Recent Highlights in Charm Physics at BESIII

董燎原（代表BESIII合作组）

中国科学院高能物理研究所

第三届BESIII-Belle II-LHCb粲强子物理联合研讨会

湖南长沙 6月28日

BEPCII @ IHEP

Beijing Electron Positron Collider II

$E_{\rm cm} = 1.84 - 4.95$ GeV

2009-2024, BESIII Physics run

Design Luminosity:

$\mathcal{L}_D = 1 \times 10^{33} {\rm cm}^{-2} s^{-1}$@$E_{\rm cm}$= 3.773 GeV

Peak luminosity:

2016 achieved $1.0 \times \mathcal{L}_D$

2023 achieved $1.1 \times \mathcal{L}_D$

Jul. 1, 2024 – Aug. 31, 2028:

BEPCII upgrade → BEPCII-U

January 2025, restart

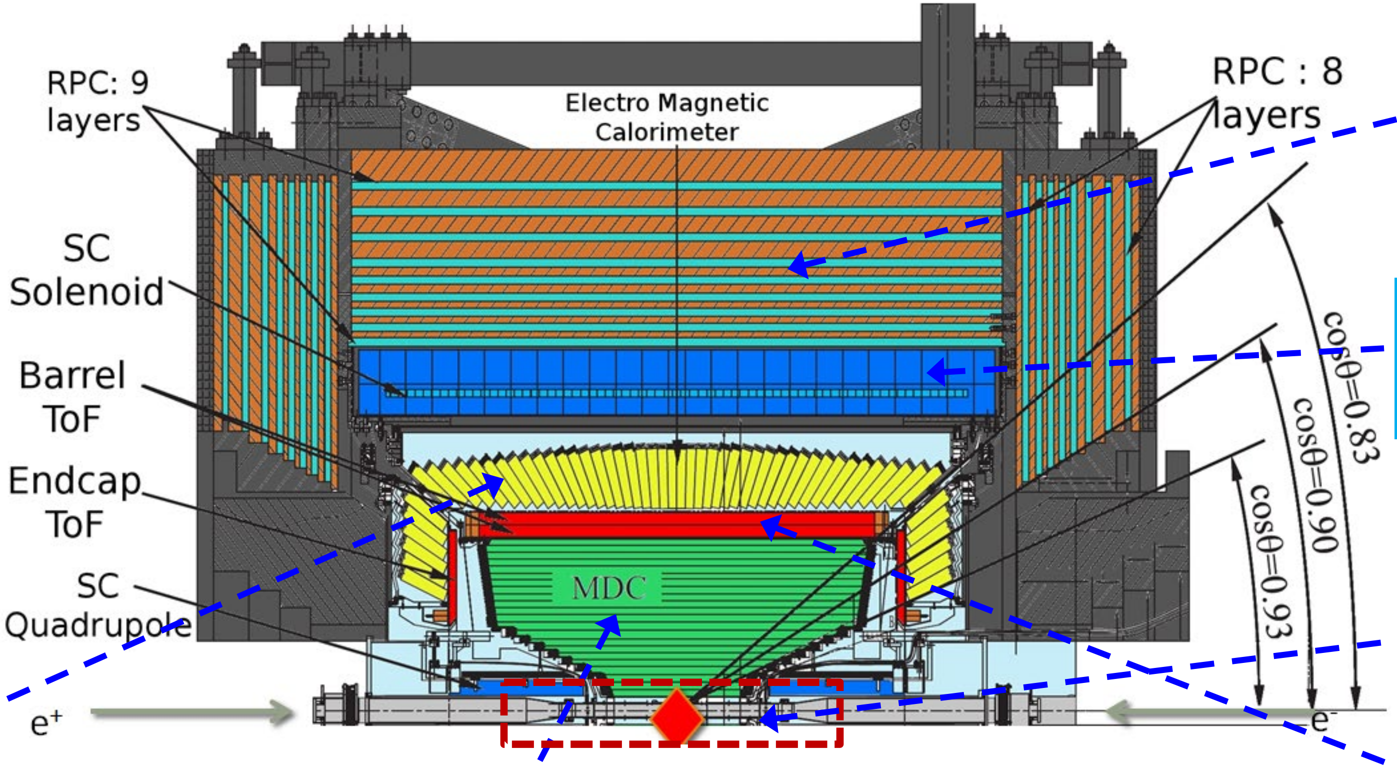
- Luminosity × 3 @$E_{\rm cm}$= 4.7 GeV

$\mathcal{L}_D = 1 \times 10^{33} {\rm cm}^{-2} s^{-1}$@$E_{\rm cm}$= 3.773-4.7 GeV

- Beam energy up to 2.8 GeV (2028)

BESIII @ BEPCII

- Optimized for flavor physics
- Cover 93% of 4π solid angle



Muon counters (MUC)
$\sigma_{r\phi} = 1.4 - 1.7$ cm

Superconducting solenoid
1 Tesla Magnetic field

inner MDC

Electro Magnetic Calorimeter (EMC)
$\Delta E/E = 2.5\%$ @1.0 GeV
$\sigma_{\phi z} = 0.6$cm @ 1.0 GeV

Main Drift Chamber (MDC)
$\Delta P/P = 0.5\%$ @1.0 GeV
$\sigma_{xy} = 130$ um, $\sigma_{dE/dX} = 6 - 7\%$

Time Of Flight (TOF)
$\sigma_t = 90$ ps @ barrel
$\sigma_t = 60$ ps @ end cap (upgrade in 2016)

July 1 - December 31, 2024: Replace the inner MDC with 3 layers of cylindrical triple-GEM detectors

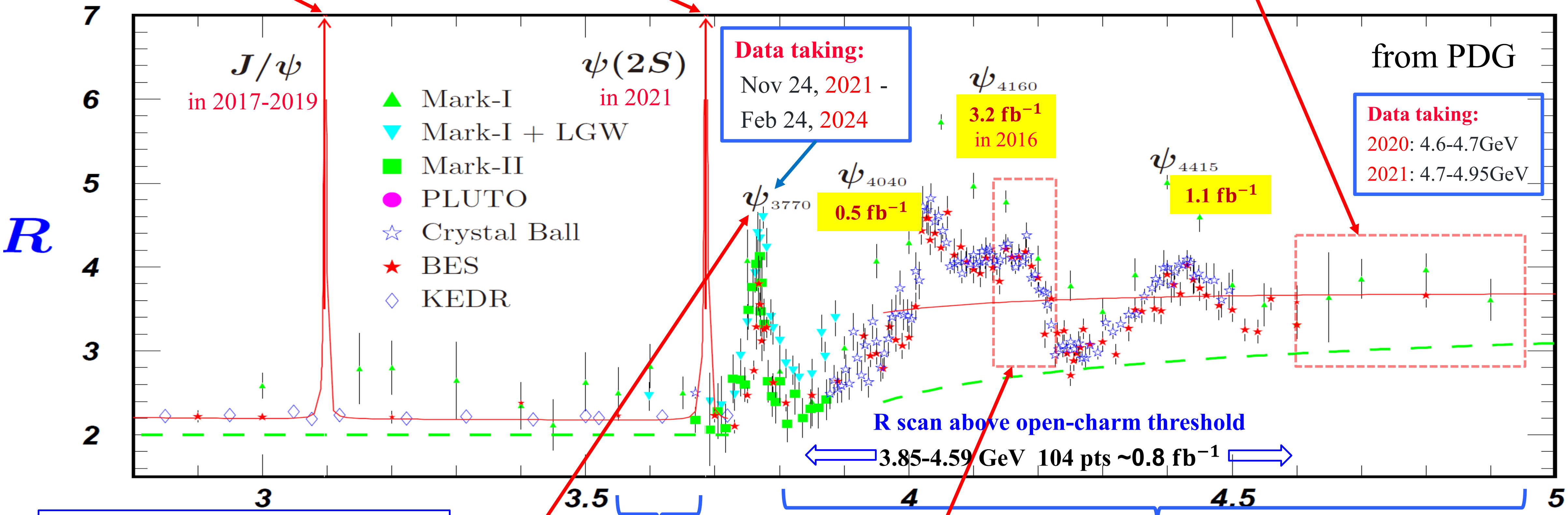
Datasets (totally ~50 fb^{-1} from 1.84 – 4.95 GeV)

BESIII

10B: light hadron, hyperon

2.7B: charmonium

6.4 fb^{-1}: ~1.0M $\Lambda_c^+\bar{\Lambda}_c^-$ pairs produced @4.5995-4.9509 GeV



R scan below open-charm threshold
1.84-1.97 GeV 13 pts ~25 pb^{-1}
2.00-3.08 GeV 21 pts ~550 pb^{-1}
2.23-3.67 GeV 14 pts ~110 pb^{-1}

Tau mass scan

3.8-4.96 GeV: ~22.5 fb^{-1}, XYZ, $D_s^+D_s^-$, $\Lambda_c^+\bar{\Lambda}_c^-$ …

7.33 fb^{-1}: ~6.5M $D_s^+D_s^-$ pairs produced @4.128-4.226 GeV

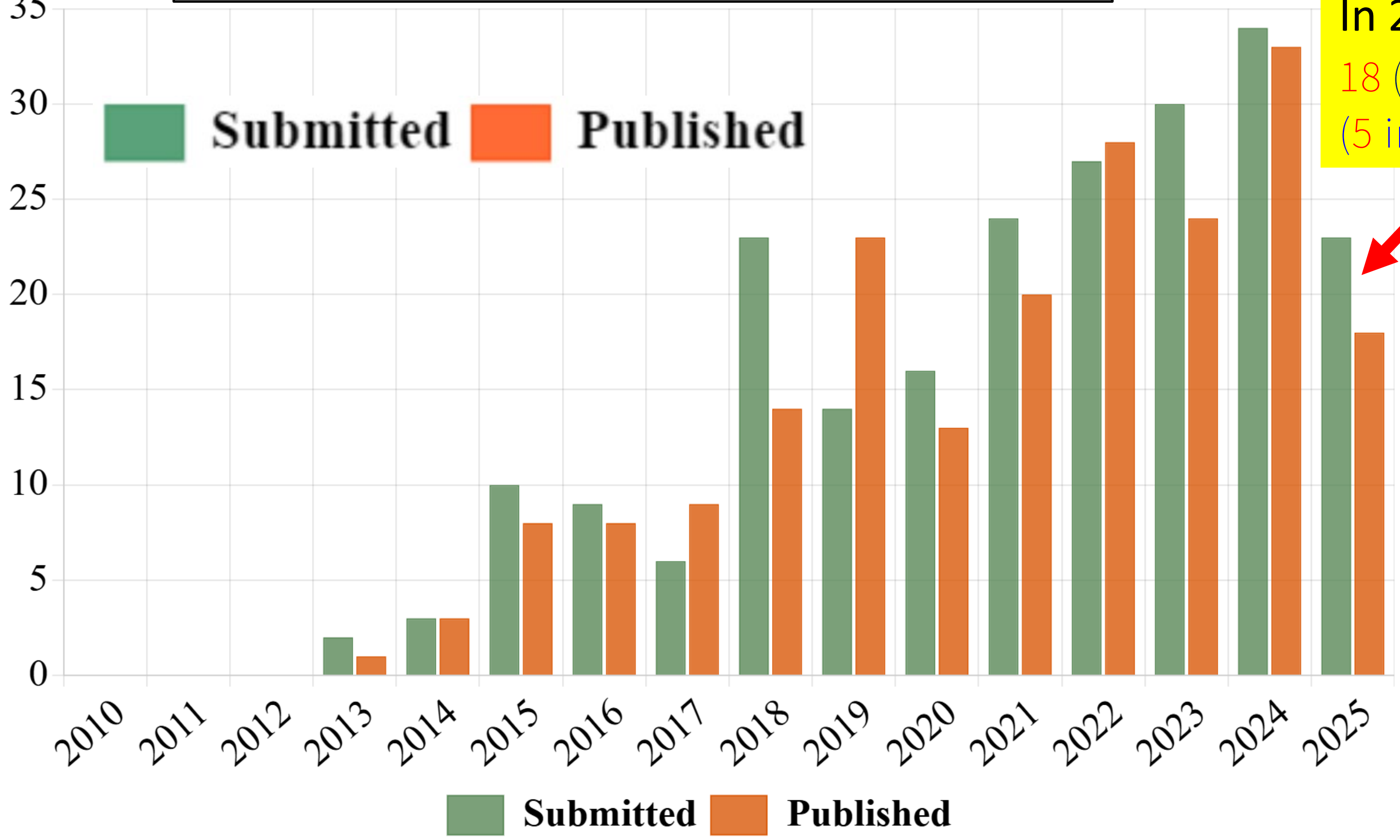
20.3 fb^{-1}: ~73.3M $D^0\bar{D}^0$ pairs produced @3.773 GeV
~57.4M D^+D^- pairs produced @3.773 GeV

Data taking plan
Mar 2025 - Jul 2025: ψ(3686); Oct 2025-Jul 2026: 4.7 GeV;
Oct 2026 - Aug 2028: 4.2-5.0 GeV; Sep 2028-Jul 2030 :5.0-5.6 GeV

Charm physics publication

Published: 202 (PRL&Nature Commun. **39**)
(by 2025-06-26) + 5 (accepted)

In 2025,
18 (published)+5(accepted)+14 (submitted)
(5 in PRL/Nature Commun.)



In this talk, a selection of latest results in charm physics from BESIII is presented.

CKM Matrix

BESIII

- CKM matrix elements are fundamental parameters of the Standard Model (SM):

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Charm decays + LQCD
Expected precision **< 1%** at BESIII

B decays + LQCD

- 3x3 unitary complex matrix
- 4 parameters: 3 mixing angles and 1 phase
- Unitarity: $\sum_i V_{ij}V^*_{ik} = \delta_{jk}$ and $\sum_j V_{ij}V^*_{kj} = \delta_{ik}$

- Any deviation of $V_{\rm CKM}$ from unitarity indicates new physics

→ Measurements of CKM matrix elements [from PDG2024]

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9984 \pm 0.0009$=1(SM)

$|V_{cd}|^2+|V_{cs}|^2+|V_{cb}|^2 = 1.001 \pm 0.007$ =1(SM)

Precision: 0.7%

Precision: (0.6-1.8)%

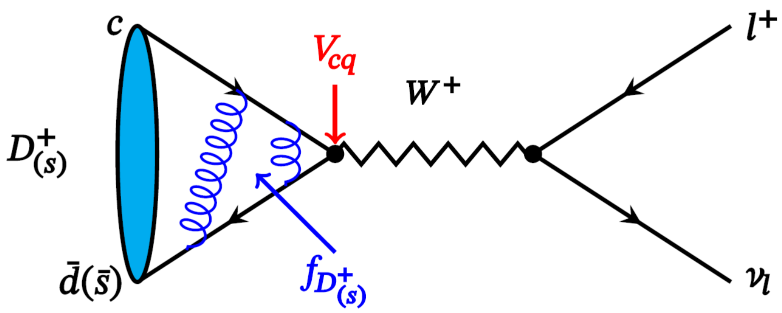
$|V_{cd}| = 0.221 \pm 0.004$
$|V_{cs}| = 0.975 \pm 0.006$
$|V_{cb}| = 0.0410 \pm 0.0012$

- ***D/D_s* (Semi-)leptonic decays** provide direct measurements of $|V_{cs}|$ and $|V_{cd}|$

Charm leptonic decays $D^+_{(s)} \to l^+\nu_l$

BESIII

$l = e, \mu, \tau$



Decay constant $f_{D_{(s)}}$ (LQCD)

Decay rate

CKM matrix element

$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} f^2_{D^+_{(s)}} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

- **Charm leptonic decays involve weak and strong interactions**

  Weak interaction: annihilation of the quark-antiquark pair via W^+ → $|V_{cd(s)}|$

  Strong interaction: glue exchanges between charm quark and light quark → $f_{D_{(s)}}$

- Exp. decay rate + $|V_{cd(s)}|^{\text{CKMfitter}}$ → $f_{D_{(s)}}$

  Calibrate LQCD @charm

  Extrapolate to Beauty

- Exp. decay rate + $f_{D_{(s)}}$ of LQCD

  → **CKM matrix elements** $|V_{cd(s)}|$

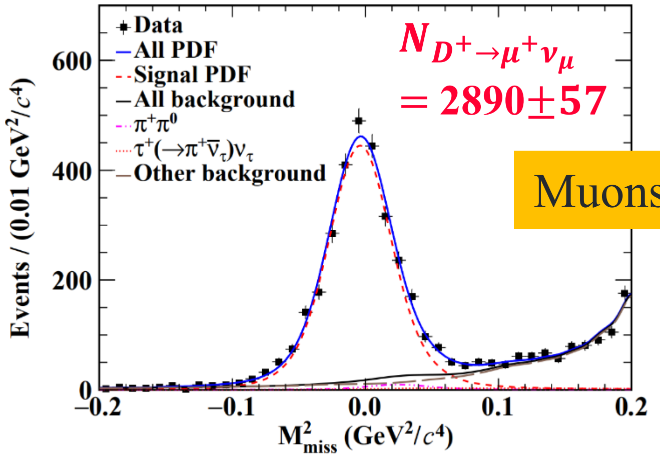
High precision: 0.2% - 0.33%
FLAG, PRD 107, 052008 (2023)

SM expected relative decay widths:

	$e^+\nu_e$	: $\mu^+\nu_\mu$	: $\tau^+\nu_\tau$
D^+	2.35×10^{-5}	: 1	: 2.67
D_s^+	2.35×10^{-5}	: 1	: 9.75

→ **Test lepton flavor universality (LFU)**

$|V_{cd}|$ from $D^+ \to \mu^+\nu_\mu$ and $D^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$



20.3 fb^{-1}@ 3.773 GeV

arXiv:2410:07626

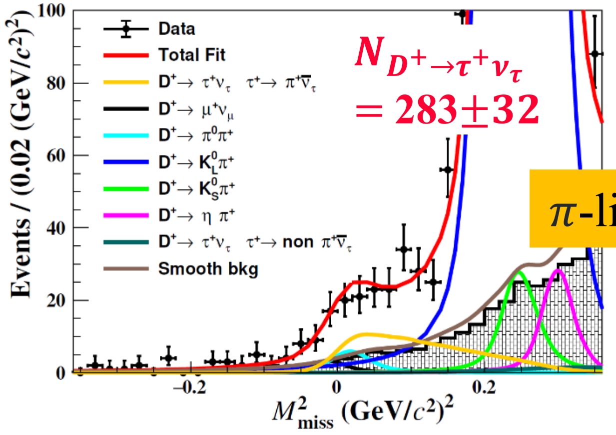
Muons identified from MUC

$$\mathcal{B}_{D^+\to\mu^+\nu_\mu} = (3.98 \pm 0.08_{\rm stat.} \pm 0.04_{\rm syst.}) \times 10^{-4}$$

$$f_{D^+}|V_{cd}| = (47.53 \pm 0.48_{\rm stat} \pm 0.24_{\rm syst} \pm 0.12_{\rm input})\ \mathrm{MeV}$$

$$f_{D^+} = (211.5 \pm 2.1_{\rm stat} \pm 1.1_{\rm syst} \pm 0.8_{\rm input})\ \mathrm{MeV}$$

$$|V_{cd}| = 0.2242 \pm 0.0023_{\rm stat} \pm 0.0011_{\rm syst} \pm 0.0009_{\rm input}$$



7.9 fb^{-1}@ 3.773 GeV

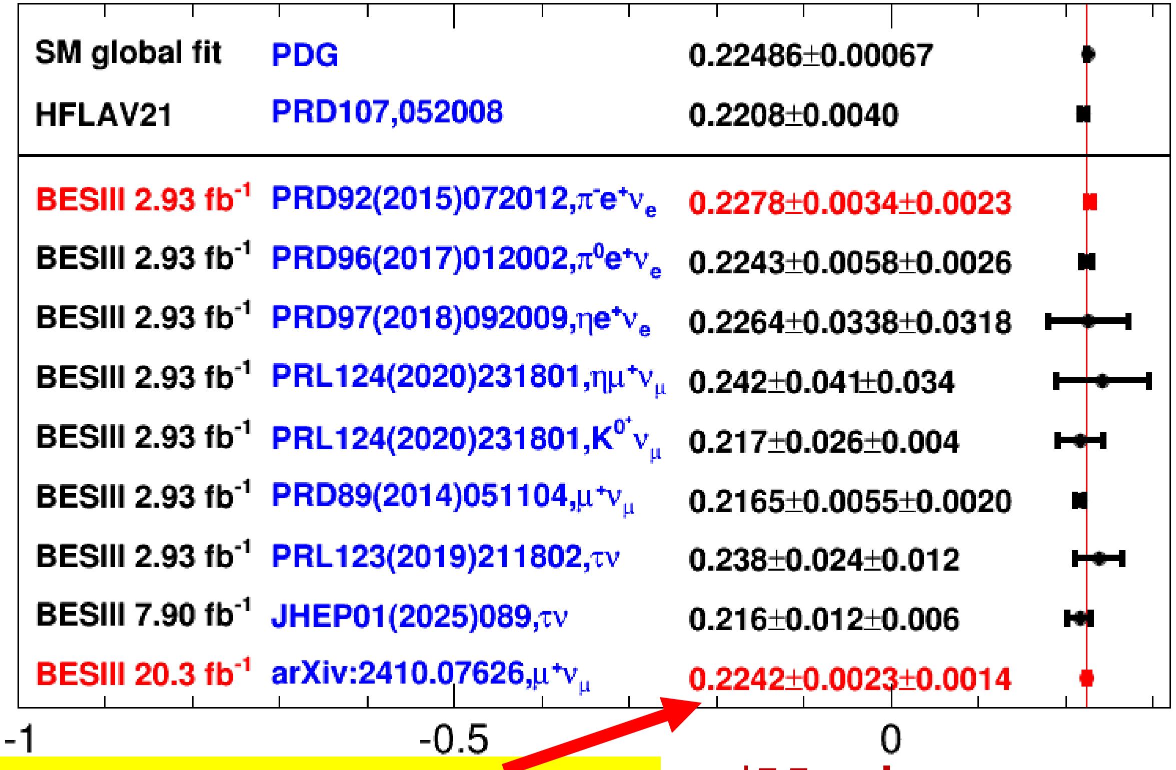
JHEP01(2025)089

π-like: $E_{\rm EMC} > 300\mathrm{MeV}$

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

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

$$|V_{cd}| = (0.216 \pm 0.012_{\rm stat} \pm 0.006_{\rm syst} \pm 0.001_{\rm input})$$



LFU test: $\mathcal{R}_{\tau/\mu} = \dfrac{\mathcal{B}_{D^+\to\tau^+\nu_\tau}}{\mathcal{B}_{D^+\to\mu^+\nu_\mu}} = 2.49 \pm 0.31$

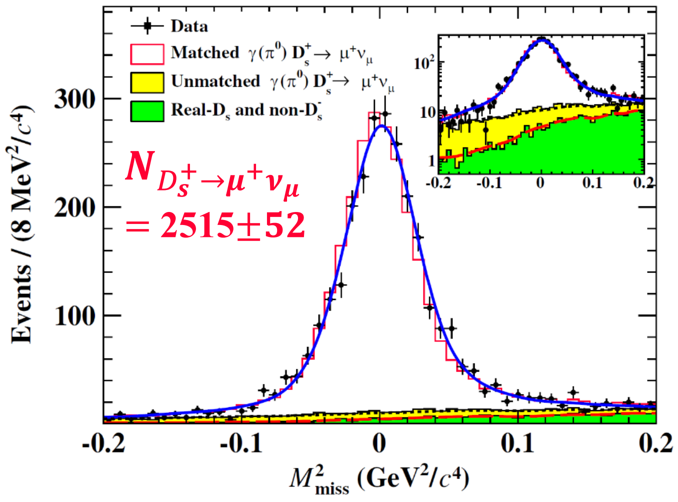
SM=2.67

Highest precision of $|V_{cd}|$ to date: ~1.2%

$|V_{cs}|$ from $D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$

7.33 fb^{-1}@ 4.128-4.226 GeV
PRD 108, 112001 (2023)

via $e^+e^- \to D_s^{*\pm}D_s^{\mp}$



$$\mathcal{B}_{D_s^+\to\mu^+\nu_\mu} = (0.5294 \pm 0.0108_{stat} \pm 0.0085_{syst})\%$$

$$f_{D_s^+}|V_{cs}| = 241.8 \pm 2.5_{stat} \pm 2.2_{syst} \text{ MeV}$$

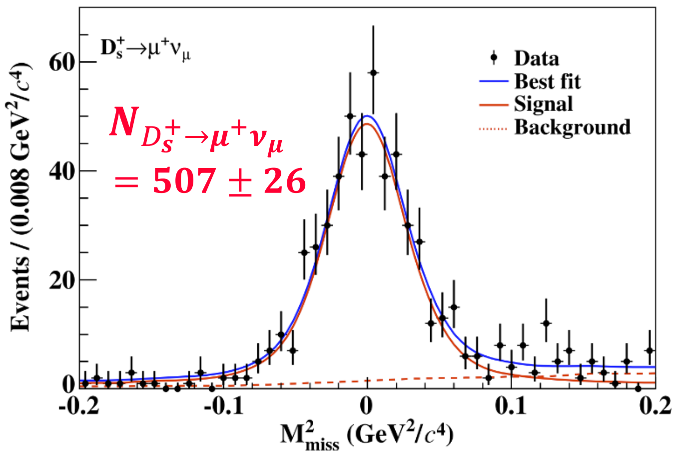
$$f_{D_s^+} = 248.4 \pm 2.5_{stat} \pm 2.2_{syst} \text{ MeV}$$

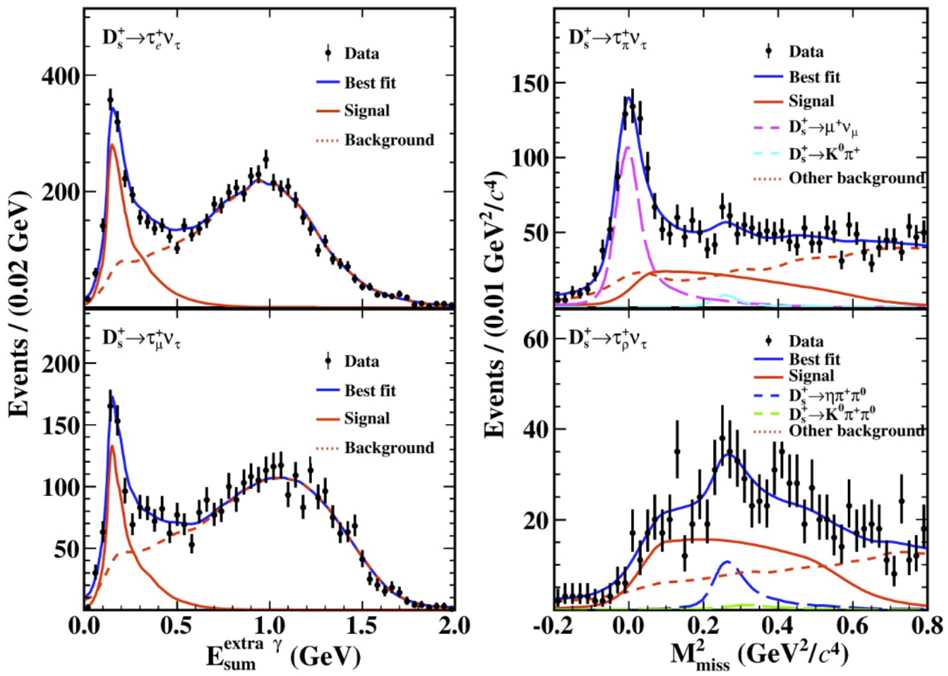
$$|V_{cs}| = 0.968 \pm 0.010_{stat} \pm 0.009_{syst}$$

Precision : ~1.4%

10.64 fb^{-1}@ 4.237-4.699 GeV， PRD 110, 052002 (2024)

via $e^+e^- \to D_s^{*+}D_s^{*-}$





$N_{D^+\to\tau^+\nu_\tau} = 2845 \pm 83$

$$\mathcal{B}_{D_s^+\to\mu^+\nu_\mu} = (0.547 \pm 0.026_{stat} \pm 0.016_{syst})\%$$

$$f_{D_s^+} = (253.2 \pm 6.0_{stat} \pm 3.7_{syst} \pm 0.6_{input})$$

$$|V_{cs}| = (0.986 \pm 0.023_{stat} \pm 0.014_{syst} \pm 0.003_{input})$$

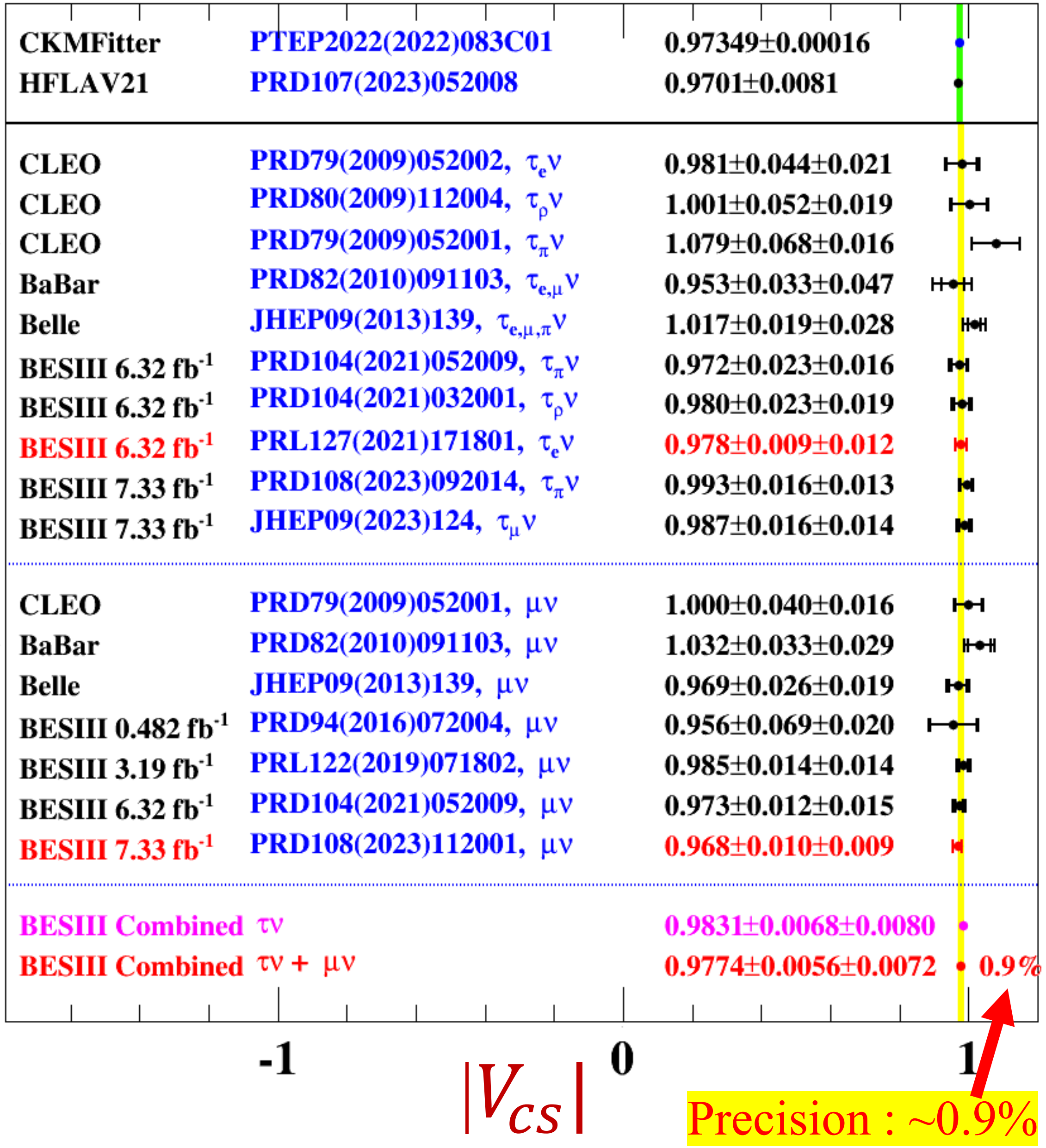
$$\mathcal{B}_{D_s^+\to\tau^+\nu_\tau} = (5.60 \pm 0.16_{stat} \pm 0.20_{syst})\%$$

