Recent results of semi-leptonic $D \to P/S\ell^+\nu_\ell$ decays at BESIII

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2 Dataset and method

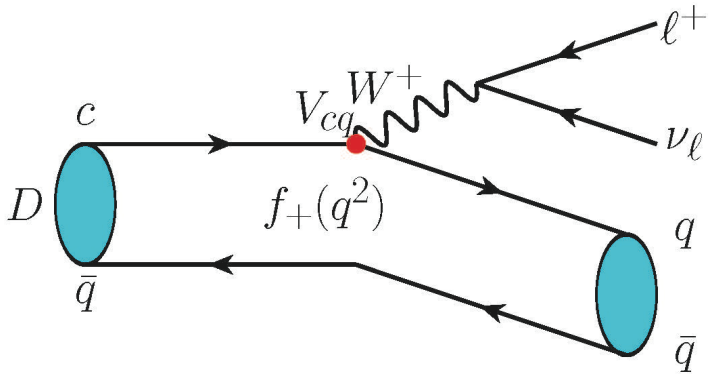
3 Pseudoscalar $D \to P\ell^+\nu_\ell$

4 Scalar $D \to S\ell^+\nu_\ell$

5 Other $D \to P/S\ell^+\nu_\ell$

6 Summary

Motivations



$$M = \frac{G_F}{\sqrt{2}} V_{cq} \times \langle P(S) | \bar{q} \gamma_\mu (1-\gamma_5) c | D \rangle \times \bar{\nu}_\ell \gamma^\mu (1-\gamma_5) \ell$$

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

- **Determination of $|V_{cq}|$: Validation of Unitary of CKM matrix & Basic parameters of Standard Model**
  - HFLAV 2023: $|V_{cs}| = 0.9639(44)(32_{\mathrm{LQCD}})(\sigma = 0.5\%)$
    $|V_{cd}| = 0.2265(29)(18_{\mathrm{LQCD}})(\sigma = 1.3\%)$
- **Extraction of Form Factors $f_+^{D\to P/S}(q^2)$: Test and Calibrate various theoretical calculations (LQCD, *et al*)**
  - Latest LQCD: $f_+^{D\to K}(q^2) = 0.7452(31)(\sigma = 0.4\%)$ and $f_+^{D\to\pi}(q^2) = 0.6300(51)(\sigma = 0.8\%)$
  - HFLAV 2023: $f_+^{D\to K}(q^2) = 0.7376(34)(\sigma = 0.5\%)$ and $f_+^{D\to\pi}(q^2) = 0.6342(82)(\sigma = 1.3\%)$
- **Search for New Physics: lepton flavor universality, beyond Standard Model, scalar contributions**

Motivations

$D \to P\ell^+\nu_\ell$ (Point-like)

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|\vec{\mathbf{q}}|q^2}{96\pi^3 m_D^2}\left|V_{cq}\right|^2\left(1-\frac{m_\ell^2}{q^2}\right)^2\left[\left(1+\frac{m_\ell^2}{2q^2}\right)|\mathcal{H}_0(q^2)|^2+\frac{3m_\ell^2}{2q^2}|\mathcal{H}_t(q^2)|^2\right]$$

- $\mathcal{H}_0(q^2) = \frac{2m_D|\vec{\mathbf{q}}|}{\sqrt{q^2}} f_+^{D\to P}(q^2)$
- $\mathcal{H}_+(q^2) = \frac{m_D^2-m_P^2}{\sqrt{q^2}} f_0^{D\to P}(q^2)$

$D \to S\ell^+\nu_\ell$ (Resonance's width)

$$\frac{d^2\Gamma}{dsdq^2} = \frac{G_F^2}{192\pi^4 m_D^3}\left|V_{cq}\right|^2\lambda^{\frac{1}{2}}(m_D^2,S_{1,2},q^2)\left(1-\frac{m_\ell^2}{q^2}\right)^2\left[\left(1+\frac{m_\ell^2}{2q^2}\right)\lambda\left(m_D^2,S_{1,2},q^2\right)\left|f_+^{D\to S}(q^2)\right|^2+\frac{3m_\ell^2}{2q^2}(m_D^2-m_S^2)\left|f_0^{D\to S}(q^2)\right|^2\right]P(S)$$

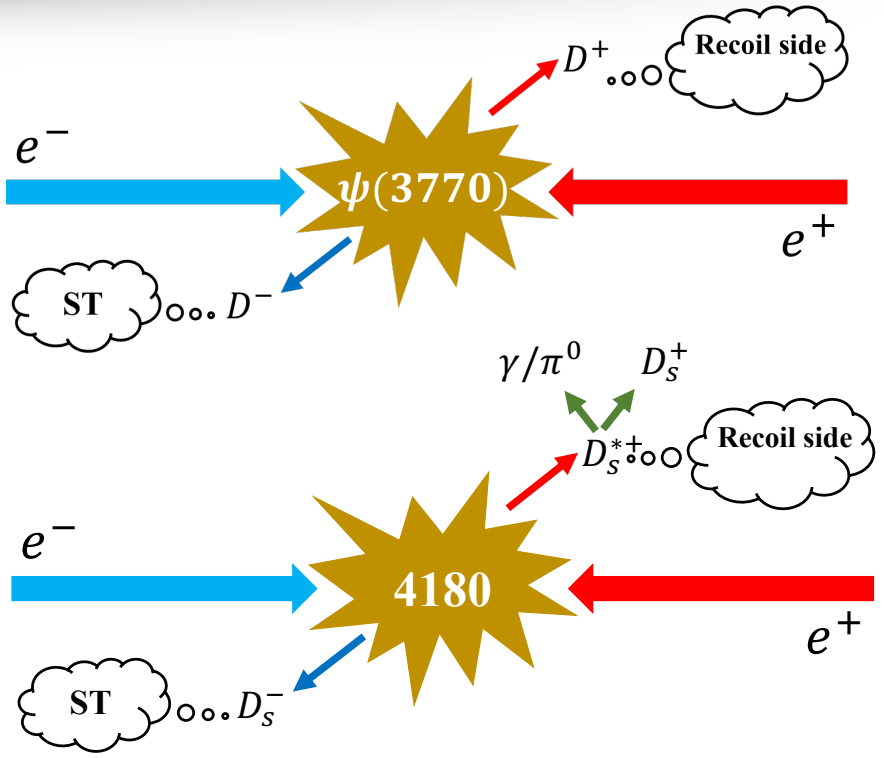
- $P(S) = \frac{g_{1,2}\rho_{1,2}}{\left|m_S^2-S_{1,2}-i(g_{1,2}\rho_{1,2}+g_{K\bar{K}}\rho_{K\bar{K}})\right|^2}$
- $S \to 1,2$

Paramertization of q^2 −dependence:

- Single pole: $f_+^{D\to P}(q^2) = \frac{f_0^{D\to P}(q^2)}{1-\frac{q^2}{M_{pole}^2}}$
- Modified pole: $f_+^{D\to P}(q^2) = \frac{f_0^{D\to P}(q^2)}{\left(1-\frac{q^2}{M_{pole}^2}\right)\left(1-\alpha\frac{q^2}{M_{pole}^2}\right)}$
- Series expansion: $f_+^{D\to P}(q^2) = \frac{1}{P(q^2)\Phi(q^2)}\sum a_k(t_0)[z(q^2,t_0)]^k$

2 Dataset and method

Data sample	$E_{\rm cm}$(GeV)	$\mathcal{L}_{\rm int}(\rm fb^{-1})$
$e^+e^- \to \psi(3770) \to D\bar{D}$	3.773	20.3
$e^+e^- \to D_s^{\pm}D_s^{*\mp}$	4.128-4.226	7.33
$e^+e^- \to D_s^{*+}D_s^{*-}$	4.237-4.669	10.64



