Charmed meson hadronic decays at BESIII

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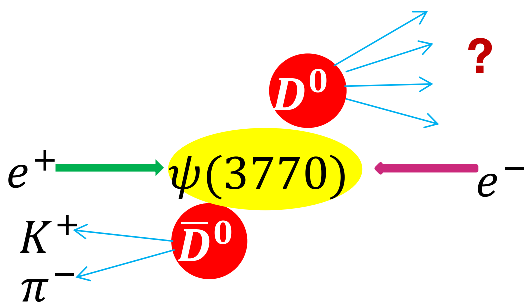
BESIII Data Taken near Threshold

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

Production of charm hadron pair



Tag one side to study another side

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

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

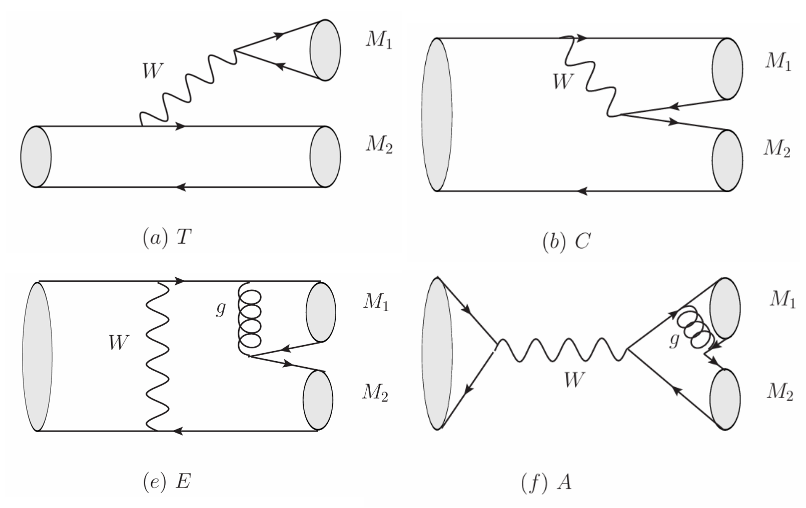
Absolute branching fraction

Amplitude analysis

etc.

Why study hadronic decays of charmed mesons?

- **Topological Diagram Approach**



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

- **$D \to PP$: high efficiency, low background, no interference, (usually) high precision. Good for Acp, η - η' mixing etc..**

- **$D \to SP$, $D \to SV$, ($D \to SS$): Understand the nature of light scalar mesons, $a_0(980), f_0(980)$, $K(700)$, $f_0(500)$ etc..**

- **$D \to VP$: Clarifying the nonperturbative mechanism. Well defined quark content of V. Better than the PP and VV, due to the multiple-amplitude composition of P and the polarization in VV.**

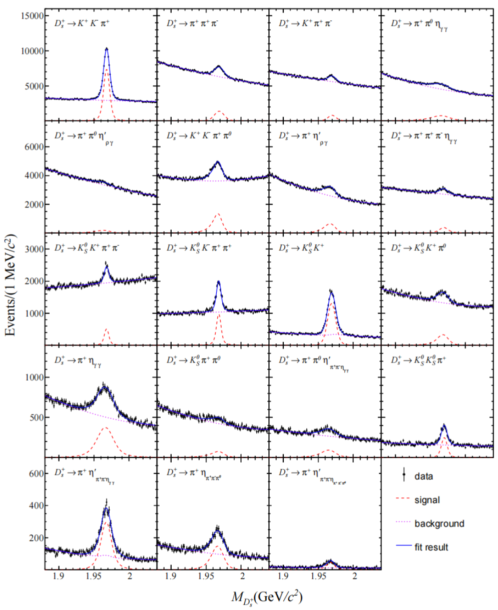
- **$D \to VV$: Polarization in charmed decays.**

- **$D \to AP$: Study axial-vector mesons, a1(1260) K1(1400)etc..**

D_s^+ hadronic decays

Method: Double Tag

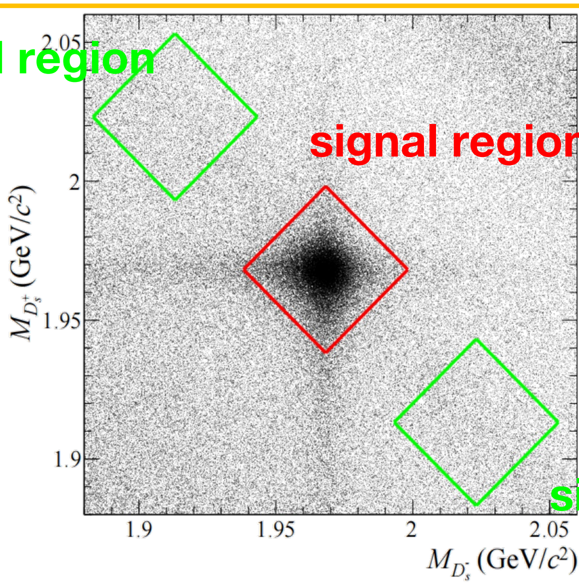
Data: 7.33 fb^{-1} 4.128 - 4.226 GeV



Mode
$D_s^+ \to K_S^0 K^+$
$D_s^+ \to K^+ K^- \pi^+$
$D_s^+ \to K_S^0 K^+ \pi^0$
$D_s^+ \to K_S^0 K_S^0 \pi^+$
$D_s^+ \to K^+ K^- \pi^+ \pi^0$
$D_s^+ \to K_S^0 K^+ \pi^+ \pi^-$
$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$
$D_s^+ \to \pi^+ \pi^+ \pi^-$
$D_s^+ \to \pi^+ \eta\ (\eta \to \gamma\gamma)$
$D_s^+ \to \pi^+ \pi^0 \eta\ (\eta \to \gamma\gamma)$
$D_s^+ \to \pi^+ \pi^+ \pi^- \eta\ (\eta \to \gamma\gamma)$
$D_s^+ \to \pi^+ \eta\ (\eta \to \pi^+ \pi^- \pi^0)$
$D_s^+ \to \pi^+ \eta'\ (\eta' \to \pi^+ \pi^- \eta,\ \eta \to \gamma\gamma)$
$D_s^+ \to \pi^+ \pi^0 \eta'\ (\eta' \to \pi^+ \pi^- \eta,\ \eta \to \gamma\gamma)$
$D_s^+ \to \pi^+ \eta'\ (\eta' \to \pi^+ \pi^- \eta,\ \eta \to \pi^+ \pi^+ \pi^0)$
$D_s^+ \to \pi^+ \eta'\ (\eta' \to \rho\gamma,\ \rho \to \pi^+ \pi^-)$
$D_s^+ \to \pi^+ \pi^0 \eta'\ (\eta' \to \rho\gamma,\ \rho \to \pi^+ \pi^-)$
$D_s^+ \to K_S^0 \pi^+ \pi^0$
$D_s^+ \to K^+ \pi^+ \pi^-$

tag

sig



JHEP 05(2024)335

Global fit

15 decay modes (19 final states)

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

much improved precision!!!

D_s^+ hadronic decays

Method: Double Tag

7.33 fb^{-1} 4.128 - 4.226 GeV

JHEP 05(2024)335

Numbers of producted $D_s^+ D_s^-$ pairs:

$\sqrt{s}$ (GeV)	$N^{D_s^+ D_s^-}$ ($\times 10^5$)
4.128 and 4.157	6.29±0.06±0.01
4.178	31.79±0.24±0.06
4.189	5.51±0.05±0.01
4.199	4.92±0.05±0.01
4.209	5.07±0.05±0.01
4.219	4.32±0.04±0.01
4.226	6.82±0.07±0.02

Provides important input for the relative BF measurements of BESIII.

$\mathcal{A}_{CP}$ calculation

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

No significant asymmetries are observed.

Achieved the desired goal of D_s^+ BF measurement!

