Recent progress on charmed hadron decays at BESIII

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on behalf of the BESIII collaboration
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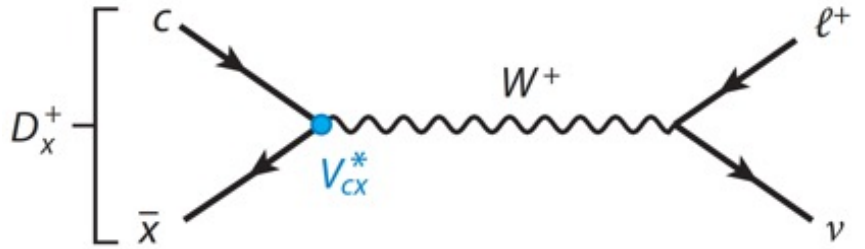
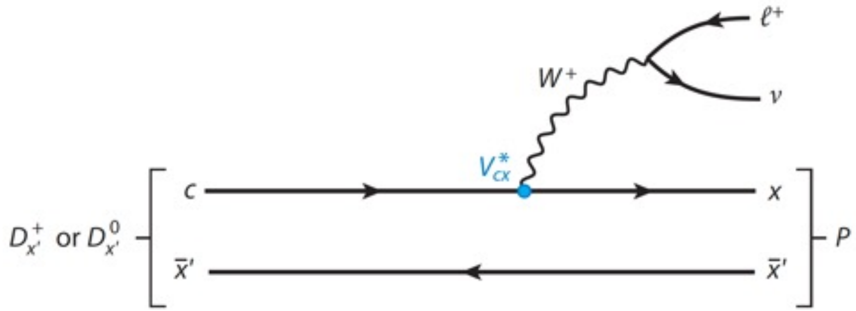
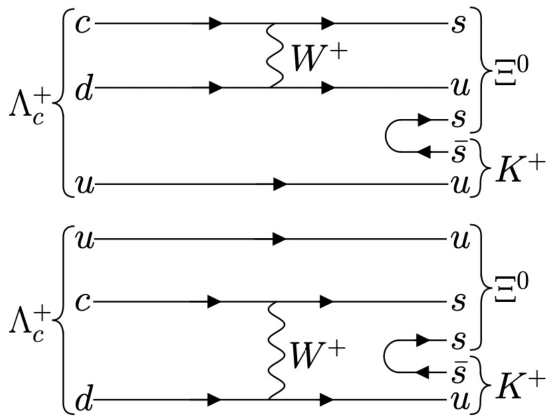
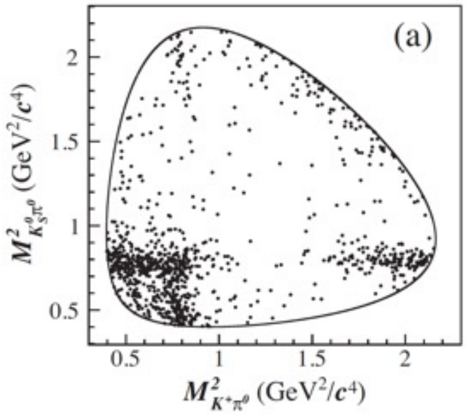
Outline

- BESIII dataset
- Charmed meson (D^0, D^+, D_s^+)
  - pure leptonic decays
  - semi-leptonic decays
  - hadronic decays
  - rare decays
- Charmed baryon (Λ_c^+)
  - semi-leptonic decays
  - hadronic decays
- Prospect









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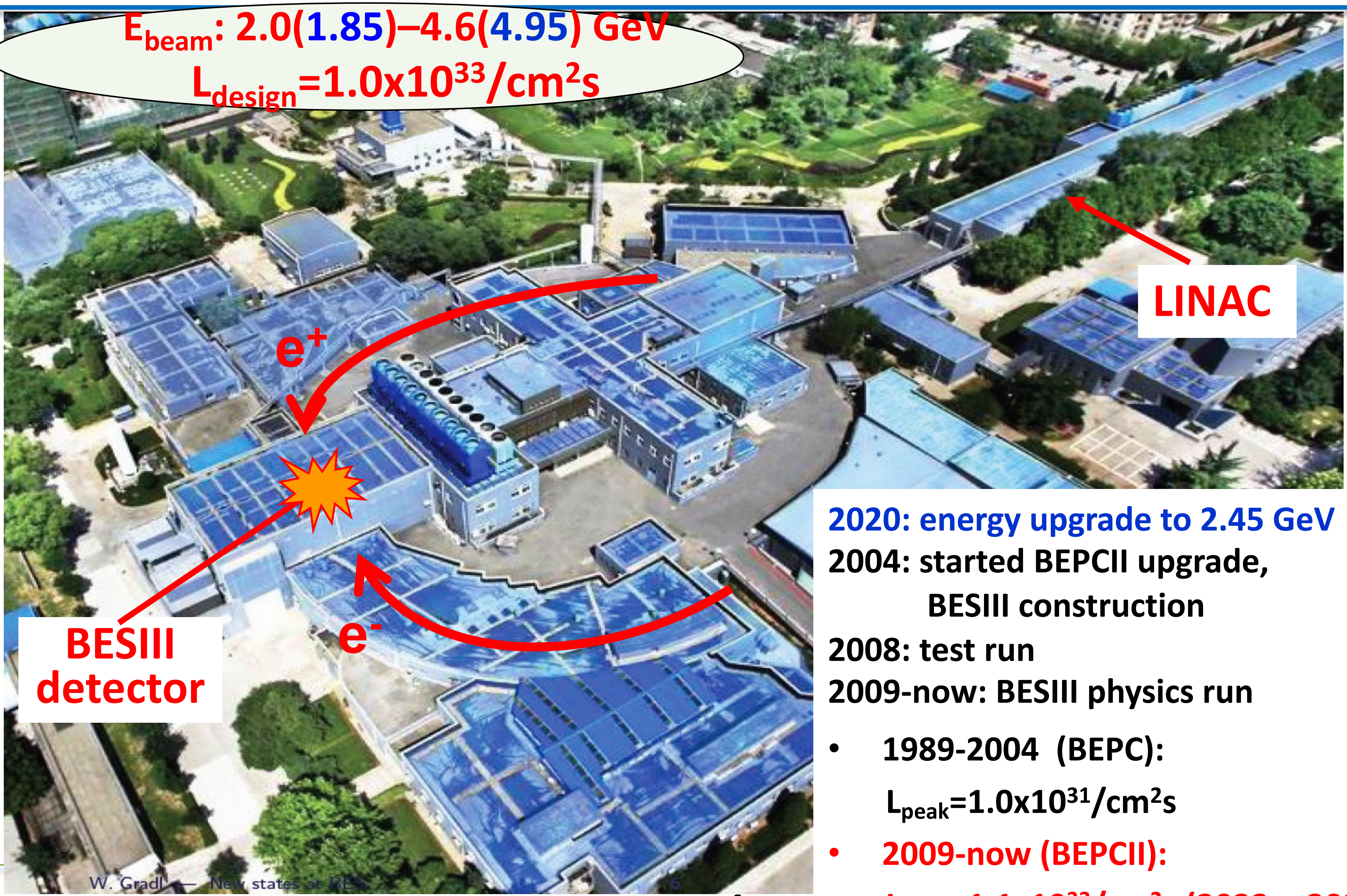
The Beijing Electron-Positron Collider II (BEPC II)

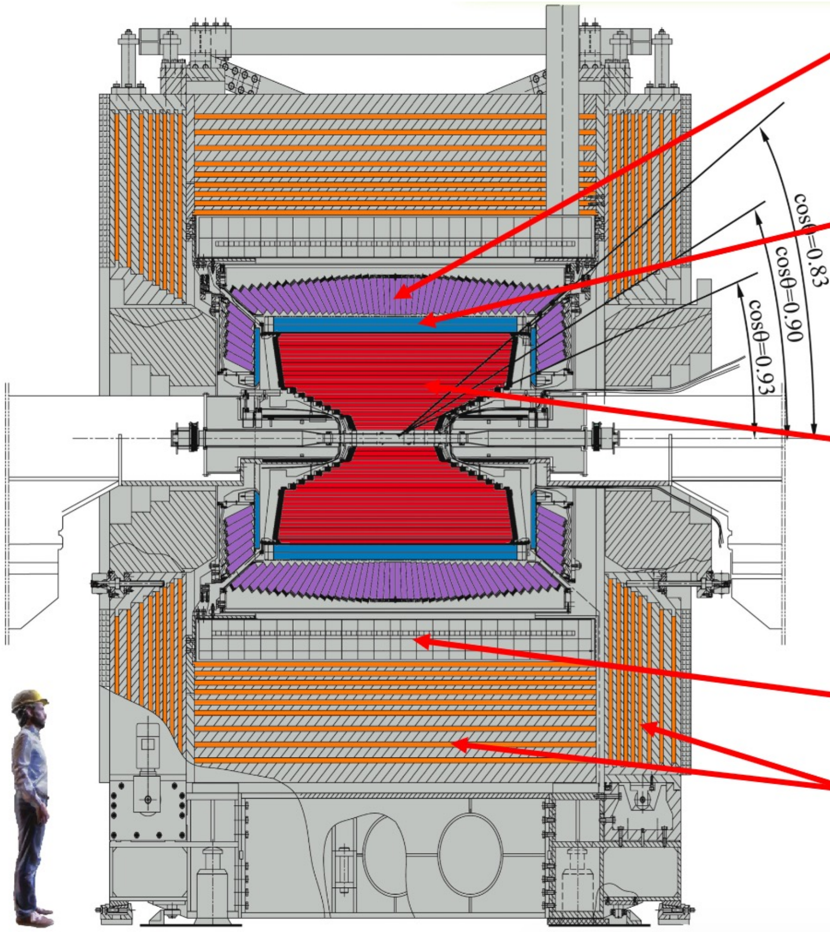


2020: energy upgrade to 2.45 GeV
2004: started BEPCII upgrade, BESIII construction
2008: test run
2009-now: BESIII physics run

- 1989-2004 (BEPC): $L_{peak}=1.0x10^{31}/cm^2s$
- 2009-now (BEPCII): $L_{peak}=1.1x10^{33}/cm^2s$ (2022、2023)

The BEijing Spectrum III (BESIII)

NIMA614(2010)345



EMC: CsI crystals
$\Delta E/E$ = 2.5% @ 1 GeV - Barrel
$\Delta E/E$ = 5.0% @ 1 GeV - Endcaps

TOF:
σ_T = 80 ps Barrel
σ_T = 110 (60) ps Endcap

MDC: small cell & He gas
σ_{xy}= 130 μm
σ_p/p = 0.5% @1GeV
dE/dx = 6%

Magnet: 1T Super conducting

Muon ID: 9 layer RPC

Trigger: Tracks & Showers

Excellent resolution, particle identification, and large coverage for neutral and charged particles

BESIII Collaboration

Europe (18)

Germany(6): Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen, University of Münster

Italy(3): Ferrara University, INFN, University of Turin,

Netherlands(1): KVI/University of Groningen

Russia(2): Budker Institute of Nuclear Physics, Dubna JINR

Sweden(1): Uppsala University

Turkey (1): Turkish Accelerator Center Particle Factory Group

UK(3): University of Manchester, University of Oxford, University of Bristol

Poland(1): National Centre for Nuclear Research

Mongolia(1)

Institute of Physics and Technology

Korea(1)

Chung-Ang University

Thailand(1)

Suranaree University of Technology

USA(3)

Carnegie Mellon University
Indiana University
University of Hawaii

Pakistan(2)

COMSATS Institute of Information Technology
University of the Punjab

India(1)

Indian Institute of Technology madras

China (54)

Beihang University, Central China Normal University, Central South University, China Center of Advanced Science and Technology, China University of Geosciences, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Hebei University, Henan University, Henan Normal University, Henan University of Science and Technology, Henan University of Technology, Huangshan College, Hunan University, Hunan Normal University, Inner Mongolia University, Institute of High Energy Physics, Institute of Modern Physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University, Peking University, Qufu Normal University, Renmin University of China, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shandong University of Technology, Shanghai Jiao Tong University, Soochow University, South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Scienc University of Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Yantai University , Yunnan University , Zhejiang University, Zhengzhou University

Chile(1)

University of Tarapaca

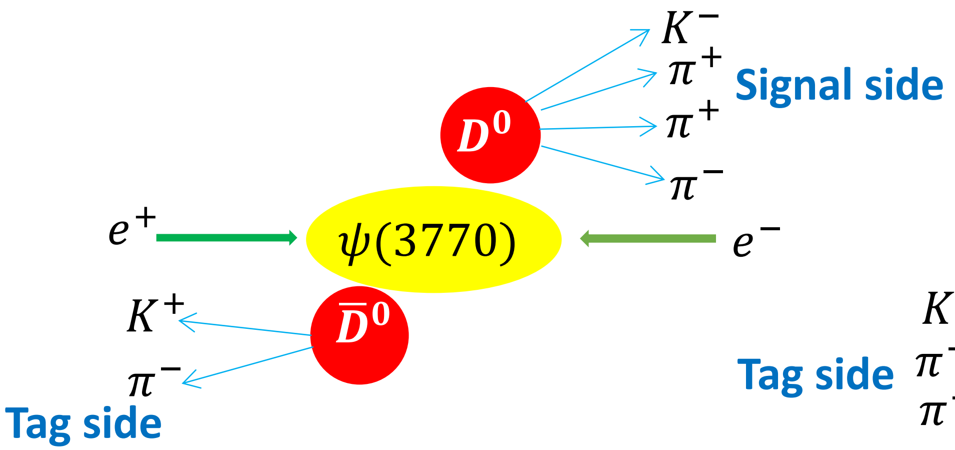
> 600 members
From 82 institutions
in 16 countries

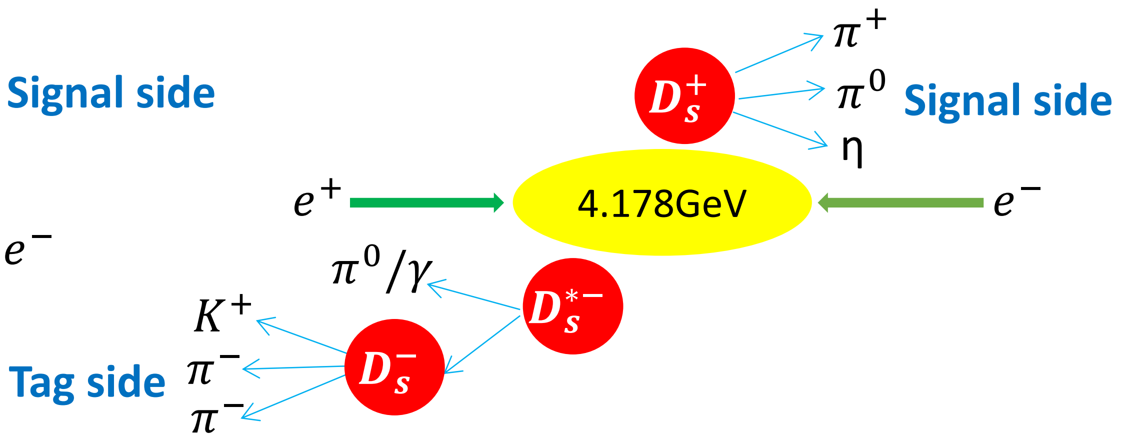
BESIII Data Taken near Threshold

- 7.9 fb^{-1} at Ecm = 3.773 GeV:
  $e^+e^- \to \psi(3770) \to D\bar{D}$ (totally 57M D^0 and 45M D^+)
  (Total 20 fb^{-1} at Ecm = 3.773 GeV is ready, publications based on new dataset is on the way)
- 7.33 fb^{-1} at Ecm = 4.128-4.226 GeV
  $e^+e^- \to D_s^{\pm}D_s^{*\mp}, D_s^{*\mp} \to \pi^0/\gamma D_s^{\mp}$ (~600k D_s)
- 4.5 fb^{-1} at Ecm = 4.600-4.699 GeV $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

- **Single Tag (ST):** reconstruct only one of the hadron
- **Double Tag (DT):** reconstruct both of the hadrons

access to absolute BFs; clean samples





(Charge-conjugate states are implied throughout this talk)

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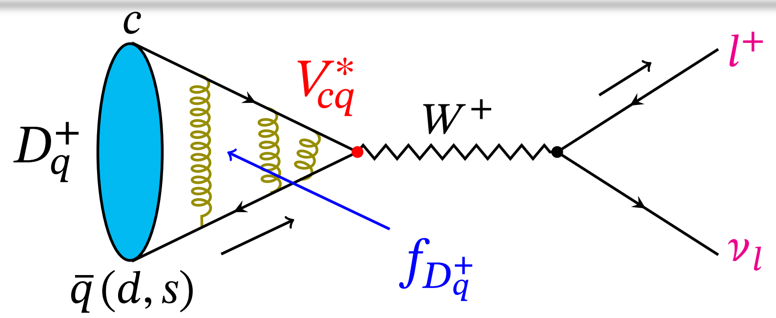
Pure leptonic D decay

In the SM:



- Charm leptonic decays involve both weak and strong interactions.
- The weak part is easy to be described as the annihilation of the quark-antiquark pair via the standard model W^+boson.
- The strong interactions arise due to gluon exchanges between the charm quark and the light quark. These are parameterized in terms of the 'decay constant', i.e $f_{D_q^+}$.

CKM matrix element

Decay rate (Exp.) ⟵

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

Decay constant (LQCD)

Decay constant $f_{D_{(s)}^+}$, if inputting the $|\boldsymbol{V}_{\mathbf{cd(s)}}|$ from SM global fit. → Calibrate Lattice QCD calculations.

