Measurements of $|V_{cd(s)}|$, decay constants, and form factors in (semi)-leptonic D decays at BESIII

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On behalf of BESIII Collaboration

中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会，广州

Outline

① Motivation

② BESIII dataset and double tag method

③ Leptonic $D_{(s)}$ decays

④ Semi-leptonic $D_{(s)}$ decays

- $D_{(s)} \to P l^+ \nu_l$, $D_{(s)} \to S l^+ \nu_l$, $D_{(s)} \to V l^+ \nu_l$, $D_{(s)} \to A l^+ \nu_l$

(P: $psuedoscalar$; S:$scalar$; V:$vector$; A: $axial$-$vector$)

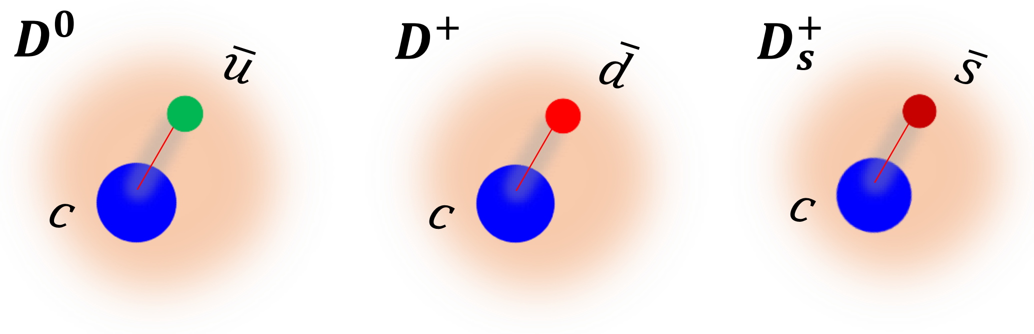
⑤ Summary and prospect

Motivation

- Charm physics

➢ Nonperturbative region ⇒ QCD

➢ High precision frontier ⇒ Test SM



- Measure $|V_{cd(s)}|$ ⇒ Validate the unitarity of CKM matrix

$$|V_{\mathrm{CKM}}|_{\mathrm{PDG}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97367 \pm 0.00032 & 0.22431 \pm 0.00085 & 0.00389 \pm 0.00016 \\ 0.2261 \pm 0.0027 & 0.9669 \pm 0.0038 & 0.0407 \pm 0.0013 \\ 0.0086 \pm 0.0002 & 0.0415 \pm 0.0009 & 1.002 \pm 0.024 \end{pmatrix}$$

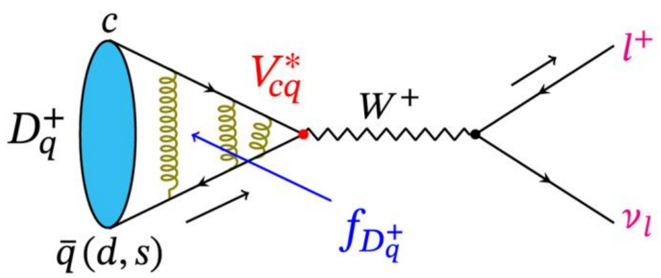
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0007 \qquad |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 0.991 \pm 0.010$$

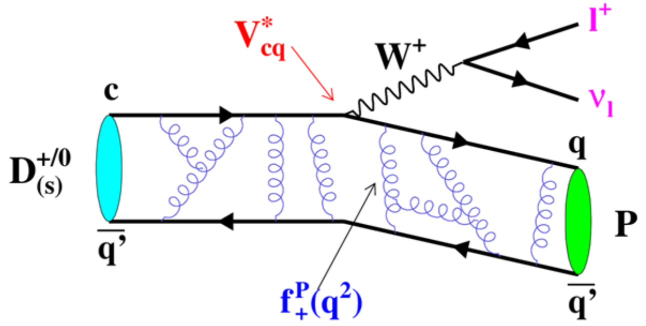
$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 0.9986 \pm 0.0011 \qquad |V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 0.991 \pm 0.010$$

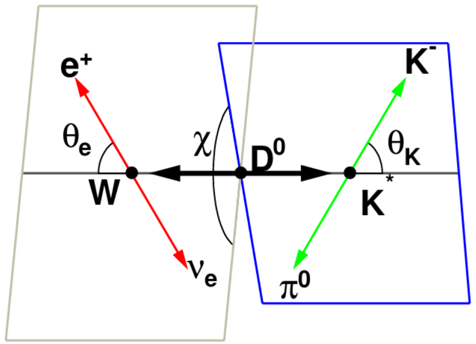
- Current precision of $|V_{cd}|$: $\sigma = 1.2\%$ $\quad |V_{cs}|$: $\sigma = 0.4\%$

Motivation

leptonic decay | **semi-leptonic decay**







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

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

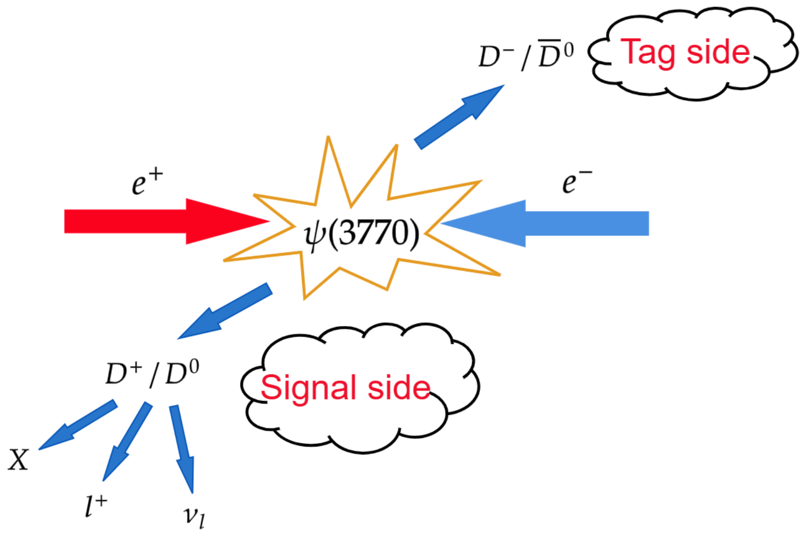
X is a multiplicative factor due to isospin

$$\Gamma(D_{(s)} \to V(S)l^+\nu_l) \propto \left|V_{cd(s)}\right|^2 I(A_1(q^2), A_2(q^2), V(q^2), \ldots)\, dm^2 dq^2 d\cos(\theta_h)\, d\cos(\theta_l) d\chi$$

- Decay constants and hadronic Form factor (FF) ⇒ Test and calibrate LQCD
- Branching fraction (BF) ratios $\mathcal{R}^X_{\tau/\mu}$, $\mathcal{R}^X_{\mu/e}$ ⇒ Test Lepton flavor universality (LFU)
- BF and FF measurement in semi-leptonic decays ⇒ Study light hadrons

BESIII dataset and double tag method

Process	Data size	Energy region	Tag yields($\times 10^6$)
$e^+e^- \to \psi(3770) \to D\bar{D}$	$20.3\ \mathrm{fb}^{-1}$	3.773 GeV	$N_{ST}^{\bar{D}^0} \sim 16.9, N_{ST}^{D^-} \sim 11.5$
$e^+e^- \to D_s^{\pm}D_s^{*\mp}$	$7.33\ \mathrm{fb}^{-1}$	4.128-4.226 GeV	$N_{ST}^{D_s^-} \sim 0.8$
$e^+e^- \to D_s^{*\pm}D_s^{*\mp}$	$10.64\ \mathrm{fb}^{-1}$	4.237-4.669 GeV	$N_{ST}^{D_s^-} \sim 0.12$



- Near threshold ⇒ clean environment
- Identify neutrino with missing energy

$$U_{\mathrm{miss}} = E_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|$$
$$M^2_{\mathrm{miss}} = E^2_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|^2$$

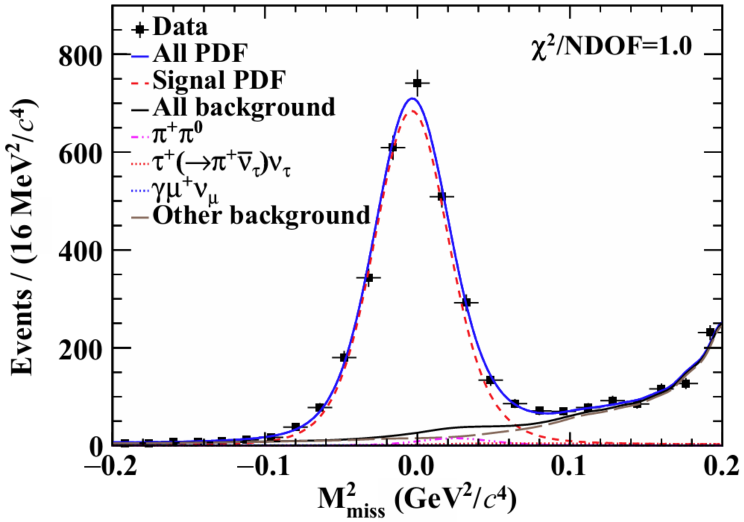
- Systematic uncertainties from single tag mostly canceled

$$\mathcal{B}_{\mathrm{sig}} = \frac{N^i_{\mathrm{DT}}}{N^i_{\mathrm{ST}}\epsilon^i_{\mathrm{DT}}/\epsilon^i_{\mathrm{ST}}}$$

$D^+_{(s)} \to l^+\nu_l$

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

PRL 135, 061801 (2025)



- data sample: 20.3 fb^{-1}@3.773 GeV

$$\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (4.034 \pm 0.080_{\text{stat}} \pm 0.040_{\text{syst}}) \times 10^{-4} \quad (\sigma\sim 2.2\%)$$

$$f_{D^+}|V_{cd}| = (48.02 \pm 0.48_{\text{stat}} \pm 0.24_{\text{syst}} \pm 0.12_{\text{input}} \pm 0.15_{\text{EM}})\ \text{MeV} \quad (\sigma\sim 1.2\%)$$

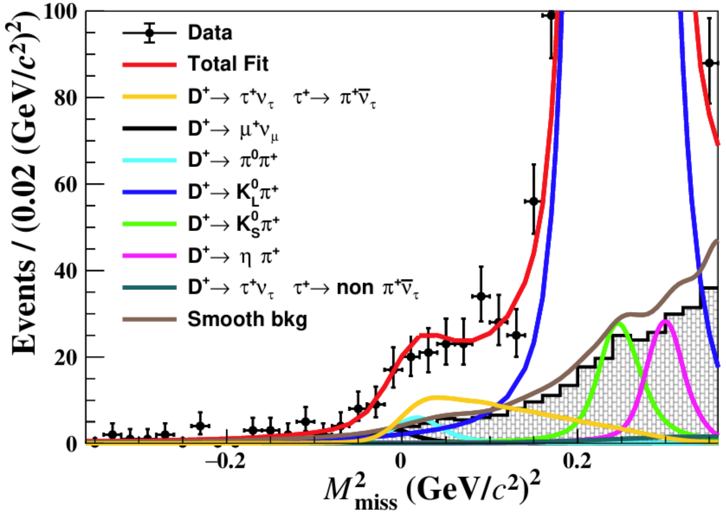
$$f_{D^+} = (213.5 \pm 2.1_{\text{stat}} \pm 1.1_{\text{syst}} \pm 0.8_{\text{input}} \pm 0.7_{\text{EM}})\ \text{MeV}$$

$$|V_{cd}| = 0.2265 \pm 0.0023_{\text{stat}} \pm 0.0011_{\text{syst}} \pm 0.0009_{\text{input}} \pm 0.0007_{\text{EM}}$$

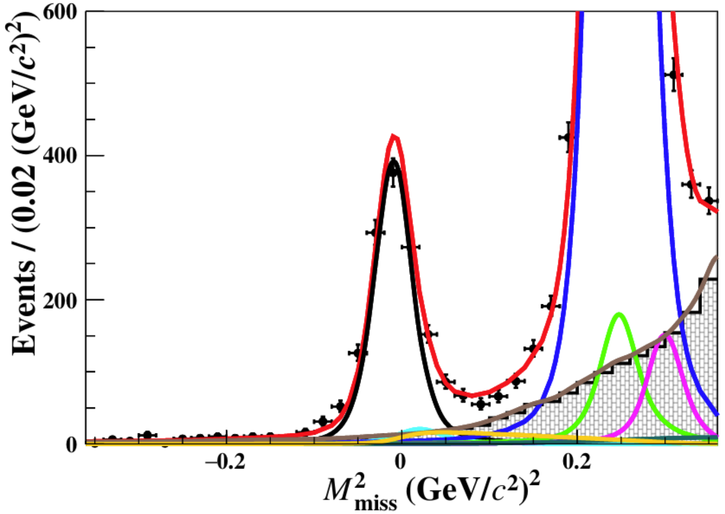
$$\mathcal{R}_{\tau/\mu} = 2.97 \pm 0.67$$

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

JHEP01(2025)089



π-like: $E_{EMC} > 300$ MeV



μ-like: $E_{EMC} < 300$ MeV

- data sample: 7.93 fb^{-1}@3.773 GeV

$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (9.9 \pm 1.1_{\text{stat}} \pm 0.5_{\text{syst}}) \times 10^{-4} \quad (\sigma\sim 12.2\%)$$

$$f_{D^+}|V_{cd}| = (45.9 \pm 2.5_{\text{stat}} \pm 1.2_{\text{syst}} \pm 0.1_{\text{input}})\ \text{MeV} \quad (\sigma\sim 6.0\%)$$

$$f_{D^+} = (204 \pm 11_{\text{stat}} \pm 5_{\text{syst}} \pm 1_{\text{input}})\ \text{MeV}$$

$$|V_{cd}| = (0.216 \pm 0.012_{\text{stat}} \pm 0.006_{\text{syst}} \pm 0.001_{\text{input}})$$

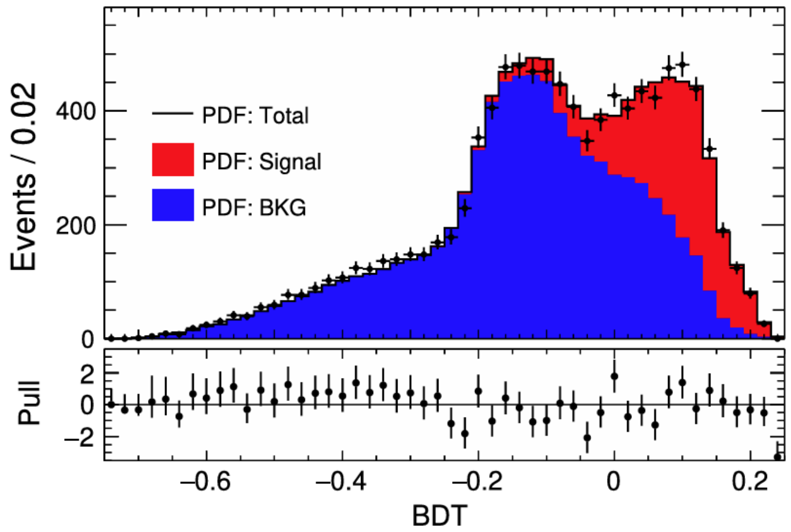
Consistent with SM prediction: 2.67
$\Rightarrow$ No LFUV

$$\mathcal{R}_{\tau/\mu} = 2.49 \pm 0.31$$

$D_{(s)}^+ \to l^+\nu_l$

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

PRD 108, 092014 (2023)



- data sample: $7.33\ \mathrm{fb}^{-1}$@$4.128-4.226$ GeV

$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.44 \pm 0.17_{\rm stat} \pm 0.13_{\rm syst})\%$$ **(σ~3.9%)**

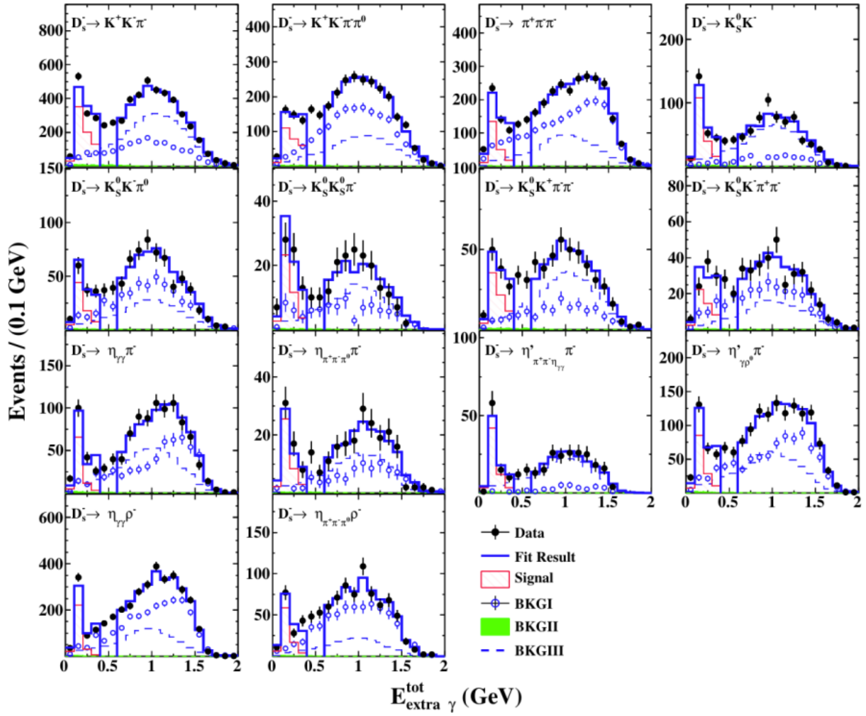
$$f_{D_s^+}|V_{cs}| = (248.3 \pm 3.9_{\rm stat} \pm 3.0_{\rm syst} \pm 1.0_{\rm input})\ \mathrm{MeV}$$ **(σ~2.0%)**

$$f_{D_s^+} = (255.0 \pm 4.0_{\rm stat} \pm 3.1_{\rm syst} \pm 1.0_{\rm input})\ \mathrm{MeV}$$

$$|V_{cs}| = 0.993 \pm 0.015_{\rm stat} \pm 0.012_{\rm syst} \pm 0.004_{\rm input}$$

