



Recent results of (semi-)leptonic $D_{(s)}$ decays at BESIII

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(on behalf of BESIII Collaboration)

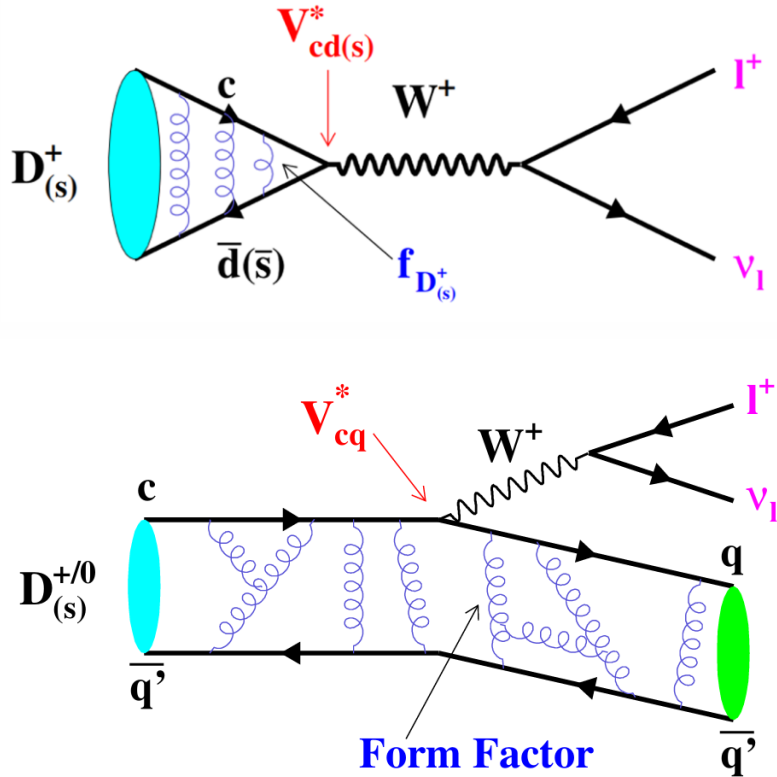
第六届中国格点量子色动力学研讨会，深圳

Outline

- Motivations
- BESIII Experiment
- Leptonic Decays: $D_{(s)} \rightarrow \ell^+ \nu_\ell$
- Semi-Leptonic Decays: $D \rightarrow X \ell^+ \nu_\ell$
- Summary

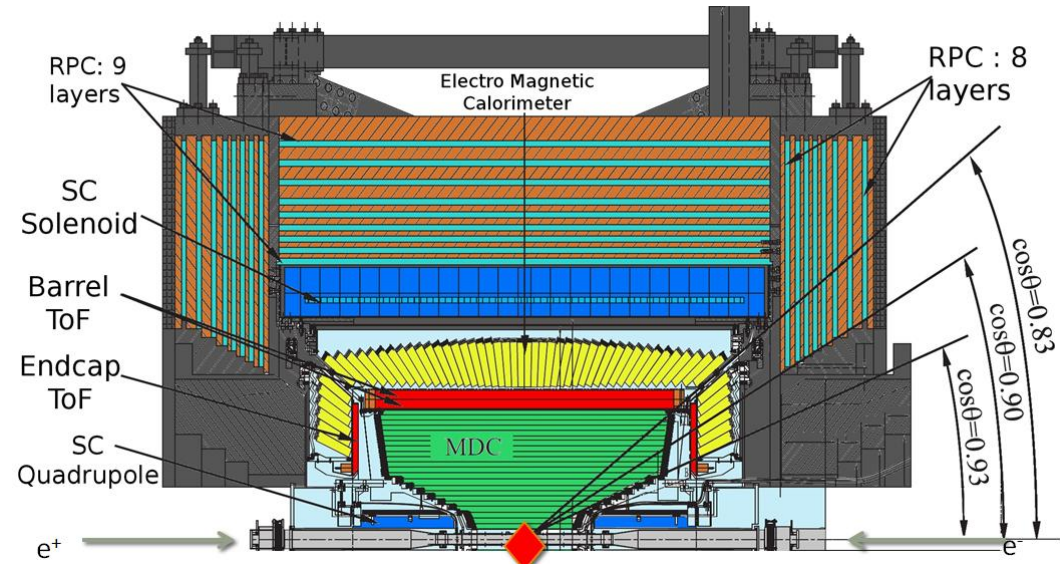
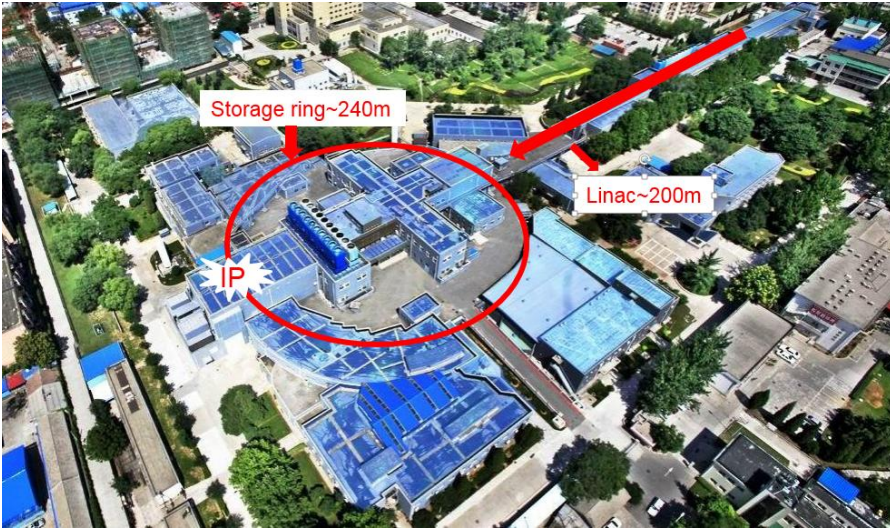
Motivations

$$M_{fi} = \frac{G_F}{\sqrt{2}} V_{cq} \times \langle 0, P, S, V, A | q \gamma_\mu (1 - \gamma_5) c | D \rangle \times \bar{u}_\nu \gamma^\mu (1 - \gamma_5) \nu_{\ell^+}$$



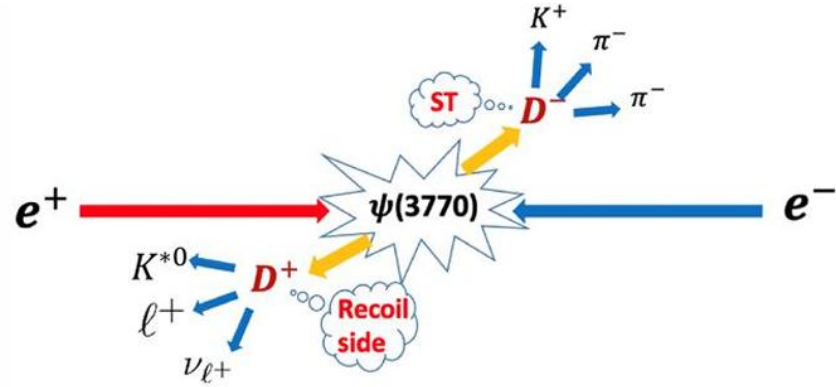
- **Determination of $|V_{cq}|$:** Validation of Unitarity of CKM matrix & Basic parameters of SM
- **Extraction of Form Factors:** Test & Calibrate various theoretical calculations, e.g. **LQCD**
- **Search for BSM:** lepton flavor universality & BSM scalar/vector/tensor contributions

BESIII experiment

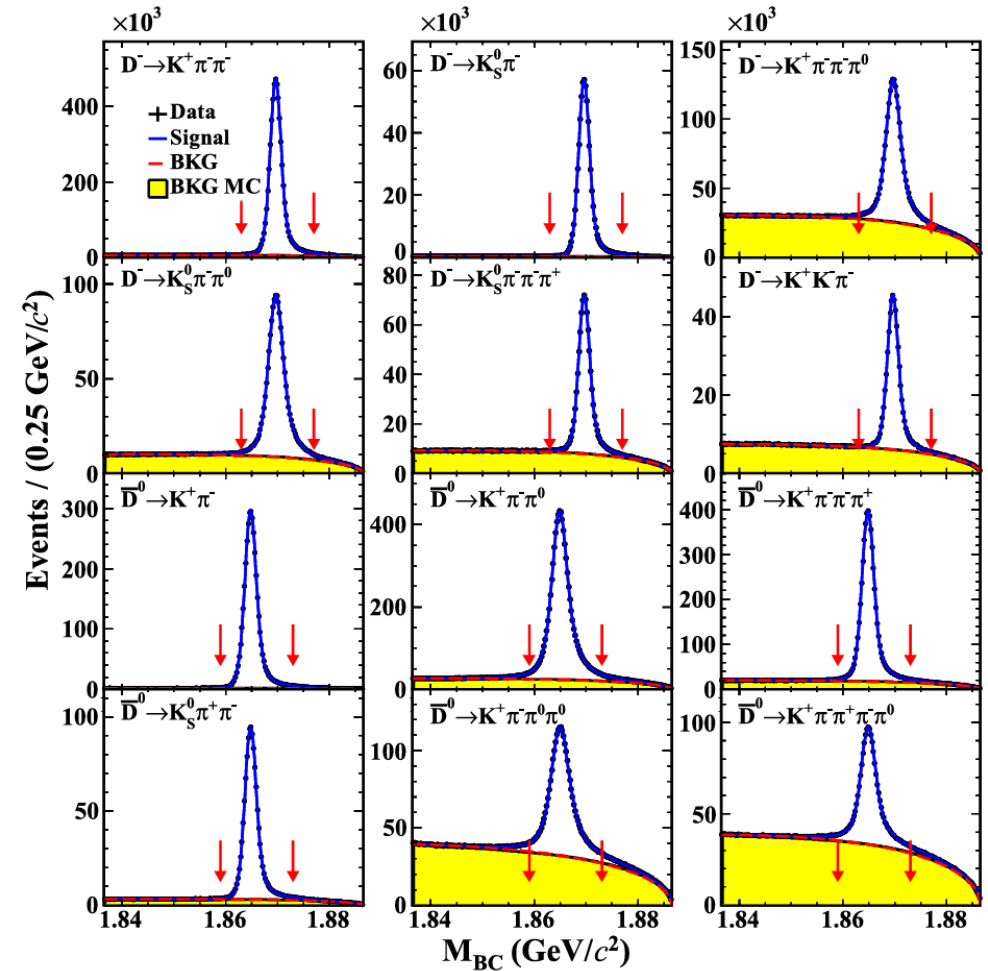


- $\sqrt{s} = (1.85 - 4.95) \text{ GeV}$ with Peak luminosity: $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ @3.773 GeV
- MDC: $\sigma_p/P = 0.5\%$ @ 1 GeV; $\sigma_{dE/dx} = 6\%$
- TOF: $\sigma_T = 68(60/110) \text{ ps}$ for barrel (endcap)
- EMC: $\sigma_E/E = 2.5\%(5\%)$ for barrel (endcap)

