Charmed meson decays at BESIII

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On behalf of the BESIII Collaboration

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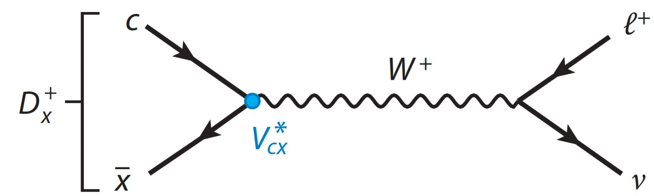
第二十二届全国重味物理和CP破坏研讨会（HFCPV2025）

Outline

- BESIII dataset
- Charmed meson
  - pure leptonic decays
  - semi-leptonic decays
  - hadronic decays
  - quantum correlation
- Prospect



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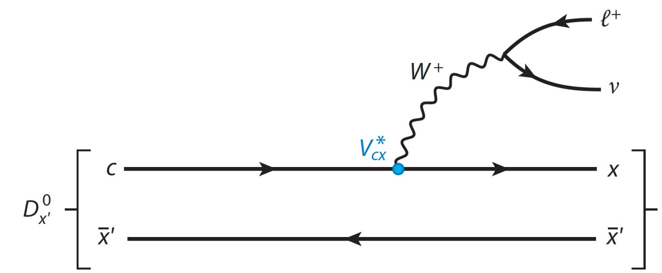

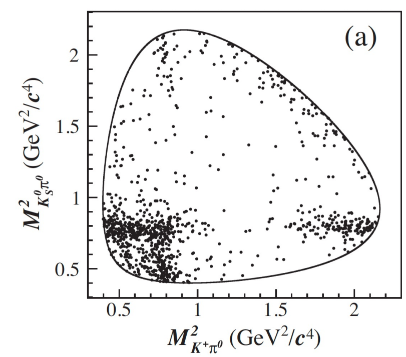

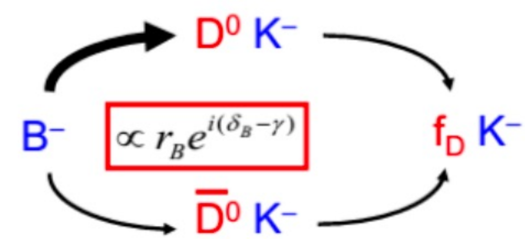

Outline

- **BESIII dataset**
- Charmed meson
  - pure leptonic decays
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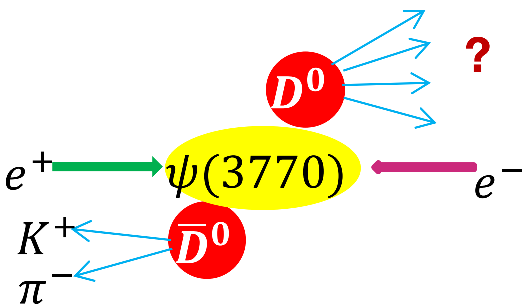
BESIII Data near Threshold

- 20.3 fb^{-1} at E$_{cm}$ 3.773 GeV: $e^+e^-\rightarrow$ ψ(3770)$\rightarrow D\bar{D}$
- 7.33 fb^{-1} at E$_{cm}$ 4.128 - 4.226 GeV: $e^+e^-\rightarrow D_sD_s^*$

Production of charm hadron pair



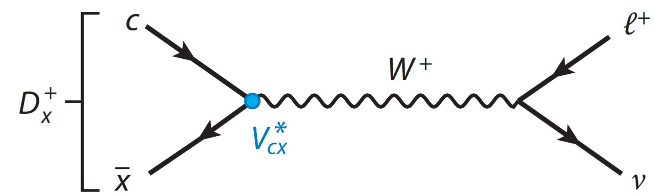
Tag one side to study another side

Fully reconstruction → **Clean sample** → **Hadronic decays**

Recoil four-momentum → **missing particle (neutrino)** → **(Semi)-leptonic decays**

Absolute branching fraction
Amplitude analysis
etc.

Outline



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Motivation

- **Charm Decays: The Best Probe of $|V_{cd}|$ and $|V_{cs}|$**

  Pure & semi-leptonic channels provide the most precise measurement.

$$V_{\mathrm{CKM}}^{\mathrm{PDG2024}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.97367 \pm 0.00032 & 0.22431 \pm 0.00085 & 0.00382 \pm 0.00020 \\ 0.221 \pm 0.004 & 0.975 \pm 0.006 & 0.0411 \pm 0.0012 \\ 0.0086 \pm 0.0002 & 0.0415 \pm 0.0009 & 1.010 \pm 0.027 \end{pmatrix}$$

- Verifying the unitarity of the CKM matrix to test the SM.

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = \mathbf{0.9984 \pm 0.0007} \quad \sim\mathbf{0.07\%}$$

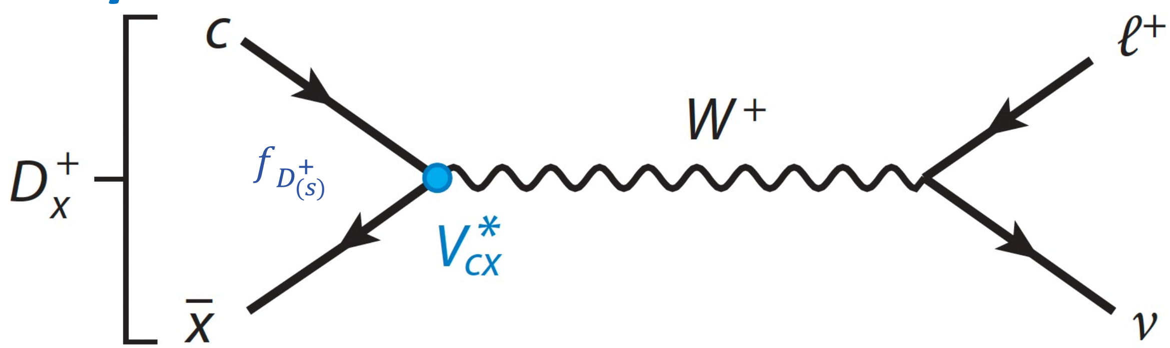
$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = \mathbf{1.001 \pm 0.012} \quad \sim\mathbf{1\%}$$

Precision of the second row is dominated by that of $|V_{cd}|$ and $|V_{cs}|$

Precise measurement of $|V_{cd}|$ and $|V_{cs}|$ is crucial

Motivation

Leptonic decays



$J^p = 0^-$
$$\Gamma(D_{(s)}^+ \to l^+\nu) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} |V_{cd(s)}|^2 m_l^2 m_{D_{(s)}^+} \left(1 - \frac{m_l^2}{m_{D_{(s)}^+}^2}\right)^2$$

$J^p = 1^-$
$$\Gamma(D_{(s)}^{*+} \to l^+\nu) = \frac{G_F^2 f_{D_{(s)}^{*+}}^2}{8\pi} |V_{cd(s)}|^2 m_{D_{(s)}^{*+}} \left(1 - \frac{m_l^2}{m_{D_{(s)}^{*+}}^2}\right)^2 \left(1 + \frac{m_l^2}{m_{D_{(s)}^{*+}}^2}\right)$$

- $|V_{cd(s)}|$ measurement ⟹ Test CKM matrix unitarity
- Decay constant measurements ⟹ Calibrate LQCD calculations
- Branching Fractions $\mathcal{B}_{\mu/\tau}$ ⟹

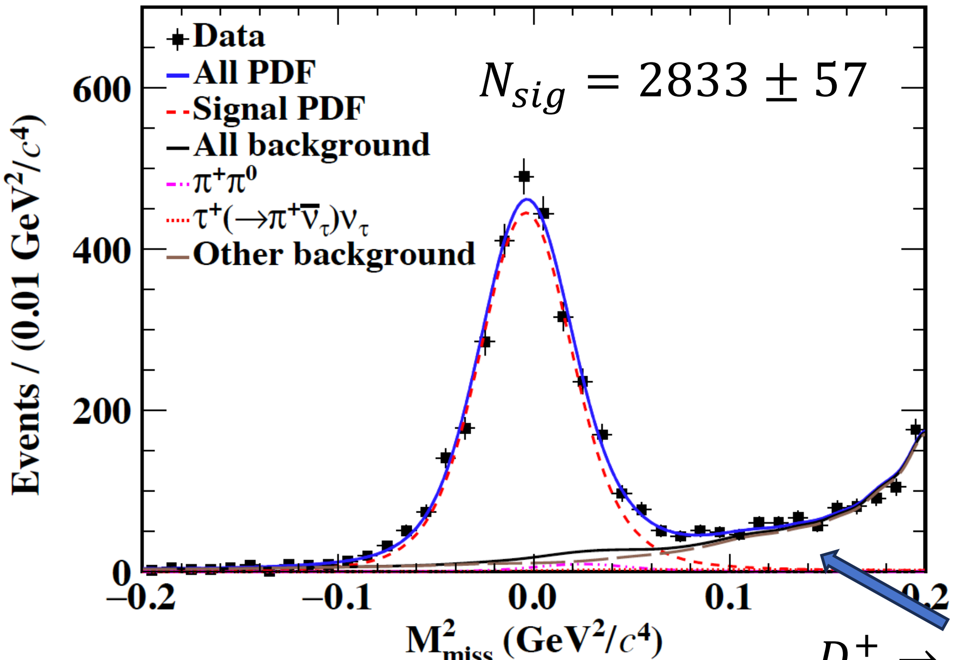
  Test lepton flavor universality (LFU)

	$e^+\nu_e$	$\mu^+\nu_\mu$	$\tau^+\nu_\tau$
D^+	10^{-5}	1	2.67
D_s^+	10^{-5}	1	9.75

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

20.3 fb^{-1}@E_{cm}=3.773 GeV

PRL 135, 061081 (2025)



- $\Gamma_{D^+\to\ell^+\nu_\ell} = \Gamma^0_{D^+\to\ell^+\nu_\ell}[1 + \frac{\alpha}{\pi} C_p] \Rightarrow$ Radiative correction term

1. Short-distance electroweak correction increases BF by 1.8% [PRD98,074512, NPB196,83]
2. Long-distance electroweak correction [inner bremsstrahlung and virtual photon] reduce BF by 2.5% with 0.6% uncertainty of unknown electromagnetic correction [PRD98,074512]

$D^+ \to \gamma\mu^+\nu_\mu$ background is simulated in the fit

$$\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (4.034 \pm 0.080 \pm 0.040)\times 10^{-4}$$

Precision is improved by 2.4x

$$f_{D^+}|V_{cd}| = (48.02 \pm 0.48 \pm 0.24 \pm 0.12_{\text{input}} \pm 0.15_{\text{EM}}) \text{ MeV}$$

$f_{D^+} = (213.5 \pm 2.1 \pm 1.1 \pm 0.8 \pm 0.7)$ MeV (~1.2%) Most precise

$$|V_{cd}| = (0.2265 \pm 0.0023 \pm 0.0011 \pm 0.0009 \pm 0.0007)$$

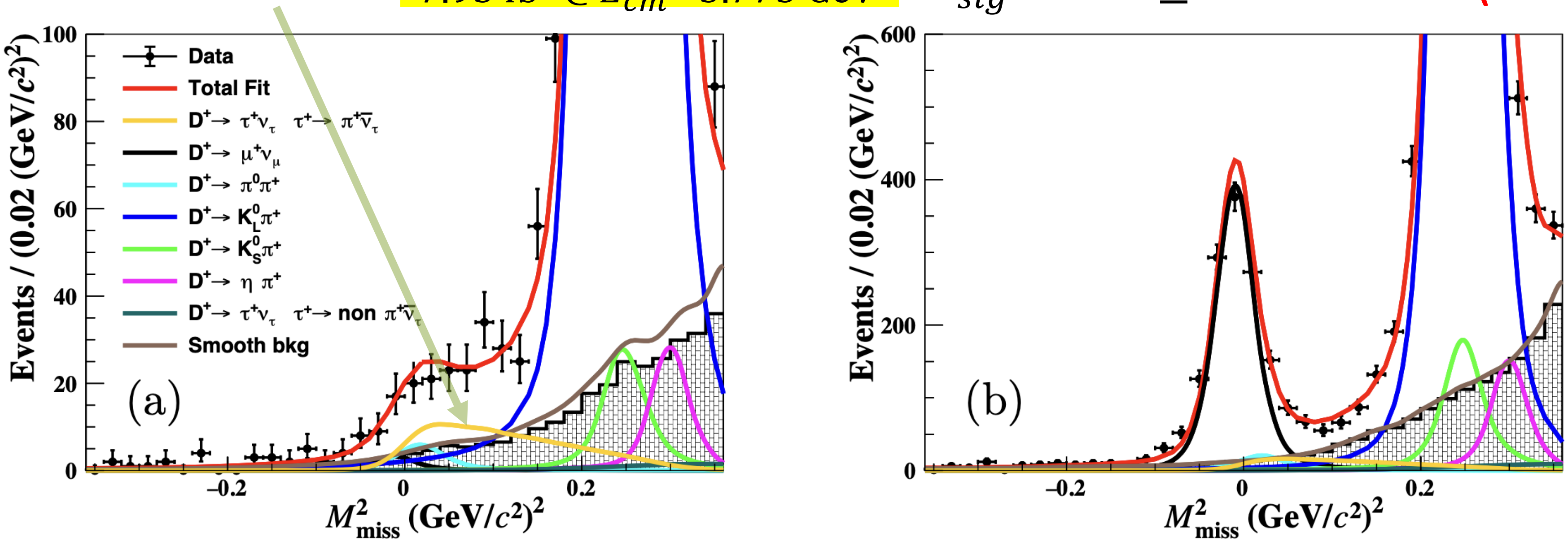
$D^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\nu_\tau$

$D^+ \to \tau^+\nu_\tau$

7.93 fb^{-1}@E_{cm}=3.773 GeV

$N_{sig} = 283 \pm 32$

JHEP01(2025)089



$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (9.9 \pm 1.1 \pm 0.5)\times 10^{-4}$

$f_{D^+}|V_{cd}| = (45.9 \pm 2.5 \pm 1.2 \pm 0.1_{\text{input}})$ MeV

$f_{D^+} = (204 \pm 11 \pm 5 \pm 1)$ MeV (~5.9%)

$|V_{cd}| = 0.216 \pm 0.012 \pm 0.006 \pm 0.001$ (~6.2%)

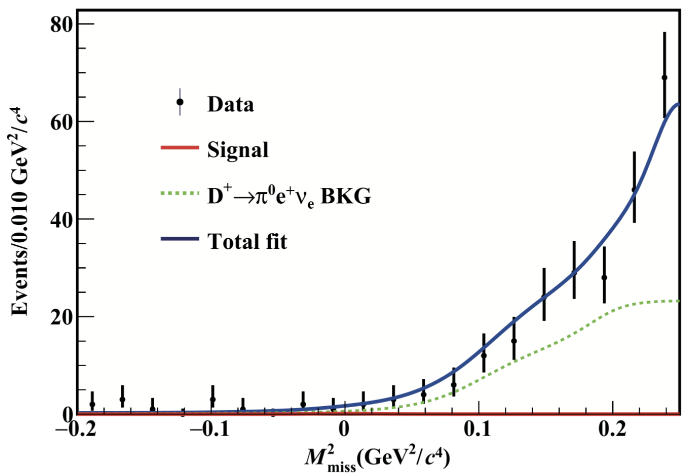
LFU: $\frac{\Gamma_\tau}{\Gamma_\mu} = 2.45 \pm 0.31$ consistent with SM 2.66 ± 0.01

To be updated using the 20 fb^{-1} full dataset

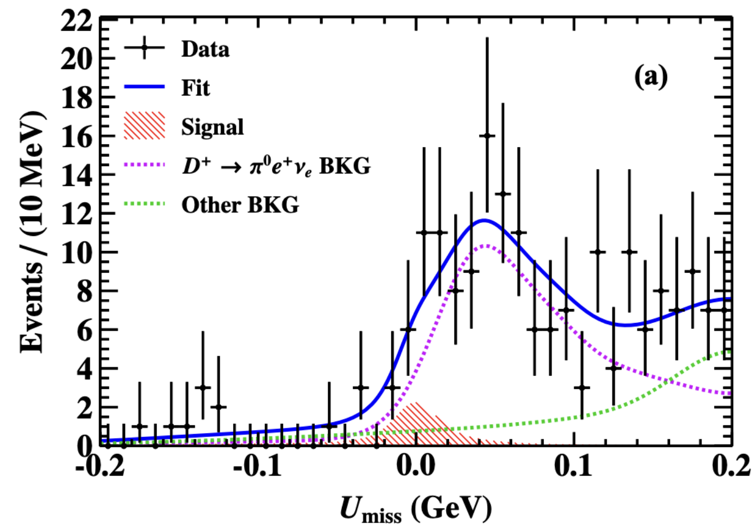
$D^+ \to e^+\nu_e$ and $D^+ \to \gamma e^+\nu_e$

20.3 fb^{-1}@E_{cm}=3.773 GeV

CPC 49, 063001 (2025)



CPC 49, 083001 (2025)



$D^+ \to e^+\nu_e$ is helicity suppressed. $D^+ \to \gamma e^+\nu_e$ can reduce this suppression.

