The (semi-)leptonic decays of charmed mesons at BESIII

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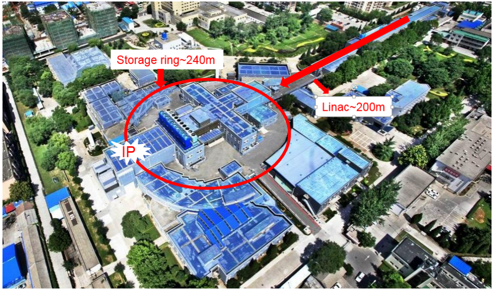
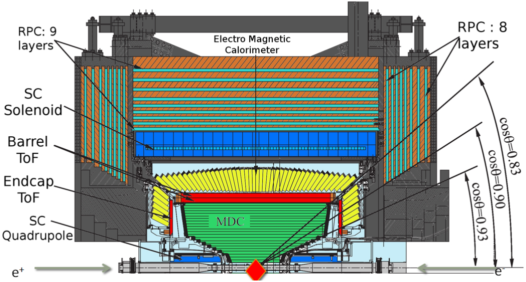
BESIII experiment

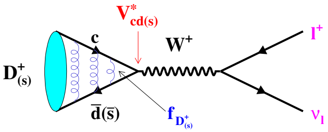


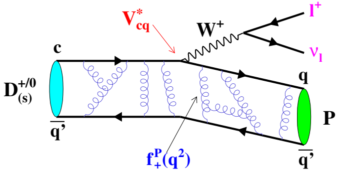


- $\sqrt{s} = (1.85 - 4.95)$ GeV
- Peak luminosity: 1.1×10^{33} cm^{-2}s^{-1} @3.773 GeV
- MDC: $\sigma_P/P = 0.5\%$ @ 1 GeV; $\sigma_{dE/dx} = 6\%$

- 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)

Main goal





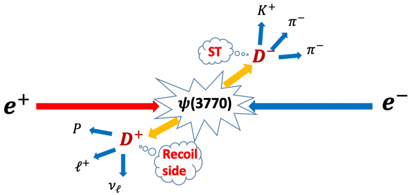
$$\Gamma = \frac{G_F^2}{8\pi}|V_{cq}|^2|f_{D^+_{(s)}}|^2 m_\ell^2 m_{D^+_{(s)}}\left(1-\frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

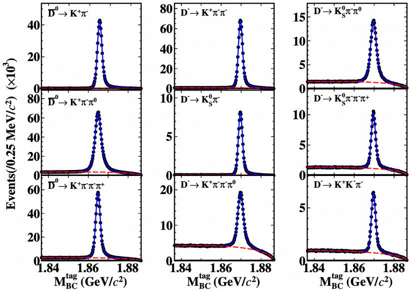
$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2|\vec{p}_P|^3}{24\pi^3}|V_{cq}|^2|f_+(q^2)|^2$$

- Leptonic and semileptonic D decays are the most important way to determine $|V_{cd(s)}|$
- Latest LQCD: $f_{D_s^+} = 249.9(05)$ MeV ($\sigma = 0.2\%$), $f_{D^+} = 212.1(07)$ MeV ($\sigma = 0.3\%$), $f_+^{D\to K}(0) = 0.7452(31)$ ($\sigma = 2.4\% \to 0.4\%$), $f_+^{D\to\pi}(0) = 0.6300(51)$ ($\sigma = 4.4\% \to 0.8\%$)
- Decay constant $f_{D^+_{(s)}}$ and FF $f_+(0)$ measurements⇒Calibrate LQCD calculations
- BF ratios⇒Test lepton flavor universality (LFU)