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

JHEP09(2023)124



$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.37 \pm 0.17_{\rm stat} \pm 0.15_{\rm syst})\%$$ **(σ~4.2%)**

$$f_{D_s^+}|V_{cs}| = (246.7 \pm 3.9_{\rm stat} \pm 3.6_{\rm syst})\ \mathrm{MeV}$$ **(σ~2.2%)**

$$f_{D_s^+} = (253.4 \pm 4.0_{\rm stat} \pm 3.7_{\rm syst})\ \mathrm{MeV}$$

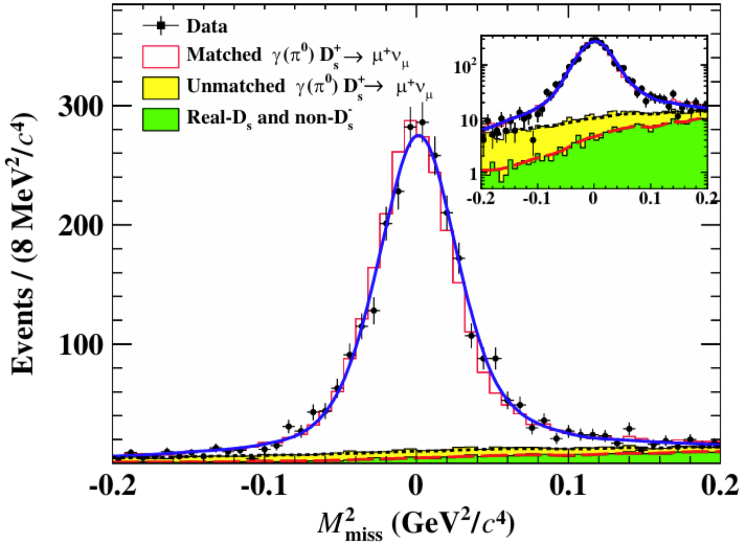
$$|V_{cs}| = 0.987 \pm 0.016_{\rm stat} \pm 0.014_{\rm syst}$$

$R_{\tau/\mu} = 9.81 \pm 0.33$ Consistent with SM prediction: 9.75±0.01 $R_{\tau/\mu} = 9.89 \pm 0.50$

$D_{(s)}^{+} \rightarrow l^{+}\nu_{l}$

$D_s^+ \rightarrow \mu^+\nu_\mu$

PRD 108.112001(2023)



- data sample: 7.33 fb^{-1}@4.128 – 4.226 GeV

$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.5294 \pm 0.0108_{\rm stat} \pm 0.0085_{\rm syst})\%$$

(σ~2.6%)

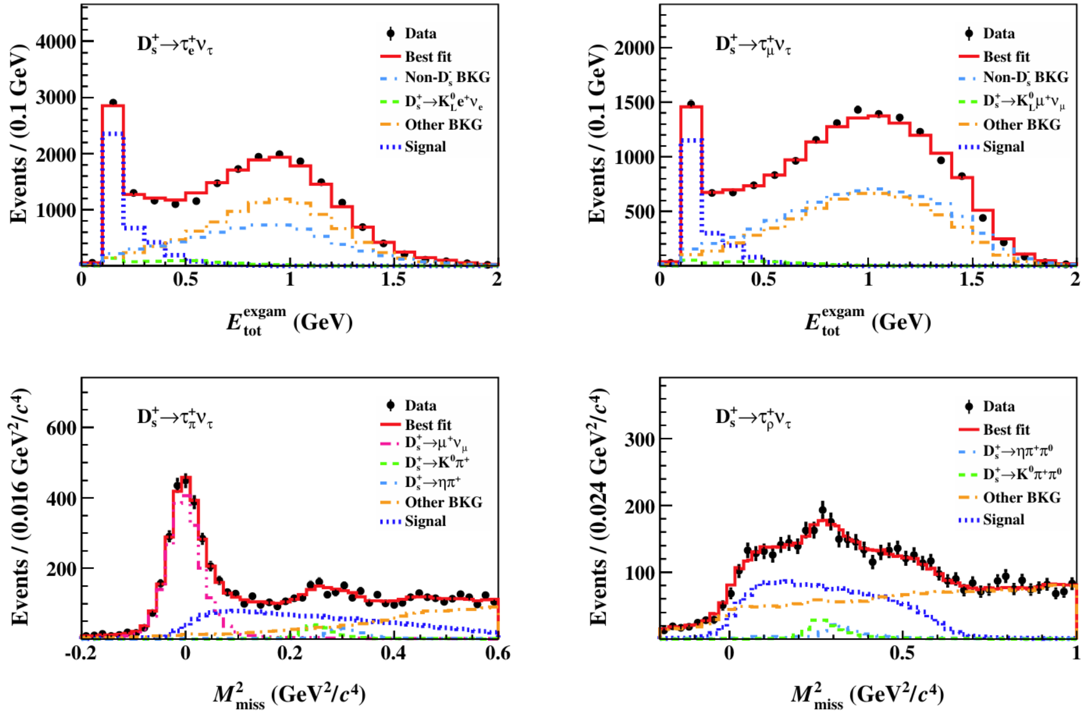
$$f_{D_s^+}|V_{cs}| = (241.8 \pm 2.5_{\rm stat} \pm 2.2_{\rm syst})\ \text{MeV}$$ **(σ~1.4%)**

$$f_{D_s^+} = (248.4 \pm 2.5_{\rm stat} \pm 2.2_{\rm syst})\ \text{MeV}$$

$$|V_{cs}| = 0.968 \pm 0.010_{\rm stat} \pm 0.009_{\rm syst}$$

$D_s^+ \rightarrow \tau^+\nu_\tau$, $\tau^+ \rightarrow e^+\nu_e\bar{\nu}_\tau$, $\mu^+\nu_\mu\bar{\nu}_\tau$, $\pi^+\bar{\nu}_\tau$, $\pi^+\pi^0\bar{\nu}_\tau$

arXiv:2606.11593v1



$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.37 \pm 0.08_{\rm stat} \pm 0.06_{\rm syst})\%$$ **(σ~1.9%)**

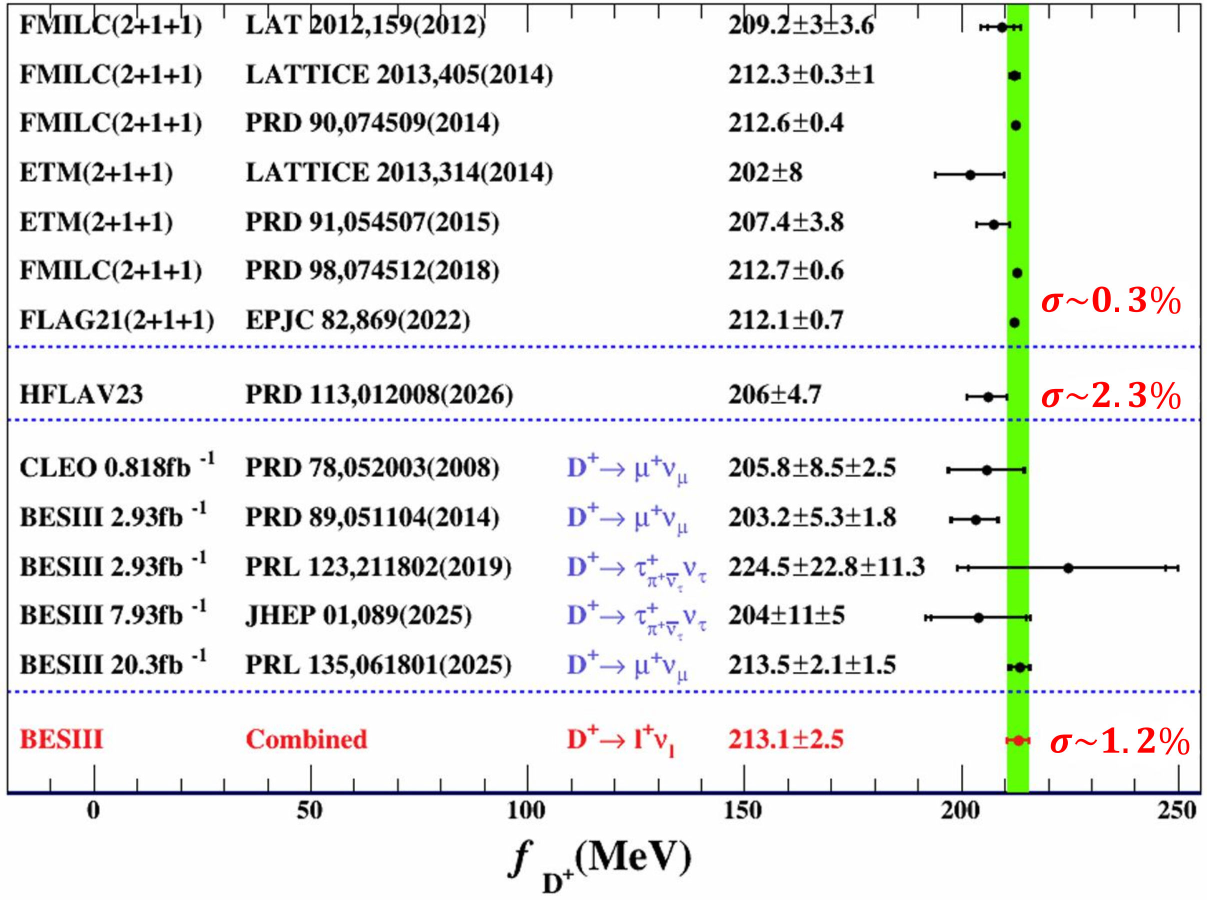
$$f_{D_s^+}|V_{cs}| = (248.2 \pm 1.9_{\rm stat} \pm 1.4_{\rm syst} \pm 0.6_{\rm input} \pm 0.8_{\rm EM})\ \text{MeV}$$ **(σ~1.0%)**

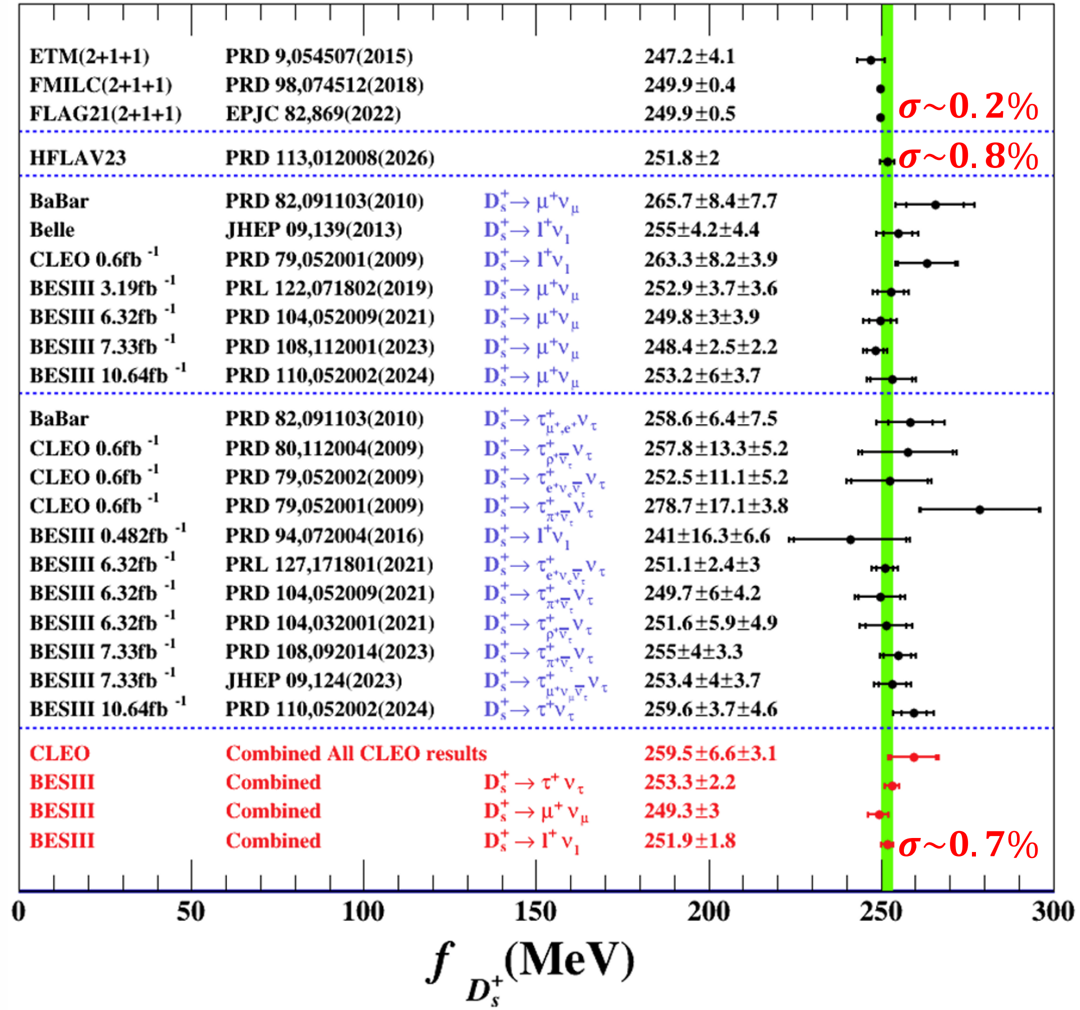
$$f_{D_s^+} = (255.0 \pm 1.9_{\rm stat} \pm 1.4_{\rm syst} \pm 0.6_{\rm input} \pm 0.8_{\rm EM})\ \text{MeV}$$

$$|V_{cs}| = 0.993 \pm 0.008_{\rm stat} \pm 0.006_{\rm syst} \pm 0.003_{\rm input} \pm 0.003_{\rm EM}$$

$R_{\tau/\mu} = 10.05 \pm 0.35$ Consistent with SM prediction: 9.75±0.01 $R_{\tau/\mu} = 10.04 \pm 0.29$

Decay constant $f_{D^+_{(s)}}$

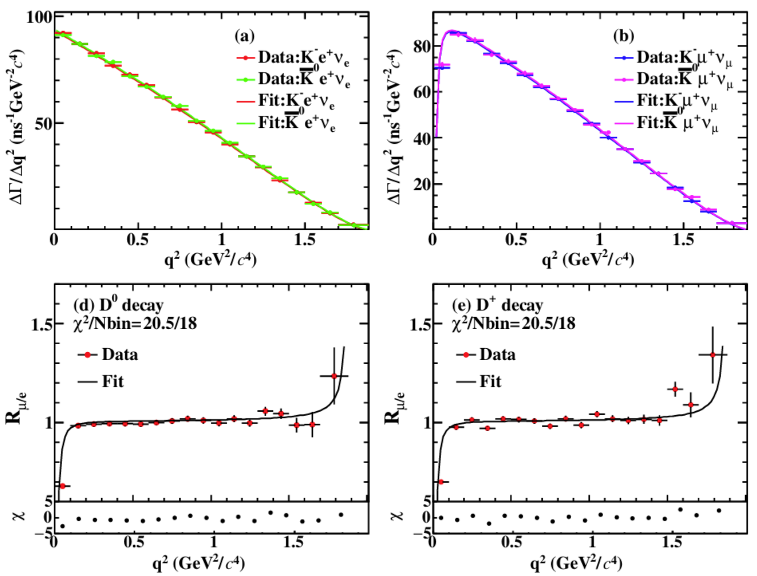


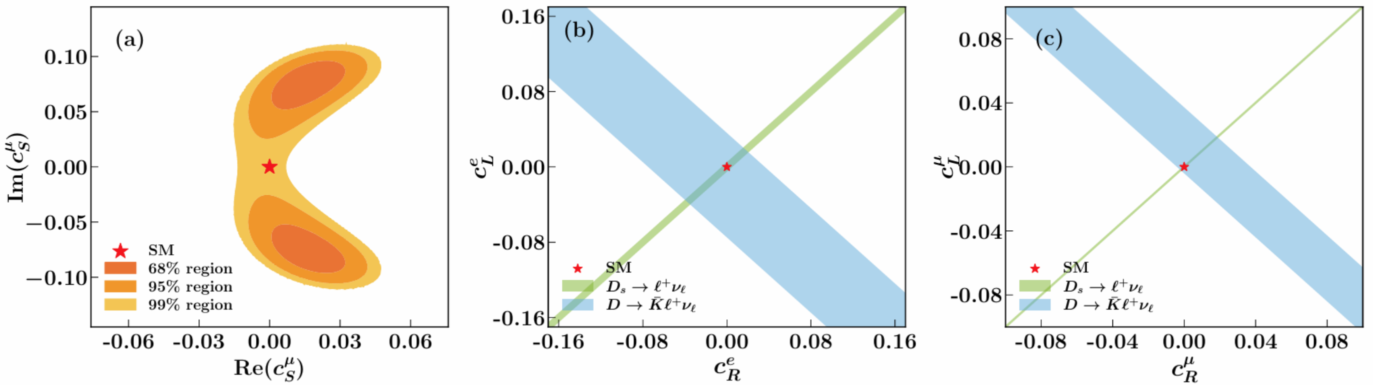


- f_{D^+} and $f_{D_s^+}$ are measured with precision of 1.2% and 0.7% at BESIII, and they are consistent with the LQCD calculations.

