Amplitude analyses of multibody hadronic D decays at BESIII

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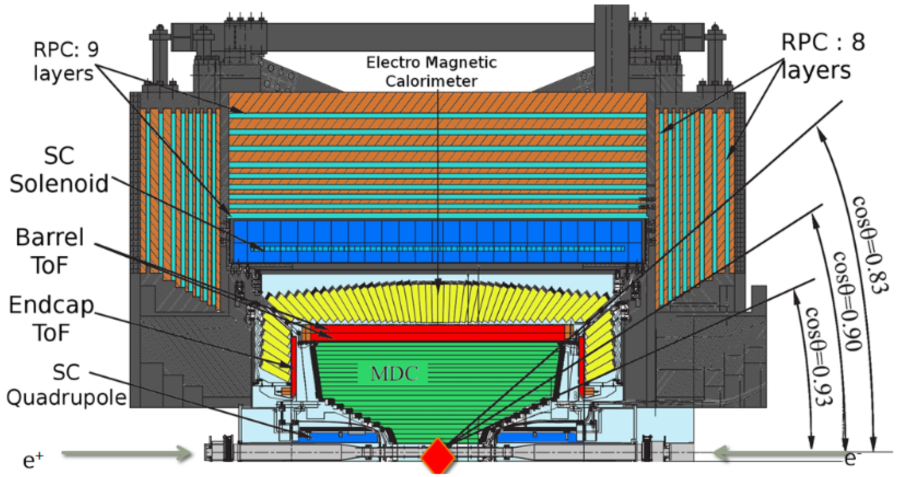
Outline

- Introduction
- Strategy
- Amplitude analyses and BF measurements
- Summary

Introduction

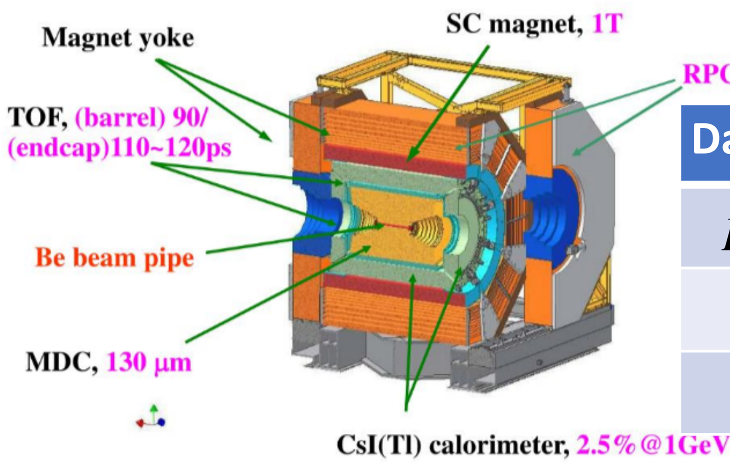
- Amplitude (Dalitz plot) analyses provide a method to study the hadronic decays of D_s^+/D^+.
  - Hadron spectroscopy & Structure of the resonance
  - Determine the phase of the intermediate mode
- Understand the dynamics of 2-body decays of D_s^+/D^+.
  - $D_s^+ \to SP$, $D_s^+ \to AP$, $D_s^+/D^+ \to VP$... (test $SU(3)_F$ symmetry)
- Reduce the systematic uncertainties related to the substructures in branching fraction measurement
- Analyses of
  - $D_s^+ \to K^-K^+\pi^+$ [arXiv:2011.08041]
  - $D_s^+ \to K_s^0\pi^+\pi^0$ [JHEP06(2021)181]
  - $D_s^+ \to K_s^0K^-\pi^+\pi^+$ [Phys. Rev. D **103**, 092006 (2021)]
  - $D_s^+ \to K^-K^+\pi^+\pi^0$ [arXiv:2103.02482]
  - $D_s^+ \to \eta\pi^+\pi^+\pi^-$ [arXiv:2106.13536]
  - $D^+ \to K_s^0K^+\pi^0$ [Phys. Rev. D **104**, 012006 (2021)]

Data sets



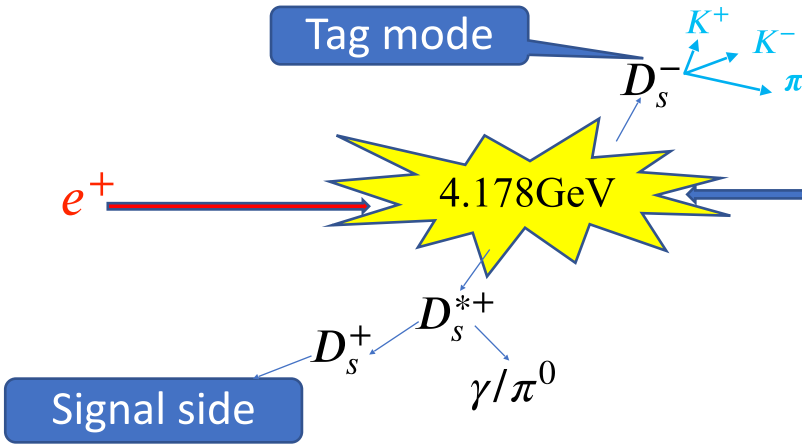
BESIII detector

- pair production at threshold
- Fully reconstructed event
- Almost free of background



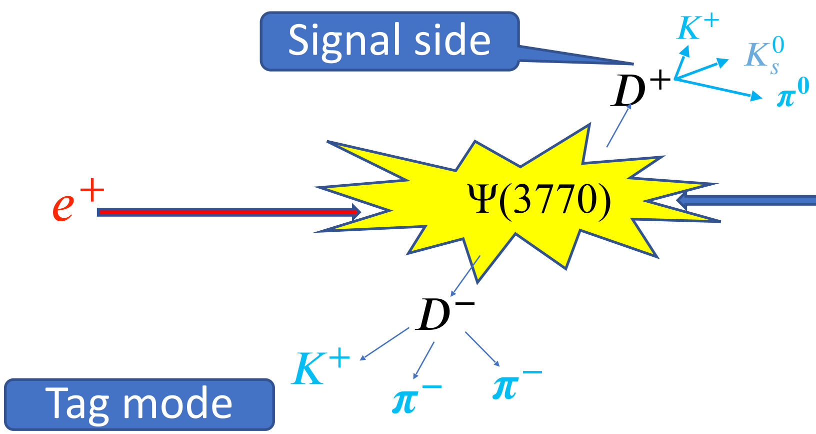
Data samples	(GeV)	Lum. ()	xCLEO-c
$D^0\bar{D}^0/D^-D^+$	3.773	2.93	3.6x
$D_sD_s^*$	4.178	3.19	5.3x
$D_sD_s^*$	4.189-4.226	3.13	-

Double tag technique



Tag mode: $M_{rec} = \sqrt{(E_{cm} - \sqrt{\vec{p}^2_{D_s} + m^2_{D_s}})^2 - |\vec{p}_{D_s}|^2},$

Double tag: $\mathscr{B}_{sig} = \dfrac{Y^{\alpha}_{DT}}{\sum_{\alpha} Y^{\alpha}_{ST} \bullet \frac{\varepsilon^{\alpha}_{DT}}{\varepsilon^{\alpha}_{ST}}}$



Tag mode: $M^{\text{tag}}_{\text{BC}} \equiv \sqrt{E^2_{\text{beam}}/c^4 - \boldsymbol{p}^2_{D^-}/c^2}$

$\Delta E_{\text{tag}} = E_{D^-} - \text{E}_{\text{beam}}$

signal side: $\Delta E_{\text{sig}} = E_{D^+} - \text{E}_{\text{beam}}$

DT method

- **M(D_s)**
- **Background analysis**
  - **MC simulation**
  - **sideband**
  - **multivariate analysis**
- **Description of signal spectrum (M(D_s))**
  - **MC shape ⊗ Gaussian**
  - **MC shape or polynomial for background**

