



# The hadronic decays of charmed mesons at BESIII

Tianyou Li<sup>1,2</sup> and Hui Li<sup>1,2</sup>  
(On behalf of the BESIII Collaboration)

<sup>1</sup>Nankai University <sup>2</sup>Institute of High Energy Physics, CAS

WIN 2025 • Sussex University • Brighton, UK

- BEPCII, BESIII detector and data samples
- The  $D$  hadronic decays
- The  $D_s$  hadronic decays
- The quantum-correlated  $D$  decays
- Summary and outlooks

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# BEPCII, BESIII detector and data samples



Beam energy @ 0.8-2.5 (2.8) GeV



LINAC

$e^+$

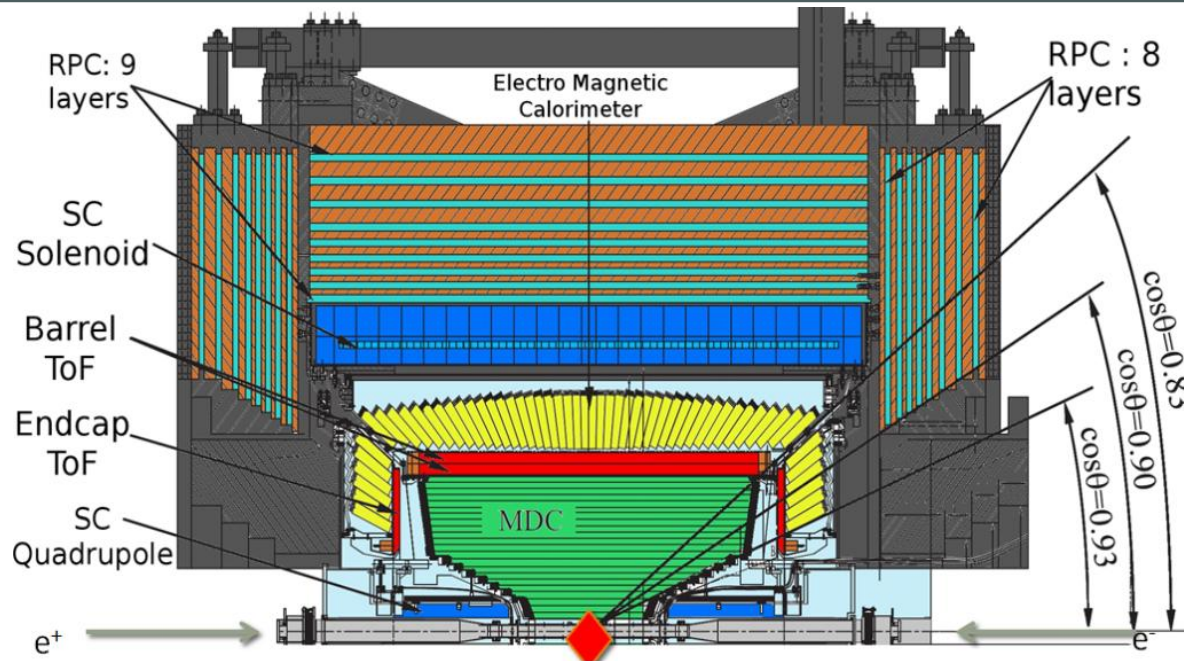
BESIII detector

$e^-$

2004: BEPCII upgrade, BESIII construction  
2009-2024: BESIII physics and SR run  
2024.7-2024.12: BEPCII upgrade to BEPCII-U

1989-2004 (BEPC):  $L_{\text{peak}} = 1.0 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$   
2009-2024 (BEPCII):  
 $L_{\text{peak}} = 1.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  (2016, designed  $L$ )  
2024-now (BEPCII-U): Beam energy up to 2.8 GeV

# BEPCII, BESIII detector and data samples



Recording data from **symmetric electron-positron collisions**

MDC:  $\sigma_{xy} = 130 \mu m$   
 $\sigma_p/p = 0.5\% @ 1 \text{ GeV}$   
 $dE/dx = 6 \%$

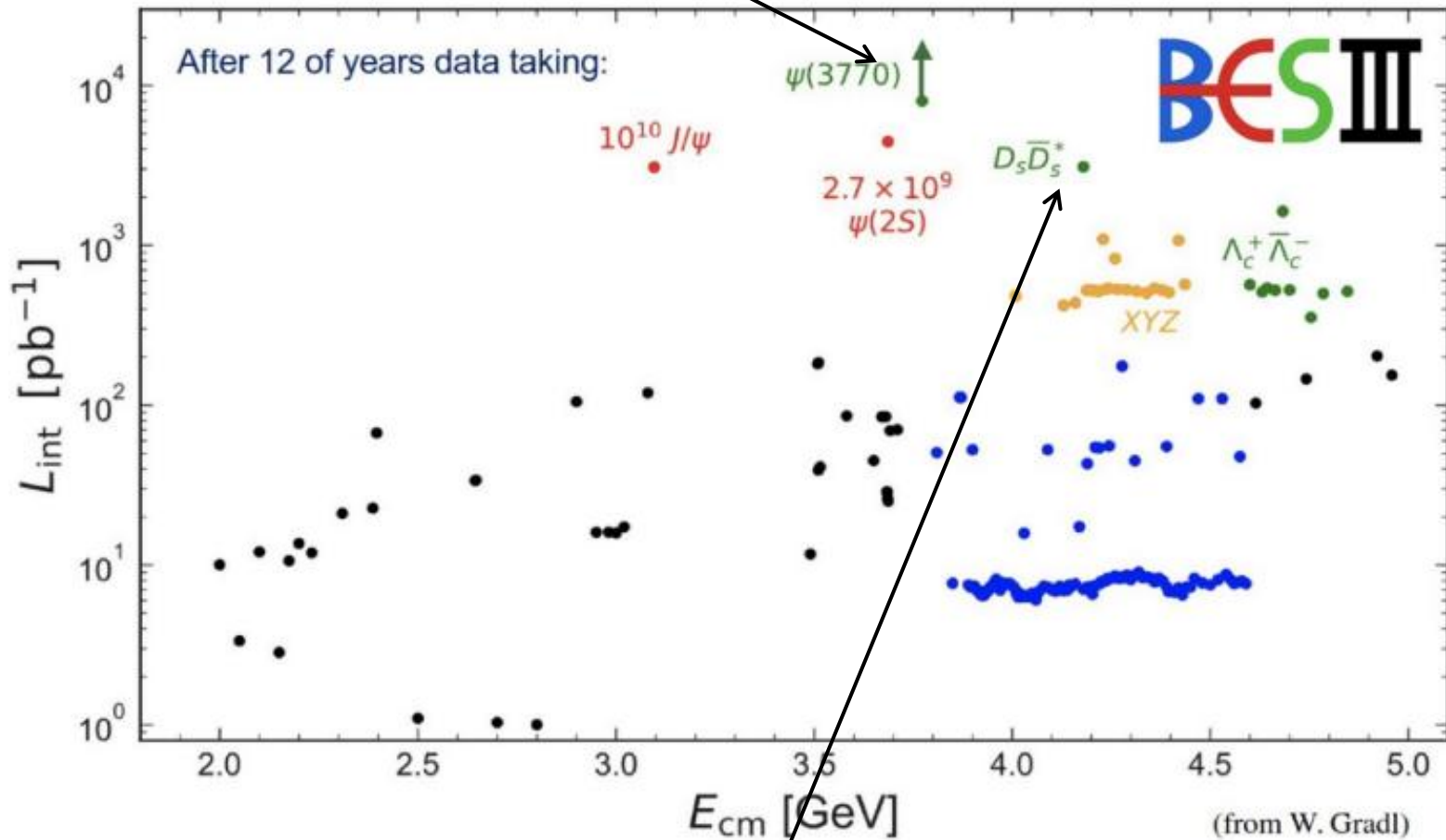
TOF:  $\sigma_T = 80 \text{ ps}$  (Barrel)  
 $\sigma_T = 110 \text{ ps}$  (Endcap)

EMC:  $\Delta E/E = 2.5\% @ 1 \text{ GeV}$  (Barrel)  
 $\Delta E/E = 5.0\% @ 1 \text{ GeV}$  (Endcap)

# BEPCII, BESIII detector and data samples



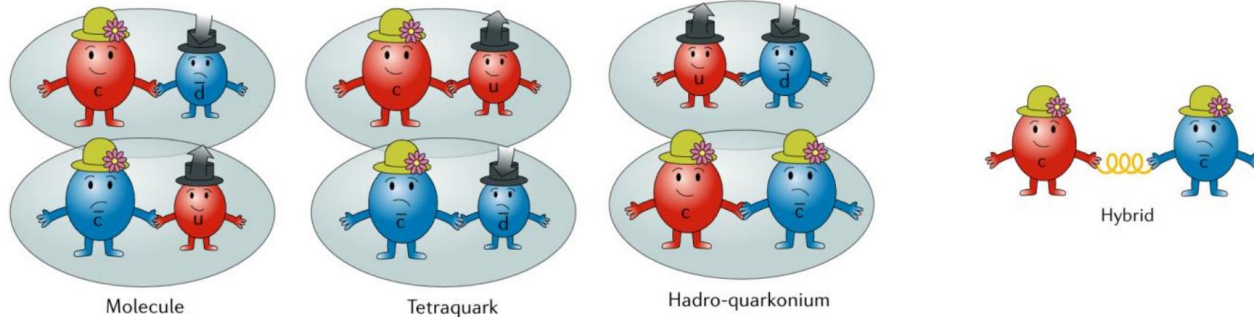
3.773 GeV data sample,  $20.3 \text{ fb}^{-1}$ , *Chin.Phys.C.* 48,123001 (2024)



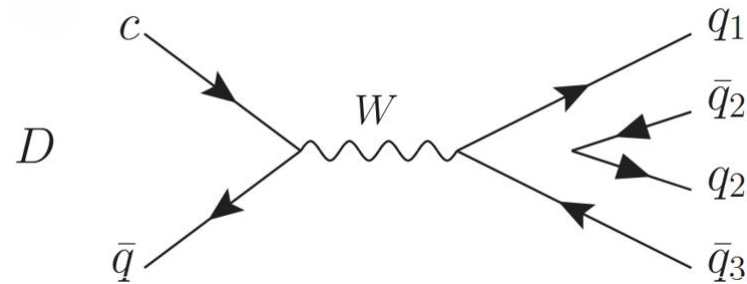
4.128-4.226 GeV data sample,  $7.33 \text{ fb}^{-1}$ , *Chin.Phys.C.* 46,113002 (2022)

- BEPCII, BESIII detector and data samples
- **The  $D$  hadronic decays**
- The  $D_s$  hadronic decays
- The quantum-correlated  $D$  decays
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# The $D$ hadronic decays



- There are interpretations ( $q\bar{q}$ ,  $q^2\bar{q}^2$  or Hybrid) for  $a_0(980)$ ,  $f_0(980)$  and  $f_0(500)$ . Study  $D$  hadronic decays helpful to understand.