Double Tag



- Single tag side: $\bar{D}$ decays into hadron final states
- Double tag side: $D \rightarrow X\ell^+\nu_{\ell}, X = 0, P, \dots$
- $p_{\nu} = (E_{\nu}, \vec{p}_{\nu})$, obtained by recoiling method



Data sample	Energy (GeV)	L_{int} (fb^{-1})	Single tag yield ($\times 10^6$)
$e^+e^- \rightarrow D\bar{D}$	3.773	20.3	$D^0 \sim 20; D^+ \sim 11$
$e^+e^- \rightarrow D_s^\pm D_s^{*\mp}$	4.128-4.226	7.33	$D_s^+ \sim 0.8$

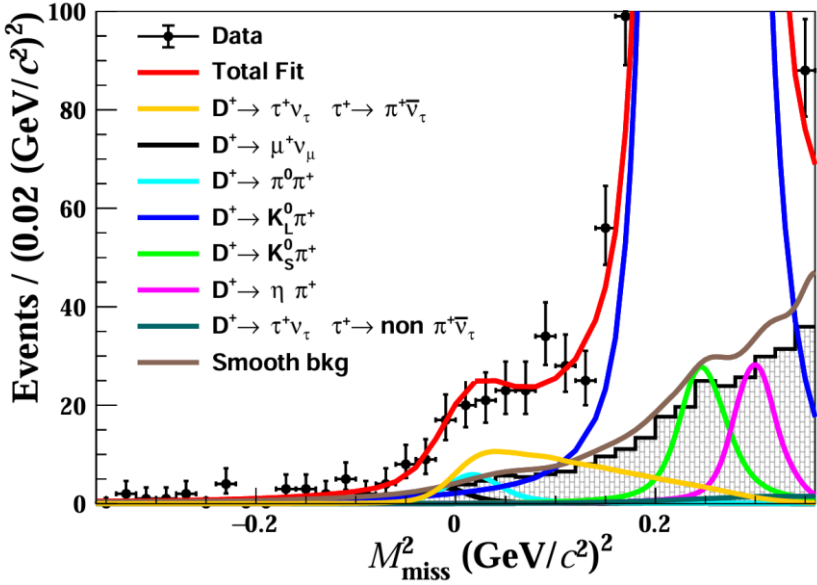
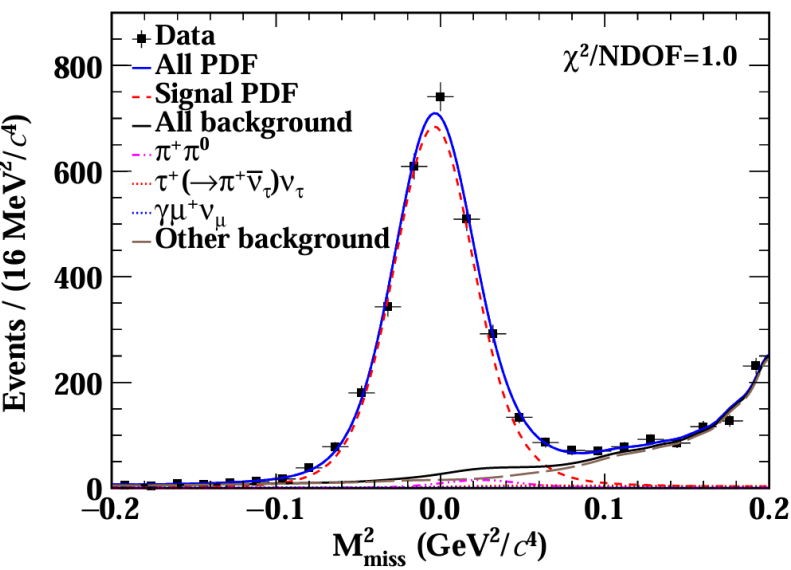
Precision measurement of $D^+ \rightarrow \ell^+ \nu_\ell$

$$D^+ \rightarrow \mu^+ \nu_\mu$$

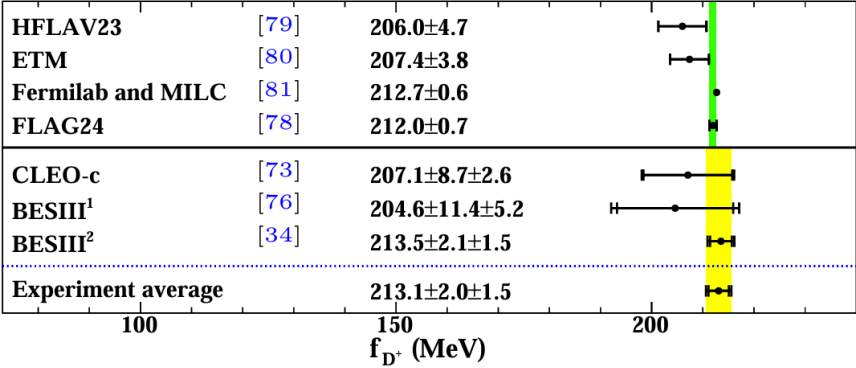
PRL 135 (2025) 061801

$$D^+ \rightarrow \tau^+ (\rightarrow \pi \bar{\nu}_\tau) \nu_\tau$$

JHEP01(2025)089



Quote $|V_{cd}| = (0.2249 \pm 0.0007)$



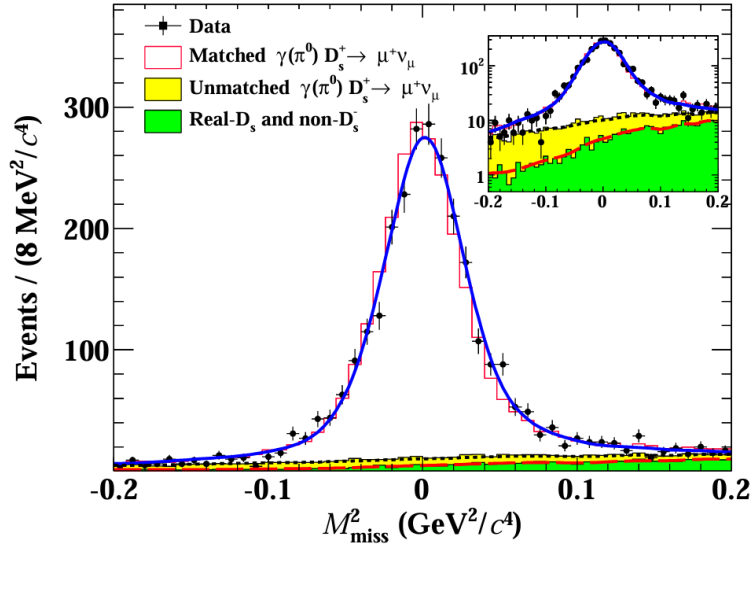
- $\Gamma \propto |V_{cd}|^2 f_{D^+}^2 m_\ell^2 (m_D^2 - m_\ell^2)^2 (1 + f_{corr}^{EM})$
- $R_{\tau/\mu} = 2.49 \pm 0.31$, consistent with SM value 2.69

Channel	$L_{int} (fb^{-1})$	BF ($\times 10^{-4}$)	$ V_{cd} f_{D^+}$
$D^+ \rightarrow \mu^+ \nu_\mu$	20.3	$4.03 \pm 0.08 \pm 0.04$	$48.2 \pm 0.48 \pm 0.31$
$D^+ \rightarrow \tau^+ \nu_\tau$	7.93	$9.9 \pm 1.1 \pm 0.5$	$45.9 \pm 2.5 \pm 1.2$

Precision measurement of $D_s^+ \rightarrow \ell^+ \nu_\ell$

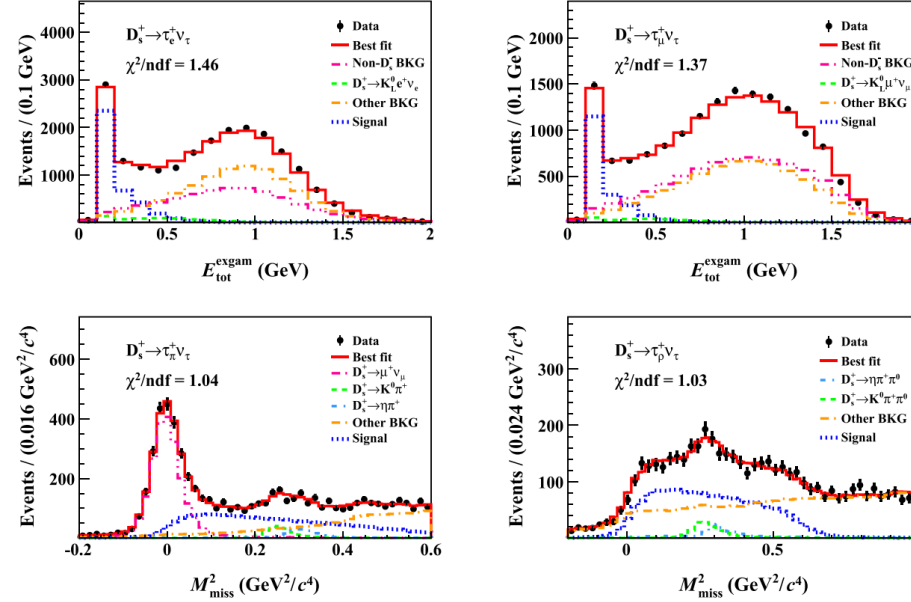
$$D_s^+ \rightarrow \mu^+ \nu_\mu$$

PRD 108 (2023) 092014



$$D_s^+ \rightarrow \tau^+ \nu_\tau \text{ with } \tau \rightarrow e, \mu, \pi, \rho$$

