



湖南大学

HUNAN UNIVERSITY

# 北京谱仪III上粲介子半轻衰变研究

张书磊

湖南大学

第八届全国重味物理与量子色动力学研讨会

2026/4/26@重庆大学

Email: zhangshulei@hnu.edu.cn

# Content

01

Physics motivation ✓

02

Data and analysis method

03

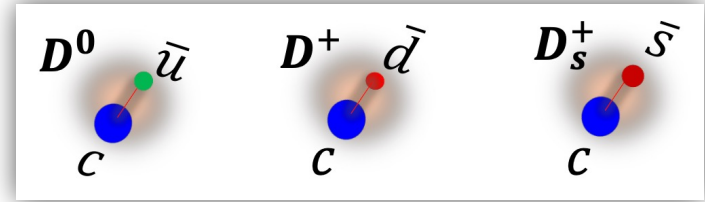
Some recent results

04

Summary and prospect

# Physics motivation

mass →	≈2.3 MeV/c <sup>2</sup>	≈1.275 GeV/c <sup>2</sup>	≈173.07 GeV/c <sup>2</sup>	0	≈126 GeV/c <sup>2</sup>
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs boson
<b>QUARKS</b>					
	≈4.8 MeV/c <sup>2</sup>	≈95 MeV/c <sup>2</sup>	≈4.18 GeV/c <sup>2</sup>	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon	
	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson	
<b>LEPTONS</b>					
	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson	
					<b>GAUGE BOSONS</b>

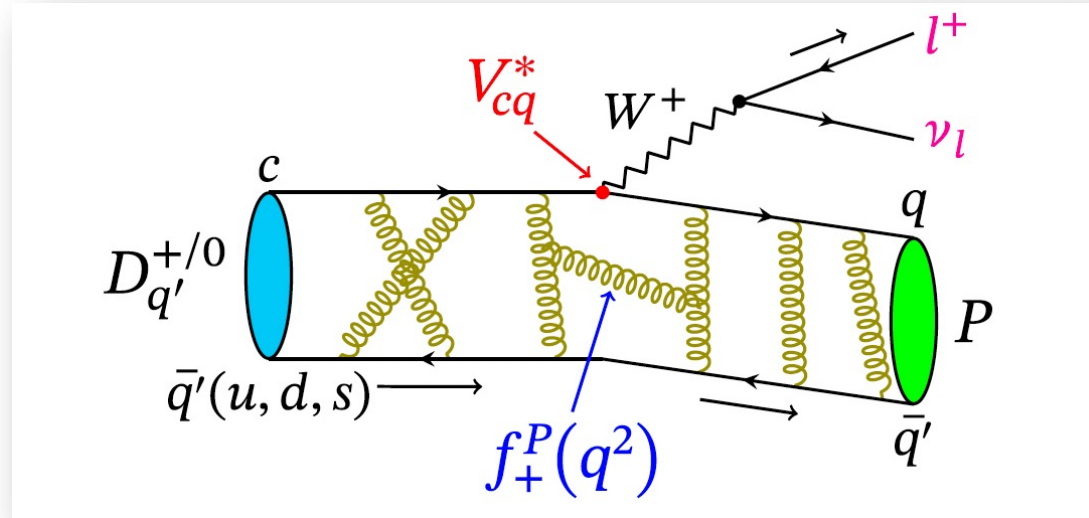


**Charm physics**

- High precision frontier → **SM Test**
- Nonperturbative region → **QCD**

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

# Physics motivation



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

( $X = 1$  for  $K/\pi^-/\eta^{(\prime)}$ ;  $X = 1/2$  for  $\pi^0$ )

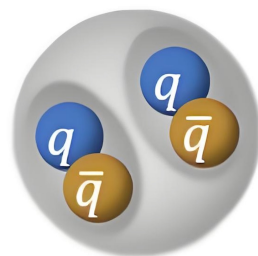
- CKM matrix elements  $|V_{cd(s)}| \rightarrow$  Test CKM matrix unitarity
- Branching fraction (BF) ratios  $\mathcal{R}_X^{\tau/\mu}, \mathcal{R}_X^{\mu/e} \rightarrow$  Test Lepton flavor universality (LFU)
- Hadronic Form factor (FF)  $\rightarrow$  Test various QCD model and calibrate LQCD
- BF and FF measurement in semi-leptonic decays  $\rightarrow$  Help to study light hadron

- $D_{(s)} \rightarrow P \ell^+ \nu_\ell$
- $D_{(s)} \rightarrow S \ell^+ \nu_\ell$  ✓
- $D_{(s)} \rightarrow V \ell^+ \nu_\ell$  ✓
- $D_{(s)} \rightarrow A \ell^+ \nu_\ell$  ✓

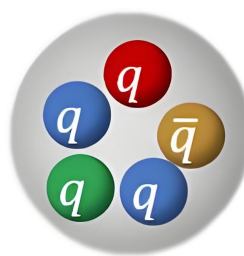
$P$  = pseudoscalar  $S$  = scalar  
 $V$  = vector  $A$  = axial-vector



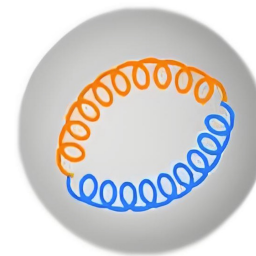
Tetraquark



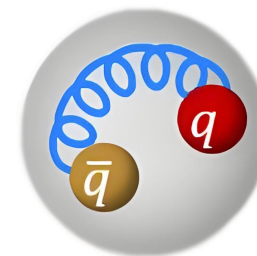
Hadronic molecules



Pentaquark



Glueball



hybrid

➤ Quark model allows for them.

➤ How about scalar mesons:

$f_0(500)$ ,  $K^*(700)$ ,  $f_0(980)$  and  $a_0(980)$ , etc

→  $q\bar{q}$  mixture, tetraquark, hadronic molecule or hybrid?

★ Semi-leptonic decay of charmed meson is an ideal probe for their nature!

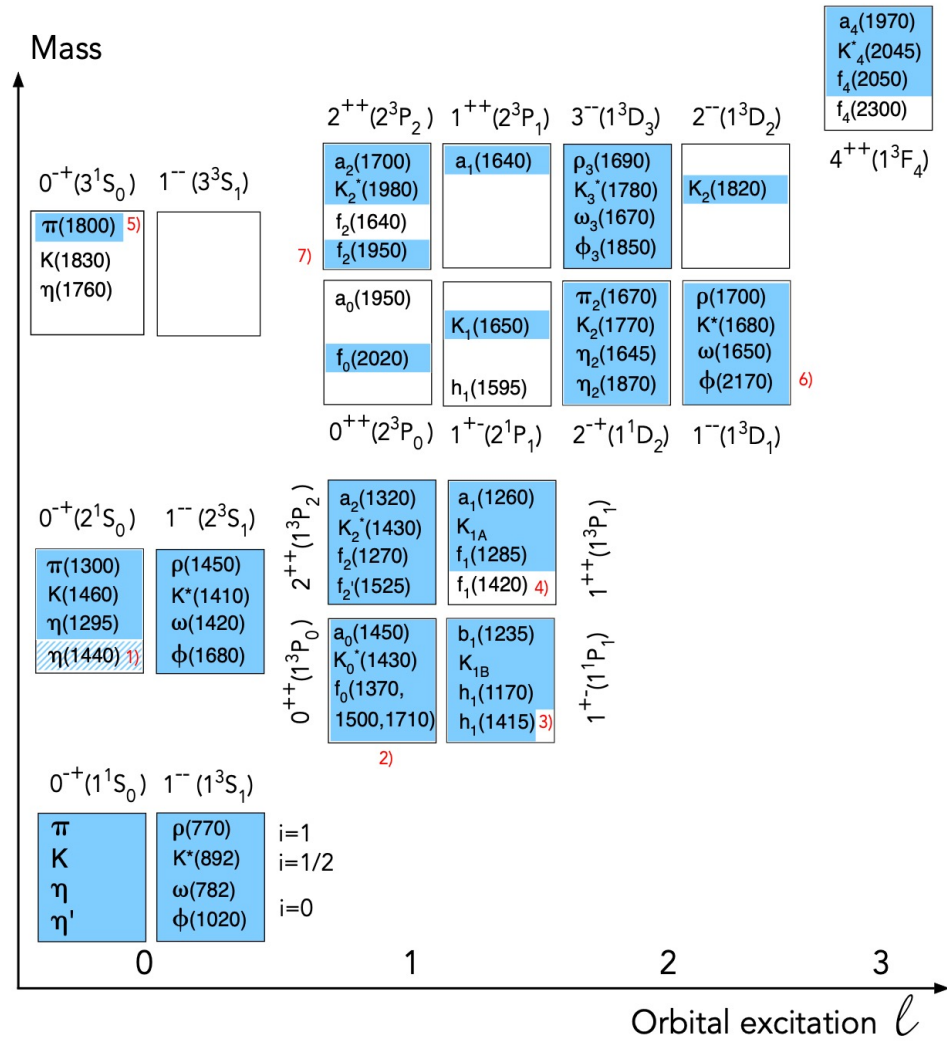
## ➤ How about orbitally and radially excited states of strange and light mesons ?

→  $K_0^*(1430)$ ,  $K^*(1410)$ ,  $K_1(1270)$ ,  $K_1(1400)$ ,  $K_2^*(1430)$

→  $f_0(1370)$ ,  $f_0(1500)$ ,  $f_1(1285)$ ,  $f_1(1420)$ ,  $f_2(1270)$

→  $a_0(1450)$ ,  $a_1(1260)$ ,  $a_2(1320)$ ,  $b_1(1235)$ , ...

★ Semi-leptonic decay of charmed meson is an ideal probe for their nature!



# Content

01

Physics motivation ✓

02

Data and analysis method ✓

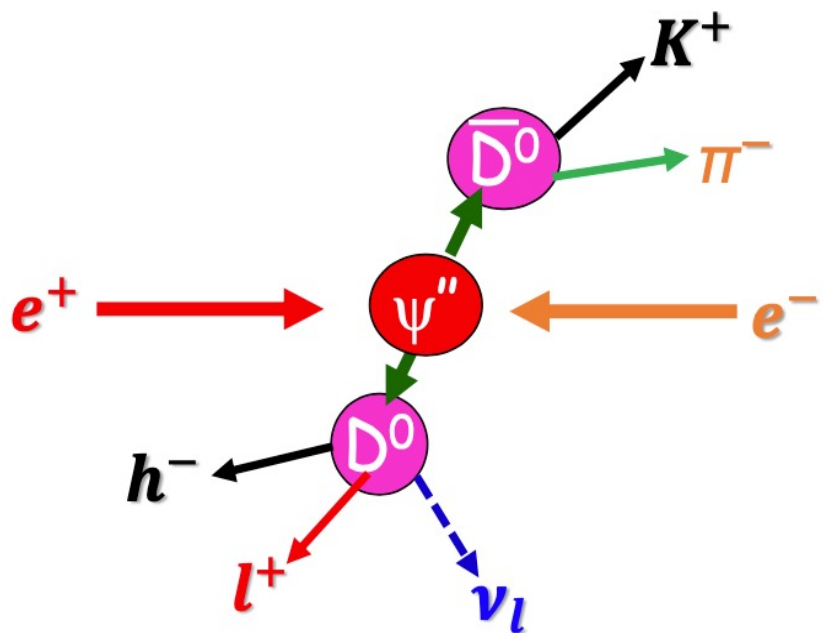
03

Some recent results

04

Summary and prospect

Data sample	$E_{cm}$ (GeV)	$\mathcal{L}_{int}$ (fb <sup>-1</sup> )	Tag yields( $\times 10^6$ )
$e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$	3.773	7.9	$N_{ST}^{\bar{D}^0} \sim 6.3, N_{ST}^{D^-} \sim 4.1$
		20.3	$N_{ST}^{\bar{D}^0} \sim 16.9, N_{ST}^{D^-} \sim 11$
$e^+e^- \rightarrow \psi(4160) \rightarrow D_s^\pm D_s^{*\mp}$	4.128 - 4.226	7.33	$N_{ST}^{D_s^-} \sim 0.8$



- Production near threshold  $\rightarrow$  Clean environment
- Systematic uncertainties from tag mostly canceled
- Almost full reconstruction

$$U_{miss} = E_{miss} - |\vec{p}_{miss}|$$

$$M_{miss}^2 = E_{miss}^2 - |\vec{p}_{miss}|^2$$

$$\mathcal{B} = \frac{N_{sig}/\epsilon_{sig}}{N_{tag}/\epsilon_{tag}} \star$$



# The differential decay rate of $D_{(s)} \rightarrow S \ell \nu_\ell$

$$\Gamma(D_{(s)} \rightarrow S \ell^+ \nu_\ell) / dq^2 \propto |V_{cd(s)}|^2 |f_+(q^2)|^2$$

$$S: a_0(980), f_0(500), f_0(980)$$

- Use least  $\chi^2$  method to fit the measured partial decay width in different  $q^2$  bin.
- Taking the correlations among  $q^2$  bins into account.
- **FF** in different form (The width needs to be considered ?)