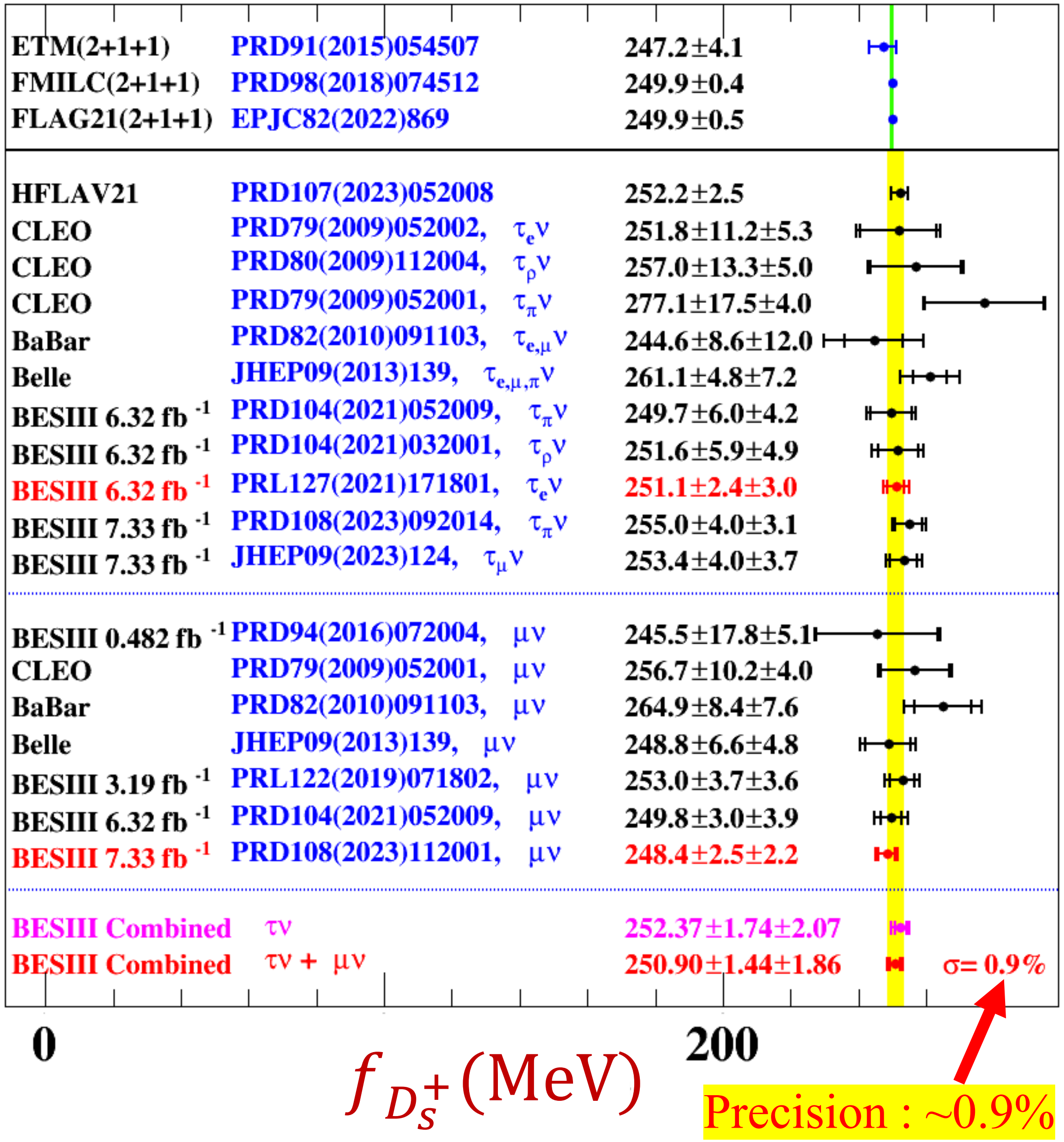
$$f_{D_s^+} = (259.6 \pm 3.7_{stat} \pm 4.6_{syst} \pm 0.6_{input})$$

$$|V_{cs}| = (1.011 \pm 0.014_{stat} \pm 0.018_{syst} \pm 0.003_{input})$$

LFU test: $\frac{\Gamma_{D_s^+\to\tau^+\nu_\tau}}{\Gamma_{D_s^+\to\mu^+\nu_\mu}} = 10.24 \pm 0.57$ SM=9.75

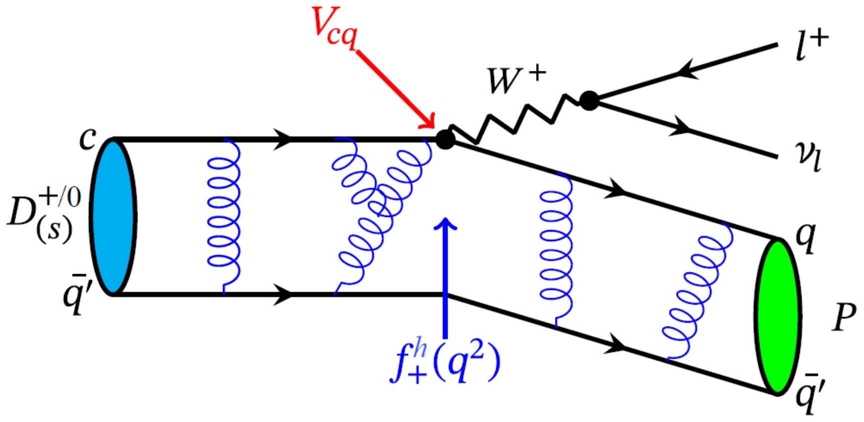
$|V_{cs}|$ and $f_{D_s^+}$ from $D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$





Charm semi-leptonic decays $D^+_{(s)} \to \pi(K) l^+ \nu_l$

BESIII



Form factor (LQCD)

Partial decay rate

CKM matrix element

$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2}{24\pi^3} |f^h_+(0)|^2 |V_{cq}|^2 |\vec{p}_h|^3$$

(X = 1 for K^-, π^-, $\bar{K}^0$, $\eta^{(\prime)}$; $X = \frac{1}{2}$ for π^0)

- **The weak and strong interactions can be separated:**

  Weak interaction: CKM matrix elements $|V_{cd(s)}|$

  Form factors $f^h_+(0)$ describe strong interaction can be calculated in LQCD

- Exp. partial decay rate → q^2 dependence of $f^{\pi(K)}_+(q^2)$,

  → **extract** $f^{\pi(K)}_+(0)$ with $|V_{cd(s)}|^{\text{CKMfitter}}$ as input → **calibrate QCD**

- Exp. partial decay rate + LQCD calculation of $f^{\pi(K)}_+(0)$

  → **CKM matrix elements** $|V_{cd(s)}|$

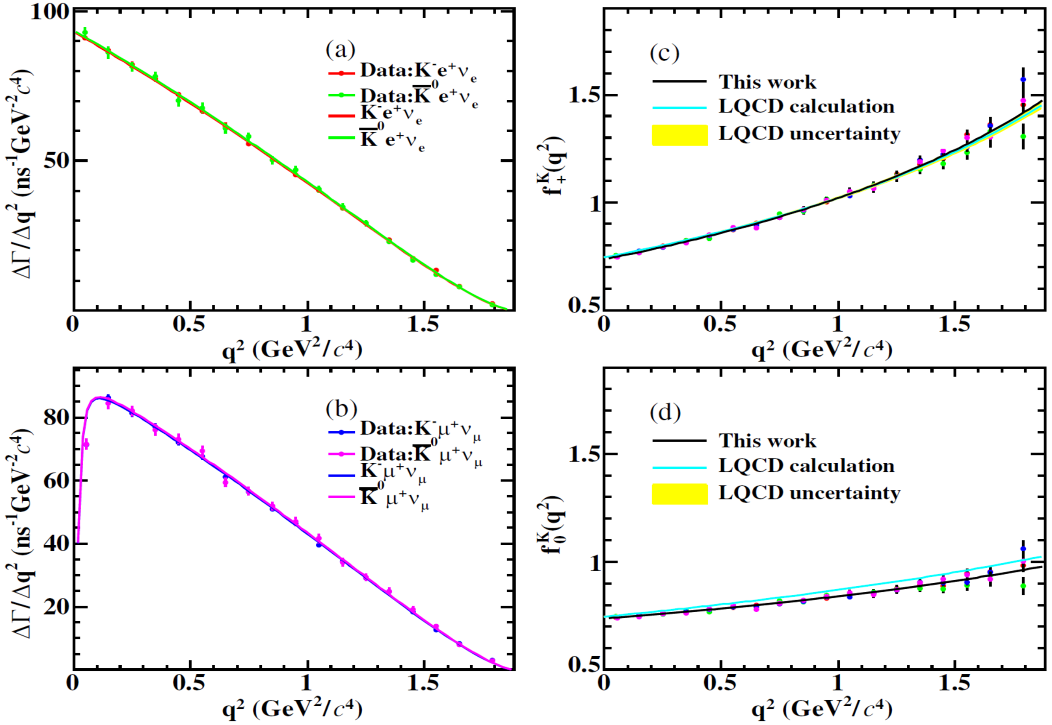
Low precision: **>1.5%**
FLAG, PRD 107, 052008 (2023)

$|V_{cs}|$, $f_+^K(0)$ from $D^0 \to K^- l^+ \nu_l$ and $D^+ \to \bar{K}^0 l^+ \nu_l$

BESIII

Branching fractions:

Signal decay	N_{DT}	$\mathcal{B}_{sig}$ (%)
$D^0 \to K^- e^+ \nu_e$	190605±471	3.521±0.009±0.016
$D^0 \to K^- \mu^+ \nu_\mu$	147596±488	3.419±0.011±0.016
$D^+ \to \bar{K}^0 e^+ \nu_e$	57846±256	8.864±0.039±0.082
$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	47229±248	8.665±0.046±0.084



Simultaneous fit to the partial decay rates

Extract $|V_{cs}|$

7.93 fb^{-1}@ 3.773 GeV, PRD 110, 112006 (2024)

$$|V_{cs}| = 0.9623 \pm 0.0015_{\rm stat} \pm 0.0017_{\rm syst} \pm 0.0040_{\rm LQCD}$$

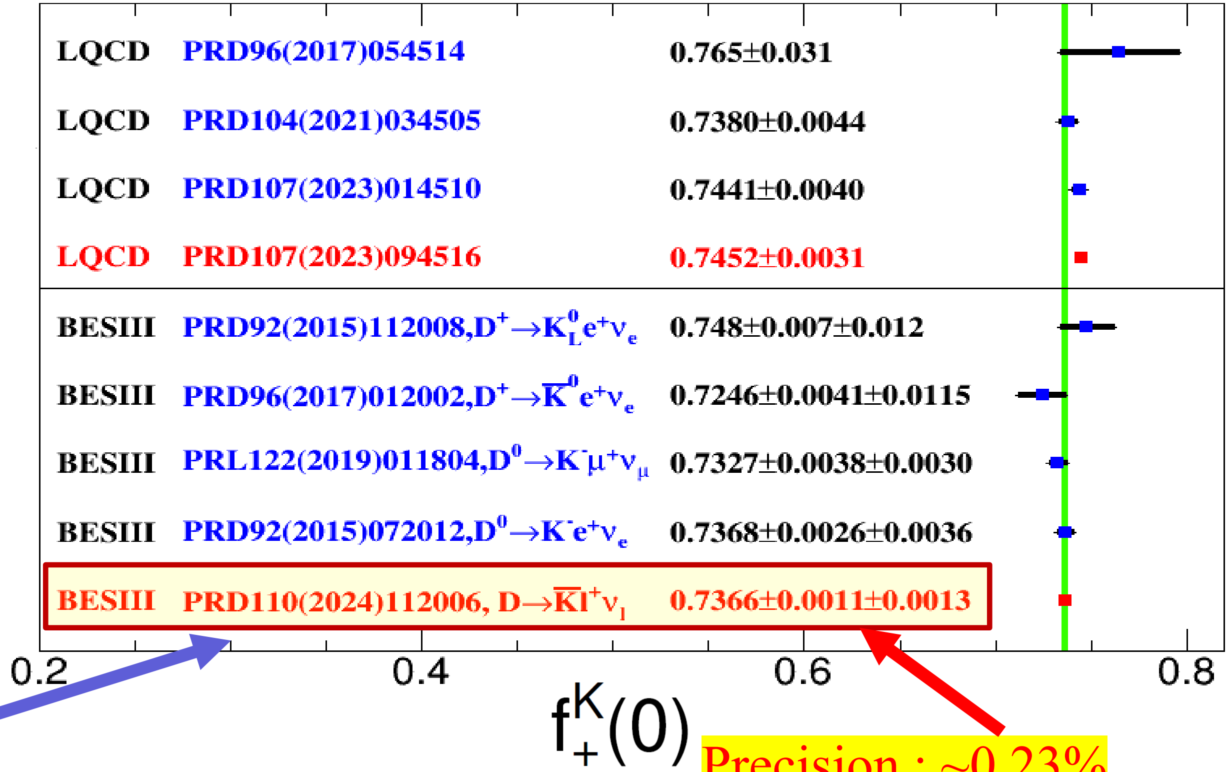
Precision: 0.4%

Test LFU:

$$\frac{\mathcal{B}_{D^+\to\bar{K}^0\mu^+\nu_\mu}}{\mathcal{B}_{D^+\to\bar{K}^0e^+\nu_e}} = 0.978 \pm 0.007_{\rm stat} \pm 0.013_{\rm syst}$$

$$\frac{\mathcal{B}_{D^0\to K^-\mu^+\nu_\mu}}{\mathcal{B}_{D^0\to K^-e^+\nu_e}} = 0.971 \pm 0.004_{\rm stat} \pm 0.006_{\rm syst}$$

SM=9.75



Precision : ~0.23%

$|V_{cs}|$ from $D_s^+ \to \eta^{(\prime)} l^+ \nu_l$

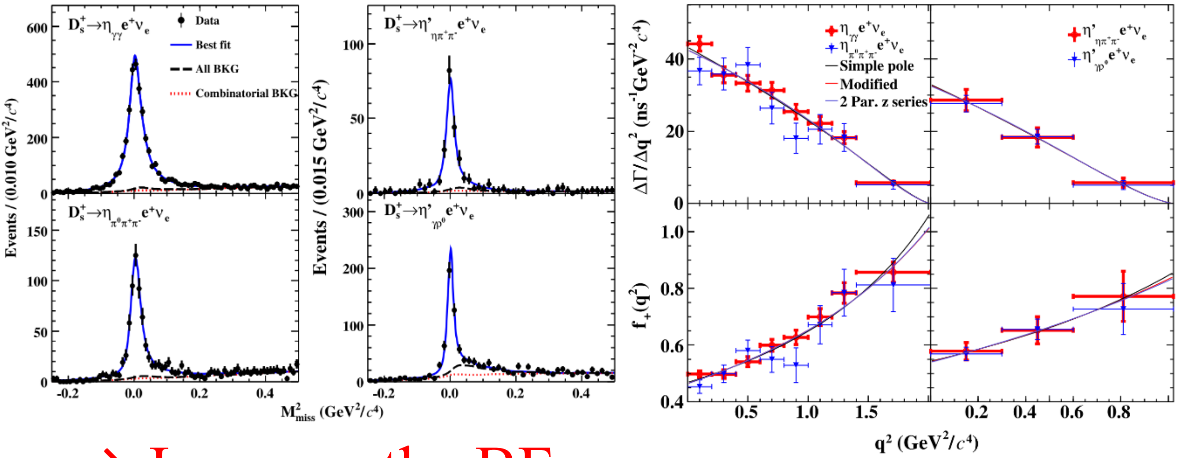
7.33 fb^{-1}@ 4.128-4.226 GeV

BESIII

PRL132,091802(2024)

$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$

PRD108,092003(2023)



→ Improve the BFs:

$\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = (2.255 \pm 0.039_{\rm stat} + 0.051_{\rm syst})\%$

$\mathcal{B}(D_s^+ \to \eta' e^+ \nu_e) = (0.810 \pm 0.038_{\rm stat} \pm 0.024_{\rm syst})\%$

→ Form factor and $|V_{cs}|$:

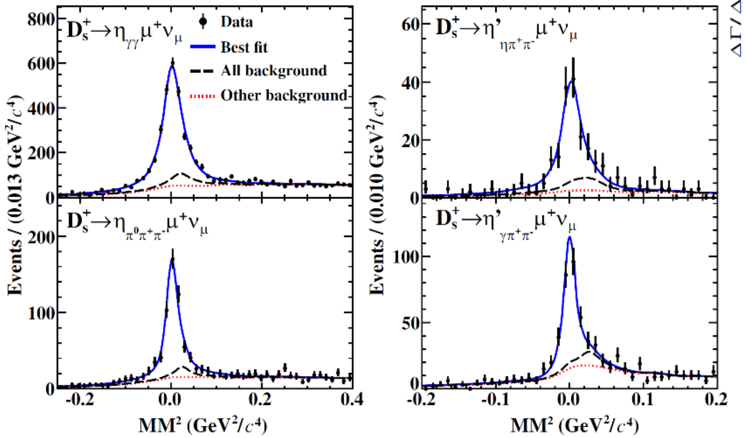
$$f_{+,0}^{\eta}(0) = 0.4642 \pm 0.0073_{\rm stat} \pm 0.0066_{\rm syst}$$

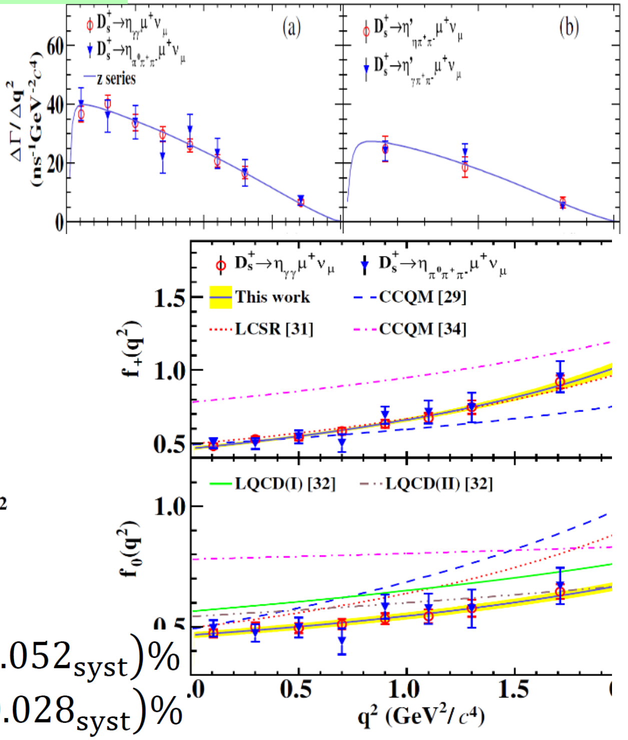
$$f_{+,0}^{\eta'}(0) = 0.540 \pm 0.025_{\rm stat} \pm 0.008_{\rm syst}$$

$$|V_{cs}|_{\eta} = 0.913 \pm 0.014_{\rm stat} \pm 0.013_{\rm syst}{}^{+0.055}_{-0.053}{}_{\rm theo}$$

$$|V_{cs}|_{\eta'} = 0.941 \pm 0.044_{\rm stat} \pm 0.016_{\rm syst}{}^{+0.078}_{-0.076}{}_{\rm theo}$$

$D_s^+ \to \eta^{(\prime)} \mu^+ \nu_\mu$





→ Improve the BFs:

$\mathcal{B}(D_s^+ \to \eta \mu^+ \nu_\mu) = (2.235 \pm 0.051_{\rm stat} + 0.052_{\rm syst})\%$

$\mathcal{B}(D_s^+ \to \eta' \mu^+ \nu_\mu) = (0.801 \pm 0.055_{\rm stat} \pm 0.028_{\rm syst})\%$

→ Form factor and $|V_{cs}|$:

$$f_{+,0}^{\eta}(0) = 0.465 \pm 0.010_{\rm stat} \pm 0.007_{\rm syst}$$

$$f_{+,0}^{\eta'}(0) = 0.518 \pm 0.038_{\rm stat} \pm 0.012_{\rm syst}$$

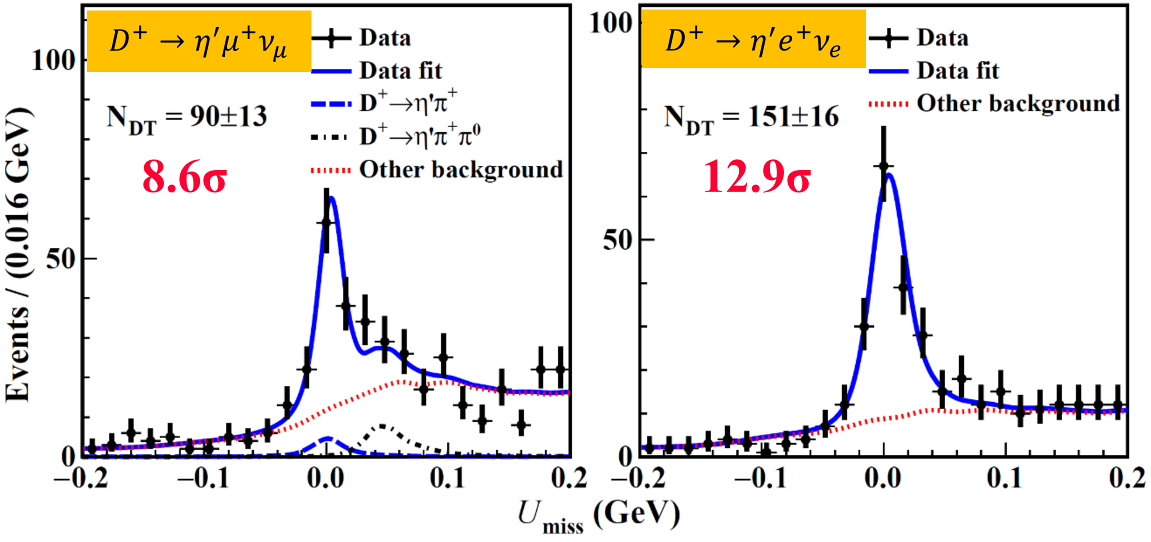
$$|V_{cs}|_{\eta} = 0.913 \pm 0.020_{\rm stat} \pm 0.014_{\rm syst}{}^{+0.055}_{-0.053}{}_{\rm theo}$$

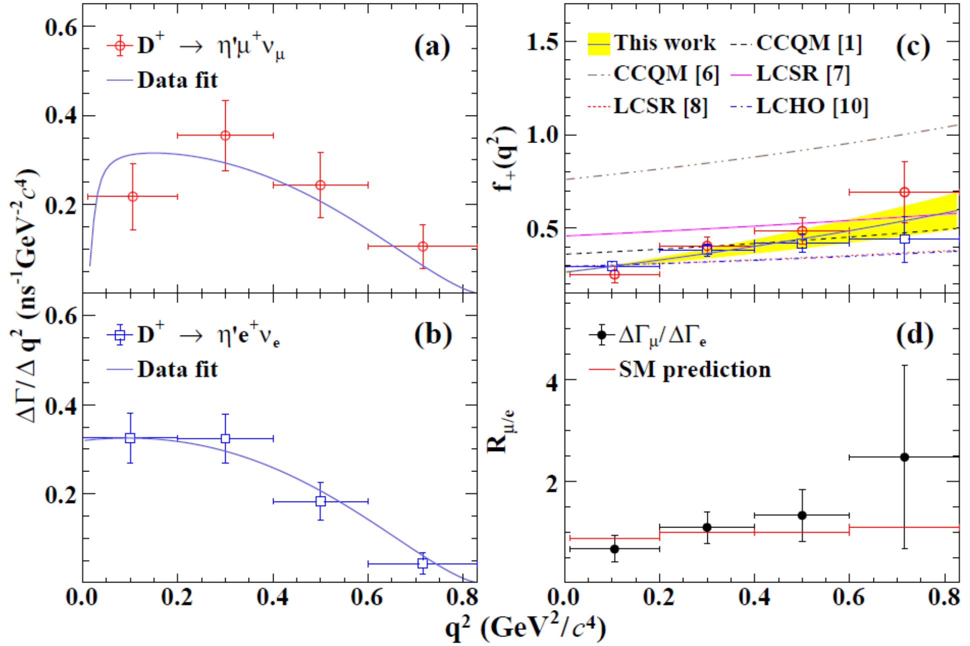
$$|V_{cs}|_{\eta'} = 0.904 \pm 0.067_{\rm stat} \pm 0.021_{\rm syst}{}^{+0.076}_{-0.073}{}_{\rm theo}$$

$f_+^{\eta'}(0)|V_{cd}|$ from $D^+ \to \eta' l^+ \nu_l$

20.3 fb^{-1}@ 3.773 GeV, PRL 134, 111801 (2025)

Observe $D^+ \to \eta' l^+ \nu_l$





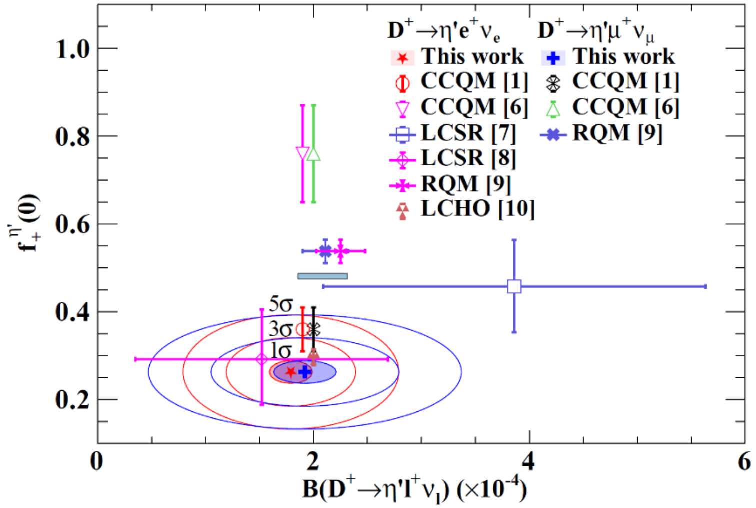
Decay	$\eta'\mu^+\nu_\mu$		$\eta' e^+\nu_e$	
η' decay	$\eta\pi^+\pi^-$	$\gamma\pi^+\pi^-$	$\eta\pi^+\pi^-$	$\gamma\pi^+\pi^-$
$\mathcal{B}$ ($\times 10^{-4}$)	$1.92 \pm 0.28 \pm 0.08$		$1.79 \pm 0.19 \pm 0.07$	

$$f_+^{\eta'}(0)|V_{cd}| = (5.92 \pm 0.56_{\rm stat} \pm 0.13_{\rm syst}) \times 10^{-2}$$

→ Form factor: $f_+^{\eta'}(0) = 0.263 \pm 0.025_{\rm stat} \pm 0.006_{\rm syst}$

→ LFU: $\mathcal{R}_{\mu/e}^{\eta'} = \frac{\mathcal{B}_{D^+\to\eta'\mu^+\nu_\mu}}{\mathcal{B}_{D^+\to\eta' e^+\nu_e}} = 1.07 \pm 0.19 \pm 0.03$

SM=0.94-0.95



$f_+^{f_0}(0)$ in $D_s^+ \to \pi^+\pi^-e^+\nu_e$

7.33 fb^{-1}@ 4.128-4.226 GeV

BESIII

PRL132,141901(2024)

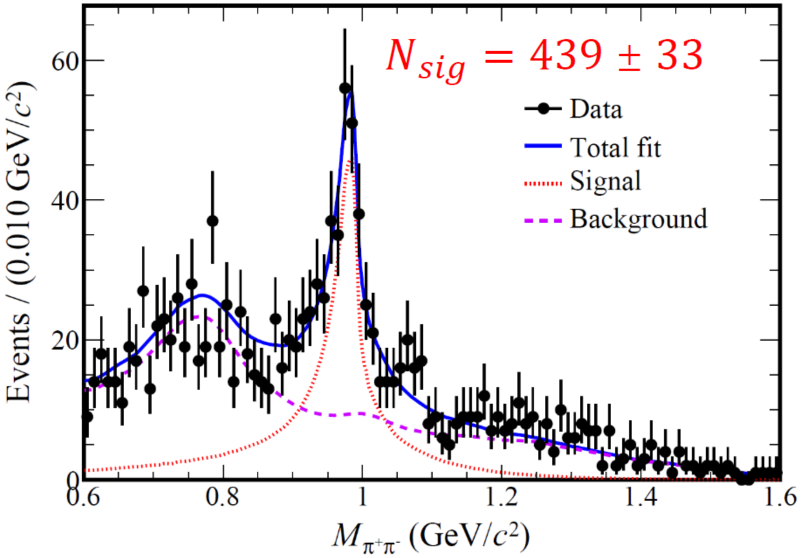
$$\frac{d^2\Gamma(D_s^+ \to f_0(980)e^+\nu_e)}{dsdq^2} = \frac{G_F^2|V_{cs}|^2}{192\pi^4 m_{D_s^+}^3}\lambda^{3/2}(m_{D_s^+}^2, s, q^2) \times |f_+^{f_0}(q^2)|^2 P(s)$$

Flatté model

$$P(s) = \frac{g_1\rho_{\pi\pi}}{|m_0^2 - s - i(g_1\rho_{\pi\pi} + g_2\rho_{K\bar{K}})|^2}$$

Simple pole parameterization

$$f_+^{f_0}(q^2) = \frac{f_+^{f_0}(0)}{1 - q^2/M_{\text{pole}}^2}$$



Observation of $f_0(980)$

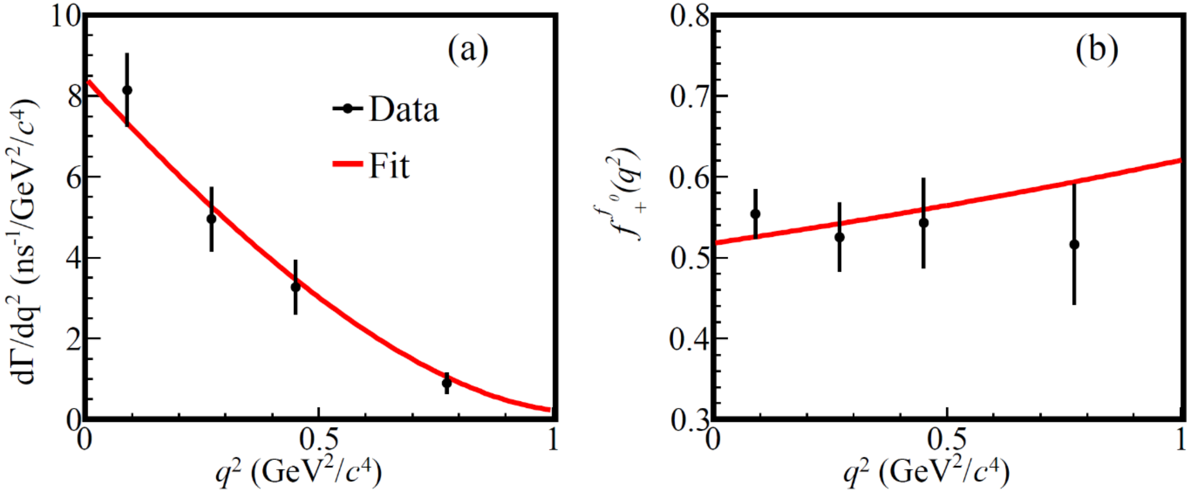
$$\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi + \pi -) = (1.72 \pm 0.13 \pm 0.19) \times 10^{-3}$$

$$\mathcal{B}(D_s^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi + \pi -) < 3.3 \times 10^{-4} \text{ @ } 90\% \ C.L.$$

Form factor

$$f_+^{f_0}(0)\,|V_{cs}| = 0.504 \pm 0.017_{\text{stat.}} \pm 0.035_{\text{syst.}}$$

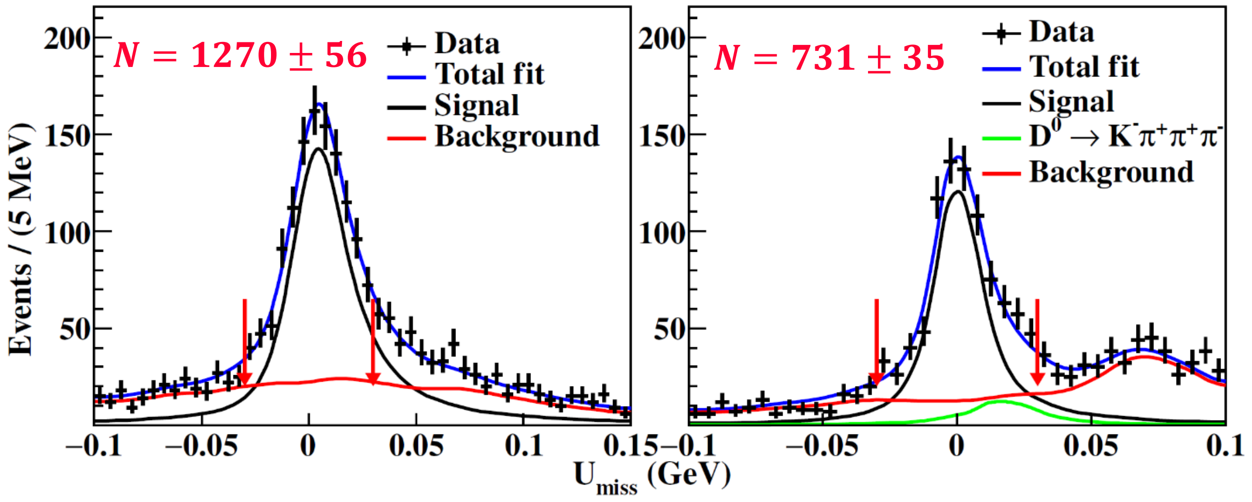
$$f_+^{f_0}(0) = 0.518 \pm 0.018_{\text{stat.}} \pm 0.036_{\text{syst.}}$$



Amplitude analysis of $D^{0(+)} \to K^-\pi^+\pi^{0(-)}e^+\nu_e$

20.3 fb^{-1}@ 3.773 GeV, arXiv:2503.02196

$D^+ \to K^-\pi^+\pi^0 e^+\nu_e$ $\quad$ $D^0 \to K^-\pi^+\pi^- e^+\nu_e$



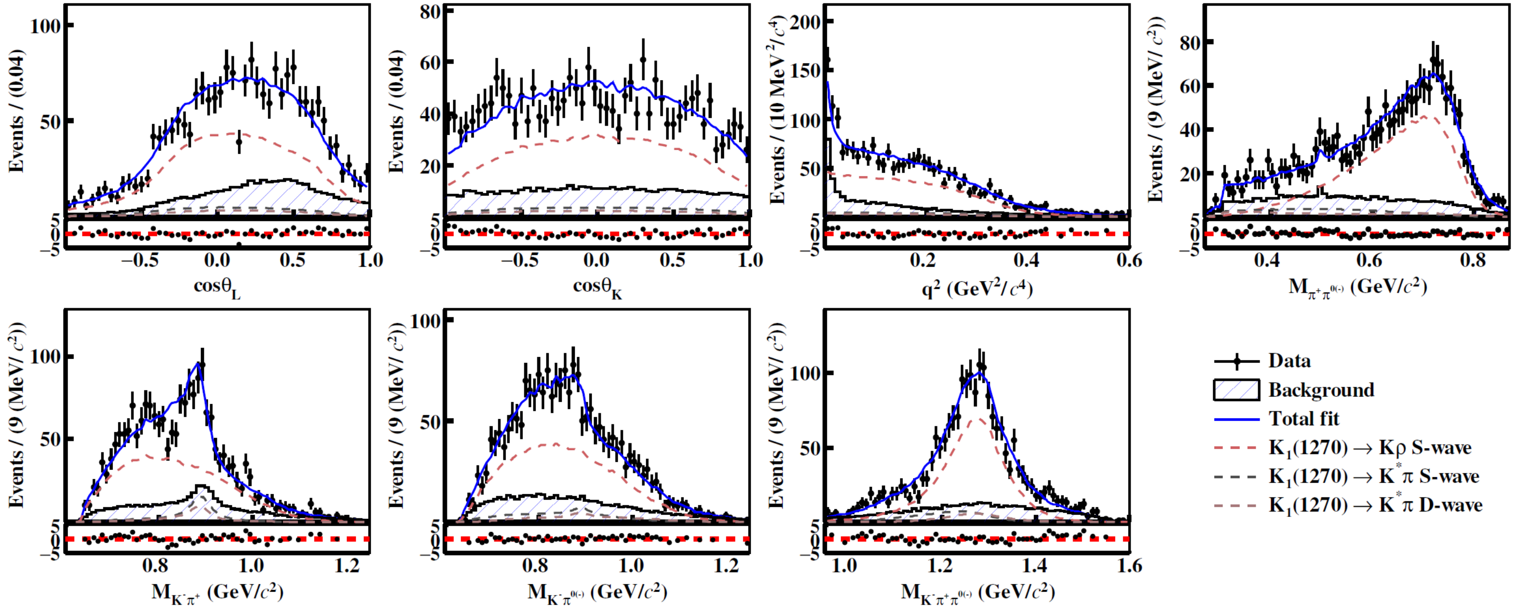
Measurement of BFs

$$\mathcal{B}_{D^+\to K^-\pi^+\pi^0 e^+\nu_e} = (1.27 \pm 0.05 \pm 0.04) \times 10^{-3}$$

$$\mathcal{B}_{D^0\to K^-\pi^+\pi^- e^+\nu_e} = (0.32 \pm 0.02 \pm 0.02) \times 10^{-3}$$