BESIII dataset and double-tag method

- $D^{0(+)}$ meson: $e^+e^- \to \psi(3770) \to D\bar{D}$ @3.773 GeV
  $\mathcal{L}_{\rm int}$=(2.932+4.995+8.157+4.191) fb^{-1}=20.27 fb^{-1}
- D_s^+ meson:
  $e^+e^- \to D_s^{\pm} D_s^{*\mp}$@4.128-4.226 GeV, $\mathcal{L}_{\rm int}$=7.33 fb^{-1}
  $e^+e^- \to D_s^{*+} D_s^{*-}$@4.237-4.669 GeV, $\mathcal{L}_{\rm int}$=10.64 fb^{-1}
- Advantages: Clean, double tag method
- Single-tag yields in data:
- 2.93 fb^{-1} (7.9 fb^{-1}) (20.27 fb^{-1}) data
  $N_{\rm ST}^{\bar{D}^0} \sim 2.4$M (6.6M) (16.9M) with 3 golden tags
  $N_{\rm ST}^{D^-} \sim 1.6$M (4.3M) (11.0M) with 6 golden tags
- 7.33 fb^{-1} (10.64 fb^{-1}) data
  $N_{\rm ST}^{D_s^-} \sim 0.8$M (0.12M) with 16 possible tags

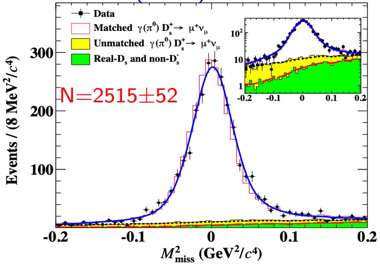




$D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$ via $e^+e^- \to D_s^\pm D_s^{*\mp}$

7.33 fb^{-1}@4.128-4.226 GeV

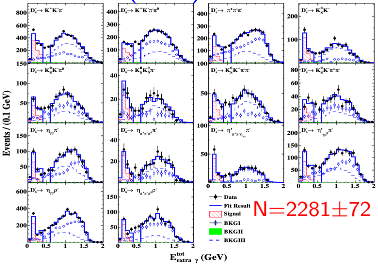
PRD108(2023)112001



- $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.294 \pm 0.108 \pm 0.085) \times 10^{-3}$
- $f_{D_s^+} = (248.4 \pm 2.5 \pm 2.2)$ MeV
- $|V_{cs}| = 0.968 \pm 0.010 \pm 0.009$ Highest precision to date $\sim 1.4\%$

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$

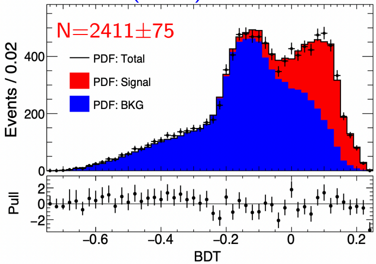
JHEP09(2023)124



- $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.37 \pm 0.17 \pm 0.15)\%$
- $f_{D_s^+} = (253.4 \pm 4.0 \pm 3.7)$ MeV
- $|V_{cs}| = 0.987 \pm 0.016 \pm 0.014$ Precision $\sim 2.2\%$

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

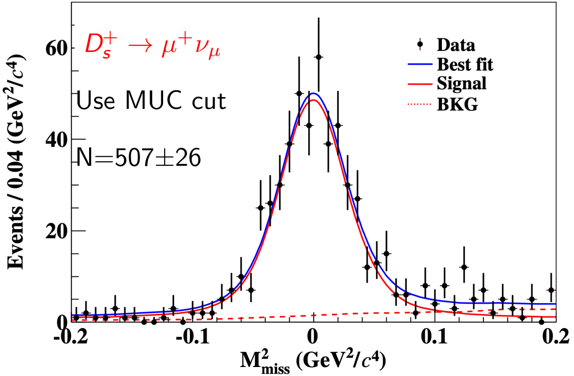
PRD108(2023)092014



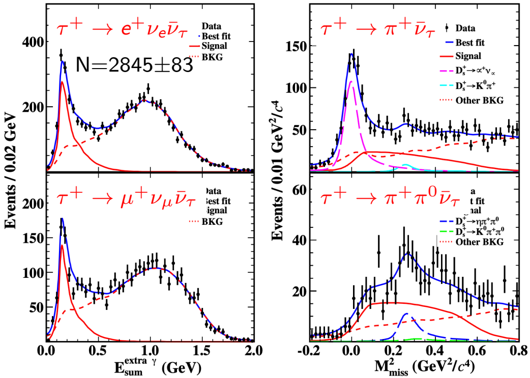
- Boosted decision tree method
- $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.44 \pm 0.17 \pm 0.13)\%$
- $f_{D_s^+} = (255.0 \pm 4.0 \pm 3.4)$ MeV
- $|V_{cs}| = 0.993 \pm 0.015 \pm 0.013$ Precision $\sim 2.0\%$