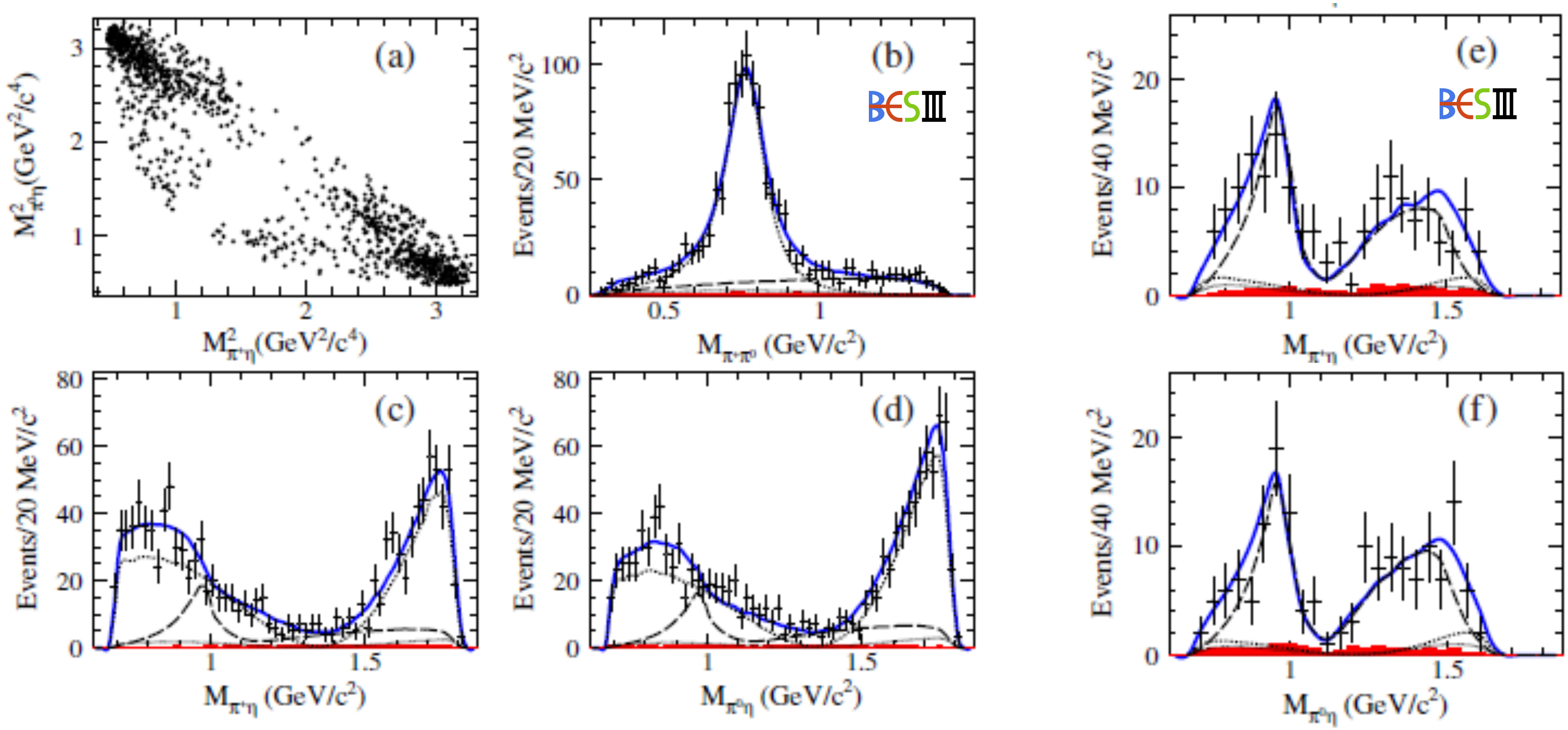
Amplitude analysis of $D_s^+ \to \pi^+\pi^0\eta$
- Observation of $D_s^+ \to a_0(980)\pi$

PRL123, 112001 (2019)

$D_s^+ \to \pi^+\pi^0\eta$

Full sample

Sub-sample with $M_{\pi^+\pi^0} > 1.0$ GeV/c^2



Dots with error bar: data; solid: total fit; dotted: $D_s^+ \to \rho^+\eta$; dashed: $D_s^+ \to a_0(980)\pi$ (**with a stat. significance of 16.2σ**).

Branching Fraction Results of $D_s^+ \to \pi^+\pi^0\eta$

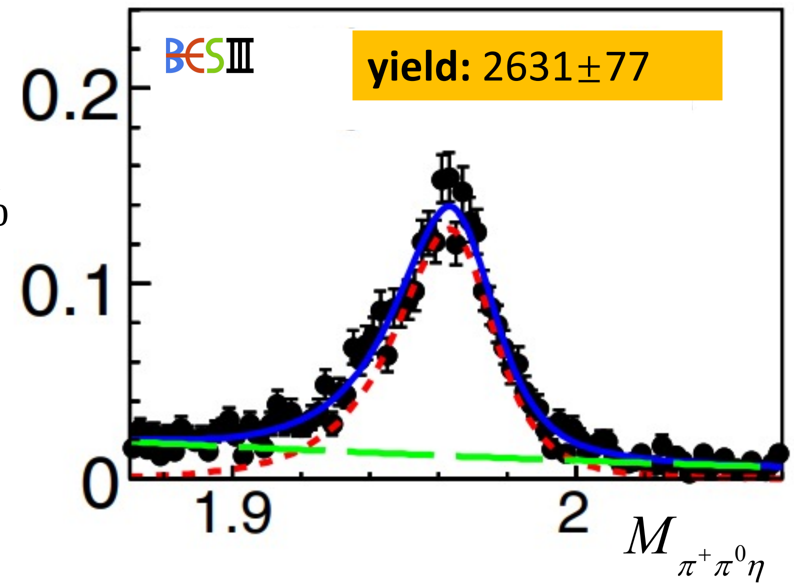
PRL123， 112001 （2019）

Fit to the invariant mass $M_{\pi^+\pi^0\eta}$ to get the yield.

$$\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta) = (9.50 \pm 0.28_{stat.} \pm 0.41_{syst.})\%$$

PDG value = $(9.2 \pm 1.2)\%$

BF(sub-mode n) = $\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta)FF(n)$



Branching fraction (%) BESIII
$\mathcal{B}(D_s^+ \to \rho^+\eta) = 7.44 \pm 0.52_{stat.} \pm 0.38_{sys.}$
$\mathcal{B}(D_s^+ \to a_0(980)^+\pi^0)^* = 1.46 \pm 0.15_{stat.} \pm 0.23_{sys.}$
$\mathcal{B}(D_s^+ \to a_0(980)^0\pi^+)^* = 1.46 \pm 0.15_{stat.} \pm 0.23_{sys.}$

*here, $a_0(980) \to \pi\eta$

PDG value = $(8.9 \pm 0.9)\%$

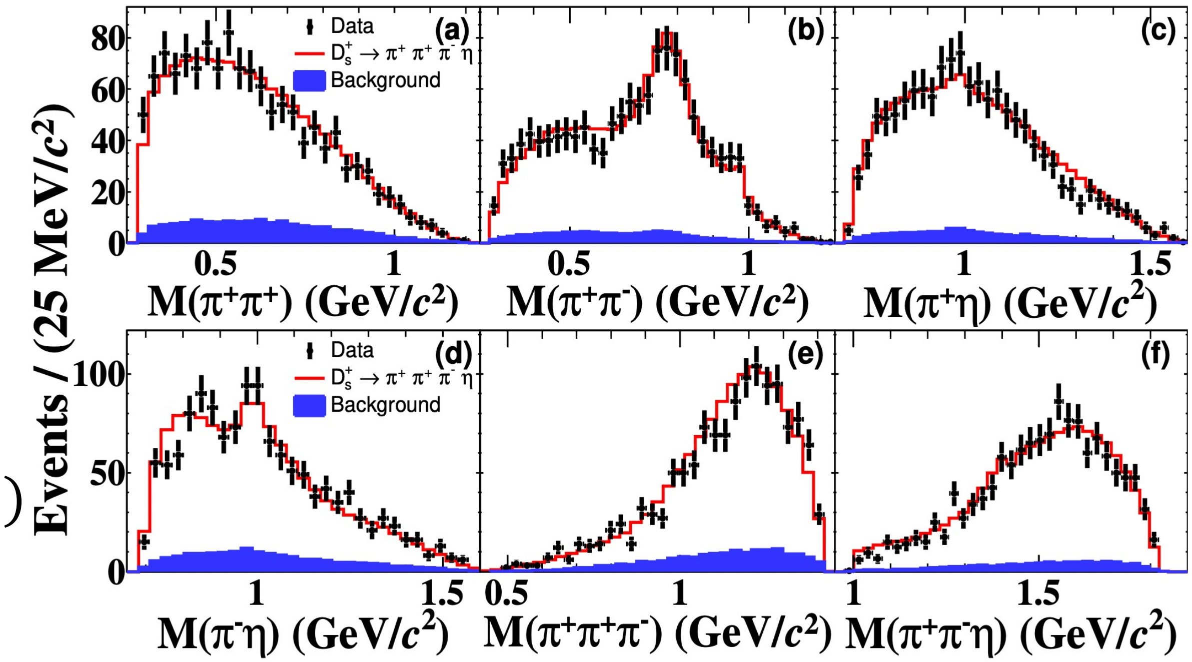
First observation !

- $\mathcal{B}(D_s^+ \to a_0(980)^+\pi^0$ is larger than other measured pure W-annihilation decays ($D_s^+ \to p\bar{n}$, $D_s^+ \to \omega\pi^+$) by one order.