– **Single pole form**

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

– **Modified pole model**

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M_{pole}^2}\right) \left(1 - \alpha \frac{q^2}{M_{pole}^2}\right)}$$

– **ISGW2 model**

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

– **Series expansion model**

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

# The differential decay rate of $D_{(s)} \rightarrow S \ell \nu_\ell$

- Point-like differential decay rate:

$$\frac{d\Gamma(D_{(s)} \rightarrow S \ell^+ \nu_\ell)}{dq^2} = \frac{G_F^2 |V_{cd(s)}|^2}{24\pi^3} p_S^3(m_\ell) |f_+(q^2)|^2$$

- Double differential decay rate:

(N.N.Achasov *et al.*, PRD102,016022(2020); W. Wang, PLB759,501(2016) )

$$\frac{d^2\Gamma(D_{(s)} \rightarrow S \ell^+ \nu_\ell)}{dsdq^2} = \frac{G_F^2 |V_{cd(s)}|^2}{192\pi^4 m_{D_{(s)}}^3} \lambda^{\frac{3}{2}}(m_{D_{(s)}}^2, s, q^2) |f_+(q^2)|^2 P(s)$$

$$P(s) = \begin{cases} \frac{g_1 \rho_{\pi\pi/\pi\eta}}{|m_0^2 - s - i(g_1 \rho_{\pi\pi/\pi\eta} + g_1 \rho_{KK})|^2}, & \text{Flatte: } f_0(980)/a_0(980) \\ \frac{m_{f_0} \Gamma(s)}{(s - m_{f_0}^2)^2 + m_{f_0}^2 \Gamma^2(s)}, & \text{RBW: } f_0(500) \\ \frac{m_r \Gamma_{tot}(s)}{(m_r^2 - s - g_1^2 \frac{s - s_A}{m_r^2 - s_A} z(s))^2 + m_r^2 \Gamma_{tot}^2(s)}, & \text{Bugg: } f_0(500) \end{cases}$$



$$\Gamma(D_{(s)} \rightarrow V(S)\ell^+ \nu_\ell) \propto |V_{cd(s)}|^2 \mathfrak{I}(A_1(q^2), A_2(q^2), V(q^2), \dots) dm^2 dq^2 d\cos(\theta_h) d\cos(\theta_\ell) d\chi$$

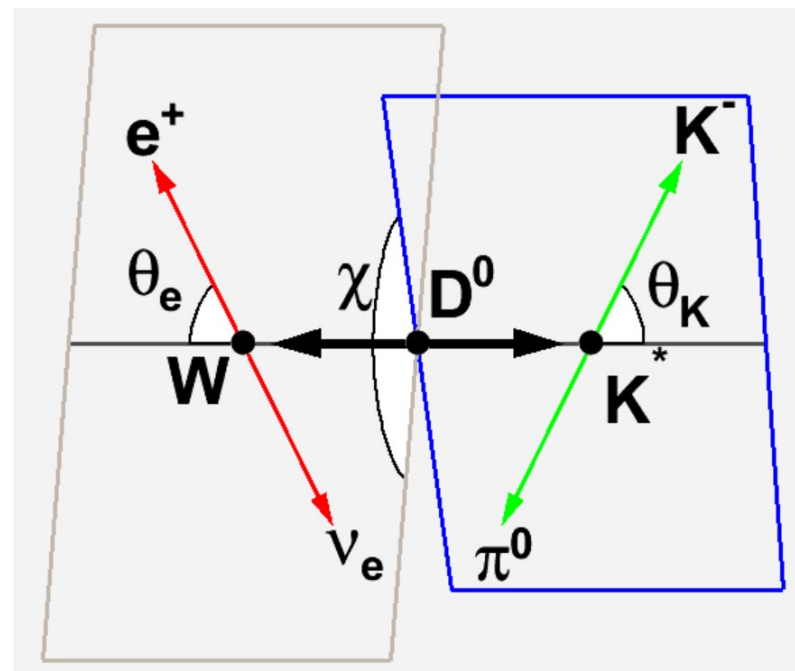
$V: \rho, \omega, K^*, \phi$   
 $S: f_0(500), f_0(980)$

Formula: Phys. Rev. **137**, B438 (1965)  
 Phys. Rev. D **46**, 5040 (1992)

- Decay intensity  $\mathfrak{I}$  include  $S, P, D$  wave components
- Un-binned Maximum likelihood (Based on RooFit)
- **FF** parameterization (single pole)

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2} \quad V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$$

$$r_V = \frac{V(0)}{A_1(0)} \quad r_2 = \frac{A_2(0)}{A_1(0)}$$





- Negative likelihood log (*NLL*) minimizing :

$$NLL = - \sum_{i=1}^N \ln \frac{\omega(\xi_i, \eta)}{\sigma_s}$$

$\omega(\xi_i, \eta)$ : decay intensity,  $\sigma_s$ : integral normalized factor is realized by MC sample:

$$\sigma_s = \int d\xi \omega(\xi, \eta) \epsilon(\xi) \propto \frac{1}{N_{selected}} \sum_{k=1}^{N_{selected}} \frac{\omega(\xi_k, \eta)}{\omega(\xi_k, \eta_0)}$$

- Low background: subtracted directly in *NLL*:

$$NLL = (-\ln L_{data}) - (-\ln L_{bkg})$$

- High background:

$$-\sum_{i=1}^N \ln \left( (1-f_b) \frac{\omega(\xi_i, \eta)}{\int d\xi_i \omega(\xi_i, \eta) \epsilon(\xi_i)} + f_b \frac{B_\epsilon(\xi_i)}{\int d\xi_i B_\epsilon(\xi_i) \epsilon(\xi_i)} \right)$$

# Content

01

Physics motivation ✓

02

Data and analysis method ✓

03

Some recent results ✓

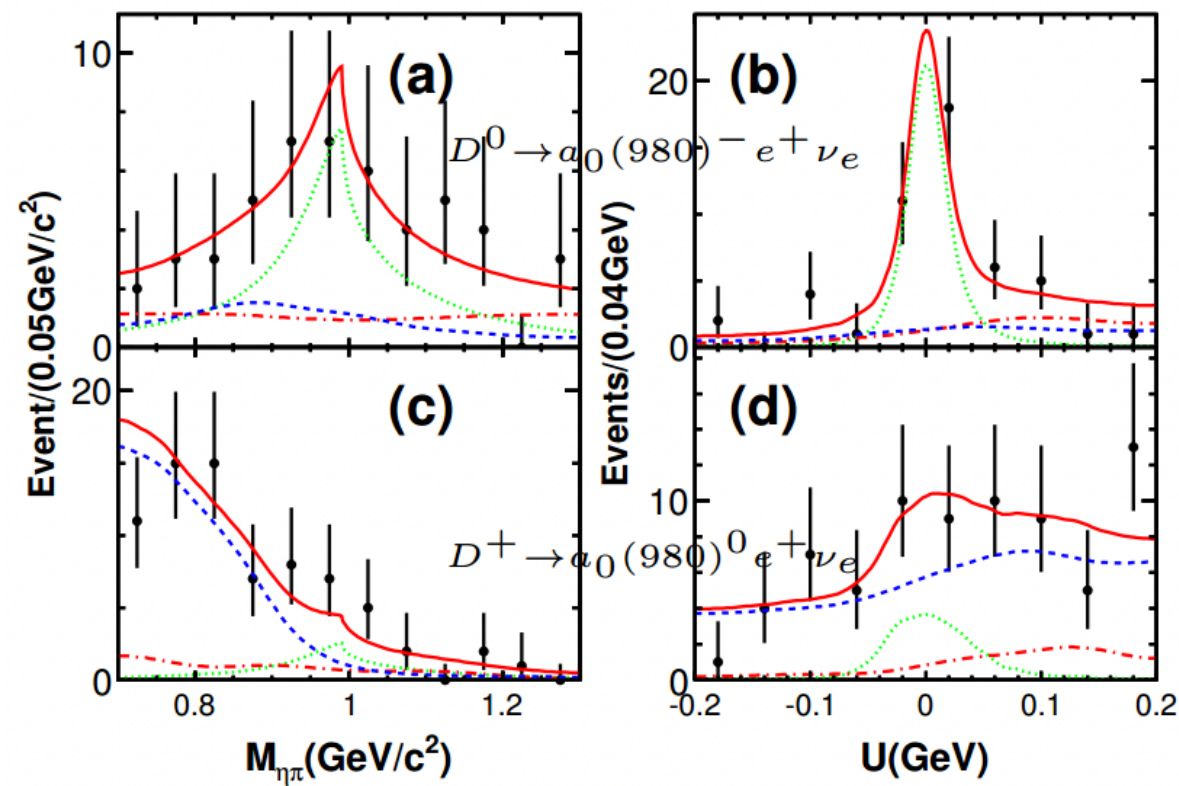
04

Summary and prospect

# First observation of $D^0 \rightarrow a_0(980)^- e^+ \nu_e$

*Phys. Rev. Lett. 121, 081802 (2018)*

- 2.93 fb<sup>-1</sup> data @ 3.773 GeV
- $N_{sig}^{D^0} = 25.7^{+6.4}_{-5.7}$
- $N_{sig}^{D^+} = 10.2^{+5.0}_{-4.1}$
- BFs help to understand the nature of the  $a_0(980)$



Decay	BF ( $\times 10^{-4}$ )	Significance
$D^0 \rightarrow a_0(980)^- e^+ \nu_e, a_0(980)^- \rightarrow \eta \pi^-$	$1.33^{+0.33}_{-0.29} \pm 0.09$	$6.4\sigma$
$D^+ \rightarrow a_0(980)^0 e^+ \nu_e, a_0(980)^0 \rightarrow \eta \pi^0$	$1.66^{+0.81}_{-0.66} \pm 0.11$ < 3.0 (90% C.L.)	$2.9\sigma$

*Phys. Rev. D 111, L091501 (2025)*

➤ 7.93 fb<sup>-1</sup> data @ 3.773 GeV →  $N_{\text{sig}} = 51.8 \pm 10.0$

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

$\mathcal{B}(D^0 \rightarrow a_0(980)^- e^+ \nu_e, a_0(980)^- \rightarrow (\eta\pi^-))$