$D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$ via $e^+e^- \to D_s^{*+}D_s^{*-}$

10.64 fb^{-1}@ 4.237-4.669 GeV arXiv:2407.11727



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

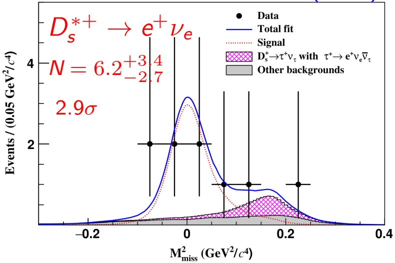


- $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.547 \pm 0.026 \pm 0.016)\%$
- $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.60 \pm 0.16 \pm 0.20)\%$
- $\mathcal{R}(\tau/\mu) = 10.24 \pm 0.57$ (SM:9.75±0.01)

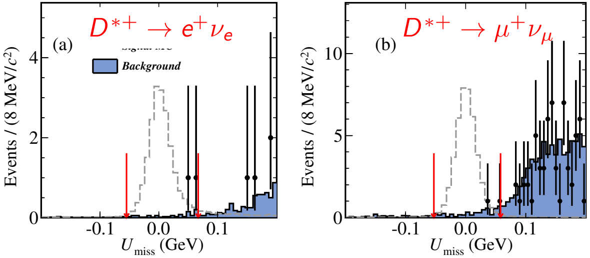
- $f_{D_s}|V_{cs}|_{\mu\nu_\mu} = (246.5 \pm 5.9 \pm 3.6)$ MeV ($\sim 2.8\%$)
- $f_{D_s}|V_{cs}|_{\tau\nu_\tau} = (252.7 \pm 3.6 \pm 4.5)$ MeV ($\sim 2.3\%$)

$D_s^{*+} \to e^+\nu_e$ and $D^{*+} \to \ell^+\nu_\ell$

7.33 fb^{-1}@4.128-4.226 GeV PRL131(2023)141802



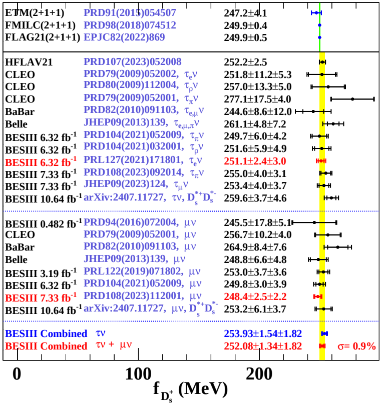
6.32 fb^{-1}@4.178-4.226 GeV PRD110(2024)012003

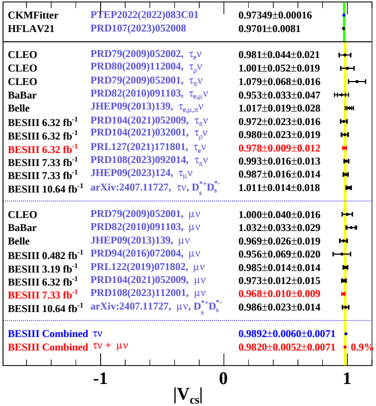


- First experimental study of the $D_{(s)}^{*+}$ purely leptonic decay
- $\mathcal{B}(D_s^{*+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9} \pm 0.2) \times 10^{-5}$
- $\Gamma^{\mathrm{total}}_{D_s^{*+}} = 70 \pm 28$ eV (LQCD) $\Rightarrow f_{D_s^{*+}} = (214^{+61}_{-46} \pm 44)$ MeV
- $f_{D_s^{*+}}/f_{D_s^+} = 1.12 \pm 0.01$ (LQCD) $\Rightarrow \Gamma^{\mathrm{total}}_{D_s^{*+}} = (122^{+70}_{-52} \pm 12)$ eV
- Indirectly constrains the upper limit on the $\Gamma^{\mathrm{total}}_{D_s^{*+}}$ from the MeV (<1.9 MeV@90% C.L. PDG2024) to sub-keV level

