BESIII 实验上粲介子含轻衰变研究进展

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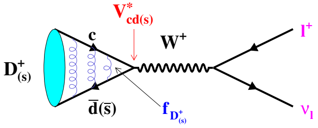
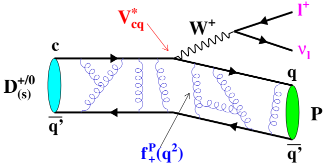
第八届全国重味物理与量子色动力学研讨会
重庆大学
2026 年 4 月 24 日至 28 日

Outline

Introduction

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

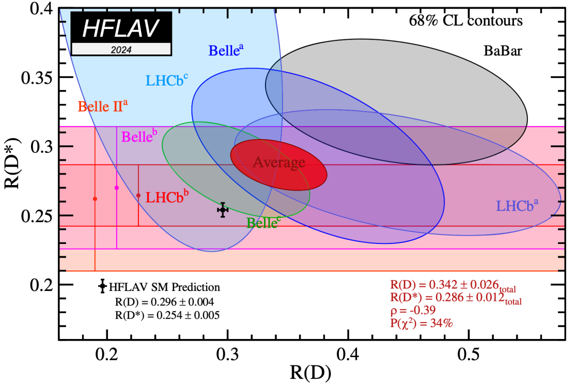




$$V^\dagger V = 1 \qquad \Gamma = \frac{G_F^2}{8\pi}|V_{cq}|^2|f_{D^+_{(s)}}|^2 m_\ell^2 m_{D^+_{(s)}}(1-m_\ell^2/m^2_{D^+_{(s)}})^2 \qquad \frac{d\Gamma}{dq^2} = X\frac{G_F^2|\vec{p}_P|^3}{24\pi^3}|V_{cq}|^2|f_+(q^2)|^2$$

- 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

Introduction



- Evidence (3.14σ) of LFU violation in $B \to D^{(*)}\ell^+\nu_\ell$

- Precision test of LFU in charm sector
- Leptonic decay

$$\mathcal{R}^{\rm SM}_{D^+:\tau/\mu} = \frac{m_\tau^2(1-m_\tau^2/m_{D^+}^2)^2}{m_\mu^2(1-m_\mu^2/m_{D^+}^2)^2} = 2.66 \pm 0.01$$

$$\mathcal{R}^{\rm SM}_{D_s^+:\tau/\mu} = \frac{m_\tau^2(1-m_\tau^2/m_{D_s^+}^2)^2}{m_\mu^2(1-m_\mu^2/m_{D_s^+}^2)^2} = 9.75 \pm 0.01$$

- Semileptonic decay [PRD107(2023)094516]

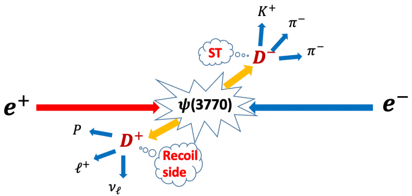
$$\mathcal{R}^{\rm SM}_{D\to\bar{K}:\mu/e} = 0.97606(16)^{\rm QED}[500]^{\rm QED}$$

$$\mathcal{R}^{\rm SM}_{D\to\pi:\mu/e} = 0.98671(17)^{\rm QED}[500]^{\rm QED}$$

$$\mathcal{R}^{\rm SM}_{D_s\to K^0:\mu/e} = 0.98099(10)^{\rm QCD}[500]^{\rm QED}$$

- Other $D \to P\ell^+\nu_\ell$: $\mathcal{R}_{\mu/e} \in (0.95 - 0.99)$ based on different quark models

BESIII dataset and double-tag method



- e^+e^- annihilations data near threshold

  ⇒Double-tag method& Clean environment
- Undetectable neutrinos⇒extract the leptonic signals

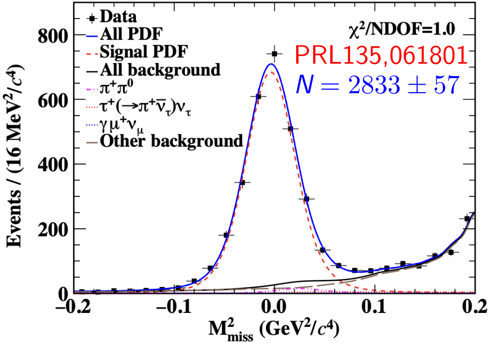
  $U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$, $M^2_{\text{miss}} = E^2_{\text{miss}} - |\vec{p}_{\text{miss}}|^2$
- BF with double-tag method: $\mathcal{B} = \frac{N_{\text{DT}}}{N_{\text{ST}}\epsilon_{\text{DT}}/\epsilon_{\text{ST}}}$