$= (0.86 \pm 0.17 \pm 0.05) \times 10^{-4}$

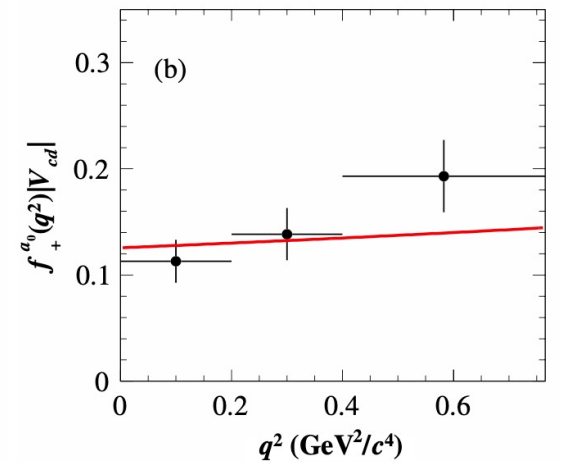
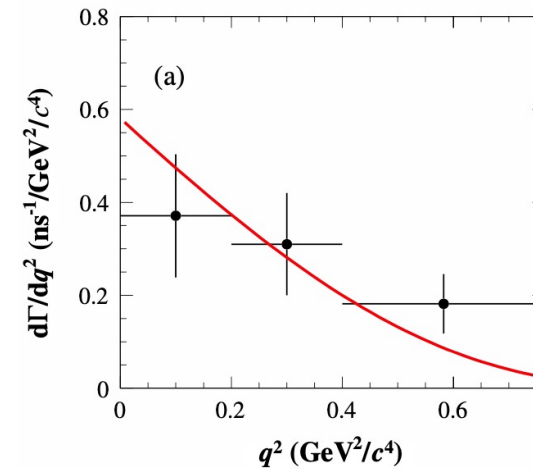
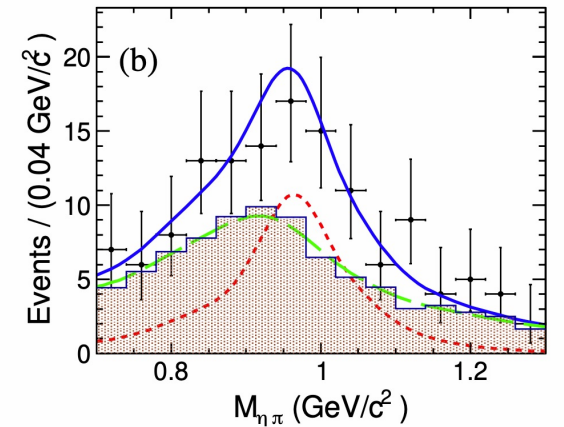
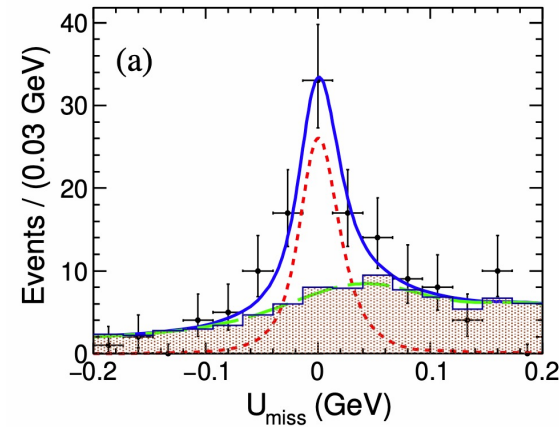
➤ First FF measurement:

Single-pole form for FF and Bugg form for  $a_0(980)^-$

→  $f_+^{a_0}(0)|V_{cd}| = 0.126 \pm 0.013 \pm 0.003$

→  $f_+^{a_0}(0) = 0.559 \pm 0.056 \pm 0.013$

ps:  $|V_{cd}| = 0.22487 \pm 0.00068$  from SM global fit (PDG2024)



*Phys. Rev. D 111, L091501 (2025)*

➤ 7.93 fb<sup>-1</sup> data @ 3.773 GeV → N<sub>sig</sub> = 51.8

➤ Updated BF measurement of  $D^0 \rightarrow a_0(980)$

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

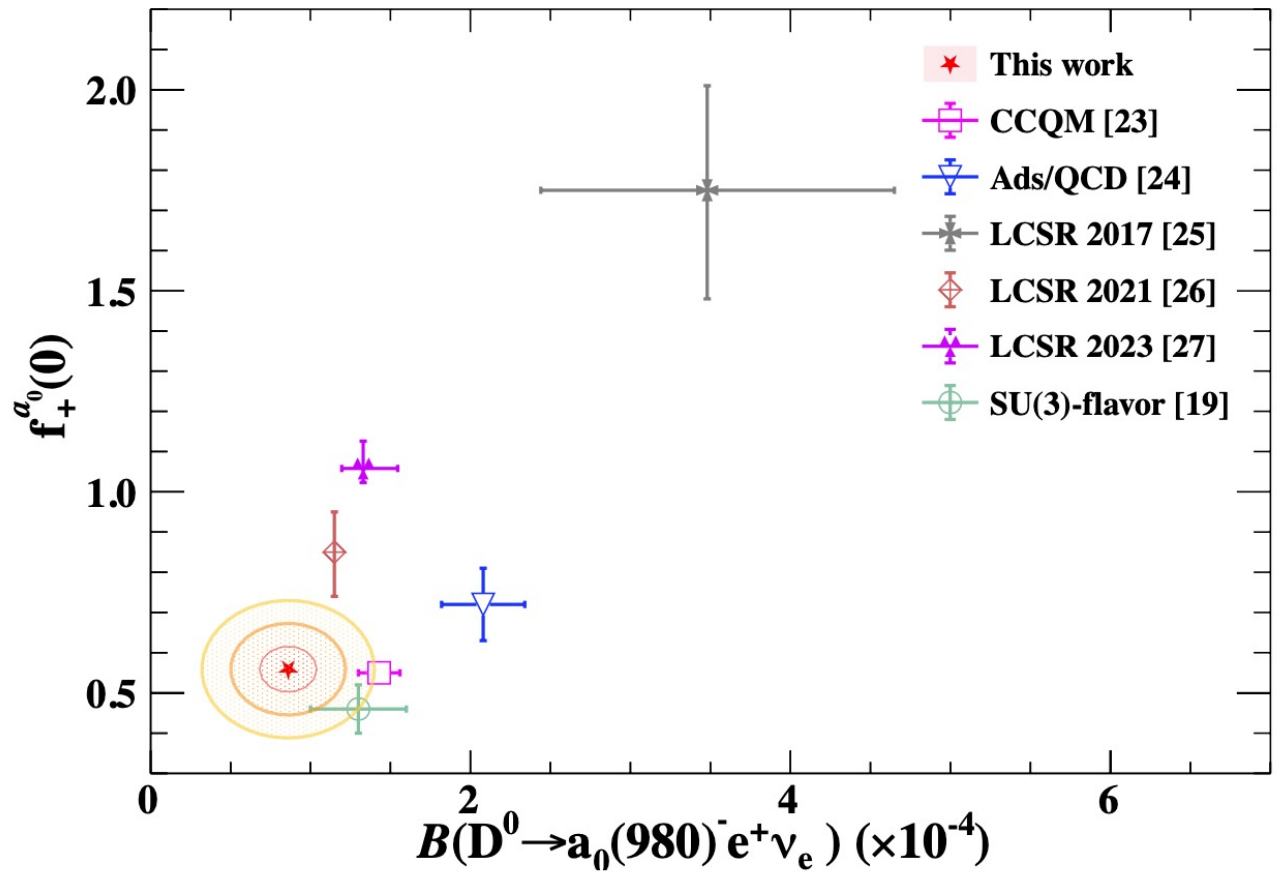
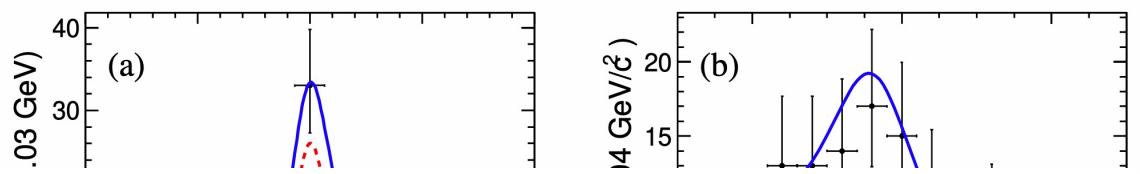
➤ First FF measurement:

Single-pole form for FF and Bugg form for  $a_0($

$$\rightarrow f_+^{a_0}(0) |V_{cd}| = 0.126 \pm 0.013 \pm 0.003$$

$$\rightarrow f_+^{a_0}(0) = 0.559 \pm 0.056 \pm 0.013$$

ps:  $|V_{cd}| = 0.22487 \pm 0.00068$  from SM glob:

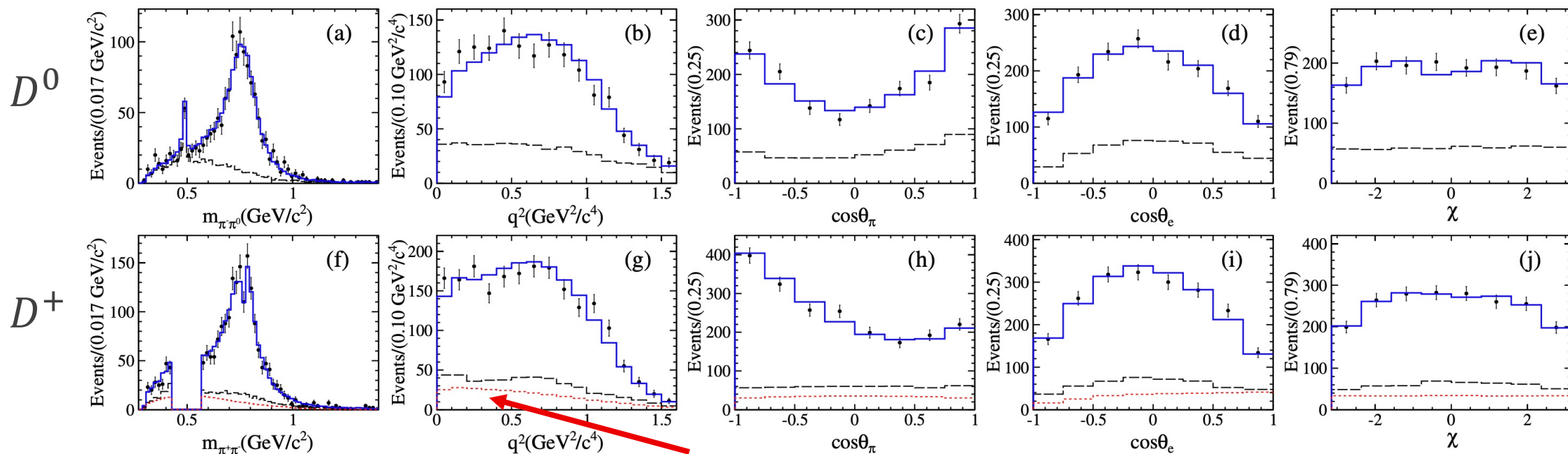


# First observation of $D^+ \rightarrow f_0(500)e^+\nu_e$

*Phys. Rev. Lett. 122, 062001 (2019)*

$$N_{sig}^{D^0} = 1498 \text{ (Bkg: } \sim 33.3\%)$$

$$N_{sig}^{D^+} = 2017 \text{ (Bkg: } \sim 23.8\%)$$



➤ 2.93 fb<sup>-1</sup> data @ 3.773 GeV

$$f_{f_0(500)} = (25.7 \pm 1.6 \pm 1.1)\%$$

➤  $R = \frac{B(D^+ \rightarrow f_0(500)e^+\nu_e) + B(D^+ \rightarrow f_0(980)e^+\nu_e)}{B(D^+ \rightarrow a_0(980)e^+\nu_e)} > 2.7 @ 90\% \text{ C.L.}$

➤ Favor tetraquark (R=3, PRD82, 034016(2010)) for  $f_0$  and  $a_0$

Signal mode	This analysis ( $\times 10^{-3}$ )
$D^0 \rightarrow \pi^- \pi^0 e^+ \nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^0 \rightarrow \rho^- e^+ \nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^+ \rightarrow \pi^- \pi^+ e^+ \nu_e$	$2.449 \pm 0.074 \pm 0.073$
$D^+ \rightarrow \rho^0 e^+ \nu_e$	$1.860 \pm 0.070 \pm 0.061$
$D^+ \rightarrow \omega e^+ \nu_e$	$2.05 \pm 0.66 \pm 0.30$
$D^+ \rightarrow f_0(500)e^+\nu_e, f_0(500) \rightarrow \pi^+\pi^-$	$0.630 \pm 0.043 \pm 0.032$
$D^+ \rightarrow f_0(980)e^+\nu_e, f_0(980) \rightarrow \pi^+\pi^-$	$< 0.028$

# Study of the decay $D^+ \rightarrow f_0(500)\ell^+\nu_\ell$

*Phys. Rev. D 110, 092008 (2024)*

- 2.93 fb<sup>-1</sup> data @ 3.773 GeV
- First observation of  $D^+ \rightarrow f_0(500)(\pi^+\pi^-)\mu^+\nu_\mu$ .

