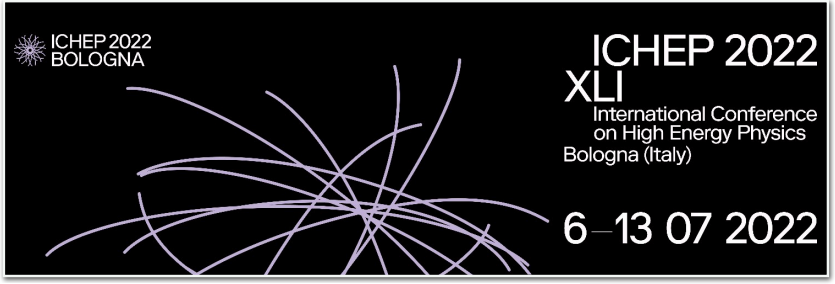

Hadronic D decays at BESIII

Anita Lavania
IIT Madras, India

For the BESIII collaboration

July 7, 2022

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1 Introduction

- Introduction
- Branching fraction measurements and more
  - $D^0 \to K^0_{\mathrm{L/S}} X$
  - $D^0 \to \omega\phi$
- Amplitude analyses

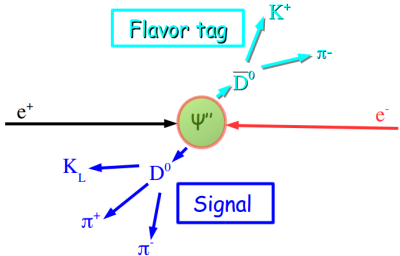
Charm production at BESIII

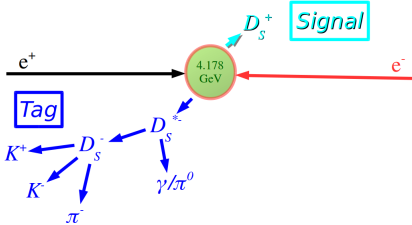
1 Introduction

- Quantum-correlated $D\bar{D}$ pairs produced at $\sqrt{s}$:

3.773 GeV	$D^0\bar{D}^0$, D^+D^-	$\mathcal{L}_{\rm int} = 2.93$ fb^{-1}
$4.178 - 4.226$ GeV	$D_s^+D_s^{*-}$	$\mathcal{L}_{\rm int} = 6.32$ fb^{-1}

- Flavor, CP tagging
- Clean production
- Reconstruct both (tag & signal) D mesons
  ⇒ Precise *absolute* charm BF measurement
  † Tag-side reconstruction and systematics cancel out
  ⇒ Amplitude analyses
  ⇒ Strong-phases with quantum-correlated $D^0\bar{D}^0$





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- Branching fraction measurements and more
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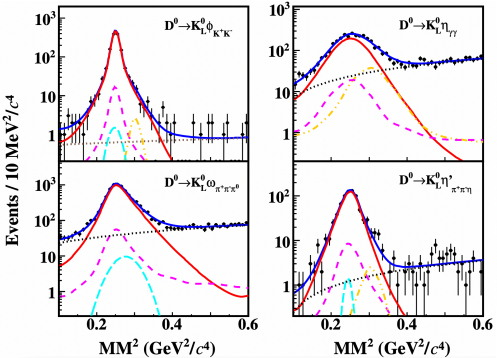
  - $D^0 \to \omega\phi$
- Amplitude analyses

$\mathcal{B}(D^0 \to K^0_{\rm L} X)$ and $K^0_{\rm S}/K^0_{\rm L}$ asymmetries

2 Branching fraction measurements and more



Phys. Rev. D **105** 092010 (2022)

- First measurement of *absolute* $\mathcal{B}(D^0 \to K^0_{\rm L}\phi, K^0_{\rm L}\omega, K^0_{\rm L}\eta, K^0_{\rm L}\eta')$
- Double-tag method with $K\pi, K3\pi, K\pi\pi^0$ flavor tags

$$\mathcal{B} = \frac{N_{\rm DT}}{\sum_i \epsilon^i_{\rm DT}(N^i_{\rm ST}/\epsilon^i_{\rm ST})}$$