- e^+e^- annihilations data near threshold
  - Double-tag method
  - Clean environment
- Undetectable neutrinos
  - extract the semi-leptonic signals
  - $U_{\rm miss} = E_{\rm miss} - |p_{\rm miss}|$ and $M^2_{\rm miss} = E^2_{\rm miss} - |p^2_{\rm miss}|$
- Measurement of the branching fraction with double-tag method:
  - $\mathcal{B}_{\rm sig} = \frac{N_{\rm tag,sig}}{N_{\rm tag}\frac{\varepsilon_{\rm tag,sig}}{\varepsilon_{\rm tag}}}$ Systematic uncertainties from the ST mostly canceled

3 $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$

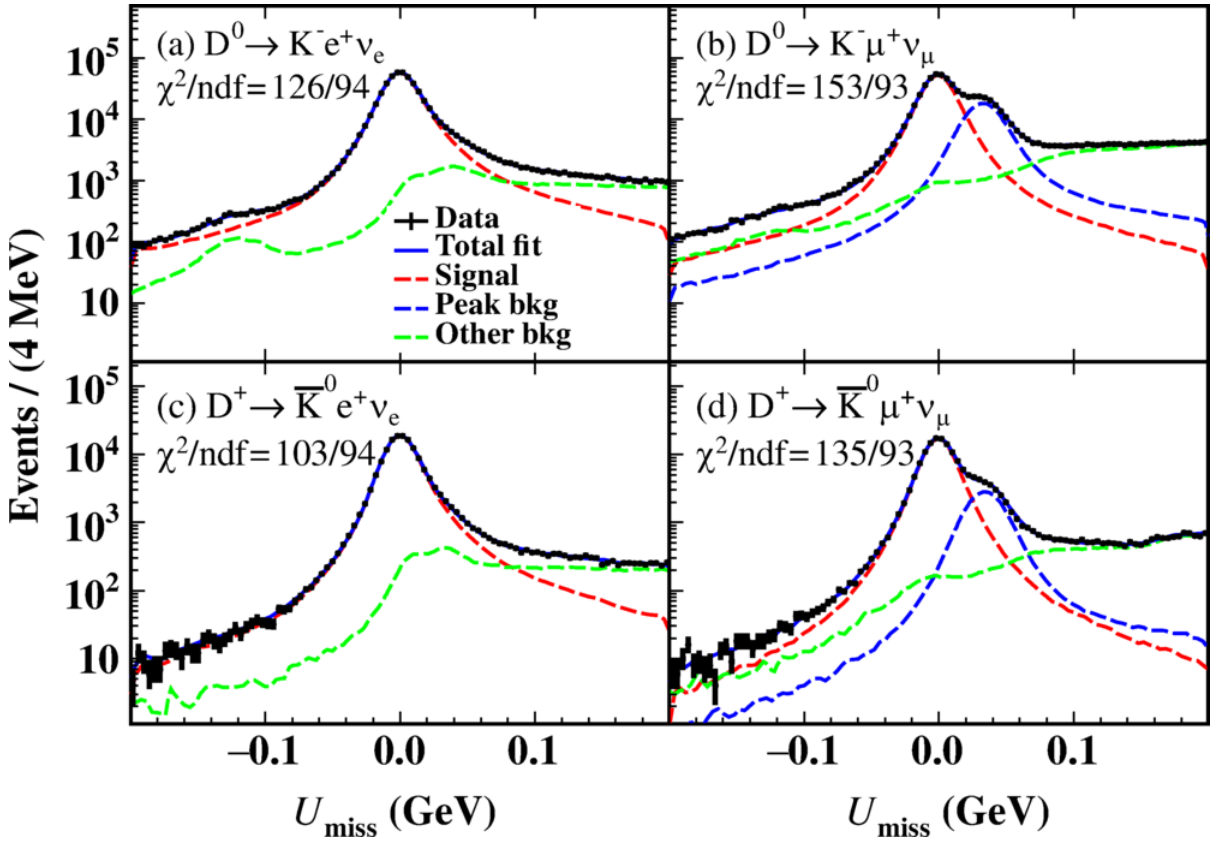
Precise measurements

- **20.3 fb^{-1}@3.773 GeV**
- Phys. Rev. Lett. 137, 091803 (2026)
- Phys. Rev. D. 114, 033008 (2026)

- **Branching fractions:**
  - $\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.548 \pm 0.006 \pm 0.017)\%$
  - $\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu) = (3.445 \pm 0.007 \pm 0.017)\%$
  - $\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.928 \pm 0.025 \pm 0.050)\%$
  - $\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu) = (8.770 \pm 0.029 \pm 0.053)\%$

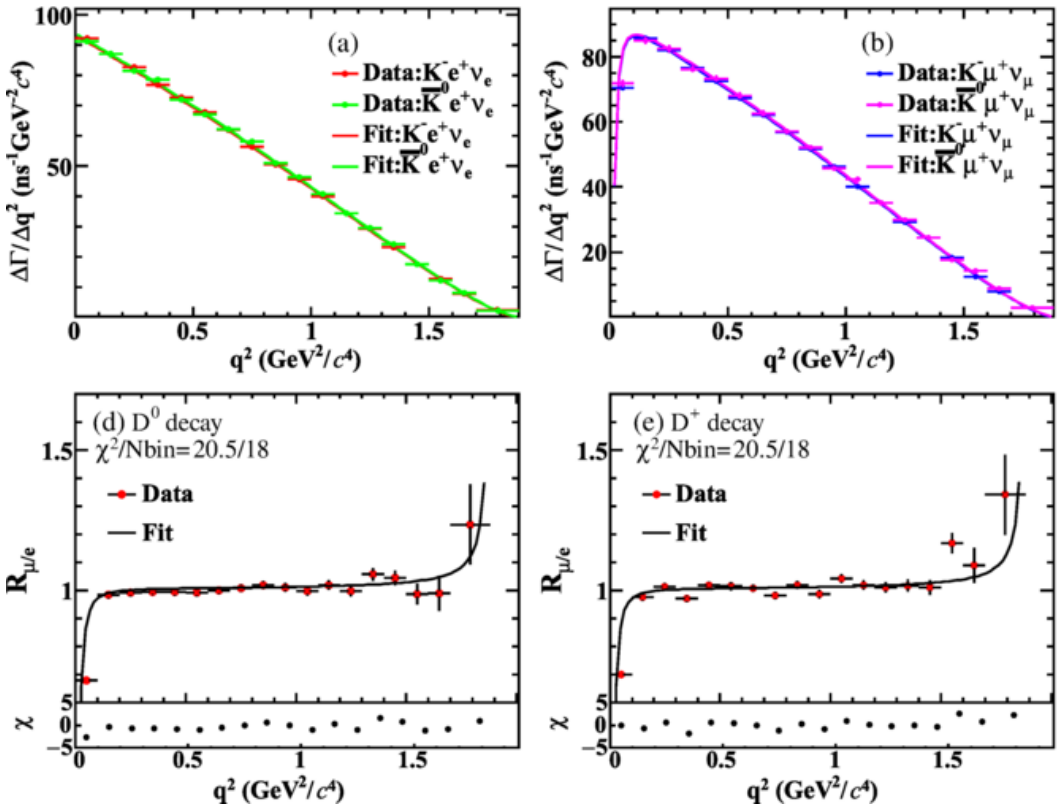
- **LFU test:**
  - $\frac{\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \to K^- e^+ \nu_e)} = 0.971 \pm 0.003 \pm 0.004$
  - $\frac{\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)} = 0.982 \pm 0.004 \pm 0.002$