  ⇒Systematic uncertainties on the ST mostly canceled

Data sample	E_{cm} (GeV)	$\mathcal{L}_{\text{int}}$ (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

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, PRL135,061801	20.3	4.034(80)(40)	213.5(21)(11)(08)	0.2265(23)(11)(09)	1.2 ★

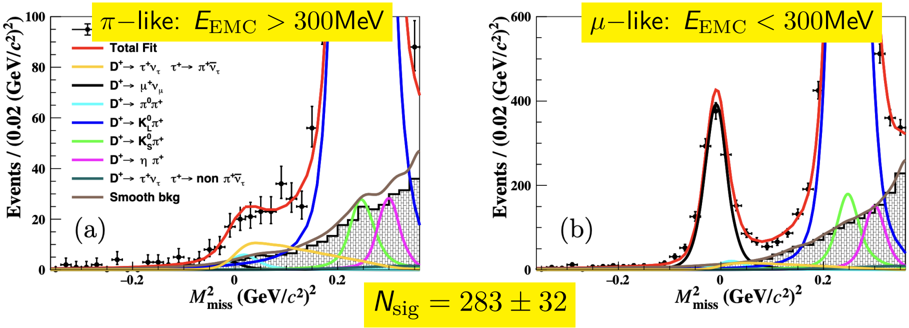


$$\Gamma_{D^+\to\ell^+\nu_\ell} = \Gamma^{(0)}_{D^+\to\ell^+\nu_\ell}\left[1+\frac{\alpha}{\pi}C_p\right]$$
$$= \frac{G_F^2 f_{D^+}^2 m_{D^+}^3}{8\pi}\lvert V_{cd}\rvert^2 \mu_\ell^2\left(1-\mu_\ell^2\right)^2\left[1+\frac{\alpha}{\pi}C_p\right]$$

- the radiative correction term [1]: $\left[1+\frac{\alpha}{\pi}C_p\right]$
- Structure-dependent bremsstrahlung [2,3] $\Longrightarrow$ Subtracted in the fit
- Short-distance (+1.8%)[4,5] and Long-distance (-2.5%) [6]electroweak correction

1 D. Silverman and H. Yao, Phys. Rev. D 38, 214 (1988).
2 G. Burdman, J.T. Goldman, and D. Wyler, Phys. Rev. D 51, 111 (1995).
3 A. Bazavov *et al.*, Phys. Rev. D 98, 074512 (2018).
4 J. C. Yang and M.Z. Yang, Nucl. Phys. B914, 301 (2017).
5 A. Sirlin, Nucl. Phys. B196, 83 (1982).
6 T. Kinoshita, Phys. Rev. Lett. 2, 477 (1959).

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

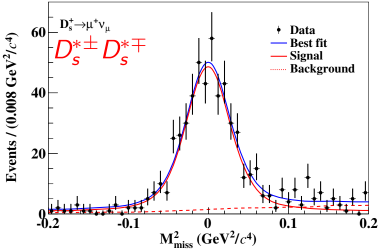


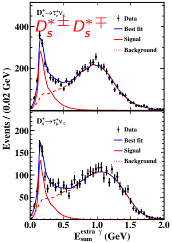
- 7.93 fb^{-1}@3.773 GeV [JHEP01(2025)89]
- Precision of BF is improved by 1.8×: $\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (9.9 \pm 1.1 \pm 0.5) \times 10^{-4}$
- $f_{D^+} = (204.6 \pm 11.4 \pm 5.2)$MeV $(\sim 5.9\%)$ $|V_{cd}| = 0.217 \pm 0.012 \pm 0.006$ $(\sim 6.2\%)$
- LFU test: $\mathcal{R}_{\tau/\mu} = \frac{\Gamma_{D^+\to\tau^+\nu_\tau}}{\Gamma_{D^+\to\mu^+\nu_\mu}} = 2.45 \pm 0.31$, consistent with $\mathcal{R}^{\rm SM}_{\tau/\mu} = 2.66 \pm 0.01$