- Missing-mass technique for $K^0_{\rm L}$ at BESIII

$$p_{\rm miss} = p_{e^+e^-} - p_{\rm tag} - p_X$$

Decay	$\mathcal{B}_{\rm exp}$ (%)	$\mathcal{B}_{\rm FAT}$ (%)	Difference	$\mathcal{A}^{\rm sig}_{CP}$ (%)
$D^0 \to K^0_L\phi$	$0.414 \pm 0.021 \pm 0.010$	0.33 ± 0.03	2.2σ	$2.7 \pm 5.4 \pm 0.7$
$D^0 \to K^0_L\eta$	$0.433 \pm 0.012 \pm 0.010$	0.40 ± 0.07	0.5σ	$2.8 \pm 2.9 \pm 0.4$
$D^0 \to K^0_L\omega$	$1.164 \pm 0.022 \pm 0.028$	0.95 ± 0.15	1.4σ	$3.4 \pm 1.9 \pm 0.6$
$D^0 \to K^0_L\eta'$	$0.809 \pm 0.020 \pm 0.016$	0.77 ± 0.07	0.5σ	$-2.2 \pm 2.5 \pm 0.4$

$$\mathcal{A}^{\rm sig}_{CP} = \frac{\mathcal{B}(D) - \mathcal{B}(\bar{D})}{\mathcal{B}(D) + \mathcal{B}(\bar{D})}$$

$\mathcal{B}(D^0 \to K^0_{\rm L} X)$ and $K^0_{\rm S}/K^0_{\rm L}$ asymmetries

- For better understanding of U-spin and SU(3)-flavor symmetry breaking

$$\mathcal{R}(D^0, X) = \frac{\mathcal{B}(D^0 \to K^0_{\rm S} X) - \mathcal{B}(D^0 \to K^0_{\rm L} X)}{\mathcal{B}(D^0 \to K^0_{\rm S} X) + \mathcal{B}(D^0 \to K^0_{\rm L} X)} = -2r\cos\delta + y_D$$

$$\mathcal{R}(D^0)_{\rm FAT} = 2\tan^2\theta_C = 0.113$$

Decay	$\mathcal{B}_{\rm exp}$ (%)	$\mathcal{B}_{\rm FAT}$ (%)	Difference	$\mathcal{R}(D^0)_{\rm exp}$	$\mathcal{B}(D^0)_{\rm FAT}$	Difference
$D^0 \to K^0_L \phi$	$0.414 \pm 0.021 \pm 0.010$	0.33 ± 0.03	2.2σ	-0.001 ± 0.047	0.113 ± 0.001	2.4σ
$D^0 \to K^0_L \eta$	$0.433 \pm 0.012 \pm 0.010$	0.40 ± 0.07	0.5σ	0.080 ± 0.022		1.5σ
$D^0 \to K^0_L \omega$	$1.164 \pm 0.022 \pm 0.028$	0.95 ± 0.15	1.4σ	-0.024 ± 0.031		4.4σ
$D^0 \to K^0_L \eta'$	$0.809 \pm 0.020 \pm 0.016$	0.77 ± 0.07	0.5σ	0.080 ± 0.023		1.6σ

- $D^0 \to K^0_{\rm L}\omega$ and $D^0 \to K^0_{\rm L}\phi$ away from theoretical SU(3) symmetry predictions
- Difference in PP and PV amplitudes?