Signal mode	$N_{\text{obs}}$	$\mathcal{S}$ ( $\sigma$ )	$\epsilon_{\text{sig}}$ (%)	$\mathcal{B}_{\text{sig}} (\times 10^{-3})$
$f_0(500)\mu^+\nu_\mu$	$209 \pm 38$	5.9	$18.93 \pm 0.13$	$0.72 \pm 0.13$
$\rho^0\mu^+\nu_\mu$	$496 \pm 38$	> 10	$19.86 \pm 0.13$	$1.64 \pm 0.13$
$f_0(500)e^+\nu_e$	$412 \pm 43$	> 10	$44.76 \pm 0.25$	$0.60 \pm 0.06$
$\rho^0e^+\nu_e$	$1237 \pm 47$	> 10	$44.12 \pm 0.25$	$1.84 \pm 0.07$

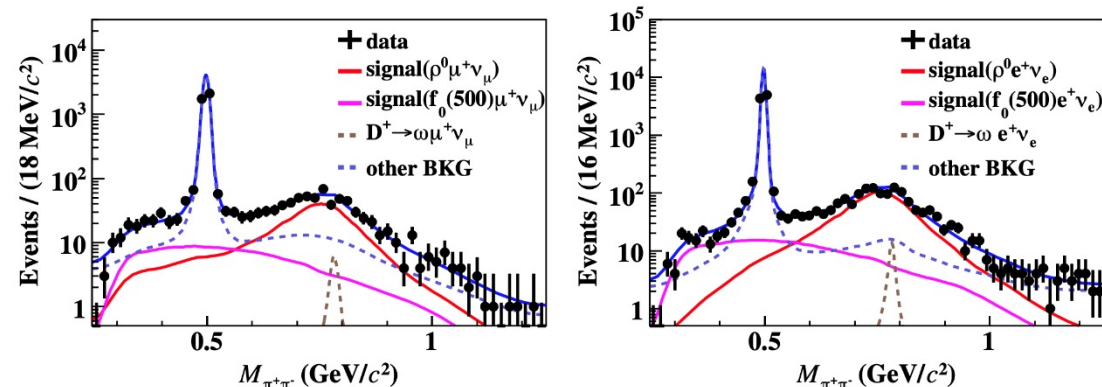
- First FF measurement of  $D^+ \rightarrow f_0(500)(\pi^+\pi^-)\ell^+\nu_\ell$ .

Z series expansion for FF and Bugg form for  $f_0(500)$

➔  $f_+^{f_0}(0)|V_{cd}| = 0.143 \pm 0.014 \pm 0.011$

➔  $f_+^{f_0}(0) = 0.63 \pm 0.06 \pm 0.05$

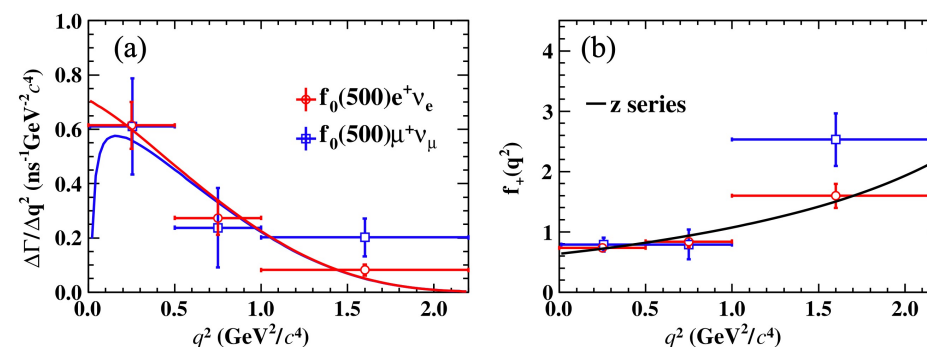
ps:  $|V_{cd}| = 0.22486 \pm 0.00067$  from SM global fit (PDG2022)



➔ The measured BF of  $D^+ \rightarrow f_0(500)\ell^+\nu_\ell$  are closer to **tetraquark assumption**.

R.M. Wang et al, PRD107,056022 (2023)

Y.K. Hsiao et al, JHEP12 (2024) 226

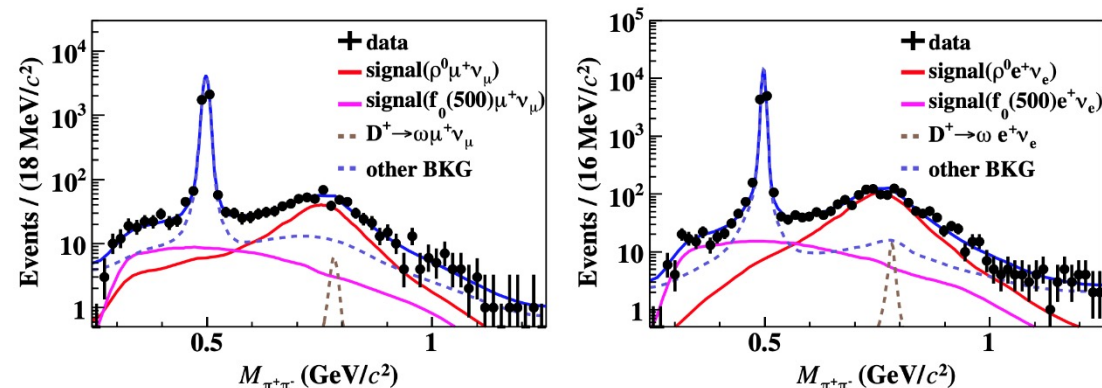


# Study of the decay $D^+ \rightarrow f_0(500)\ell^+\nu_\ell$

*Phys. Rev. D 110, 092008 (2024)*

- 2.93 fb<sup>-1</sup> data @ 3.773 GeV
- First observation of  $D^+ \rightarrow f_0(500)(\pi^+\pi^-)\mu^+\nu_\mu$ .

Signal mode	$N_{\text{obs}}$	$S$ ( $\sigma$ )	$\epsilon_{\text{sig}}$ (%)	$\mathcal{B}_{\text{sig}} (\times 10^{-3})$
$f_0(500)\mu^+\nu_\mu$	$209 \pm 38$	5.9	$18.93 \pm 0.13$	$0.72 \pm 0.13$
$\rho^0\mu^+\nu_\mu$	$496 \pm 38$	> 10	$19.86 \pm 0.13$	$1.64 \pm 0.13$
$f_0(500)e^+\nu_e$	$412 \pm 43$	> 10	$44.76 \pm 0.25$	$0.60 \pm 0.06$
$\rho^0e^+\nu_e$	$1237 \pm 47$	> 10	$44.12 \pm 0.25$	$1.84 \pm 0.07$



➔ The measured BF of  $D^+ \rightarrow f_0(500)\ell^+\nu_\ell$  are closer to **tetraquark assumption**.

R.M. Wang et al, PRD107,056022 (2023)

Y.K. Hsiao et al, JHEP12 (2024) 226

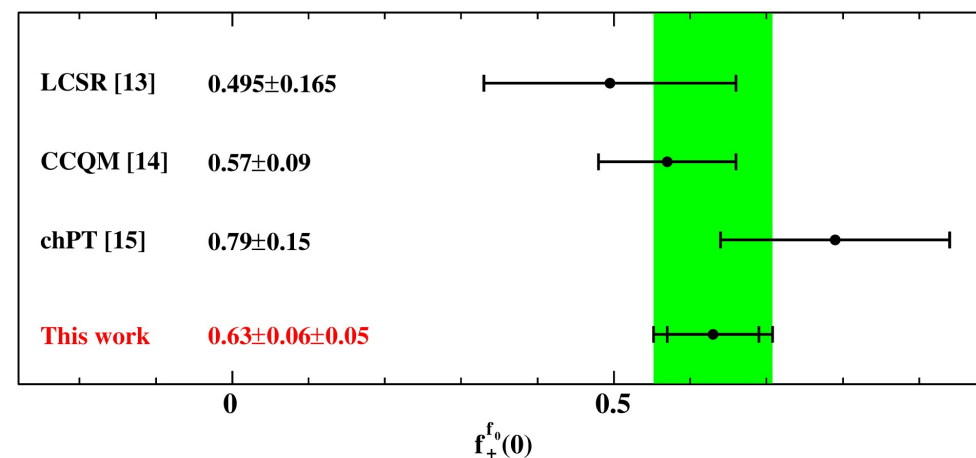
- First **FF** measurement of  $D^+ \rightarrow f_0(500)(\pi^+\pi^-)\ell^+\nu_\ell$ .

Based Z series expansion for **FF** and Bugg form for  $f_0(500)$

➔  $f_+^{f_0}(0)|V_{cd}| = 0.143 \pm 0.014 \pm 0.011$

➔  $f_+^{f_0}(0) = 0.63 \pm 0.06 \pm 0.05$

ps:  $|V_{cd}| = 0.22486 \pm 0.00067$  from SM global fit (PDG202

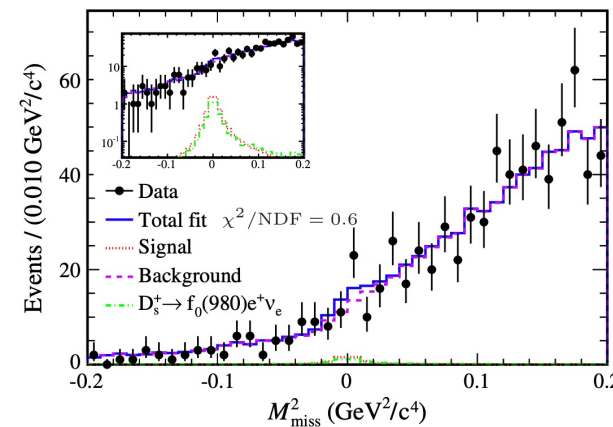
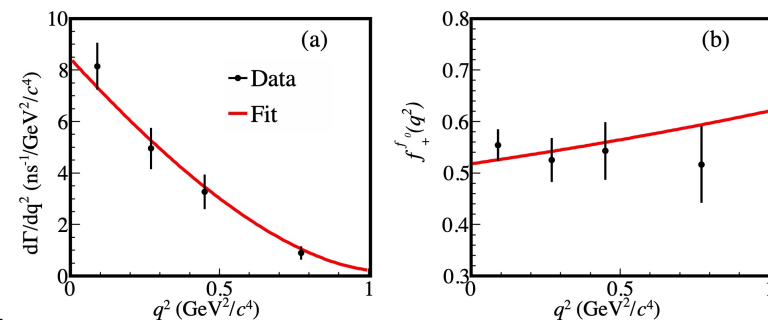
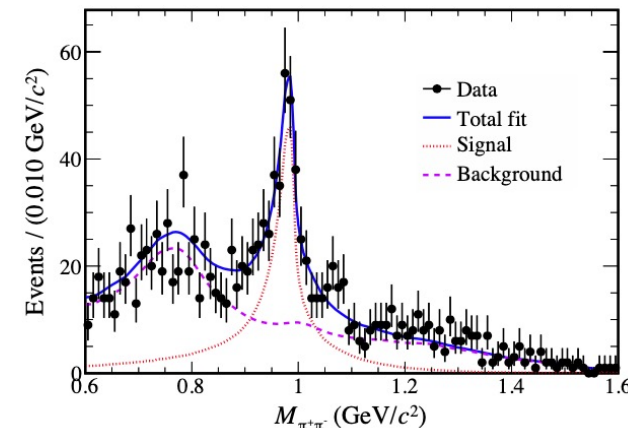