Tag mode	M_{tag} (GeV/c^2)
$D_s^- \to K_S^0 K^-$	[1.948, 1.991]
$D_s^- \to K^+ K^- \pi^-$	[1.950, 1.986]
$D_s^- \to K_S^0 K^- \pi^0$	[1.946, 1.987]
$D_s^- \to K^+ K^- \pi^- \pi^0$	[1.947, 1.982]
$D_s^- \to K_S^0 K^- \pi^- \pi^+$	[1.958, 1.980]
$D_s^- \to K_S^0 K^+ \pi^- \pi^-$	[1.953, 1.983]
$D_s^- \to \pi^- \eta_{\gamma\gamma}$	[1.930, 2.000]
$D_s^- \to \pi^- \eta'_{\pi^-\pi^+\eta_{\gamma\gamma}}$	[1.940, 1.996]

- ΔE_{tag}
- M_{BC}^{tag}: **within (1.863, 1.879) GeV/c^2**

Tag mode	ΔE_{tag} (GeV)
$D^- \to K^+ \pi^- \pi^-$	[-0.022, 0.021]
$D^- \to K^+ \pi^- \pi^- \pi^0$	[-0.060, 0.034]
$D^- \to K_s^0 \pi^-$	[-0.019, 0.021]
$D^- \to K_s^0 \pi^- \pi^0$	[-0.071, 0.041]
$D^- \to K_s^0 \pi^+ \pi^- \pi^-$	[-0.025, 0.023]
$D^- \to K^+ K^- \pi^-$	[-0.019, 0.018]

Formalism

- **Amplitude analysis:**
  - **Unbinned maximum likelihood Fit:**
    - PDF = $f_s S + (1-f_s)B = \epsilon(p_j)R_4(p_j)[f_s \frac{|A_{D_s}(a_i,p_j)|^2}{\int \epsilon(p_j)|A_{D_s}(a_i,p_j)|^2 R_4(p_j)dp_j} + (1-f_s)\frac{B_\epsilon(p_j)}{\int B(p_j)R_4(p_j)dp_j}]$

Bkg function (RooNDKeysPdf)

Acceptance function

MC integration

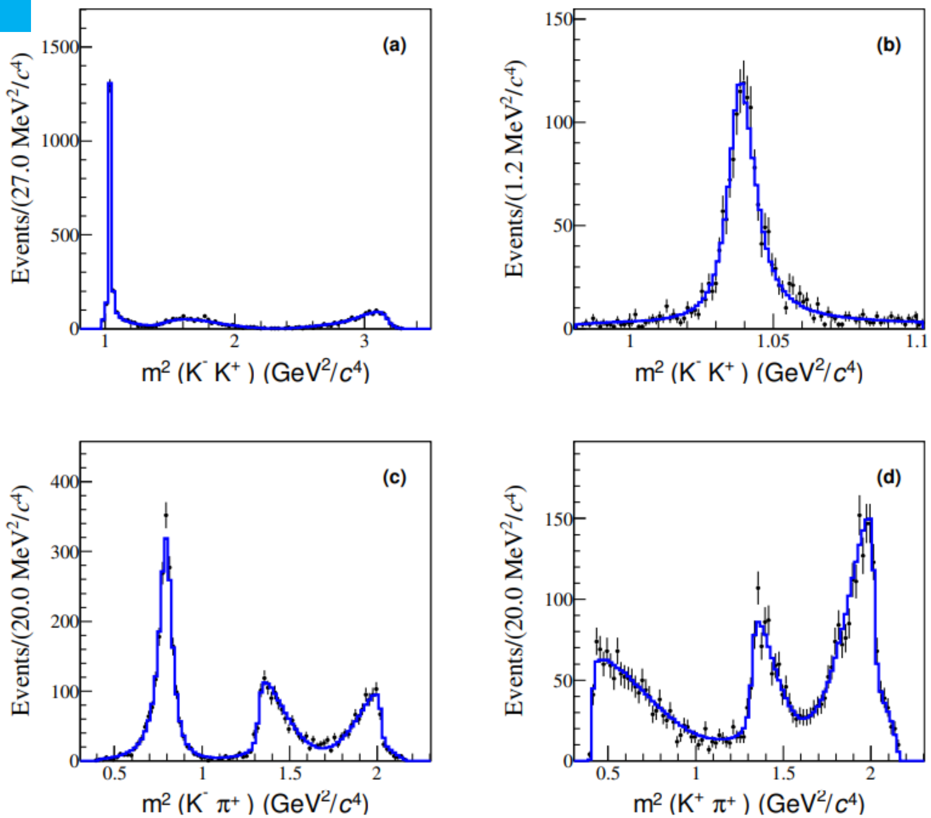
$B_\epsilon = B/\epsilon$

$For\, D^+ \to K_s^0 K^+ \pi^0,\ f_s = 1$

  - $A_{D_s \to sig} = \Sigma_n c_n A_n,\ c_n = \rho_n e^{i\phi_n}$
  - **Covariant tensor formalism**
  - $A_n = P_n^1 P_n^2 S_n F_n^1 F_n^2 F_n^{D_s}$, P_n^i **propagator,** F_n^i **barrier,** S_n **angular distribution.**
  - **Log-likelihood:**
    - $\ln\mathcal{L}_{total} = \Sigma_k^{N_{data}} \ln(f_s S(p_k) + (1-f_s)B(p_k))$. RooNDKeysPdf
  - **For** $D_s^+ \to \pi^+\pi^0\eta$**:**
    - $\ln\mathcal{L}_{total} = \Sigma_k^{N_{data}} \ln(S(p_k)) - \Sigma_k^{N_{data}} w_{bkg}^k \ln(S(p_k))$ adding the negative weight
- **BF Measurement**
  - **Update the MC samples with the results of amplitude analysis.**
  - **Looser selection criteria, more statistics.**

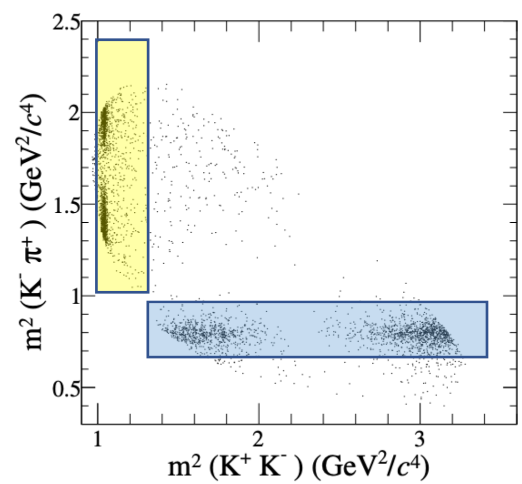
Amplitude analysis of $D_s^+ \to K^- K^+ \pi^+$

arXiv:2011.08041



4397 DT events with a purity of 99.6%@ $\sqrt{s} = 4.178$ GeV

- **$D_s^+ \to K^- K^+ \pi^+$ is a golden channel which is often used as the normalization mode.**
- **BF of $D_s^+ \to f_0(980)\pi^+$**
  PRD 79, 072008 (CLEO-c)
  PRD 83, 052001 (BABAR)
- **Do not distinguish between $f_0(980)/a_0(980)$**
- **Background free**

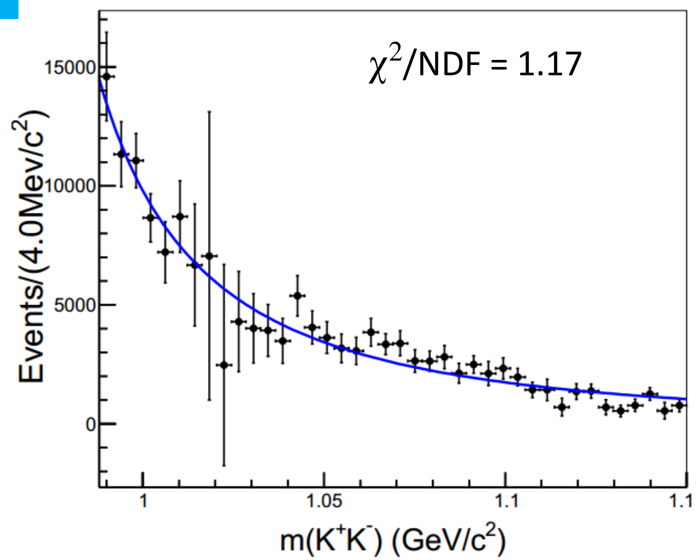


Fit model: χ^2/ndf = 290/280

Amplitude	BABAR	CLEO	BESIII (this analysis)
$D_s^+ \to \bar{K}^*(892)^0 K^+$	47.9±0.5±0.5	47.4±1.5±0.4	48.3±0.9±0.6
$D_s^+ \to \phi(1020)\pi^+$	41.4±0.8±0.5	42.2±1.6±0.3	40.5±0.7±0.9
$D_s^+ \to S(980)\pi^+$	16.4±0.7±2.0	28.2±1.9±1.8	19.3±1.7±2.0
$D_s^+ \to K_0^*(1430)^0 K^+$	2.4±0.3±1.0	3.9±0.5±0.5	3.0±0.6±0.5
$D_s^+ \to f_0(1710)\pi^+$	1.1±0.1±0.1	3.4±0.5±0.3	1.9±0.4±0.6
$D_s^+ \to f_0(1370)\pi^+$	1.1±0.1±0.2	4.3±0.6±0.5	1.2±0.4±0.2
$\sum FF(\%)$	110.2±0.6±2.0	129.5±4.4±2.0	114.2±1.7±2.3
χ^2/NDF	2843/2291=1.2	170/117=1.5	290/280=1.04
Events	96307 ± 369(purity 95%)	14400(purity 85%)	4397(purity 99.6%)