CKM matrix element $|V_{cd(s)}|$, with the $f_{D_{(s)}^+}$ predicted by LQCD. → Test the unitarity of CKM matrix

Pure leptonic D decay

- **Lepton flavor universality (LFU) test in $\tau - \mu$ cases**

$$R_{\tau/\mu} = \frac{\Gamma\left(D^+_{(s)} \to \tau^+\nu_\tau\right)}{\Gamma\left(D^+_{(s)} \to \mu^+\nu_\mu\right)} = \frac{m^2_{\tau^+}\left(1-\frac{m^2_{\tau^+}}{m^2_{D^+_{(s)}}}\right)^2}{m^2_{\mu^+}\left(1-\frac{m^2_{\mu^+}}{m^2_{D^+_{(s)}}}\right)^2} = 2.67\ (9.75),$$

SM prediction

$$R\left(D^+ \to \tau^+\nu_\tau:\ \mu^+\nu_\mu:\ e^+\nu_e\right) = 2.67:\ 1:\ 2.35\times10^{-5}$$

SM prediction

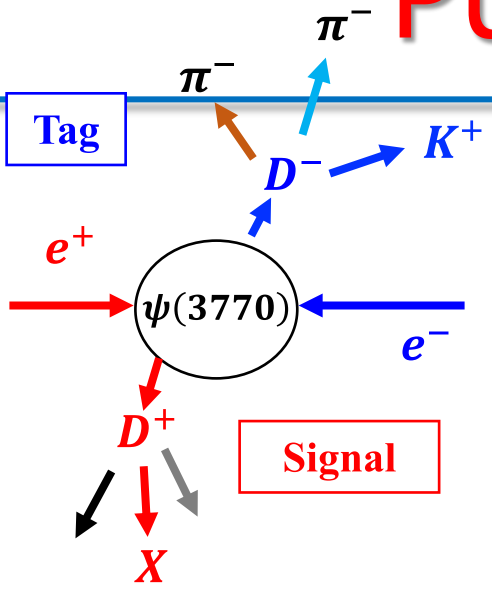
$$R\left(D_s^+ \to \tau^+\nu_\tau:\ \mu^+\nu_\mu:\ e^+\nu_e\right) = 9.75:\ 1:\ 2.35\times10^{-5}$$

SM prediction: $B(D^+_{(s)} \to e^+\nu_e) < 10^{-8}$, not yet experimentally observed.

Any deviation potentially indicates the existence of New Physics beyond SM.

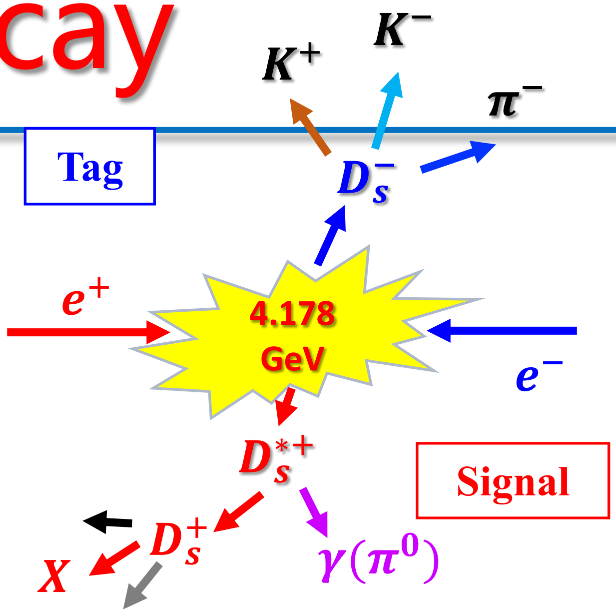
HFLAV, Phys. Rev. D 107, 052008 (2023)

Pure leptonic D decay



The signal branching fraction:

$$B_{sig} = \frac{N_{DT}^{signal}}{N_{D_{(s)}}^{ST} \times \bar{\epsilon}_{sig}}$$



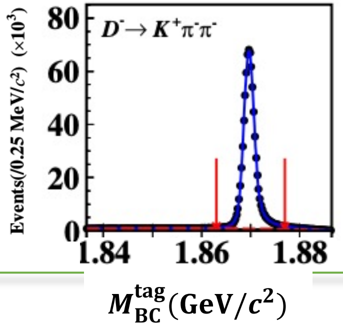
- **Single tag (ST):**

fully reconstruct one D^-

$$\Delta E = E_{D^-} - E_{beam}$$

$$M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_{D^-}|^2}$$

PRL124(2020)231801



□ **Double tag (DT):**

in the recoil ST $D_{(s)}^-$,

analyze the signal $D_{(s)}^+$

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

$$E_{miss} = E_{cm} - \sqrt{\left|\vec{p}_{D_{(s)}^-}\right|^2 + M_{D_{(s)}}^2} - E_X$$

$$\vec{p}_{miss} = -\vec{p}_{D_{(s)}^-} - \vec{p}_X$$

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

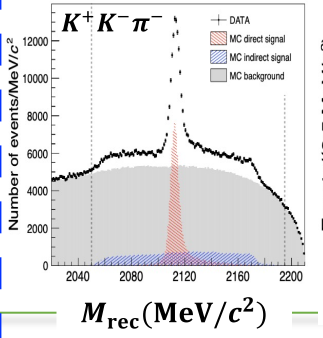
or other variables

- **Single tag (ST):**

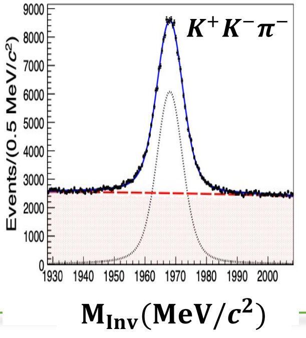
fully reconstruct one D_s^-

$$M_{rec} = \sqrt{\left(E_{cm} - \sqrt{|\vec{p}_{D_s^-}|^2 + m_{D_s^-}^2}\right)^2 - |-\vec{p}_{D_s^-}|^2}$$

PRD 104, 052009 (2021)

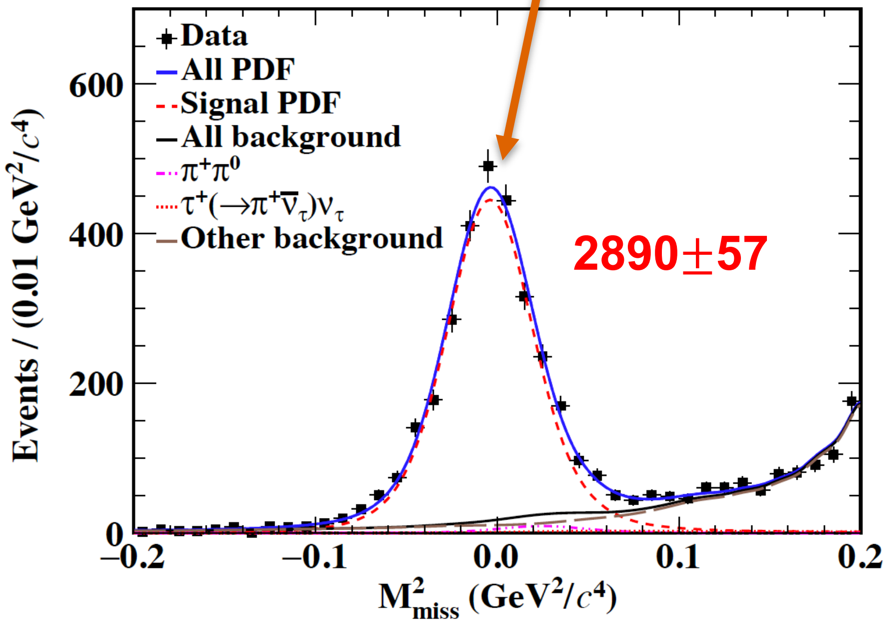


PRD 104, 012003 (2021)



$D^+ \to l^+\nu_l\ (\ell = \mu, \tau)$

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



$\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.981 \pm 0.079 \pm 0.040)\times 10^{-4}$

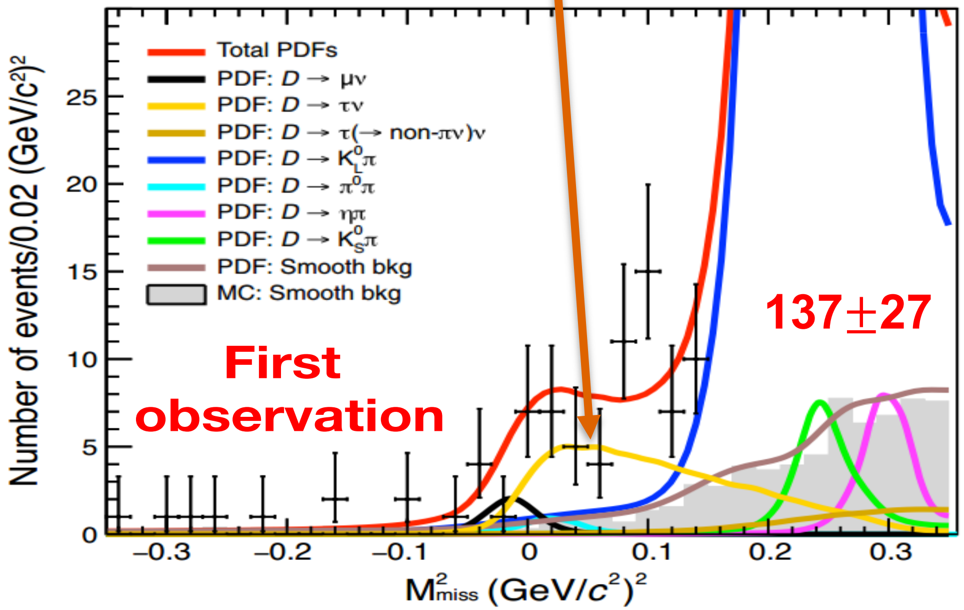
$f_{D^+}|V_{cd}| = (47.53 \pm 0.48_{\rm stat} \pm 0.24_{\rm syst} \pm 0.12_{\rm input})$ MeV

Precision~1.2%

arXiv: 2410.07626

This result is a factor of 2.3 more precise than the previous best measurement. The most precise to date.

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



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

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

Phys. Rev. Lett. 123, 211802 (2019) Editor's suggestion

Precision~11%

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

Results based on the 20 fb^{-1} full dataset @3.773GeV

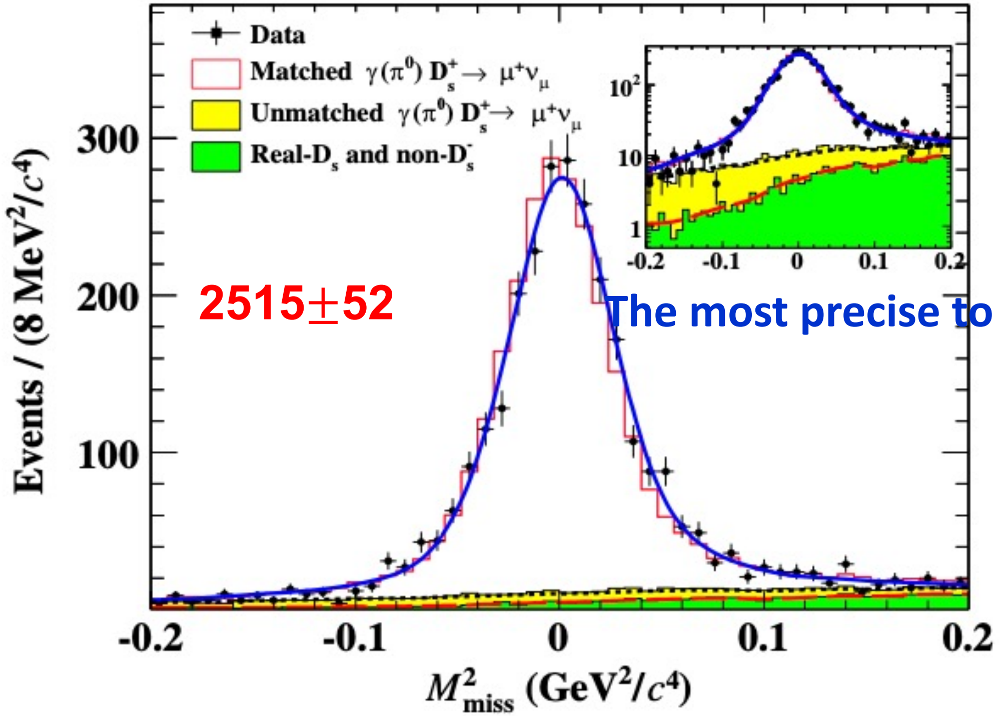
2.93 fb^{-1}@3.773 GeV

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

$D_s^+ \to \mu^+\nu$

Phys. Rev. D108,112001 (2023)

7.33 fb^{-1}@4.128~4.266 GeV



$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.294 \pm 0.108 \pm 0.085)\times 10^{-3}$$

$$f_{D_s^+}|V_{cs}| = 241.8 \pm 2.5_{stat} \pm 2.2_{syst}\ \text{MeV}$$

$\delta f_{D_s^+}|V_{cs}|$ ~ 1.4%; The most precise to date.

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

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

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

Phys. Rev. D 104, 032001 (2021)

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

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

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

PRL 127, 171801 (2021) **$\delta f_{D_s^+}|V_{cs}|$ ~ 1.5%**

$D_s^+ \to \tau^+(\mu^+\nu\nu)\nu$ *JHEP 09(2023)124*

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.37 \pm 0.17 \pm 0.15)\%$$

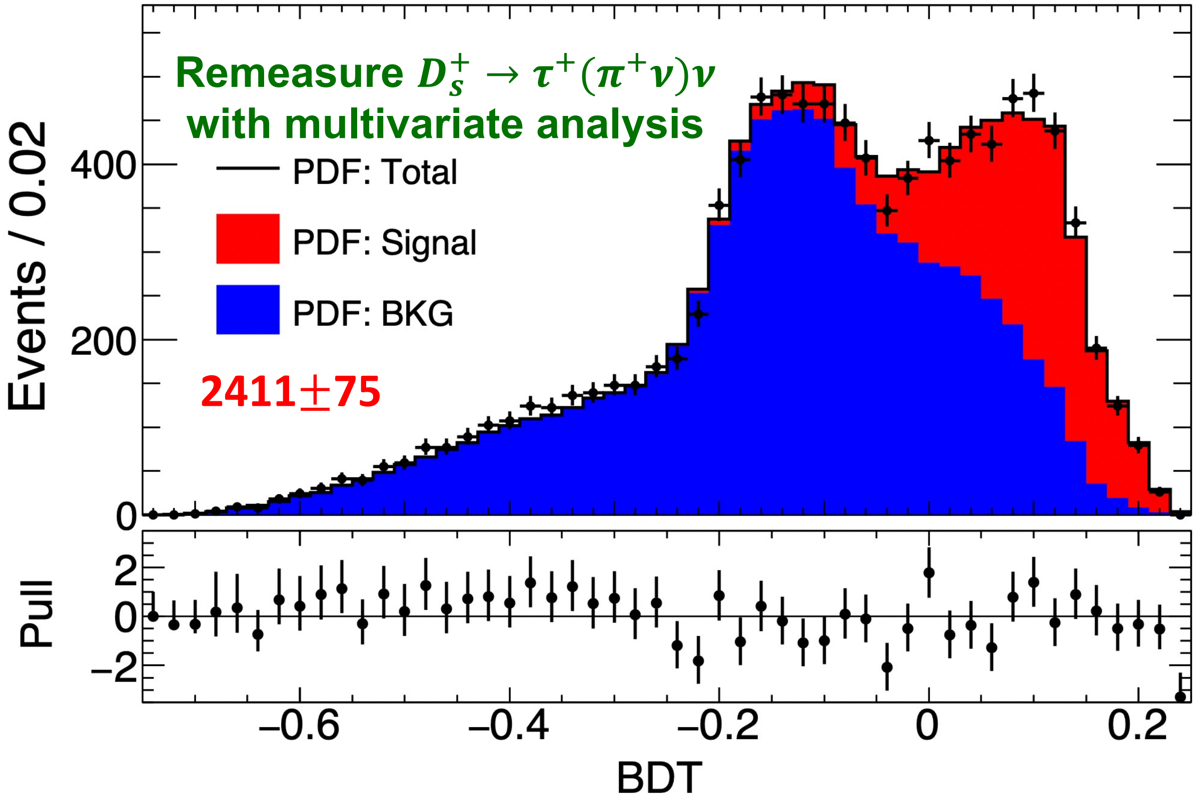
$$f_{D_s^+}|V_{cs}| = (246.7 \pm 3.9_{stat} \pm 3.6_{syst})\ \text{MeV}$$

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

$D_s^+ \to \tau^+\nu_\tau$

PRD 108, 092014 (2023)

Fit to BDT score on signal channel

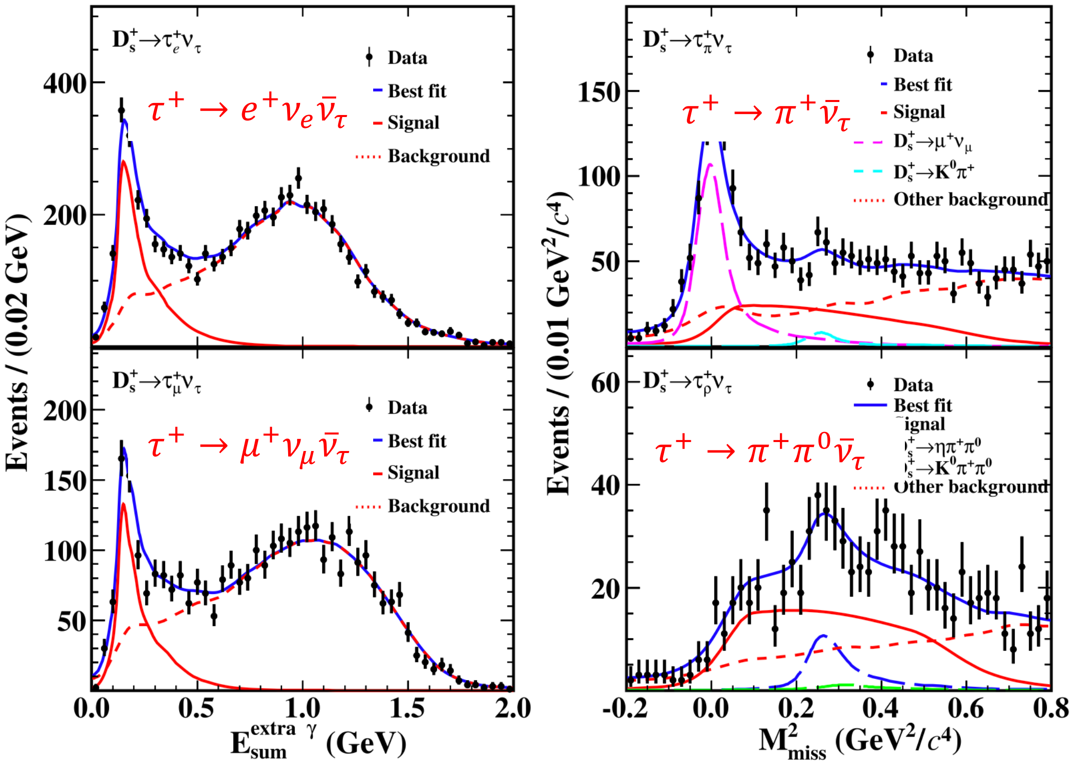


$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.41 \pm 0.17 \pm 0.13)\%$

Compared to the previous results (PRD 104(2021) 052009) based on the same dataset, statistical precision is improved by a factor of 1.5