$D_{(s)} \to P l^+ \nu_l$: $D \to \bar{K} l^+ \nu_l$

arXiv:2601.21185, 2601.21196





- data sample: 20.3 fb^{-1}@3.773 GeV

Improved precision

$$\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.548 \pm 0.006_{\rm stat} \pm 0.017_{\rm syst})\% \quad (\sigma\sim 0.5\%)$$

$$\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu) = (3.445 \pm 0.007_{\rm stat} \pm 0.017_{\rm syst})\% \quad (\sigma\sim 0.5\%)$$

$$\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.928 \pm 0.025_{\rm stat} \pm 0.050_{\rm syst})\% \quad (\sigma\sim 0.6\%)$$

$$\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu) = (8.770 \pm 0.029_{\rm stat} \pm 0.053_{\rm syst})\% \quad (\sigma\sim 0.7\%)$$

$$R_{\mu/e}^{D^0} = 0.971 \pm 0.003_{\rm stat} \pm 0.004_{\rm syst}$$

$$R_{\mu/e}^{D^+} = 0.982 \pm 0.004_{\rm stat} \pm 0.002_{\rm syst}$$

Consistent with SM prediction: 0.975±0.001

$$\mathrm{Re}(c_S^\mu) = 0.017 \pm 0.008_{\rm stat} \pm 0.006_{\rm syst}$$

$$\mathrm{Im}(c_S^\mu) = \pm(0.077 \pm 0.011_{\rm stat} \pm 0.009_{\rm syst})$$

Extracted Wilson coefficient deviates from the SM prediction with a significance of 1.9σ

$$f_+(0)|V_{cs}| = 0.7183 \pm 0.0007_{\rm stat} \pm 0.0014_{\rm syst} \quad (\sigma\sim 0.2\%)$$

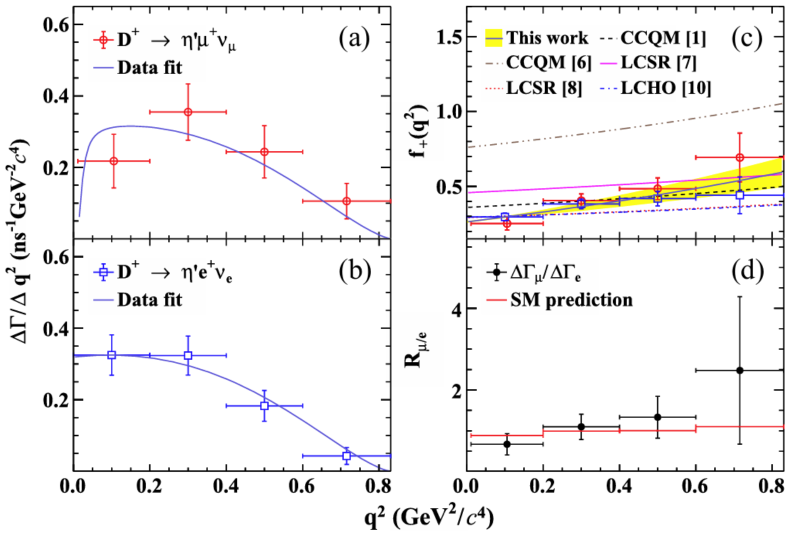
$$f_+(0) = 0.7378 \pm 0.0007_{\rm stat} \pm 0.0014_{\rm syst}$$

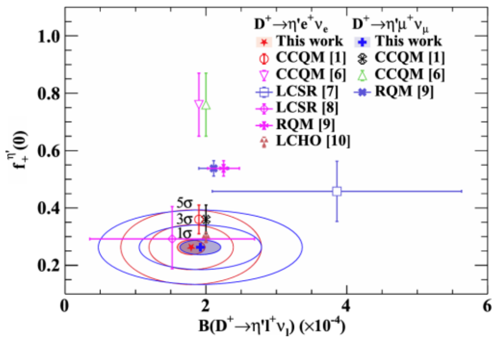
Best precision!!

$$|V_{cs}| = 0.9639 \pm 0.0009_{\rm stat} \pm 0.0018_{\rm syst} \pm 0.0040_{\rm LQCD}$$

$D_{(s)} \to P l^+ \nu_l$: $D \to \eta^{(\prime)} l^+ \nu_l$

$D^+ \to \eta' l^+ \nu_l$ PRL 134, 111801 (2025)





(first observation)

$$\mathcal{B}(D^+ \to \eta' \mu^+ \nu_\mu) = (1.92 \pm 0.28_{\rm stat} \pm 0.08_{\rm syst}) \times 10^{-4} \quad (\sigma\sim15.2\%)$$

$$\mathcal{B}(D^+ \to \eta' e^+ \nu_e) = (1.79 \pm 0.19_{\rm stat} \pm 0.07_{\rm syst}) \times 10^{-4} \quad (\sigma\sim11.3\%)$$

$$f_+^{\eta'}(0)|V_{cd}| = (5.92 \pm 0.56_{\rm stat} \pm 0.13_{\rm syst}) \times 10^{-2} \quad (\sigma\sim9.7\%)$$

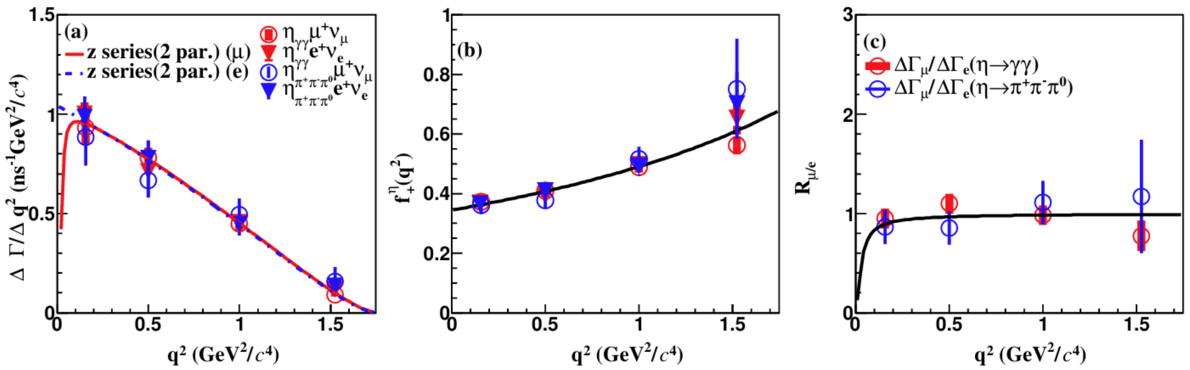
$$f_+^{\eta'}(0) = 0.263 \pm 0.025_{\rm stat} \pm 0.006_{\rm syst} \quad (\sigma\sim9.8\%)$$

$\eta - \eta'$ mixing angle: $\phi_{\rm p} = (39.8 \pm 0.8_{\rm stat} \pm 0.3_{\rm syst})^\circ$

$$R_{\mu/e} = 1.07 \pm 0.19_{\rm stat} \pm 0.03_{\rm syst}$$

No LFUV

$D^+ \to \eta l^+ \nu_l$ arXiv: 2506.02521v2



➢ data sample: $20.3\ \text{fb}^{-1}$@3.773 GeV

Improved precision

$$\mathcal{B}(D^+ \to \eta \mu^+ \nu_\mu) = (9.08 \pm 0.35_{\rm stat} \pm 0.23_{\rm syst}) \times 10^{-4} \quad (\sigma\sim4.6\%)$$

$$\mathcal{B}(D^+ \to \eta e^+ \nu_e) = (9.75 \pm 0.29_{\rm stat} \pm 0.28_{\rm syst}) \times 10^{-4} \quad (\sigma\sim4.1\%)$$

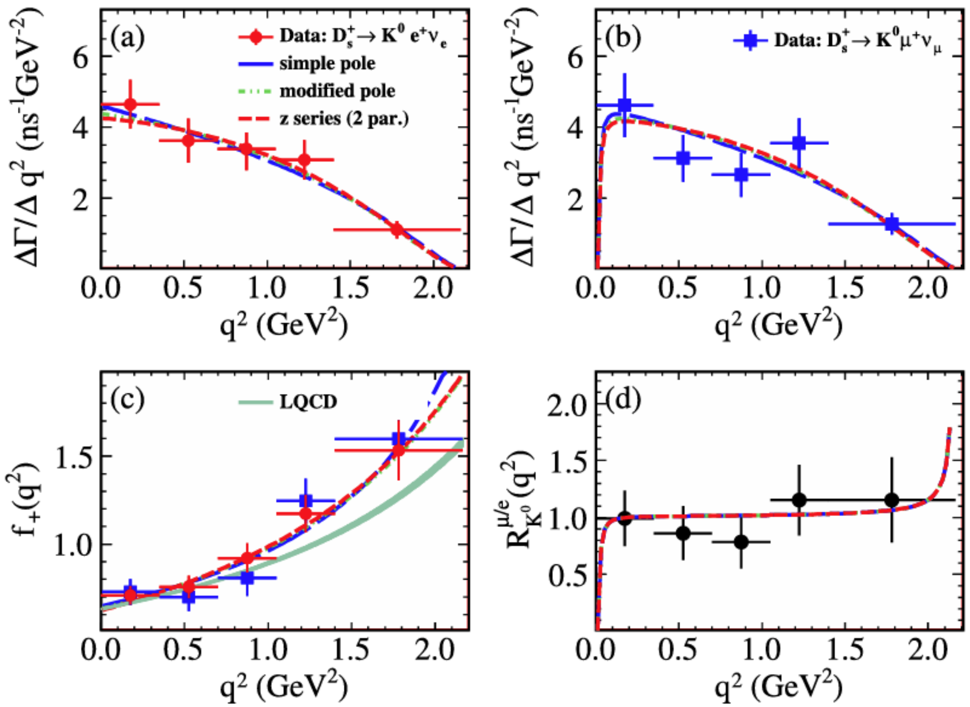
$$f_+^{\eta}(0)|V_{cd}| = 0.078 \pm 0.002_{\rm stat} \pm 0.001_{\rm syst} \quad (\sigma\sim2.9\%)$$

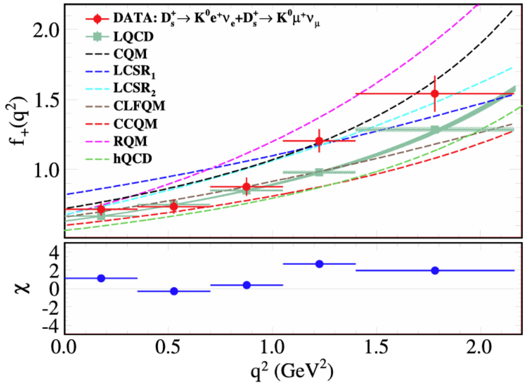
$$f_+^{\eta}(0) = 0.345 \pm 0.008_{\rm stat} \pm 0.003_{\rm syst} \quad (\sigma\sim2.5\%)$$

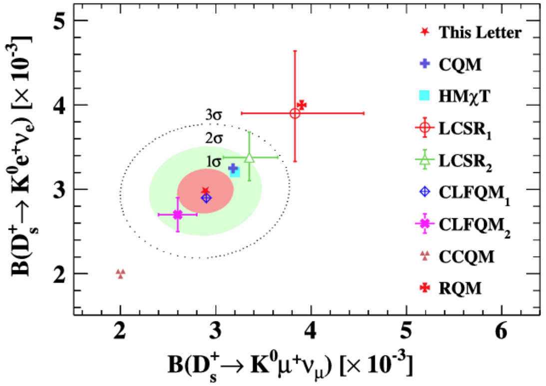
$$R_{\mu/e} = 0.93 \pm 0.05_{\rm stat} \pm 0.02_{\rm syst}$$

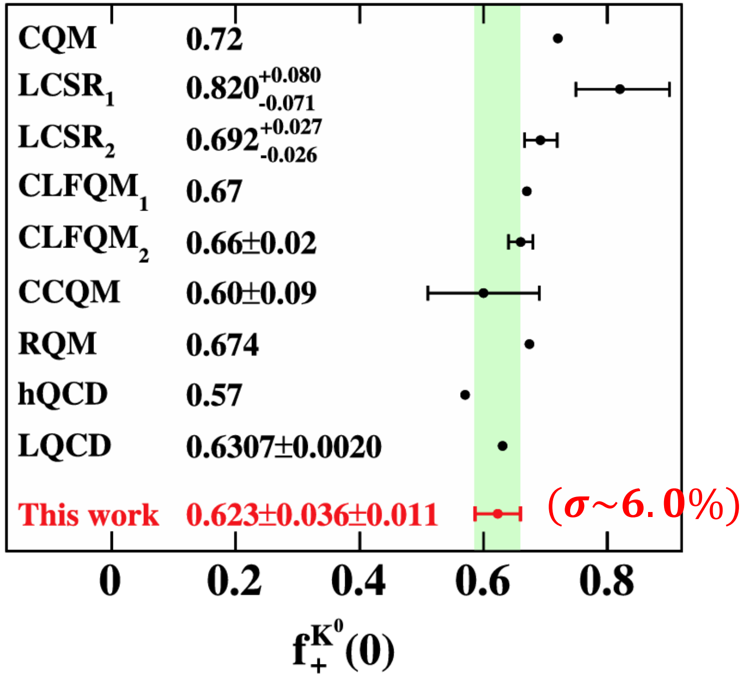
$D_{(s)} \to P l^+ \nu_l$: $D_s^+ \to \bar{K} l^+ \nu_l$

PRL 136, 161802 (2026)









- data sample: 7.33 fb^{-1}@4.128 – 4.226 GeV

$$\mathcal{B}(D_s^+ \to K^0 \mu^+ \nu_\mu) = (2.89 \pm 0.27_{\text{stat}} \pm 0.12_{\text{syst}}) \times 10^{-3}$$ **$(\sigma\sim 10.2\%)$**

First measurement

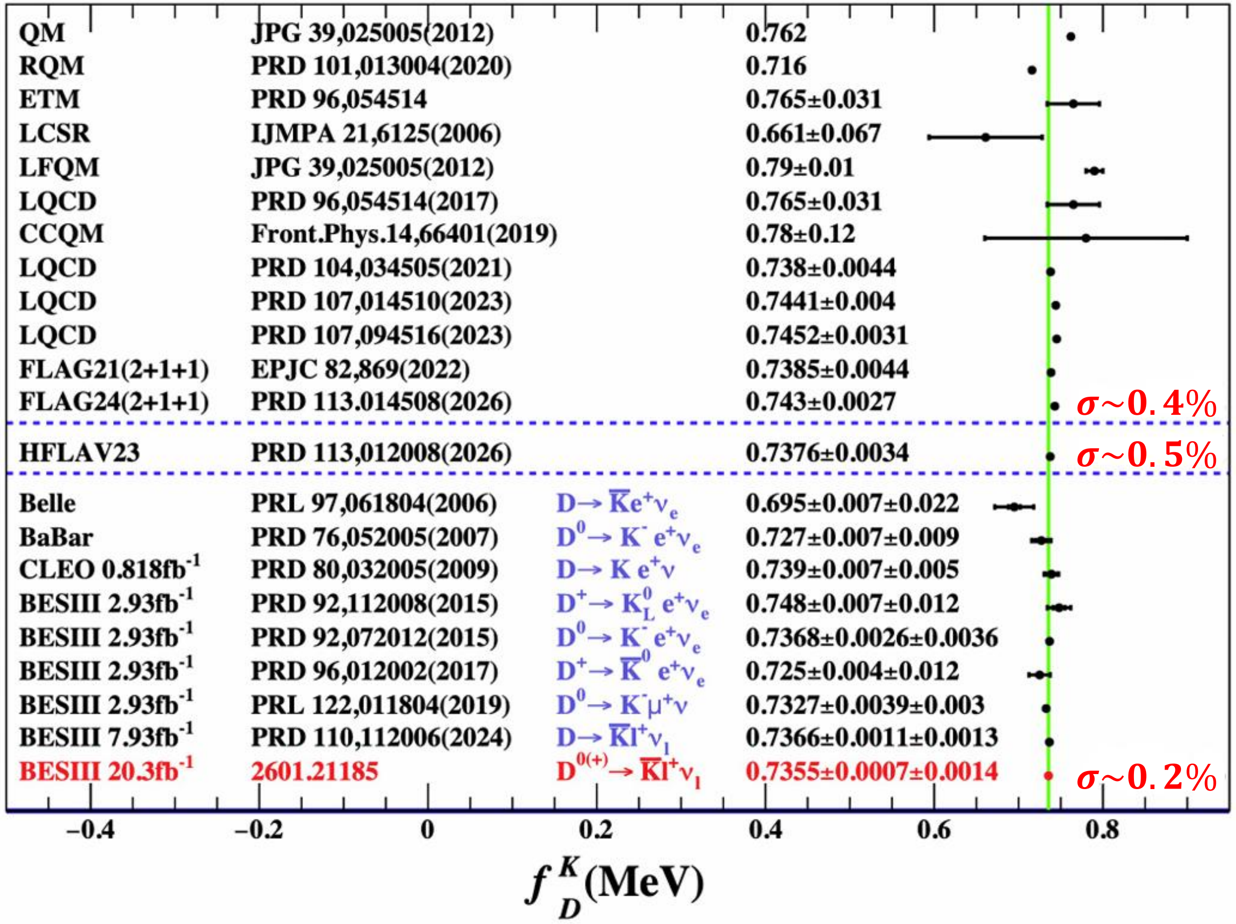
$$R^{\mu/e}_{K^0} = 0.97 \pm 0.12_{\text{stat}} \pm 0.04_{\text{syst}}$$ No LFUV

