## Hadronic decays of D<sub>(s)</sub> at BESIII Bai-Cian Ke IHEP

## Outline

## Introduction

- Important variables
- D<sup>0</sup>, D<sup>+</sup>, and D<sub>s</sub> Dataset
- DTag and Branching Fraction
- •Branching Fraction Measurement of D Hadronic decays

•Eta X, omega  $\pi$ , K<sub>S</sub>K<sub>S</sub>K( $\pi$ ), p n<sup>bar</sup>, etc.

- Amplitude Analysis of Kπππ
  - K-π+π+π-, K<sub>S</sub>π+π+π-, K-π+π<sup>0</sup>π<sup>0</sup>, etc.

• Summary

### **Important Variables**

Beam-Constrained Mass (M<sub>BC</sub>)

$$M_{\rm BC} = \sqrt{E_{\rm beam}^2 - |\vec{p_D}|^2}$$

*M*<sub>BC</sub> peaks at D mass: momentum conservation

Energy Difference (ΔE)

$$\Delta E = E_D - E_{\text{beam}}$$

 $\Delta E$  peaks at zero: energy conservation

Typically cut on  $\Delta E$ , then fit to  $M_{\rm BC}$  obtain yield

## **BESIII Data Taken near DD**<sup>bar</sup> Threshold

- BEPCII collider:  $e^+e^- \rightarrow \psi(3770) \rightarrow DD^{bar}$
- 2.9 fb<sup>-1</sup> dataset at  $\psi(3770)$  resonance

 $M_{D0}$ = 1864.84 MeV  $M_{D+}$ = 1869.62 MeV

2M<sub>D0</sub>= 3729.68 MeV 2M<sub>D+</sub>= 3739.24 MeV

- New 3.19 fb<sup>-1</sup> dataset at  $E_{cm}$  4.178GeV
  - $D_s$  are produced mostly via  $e^+e^- \rightarrow D_s D_s^*$
- Advantages of DD<sup>bar</sup> pair production near threshold
  - The DD<sup>bar</sup> events are clean; not enough energy for even one additional pion
  - Tagging reduces background from light-quark "continuum" and other charm final states
  - Double tag technique can provide access to absolute BFs
  - Many systematic uncertainties cancel with tagging technique

## DTag Technique

- There are two types of samples used in the Dtag technique: single tag (ST) and double tag (DT).
- Single tag: only one D meson is reconstructed through a chosen hadronic decay.
- Double tag: both D and  $\overline{D}$  are reconstructed,
- the D reconstructed through the studied hadronic decay is called "the signal side".
- the D reconstructed through well-known and clean hadronic decay modes is called "the tag side".
- (Charge-conjugate states are implied throughout this talk.)



## **Branching Fraction and Tagging**

Single tag (ST)

$$N_{\rm tag}^{\rm ST} = 2N_{D^0\bar{D}^0}\mathcal{B}_{\rm tag}\varepsilon_{\rm tag}$$

- Double tag (DT)
  - $N_{\rm tag,sig}^{\rm DT} = 2N_{D^0\bar{D}^0}\mathcal{B}_{\rm tag}\mathcal{B}_{\rm sig}\varepsilon_{\rm tag,sig}$

 $\varepsilon_{\mathrm{tag,sig}} \approx \varepsilon_{\mathrm{tag}} \varepsilon_{\mathrm{sig}}$  (factorization)

where  $N_{D^0\bar{D}^0}$  is the total number of produced  $D^0\bar{D}^0$  pairs,  $\mathcal{B}_{\text{tag(sig)}}$  is the branching fraction of the tag (signal) side, and the  $\varepsilon$  are the corresponding efficiencies.

$$\blacktriangleright \mathcal{B}_{\text{sig}} = \frac{N_{\text{tag,sig}}^{\text{DT}}}{N_{\text{tag}}^{\text{ST}}} \frac{\varepsilon_{\text{tag}}}{\varepsilon_{\text{tag,sig}}}$$

 $N_{D^0\bar{D}^0}$ ,  $\mathcal{B}_{tag}$  are canceled.  $\varepsilon_{tag}$  is approximately canceled due to factorization

This is the basic idea for branching fraction. Equations used in analysis vary case by case.