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

Form factors and fit fractions



Variable	Value
r_A $(\times 10^{-2})$	$-11.2 \pm 1.0 \pm 0.9$
r_V $(\times 10^{-2})$	$-4.3 \pm 1.0 \pm 2.4$
$f^{D^+}_{\rho K^-}$ (%)	$79.3 \pm 2.0 \pm 25.7$
$f^{D^+}_{\pi \bar{K}^*(892)}$ (%)	$10.9 \pm 1.2 \pm 3.0$
$f^{D^0}_{\rho K^-}$ (%)	$71.8 \pm 2.3 \pm 23.9$
$f^{D^0}_{\pi \bar{K}^*(892)}$ (%)	$19.5 \pm 1.9 \pm 5.2$
$m_{K_1(1270)}$ (MeV/c^2)	$1271 \pm 3 \pm 7$
$\Gamma_{K_1(1270)}$ (MeV)	$168 \pm 10 \pm 20$

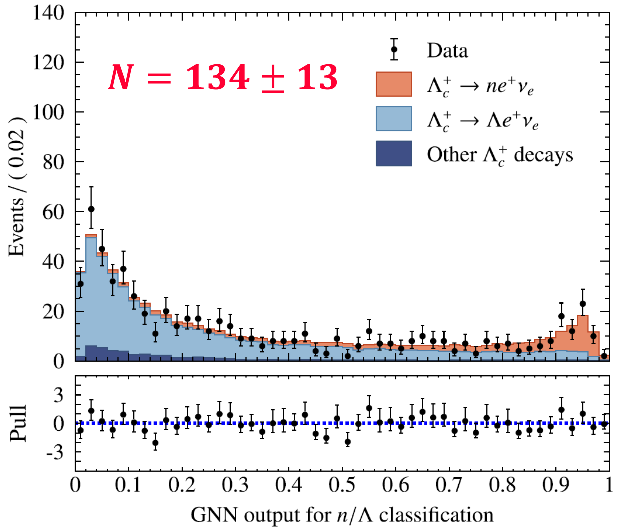
$|V_{cd}|$ from $\Lambda_c^+ \to n e^+ \nu_e$

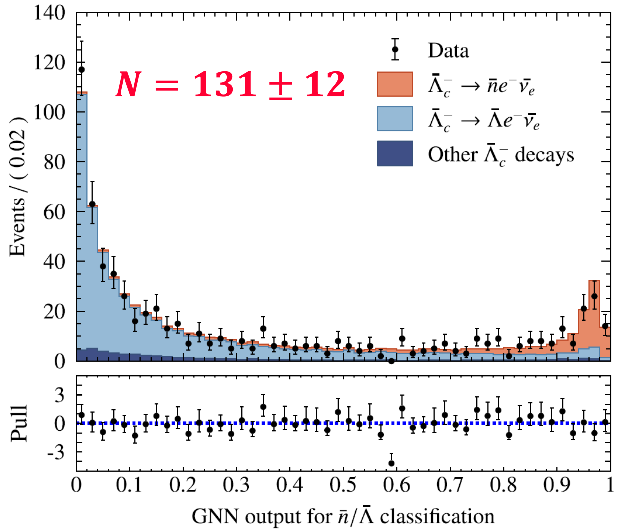
Nat Commun **16**, 681 (2025)

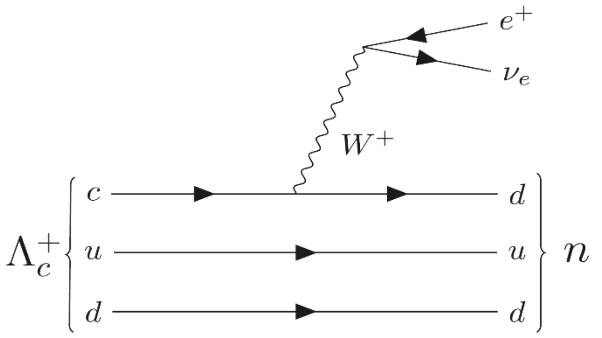
$4.5\ \text{fb}^{-1}@E_{\text{cm}} = 4.60 - 4.699\text{GeV}$

Observation of a rare beta decay $\Lambda_c^+ \to n e^+ \nu_e$ with machine learning of Graph Neural Network

Machine learning → discriminate energy deposition patterns of neutrons from those of Λ in the EMC of BESIII detector





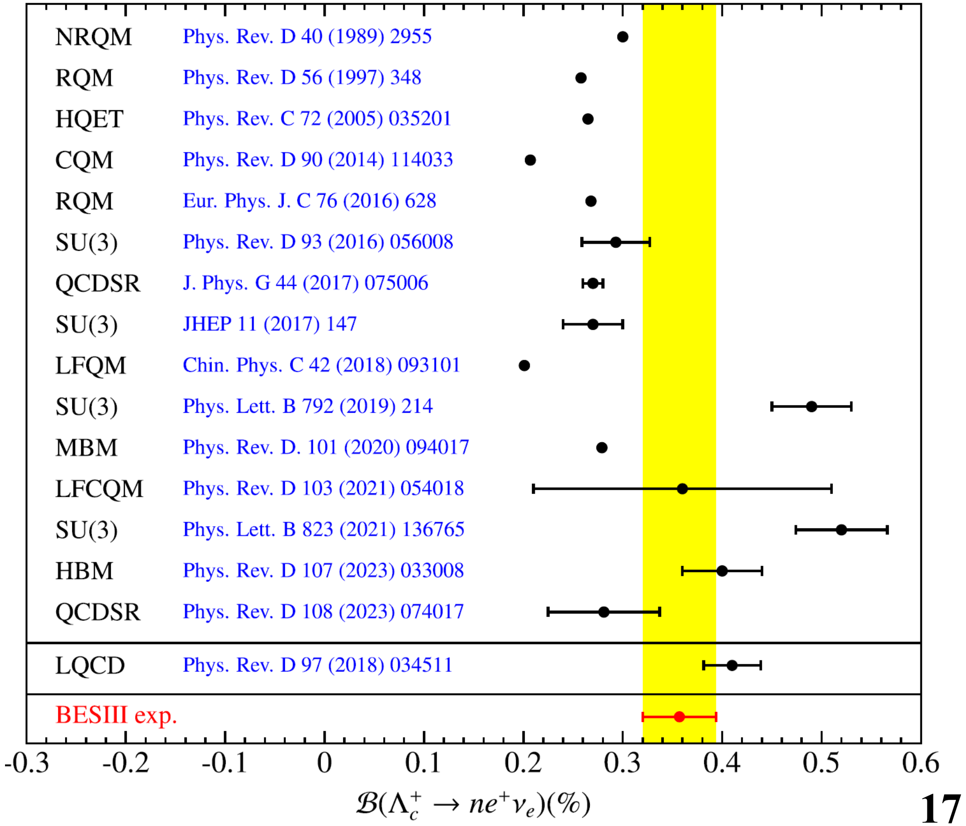


→ $\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = \left(0.357 \pm 0.034_{\text{stat.}} \pm 0.014_{\text{syst.}}\right)\%$

Using $\Gamma(\Lambda_c^+ \to n e^+ \nu_e) = |V_{cd}|^2 (0.405 \pm 0.016 \pm 0.020)\ \text{ps}^{-1}$ [PRD97,034511(2018)]

→ $|V_{cd}| = 0.208 \pm 0.011_{\text{exp.}} \pm 0.007_{\text{LQCD}} \pm 0.001_{\tau_{\Lambda_c^+}}$

First determination from charmed baryon decays



Charmed mesons hadronic decays

Measurements of the BFs

- → Are important component of heavy-flavor physics program.
- → Probe and calibrate non-perturbative QCD
- → Understand SU(3) flavor symmetry and its breaking effect
- → Test theoretical calculations of BFs and improve theoretical predictions of *CP* violation

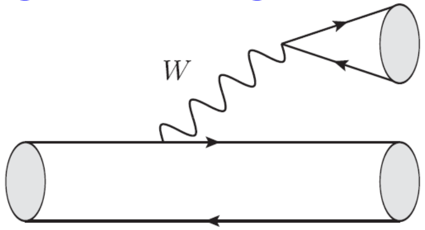
Amplitude analysis of multi-body decays

- → Information of $D \to VP, PP, SP, SV, VV, AP, AV, TP$ ...
- → Light hadron spectroscopy

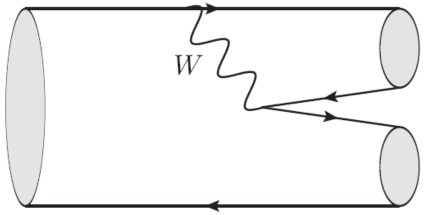
P: pseudo-scalar
V: vector
S: scalar
A: axial-vector
T: tensor

Topological Diagrammatic for D/D_s^+ decays:

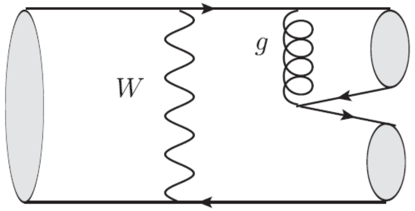
H.-Y. Cheng, *et al.* PRD 85, 034036



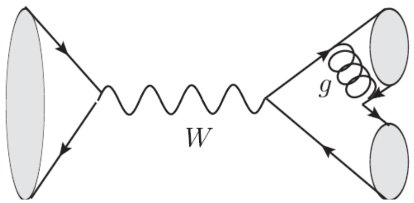
Color-allowed tree *T*



Color-suppressed tree *C*



W-exchange *E*



W-annihilation *A*

Calculation is not reliable, need exp. input

Amplitude analysis of $D_s^+ \to \pi^+\pi^+\pi^-\pi^0$

$7.33\,\mathrm{fb}^{-1}$ @ $4.178 - 4.226\,\mathrm{GeV}$, PRL 134, 011904 (2025)

1552 candidates with >75% purity

Observation of $D_s^+ \to f_0(980)\rho(770)^+$

(Mainly involves W-external-emission diagram)

$$\mathcal{B}(D_s^+ \to \pi^+\pi^+\pi^-\pi^0|_{\mathrm{non}-\eta}) = (2.04 \pm 0.08_{\mathrm{stat.}} \pm 0.05_{\mathrm{syst.}})\%$$

$$\mathcal{B}(D_s^+ \to \eta\pi^+) = (1.56 \pm 0.09_{\mathrm{stat.}} \pm 0.04_{\mathrm{syst.}})\%$$

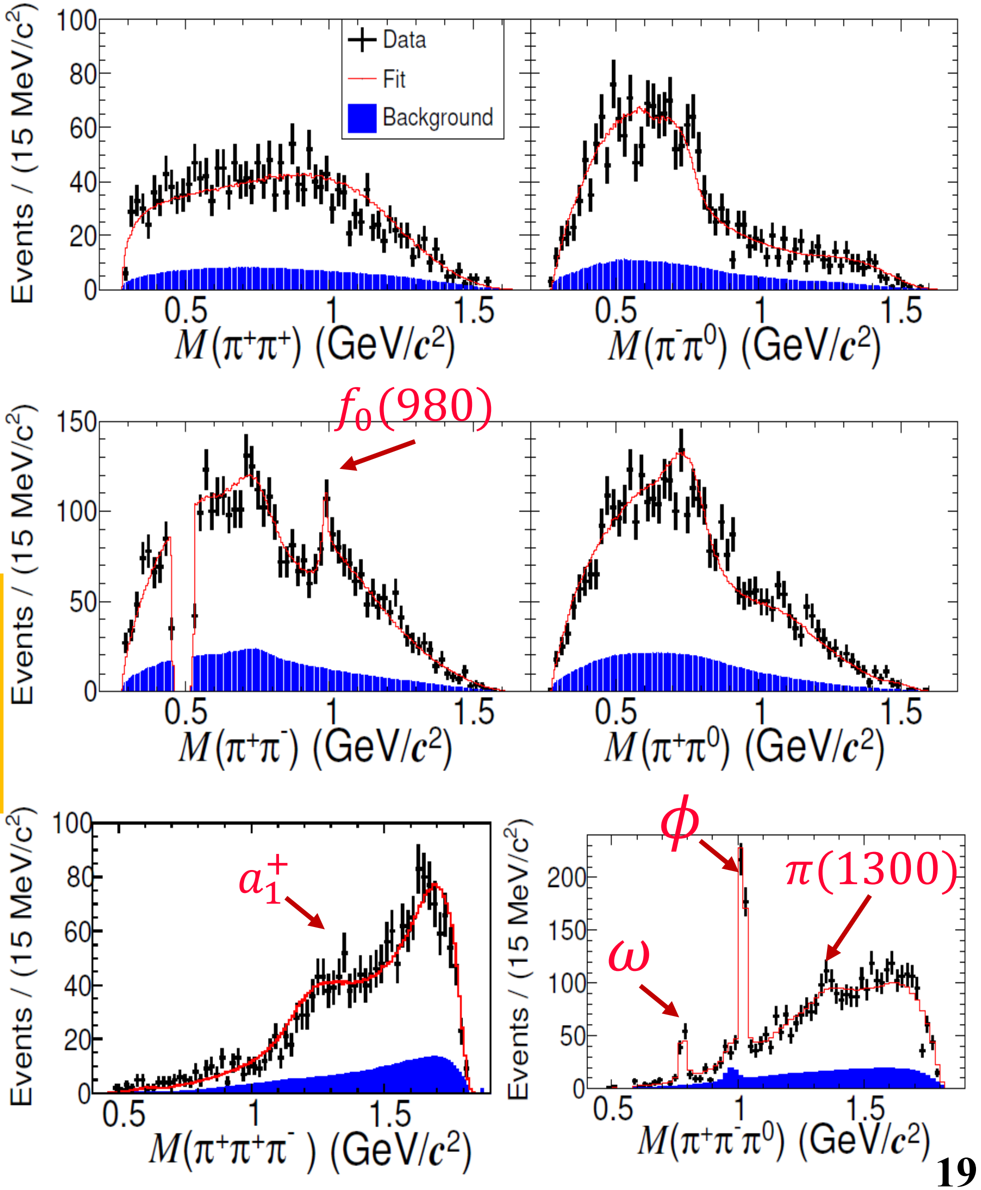
$$\frac{\mathcal{B}(\phi(1020) \to \pi^+\pi^-\pi^0)}{\mathcal{B}(\phi(1020) \to K^+K^-)} = 0.230 \pm 0.014_{\mathrm{stat.}} \pm 0.010_{\mathrm{syst.}}$$

Taking from $D_s^+ \to K^+K^-\pi^+$
BESIII, PRD 104, 012016 (2021)

Deviates from PDG value (0.313±0.010) by >4σ

Component	Phase (rad)	BF (10^{-3})
$f_0(1370)\rho^+$	0.0(fixed)	$5.08 \pm 0.80 \pm 0.43$
$f_0(980)\rho^+$	$3.99 \pm 0.13 \pm 0.07$	$2.57 \pm 0.44 \pm 0.20$
$f_2(1270)\rho^+$	$1.11 \pm 0.10 \pm 0.10$	$1.94 \pm 0.36 \pm 0.12$
$(\rho^+\rho^0)_S$	$1.10 \pm 0.18 \pm 0.10$	$0.71 \pm 0.25 \pm 0.12$
$(\rho(1450)^+\rho^0)_S$	$0.43 \pm 0.18 \pm 0.17$	$0.94 \pm 0.27 \pm 0.16$
$(\rho^+\rho(1450)^0)_P$	$4.58 \pm 0.16 \pm 0.09$	$1.75 \pm 0.27 \pm 0.08$
$\phi((\rho\pi) \to \pi^+\pi^-\pi^0)\pi^+$	$2.90 \pm 0.15 \pm 0.18$	$5.08 \pm 0.32 \pm 0.10$
$\omega((\rho\pi) \to \pi^+\pi^-\pi^0)\pi^+$	$3.22 \pm 0.21 \pm 0.09$	$1.41 \pm 0.17 \pm 0.06$
$a_1^+(\rho^0\pi^+)_S\pi^0$	$3.78 \pm 0.16 \pm 0.12$	$2.55 \pm 0.34 \pm 0.20$
$a_1^0((\rho\pi)_S \to \pi^+\pi^-\pi^0)\pi^+$	$4.82 \pm 0.15 \pm 0.12$	$1.29 \pm 0.39 \pm 0.24$
$\pi(1300)^0((\rho\pi)_P \to \pi^+\pi^-\pi^0)\pi^+$	$2.22 \pm 0.14 \pm 0.08$	$2.39 \pm 0.48 \pm 0.45$