PRD 110, 052002 (2024)

10.64 fb^{-1} from 4.237 to 4.699



Study $D_s^+ \to \tau^+\nu_\tau$ and $D_s^+ \to \mu^+\nu_\mu$ at the same time via $e^+e^- \to D_s^{*+}D_s^{*-}$

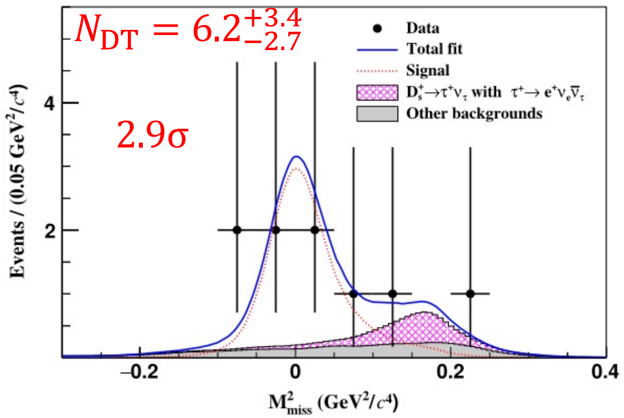
$N_{DT}^{\tau} = 2845 \pm 83$ $N_{DT}^{\mu} = 507 \pm 26$

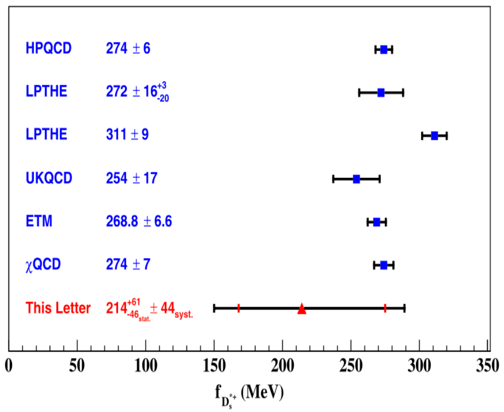
$B_{D_s^+\to\tau^+\nu_\tau} = (5.60 \pm 0.16 \pm 0.20)\%$

$D_{(s)}^{*+} \to \ell^+ \nu_\ell \ (\ell = e, \mu)$

- $D_s^{*+} \to e^+ \nu_e$ @4.128 – 4.226 GeV

PRL131(2023)141802





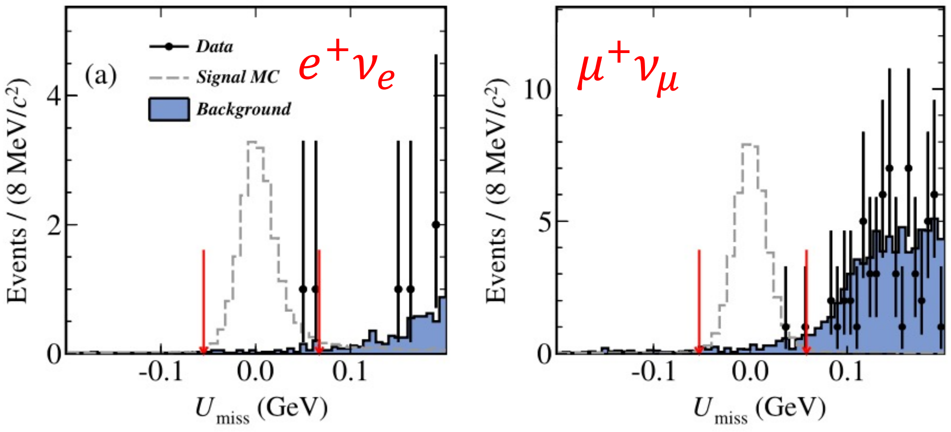
$$B(D_s^{*+} \to e^+\nu_e) = \left(2.1^{+1.2}_{-0.9} \pm 0.2\right)\times 10^{-5}$$
$$\leq 4.0\times 10^{-5} @90\% \text{ C.L.}$$

$$f_{D_s^{*+}}|V_{cs}| = \left(208^{+59}_{-45} \pm 43\right) \text{ MeV}$$

$$f_{D_s^{*+}} = \left(214^{+61}_{-46} \pm 44\right) \text{ MeV}$$

- $D^{*+} \to \ell^+ \nu_\ell \ (\ell = e, \mu)$ @4.178 – 4.226 GeV

PRD110(2024)012003



No significant signal. Profile likelihood method.

$$B(D^{*+} \to e^+\nu_e) < 1.1\times 10^{-5} \ @\ 90\% \text{ C.L.}$$

$$B(D^{*+} \to \mu^+\nu_\mu) < 4.3\times 10^{-6} \ @\ 90\% \text{ C.L.}$$

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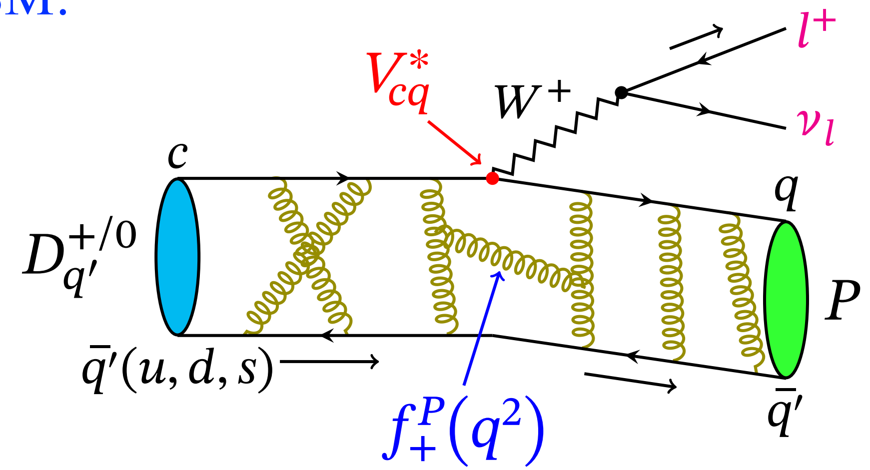
Semi−leptonic $D \to P e^+ \nu$

In the SM:



Differential decay rate (Exp.) — Form factor (LQCD) — CKM matrix element

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

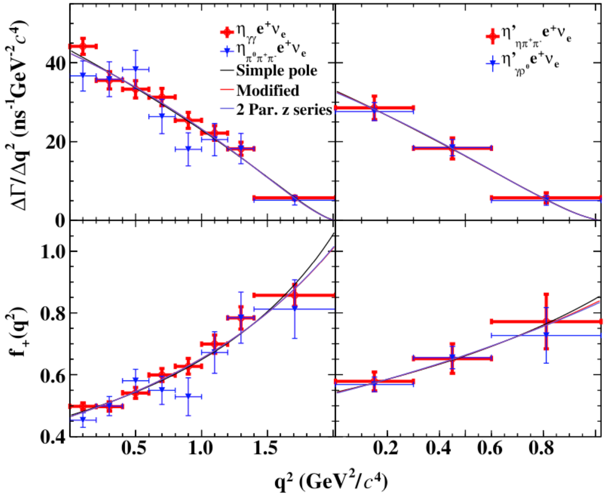
$$(X = 1 for K^-, \pi^-, \bar{K}^0, \eta^{(\prime)}; X = \frac{1}{2} for\ \pi^0)$$

- The effects of the strong and weak interactions can be separated in semi-leptonicdecays
- Good place to measure CKM matrix elements and study the weak decay mechanism of charm mesons; calibrate LQCD
- $R_{\mu/e}^P = \frac{\Gamma(D \to P \mu \nu_\mu)}{\Gamma(D \to P e \nu_e)}$: Test e − μ Lepton flavor universality

➢ Analyze exp. partial decay rates → q^2 dependence of $f_+(q^2)$, extract $f_+(0)$ with $\left|V_{cd(s)}\right|^{\text{CKMfitter}}$ as input – calibrate QCD

➢ Exp. + LQCD calculation of $f_+(0) \to V_{cd(s)}$ – constrain CKM matrix

Semi−leptonic $D \to Pe^{+}\nu$



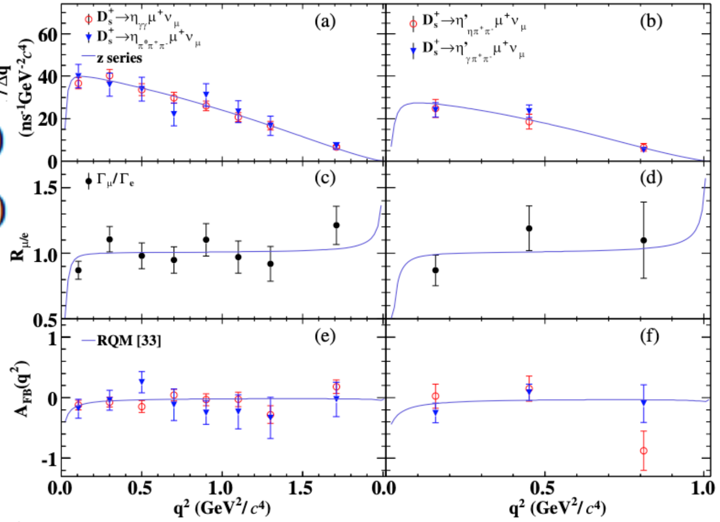
$D_s^+ \to \eta^{(\prime)} e^+\nu$

$f_+^{D_s\to\eta}(0)|V_{cs}| = 0.452(07)(07)$

$f_+^{D_s\to\eta'}(0)|V_{cs}| = 0.525(24)(09)$

$$\cot^4\phi_P = \frac{\Gamma_{D_s^+\to\eta' e^+\nu_e}/\Gamma_{D_s^+\to\eta e^+\nu_e}}{\Gamma_{D^+\to\eta' e^+\nu_e}/\Gamma_{D^+\to\eta e^+\nu_e}}$$

PRL123,121801(2019) → PRD108,092003(2023)



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

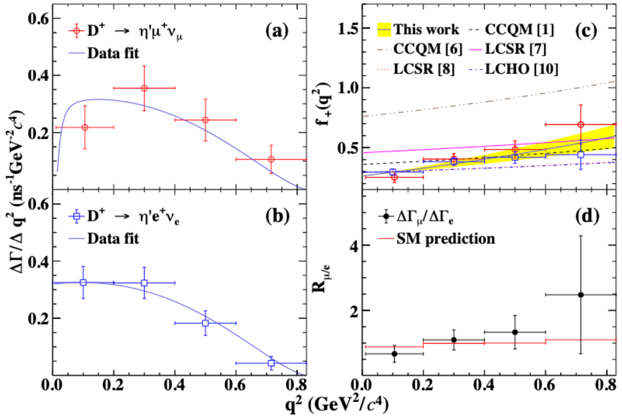
$f_+^{D_s\to\eta}(0)|V_{cs}| = 0.451(10)(08)$

$f_+^{D_s\to\eta'}(0)|V_{cs}| = 0.506(37)(11)$

Phys. Rev. Lett. 132, 091802 (2024)

First observation of $D_s^+ \to \eta'\mu^+\nu$, the most precise measuremet to date for these two decays.

$\eta - \eta'$ mixing angle in the quark flavor basis is determined



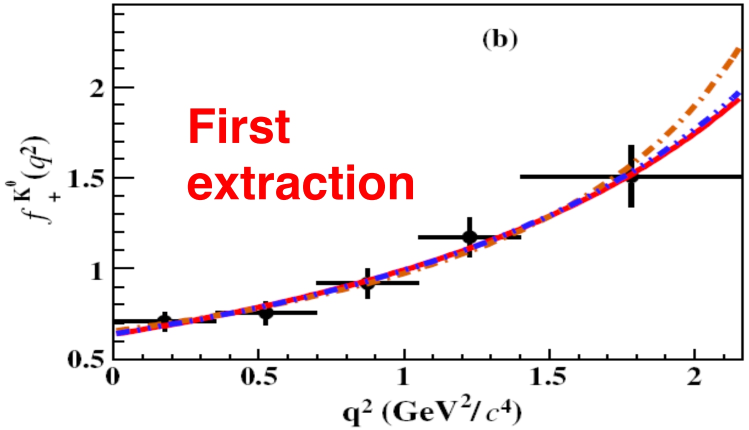
$D^+ \to \eta' l^+\nu$

20.3 fb^{-1}@3.773 GeV

$f_+^{D\to\eta'}|V_{cd}| = 0.0592(56)(13)$

arXiv:2410.08603

Precision ~10%



$D_s^+ \to K^0 e^+\nu$

$f_+^{D_s\to K^{(0)}}|V_{cd}| = 0.143(11)(03)$

Precision ~8%

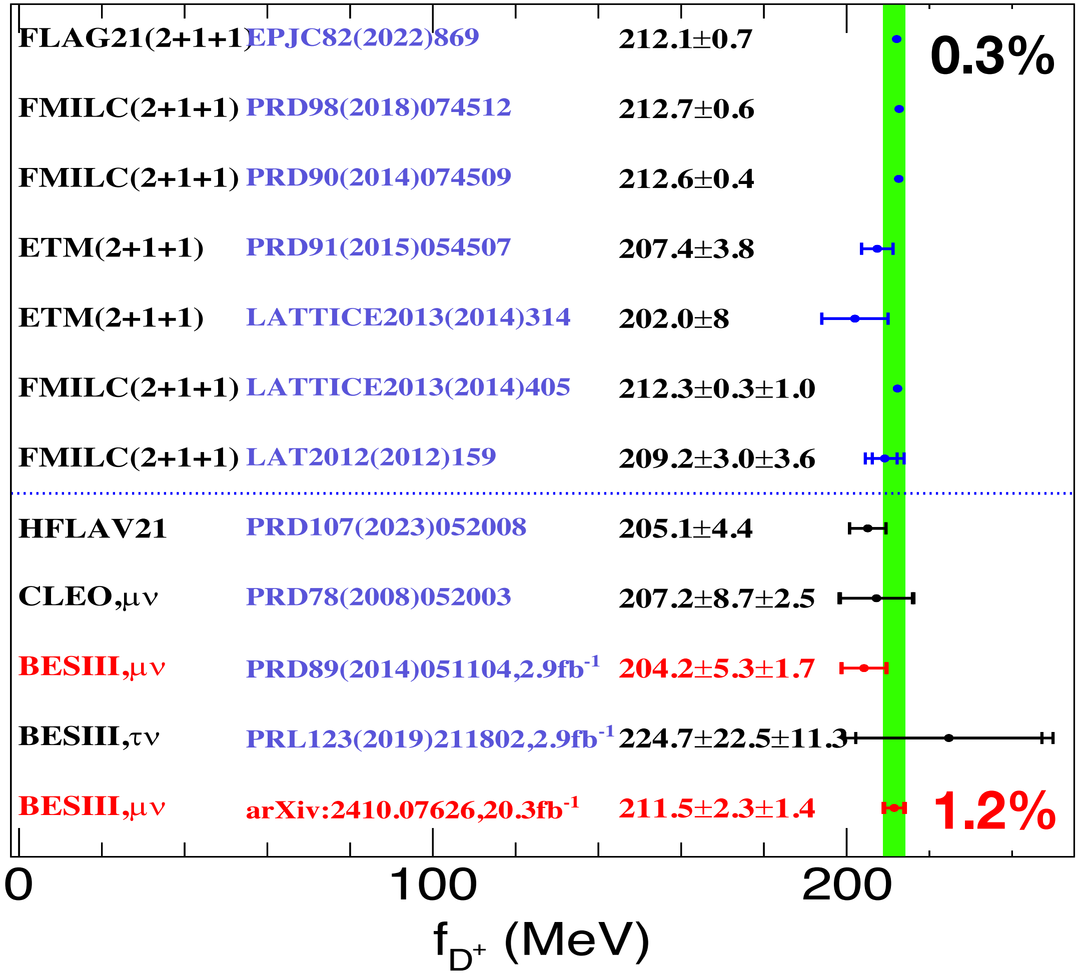
PRL122(2019)061801 → arXiv:2406.19190

First observation of $D^+ \to \eta'\mu^+\nu$ and first study of $D^+ \to \eta' l^+\nu$ decay parameters

The most precise measurement of Br. and FF. to date. Obviously deviate from simple pole model in the high moment transfer region.