PRD 114 (2026) 033004



Quote $|V_{cs}| = (0.9735 \pm 0.0002)$

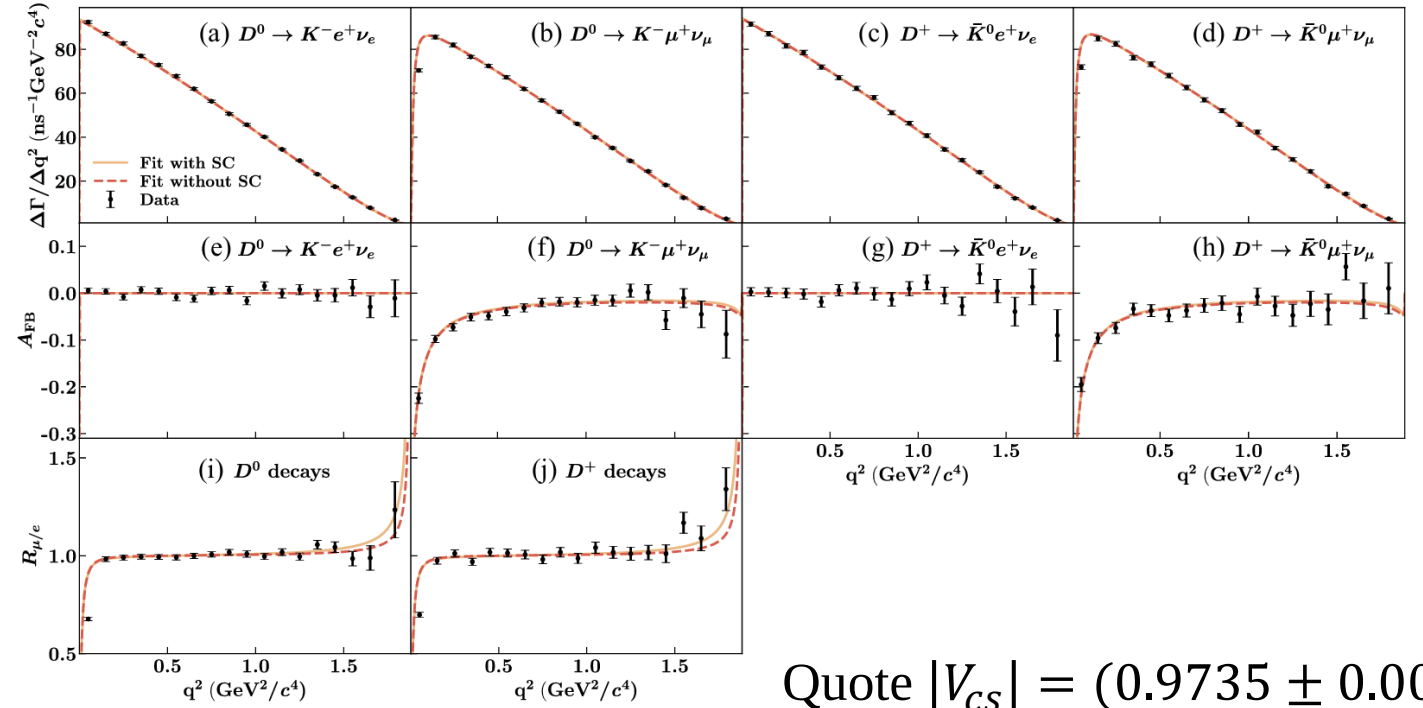
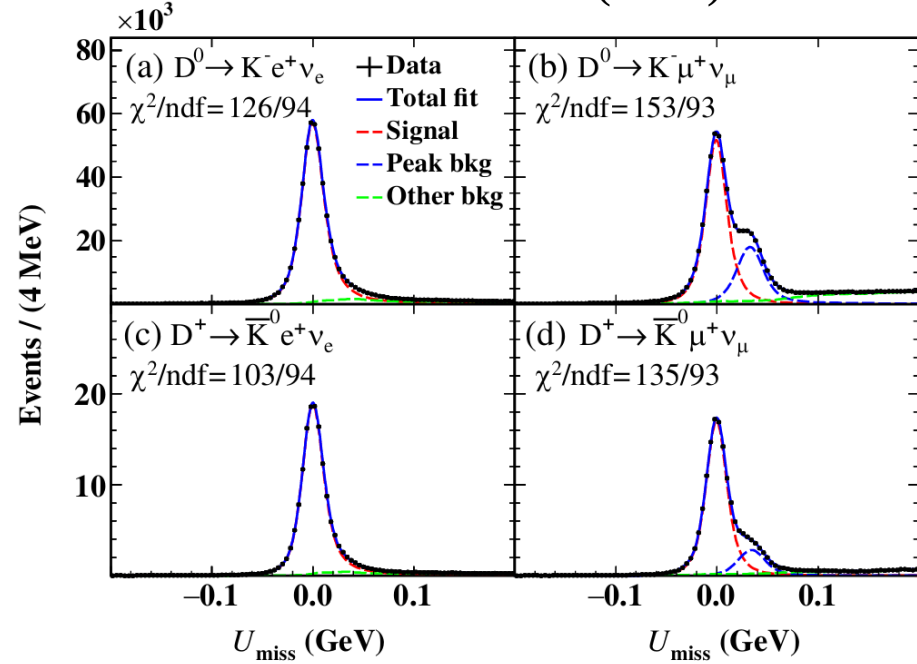
HFLAV23	[79]	251.8±2.0	
ETM	[80]	247.2±4.1	
Fermilab and MILC	[81]	249.9±0.4	
FLAG24	[78]	249.9±0.5	
CLEO-c ¹	[100, 105, 106]	259.1±7.7±3.1	
BaBar ¹	[103]	244.3±9.1±14.0	
Belle ¹	[102]	261.9±4.8±7.1	
BESIII ¹	[109–114]	253.9±1.6±1.9	
CLEO-c ²	[100]	257.3±10.2±3.9	
BaBar ²	[103]	265.6±8.4±7.5	
Belle ²	[102]	249.4±6.6±4.7	
BESIII ²	[40, 113, 114]	249.4±2.3±1.4	
Experiment average		253.2±1.2±1.6	

- $R_{\tau/\mu} = 10.04 \pm 0.29$, consistent with SM value 9.75

Channel	Data set	BF (%)	$ V_{cs} f_{D_s^+}$
$D_s^+ \rightarrow \mu^+ \nu_\mu$	$e^+e^- \rightarrow D_s^\pm D_s^{*\mp}, D_s^+ D_s^-, D_s^{*\pm} D_s^{*\mp}$	$0.531 \pm 0.010 \pm 0.005$	$242.8 \pm 2.3 \pm 1.3$
$D_s^+ \rightarrow \tau^+ \nu_\tau$	$e^+e^- \rightarrow D_s^\pm D_s^{*\mp}$, with $\tau \rightarrow e, \mu, \pi, \rho$	$5.37 \pm 0.08 \pm 0.06$	$248.2 \pm 1.9 \pm 1.7$

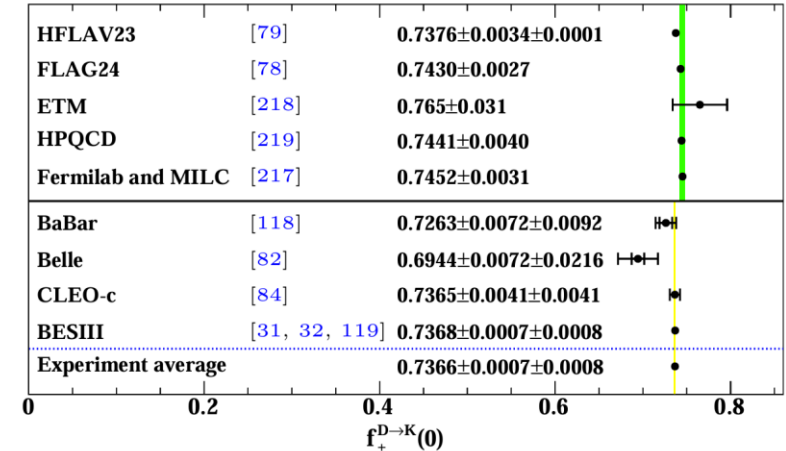
Precision measurement of $D \rightarrow \bar{K} \ell^+ \nu_\ell$

$D \rightarrow \bar{K} \ell^+ \nu_\ell$ PRL 137 (2026) 091803
PRD 114 (2026) 033008



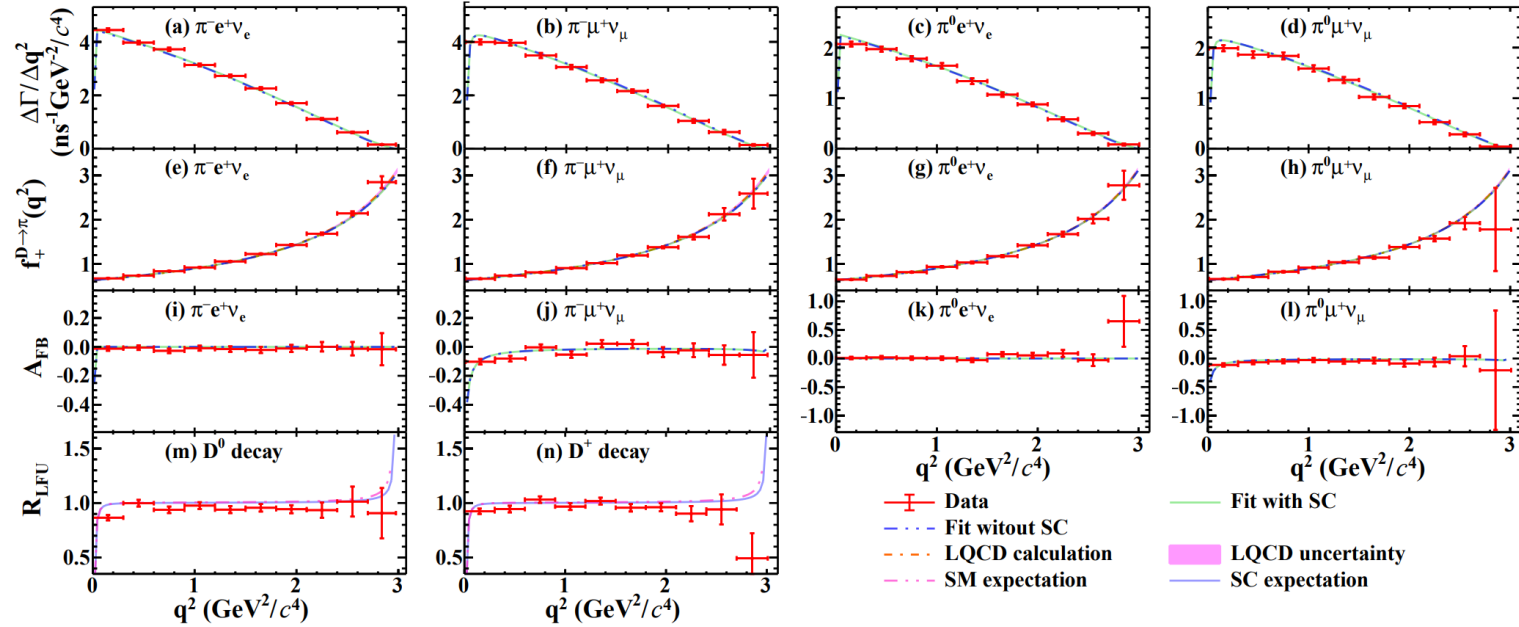
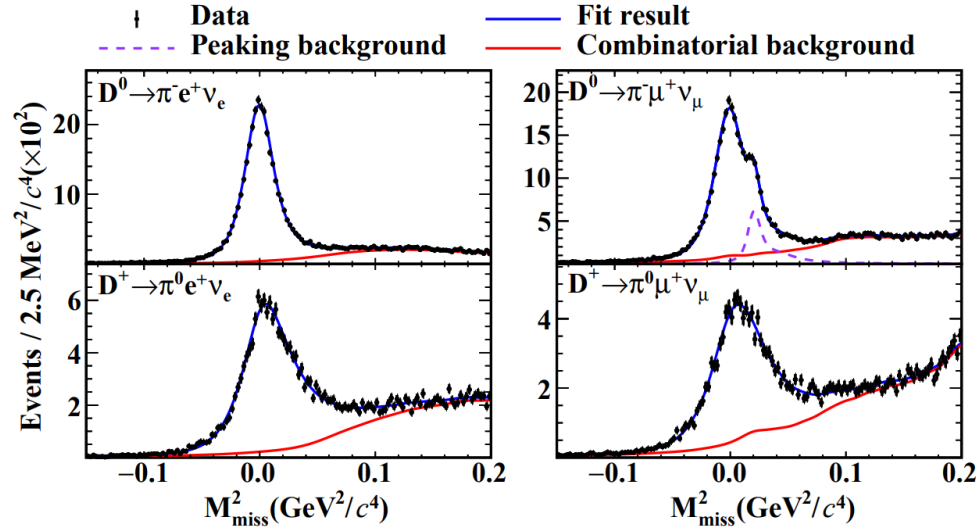
Quote $|V_{cs}| = (0.9735 \pm 0.0002)$