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

2139 events with purity > 85%

PRD 104, L071101 (2021)



$\mathcal{B}(D_s^+ \to \pi^+\pi^+\pi^-\eta)$
$=(3.12\pm0.13\pm0.09)\%$

$\mathcal{B}(D_s^+ \to a_0^+(980)\rho^0, a_0^+(980) \to \pi^+\eta)$
$=(0.21\pm0.08\pm0.05)\%$

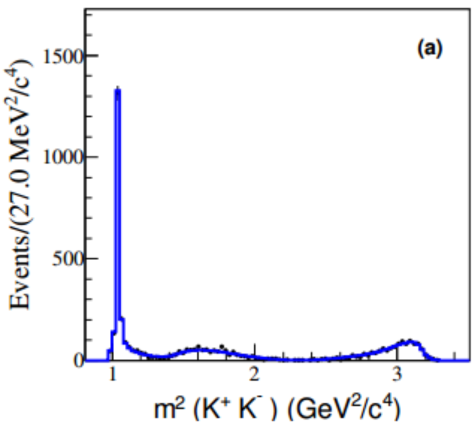
Amplitude	Phase	FF(%)
$a_1(1260)^+(\rho(770)^0\pi^+)\eta$	0.0(fixed)	$55.4 \pm 3.9 \pm 2.0$
$a_1(1260)^+(f_0(500)\pi^+)\eta$	$5.0 \pm 0.1 \pm 0.1$	$8.1 \pm 1.9 \pm 2.1$
$a_0(980)^+\rho(770)^0$	$2.5 \pm 0.1 \pm 0.1$	$6.7 \pm 2.5 \pm 1.5$
$\eta(1405)(a_0(980)^-\pi^+)\pi^+$	$0.2 \pm 0.2 \pm 0.1$	$0.7 \pm 0.2 \pm 0.1$
$\eta(1405)(a_0(980)^+\pi^-)\pi^+$	$0.2 \pm 0.2 \pm 0.1$	$0.7 \pm 0.2 \pm 0.1$
$f_1(1420)(a_0(980)^-\pi^+)\pi^+$	$4.3 \pm 0.2 \pm 0.4$	$1.9 \pm 0.5 \pm 0.3$
$f_1(1420)(a_0(980)^+\pi^-)\pi^+$	$4.3 \pm 0.2 \pm 0.4$	$1.7 \pm 0.5 \pm 0.3$
$[a_0(980)^-\pi^+]_S\pi^+$	$0.1 \pm 0.2 \pm 0.2$	$5.1 \pm 1.2 \pm 0.9$
$[a_0(980)^+\pi^-]_S\pi^+$	$0.1 \pm 0.2 \pm 0.2$	$3.4 \pm 0.8 \pm 0.6$
$[f_0(980)\eta]_S\pi^+$	$1.4 \pm 0.2 \pm 0.3$	$6.2 \pm 1.7 \pm 0.9$
$[f_0(500)\eta]_S\pi^+$	$2.5 \pm 0.2 \pm 0.3$	$12.7 \pm 2.6 \pm 2.0$

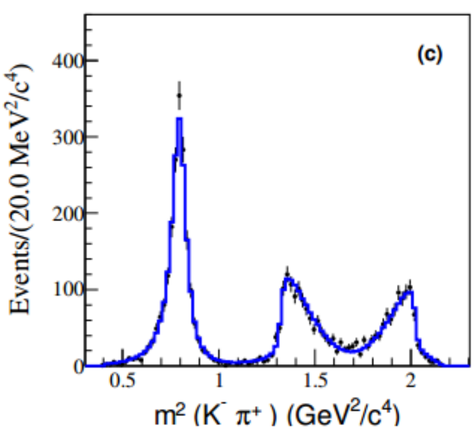
Larger than other w-annihilation decays.

How about $D_s^+ \to a_0^+(980)\rho^0$? Does it have the same branching fraction?

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

Dalitz plot projections:





Black dots with error bars: data

Blue solid lines: fit results

PRD 104. 012016 (2021)

The best precision at present

$$\mathcal{B}(D_s^+ \to K^+K^-\pi^+) = (5.47 \pm 0.08_{stat.} \pm 0.13_{syst.})\%$$

Process	BF (%) BESIII (this analysis)	BF (%) PDG
$D_s^+ \to \bar{K}^*(892)^0 K^+$, $\bar{K}^*(892)^0 \to K^-\pi^+$	$2.64 \pm 0.06_{\rm stat} \pm 0.07_{\rm sys}$	2.58 ± 0.08
$D_s^+ \to \phi(1020)\pi^+$, $\phi(1020) \to K^+K^-$	$2.21 \pm 0.05_{\rm stat} \pm 0.07_{\rm sys}$	2.24 ± 0.08
$D_s^+ \to S(980)\pi^+$, $S(980) \to K^+K^-$	$1.05 \pm 0.04_{\rm stat} \pm 0.06_{\rm sys}$	1.14 ± 0.31
$D_s^+ \to \bar{K}_0^*(1430)^0 K^+$, $\bar{K}_0^*(1430)^0 \to K^-\pi^+$	$0.16 \pm 0.03_{\rm stat} \pm 0.03_{\rm sys}$	0.18 ± 0.04
$D_s^+ \to f_0(1710)\pi^+$, $f_0(1710) \to K^+K^-$	$0.10 \pm 0.02_{\rm stat} \pm 0.03_{\rm sys}$	0.07 ± 0.03
$D_s^+ \to f_0(1370)\pi^+$, $f_0(1370) \to K^+K^-$	$0.07 \pm 0.02_{\rm stat} \pm 0.01_{\rm sys}$	0.07 ± 0.05
$D_s^+ \to K^+K^-\pi^+$ total BF	$5.47 \pm 0.08_{\rm stat} \pm 0.13_{\rm sys}$	5.39 ± 0.15

Both $a_0(980)$ and $f_0(980)$ decays to K^+K^-.
Impossible to separate them here

Isospin configurations:

$a_0(980)$ I=1 $\to$ ($|K^+K^- >$ - $|K^0\overline{K^0} >$)

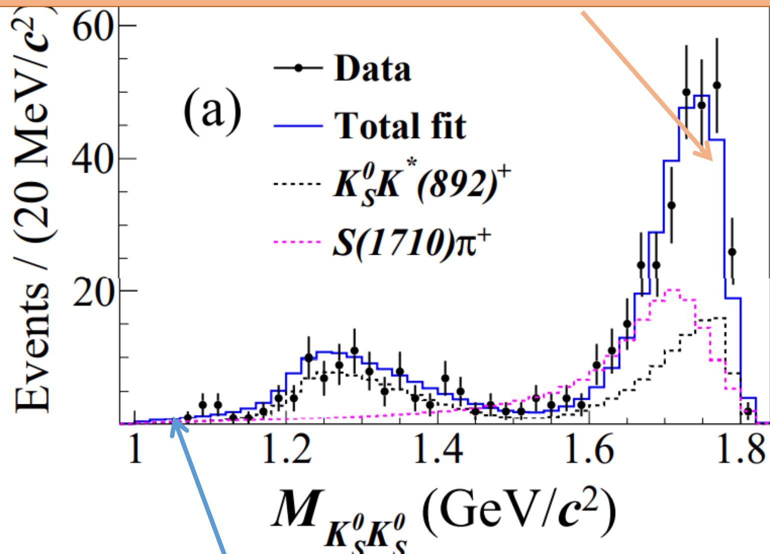
$f_0(980)$ I=0 $\to$ ($|K^+K^- >$ + $|K^0\overline{K^0} >$)

The comparison of K^+K^- and $K_S^0K_S^0$ spectrum will reveal more information!

Observation of new a_0-like triplet in D_s decays

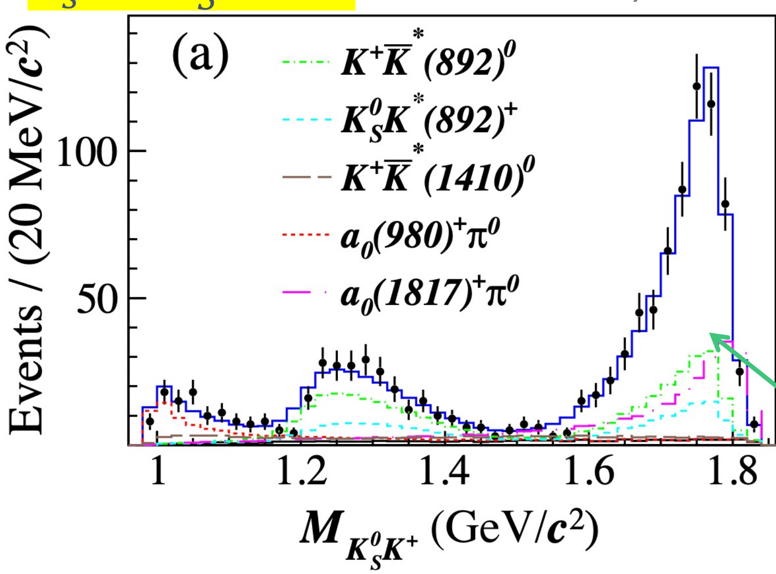
$D_s^+ \to K_S^0 K_S^0 \pi^+$ PRD 105, L051103

constructive interference: new neutral a_0-like and $f_0(1710)$



destructive interference: $a_0(980)$ and $f_0(980)$

$D_s^+ \to K_S^0 K^+ \pi^0$ PRL 129, 182001



[1] Eur. Phys. J. C 82, 225 (2022).
[2] Phys.Rev. D105, 114014 (2022).
[3] PRD 104, 072002 (2021)

A new a_0 isospin triplet!