W-annihilation decay
$BF = (1.92 \pm 0.30) \times 10^{-3}$ **(PDG)**

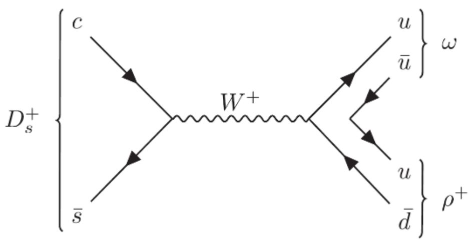


Amplitude analysis of $D_s^+ \to \pi^+\pi^+\pi^-\pi^0\pi^0$

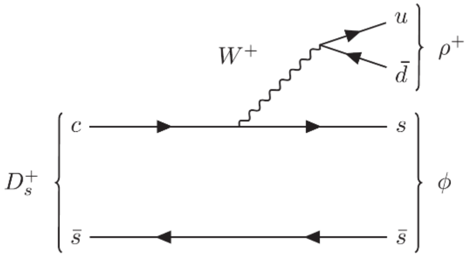
$7.33\,\mathrm{fb}^{-1}$ @ $4.178 - 4.226\,\mathrm{GeV}$, PRL 134, 201902 (2025)

1888 candidates with >79% purity

First observation of $D_s^+ \to \omega\rho(770)^+$



Pure W-annihilation



Pure W-external emission

Amplitude	BF (%)
$D_s^+ \to \rho(1450)^+\pi^0$, $\rho(1450)^+ \to \omega\pi^+$	$0.39 \pm 0.04\,^{+0.03}_{-0.03}$
$D_s^+[S] \to a_1(1260)^0\rho^+$, $a_1(1260)^0[S] \to \rho^+\pi^-$	$0.23 \pm 0.02\,^{+0.01}_{-0.01}$
$D_s^+[P] \to a_1(1260)^0\rho^+$, $a_1(1260)^0[S] \to \rho^+\pi^-$	$0.50 \pm 0.04\,^{+0.02}_{-0.02}$
$D_s^+ \to a_1(1260)^0\rho^+$, $a_1(1260)^0 \to \rho^+\pi^-$	$0.50 \pm 0.04\,^{+0.02}_{-0.02}$
$D_s^+[S] \to a_1(1260)^0\rho^+$, $a_1(1260)^0[S] \to \rho^-\pi^+$	$0.16 \pm 0.02\,^{+0.01}_{-0.01}$
$D_s^+[P] \to a_1(1260)^0\rho^+$, $a_1(1260)^0[S] \to \rho^-\pi^+$	$0.17 \pm 0.01\,^{+0.01}_{-0.01}$
$D_s^+ \to a_1(1260)^0\rho^+$, $a_1(1260)^0 \to \rho^-\pi^+$	$0.33 \pm 0.02\,^{+0.02}_{-0.02}$
$D_s^+[S] \to a_1(1260)^+\rho^0$, $a_1(1260)^+[S] \to \rho^+\pi^0$	$0.41 \pm 0.05\,^{+0.05}_{-0.05}$
$D_s^+[P] \to a_1(1260)^+\rho^0$, $a_1(1260)^+[S] \to \rho^+\pi^0$	$0.31 \pm 0.04\,^{+0.02}_{-0.02}$
$D_s^+ \to a_1(1260)^+\rho^0$, $a_1(1260)^+ \to \rho^+\pi^0$	$0.73 \pm 0.07\,^{+0.07}_{-0.07}$
$D_s^+ \to b_1(1235)^+\pi^0$, $b_1(1235)^+[S] \to \omega\pi^+$	$0.53 \pm 0.05\,^{+0.03}_{-0.03}$
$D_s^+ \to b_1(1235)^0\pi^+$, $b_1(1235)^0[S] \to \omega\pi^0$	$0.72 \pm 0.06\,^{+0.05}_{-0.05}$

Polarization puzzle

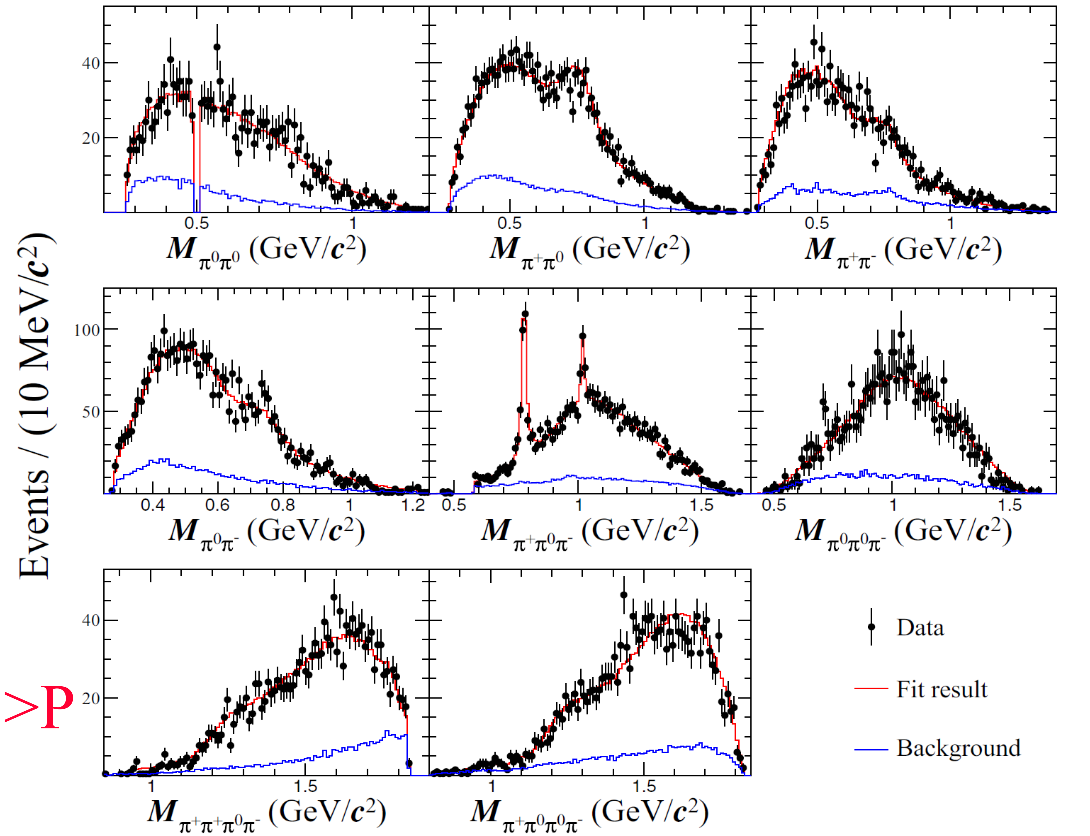
Amplitude	BF (%)
$D_s^+[S] \to \omega\rho^+$	$0.30 \pm 0.07\,^{+0.02}_{-0.03}$
$D_s^+[P] \to \omega\rho^+$	$0.25 \pm 0.04\,^{+0.04}_{-0.04}$
$D_s^+[D] \to \omega\rho^+$	$0.52 \pm 0.07\,^{+0.04}_{-0.07}$
$D_s^+ \to \omega\rho^+$	$0.99 \pm 0.08\,^{+0.05}_{-0.07}$
$D_s^+[S] \to \phi\rho^+$	$3.32 \pm 0.29\,^{+0.19}_{-0.17}$
$D_s^+[P] \to \phi\rho^+$	$0.63 \pm 0.12\,^{+0.05}_{-0.06}$
$D_s^+ \to \phi\rho^+$	$3.98 \pm 0.33\,^{+0.21}_{-0.19}$

D>S>P

S>P>D

Naive prediction: PRL 128,011803

transverse dominates than longitudinal in charm decays



$$\frac{\mathcal{B}(\phi(1020) \to \pi^+\pi^-\pi^0)}{\mathcal{B}(\phi(1020) \to K^+K^-)} = 0.222 \pm 0.019_{\mathrm{stat}} \pm 0.016_{\mathrm{syst}}$$

Deviates from PDG value (0.313±0.010) by $>3\sigma$

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

$7.33\,\mathrm{fb}^{-1}$ @ 4.178 – 4.226GeV, arXiv:2503.11383

2310 candidates with >78% purity

Measurement of $\phi \to K_S^0 K_L^0$

$$\mathcal{B}_{D_s^+ \to K_S^0 K_L^0 \pi^+} = (1.86 \pm 0.06_{\text{stat}} \pm 0.003_{\text{syst}})\%$$

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

$$\frac{\mathcal{B}(\phi(1020) \to K_S^0 K_L^0)}{\mathcal{B}(\phi(1020) \to K^+ K^-)} = 0.597 \pm 0.023_{\text{stat}} \pm 0.018_{\text{syst}} \pm 0.016_{\text{PDG}}$$

Taking from PDG

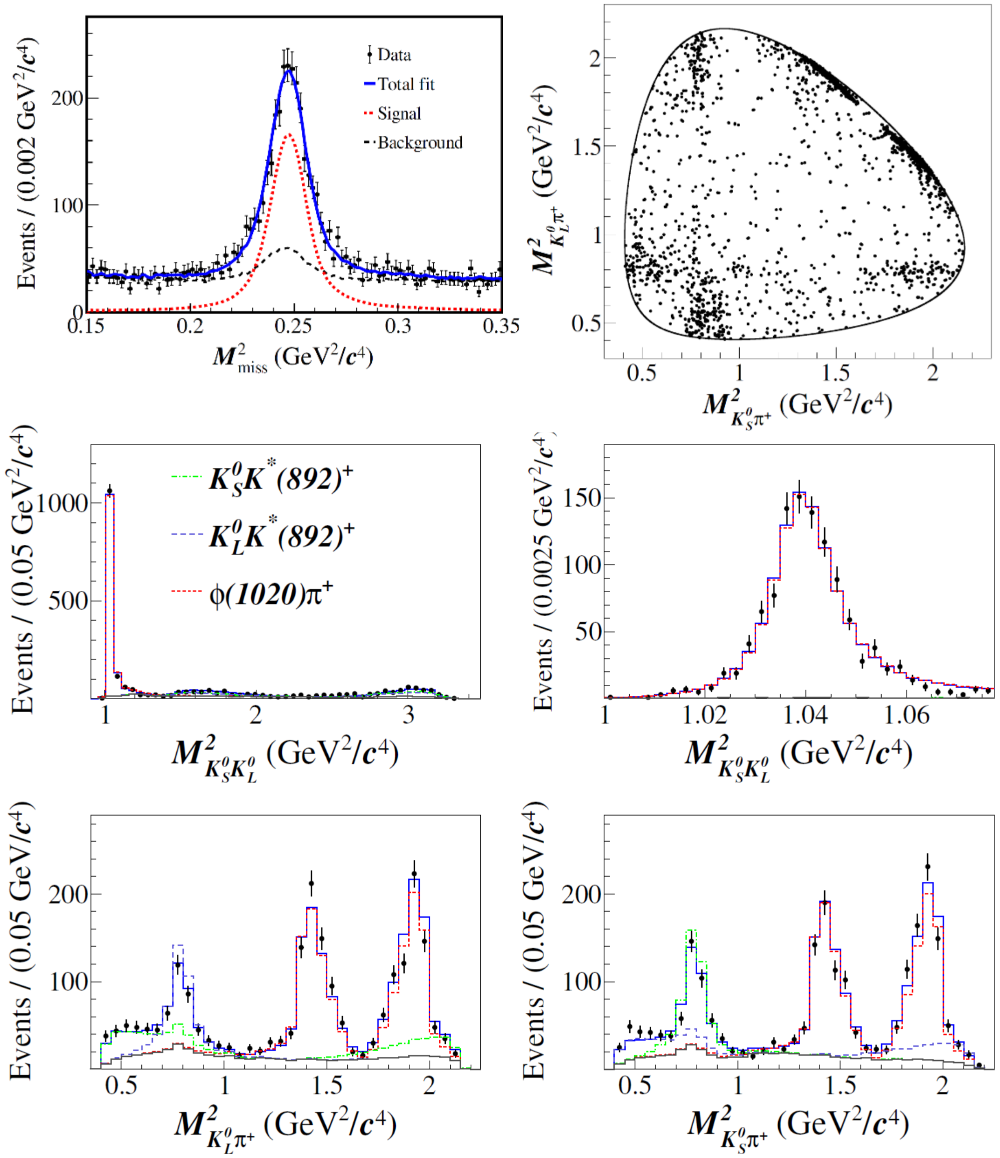
Deviates from PDG value (0.740±0.031) by $>3\sigma$

First observation of $K_S^0 - K_L^0$ asymmetry

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

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（2024）



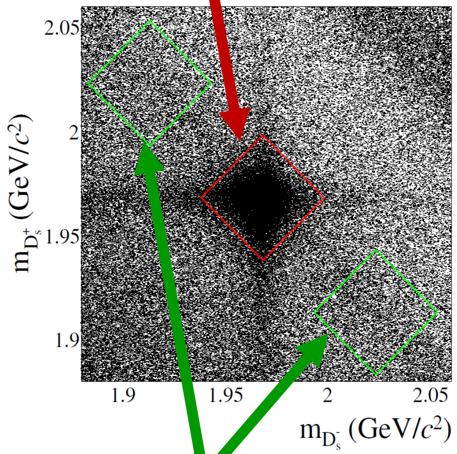
BF of D_s^+ hadronic decays

$7.33\ \mathrm{fb}^{-1}$ @4.178 – 4.226 GeV, **JHEP05(2024)335**

BESIII

Global fit to ST and DT yields and obtain:

42965 events in signal region



14728 events in combined sideband

Mode	$\mathcal{B}$ (%)	$\mathcal{A}_{CP}$ (%)
$D_s^+ \to K_S^0 K^+$	$1.502 \pm 0.012 \pm 0.009$	$0.29 \pm 0.50 \pm 0.21$
$D_s^+ \to K^+ K^- \pi^+$	$5.49 \pm 0.04 \pm 0.07$	$0.48 \pm 0.26 \pm 0.24$
$D_s^+ \to K_S^0 K^+ \pi^0$	$1.47 \pm 0.02 \pm 0.02$	$-0.85 \pm 1.97 \pm 0.46$
$D_s^+ \to K_S^0 K_S^0 \pi^+$	$0.73 \pm 0.01 \pm 0.01$	$1.14 \pm 1.58 \pm 0.44$
$D_s^+ \to K^+ K^- \pi^+ \pi^0$	$5.50 \pm 0.05 \pm 0.11$	$-0.66 \pm 0.91 \pm 0.33$
$D_s^+ \to K_S^0 K^+ \pi^+ \pi^-$	$0.93 \pm 0.02 \pm 0.01$	$2.00 \pm 2.37 \pm 0.70$
$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$	$1.56 \pm 0.02 \pm 0.02$	$-0.24 \pm 1.05 \pm 1.07$
$D_s^+ \to \pi^+ \pi^+ \pi^-$	$1.09 \pm 0.01 \pm 0.01$	$-0.88 \pm 1.17 \pm 0.38$
$D_s^+ \to \pi^+ \eta$	$1.69 \pm 0.02 \pm 0.02$	$-0.44 \pm 0.89 \pm 0.19$
$D_s^+ \to \pi^+ \pi^0 \eta$	$9.10 \pm 0.09 \pm 0.15$	$1.05 \pm 1.45 \pm 0.62$
$D_s^+ \to \pi^+ \pi^+ \pi^- \eta$	$3.08 \pm 0.06 \pm 0.05$	$2.42 \pm 2.85 \pm 0.78$
$D_s^+ \to \pi^+ \eta'$	$3.95 \pm 0.04 \pm 0.07$	$-0.59 \pm 0.76 \pm 0.20$
$D_s^+ \to \pi^+ \pi^0 \eta'$	$6.17 \pm 0.12 \pm 0.14$	$-1.60 \pm 2.57 \pm 0.64$
$D_s^+ \to K_S^0 \pi^+ \pi^0$	$0.51 \pm 0.02 \pm 0.01$	$-2.17 \pm 4.65 \pm 1.10$
$D_s^+ \to K^+ \pi^+ \pi^-$	$0.620 \pm 0.009 \pm 0.006$	$1.81 \pm 2.01 \pm 0.45$