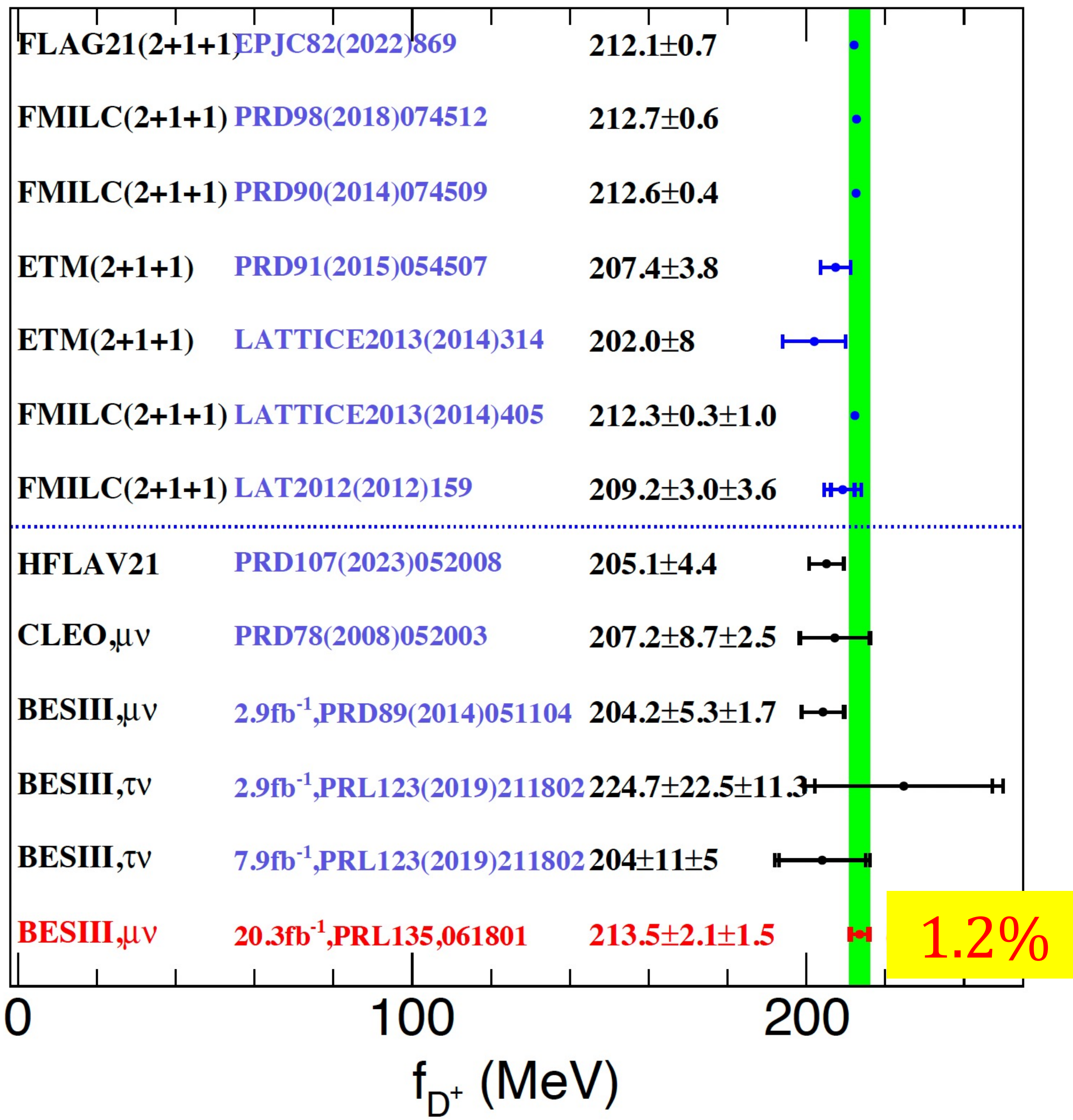
Theo. Prediction: $\mathcal{B}(D^+ \to e^+\nu_e) < 10^{-8}$; $\mathcal{B}(D^+ \to \gamma e^+\nu_e) = 10^{-5} \sim 10^{-3}$

$\mathcal{B}(D^+ \to e^+\nu_e) < 9.7\times10^{-8}$ @90% C.L.

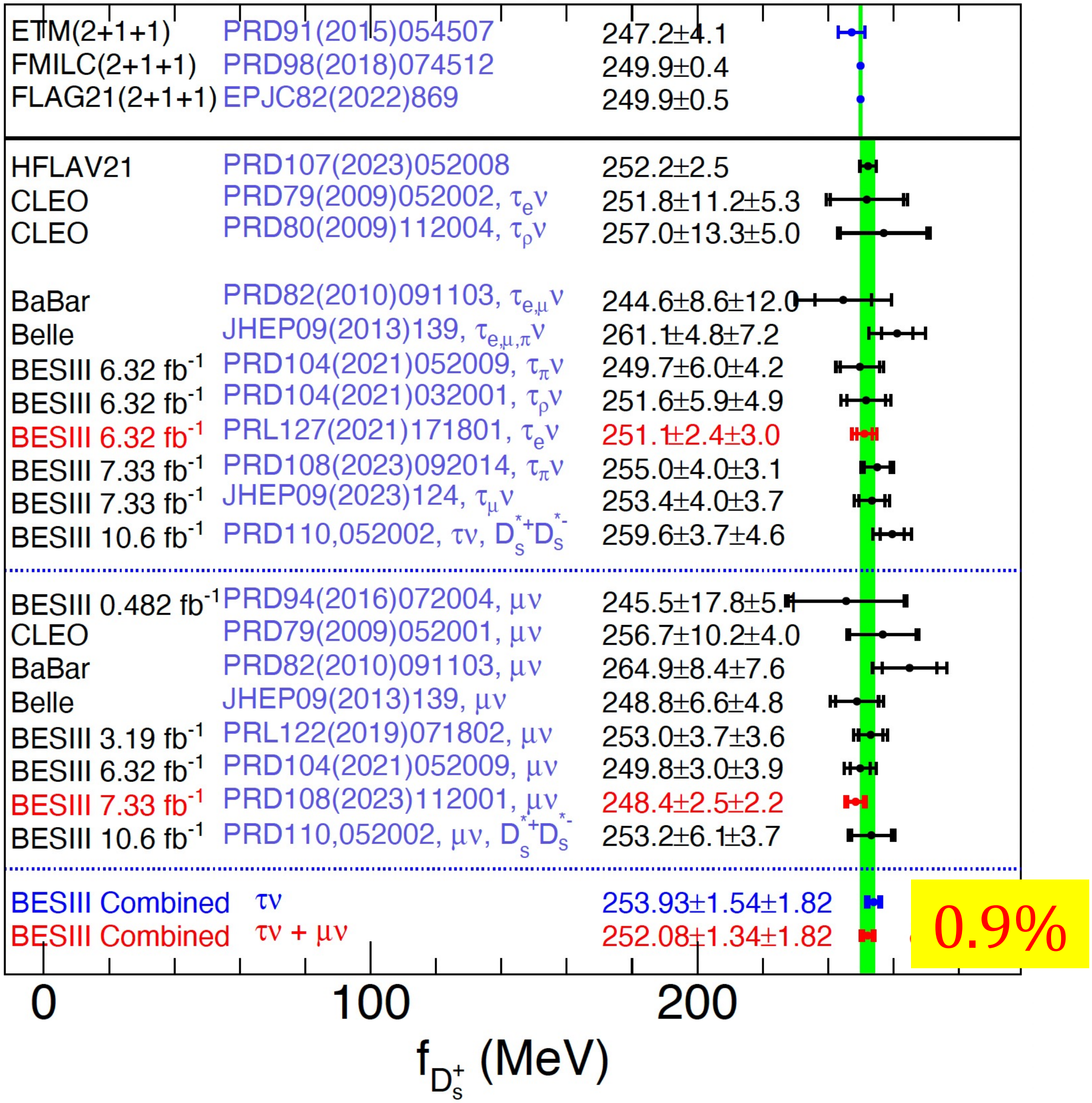
$\mathcal{B}(D^+ \to \gamma e^+\nu_e) = 1.2\times10^{-5}$ @90% C.L.

Help to estimate background in $D^+ \to \mu^+\nu_\mu$

Comparison of f_{D^+}



Comparison of $f_{D_s^+}$



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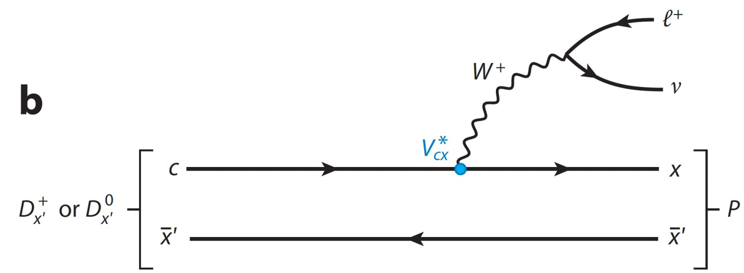
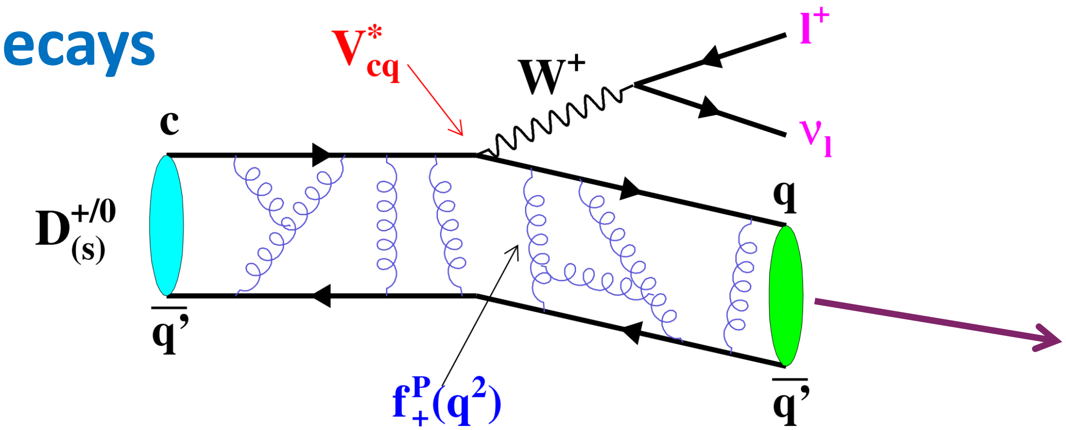


Motivation

Semileptonic decays



P, S, V, A
P = pseudoscalar
S = scalar
V = vector
A = axial-vector

$$d\Gamma/dq^2 = X\frac{G_F^2 p^3}{24\pi^3}\left|V_{cd(s)}\right|^2\left|f_+(q^2)\right|^2$$

Weak interaction:
CKM matrix

Strong interaction：
Form factor

- $|V_{cd(s)}|$ measurement $\Longrightarrow$ Test CKM matrix unitarity
- Form factor $f_+(0)$ measurements $\Longrightarrow$ Calibrate LQCD calculations
- Branching Fractions $\mathcal{B}_{\mu/e}$ $\Longrightarrow$ Test lepton flavor universality (LFU)
- Rare decays $\Longrightarrow$ Search for new physics effects beyond the SM

$D \to P\, l^+ \upsilon_l$

$$\Gamma(D \to P l^+ \upsilon_l)/dq^2 \propto |V_{cd(s)}|^2 |f_+(q^2)|^2$$

P: K, π, η, η'

$$q^2 = (E_{\ell^+} + E_{\nu_\ell})^2 - |\vec{p}_{\ell^+} + \vec{p}_{\nu_\ell}|^2$$

- **Fit the measured partial decay width in different q^2 bin**
- Taking the correlations among q^2 bins into account
- FF parameterized in different form

✓ Single pole model

$$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M^2_{pole}}}$$

✓ Modified pole model

$$f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{M^2_{pole}})(1 - \alpha \frac{q^2}{M^2_{pole}})}$$

✓ ISGW2 model

$$f_+(q^2) = f_+(q^2_{max})(1 + \frac{r^2}{12}(q^2_{max} - q^2))^{-2}$$

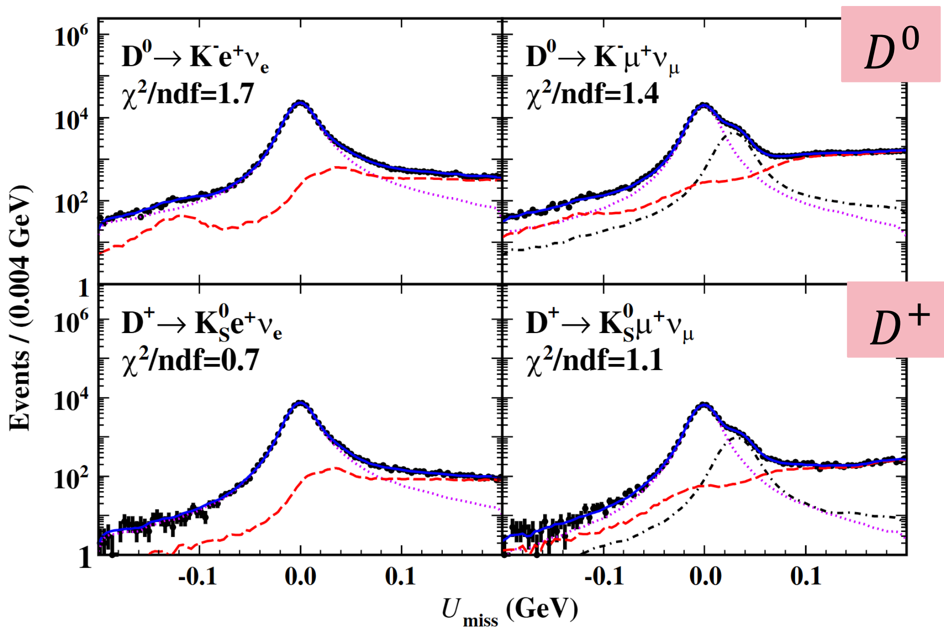
✓ Series expansion mode

$$f_+(t) = \frac{1}{P(t)\Phi(t,t_0)} a_0(t_0)(1 + \sum_{k=1}^{\infty} r_k(t_0)\,[z(t,t_0)])^k$$

