Recent results of (semi)leptonic decays of charm hadrons at BESIII

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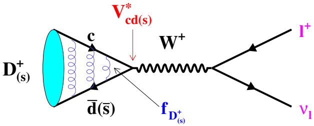
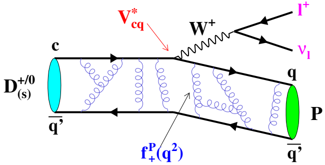
Outline

1. Main goal
2. BESIII experiment
3. Leptonic decays
   - $D^+ \to \mu^+\nu_\mu$
   - $D^+ \to \tau^+\nu_\tau$
4. Semileptonic decays
   - $D \to \bar{K}\ell^+\nu_\ell$
   - $D^+ \to \eta'\ell^+\nu_\ell$
   - $\Lambda_c^+ \to ne^+\nu_e$
5. Comparison of $|V_{cs}|$ and $|V_{cd}|$
6. Comparison of decay constant f_{D^+} and FFs $f_+(0)$
7. Other highlight works
8. Summary and prospect

Main goal

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



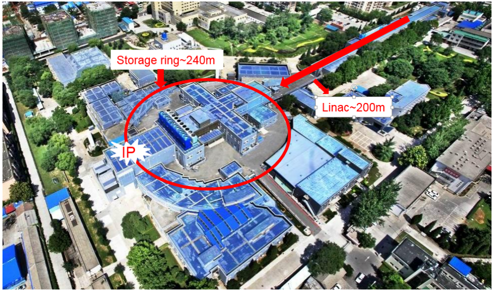


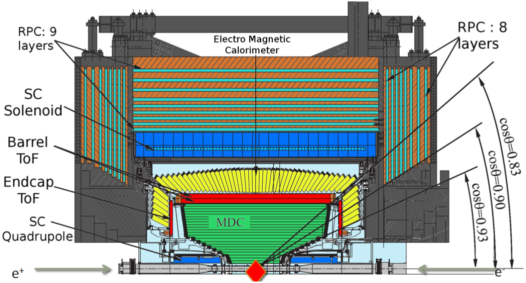
$$\Gamma = \frac{G_F^2}{8\pi}|V_{cq}|^2|f_{D^+_{(s)}}|^2 m_\ell^2 m_{D^+_{(s)}}(1 - m_\ell^2/m^2_{D^+_{(s)}})^2 \qquad \frac{d\Gamma}{dq^2} = X\frac{G_F^2|\vec{p}_P|^3}{24\pi^3}|V_{cq}|^2|f_+(q^2)|^2$$

- Uncertainties of $V_{\rm CKM}\Rightarrow$ mainly contributed by $|V_{cs}|$ $(\sigma = 0.6\%)$ and $|V_{cd}|$ $(\sigma = 1.8\%)$
- Latest LQCD: $f_{D_s^+} = 249.9(05)$ MeV $(\sigma = 0.2\%)$; $f_{D^+} = 212.1(07)$ MeV $(\sigma = 0.3\%)$;

  $f_+^{D\to\bar{K}}(0) = 0.7452(31)$ $(\sigma = 0.4\%)$; $f_+^{D\to\pi}(0) = 0.6300(51)$ $(\sigma = 0.8\%)$
- Decay constant $f_{D^+_{(s)}}$ and FF $f_+(0)$ measurements$\Rightarrow$Calibrate LQCD calculations
- $|V_{cq}|$ measurement $\Rightarrow$Test CKM matrix unitarity
- BF ratios$\Rightarrow$Test lepton flavor universality (LFU)

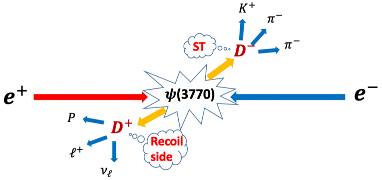
BESIII experiment





- $\sqrt{s} = (1.85 - 4.95)$ GeV
- Peak luminosity: $1.1{\times}10^{33}$ cm^{-2}s^{-1} @3.773 GeV
- MDC: $\sigma_P/P = 0.5\%$ @ 1 GeV; $\sigma_{dE/dx} = 6\%$
- TOF: $\sigma_T = 68(110)$ ps for barrel (endcap); endcap upgraded in 2015 $\sigma_T = 60$ ps
- EMC: σ_E/E =2.5%(5%) for barrel (endcap)

