Doubly Cabibbo-Suppressed *D* decays at BESIII

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(on behalf of the BESIII Collaboration)

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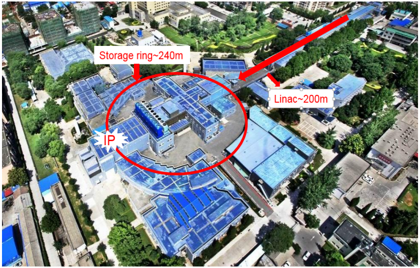
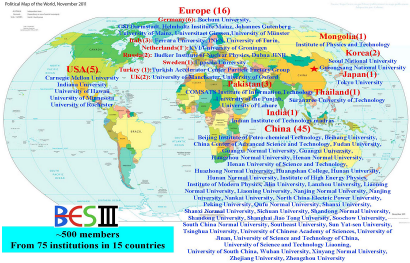
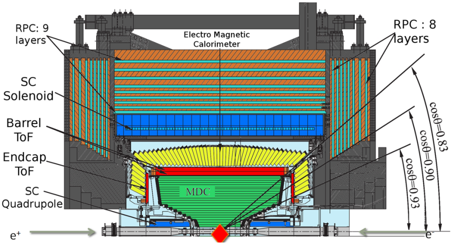
BESIII experiment (See Panting's talk)







- $\sqrt{s} = (2.0 - 4.95)$ GeV
- MDC: $\sigma_P/P = 0.5\%$ @ 1 GeV; $\sigma_{dE/dx} = 6\%$
- TOF: $\sigma_T = 68(60)$ ps for barrel (endcap)
- EMC: σ_E/E =2.5%(5%) for barrel (endcap)

Introduction

- The information of the Doubly Cabibbo-Suppressed (DCS) decays is very poor due to the limit of its small BF ($\sim 10^{-4} - 10^{-5}$)

Doubly Cabibbo-suppressed modes

Γ_{138}	$K^+\pi^0$	$(2.08 \pm 0.21) \times 10^{-4}$	S=1.4	864
Γ_{139}	$K^+\eta$	$(1.25 \pm 0.16) \times 10^{-4}$	S=1.1	776
Γ_{140}	$K^+\eta'(958)$	$(1.85 \pm 0.20) \times 10^{-4}$		571
Γ_{141}	$K^+\pi^+\pi^-$	$(4.91 \pm 0.09) \times 10^{-4}$		846
Γ_{142}	$K^+\rho^0$	$(1.9 \pm 0.5) \times 10^{-4}$		679
Γ_{143}	$K^*(892)^0\pi^+$, $K^*(892)^0 \to K^+\pi^-$	$(2.3 \pm 0.4) \times 10^{-4}$		714
Γ_{144}	$K^+ f_0(980)$, $f_0(980) \to \pi^+\pi^-$	$(4.4 \pm 2.6) \times 10^{-5}$		
Γ_{145}	$K_2^*(1430)^0\pi^+$, $K_2^*(1430)^0 \to K^+\pi^-$	$(3.9 \pm 2.7) \times 10^{-5}$		
Γ_{146}	$K^+\pi^+\pi^-$ nonresonant	not seen		846
Γ_{147}	$K^+\pi^+\pi^-\pi^0$	$(1.21 \pm 0.09) \times 10^{-3}$		817
Γ_{148}	$K^+\omega$	$(5.7^{+2.5}_{-2.1}) \times 10^{-5}$		675
Γ_{149}	2 K^+K^-	$(6.14 \pm 0.11) \times 10^{-5}$		550
Γ_{150}	$\phi(1020)^0 K^+$	$< 2.1 \times 10^{-5}$	CL=90%	
Γ_{151}	$K^+\phi(1020)$, $\phi \to K^+K^-$	$(4.4 \pm 0.6) \times 10^{-6}$		
Γ_{152}	$K^+(K^+K^-)_{S-wave}$	$(5.77 \pm 0.12) \times 10^{-5}$		550

