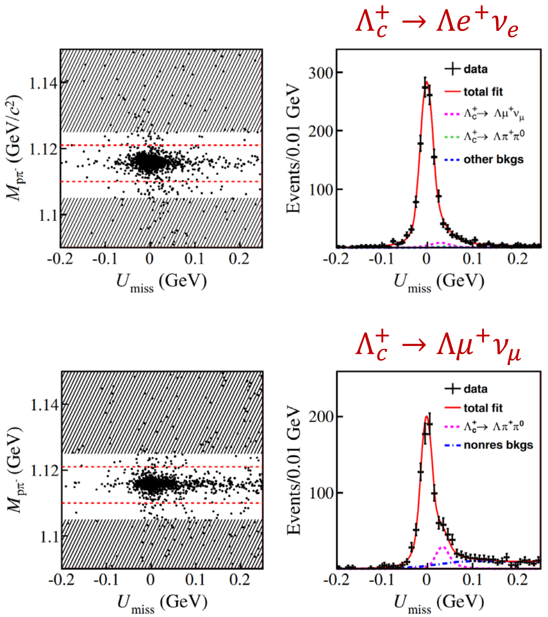
$\Lambda_c^+ \to B l^+ \nu_l$

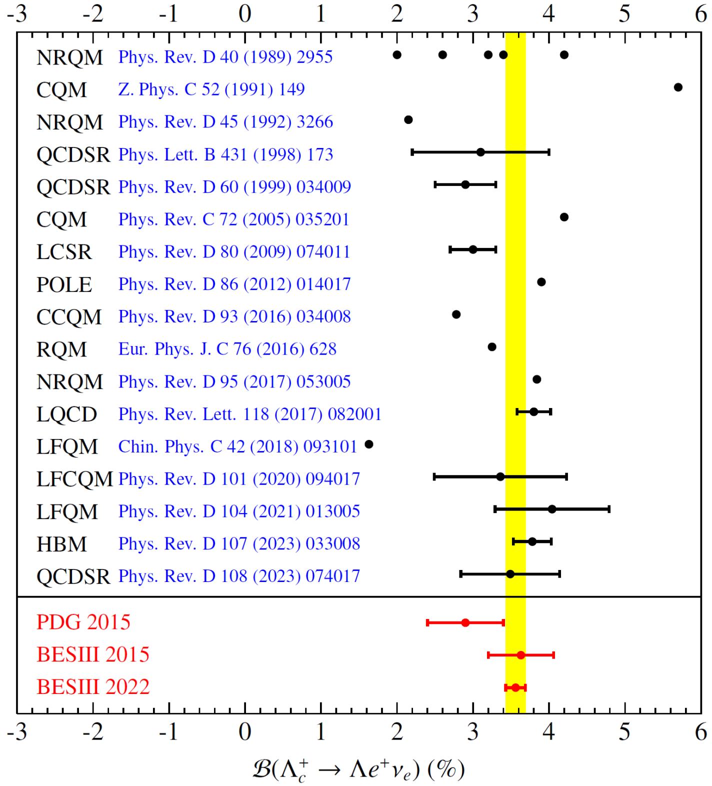
$\Lambda_c^+ \to \Lambda l^+ \nu_l$ (I)

PRL **129**, 231803 (2022)
PRD **108**, L031105 (2023)

Precise measurement on BFs

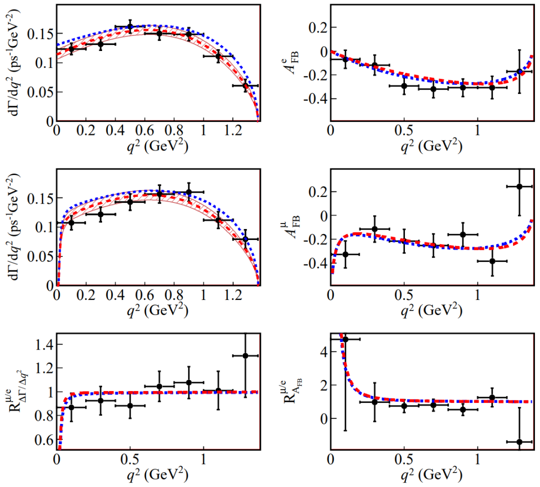
- $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11_{\text{stat.}} \pm 0.07_{\text{syst.}})\%$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.48 \pm 0.14_{\text{stat.}} \pm 0.10_{\text{syst.}})\%$