BESIII dataset and double-tag method

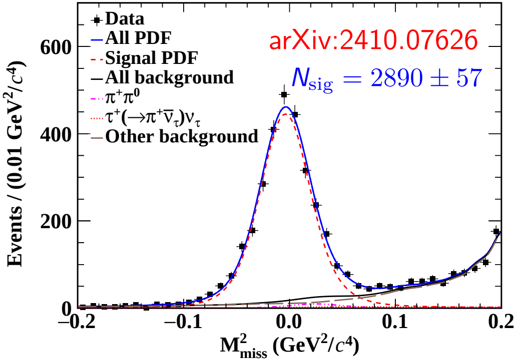


- e^+e^- annihilations data near threshold
  $\Rightarrow$Double-tag method& Clean environment
- Undetectable neutrinos$\Rightarrow$extract the (semi-)leptonic signals
  $U_{\rm miss} = E_{\rm miss} - |\vec{p}_{\rm miss}|$, $M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2$
- Branching fraction with double-tag method: $\mathcal{B} = \frac{N_{\rm DT}}{N_{\rm ST}\epsilon_{\rm DT}/\epsilon_{\rm ST}}$
  $\Rightarrow$Systematic uncertainties on the ST mostly canceled

Data sample	$E_{\rm cm}$ (GeV)	$\mathcal{L}_{\rm int}$ (fb^{-1})	Single tag yields ($\times 10^6$)
$e^+e^- \to \psi(3770) \to D\bar{D}$	3.773	20.3	$\bar{D}^0$ ~16.9; D^- ~11.0
$e^+e^- \to D_s^{\pm}D_s^{*\mp}$	4.128-4.226	7.33	D_s^- ~0.8
$e^+e^- \to D_s^{*+}D_s^{*-}$	4.237-4.669	10.64	D_s^- ~0.12
$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$	4.600-4.669	4.5	$\bar{\Lambda}_c^-$ ~0.12

Precision measurement of the branching fraction of $D^+ \to \mu^+\nu_\mu$

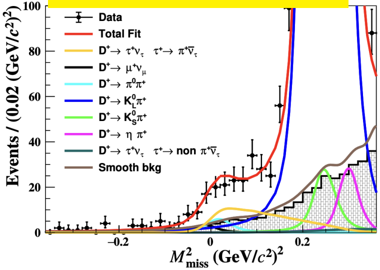
Reference	$\mathcal{L}$ (fb^{-1})	BF($\times 10^{-4}$)	f_{D^+} (MeV)	$\lvert V_{cd}\rvert$	Precision (%)
CLEO, PRD78,052003	0.818	3.82(32)(09)	207.1(87)(24)(08)	0.2195(92)(26)(09)	4.4
BESIII, PRD89,051104	2.93	3.71(19)(06)	204.1(52)(17)(08)	0.2164(55)(17)(09)	2.7
BESIII, arXiv:2410.07626	20.3	3.981(79)(40)	211.5(21)(11)(08)	0.2242(23)(11)(09)	1.2 ★



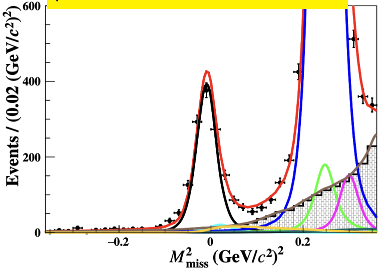
Measurement of the branching fraction of $D^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$

Reference	$\mathcal{L}$ (fb^{-1})	BF($\times 10^{-3}$)	f_{D^+} (MeV)	$\lvert V_{cd}\rvert$	Precision (%)
PRL123,211802	2.93	1.20(24)(12)	225(23)(11)(01)	0.238(24)(12)(01)	11
JHEP01(2025)89	7.93	0.99(11)(05)	204(11)(05)(01)	0.216(12)(06)(01)	6.1 ★