- $20.3 \text{ fb}^{-1} \psi(3770)$ data sample
- $d\Gamma/dq^2 \propto |V_{cs}|^2 \left[\left(1 + \frac{m_\ell^2}{2q^2} \right) |h_0(q^2)|^2 + \frac{3m_\ell^2}{2q^2} |h_t(q^2)|^2 \right]$
- $f_+(0)|V_{cs}| = (0.7183 \pm 0.0007 \pm 0.0014)$
- LFU test: $R_{\mu/e}^{D^0} = 0.971 \pm 0.005$ & $R_{\mu/e}^{D^+} = 0.982 \pm 0.005$, SM 0.975

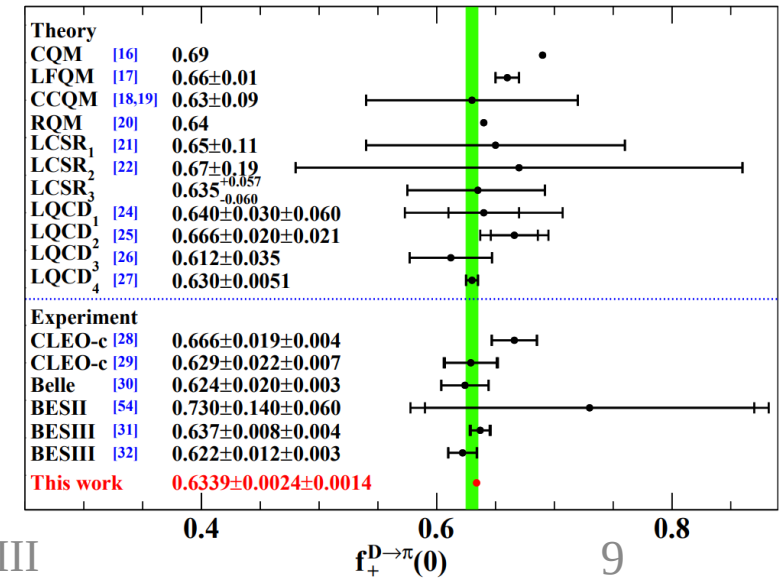


Precision measurement of $D \rightarrow \pi \ell^+ \nu_\ell$

$D \rightarrow \pi \ell^+ \nu_\ell$ arXiv 2607.23949
arXiv 2607.23945



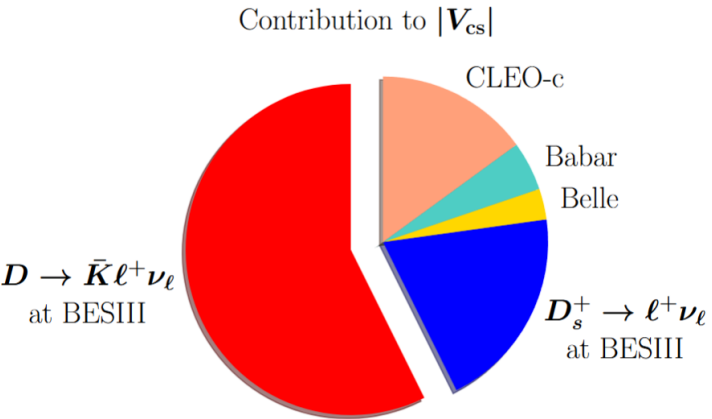
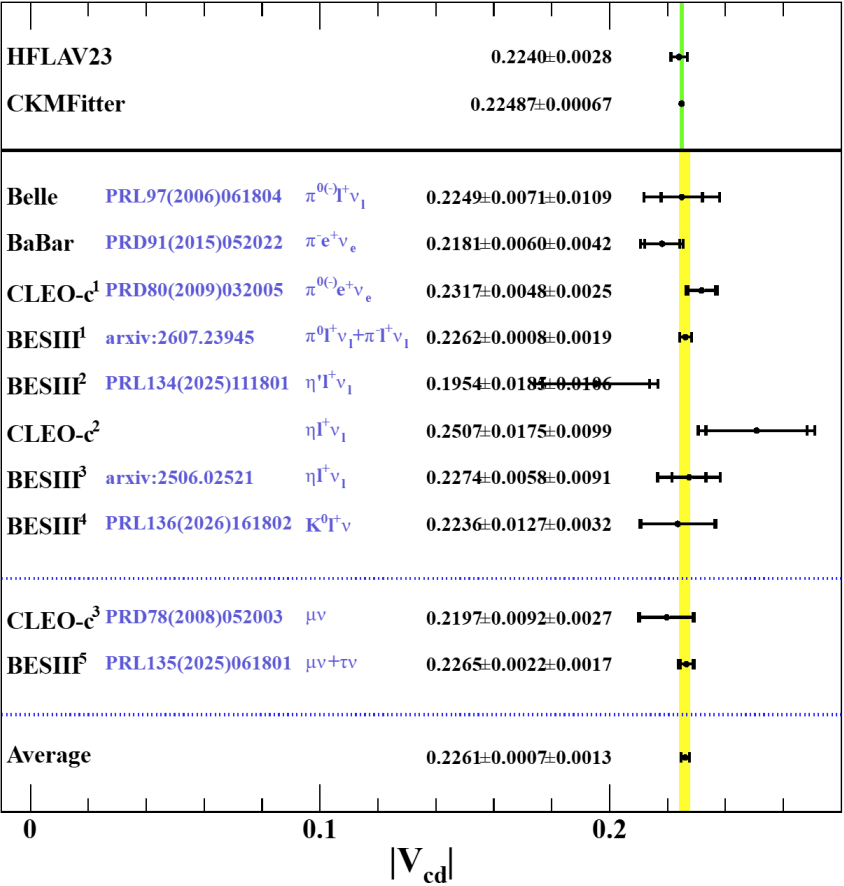
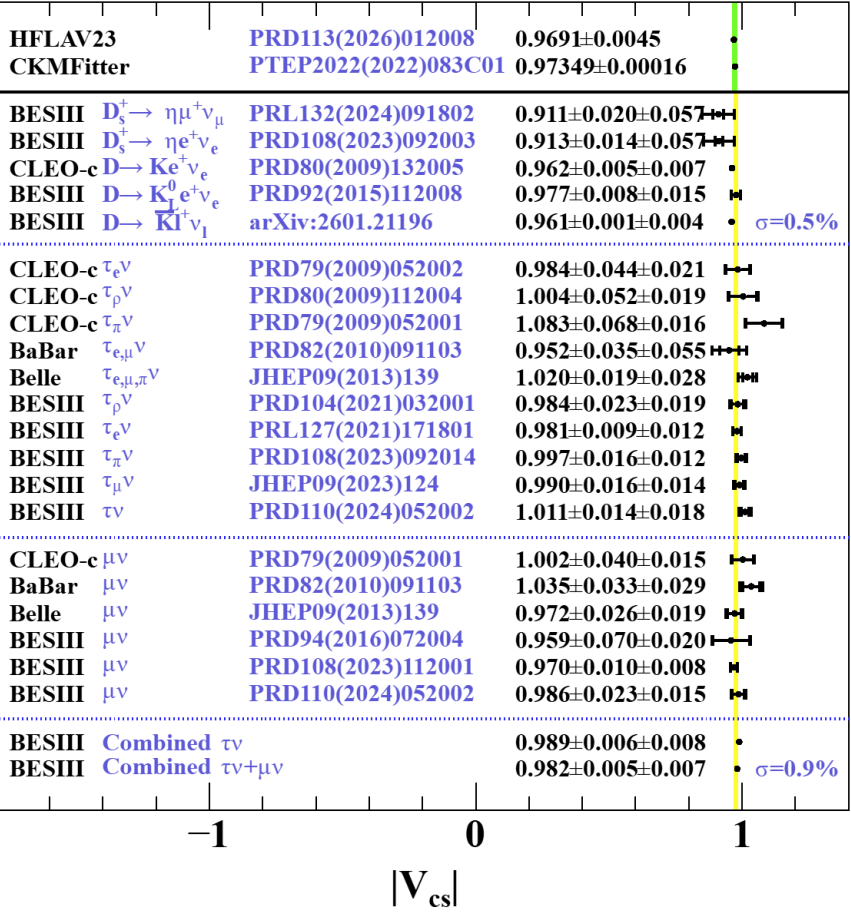
- $20.3 \text{ fb}^{-1} \psi(3770)$ data sample, ~ 7 times of 2.93 fb^{-1}
- $f_+(0)|V_{cd}| = (0.1425 \pm 0.0005 \pm 0.0003)$
- LFU test: $R_{\mu/e}^{D^0} = 0.947 \pm 0.016$ & $R_{\mu/e}^{D^+} = 0.973 \pm 0.017$,
2.5 σ tension with SM value 0.985.