$\mathcal{B}(D^0 \to \omega\phi)$ and polarization measurement

Phys. Rev. Lett. **128**, 011803 (2022)

- Long-distance contributions to $D^0 - \bar{D}^0$ mixing arise in $D \to VV$ decays
- First observation of $D^0 \to \omega\phi$
- Single-tag method with $\phi \to K^+K^-$ and $\omega \to \pi^+\pi^-\pi^0$

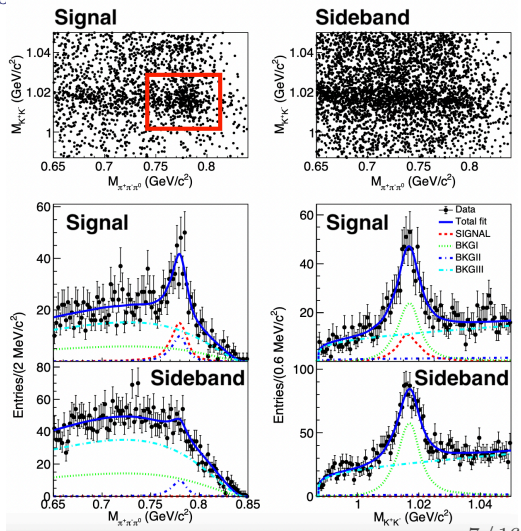
Signal: $1.86 < M_{\rm BC} < 1.87$ GeV/c^2

Sideband: $(1.840, 1.855) \cup (1.873, 1.890)$ GeV/c^2 in $M_{\rm BC}$

- $N_{\rm sig}^{\rm ST} = 195.9 \pm 29.1$

$$\mathcal{B} = \frac{N_{\rm sig}^{\rm ST}}{2.N_{D^0\bar{D}^0}.\epsilon.\mathcal{B}_{sub}} = (6.48 \pm 0.96 \pm 0.40) \times 10^{-4}$$

with 6.3σ significance

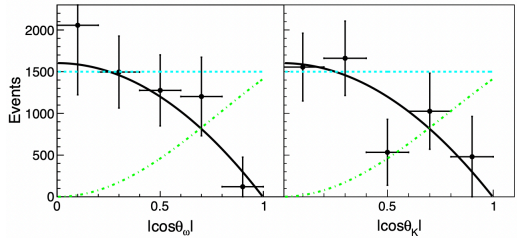


$\mathcal{B}(D^0 \to \omega\phi)$ and polarization measurement

– Fit

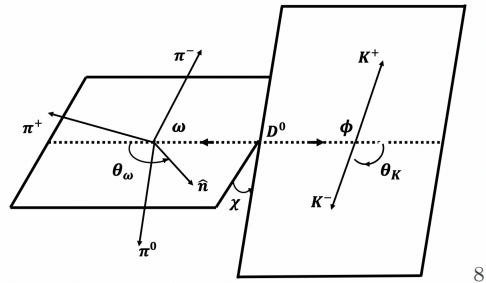
– Longitudinal hypothesis

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} \propto \frac{1}{2}(1 - f_L)\sin^2\theta + f_L\cos^2\theta$$



- $f_L < 0.24$ at 95% CL
- ω and ϕ found to be transversely polarized

- Contradicts model based predictions
  - Factorization model: $f_L \sim 0.5$
  - LI based symmetry models: $f_L \sim 0.33$

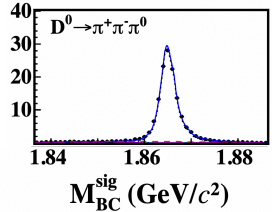


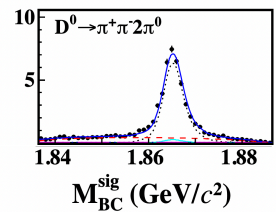
Cabibbo-suppressed pionic modes

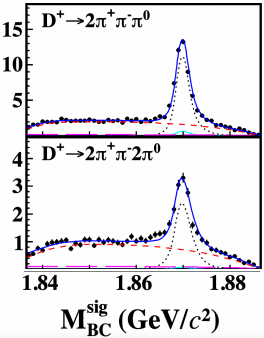
2 Branching fraction measurements and more

[arXiv:2206.13864]

- First absolute BF measurement of 20 Cabibbo suppressed $D^{0(+)}$ pionic decay modes.
- Constitute background in LFU studies in B decays
- CPV in charm with $D \to \rho\pi$