# Measurements of the branching fraction of $D_s^+ \rightarrow \eta' X$

Single tag nine tag modes



A two-dimensional fit to  $M_{BC}$  (tag) vs.  $M(\eta'_{\pi+\pi-\eta})$  (signal) is performed to obtain the DT yields.



#### $\mathcal{B}(D_s^+ \to \eta' X) = (8.8 \pm 1.8 \pm 0.5)\%$

# Measurements of the branching fraction of $D_s^+ \rightarrow \eta' \rho^+$

Using the DT samples from  $D_s^+ \rightarrow \eta' X$  analysis, invariant mass cuts on  $\eta'$  and  $\rho^+$  are applied to enrich the  $D_s^+ \rightarrow \eta' \rho^+$  signal events.

A two-dimensional fit to the distribution of  $M_{_{BC}}$  vs.  $cos\theta_{_{\pi^+}}$  to determine the signal yield.



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### Observation of the Singly Cabibbo-Suppressed Decay $D^+ \rightarrow \omega \pi^+$ and Evidence for $D^0 \rightarrow \omega \pi^0$

Chose six (five) decay modes for  $D^{+(0)}$ .

In order to have a better solution for  $D^{+(0)} \rightarrow \pi^{+}\pi^{-}\pi^{0}\pi^{+(0)}$  background, DT samples  $D^{+(0)} \rightarrow \pi^{+}\pi^{-}\pi^{0}\pi^{+(0)}$  vs. tag modes are reconstructed first. Then fits to  $\pi^{+}\pi^{-}\pi^{0}$  mass are performed.

Note that we are searching for  $\omega \rightarrow \pi^+\pi^-\pi^0$ .

$$\mathcal{B}_{\rm sig} = \frac{\sum_{\alpha} N_{\rm sig}^{\rm obs,\alpha}}{\sum_{\alpha} N_{\rm tag}^{\rm obs,\alpha} \epsilon_{\rm tag,sig}^{\alpha} / \epsilon_{\rm tag}^{\alpha}}$$



FIG. 1.  $M_{\rm BC}$  distributions of ST samples for different tag modes. The first two rows show charged *D* decays: (a)  $K^+\pi^-\pi^-$ , (b)  $K^+\pi^-\pi^-\pi^0$ , (c)  $K_S^0\pi^-$ , (d)  $K_S^0\pi^-\pi^0$ , (e)  $K_S^0\pi^+\pi^-\pi^-$ , (f)  $K^+K^-\pi^-$ , the latter two rows show neutral *D* decays: (g)  $K^+\pi^-$ , (h)  $K^+\pi^-\pi^0$ , (i)  $K^+\pi^-\pi^+\pi^-$ , (j)  $K^+\pi^-\pi^0\pi^0$ , (k)  $K^+\pi^-\pi^+\pi^-\pi^0$ . Data are shown as points, the (red) solid lines are the total fits and the (blue) dashed lines are the background shapes. *D* and  $\overline{D}$  candidates are combined.

#### DT $D^{+(0)} \rightarrow \pi^+\pi^-\pi^0\pi^{+(0)}$ vs. tag modes

Fits to  $M3\pi$  distributions of signal and sideband regions to obtain the signal and peaking background yields, respectively.

Events counts in sidebands are projected into the signal region with scale factors.



ModeH	$N_{\omega(\eta)}$	$N^{ m bkg}_{\omega(\eta)}$	$N_{ m sig}^{ m obs}$
$D^+ \rightarrow \omega \pi^+$	$100 \pm 16$	$21 \pm 4$	79±16
$D^0 \to \omega \pi^0$	$50\pm12$	$5\pm5$	$45\pm13$
$D^+  o \eta \pi^+$	$264 \pm 17$	$6\pm 2$	$258\pm18$
$D^0 \to \eta \pi^0$	$78\pm10$	$3\pm 2$	$75\pm10$