$|V_{cs}|$ & $|V_{cd}|$ in $D_{(s)}$ decays

Leptonic decay: Dominated by EXP's Uncertainty.

Semi-Leptonic decay: Dominated by **LQCD's Uncertainty**.



Un. (%)	EXP	LQCD
$D \rightarrow \ell^+ \nu_\ell$	1.2	0.3
$D_s \rightarrow \ell^+ \nu_\ell$	0.9	0.2
$D \rightarrow \bar{K} \ell^+ \nu_\ell$	0.2	0.4
$D \rightarrow \pi \ell^+ \nu_\ell$	0.4	0.8

Scalar current in $D \rightarrow P \ell^+ \nu_\ell$

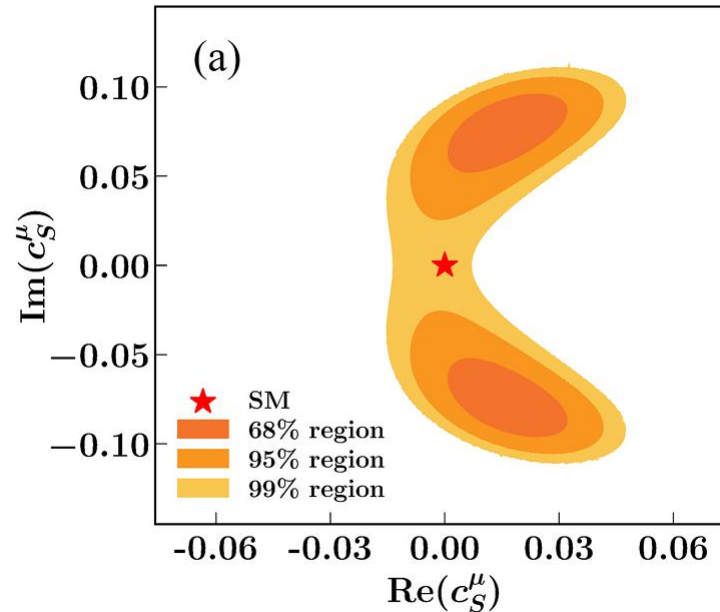
Weak decay is $(V - A)$ in SM, but one may have BSM scalar current:

$$O_{R(L)}^l = (\bar{q} P_{R(L)} c)(\bar{\nu}_\ell P_R \ell)$$

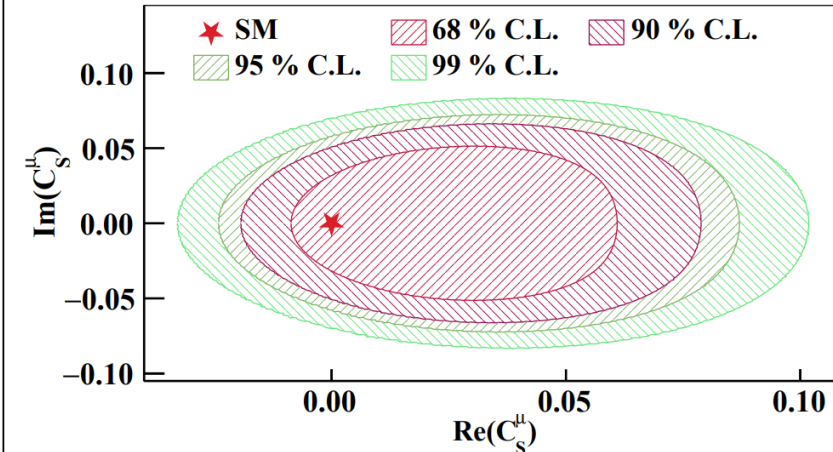
Affect $d\Gamma/dq^2$ & A_{FB} by: $h_t(q^2) \propto \left(1 + \mathbf{c}_S^\ell \frac{q^2}{m_\ell(m_q - m_c)}\right) f_0(q^2)$

$$D \rightarrow \bar{K} \ell^+ \nu_\ell$$

- Combined fit to $d\Gamma/dq^2$ & A_{FB}
- 2.3σ significance in $D \rightarrow \bar{K} \mu^+ \nu_\mu$
- No significance in $D \rightarrow \pi \mu^+ \nu_\mu$
- No significance for $\ell^+ = e^+$

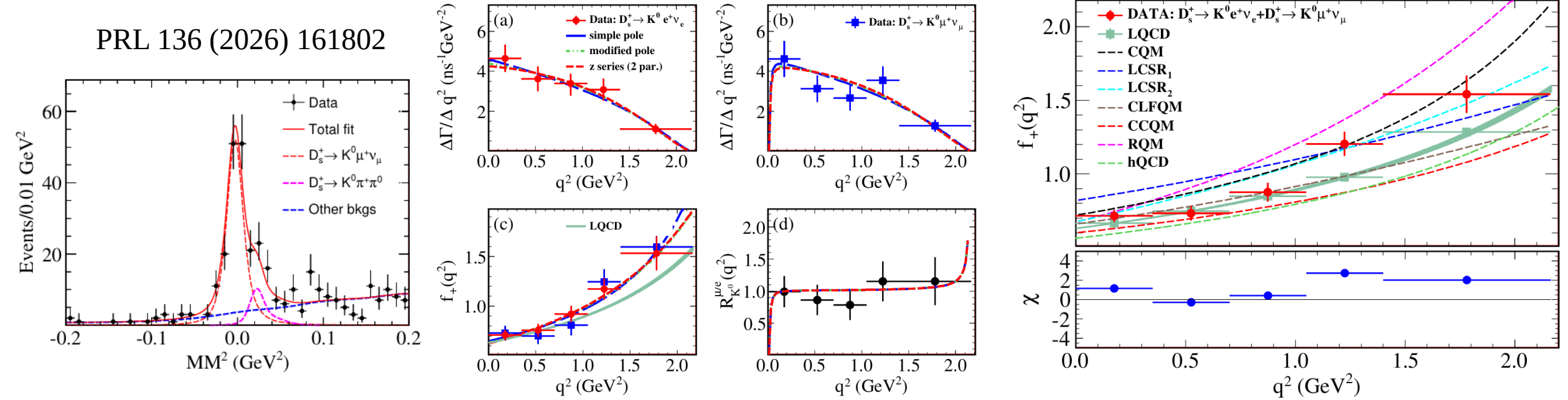


$$D \rightarrow \pi \ell^+ \nu_\ell$$



Observation of $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$

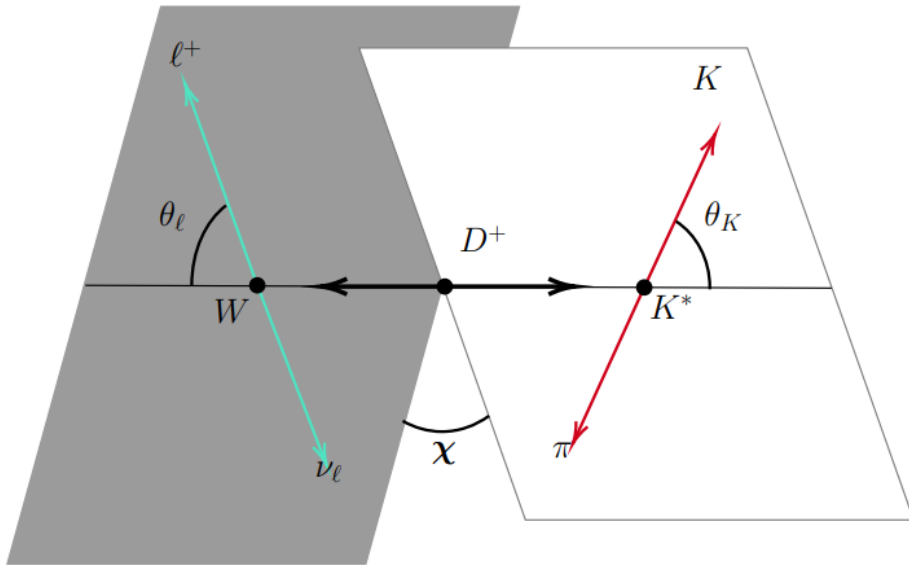
PRL 136 (2026) 161802



- Data sample: $7.33 \text{ fb}^{-1} D_s^\pm D_s^{*\mp}$
- $B_e = (2.98 \pm 0.23 \pm 0.12) \times 10^{-3}$ & $B_\mu = (2.89 \pm 0.27 \pm 0.12) \times 10^{-3}$
- $f_+(0) = (0.623 \pm 0.036 \pm 0.009)$, consistent with LQCD (0.631 ± 0.002)
- LFU: $R = 0.97 \pm 0.12 \pm 0.04$, consistent with SM 0.98 ± 0.01

Decay formalism of $D \rightarrow V \ell^+ \nu_\ell, V \rightarrow P_1 P_2$

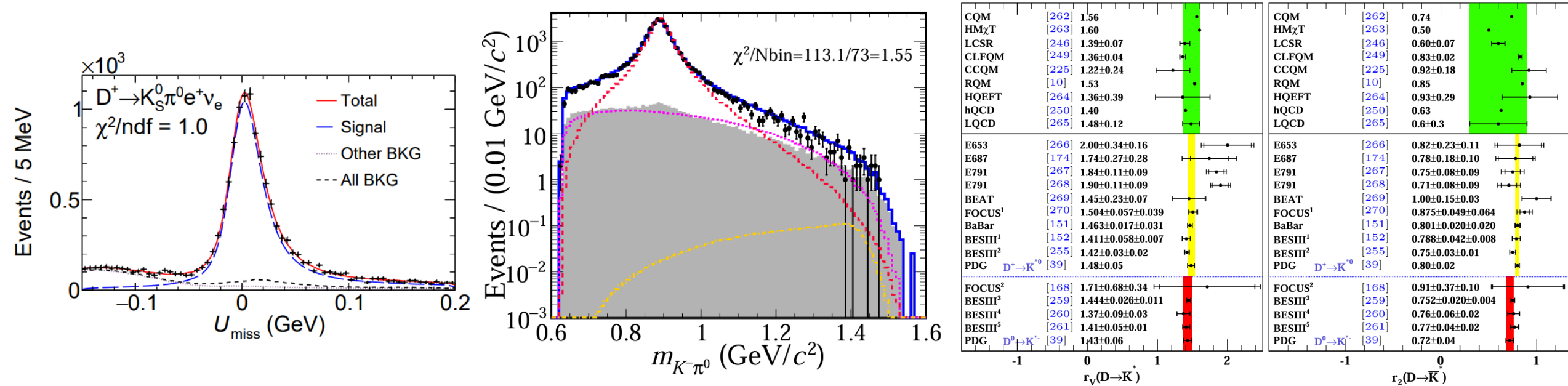
$$d^5\Gamma = \frac{G_F^2 |V_{cq}|^2}{(4\pi)^6 m_D^3} X \beta \beta_l I(S_{p_1 p_2}, q^2, \theta_K, \theta_l, \chi) ds_{p_1 p_2} dq^2 d\cos\theta_{p_1} d\cos\theta_l d\chi$$