Our results

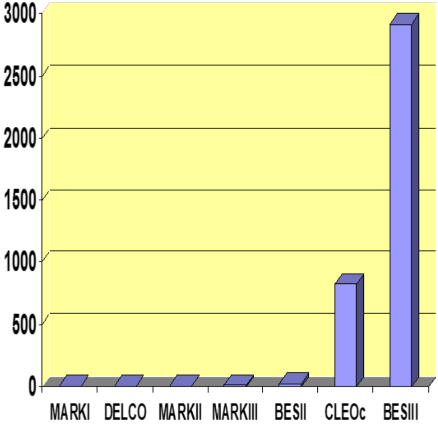
Introduction

- $\mathcal{R} = \mathcal{B}(\mathrm{DCS})/\mathcal{B}(\mathrm{CF})$ is expected to be of approximately $\tan^4\theta_C(\sim 0.29\%)$ level, the known $\mathcal{R}$ in D sector roughly support this expectation. More DCS study can check this expectation

DCS mode	BF($\times10^{-4}$)	CF mode	BF($\times10^{-2}$)	$\mathcal{R}(\times10^{-3})$
$D^0 \to K^+\pi^-$	1.50±0.07	$D^0 \to K^-\pi^+$	3.946±0.03	3.80±0.18
$D^0 \to K^+\pi^-\pi^0$	3.05±0.15	$D^0 \to K^-\pi^+\pi^0$	14.4±0.5	2.12±0.13
$D^0 \to K^+\pi^-\pi^-\pi^+$	2.65±0.06	$D^0 \to K^-\pi^+\pi^+\pi^-$	8.22±0.14	3.22±0.09
$D^+ \to K^+\pi^+\pi^-$	4.91±0.09	$D^+ \to K^-\pi^+\pi^+$	9.38±0.16	5.23±0.13

- Investigation of $D^+ \to K^+\pi^+\pi^-\pi^0$ offers an ideal opportunity to determine the BF of DCS $D \to VP$ decay $D^+ \to K^+\omega$, which is helpful to improve the understanding of SU(3) asymmetry
- Searching for CP violation in DCS decays offers complementary information about CP violation in the charm sector

D^+D^- data sample @3.773 GeV at BESIII



- $e^+e^- \to \psi(3770) \to D^+D^-$, $\mathcal{L}_{\rm int} = 2.93\ \text{fb}^{-1}$, $N_{D^+D^-} \sim 8.3$ M
- D^+D^- is produced near threshold, $E_{\rm cms} - 2M_{D^+} = 35$ MeV
- Clean environment, good to detect neutral particles

Double-tag method

- Tagged by hadronic decays
  - $D^- \to K^+\pi^-\pi^-$
  - $D^- \to K^0_S\pi^-$
  - $D^- \to K^+\pi^-\pi^-\pi^0$
- Feature
  - Absolute branching fraction
  - Large ST data samples
  - Clean environment

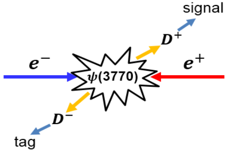
$$N_{\rm ST} = 2N_{D^+D^-}\mathcal{B}_{\rm tag}\epsilon_{\rm tag}$$

$$N_{\rm DT} = 2N_{D^+D^-}\mathcal{B}_{\rm tag}\mathcal{B}_{\rm sig}\epsilon_{\rm tag,sig}$$

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}}{N_{\rm ST}\epsilon_{\rm DT}/\epsilon_{\rm ST}}$$

- Tagged by semileptonic decays
  - $D^- \to K^0 e^-\bar{\nu}_e$
  - $D^- \to K^+\pi^- e^-\bar{\nu}_e$
- Feature
  - New idea to determine BF with statistical independent
  - Confirm the result tagged by hadronic decays

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm SL,DCS}}{2 \cdot N_{D^+D^-} \cdot \mathcal{B}_{\rm SL} \cdot \epsilon_{\rm SL,DCS} \cdot \mathcal{B}_{\rm sub}}$$

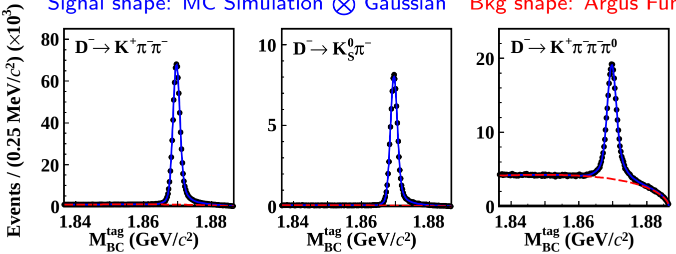


Tagged by hadronic decays [Phys. Rev. Lett. **125**. 141802 (2020)]

- Fit to $M_{\rm BC}$ distribution of three single tags $\quad M_{\rm BC} = \sqrt{E^2_{\rm beam} - |\overrightarrow{p}_{D^-}|^2}$