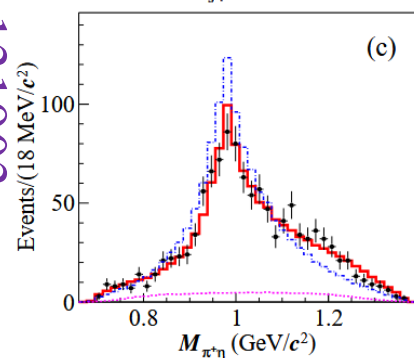
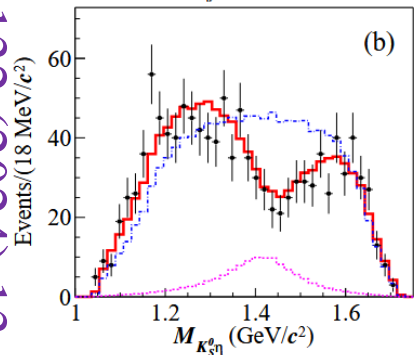
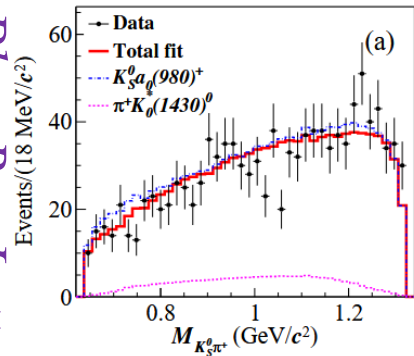
- The reason of large discrepancy between experimental results and theoretical predictions of  $\mathcal{B}(D^{+,0} \rightarrow a_0(980)P)$  may be ascribed to the contribution of the Weak-annihilation amplitudes in  $D$  decays. Search for W-annihilation free mode can provide key experimental input.

# The $D$ hadronic decays

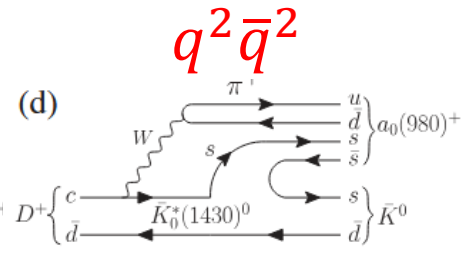
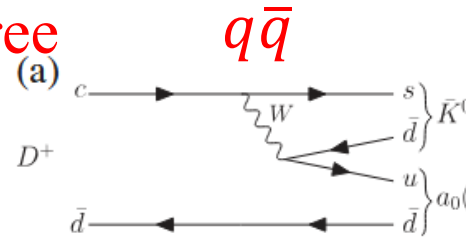
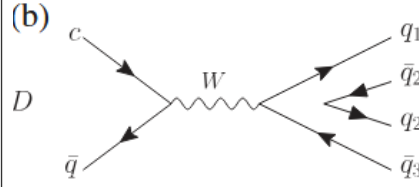
$$D^+ \rightarrow K_S^0 \pi^+ \eta, 2.93 \text{ fb}^{-1}$$

$a_0(980)^+$ :  $q\bar{q}$  or  $q^2\bar{q}^2$ ?

Phys. Rev. Lett. 132 (2024) 13, 131903



**W-annihilation free**



| Amplitude                                   | Phase $\phi$ (rad)                | FF (%)                              | Significance |
|---------------------------------------------|-----------------------------------|-------------------------------------|--------------|
| $D^+ \rightarrow K_S^0 a_0(980)^+$          | 0.0 (fixed)                       | $105.00 \pm 0.94 \pm 1.04 \pm 0.07$ | $> 10\sigma$ |
| $D^+ \rightarrow \bar{K}_0^*(1430)^0 \pi^+$ | $2.58 \pm 0.06 \pm 0.09 \pm 0.01$ | $10.83 \pm 1.50 \pm 1.27 \pm 0.08$  | $> 10\sigma$ |

- $\mathcal{B}(D^+ \rightarrow K_S^0 \pi^+ \eta) = (1.27 \pm 0.04_{\text{stat}} \pm 0.03_{\text{syst}})\%$ ,
- $\mathcal{B}(D^+ \rightarrow K_S^0 a_0(980)^+) = (1.33 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}})\%$ ,
- $\mathcal{B}(D^+ \rightarrow \bar{K}_0^*(1430) \pi^+) = (0.14 \pm 0.03_{\text{stat}} \pm 0.01_{\text{syst}})\%$ ,

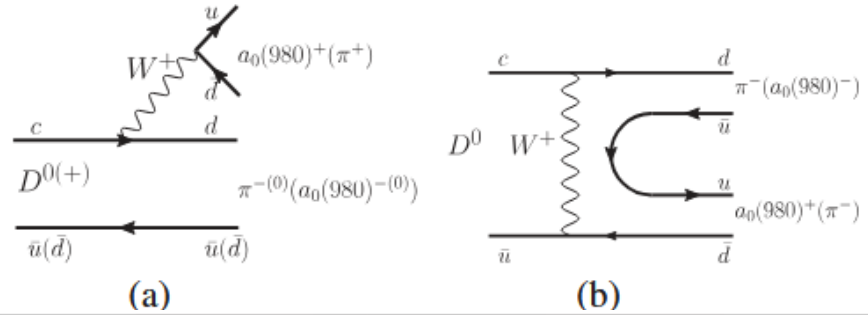
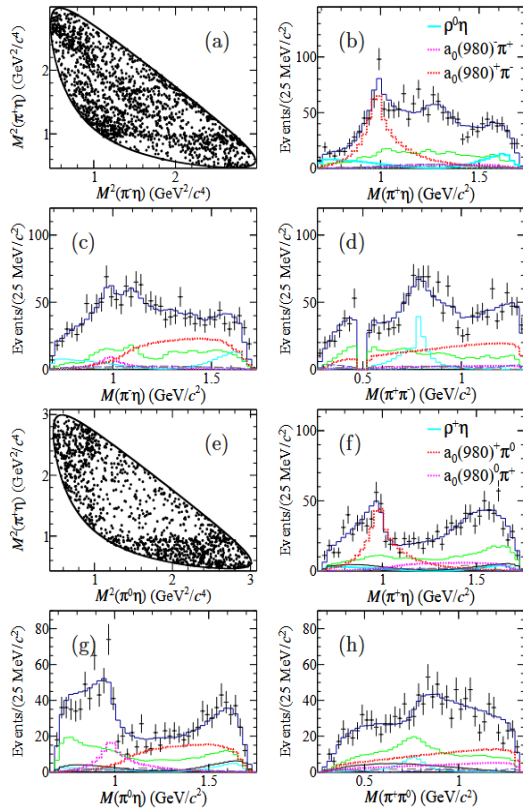
**Implying significant final-state interaction!**

# The $D$ hadronic decays

$$D^{0(+)} \rightarrow \eta \pi^+ \pi^{-(0)}, 7.93 \text{ fb}^{-1}$$

$$a_0(980)^+ : q\bar{q} \text{ or } q^2\bar{q}^2?$$

Phys. Rev. D. 110 (2024) 9, L111102



| Amplitude                                            | Phase (in unit rad)       | FF (%)                      | Significance ( $\sigma$ ) | BF ( $\times 10^{-3}$ )  |
|------------------------------------------------------|---------------------------|-----------------------------|---------------------------|--------------------------|
| $D^0 \rightarrow \rho^0 \eta$                        | 0 (fixed)                 | $15.2 \pm 1.7 \pm 1.0$      | $> 10$                    | $0.19 \pm 0.02 \pm 0.01$ |
| $D^0 \rightarrow a_0(980)^- \pi^+$                   | $0.06 \pm 0.16 \pm 0.12$  | $5.9 \pm 1.3 \pm 1.0$       | 8.9                       | $0.07 \pm 0.02 \pm 0.01$ |
| $D^0 \rightarrow a_0(980)^+ \pi^-$                   | $-1.06 \pm 0.12 \pm 0.10$ | $44.0 \pm 4.0 \pm 5.3$      | $> 10$                    | $0.55 \pm 0.05 \pm 0.07$ |
| $D^0 \rightarrow a_2(1320)^+ \pi^-$                  | $-1.16 \pm 0.25 \pm 0.23$ | $2.1 \pm 0.9 \pm 0.8$       | 4.5                       | $0.03 \pm 0.01 \pm 0.01$ |
| $D^0 \rightarrow a_2(1700)^+ \pi^-$                  | $0.08 \pm 0.17 \pm 0.23$  | $5.5 \pm 1.8 \pm 2.7$       | 6.1                       | $0.07 \pm 0.02 \pm 0.03$ |
| $D^0 \rightarrow (\pi^+ \pi^-)_{s\text{-wave}} \eta$ | $-0.92 \pm 0.29 \pm 0.14$ | $3.9 \pm 1.8 \pm 2.1$       | 5.3                       | $0.05 \pm 0.02 \pm 0.03$ |
| $r_{+/-}$                                            |                           | $7.5^{+2.5}_{-0.8} \pm 1.7$ | 7.7 <sup>a</sup>          | ...                      |
| $D^+ \rightarrow \rho^+ \eta$                        | $-4.03 \pm 0.19 \pm 0.13$ | $9.3 \pm 3.0 \pm 2.1$       | 6.0                       | $0.20 \pm 0.07 \pm 0.05$ |
| $D^+ \rightarrow (\pi^+ \pi^0)_{\nu} \eta$           | $-0.64 \pm 0.22 \pm 0.19$ | $15.8 \pm 4.8 \pm 5.2$      | 4.7                       | $0.34 \pm 0.11 \pm 0.11$ |
| $D^+ \rightarrow a_0(980)^+ \pi^0$                   | 0 (fixed)                 | $43.7 \pm 5.6 \pm 1.9$      | 9.1                       | $0.95 \pm 0.12 \pm 0.05$ |
| $D^+ \rightarrow a_0(980)^0 \pi^+$                   | $2.44 \pm 0.20 \pm 0.10$  | $17.0 \pm 4.4 \pm 1.7$      | 7.9                       | $0.37 \pm 0.10 \pm 0.04$ |
| $D^+ \rightarrow a_2(1700)^+ \pi^0$                  | $0.92 \pm 0.20 \pm 0.14$  | $4.2 \pm 2.1 \pm 0.7$       | 3.6                       | $0.09 \pm 0.05 \pm 0.02$ |
| $D^+ \rightarrow a_0(1450)^+ \pi^0$                  | $0.63 \pm 0.41 \pm 0.30$  | $7.0 \pm 2.8 \pm 0.7$       | 4.7                       | $0.15 \pm 0.06 \pm 0.02$ |
| $r_{+/0}$                                            |                           | $2.6 \pm 0.6 \pm 0.3$       | 4.0 <sup>a</sup>          | ...                      |