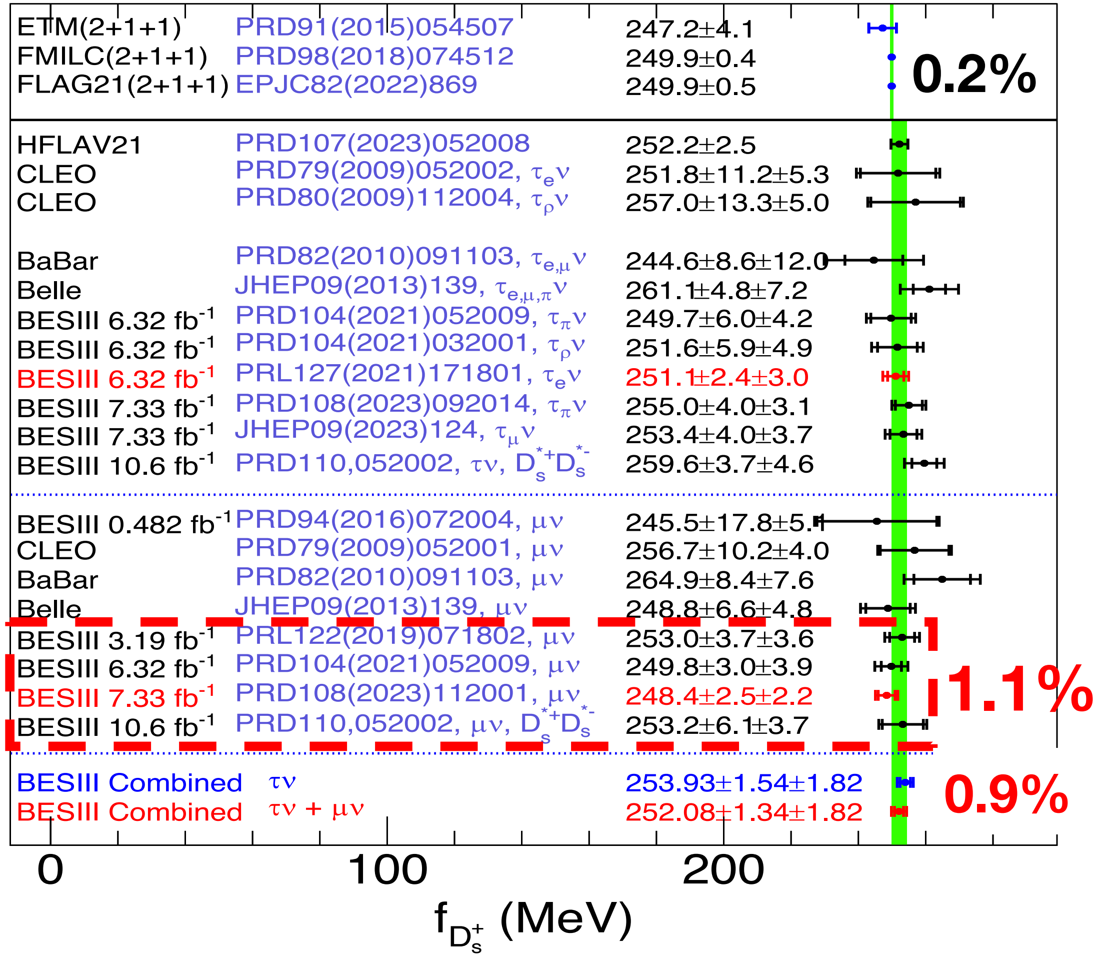
Comparison of decay constant

f_{D^+}



- Input $|V_{cd}| = 0.22487 \pm 0.00068$ from CKM global fit

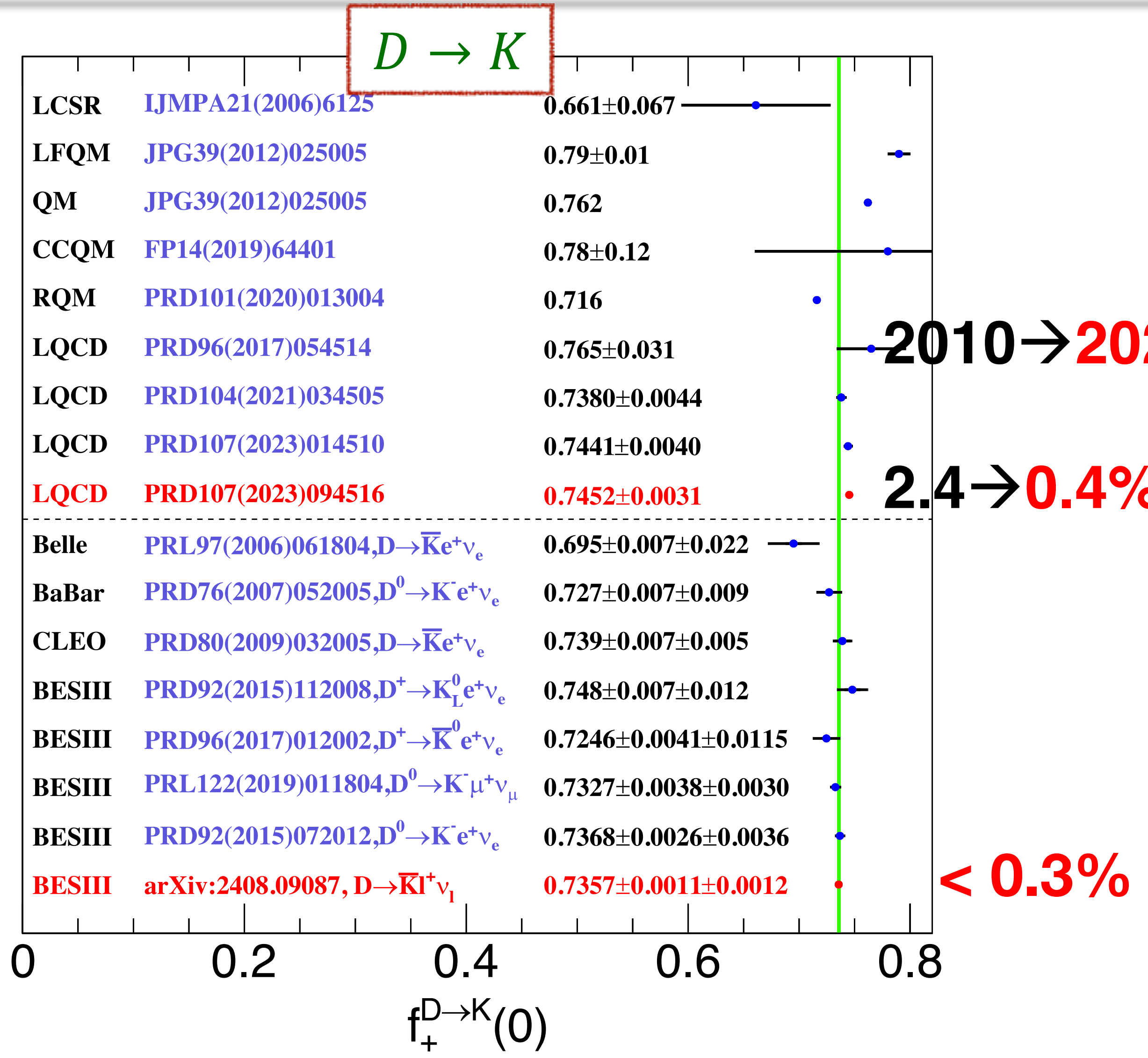
$f_{D_s^+}$

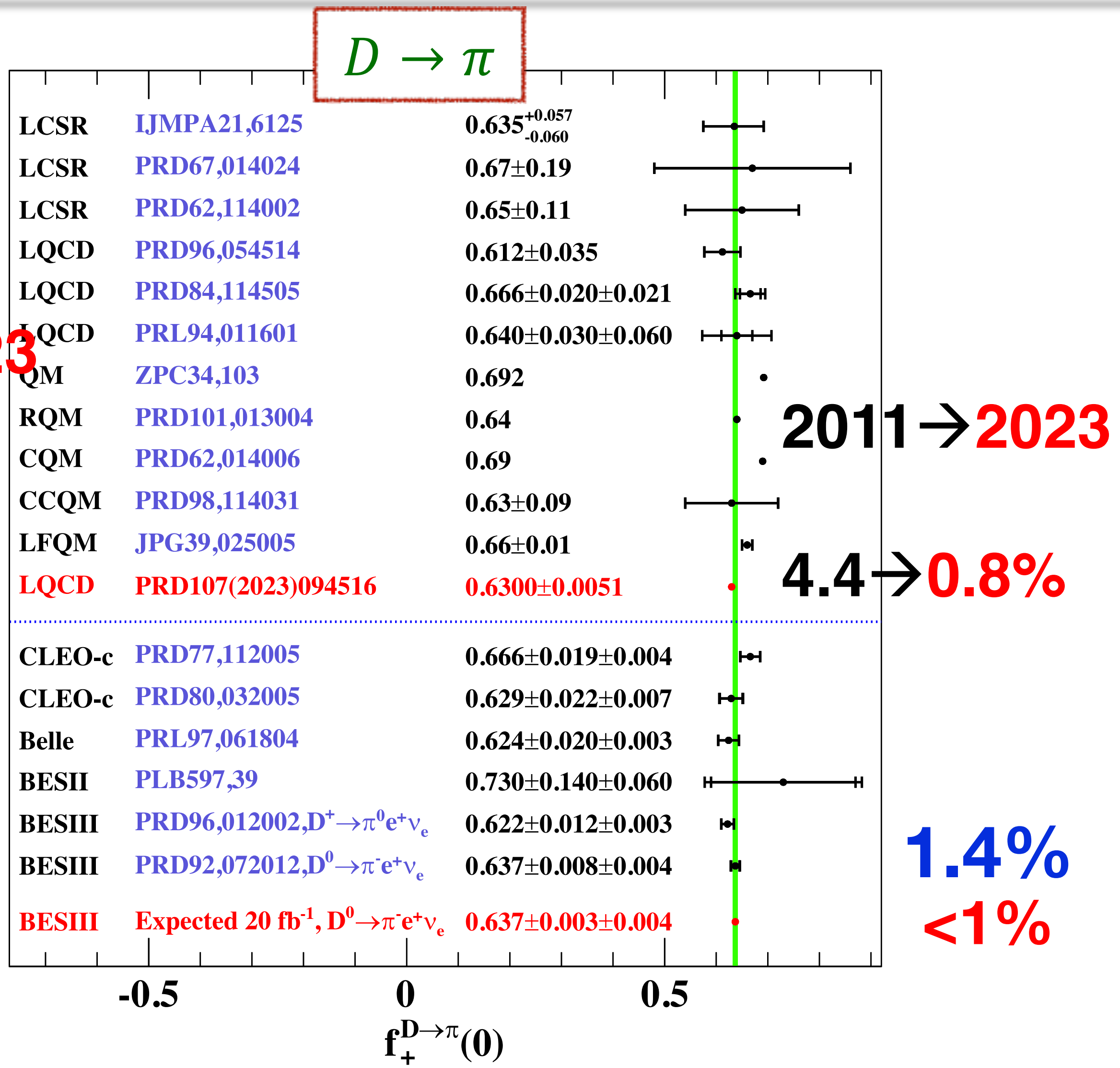


- Input $|V_{cs}| = 0.97320 \pm 0.00011$ from CKM global fit

The errors from the exps. are still larger than those from LQCD calculations.

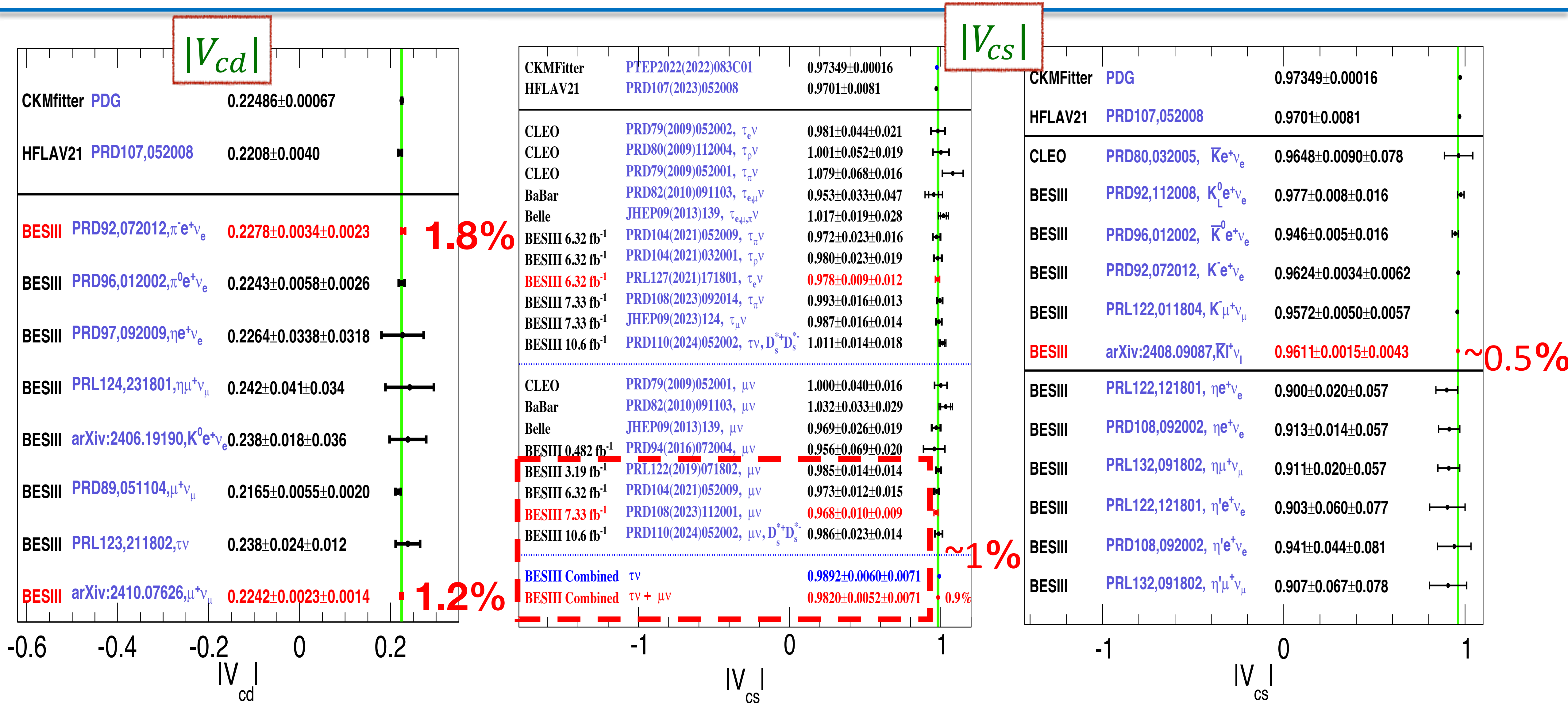
Comparison of form factor





Experimental precision is comparable to the latest QCD result!

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

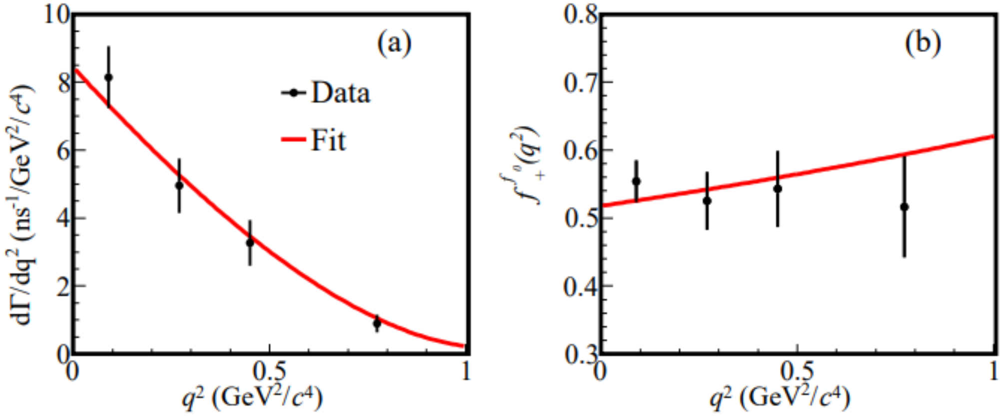


Both pure- and semi-leptonic decays contribute

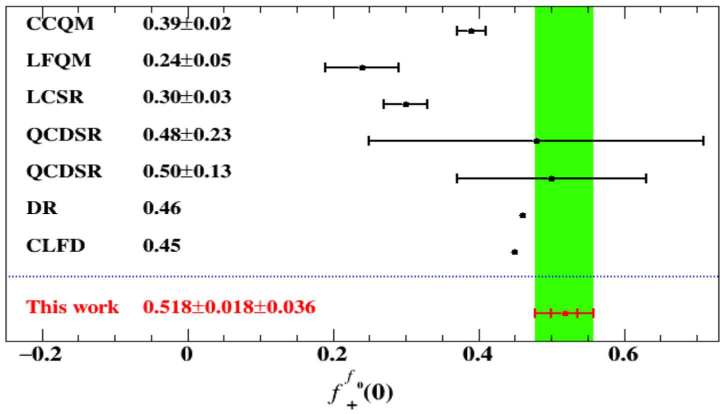
$D \to Sl\nu$

First extraction of form factors for D→scalar mesons

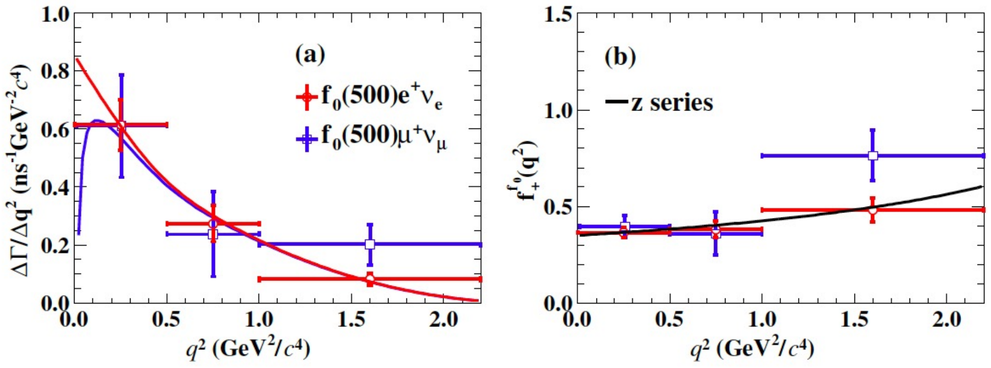
$D_s^+ \to f_0(980)e^+\nu_e$ PRL132(2024)141901



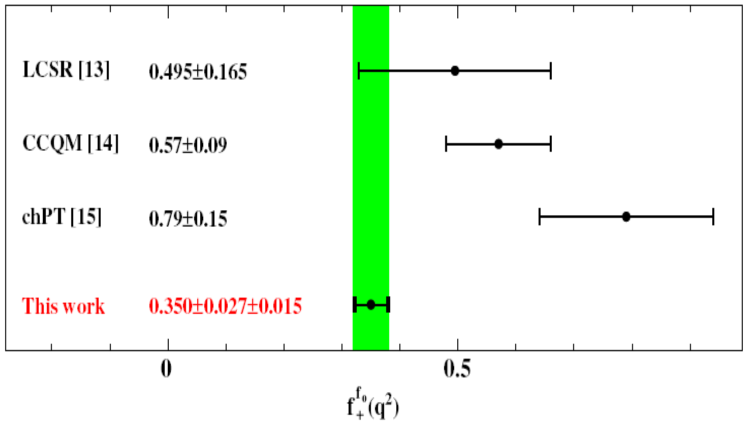
$$f_+^{D_s \to f_0(980)}(0)|V_{cs}| = 0.504(17)(35)$$