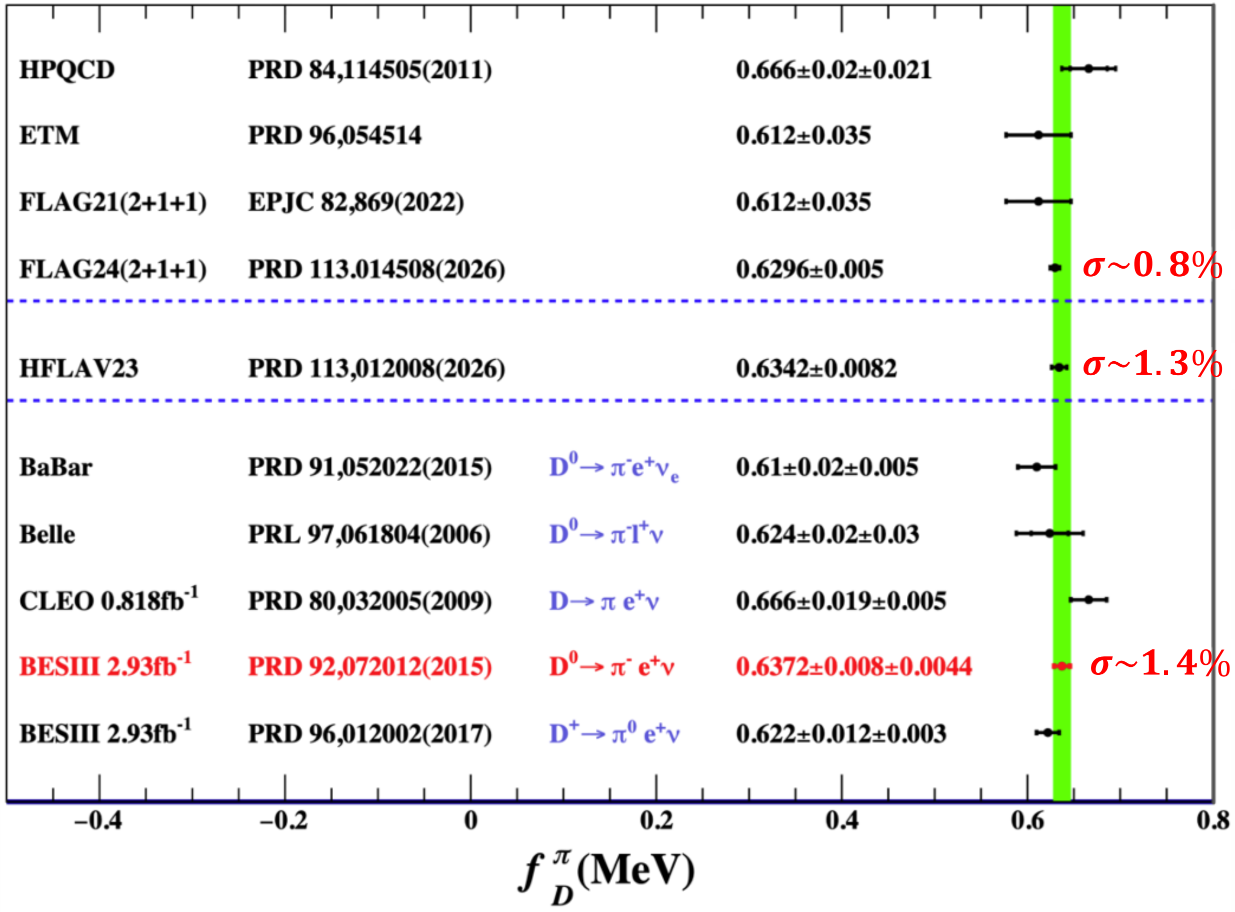
$$f_+^{K^0}(0)|V_{cd}| = 0.140 \pm 0.008_{\text{stat}} \pm 0.003_{\text{syst}}$$ **$(\sigma\sim 6.1\%)$**

$$f_+^{K^0}(0) = 0.623 \pm 0.036_{\text{stat}} \pm 0.011_{\text{syst}}$$

$$|V_{cd}| = 0.222 \pm 0.013_{\text{stat}} \pm 0.005_{\text{syst}} \pm 0.001_{\text{LQCD}}$$

Form factor $f_+^P(0)$



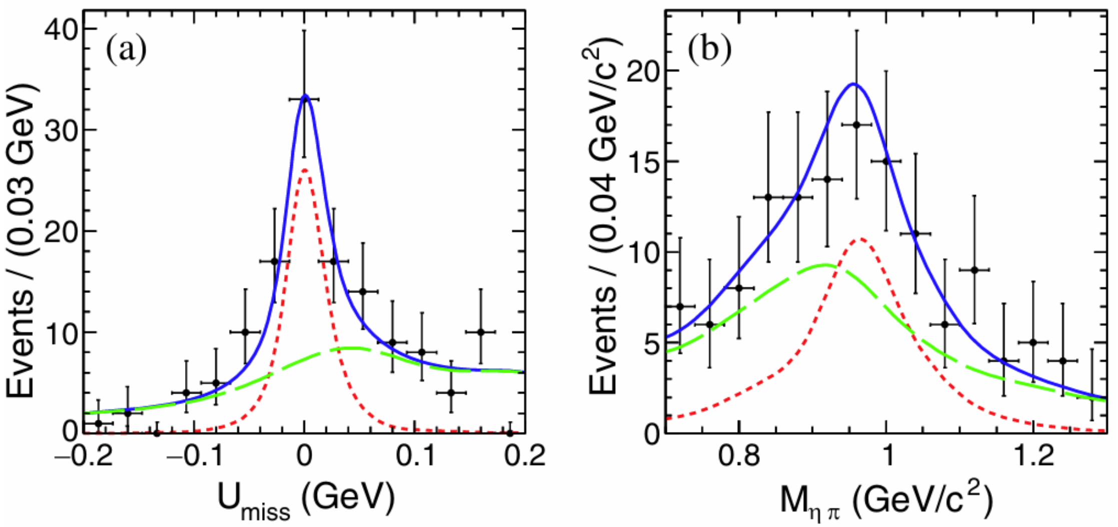


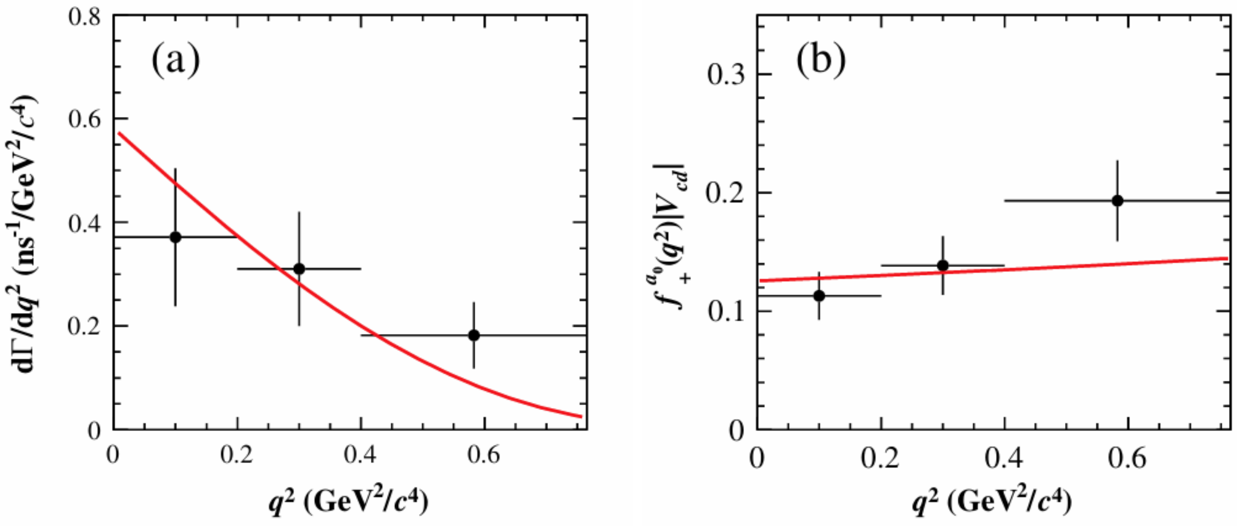
- $f_+^K(0)$ and $f_+^\pi(0)$ are measured with precision of 0.2% and 1.4% at BESIII, and they are consistent with the LQCD calculations.
- The precision of FF $f_+^\pi(0)$ is expected to be ~0.5% with 20.3 fb^{-1} data (results will soon be ready).

$D_{(s)} \to Sl^+\nu_l$: $D^0 \to a_0(980)^- e^+ \nu_e$

- data sample: 7.93 fb^{-1}@3.773 GeV

PRD 111, L091501 (2025)





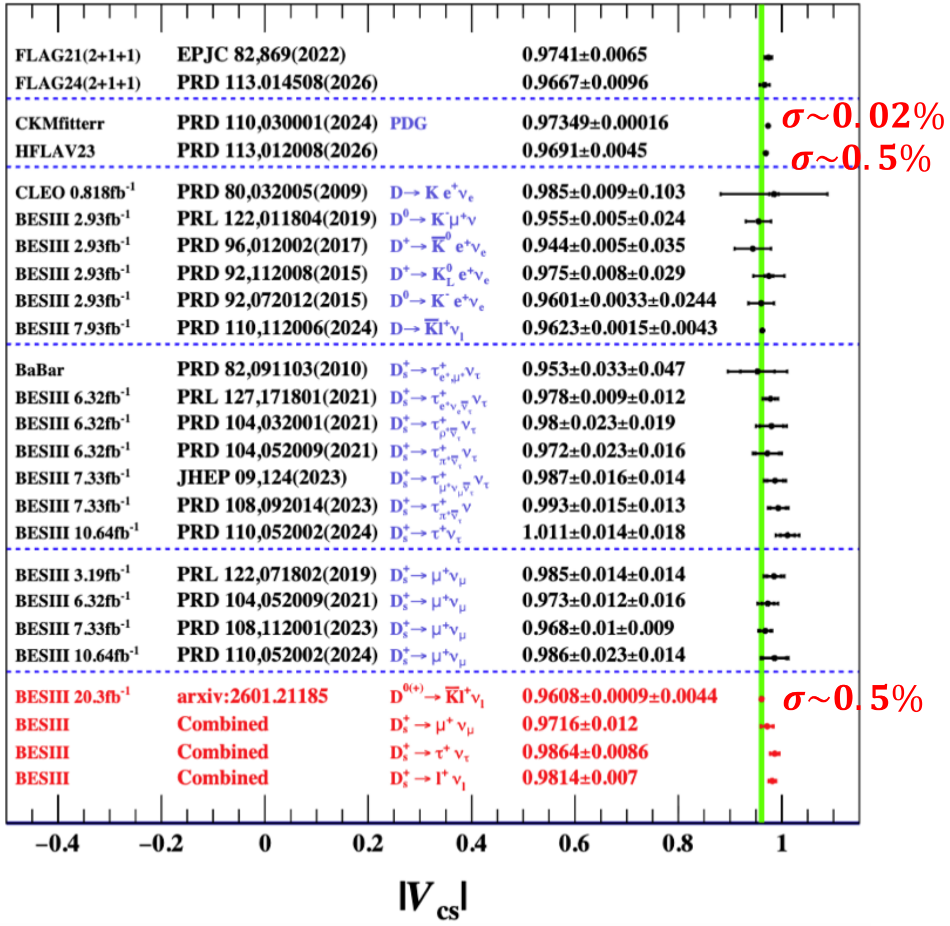
$$\mathcal{B}(D^0 \to a_0(980)^- e^+ \nu_e) \cdot \mathcal{B}(a_0(980)^- \to \eta\pi^-) = (0.86 \pm 0.17_{\rm stat} \pm 0.05_{\rm syst}) \times 10^{-4}$$

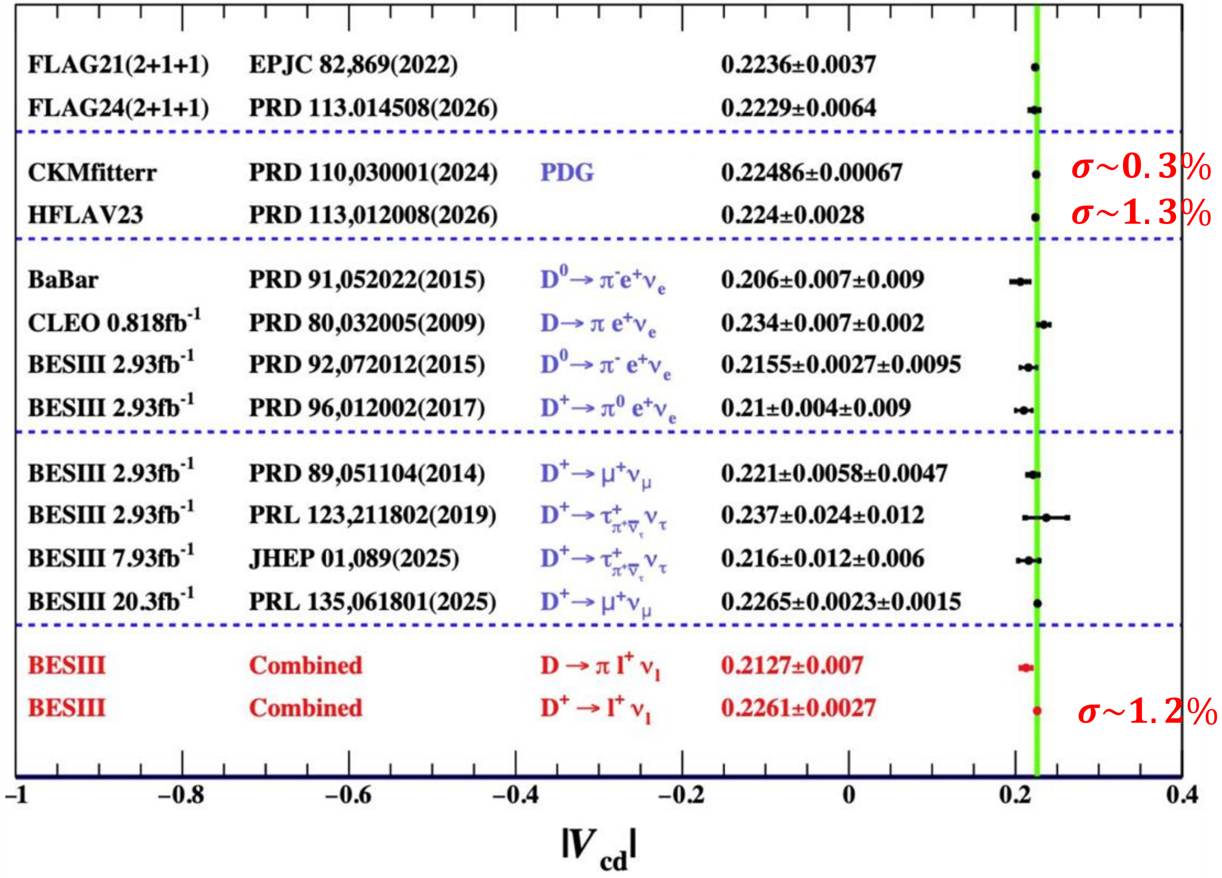
$$f_+^{a_0}(0)|V_{cd}| = 0.126 \pm 0.013_{\rm stat} \pm 0.003_{\rm syst}$$