- Upper limits are set at 90% C. L.
- $\mathcal{B}(D^{*+} \to e^+\nu_e) < 1.1 \times 10^{-5}$
- $\mathcal{B}(D^{*+} \to \mu^+\nu_\mu) < 4.3 \times 10^{-6}$

Summary of leptonic D_s decays



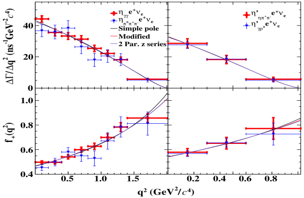


- Averaged BESIII results, precisions of f_{D_s} and $|V_{cs}|$: 0.9%
- $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.5310 \pm 0.0099 \pm 0.0053)\%$ and $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.359 \pm 0.067 \pm 0.074)\%$ $\mathcal{R}(\tau/\mu) = 10.09 \pm 0.28$ ($\sigma \sim 2.8\%$), consistent within SM (9.75±0.01) 1.2σ

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

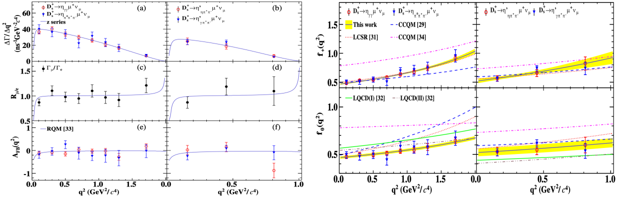
Data: 7.33 fb^{-1}@4.128-4.226 GeV

$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$ PRD108(2023)092003



- Precision of BFs and FFs are improved by a factor of ∼1.4
  $\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = (2.255 \pm 0.039 \pm 0.051)\%$
  $\mathcal{B}(D_s^+ \to \eta' e^+ \nu_e) = (0.810 \pm 0.038 \pm 0.024)\%$
- $f_+^{\eta}(0) = 0.4642 \pm 0.0073 \pm 0.0066$
  $f_+^{\eta'}(0) = 0.540 \pm 0.025 \pm 0.009$
- $\eta - \eta'$ mixing angle
  $\phi_P = (40.0 \pm 2.0 \pm 0.6)^\circ$

$D_s^+ \to \eta^{(\prime)} \mu^+ \nu_\mu$ PRL132(2024)091802

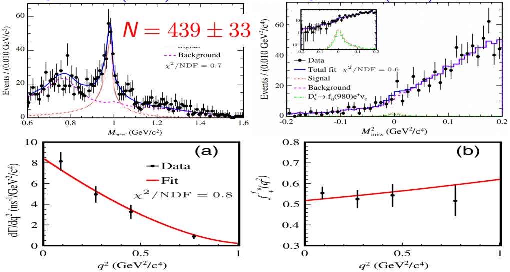


- Precision of BFs are improved by a factor of ∼6
  $\mathcal{B}(D_s^+ \to \eta \mu^+ \nu_\mu) = (2.235 \pm 0.051 \pm 0.052)\%$
  $\mathcal{B}(D_s^+ \to \eta' \mu^+ \nu_\mu) = (0.801 \pm 0.055 \pm 0.028)\%$
- First extraction of the FFs via semimuonic decays
  $f_+^{\eta}(0) = 0.465 \pm 0.010 \pm 0.007$; $f_+^{\eta'}(0) = 0.518 \pm 0.038 \pm 0.012$
- 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
  $\langle A^{\eta}_{\rm FB} \rangle = -0.059 \pm 0.031 \pm 0.005$; $\langle A^{\eta'}_{\rm FB} \rangle = -0.064 \pm 0.079 \pm 0.006$