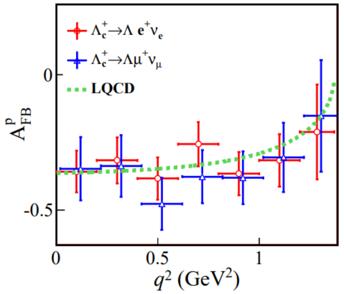


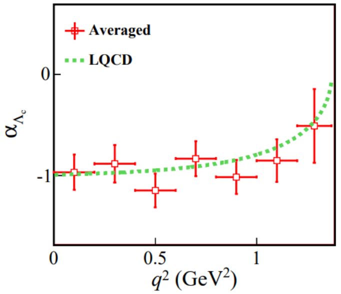


LFU tests

- In ratio of integrated BFs
- In differential decay rates in q^2 binning
- In forward-backward asymmetries





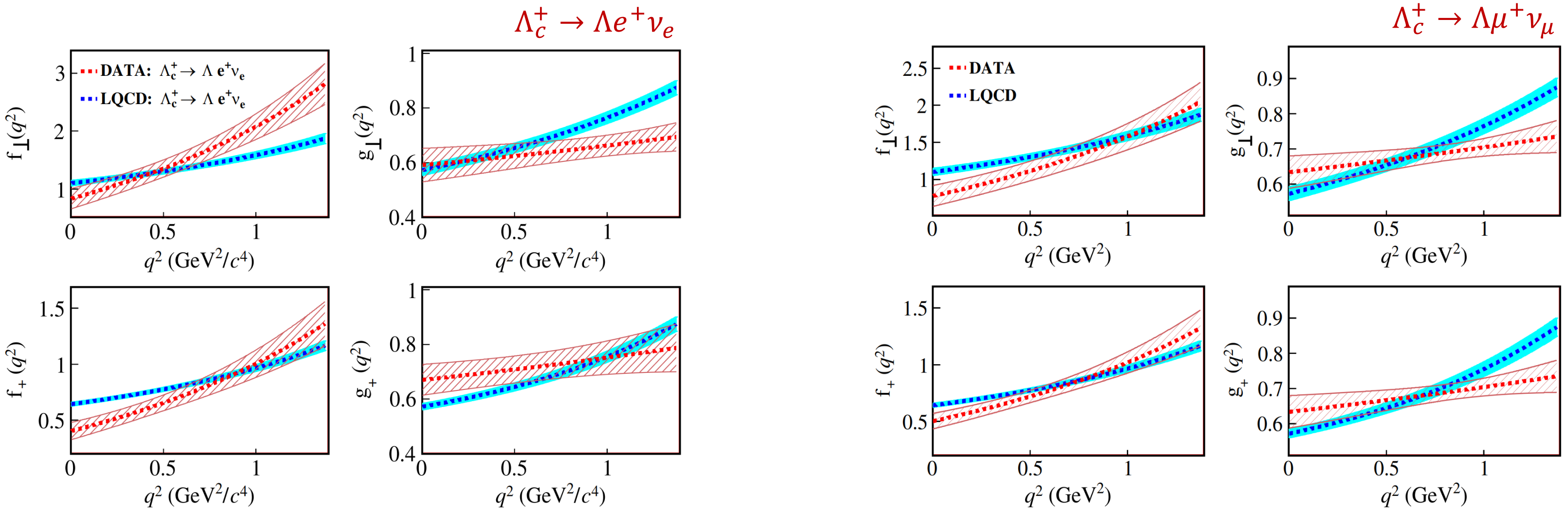


$\Lambda_c^+ \to \Lambda l^+ \nu_l$ (II)