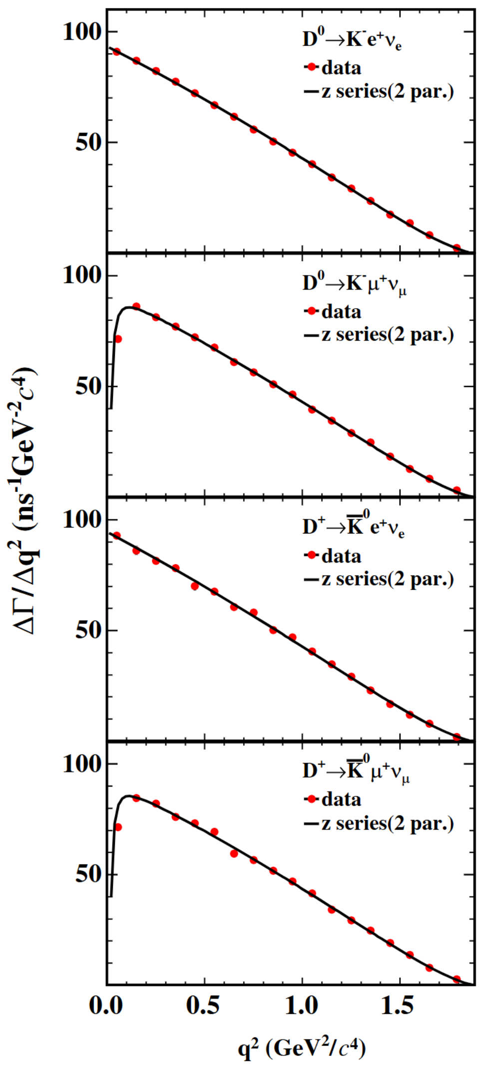
$D \to \bar{K}\ell^+\nu_\ell(\ell = e, \mu)$

7.9fb^{-1}@E_{cm}=3.773 GeV

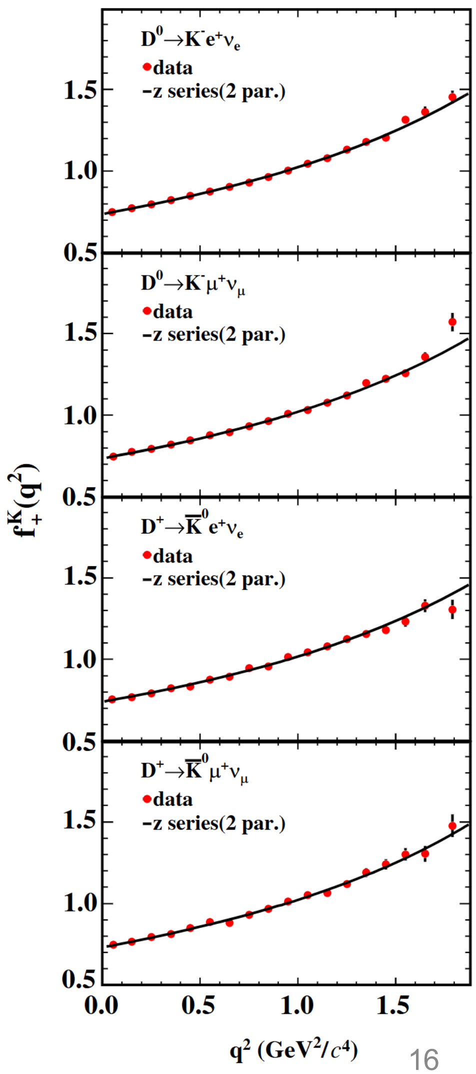
PRD 110, 112006 (2024)



Decay width in q^2 bin



Form factor in q^2 bin



- BF measurement:

$\mathcal{B}(D^0 \to K^-e^+\nu_e) = (3.521 \pm 0.009 \pm 0.016)\%$

$\mathcal{B}(D^0 \to K^-\mu^+\nu_\mu) = (3.419 \pm 0.011 \pm 0.016)\%$

$\mathcal{B}(D^+ \to \bar{K}^0e^+\nu_e) = (8.864 \pm 0.039 \pm 0.082)\%$

$\mathcal{B}(D^+ \to \bar{K}^0\mu^+\nu_\mu) = (8.665 \pm 0.046 \pm 0.084)\%$

- LFU test (SM: 0.975±0.001):

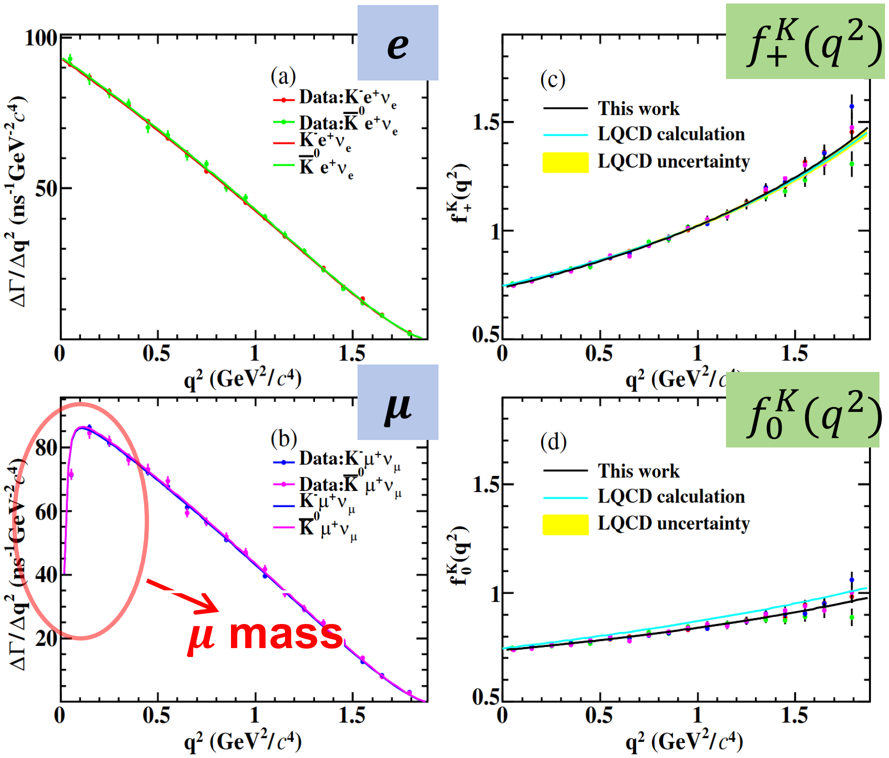
$\mathcal{R}^{D^0\to K^-}_{\mu/e} = 0.971 \pm 0.004 \pm 0.006(\sim 0.7\%)$

$\mathcal{R}^{D^+\to \bar{K}^0}_{\mu/e} = 0.978 \pm 0.007 \pm 0.013(\sim 1.5\%)$

$D \to \bar{K}\ell^+\nu_\ell(\ell = e, \mu)$

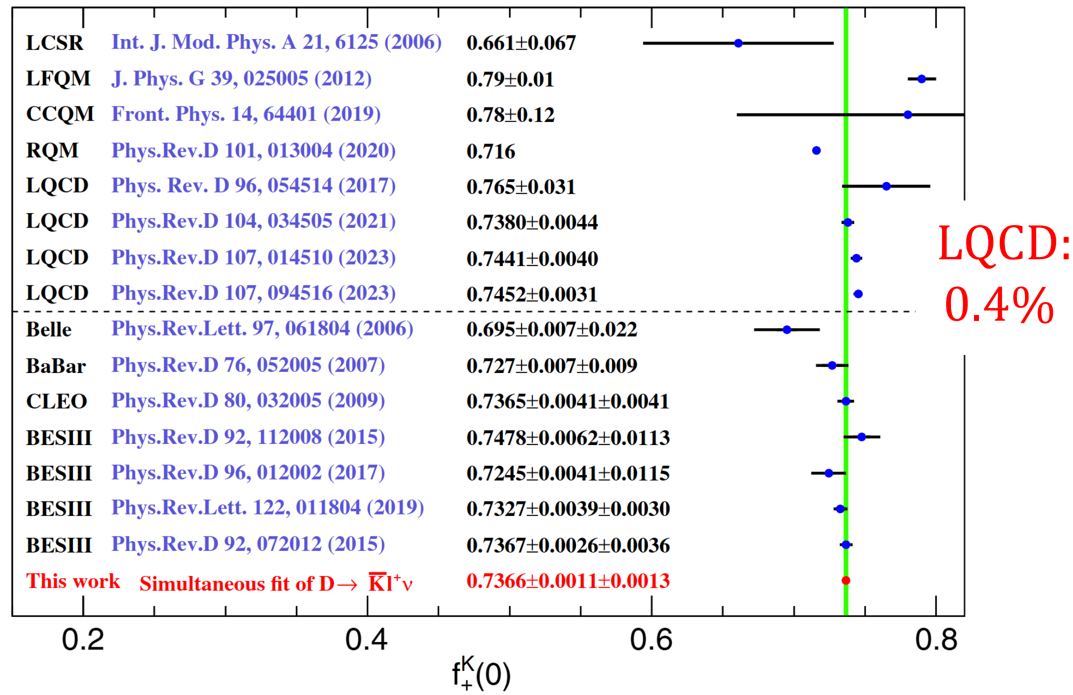
Simultaneous fit

PRD 110, 112006 (2024)



decay width in q^2 bin

Form factor in q^2 bin



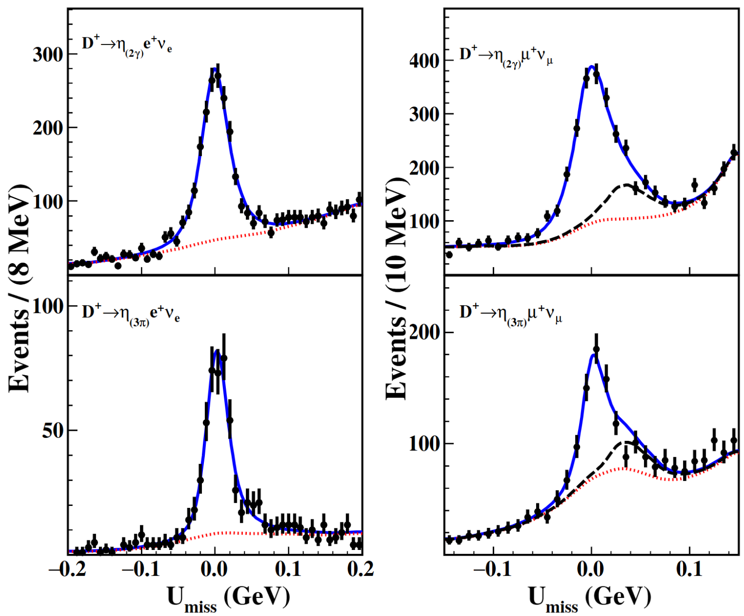
- $f_+^K(0) = 0.7366 \pm 0.0011 \pm 0.0013$ ($\sim 0.24\%$) improved by > a factor of 2
- $|V_{cs}| = (0.9623 \pm 0.0015 \pm 0.0017 \pm 0.0040_{\mathrm{LQCD}})(\sim 0.48\%)$ most precise
- Main uncertainty of $|V_{cs}|$ from the LQCD calculations in the input $f_+^K(0)(\sim 0.42\%)$

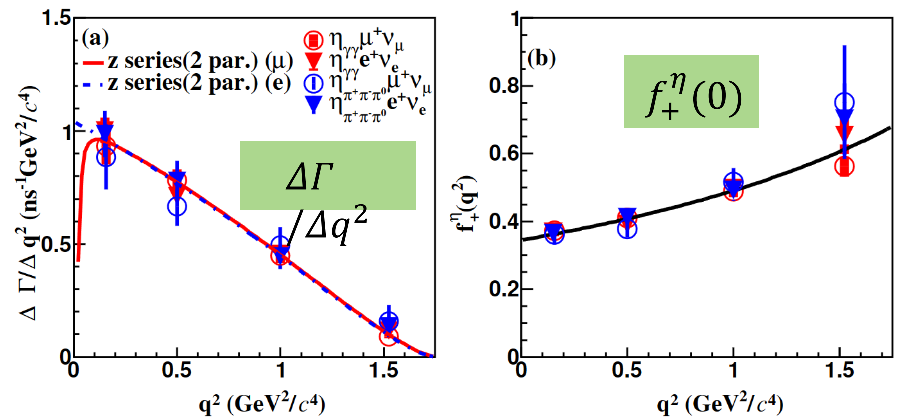
($\sim 2\%$ before)

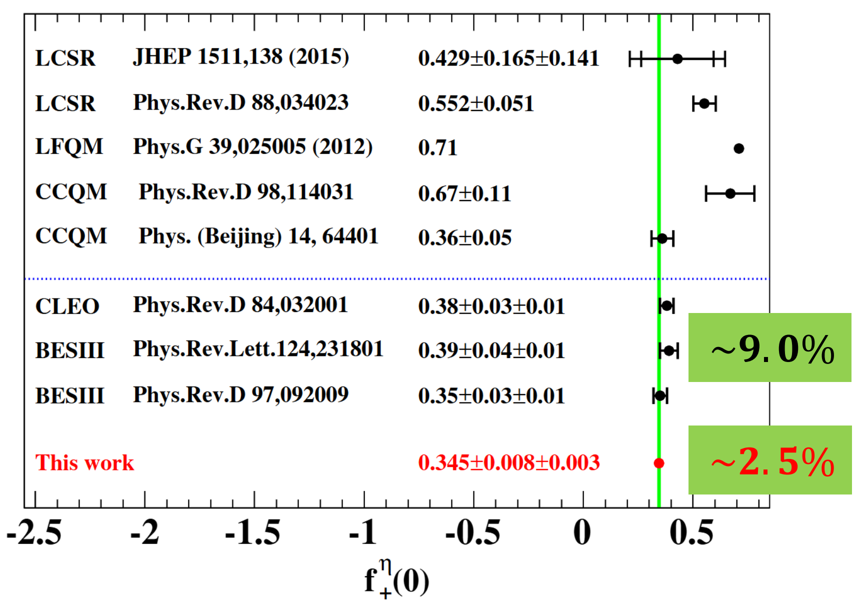
$D^+ \to \eta\ell^+\nu_\ell(\ell = e, \mu)$