$D_s^+ \to \pi^+\pi^- e^+\nu_e$ and $D^+ \to \pi^+\pi^-\ell^+\nu_\ell$

7.33 fb^{-1}@4.128-4.226 GeV PRL132(2024)141901

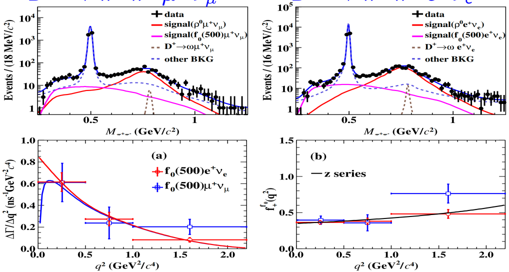
$D_s^+ \to f_0(980)^0 e^+\nu_e$ $D_s^+ \to f_0(500)^0 e^+\nu_e$



- $\mathcal{B}(D_s^+ \to f_0(980)_{\pi^+\pi^-} e^+\nu_e) = (1.72 \pm 0.13 \pm 0.10) \times 10^{-3} = 4.22 \times 10^{-3} \cos^2\phi$
- $q\bar{q}$ mixing angle: $\sin\phi(1/\sqrt{2})(u\bar{u} + d\bar{d}) + \cos\phi s\bar{s}$
  $\phi = (19.7 \pm 12.8)^\circ \Rightarrow$ $s\bar{s}$ component dominates
- $f_+^{D_s^+ \to f_0(980)}(0) = 0.518 \pm 0.018 \pm 0.036$
- $\mathcal{B}(D_s^+ \to f_0(500)_{\pi^+\pi^-} e^+\nu_e) < 3.3 \times 10^{-4}$@90% C. L.

2.93 fb^{-1}@3.773 GeV arXiv:2401.13225

$D^+ \to \pi^+\pi^-\mu^+\nu_\mu$ $D^+ \to \pi^+\pi^- e^+\nu_e$



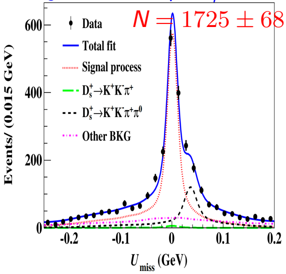
- $\mathcal{B}_{D^+ \to f_0(500)_{\pi^+\pi^-}\mu^+\nu_\mu} = (0.72 \pm 0.13 \pm 0.10) \times 10^{-3}$
  $\Rightarrow$closer to tetraquark assumation
- $\mathcal{B}_{D^+ \to \rho^0_{\pi^+\pi^-}\mu^+\nu_\mu} = (1.64 \pm 0.13 \pm 0.11) \times 10^{-3}$
- $f_+^{D^+ \to f_0(500)}(0) = 0.350 \pm 0.027 \pm 0.015$
- $\mathcal{R}^{\rho^0}_{\mu/e} = 0.88 \pm 0.10$ (SM$\sim$0.96),
  $\mathcal{R}^{f_0(500)}_{\mu/e} = 1.14 \pm 0.28$ (SM$\sim$0.90)

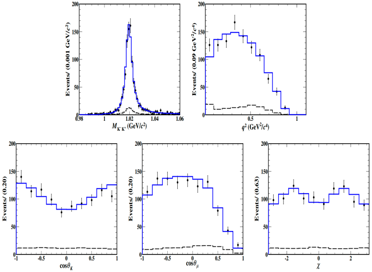
$D_s^+ \to K^+K^-\mu^+\nu_\mu$ and $D \to K\bar{K}e^+\nu_e$

7.33 fb^{-1}@4.128-4.226 GeV

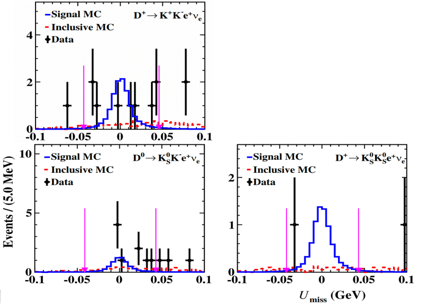
$D_s^+ \to K^+K^-\mu^+\nu_\mu$ JHEP12(2023)072