PRL **129**, 231803 (2022)
PRD **108**, L031105 (2023)

Extraction of FFs

- Show different kinematic behaviors compared to LQCD predictions

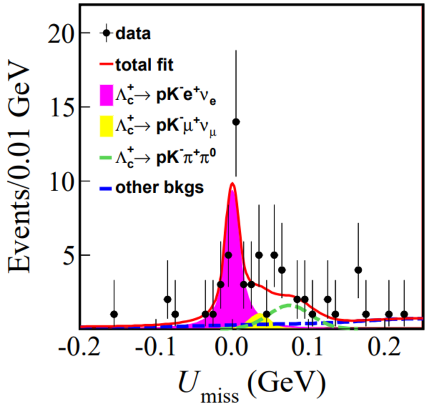


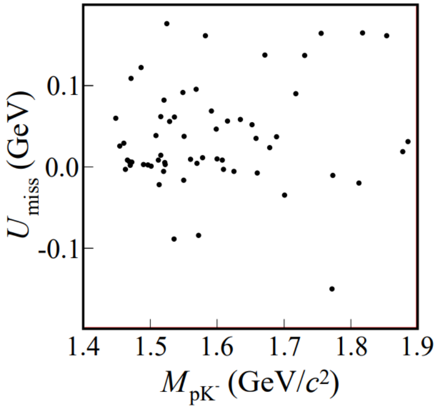
Extraction of CKM matrix element $|V_{cs}|$

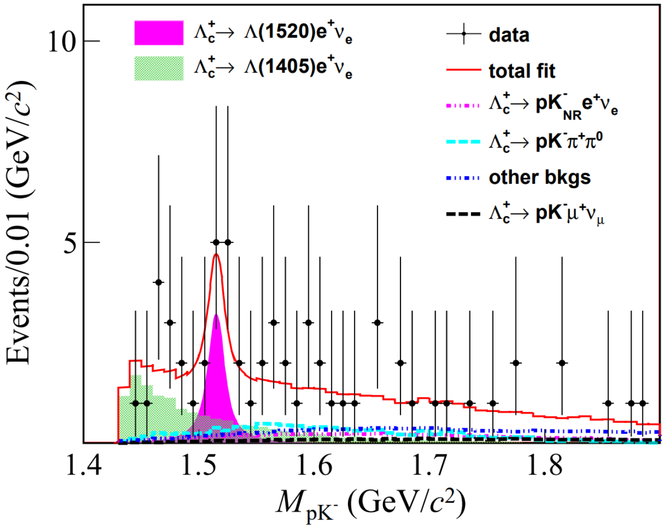
- Combine measured BFs of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ & $\Lambda \mu^+ \nu_\mu$
- Take FFs from LQCD and τ_{Λ_c} from PDG as input
- Yield $|V_{cs}| = 0.937 \pm 0.014_{\mathcal{B}} \pm 0.024_{\text{LQCD}} \pm 0.007_{\tau_{\Lambda_c}}$
  - Consistent with $D \to K l^+ \nu_l$ measurement within 1.2σ

$\Lambda_c^+ \to pK^- e^+ \nu_e$

PRD **106**, 112010 (2022)







- **The second observed Λ_c^+ semi-leptonic decay**
  - $\mathcal{B}(\Lambda_c^+ \to pK^- e^+ \nu_e) = (0.88 \pm 0.17 \pm 0.07) \times 10^{-3}$ with 8.2σ