  (Charge conjugation are implied)

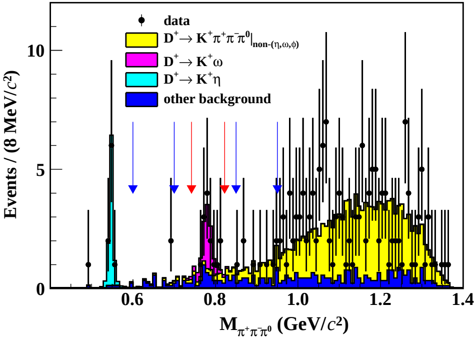
Signal shape: MC Simulation $\otimes$ Gaussian Bkg shape: Argus Function



- Summary of single tag yields ($N^i_{\rm tag}$) and reconstructed efficiencies ($\epsilon^i_{\rm tag}$)

Tag mode	$N^i_{\rm tag}$	$\epsilon^i_{\rm tag}$ (%)
$D^- \to K^+\pi^-\pi^-$	798935 ± 1011	51.90 ± 0.08
$D^- \to K^0_S\pi^-$	93308 ± 329	51.80 ± 0.17
$D^- \to K^+\pi^-\pi^-\pi^0$	258044 ± 1036	26.92 ± 0.09
Sum	1150287 ± 1484	

Tagged by hadronic decays [Phys. Rev. Lett. **125**. 141802 (2020)]



(Red and blue arrows point the signal and sideband regions for ω)

- Observable ω and η resonances
- $D^+ \to K^+\eta$ has been measured with ST method and $\eta \to \gamma\gamma$(439±72 events)[BESIII: PRD 97, 072004]
- $D^+ \to K^+\omega$ will be measured for the first time

Tagged by hadronic decays [Phys. Rev. Lett. **125**. 141802 (2020)]

♢$D^+ \to K^+\pi^+\pi^-\pi^0$ yields obtained by 2D fit to $M_{\rm BC}^{\rm tag}$ vs. $M_{\rm BC}^{\rm sig}$ distributions

- BKGI(float): Only one D is reconstructed correctly
- BKGII(float): $e^+e^- \to q\bar{q}$
- BKGIII(float): Both $D^\pm$ are reconstructed incorrectly
- Peaking BKG(fixed): Tag correct and sig: $D^+ \to K^+K^-(\to \pi^-\pi^0)\pi^+$, $D^+ \to K_S^0(\to \pi^+\pi^-)K^+\pi^0$

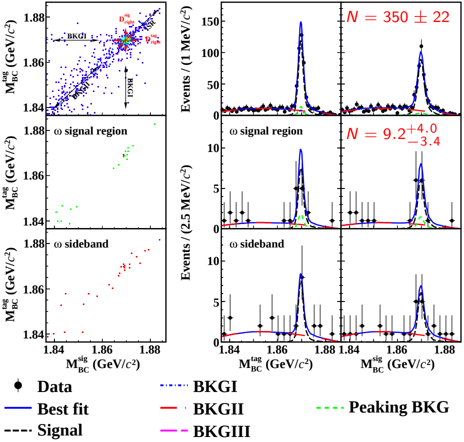
♢$D^+ \to K^+\omega$ yields obtained by 2D simultaneous fit to $M_{\rm BC}^{\rm tag}$ vs. $M_{\rm BC}^{\rm sig}$ distributions in ω signal and sideband regions

- Peaking BKG from ω sideband is $D^+ \to K^+\pi^+\pi^-\pi^0$

Top: 2D fit of all events

Middle: 2D fit of events lying in ω signal region

Bottom: 2D fit of events lying in ω sideband region



Tagged by hadronic decays [Phys. Rev. Lett. **125**. 141802 (2020)]