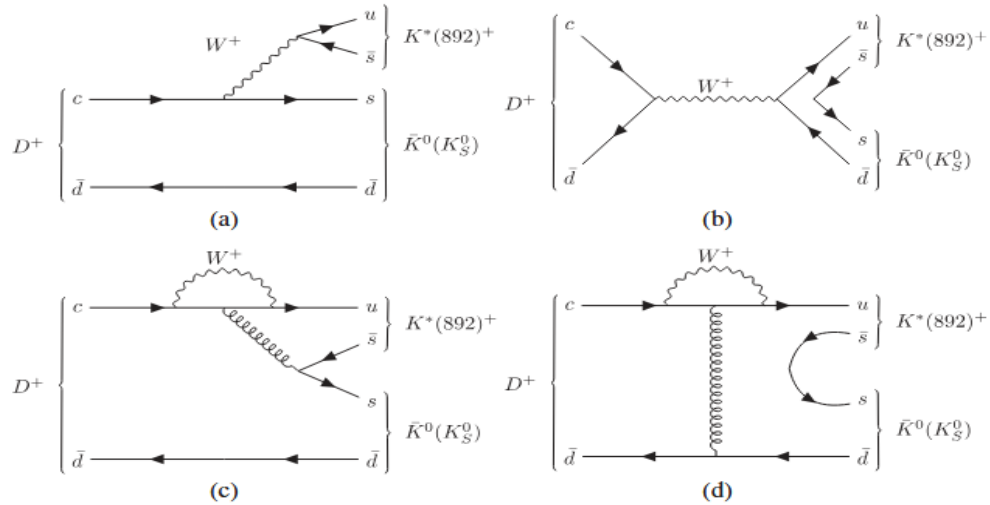
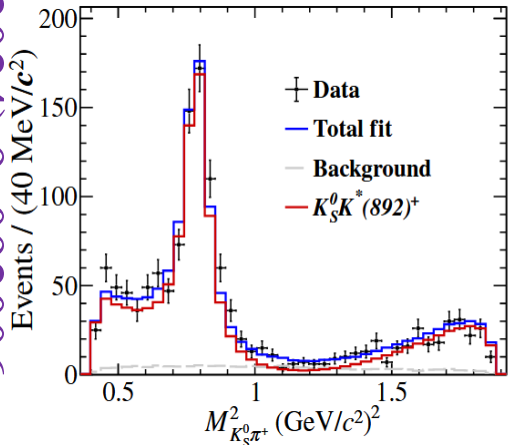
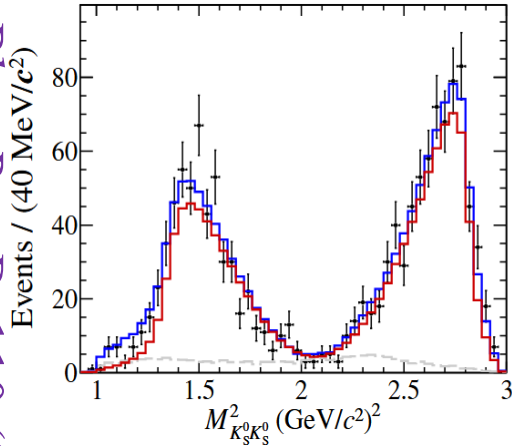
➤  $r_{+/-}$  disagrees with theoretical predictions with 2 order, implying a substantial contribution from final-state interactions.

# The $D$ hadronic decays

$$D^+ \rightarrow K_S^0 K_S^0 \pi^+, 7.93 \text{ fb}^{-1}$$

Improved precision

Phys. Rev. D. 110 (2024) 9, 092006



$$\mathfrak{B}(D^+ \rightarrow K_S^0 K_S^0 \pi^+) = (2.97 \pm 0.09_{\text{stat}} \pm 0.05_{\text{syst}}) \times 10^{-3}$$

$$\mathfrak{B}(D^+ \rightarrow K_S^0 K^*(892)^+) = (8.72 \pm 0.28_{\text{stat}} \pm 0.15_{\text{syst}}) \times 10^{-3}$$

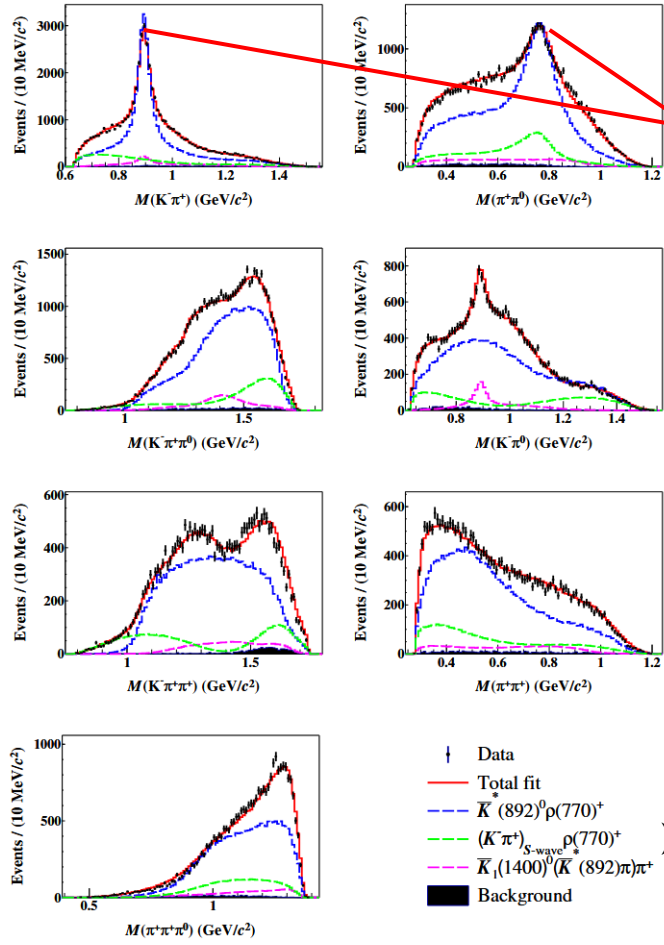
| Model                   | $\mathcal{B}(D^+ \rightarrow K_S^0 K^*(892)^+) (\times 10^{-3})$          |
|-------------------------|---------------------------------------------------------------------------|
| Pole [12]               | $6.2 \pm 1.2$                                                             |
| FAT (mix) [13]          | 5.5                                                                       |
| TDA (tree) [1]          | $5.02 \pm 1.31$                                                           |
| TDA (QCD-penguin) [2]   | $4.90 \pm 0.21$                                                           |
| TDA [14]                | $7.90 \pm 0.25$                                                           |
| BESIII measurement [11] | $8.69 \pm 0.40_{\text{stat}} \pm 0.64_{\text{syst}} \pm 0.51_{\text{BF}}$ |

# The $D$ hadronic decays

$$D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0, 7.93 \text{ fb}^{-1}$$

Search  $D \rightarrow VV/AP/PP$

JHEP 05 (2025) 195



Dominant resonance

| Intermediate process                                                                                                          | BF ( $10^{-2}$ )         |
|-------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| $D^+ \rightarrow K^*(892)^0 \rho(770)^+, K^*(892)^0 \rightarrow K^- \pi^+, \rho(770)^+ \rightarrow \pi^+ \pi^0$               | $4.15 \pm 0.07 \pm 0.17$ |
| $D^+ \rightarrow \bar{K}_1(1270)^0 \pi^+, \bar{K}_1(1270)^0 \rightarrow K^- \rho(770)^+, \rho(770)^+ \rightarrow \pi^+ \pi^0$ | $0.23 \pm 0.02 \pm 0.02$ |
| $D^+ \rightarrow \bar{K}_1(1400)^0 \pi^+, \bar{K}_1(1400)^0 \rightarrow \bar{K}^*(892) \pi, \bar{K}^*(892) \rightarrow K \pi$ | $0.44 \pm 0.01 \pm 0.02$ |
| $D^+ \rightarrow \bar{K}(1460)^0 \pi^+, \bar{K}(1460)^0 \rightarrow \bar{K}^*(892) \pi, \bar{K}^*(892) \rightarrow K \pi$     | $0.31 \pm 0.01 \pm 0.02$ |
| $D^+ \rightarrow \bar{K}(1680)^* \pi^+, \bar{K}(1680)^* \rightarrow \bar{K}^*(892) \pi, \bar{K}^*(892) \rightarrow K \pi$     | $0.23 \pm 0.02 \pm 0.02$ |
| $D^+ \rightarrow (K^- \pi^+)_{S\text{-wave}} \rho(770)^+, \rho(770)^+ \rightarrow \pi^+ \pi^0$                                | $1.11 \pm 0.04 \pm 0.04$ |
| $D^+ \rightarrow \bar{K}(1460)^0 \pi^+, \bar{K}(1460)^0 \rightarrow K^- (\pi^+ \pi^0)_V$                                      | $0.51 \pm 0.04 \pm 0.03$ |
| $D^+ \rightarrow \bar{K}(1460)^0 \pi^+, \bar{K}(1460)^0 \rightarrow (K^- \pi)_V \pi$                                          | $0.22 \pm 0.03 \pm 0.03$ |
| $D^+ \rightarrow (K^- \rho(770)^+)_{A \pi^+}, \rho(770)^+ \rightarrow \pi^+ \pi^0$                                            | $0.11 \pm 0.01 \pm 0.01$ |
| $D^+ \rightarrow (\bar{K}^*(892) \pi)_{A \pi^+}, \bar{K}^*(892) \rightarrow K \pi$                                            | $0.05 \pm 0.01 \pm 0.01$ |
| $D^+ \rightarrow (\bar{K}^*(892)^0 \pi^+)_{A \pi^0}, \bar{K}^*(892)^0 \rightarrow K^- \pi^+$                                  | $0.05 \pm 0.01 \pm 0.02$ |
| $D^+ \rightarrow (K^- \pi^+)_{V \rho(770)^+}, \rho(770)^+ \rightarrow \pi^+ \pi^0$                                            | $0.03 \pm 0.01 \pm 0.01$ |
| $D^+ \rightarrow (K^- (\pi^+ \pi^0)_V)_P \pi^+$                                                                               | $0.05 \pm 0.01 \pm 0.01$ |