20.3fb^{-1}@E_{cm}=3.773 GeV

arXiv: 2506.02521, submitted to JHEP







- BF measurement:

$$\mathcal{B}(D^+ \to \eta e^+\nu_e) = (9.75 \pm 0.29 \pm 0.28)\times 10^{-4}$$

$$\mathcal{B}(D^+ \to \eta \mu^+\nu_\mu) = (9.08 \pm 0.35 \pm 0.29)\times 10^{-4}$$

- LFU test :

$$\mathcal{R}_{\mu/e} = 0.93 \pm 0.05 \pm 0.02(\sim 5.8\%)$$

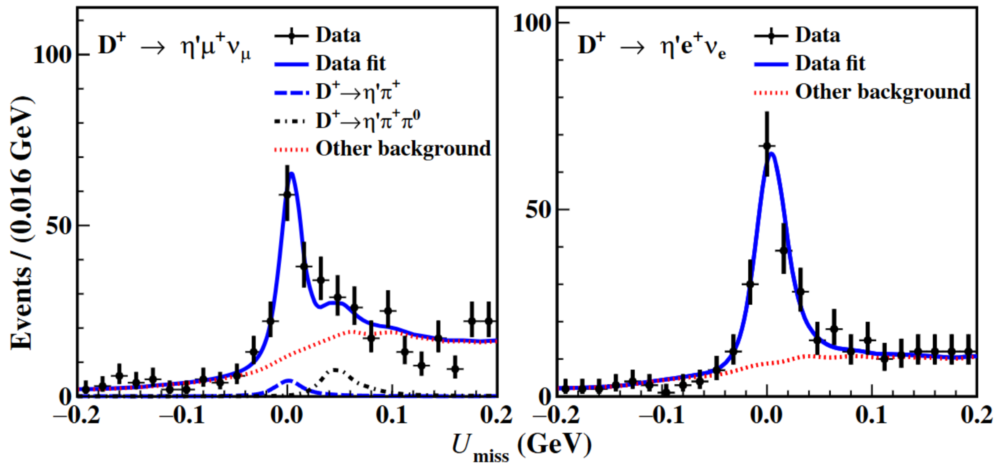
- Form factor

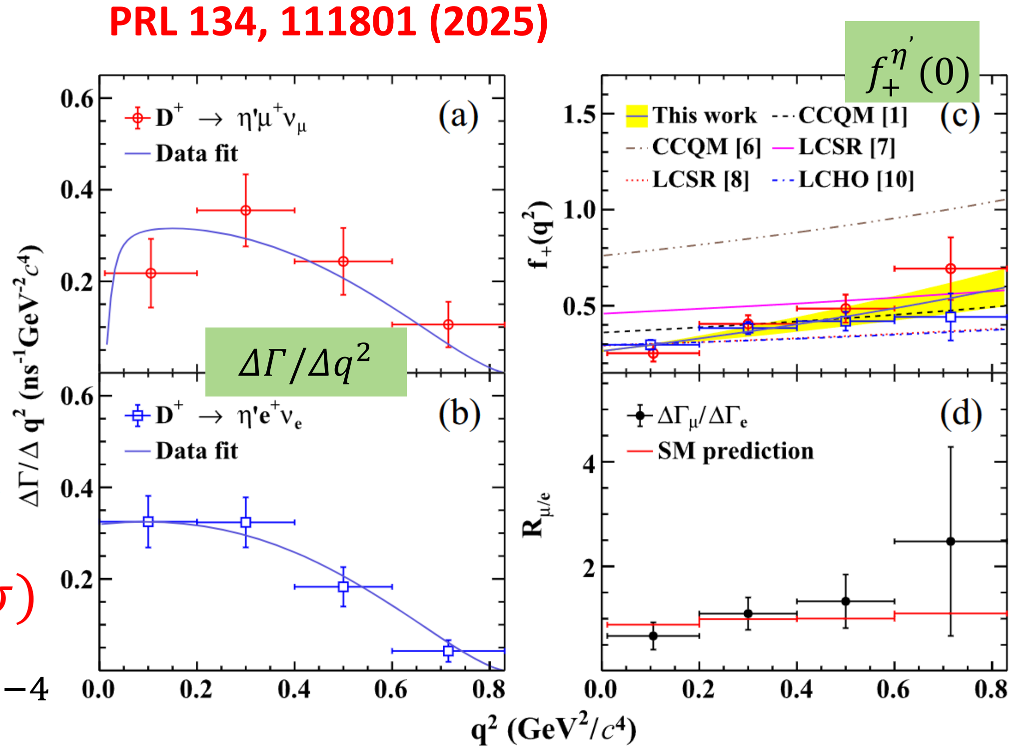
$$f_+^{D^+\to\eta}(0) = \mathbf{0.345 \pm 0.008 \pm 0.003}(\sim 2.5\%)$$

$D^+ \to \eta^{'} \ell^+ \nu_\ell (\ell = e, \mu)$

$20.3\text{fb}^{-1}@E_{cm}$=3.773 GeV

PRL 134, 111801 (2025)





- First observation of $D^+ \to \eta^{'} \mu^+ \nu_\mu$ (8.6σ)

$\mathcal{B}(D^+ \to \eta^{'} \mu^+ \nu_\mu) = (1.92 \pm 0.28 \pm 0.08) \times 10^{-4}$

$\mathcal{B}(D^+ \to \eta^{'} e^+ \nu_e) = (1.79 \pm 0.19 \pm 0.07) \times 10^{-4}$ (precision improved by 2.4 times)

- LFU test :

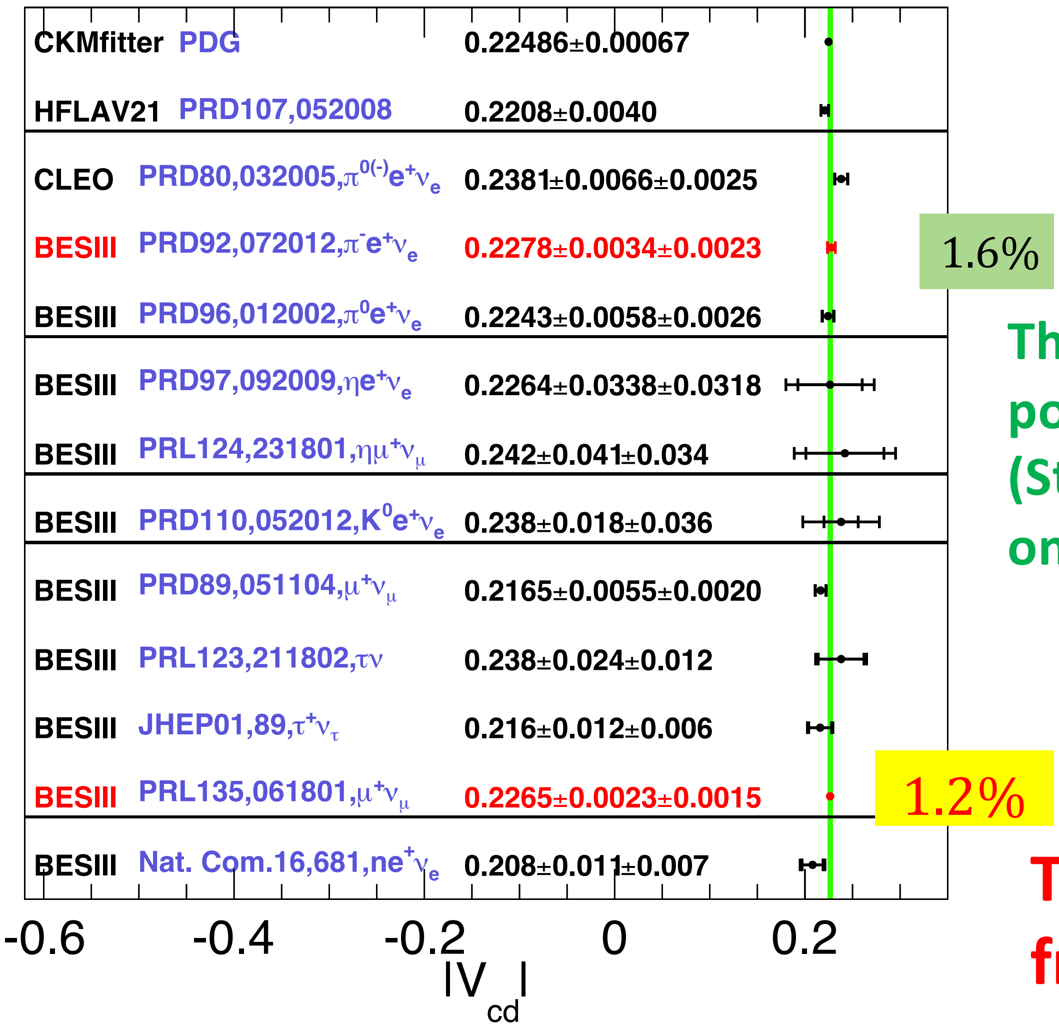
$$\mathcal{R}_{\mu/e} = 1.09 \pm 0.19 \pm 0.03$$

$\eta - \eta^{'}$ mixing angle：

$$\phi_P = (39.8 \pm 0.8 \pm 0.3)^\circ$$

- $f_+^{\eta^{'}}(0)|V_{cd}| = (5.92 \pm 0.56 \pm 0.13) \times 10^{-2}$
- $f_+^{\eta^{'}}(0) = 0.263 \pm 0.025 \pm 0.006$

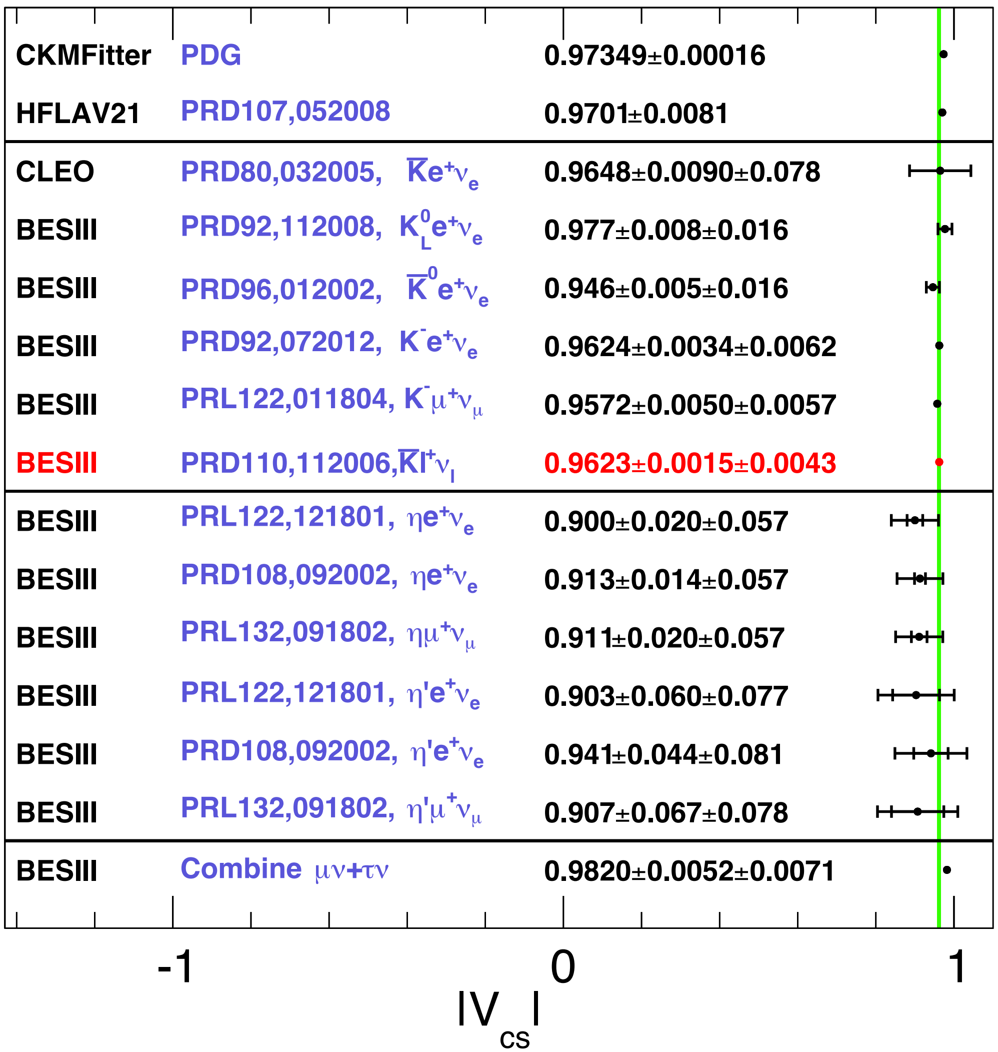
Comparison of $|V_{cd}|$



The semi-leptonic decays have potential to yield better precision (Stat. Uncertainty < 0.5%) depending on the uncertainty from LQCD.

The current best precision is from pure-leptonic decays

Comparison of $|V_{cs}|$



$\bar{K}\ell^+\nu_\ell$ simultaneous fit (stat sys~0.2%)

Main systematic uncertainty from the LQCD input $f_+^K(0)$)

0.5%

1.0%

The best precision for pure-leptonic decays is 1%

$D \to K^*(892)l^+\nu_l(\ell = e, \mu)$

- BF measurement:

7.93fb^{-1}@E_{cm}=3.773 GeV

$\mathcal{B}(D^0 \to \bar{K}^0\pi^-\mu^+\nu_\mu) = (1.373 \pm 0.020 \pm 0.023)\%$

$\mathcal{B}(D^0 \to \bar{K}^0\pi^-e^+\nu_e) = (1.444 \pm 0.022 \pm 0.024)\%$

$\mathcal{B}(D^+ \to K_S^0\pi^0e^+\nu_e) = (0.943 \pm 0.012 \pm 0.010)\%$

$\mathcal{B}(D^+ \to K_S^0\pi^0\mu^+\nu_\mu) = (0.896 \pm 0.017 \pm 0.008)\%$

PRL 134, 011803 (2025)

JHEP 03 (2025) 197

JHEP 10 (2024) 199

PRL 135, 171801 (2025)

- Using the Partial wave analysis method

$\mathcal{B}(D^0 \to K^*(892)^-\mu^+\nu_\mu) = (2.062 \pm 0.039 \pm 0.032)\%$

$\mathcal{B}(D^0 \to K^*(892)^-e^+\nu_e) = (2.039 \pm 0.032 \pm 0.034)\%$

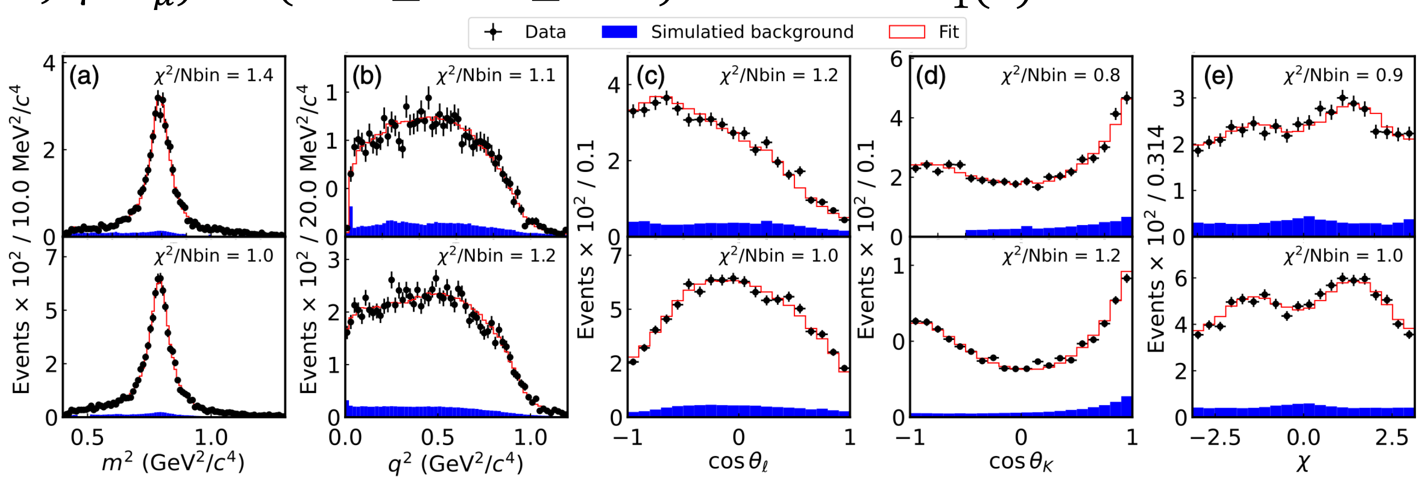
$\mathcal{B}(D^+ \to K^*(892)^0e^+\nu_e) = (5.29 \pm 0.07 \pm 0.06)\%$