*Phys. Rev. Lett. 132, 141901 (2024)*

- $7.33 \text{ fb}^{-1}$  data @ 4.128-4.226 GeV  $\rightarrow N_{\text{sig}} = 439 \pm 33$
- $\mathcal{B}(D_s^+ \rightarrow f_0(980)e^+ \nu_e, f_0(980) \rightarrow \pi^+ \pi^-) = (1.72 \pm 0.13 \pm 0.10) \times 10^{-3}$   
 $\rightarrow$   **$s\bar{s}$  is dominant** based on  $|f_0(980)\rangle = \sin \phi |\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\rangle + \cos \phi |s\bar{s}\rangle$   
 $\phi = (19.7 \pm 12.8)^\circ$
- **First FF measurement** with simple pole form:
  - $\rightarrow f_+^{f_0}(0) |V_{cs}| = 0.504 \pm 0.017 \pm 0.035$
  - $\rightarrow f_+^{f_0}(0) = 0.518 \pm 0.018 \pm 0.036$  ( $|V_{cs}| = 0.97349 \pm 0.00016$  PDG2022)

	This work	CLFD [6]	DR [6]	QCDSR [7]	QCDSR [8]	LCSR [9]	LFQM [11]	CCQM [12]
$f_+^{f_0}(0)$	$0.518 \pm 0.018_{\text{stat}} \pm 0.036_{\text{syst}}$	0.45	0.46	$0.50 \pm 0.13$	$0.48 \pm 0.23$	$0.30 \pm 0.03$	$0.24 \pm 0.05$	$0.36 \pm 0.02$
Difference ( $\sigma$ )	—	1.7	1.4	0.1	0.2	4.3	4.3	2.8
$\phi$	$\phi = (19.7 \pm 12.8)^\circ$	$(32 \pm 4.8)^\circ$	$(41.3 \pm 5.5)^\circ$	$35^\circ$	$(8_{-8}^{+21})^\circ$	—	$(56 \pm 7)^\circ$	$31^\circ$

- **First search** of  $D_s^+ \rightarrow f_0(500)e^+ \nu_e, f_0(500) \rightarrow \pi^+ \pi^-$  ( $M_{\pi^+ \pi^-} < 0.45 \text{ GeV}/c^2$ )
- $\mathcal{B}(D_s^+ \rightarrow f_0(500)e^+ \nu_e, f_0(500) \rightarrow \pi^+ \pi^-) < 3.3 \times 10^{-4}$

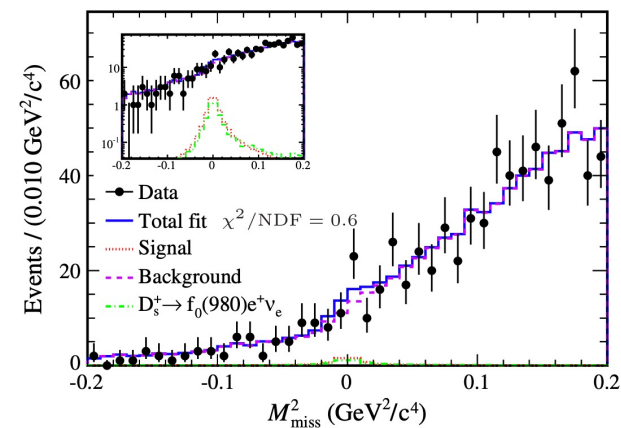
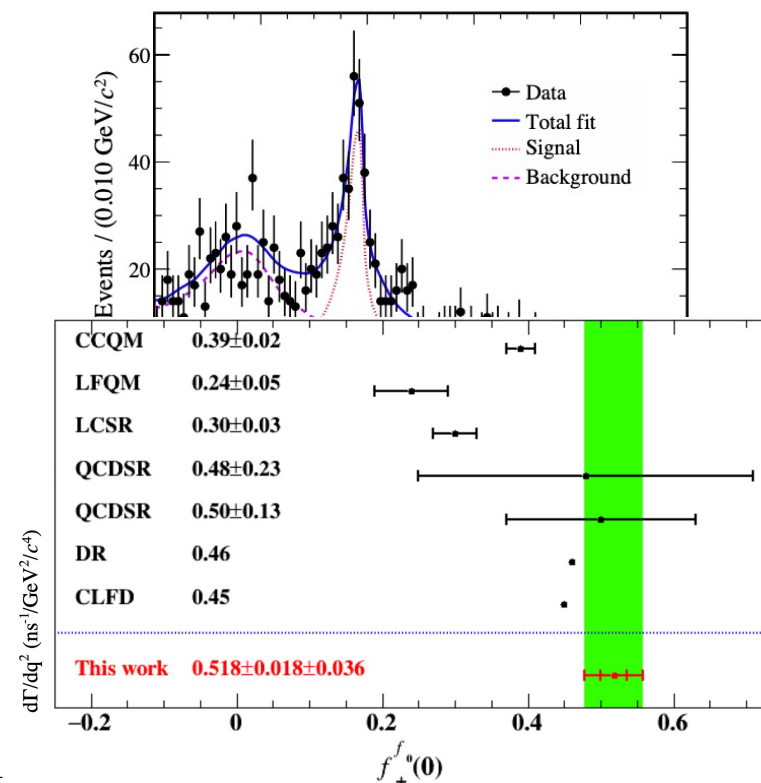


*Phys. Rev. Lett. 132, 141901 (2024)*

- $7.33 \text{ fb}^{-1}$  data @ 4.128-4.226 GeV  $\rightarrow N_{\text{sig}} = 439 \pm 33$
- $\mathcal{B}(D_s^+ \rightarrow f_0(980)e^+ \nu_e, f_0(980) \rightarrow \pi^+ \pi^-) = (1.72 \pm 0.13 \pm 0.10) \times 10^{-3}$   
 $\rightarrow$   **$s\bar{s}$  is dominant** based on  $|f_0(980)\rangle = \sin \phi |\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\rangle + \cos \phi |s\bar{s}\rangle$   
 $\phi = (19.7 \pm 12.8)^\circ$
- **First FF measurement** with simple pole form:
  - $\rightarrow f_+^{f_0}(0) |V_{cs}| = 0.504 \pm 0.017 \pm 0.035$
  - $\rightarrow f_+^{f_0}(0) = 0.518 \pm 0.018 \pm 0.036$  ( $|V_{cs}| = 0.97349 \pm 0.00016$  PDG2022)

	This work	CLFD [6]	DR [6]	QCDSR [7]	QCDSR [8]	LCSR [9]	LFQM [11]	CCQM [12]
$f_+^{f_0}(0)$	$0.518 \pm 0.018_{\text{stat}} \pm 0.036_{\text{syst}}$	0.45	0.46	$0.50 \pm 0.13$	$0.48 \pm 0.23$	$0.30 \pm 0.03$	$0.24 \pm 0.05$	$0.36 \pm 0.02$
Difference ( $\sigma$ )	—	1.7	1.4	0.1	0.2	4.3	4.3	2.8
$\phi$	$\phi = (19.7 \pm 12.8)^\circ$	$(32 \pm 4.8)^\circ$	$(41.3 \pm 5.5)^\circ$	$35^\circ$	$(8_{-8}^{+21})^\circ$	—	$(56 \pm 7)^\circ$	$31^\circ$

- **First search** of  $D_s^+ \rightarrow f_0(500)e^+ \nu_e, f_0(500) \rightarrow \pi^+ \pi^-$  ( $M_{\pi^+ \pi^-} < 0.45 \text{ GeV}/c^2$ )
- $\mathcal{B}(D_s^+ \rightarrow f_0(500)e^+ \nu_e, f_0(500) \rightarrow \pi^+ \pi^-) < 3.3 \times 10^{-4}$



# Study of the decay $D^0 \rightarrow K^- \pi^0 \mu^+ \nu_\mu$

*Phys. Rev. Lett. 134, 011803 (2025)*

- 7.93 fb<sup>-1</sup> data @3.773GeV →  $N_{\text{sig}} = 6436 \pm 119$
- **First BF** measurement and **LFU** test on this channel:

$$\mathcal{B}(D^0 \rightarrow K^- \pi^0 \mu^+ \nu_\mu) = (0.729 \pm 0.014 \pm 0.011)\%$$

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

(精度2.4%，相比之前5倍提升)

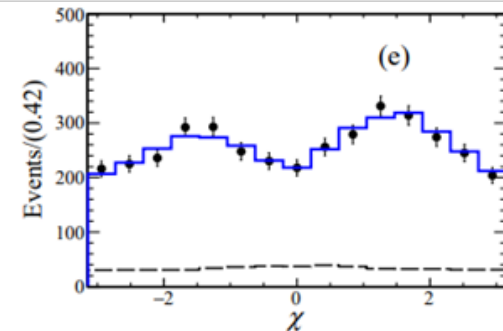
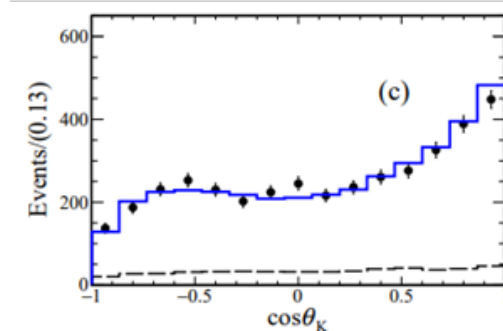
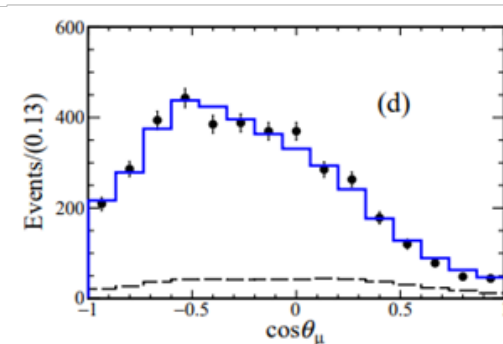
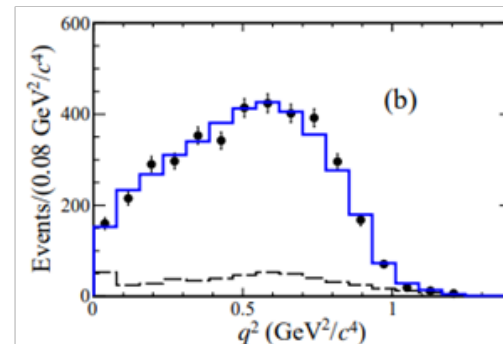
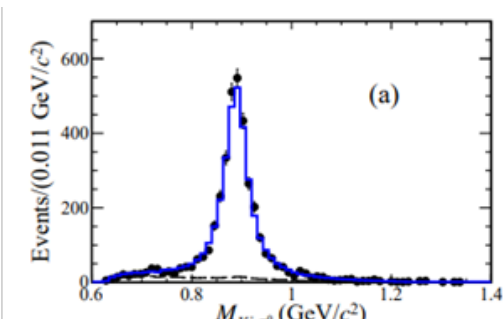
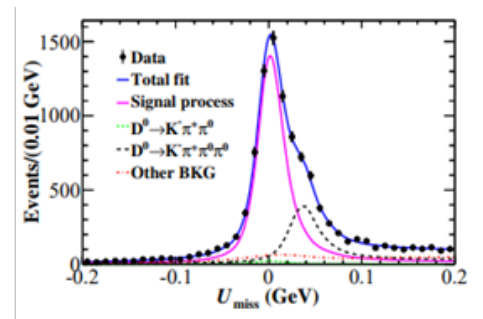
$$f_{S\text{-wave}} = (5.76 \pm 0.35 \pm 0.29)\%$$

$$f_{P\text{-wave}} = (94.24 \pm 0.35 \pm 0.29)\%$$

$$\mathcal{R}_{K^*(892)^-}^{\mu/e} = 1.020 \pm 0.030 \pm 0.028 (\sim 4\% \text{ level})$$

- First **FF** measurement :

$$r_V = 1.37 \pm 0.09 \pm 0.03, r_2 = 0.76 \pm 0.06 \pm 0.02$$



$|U_{\text{miss}}| < 0.015 \text{ GeV}$   
 $N_{\text{Event}}^{SL} = 3375, \text{Bkg: } (12.6 \pm 0.7)\%$

TABLE IV. Measured the BF and FF ratios of  $D^0 \rightarrow K^*(892)^- \mu^+ \nu_\mu$ , and compared them with theoretical calculations and previous measurements.