$D \rightarrow VV$   
 $D \rightarrow AP$   
 $D \rightarrow PP$

| Decay channel and Collaboration                            | $\mathcal{B}(D^+ \rightarrow \bar{K}^*(892)^0 \rho(770)^+) (\times 10^{-2})$ |
|------------------------------------------------------------|------------------------------------------------------------------------------|
| $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$ , current analysis | $6.23 \pm 0.11 \pm 0.25$                                                     |
| $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$ , MARK-III [1]     | $7.2 \pm 1.8 \pm 2.1$                                                        |
| $D^+ \rightarrow K_S^0 \pi^+ \pi^0 \pi^0$ , BESIII [18]    | $5.82 \pm 0.49 \pm 0.29$                                                     |

$$\mathcal{B}(D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0) = (6.06 \pm 0.04_{\text{stat}} \pm 0.07_{\text{syst}})\%$$

Higher precision!

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# The $D_s$ hadronic decays

| $\phi(1020)$             |               | $I^G(J^{PC}) = 0^-(1^{--})$      |                              |          |
|--------------------------|---------------|----------------------------------|------------------------------|----------|
| $\phi(1020)$ MASS        |               | $1019.461 \pm 0.016$ MeV         |                              | ▼        |
| $\phi(1020)$ WIDTH       |               | $4.249 \pm 0.013$ MeV (S = 1.1)  |                              | ▼        |
| $\phi(1020)$ DECAY MODES |               | ▶ Expand all decays              |                              |          |
| Mode                     |               | Fraction ( $\Gamma_i / \Gamma$ ) | Scale Factor/<br>Conf. Level | P(MeV/c) |
| $\Gamma_1$               | $K^+ K^-$     | $(49.1 \pm 0.5)\%$               | S=1.3                        | 127 ▼    |
| $\Gamma_2$               | $K_L^0 K_S^0$ | $(33.9 \pm 0.4)\%$               | S=1.2                        | 110 ▼    |

- The main decay mode  $\phi(1020)$  meson has not been updated in the last 30 years. Previously measured mainly in the  $e^+ e^-$  annihilation and  $K - P$  scattering. Study  $D_s \rightarrow \phi h$  decay can provide new information.

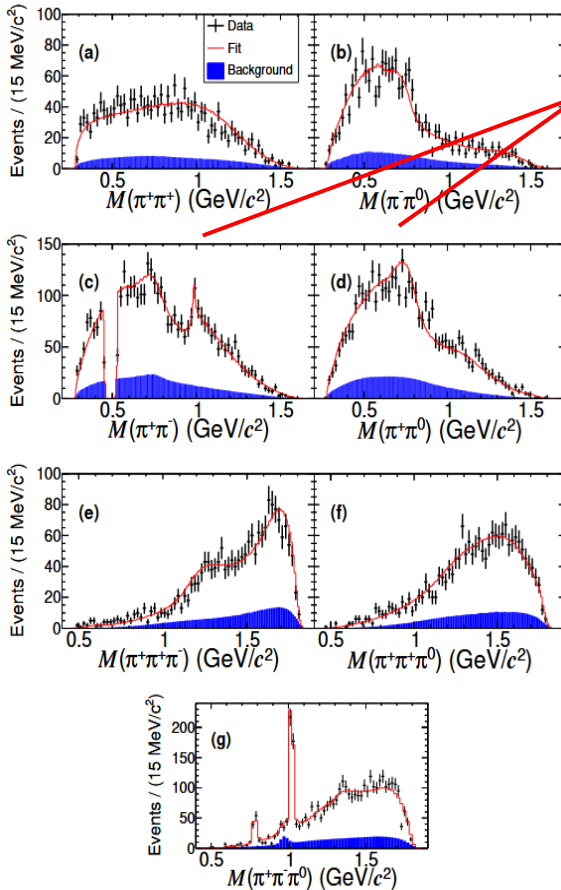
$$\mathcal{A}_{cp} = \frac{\mathfrak{B}^+ - \mathfrak{B}^-}{\mathfrak{B}^+ + \mathfrak{B}^-}$$

- The  $CP$  asymmetry ( $\mathcal{A}_{cp}$ ) need to be test in  $D_s$  decay, precise measurement of  $D_s$  decay is important to test  $CP$  asymmetry.

# The $D_s$ hadronic decays

Phys.Rev.Lett. 134 (2025) 1, 011904

$D_s^+ \rightarrow \pi^+ \pi^+ \pi^- \pi^0$   
Measure  $\phi$  decay ratio



➤ First observation of  $D_s^+ \rightarrow f_0(980) \rho^+$

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

➤  $D_s^+ \rightarrow \omega\pi^+$  is measured with 2 factor precision.

➤  $\frac{\mathfrak{B}(\phi(1020) \rightarrow \pi^+\pi^-\pi^0)}{\mathfrak{B}(\phi(1020) \rightarrow K^+K^0)} = (0.230 \pm 0.014_{\text{stat}} \pm 0.010_{\text{sys}})$ ,

significantly deviates with PDG value ( $0.310 \pm 0.010$ ).

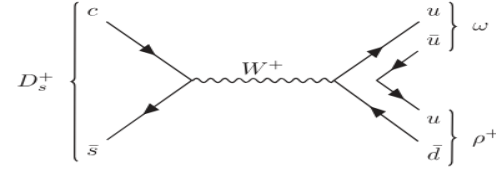
Possible interference between  $e^+e^- \rightarrow \gamma^* \rightarrow \rho\pi$  and

$e^+e^- \rightarrow \phi \rightarrow \rho\pi$  not be well considered.