Mode	This work	Previous measurements
$D^+ \rightarrow \omega \pi^+$	$(2.79 \pm 0.57 \pm 0.16) \times 10^{-4}$	$< 3.4 \times 10^{-4}$ at 90% C.L.
$D^0 \rightarrow \omega \pi^0$	$(1.17 \pm 0.34 \pm 0.07) \times 10^{-4}$	$< 2.6 \times 10^{-4}$ at 90% C.L.
$D^+ \rightarrow \eta \pi^+$	$(3.07 \pm 0.22 \pm 0.13) \times 10^{-3}$	$(3.53\pm0.21)\times10^{-3}$
$D^0 \rightarrow \eta \pi^0$	$(0.65\pm0.09\pm0.04)\times10^{-3}$	$(0.68\pm0.07)\times10^{-3}$

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# Preliminary results on observation of $D_s^{\ +} \rightarrow \omega \pi^+ \ and \ \omega K^+$

With 3.19 fb<sup>-1</sup> data @ 4.178GeV collected by the BESIII

Double tag: One  $M_{rec} > 2.1 \text{ GeV}$ 

- Best candidate: average mass of two D<sub>s</sub> mesons closet to PDG value.
- $K_s^0$  veto for  $D_s^+ \to \omega K^+$  to suppress the background from  $D_s^+ \to \overline{K}^{*0}K^+$ : If  $|m_{\pi\pi} - 0.4976| < 0.03 \text{GeV}$ ,  $L_{decay}/\sigma_{L_{decay}} > 2.0$ , veto this event.



Signal mode	Branching fraction ( ${f 10^{-3}}$ )	Statistical significance ( $\sigma$ )
$D_s^+ \to \omega \pi^+$	$1.85 \pm 0.30(stat.) \pm 0.19(sys.)$	7.7
$D_s^+ \to \omega K^+$	$1.13 \pm 0.24(stat.) \pm 0.14(sys.)$	6.2

## Measurements of the branching fractions for $D^+ \rightarrow K_s K_s K^+$ , $K_s K_s \pi^+$ and $D^0 \rightarrow K_s K_s (K_s)$

Single tag the signal mode.

The combinatorial  $\pi^+\pi^-$  pair background is the main issue.

An invariant mass cut,  $M_{\pi^+\pi^-}$ , is applied during the reconstruction of  $K_s$ , but the combinatorial  $\pi^+\pi^-$  (not from  $K_s$ ) pairs may also satisfy the cut. To remove this background, the 2D or 3D sideband regions are studied.





For modes with two K<sub>s</sub>: 
$$N_{\text{net}} = N_{K_s^0 \text{sig}} - \frac{1}{2}N_{\text{sb1}} + \frac{1}{4}N_{\text{sb2}} - N_{\text{other}}^b$$
  
For mode with three K<sub>s</sub>:  $N_{\text{net}} = N_{K_s^0 \text{sig}} - \frac{1}{2}N_{\text{sb1}} + \frac{1}{4}N_{\text{sb2}} - \frac{1}{8}N_{\text{sb3}} - N_{\text{other}}^b$ 

Decay modes	N <sub>KS</sub> sig	N <sub>sb1</sub>	N <sub>sb2</sub>	N <sub>sb3</sub>	N <sup>b</sup> <sub>other</sub>	N <sub>net</sub>	<i>€</i> (%)	$\mathcal{B}$ (×10 <sup>-4</sup> )
$D^+ \rightarrow K^0_S K^0_S K^+$	$3616\pm66$	$97 \pm 19$	$6\pm8$	-	$18\pm2$	$3551\pm67$	$8.27\pm0.04$	$25.4\pm0.5$
$D^+ \rightarrow K^0_S K^0_S \pi^+$	$5643 \pm 88$	$1464\pm68$	$69 \pm 19$	-	$31\pm3$	$4897\pm94$	$10.72\pm0.04$	$27.0 \pm 0.5$
$D^0 \rightarrow K^0_S K^0_S$	$888\pm36$	$626 \pm 31$	$3\pm 6$	_	0	$576 \pm 39$	$16.28\pm0.30$	$1.67\pm0.11$
$D^0 \to K^0_S K^0_S K^0_S$	$622\pm27$	$24\pm8$	$14\pm 6$	0	$16\pm3$	$597\pm27$	$3.92\pm0.05$	$7.21 \pm 0.33$