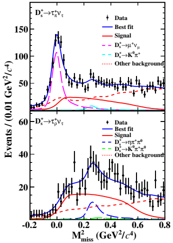
Measurement of $D_s^+ \to \ell^+\nu_\ell$

PRD110(2024)052002

$$\tau^+ \to \begin{cases} e^+\nu_e\bar{\nu}_\tau \\ \mu^+\nu_\mu\bar{\nu}_\tau \\ \pi^+\bar{\nu}_\tau \\ \pi^+\pi^0\bar{\nu}_\tau \end{cases}$$

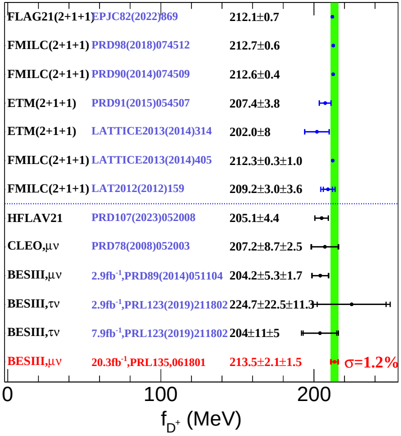


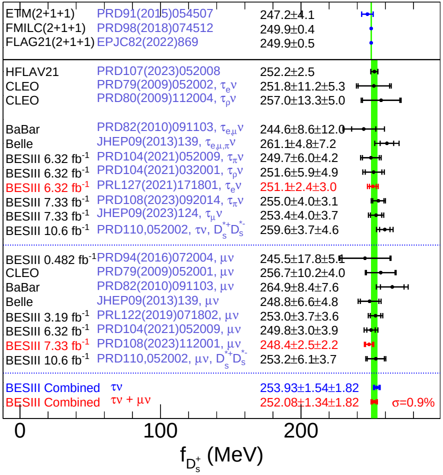




Reference	Data set (fb^{-1})	$\mathcal{B}$(%)	$f_{D_s^+}$	$\lvert V_{cs}\rvert$	Stat
			$D_s^+ \to \mu^+\nu_\mu$		
PRD 108, 112001(2023)	7.33 $D_s^{\pm}D_s^{*\mp}$	$0.5294 \pm 0.0108 \pm 0.0085$	$248.4 \pm 2.5 \pm 2.2(\sigma = 1.4\%)$	$0.968 \pm 0.010 \pm 0.009(\sigma = 1.4\%)$	
PRD 110, 052002 (2024)	10.64 $D_s^{*\pm}D_s^{*\mp}$	$0.547 \pm 0.026 \pm 0.016$	$246.5 \pm 5.9 \pm 3.6(\sigma = 2.8\%)$	$0.986 \pm 0.023 \pm 0.014(\sigma = 2.8\%)$	
			$D_s^+ \to \tau^+\nu_\tau$		
PRL 127, 171801 (2021)	6.32 $D_s^{\pm}D_s^{*\mp}$	$5.27 \pm 0.10 \pm 0.12$	$251.1 \pm 2.4 \pm 3.0(\sigma = 1.5\%)$	$0.978 \pm 0.009 \pm 0.012(\sigma = 1.5\%)$	$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$
PRD 104, 052009 (2021)	6.32 $D_s^{\pm}D_s^{*\mp}$	$5.21 \pm 0.25 \pm 0.17$	$249.7 \pm 6.0 \pm 4.2(\sigma = 2.9\%)$	$0.972 \pm 0.023 \pm 0.016(\sigma = 2.9\%)$	$\tau^+ \to \pi^+\bar{\nu}_\tau$
PRD 104, 032001 (2021)	6.32 $D_s^{\pm}D_s^{*\mp}$	$5.29 \pm 0.25 \pm 0.20$	$251.6 \pm 5.9 \pm 4.9(\sigma = 3.0\%)$	$0.980 \pm 0.023 \pm 0.019(\sigma = 3.0\%)$	Simultaneous fit at various energy points $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$
JHEP 09, 124 (2023)	7.33 $D_s^{\pm}D_s^{*\mp}$	$5.37 \pm 0.17 \pm 0.15$	$253.4 \pm 4.0 \pm 3.7(\sigma = 2.2\%)$	$0.987 \pm 0.016 \pm 0.014(\sigma = 2.2\%)$	$\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$
PRD 108, 092014 (2023)	7.33 $D_s^{\pm}D_s^{*\mp}$	$5.44 \pm 0.17 \pm 0.13$	$255.0 \pm 4.0 \pm 3.4(\sigma = 2.1\%)$	$0.993 \pm 0.015 \pm 0.013(\sigma = 2.1\%)$	$\tau^+ \to \pi^+\bar{\nu}_\tau$ with BDT
PRD 110, 052002 (2024)	10.64 $D_s^{*\pm}D_s^{*\mp}$	$5.60 \pm 0.16 \pm 0.20$	$252.7 \pm 3.6 \pm 4.5(\sigma = 2.3\%)$	$1.011 \pm 0.014 \pm 0.018(\sigma = 2.3\%)$	constrain the same BF $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau, e^+\nu_e\bar{\nu}_\tau, \pi^+\bar{\nu}_\tau, \pi^+\pi^0\bar{\nu}_\tau$