First measurement of $f_+^{a_0}(0)$

$$f_+^{a_0}(0) = 0.559 \pm 0.056_{\rm stat} \pm 0.013_{\rm syst}$$

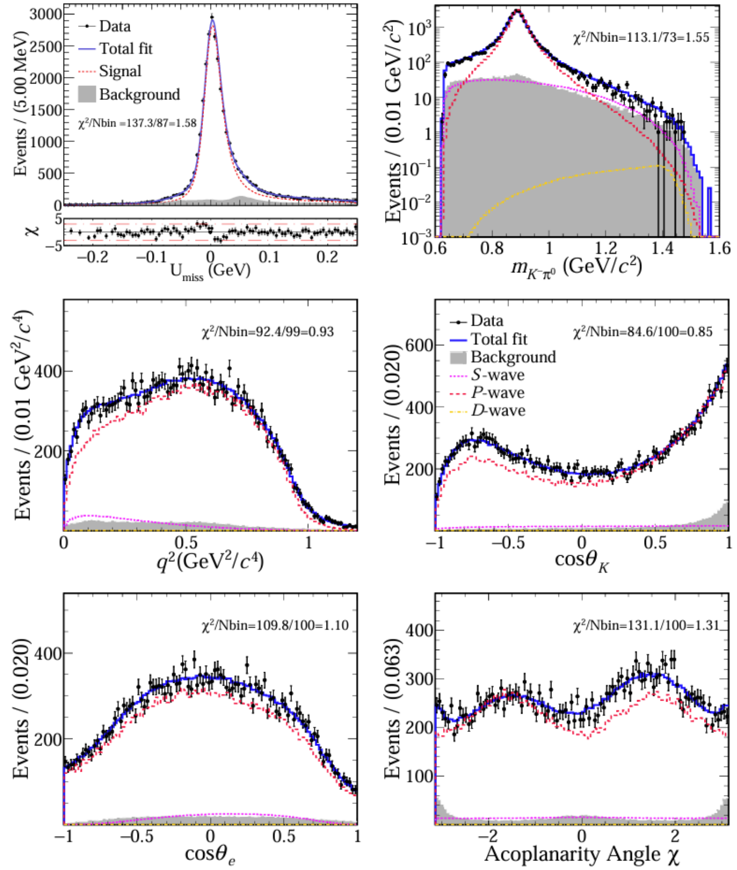
$|V_{cs}|$ & $|V_{cd}|$

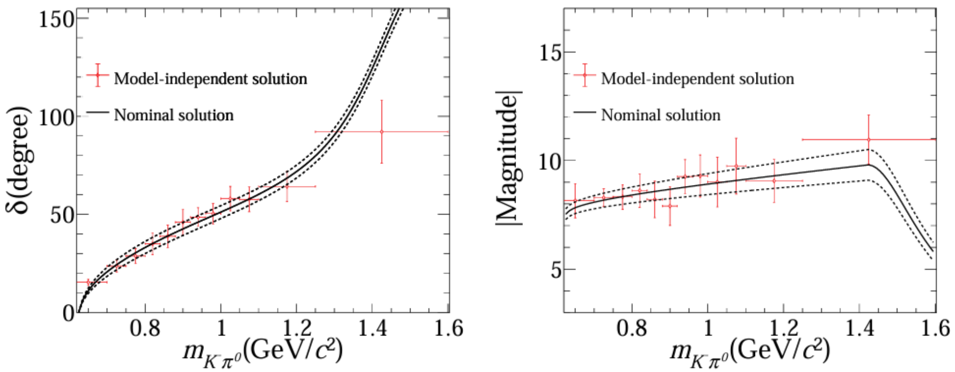




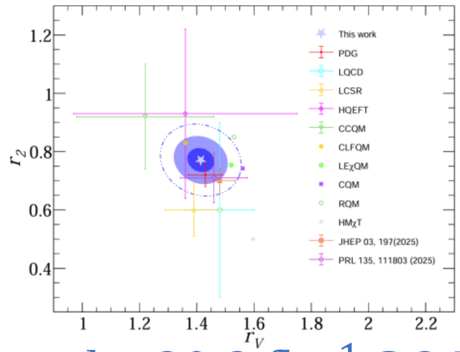
- The $D \to \bar{K} l^+ \nu_l$ processes provide $|V_{cs}|$ with the highest precision (~0.5%).
- The $D \to l^+ \nu_l$ processes provide $|V_{cd}|$ with the highest precision (~1.2%); The precision of $|V_{cd}|$ is expected to be ~0.9% with 20.3 fb^{-1} data via $D \to \pi l^+ \nu_l$ process.

$D_{(s)} \to V(S) l^+ \nu_l$: $D^0 \to K^- \pi^0 e^+ \nu_e$





First model-independent measurement of the phase shift (magnitude) of the S-wave



arXiv: 2603.00743v1

Variable	Value
$r_S(\mathrm{GeV})^{-1}$	$-7.53 \pm 0.22 \pm 0.11$
$r_S^{(1)}$	$0.14 \pm 0.04 \pm 0.01$
$a_{S,\mathrm{BG}}^{1/2}\ (\mathrm{GeV}/c)^{-1}$	$1.98 \pm 0.10 \pm 0.13$
$b_{S,\mathrm{BG}}^{1/2}\ (\mathrm{GeV}/c)^{-1}$	$0.57 \pm 0.53 \pm 0.27$
$m_A(\mathrm{GeV}/c^2)$	$2.72 \pm 0.18 \pm 0.11$
$m_V(\mathrm{GeV}/c^2)$	$1.70 \pm 0.11 \pm 0.02$
r_V	$1.41 \pm 0.05 \pm 0.01$
r_2	$0.77 \pm 0.04 \pm 0.02$
$m_{K^*(892)^-}(\mathrm{MeV}/c^2)$	892.9 ± 0.2
$\Gamma^0_{K^*(892)^-}(\mathrm{MeV})$	$47.9 \pm 0.5 \pm 0.4$
$r_{\mathrm{BW}}\ (\mathrm{GeV}/c)^{-1}$	$3.38 \pm 0.17 \pm 0.16$
$r_{\mathcal{D}}(\mathrm{GeV})^{-4}$	$11.0 \pm 1.6 \pm 1.7$
$\phi_{\mathcal{D}}$ (degree)	$-16.9 \pm 7.7 \pm 3.0$
f_S (%)	$5.86 \pm 0.18 \pm 0.21$
f_P (%)	$93.97 \pm 0.19 \pm 0.21$
f_D (%)	$0.16 \pm 0.05 \pm 0.02$

- data sample: 20.3 fb^{-1}@3.773 GeV

$$\mathcal{B}(D^0 \to K^-\pi^0 e^+\nu_e) = (7.878 \pm 0.063_{\mathrm{stat}} \pm 0.048_{\mathrm{syst}}) \times 10^{-3}$$ **(σ~1.0%)**

$$\mathcal{B}(D^0 \to (K^-\pi^0)_{P\text{-wave}} e^+\nu_e) = (7.403 \pm 0.061_{\mathrm{stat}} \pm 0.048_{\mathrm{syst}}) \times 10^{-3}$$ **$K^*(892)^-$**

$$\mathcal{B}(D^0 \to (K^-\pi^0)_{D\text{-wave}} e^+\nu_e) = (1.265 \pm 0.409_{\mathrm{stat}} \pm 0.032_{\mathrm{syst}}) \times 10^{-5}$$

$$\mathcal{B}(D^0 \to K_2^*(1430)^- e^+\nu_e) = (7.603 \pm 2.457_{\mathrm{stat}} \pm 0.194_{\mathrm{syst}}) \times 10^{-5}$$

First amplitude analysis giving the observation of $K_2^*(1430)$

(significance: 7.9σ)

$$|V_{cs}|A_1(0) = 0.618 \pm 0.010_{\mathrm{stat}} \pm 0.008_{\mathrm{syst}}$$ **(σ~2.1%)**

$$R_{\mu/e} = \frac{\mathcal{B}(D^0 \to K^*(892)^-\mu^+\nu_\mu)}{\mathcal{B}(D^0 \to K^*(892)^-e^+\nu_e)} = 0.928 \pm 0.020_{\mathrm{stat}} \pm 0.012_{\mathrm{syst}}$$

No LFUV

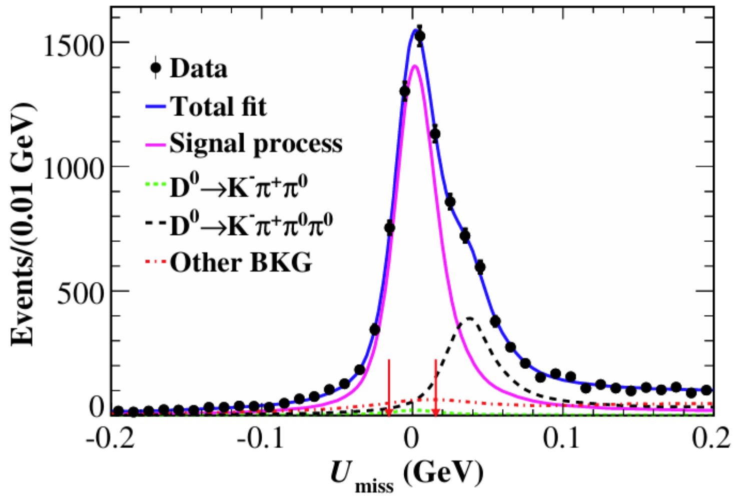
- isospin conservation test:

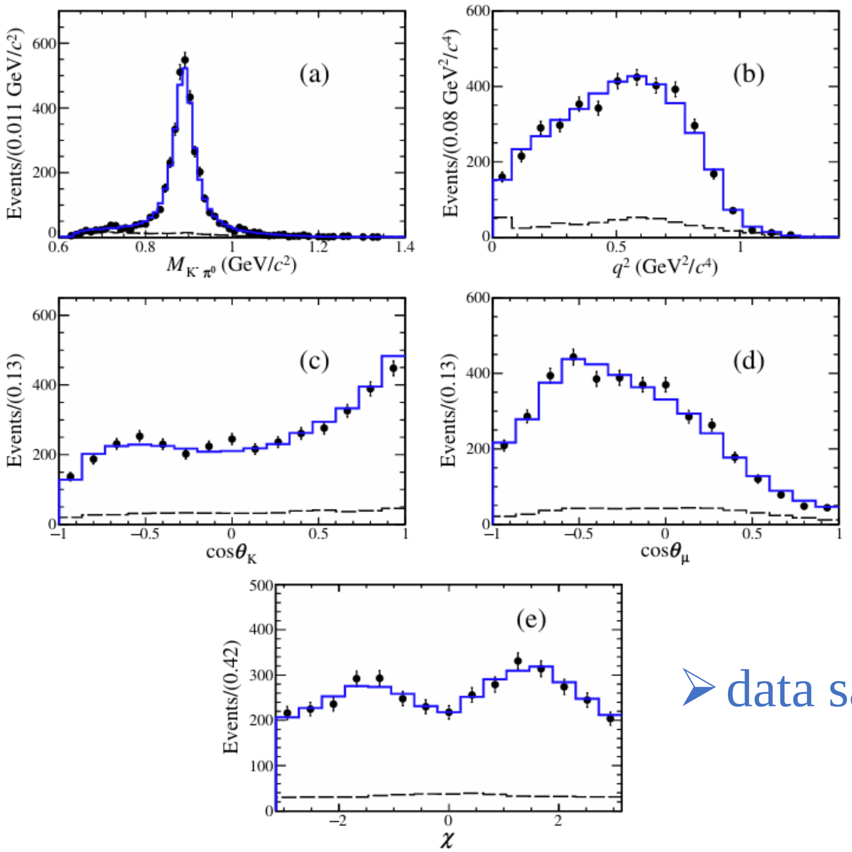
$$\mathcal{R}_{K^{*-}} = \frac{\mathcal{B}(K^*(892)^- \to K^-\pi^0)}{\mathcal{B}(K^*(892)^- \to K_S^0\pi^-)} = \begin{cases} 1.09 \pm 0.02 \pm 0.02\ (e\text{ channel}) \\ 1.07 \pm 0.02 \pm 0.03\ (\mu\text{ channel}) \end{cases}$$

Hints of isospin breaking effect

$D_{(s)} \to V(S)l^{+}\nu_l$: $D^0 \to K^-\pi^0\mu^+\nu_\mu$

PRL 134, 011803(2025)





First measurement

➢ data sample: 7.93 fb^{-1}@3.773 GeV

Variable		Value
r_V	$(\sigma\sim6.9\%)$	$1.37 \pm 0.09 \pm 0.03$
r_2	$(\sigma\sim8.3\%)$	$0.76 \pm 0.06 \pm 0.02$
$M_{K^*(892)^-}$ (MeV/c^2)		$892.89 \pm 0.56 \pm 0.07$
$\Gamma_{K^*(892)^-}$ (MeV)		$47.65 \pm 1.26 \pm 0.36$
r_S $(\mathrm{GeV})^{-1}$		$-8.40 \pm 0.34 \pm 0.38$
$a^{1/2}_{\mathrm{S,BG}}$ $(\mathrm{GeV}/c)^{-1}$		$1.71 \pm 0.22 \pm 0.12$
$f_{K^*(892)^-}$ (%)		$94.24 \pm 0.35 \pm 0.29$
$f_{S\,\mathrm{wave}}$ (%)		$5.76 \pm 0.35 \pm 0.29$

$$\mathcal{B}(D^0 \to K^-\pi^0\mu^+\nu_\mu) = (0.733 \pm 0.014_{\rm stat} \pm 0.011_{\rm syst})\% \qquad (\sigma\sim2.4\%)$$

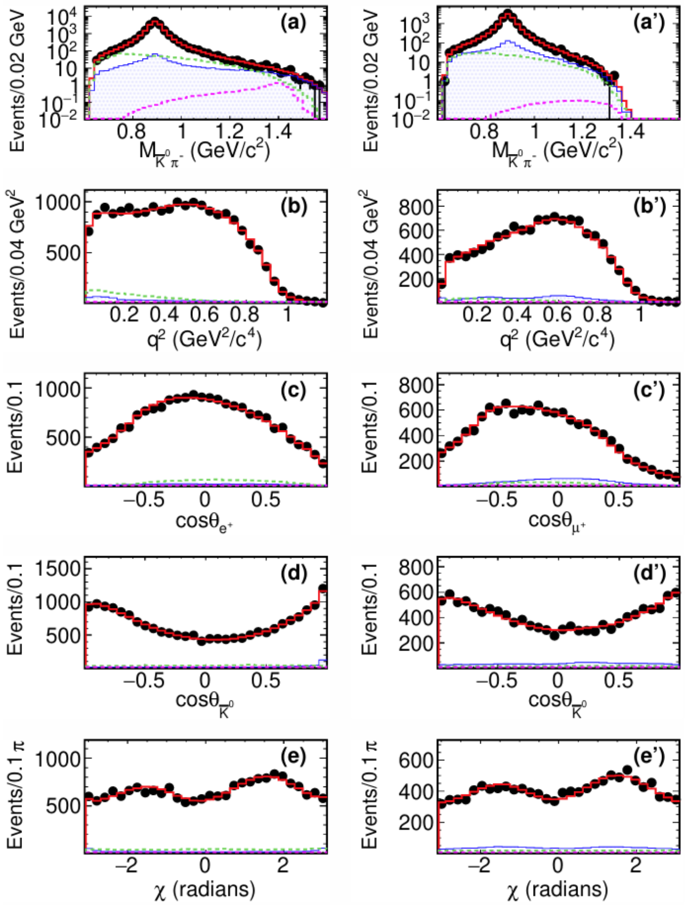
$$\mathcal{B}(D^0 \to K^*(892)^-\mu^+\nu_\mu)\cdot\mathcal{B}(K^*(892)^- \to K^-\pi^0) = (2.073 \pm 0.039_{\rm stat} \pm 0.032_{\rm syst})\%$$

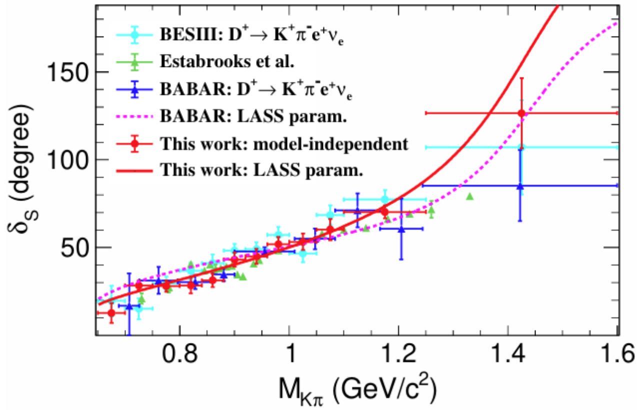
$$\mathcal{B}(D^0 \to (K^-\pi^0)_{S\text{-wave}}\mu^+\nu_\mu) = (4.223 \pm 0.268_{\rm stat} \pm 0.222_{\rm syst}) \times 10^{-4}$$

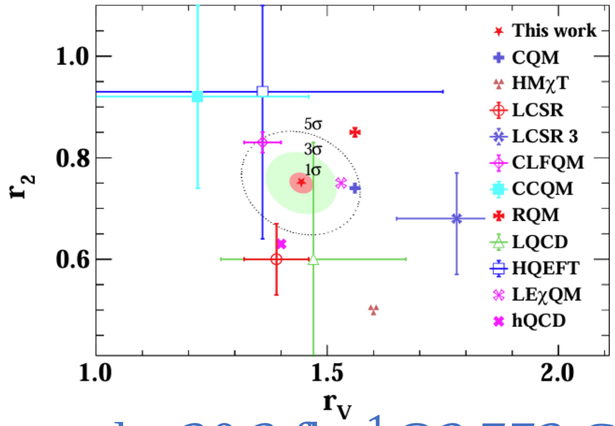
$$R_{\mu/e} = \frac{\mathcal{B}(D^0 \to K^*(892)^-\mu^+\nu_\mu)}{\mathcal{B}(D^0 \to K^*(892)^-e^+\nu_e)} = 1.020 \pm 0.030_{\rm stat} \pm 0.028_{\rm syst}$$