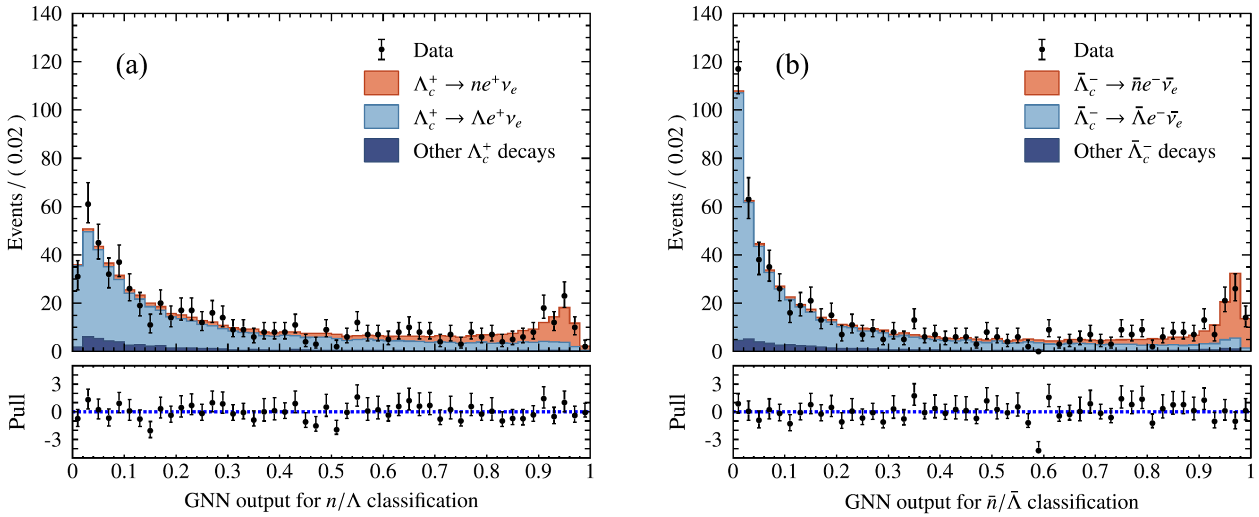
- **Evidences found for $\Lambda_c^+ \to \Lambda^* e^+ \nu_e$**
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520) e^+ \nu_e) = (1.02 \pm 0.52 \pm 0.11) \times 10^{-3}$ with 3.3σ
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)[\to pK^-] e^+ \nu_e) = (0.42 \pm 0.19 \pm 0.04) \times 10^{-3}$ with 3.2σ

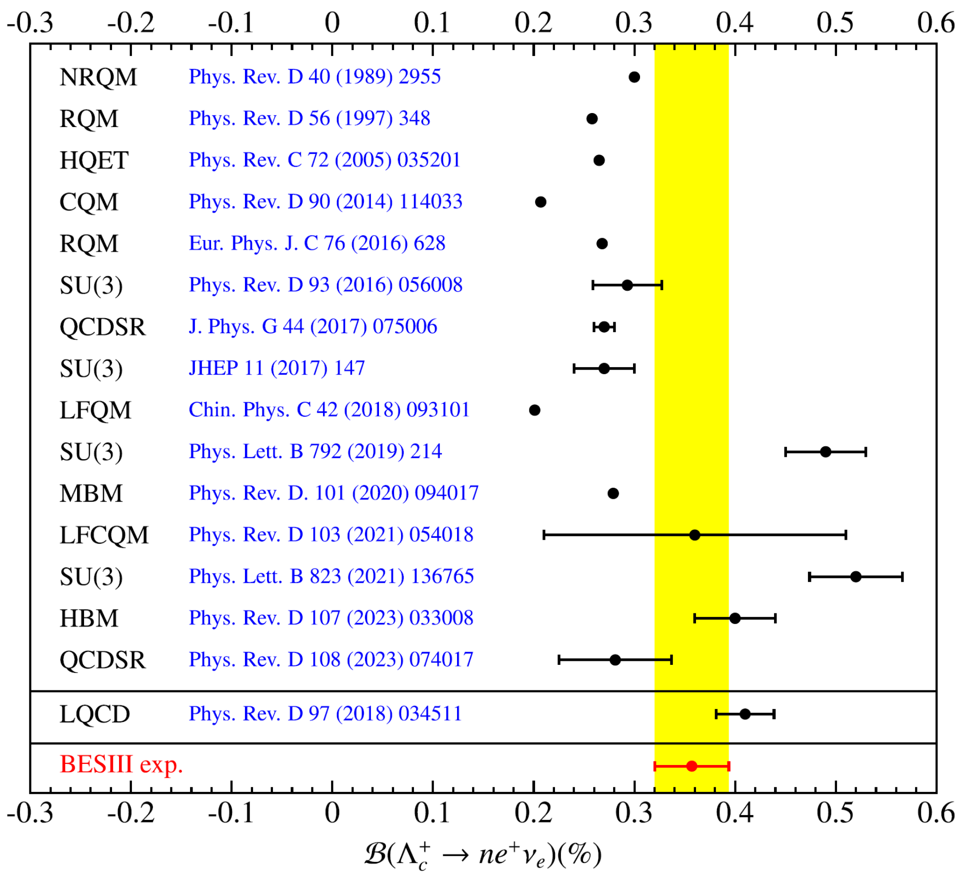
Elusive nature,
Potential molecular state or pentaquark candidate