Agree with PDG with much improved precision

Multi-body decays based on amplitude models

17 Amplitude analyses published/submitted

$D_s^+ \to K^+ K^- \pi^+$	Phys. Rev. D **104** (2021) 012016
$D_s^+ \to K_S^0 K^+ \pi^0$	Phys. Rev. Lett. **129** (2022) 182001
$D_s^+ \to \pi^+ \pi^+ \pi^-$	Phys. Rev. D **106** (2022) 112006
$D_s^+ \to \pi^+ \pi^+ \pi^- \eta$	Phys. Rev. D **104** (2021) L071101
$D_s^+ \to \pi^+ \pi^0 \eta'$	**JHEP 04** (2022) 058
$D_s^+ \to \pi^+ \pi^0 \pi^0$	**JHEP 01** (2022) 052
$D_s^+ \to K^+ \pi^+ \pi^-$	**JHEP 08** (2022) 196
$D_s^+ \to K^+ \pi^+ \pi^- \pi^0$	**JHEP 09** (2022) 242
$D_s^+ \to K_S^0 K_S^0 \pi^+$	Phys. Rev. D **105** (2022) L051103
$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$	Phys. Rev. D **103** (2021) 092006
$D_s^+ \to K^+ K^- \pi^+ \pi^0$	Phys. Rev. D **104** (2021) 032011
$D_s^+ \to K^+ K^- \pi^+ \pi^+ \pi^-$	**JHEP 07** (2022) 051
$D_s^+ \to K_S^0 \pi^+ \pi^0$	**JHEP 06** (2021) 181
$D_s^+ \to \pi^+ \pi^0 \eta$	Phys. Rev. Lett. **123** (2019) 112001
$D_s^+ \to \pi^+ \pi^+ \pi^- \pi^0$	Phys. Rev. Lett. **134** (2025) 011904
$D_s^+ \to \pi^+ \pi^+ \pi^- \pi^0 \pi^0$	Phys. Rev. Lett. **134** (2025) 201902
$D_s^+ \to K_S^0 K_L^0 \pi^+$	arXiv:2503.11383
$D_s^+ \to \pi^+ \pi^0 \pi^0 \eta$	to be submitted soon

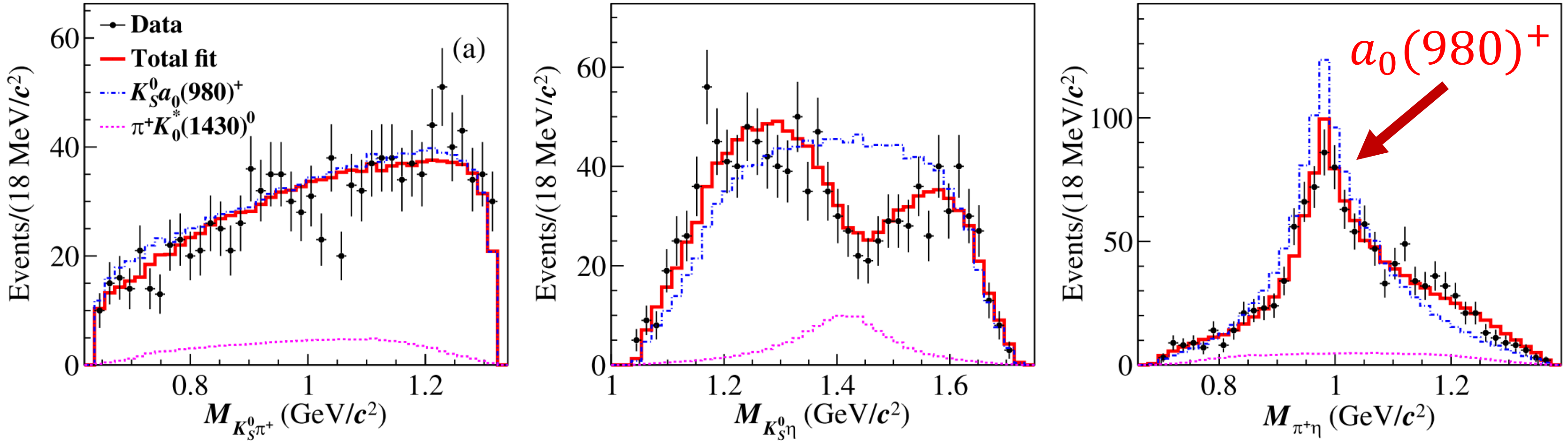
Amplitude analysis of $D^+ \to K_S^0 \pi^+ \eta$

PRL 132, 131903 (2024)

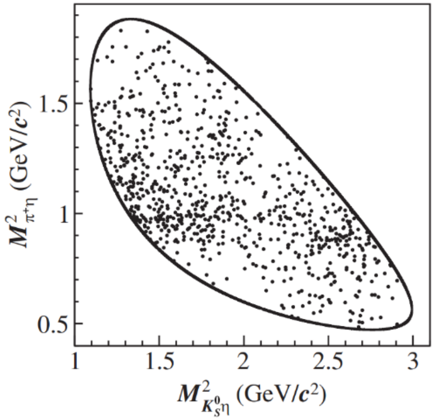
BESIII

2.93fb^{-1} @3.773GeV

Observation of *W*-annihilation-free decay $D^+ \to K_S^0 a_0(980)^+$



1113 candidates with 98% purity

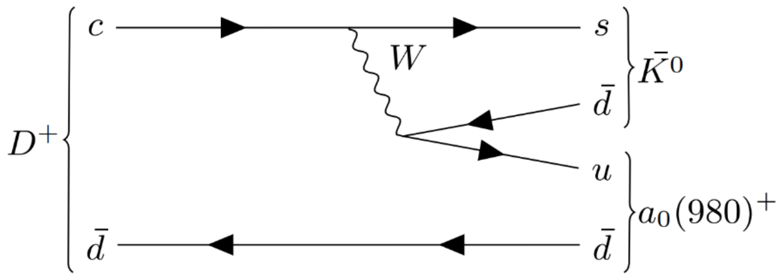


$$\mathcal{B}(D^+ \to K_S^0 a_0(980)^+, a_0(980)^+ \to \pi^+\eta) = (1.33 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}})\%$$

$$\mathcal{B}(D^+ \to \bar{K}_0^*(1430)^0 \pi^+,\ \bar{K}_0^*(1430)^0 \to K_S^0\eta) = (0.14 \pm 0.02_{\text{stat}} \pm 0.02_{\text{syst}})\%$$

$$\mathcal{B}(D^+ \to K_S^0 \pi^+ \eta) = (1.27 \pm 0.04_{\text{stat}} \pm 0.03_{\text{syst}})\%$$

Provide sensitive constraints in the extraction of contributions from internal W-emission diagrams →



Amplitude analysis of $D^0 \to \pi^+\pi^-\eta$, $D^+ \to \pi^+\pi^0\eta$

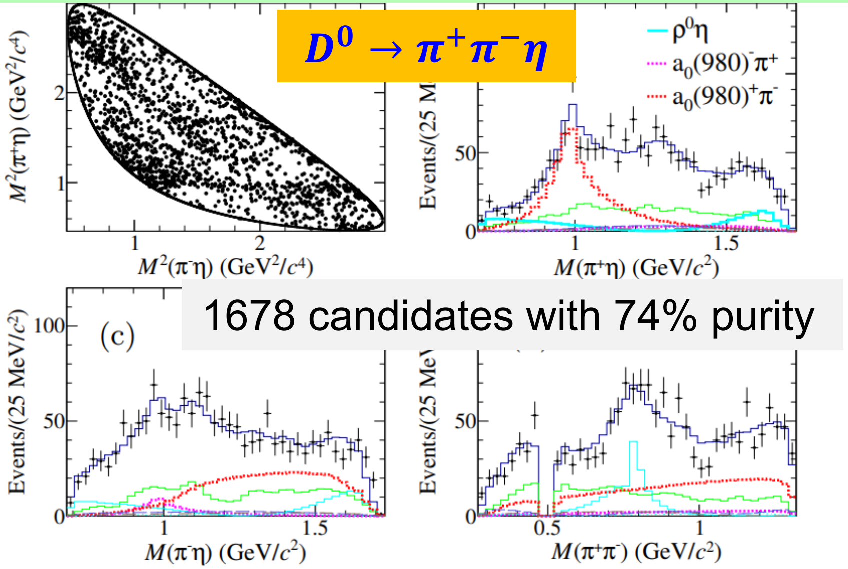
Observation of $D \to a_0(980)\pi$

$7.9\ \mathrm{fb}^{-1}@E_{cm} = 3.773\mathrm{GeV}$, PRD 110, L111102 (2024)

$\mathcal{B}(D^0 \to \pi^+\pi^-\eta) = (1.24 \pm 0.04 \pm 0.03)\%$

$\mathcal{B}(D^+ \to \pi^+\pi^0\eta) = (2.18 \pm 0.12 \pm 0.03)\%$

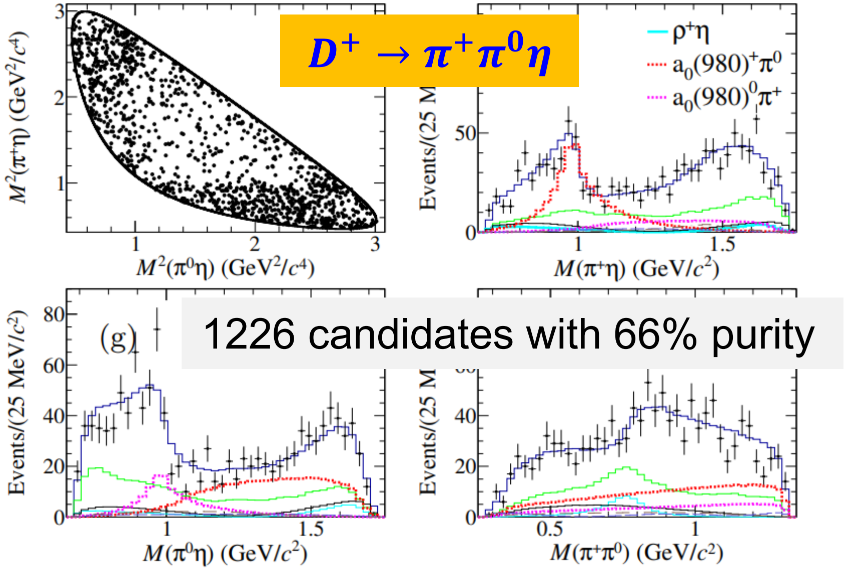
Amplitude	Phase (in unit rad)	BF ($\times 10^{-3}$)
$D^0 \to \rho^0\eta$	0 (fixed)	$0.19 \pm 0.02 \pm 0.01$
$D^0 \to a_0(980)^-\pi^+$	$0.06 \pm 0.16 \pm 0.12$	$0.07 \pm 0.02 \pm 0.01$
$D^0 \to a_0(980)^+\pi^-$	$-1.06 \pm 0.12 \pm 0.10$	$0.55 \pm 0.05 \pm 0.07$
$D^0 \to a_2(1320)^+\pi^-$	$-1.16 \pm 0.25 \pm 0.23$	$0.03 \pm 0.01 \pm 0.01$
$D^0 \to a_2(1700)^+\pi^-$	$0.08 \pm 0.17 \pm 0.23$	$0.07 \pm 0.02 \pm 0.03$
$D^0 \to (\pi^+\pi^-)_{S-\mathrm{wave}}\eta$	$-0.92 \pm 0.29 \pm 0.14$	$0.05 \pm 0.02 \pm 0.03$
$D^+ \to \rho^+\eta$	$-4.03 \pm 0.19 \pm 0.13$	$0.20 \pm 0.07 \pm 0.05$
$D^+ \to (\pi^+\pi^0)_V\eta$	$-0.64 \pm 0.22 \pm 0.19$	$0.34 \pm 0.11 \pm 0.11$
$D^+ \to a_0(980)^+\pi^0$	0 (fixed)	$0.95 \pm 0.12 \pm 0.05$
$D^+ \to a_0(980)^0\pi^+$	$2.44 \pm 0.20 \pm 0.10$	$0.37 \pm 0.10 \pm 0.04$
$D^+ \to a_2(1700)^+\pi^0$	$0.92 \pm 0.20 \pm 0.14$	$0.09 \pm 0.05 \pm 0.02$
$D^+ \to a_0(1450)^+\pi^0$	$0.63 \pm 0.41 \pm 0.30$	$0.15 \pm 0.06 \pm 0.02$



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

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

→ Disagrees with theoretical predictions by orders of magnitude



Observation of $D_s^+ \to a_0(980)\pi$

$3.19\ \mathrm{fb}^{-1}@E_{cm} = 4.176\mathrm{GeV}$
PRL123, 112001(2019)

$$\mathcal{B}(D_s^+ \to a_0(980)^+\pi^0) = \mathcal{B}(D_s^+ \to a_0(980)^0\pi^+) = (1.46 \pm 0.15 \pm 0.23)\%$$

→ Larger than pure W-annihilation decays $D_s^+ \to \omega\pi^+$, $D_s^+ \to \rho\pi^+$ by one order of magnitude

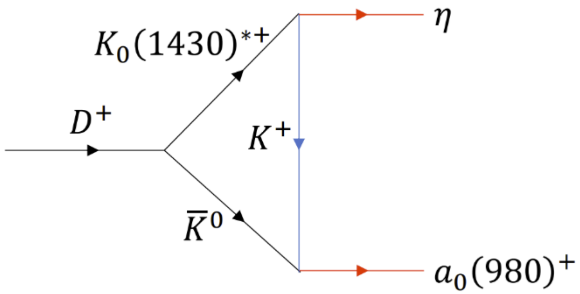
Amplitude analysis of $D^+ \to K_S^0 \pi^+ \eta$

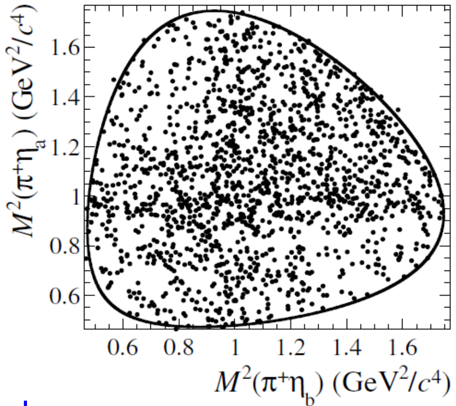
arXiv: 2505.12086

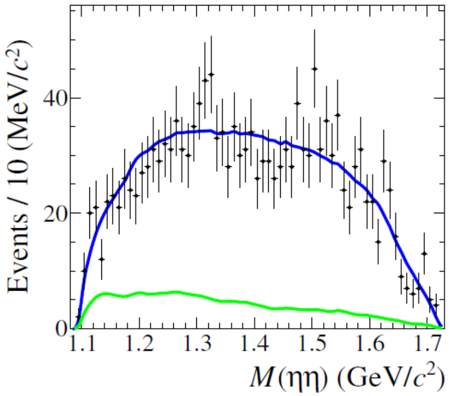
20.3fb^{-1} @3.773GeV

1624 candidates with 85% purity

- First observation of an altered $a_0(980)$ line-shape due to triangle loop rescattering







Fit1: $P_{a_0(980)}$ three-channel coupled Flatte formulae, the fitted pole position is inconsistent with previous measurement.

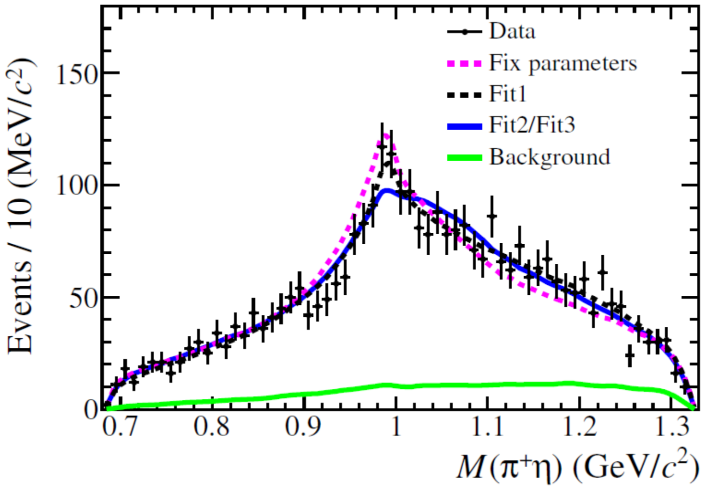
To consider the rescattering process $D^+ \to \bar{K}_0^*(1430)^0 K^+ \to a_0(980)^+ \eta$

we perform Fit2 and Fit3

Fit2: $(1 + |C| e^{i\phi_C} A_{\text{loop}}) P_{a_0(980)}$

Fit3: $(1 + |C| A_{\text{loop}}) P_{a_0(980)}$ with ϕ_C fixed to zero.

$$|C| = 0.113 \pm 0.015_{\text{stat.}} \pm 0.048_{\text{syst.}}$$



Fit2 and Fit3 give good descriptions of the altered $a_0(980)$ line-shape.