Theory	$\mathcal{B}$ (%)	$r_V$	$r_2$
LCSR [7,16]	$2.01^{+0.09}_{-0.08}$	1.39	0.60
$\chi$ UA [17]	1.98	...	...
CCQM [6]	2.80	$1.22 \pm 0.24$	$0.92 \pm 0.18$
CQM [8,18]	3.09	1.56	0.74
LFQM [9]	...	1.36	0.83
HM $_\chi$ T [10]	...	1.60	0.50
Experiments	$\mathcal{B}$ (%)	$r_V$	$r_2$
BESIII [39]	...	$1.46 \pm 0.07 \pm 0.02$	$0.67 \pm 0.06 \pm 0.01$
FOCUS [11]	$1.89 \pm 0.24$	$1.71 \pm 0.68 \pm 0.34$	$0.91 \pm 0.37 \pm 0.10$
This Letter	$2.073 \pm 0.039 \pm 0.032$	$1.37 \pm 0.09 \pm 0.03$	$0.76 \pm 0.06 \pm 0.02$

$$r_V = 1.37 \pm 0.09 \pm 0.03, r_2 = 0.76 \pm 0.06 \pm 0.02$$

# Study of the decay $D^0 \rightarrow \bar{K}^0 \pi^- \mu^+ \nu_\mu$

*Phys. Rev. Lett. 135, 111803 (2025)*

➤  $7.9 \text{ fb}^{-1}$  data @  $3.773 \text{ GeV} \rightarrow N_{\text{sig}} = 6796 \pm 98$

➤ **First BF** measurement and **LFU** test on this channel:

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

$$\mathcal{B}(D^0 \rightarrow K^{*(892)-} e^+ \nu_e) = (1.948 \pm 0.033 \pm 0.036)\% (\sim 2.4\%)$$

$$\mathcal{R}_{K^{*(892)-}}^{\mu/e} = 0.955 \pm 0.022 \pm 0.017, \mathcal{R}_{\bar{K}^0 \pi^-}^{\mu/e} = 0.951 \pm 0.020 \pm 0.016$$

$$f_{\text{S-wave}} = (5.35 \pm 0.87 \pm 0.71)\%$$

$$f_{\text{P-wave}} = (94.60 \pm 0.87 \pm 0.71)\%$$

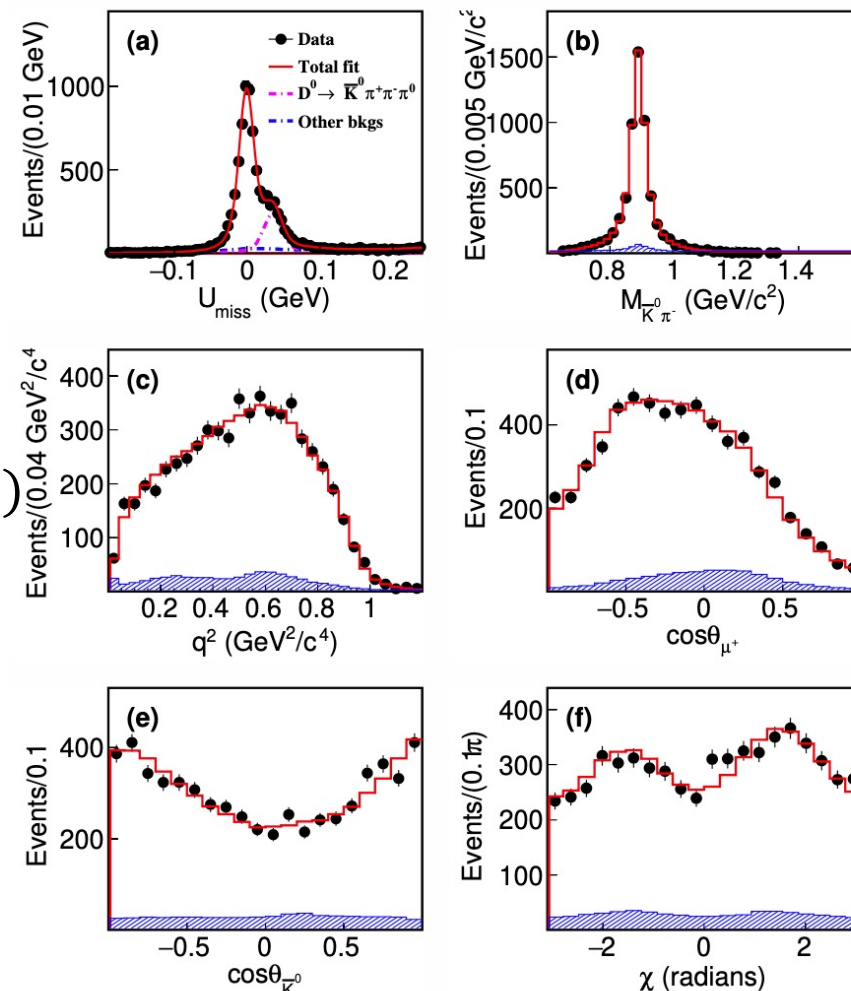
➤ **First FF** measurement at BESIII :

$$r_V = 1.46 \pm 0.11 \pm 0.04, r_2 = 0.71 \pm 0.08 \pm 0.03$$

$$A_1(0) = 0.623 \pm 0.008 \pm 0.008 \text{ (First measurement from this decay)}$$

April/26/2026

张书磊@BESIII



$|U_{\text{miss}}| < 0.02 \text{ GeV}$   
 $N_{\text{sig}} \sim 6\text{K}, \text{Bkg: } \sim 10\%$

*Phys. Rev. Lett. 135, 111803 (2015)*

➤ 7.9 fb<sup>-1</sup> data @3.773GeV →  $N_{\text{sig}} = 679$

➤ **First BF** measurement and **LFU** test on the

$$\mathcal{B}(D^0 \rightarrow \bar{K}^0 \pi^- \mu^+ \nu_\mu) = (1.373 \pm 0.020 \pm 0.017) \times 10^{-4}$$

$$\mathcal{B}(D^0 \rightarrow K^{*(892)-} e^+ \nu_e) = (1.948 \pm 0.020 \pm 0.017) \times 10^{-4}$$

$$\mathcal{R}_{K^{*(892)-}}^{\mu/e} = 0.955 \pm 0.022 \pm 0.017, \mathcal{R}_{\bar{K}^0 \pi^-}^{\mu/e} = 1.0$$

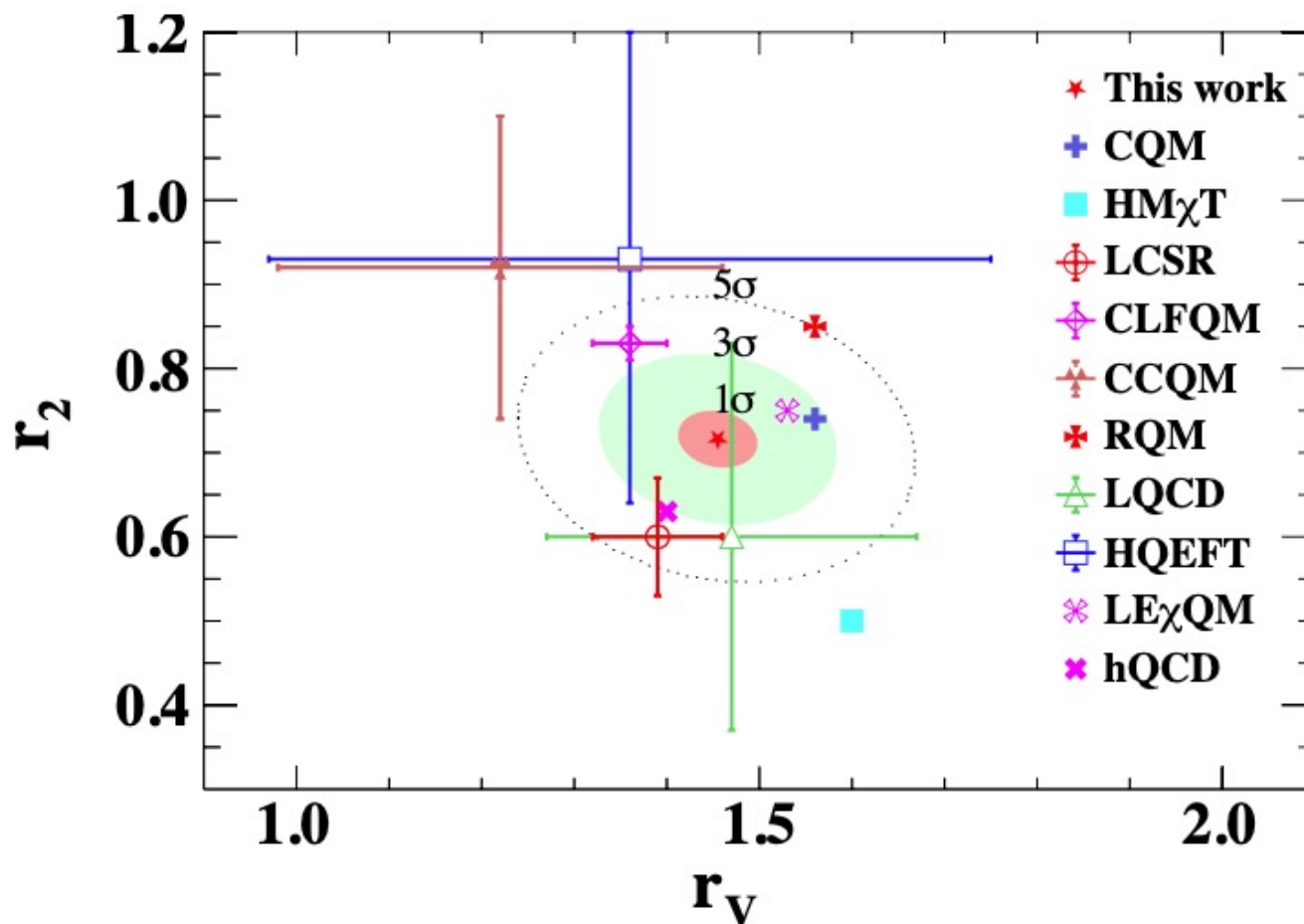
$$f_{\text{S-wave}} = (5.35 \pm 0.87 \pm 0.71)\%$$

$$f_{\text{P-wave}} = (94.60 \pm 0.87 \pm 0.71)\%$$

➤ **First FF** measurement at BESIII :

$$r_V = 1.46 \pm 0.11 \pm 0.04, r_2 = 0.71 \pm 0.08 \pm 0.03$$

$$A_1(0) = 0.623 \pm 0.008 \pm 0.008 \text{ (First measurement from this decay)}$$