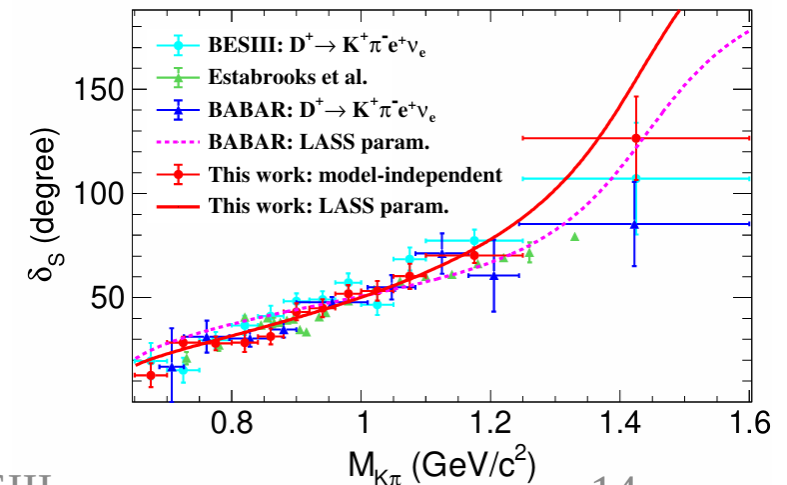
- Formalism based on [Phys. Rev. D 46 5040 \(1992\)](#)
- Five kinematic variables: $S_{p_1 p_2}, q^2, \theta_K, \theta_l, \chi$
- Decay intensity: $I = \sum_1^9 I_i(\theta_K, q^2, S_{p_1 p_2}) \times f_i(\theta_l, \chi)$
- The detailed expressions of I_i are given in reference.
- Three FFs: $A_{1,2}(q^2)$ & $V(q^2) \rightarrow r_2 = \frac{A_2(0)}{A_1(0)}$ & $r_V = \frac{V(0)}{A_1(0)}$

Precision measurement of $D \rightarrow \bar{K} \pi \ell^+ \nu_\ell$

$D^+ \rightarrow \bar{K}^0 \pi^0 \ell^+ \nu_\ell$: PRL 135 (2025)171801; $D^0 \rightarrow \bar{K}^0 \pi^- \ell^+ \nu_\ell$: arXiv 2603.04136; $D^0 \rightarrow K^- \pi^0 e^+ \nu_e$: arXiv 2603.00743

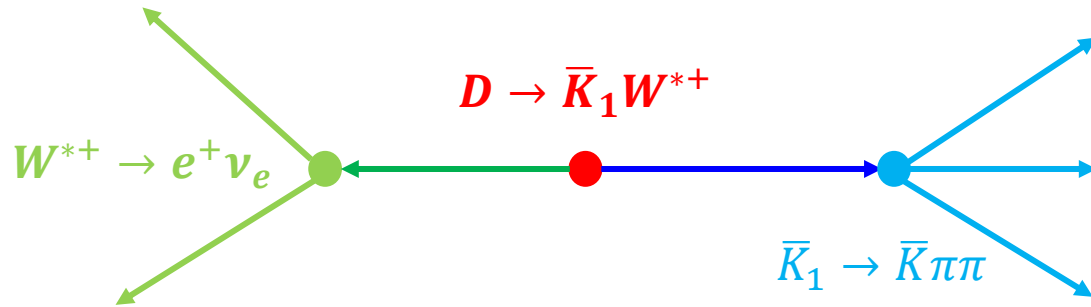


- $K^*(892)$: precision $r_2 = A_2(0)/A_1(0)$ & $r_V = V(0)/A_1(0)$
- $(K\pi)_{S\text{-wave}}$: model independent magnitude & phase
- $K_2^*(1430)$: first observation of tensor meson at 0.2% level



Decay formalism of $D \rightarrow Ae^+\nu_e, A \rightarrow P_1P_2P_3$

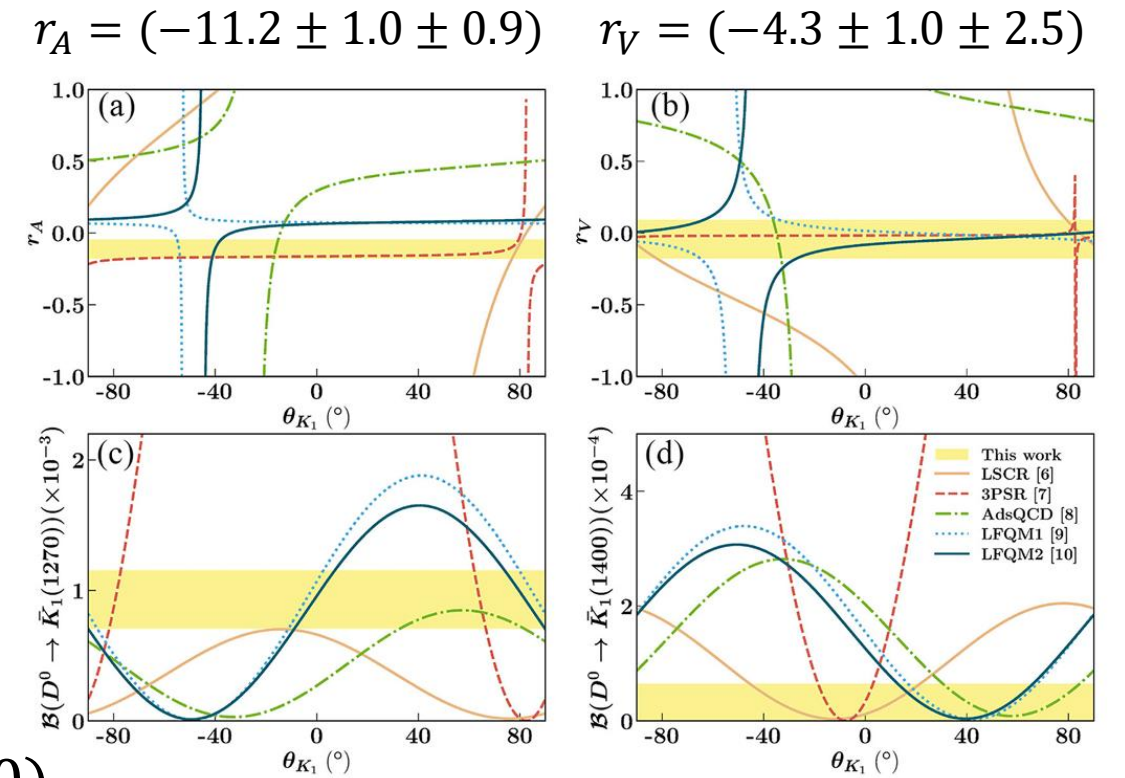
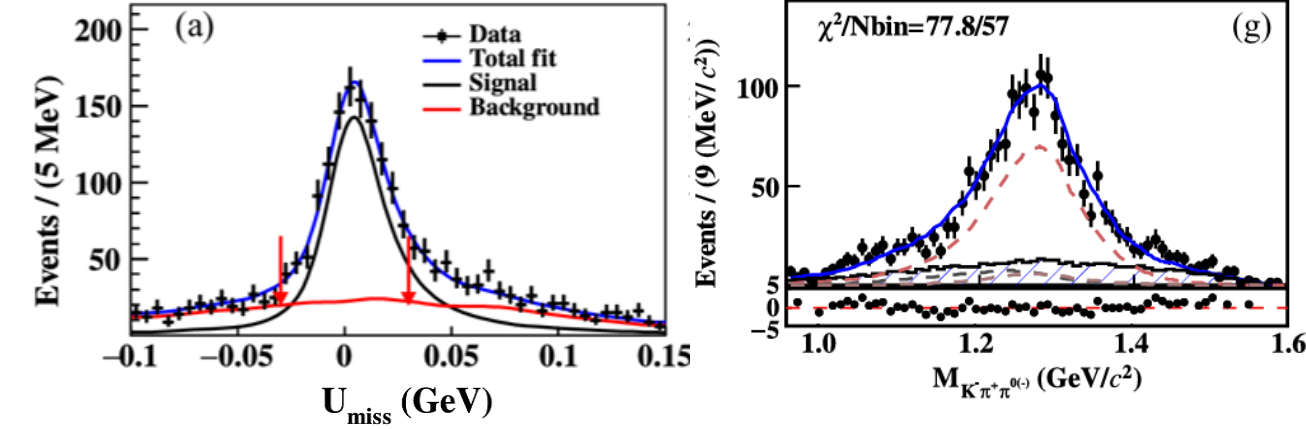
$$M = (V - A)^{\mu\eta} \cdot \left[\sum_{\lambda_{W^*}} \epsilon^*(\lambda_{W^*})_\mu \epsilon(\lambda_{W^*})_\rho \right] \cdot \left[\sum_{\lambda_{\bar{K}_1}} \epsilon^*(\lambda_{\bar{K}_1})_\eta \epsilon(\lambda_{\bar{K}_1})_\sigma \right] \cdot R_{\bar{K}_1} \cdot J^\sigma \cdot [\bar{u}_\nu \gamma^\rho (1 - \gamma_5) \nu_l]$$



- More independent kinematic variables of **five body** semi-leptonic decay $\rightarrow$ general formalism is required!
- $D \rightarrow \bar{K}_1 W^{*+}$: $\langle \bar{K}_1 | s \gamma_\mu (1 - \gamma_5) | D \rangle$, cited from [PRD 104, 053003 \(2021\)](#) $\rightarrow V_{1,2}$ & $A \rightarrow r_A = \frac{A(0)}{V_1(0)}$ & $r_V = \frac{V_2(0)}{V_1(0)}$
- $\bar{K}_1 \rightarrow \bar{K} \pi \pi$: Constructed in covariant tensor formalism, following [Eur. Phys. J. A 16, 537\(2003\)](#)
- $m_e \rightarrow 0$: $q^\mu [\bar{u}_\nu \gamma_\mu (1 - \gamma_5) \nu_l] = 0$ is used.