Amplitude	BF (10^{-3})
$D_s^+ \to \bar{K}^*(892)^0 K^+$	$4.77 \pm 0.38 \pm 0.32$
$D_s^+ \to K^*(892)^+ K_S^0$	$2.03 \pm 0.26 \pm 0.20$
$D_s^+ \to a_0(980)^+ \pi^0$	$1.12 \pm 0.25 \pm 0.27$
$D_s^+ \to \bar{K}^*(1410)^0 K^+$	$0.88 \pm 0.21 \pm 0.19$
$D_s^+ \to a_0(1817)^+ \pi^0$	$3.44 \pm 0.52 \pm 0.32$

- Double tag method
- $D_s^+ \to a_0(1817)^+\pi^0$ is observed for the first time
- Significance $> 10\sigma$
- M=$1.817 \pm 0.008 \pm 0.020$ GeV/c^2
- Γ= $0.097 \pm 0.022 \pm 0.015$ GeV/c^2

- The isovector partner of $f_0(1710)$[1] or $X(1812)$?[2]
- Same resonance observed in η_c to $\pi\pi\eta$ by BaBar[3]?

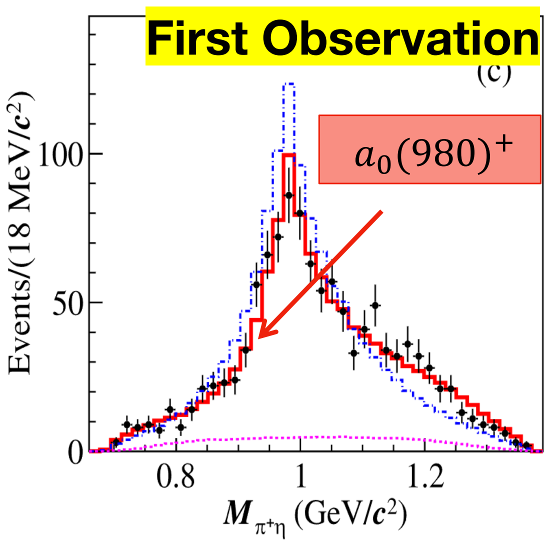
new charged a_0-like in $K_S^0 K^+$ mass spectrum

Study of $D^+ \to K_S^0 a_0(980)^+$

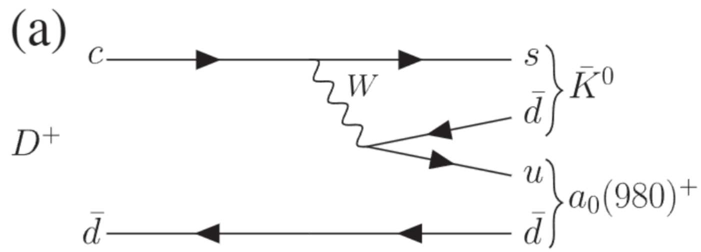
PRL 132, 131903 (2024)

Among $D \to$ SP, $D^+ \to K_S^0 a_0(980)^+$ is, except $\kappa\pi$, the only decay free of weak-annihilation contributions.

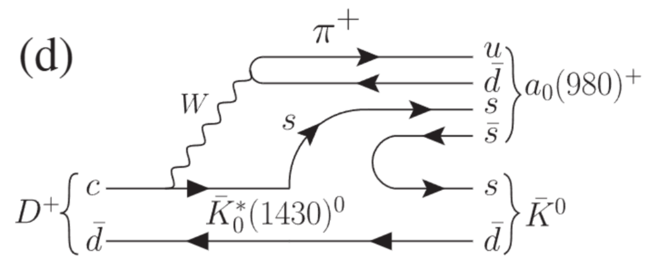
2.93fb^{-1}@E_{cm}=3.773 GeV
1113 candidates with 98.2% purity



two-quark
internal W-emission



tetraquark state-
rescattering



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

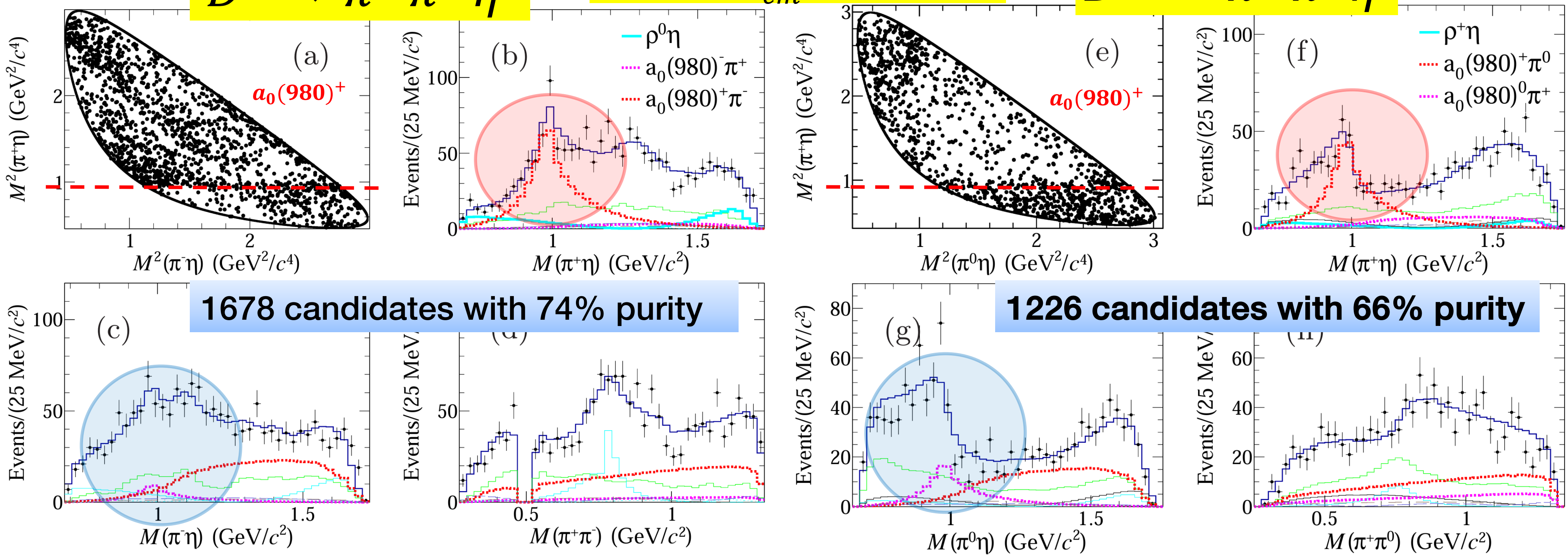
- $\mathcal{B}(D^+ \to K_S^0 a_0(980)^+, a_0(980)^+ \to \pi^+\eta) = (1.33 \pm 0.05_{stat} \pm 0.04_{syst})\%$
- **Provide sensitive constraints in the extraction of contributions from external and internal W-emission diagrams of $D \to SP$**
- Understand the inconsistency between theory and experiment of the $D \to a_0(980)^+ P$[1-3].

[1]Phys. Rev. D 105, 033006 (2022).
[2]Phys. Rev. D 67, 034024 (2003).
[3] Phys. Rev. D 81, 074031 (2010)

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

Phys. Rev. D 110, L111102 (2024)

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



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

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

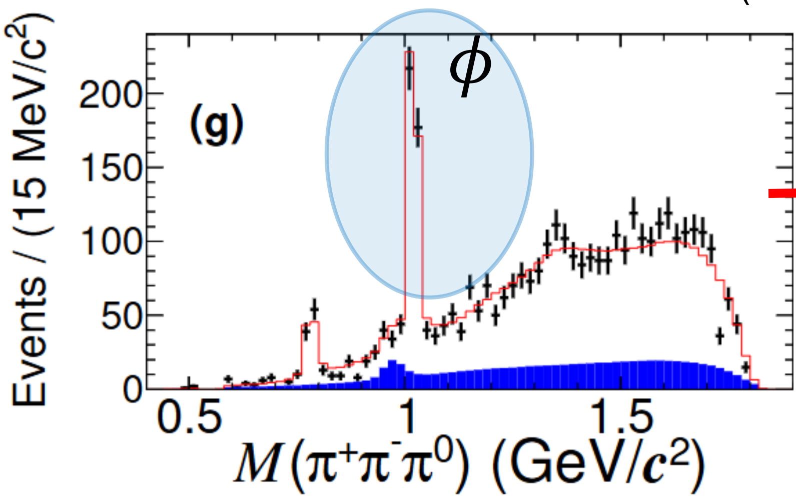
The external W-emission dominates the $D \to a_0(980)\pi$ decays in the diquark scenario, contrary to expectations of its negligible contribution due to the very small $a_0(980)$ decay constant[1].