$N = 1725 \pm 68$





7.9 fb^{-1}@3.773 GeV PRD109(2024)072003



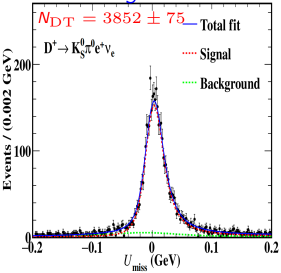
- $\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu) = (2.25 \pm 0.09 \pm 0.07)\%$, precision improved by 4.3
- Assume S−wave is $f_0(980)$:
  $\mathcal{B}(D_s^+ \to f_0(980)\mu^+\nu_\mu, f_0(980) \to K^+K^-) < 5.45 \times 10^{-4}$@90% C. L.
- $\mathcal{R}^{\phi}_{\mu/e} = 0.94 \pm 0.08$
- $r_V = \frac{V(0)}{A_1(0)} = 1.58 \pm 0.17 \pm 0.02$, $r_2 = \frac{A_2(0)}{A_1(0)} = 0.71 \pm 0.14 \pm 0.02$

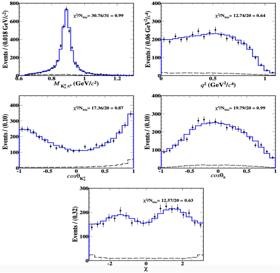
- Explore $a_0(980) \to K\bar{K}$, $D \to a_0(980)_{K\bar{K}}e^+\nu_e$ is expected within $(1 \sim 3) \times 10^{-5}$
- Upper limits are set at 90% C. L.
- $\mathcal{B}(D^0 \to K_S^0K^-e^+\nu_e) < 2.13 \times 10^{-5}$
- $\mathcal{B}(D^+ \to K_S^0K_S^0e^+\nu_e) < 1.54 \times 10^{-5}$
- $\mathcal{B}(D^+ \to K^+K^-e^+\nu_e) < 2.10 \times 10^{-5}$

$D^+ \to K_S^0\pi^0 e^+\nu_e$ and $D^0 \to K^-\pi^0\mu^+\nu_\mu$

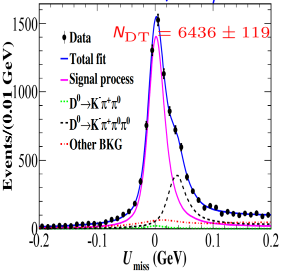
$7.9\ \mathrm{fb}^{-1}$@3.773 GeV

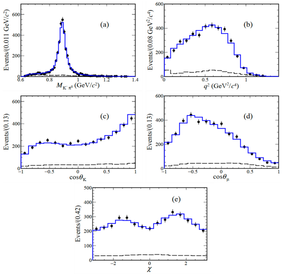
$D^+ \to K_S^0\pi^0 e^+\nu_e$ arXiv:2408.04422





$D^0 \to K^-\pi^0\mu^+\nu_\mu$ arXiv:2403.10877





- $\mathcal{B}(D^+ \to K_S^0\pi^0 e^+\nu_e) = (0.881 \pm 0.017 \pm 0.016)\%$
  $\mathcal{B}(D^+ \to \bar{K}^*(892)^0 e^+\nu_e) = (4.97 \pm 0.11 \pm 0.12)\%$
- $r_V = \frac{V(0)}{A_1(0)} = 1.43 \pm 0.07 \pm 0.03$
  $r_2 = \frac{A_2(0)}{A_1(0)} = 0.72 \pm 0.06 \pm 0.02$