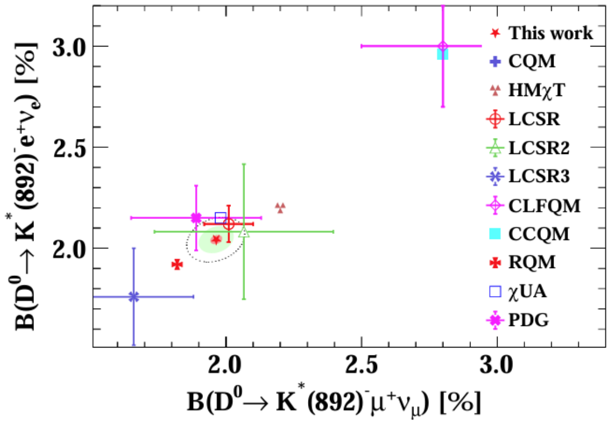
No LFUV

$D_{(s)} \to V(S) l^+ \nu_l$: $D^0 \to \bar{K}^0 \pi^- l^+ \nu_l$









Variable	Value	
r_V	$1.444 \pm 0.026 \pm 0.011$	$(\sigma\sim1.9\%)$
r_2	$0.752 \pm 0.020 \pm 0.004$	$(\sigma\sim2.7\%)$
r_S	$-13.21 \pm 0.49 \pm 0.36$	
$a_{S,\mathrm{BG}}^{1/2}$ $(\mathrm{GeV}/c)^{-1}$	$1.24 \pm 0.11 \pm 0.08$	
$b_{S,\mathrm{BG}}^{1/2}$ $(\mathrm{GeV}/c)^{-1}$	$-2.71 \pm 0.75 \pm 0.71$	
$r_S^{(1)}$	$-0.05 \pm 0.04 \pm 0.03$	
r_D	$11.52 \pm 2.00 \pm 1.16$	
$f_{K^*(892)^-}$	$(94.12 \pm 0.19 \pm 0.09)\%$	
$f_{S-\mathrm{wave}}$	$(5.81 \pm 0.19 \pm 0.09)\%$	
$f_{D-\mathrm{wave}}$	$(0.092 \pm 0.028 \pm 0.018)\%$	

➤ data sample: 20.3 fb^{-1}@3.773 GeV

arXiv: 2603.04136v1

$\mathcal{B}(D^0 \to \bar{K}^0\pi^- e^+\nu_e) = (1.447 \pm 0.012_{\mathrm{stat}} \pm 0.009_{\mathrm{syst}})\%$ $(\sigma\sim1.0\%)$

$\mathcal{B}(D^0 \to \bar{K}^0\pi^- \mu^+\nu_\mu) = (1.391 \pm 0.013_{\mathrm{stat}} \pm 0.008_{\mathrm{syst}})\%$ $(\sigma\sim1.1\%)$

$\mathcal{B}(D^0 \to K_2^*(1430)^- e^+\nu_e) = (4.00 \pm 1.22_{\mathrm{stat}} \pm 0.78_{\mathrm{syst}}) \times 10^{-5}$

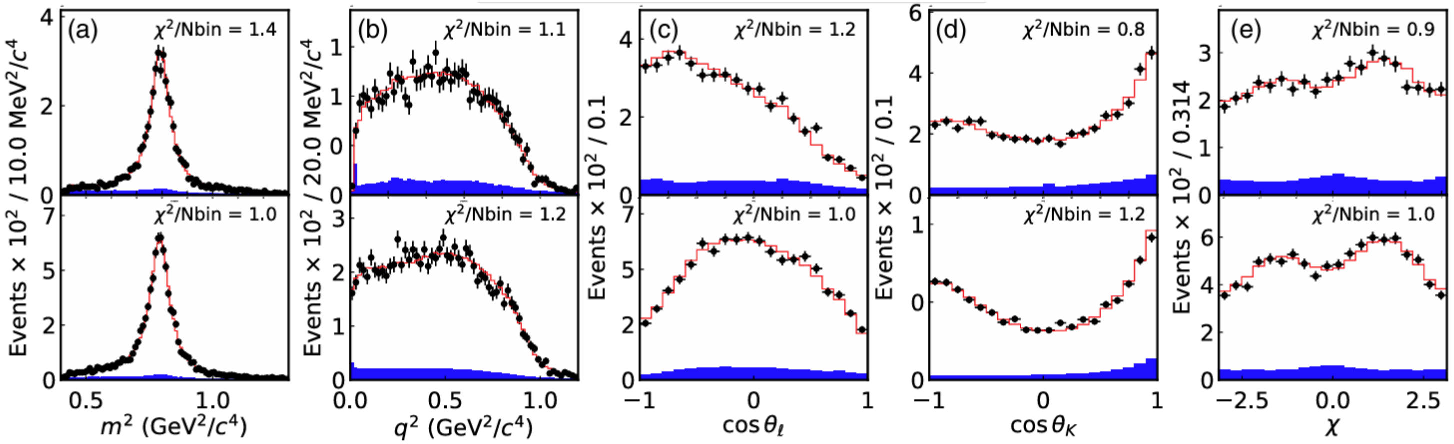
$\mathcal{B}(D^0 \to K_2^*(1430)^- \mu^+\nu_\mu) = (3.85 \pm 1.17_{\mathrm{stat}} \pm 0.75_{\mathrm{syst}}) \times 10^{-5}$

(first observation)

$A_1(0) = 0.618 \pm 0.002_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$ $(\sigma\sim0.7\%)$

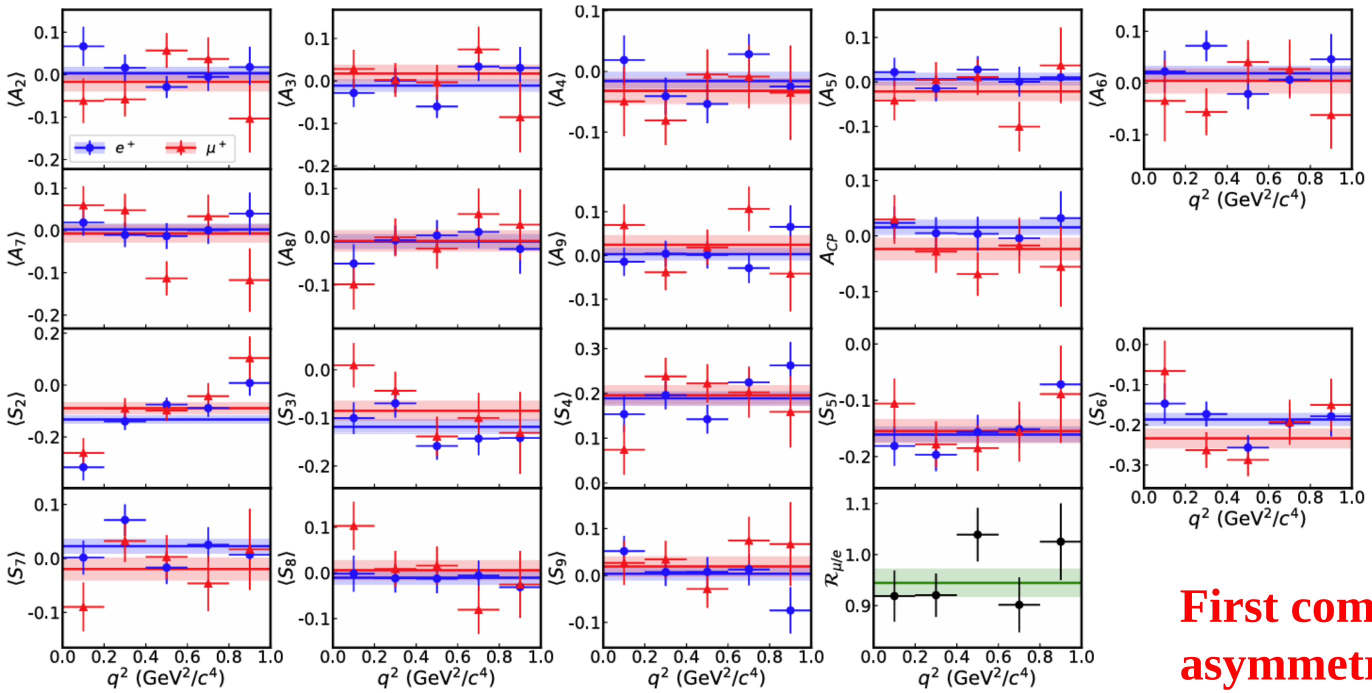
$\mathcal{R}^{\mu/e}_{K^*(892)} = 0.961 \pm 0.012_{\mathrm{stat}} \pm 0.005_{\mathrm{syst}}$ No LFUV

$D_{(s)} \to V(S)l^+\nu_l$: $D^+ \to K_S^0\pi^0 l^+\nu_l$



PRL 135, 171801(2025)

Variable	$D^+ \to K_S^0\pi^0 e^+\nu_e$	$D^+ \to K_S^0\pi^0\mu^+\nu_\mu$	
$m_{\bar{K}^{*0}}$ (MeV/c^2)	$897.3 \pm 0.3 \pm 2.2$		
$\Gamma_{\bar{K}^{*0}}$ (MeV/c^2)	$45.2 \pm 0.6 \pm 0.5$		
r_V	$1.42 \pm 0.03 \pm 0.02$		**(σ~2.5%)**
r_2	$0.75 \pm 0.03 \pm 0.01$		**(σ~4.3%)**
$a^{1/2}_{S,\mathrm{BG}}$ (GeV/c)$^{-1}$	$2.32 \pm 0.11 \pm 0.25$	$1.47 \pm 0.25 \pm 0.22$	
r_S (GeV)$^{-1}$	$-8.44 \pm 0.13 \pm 0.37$	$-9.59 \pm 0.46 \pm 0.58$	
$f_{S\text{-wave}}$	$6.39 \pm 0.17 \pm 0.14$	$7.10 \pm 0.68 \pm 0.41$	
$f_{\bar{K}^{*0}}$	$93.50 \pm 0.18 \pm 0.28$	$92.81 \pm 0.67 \pm 0.47$	



- data sample: 20.3 fb^{-1}@3.773 GeV

$$\mathcal{B}(D^+ \to K_S^0\pi^0\mu^+\nu_\mu) = (0.896 \pm 0.017_{\mathrm{stat}} \pm 0.008_{\mathrm{syst}})\%$$ **(σ~2.1%)**

(first observation)

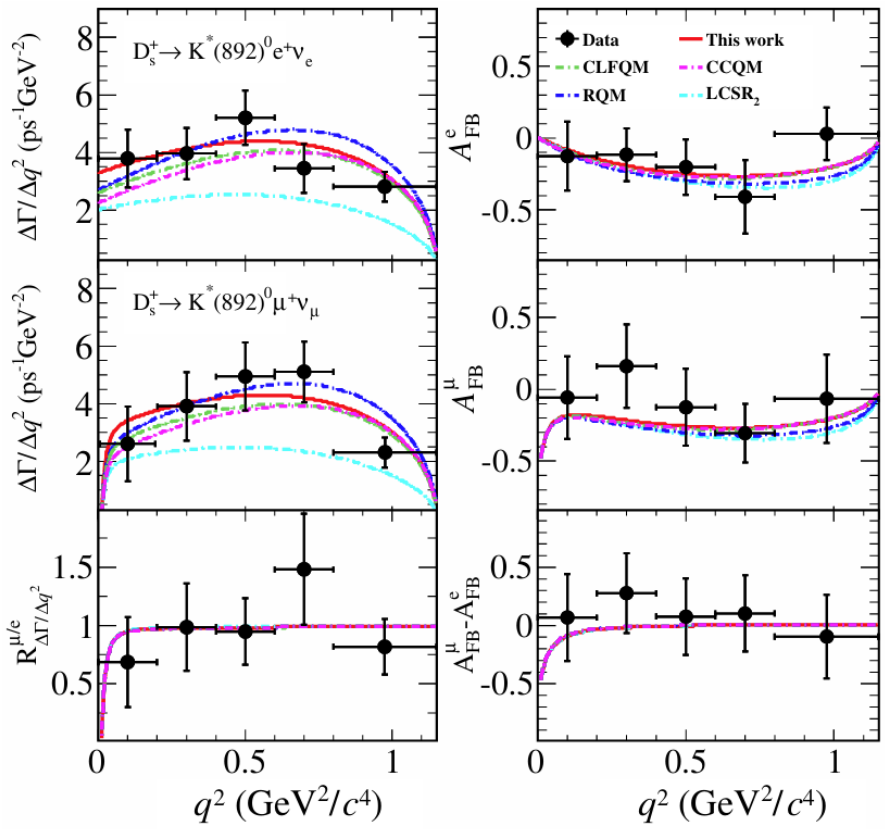
$$\mathcal{B}(D^+ \to K_S^0\pi^0 e^+\nu_e) = (0.943 \pm 0.012_{\mathrm{stat}} \pm 0.010_{\mathrm{syst}})\%$$ **(σ~1.7%)**

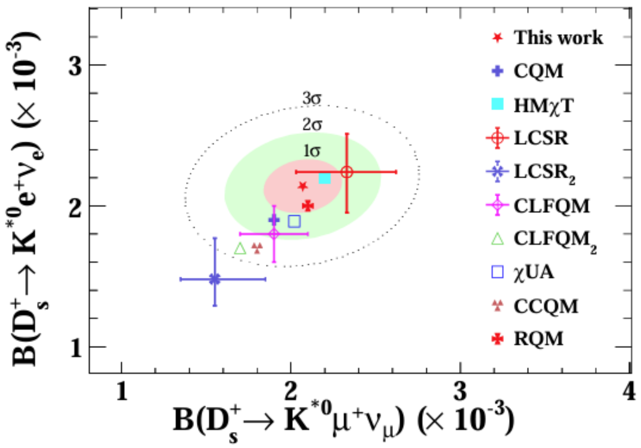
$$R_{\mu/e} = \frac{\mathcal{B}(D^+ \to K_S^0\pi^0\mu^+\nu_\mu)}{\mathcal{B}(D^+ \to K_S^0\pi^0 e^+\nu_e)} = 0.94 \pm 0.02_{\mathrm{stat}} \pm 0.01_{\mathrm{syst}}$$

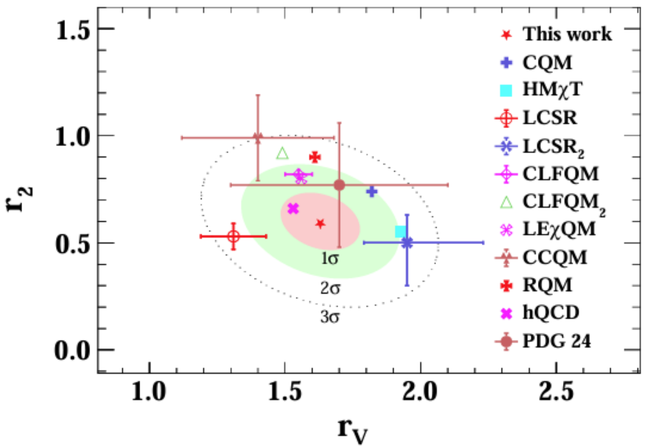
No LFUV

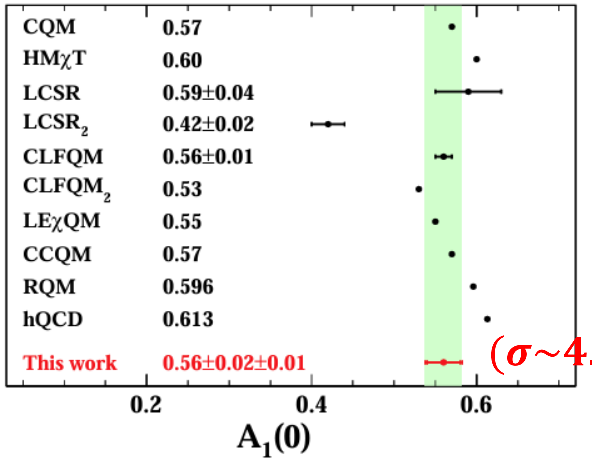
First comprehensive angular and the decay-rate CP asymmetry analysis

$D_{(s)} \to V(S) l^+ \nu_l$: $D_s^+ \to K^- \pi^+ l^+ \nu_l$

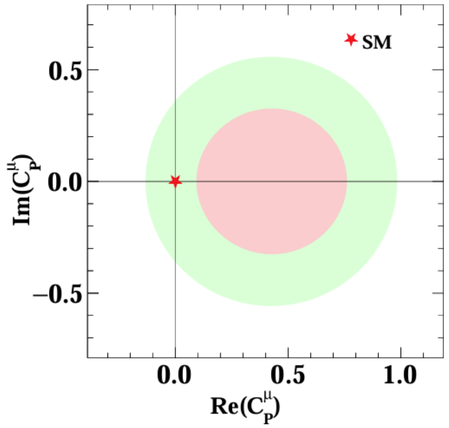








(σ~4.0%)