- $\mathcal{B}(D^0 \to \pi^+\pi^-\eta) = (1.24 \pm 0.04_{stat} \pm 0.03_{syst})\%$
- $\mathcal{B}(D^+ \to \pi^+\pi^0\eta) = (2.18 \pm 0.12_{stat} \pm 0.03_{syst})\%$

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

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

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

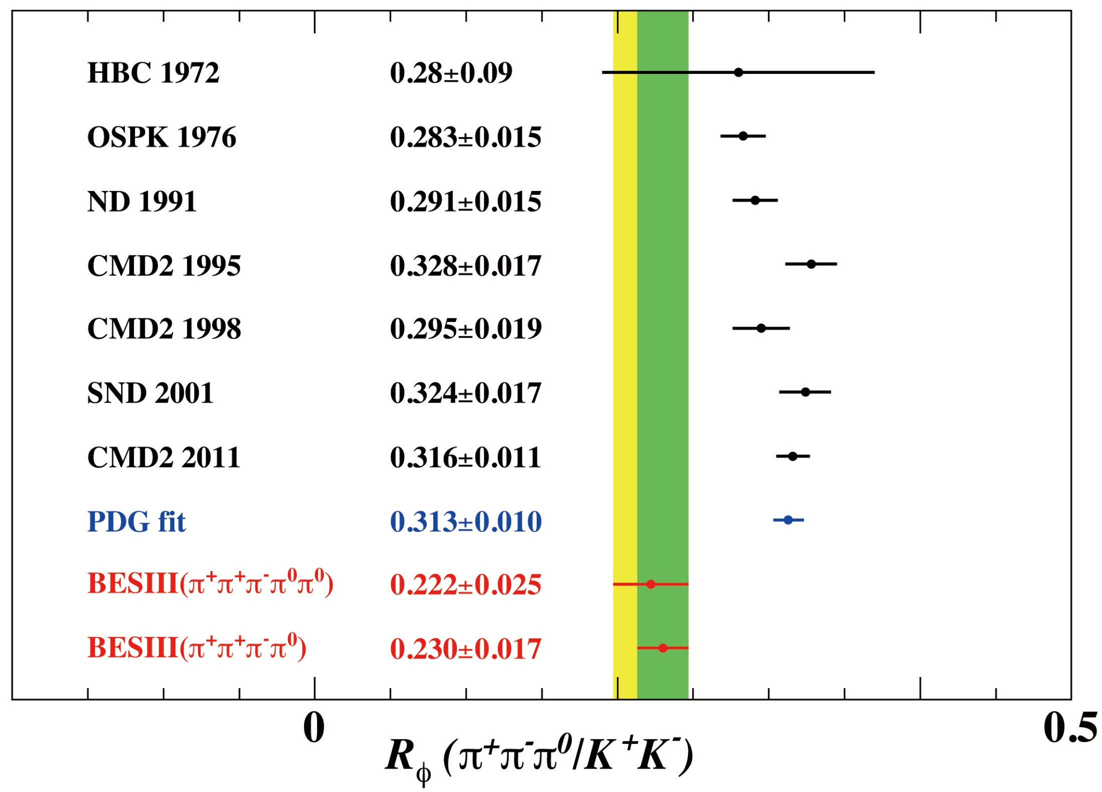


First Measurement

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

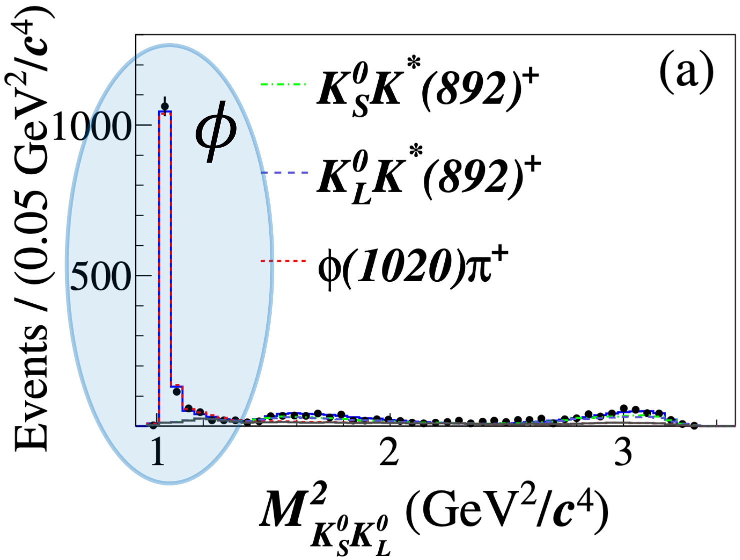
- $\mathcal{B}(D_s^+ \to \phi\pi^+, \phi \to \pi^+\pi^-\pi^0) = (5.08 \pm 0.32 \pm 0.10)\times 10^{-3}$
- $\mathcal{B}(D_s^+ \to \phi\pi^+, \phi \to K^+K^-) = (2.21 \pm 0.05 \pm 0.07)\%$

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



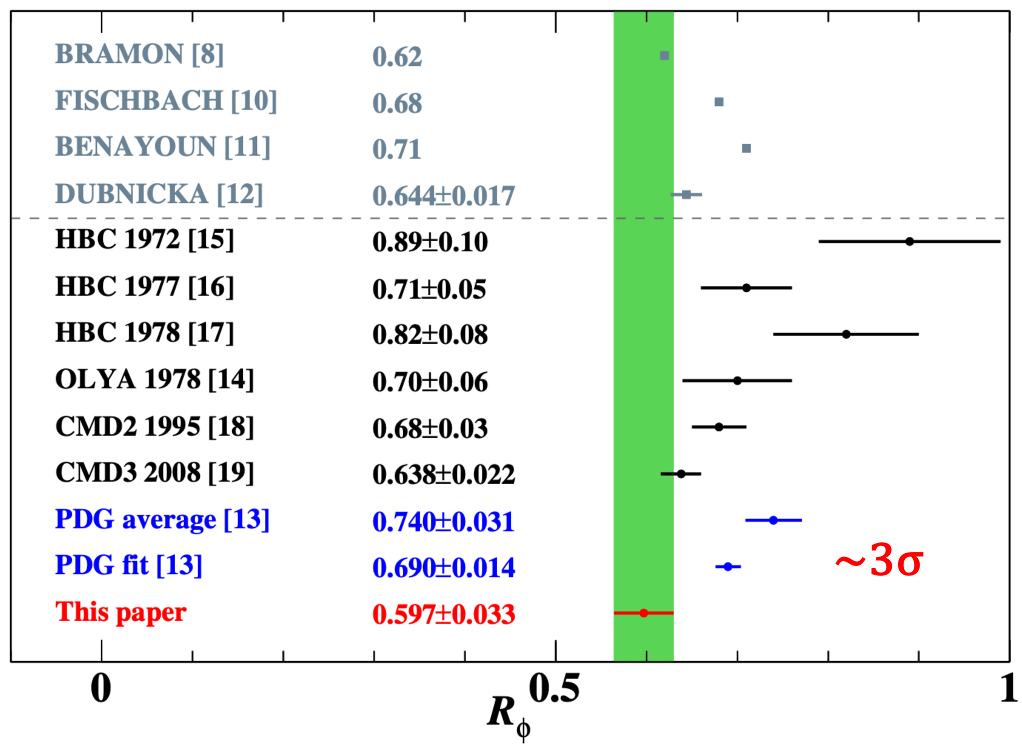
Study of $D_s^+ \to \phi(K_S^0 K_L^0)\pi^+$

$D_s^+ \to K_S^0 K_L^0 \pi^+$ arXiv:2503.11383



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

$$\mathcal{B}(\phi \to K_S^0 K_L^0)/\mathcal{B}(\phi \to K^+ K^-)$$



Test KS-KL asymmetry

$$\frac{\mathcal{B}(D_s^+ \to K_S^0 K^*(892)^+) - \mathcal{B}(D_s^+ \to K_L^0 K^*(892)^+)}{\mathcal{B}(D_s^+ \to K_S^0 K^*(892)^+) + \mathcal{B}(D_s^+ \to K_L^0 K^*(892)^+)}$$

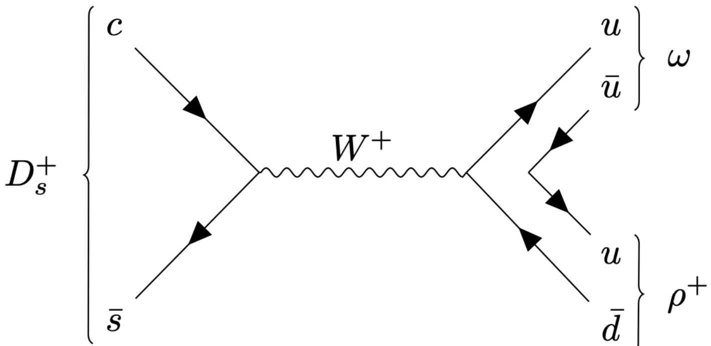
$$(-13.4 \pm 5.0_{\rm stat} \pm 3.4_{\rm syst})\%$$

Interefrence of CF and DCS decays

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

PRL 134, 201902

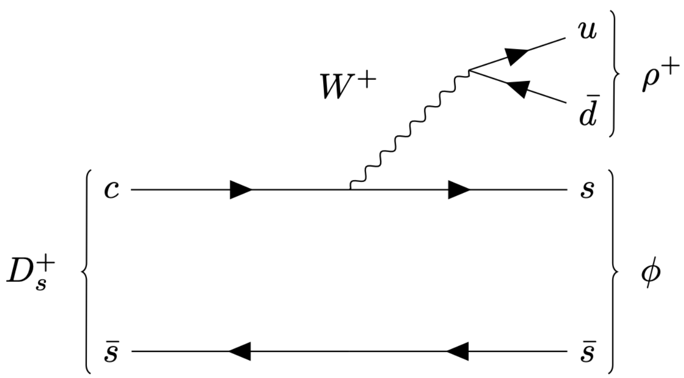
First observation.
Larger than other WA decays