Decay	$\Delta E_{\rm sig}$ (MeV)	$N_{\rm DT}$	$\epsilon_{\rm sig}$ (%)	$\mathcal{B}_{\rm sig}$ ($\times 10^{-4}$)
$\pi^+\pi^-\pi^0$	$(-62, 36)$	12792.6(120.1)	40.91	134.3(13)(16)
$\pi^+\pi^-2\pi^0$	$(-75, 37)$	3783.7(70.5)	16.29	99.8(19)(24)
$2\pi^+\pi^-\pi^0$	$(-59, 35)$	4649.5(83.5)	25.42	117.4(21)(21)
$2\pi^+\pi^-2\pi^0$	$(-74, 39)$	1207.1(45.4)	7.21	107.4(40)(30)
$2\pi^+2\pi^-\pi^0$	$(-52, 33)$	942.4(40.0)	11.70	34.6(15)(15)
$2\pi^+\pi^-$	$(-30, 28)$	2614.3(58.0)	50.63	33.1(07)(05)
$\pi^+2\pi^0$	$(-96, 44)$	1968.0(51.7)	27.33	46.2(12)(09)
$3\pi^+2\pi^-$	$(-37, 33)$	462.1(28.7)	16.26	18.2(11)(10)

- BF precision improved by factor $1.2 - 2.9$ for 7 modes compared to PDG (relative measurements)
- First measurement for the rest

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3 Amplitude analyses

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  - $D^0 \to K^0_{\mathrm{L/S}} X$
  - $D^0 \to \omega\phi$
- Amplitude analyses

Study of $D_s^+ \to K_S^0 K^+ \pi^0$

3 Amplitude analyses

- First amplitude analysis of $D_s^+ \to K_S^0 K^+ \pi^0$
- Isovector partner to $f_0(1710)$ and $f_0(1770)$ *i.e.* $a_0(1710)^+$ observed
- $D_s^+ \to K_S^0 K^+ \pi^0$ can be used as a reference channel

$$\mathcal{B}(D_s^+ \to K_S^0 K^+ \pi^0) = (1.46 \pm 0.06_{\text{stat.}} \pm 0.05_{\text{syst.}})\%$$

[arXiv:2204.09614]

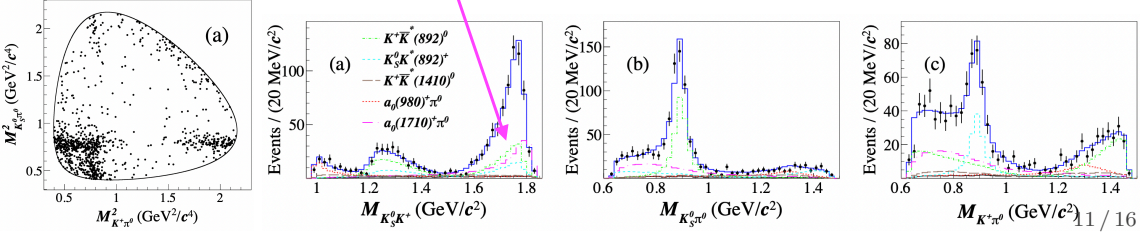
1050 events, 95% purity

Amplitude	Phase (rad)	FF (%)	BF (10^{-3})	σ
$D_s^+ \to \bar{K}^*(892)^0 K^+$	0.0(fixed)	$32.7 \pm 2.2 \pm 1.9$	$4.77 \pm 0.38 \pm 0.32$	> 10
$D_s^+ \to K^*(892)^+ K_S^0$	$-0.16 \pm 0.12 \pm 0.11$	$13.9 \pm 1.7 \pm 1.3$	$2.03 \pm 0.26 \pm 0.20$	> 10
$D_s^+ \to a_0(980)^+ \pi^0$	$-0.97 \pm 0.27 \pm 0.25$	$7.7 \pm 1.7 \pm 1.8$	$1.12 \pm 0.25 \pm 0.27$	6.7
$D_s^+ \to \bar{K}^*(1410)^0 K^+$	$0.17 \pm 0.15 \pm 0.08$	$6.0 \pm 1.4 \pm 1.3$	$0.88 \pm 0.21 \pm 0.19$	7.6
$D_s^+ \to a_0(1710)^+ \pi^0$	$-2.55 \pm 0.21 \pm 0.07$	$23.6 \pm 3.4 \pm 2.0$	$3.44 \pm 0.52 \pm 0.32$	> 10