- data sample: $7.33\ \mathrm{fb}^{-1}$@$4.128 - 4.226$ GeV

$$\mathcal{B}(D_s^+ \to K^*(892)^0 e^+ \nu_e) = (2.14 \pm 0.18_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}}) \times 10^{-3}$$

$$\mathcal{B}(D_s^+ \to K^*(892)^0 \mu^+ \nu_\mu) = (2.07 \pm 0.22_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}}) \times 10^{-3}$$ **(first observation)**

$$r_V = 1.63 \pm 0.14_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}} \qquad r_2 = 0.60 \pm 0.13_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}}$$

$$R_{\mu/e} = \frac{\mathcal{B}(D_s^+ \to K^*(892)^0 \mu^+ \nu_\mu)}{\mathcal{B}(D_s^+ \to K^*(892)^0 e^+ \nu_e)} = 0.97 \pm 0.13_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$$

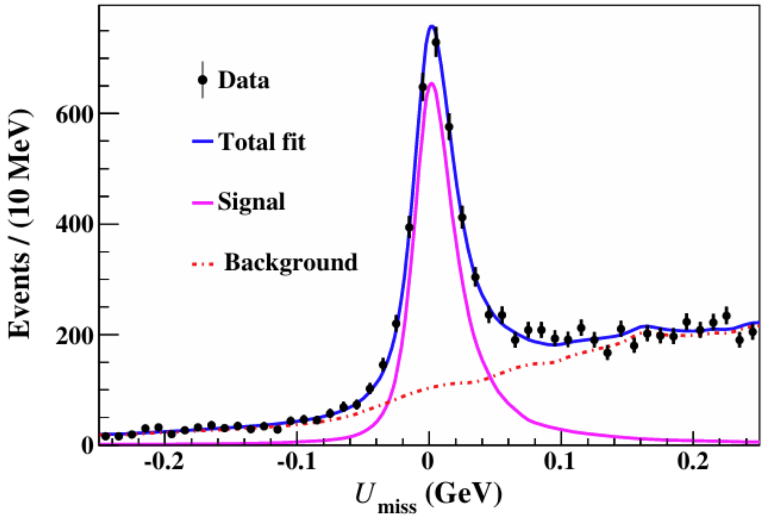
arXiv:2605.07176v1

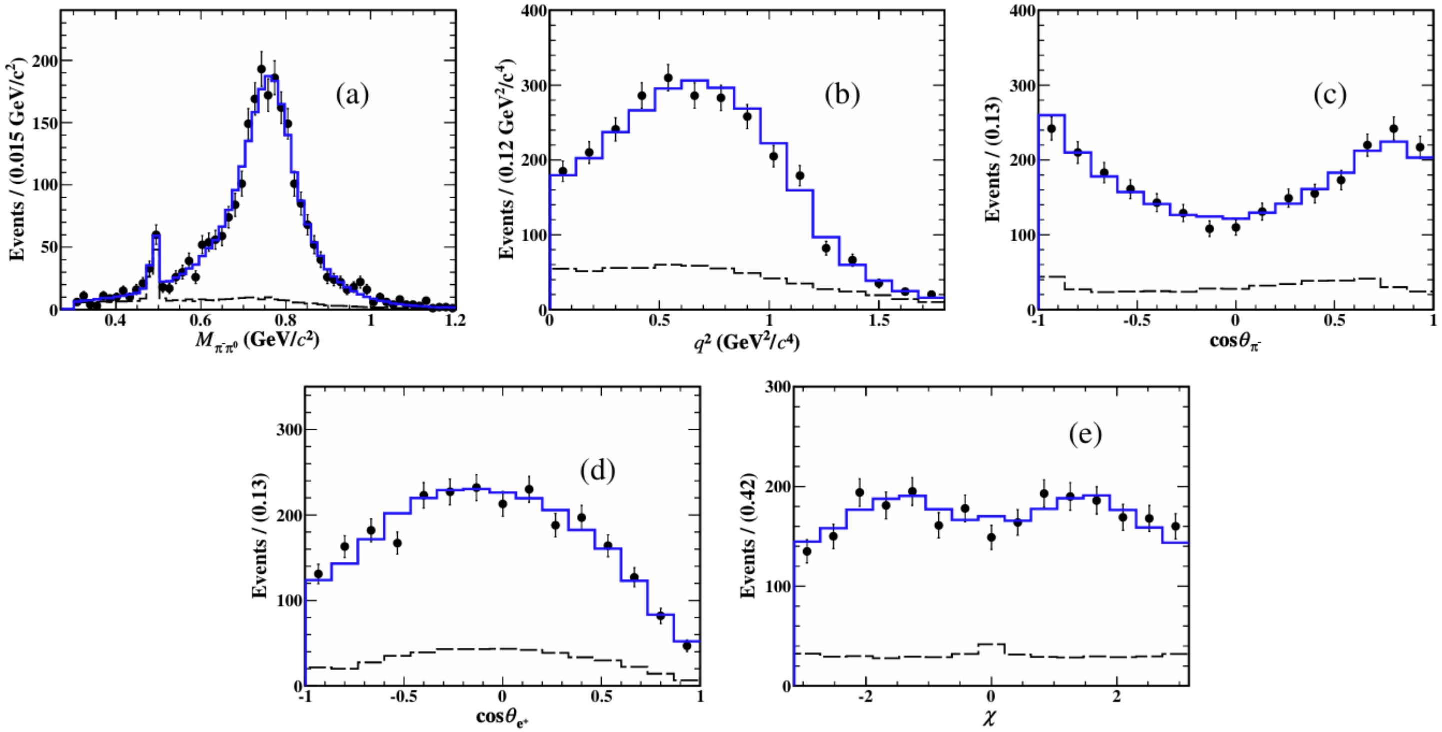
No LFUV

First model-independent measurement of the differential decay rates and the forward backward asymmetries

$D_{(s)} \to V(S)l^+\nu_l$: $D^0 \to \rho(770)^- e^+\nu_e$

PRD 110, 112018 (2024)





Improved precision

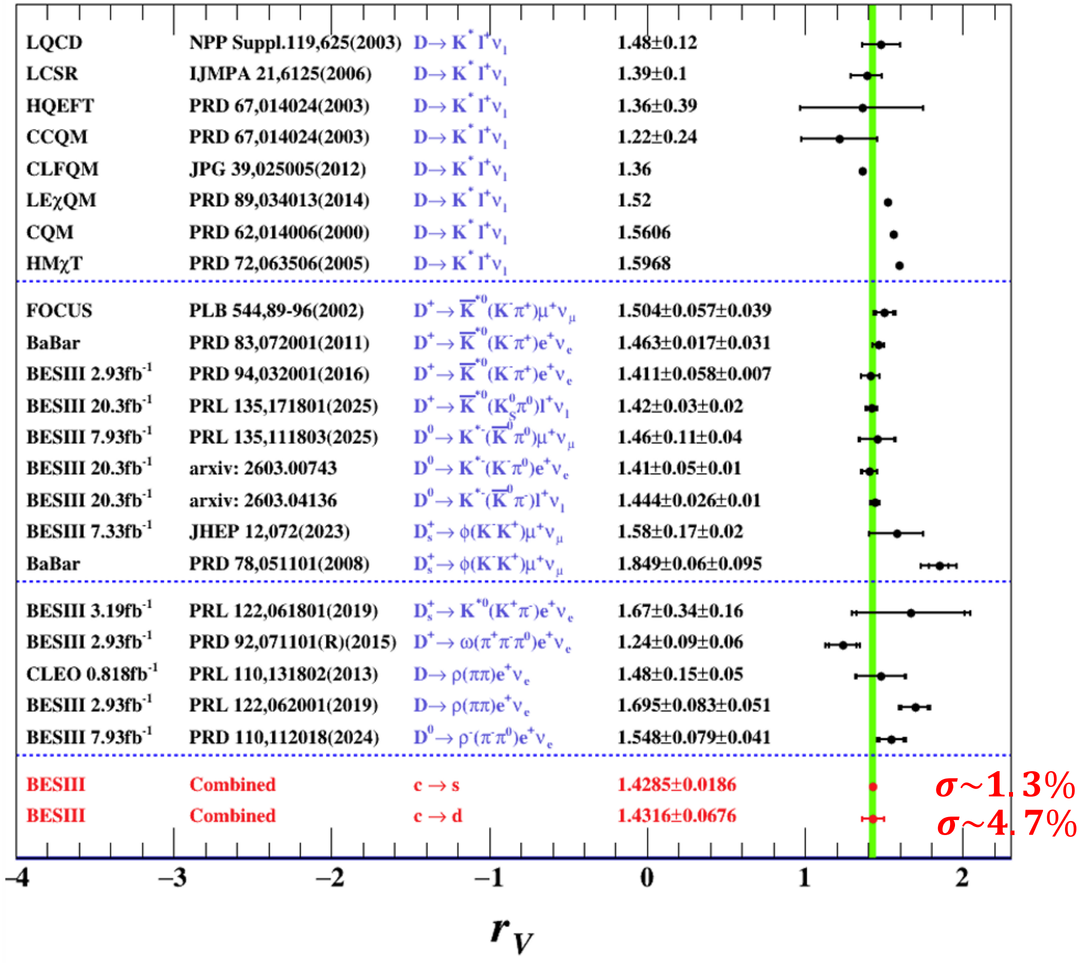
- data sample: 7.93 fb^{-1}@3.773 GeV

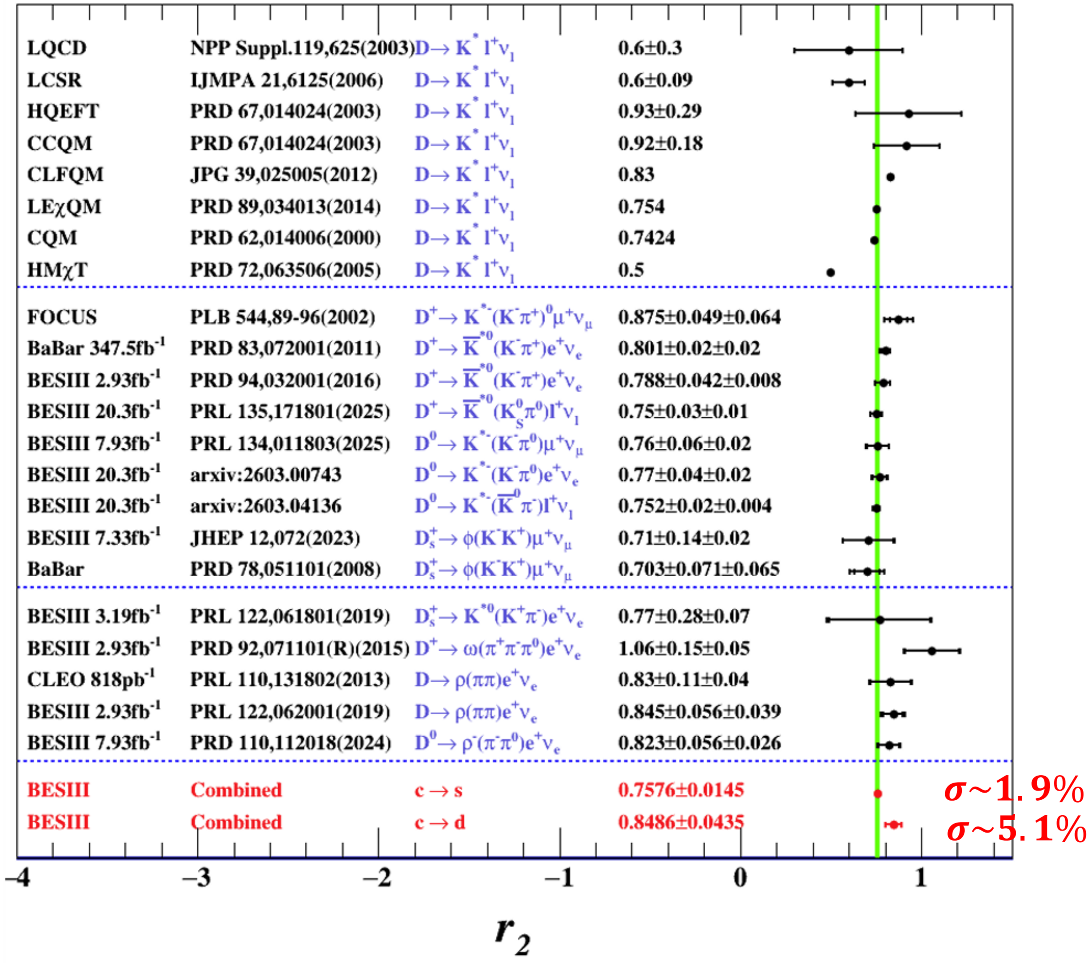
$$\mathcal{B}(D^0 \to \rho(770)^- e^+\nu_e) = (1.439 \pm 0.033_{\rm stat} \pm 0.027_{\rm syst}) \times 10^{-3}$$

$(\sigma \sim 3.0\%)$

Experiments	r_V $(\sigma \sim 5.8\%)$	r_2 $(\sigma \sim 7.5\%)$
This analysis	$1.548 \pm 0.079 \pm 0.041$	$0.823 \pm 0.056 \pm 0.026$
BESIII [39]	$1.695 \pm 0.083 \pm 0.051$	$0.845 \pm 0.056 \pm 0.039$
CLEO [40]	$1.48 \pm 0.15 \pm 0.05$	$0.83 \pm 0.11 \pm 0.04$

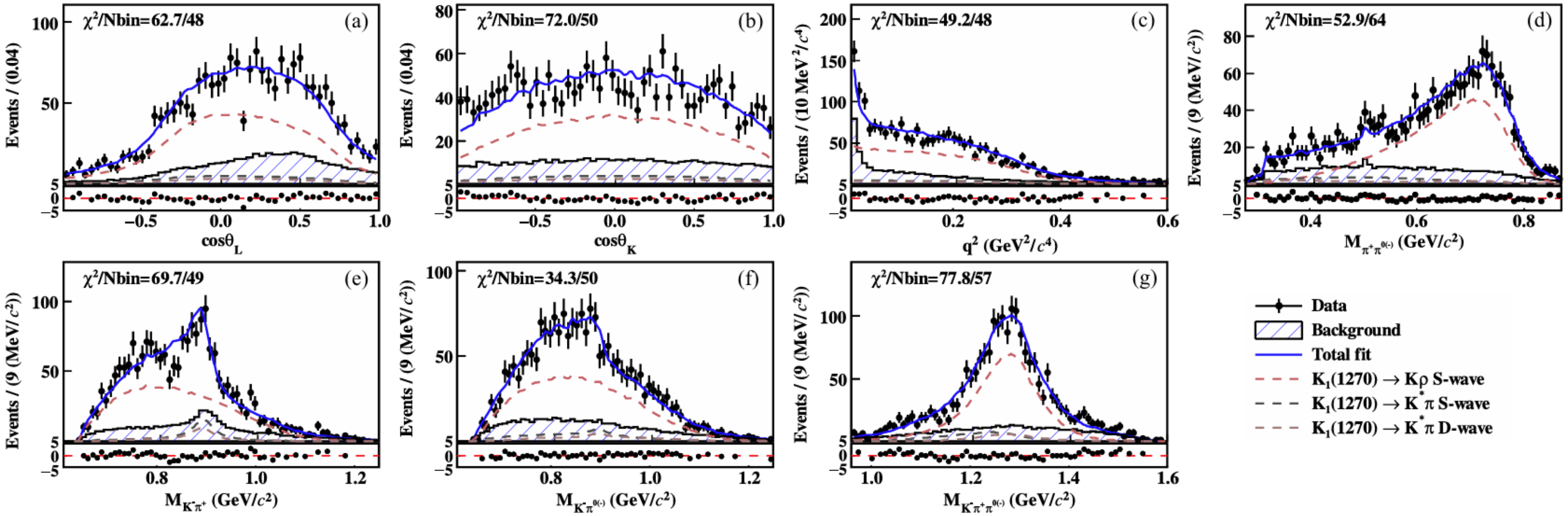
r_V & r_2

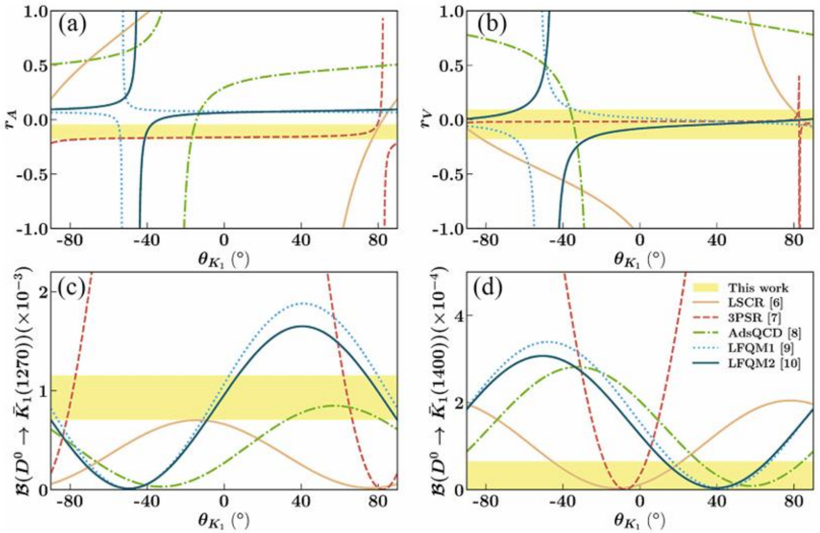




- The precision of r_V and r_2 reach 1.3% and 1.9% at BESIII.
- More accurate theoretical calculations are needed.