$\mathcal{B}(D^+ \to K^*(892)^0\mu^+\nu_\mu) = (5.00 \pm 0.10 \pm 0.06)\%$

- **FF of $D \to K^*(892)$**

$$r_V = \frac{V(0)}{A_1(0)} = 1.42 \pm 0.03 \pm 0.02\ (3\% - 4\%)$$

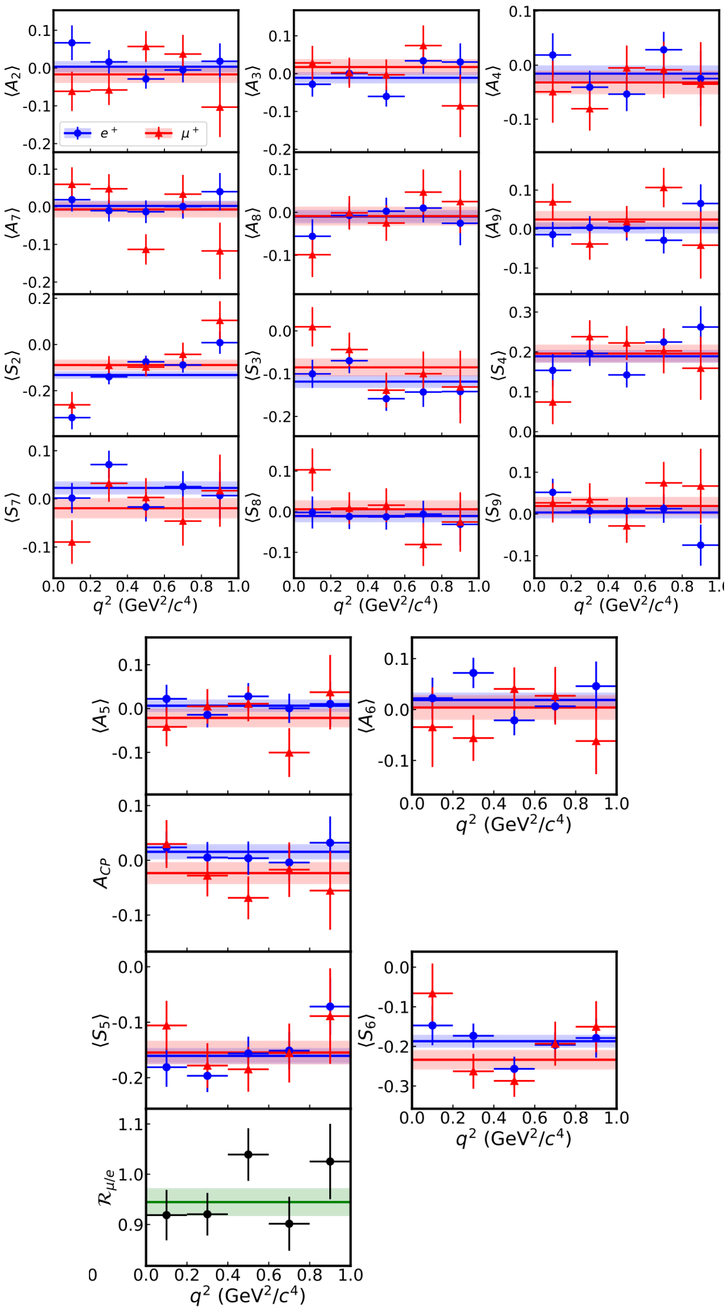
$$r_2 = \frac{A_2(0)}{A_1(0)} = 0.75 \pm 0.03 \pm 0.01\ (5\% - 6\%)$$



$D \to K^*(892)l^+\nu_l(\ell = e, \mu)$

7.93fb^{-1}@E_{cm}=3.773 GeV

PRL 135, 171801 (2025)



- LFU test:

$$R_{\mu/e} = 0.94 \pm 0.02 \pm 0.01$$

- **Isospin test:**

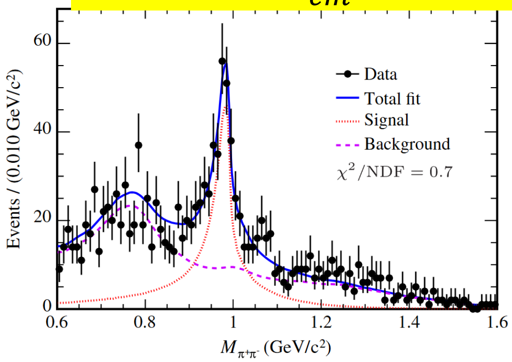
$$R_{K^-\pi^+/K_S^0\pi^0} = 4.02 \pm 0.06 \pm 0.10$$

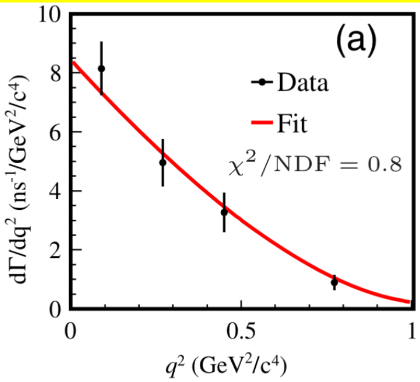
- **First measurement of full set of CP asymmetries and averaged angular observables with A_{CP}**
- **All measured null-test observables A_{CP}, $< S_{7-9} >$ and $< A_{2-9} >$ agree with the SM predictions.**

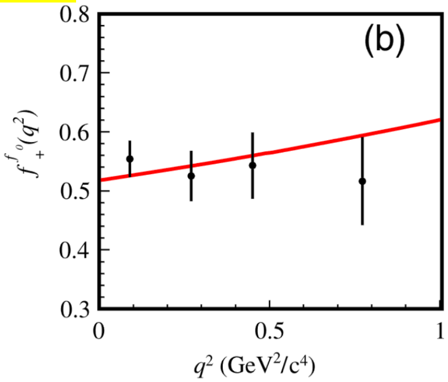
$D_s^+ \to f_0 e^+ \nu_e$

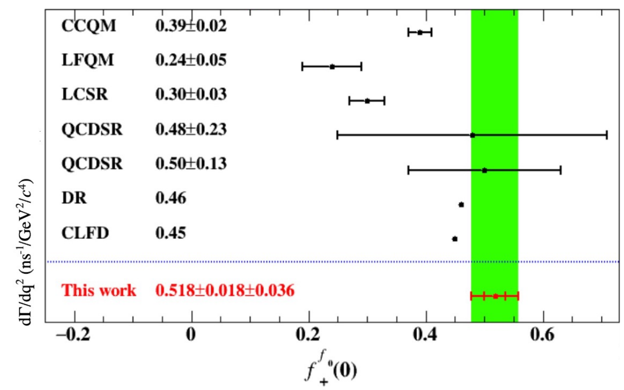
7.33fb^{-1}@E_{cm}=4.128-4.226 GeV ($e^+e^- \to D_s^{*\pm} D_s^{\mp}$)

PRL 132, 141901 (2024)









- BF measurement:

$$\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^+\pi^-) = (1.72 \pm 0.13 \pm 0.10)\times 10^{-3}$$

$\phi = (19.7 \pm 12.8)^\circ$($s\bar{s}$ is dominant based on $|f_0(980)\rangle = sin\phi \left|\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\right\rangle + cos\phi|s\bar{s}\rangle$)

- First form factor measurement with simple pole model and Flatte formula:

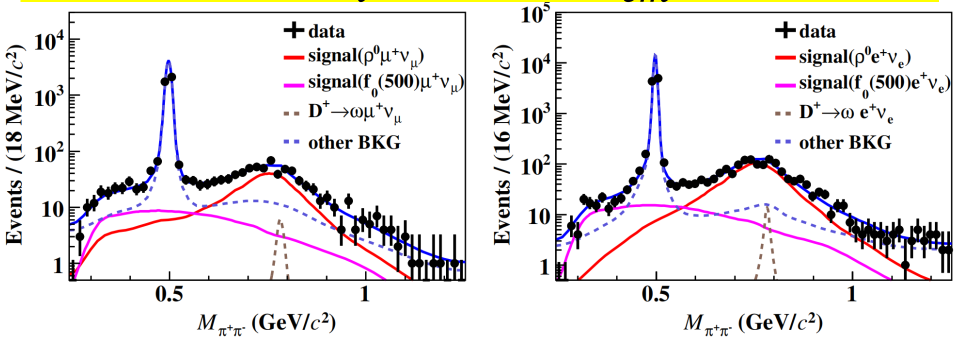
	This work	CLFD [6]	DR [6]	QCDSR [7]	QCDSR [8]	LCSR [9]	LFQM [11]	CCQM [12]
$f_+^{f_0}(0)$	$0.518 \pm 0.018_{\rm stat} \pm 0.036_{\rm syst}$	0.45	0.46	0.50 ± 0.13	0.48 ± 0.23	0.30 ± 0.03	0.24 ± 0.05	0.39 ± 0.02
Difference (σ)	—	—	—	0.1	0.2	4.3	4.3	2.8
ϕ in theory	—	$(32 \pm 4.8)^\circ$	$(41.3 \pm 5.5)^\circ$	35°	$(8^{+21}_{-8})^\circ$	—	$(56 \pm 7)^\circ$	31°

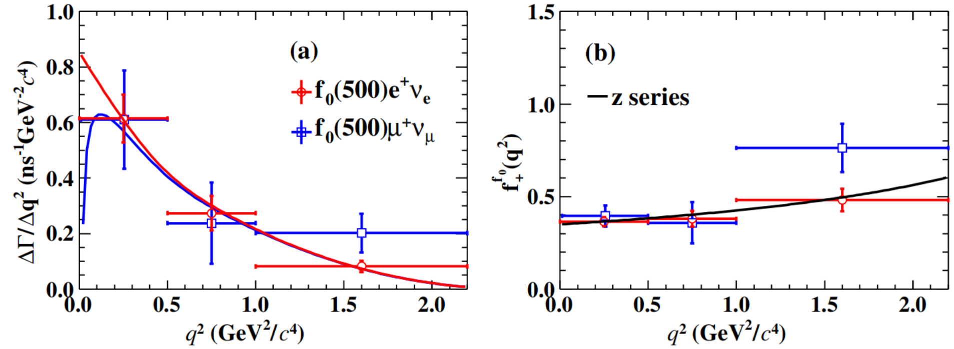
- $f_+^{f_0}(0)|V_{cs}|$=0.504 $\pm$ 0.017 $\pm$ 0.035
- Form factor $f_+^{f_0}(0)$=0.518 $\pm$ 0.018 $\pm$ 0.036
- $\mathcal{B}(D_s^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^+\pi^-) < 3.3\times 10^{-4}$ at 90% C.L.

$D \to a_0/f_0 l^+ \nu_l (\ell = e, \mu)$

$D^+ \to \pi^+\pi^- l^+\nu_l$ 2.93fb^{-1} @E_{cm}=3.773 GeV

PRD 110, 092008 (2024)





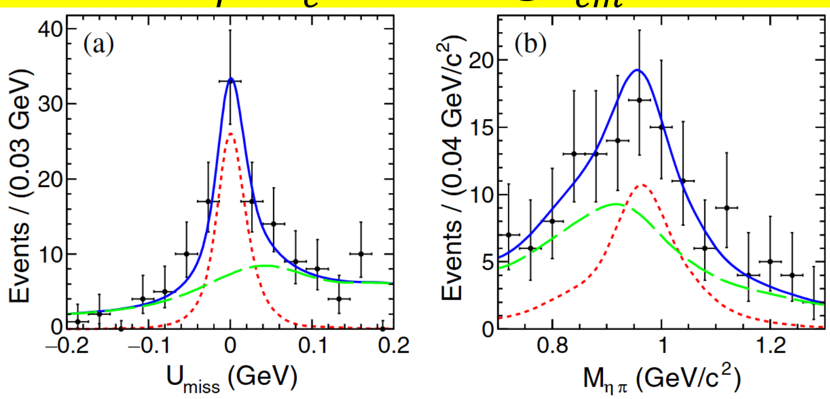
- BF measurement:

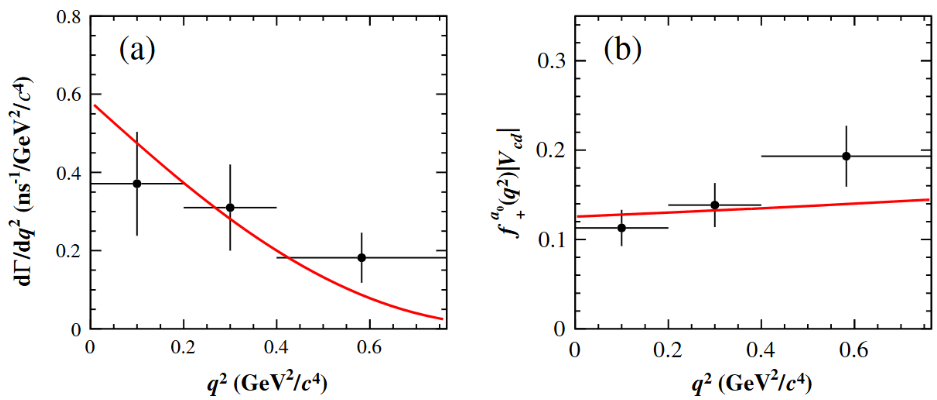
$$\mathcal{B}(D^+ \to f_0(500)\mu^+\nu_\mu) = (0.72 \pm 0.13 \pm 0.08)\times 10^{-3}$$
$$\mathcal{B}(D^+ \to f_0(500)e^+\nu_e) = (0.60 \pm 0.06 \pm 0.05)\times 10^{-3}$$

- FF measurement: $f_+^{f_0}(0)$=0.350 $\pm$ 0.027 $\pm$ 0.015

$D^0 \to \pi^-\eta e^+\nu_e$ 7.93fb^{-1} @E_{cm}=3.773 GeV

PRD 111, L091501 (2025)





- BF measurement:

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

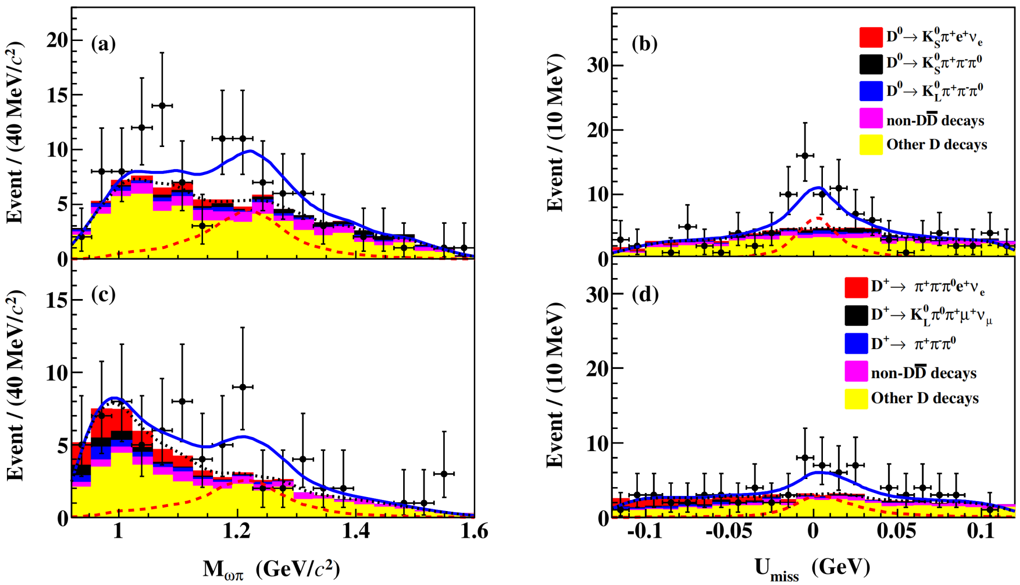
- First FF measurement: $f_+^{a_0}(0)$=0.559 $\pm$ 0.056 $\pm$ 0.013

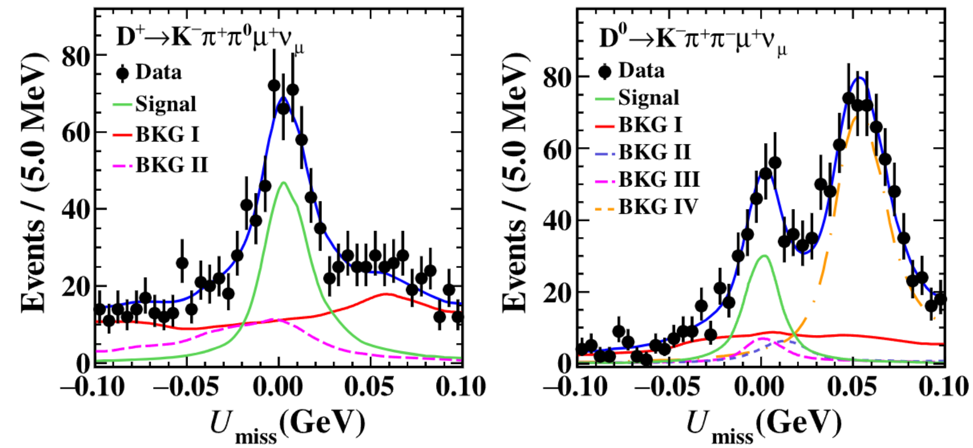
$D \to A\ell^+\nu_\ell$

arXiv: 2407.20551

$7.93\text{fb}^{-1}@E_{cm}=3.773$ GeV

PRD111, L071101 (2025)





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

$D \to K_1(1270)\mu^+\nu_\mu$

- First observation of $D^0 \to b_1(1235)^- e^+\nu_e$ and evidence for $D^+ \to b_1(1235)^0 e^+\nu_e$

$$\mathcal{B}(D^0 \to b_1(1235)^- e^+\nu_e, b_1(1235)^- \to \omega\pi^-) = (0.72 \pm 0.18^{+0.06}_{-0.08})\times 10^{-4} (5.2\sigma)$$

$$\mathcal{B}(D^+ \to b_1(1235)^0 e^+\nu_e, b_1(1235)^0 \to \omega\pi^0) = (1.16 \pm 0.44 \pm 0.16)\times 10^{-4} (3.1\sigma)$$

- First observation of $D \to K_1(1270)\mu^+\nu_\mu$

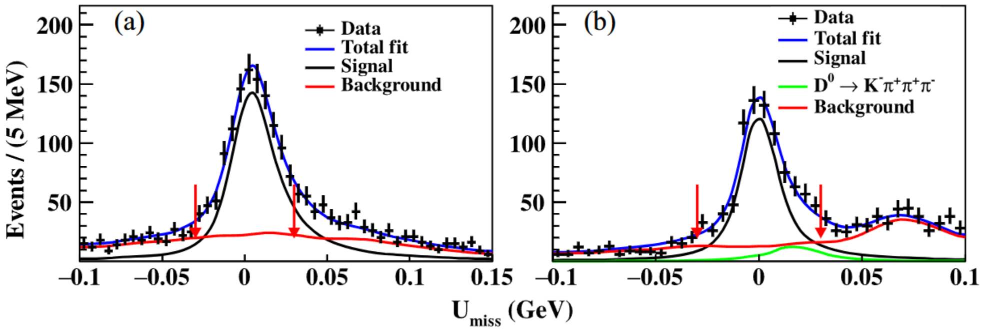
$$\mathcal{B}(D^0 \to K_1(1270)^- \mu^+\nu_\mu) = (0.78 \pm 0.11^{+0.05}_{-0.09} \pm 0.15)\times 10^{-3}$$

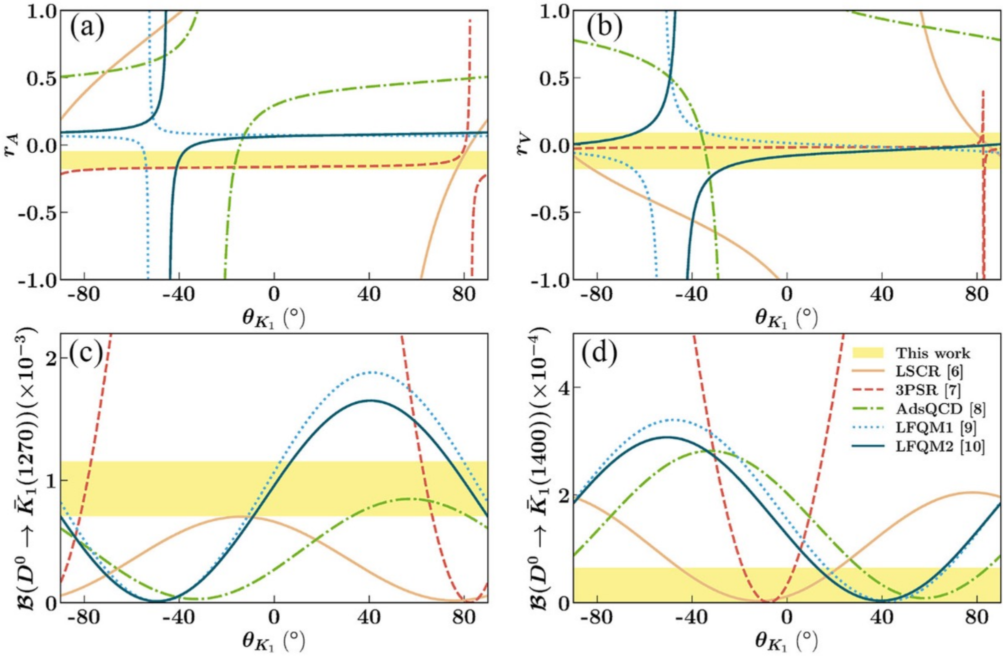
$$\mathcal{B}(D^+ \to \bar{K}_1(1270)\mu^+\nu_\mu) = (2.36 \pm 0.20^{+0.18}_{-0.27} \pm 0.48)\times 10^{-3}$$

$D \to \bar{K}_1(1270)e^+\nu_e$

$20.3\,\mathrm{fb}^{-1}@E_{cm}=3.773$ GeV

Phys. Rev. Lett. 135, 091801 (2025)





- First determination of the FF of $D \to \bar{K}_1(1270)e^+\nu_e$ and extract the θ_K

$r_V = -(4.3 \pm 1.0 \pm 2.4)\times 10^{-2}$

$r_2 = -(11.2 \pm 1.0 \pm 0.9)\times 10^{-2}$

$f_{D_q \to K_1(1270)} = f_{D_q \to K_{1A}} \sin\theta_K + f_{D_q \to K_{1B}} \cos\theta_K$

θ_K: the mixing angle between $K_1(1270)$ and $K_1(1400)$

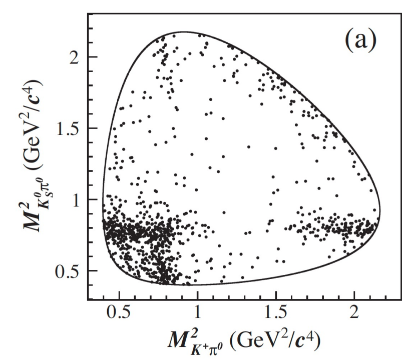
- The BF ratio of the two dominant components in the $K_1(1270)$ decay to be

$$\frac{\mathcal{B}(K_1(1270)\to K^*\pi)}{\mathcal{B}(K_1(1270)\to K^*\rho)} = (20.3 \pm 2.1 \pm 8.7)\%$$

- Up-down asymmetry $A'_{ud} = 0.01 \pm 0.11$ (Consistent with SM predicted values 0.092 ± 0.022)

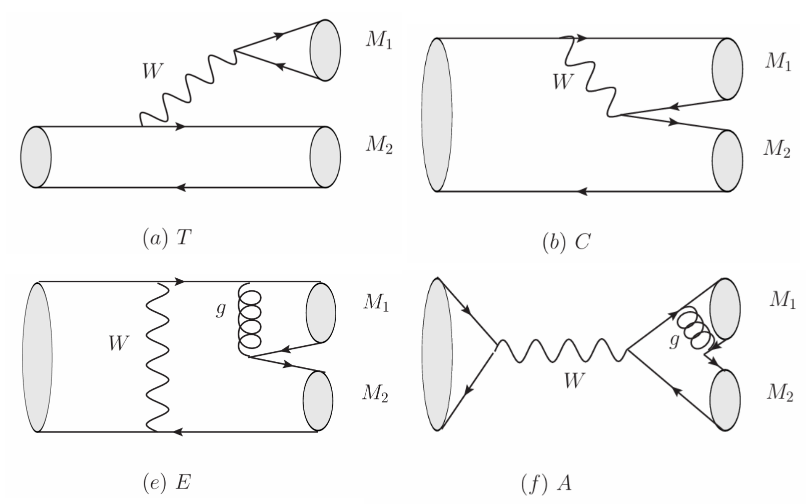
Outline

- BESIII dataset
- Charmed meson
  - pure leptonic decays
  - semi-leptonic decays
  - hadronic decays
  - quantum correlation
- Prospect



Why study hadronic decays of charmed mesons?

- **Topological Diagram Approach**



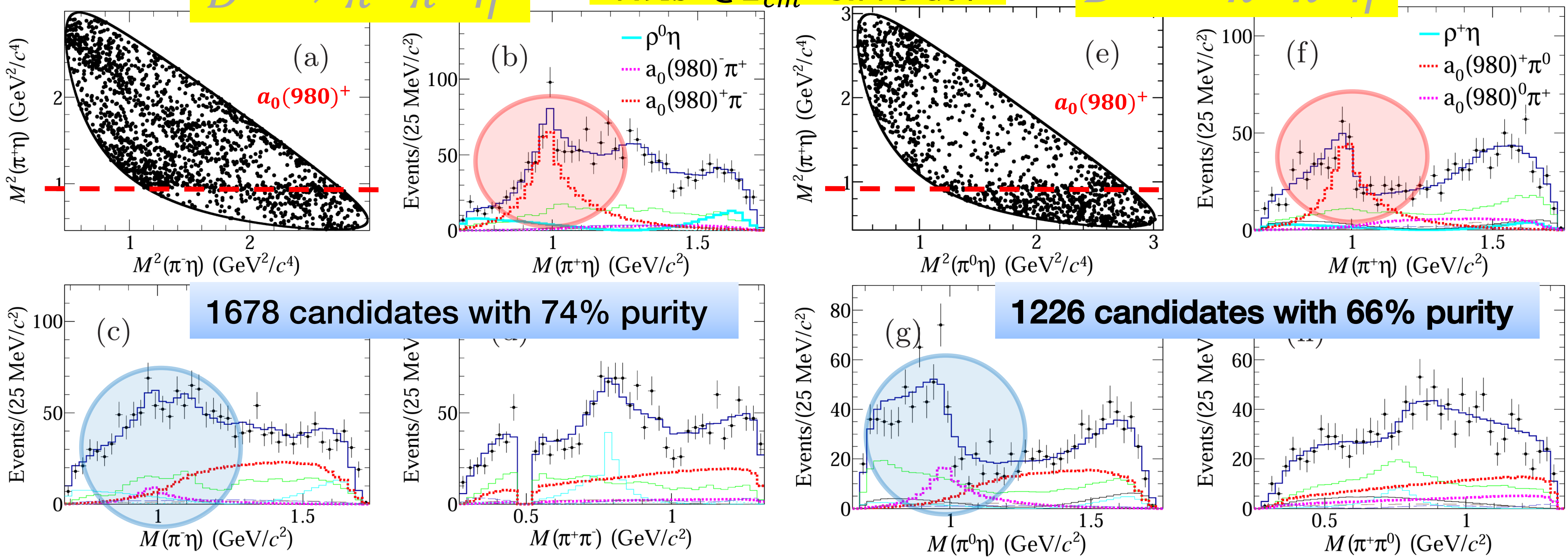
Mode	Amplitude
$D^0 \to K^+\pi^-$	$\lambda_{ds}(1.23T + E)$
$D^0 \to K^0\pi^0$	$\frac{1}{\sqrt{2}}\lambda_{ds}(C - E)$
$D^0 \to K^0\eta$	$\lambda_{ds}\left[\frac{1}{\sqrt{2}}(C+E)\cos\phi - E\sin\phi\right]$
$D^0 \to K^0\eta'$	$\lambda_{ds}\left[\frac{1}{\sqrt{2}}(C+E)\sin\phi + E\cos\phi\right]$
$D^+ \to K^0\pi^+$	$\lambda_{ds}(C + 0.71A)$
$D^+ \to K^+\pi^0$	$\frac{1}{\sqrt{2}}\lambda_{ds}(1.23T - 0.71A)$
$D^+ \to K^+\eta$	$\lambda_{ds}\left[\frac{1}{\sqrt{2}}(1.05T + A)\cos\phi - 0.81A\sin\phi\right]$
$D^+ \to K^+\eta'$	$\lambda_{ds}\left[\frac{1}{\sqrt{2}}(1.05T + A)\sin\phi + 0.81A\cos\phi\right]$
$D_s^+ \to K^0K^+$	$\lambda_{ds}(1.27T + 1.03C)$