$|U_{\text{miss}}| < 0.02 \text{ GeV}$   
 $N_{\text{sig}} \sim 6\text{K}, \text{Bkg: } \sim 10\%$

*arXiv: 2603.00743 (Submitted to PRL)*

➤ 20.3 fb<sup>-1</sup> data @ 3.773 GeV →  $N_{\text{sig}} = 28900 \pm 224$

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

$$f_D(\%) = 0.16 \pm 0.05 \pm 0.02 \text{ (7.9}\sigma\text{)}$$

$$\mathcal{B}(D^0 \rightarrow K_2^*(1430)e^+\nu_e) = (7.603 \pm 2.457 \pm 0.194) \times 10^{-4}$$

$$\mathcal{B}(D^0 \rightarrow K^*(892)^- e^+ \nu_e, K^*(892)^- \rightarrow K^- \pi^0)$$

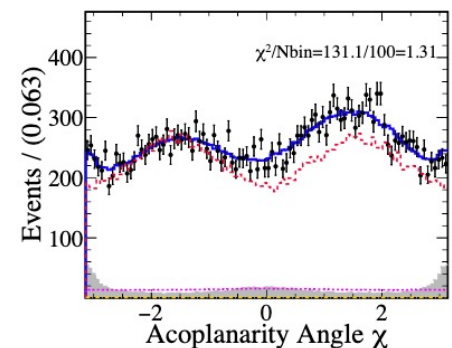
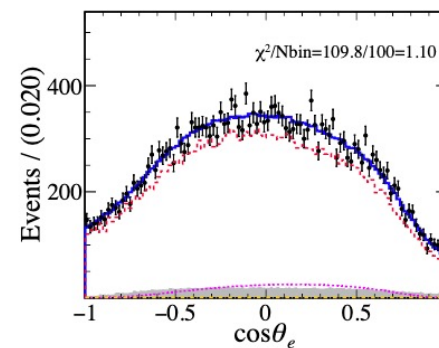
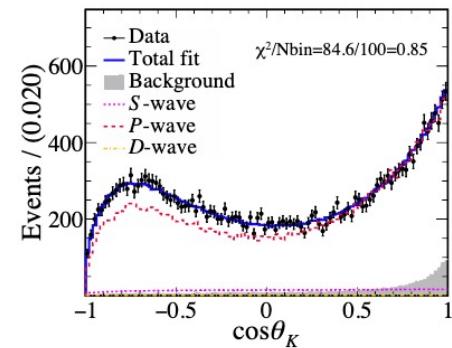
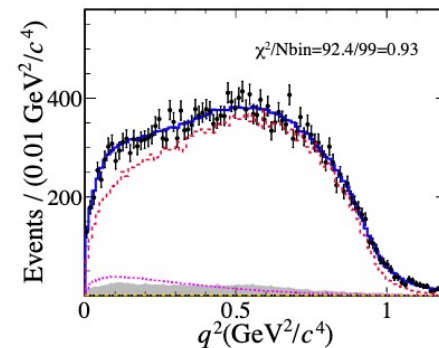
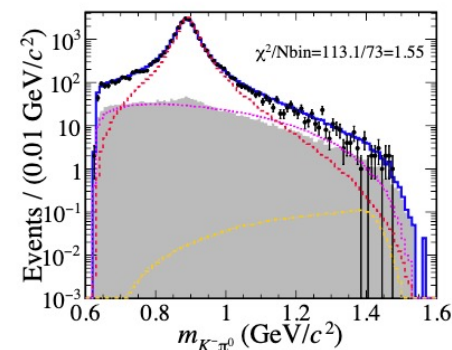
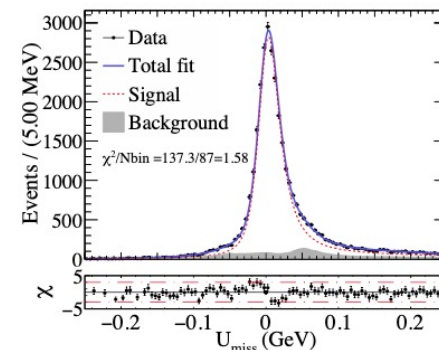
$$= (7.403 \pm 0.061 \pm 0.048) \times 10^{-3} \text{ (}\sim 1\%\text{ level!)}$$

$$|V_{cs}|A_1(0) = 0.618 \pm 0.010 \pm 0.008 \text{ (}\sim 2\%\text{ level)}$$

➤ First test of isospin-breaking effect:

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

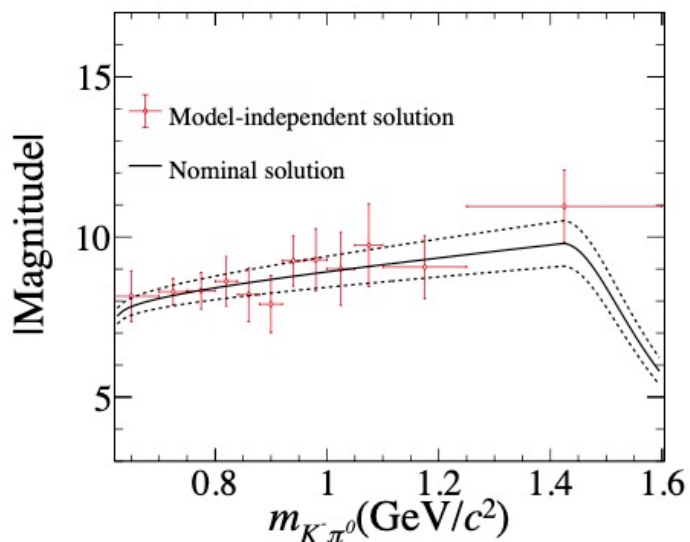
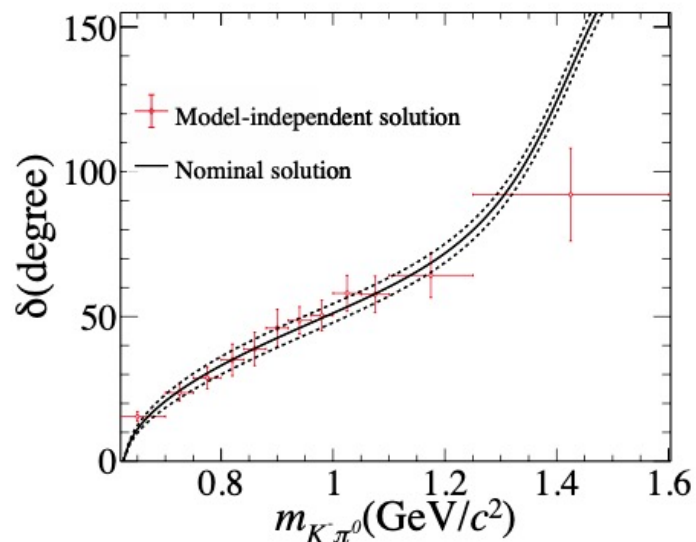
➤ LFU test :  $\mathcal{R}_{K^*(892)^-}^{\mu/e} = 0.928 \pm 0.020 \pm 0.012 \text{ (}\sim 2.5\%\text{ level)}$



$|U_{\text{miss}}| < 0.06 \text{ GeV}$   
 $N_{\text{sig}} \sim 26\text{K}, \text{Bkg: } \sim 5.5\%$

*arXiv: 2603.00743 (Submitted to PRL)*

放开几乎全部参数



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

- First measurement of the phase shift (magnitude) of the S-wave in a model-independent way in this channel.
- Additional measurement in a clean environment to constrain the pole parameters of the  $K_0^*(700)$

*arXiv: 2601.16938 (Submitted to PRD)*

➤ 7.33 fb<sup>-1</sup> data @ 4.128-4.226 GeV

➤ **First evidence of  $D_s^+ \rightarrow f_1(1420)e^+\nu_e \rightarrow N_{\text{sig}} = 13.2^{+5.8}_{-5.0}$**

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

$$\mathcal{B}(D_s^+ \rightarrow f_1(1420)e^+\nu_e \rightarrow K^+K^-\pi^0) < 7.6 \times 10^{-4} @ 90\% \text{C.L.}$$

➤ **First search of  $D_s^+ \rightarrow f_1(1285)e^+\nu_e (<1\sigma)$**

$$\mathcal{B}(D_s^+ \rightarrow f_1(1285)e^+\nu_e \rightarrow \pi^+\pi^-\eta) < 1.7 \times 10^{-4} @ 90\% \text{C.L.}$$

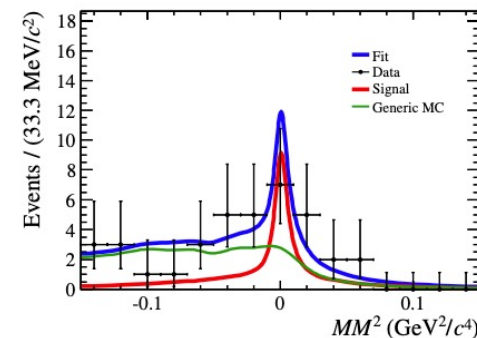
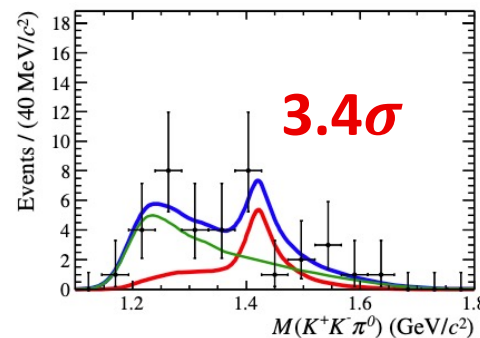
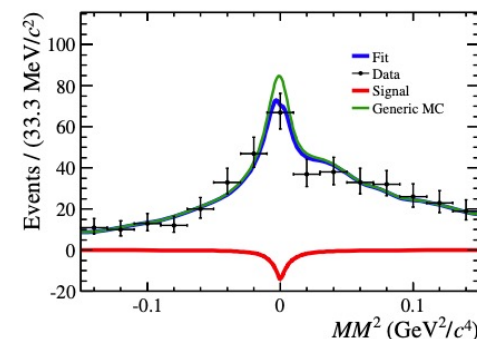
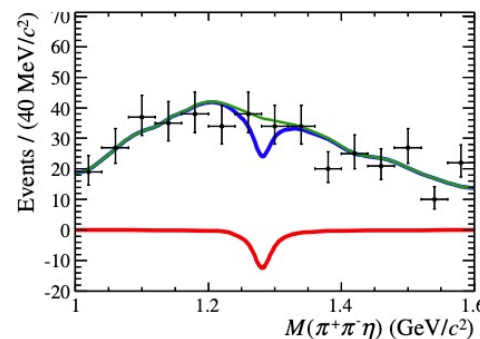
Unit ( $\times 10^{-4}$ )

Decay	Ref. [4]	Ref. [12]	Ref. [13]	Our result
$D_s^+ \rightarrow f_1(1285)e^+\nu_e$	[0.6, 3.6]	$8.6 \pm 7.3$	$1.17 \pm 0.18$	$< 5.0$
$D_s^+ \rightarrow f_1(1420)e^+\nu_e$	$2.5 \pm 0.5$	$2.1 \pm 2.1$	$3.9 \pm 0.4$	—

[4] H. Y. Cheng *et al.*, Eur. Phys. J. C **77**, 587 (2017).

[12] Y. Qiao, Y. X. Liu, Y. G. Xu, and R. M. Wang, The European Physical Journal C **84** (2024).