$D^+ \to f_0(500)l^+\nu_l$ arXiv:2401.13225



$$f_+^{D^+ \to f_0(500)}(0)|V_{cd}| = 0.0787(60)(33)$$



2.93 fb^{-1}@3.773 GeV

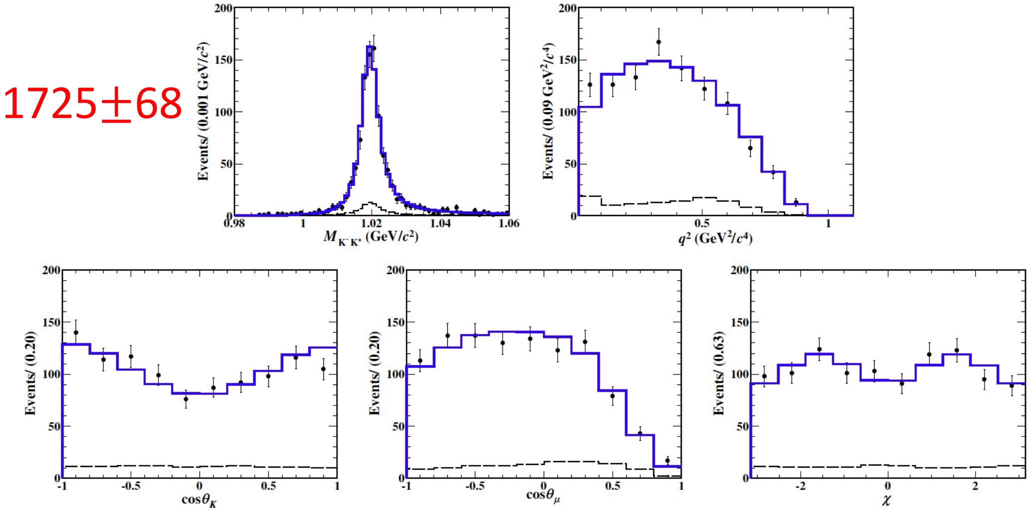
First observation of $D^+ \to f_0(500)^0\mu^+\nu_\mu$

Obvious discrepancy between experiments and some theory calculations based on two quarks assumption may indicate there are possible four quarks component in $f_0(500)$ and $f_0(980)$

$D \to Vl\nu$

$D_s^+ \to \phi\mu^+\nu_\mu$ JHEP12(2023)072

1725±68

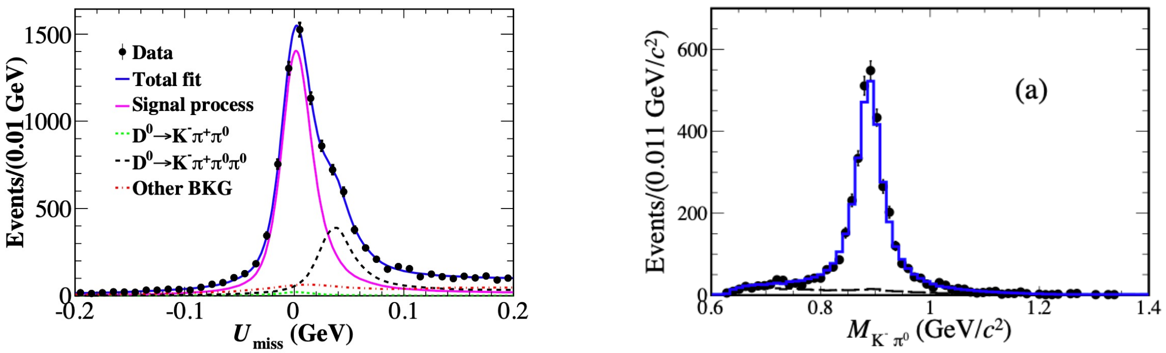


$r_V = 1.58 \pm 0.17 \pm 0.02$ $r_2 = 0.71 \pm 0.14 \pm 0.02$

- The absolute branching fraction is the most precise measurement to date.
- PWA is used to extract the FFs.
- No significant S-wave contribution from $f_0(980) \to K^+K^-$ is found.

$D^0 \to K^{*-}\mu^+\nu_\mu$ arXiv:2403.10877

7.9 fb^{-1}@3.773 GeV



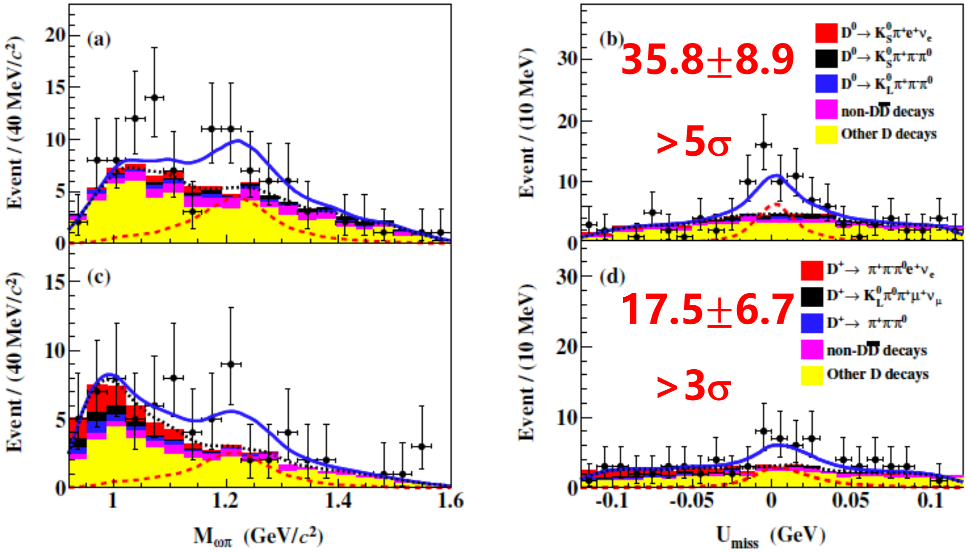
$r_V = 1.37 \pm 0.09 \pm 0.03$ $r_2 = 0.76 \pm 0.06 \pm 0.02$

- The first study of the $D^0 \to K^-\pi^0\mu^+\nu_\mu$ decay.
- An S-wave component is observed.
- The branching fraction of $D^0 \to K^{*-}\mu^+\nu_\mu$ is improved in precision by a factor of five over the current world average, which excludes the covariant quark model and the covariant confining quark model calculations by more than 5σ
- The most precise FF ratios of the $D^0 \to K^{*-}\mu^+\nu_\mu$ decay are determined

$D \to A l \nu$

First observation of $D^0 \to b_1(1235)^- e^+ \nu_e$

arXiv:2407.20551 **7.9 fb^{-1}@3.773 GeV**



$$\mathcal{B}(D^0 \to b_1(1235)^- e^+ \nu_e) \times \mathcal{B}(b_1(1235)^- \to \omega\pi^-) = (0.72 \pm 0.18^{+0.06}_{-0.08}) \times 10^{-4}$$

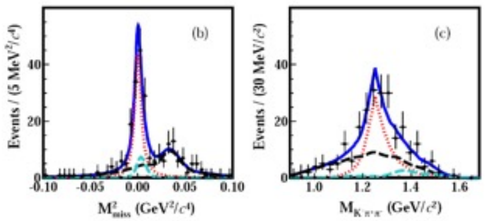
$$\mathcal{B}(D^+ \to b_1(1235)^0 e^+ \nu_e) \times \mathcal{B}(b_1(1235)^0 \to \omega\pi^0) = (1.16 \pm 0.44 \pm 0.16) \times 10^{-4}$$

- **The results support the assumption the ωπ final state is the dominant decay mode of the axial-vector b1 meson**

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

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

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



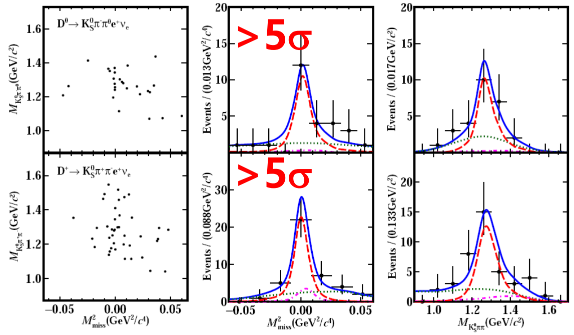
$D^+ \to K_1(1270)^0(\to K^-\pi\pi) e^+ \nu$

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

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

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

JHEP09(2024)089



2.93 fb^{-1}@3.773 GeV

- **LHCb reported a large up-down asymmetry in $B^- \to K_{res}^-(\to K^-\pi^+\pi^-)\gamma$ in the $K^-\pi^+\pi^-$ invariant mass bin of [1.1, 1.3]GeV/c^2 which is dominated by a $K_1(1270)^-$ contribution (PRL 112, 161801 (2014)), $D^0 \to K_1(1270)^-(\to K^-\pi\pi)e^+\nu$ is desired to quantify the hadronic effects of $K_1(1270)^- \to K^-\pi\pi$.**
- **These semi-leptonic decays are useful to undertand the internal structure of the axial-vector meson $K_1(1270)$.**

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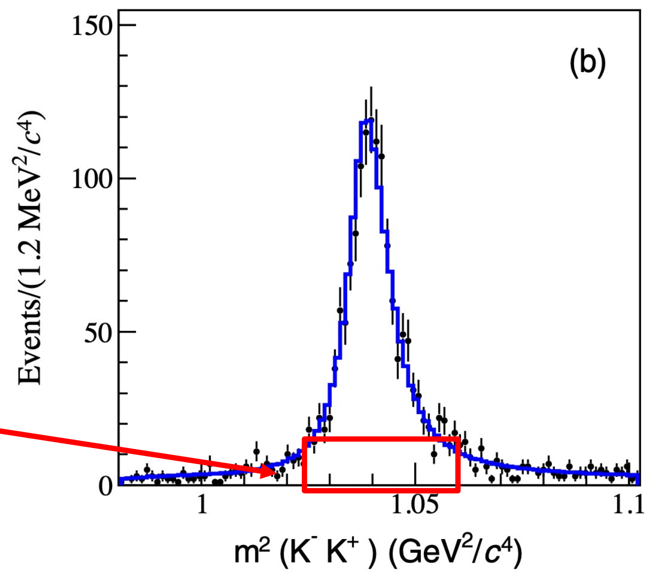
  - semi-leptonic decays
  - hadronic decays
- Prospect

Why amplitude analysis?

Measuring intermediate resonance with considering interference

Interference of $D_s \to \phi\pi$ and other processes

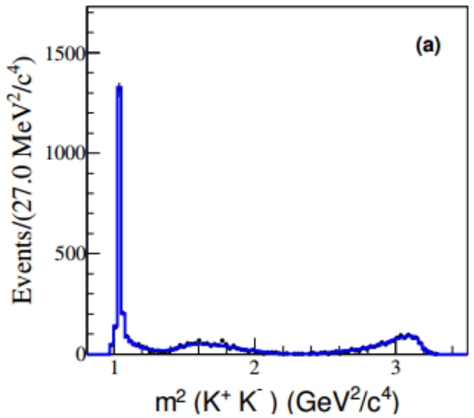


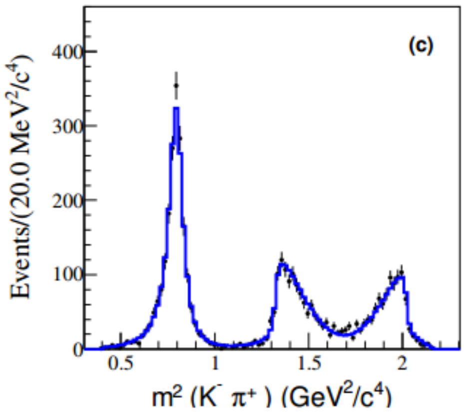
A bridge connecting theories (two-body) and experiments (three or four-body with e, μ, π, K, p as the final state particles)

Providing accurate models for simulation

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

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

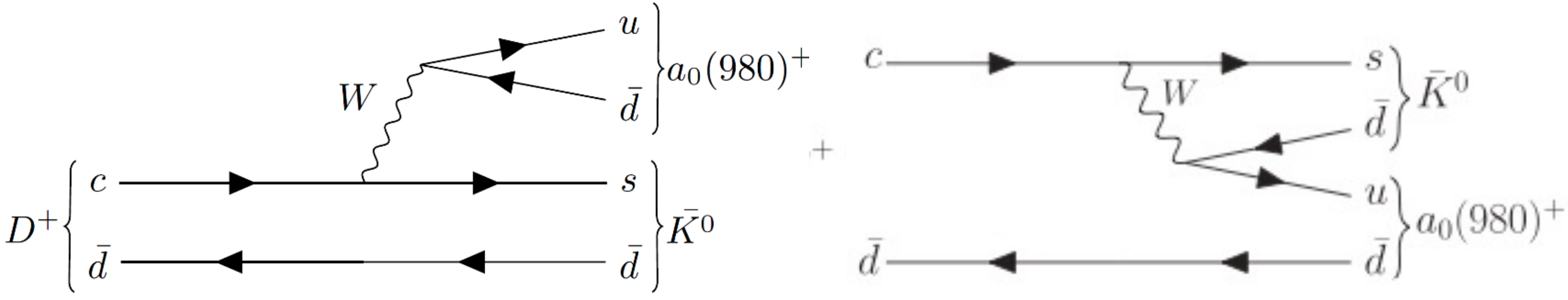
Process	BF (%) BESIII (this analysis)	PDG
$D_s^+ \to \bar{K}^*(892)^0K^+$, $\bar{K}^*(892)^0 \to K^-\pi^+$	$2.64 \pm 0.06_{stat} \pm 0.07_{sys}$	2.58 ± 0.08
$D_s^+ \to \phi(1020)\pi^+$, $\phi(1020) \to K^+K^-$	$2.21 \pm 0.05_{stat} \pm 0.07_{sys}$	2.24 ± 0.08
$D_s^+ \to S(980)\pi^+$, $S(980) \to K^+K^-$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

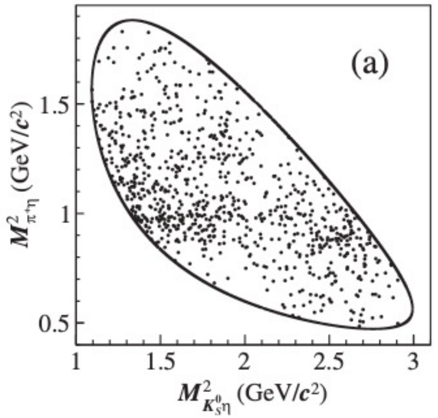
PRD 104. 012016 (2021)

Observation of $D^+ \to K_S^0 a_0(980)^+$ in the Amplitude Analysis of $D^+ \to K_S^0 \pi^+ \eta$

Observe W-annihilation-free decay $D^+ \to K_S^0 a_0(980)^+$ in the first amplitude analysis of $D^+ \to K_S^0 \pi^+ \eta$

PRL 132, 131903 (2024)

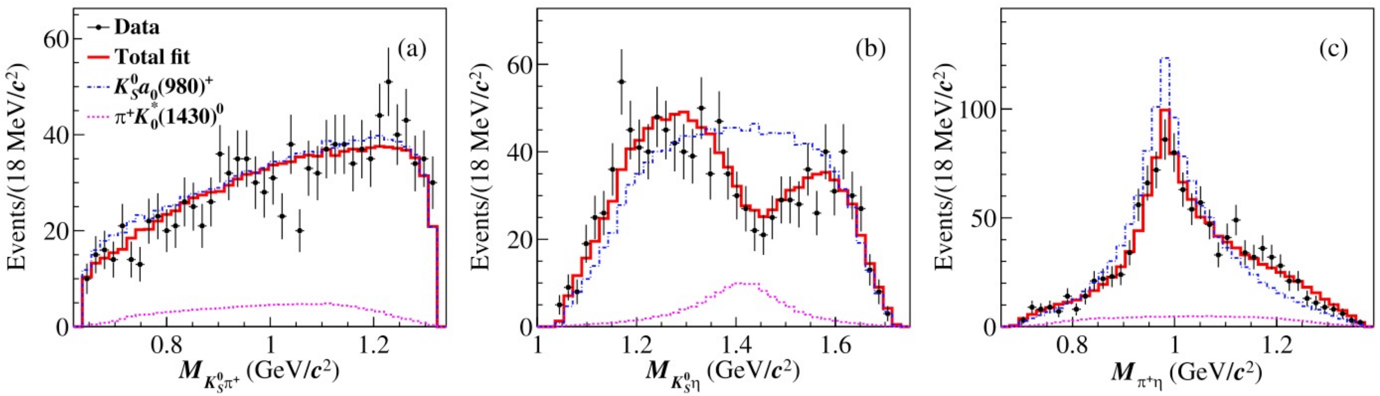




$\mathcal{B}(D^+ \to K_S^0 a_0(980)^+, a_0(980)^+ \to \pi^+\eta) = (1.33 \pm 0.05 \pm 0.04)\%$

$\mathcal{B}(D^+ \to \bar{K}_0^*(1430)^0 \pi^+, \bar{K}_0^*(1430)^0 \to K_S^0\eta) = (0.14 \pm 0.03 \pm 0.01)\%$

$\mathcal{B}(D^+ \to K_S^0 \pi^+ \eta) = (1.27 \pm 0.04 \pm 0.03)\%$



$D^+ \to K_S^0 a_0(980)^+$ is the only W-annihilation-free decay among D to $a_0(980)^+$ pseudoscalar, so $D^+ \to K_S^0 a_0(980)^+$ is the ideal decay in extracting the contributions of the W-emission amplitudes involving $a_0(980)^+$ and to study the final-state interactions.

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

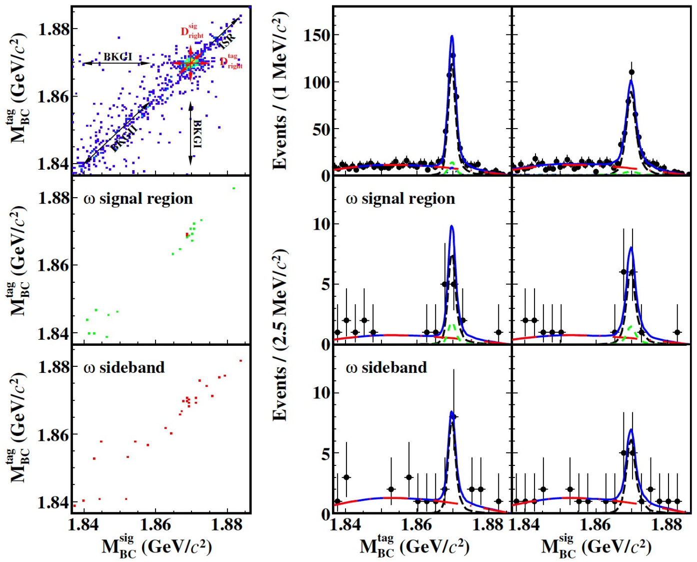
Use hadronic tags. 350 signal events

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

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

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

One order larger than normal, may be caused by final state interactions and very different resonance structures in these two decays.