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## Preliminary result for $D_s \rightarrow pn^{bar}$

With 3.19 fb<sup>-1</sup> data @ 4.178GeV collected by the BESIII

### Double tag

- Kinematic fit to improve missing neutron resolution
  Constraint the 4 momenta of the total events. <sup>50</sup>/<sub>60</sub>
- Constraint the 4 momenta of the total events.
   the two Ds and Ds\* mass, set anti-neutron 4 momenta free: (7-4)C
- Set two hypotheses to select the one with smaller  $\chi^2$ 
  - $Ds^* \rightarrow \gamma Ds(\rightarrow tag modes)$
  - $Ds^* \rightarrow \gamma Ds(\rightarrow p\bar{n})$
- No peaking background
- Signal efficiency  $\sim 48\%$  from inclusive MC



#### **Preliminary result**

$$\mathcal{B}_{D_s \to p\bar{n}} = \frac{1}{\mathcal{B}_{D_s^* \to \gamma D_s}} \cdot \frac{N_{DT}}{N_{ST}} \cdot \frac{\epsilon_{ST}}{\epsilon_{DT}}$$
$$= \frac{1}{\mathcal{B}_{D_s^* \to \gamma D_s}} \cdot \frac{\sum N_{DT}}{\sum (N_{ST} \cdot \frac{\epsilon_{DT}}{\epsilon_{ST}})}$$

By combining the 11 tag modes together, we obtain (only statistic error here):

$$\mathcal{B}_{D_s^+ \to p\bar{n}} = (1.22 \pm 0.10) \times \frac{10^{-3}}{\text{BESII}}$$
 preliminary



Signal: MC shape  $\otimes$ Gaussian Background: Argus function

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- Statistically limited.
- Uncertainty due to baryon ID dominates the systematic
- Confirm CLEO-c's measurement with greatly improved accuracy
- Consistent with the prediction of the enhanced BR due to long-distance effect via hadronic loop

## **Amplitude Analysis of Κπππ**

#### •There are seven $D \to K3\pi$ modes:

- $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$  (published on PRD) PhysRevD.95.072010
- $D^0 \rightarrow K^-\pi^+\pi^0\pi^0$  (expected to publish on PRD soon)
- $D^0 {\rightarrow} \ K_S \pi^0 \pi^0 \pi^0$
- $D^0 \rightarrow K_S \pi^+ \pi^- \pi^0$  (on-going)
- $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$  (on-going)
- $D^+ \rightarrow K_S \pi^+ \pi^0 \pi^0$  (on-going)
- $D^+ \rightarrow K_S \pi^+ \pi^+ \pi^-$  (expected to publish on PRD soon)
- Four-body decays are in five-dimensions

#### •We have

- Partial Wave Analysis Tools based on CPU and GPU kernel
- Great Electro-Magnetic Calorimeter (EMC) with Csl
  - $\rightarrow$  superior resolution and efficiency of  $\pi^0$
- Largest dataset at  $\psi(3770)$  resonance
  - $\rightarrow$  small statistical errors and clean background

## **Partial Wave Analysis**



where  $p_j$  is the daughter particles' four momenta and  $\underline{a_i}$  is the complex coefficient for amplitude modes.  $\epsilon(p_j)$  is the efficiency parameterized in terms of the daughter particles' four momenta.  $R_4$  is the 4-body phase space

$$A_i(p_j) = P_i^1(p_j) P_i^2(p_j) S_i(p_j) F_i^1(p_j) F_i^2(p_j) F_i^D(p_j)$$

where  $F_i^D(p_j)$  is the Blatt-Weisskopf <u>Barrier factor</u> for D meson.  $P_i^{1,2}(p_j)$  and  $F_i^{1,2}(p_j)$ is the propagator and the Blatt-Weisskopf Barrier factor, respectively, of the two resonance states for the quasi-two-body type or of the first and the second resonance states for the cascade type.  $S_i(p_j)$  is the spin factor. Finally, the likelihood can be defined as