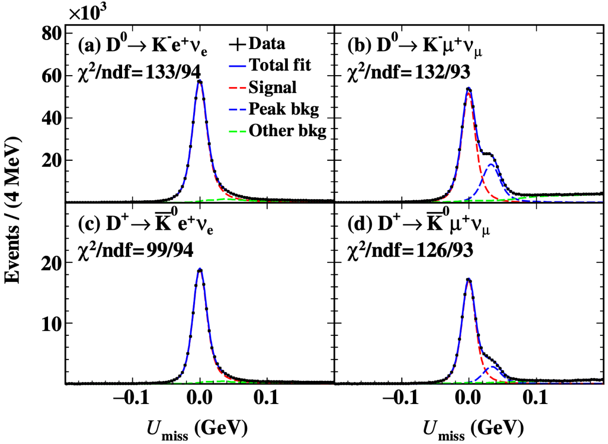
Comparison of f_{D^+} and $f_{D_s^+}$





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

arXiv:2601.21196, 2601.21185, submitted to PRL



- Data: 20.3 fb^{-1}@3.773 GeV
- **Improved measurement of BFs**

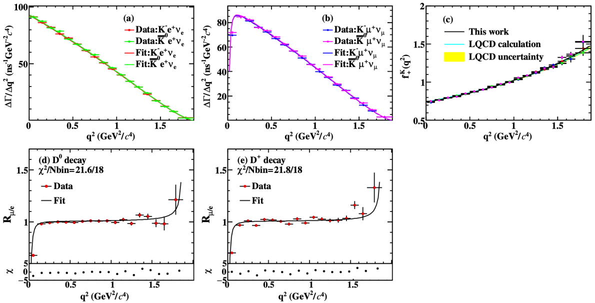
$$\mathcal{B}(D^0 \to K^- e^+\nu_e) = (3.527 \pm 0.005 \pm 0.016)\%$$
$$\mathcal{B}(D^0 \to K^- \mu^+\nu_\mu) = (3.429 \pm 0.007 \pm 0.017)\%$$
$$\mathcal{B}(D^+ \to \bar{K}^0 e^+\nu_e) = (8.918 \pm 0.025 \pm 0.050)\%$$
$$\mathcal{B}(D^+ \to \bar{K}^0 \mu^+\nu_\mu) = (8.763 \pm 0.029 \pm 0.052)\%$$

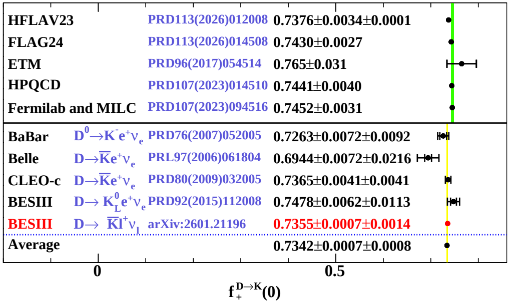
- **Most precision LFU test:** Consistent with $\mathcal{R}_{\rm SM} = 0.975 \pm 0.001$

$$\frac{\mathcal{B}(D^0 \to K^- \mu^+\nu_\mu)}{\mathcal{B}(D^0 \to K^- e^+\nu_e)} = 0.972 \pm 0.003 \pm 0.004$$
$$\frac{\mathcal{B}(D^+ \to \bar{K}^0 \mu^+\nu_\mu)}{\mathcal{B}(D^+ \to \bar{K}^0 e^+\nu_e)} = 0.982 \pm 0.004 \pm 0.002$$