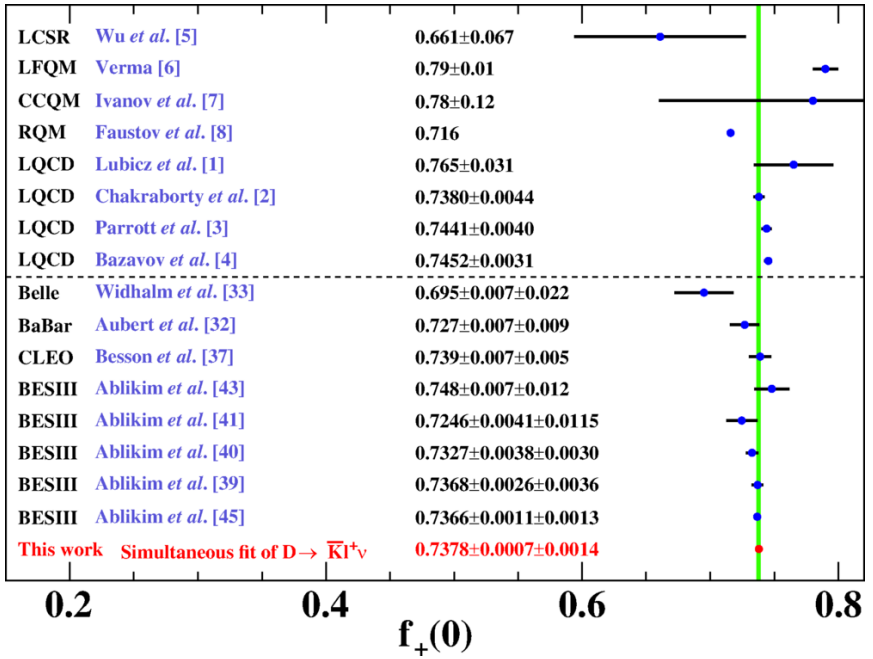
consistent with SM: 0.975±0.001



Precise measurements

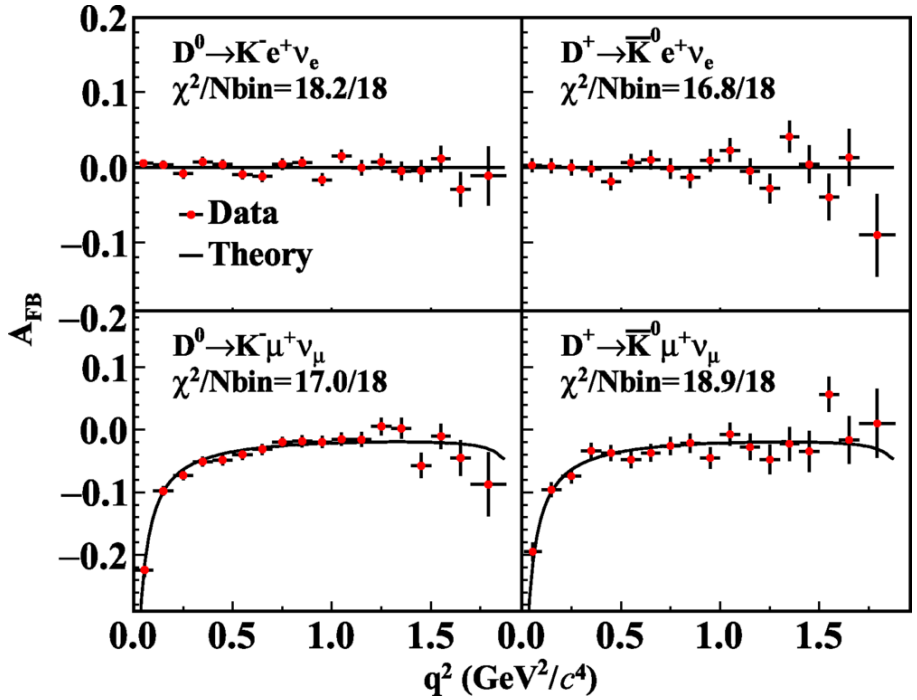
- Simultaneous fit to $\frac{d\Gamma}{dq^2}$ to all four channels:
  - $f_+^K(0) = 0.7383 \pm 0.0007_{\text{stat.}} \pm 0.0014_{\text{syst.}}$ $(\sigma_{\text{exp.}} = 0.21\%)$
  - $|V_{cs}| = 0.9639 \pm 0.0009_{\text{stat.}} \pm 0.0018_{\text{syst.}} \pm 0.0040_{\text{LQCD}}$ $(\sigma_{\text{exp.}} = 0.21\% \& \sigma_{\text{LQCD.}} = 0.46\%)$





Forward-backward asymmetry

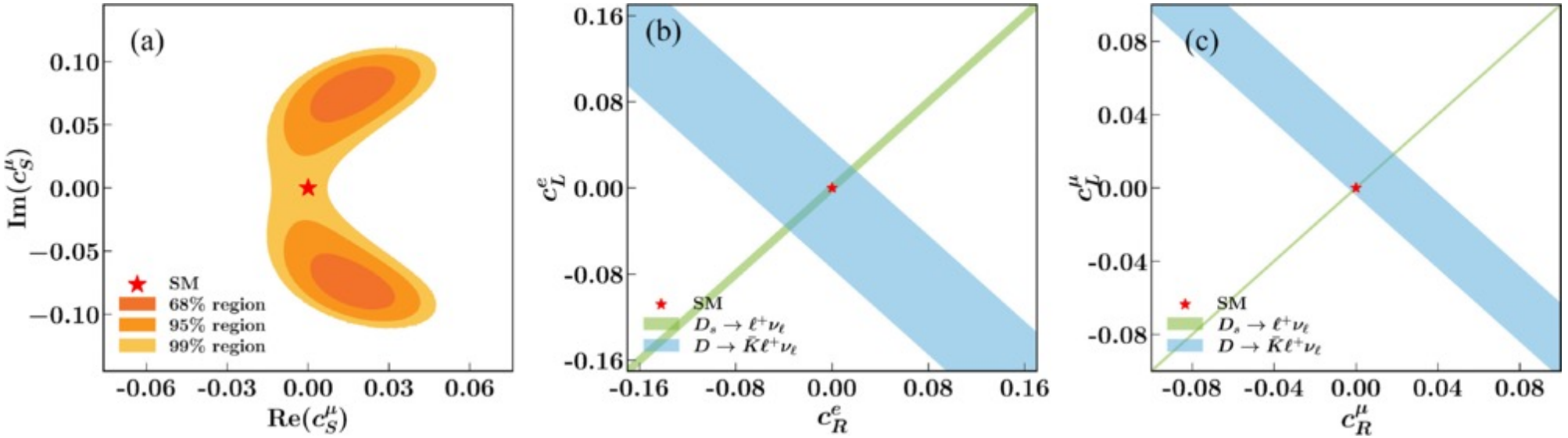
- **Angular observable** $A_{\rm FB}(q^2) = \frac{d\Gamma^\ell(\cos\theta_W>0) - d\Gamma^\ell(\cos\theta_W<0)}{d\Gamma^\ell(\cos\theta_W>0) + d\Gamma^\ell(\cos\theta_W<0)}$
- **Theoretical expression:** $A_{\rm FB}(q^2) = \frac{3N(q^2)}{2}\frac{1}{d\Gamma^\ell/dq^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2\frac{m_\ell^2}{q^2}\Re\left(h_0(q^2)h_t(q^2)\right)$
- $\boldsymbol{\theta_W}$ is the angle between the lepton momentum and the direction opposite to the D-meson momentum in the $\ell\nu_\ell$ rest frame
- **Overall**
  - $A_{FB}(D^0 \to K^- e^+ \nu_e) = (+0.2 \pm 1.6 \pm 1.6)\times 10^{-3}$
  - $A_{FB}(D^0 \to K^- \mu^+ \nu_\mu) = (-59.2 \pm 2.2 \pm 2.2)\times 10^{-3}$
  - $A_{FB}(D^+ \to \bar{K}^0 e^+ \nu_e) = (+0.0 \pm 2.9 \pm 1.5)\times 10^{-3}$
  - $A_{FB}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu) = (-53.1 \pm 3.5 \pm 0.7)\times 10^{-3}$
- **q^2 – dependence**