For n events 
$$\prod_{j=1}^{n} S(a_i, p_j)$$
  
Define the likelihood  $L = \prod_{j=1}^{n} S(a_i, p_j)$ 

## Partial Wave Analysis Ind

Independent of a<sub>i</sub>

$$\ln L = \sum_{j}^{N_{selected}} \ln \left( \frac{|A(a_i, p_j)|^2 R_4(p_j)}{\int \epsilon(p_j) |A(a_i, p_j)|^2 R_4(p_j) dp_j} \right) + \sum_{j}^{N_{selected}} \ln \epsilon(p_j)$$
$$\int \epsilon(p_j) |A(a_i, p_j)|^2 R_4(p_j) dp_j \approx \frac{1}{N_{generated}} \sum_{j}^{N_{selected}} |A(a_i, p_j)|^2$$

Phase space MC sample can be used to deal with the MC integration. We replace phase space MC sample by signal MC sample for better precision.

$$\int \epsilon(p_j) |A(a_i, p_j)|^2 R_4(p_j) dp_j \approx \frac{1}{N_{MC}} \sum_{j}^{N_{MC}} \frac{|A(a_i, p_j)|^2}{|A(a_i^{gen}, p_j)|^2}$$

We further consider the effects of detector efficiency difference between data and MC simulation for pi0 reconstruction, PID, and tracking

$$\int \epsilon(p_j) |A(a_i, p_j)|^2 R_4(p_j) dp_j \approx \frac{1}{N_{MC}} \sum_{j}^{N_{MC}} \frac{|A(a_i, p_j)|^2 \gamma_\epsilon(p_j)}{|A(a_i^{gen}, p_j)|^2}$$

where 
$$\gamma_{\epsilon}(p_j) = \prod_j \frac{\epsilon_{j,\text{data}}(p_j)}{\epsilon_{j,\text{MC}}(p_j)}$$

## Amplitude Analysis of $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$

- This decay is one of the golden decay modes of DTag.
- The knowledge of intermediate process can be Widely used in many measurements, such as:

Branching fraction measurement

- Strong phase measurement
- CKM unitary triangle measurement
- Previous measurements (fit fractions) have been performed by MarkIII and E691

Decay mode	Mark III	E691
$D^0 \to K^- a_1^+(1260)$	$0.492 \pm 0.024 \pm 0.08$	$0.47 \pm 0.05 \pm 0.10$
$D^0 \to \bar{K}^{*0} \rho^0$	$0.142 \pm 0.016 \pm 0.05$	$0.13 \pm 0.02 \pm 0.02$
$D^0 \to K_1^-(1270)\pi^+$	$0.066 \pm 0.019 \pm 0.03$	
$D^0 \to \bar{K}^{*0} \pi^- \pi^+$	$0.140 \pm 0.018 \pm 0.04$	$0.11 \pm 0.02 \pm 0.03$
$D^0 \to K^- \pi^+ \rho^0$	$0.084 \pm 0.022 \pm 0.04$	$0.05 \pm 0.03 \pm 0.02$
$D^0 \rightarrow 4$ -body non-resonance	$0.242 \pm 0.025 \pm 0.06$	$0.23 \pm 0.02 \pm 0.03$

• With the 2.93 fb-1  $\psi$ (3770) data sample collected by BESIII, much more precise results are expected.