Study of $D \rightarrow \bar{K}_1(1270)e^+\nu_e$

PRL 135 (2025)091801



- $\bar{K}\pi\pi$ dominated by $K_1(1270)$, without $K_1(1400)$
- $K_1(1270) \rightarrow K\pi\pi$ dominated by $K^*(892)$ & $\rho(770)$
- BFs & FFs as a function of θ_{K_1} in various model
- Up-down asymmetry $A'_{ud} = 0.01 \pm 0.11$, consistent with $\lambda_\gamma = 1$ in $b \rightarrow s\gamma$

Channel	BF ($\times 10^{-3}$)
$D^+ \rightarrow K_1(1270)^0 e^+ \nu_e$	$2.27 \pm 0.11 \pm 0.10$
$D^0 \rightarrow K_1(1270)^+ e^+ \nu_e$	$1.02 \pm 0.06 \pm 0.07$
$D^+ \rightarrow K_1(1400)^0 e^+ \nu_e$	< 0.14
$D^0 \rightarrow K_1(1400)^+ e^+ \nu_e$	< 0.07

Summary

$$M_{fi} = \frac{G_F}{\sqrt{2}} V_{cq} \times \langle 0, P, S, V, A | q \gamma_\mu (1 - \gamma_5) c | D \rangle \times \bar{u}_\nu \gamma^\mu (1 - \gamma_5) \nu_\ell +$$

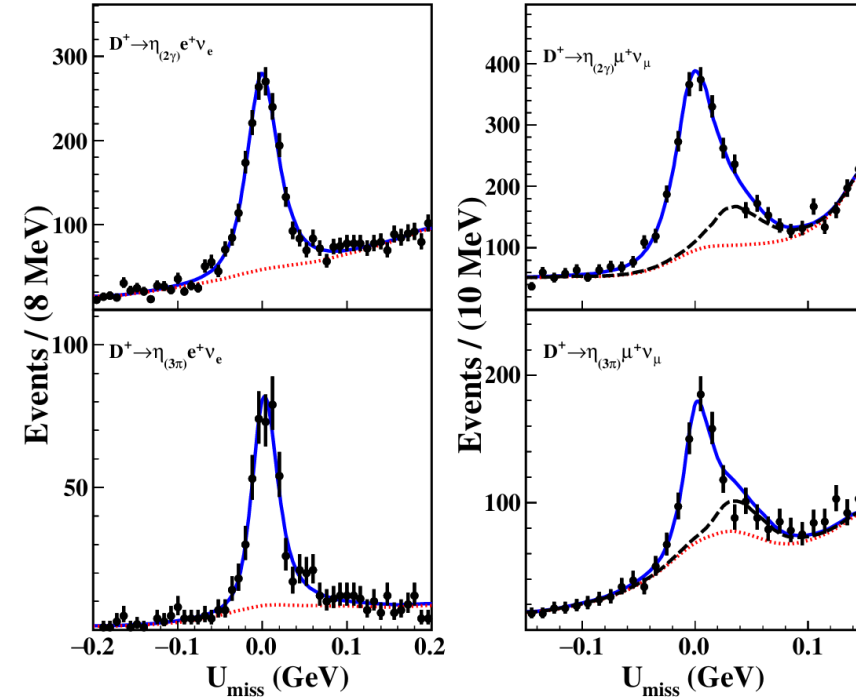
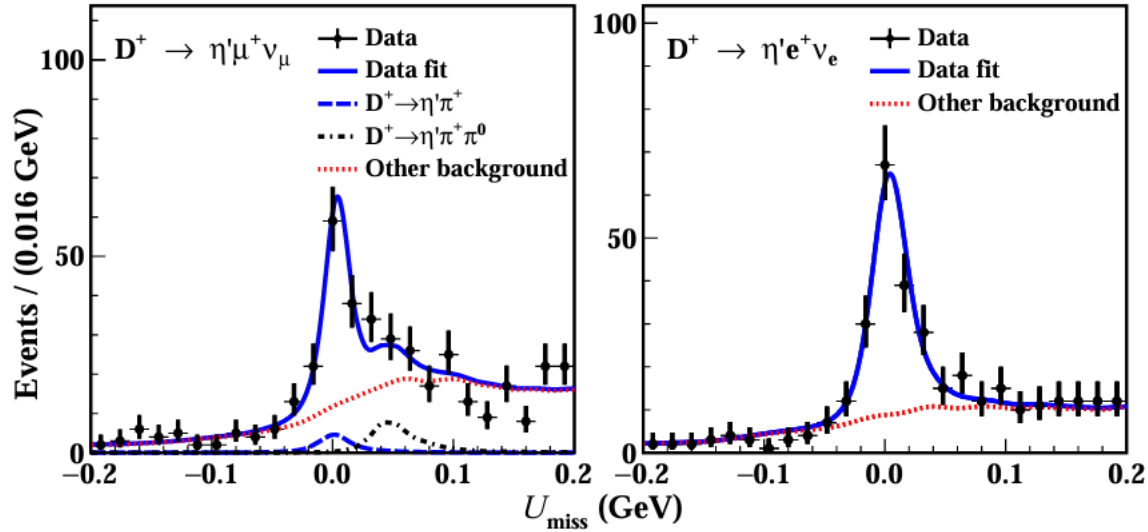
- **$|V_{cq}|$ related**: Precision $|V_{cs}|$ & $|V_{cd}|$ determined in $D_{(s)} \rightarrow \ell^+ \nu_\ell$ & $D \rightarrow \bar{K}/\pi \ell^+ \nu_\ell$ with input from LQCD calculations.
- **FFs related**: FFs at $q^2 = 0$ extracted from $D_{(s)} \rightarrow P, S, V, A$, as well as T
- **NP related**: LFU test in various channels, scalar current searched in $D \rightarrow \bar{K}/\pi \ell^+ \nu_\ell$

Backup Slides

Observation of $D \rightarrow \eta^{(\prime)} \ell^+ \nu_\ell$

arXiv: 2506.02521

PRL 134 (2025) 111801



Channel	BF ($\times 10^{-4}$)	$ V_{cd} f_+(0) (\times 10^{-3})$
$D^+ \rightarrow \eta' e^+ \nu_e$	$1.79 \pm 0.19 \pm 0.07$	$59.2 \pm 5.6 \pm 1.3$
$D^+ \rightarrow \eta' \mu^+ \nu_\mu$	$1.92 \pm 0.28 \pm 0.08$	
$D^+ \rightarrow \eta e^+ \nu_e$	$9.08 \pm 0.35 \pm 0.23$	$78 \pm 2 \pm 1$
$D^+ \rightarrow \eta \mu^+ \nu_\mu$	$9.75 \pm 0.29 \pm 0.28$	

$$\frac{\Gamma_{D^+ \rightarrow \eta' \mu^+ \nu_\mu}}{\Gamma_{D^+ \rightarrow \eta' e^+ \nu_e}} = 1.07 \pm 0.19$$

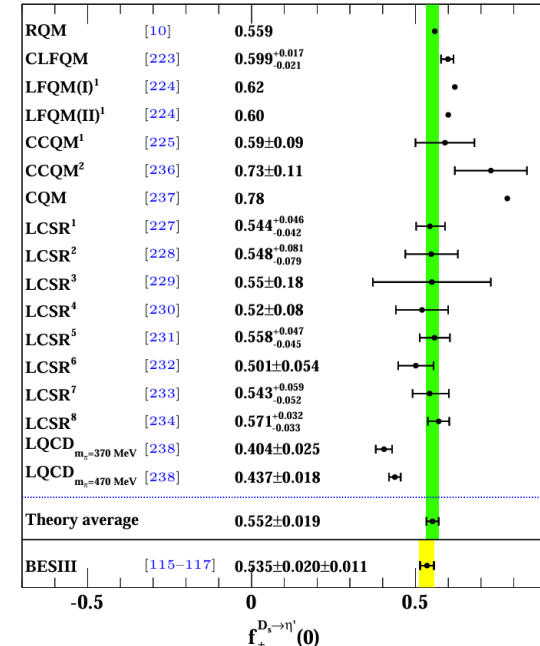
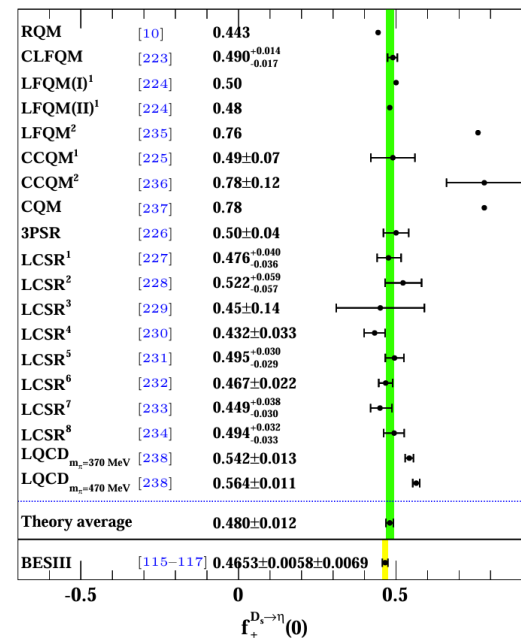
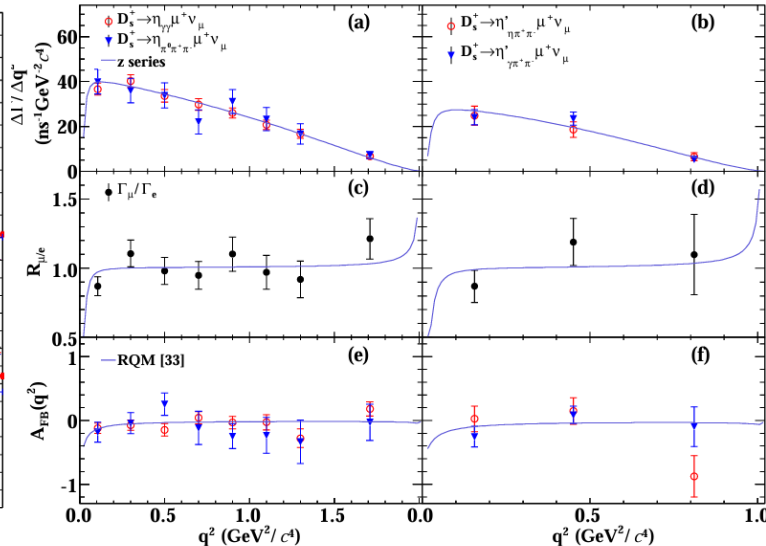
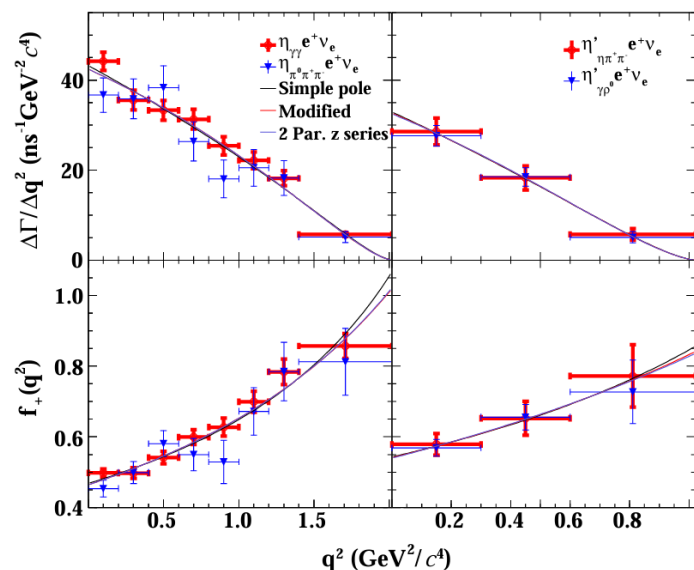
$$\frac{\Gamma_{D^+ \rightarrow \eta \mu^+ \nu_\mu}}{\Gamma_{D^+ \rightarrow \eta e^+ \nu_e}} = 0.93 \pm 0.05$$