3 $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$

Constraint on the Scalar Current

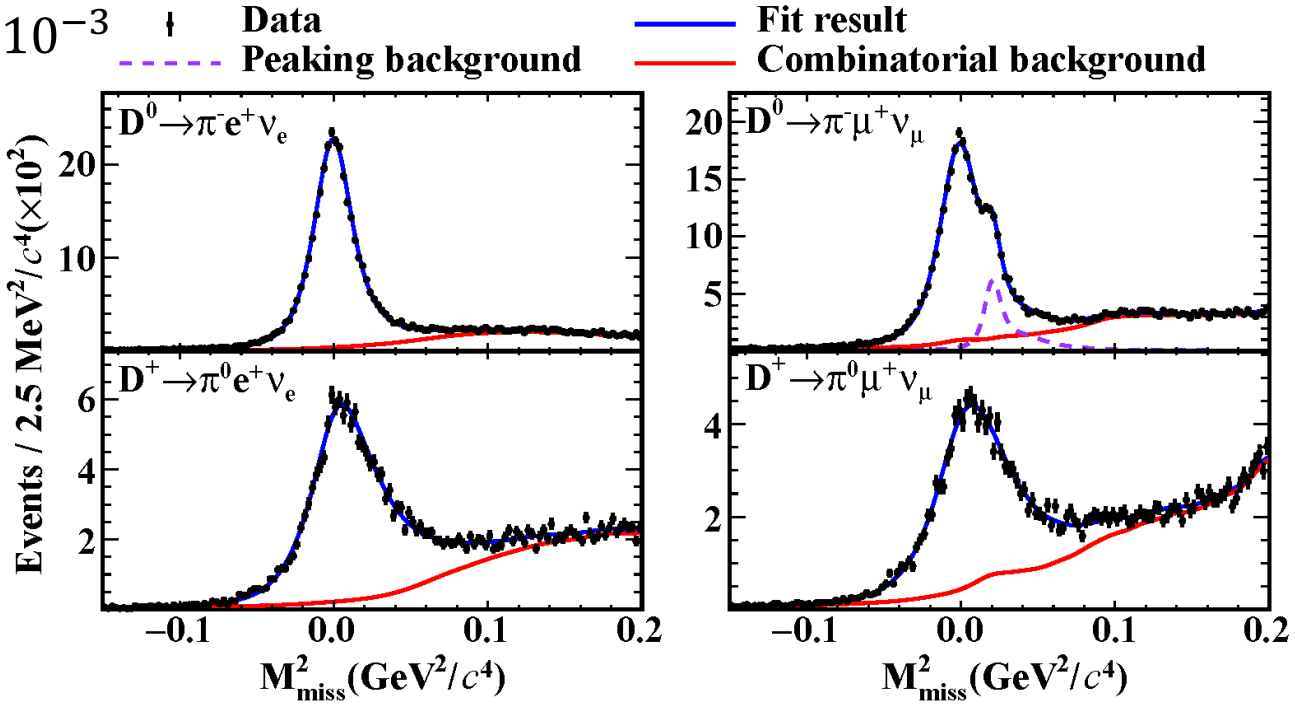
- Corresponding effective Lagrangian: $\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cs}^* \sum_{\ell=e,\mu,\tau} \sum_i c_i^\ell \mathcal{O}_i^\ell + \text{H.C.}$
  - SM: $\mathcal{O}_{\text{SM}}^\ell = (\bar{s}\gamma_\mu P_L c)(\bar{\nu}_\ell \gamma^\mu P_L \ell)$ with coefficient $c_{\text{SM}}^\ell = 1$
  - NP: Potential right(left)-handed scalar current $\mathcal{O}_{R(L)}^\ell = (\bar{s} P_{R(L)} c)(\bar{\nu}_\ell P_{R(L)} \ell)$ with complex Wilson coefficient $c_{R(L)}^\ell$
- Simultaneous fit to the partial decay rates and forward-backward asymmetries to constraints on the scalar current with input the BF of $D_s^+ \to \ell^+\nu_\ell$
  - $\mathcal{H}_t(q^2) = \left(1 + c_S^\ell \frac{q^2}{m_\ell(m_s - m_c)}\right) \frac{m_D^2 - m_K^2}{\sqrt{q^2}} f_0(q^2)$
  - $\mathcal{B}(D_s^+ \to \ell^+\nu_\ell) = \tau_{D_s} \frac{m_{D_s}}{8\pi} f_{D_s}^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2 G_F^2 \times |V_{cs}|^2 m_\ell^2 \left|1 - c_P^\ell \frac{m_{D_s}^2}{(m_c + m_s) m_\ell}\right|^2$
  - $\text{Re}(c_S^\mu) = 0.017 \pm 0.008 \pm 0.006$
  - $\text{Im}(c_S^\mu) = \pm(0.077 \pm 0.011 \pm 0.009)$



3 $D^{0(+)} \to \pi^{-(0)}\ell^+\nu_\ell$

Precise measurements

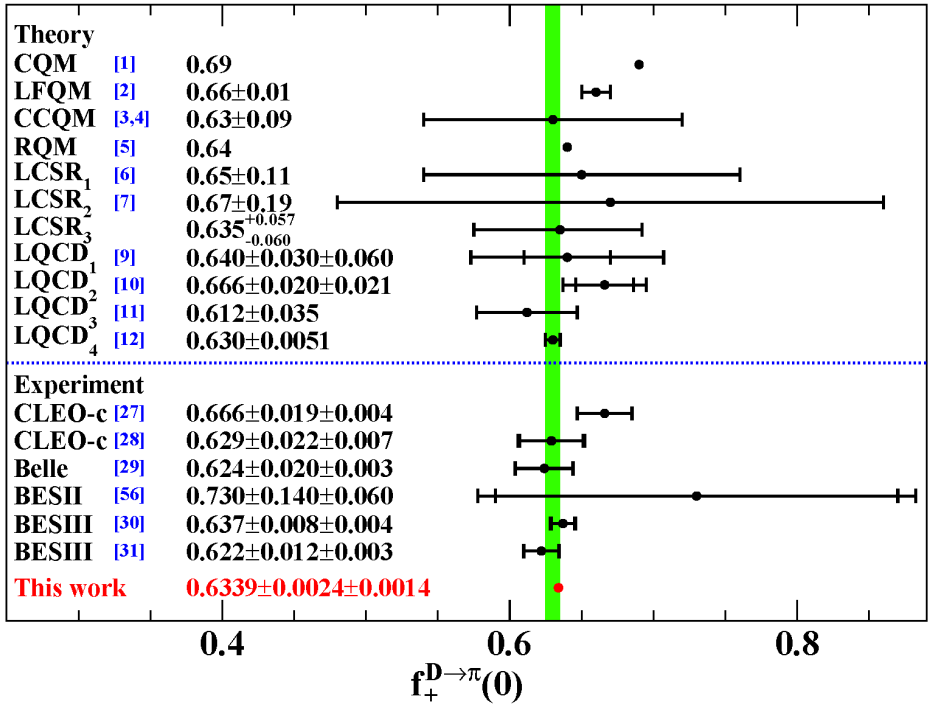
- 20.3 fb^{-1}@3.773 GeV
- arXiv:2607.23949
- arXiv:2607.23945
- **Branching fractions:**
  - $\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = (2.950 \pm 0.017 \pm 0.017)\times 10^{-3}$
  - $\mathcal{B}(D^0 \to \pi^- \mu^+ \nu_\mu) = (2.817 \pm 0.037 \pm 0.019)\times 10^{-3}$
  - $\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e) = (3.622 \pm 0.034 \pm 0.018)\times 10^{-3}$
  - $\mathcal{B}(D^+ \to \pi^0 \mu^+ \nu_\mu) = (3.507 \pm 0.043 \pm 0.026)\times 10^{-3}$
- **LFU test:**
  - $\frac{\mathcal{B}(D^0\to\pi^-\mu^+\nu_\mu)}{\mathcal{B}(D^0\to\pi^-e^+\nu_e)} = 0.947 \pm 0.014 \pm 0.005$
  - $\frac{\mathcal{B}(D^+\to\pi^0\mu^+\nu_\mu)}{\mathcal{B}(D^+\to\pi^0e^+\nu_e)} = 0.973 \pm 0.015 \pm 0.006$
- **Combining with the *D* meson lifetimes**
  - $\frac{\Gamma(D^0\to\pi^-e^+\nu_e)}{2\Gamma(D^+\to\pi^0e^+\nu_e)} = 1.025 \pm 0.013 \pm 0.007$
  - $\frac{\Gamma(D^0\to\pi^-\mu^+\nu_\mu)}{2\Gamma(D^+\to\pi^0\mu^+\nu_\mu)} = 1.011 \pm 0.019 \pm 0.010$