- Comparison with quark models and LQCD

	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520) e^+ \nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405) e^+ \nu_e)$
Constituent quark model [8]	1.01	3.04
Molecular state [9]	…	0.02
Nonrelativistic quark model [10]	0.60	2.43
Lattice QCD [12,13]	0.512 ± 0.082	…
Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42 \pm 0.19 \pm 0.04}{\mathcal{B}(\Lambda(1405) \to pK^-)}$

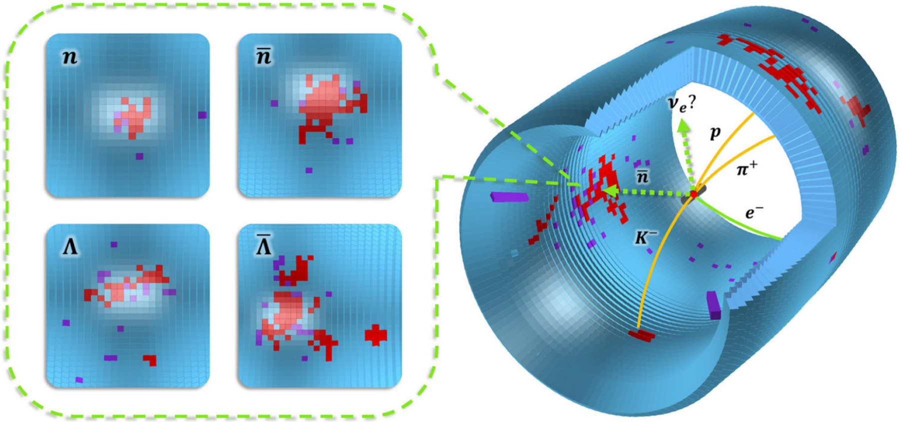
$\Lambda_c^+ \to ne^+\nu_e$ (I)