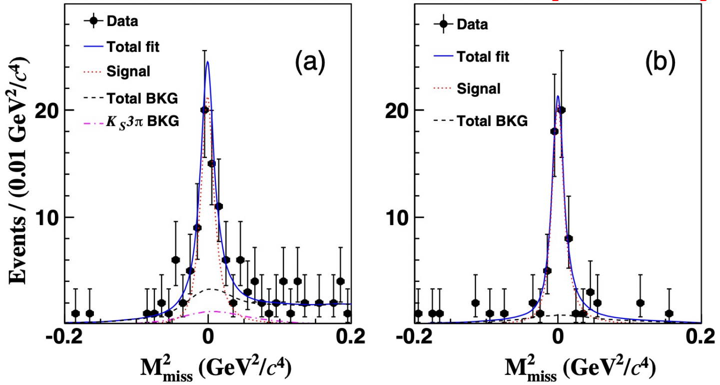


PRL 125, 141802 (2020)

Use semileptonic tags. 112 signal events

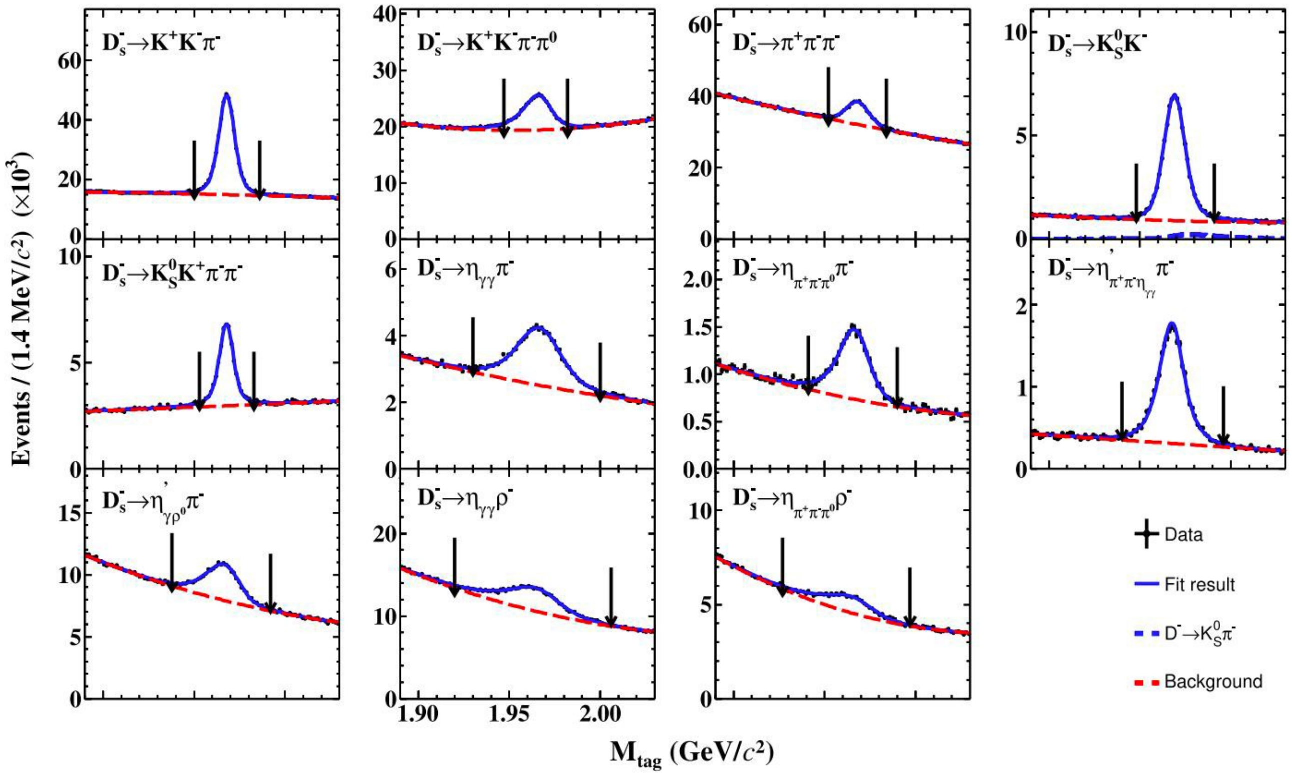
$$\mathcal{B}(D^+ \to K^+\pi^+\pi^-\pi^0) = (1.03 \pm 0.12 \pm 0.06) \times 10^{-3}$$

First try of semileptonic tag at BESIII



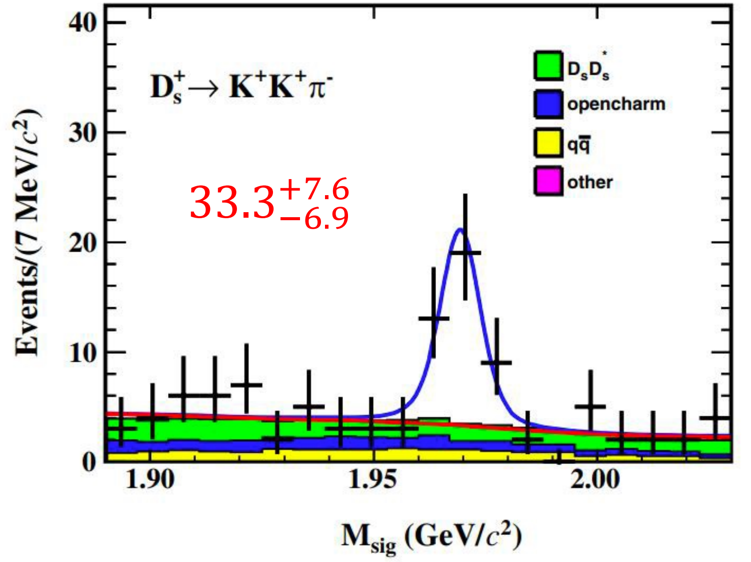
PRD 104, 072005 (2021)

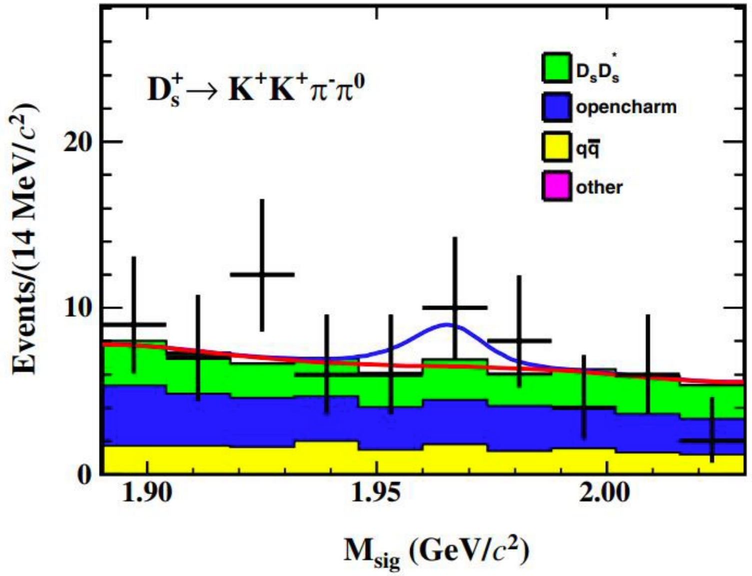
Observation of the DCSD $D_s^+ \to K^+K^+\pi^-(\pi^0)$



DCS decay	$\mathcal{B}_{\rm DCS}^{\rm this\ work}$ $(\times 10^{-4})$	CF decay	$\mathcal{B}_{\rm CF}^{\rm PDG}$ $(\times 10^{-2})$	$\mathcal{B}_{\rm DCS}^{\rm this\ work}/\mathcal{B}_{\rm CF}^{\rm PDG}$ $(\times 10^{-3})$	$\times \tan^4\theta_C$
$D_s^+ \to K^+K^+\pi^-$	$1.24^{+0.28}_{-0.26} \pm 0.06$	$D_s^+ \to K^+K^-\pi^+$	5.37 ± 0.10	$2.31^{+0.52}_{-0.48}$	$0.80^{+0.18}_{-0.16}$
$D_s^+ \to K^+K^+\pi^-\pi^0$	< 1.7	$D_s^+ \to K^+K^-\pi^+\pi^0$	5.50 ± 0.24	< 3.09	< 1.07

No significant deviation from naive expectation of (0.5–2.0)$\times$ $tan^4\theta_C$ is found





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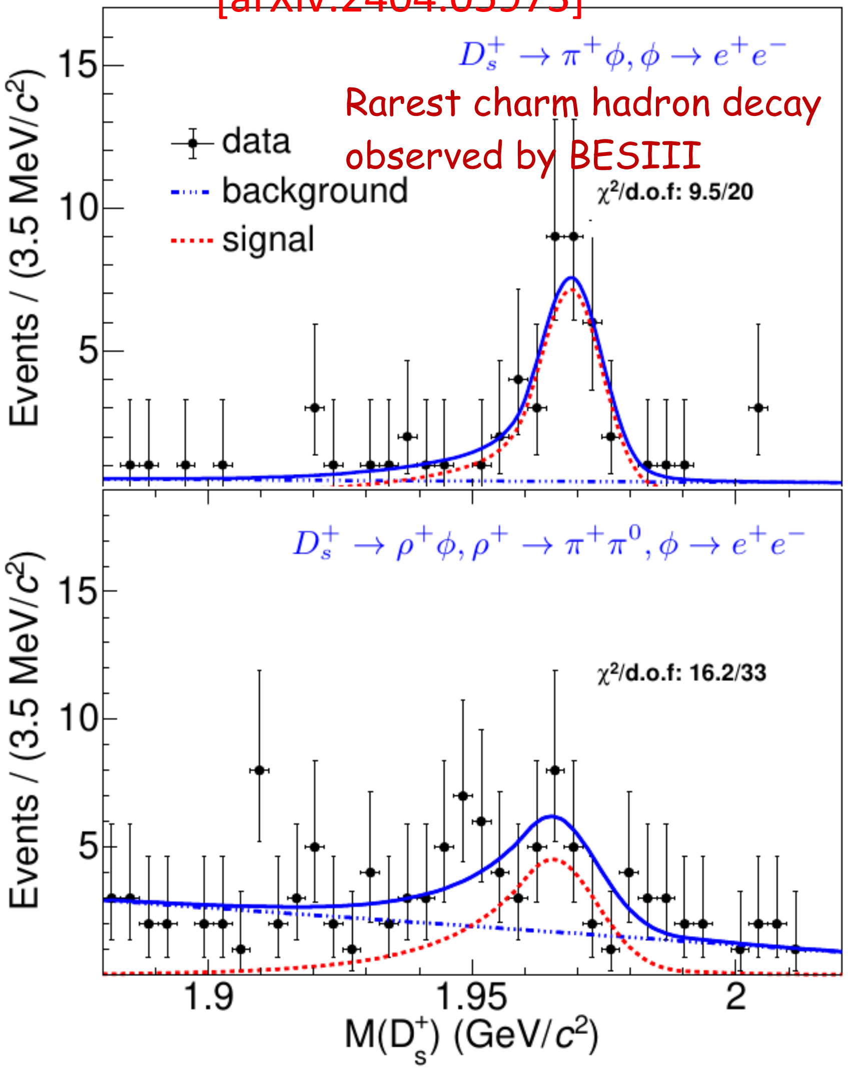
- Prospect

$D_s^+ \to h(h^0)\phi(e^+e^-)$

[arXiv:2404.05973]



- $M(e^+e^-) \in [0.98, 1.04]$ GeV/c^2
- $M(\pi^+\pi^0) \in [0.60, 0.95]$ GeV/c^2
- Unbinned maximum likelihood fits to the $M(D_s^+)$ distributions

Decay	N_{sig}	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
$D_s^+ \to \pi^+\phi, \phi \to e^+e^-$	$38.2^{+7.8}_{-6.8}$	25.1	$1.17^{+0.23}_{-0.21} \pm 0.03$
$D_s^+ \to \rho^+\phi, \phi \to e^+e^-$	$37.8^{+10.3}_{-9.6}$	12.1	$2.44^{+0.67}_{-0.62} \pm 0.16$

7.8σ for $D_s^+ \to \pi^+\phi, \phi \to e^+e^-$ — improved by a factor of three

4.4σ for $D_s^+ \to \rho^+\phi, \phi \to e^+e^-$ — first evidence

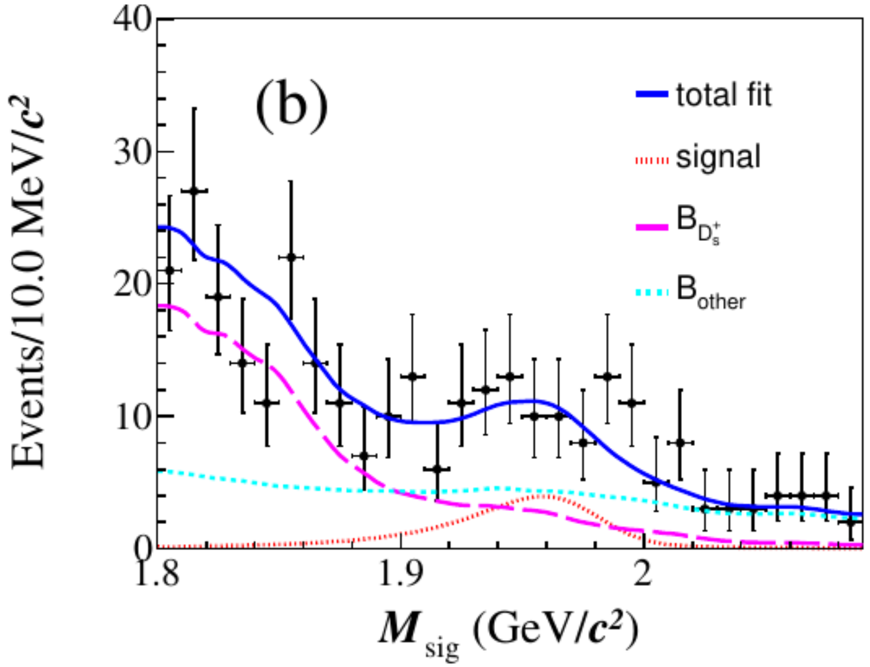
NB: Using $D_{(s)}^+ \to \pi^+\phi$, LHCb measured

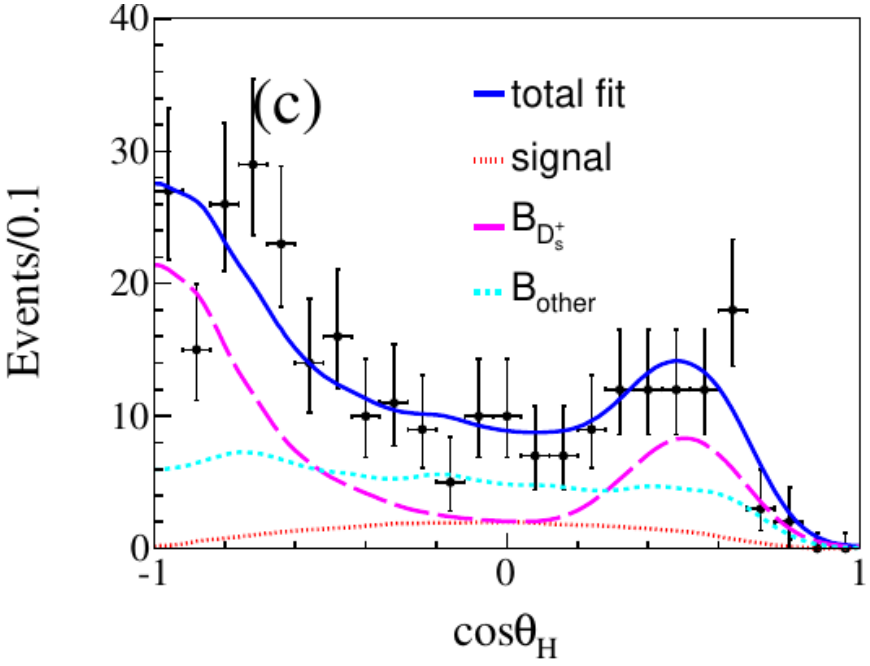
$R_{\phi\pi} = 1.022 \pm 0.012\,(\text{stat}) \pm 0.048\,(\text{syst})$

[JHEP 05 (2024) 293]

Search for $D_s^+ \to \gamma\rho(770)^+$

2D fit to extract signal yield N_{DT} = 33 ± 14 with statistical significance of 2.5σ





- First search for a radiative D_s^+ decay
- BF important to test QCD-based LD calculations & predictions of CPV in D decays
- 7.33 fb^{-1} data @ $E_{cm} \in [4.128, 4.226]$ GeV
- Double-tag method with five modes

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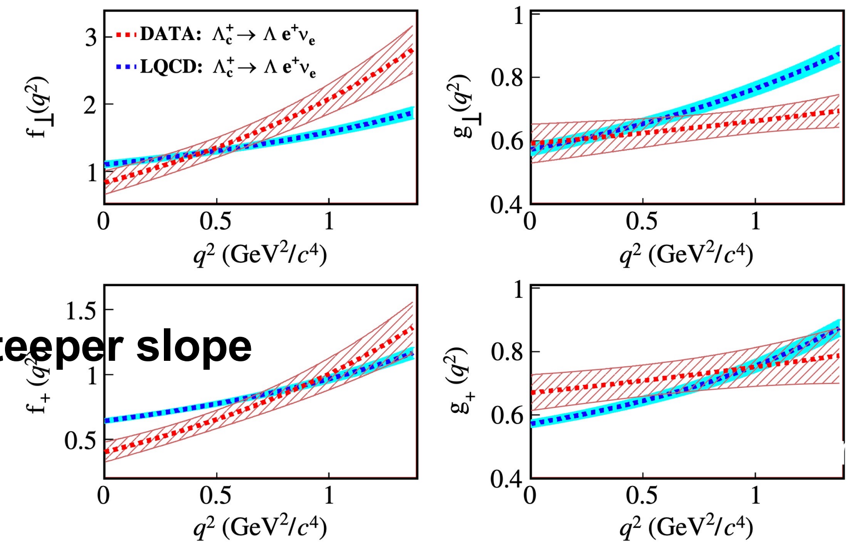
Semi-leptonic Λ_c^+ decays