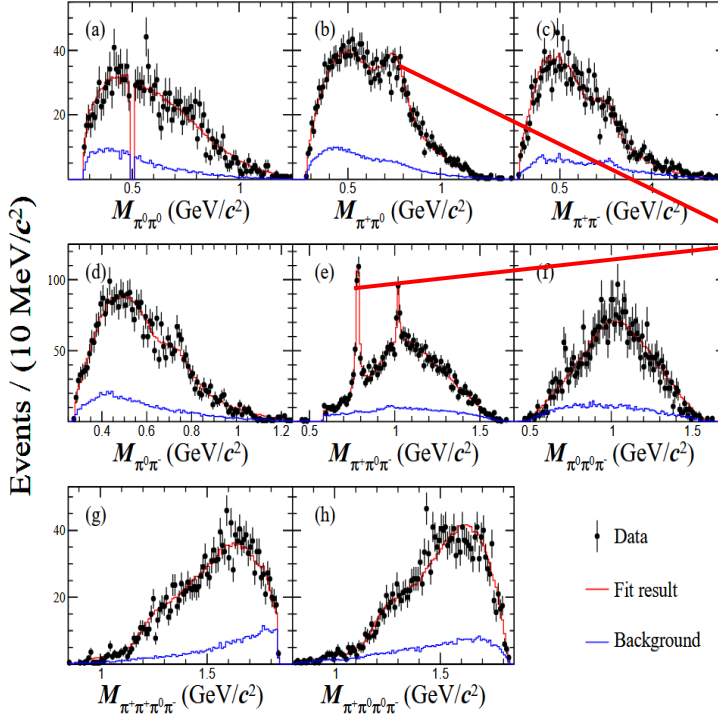
# The $D_s$ hadronic decays

$$D_s^+ \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0$$

Measure  $\phi$  decay ratio



(a) First observation of  $W$ -Annihilation  $D_s^+ \rightarrow \omega \rho^+$



| Amplitude                                                                          | Phase $\phi$ (rad)              | FF (%)                           | BF (%)                          | Significance |
|------------------------------------------------------------------------------------|---------------------------------|----------------------------------|---------------------------------|--------------|
| $D_s^+[S] \rightarrow \omega \rho^+$                                               | 0.0 (fixed)                     | $6.12 \pm 1.34^{+0.44}_{-0.52}$  | $0.30 \pm 0.07^{+0.02}_{-0.03}$ | $> 10\sigma$ |
| $D_s^+[P] \rightarrow \omega \rho^+$                                               | $2.92 \pm 0.13^{+0.05}_{-0.07}$ | $5.05 \pm 0.86^{+0.83}_{-0.79}$  | $0.25 \pm 0.04^{+0.04}_{-0.04}$ | $6.1\sigma$  |
| $D_s^+[D] \rightarrow \omega \rho^+$                                               | $4.91 \pm 0.09^{+0.04}_{-0.09}$ | $10.36 \pm 1.26^{+0.70}_{-1.45}$ | $0.52 \pm 0.07^{+0.04}_{-0.07}$ | $> 10\sigma$ |
| $D_s^+ \rightarrow \omega \rho^+$                                                  | ...                             | $19.98 \pm 1.40^{+0.92}_{-1.70}$ | $0.99 \pm 0.08^{+0.05}_{-0.07}$ | ...          |
| $D_s^+[S] \rightarrow \phi \rho^+$                                                 | $0.72 \pm 0.11^{+0.06}_{-0.09}$ | $11.62 \pm 0.94^{+0.46}_{-0.39}$ | $3.32 \pm 0.29^{+0.19}_{-0.17}$ | $> 10\sigma$ |
| $D_s^+[P] \rightarrow \phi \rho^+$                                                 | $1.34 \pm 0.15^{+0.07}_{-0.30}$ | $2.22 \pm 0.42^{+0.15}_{-0.15}$  | $0.63 \pm 0.12^{+0.05}_{-0.06}$ | $> 10\sigma$ |
| $D_s^+ \rightarrow \phi \rho^+$                                                    | ...                             | $13.86 \pm 1.03^{+0.47}_{-0.35}$ | $3.98 \pm 0.33^{+0.21}_{-0.19}$ | ...          |
| $D_s^+ \rightarrow \rho(1450)^+ \pi^0, \rho(1450)^+ \rightarrow \omega \pi^+$      | $1.55 \pm 0.11^{+0.06}_{-0.08}$ | $7.84 \pm 0.83^{+0.49}_{-0.58}$  | $0.39 \pm 0.04^{+0.03}_{-0.03}$ | $6.3\sigma$  |
| $D_s^+[S] \rightarrow a_1(1260)^0 \rho^+, a_1(1260)^0[S] \rightarrow \rho^+ \pi^-$ | $4.61 \pm 0.10^{+0.14}_{-0.15}$ | $5.19 \pm 0.50^{+0.22}_{-0.21}$  | $0.23 \pm 0.02^{+0.01}_{-0.01}$ | $> 10\sigma$ |
| $D_s^+[P] \rightarrow a_1(1260)^0 \rho^+, a_1(1260)^0[S] \rightarrow \rho^+ \pi^-$ | $0.06 \pm 0.10^{+0.14}_{-0.15}$ | $6.25 \pm 0.52^{+0.23}_{-0.25}$  | $0.50 \pm 0.04^{+0.02}_{-0.02}$ | $> 10\sigma$ |
| $D_s^+ \rightarrow a_1(1260)^0 \rho^+, a_1(1260)^0 \rightarrow \rho^+ \pi^-$       | ...                             | $11.43 \pm 0.67^{+0.35}_{-0.35}$ | $0.50 \pm 0.04^{+0.02}_{-0.02}$ | ...          |
| $D_s^+[S] \rightarrow a_1(1260)^0 \rho^+, a_1(1260)^0[S] \rightarrow \rho^- \pi^+$ | $4.61 \pm 0.10^{+0.14}_{-0.15}$ | $3.64 \pm 0.35^{+0.17}_{-0.17}$  | $0.16 \pm 0.02^{+0.01}_{-0.01}$ | $> 10\sigma$ |
| $D_s^+[P] \rightarrow a_1(1260)^0 \rho^+, a_1(1260)^0[S] \rightarrow \rho^- \pi^+$ | $0.06 \pm 0.10^{+0.14}_{-0.15}$ | $3.76 \pm 0.31^{+0.20}_{-0.20}$  | $0.17 \pm 0.01^{+0.01}_{-0.01}$ | $> 10\sigma$ |
| $D_s^+ \rightarrow a_1(1260)^0 \rho^+, a_1(1260)^0 \rightarrow \rho^- \pi^+$       | ...                             | $7.39 \pm 0.44^{+0.26}_{-0.26}$  | $0.33 \pm 0.02^{+0.02}_{-0.02}$ | ...          |
| $D_s^+[S] \rightarrow a_1(1260)^+ \rho^0, a_1(1260)^+[S] \rightarrow \rho^+ \pi^0$ | $1.85 \pm 0.11^{+0.18}_{-0.19}$ | $9.43 \pm 1.14^{+1.13}_{-1.13}$  | $0.41 \pm 0.05^{+0.05}_{-0.05}$ | $9.2\sigma$  |
| $D_s^+[P] \rightarrow a_1(1260)^+ \rho^0, a_1(1260)^+[S] \rightarrow \rho^+ \pi^0$ | $3.52 \pm 0.12^{+0.20}_{-0.21}$ | $7.10 \pm 0.88^{+0.51}_{-0.51}$  | $0.31 \pm 0.04^{+0.02}_{-0.02}$ | $> 10\sigma$ |
| $D_s^+ \rightarrow a_1(1260)^+ \rho^0, a_1(1260)^+ \rightarrow \rho^+ \pi^0$       | ...                             | $16.53 \pm 1.37^{+1.52}_{-1.32}$ | $0.73 \pm 0.07^{+0.07}_{-0.07}$ | ...          |
| $D_s^+ \rightarrow b_1(1235)^+ \pi^0, b_1(1235)^+[S] \rightarrow \omega \pi^+$     | $4.27 \pm 0.10^{+0.05}_{-0.06}$ | $10.79 \pm 0.98^{+0.68}_{-0.68}$ | $0.53 \pm 0.05^{+0.03}_{-0.03}$ | $9.7\sigma$  |
| $D_s^+ \rightarrow b_1(1235)^0 \pi^+, b_1(1235)^0[S] \rightarrow \omega \pi^0$     | $1.22 \pm 0.09^{+0.04}_{-0.06}$ | $14.60 \pm 1.20^{+0.52}_{-0.49}$ | $0.72 \pm 0.06^{+0.05}_{-0.05}$ | $> 10\sigma$ |

$\mathfrak{B}(\phi(1020) \rightarrow \pi^+ \pi^- \pi^0) / \mathfrak{B}(\phi(1020) \rightarrow K^+ K^-) = (0.222 \pm 0.019_{\text{stat}} \pm 0.016_{\text{syst}})$  is consistent with  $D_s^+ \rightarrow$

$\pi^+ \pi^+ \pi^- \pi^0$  but inconsistent with PDG.

# The $D_s$ hadronic decays

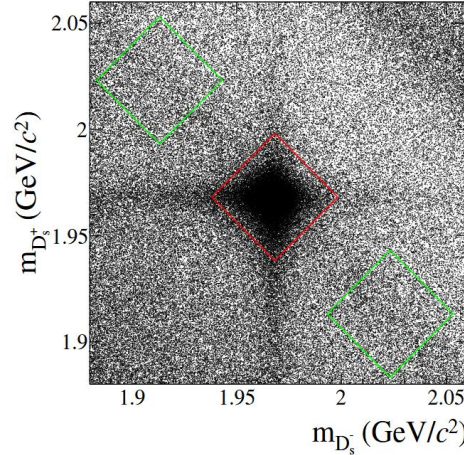
JHEP 05 (2024) 335

| Mode                                       | $\mathcal{B}$ (%)           | PDG $\mathcal{B}$ (%) |
|--------------------------------------------|-----------------------------|-----------------------|
| $D_s^+ \rightarrow K_S^0 K^+$              | $1.502 \pm 0.012 \pm 0.009$ | $1.453 \pm 0.035$     |
| $D_s^+ \rightarrow K^+ K^- \pi^+$          | $5.49 \pm 0.04 \pm 0.07$    | $5.37 \pm 0.10$       |
| $D_s^+ \rightarrow K_S^0 K^+ \pi^0$        | $1.47 \pm 0.02 \pm 0.02$    | $1.47 \pm 0.07$       |
| $D_s^+ \rightarrow K_S^0 K_S^0 \pi^+$      | $0.73 \pm 0.01 \pm 0.01$    | $0.71 \pm 0.04$       |
| $D_s^+ \rightarrow K^+ K^- \pi^+ \pi^0$    | $5.50 \pm 0.05 \pm 0.11$    | $5.50 \pm 0.24$       |
| $D_s^+ \rightarrow K_S^0 K^+ \pi^+ \pi^-$  | $0.93 \pm 0.02 \pm 0.01$    | $0.95 \pm 0.08$       |
| $D_s^+ \rightarrow K_S^0 K^- \pi^+ \pi^+$  | $1.56 \pm 0.02 \pm 0.02$    | $1.53 \pm 0.08$       |
| $D_s^+ \rightarrow \pi^+ \pi^+ \pi^-$      | $1.09 \pm 0.01 \pm 0.01$    | $1.08 \pm 0.04$       |
| $D_s^+ \rightarrow \pi^+ \eta$             | $1.69 \pm 0.02 \pm 0.02$    | $1.67 \pm 0.09$       |
| $D_s^+ \rightarrow \pi^+ \pi^0 \eta$       | $9.10 \pm 0.09 \pm 0.15$    | $9.5 \pm 0.5$         |
| $D_s^+ \rightarrow \pi^+ \pi^+ \pi^- \eta$ | $3.08 \pm 0.06 \pm 0.05$    | $3.12 \pm 0.16$       |
| $D_s^+ \rightarrow \pi^+ \eta'$            | $3.95 \pm 0.04 \pm 0.07$    | $3.94 \pm 0.25$       |
| $D_s^+ \rightarrow \pi^+ \pi^0 \eta'$      | $6.17 \pm 0.12 \pm 0.14$    | $6.08 \pm 0.29$       |
| $D_s^+ \rightarrow K_S^0 \pi^+ \pi^0$      | $0.51 \pm 0.02 \pm 0.01$    | $0.54 \pm 0.03$       |
| $D_s^+ \rightarrow K^+ \pi^+ \pi^-$        | $0.620 \pm 0.009 \pm 0.006$ | $0.620 \pm 0.019$     |