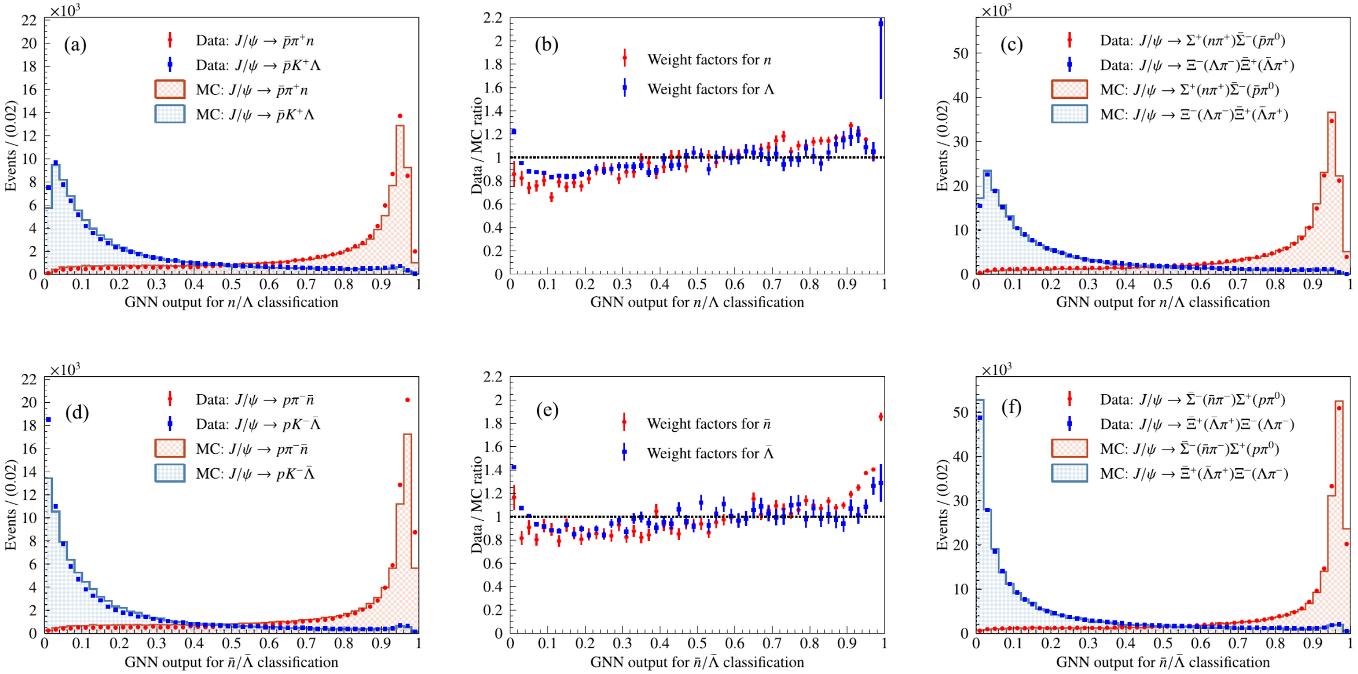




- **First observation of Cabibbo-suppressed $c \to d$ transition in Λ_c^+ SL decays**
  - $\mathcal{B} = (0.357 \pm 0.334_{\text{stat.}} \pm 0.014_{\text{syst.}})\%$ ($> 10\sigma$)
- **First determination of $|V_{cd}|$ from charmed baryon decays**
  - Take form factors from LQCD as input
  - $|V_{cd}| = 0.208 \pm 0.011_{\text{exp.}} \pm 0.007_{\text{LQCD}} \pm 0.011_{\tau_{\Lambda_c^+}}$
- **Examination for various theoretical models**

- **A novel deep learning method is developed to separate signal from dominant background $\Lambda_c^+ \to \Lambda(n\pi^0)e^+\nu_e$.**
  - Use Graph Neural Network to classify n/Λ energy deposition patterns on EMC
  - Establish a data-driven pipeline for GNN training, calibration, validation and systematic uncertainty quantification.
    - Extensively utilize control samples from 10 billion J/ψ events collected at BESIII.