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

arXiv:2011.08041



The parameterization of S(980):

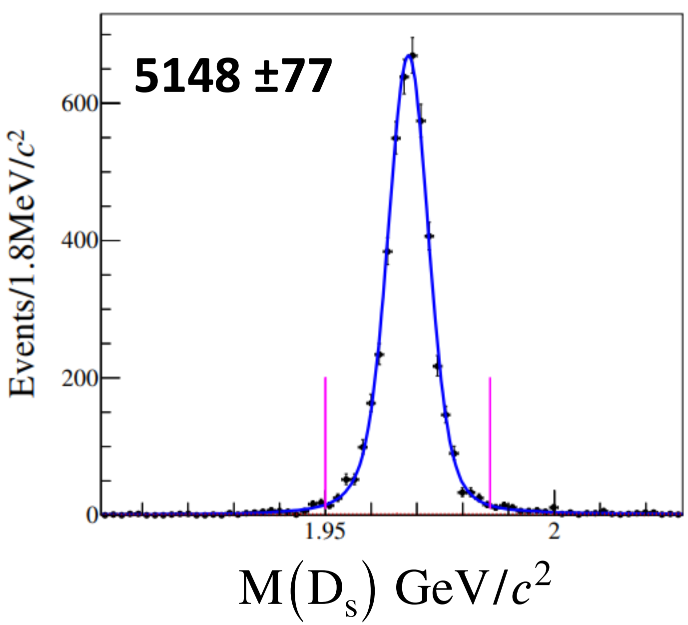
$$A_{S(980)} = \frac{1}{m_0^2 - m^2(K^+K^-) - i m_0 \Gamma_0 \rho_{K^+K^-}}$$

$$\rho_{K^+K^-} = \frac{1}{\sqrt{((1-4m(K)^2)/m(K^+K^-)^2)}}$$

$$m_0 = (0.919 \pm 0.006_{stat} \pm 0.030 sys) GeV/c^2$$

$$\Gamma_0 = (0.272 \pm 0.040 \pm 0.024) GeV$$

$K^+ K^-$ S-wave ($S(980)$) is extracted from model-independent partial wave analysis



Branching Fraction:

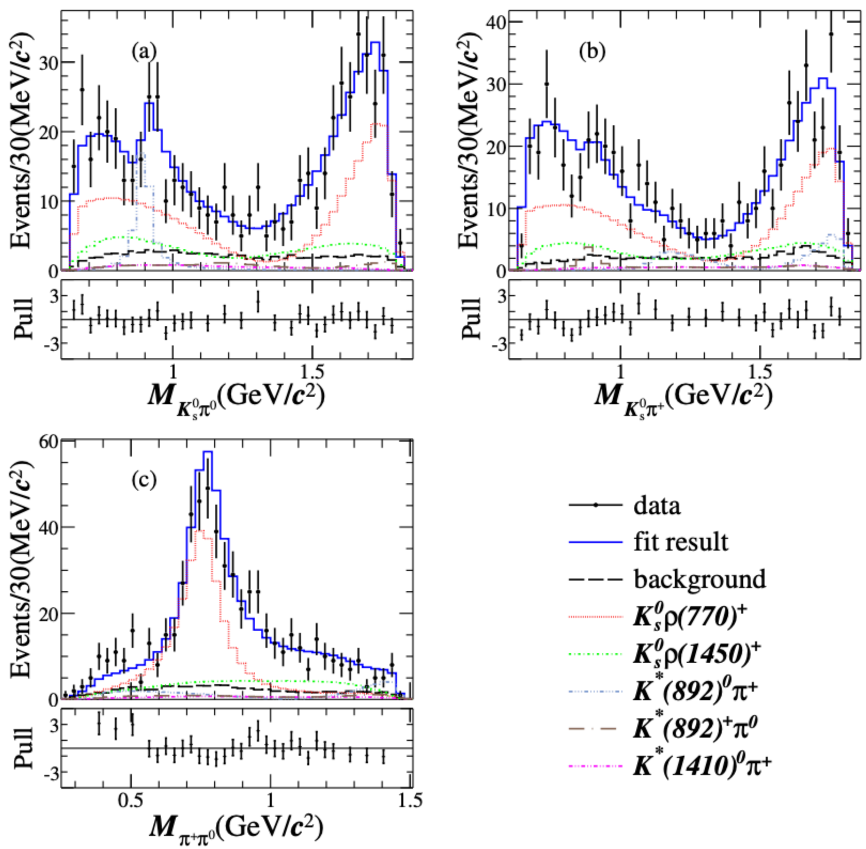
- $\mathcal{B}(D_s^+ \to K^- K^+ \pi^+) = (5.47 \pm 0.08 \pm 0.13)\%$
- $\mathcal{B}(D_s^+ \to \phi(1020)\pi^+) = (4.60 \pm 0.17)\,\%$
- $\mathcal{B}(D_s^+ \to \bar{k}^*(892)^0 K^+) = (3.94 \pm 0.12)\,\%$

Consistent with theoretical predictions
Phys. Rev. D **93**, 114010 (2016)

Best precision

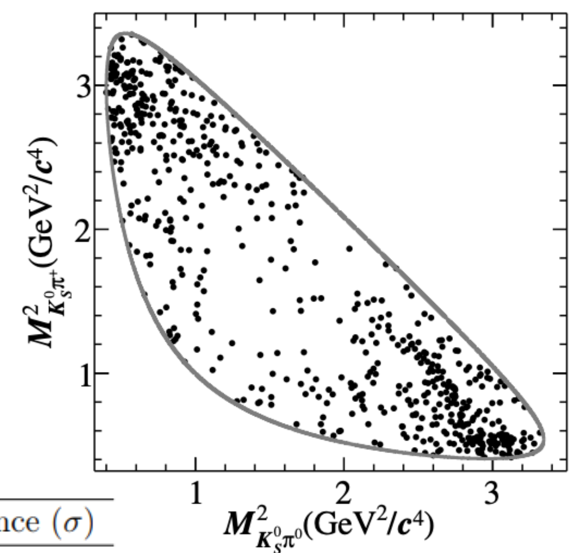
Amplitude analysis of $D_s^+ \to K_S^0 \pi^+ \pi^0$

JHEP06(2021)181



352 DT events with purity of 88.9% @$\sqrt{s} = 4.178$ GeV

$D_s^+ \to K^{*+}\pi^0, K^{*0}\pi^+$ are good modes to search for CPV and study the $SU(3)_F$ symmetry and its breaking effect.