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



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

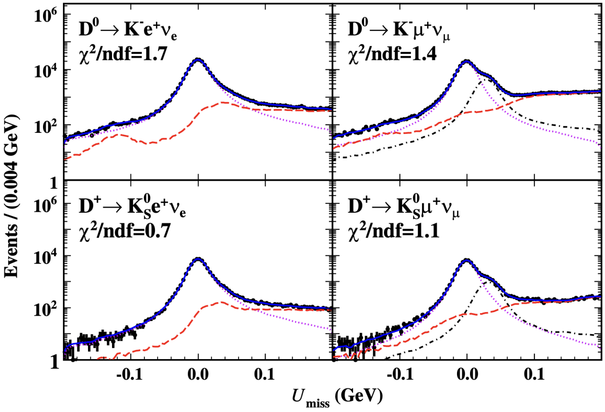


- LFU test:

$$\mathcal{R}_{\tau/\mu} = \Gamma_{D^+\to\tau^+\nu_\tau}/\Gamma_{D^+\to\mu^+\nu_\mu} = 2.49 \pm 0.31,\text{ consistent with } \mathcal{R}^{\mathrm{SM}}_{\tau/\mu} = \frac{m_\tau^2(1-m_\tau^2/m_{D^+}^2)^2}{m_\mu^2(1-m_\mu^2/m_{D^+}^2)^2} = 2.69$$

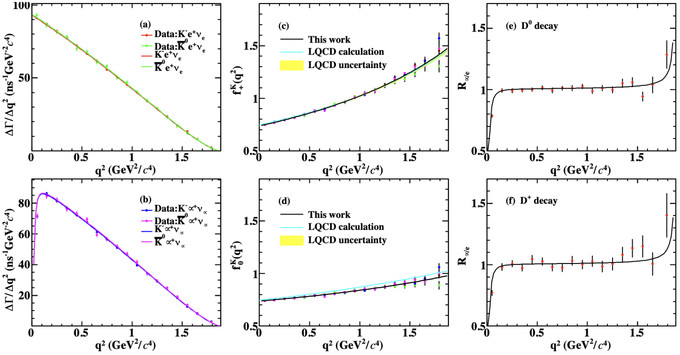
Improved measurements of $D^0 \to K^-\ell^+\nu_\ell$ and $D^+ \to \bar{K}^0\ell^+\nu_\ell$

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



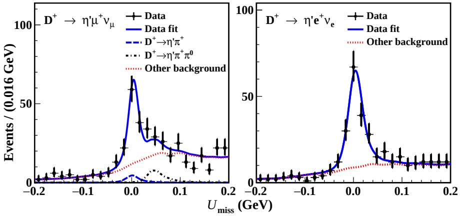
- $\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.521 \pm 0.009 \pm 0.016)\%$
  $\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu) = (3.419 \pm 0.011 \pm 0.016)\%$
  $\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.864 \pm 0.039 \pm 0.082)\%$
  $\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu) = (8.665 \pm 0.046 \pm 0.084)\%$
- LFU test (SM: 0.975±0.001) ∼consistent
  $$\frac{\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \to K^- e^+ \nu_e)} = 0.971 \pm 0.004 \pm 0.006$$
  $$\frac{\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)} = 0.978 \pm 0.007 \pm 0.013$$
- Isospin test ∼consistent
  $$\frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)} = 1.000 \pm 0.007 \pm 0.012$$
  $$\frac{\Gamma(D^0 \to K^- \mu^+ \nu_\mu)}{\Gamma(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)} = 0.993 \pm 0.008 \pm 0.012$$

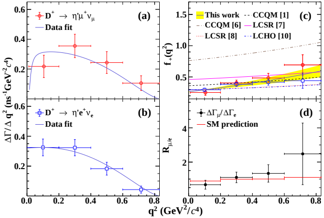
Improved measurements of $D^0 \to K^-\ell^+\nu_\ell$ and $D^+ \to \bar{K}^0\ell^+\nu_\ell$