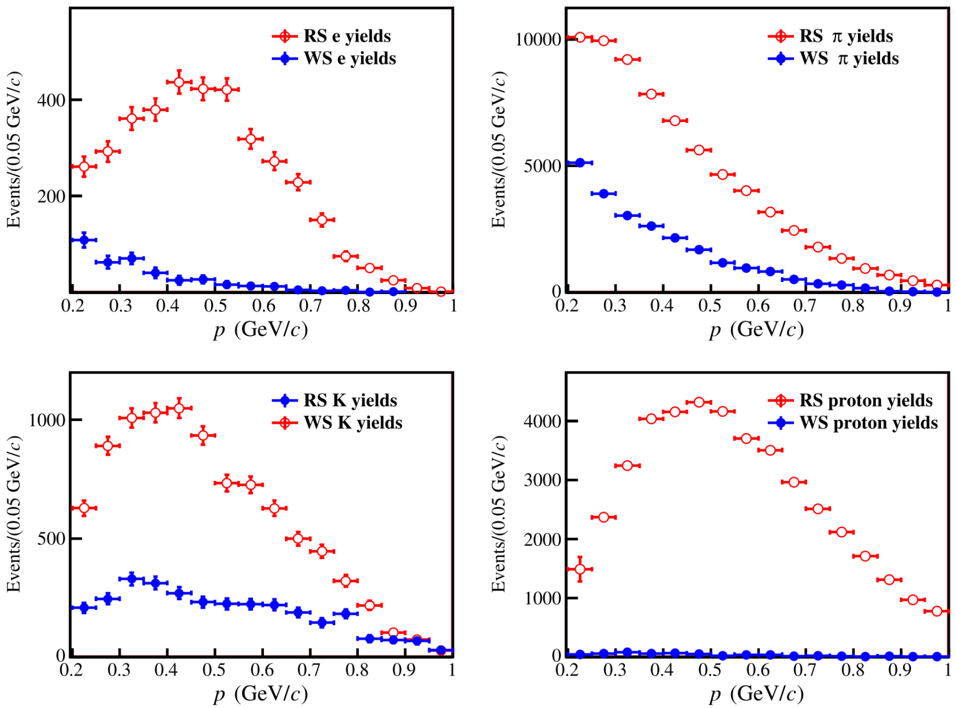
Extendable to more BESIII studies involving neutral hadrons, especially those who can't be reconstructed by recoil masses.

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

PRD **107**, 052005 (2023)

- **Improved measurement of inclusive Λ_c^+ semi-leptonic decays**
  - $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = \left(4.06 \pm 0.10_{\text{stat.}} \pm 0.09_{\text{syst.}}\right)\%$
- **Ratio between charmed meson/baryon decay widths**
  - $\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\bar{\Gamma}(D \to X e^+ \nu_e)} = 1.28 \pm 0.05$
- **Use unfolding method to calibrate particle misidentification**

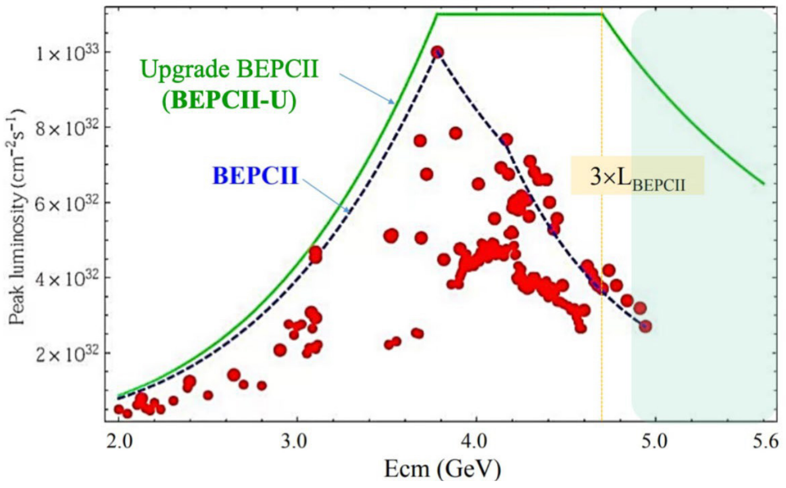
$$\begin{bmatrix} N_e^{\text{obs}} \\ N_\pi^{\text{obs}} \\ N_K^{\text{obs}} \\ N_p^{\text{obs}} \end{bmatrix} = \begin{bmatrix} P_{e\to e} & P_{\pi\to e} & P_{K\to e} & P_{p\to e} \\ P_{e\to\pi} & P_{\pi\to\pi} & P_{K\to\pi} & P_{p\to\pi} \\ P_{e\to K} & P_{\pi\to K} & P_{K\to K} & P_{p\to K} \\ P_{e\to p} & P_{\pi\to p} & P_{K\to p} & P_{p\to p} \end{bmatrix} \begin{bmatrix} N_e^{\text{true}} \\ N_\pi^{\text{true}} \\ N_K^{\text{true}} \\ N_p^{\text{true}} \end{bmatrix}$$