$D_{(s)} \to A l^+ \nu_l$: $D \to \bar{K}_1 e^+ \nu_e$





Variable	Value
$r_A(\times 10^{-2})$	$-11.2 \pm 1.0 \pm 0.9$
$r_V(\times 10^{-2})$	$-4.3 \pm 1.0 \pm 2.5$
$f^{D^+}_{\rho K^-}$ (%)	$79.3 \pm 2.0 \pm 25.7$
$f^{D^+}_{\pi \bar{K}^*(892)}$ (%)	$10.9 \pm 1.2 \pm 3.0$
$f^{D^+}_{\bar{K}_1(1400)}$ (%)	< 5
$f^{D^0}_{\rho K^-}$ (%)	$71.8 \pm 2.3 \pm 23.9$
$f^{D^0}_{\pi \bar{K}^*(892)}$ (%)	$19.5 \pm 1.9 \pm 5.2$
$f^{D^0}_{\bar{K}_1(1400)}$ (%)	< 9
$m_{K_1(1270)}$ (MeV$/c^2$)	$1271 \pm 3 \pm 7$
$\Gamma_{K_1(1270)}$ (MeV)	$168 \pm 10 \pm 20$

➢ data sample: 20.3 fb^{-1}@3.773 GeV

PRL 135, 091801 (2025)

$$\mathcal{B}(D^+ \to K^-\pi^+\pi^0 e^+\nu_e) = (1.27 \pm 0.06_{\rm stat} \pm 0.04_{\rm syst}) \times 10^{-3}$$

$$\mathcal{B}(D^0 \to K^-\pi^+\pi^- e^+\nu_e) = (0.32 \pm 0.02_{\rm stat} \pm 0.02_{\rm syst}) \times 10^{-3}$$

$$\mathcal{B}(D^+ \to \bar{K}_1(1270)^0 e^+\nu_e) = (2.27 \pm 0.11_{\rm stat} \pm 0.07_{\rm syst} \pm 0.07_{\rm input}) \times 10^{-3}$$

$$\mathcal{B}(D^0 \to K_1(1270)^- e^+\nu_e) = (1.02 \pm 0.06_{\rm stat} \pm 0.06_{\rm syst} \pm 0.03_{\rm input}) \times 10^{-3}$$

$$\mathcal{B}(D^+ \to \bar{K}_1(1400)^0 e^+\nu_e) < 1.4 \times 10^{-4}$$

$$\mathcal{B}(D^0 \to K_1(1400)^- e^+\nu_e) < 0.7 \times 10^{-4}$$

➢ up-down asymmetry : $\mathcal{A}'_{\rm ud} = 0.01 \pm 0.11$

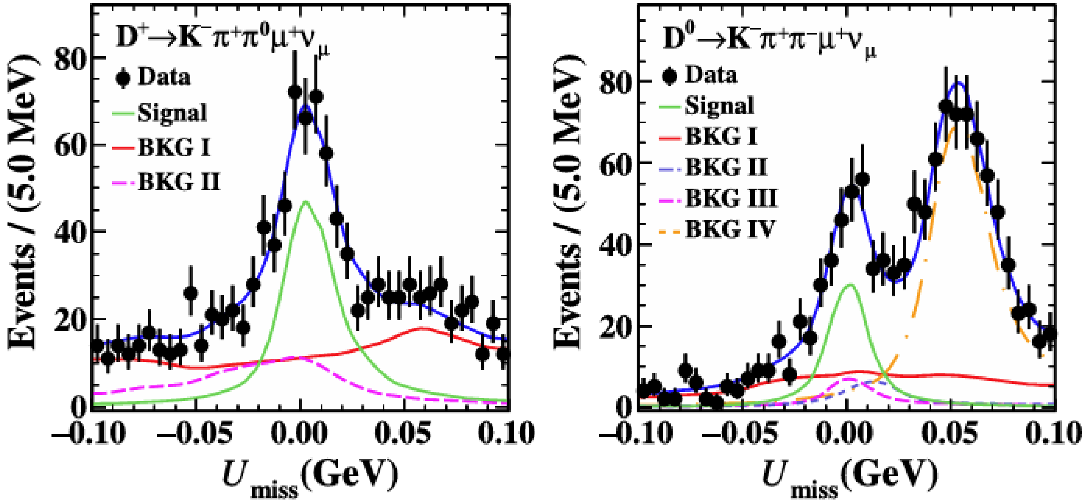
Consistent with SM prediction: 0.092±0.022

First measurements of the hadronic FFs in the SL transitions of heavy mesons into axial-vector mesons

$D_{(s)} \to A l^+ \nu_l$: $D \to \bar{K}_1 \mu^+ \nu_\mu$

PRD 111, L071101 (2025)

First observation



- data sample: 7.93 fb^{-1}@3.773 GeV

$$R_{\mu/e}^{D^+} = \frac{\mathcal{B}(D^+ \to \bar{K}_1(1270)^0 \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e)} = 1.03 \pm 0.14_{\text{stat}}\,{}^{+0.11}_{-0.15}{}_{\text{syst}}$$

$$R_{\mu/e}^{D^0} = \frac{\mathcal{B}(D^0 \to K_1(1270)^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \to K_1(1270)^- e^+ \nu_e)} = 0.74 \pm 0.13_{\text{stat}}\,{}^{+0.08}_{-0.13}{}_{\text{syst}}$$

No LFUV

- isospin conservation test:

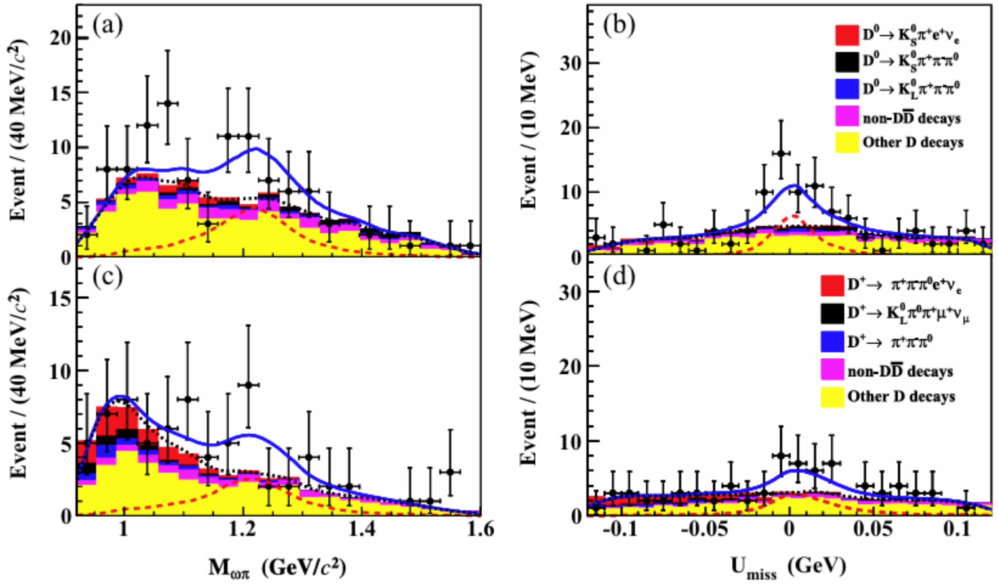
$$\frac{\Gamma(D^+ \to \bar{K}_1(1270)^0 \mu^+ \nu_\mu)}{\Gamma(D^0 \to K_1(1270)^- \mu^+ \nu_\mu)} = 1.22 \pm 0.10_{\text{stat}} \pm 0.09_{\text{syst}}$$

		CLFQM [10]	3PSR [9]	LCSR [11]	LCSR [11]	LCSR [11]	CLFQM [12]	LFQM [12]	LCSR [12]	This work	
Decay	θ_{K1}	33°	37°		$-(34 \pm 13)°$			45°		$\cdots$	
$D^+ \to \bar{K}_1^0 \mu^+ \nu_\mu$	Predicted	2.60 ± 0.30	2.70 ± 0.25	18.59 ± 0.31	16.86 ± 0.27	19.73 ± 0.32	$5.9^{+0.47}_{-0.11}$	$3.7^{+0.00}_{-0.41}$	$1.4^{+0.15}_{-0.27}$	$2.36 \pm 0.20^{+0.18}_{-0.27} \pm 0.48$	**12.5σ**
	Deviation (σ)	0.4	0.6	27.3	25.2	29.0	6.8	2.6	1.8		
$D^0 \to K_1^- \mu^+ \nu_\mu$	Predicted	$\cdots$	1.03 ± 0.1	8.09 ± 0.15	6.78 ± 0.12	8.92 ± 0.16	$2.3^{+0.19}_{-0.44}$	$1.5^{+0.00}_{-0.16}$	$0.54^{+0.06}_{-0.11}$	$0.78 \pm 0.11^{+0.05}_{-0.09} \pm 0.15$	**6.0σ**
	Deviation (σ)	$\cdots$	1.1	28.6	25.1	31.1	5.4	2.8	1.1		

$D_{(s)} \to Al^+\nu_l$: $D \to b_1 e^+\nu_e$ & $D_s^+ \to f_1 e^+\nu_e$

$D \to b_1(1235)e^+\nu_e$

PRL 136, 021801 (2026)



- data sample: 7.93 fb^{-1}@3.773 GeV

(first observation)

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

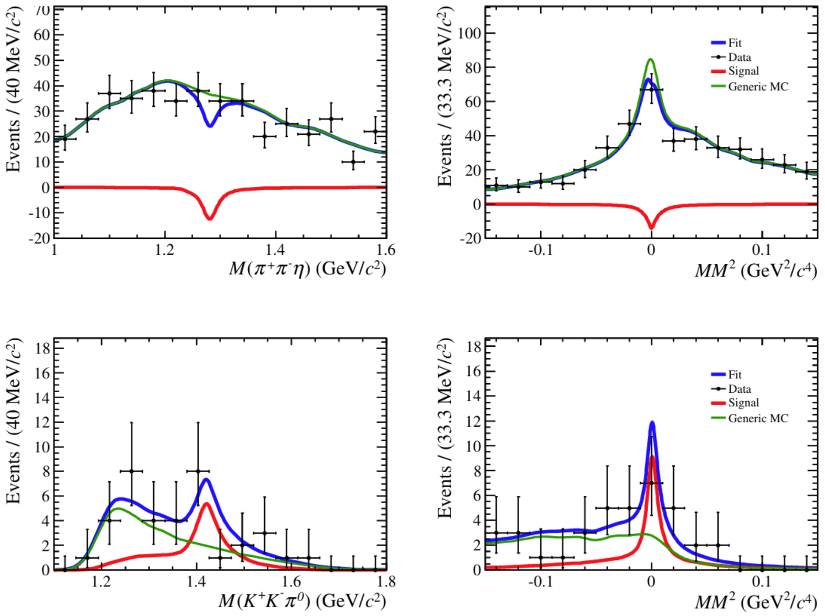
(first evidence)

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

- isospin conservation test: $\frac{\Gamma(D^0 \to b_1(1235)^- e^+\nu_e)}{2\Gamma(D^+ \to b_1(1235)^0 e^+\nu_e)} = 0.78 \pm 0.19_{\rm stat} {}^{+0.04}_{-0.05}{}_{\rm syst}$

$D_s^+ \to f_1 e^+\nu_e$

arXiv: 2601.16938v1



- data sample: 7.33 fb^{-1}@4.128 – 4.226 GeV

(first evidence)

$$\mathcal{B}(D_s^+ \to f_1(1420)e^+\nu_e) \cdot \mathcal{B}(f_1(1420) \to K^+K^-\pi^0) = (4.5^{+2.0}_{-1.7}{}_{\rm stat} \pm 0.4_{\rm syst}) \times 10^{-4}$$

$$\mathcal{B}(D_s^+ \to f_1(1420)e^+\nu_e) \cdot \mathcal{B}(f_1(1420) \to K^+K^-\pi^0) < 7.6 \times 10^{-4} \quad (90\%\ \rm CL)$$

(first upper limit)

$$\mathcal{B}(D_s^+ \to f_1(1285)e^+\nu_e) \cdot \mathcal{B}(f_1(1285) \to \pi^+\pi^-\eta) < 1.7 \times 10^{-4} \quad (90\%\ \rm CL)$$

Summary and prospect

- Publications covered in this talk

Process	Decay channel	$\mathcal{L}_{\rm int}$ (fb^{-1}) / $E_{\rm cm}$ (GeV)	Reference
$D^+ \to \ell^+\nu_\ell$	$D^+ \to \mu^+\nu_\mu$	20.3 / 3.773	PRL 135, 061801 (2025)
	$D^+ \to \tau^+\nu_\tau$	7.93 / 3.773	JHEP01(2025)089
$D_s^+ \to \ell^+\nu_\ell$	$D_s^+ \to \tau^+\nu_\tau$ ($\tau^+ \to \pi^+\bar{\nu}_\tau$)	7.33 / 4.128-4.226	PRD 108, 092014 (2023)
	$D_s^+ \to \tau^+\nu_\tau$ ($\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$)	7.33 / 4.128-4.226	JHEP09(2023)124
	$D_s^+ \to \mu^+\nu_\mu$	7.33 / 4.128-4.226	PRD 108.112001(2023)
	$D_s^+ \to \tau^+\nu_\tau$ ($\tau^+ \to e^+\nu_e\bar{\nu}_\tau, \mu^+\nu_\mu\bar{\nu}_\tau, \pi^+\bar{\nu}_\tau, \pi^+\pi^0\bar{\nu}_\tau$)	7.33 / 4.128-4.226	arXiv:2606.11593v1
$D_{(s)} \to P\ell^+\nu_\ell$	$D \to \bar{K}\ell^+\nu_\ell$	20.3 / 3.773	arXiv:2601.21185, 2601.21196
	$D^+ \to \eta'\ell^+\nu_\ell$	20.3 / 3.773	PRL 134, 111801 (2025)
	$D^+ \to \eta\ell^+\nu_\ell$	20.3 / 3.773	arXiv: 2506.02521v2
	$D_s^+ \to \bar{K}\ell^+\nu_\ell$	7.33 / 4.128-4.226	PRL 136, 161802 (2026)
$D_{(s)} \to S\ell^+\nu_\ell$	$D^0 \to a_0(980)^-e^+\nu_e$	7.93 / 3.773	PRD 111, L091501 (2025)
$D_{(s)} \to V(S)\ell^+\nu_\ell$	$D^0 \to K^-\pi^0e^+\nu_e$	20.3 / 3.773	arXiv:2603.00743v1
	$D^0 \to K^-\pi^0\mu^+\nu_\mu$	7.93 / 3.773	PRL 134, 011803(2025)
	$D^0 \to \bar{K}^0\pi^-\ell^+\nu_\ell$	20.3 / 3.773	arXiv: 2603.04136v1
	$D^+ \to K_S^0\pi^0\ell^+\nu_\ell$	20.3 / 3.773	PRL 135, 171801(2025)
	$D_s^+ \to K^-\pi^+\ell^+\nu_\ell$	7.33 / 4.128-4.226	arXiv:2605.07176v1
	$D^0 \to \rho(770)^-e^+\nu_e$	7.93 / 3.773	PRD 110, 112018 (2024)
$D_{(s)} \to A\ell^+\nu_\ell$	$D \to \bar{K}_1(1270)e^+\nu_e$	20.3 / 3.773	PRL 135, 091801 (2025)
	$D \to \bar{K}_1(1270)\mu^+\nu_\mu$	7.93 / 3.773	PRD 111, L071101 (2025)
	$D \to b_1(1235)e^+\nu_e$	7.93 / 3.773	PRL 136, 021801 (2026)
	$D_s^+ \to f_1e^+\nu_e$	7.33 / 4.128-4.226	arXiv:2601.16938v1

Summary and prospect

- Summary

- Precise measurements of f_{D^+} and $f_{D_s^+}$ in leptonic $D_{(s)}$ decays ⇒ 1.2%/0.7%
- Precise measurements of $|V_{cs}|$ and $|V_{cd}|$ in (semi)-leptonic$D_{(s)}$ decays ⇒ 0.5%/1.2%
- Precise measurements of form factors $f_+^K(0)$ (0.2%), r_V (1.3%), r_2 (1.9%)... in semi-leptonic $D_{(s)}$ decays
- No evidence of LFU violation found in charm sector
- Study of the nature of light hadrons (a_0, f_0, K_1......)
- More accurate theoretical calculations are still needed

Thank you!

- Prospect

- More precision measurements and search of rare (semi-)leptonic $D_{(s)}$ decays will be presented. More analyses of inclusive semileptonic $D_{(s)}$ decays at BESIII are also undergoing.
- BEPCII-U has demonstrated successful high-energy operation. Additional 3 fb^{-1} data @4.178 GeV in the near future will further improve the precisions in D_s sector [CPC44(2020)040001].