BF measurement

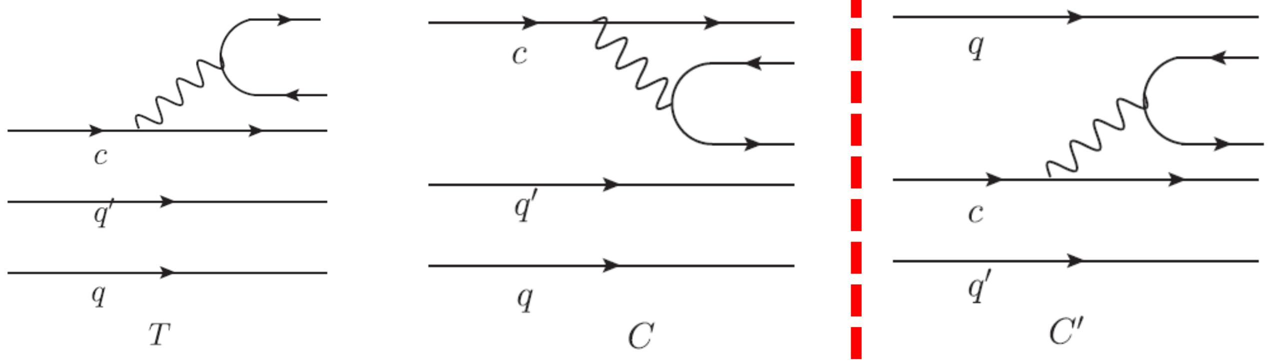
$$\left.\begin{matrix}\mathcal{B}(D^+ \to \pi^+\eta\eta) \\ \mathcal{B}(D^+ \to a_0(980)^+\eta)\ \mathcal{B}(a_0(980)^+ \to \pi^+\eta)\end{matrix}\right\} = (3.67 \pm 0.12_{\text{stat.}} \pm 0.06_{\text{syst.}}) \times 10^{-3}$$

Charmed baryon decay

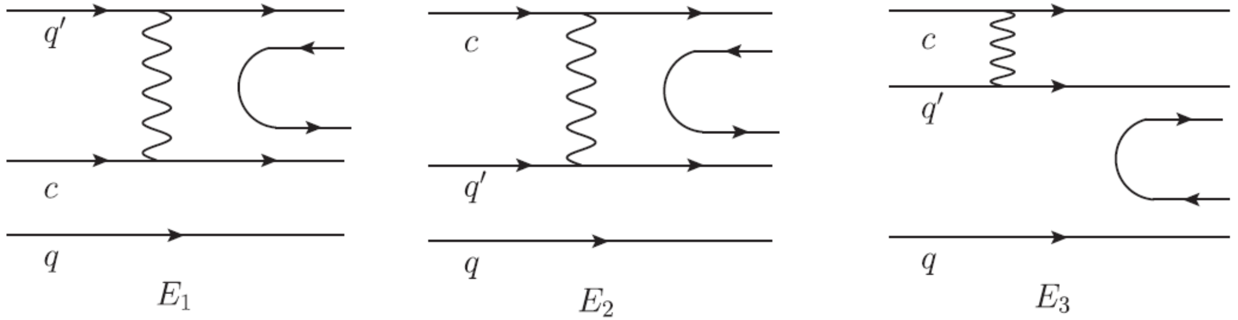
- Λ_c^+ may reveal more information of strong- and weak-interactions in charm region, complementary to D/D_s

  → Most charmed baryons eventually decay to Λ_c^+

Topological Diagrams for Λ_c^+ decays:



W-emission T internal W-emission C inner W-emission C'



W-exchange E_1, E_2, and E_3

H.-Y. Cheng *et al.*, *Chinese Journal of Physics*, 78(2022) 324-362

Non-factorization amplitude
→ Calculation is not reliable, need exp. input

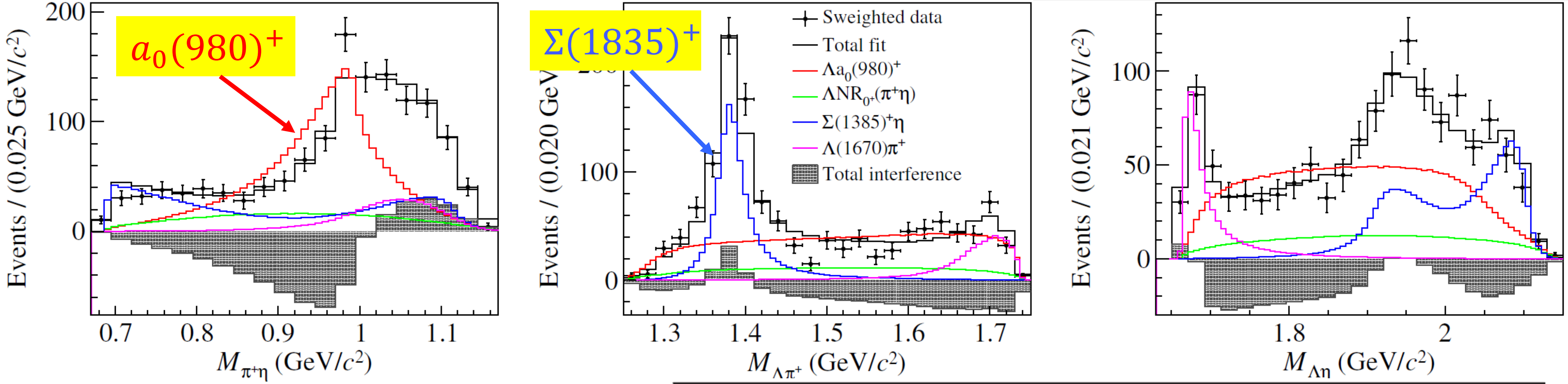
Observation $a_0(980)^+$ in $\Lambda_c^+ \to \Lambda\pi^+\eta$

BESIII

6.1 fb^{-1}@$E_{\mathrm{cm}} = 4.600 - 4.843$GeV, PRL 134, 021901(2025)

Observation of $\Lambda_c^+ \to \Lambda a_0(980)^+$

1312 ± 45 signal events with 80% purity



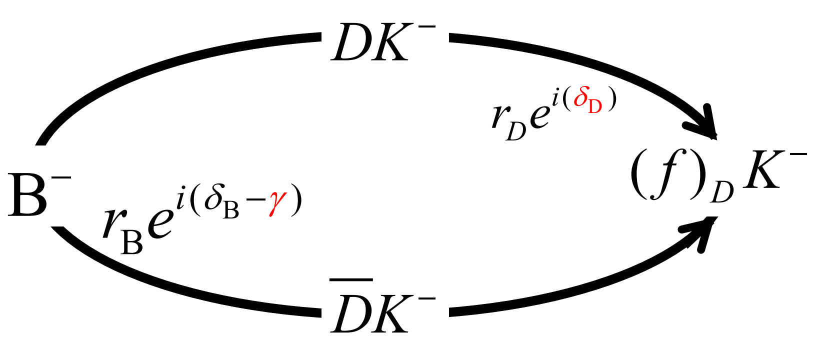
$$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\eta) = (1.94 \pm 0.07_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}})\%$$

Process	FF (%)	significance	decay asymmetry α
$\Lambda a_0(980)^+$	$54.0 \pm 8.4 \pm 2.6$	13.1σ	$-0.91^{+0.18}_{-0.09} \pm 0.08$
$\Sigma(1385)^+\eta$	$30.4 \pm 2.6 \pm 0.7$	22.5σ	$-0.61 \pm 0.15 \pm 0.04$
$\Lambda(1670)\pi^+$	$14.1 \pm 2.8 \pm 1.2$	11.7σ	$0.21 \pm 0.27 \pm 0.33$
ΛNR_{0^+}	15.4 ± 5.3	6.7σ	···

$$\mathcal{B}(\Lambda_c^+ \to \Lambda a_0(980)^+, a_0(980)^+ \to \pi^+\eta) = (1.05 \pm 0.16_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}} \pm 0.07_{\mathrm{ext}})\%$$

$\to$ $\mathcal{B}(\Lambda_c^+ \to \Lambda a_0(980)^+) = (1.23 \pm 0.21)\%$ Larger than theoretical calculations by 1-2 orders.

Strong-phase inputs for γ measurement



- **CKM angle γ can be determined directly in $B^\pm \to DK^\pm$ (golden mode) decay**

  → **Phase-space integrated decay rate:**

$$\Gamma(B^\mp \to DK^\mp) \propto (r_D^f)^2 + r_B^2 + 2 r_B r_D^f R_D^f \cos(\delta_B \mp \gamma - \delta_D^f)$$

Magnitude ratio between $D^0 \to f$ and $\overline{D}^0 \to f$ *amplitudes*	Coherence factor	Strong-phase difference between $D^0 \to f$ and $\overline{D}^0 \to f$

May limit precision to γ

- **Extract γ using different *D* decays:**

  → Self-conjugate decays (e.g. $K_S^0 h^+ h^-$): "GGSZ " → c_i, s_i (amplitude-weighted cos[sin]$\Delta\delta_D$ in phase-space *i*)

  [PRD 68 (2003) 054018; PRD 67 (2003) 071301]

  → CF and DCS decays (e.g. $K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$): "ADS" → δ_D^f, R_D^f

  [PRL 78 (1997) 3257; PRD 63 (2001) 036005]

  → (Quasi-)*CP* eigenstates (e.g. h^+h^-): "GLW" → *CP* fraction F_+; ...

  [PLB 265 (1991) 172; PLB 253 (1991) 483]

- *D* strong-phase parameters provide the crucial inputs for γ measurement

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

$7.13\ \text{fb}^{-1}$ @4.13 – 4.23 GeV
arXiv:2506.07906

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

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

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

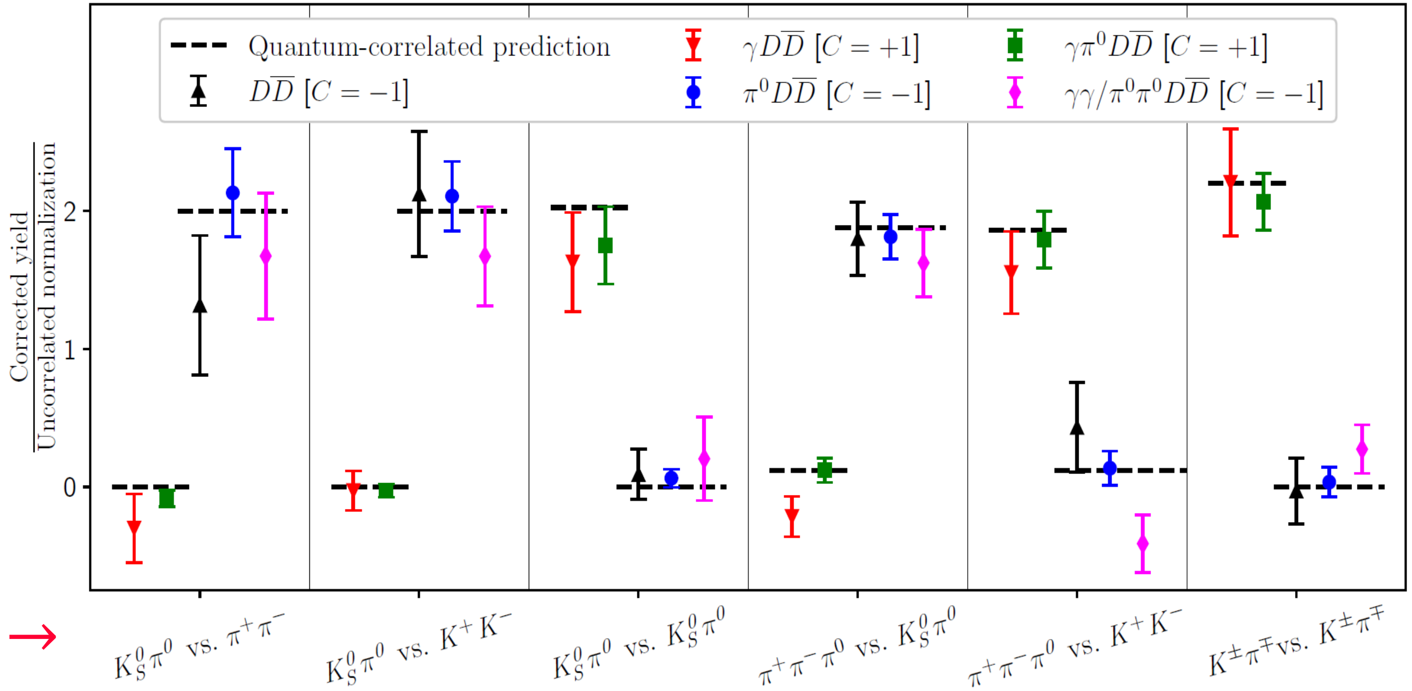
Production mechanism	C
$e^+e^- \to D\bar{D}$	-1
$e^+e^- \to D^*\bar{D} \to D\bar{D}\,\gamma$	$+1$
$e^+e^- \to D^*\bar{D} \to D\bar{D}\,\pi^0$	-1
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\,\gamma\gamma$	-1
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\,\pi^0\gamma$	$+1$
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\,\pi^0\pi^0$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

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

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, -

Measurement of $\delta_{K\pi}$

7.13 fb^{-1} @4.13 – 4.23 GeV
arXiv:2506.07907

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

→ is an 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 (combined fit with BESIII measurement using 2.93 fb^{-1} $\psi(3770)$ data)

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

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

[BESIII, EPJC 82,1009(2022)]

Strong-phase measurement of $D^0 \to K^0_{S/L}\pi^+\pi^-$

7.93 fb^{-1} @3.773 GeV, JHEP 06(2025)086

- Measurement of $D^0 \to K^0_{S/L}\pi^+\pi^-$ strong phase parameters:

  $c_i[s_i] \equiv$ amplitude-weighted $\cos[\sin]\Delta\delta_D$ in phase-space i

  → is an key input for direct measurement of CKM angle γ

- Impact on the γ measurement

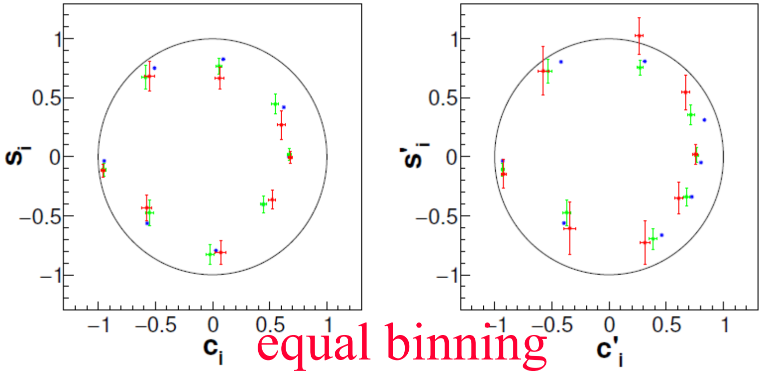
  → Uncertainty: 0.9° with constraints
  → Uncertainty: 1.5° without constraints
  } with optimal binning

  Statistical uncertainty of current γ measurement: 5° [LHCb, JHEP02(2021)169]

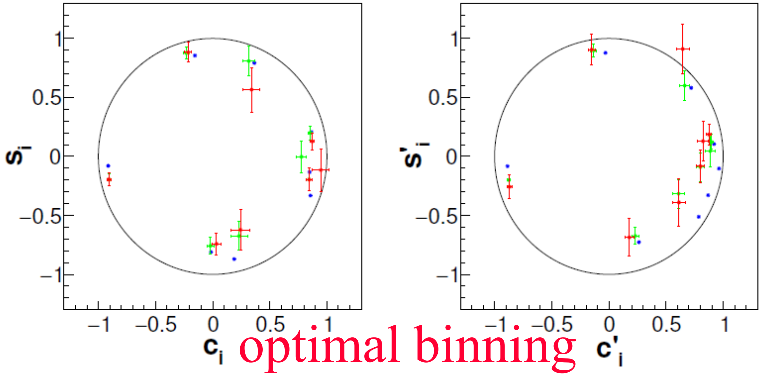
- Expected γ precision

Belle II [PTEP 2019, 123C01 (2019)]:
$\mathbf{1.5}^\circ$ with 50 ab^{-1}
LHCb [LHCb-PUB-2016-025 (2016)]:
$< \mathbf{1}^\circ$ with 50 fb^{-1}, phase-1 upgrade (2030),
$< \mathbf{0.4}^\circ$ with 300 fb^{-1}, phase-2 upgrade (>2035)

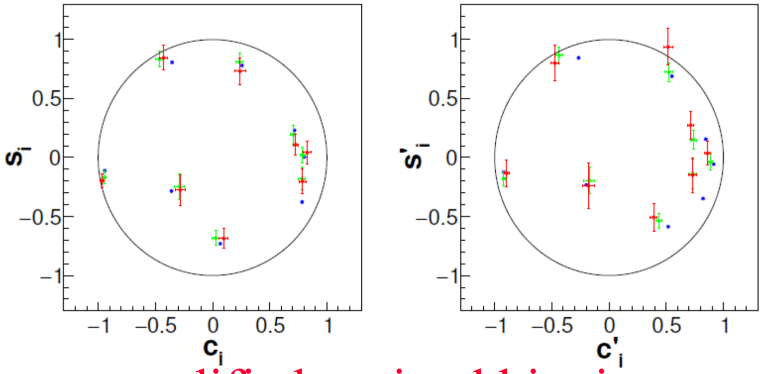
Uncertainties due to strong-phases in $D \to K^0_S h^+ h^-$ decays with 20fb^{-1}data → 0.5°
BESIII white paper



equal binning



optimal binning



modified-optimal binning

Summary and Prospects

BESIII

- BESIII made **significant contributions** to charmed flavor physics and hadron physics.
- Charm (semi-)leptonic decays are crucial for calibrating lattice QCD; determining CKM matrix elements; and testing lepton flavor universality.

  $f_{D^+}\sim1.2\%$, $f_{D_s^+}\sim0.9\%$, $|V_{cd}|\sim1.2\%$, $|V_{cs}|\sim0.9\%$, $f_+^K(0)\sim0.23\%$
- Charm hadronic decays are key labs to understand non-perturbative QCD; study the properties of light hadron ($a_0(980)$, $f_0(980)$, $f_0(500)$…); and provide crucial inputs to model-independent determination of γ and charm mixing/CPV

  Strong-phase measurement: 0.9° on γ ($<0.5^\circ$ with 20fb^{-1})
- BESIII's Future prospects

  → More interesting results are coming using $20.3\ \text{fb}^{-1}\ \psi(3770)$ data.

  → BEPCII-U will extend the lifetime of BESIII (**will continue to run till ~2030**).
  3× luminosity above 4 GeV & max energy to 5.6 GeV

谢谢！