$$\mathrm{M}(a_0(1710)^+) = (1.817 \pm 0.008_{\text{stat.}} \pm 0.020_{\text{syst.}})\ \mathrm{GeV}/c^2$$

$$\Gamma(a_0(1710)^+) = (0.097 \pm 0.022_{\text{stat.}} \pm 0.015_{\text{syst.}})\ \mathrm{GeV}/c^2$$

BF prediction from EPJC 82,225 (2022): $(1.3 \pm 0.4) \times 10^{-3}$



Study of $D_s^+ \to K^+\pi^+\pi^-$

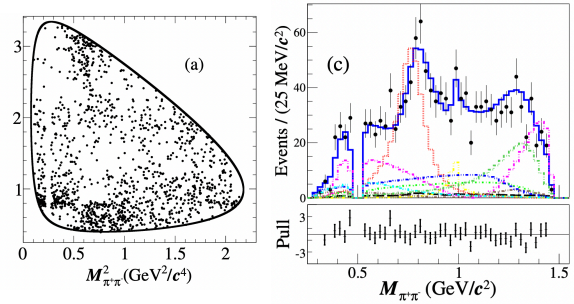
3 Amplitude analyses

- SU(3)-flavor breaking observation with higher precision
- Large NR in PDG: new resonances?
- $f_0(500)$, $f_0(980)$ and $f_0(1370)$: first observation in the decay, replaces NR

Intermediate process	BF(10^{-3})	PDG(10^{-3})
$D_s^+ \to K^+\rho^0$	$1.99 \pm 0.20 \pm 0.22$	2.5 ± 0.4
$D_s^+ \to K^+\rho(1450)^0$	$0.78 \pm 0.20 \pm 0.17$	0.69 ± 0.64
$D_s^+ \to K^*(892)^0\pi^+$	$1.85 \pm 0.13 \pm 0.11$	1.41 ± 0.24
$D_s^+ \to K^*(1410)^0\pi^+$	$0.29 \pm 0.13 \pm 0.13$	1.23 ± 0.28
$D_s^+ \to K_0^*(1430)^0\pi^+$	$1.15 \pm 0.16 \pm 0.15$	0.50 ± 0.35
$D_s^+ \to K^+f_0(500)$	$0.43 \pm 0.14 \pm 0.24$	-
$D_s^+ \to K^+f_0(980)$	$0.27 \pm 0.08 \pm 0.07$	-
$D_s^+ \to K^+f_0(1370)$	$1.22 \pm 0.19 \pm 0.18$	-
$D_s^+ \to (K^+\pi^+\pi^-)_{NR}$	-	1.03 ± 0.34

[arXiv:2205.08844]

1356 events, 95% purity



- $\mathcal{B}(D_s^+ \to K^+\pi^+\pi^-) = (6.11 \pm 0.18_{\text{stat.}} \pm 0.11_{\text{syst.}}) \times 10^{-3}$
- CP asymmetry (D_s^+/D_S^-): $(3.3 \pm 3.7_{\text{stat}} \pm 1.3_{\text{syst}})\%$

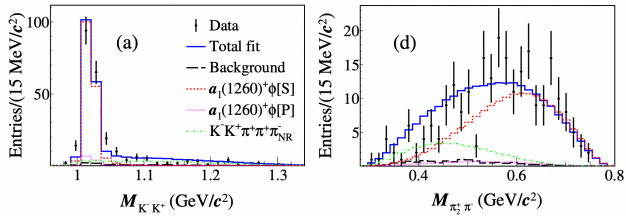
Study of $D_s^+ \to K^+K^-\pi^+\pi^-\pi^+$