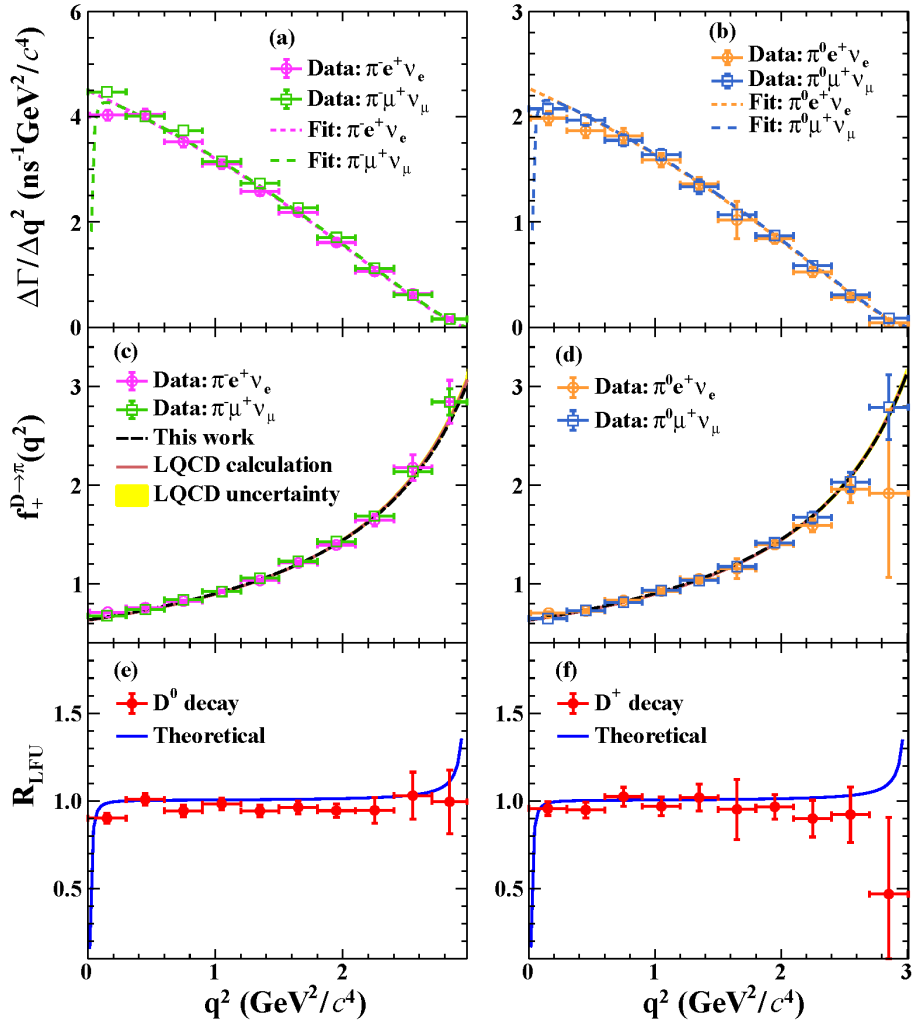


Precise measurements

➢ **Simultaneous fit to $\frac{d\Gamma}{dq^2}$ to all four channels:**

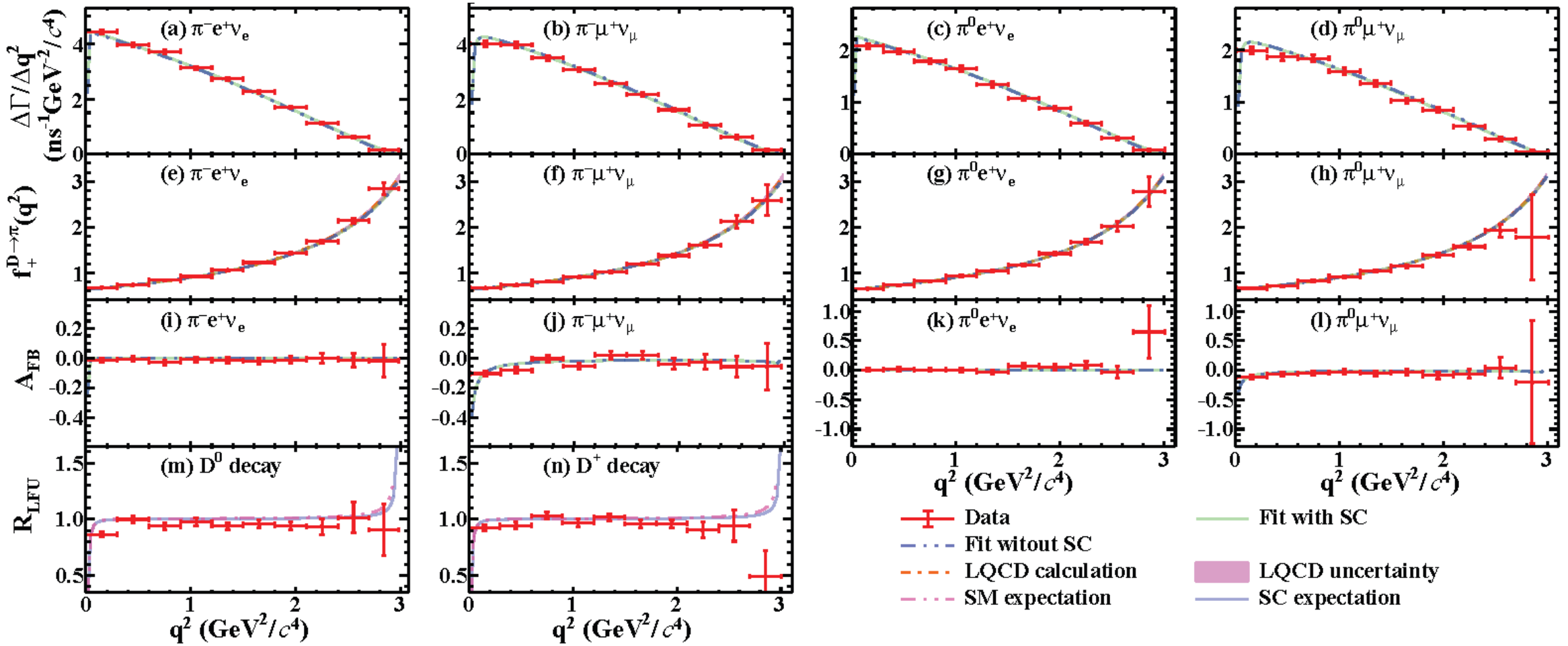
- $f_+^\pi(0) = 0.6339 \pm 0.0024_{\text{stat.}} \pm 0.0014_{\text{syst.}}$
  $(\sigma_{\text{exp.}} = 0.44\%)$
- $|V_{cd}| = 0.2262 \pm 0.0008_{\text{stat.}} \pm 0.0005_{\text{syst.}} \pm 0.0018_{\text{LQCD}}$
  $(\sigma_{\text{exp.}} = 0.42\% \& \sigma_{\text{LQCD.}} = 0.90\%)$
- Precision improved 3.0 times compared to the previous best results.