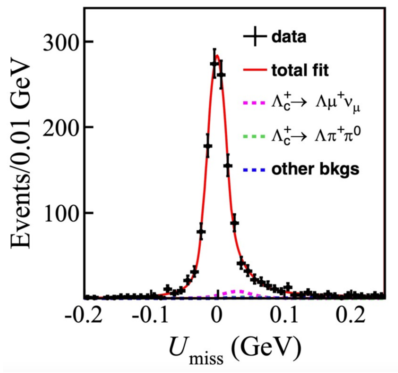
Study of $\Lambda_c^+ \to \Lambda e^+ \nu$

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



Steeper slope

Different kinematic behavior compared to LQCD predictions,



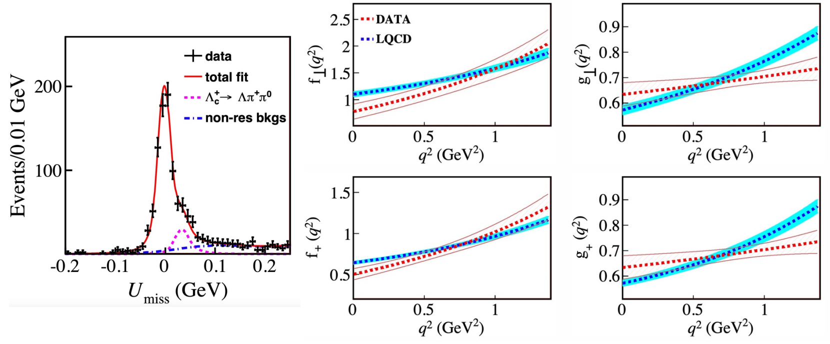
Updated BF and first FF measurement:

~4% most precise

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

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

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



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

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

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

PRD 108, L031105 (2023)

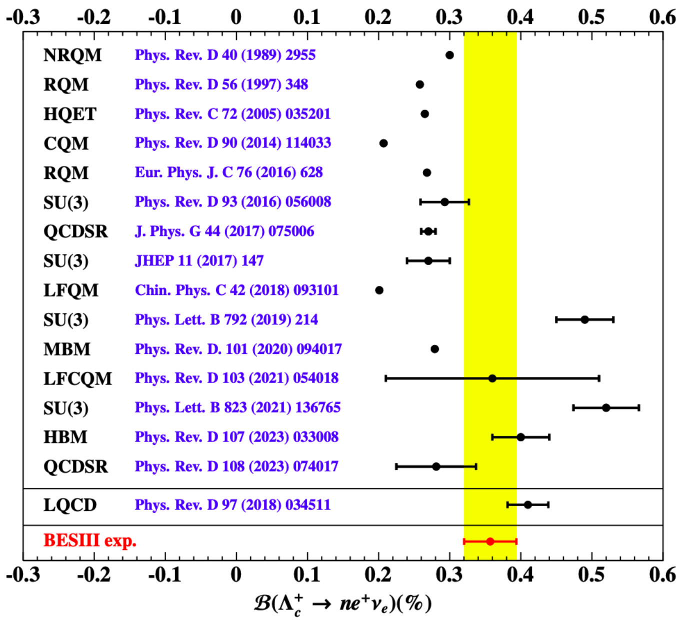
PRL 129, 231803 (2022)

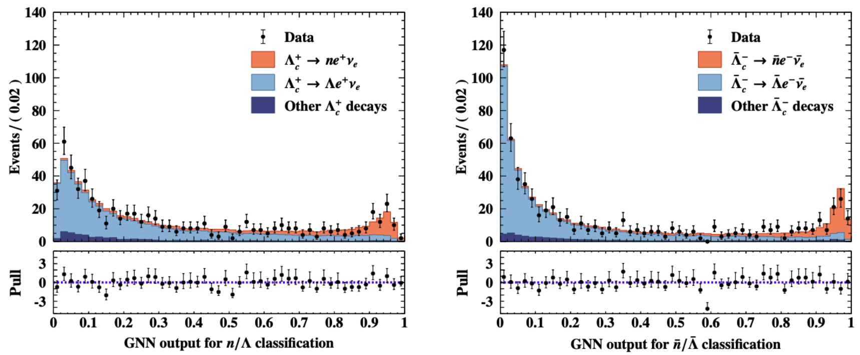
Agree with PDG 2022

Observation of $\Lambda_c^+ \to n e^+ \nu_e$ with Deep Learning

arXiv:2410.13515 (submitted to NatComm)

- A novel Deep Learning is utilized to separate signals from dominant background.
- First observation of $\Lambda_c^+ \to n e^+ \nu_e$
  - $\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = (0.357 \pm 0.034_{\rm stat} \pm 0.014_{\rm syst})\%$ ($> 10\sigma$)
  - $|V_{cd}| = 0.208 \pm 0.011_{\rm exp.} \pm 0.005_{\rm LQCD} \pm 0.001_{\tau_{\Lambda_c^+}}$
- This measurement demonstrates a level of precision comparable to the LQCD prediction.
- The absence of HCAL restricted us to extract the form factors.
- The CKM matrix element $|V_{cd}|$ are determined for the first time from charmed baryon





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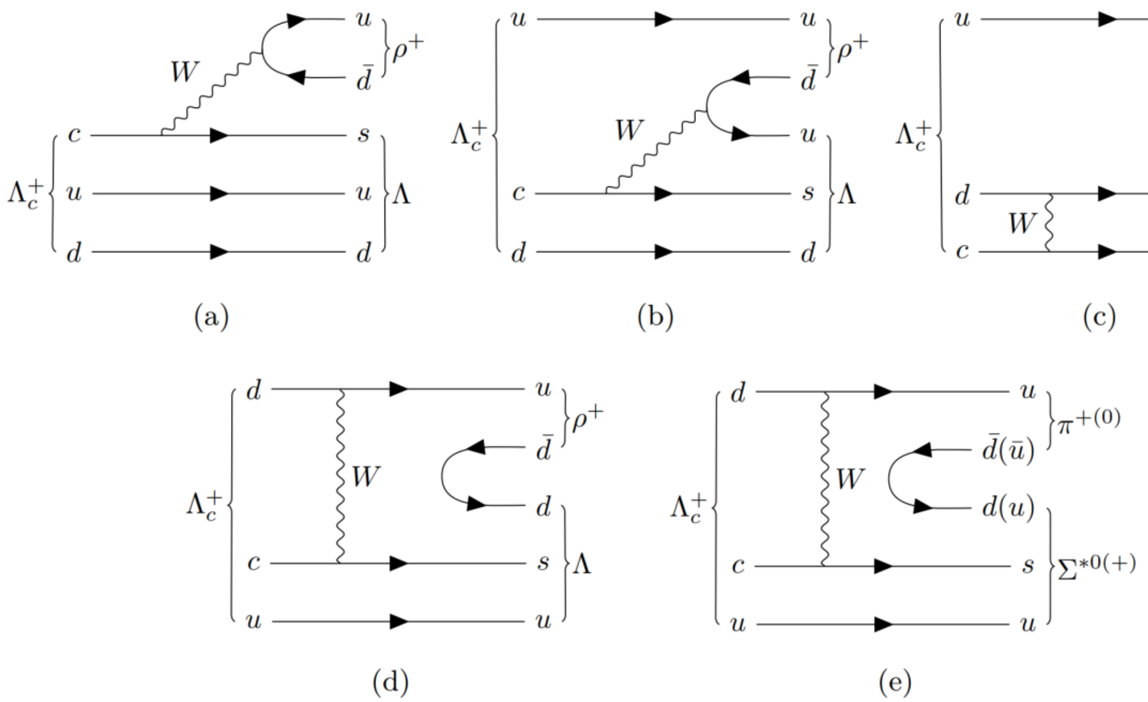
Partial wave analysis of the charmed baryon hadronic decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$



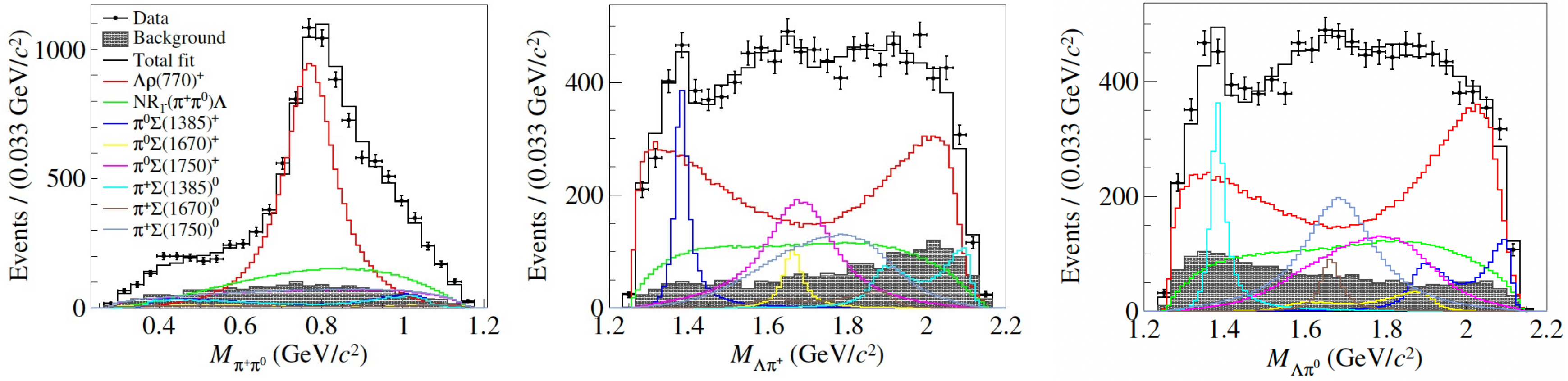
$\Lambda_c^+ \to \Lambda\rho^+$: both factorizable(a) and non-factorizable(b-d)
$\Lambda_c^+ \to \Sigma(1385)\pi$: pure non-factorizable(e)

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 $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP12 (2022) 033



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

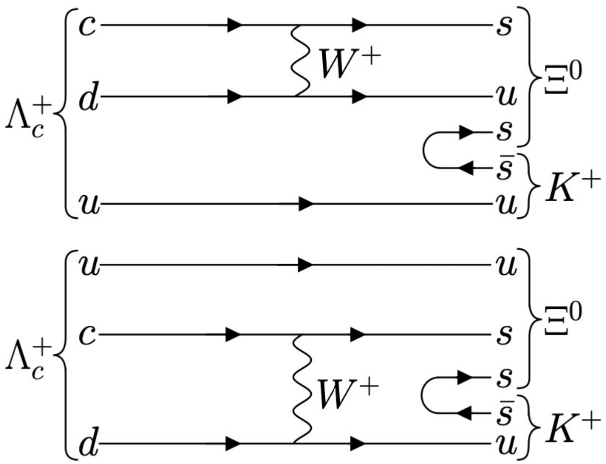
	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$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

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

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

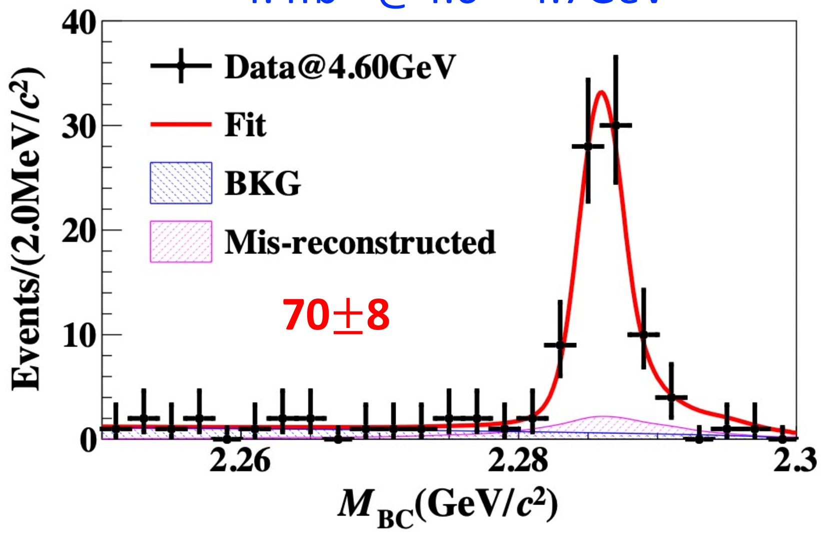
First Measurement of the Decay Asymmetry in the pure W-boson-exchange Decay $\Lambda_c^+ \to \Xi^0 K^+$

Only receives the non-factorization contribution



PRL 132, 031801 (2024)

4.4fb^{-1} @4.6 ~ 4.7GeV



$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

Two individual helicity $H_{\frac{1}{2},\frac{1}{2}}$ and $H_{\frac{1}{2},-\frac{1}{2}}$

$$\alpha_0 = \frac{\left|H_{\frac{1}{2},-\frac{1}{2}}\right|^2 - 2\left|H_{\frac{1}{2},\frac{1}{2}}\right|^2}{\left|H_{\frac{1}{2},-\frac{1}{2}}\right|^2 + 2\left|H_{\frac{1}{2},\frac{1}{2}}\right|^2}$$

Δ_0 is phase shift between them

Lee-Yang parameters
Phys. Rev. 108, 1645 (1957).

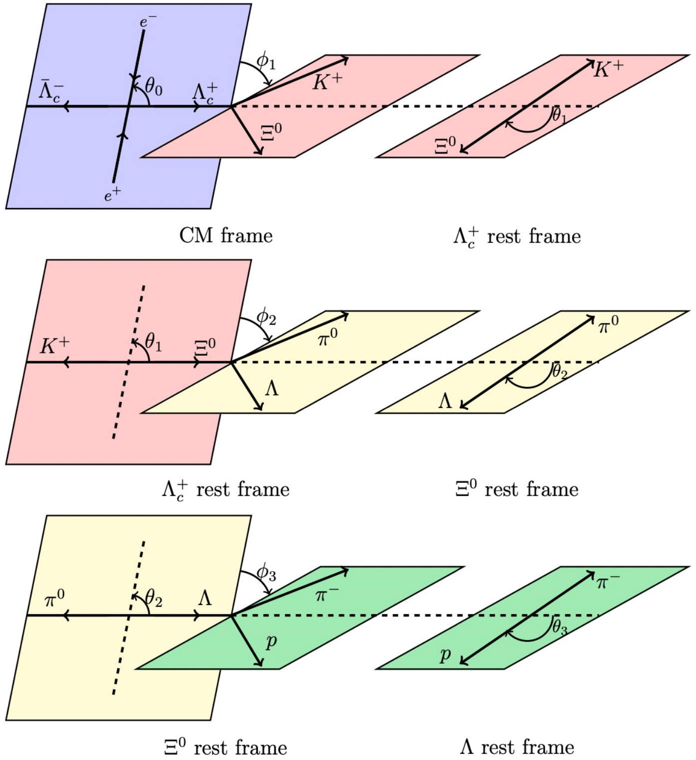
$\Lambda_c^+ \to \Xi^0 K^+$

$$\alpha^2 + \beta^2 + \gamma^2 = 1 \qquad \beta = \sqrt{1-\alpha^2}\sin\Delta$$

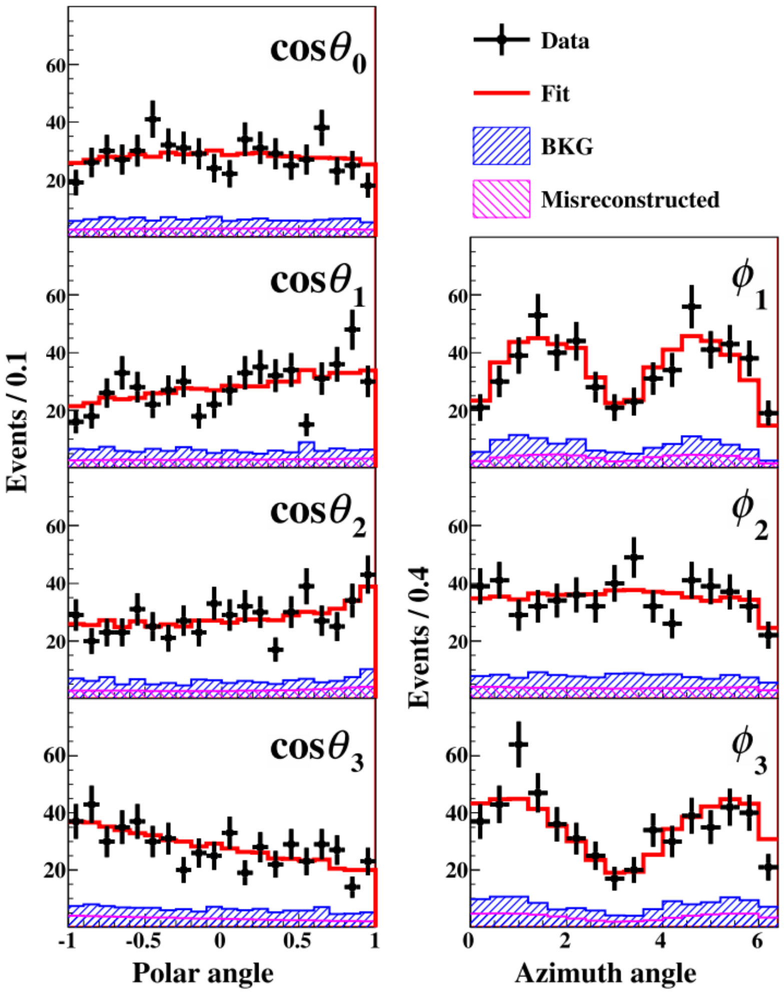
$$\alpha = \frac{2Re(S^*P)}{|S|^2 + |P|^2} \qquad \gamma = \sqrt{1-\alpha^2}\cos\Delta$$

First Measurement of the Decay Asymmetry in the pure W-boson-exchange Decay $\Lambda_c^+ \to \Xi^0 K^+$