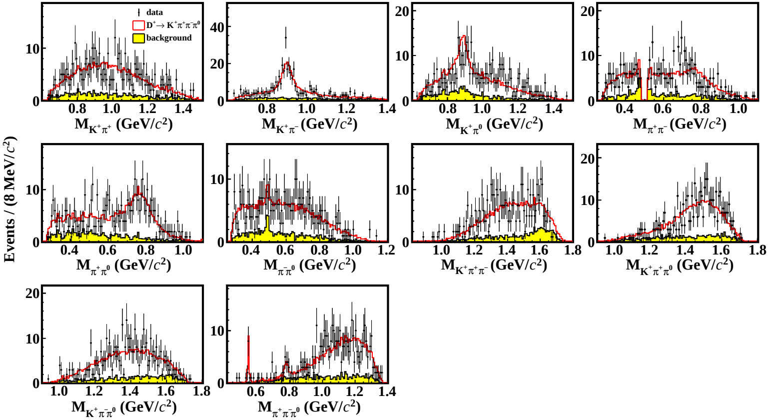
Decay mode	$N_{\rm ST}$ ($\times 10^3$)	$N_{\rm DT}$	$\epsilon_{\rm sig}$ (%)	$\mathcal{B}_{\rm sig}$ ($\times 10^{-3}$)	$\mathcal{B}^*_{\rm sig}$ ($\times 10^{-3}$)
$D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0$	1150.3 ± 1.5	350 ± 22	25.03 ± 0.13	$1.21 \pm 0.08 \pm 0.03$	$1.13 \pm 0.08 \pm 0.03$
$D^\pm \to K^\pm\omega$	1150.3 ± 1.5	$9.2^{+4.0}_{-3.4}$	14.14 ± 0.09	$(5.7^{+2.5}_{-2.1} \pm 0.2) \times 10^{-2}$	-
$D^+ \to K^+\pi^+\pi^-\pi^0$	573.5 ± 1.0	181 ± 15	25.20 ± 0.18	$1.25 \pm 0.11 \pm 0.03$	$1.17 \pm 0.11 \pm 0.03$
$D^- \to K^-\pi^-\pi^+\pi^0$	572.7 ± 1.0	165 ± 15	24.95 ± 0.18	$1.16 \pm 0.11 \pm 0.03$	$1.08 \pm 0.11 \pm 0.03$

(Note: $\mathcal{B}^*_{\rm sig}$: Remove the contributions from $D^\pm \to K^\pm\eta$, $D^\pm \to K^\pm\omega$, and $D^\pm \to K^\pm\phi$)

- Branching fractions for $D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0$ (statistical significance=23.3σ), $D^\pm \to K^\pm\omega$ (statistical significance=3.3σ), and charge-conjugated decays $D^+ \to K^+\pi^+\pi^-\pi^0$ and $D^- \to K^-\pi^-\pi^+\pi^0$ are determined for the first time
- $\mathcal{B}^*_{D^+\to K^+\pi^+\pi^-\pi^0}/\mathcal{B}_{D^+\to K^-\pi^+\pi^+\pi^0} = (1.81 \pm 0.15)\% = (6.28 \pm 0.52)\tan^4\theta_C$, significantly larger than the values (0.21-0.58)% measured for the other DCS decays
- $\mathcal{A}_{CP} = \frac{\mathcal{B}_{D^+\to K^+\pi^+\pi^-\pi^0} - \mathcal{B}_{D^-\to K^-\pi^-\pi^+\pi^0}}{\mathcal{B}_{D^+\to K^+\pi^+\pi^-\pi^0} + \mathcal{B}_{D^-\to K^-\pi^-\pi^+\pi^0}} = -0.04 \pm 0.06 \pm 0.01$

Tagged by hadronic decays [Phys. Rev. Lett. **125**. 141802 (2020)]

- Comparison of invariant masses for different particles combinations between data and MC

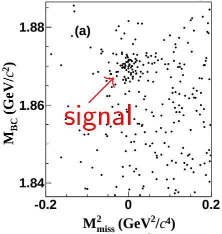


- Some possible sub-resonances, such as K^*, ρ..., can be seen

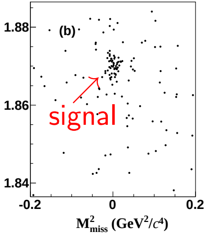
Tagged by semileptonic decays [arXiv:2105.14310]

- Search for $D^- \to K^0(\to \pi^+\pi^-)e^-\bar{\nu}_e / K^+\pi^-e^-\bar{\nu}_e$ vs. $D^+ \to K^+\pi^+\pi^-\pi^0$

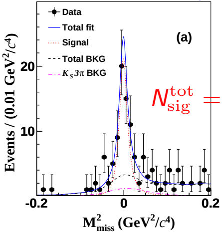
$D^- \to K^0 e^- \bar{\nu}_e$



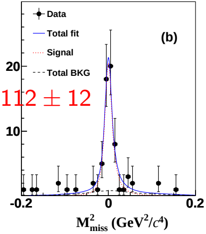
$D^- \to K^+\pi^- e^- \bar{\nu}_e$



$D^- \to K^0 e^- \bar{\nu}_e$



$D^- \to K^+\pi^- e^- \bar{\nu}_e$



$$E_{\text{miss}} = E_{\text{beam}} - E_h - E_{e^-}$$
$$\vec{p}_{\text{miss}} = \vec{p}_{D^-} - \vec{p}_h - \vec{p}_{e^-}$$
$$M^2_{\text{miss}} = E^2_{\text{miss}} - |\vec{p}_{\text{miss}}|^2$$