$D^{0(+)} \to \pi^{-(0)} \ell^+ \nu_\ell$ Constraint on the Scalar Current

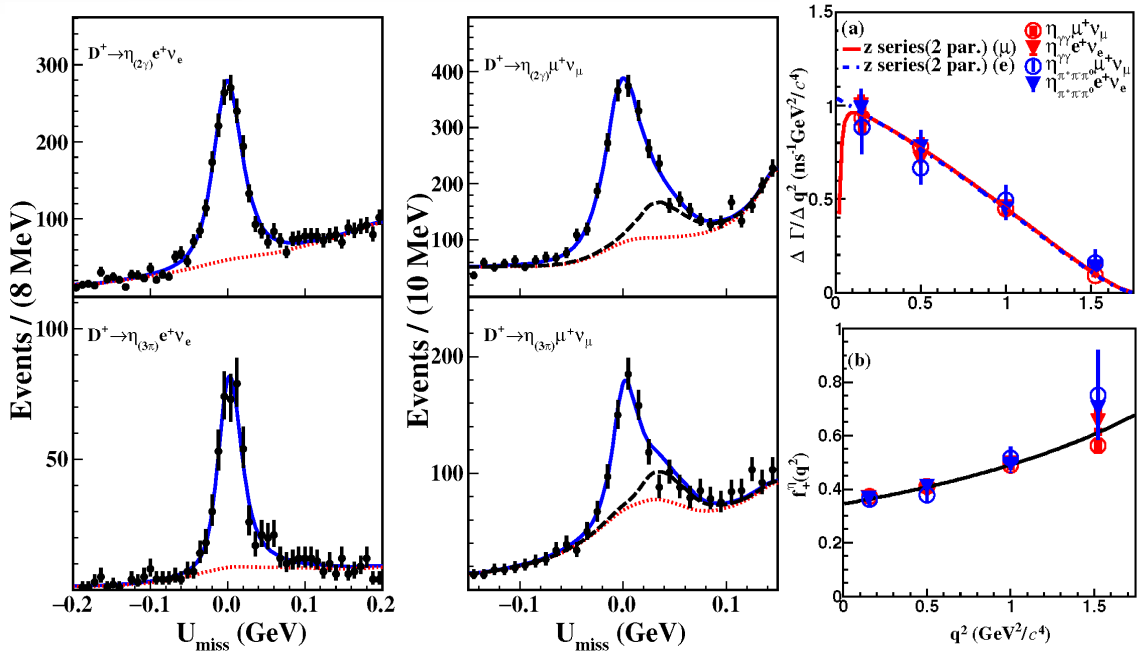
- **Simultaneous fit to the measured partial decay rates and forward-backward asymmetries to constraints on the scalar current contribution**
  - $\mathrm{Re}(c_S^\mu) = 0.022 \pm 0.023 \pm 0.003$
  - $\mathrm{Im}(c_S^\mu) = \pm(0.000 \pm 0.038 \pm 0.012)$

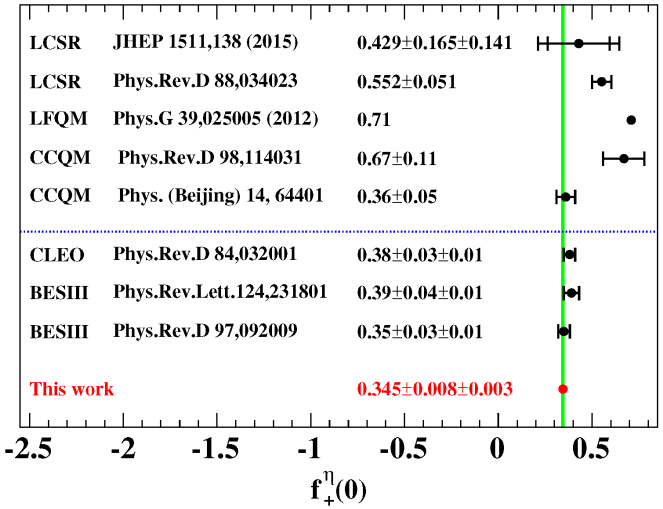


3 $D^+ \to \eta \ell^+ \nu_\ell$

Improved Measurements

- **20.3 fb^{-1}@3.773 GeV**
- **arXiv:2506.02521**
- **η** reconstructed with $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$
- **Branching fractions:**
  - $\mathcal{B}(D^+ \to \eta e^+ \nu_e) = (9.75 \pm 0.29 \pm 0.28) \times 10^{-4}$
  - $\mathcal{B}(D^+ \to \eta \mu^+ \nu_\mu) = (9.08 \pm 0.35 \pm 0.23) \times 10^{-4}$
- **LFU test:**
  - $\frac{\mathcal{B}(D^+ \to \eta \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \to \eta e^+ \nu_e)} = 0.93 \pm 0.05 \pm 0.02$
- **Simultaneous fit to the partial decay rates :**
  - $f_+^\eta(0)|V_{cd}| = 0.078 \pm 0.002_{\text{stat.}} \pm 0.001_{\text{syst.}}$
  - $f_+^\eta(0) = 0.345 \pm 0.008_{\text{stat.}} \pm 0.003_{\text{syst.}}$
  - **Precision improved 3.4 times compared to the previous best results.**