- **$D \to PP$: high efficiency, low background, no interference, (usually) high precision. Good for Acp, η - η' mixing etc..**
- **$D \to SP$, $D \to SV$, ($D \to SS$): Understand the nature of light scalar mesons, $a_0(980)$, $f_0(980)$, $K(700)$, $f_0(500)$ etc..**
- **$D \to VP$: Clarifying the nonperturbative mechanism. Well defined quark content of V. Better than the PP and VV, due to the multiple-amplitude composition of P and the polarization in VV.**
- **$D \to VV$: Polarization in charmed decays.**
- **$D \to AP$: Study axial-vector mesons, a1(1260) K1(1400)etc..**

Observation of $D \to a_0(980)\pi$

Phys. Rev. D 110, L111102

$D^0 \to \pi^+\pi^-\eta$ 7.9fb^{-1}@E_{cm}=3.773 GeV $D^+ \to \pi^+\pi^0\eta$



$$\mathcal{B}(D^0 \to a_0(980)^+\pi^-)/\mathcal{B}(D^0 \to a_0(980)^-\pi^+) = 7.5\,{}^{+2.5}_{-0.8}{}_{\text{stat.}} \pm 1.7_{\text{syst.}}$$

$$\mathcal{B}(D^+ \to a_0(980)^+\pi^0)/\mathcal{B}(D^+ \to a_0(980)^0\pi^+) = 2.6 \pm 0.6_{\text{stat.}} \pm 0.3_{\text{syst.}}$$

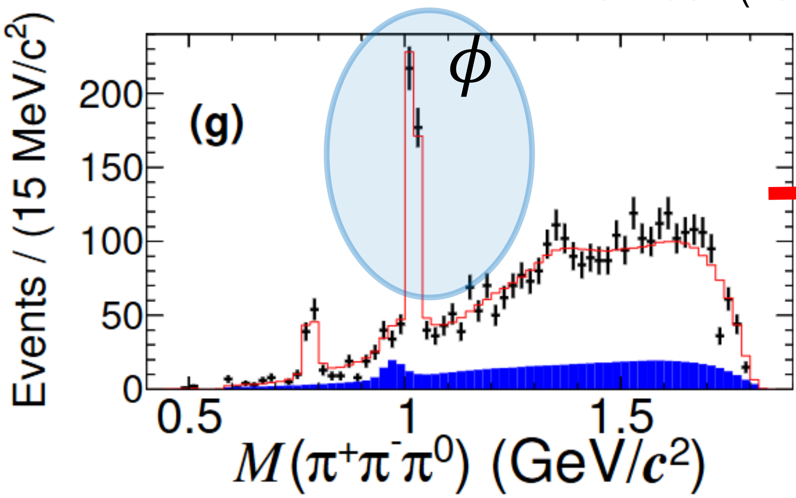
⟹ Disagrees with theoretical predictions by orders of magnitude

The external W-emission diagram dominates the $D \to a_0(980)\pi$ decays in the diquark scenario, contrary to expectations of its negligible contribution due to the very small $a_0(980)$ decay constant[1].

[1] Phys. Rev. D **105**, 033006(2022).

Study of $D_s^+ \to \phi(\pi^+\pi^-\pi^0, K^+K^-)\pi^+$

$D_s^+ \to \pi^+\pi^-\pi^0\pi^+$ Phys. Rev. Lett. 134, 011904 (2025)



First Measurement

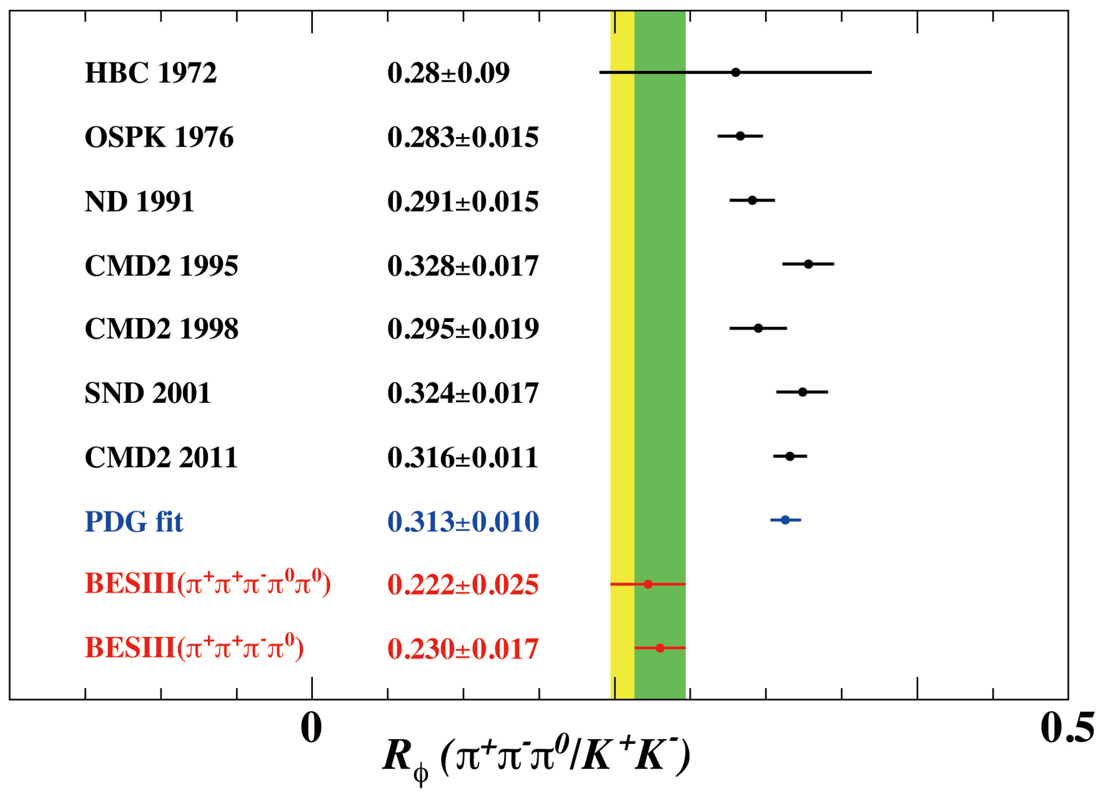
Component	Phase (rad)	FF (%)	BF (10^{-3})
$f_0(1370)\rho^+$	0.0(fixed)	$24.9 \pm 3.8 \pm 2.1$	$5.08 \pm 0.80 \pm 0.43$
$f_0(980)\rho^+$	$3.99 \pm 0.13 \pm 0.07$	$12.6 \pm 2.1 \pm 1.0$	$2.57 \pm 0.44 \pm 0.20$
$f_2(1270)\rho^+$	$1.11 \pm 0.10 \pm 0.10$	$9.5 \pm 1.7 \pm 0.6$	$1.94 \pm 0.36 \pm 0.12$
$(\rho^+\rho^0)_S$	$1.10 \pm 0.18 \pm 0.10$	$3.5 \pm 1.2 \pm 0.6$	$0.71 \pm 0.25 \pm 0.12$
$(\rho(1450)^+\rho^0)_S$	$0.43 \pm 0.18 \pm 0.17$	$4.6 \pm 1.3 \pm 0.8$	$0.94 \pm 0.27 \pm 0.16$
$(\rho^+\rho(1450)^0)_P$	$4.58 \pm 0.16 \pm 0.09$	$8.6 \pm 1.3 \pm 0.4$	$1.75 \pm 0.27 \pm 0.08$
$\phi((\rho\pi) \to \pi^+\pi^-\pi^0)\pi^+$	$2.90 \pm 0.15 \pm 0.18$	$24.9 \pm 1.2 \pm 0.4$	$5.08 \pm 0.32 \pm 0.10$
$\omega((\rho\pi) \to \pi^+\pi^-\pi^0)\pi^+$	$3.22 \pm 0.21 \pm 0.09$	$6.9 \pm 0.8 \pm 0.3$	$1.41 \pm 0.17 \pm 0.06$
$a_1^+(\rho^0\pi^+)_S\pi^0$	$3.78 \pm 0.16 \pm 0.12$	$12.5 \pm 1.6 \pm 1.0$	$2.55 \pm 0.34 \pm 0.20$
$a_1^0((\rho\pi)_S \to \pi^+\pi^-\pi^0)\pi^+$	$4.82 \pm 0.15 \pm 0.12$	$6.3 \pm 1.9 \pm 1.2$	$1.29 \pm 0.39 \pm 0.24$
$\pi(1300)^0((\rho\pi)_P \to \pi^+\pi^-\pi^0)\pi^+$	$2.22 \pm 0.14 \pm 0.08$	$11.7 \pm 2.3 \pm 2.2$	$2.39 \pm 0.48 \pm 0.45$

- $\mathcal{B}(D_s^+ \to \phi\pi^+, \phi \to \pi^+\pi^-\pi^0) = (5.08 \pm 0.32 \pm 0.10)\times 10^{-3}$
- $\mathcal{B}(D_s^+ \to \phi\pi^+, \phi \to K^+K^-) = (2.21 \pm 0.05 \pm 0.07)\%$

$D_s^+ \to K^+K^-\pi^+$ **PRD 104, 012016**

$$\frac{\mathcal{B}(\phi\to\pi^+\pi^-\pi^0)}{\mathcal{B}(\phi\to K^+K^-)} = 0.230 \pm 0.014 \pm 0.010$$

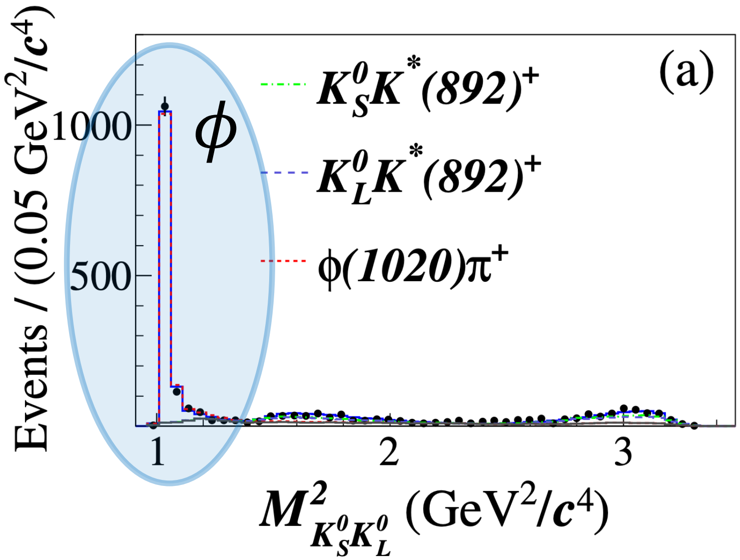
deviates from PDG 0.313 ± 0.010 by $> 4\sigma$.



Amplitude analysis of $D_s^+ \to \phi(K_S^0 K_L^0)\pi^+$

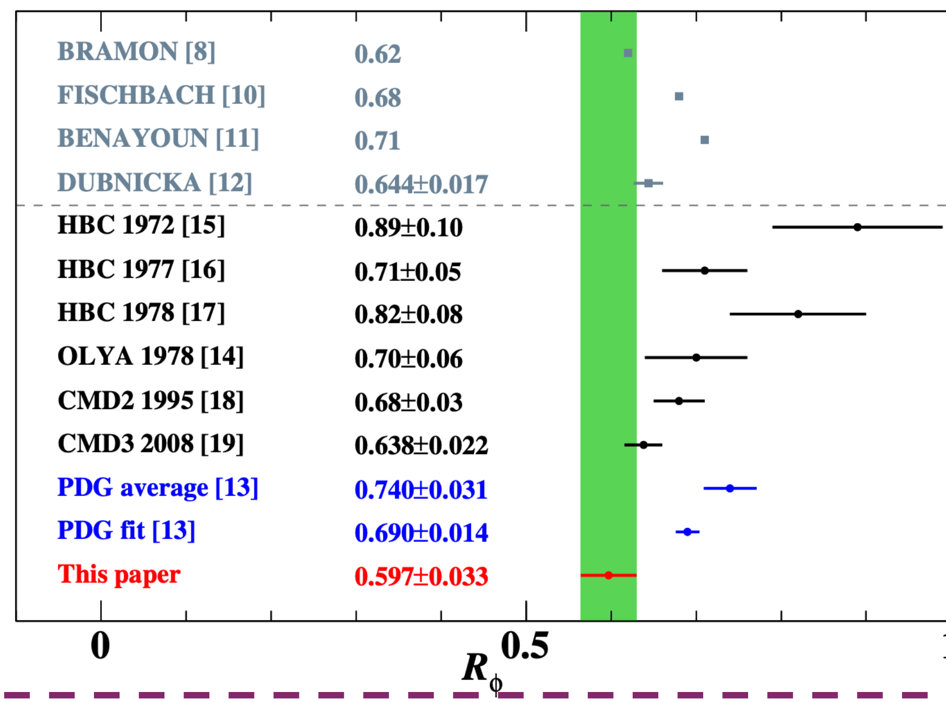
$D_s^+ \to K_S^0 K_L^0 \pi^+$

Phys. Rev. Lett. 135, 161902 (2025)



Amplitude	Phase (rad)	FF (%)	BF (%)
$D_s^+ \to \phi\pi^+$	0.0(fixed)	$70.9 \pm 1.3 \pm 1.5$	$1.32 \pm 0.05 \pm 0.04$
$D_s^+ \to K_L^0 K^*(892)^+$	$0.68 \pm 0.17 \pm 0.21$	$22.8 \pm 1.3 \pm 1.5$	$0.42 \pm 0.03 \pm 0.03$
$D_s^+ \to K_S^0 K^*(892)^+$	$-2.40 \pm 0.18 \pm 0.31$	$17.4 \pm 1.2 \pm 0.9$	$0.31 \pm 0.02 \pm 0.02$

✓ Measurement of ϕ



✓ Observation of the $K_S^0 - K_L^0$ asymmetry in the $D \to K^0_{S/L}V$

(Interefrence of CF and DCS decays)

- $$\frac{\mathcal{B}(D_s^+ \to K_S^0 K^*(892)^+) - \mathcal{B}(D_s^+ \to K_L^0 K^*(892)^+)}{\mathcal{B}(D_s^+ \to K_S^0 K^*(892)^+) + \mathcal{B}(D_s^+ \to K_L^0 K^*(892)^+)}$$
  $$= -0.134 \pm 0.05_{\text{stat.}} + 0.034_{\text{syst.}}$$

Model	DAT(F4)	DAT(F1′)
$D_s^+ \to \bar{K}^0 K^{*+}$	-0.164 ± 0.032	-0.159 ± 0.028