- Top: Distributions of M_{BC} vs. M^2_{miss}
- Bottom: Simultaneous fits to the M^2_{miss} distributions tagged by $D^- \to K^0 e^- \bar{\nu}_e$ and $D^- \to K^+\pi^- e^-\bar{\nu}_e$ with $M_{\text{BC}} \in (1.864, 1.874)$ GeV$/c^2$

$$\mathcal{B}^*(D^+ \to K^+\pi^+\pi^-\pi^0) = (1.03 \pm 0.12 \pm 0.06) \times 10^{-3}$$

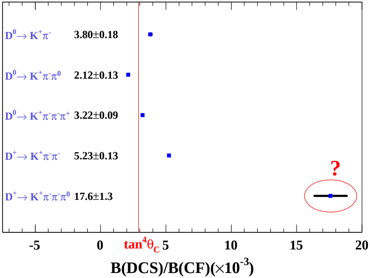
(Note: The contributions from $D^\pm \to K^\pm\eta$, $D^\pm \to K^\pm\omega$, and $D^\pm \to K^\pm\phi$ are removed)

Combined result

BESIII results		
Tag side	$\mathcal{B}(D^+ \to K^+\pi^+\pi^-\pi^0)(\%)$	Precision(%)
Hadronic decays	$1.13 \pm 0.08 \pm 0.03$	7.56
Semileptonic decays	$1.03 \pm 0.12 \pm 0.06$	13.03
Average	$1.10 \pm 0.07 \pm 0.03$	6.92

(Note: The contributions from $D^\pm \to K^\pm\eta$, $D^\pm \to K^\pm\omega$, and $D^\pm \to K^\pm\phi$ are removed)

- The correlated uncertainties of $K^\pm$, $\pi^+\pi^-$ tracking/PID, π^0 reconstruction, and MC model are considered
- $\mathcal{R}(\mathrm{DCS/CF})_{\mathrm{ave}} = (1.76 \pm 0.13)\% = (6.11 \pm 0.52)\tan^4\theta_C$



Future prospect

BESIII plan to take $\sim$20 fb^{-1} (3+17) data @$\sqrt{s} = 3.773$ GeV [Chin. Phys. C, 2020, 44(4)]

With about 6.5$\times$ data

- Precision of $\mathcal{B}(D^+ \to K^+\pi^+\pi^-\pi^0)$: 6.9%$\to\sim$2.7%
- $N(D^+ \to K^+\pi^+\pi^-\pi^0)$ is expected to be larger than 2000, PWA will be available$\to$explain the unusual $\mathcal{R}$?
- $\mathcal{A}_{CP}$: $(-0.04 \pm 0.06) \to (-0.04 \pm 0.02)$ (assume central value is the same)
- Statistical significance for $D^+ \to K^+\omega$ is expected to be larger 5σ
- More DCS decays can be studied
  - $D^0 \to K^+\pi^-\eta$
  - $D^+ \to K^+\eta\eta$
  - $D^+ \to K^+\pi^+\pi^-\eta$
  - ....

Summary

Precise measurement of DCS decay $D^+ \to K^+\pi^+\pi^-\pi^0$ using 2.93 fb^{-1} data @$\sqrt{s} = 3.773$ GeV have been reported by BESIII

- The results of two tagged methods are consistent with each other
- At present, $D^+ \to K^+\pi^+\pi^-\pi^0$ has the largest branching fraction among the doubly-Cabibbo suppressed D decay
- $\mathcal{R}(\mathrm{DCS/CF}) = (6.11 \pm 0.52)\tan^4\theta_C$, significantly larger than other DCS decays
- $\mathcal{B}(D^+ \to K^+\omega)$ is also measured with 3.3σ statistical significance
- No evidence for CP violation is found in $D^+ \to K^+\pi^+\pi^-\pi^0$
- BESIII will collect 20 fb^{-1} data at $\psi(3770)$ in the next two years, which provide a good chance to further study this decay and other DCS decays

Thanks for your attention!