| Mode                                              | $\mathcal{A}_{CP}$ (%)    | PDG $\mathcal{A}_{CP}$ (%) |
|---------------------------------------------------|---------------------------|----------------------------|
| $D_s^\pm \rightarrow K_S^0 K^\pm$                 | $0.29 \pm 0.50 \pm 0.21$  | $0.09 \pm 0.26$            |
| $D_s^\pm \rightarrow K^+ K^- \pi^\pm$             | $0.48 \pm 0.26 \pm 0.24$  | $-0.5 \pm 0.9$             |
| $D_s^\pm \rightarrow K_S^0 K^\pm \pi^0$           | $-0.85 \pm 1.97 \pm 0.46$ | $-2 \pm 6$                 |
| $D_s^\pm \rightarrow K_S^0 K_S^0 \pi^\pm$         | $1.14 \pm 1.58 \pm 0.44$  | $3 \pm 5$                  |
| $D_s^\pm \rightarrow K^+ K^- \pi^\pm \pi^0$       | $-0.66 \pm 0.91 \pm 0.33$ | $0.0 \pm 3.0$              |
| $D_s^\pm \rightarrow K_S^0 K^\pm \pi^+ \pi^-$     | $2.00 \pm 2.37 \pm 0.70$  | $-6 \pm 5$                 |
| $D_s^\pm \rightarrow K_S^0 K^\mp \pi^\pm \pi^\pm$ | $-0.24 \pm 1.05 \pm 1.07$ | $4.1 \pm 2.8$              |
| $D_s^\pm \rightarrow \pi^\pm \pi^+ \pi^-$         | $-0.88 \pm 1.17 \pm 0.38$ | $-0.7 \pm 3.1$             |
| $D_s^\pm \rightarrow \pi^\pm \eta$                | $-0.44 \pm 0.89 \pm 0.19$ | $0.3 \pm 0.4$              |
| $D_s^\pm \rightarrow \pi^\pm \pi^0 \eta$          | $1.05 \pm 1.45 \pm 0.62$  | $-1 \pm 4$                 |
| $D_s^\pm \rightarrow \pi^\pm \pi^+ \pi^- \eta$    | $2.42 \pm 2.85 \pm 0.78$  | -                          |
| $D_s^\pm \rightarrow \pi^\pm \eta'$               | $-0.59 \pm 0.76 \pm 0.20$ | $-0.9 \pm 0.5$             |
| $D_s^\pm \rightarrow \pi^\pm \pi^0 \eta'$         | $-1.60 \pm 2.57 \pm 0.64$ | $0 \pm 8$                  |
| $D_s^\pm \rightarrow K_S^0 \pi^\pm \pi^0$         | $-2.17 \pm 4.65 \pm 1.10$ | $3 \pm 6$                  |
| $D_s^\pm \rightarrow K^\pm \pi^+ \pi^-$           | $1.81 \pm 2.01 \pm 0.45$  | $4 \pm 5$                  |

## $D_s^+$ fifteen hadronic decays

Test CP asymmetry



➤ Fifteen hadronic  $D_s^+$  decays are measured with higher precision by a **global fit**.

➤ The  $\mathcal{A}_{cp} = \frac{N^{ST}/\epsilon^{ST} - \bar{N}^{ST}/\bar{\epsilon}^{ST}}{N^{ST}/\epsilon^{ST} + \bar{N}^{ST}/\bar{\epsilon}^{ST}}$ , of fifteen

hadronic  $D_s^+$  decays are also measured and all are found to be compatible with zero.

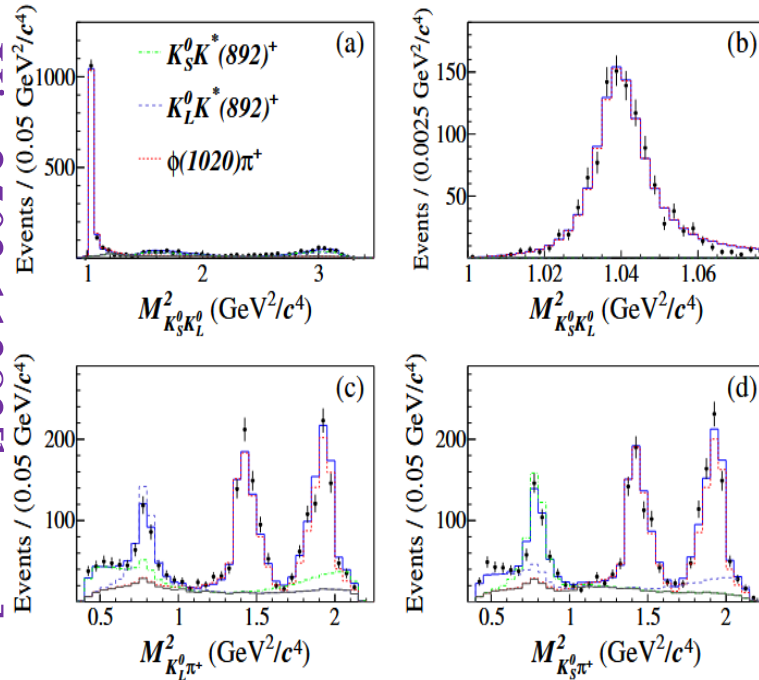
# The $D_s$ hadronic decays

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

Measure  $\phi$  decay ratio

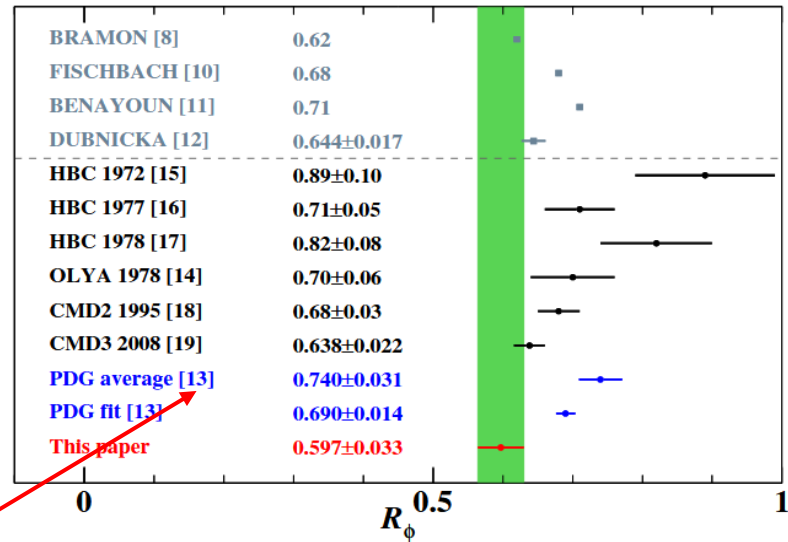
| Amplitude                            | Phase (rad)               | FF (%)                 | BF (%)                   | $\sigma$ |
|--------------------------------------|---------------------------|------------------------|--------------------------|----------|
| $D_s^+ \rightarrow \phi \pi^+$       | 0.0(fixed)                | $70.9 \pm 1.3 \pm 1.5$ | $1.32 \pm 0.05 \pm 0.04$ | $>10$    |
| $D_s^+ \rightarrow K_L^0 K^*(892)^+$ | $0.68 \pm 0.17 \pm 0.21$  | $22.8 \pm 1.3 \pm 1.5$ | $0.42 \pm 0.03 \pm 0.03$ | $>10$    |
| $D_s^+ \rightarrow K_S^0 K^*(892)^+$ | $-2.40 \pm 0.18 \pm 0.31$ | $17.4 \pm 1.2 \pm 0.9$ | $0.31 \pm 0.02 \pm 0.02$ | $>10$    |

arXiv:2503.11383 [hep-ex]



$$\frac{\mathfrak{B}(D_s^+ \rightarrow K_S^0 K^*(892)) - \mathfrak{B}(D_s^+ \rightarrow K_L^0 K^*(892))}{\mathfrak{B}(D_s^+ \rightarrow K_S^0 K^*(892)) + \mathfrak{B}(D_s^+ \rightarrow K_L^0 K^*(892))} = (-13.4 \pm 5.0_{\text{stat}} \pm 3.4_{\text{syst}})\%$$

$5.0_{\text{stat}} \pm 3.4_{\text{syst}}\%$



$\frac{\mathfrak{B}(\phi \rightarrow K_S^0 K_L^0)}{\mathfrak{B}(\phi \rightarrow K^+ K^-)}$  is deviated from PDG values with  $3\sigma$ .

- BEPCII, BESIII detector and data samples
- The  $D$  hadronic decays
- The  $D_s$  hadronic decays
- **The quantum-correlated  $D$  decays**
- Summary and outlooks

# The quantum-correlated $D$ decays

The  $\gamma$  angle (or denoted as  $\phi_3$ ) and  $D^0$  meson mixing depend on follow parameters:

- The  $\frac{D^0 \rightarrow X}{\bar{D}^0 \rightarrow X}$  amplitude  $r_D^X$ .
- Strong phase between amplitudes  $\delta_D^X$
- Coherence factor  $R_D^X$  ( $R_D^X e^{-i\delta_D^X} \equiv \frac{\int \mathcal{A}(x)\bar{\mathcal{A}}(x)dx}{\sqrt{\int |\mathcal{A}(x)|^2 dx \int |\bar{\mathcal{A}}(x)|^2 dx}}$ ) of multibody  $D^0$  decays
- Some combination of above e.g.  $c_i/s_i$  or  $F_+^{\pi\pi\pi}$

Study the quantum-correlated  $D\bar{D}$  system provide  $\gamma$  measurement input and **pQCD** test.

The BESIII data is collected in the  $D\bar{D}$  threshold. Thus it is guaranteed  $D\bar{D}$  pair and provide unique opportunity of quantum-correlated  $D\bar{D}$ . There are different measurement methods depending on the D final states:

- GLW: D decays to CP eigenstates.
- ADS: D decays to CF/DCS eigenstates.
- BPGGSZ: D decays to multi-body self-conjugate eigenstates

---

|                |                                                                                                      |
|----------------|------------------------------------------------------------------------------------------------------|
| Flavour        | $K^\pm \pi^\mp \pi^\mp \pi^\pm, K^\pm \pi^\mp \pi^0, K^\pm \pi^\mp, \dots$                           |
| CP-even        | $K^+ K^-, \pi^+ \pi^-, \pi^0 \pi^0, K_S^0 \pi^0 \pi^0, K_L^0 \pi^0, K_L^0 \omega, \pi^+ \pi^- \pi^0$ |
| CP-odd         | $K_S^0 \pi^0, K_S^0 \eta, K_S^0 \omega, K_S^0 \eta', K_S^0 \phi, K_L^0 \pi^0 \pi^0$                  |
| Self-conjugate | $K_S^0 \pi^+ \pi^-, K_S^0 K^+ K^-, \dots$                                                            |

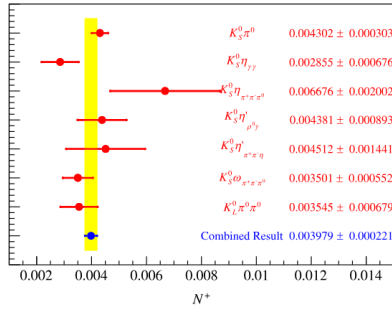
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# The quantum-correlated $D$ decays