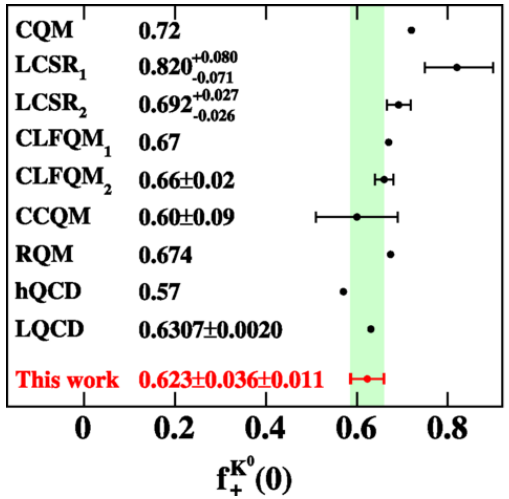


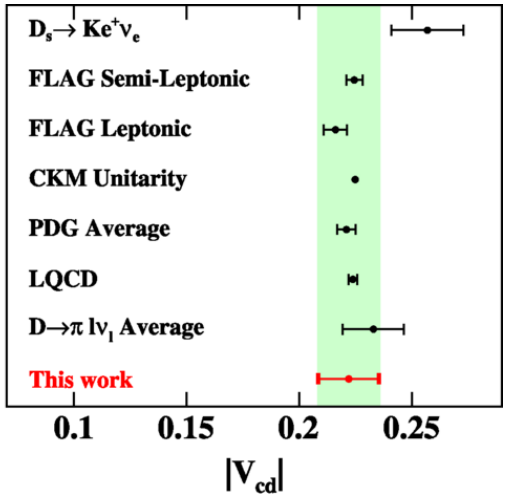


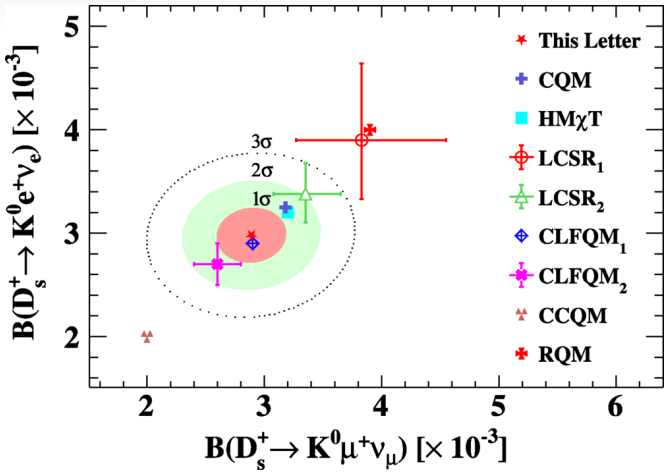
3 $D_s^+ \to \bar{K}^0 \mu^+ \nu_\mu$

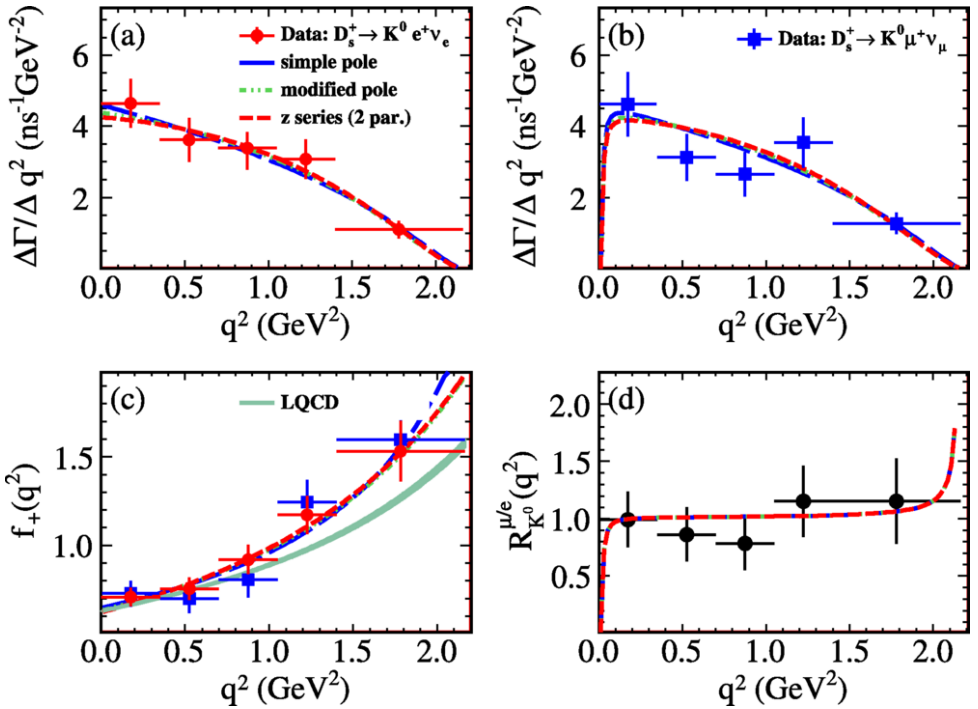
Frist Measurements

- 7.33 fb^{-1}@4.128-4.226 GeV
- Phys. Rev. Lett. 136, 161802 (2026)
- Branching fractions: $(2.89 \pm 0.27 \pm 0.12)\times 10^{-3}$
- LFU test: $\frac{\mathcal{B}(D_s^+ \to \bar{K}^0 \mu^+ \nu_\mu)}{\mathcal{B}(D_s^+ \to \bar{K}^0 e^+ \nu_e)} = 0.97 \pm 0.12 \pm 0.04$
- Simultaneous fit to the partial decay rates :
  - Simple pole: $f_+^{\bar{K}^0}(0) = 0.640 \pm 0.031_{\text{stat.}} \pm 0.008_{\text{syst.}}$
  - Modified pole: $f_+^{\bar{K}^0}(0) = 0.623 \pm 0.036_{\text{stat.}} \pm 0.011_{\text{syst.}}$
  - Series expansion : $f_+^{\bar{K}^0}(0) = 0.623 \pm 0.036_{\text{stat.}} \pm 0.011_{\text{syst.}}$