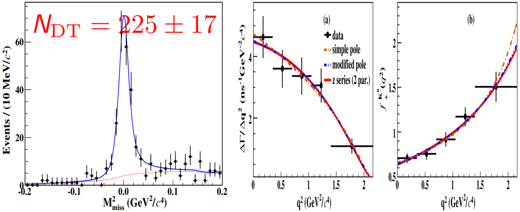
- Precision of BF is improved by a factor of 5
  $\mathcal{B}(D^0 \to K^-\pi^0\mu^+\nu_\mu) = (0.729 \pm 0.014 \pm 0.011)\%$
  $\mathcal{B}(D^0 \to K^*(892)^-\mu^+\nu_\mu) = (2.062 \pm 0.039 \pm 0.032)\%$
- $r_V = \frac{V(0)}{A_1(0)} = 1.37 \pm 0.09 \pm 0.03$
  $r_2 = \frac{A_2(0)}{A_1(0)} = 0.76 \pm 0.06 \pm 0.02$
- $\frac{\mathcal{B}(D^0 \to K^*(892)^-\mu^+\nu_\mu)}{\mathcal{B}(D^0 \to K^*(892)^- e^+\nu_e)} = 0.96 \pm 0.08$, agree with LFU

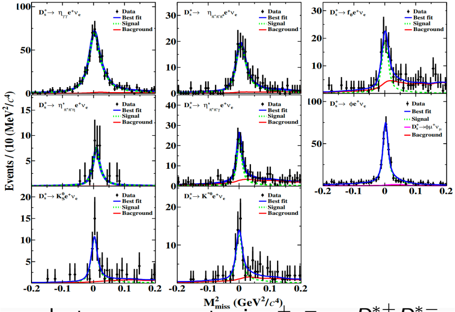
$D_s^+ \to K^0 e^+ \nu_e$ and $D_s^+ \to h e^+ \nu_e$

10.64 fb^{-1}@4.237-4.699 GeV arXiv:2406.01332

7.33 fb^{-1}@4.128-4.226 GeV

$D_s^+ \to K^0 e^+ \nu_e$ arXiv:2406.19190



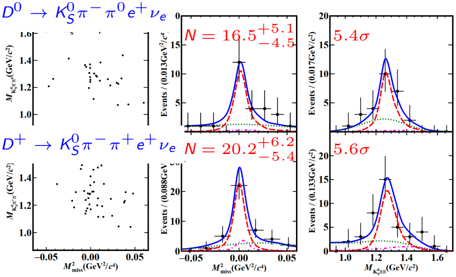


- Precision of BF is improved by a factor of 1.6
  $\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e) = (2.93 \pm 0.23 \pm 0.12) \times 10^{-3}$
- Precision of FF is improved by a factor of 1.7
  $f_+^{K^0}(0) = 0.636 \pm 0.049 \pm 0.013$

- Independent measurements via $e^+e^- \to D_s^{*+} D_s^{*-}$
  $\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = (2.35 \pm 0.11 \pm 0.10)\%$
  $\mathcal{B}(D_s^+ \to \eta' e^+ \nu_e) = (0.82 \pm 0.09 \pm 0.02)\%$
  $\mathcal{B}(D_s^+ \to \phi e^+ \nu_e) = (2.21 \pm 0.16 \pm 0.11)\%$
  $\mathcal{B}(D_s^+ \to f_0(980)|_{\pi^+\pi^-} e^+ \nu_e) = (0.15 \pm 0.02 \pm 0.01)\%$
  $\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e) = (0.24 \pm 0.04 \pm 0.01)\%$
  $\mathcal{B}(D_s^+ \to K^{*0} e^+ \nu_e) = (0.19 \pm 0.03 \pm 0.01)\%$

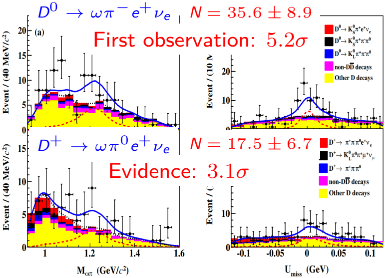
$D_{(s)} \to K_1(1270)e^+\nu_e$ and $D_{(s)} \to b_1(1235)e^+\nu_e$