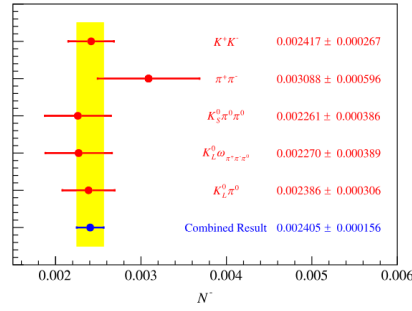
$$D^0 \rightarrow \pi^+ \pi^- \pi^0 / K^+ K^- \pi^0, 7.93 \text{ fb}^{-1}$$

$$\text{Measure } F_+^{K^+ K^- \pi^0} / F_+^{\pi^+ \pi^- \pi^0}$$

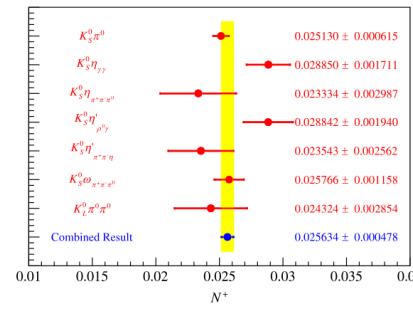
Phys. Rev. D. 111 (2025), 1, 012007



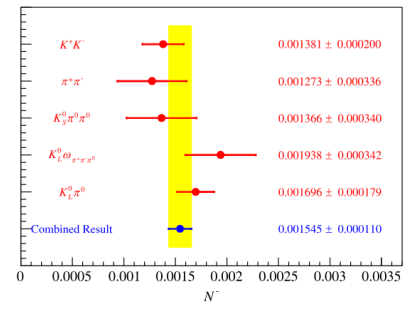
(c)



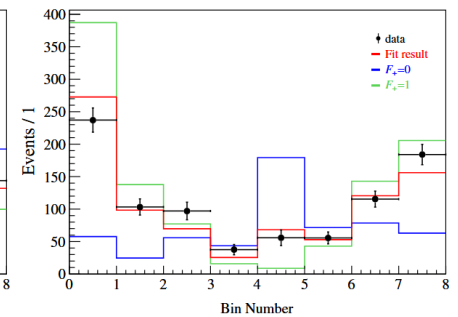
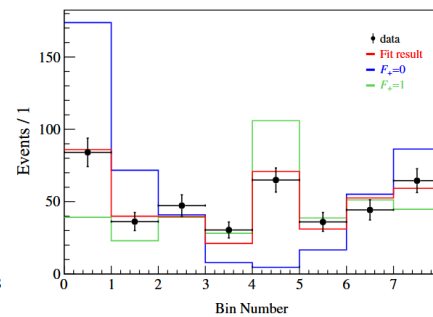
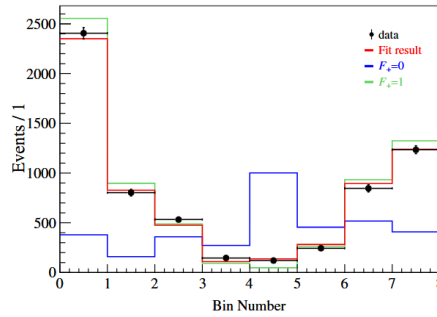
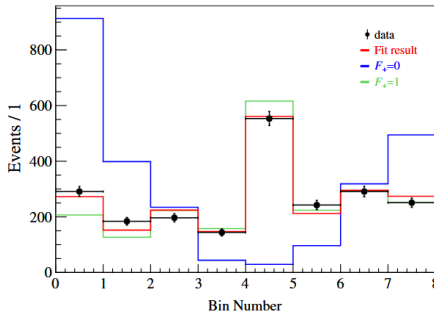
(d)



(a)



(b)



➤  $F_+^{K^+ K^- \pi^0} = 0.631 \pm 0.014_{\text{stat}} \pm 0.011_{\text{syst}}$   
**2.6 times more precise.**

➤  $F_+^{\pi^+ \pi^- \pi^0} = 0.9406 \pm 0.0036_{\text{stat}} \pm 0.0021_{\text{syst}}$   
**2.6 times more precise.**

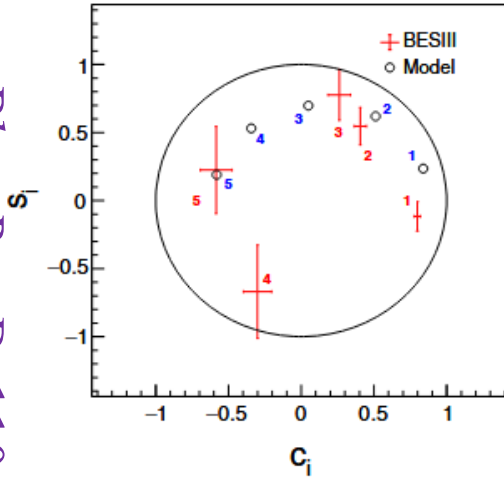
# The quantum-correlated $D$ decays



$$D^0/\bar{D}^0 \rightarrow \pi^+\pi^+\pi^-\pi^-, 2.93 \text{ fb}^{-1}$$

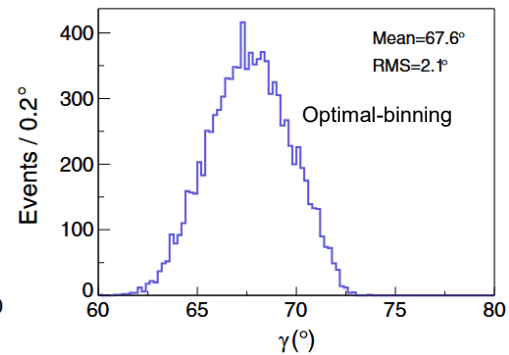
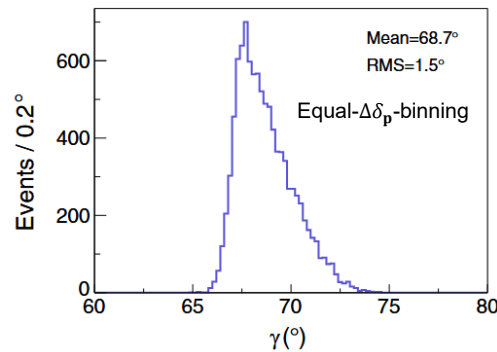
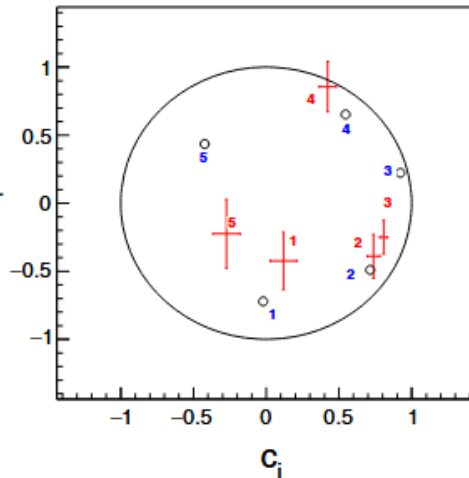
Measure  $F_+^{4\pi}$

Phys. Rev. D. 110 (2024), 112008



| $i$ | Equal- $\Delta\delta_D$ -binning scheme |                    | Optimal-binning scheme |                    |
|-----|-----------------------------------------|--------------------|------------------------|--------------------|
|     | $T_i$                                   | $K_i^S$            | $T_i$                  | $K_i^S$            |
| -5  | $0.023 \pm 0.002$                       | $464.0 \pm 45.6$   | $0.021 \pm 0.003$      | $413.4 \pm 50.9$   |
| -4  | $0.031 \pm 0.003$                       | $619.4 \pm 51.9$   | $0.041 \pm 0.003$      | $823.3 \pm 59.4$   |
| -3  | $0.049 \pm 0.003$                       | $967.8 \pm 64.8$   | $0.150 \pm 0.006$      | $2973.6 \pm 97.5$  |
| -2  | $0.127 \pm 0.005$                       | $2505.7 \pm 93.2$  | $0.056 \pm 0.004$      | $1119.9 \pm 65.3$  |
| -1  | $0.242 \pm 0.006$                       | $4780.7 \pm 121.4$ | $0.021 \pm 0.002$      | $420.6 \pm 45.1$   |
| 1   | $0.256 \pm 0.007$                       | $5054.4 \pm 126.1$ | $0.099 \pm 0.004$      | $1964.6 \pm 81.4$  |
| 2   | $0.156 \pm 0.005$                       | $3086.4 \pm 102.6$ | $0.152 \pm 0.005$      | $3015.9 \pm 98.0$  |
| 3   | $0.059 \pm 0.003$                       | $1174.5 \pm 64.8$  | $0.194 \pm 0.006$      | $3865.9 \pm 110.0$ |
| 4   | $0.031 \pm 0.003$                       | $607.2 \pm 52.1$   | $0.184 \pm 0.005$      | $3662.2 \pm 107.3$ |
| 5   | $0.026 \pm 0.002$                       | $516.8 \pm 46.4$   | $0.082 \pm 0.004$      | $1627.7 \pm 73.7$  |

| $i$ | Equal- $\Delta\delta_D$ -binning scheme |                              | Optimal-binning scheme       |                              |
|-----|-----------------------------------------|------------------------------|------------------------------|------------------------------|
|     | $c_i$                                   | $s_i$                        | $c_i$                        | $s_i$                        |
| 1   | $0.798 \pm 0.022 \pm 0.008$             | $-0.116 \pm 0.108 \pm 0.029$ | $0.119 \pm 0.091 \pm 0.021$  | $-0.424 \pm 0.210 \pm 0.043$ |
| 2   | $0.406 \pm 0.041 \pm 0.010$             | $0.546 \pm 0.137 \pm 0.036$  | $0.738 \pm 0.044 \pm 0.017$  | $-0.390 \pm 0.161 \pm 0.058$ |
| 3   | $0.262 \pm 0.077 \pm 0.017$             | $0.777 \pm 0.187 \pm 0.050$  | $0.808 \pm 0.027 \pm 0.012$  | $-0.250 \pm 0.124 \pm 0.030$ |
| 4   | $-0.301 \pm 0.097 \pm 0.031$            | $-0.669 \pm 0.343 \pm 0.095$ | $0.423 \pm 0.059 \pm 0.017$  | $0.857 \pm 0.186 \pm 0.074$  |
| 5   | $-0.585 \pm 0.109 \pm 0.029$            | $0.225 \pm 0.321 \pm 0.092$  | $-0.273 \pm 0.094 \pm 0.025$ | $-0.225 \pm 0.252 \pm 0.081$ |