## Amplitude Analysis of $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$

Event selection: Double tag  $D^0 \rightarrow K^-\pi^+\pi^- vs. D^{0bar} \rightarrow K^+\pi^-$ 

Peaking background:

K-K<sub>S</sub>π<sup>+</sup> with Ks→ $\pi$ <sup>+</sup> $\pi$ <sup>-</sup> is the dominate background and peaks as the signal. Its number is estimated to be 96.8 +- 14.5 based on MC Other background: < 10

The number of event selected is 15912 with a purity of 99.4%

#### Amplitude Analysis Results of $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$

Amplitude	$\phi_i$	Fit fraction (%)
$D^0[S] \to \bar{K}^* \rho^0$	$2.35 \pm 0.06 \pm 0.18$	$6.5\pm0.5\pm0.8$
$D^0[P] \to \bar{K}^* \rho^0$	$-2.25 \pm 0.08 \pm 0.15$	$2.3 \pm 0.2 \pm 0.1$
$D^0[D]  o \bar{K}^* \rho^0$	$2.49 \pm 0.06 \pm 0.11$	$7.9 \pm 0.4 \pm 0.7$
$D^0 \to K^- a_1^+(1260), a_1^+(1260)[S] \to \rho^0 \pi^+$	0(fixed)	$53.2 \pm 2.8 \pm 4.0$
$D^0 \to K^- a_1^+(1260), a_1^+(1260)[D] \to \rho^0 \pi^+$	$-2.11 \pm 0.15 \pm 0.21$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+, K_1^-(1270)[S] \to \bar{K}^{*0}\pi^-$	$1.48 \pm 0.21 \pm 0.24$	$0.1 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,  K_1^-(1270)[D] \to \bar{K}^{*0}\pi^-$	$3.00 \pm 0.09 \pm 0.15$	$0.7\pm0.2\pm0.2$
$D^0 \to K_1^-(1270)\pi^+, K_1^-(1270) \to K^-\rho^0$	$-2.46 \pm 0.06 \pm 0.21$	$3.4 \pm 0.3 \pm 0.5$
$D^0 \to (\rho^0 K^-)_{\rm A} \pi^+, \ (\rho^0 K^-)_{\rm A} [D] \to K^- \rho^0$	$-0.43 \pm 0.09 \pm 0.12$	$1.1\pm0.2\pm0.3$
$D^0 \to (K^- \rho^0)_{\rm P} \pi^+$	$-0.14 \pm 0.11 \pm 0.10$	$7.4\pm1.6\pm5.7$
$D^0 \rightarrow (K^- \pi^+)_{\rm S} \rho^0$	$-2.45 \pm 0.19 \pm 0.47$	$2.0\pm0.7\pm1.9$
$D^0 \rightarrow (K^- \rho^0)_V \pi^+$	$-1.34 \pm 0.12 \pm 0.09$	$0.4\pm0.1\pm0.1$
$D^0 \to (\bar{K}^{*0}\pi^-)_{\rm P}\pi^+$	$-2.09 \pm 0.12 \pm 0.22$	$2.4\pm0.5\pm0.5$
$D^0 \to \bar{K}^{*0}(\pi^+\pi^-)_{\rm S}$	$-0.17 \pm 0.11 \pm 0.12$	$2.6\pm0.6\pm0.6$
$D^0 \rightarrow (\bar{K}^{*0}\pi^-)_{\rm V}\pi^+$	$-2.13 \pm 0.10 \pm 0.11$	$0.8\pm0.1\pm0.1$
$D^0 \rightarrow ((K^-\pi^+)_{\rm S}\pi^-)_{\rm A}\pi^+$	$-1.36 \pm 0.08 \pm 0.37$	$5.6\pm0.9\pm2.7$
$D^0 \to K^-((\pi^+\pi^-)_{\rm S}\pi^+)_{\rm A}$	$-2.23 \pm 0.08 \pm 0.22$	$13.1 \pm 1.9 \pm 2.2$
$D^0 \to (K^- \pi^+)_{\rm S} (\pi^+ \pi^-)_{\rm S}$	$-1.40 \pm 0.04 \pm 0.22$	$16.3 \pm 0.5 \pm 0.6$
$D^0[S] \to (K^- \pi^+)_V (\pi^+ \pi^-)_V$	$1.59 \pm 0.13 \pm 0.41$	$5.4\pm1.2\pm1.9$
$D^0 \to (K^- \pi^+)_{\rm S} (\pi^+ \pi^-)_{\rm V}$	$-0.16 \pm 0.17 \pm 0.43$	$1.9\pm0.6\pm1.2$
$D^0 \to (K^- \pi^+)_V (\pi^+ \pi^-)_S$	$2.58 \pm 0.08 \pm 0.25$	$2.9 \pm 0.5 \pm 1.7$
$D^0 \to (K^- \pi^+)_{\rm T} (\pi^+ \pi^-)_{\rm S}$	$-2.92 \pm 0.14 \pm 0.12$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to (K^- \pi^+)_{\rm S} (\pi^+ \pi^-)_{\rm T}$	$2.45 \pm 0.12 \pm 0.37$	$0.5 \pm 0.1 \pm 0.1$