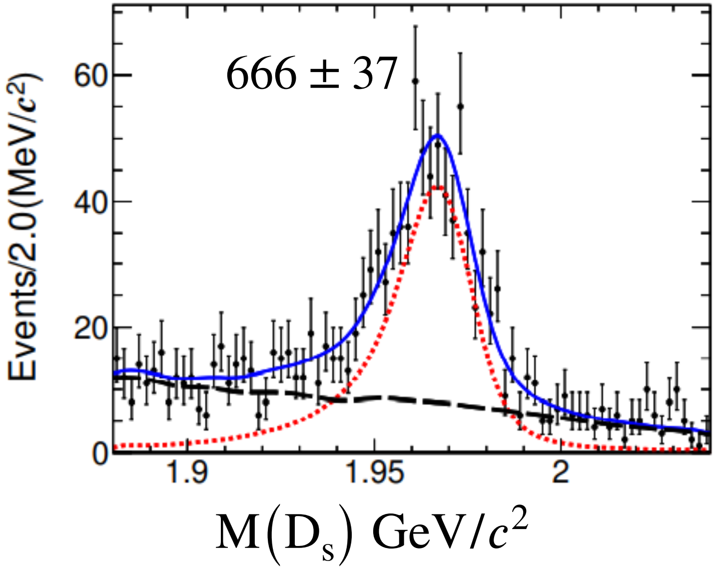


Fit model:

Amplitude	Magnitude (ρ_n)	Phase (ϕ_n)	FF (%)	Significance (σ)
$D_s^+ \to K_S^0\rho^+$	1.0(fixed)	0.0(fixed)	$50.2 \pm 7.2 \pm 3.9$	>10
$D_s^+ \to K_S^0\rho(1450)^+$	2.7 ± 0.5	$2.2 \pm 0.2 \pm 0.1$	$20.4 \pm 4.3 \pm 4.4$	>10
$D_s^+ \to K^*(892)^0\pi^+$	0.4 ± 0.1	$3.2 \pm 0.2 \pm 0.1$	$8.4 \pm 2.2 \pm 0.9$	5.0
$D_s^+ \to K^*(892)^+\pi^0$	0.3 ± 0.1	$0.2 \pm 0.2 \pm 0.2$	$4.6 \pm 1.4 \pm 0.4$	4.0
$D_s^+ \to K^*(1410)^0\pi^+$	0.8 ± 0.2	$0.2 \pm 0.3 \pm 0.1$	$3.3 \pm 1.6 \pm 0.5$	3.7

BF measurement of $D_s^+ \to K_s^0\pi^+\pi^0$

JHEP06(2021)181



Showing the measured BFs of $D_s \to VP$ and theoretical predictions from various models ($\times 10^{-3}$)

Channel	PDG [1]	Y.L. Wu et al. [7]	H.Y. Cheng et al. [8]	F.S. Yu et al. [4]
$K^0\rho^+$	—	9.1 ± 7.7	11.47 ± 0.48	7.5 ± 2.1
$K^*(892)^0\pi^+$	2.13 ± 0.36	3.3 ± 3.5	3.65 ± 0.24	1.5 ± 0.7
$K^*(892)^+\pi^0$	—	1.3 ± 1.3	1.02 ± 0.07	0.1 ± 0.1

[4] PRD 84 (2011) 074019
[7] EPJC 42, (2005) 391
[8] PRD 100, (2019) 093002

- Signal shape: MC simulated shape ⊗ Gaussian
- Background shape: MC simulated shape

Test the CP conservation:

- $A_{CP} = \frac{\mathcal{B}(D_s^+) - B(D_s^-)}{\mathcal{B}(D_s^+) + B(D_s^-)} = (2.7 \pm 5.5 \pm 0.9)\%$

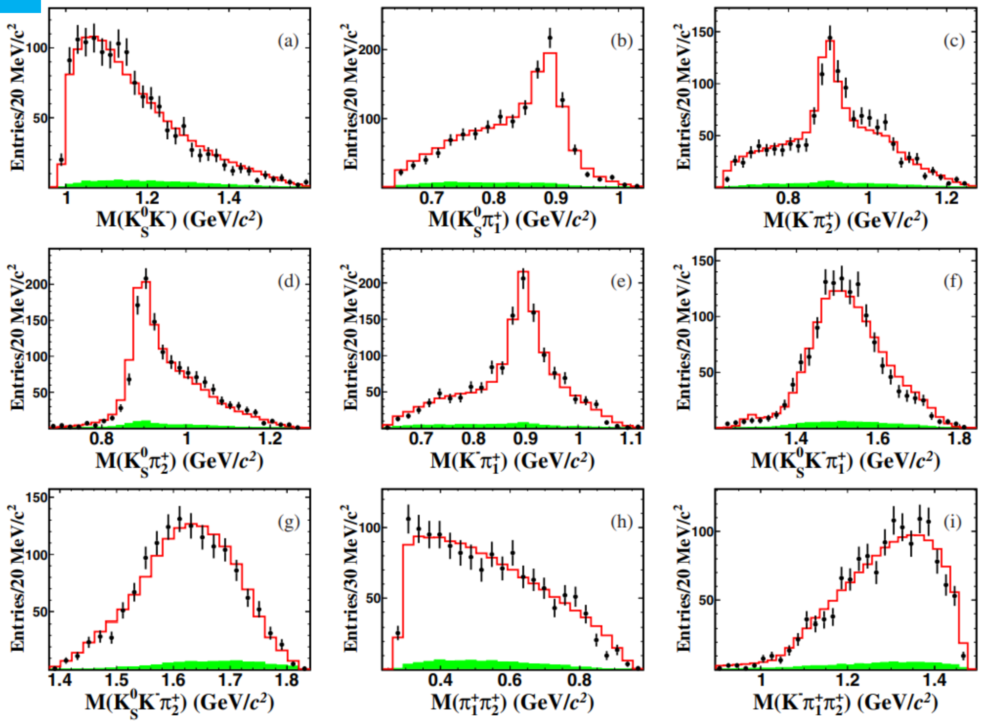
- $\mathcal{B}(D_s^+ \to K_s^0\pi^+\pi^0) = (5.43 \pm 0.30 \pm 0.15) \times 10^{-3}$
- $\mathcal{B}(D_s^+ \to K^0\rho^+) = (5.46 \pm 0.84 \pm 0.44) \times 10^{-3}$
- $\mathcal{B}(D_s^+ \to K^{*0}\pi^+) = (2.71 \pm 0.72 \pm 0.30) \times 10^{-3}$
- $\mathcal{B}(D_s^+ \to K^{*+}\pi^0) = (0.75 \pm 0.24 \pm 0.06) \times 10^{-3}$

Statistical error dominant.
No CPV is observed.

Most precise measurements

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

Phys. Rev. D **103**, 092006 (2021)



Argus Collaboration (1992):

$$B\left(D_s^+ \to K^{*+}\bar{K}^{*0}\right) = (7.2 \pm 2.6)\%$$

Z.Phys.C 53 (1992) 361

1308 DT events with a purity of 94.9% @ $\sqrt{s} = 4.178 \sim 4.226$ GeV

- $\mathscr{B}(D_s^+ \to K_s^0 K^- \pi^+ \pi^+) = (1.46 \pm 0.05 \pm 0.05)\,\%$
- $\mathscr{B}(D_s \to K^{*+}\bar{K}^{*0}) = (5.34 \pm 0.39 \pm 0.64)\,\%$

Much more precise

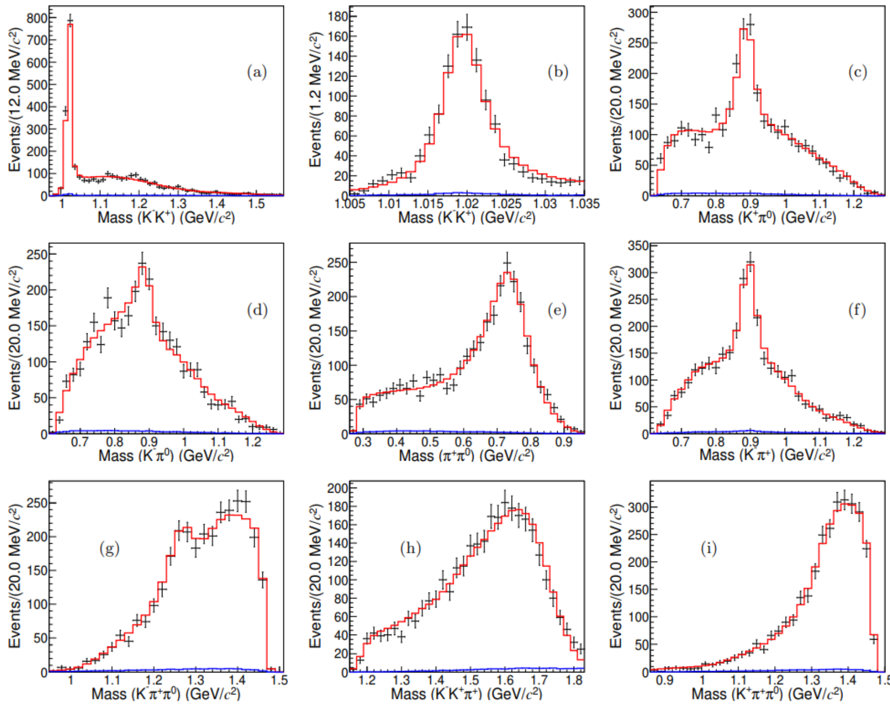
Fit model:

Label	Component	ϕ	FF(%)	Significance (σ)
I	$D_s^+[S] \to K^*(892)^+\bar{K}^*(892)^0$	0 (fixed)	$34.3 \pm 3.1 \pm 5.2$	>10.0
II	$D_s^+[P] \to K^*(892)^+\bar{K}^*(892)^0 - 1.61$	$0.08 \pm 0.03 \pm 7.5$	$1.1 \pm 0.1 \pm 8.3$	
III	$D_s^+[D] \to K^*(892)^+\bar{K}^*(892)^0$	$-0.16 \pm 0.14 \pm 0.04$	$4.5 \pm 0.8 \pm 0.3$	8.2
IV	$D_s^+ \to K^*(892)^+\bar{K}^*(892)^0$		$40.6 \pm 2.9 \pm 4.9$	
V	$D_s^+ \to K^*(892)^+(K^-\pi^+)_{S-wave}$	$1.85 \pm 0.15 \pm 0.09$	$5.0 \pm 1.2 \pm 1.0$	6.2
VI	$D_s^+ \to \bar{K}^*(892)^0(K_S^0\pi^+)_{S-wave}$	$-1.57 \pm 0.12 \pm 0.13$	$7.3 \pm 1.1 \pm 0.9$	9.1
VII	$D_s^+ \to \eta(1475)\pi^+, \eta(1475) \to a_0(980)^-\pi^+$	$-1.95 \pm 0.15 \pm 0.07$	$10.8 \pm 2.6 \pm 5.2$	4.4
VIII	$D_s^+ \to \eta(1475)\pi^+, \eta(1475) \to \bar{K}^*(892)^0K_S^0$	$0.05 \pm 0.15 \pm 0.11$	$2.2 \pm 0.6 \pm 0.2$	4.5
IX	$D_s^+ \to \eta(1475)\pi^+, \eta(1475) \to K^*(892)^+K^-$	$0.05 \pm 0.15 \pm 0.11$	$2.2 \pm 0.6 \pm 0.2$	4.5
IIX	$D_s^+ \to \eta(1475)\pi^+, \eta(1475) \to K^*(892)K$		$4.9 \pm 1.4 \pm 1.0$	
IIIX	$D_s^+ \to \eta(1475)\pi^+, \eta(1475) \to (K_S^0\pi^+)_{S-wave}K^-$	$2.30 \pm 0.11 \pm 0.07$	$23.6 \pm 3.6 \pm 7.5$	6.7
X	$D_s^+ \to f_1(1285)\pi^+, f_1(1285) \to a_0(980)^-\pi^+$	$-0.89 \pm 0.26 \pm 0.14$	$2.2 \pm 0.5 \pm 0.2$	6.0
XI	$D_s^+ \to (K^*(892)^+K^-)_P\pi^+, (K^*(892)^+K^-)_P \to K^*(892)^+K^-$	$-1.07 \pm 0.11 \pm 0.03$	$10.8 \pm 1.9 \pm 1.7$	9.2

Dominant

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

arXiv:2103.02482

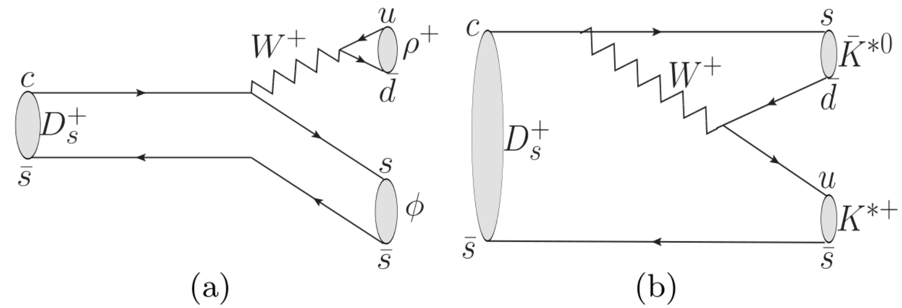


χ^2/ndf = 288.6/273

3088 DT events with purity of 97.5% @ $\sqrt{s} = 4.178 \sim 4.226$ GeV

The amplitudes of VIII, IX , X and XII are fixed by Clebsch Gordan coefficients and charge conjugation relations

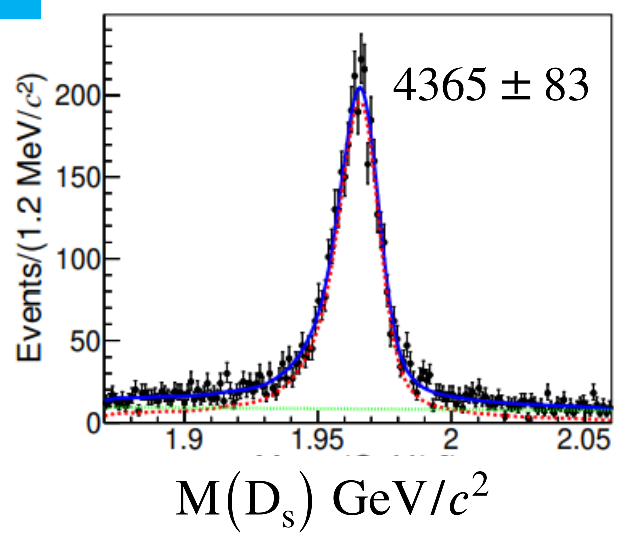
Dominated by $D_s^+ \to VV$ processes:



Label	Amplitude	Phase (ϕ_n)	FF (%)	SS (σ)
I	$D_s^+[S] \to \phi\rho^+$	0.0 (fixed)	$42.64 \pm 1.30 \pm 0.77$	>20
II	$D_s^+[P] \to \phi\rho^+$	$1.64 \pm 0.05 \pm 0.02$	$8.58 \pm 0.69 \pm 0.37$	15.2
III	$D_s^+[D] \to \phi\rho^+$	$1.58 \pm 0.06 \pm 0.02$	$4.89 \pm 0.79 \pm 0.47$	8.4
	$D_s^+ \to \phi\rho^+$	$\cdots$	$56.17 \pm 1.05 \pm 1.24$	$\cdots$
IV	$D_s^+[S] \to \bar{K}^{*0}K^{*+}$	$1.13 \pm 0.06 \pm 0.03$	$15.49 \pm 0.81 \pm 0.36$	>20
V	$D_s^+[P] \to \bar{K}^{*0}K^{*+}$	$2.82 \pm 0.07 \pm 0.03$	$6.13 \pm 0.50 \pm 0.19$	16.2
VI	$D_s^+[D] \to \bar{K}^{*0}K^{*+}$	$1.76 \pm 0.07 \pm 0.03$	$4.00 \pm 0.47 \pm 0.34$	12.5
	$D_s^+ \to \bar{K}^{*0}K^{*+}$	$\cdots$	$22.44 \pm 0.81 \pm 0.32$	$\cdots$
VII	$D_s^+ \to \bar{K}_1^0(1270)K^+,\ \bar{K}_1^0(1270) \to K^-\rho^+$	$5.36 \pm 0.06 \pm 0.10$	$9.81 \pm 0.80 \pm 0.46$	>20
	$D_s^+ \to \bar{K}_1^0(1270)K^+,\ \bar{K}_1^0(1270)[S] \to \bar{K}^{*0}\pi^0$	$\cdots$	$0.69 \pm 0.13 \pm 0.12$	$\cdots$
	$D_s^+ \to \bar{K}_1^0(1270)K^+,\ \bar{K}_1^0(1270)[S] \to K^{*-}\pi^+$	$\cdots$	$1.27 \pm 0.27 \pm 0.25$	$\cdots$
VIII	$D_s^+ \to \bar{K}_1^0(1270)K^+,\ \bar{K}_1^0(1270)[S] \to K^*\pi$	$0.09 \pm 0.14 \pm 0.12$	$1.87 \pm 0.39 \pm 0.36$	7.2
	$D_s^+ \to \bar{K}_1^0(1270)K^+,\ \bar{K}_1^0(1270)[D] \to \bar{K}^{*0}\pi^0$	$\cdots$	$0.22 \pm 0.05 \pm 0.03$	$\cdots$
	$D_s^+ \to \bar{K}_1^0(1270)K^+,\ \bar{K}_1^0(1270)[D] \to K^{*-}\pi^+$	$\cdots$	$0.41 \pm 0.10 \pm 0.05$	$\cdots$
IX	$D_s^+ \to \bar{K}_1^0(1270)K^+,\ \bar{K}_1^0(1270)[D] \to K^*\pi$	$1.62 \pm 0.15 \pm 0.12$	$0.64 \pm 0.16 \pm 0.08$	5.5
	$D_s^+ \to \bar{K}_1^0(1270)K^+,\ \bar{K}_1^0(1270) \to K^*\pi$	$\cdots$	$2.57 \pm 0.42 \pm 0.42$	$\cdots$
	$D_s^+ \to \bar{K}_1^0(1400)K^+,\ \bar{K}_1^0(1400)[S] \to \bar{K}^{*0}\pi^0$	$\cdots$	$2.67 \pm 0.36 \pm 0.17$	$\cdots$
	$D_s^+ \to \bar{K}_1^0(1400)K^+,\ \bar{K}_1^0(1400)[S] \to K^{*-}\pi^+$	$\cdots$	$4.90 \pm 0.65 \pm 0.29$	$\cdots$
X	$D_s^+ \to \bar{K}_1^0(1400)K^+,\ \bar{K}_1^0(1400)[S] \to K^*\pi$	$5.66 \pm 0.08 \pm 0.05$	$7.23 \pm 0.95 \pm 0.41$	12.0
XI	$D_s^+ \to a_0^0(980)\rho^+$	$2.33 \pm 0.10 \pm 0.09$	$1.61 \pm 0.29 \pm 0.21$	6.0
	$D_s^+ \to f_1(1420)\pi^+,\ f_1(1420) \to K^{*-}K^+$	$\cdots$	$0.87 \pm 0.17 \pm 0.07$	$\cdots$
	$D_s^+ \to f_1(1420)\pi^+,\ f_1(1420) \to K^{*+}K^-$	$\cdots$	$0.87 \pm 0.17 \pm 0.07$	$\cdots$
XII	$D_s^+ \to f_1(1420)\pi^+,\ f_1(1420) \to K^{*\mp}K^\pm$	$5.14 \pm 0.10 \pm 0.05$	$1.35 \pm 0.28 \pm 0.11$	6.5
XIII	$D_s^+ \to f_1(1420)\pi^+,\ f_1(1420) \to a_0^0(980)\pi^0$	$5.77 \pm 0.14 \pm 0.07$	$0.65 \pm 0.24 \pm 0.12$	3.6
XIV	$D_s^+ \to \eta(1475)\pi^+,\ \eta(1475) \to a_0^0(980)\pi^0$	$0.98 \pm 0.08 \pm 0.06$	$3.28 \pm 0.38 \pm 0.25$	9.7

BF measurement of $D_s^+ \to K^- K^+ \pi^+ \pi^0$

arXiv:2103.02482



- $\mathscr{B}(D_s^+ \to K^- K^+ \pi^+ \pi^0) = (5.42 \pm 0.10 \pm 0.17)\,\%$
- $\mathscr{B}(D_s^+ \to \phi\rho^+) = (6.22 \pm 0.17 \pm 0.24)\,\%$

Consistent with theoretical prediction PRD 49, 269(1994)

- $\mathscr{B}(D_s^+ \to K^{*+}\bar{K}^{*0}) = (5.46 \pm 0.23 \pm 0.18)\,\%$

$$R_{K_{1(1270)}} \equiv \frac{\mathscr{B}(K_1^0 \to K^*\pi)}{\mathscr{B}(K_1^0 \to K\rho)} = (0.99 \pm 0.15 \pm 0.18)\%$$

Our result is consistent with the results measured by LHCb [JHEP02(2019)126] and CLEO [PRD **85**, 122002]

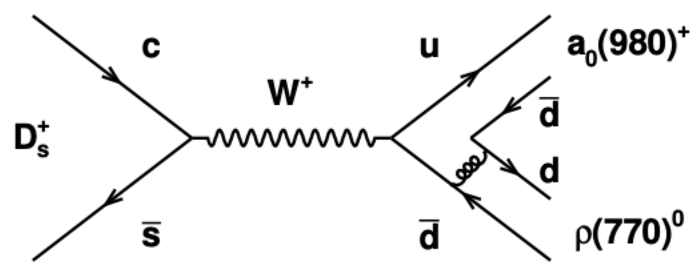
$R_{K_1(1270)}$	Process	Experiment
0.81 ± 0.10	$D^0 \to K^+K^-\pi^+\pi^-$	LHCb [19]
1.18 ± 0.43	$D^0 \to K^-K_1^+(1270)$	CLEO [20]
0.11 ± 0.06	$D^0 \to K^+K_1^-(1270)$	CLEO [20]
0.19 ± 0.10	$D^0 \to K^-\pi^+\pi^+\pi^-$	BESIII [21]
0.24 ± 0.04	$D^0 \to K^-\pi^+\pi^+\pi^-$	LHCb [22]
0.45 ± 0.05	$B^+ \to J/\psi K^+\pi^+\pi^-$	Belle [23] (Fit 1)
0.30 ± 0.04	$B^+ \to J/\psi K^+\pi^+\pi^-$	Belle [23] (Fit 2)
0.38 ± 0.13	$K^-p \to K^-\pi^-\pi^+p$	ACCMOR [24]
0.45 ± 0.14	$D^0 \to K^-K_1^+(1270)$	CLEO [25]

[19] PRD85, 122002 (2012)
[20] PRD95, 072010 (2017)
[21] EPJC78, 443 (2018)
[22] PRD83, 032005 (2011)
[23] NPB187, 1 (1981)
[24] JHEP05, 143 (2017)

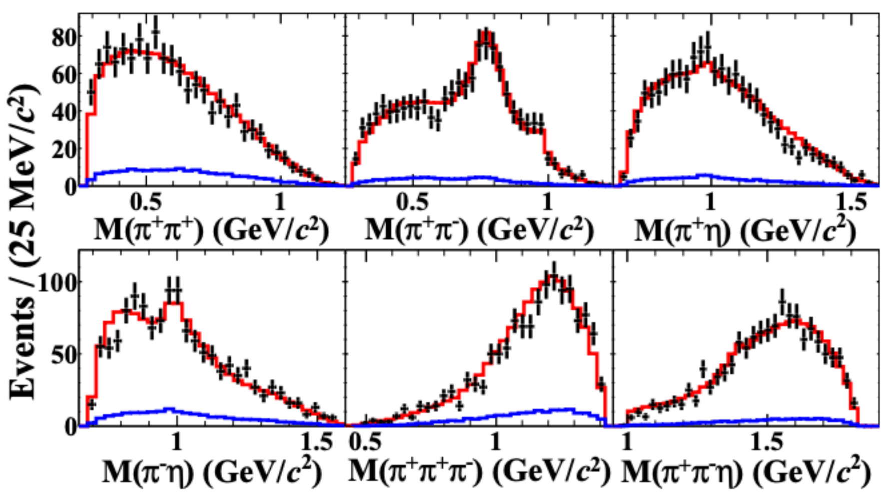
Amplitude analysis of $D_s^+ \to \eta\pi^+\pi^+\pi^-$

arXiv:2106.13536

Observe W-annihilation for $D_s^+ \to a_0(980)^+ \rho(770)^0$



1306 DT candidates with larger than 85% purity @ $\sqrt{s} = 4.178 \sim 4.226$ GeV



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

First measurement:

- $\mathscr{B}(D_s^+ \to \eta\pi^+\pi^+\pi^-) = (3.12 \pm 0.13 \pm 0.09)\,\%$

Dominant process:

- $\mathscr{B}(D_s^+ \to a_1(1260)^+\eta, a_1(1260)^+ \to \rho^0\pi^+)$ $= (1.73 \pm 0.14 \pm 0.08)\,\%$

W-annihilation contribution:

- $\mathscr{B}(D_s^+ \to a_0(980)^+\rho^+, a_0(980)^+ \to \eta\pi^+)$ $= (0.21 \pm 0.08 \pm \pm 0.05)\,\%$

Larger than the fractions of most other measured pure W-annihilation decays

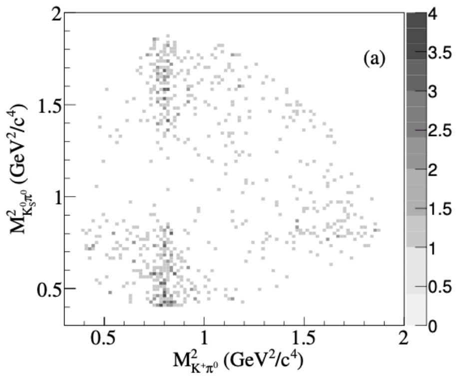
Amplitude analysis of $D^+ \to K_s^0 K^+ \pi^0$

Phys. Rev. D **104**, 012006 (2021)

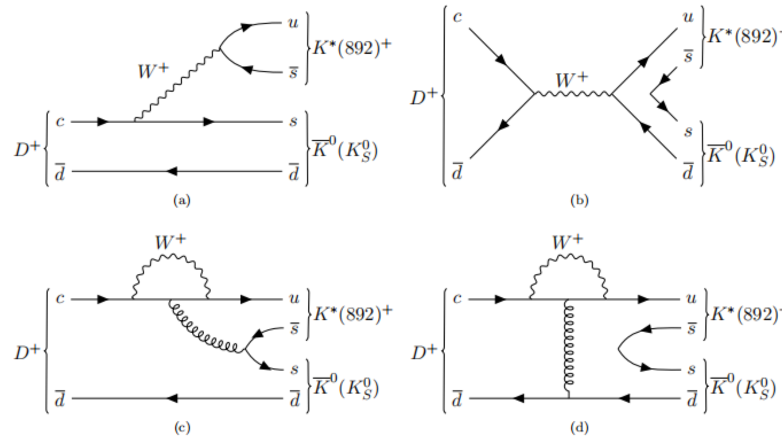
- **First amplitude analysis**
- **692 DT candidates with 97.4% @** $\sqrt{s} = 3.773$ GeV

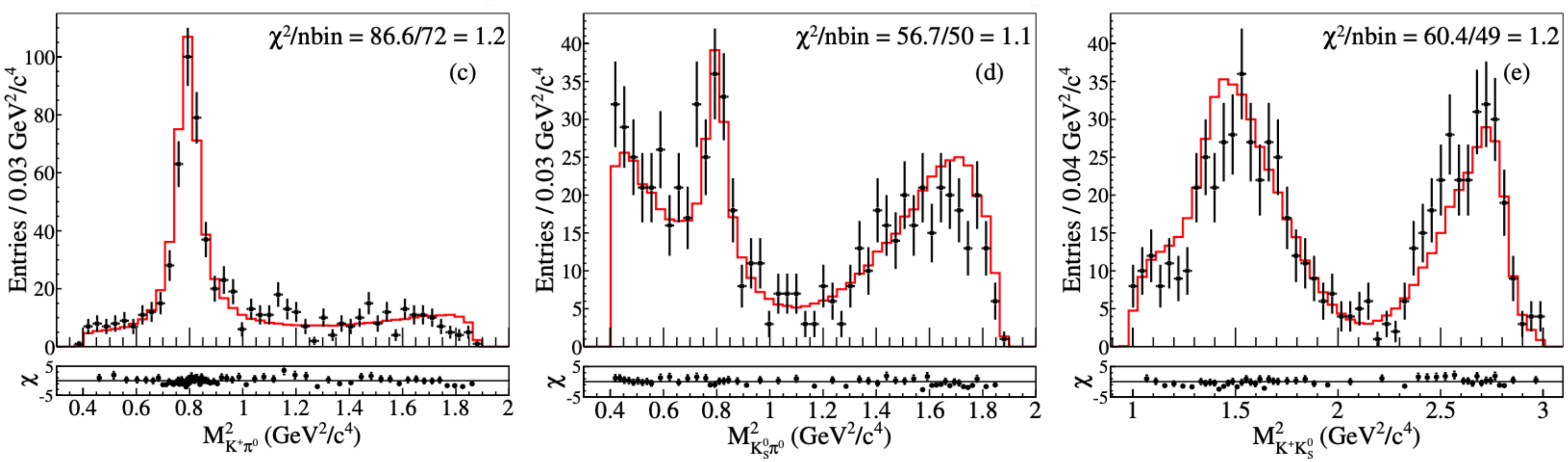
Data

Fit model



Topological diagrams for $D^+ \to K^*(892)^+ K_s^0$





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

Phys. Rev. D **104**, 012006 (2021)

A factor of 4.6 improvement for $\mathfrak{B}_{K^*(892)^+ K_S^0}$

Amplitude	Magnitude	Phase ϕ (°)	FF (%)	Significance
$D^+ \to K^*(892)^+ K_S^0$	1.0 (fixed)	0.0 (fixed)	57.1 ± 2.6	$29.6\,\sigma$
$D^+ \to \bar{K}^*(892)^0 K^+$	0.41 ± 0.04	162 ± 10	10.2 ± 1.5	$11.6\,\sigma$
$D^+ \to (K^+\pi^0)_{S-\text{wave}} K_S^0$	2.02 ± 0.37	140 ± 14	3.9 ± 1.5	$5.2\,\sigma$
$D^+ \to (K_S^0\pi^0)_{S-\text{wave}} K^+$	3.14 ± 0.46	-173.7 ± 9.7	9.7 ± 2.6	$7.4\,\sigma$

BF	This work	PDG
$\frac{\mathcal{B}(D^+ \to K^*(892)^+ (K^+\pi^0) K_S^0)}{\mathcal{B}(D^+ \to K^+ K_S^0 \pi^0)}$	$(57.1 \pm 2.6_{\text{stat.}} \pm 4.2_{\text{syst.}})\%$	—
$\frac{\mathcal{B}(D^+ \to \bar{K}^*(892)^0 (K_S^0\pi^0) K^+)}{\mathcal{B}(D^+ \to K^+ K_S^0 \pi^0)}$	$(10.2 \pm 1.5_{\text{stat.}} \pm 2.2_{\text{syst.}})\%$	—
$\mathcal{B}(D^+ \to K^*(892)^+ K_S^0)$	$(8.69 \pm 0.40_{\text{stat.}} \pm 0.64_{\text{syst.}} \pm 0.51_{\text{Br.}}) \times 10^{-3}$	$(17 \pm 8) \times 10^{-3}$
$\mathcal{B}(D^+ \to \bar{K}^*(892)^0 K^+)$	$(3.10 \pm 0.46_{\text{stat.}} \pm 0.68_{\text{syst.}} \pm 0.18_{\text{Br.}}) \times 10^{-3}$	$(3.74^{+0.12}_{-0.20}) \times 10^{-3}$

Before release of this analysis:
4.0σ variation

→

After this release: accord well
Latest calculated: arXiv: 2014.13548

Model	$\mathcal{B}(D^+ \to K^*(892)^+ K_S^0)(\times 10^{-3})$
Pole	6.2 ± 1.2
FAT[mix]	5.5
TDA[tree]	5.02 ± 1.31
TDA[QCD-penguin]	4.90 ± 0.21
PDG	17 ± 8

Mode	$\mathfrak{B}_{theory}$	$\mathfrak{B}_{exp}$
$D^+ \to K^+ \bar{K}^{*0}$	5.92+-0.18	3.71+-0.16
$D^+ \to \bar{K}^0 K^{*+}$	16.28+-0.61	17.6+-1.8