➤ The  $F_+^{4\pi} = 0.746 \pm 0.010 \pm 0.004$

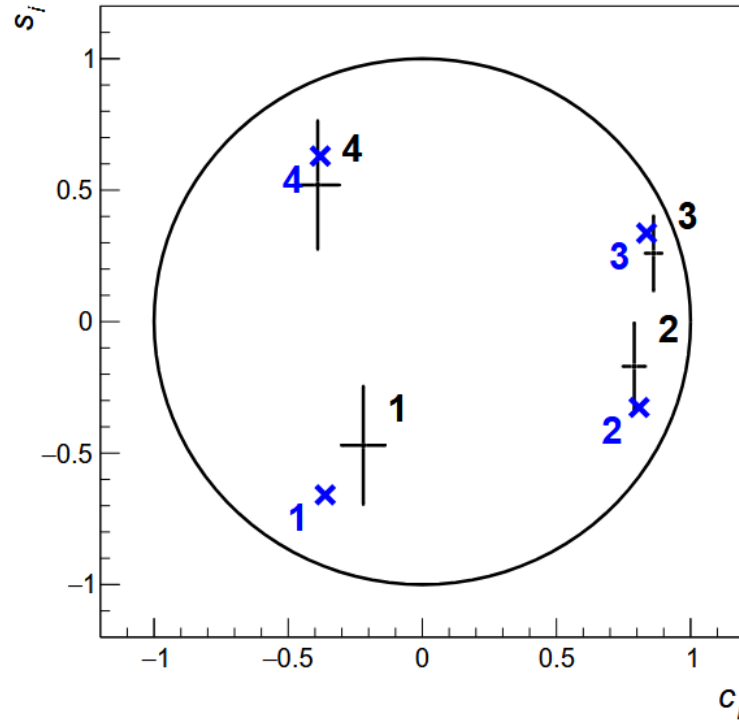
# The quantum-correlated $D$ decays

$$D^0/\bar{D}^0 \rightarrow K^+K^-\pi^+\pi^-, 20.3 \text{ fb}^{-1}$$

Measure  $F_+^{KK\pi\pi}$

| Variable                | Fit result                                   |
|-------------------------|----------------------------------------------|
| $c_1$                   | $-0.22 \pm 0.08 \pm 0.01$                    |
| $c_2$                   | $0.79 \pm 0.04 \pm 0.01$                     |
| $c_3$                   | $0.862 \pm 0.029 \pm 0.008$                  |
| $c_4$                   | $-0.39 \pm 0.08 \pm 0.01$                    |
| $s_1$                   | $-0.47 \pm 0.22 \pm 0.04$                    |
| $s_2$                   | $-0.17 \pm 0.16 \pm 0.04$                    |
| $s_3$                   | $0.26 \pm 0.14 \pm 0.02$                     |
| $s_4$                   | $0.52 \pm 0.24 \pm 0.04$                     |
| $R_{-4}$                | $0.0871 \pm 0.0027 \pm 0.0038$               |
| $R_{-3}$                | $0.294 \pm 0.005 \pm 0.006$                  |
| $R_{-2}$                | $0.400 \pm 0.007 \pm 0.003$                  |
| $R_{-1}$                | $0.252 \pm 0.007 \pm 0.012$                  |
| $R_1$                   | $0.119 \pm 0.006 \pm 0.006$                  |
| $R_2$                   | $0.405 \pm 0.012 \pm 0.002$                  |
| $R_3$                   | $0.818 \pm 0.010 \pm 0.010$                  |
| $\mathcal{B}(KK\pi\pi)$ | $(2.863 \pm 0.028 \pm 0.045) \times 10^{-3}$ |

| Variable | Fit result          | Model prediction |
|----------|---------------------|------------------|
| $R_{-4}$ | $0.0876 \pm 0.0027$ | 0.086            |
| $R_{-3}$ | $0.294 \pm 0.005$   | 0.297            |
| $R_{-2}$ | $0.399 \pm 0.007$   | 0.398            |
| $R_{-1}$ | $0.252 \pm 0.007$   | 0.267            |
| $R_1$    | $0.119 \pm 0.006$   | 0.110            |
| $R_2$    | $0.406 \pm 0.012$   | 0.401            |
| $R_3$    | $0.815 \pm 0.010$   | 0.833            |



➤  $\mathcal{B}(D^0 \rightarrow K^+K^-\pi^+\pi^-) = (2.863 \pm 0.028_{\text{stat}} \pm 0.045_{\text{syst}}) \times 10^{-3}$

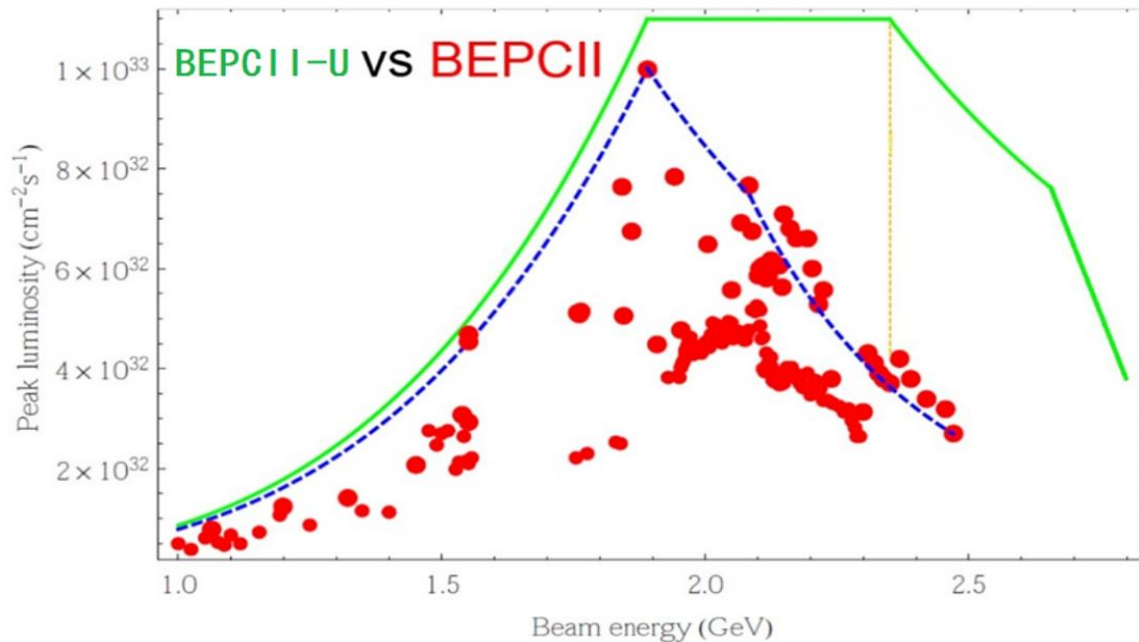
➤  $F_+^{KK\pi\pi} = 0.754 \pm 0.010 \pm 0.008$

- BEPCII, BESIII detector and data samples
- The  $D$  hadronic decays
- The  $D_s$  hadronic decays
- The quantum-correlated  $D$  decays
- **Summary and outlooks**

BESIII have achieved various results:

- New W-annihilation process
- Higher precision BFs,  $F_+$  and  $\mathcal{A}_{cp}$
- Anomalous  $\phi$  decay ratio and  $r_{+/-}$

In future, BESIII will utilize data to achieve more results in charm physics.

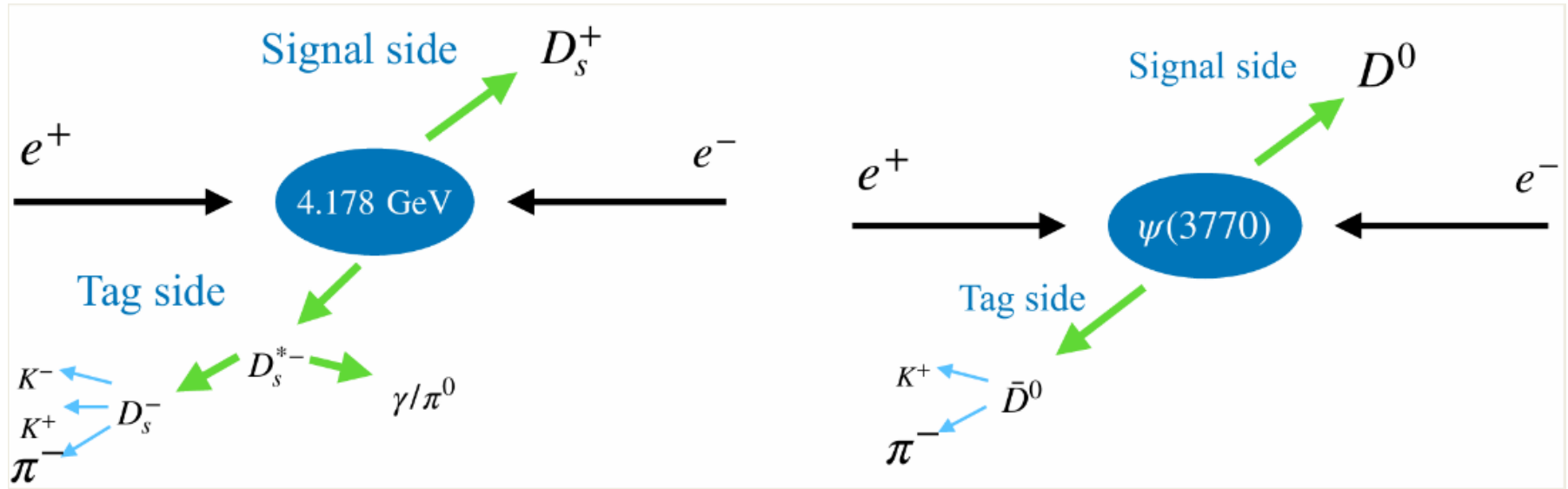




**Thanks for your attention!**

- BEPCII, BESIII detector and data samples
- The  $D$  hadronic decays
- The  $D_s$  hadronic decays
- The quantum-correlated  $D$  decays
- Summary and outlooks
- **Supplement**

# Supplement



Double Tag Method