3 Amplitude analyses

- First Amplitude analysis as well as absolute BF measurement
- Helpful in the systematics of $\mathcal{R}(D^*) = \mathcal{B}(B \to D^*\tau\nu_\tau)/\mathcal{B}(B \to D^* l\nu_l)$
- Limited knowledge on $D_s^+ \to AV$
- Proceeds primarily through $a_1(1260)^+$

[arXiv:2203.06688]

243 events, 96% purity



Intermediate process	BF (10^{-3})	PDG (10^{-3})
$D_s^+[S] \to a_1(1260)^+\phi, a_1(1260)^+[S] \to \rho^0\pi^+$	$4.8 \pm 0.4 \pm 0.3$	
$D_s^+[P] \to a_1(1260)^+\phi, a_1(1260)^+[S] \to \rho^0\pi^+$	$0.3 \pm 0.1 \pm 0.1$	
$D_s^+ \to a_1(1260)^+\phi$	$5.2 \pm 0.4 \pm 0.3$	7.4 ± 1.2
$D_s^+ \to (K^-K^+\pi^+\pi^+\pi^-)_{\mathrm{NR}}$	$1.4 \pm 0.2 \pm 0.1$	0.9 ± 0.7

- $\mathcal{B}(D_s^+ \to K^+K^-\pi^+\pi^-\pi^+) = (6.60 \pm 0.47_{\mathrm{stat.}} \pm 0.35_{\mathrm{syst.}}) \times 10^{-3}$ with 7.4σ significance

More $D^{0(+)}$, D_s^+ results

$\mathcal{B}(D^0 \to K^-\pi^+\omega)$ (DT method) — Phys. Rev. D **105** 032009 (2022)

- Improved measurement: $\mathcal{B}(D^0 \to K^-\pi^+\omega) = (3.392 \pm 0.044 \pm 0.085)\%$
- First observations: $\mathcal{B}(D^0 \to K^0_S\pi^0\omega) = (0.85 \pm 0.05 \pm 0.03)\%$, $\mathcal{B}(D^+ \to K^0_S\pi^+\omega) = (0.71 \pm 0.04 \pm 0.03)\%$

$\mathcal{B}(D^0 \to K^+\pi^-\pi^0(\pi^0))$ (DT method) — [arXiv:2203.01555]

- $\mathcal{B}(D^0 \to K^+\pi^-\pi^0)/\mathcal{B}(D^0 \to K^-\pi^+\pi^0) = (0.75 \pm 0.14)\tan^4\theta_C$
- $\mathcal{B}(D^0 \to K^+\pi^-\pi^0\pi^0)/\mathcal{B}(D^0 \to K^-\pi^+\pi^0\pi^0) < 1.37 \times \tan^4\theta_C$ at 90% CL

Amplitude analysis of $D_s^+ \to \pi^+\pi^0\pi^0$ — JHEP **01** (2022) 052

- No contamination from $a_0(980)$ or ρ^0, unlike in $D_s^+ \to \pi^+\pi^+\pi^-$ or $\pi^+K^+K^-$
- $\mathcal{B}(D_S^+ \to \pi^+\pi^0\pi^0) = (0.50 \pm 0.04_{stat.} \pm 0.02_{syst.})\%$
- Precision doubled compared with PDG

Amplitude analysis of $D_s^+ \to \pi^+\pi^0\eta'$ — JHEP **04** (2022) 058

- $\rho^+\eta'$ only significant contribution
- $\mathcal{B}(D_S^+ \to \pi^+\pi^0\eta') = (6.15 \pm 0.25_{\text{stat.}} \pm 0.18_{\text{syst.}})\%$