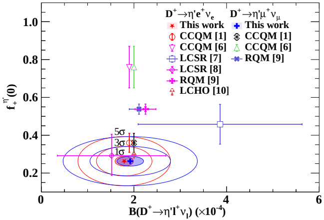


- $f_+^K(0) = 0.7366 \pm 0.0011_{\rm stat} \pm 0.0013_{\rm syst}$; $|V_{cs}| = 0.9623 \pm 0.0015_{\rm stat} \pm 0.0017_{\rm syst} \pm 0.0040_{\rm LQCD}$
- Experimental uncertainties of $f_+^K(0)$ and $|V_{cs}|$: 0.23%
- Additional uncertainty of the input $f_+^K(0)$ calculated by LQCD: 0.42%

First study of $D^+ \to \eta' \ell^+ \nu_\ell$ decay dynamics



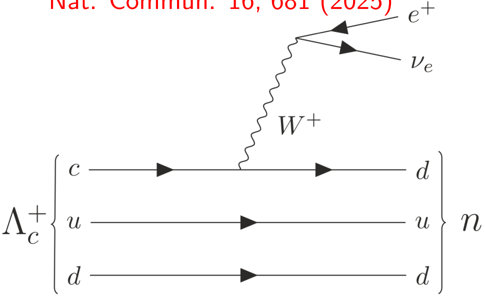


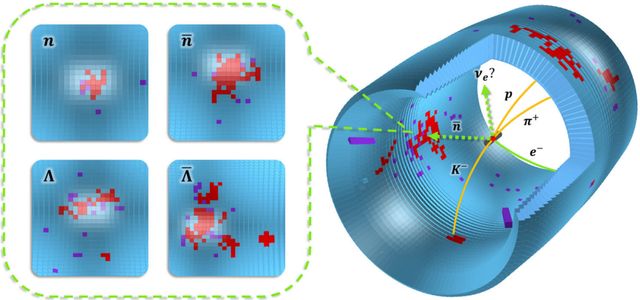


- Data: 20.3 fb^{-1}@3.773 GeV [PRL134(2025)111801]
- First observation of $D^+ \to \eta' \mu^+ \nu_\mu$ with significance of 8.6σ
  $\mathcal{B}(D^+ \to \eta' \mu^+ \nu_\mu) = (1.92 \pm 0.28 \pm 0.08) \times 10^{-4}$; $\mathcal{B}(D^+ \to \eta' e^+ \nu_e) = (1.79 \pm 0.19 \pm 0.07) \times 10^{-4}$
- First extraction of the FF of $D^+ \to \eta' \ell^+ \nu_\ell$: $f_+^{\eta'}(0) = 0.263 \pm 0.025 \pm 0.006$
- LFU test: $\mathcal{R}^{\eta'}_{\mu/e} = 1.07 \pm 0.19 \pm 0.03$
- $\eta - \eta'$ mixing angle: $\phi_P = (39.8 \pm 0.8 \pm 0.3)^\circ$ $\left(\cot^4 \phi_{\rm P} = \frac{\Gamma_{D_s^+ \to \eta' \ell^+ \nu_\ell} / \Gamma_{D_s^+ \to \eta \ell^+ \nu_\ell}}{\Gamma_{D^+ \to \eta' \ell^+ \nu_\ell} / \Gamma_{D^+ \to \eta \ell^+ \nu_\ell}}\right)$

First observation of $\Lambda_c^+ \to n e^+ \nu_e$ with a graph neural network

Nat. Commun. 16, 681 (2025)