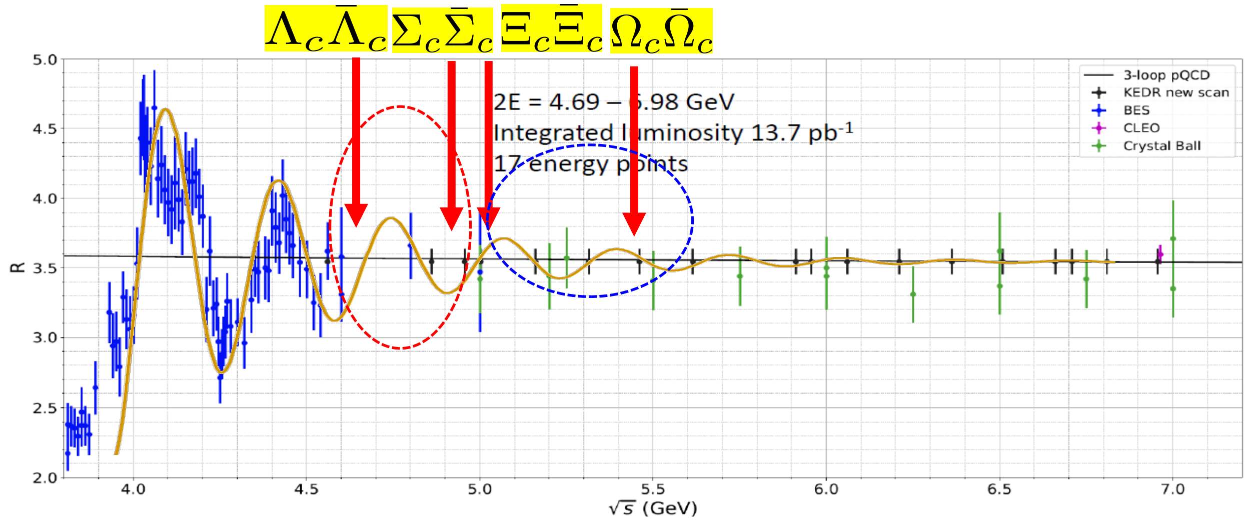


- **Constraint on unobserved Λ_c^+ semi-leptonic decays**
  - Combine inclusive & exclusive measurements, assume all uncertainties are uncorrelated:
    $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)_{X \neq \Lambda, n, pK^-} = \left(0.55 \pm 1.53_{\text{stat.}} \pm 1.15_{\text{syst.}}\right) \times 10^{-3}$
  - The majority of experimental gap has been filled.

Prospect

- **BEPCII(-U) & BESIII just finished a major machine upgrade.**
  - Triple the luminosity @ 4.7 GeV → more Λ_c^+ data
  - Extend c.m. energy up to 5.6 GeV → pair production for $\Sigma_c, \Xi_c, \Omega_c$
  - Replace inner MDC with CGEM detector





- **According to latest time schedule:**
  - New Λ_c^+ data taking will start in 2026
  - Above-5-GeV data taking will start in 2028

Summary

- **Semi-leptonic decays** of charmed hadrons provide good opportunities to study their inner dynamics and test SM.

- **BESIII made significant experimental contributions in recent years,** including
  - Precise measurements of CKM matrix elements $|V_{cs}|$ & $|V_{cd}|$ (see Chao Chen's talk on Sep 16)
  - First / improved measurements on various decay BFs and FFs
  - Accesses to light hadron spectrum via multi-body hadronic final states

- **Deep learning methods** can bring impressive and reliable physics results in these investigations.

- **BEPCII(-U) & BESIII machine upgrade** will provide more opportunities for charm hadron physics.

Thanks for your attention!