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

$$\frac{d\Gamma^\ell}{dq^2} = \frac{G_F^2|V_{cs}|^2|\mathbf{q}|q^2}{96\pi^3 m_D^2}\left(\frac{q^2-m_\ell^2}{q^2}\right)^2\left[\left(\frac{2q^2+m_\ell^2}{2q^2}\right)|h_0(q^2)|^2+\frac{3m_\ell^2}{2q^2}|h_t(q^2)|^2\right],\ h_0(q^2)=\frac{2m_D|\mathbf{q}|}{\sqrt{q^2}}f_+(q^2),\ h_t(q^2)=\frac{m_D^2-m_K^2}{\sqrt{q^2}}f_0(q^2)$$





- $f_+^K(0) = 0.7355 \pm 0.0007_{\rm stat} \pm 0.0014_{\rm syst}$; $|V_{cs}| = 0.9608 \pm 0.0009_{\rm stat} \pm 0.0019_{\rm syst} \pm 0.0040_{\rm LQCD}$
- Experimental uncertainties of $f_+^K(0)$ and $|V_{cs}|$: 0.22%
- Additional uncertainty of the input $f_+^K(0)$ calculated by LQCD: 0.42%

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

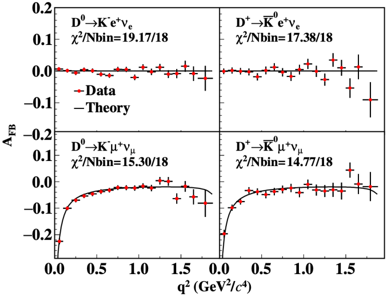
- θ_W is the angle between the lepton momentum and the direction opposite to the D-meson momentum in the $\ell\nu_\ell$ rest frame
- Forward-backward asymmetry: $A_{\rm FB}(q^2) = \frac{d\Gamma^\ell(\cos\theta_W>0)-d\Gamma^\ell(\cos\theta_W<0)}{d\Gamma^\ell(\cos\theta_W>0)+d\Gamma^\ell(\cos\theta_W<0)}$
- Theoretical expression:

$$A_{\rm FB}(q^2) = \frac{3\mathcal{N}(q^2)}{2}\frac{1}{d\Gamma^\ell/dq^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2\frac{m_\ell^2}{q^2}\,{\rm Re}\left(h_0(q^2)h_t(q^2)\right)$$

- Overall forward-backward asymmetry

$$\langle A_{\rm FB}^{K^-e^+\nu_e}\rangle = (+0.3\pm1.7\pm1.7)\times10^{-3}$$
$$\langle A_{\rm FB}^{K^-\mu^+\nu_\mu}\rangle = (-58.8\pm2.2\pm2.1)\times10^{-3}$$
$$\langle A_{\rm FB}^{\bar{K}^0e^+\nu_e}\rangle = (-0.9\pm2.9\pm1.8)\times10^{-3}$$
$$\langle A_{\rm FB}^{\bar{K}^0\mu^+\nu_\mu}\rangle = (-54.4\pm3.6\pm0.7)\times10^{-3}$$

- Agree with $\langle A_{\rm FB}^{e}\rangle = 0$ and $\langle A_{\rm FB}^{\mu}\rangle = -0.055\pm0.002$



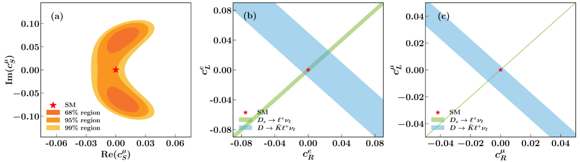
First Experimental Constraint on the Scalar Current in the $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ Transition

- Corresponding effective Lagrangian: $\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V^*_{cs} \sum_{\ell=e,\mu,\tau} \sum_i c_i^\ell \mathcal{O}_i^\ell + \mathrm{H.C.}$