#### Amplitude Analysis Results of $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$

Projections of invariant mass (a-h) and  $\chi$  distribution (i)



#### Amplitude Analysis Results of $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$

According to the intermediate resonances, we divides the 23 amplitudes into 7 subsets and call them components. Also, their fit fractions are calculated.

#### Fit fraction (%) Component $D^0 \rightarrow \bar{K}^{*0} \rho^0$ $12.3 \pm 0.4 \pm 0.5$ $D^0 \to K^- a_1^+ (1260) (\rho^0 \pi^+)$ $54.6 \pm 2.8 \pm 3.7$ $D^0 \to K_1^-(1270)(\bar{K}^{*0}\pi^-)\pi^+$ $0.8 \pm 0.2 \pm 0.2$ $D^0 \to K_1^-(1270)(K^-\rho^0)\pi^+$ $3.4 \pm 0.3 \pm 0.2$ $D^0 \rightarrow K^- \pi^+ \rho^0$ $8.4 \pm 1.1 \pm 2.2$ $D^0 \rightarrow \bar{K}^{*0} \pi^+ \pi^ 7.0 \pm 0.4 \pm 0.3$ $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^ 21.9 \pm 0.6 \pm 0.6$

#### Fit fractions(FF) for different components

#### Amplitude Analysis of $D^+ \rightarrow K_S \pi^+ \pi^+ \pi^-$

The data can be described with 12 amplitudes with corresponding phases and fit fractions shown below:

Amplitude	$\phi$	fit fraction
$D^+ \to K^0_S a_1(1260)^+, a_1(1260)^+ \to \rho^0 \pi^+[S]$	0.000(fixed)	$0.567 \pm 0.020 \pm 0.044$
$D^+ \to K_S^0 a_1(1260)^+, a_1(1260)^+ \to f_0(500)\pi^+$	$-2.023 \pm 0.068 \pm 0.113$	$0.050 \pm 0.006 \pm 0.007$
$D^+ \to \bar{K}_1(1400)^0 \pi^+, \bar{K}_1(1400)^0 \to K^{*-} \pi^+[S]$	$-2.714 \pm 0.038 \pm 0.051$	$0.380 \pm 0.013 \pm 0.014$
$D^+ \to \bar{K}_1(1400)^0 \pi^+, \bar{K}_1(1400)^0 \to K^{*-} \pi^+[D]$	$3.431 \pm 0.137 \pm 0.117$	$0.015 \pm 0.004 \pm 0.005$
$D^+ \to \bar{K}_1(1270)^0 \pi^+, \bar{K}_1(1270)^0 \to K^0_S \rho^0[S]$	$-0.418 \pm 0.070 \pm 0.087$	$0.036 \pm 0.004 \pm 0.002$
$D^+ \to \bar{K}(1460)^0 \pi^+, \bar{K}(1460)^0 \to K_S^0 \rho^0$	$-1.850 \pm 0.120 \pm 0.223$	$0.014 \pm 0.004 \pm 0.003$
$D^+ \to (K^0_S \rho^0)_A [D] \pi^+$	$2.328 \pm 0.097 \pm 0.068$	$0.011 \pm 0.003 \pm 0.002$
$D^+ \to K^0_S(\rho^0 \pi^+)_P$	$1.656 \pm 0.083 \pm 0.056$	$0.031 \pm 0.004 \pm 0.010$
$D^+ \to (K^{*-}\pi^+)_A[S]\pi^+$	$-4.321 \pm 0.047 \pm 0.073$	$0.132 \pm 0.011 \pm 0.011$
$D^+ \to (K^{*-}\pi^+)_A[D]\pi^+$	$0.989 \pm 0.158 \pm 0.229$	$0.013 \pm 0.004 \pm 0.004$
$D^+ \to (K^0_S(\pi^+\pi^-)_S)_A\pi^+$	$-2.935 \pm 0.060 \pm 0.125$	$0.051 \pm 0.004 \pm 0.003$
$D^+ \to ((K_S^0 \pi^-)_S \pi^+)_P \pi^+$	$1.864 \pm 0.069 \pm 0.288$	$0.022 \pm 0.003 \pm 0.003$