[13] V. O. Galkin and I. S. Sukhanov, Phys. Rev. D **111**, 093001 (2025).



# Content

01

Physics motivation ✓

02

Data and analysis method ✓

03

Some recent results ✓

04

Summary and prospect ✓

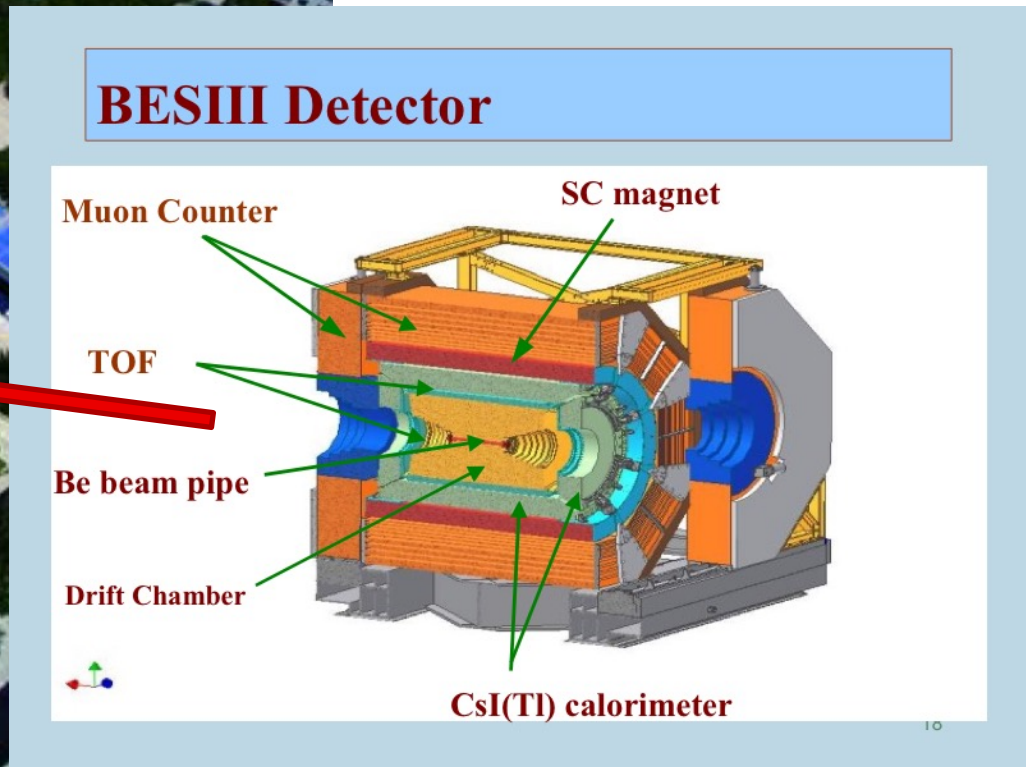
## Summary:

- BESIII has the largest data samples at  $D\bar{D}/D_S D_S^*$  threshold.
- Scalar/(axial-)vector mesons are studied systematically via semi-leptonic charm decays.
- BFs/FF measurements help to test different QCD modes and understand light hadron!

## Prospect:

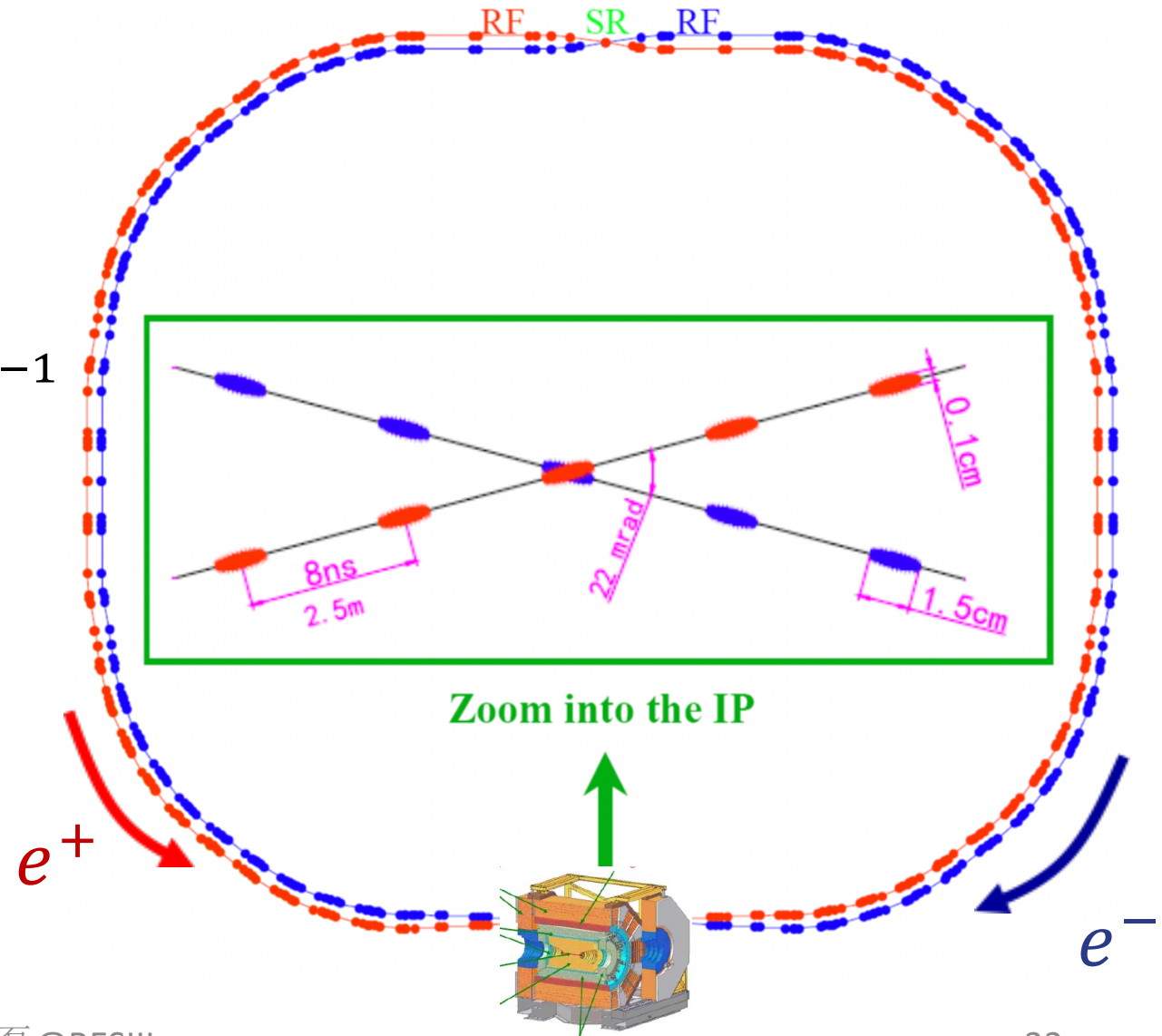
- Higher precision measurement on BFs/FF/LFU/CKM.
- More update results on scalar/(axial-)vector meson via semi-leptonic charm decays.
- More first results on scalar/axial/tensor meson via semi-leptonic charm decays.
- More results are on the way ... ..

*Thank you!*

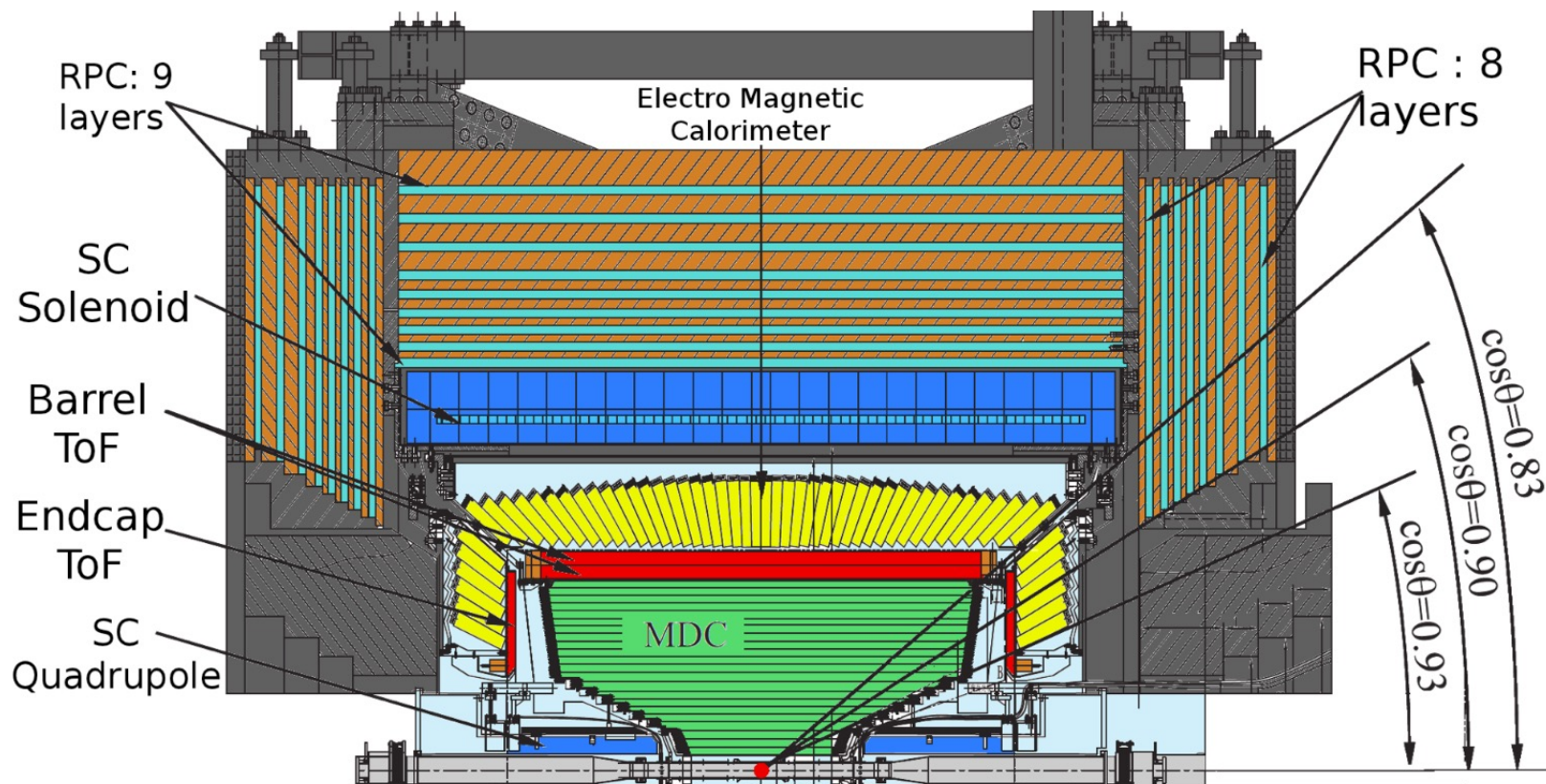


# BEPCII collider

- Two ring symmetric  $e^+e^-$  collider
- Circumference: 240 m
- Design luminosity:  $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Achieved time: 5 April, 2016
- $E_{cm}$ : 2 – 5 GeV
- Beam crossing angle: 22 mrad



# BESIII detector



## MDC

$$\frac{\delta p}{p} < 0.5\% \text{ @1 GeV}$$

$$\frac{\delta(dE/dx)}{dE/dx} < 6\%$$

## TOF

$$\delta t \text{ 80 ps Barrel}$$

$$\delta t \text{ 110 ps Endcap}$$

## EMC

$$\frac{\delta E}{E} < 2.5\% \text{ @1 GeV}$$

$$\delta z = 0.6/\sqrt{E}$$

## MUC

$$\delta(xy) < 2 \text{ cm}$$