...and many more

Summary

- ✓ Many first observations
- ✓ Overall many-folds better precision on branching fractions
- ✓ $D \to \omega\phi$ polarization and K^0_S/K^0_L asymmetry measurements contradict model predictions
- ✓ Amplitude analyses with highly pure data samples:
  - $a_0(1710)$ established in $D_s^+ \to K^0_S K^+\pi^0$
  - NR replaced with multiple scalar states in $D_s^+ \to K^+\pi^+\pi^-$
- More conclusive results with precision expected with a total of 20fb^{-1} of $\psi(3770)$ data by 2023
  - $\sim 5\text{fb}^{-1}$ already collected

Thank you

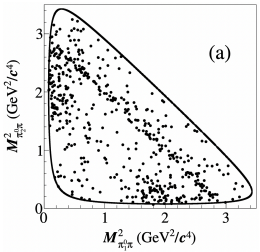
Study of $D_s^+ \to \pi^+\pi^0\pi^0$

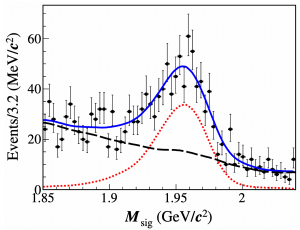
3 Amplitude analyses

JHEP **01** (2022) 052

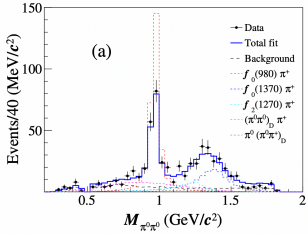
572 events, 78% purity

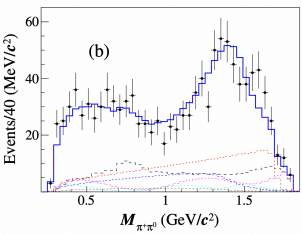
- No contamination from $a_0(980)$ or ρ^0, unlike in $D_s^+ \to \pi^+\pi^+\pi^-$ or $\pi^+K^+K^-$
- $\mathcal{B}(D_S^+ \to \pi^+\pi^0\pi^0) = (0.50 \pm 0.04_{stat.} \pm 0.02_{syst.})\%$
- Precision doubled compared with PDG
- $\mathcal{B}(f_{0(2)} \to \pi^+\pi^-)/\mathcal{B}(f_{0(2)} \to \pi^0\pi^0) \sim 2$ Consistent with isospin symmetry





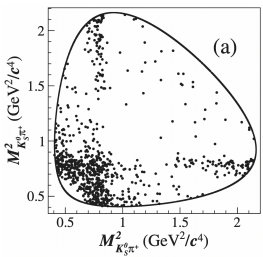
Intermediate process	BF (10^{-3})
$D_s^+ \to f_0(980)\pi^+$, $f_0(980) \to \pi^0\pi^0$	$2.8 \pm 0.4 \pm 0.4$
$D_s^+ \to f_0(1370)\pi^+$, $f_0(1370) \to \pi^0\pi^0$	$1.3 \pm 0.3 \pm 0.5$
$D_s^+ \to f_2(1270)\pi^+$, $f_2(1270) \to \pi^0\pi^0$	$0.5 \pm 0.2 \pm 0.3$
$D_s^+ \to \pi^+(\pi^0\pi^0)_D$	$1.1 \pm 0.4 \pm 0.2$
$D_s^+ \to (\pi^+\pi^0)_D\pi^0$	$0.3 \pm 0.1 \pm 0.1$
	BF listed on PDG [1] (10^{-3})
$D_s^+ \to f_0(980)\pi^+$, $f_0(980) \to \pi^+\pi^-$	6.1 ± 0.7
$D_s^+ \to f_0(1370)\pi^+$, $f_0(1370) \to \pi^+\pi^-$	3.5 ± 0.9
$D_s^+ \to f_2(1270)\pi^+$, $f_2(1270) \to \pi^+\pi^-$	1.2 ± 0.2