  SM: $\mathcal{O}^\ell_{\rm SM} = (\bar{s}\gamma_\mu P_L c)(\bar{\nu}_\ell \gamma^\mu P_L \ell)$ with coefficient $c^\ell_{\rm SM} = 1$

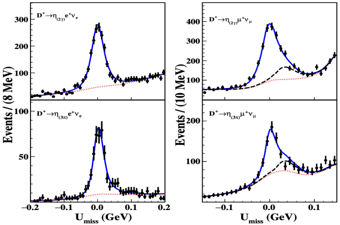
  NP: Potential right(left)-handed scalar current $\mathcal{O}^\ell_{R(L)} = (\bar{s}P_{R(L)}c)(\bar{\nu}_\ell P_R \ell)$ with complex Wilson coefficient $c^\ell_{R(L)}$
- Simultaneous fit to the measured partial decay rates and forward-backward asymmetries to constraints on the right- and left-handed components of the scalar current with input the BF of $D_s^+ \to \ell^+\nu_\ell$
- $h_t(q^2) = \left(1 + c_S^\ell \frac{q^2}{m_\ell(m_s - m_c)}\right) \frac{m_D^2 - m_K^2}{\sqrt{q^2}} f_0(q^2)$ and

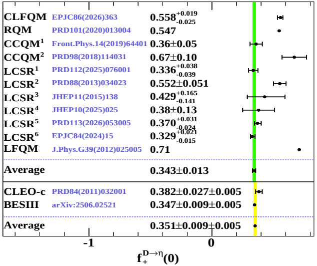
$$\mathcal{B}(D_s^+ \to \ell^+\nu_\ell) = \tau_{D_s} \frac{m_{D_s}}{8\pi} f_{D_s}^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2 G_F^2 \times |V_{cs}|^2 m_\ell^2 \left|1 - c_P^\ell \frac{m_{D_s}^2}{(m_c + m_s) m_\ell}\right|^2$$

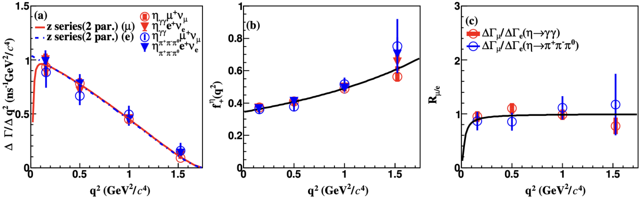


Variable	With SC	Without SC
$f_+(0)\lvert V_{cs}\rvert$	$0.7167 \pm 0.008 \pm 0.014$	$0.7160 \pm 0.007 \pm 0.014$
r_1	$-2.28 \pm 0.04 \pm 0.02$	$-2.32 \pm 0.02 \pm 0.02$
$\lvert c_S^e\rvert$	$0.02 \pm 0.02 \pm 0.02$	—
$\mathrm{Re}(c_S^\mu)$	$0.007 \pm 0.008 \pm 0.006$	—
$\mathrm{Im}(c_S^\mu)$	$\pm 0.070 \pm 0.013 \pm 0.010$	—
χ^2/ndf	$132.9/139$	$138.5/142$

$D^+ \to \eta \ell^+ \nu_\ell$





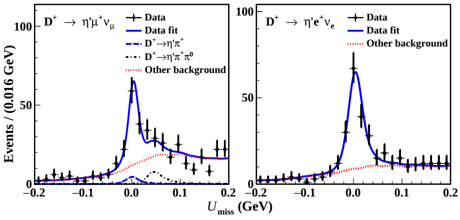


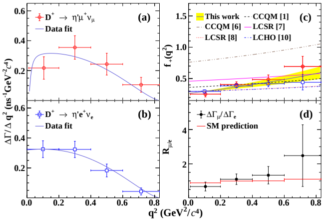
- arXiv:2506.02521, submitted to JHEP
- Data: 20.3 fb^{-1}@3.773 GeV
- **Precisions of BFs and FF are improved by $\sim 2\times$**