- Fixed the parameters in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ and Ξ^0 and Λ decays
- Free parameters of $\alpha_{\Xi^0 K^+}$ and $\Delta_{\Xi^0 K^+}$
- Six data sets between 4.6 and 4.7 GeV



PRL 132, 031801 (2024)



First Measurement of the Decay Asymmetry in the pure W-boson-exchange Decay $\Lambda_c^+ \to \Xi^0 K^+$

$$\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16 \pm 0.03$$

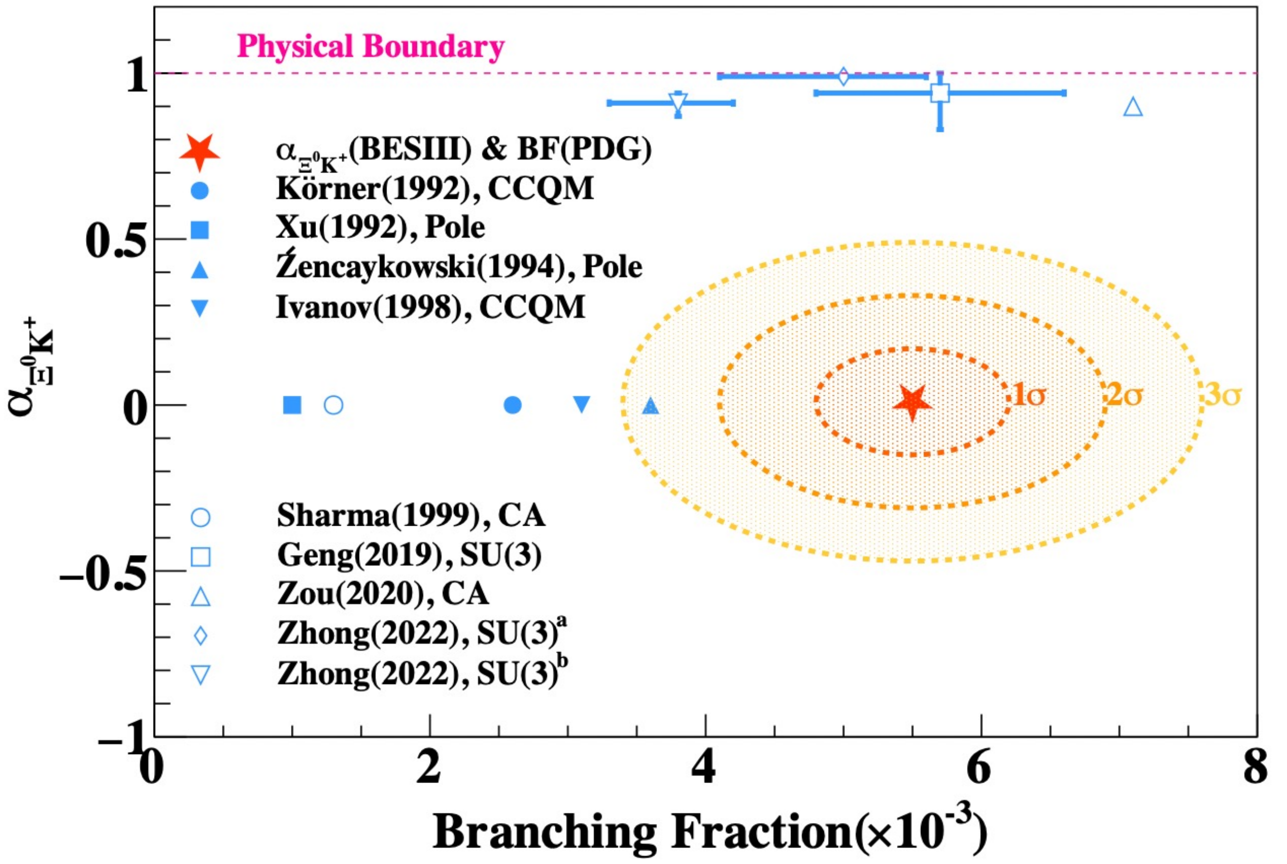
$$\Delta_{\Xi^0 K^+} = 3.84 \pm 0.90 \pm 0.17 \text{ rad}$$

$$\delta_p - \delta_s = -1.55 \pm 0.25 \pm 0.05 \text{ rad}$$

$$\text{or } 1.59 \pm 0.25 \pm 0.05 \text{ rad}$$

- **Our measurement of $\alpha_{\Xi^0 K^+}$ is in good agreement with zero, which is consistent with the theoretical predictions from the 1990s.**
- **Cos($\delta_p - \delta_s$) measured in this Letter is close to zero, an effect that had not been anticipated in previous literature.**
- **This measurement resolves the long- standing puzzle and deepens our understanding of the strong dynamics in the charmed baryon sector.**

PRL 132, 031801 (2024)



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

PRL 128, 142001 (2022)

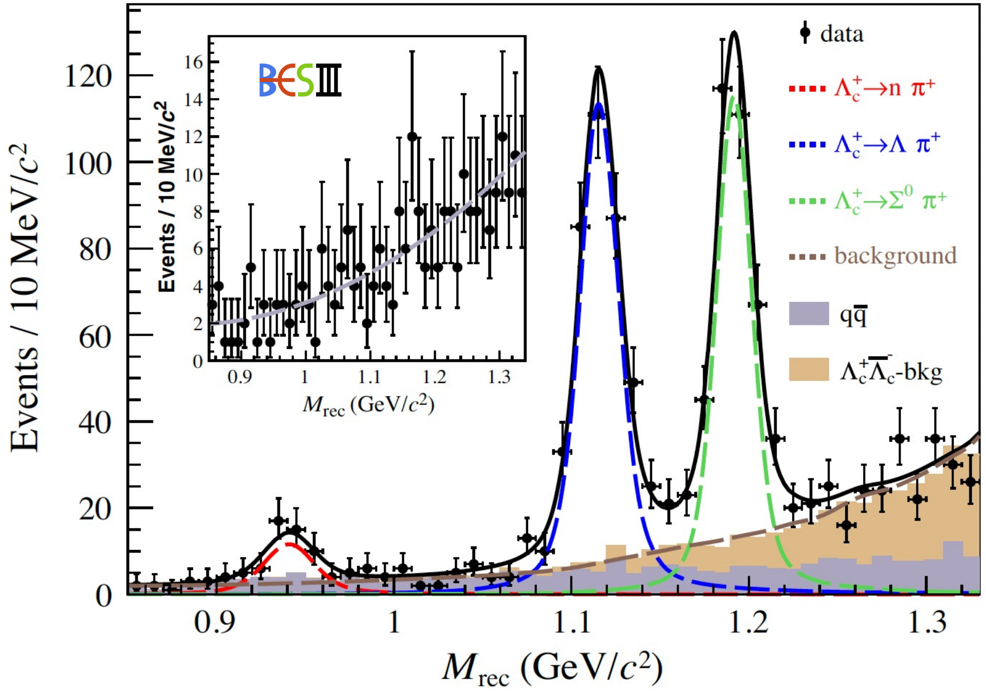
$\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2 \pm 0.4)\times10^{-4}$

First measurement

$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) = (1.31 \pm 0.08 \pm 0.05)\times10^{-2}$

$\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+) = (1.22 \pm 0.08 \pm 0.07)\times10^{-2}$

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



Use recoil mass to access neutron

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

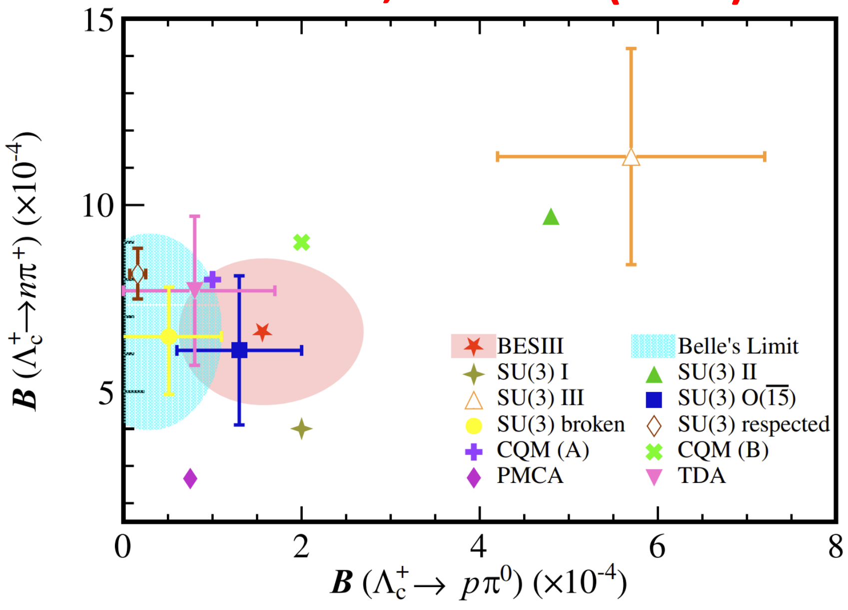
Evidence of the singly Cabibbo suppressed decay $\Lambda_c^+ \to p\pi^0$

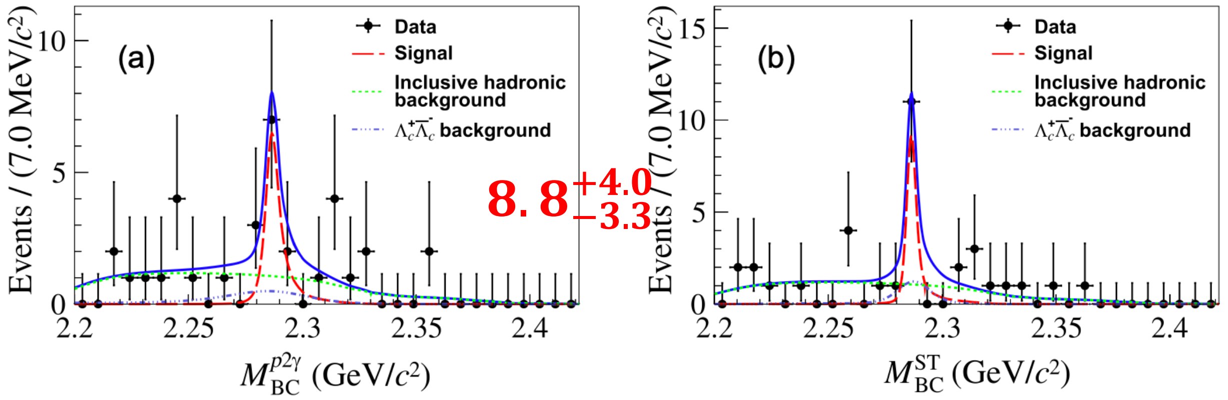
- ➢ $\mathcal{B}(\Lambda_c^+ \to p\pi^0) = (1.56^{+0.72}_{-0.58} \pm 0.20)\times 10^{-4}$

  First evidence, statistical significance 3.7σ
- Result distinctly exceeds the upper limit measured by Belle ($< 8.0\times 10^{-5}$)
- ➢ $\mathcal{B}(\Lambda_c^+ \to n\pi^+)/\mathcal{B}(\Lambda_c^+ \to p\pi^0) = 3.2^{+2.2}_{-1.2}$

- Consistent with majority of phenomenological predictions
- Indicates that the nonfactorizable contributions play an essential role in these two decays
- The interference between the factorizable contributions and nonfactorizable contributions should not be significant

PRD 109, L091101 (2024)





$8.8^{+4.0}_{-3.3}$

Released Results

Cabibbo favored (hadronic)	
$\Lambda_c^+ \to \Xi^0 K^+$	PRL 132, 031801 (2024)
$\Lambda_c^+ \to n K_S \pi^+ \pi^0$	PRD 109, 053005 (2024)
$\Lambda_c^+ \to \Lambda \pi^+ \pi^0$	JHEP 12 (2022) 033

Cabibbo suppressed (hadronic)	
$\Lambda_c^+ \to n \pi^+$	PRL 128, 142001 (2022)
$\Lambda_c^+ \to p\eta, p\omega$	JHEP 11 (2023) 137
$\Lambda_c^+ \to p\eta'$	PRD 106, 072002 (2022)
$\Lambda_c^+ \to p\pi^0$	PRD 109, L091101 (2024)
$\Lambda_c^+ \to \Lambda K^+$	PRD 106, L111101 (2022)
$\Lambda_c^+ \to \Sigma^0 K^+, \Sigma^+ K_S$	PRD 106, 052003 (2022)
$\Lambda_c^+ \to \Sigma^- K^+ \pi^+$	PRD 109, L071103 (2024)
$\Lambda_c^+ \to n K^+ \pi^0$ (DCS)	PRD 109, 052001 (2024)
$\Lambda_c^+ \to n K_S K^+, n K_S \pi^+$	arXiv: 2311.17131
$\Lambda_c^+ \to \Lambda K^+ \pi^0$, $\Lambda K^+ \pi^+ \pi^-$	PRD 109, 032003 (2024)

Semileptonic	
$\Lambda_c^+ \to \Lambda e^+ \nu_e$	PRL 129, 231803 (2022)
$\Lambda_c^+ \to \Lambda \mu^+ \nu_e$	PRD 108, 031105 (2023)
$\Lambda_c^+ \to p K^- e^+ \nu_e$	PRD 106, 112010 (2022)
$\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ $\Lambda_c^+ \to p K_S e^+ \nu_e$	PLB 843 (2023) 137993

Others	
$e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$	PRL 131, 191901 (2023)
$\Lambda_c^+ \to e^+ + X$	PRD 107, 052005 (2023)
$\bar{\Lambda}_c^- \to \bar{n} + X$	PRD 108, L031101 (2023)
$\Lambda_c^+ \to \Sigma^+ + \gamma$	PRD 107, 052002 (2023)
$\Lambda_c^+ \to p + \gamma'$	PRD 106, 072008 (2022)
$e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^{*-}$	PRD 109, L071104 (2024)
$\Lambda_c^{*+} \to \Lambda_c^+ \pi^+ \pi^-$	PRD 109, 112007 (2024)

Outline

- BESIII dataset
- Charmed meson (D^0, D^+, D_s^+)
  - pure leptonic decays
  - semi-leptonic decays
  - hadronic decays
  - rare decays
- Charmed baryon (Λ_c^+)
  - semi-leptonic decays
  - hadronic decays
- Prospect

Prospect

20 fb^{-1} of data set at 3.773 GeV is ready

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

Leptonic Decay

	2.93 fb^{-1}	20 fb^{-1}
f_{D^+}	2.6%	1.0%
$\|V_{cd}\|$	2.5%	1.0%
LFU	19%	8%

BESIII is expected to provide unique data to improve the knowledge of $\boldsymbol{f_{D^+}}$ and $|V_{cd}|$ and test LFU in $D^+ \to l^+\nu_l$ decays.

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: $\boldsymbol{D^0 \to K(1270)^- \nu_e,\ D^+ \to \overline{K}_1(1270)^0 e^+\nu_e,\ D^+ \to \eta' \mu^+\nu_\mu,\ D^0 \to a_0(980)^- e^+\nu_e,\ D^+ \to a_0(980)^0 e^+\nu_e}$
- $|V_{cd(s)}|$ with SL $\boldsymbol{D^{0(+)}}$ decays in electron channels are expected to reach to 0.3%.

	LQCD	Expected
$f_+^K(0)$	0.4%	0.3%
$f_+^\pi(0)$	0.9%	0.7%

Prospect

$20\ fb^{-1}$ of data set at 3.773 GeV is ready

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

Quantum correlation of neutral charmed meson pairs

Measuring CP fractions of self-conjugated decays of charmed mesons.

Measuring strong phase of charmed mesons.

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.

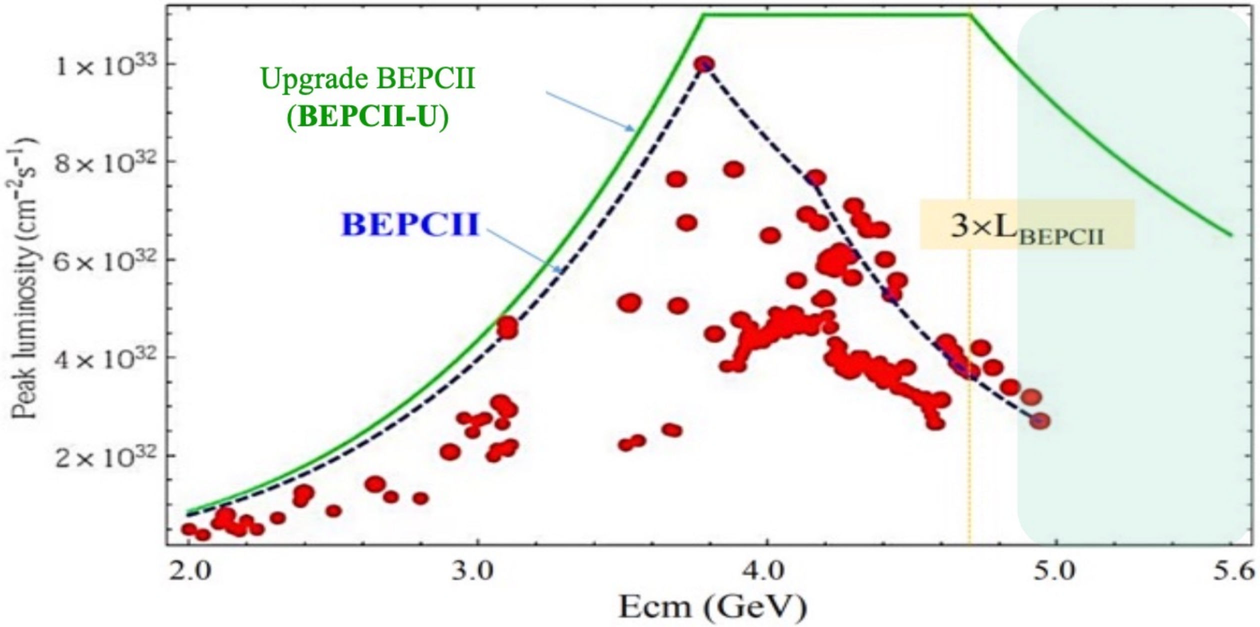
Quantum number violation processes $e^+e^+, \mu^-\mu^-$ etc.

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

Prospect

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

BEPCII upgrade (2024 –2028)： Highest beam energy: 2.8 GeV



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