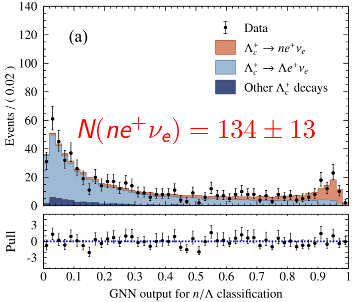


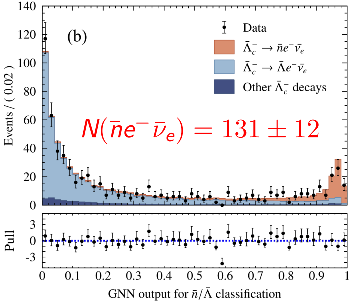


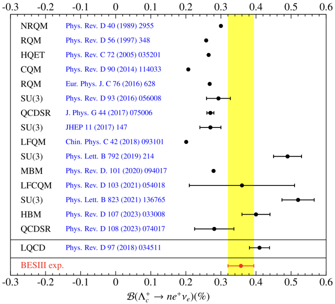
- Data: 4.5 fb^{-1}@4.6-4.7 GeV
- Significant challenges: two missing particles, neutron and neutrino;
- Dominant background: $\Lambda_c^+ \to \Lambda e^+ \nu_e$, $\Lambda \to n\pi^0$
- Machine learning of graph neural network $\Rightarrow$ discriminate the energy deposition patterns of neutrons from those of Λ in the Electromagnetic Calorimeter of BESIII detector

First observation of $\Lambda_c^+ \to n e^+ \nu_e$ with a graph neural network

Significance: $> 10\sigma$



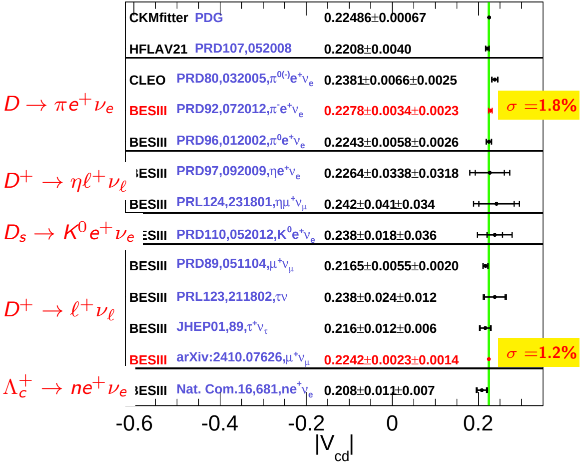


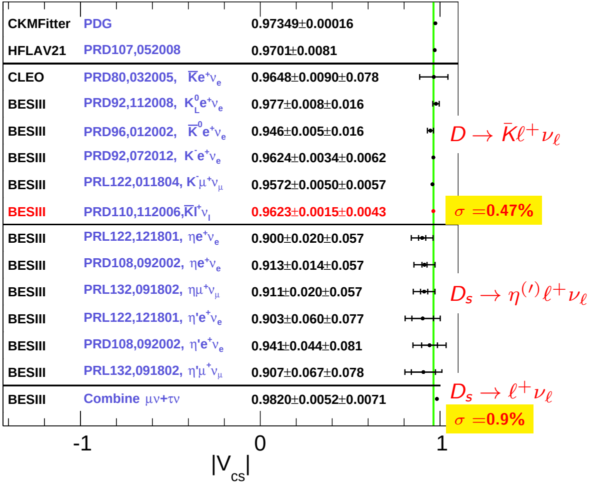


- $\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = (3.57 \pm 0.34 \pm 0.14) \times 10^{-3}$
- $\Gamma(\Lambda_c^+ \to n e^+ \nu_e) = |V_{cd}|^2 (0.405 \pm 0.016 \pm 0.020)\ \text{ps}^{-1}$ [PRD97(2018)034511]

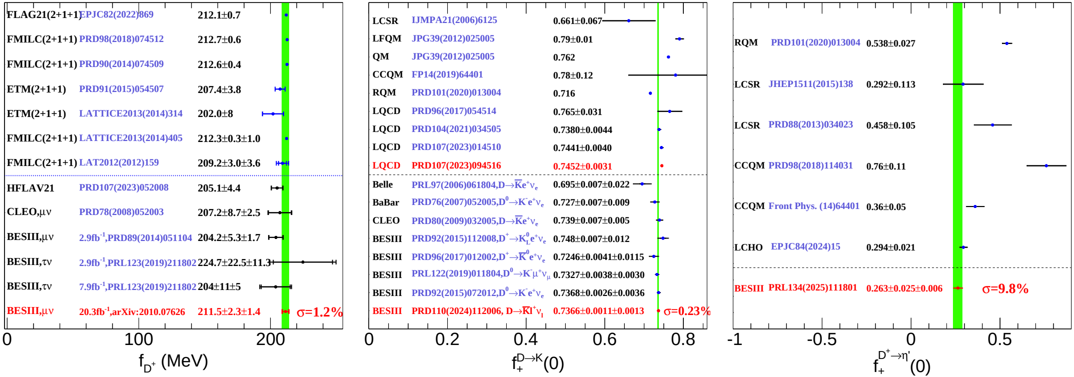
$\Longrightarrow |V_{cd}| = 0.208 \pm 0.011 \pm 0.007 \pm 0.001$ First determination from charmed baryon decays