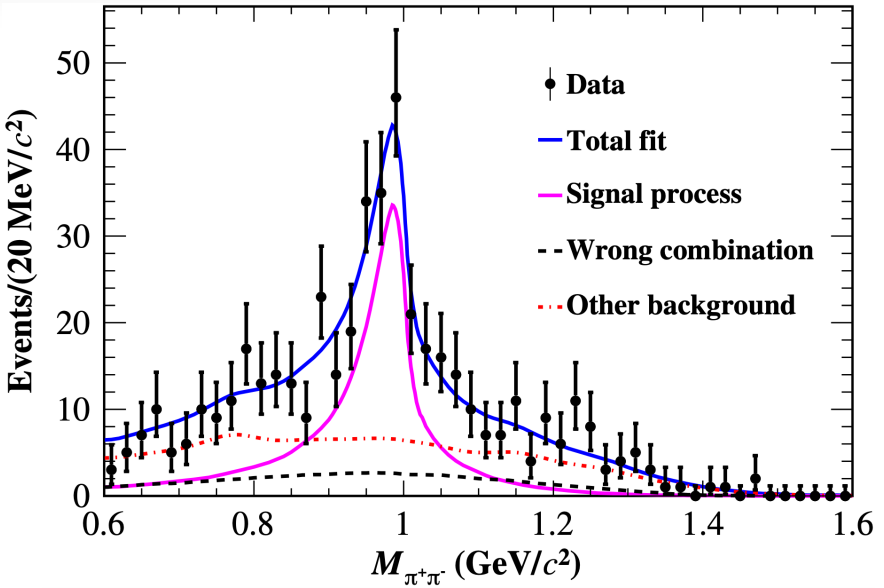


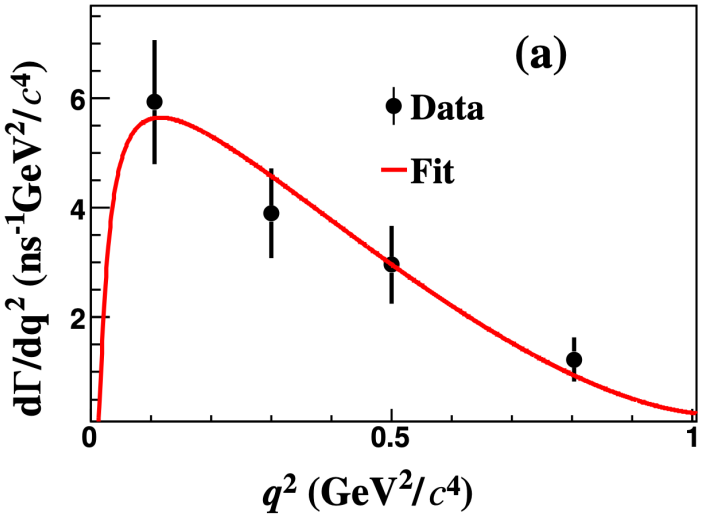


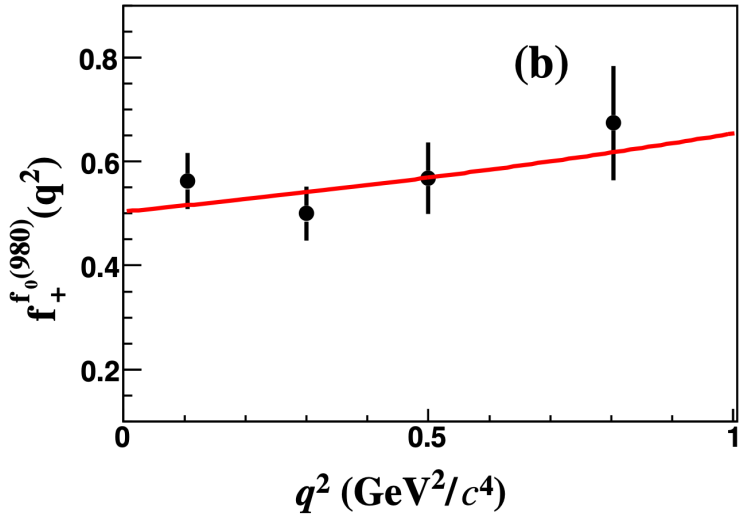


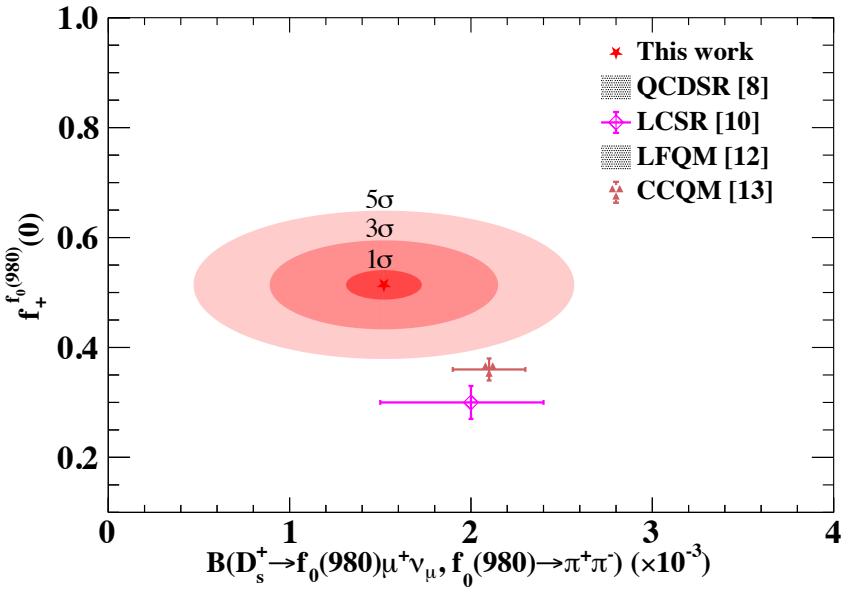
4 $D_s^+ \to f_0(980)\mu^+\nu_\mu$ Frist Measurements

- **7.33 fb^{-1}@4.128-4.226 GeV**
- **arXiv:2609.15655**
- **$f_0(980)$** reconstructed with $f_0(980) \to \pi^+\pi^-$
- **Branching fractions:** $(1.59 \pm 0.18 \pm 0.11)\times10^{-3}$
- **LFU test:** $\frac{\mathcal{B}(D_s^+\to f_0(980)\mu^+\nu_\mu)}{\mathcal{B}(D_s^+\to f_0(980)e^+\nu_e)} = 0.92 \pm 0.13 \pm 0.08$
- **Fit to the partial decay rates :**
  - $f_+^{f_0(980)}(0)|V_{cs}| = 0.490 \pm 0.059_{\text{stat.}} \pm 0.025_{\text{syst.}}$
  - $f_+^{f_0(980)}(0) = 0.514 \pm 0.017_{\text{stat.}} \pm 0.021_{\text{syst.}}$









5 Other $D \to P/S\ell^+\nu_\ell$

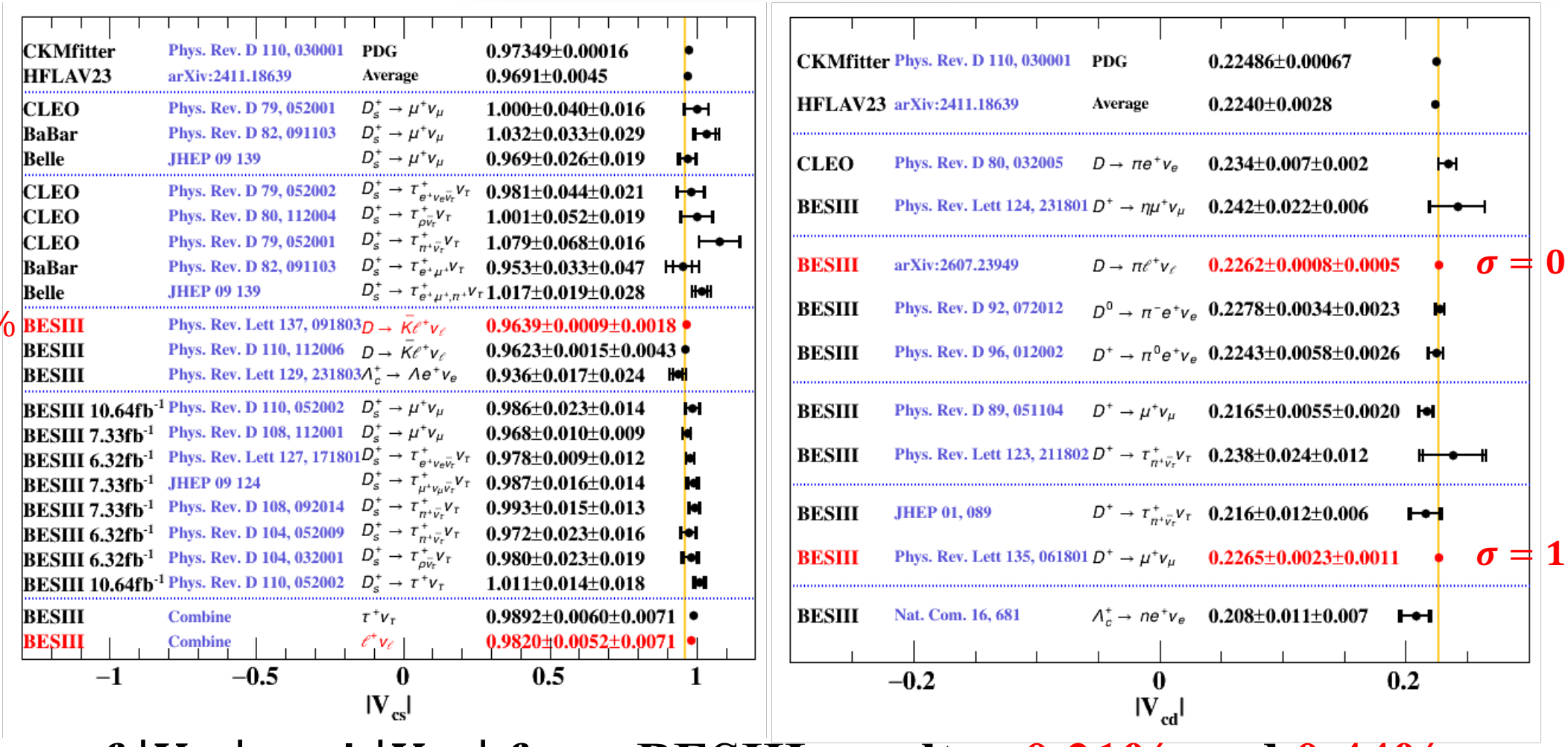
Frist Measurements

Data	Channel	Reference	$f_+(0)$
20.3 fb^{-1} 3.773 GeV	$D^+ \to \eta' e^+ \nu_e$	Phys. Rev. Lett. 134, 111801 (2025)	$0.263 \pm 0.025 \pm 0.006$
	$D^+ \to \eta' \mu^+ \nu_\mu$		
7.93 fb^{-1} 3.773 GeV	$D^0 \to a_0(980) e^+ \nu_e$	Phys. Rev. D 111, L091501 (2025)	$0.559 \pm 0.056 \pm 0.013$

With 20.3 fb^{-1} at 3.773 GeV, the form factor measurements of $D \to a_0(980)$ is ongoing with the $D \to a_0(980)\ell^+\nu_\ell$ decays.

6 Summary

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



Precisions of $|V_{cs}|$ and $|V_{cd}|$ from BESIII results : 0.21% and 0.44%

6 Summary

- Semi-leptonic decays of charm hadrons are important for determining the Hadronic transition Form Factors and CKM matrix elements.
- Precise determinations of the form factors for $f_+^{D\to\bar{K}}(0)$ and $f_+^{D\to\pi}(0)$ can be used to calibrate LQCD calculations.
- Precisions of $|V_{cs}|$ and $|V_{cd}|$ have been reduced to 0.21% and 0.44%, respectively, which validation of Unitary of CKM matrix.
- With a 20.3 fb^{-1} data sample collected at $\sqrt{s} = 3.773$ GeV, more precise measurements and rare charm decay searches will be presented, with machine-learning techniques offering promising new sensitivity.

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Thank you!

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