Pure W-annihilation

$$\mathcal{B}(D_s^+ \to \omega\rho^+) = (0.99 \pm 0.08 \pm 0.07)\%$$

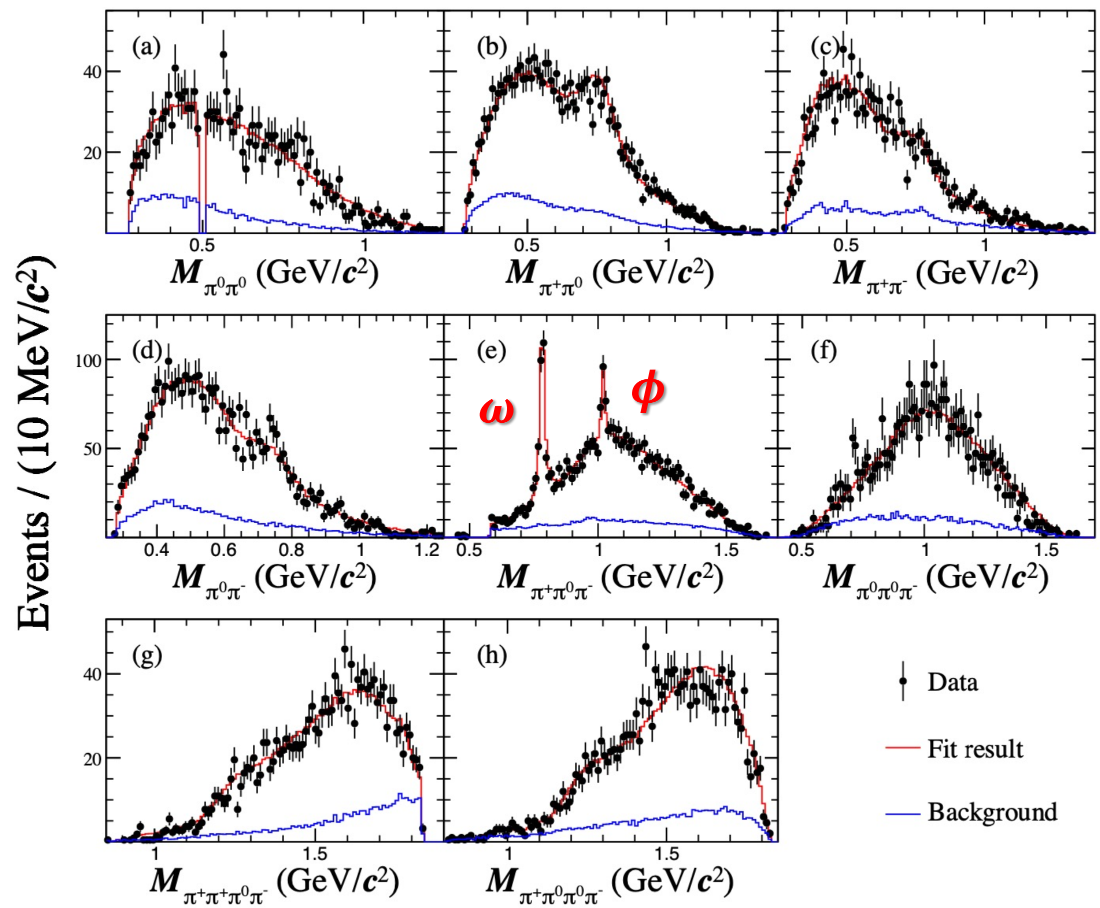
about 50% D-wave



Pure external W emission

$$\mathcal{B}(D_s^+ \to \phi\rho^+) = (3.98 \pm 0.33 \pm 0.21)\%$$

doninated by S-wave



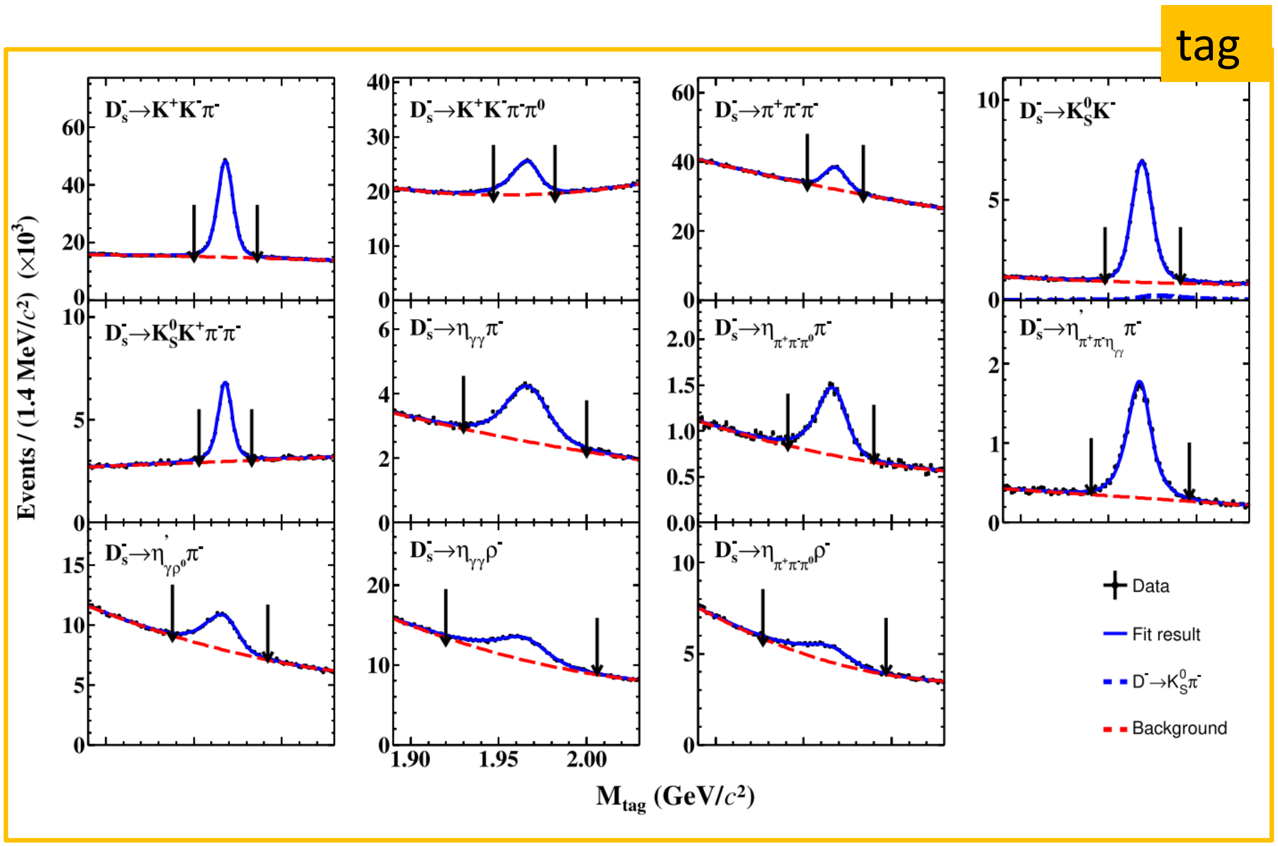
- $\frac{\mathcal{B}(\phi\to\pi^+\pi^-\pi^0)}{\mathcal{B}(\phi\to K^+K^-)} = 0.222 \pm 0.019_{stat} \pm 0.016_{syst}$
- $> 3\sigma$ from PDG value(0.313 ± 0.010) %

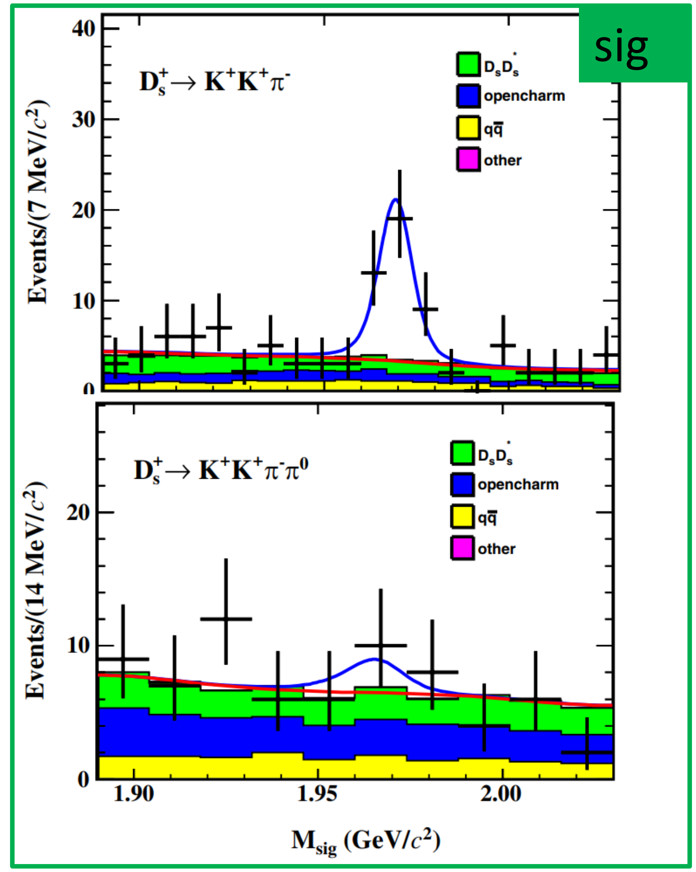
$D_s^+ \to K^+K^+\pi^-(\pi^0)$

Phys. Rev. D 109, 032011 (2024)