$2.93\ \mathrm{fb}^{-1}$@3.773 GeV arXiv:2403.19091



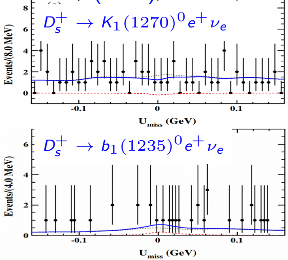
- Dominated by $K_1(1270)$
- $\mathcal{B}(D^0 \to K_1(1270)^-e^+\nu_e) = (1.05^{+0.33}_{-0.28} \pm 0.17) \times 10^{-3}$
- $\mathcal{B}(D^+ \to \bar{K}_1(1270)^0e^+\nu_e) = (1.29^{+0.40}_{-0.35} \pm 0.23) \times 10^{-3}$

$7.9\ \mathrm{fb}^{-1}$@ 3.773 GeV arXiv:2407.20551



- $\mathcal{B}(D^0 \to b_1(1235)^-|_{\omega\pi^-}e^+\nu_e) = (0.72 \pm 0.18^{+0.06}_{-0.08}) \times 10^{-4}$
- $\mathcal{B}(D^+ \to b_1(1235)^0|_{\omega\pi^0}e^+\nu_e) = (1.16 \pm 0.44 \pm 0.16) \times 10^{-4}$
- $\frac{\Gamma(D^0\to b_1^- e^+\nu_e)}{2\Gamma(D^+\to b_1^0 e^+\nu_e)} = 0.78 \pm 0.19 \pm 0.05$, consistent with isospin

$7.33\mathrm{fb}^{-1}$@4.128-4.226 GeV PRD108(2023)112002



- Upper limits are set at 90% C. L.
- $\mathcal{B}(D_s^+ \to b_1(1235)^0|_{\omega\pi^0}e^+\nu_e) < 6.4 \times 10^{-4}$
- $\mathcal{B}(D_s^+ \to K_1(1270)^0e^+\nu_e) < 4.1 \times 10^{-4}$

Summary and prospect

Channel	Current precision (%) $f_{D_s^+}$	$\lvert V_{cs}\rvert$	$\mathcal{R}(\tau/\mu)$	Expected precision (%) $f_{D_s^+}$	$\lvert V_{cs}\rvert$	$\mathcal{R}(\tau/\mu)$
$D_s^+ \to \mu^+\nu_\mu$	1.09	1.09	2.8	0.97	0.97	2.5
$D_s^+ \to \tau^+\nu_\tau$	0.94	0.94		0.88	0.88	
Channel	Form factor	$\lvert V_{cs}\rvert$	$\mathcal{R}(\mu/e)$	Form factor	$\lvert V_{cs}\rvert$	$\mathcal{R}(\mu/e)$
$D^0 \to K^- e^+\nu_e$	0.60	0.73	1.42	0.50	0.66	1.26
$D^0 \to K^- \mu^+\nu_\mu$	0.66	0.79		0.45	0.63	
$D_s^+ \to \eta e^+\nu_e$	2.1	6.4	3.3	1.9	6.3	2.9
$D_s^+ \to \eta \mu^+\nu_\mu$	2.6	6.6		2.4	6.5	
Channel	f_{D^+}	$\lvert V_{cd}\rvert$	$\mathcal{R}(\tau/\mu)$	f_{D^+}	$\lvert V_{cd}\rvert$	$\mathcal{R}(\tau/\mu)$
$D^+ \to \mu^+\nu_\mu$	2.8	2.8	24	1.3	1.3	15
$D^+ \to \tau^+\nu_\tau$	11.3	11.3		6.4	6.4	
Channel	Form factor	$\lvert V_{cd}\rvert$	$\mathcal{R}(\mu/e)$	Form factor	$\lvert V_{cd}\rvert$	$\mathcal{R}(\mu/e)$
$D^0 \to \pi^- e^+\nu_e$	1.43	1.60	4.0	0.84	1.11	2.8
$D^0 \to \pi^- \mu^+\nu_\mu$	-	-		-	-	

Expected precision with 20.27 fb^{-1}@3.773 GeV (ready now) and another 3 fb^{-1}@4.178 GeV (plan)

New and more procision (semi-)leptonic decays will be explored

Thanks for your attention