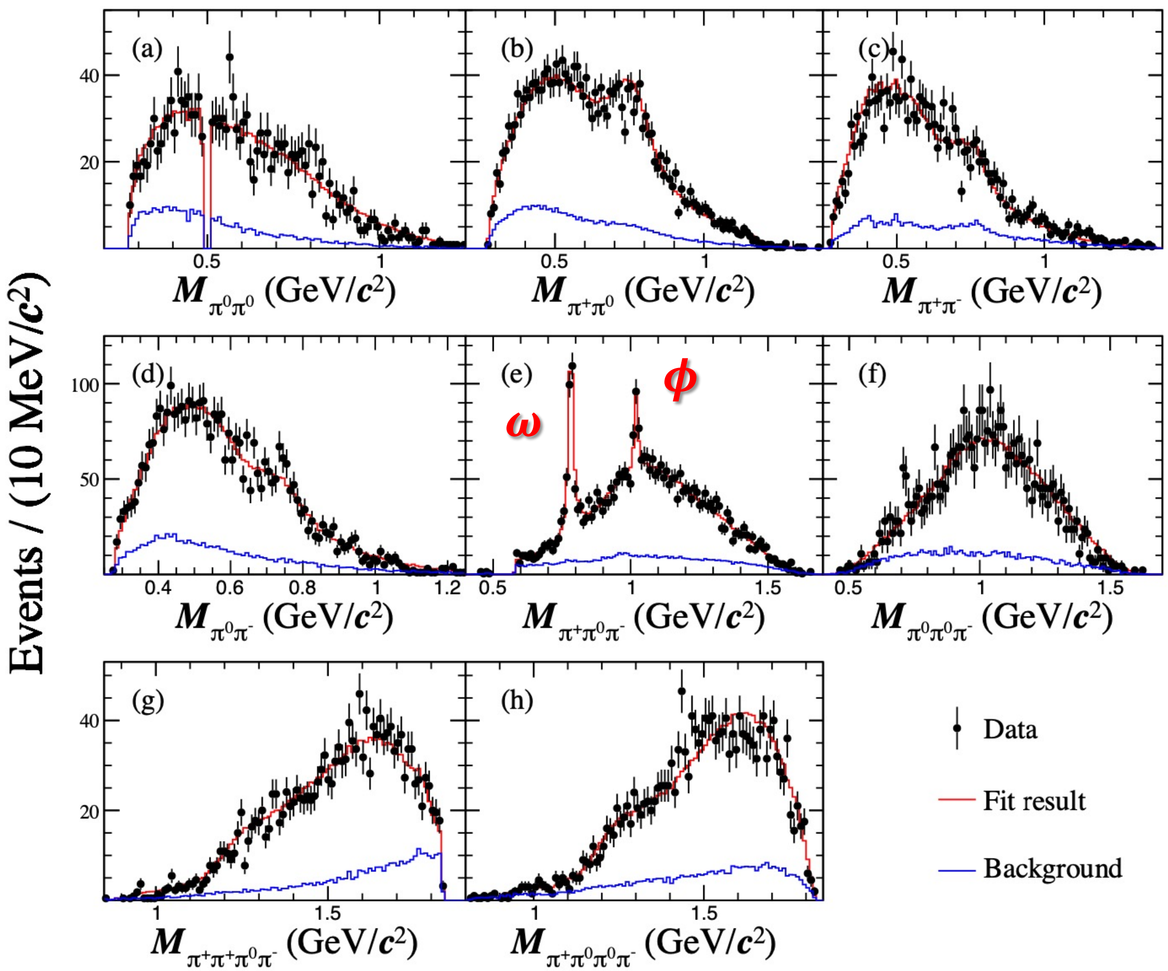
Predictions by H. Y. Cheng *et al.*, PRD109, 073008

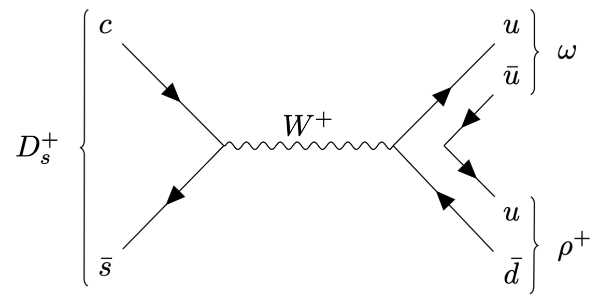
$$\frac{\mathcal{B}(\phi \to K_S^0 K_L^0)}{\mathcal{B}(\phi \to K^+K^-)} = 0.597 \pm 0.023_{\text{stat}} \pm 0.024_{\text{syst}}$$

deviates from PDG (0.740 ± 0.033) by $> 3\sigma$.

$D \to VV$ in $D_s^+ \to \pi^+\pi^+\pi^-\pi^0\pi^0$

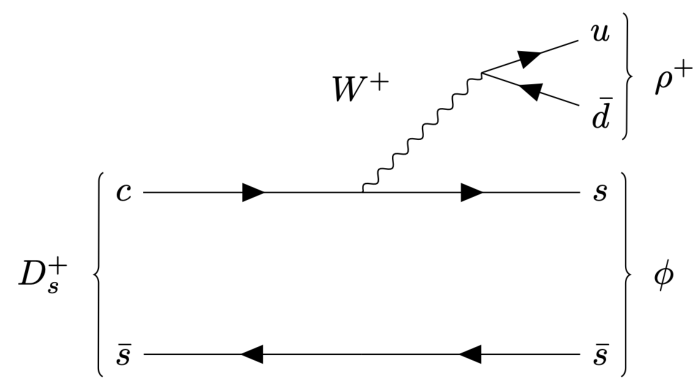
PRL 134, 201902 (2025)





pure W−annihilation $D_s^+ \to \omega\rho^+$

about 50% D-wave



Pure external W emission $D_s^+ \to \phi\rho^+$

dominated by S-wave

✓ Measurement of ϕ

$$\frac{\mathcal{B}(\phi\to\pi^+\pi^-\pi^0)}{\mathcal{B}(\phi\to K^+K^-)}=0.222 \pm 0.019_{\text{stat}} \pm 0.016_{\text{syst}}$$

deviates from PDG (0.313 ± 0.010) % by $> 3\sigma$.

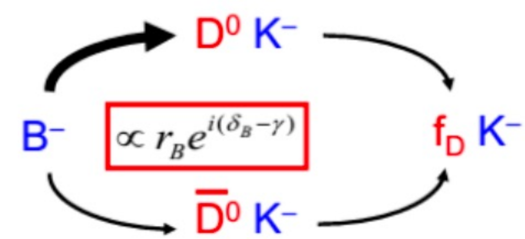
Larger than other WA decays

$$\mathcal{B}(D_s^+ \to \omega\rho^+) = (\mathbf{0.99} \pm 0.\mathbf{08} \pm 0.\mathbf{07})\%$$

$$\mathcal{B}(D_s^+ \to \phi\rho^+) = (\mathbf{3.98} \pm 0.\mathbf{33} \pm 0.21)\%$$

Outline

- BESIII dataset
- Charmed meson
  - pure leptonic decays
  - semi-leptonic decays
  - hadronic decays
  - quantum correlation
- Prospect



Quantum Correlation

Quantum correlated data: $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$

Best laboratory to measure strong-phase parameters

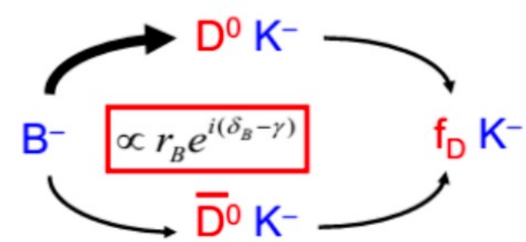
CP-odd: $\psi(3770) = \left(D^0\bar{D}^0 - D^0\,\bar{D}^0\right) = \left(D_+D_- - D_-D_+\right)$

$J^{PC} = 1^{--}$

CP-even eigenstate

CP-odd eigenstate

- **Inputs for CPV studies at B experiments**



- **The CKM angle γ/ϕ_3:**

  self-conjugated decay: CP fraction F_+ → GLW/GGSZ method;

  strong phase ci(′) and si(′) → GGSZ method

  non-self-conjugated decay: the coherence factor R and averaged strong phase difference δ → ADS method

Quantum Correlated $D^0\bar{D}^0$ pairs

7.13 fb^{-1} @4.13 – 4.23 GeV
PRL 135, 171901 (2025)
PRD 112, 072006 (2025)

BESIII

- Studies of quantum correlations in

  $e^+e^- \to \gamma^* \to XD\bar{D}$

  → Quantum correlated C-odd $D^0\bar{D}^0$ pairs used at $\psi(3770)$ for D-decay strong phase measurements

$C_\gamma = -1$
$C_{\pi^0} = +1$

Production mechanism	C
$e^+e^- \to D\bar{D}$	-1
$e^+e^- \to D^*\bar{D} \to D\bar{D}\,\gamma$	$+1$
$e^+e^- \to D^*\bar{D} \to D\bar{D}\,\pi^0$	-1
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\,\gamma\gamma$	-1
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\,\pi^0\gamma$	$+1$
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\,\pi^0\pi^0$	-1

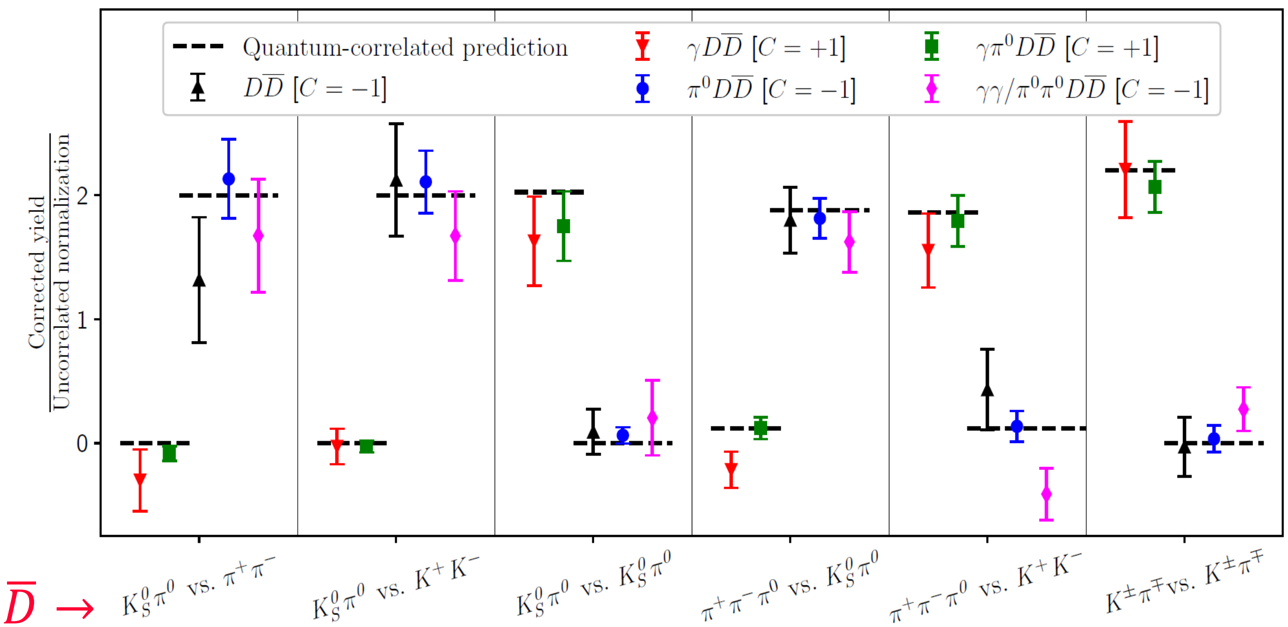
- First observation of quantum correlations in $e^+e^+ \to XD\bar{D}$ and C-even constrained $D\bar{D}$ pairs

$$\hat{C}\,|D\bar{D}\rangle = \kappa C_{\text{exp}}\,|D\bar{D}\rangle - (1-\kappa)C_{\text{exp}}\,|D\bar{D}\rangle$$

Contribute more statistics for quantum-correlation studies!!

Production mechanism	κ
$D\bar{D}$	1.015 ± 0.066
$D^*\bar{D} \to \gamma D\bar{D}$	1.044 ± 0.044
$D^*\bar{D} \to \pi^0 D\bar{D}$	1.028 ± 0.024
$D^*\bar{D}^* \to \gamma\pi^0 D\bar{D}$	1.027 ± 0.017
$D^*\bar{D}^* \to \gamma\gamma/\pi^0\pi^0 D\bar{D}$	0.963 ± 0.060

κ=1: coherent
κ=0.5: incoherent



$D\bar{D} \to$

CP eigenvalue	-1	-1	+1	-1	+1	-1

Measurement of $\delta_{K\pi}$

7.13 fb^{-1} @4.13 – 4.23 GeV
PRL 135, 171901 (2025)
PRD 112, 072006 (2025)

BESIII

- $\delta_{K\pi}$ is the strong-phase difference between $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ decays

$$r^D_{K\pi} e^{-i\delta^D_{K\pi}} = \frac{A(\overline{D}^0 \to K^-\pi^+)}{A(D^0 \to K^-\pi^+)} ,$$ $r^D_{K\pi}$ is the magnitude of the ratio

key input for measurements of the charm mixing parameters and CKM angle γ

- Use the quantum correlated pairs to measure $\delta_{K\pi}$

→ CP tags (K^+K^-, $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $K^0_S\pi^0$) ($r_{K\pi}cos\delta_{K\pi}$)

→ $K^0_S\pi^+\pi^-$ tags ($r_{K\pi}cos\delta_{K\pi}$ and $r_{K\pi}sin\delta_{K\pi}$)

Source	Observable	Value
$D \to CP$	$r^D_{K\pi} \cos \delta^D_{K\pi}$	$-0.070 \pm 0.008 \pm 0.0015$
$D \to K^0_S\pi^+\pi^-$	$r^D_{K\pi} \cos \delta^D_{K\pi}$	$-0.044 \pm 0.014 \pm 0.0018$
$D \to K^0_S\pi^+\pi^-$	$r^D_{K\pi} \sin \delta^D_{K\pi}$	$-0.022 \pm 0.017 \pm 0.0031$

- Extract $\delta_{K\pi}$

$$\delta^D_{K\pi} = \left(192.8^{+11.0+1.9}_{-12.4-2.4}\right)^\circ$$ agree with global average $$\delta^D_{K\pi} = (190.2 \pm 2.8)^\circ$$

[LHCb, CERN-LHCb-CONF-2024-004]

- BESIII combination (with BESIII 2.93 fb^{-1} $\psi(3770)$ result)

$$\delta^D_{K\pi} = \left(189.2^{+6.9+3.4}_{-7.4-3.8}\right)^\circ$$

$$\delta^D_{K\pi} = \left(187.6^{+8.9+5.4}_{-9.7-6.4}\right)^\circ$$

[BESIII, EPJC 82,1009(2022)]

Outline

- BESIII dataset
- Charmed meson
  - pure leptonic decays
  - semi-leptonic decays
  - hadronic decays
  - quantum correlation
- **Prospect**

Summary & Outlook

- Pure and semi-leptonic charm decays are idea for measuring $|\boldsymbol{V_{cd(s)}}|$, decay constants and form factors of charmed mesons.
- Current most precise measurement

  $\boldsymbol{V_{cs}}$ ⇒ **0.5%** from $D \to \bar{K}\ell^+\nu_\ell$ (dominate uncertainty: LQCD form factor)
  $\boldsymbol{V_{cd}}$ ⇒ **1.2%** from $D^+ \to \mu^+\nu_\mu$. ($D^0 \to \pi^- e^+\nu_e$ will yield the most precise $\boldsymbol{V_{cd}}$)
- No evidence of LFU violation found ⇒ 0.7% precision level.

- Charm hadronic decays are key labs to understand non-perturbative QCD
- The copious decay products provide idea platform to investigate the natures light hadrons, such as $a_0(980)$, $f_0(980)$, $f_0(500)$, $a_1(1260)$ ϕ…
- The threshold dataset at charmed meson pair is the unique place to measure strong phase of charmed meson decays.
- More studies are on the way using $20.3\ \mathrm{fb}^{-1}\psi(3770)$ data.

Thanks for the attention