Data: 7.33 fb^{-1} 4.128 - 4.226 GeV

--Doubly Cabibbo-suppressed (DCS) decays





DCS decay	$\mathcal{B}_{DCS}^{this\ work}$ ($\times 10^{-4}$)	CF decay	$\mathcal{B}_{CF}^{PDG}$ ($\times 10^{-2}$)	$\mathcal{B}_{DCS}^{this\ work}/\mathcal{B}_{CF}^{PDG}$ ($\times 10^{-3}$)	$\times \tan^4\theta_C$
$D_s^+ \to K^+K^+\pi^-$	$1.24^{+0.28}_{-0.26} \pm 0.06$	$D_s^+ \to K^+K^-\pi^+$	5.37 ± 0.10	$2.31^{+0.52}_{-0.48}$	$0.80^{+0.18}_{-0.16}$
$D_s^+ \to K^+K^+\pi^-\pi^0$	< 1.7	$D_s^+ \to K^+K^-\pi^+\pi^0$	5.50 ± 0.24	< 3.09	< 1.07

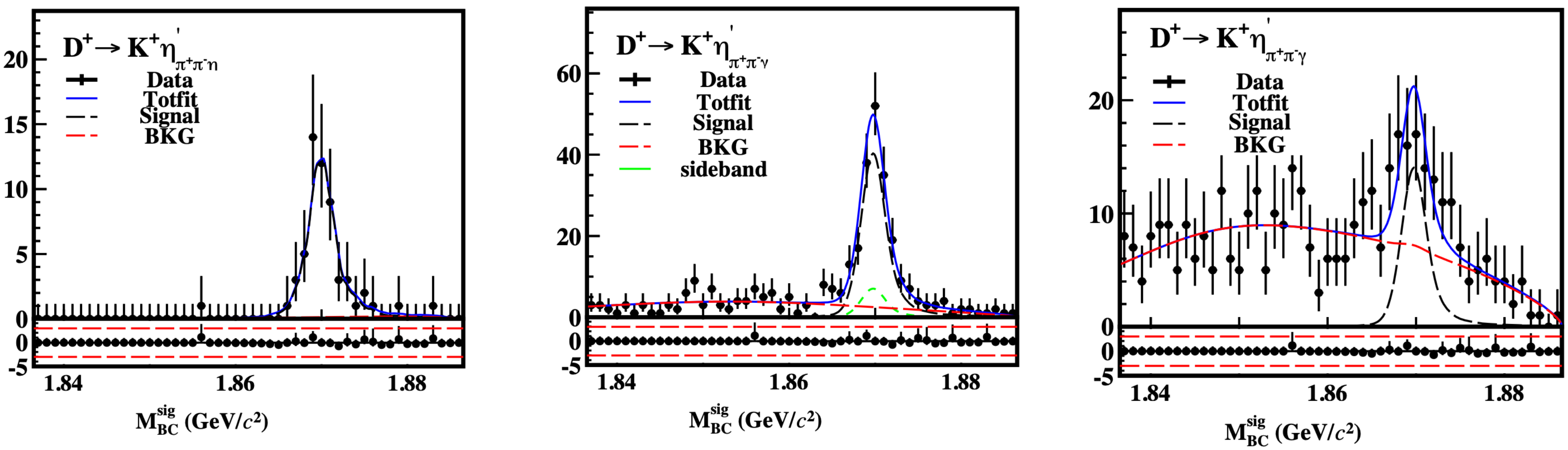
$D_s^+ \to K^+K^+\pi^-$: $33.3^{+7.6}_{-6.9}$ signal events, $D_s^+ \to K^+K^+\pi^-\pi^0$: No significant signal.

$D^+ \to K^+\pi^0, K^+\eta, K^+\eta'$

arXiv:2506.15533

Data: 20.3 fb^{-1} 3.773 GeV

--Doubly Cabibbo-suppressed (DCS) decays



Signal decay	$D^+ \to K^+\pi^0$	$D^+ \to K^+\eta$	$D^+ \to K^+\eta'$
CLEO [12]	$2.28 \pm 0.36 \pm 0.17$	...	...
Belle [13]	...	$1.15 \pm 0.16 \pm 0.05$	$1.87 \pm 0.19 \pm 0.05$
BaBar [14]	$2.52 \pm 0.47 \pm 0.26$	...	...
BESIII [15]	$2.32 \pm 0.21 \pm 0.06$	$1.51 \pm 0.25 \pm 0.14$	$1.64 \pm 0.51 \pm 0.24$
PDG [16]	2.08 ± 0.21	1.25 ± 0.16	1.85 ± 0.20
DASU(3)L [1]	1.59 ± 0.15	0.98 ± 0.04	0.91 ± 0.17
TASU(3)B [2]	2.54 ± 0.06	1.04 ± 0.01	1.07 ± 0.01
GFRE [3]	2.2 ± 0.4	1.2 ± 0.2	1.0 ± 0.1
FDWC [4]	1.97	0.66	1.14
This work	$1.45 \pm 0.06 \pm 0.06$	$1.17 \pm 0.10 \pm 0.03$	$1.88 \pm 0.15 \pm 0.06$

Quantum Correlation

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

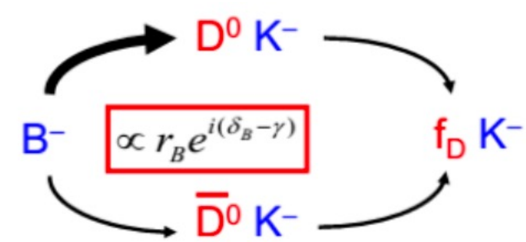
Best laboratory to measure strong-phase parameters

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

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

CP-even eigenstate

CP-odd eigenstate



- **Inputs for CPV studies at B experiments**
- **The CKM angle γ/ϕ_3:**

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

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

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

Determination of $\delta_D^{K\pi}$

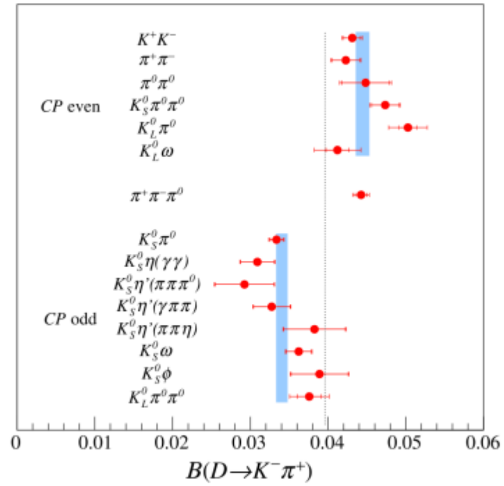
- **An update measurement of the asymmetry between CP-odd and CP-even eigenstate decays into $K^-\pi^+$**

30% more precise ！

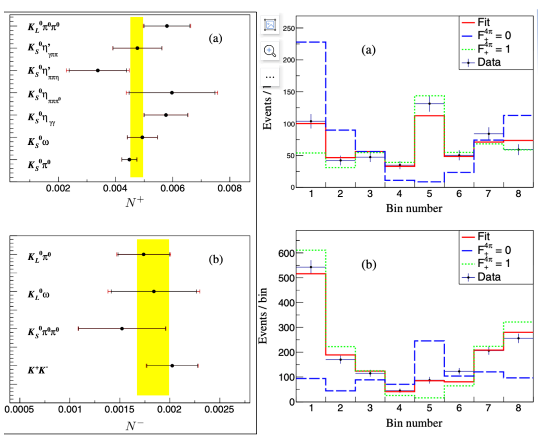
$$\mathcal{A}_{K\pi} \equiv \frac{\mathcal{B}(D_- \to K^-\pi^+) - \mathcal{B}(D_+ \to K^-\pi^+)}{\mathcal{B}(D_- \to K^-\pi^+) + \mathcal{B}(D_+ \to K^-\pi^+)} = \frac{-2r_D^{K\pi}\cos\delta_D^{K\pi} + y}{1 + \left(r_D^{K\pi}\right)^2} = 0.132 \pm 0.011 \pm 0.007$$

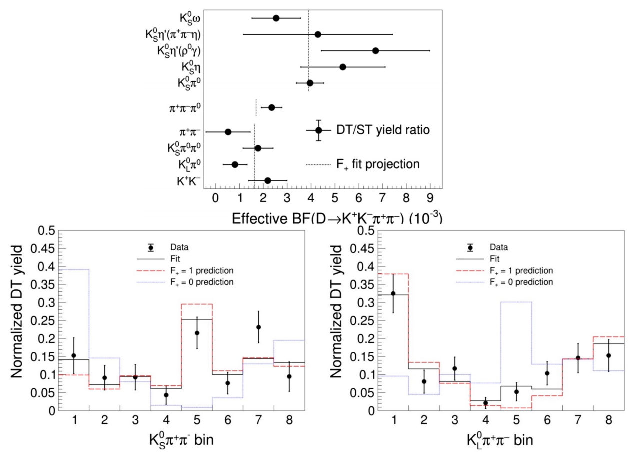
- $\delta_D^{K\pi}$=$(187.6^{+8.9+5.4}_{-9.7-6.4})$