Consistent with SM values

Observation of $D_s^+ \rightarrow \eta^{(\prime)} \ell^+ \nu_\ell$

$\ell^+ = e^+$: PRD 108 (2023) 092003

$\ell^+ = \mu^+$: PRL 132 (2024) 091802

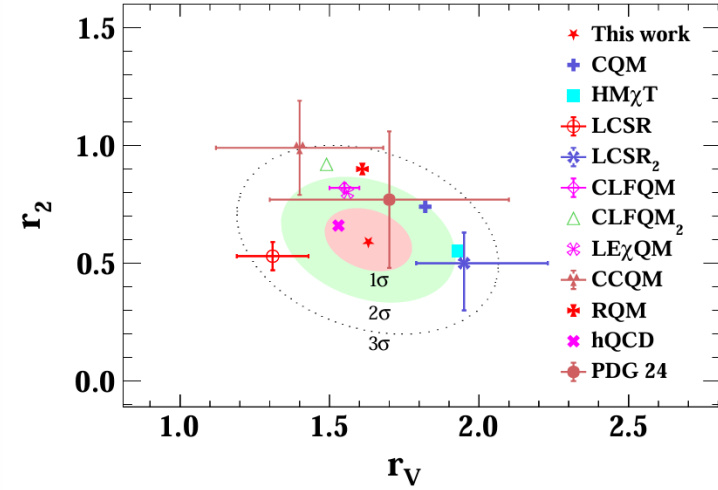
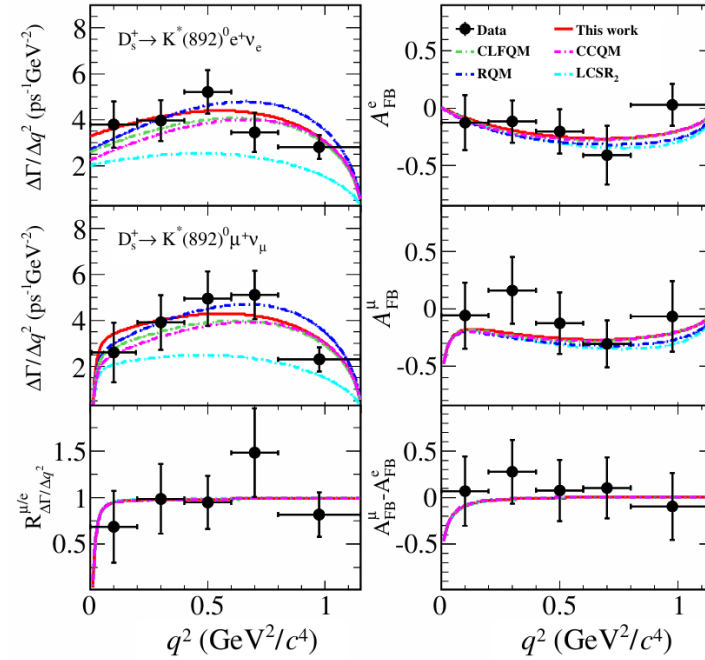
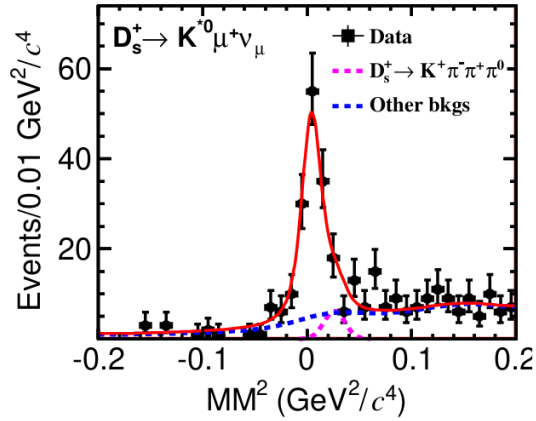
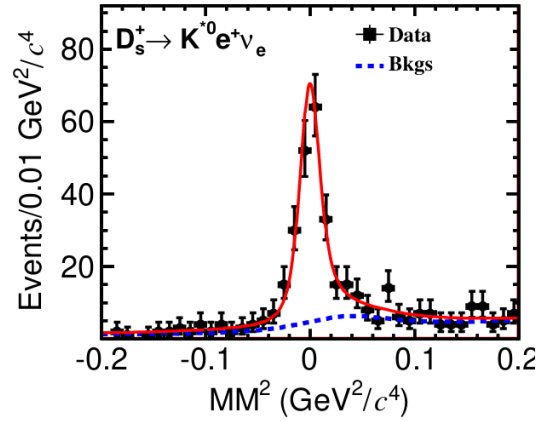


- Data sample: $7.33 \text{ fb}^{-1} D_s^\pm D_s^{*\mp}$
- LFU: $R_\eta = (0.99 \pm 0.03 \pm 0.02)$ & $R_{\eta'} = (0.99 \pm 0.08 \pm 0.03)$, consistent with SM

Channel	BF (%)	$f_+(0) V_{cs} $
$D_s^+ \rightarrow \eta' e^+ \nu_e$	$0.81 \pm 0.04 \pm 0.03$	$0.53 \pm 0.03 \pm 0.01$
$D_s^+ \rightarrow \eta' \mu^+ \nu_\mu$	$0.80 \pm 0.06 \pm 0.03$	$0.50 \pm 0.04 \pm 0.01$
$D_s^+ \rightarrow \eta e^+ \nu_e$	$2.26 \pm 0.04 \pm 0.05$	$0.45 \pm 0.01 \pm 0.01$
$D_s^+ \rightarrow \eta \mu^+ \nu_\mu$	$2.24 \pm 0.05 \pm 0.05$	$0.45 \pm 0.01 \pm 0.01$

Observation of $D_s^+ \rightarrow \bar{K} \pi \ell^+ \nu_\ell$

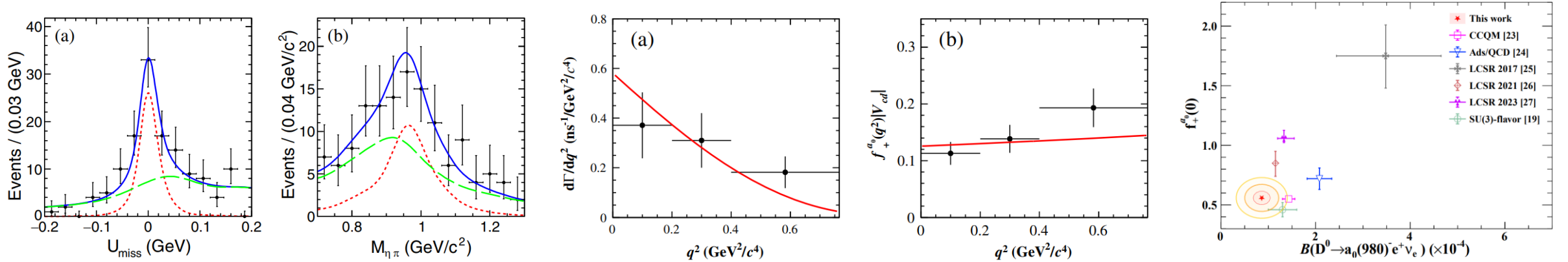
arxiv:2605.07176



- Data sample: $7.33 \text{ fb}^{-1} D_s^\pm D_s^{*\mp}$
- LFU: $R = 0.97 \pm 0.14$, consistent with SM

Channel	BF ($\times 10^{-5}$)	r_V ($\times 10^{-2}$)	r_2 ($\times 10^{-2}$)
$D_s^+ \rightarrow K^*(892)^0 e^+ \nu_e$	$214 \pm 18 \pm 10$	$163 \pm 14 \pm 8$	$56 \pm 2 \pm 1$
$D_s^+ \rightarrow K^*(892)^0 \mu^+ \nu_\mu$	$207 \pm 22 \pm 10$		

Updated measurement of $D^0 \rightarrow a_0(980)^- e^+ \nu_e$



- [Phys. Rev. D 111, L091501 \(2025\)](#), based on 7.93 fb^{-1} data sample @3.773 GeV, $N_{DT} \sim 50$
- $B(D^0 \rightarrow a_0(980)^- e^+ \nu_e) \times B(a_0(980)^- \rightarrow \eta \pi^-) = (0.86 \pm 0.17 \pm 0.05) \times 10^{-4}$
- **First extraction of the FF:** $f_+^{a_0(980)}(0) = 0.559 \pm 0.056 \pm 0.013$
- Pin down the nature of $a_0(980)$ by comparing with theoretical calculations