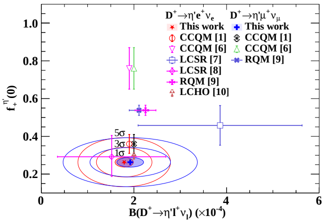
$$\mathcal{B}(D^+ \to \eta\mu^+\nu_\mu) = (9.08 \pm 0.35 \pm 0.23) \times 10^{-4}$$
$$\mathcal{B}(D^+ \to \eta e^+\nu_e) = (9.75 \pm 0.29 \pm 0.28) \times 10^{-4}$$
$$f_+^\eta(0) = 0.345 \pm 0.008 \pm 0.003$$

- **LFU test**: $\mathcal{R}^\eta_{\mu/e} = 0.93 \pm 0.05 \pm 0.02 \Longrightarrow$ Consistent with SM

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

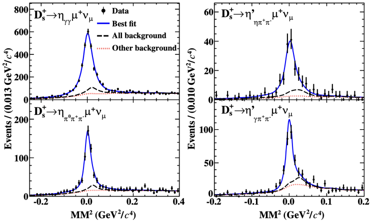


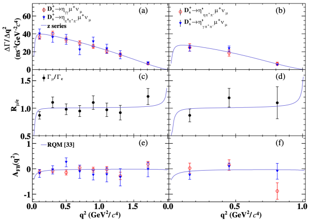


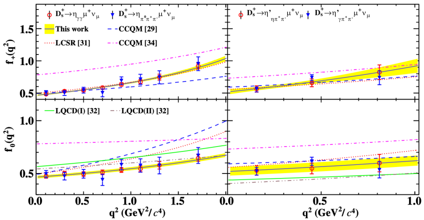


- Data: 20.3 fb^{-1}@3.773 GeV PRL134(2025)111801
- **First observation of $D^+ \to \eta' \mu^+ \nu_\mu$ with significance of 8.6σ**
  $\mathcal{B}(D^+ \to \eta' \mu^+ \nu_\mu) = (1.92 \pm 0.28 \pm 0.08) \times 10^{-4}$; $\mathcal{B}(D^+ \to \eta' e^+ \nu_e) = (1.79 \pm 0.19 \pm 0.07) \times 10^{-4}$
- **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**: $\phi_P = (39.8 \pm 0.8 \pm 0.3)^\circ$ $\left(\cot^4 \phi_P = \frac{\Gamma_{D_s^+ \to \eta' \ell^+ \nu_\ell} / \Gamma_{D_s^+ \to \eta \ell^+ \nu_\ell}}{\Gamma_{D^+ \to \eta' \ell^+ \nu_\ell} / \Gamma_{D^+ \to \eta \ell^+ \nu_\ell}}\right)$