#### Amplitude Analysis of $D^+ \rightarrow K_S \pi^+ \pi^+ \pi^-$



#### Amplitude Analysis of $D^+ \rightarrow K_S \pi^+ \pi^+ \pi^-$

With the fit fractions (FF) of every components and the branching fraction of  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^-$ , the branching fractions of the components is calculated with

 $B(Component) = FF(Componet)B(D^+ \to K_S^0 \pi^+ \pi^+ \pi^-).$ 

The results are listed in the table below:

Component	Branching fraction(%)		
$D^+ \to K_S^0 a_1(1260)^+, a_1(1260)^+ \to \rho^0 \pi^+$	$1.769 \pm 0.062 \pm 0.136 \pm 0.062$		
$D^+ \to K^0_S a_1(1260)^+, a_1(1260)^+ \to f_0(500)\pi^+$	$0.156 \pm 0.019 \pm 0.022 \pm 0.006$		
$D^+ \to \bar{K}_1(1400)^0 \pi^+, \bar{K}_1(1400)^0 \to K^{*-} \pi^+, K^{*-} \to K^0_S \pi^-$	$1.161 \pm 0.047 \pm 0.051 \pm 0.041$		
$D^+ \to \bar{K}_1(1270)^0 \pi^+, \bar{K}_1(1270)^0 \to K_S^0 \rho^0$	$0.112 \pm 0.012 \pm 0.007 \pm 0.004$		
$D^+ \to \bar{K}(1460)^0 \pi^+, \bar{K}(1460)^0 \to K^0_S \rho^0$	$0.044 \pm 0.012 \pm 0.011 \pm 0.002$		
$D^+ \to K^0_S \pi^+ \rho^0$ threshold be the second seco	$0.137 \pm 0.016 \pm 0.015 \pm 0.005$		
$D^+ \to K^{*-} \pi^+ \pi^+$ three-body, $K^{*-} \to K^0_S \pi^-$	$0.434 \pm 0.037 \pm 0.062 \pm 0.015$		
$D^+ \to K^0_S \pi^+ \pi^+ \pi^-$ nonresonant	$0.231 \pm 0.016 \pm 0.024 \pm 0.008$		

In the table, the first and second uncertainties of the branching fractions are statistical and systematic uncertainties from the fit fractions, respectively. The third errors are the uncertainties related to  $B(D^+ \rightarrow K_S^0 \pi^+ \pi^+ \pi^-)$  in PDG.

- We measure the sub-mode branching fractions in  $D^+ \to K_S^0 \pi^+ \pi^+ \pi^-$  decay, which will be helpful in understanding the  $D \to AP$  decays.
- The measurements of the decays with K<sub>1</sub>(1270) and K<sub>1</sub>(1400) involved provide some experimental information in understanding the mixture of the two excited Kaons.

## Summary

- DTag and DD<sup>bar</sup> threshold data allows us to perform inclusive and exclusive branching fraction measurement
- Double tag provides clean samples for amplitude analysis
- Many D<sup>0</sup> and D<sup>+</sup> studies have been published, including strong phase and y<sub>cp</sub> measurements, and more related measurements are on-going
- More  $D_s$  studies are on going based on our new 3.19 fb<sup>-1</sup> data at  $E_{cm} = 4.178$  GeV
  - K<sub>S</sub>K-K<sub>L</sub>K asymmetry, amplitude analyses of KKπ, ππeta, πππ, and four-body decays, such as KKππ and πππeta