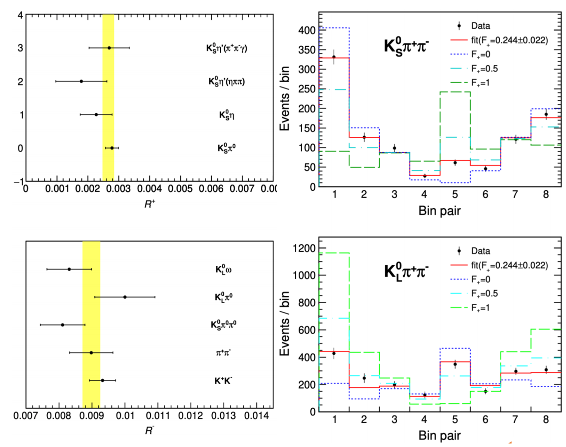
EPJC 82, 1009 (2022)



Determination of CP fraction







$D^0 \to \pi^+\pi^-\pi^+\pi^-$

$F_+ = 0.735 \pm 0.015 \ \pm 0.005$

PRD 106, 092004(2022)

$D^0 \to K^+K^-\pi^+\pi^-$

$F_+ = 0.730 \pm 0.037 \pm 0.021$

PRD 107, 032009(2023)

$D^0 \to K_S^0\pi^-\pi^+\pi^0$

$F_+ = 0.235 \pm 0.010 \pm 0.002$

PRD 108, 032003 (2023)

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

7.13 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

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

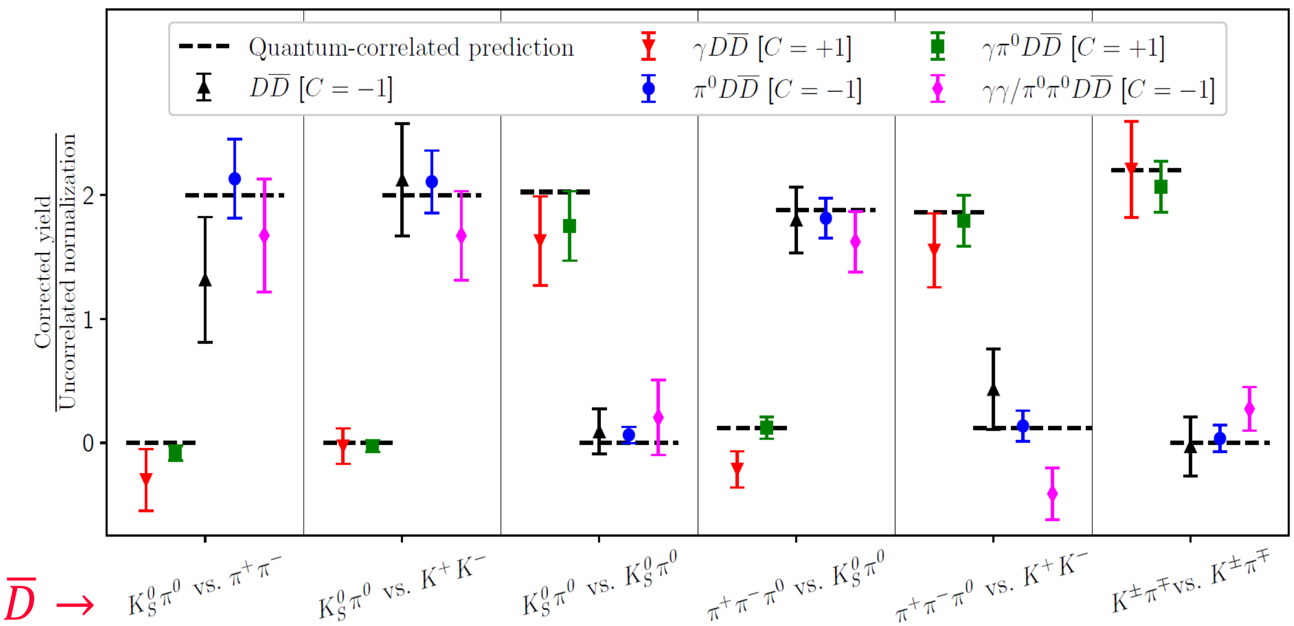
Production mechanism	C
$e^+e^- \to D\bar{D}$	-1
$e^+e^- \to D^*\bar{D} \to D\bar{D}\,\gamma$	$+1$
$e^+e^- \to D^*\bar{D} \to D\bar{D}\,\pi^0$	-1
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\,\gamma\gamma$	-1
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\,\pi^0\gamma$	$+1$
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\,\pi^0\pi^0$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

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

Contribute more statistics for quantum-correlation studies!!

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

κ=1: coherent
κ=0.5: incoherent



$D\bar{D} \to$

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

Measurement of $\delta_{K\pi}$

$7.13\ \mathrm{fb}^{-1}$ @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

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

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

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

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

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

- Extract $\delta_{K\pi}$

$$\delta^D_{K\pi} = \left(192.8^{+11.0+1.9}_{-12.4-2.4}\right)^\circ$$

agree with global average $\delta^D_{K\pi} = (190.2 \pm 2.8)^\circ$

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

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

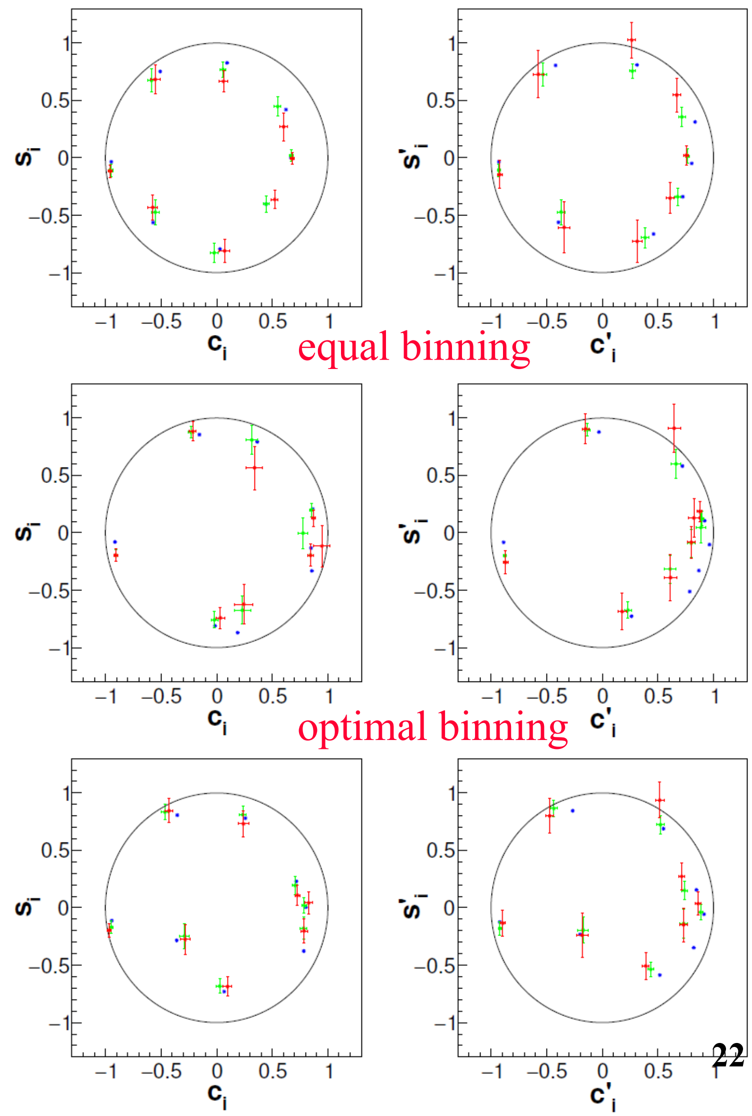
$$\delta^D_{K\pi} = \left(187.6^{+8.9+5.4}_{-9.7-6.4}\right)^\circ$$

[BESIII, EPJC 82,1009(2022)]

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

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

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



modified-optimal binning

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

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

$\to$ key input for direct measurement of CKM angle γ

Impact on the γ measurement

$\to$ Uncertainty: 0.9° with constraints

$\to$ Uncertainty: 1.5° without constraints

Statistical uncertainty of current γ measurement: 5°

[LHCb, JHEP02(2021)169]

Expected γ precision

Belle II [PTEP 2019, 123C01 (2019)]:
1.5° with 50 ab^{-1}
LHCb [LHCb-PUB-2016-025 (2016)]:
$< 1^\circ$ with 50 fb^{-1}, phase-1 upgrade (2030),
$< 0.4^\circ$ 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 $\to$ 0.5°

BESIII white paper

Summary & Outlook

- Charm hadronic decays are key labs to understand non-perturbative QCD
- The copious decay products also provide idea platform to investigate the natures of light mesons, such as $a_0(980)$, $f_0(980)$, $f_0(500)$, $a_1(1260)$, ϕ…
- Neutral DD pair 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})
- More interesting results are coming using 20.3 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

Thanks for your attention!