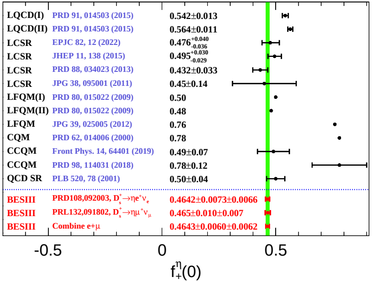
$D_s^+ \to \eta^{(\prime)}\mu^+\nu_\mu$



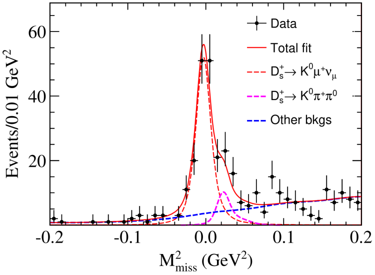


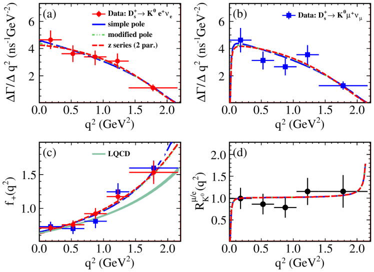


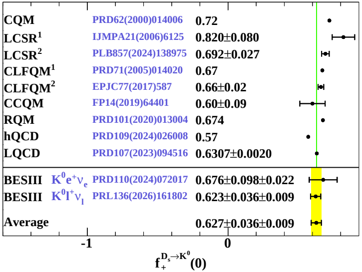
- Data: 7.33 fb^{-1}@4.128-4.226 GeV PRL132(2024)091802
- **Precision of BFs are improved by a factor of ∼6**
  $\mathcal{B}(D_s^+ \to \eta\mu^+\nu_\mu) = (2.235 \pm 0.051 \pm 0.052)\%$
  $\mathcal{B}(D_s^+ \to \eta'\mu^+\nu_\mu) = (0.801 \pm 0.055 \pm 0.028)\%$
- **First extraction of the FFs via semimuonic decays**
  $f_+^{\eta}(0) = 0.465 \pm 0.010 \pm 0.007;\ f_+^{\eta'}(0) = 0.518 \pm 0.038 \pm 0.012$
- **Most precision test of lepton flavor universality in D_s sector**
  $\mathcal{R}^{\eta}_{\mu/e} = 0.991 \pm 0.029 \pm 0.016;\ \mathcal{R}^{\eta'}_{\mu/e} = 0.988 \pm 0.082 \pm 0.031$
- **First extraction of the forward-backward asymmetry parameters**
  $\langle A_{\rm FB}^{\eta}\rangle = -0.059 \pm 0.031 \pm 0.005;\ \langle A_{\rm FB}^{\eta'}\rangle = -0.064 \pm 0.079 \pm 0.006$



First Measurement of the $D_s^+ \to K^0\mu^+\nu_\mu$ Decay

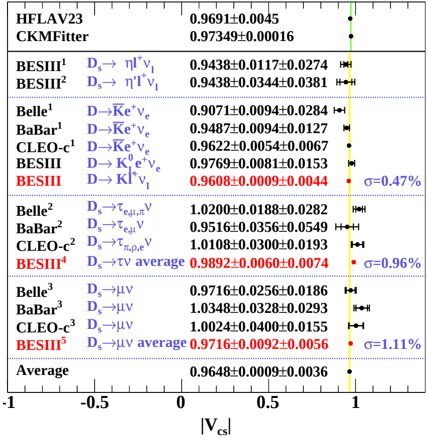


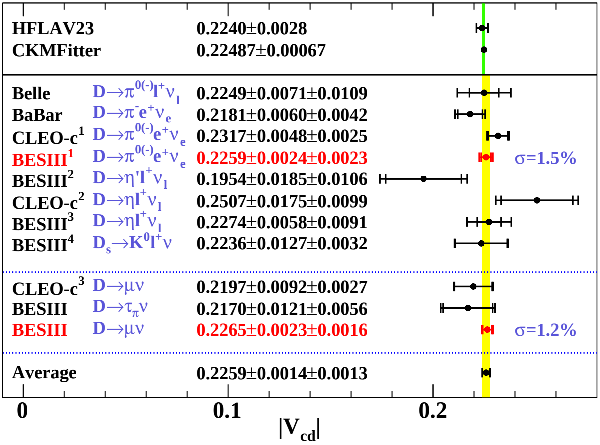




- 7.33 fb^{-1}@4.128-2.226 GeV PRL136(2026)161802
- **First observation of $D_s^+ \to K^0\mu^+\nu_\mu$**: $\mathcal{B}(D_s^+ \to K^0\mu^+\nu_\mu) = (2.89 \pm 0.27 \pm 0.12) \times 10^{-3}$
- **Improve measurement of FF combined with $D_s^+ \to K^0\ell^+\nu_\ell$**: $f_+^{K^0}(0) = 0.623 \pm 0.036 \pm 0.011$
- **LFU test**: $\mathcal{R}^{K^0}_{\mu/e} = 0.97 \pm 0.12 \pm 0.04 \Longrightarrow$ Consistent with $\mathcal{R}^{\rm SM}_{\mu/e} = 0.98099(10)(500)$

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





Summary

- (Semi)leptonic decays of charm mesons are important for determining CKM matrix elements, calibrating LQCD, testing LFU, *et al.*;
  - Precisions of $|V_{cd}|$ and $|V_{cs}|$ have been reduced to 1.2% and 0.5%, respectively;
  - Precisions of f_{D^+}, $f_{D_s^+}$ and $f_+^{D\to\bar{K}}(0)$ have been reduced to 1.2%, 0.9%, and 0.21%, respectively;
  - No evidence of LFU violation is found in charm decay
- More precision measurements ($D\to\pi\ell^+\nu_\ell$ ...) 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.
- Review of experimental studies of charmed meson decays at BESIII, arXiv:2604.20644

Thank you