Our understanding of the charmed dynamics improved

Amplitude analyses of other $D^+/D^0/D_s^+$ Decays

Amplitude analysis of $D^+ \to K_s^0\pi^+\pi^+\pi^-$ **PRD 100, 072008(2019)**

Amplitude analysis of $D^0 \to K^-\pi^+\pi^0\pi^0$ **PRD 99, 092008(2019)**

Amplitude analysis of $D_s^+ \to \pi^+\pi^0\eta$ **PRL 123, 112001 (2019)**

Amplitude analysis of $D^0 \to K^-\pi^+\pi^+\pi^-$ **PRD 95, 072010(2017)**

Amplitude analysis of $D_s^+ \to \pi^+\pi^+\pi^-$ **BESIII Preliminary**

……

Summary

- **Amplitude analyses and BF measurements of:**
  - $D_s^+ \to K^-K^+\pi^+$ $\mathscr{B} = (5.47 \pm 0.08 \pm 0.13)\%$
  - $D_s^+ \to K_s^0\pi^+\pi^0$ $\mathscr{B} = (5.43 \pm 0.30 \pm 0.15) \times 10^{-3}$ (No evidence of CPV)
  - $D_s^+ \to K_S^0K^-\pi^+\pi^+$ $\mathscr{B} = (1.46 \pm 0.05 \pm 0.05)$
  - $D_s^+ \to K^-K^+\pi^+\pi^0$ $\mathscr{B} = (5.42 \pm 0.10 \pm 0.17)\%$
  - $D_s^+ \to \eta\,\pi^+\pi^+\pi^-$ $\mathscr{B} = (3.12 \pm 0.13 \pm 0.09)\%$
  - $D^+ \to K_s^0K^+\pi^0$
- **Precise measurements of two-body decays:**
  - $\mathscr{B}(D_s^+ \to \phi\pi^+) = (4.60 \pm 0.17)\%$
  - $\mathscr{B}\left(D_s^+ \to \bar{K}^*(892)^0K^+\right) = (3.94 \pm 0.12)\%$
  - $\mathscr{B}(D_s^+ \to \phi\rho) = (6.22 \pm 0.17 \pm 0.24)\%$
  - $\mathscr{B}(D_s^+ \to K_s^0\rho^+) = (5.46 \pm 0.84 \pm 0.44) \times 10^{-3}$
  - $\mathscr{B}(D_s^+ \to K^{*0}\pi^+) = (2.71 \pm 0.72 \pm 0.30) \times 10^{-3}$
  - $\mathscr{B}(D_s^+ \to K^{*+}\pi^0) = (0.75 \pm 0.24 \pm 0.06) \times 10^{-3}$
  - $\mathscr{B}\left(D_s^+ \to K^{*+}\bar{K}^{*0}\right) = (5.46 \pm 0.23 \pm 0.18)\%$
  - $\mathscr{B}(D^+ \to K^{*0}K^+) = (2.71 \pm 0.72 \pm 0.30) \times 10^{-3}$
  - $\mathscr{B}\left(D_s^+ \to a_0(980)^+\rho(770)^0\right) = (0.21 \pm 0.08 \pm 0.05) \times 10^{-3}$ Anomaly
  - $\mathscr{B}(D^+ \to K^{*+}K_s^0) = (8.69 \pm 0.64 \pm 0.51) \times 10^{-3}$

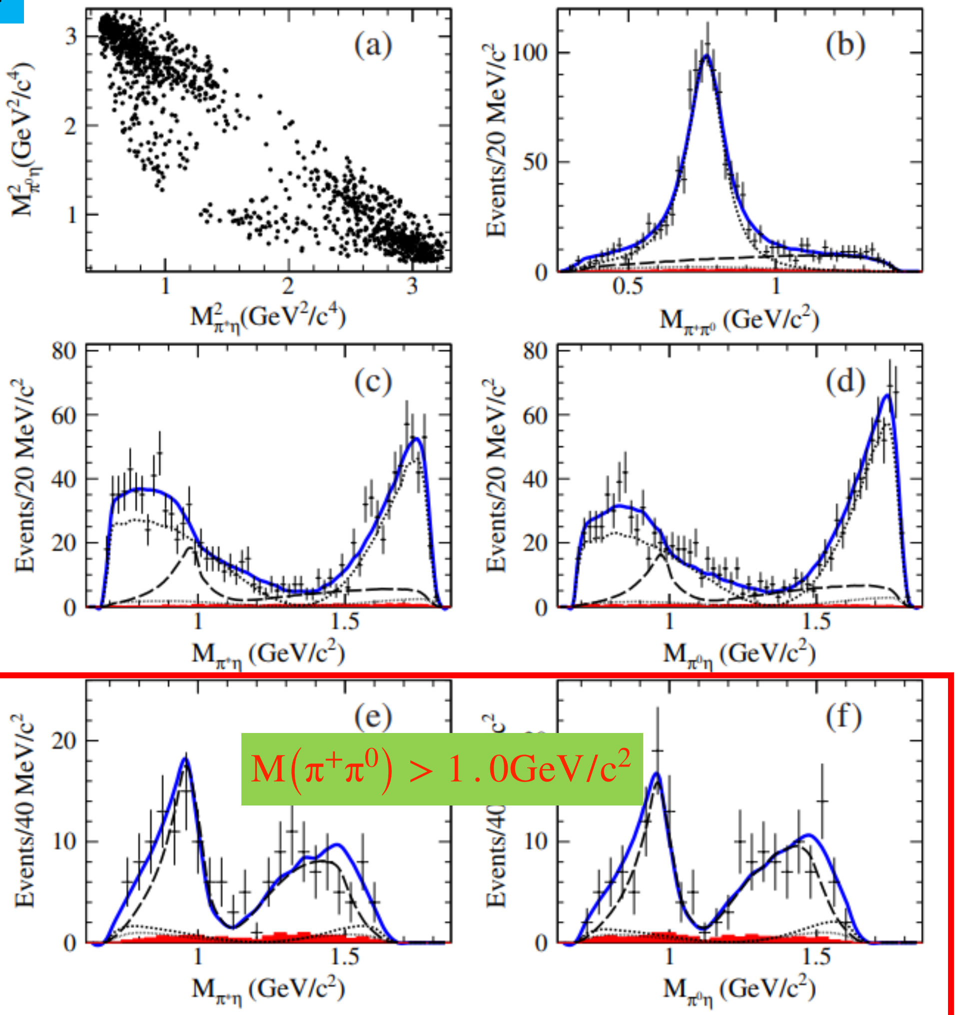
Confirm theoretical predictions

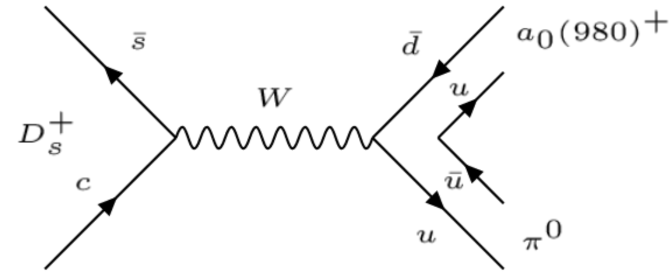
Thank you!

back up

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

PRL **123**, 112001 (2019)





1239 DT events with purity of 97.7% @$\sqrt{s} = 4.178$ GeV

- $\mathcal{B}(D_s^+ \to \pi^+\pi^0) = 3.4 \times 10^{-4}$
- $\mathcal{B}(D_s^+ \to \pi^+\rho^0) < (1.9 \pm 1.2) \times 10^{-4}$
- $\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta) = (9.50 \pm 0.28 \pm 0.41)\ \%$
- $\mathcal{B}(a_0(980)^{+(0)}\pi^{0(+)}) = (2.20 \pm 0.22 \pm 0.34)\ \%$

The BFs of $D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}$ are significantly larger than BFs of pure annihilation processes by 2 orders of magnitude.

Amplitude	ϕ_n (rad)	FF$_n$
$D_s^+ \to \rho^+\eta$	0.0 (fixed)	0.783±0.050±0.021
$D_s^+ \to (\pi^+\pi^0)_V\eta$	0.612±0.172±0.342	0.054±0.021±0.025
$D_s^+ \to a_0(980)\pi$	2.794±0.087±0.044	0.232±0.023±0.033

χ^2/ndf = 82.8/77

Significance > 5σ