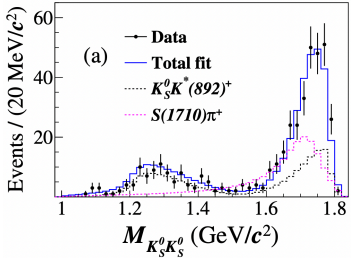


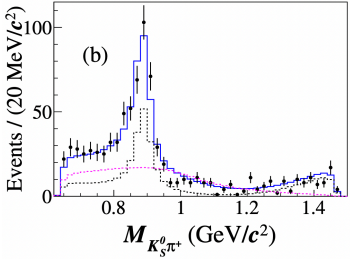


Study of $D_S^+ \to K_S^0 K_S^0 \pi^+$

3 Amplitude analyses







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- Isospin symmetry predicts: $\mathcal{B}(D_S^+ \to (K_S^0 K_S^0)_{f_0(1710)}\pi^+) = 0.05\%$
- Enhancement at $M_{K_S^0 K_S^0} \sim 1.7$ GeV/c^2

Amplitude	BF (10^{-3})
$D_s^+ \to K_S^0 K^*(892)^+ \to K_S^0 K_S^0 \pi^+$	$3.0 \pm 0.3 \pm 0.1$
$D_s^+ \to S(1710)\pi^+ \to K_S^0 K_S^0 \pi^+$	$3.1 \pm 0.3 \pm 0.1$

- $S(1710)$: Constructive interference between $f_0(1710)$ and its isospin vector partner $a_0(1710)$
- Was destructive in $D_S^+ \to K^+ K^- \pi^+$
- Double-tag method: $\mathcal{B}(D_S^+ \to K_S^0 K_S^0 \pi^+) = (0.68 \pm 0.04_{(\text{stat.})} \pm 0.01_{(\text{syst.})})\%$
- Uncertainty reduced by half

Study of $D_S^+ \to \pi^+\pi^0\eta'$

3 Amplitude analyses

Decay		$\mathcal{B}$(%)	
Theory	$D_s^+ \to \rho^+\eta'$	3.0 ± 0.5 [7]	1.7 [8] 1.6 [8]
Experiment	$D_s^+ \to \pi^+\pi^0\eta'$	$5.6 \pm 0.5 \pm 0.6$	CLEO [9]
	$D_s^+ \to \rho^+\eta'$	$5.8 \pm 1.4 \pm 0.4$	BESIII [10]
	$D_s^+ \to \pi^+\pi^0\eta'$ (nonresonant)	< 5.1 (90% confidence level)	BESIII [10]

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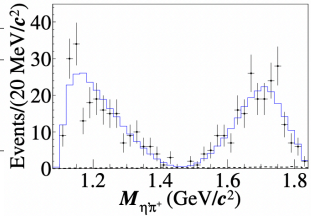

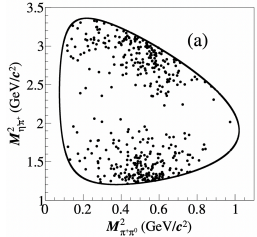

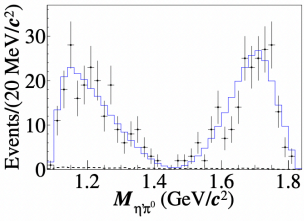

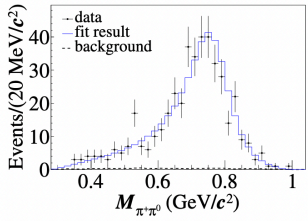

- Predictions and previous measurements show large deviations
- $\rho^+\eta'$ only significant contribution
- $\mathcal{B}(D_S^+ \to \pi^+\pi^0\eta') = (6.15 \pm 0.25_{\text{stat.}} \pm 0.18_{\text{syst.}})\%$
- $\mathcal{B}(D_S^+ \to (\pi^+\pi^0)_S\eta') < 0.1\%$ at 90% CL
- $\mathcal{B}(D_S^+ \to (\pi^+\pi^0)_P\eta') < 0.74\%$ at 90% CL