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





Comparison of decay constant f_{D^+} and FFs $f_+(0)$



- Precisions of measured f_{D^+}, $f_+^{D\to\bar{K}}(0)$, and $f_+^{D^+\to\eta'}(0)$ are 1.2%, 0.23%, and 9.8%, respectively
- Measured FF $f_+^{D\to\bar{K}}(0)$ is consistent with the LQCD calculations within 2.5σ

Other highlight works

Channel	$\mathcal{L}_{\rm int}$ (fb^{-1}) / $E_{\rm cm}$ (GeV)	Reference
$D^+ \to e^+\nu_e$	20.3 / 3.773	arXiv:2501.04760
$D_s^+ \to \ell^+\nu_\ell, \ell = \mu$ or τ	10.64 / 4.237-4.699	PRD110(2024)052002
$D^{*+} \to \ell^+\nu_\ell, \ell = e$ or μ	6.32 / 4.178-4.226	PRD110(2024)012003
$D^0 \to K^-\pi^0\mu^+\nu_\mu$	7.93 / 3.773	PRL134(2025)011803
$D^0 \to \bar{K}^0\pi^-e^+\nu_e$	7.93 / 3.773	arXiv:2412.10803
$D^+ \to K_S^0\pi^0e^+\nu_e$	7.93 / 3.773	JHEP10(2024)199
$D^0 \to \pi^-\pi^0e^+\nu_e$	7.93 / 3.773	PRD110(2024)112018
$D^{0(+)} \to b_1(1235)^{-(0)}e^+\nu_e$	7.93 / 3.773	arXiv:2407.20551
$D^{0(+)} \to \bar{K}_1(1270)^{-(0)}e^+\nu_e$	20.3 / 3.773	arXiv:2503.02196
$D^{0(+)} \to \bar{K}_1(1270)^{-(0)}\mu^+\nu_\mu$	7.93 / 3.773	arXiv:2502.03828
$D^0 \to a_0(980)^-\vert_{\eta\pi^-}e^+\nu_e$	7.93 / 3.773	arXiv:2411.07730
$D \to P\eta e^+\nu_e, P = \eta, \bar{K}$	7.93 / 3.773	PRD110(2024)112001
$D_s^+ \to K^0e^+\nu_e$	7.33 / 4.128-4.226	PRD110(2024)052012
$D_s^+ \to Pe^+\nu_e, P = \eta^{(\prime)}, K^0$	10.64 / 4.237-4.699	PRD110(2024)072017

Summary

- Purely and semileptonic decays of charm hadrons are important for determining CKM matrix elements, calibrating LQCD, testing LFU, *et al.*;
- Precisions of $|V_{cs}|$ and $|V_{cd}|$ have been reduced to 0.5% and 1.2%, respectively;
- Precisions of f_{D^+} and $f_+^{D\to\bar{K}}(0)$ have been reduced to 1.2% and 0.23%, respectively;
- No evidence of LFU violation is found within precisions of 0.74% for $\mathcal{R}(\mu/e)$ via $D\to\bar{K}\ell^+\nu_\ell$ and 12% for $\mathcal{R}(\tau/\mu)$ via $D^+\to\ell^+\nu_\ell$;
- Isospin conservation is verified within precision of 1.5% via $D\to\bar{K}\ell^+\nu_\ell$;
- Machine learning has demonstrated the power in experimental particle physics, offering the possible in searching for the rare decays of charm hadrons in future.

Prospect

- 20.3 fb^{-1}data @3.773 GeV is ready at Jul. 2024, more precision measurements and searching for rare semileptonic decays will be presented;
- Additional 3 fb^{-1}data @4.178 GeV in future [CPC44(2020)040001] will further improve the precisions in D_s sector.

Thank you