



Measurements of the branching fractions for  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $K_S^0 K_S^0 \pi^+$   
and  $D^0 \rightarrow K_S^0 K_S^0$ ,  $K_S^0 K_S^0 K_S^0$



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## ABSTRACT

By analyzing  $2.93 \text{ fb}^{-1}$  of data taken at the  $\psi(3770)$  resonance peak with the BESIII detector, we measure the branching fractions for the hadronic decays  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $D^0 \rightarrow K_S^0 K_S^0 \pi^+$ . They are determined to be  $\mathcal{B}(D^+ \rightarrow K_S^0 K_S^0 K^+) = (2.54 \pm 0.05_{\text{stat.}} \pm 0.12_{\text{sys.}}) \times 10^{-3}$ ,  $\mathcal{B}(D^+ \rightarrow K_S^0 K_S^0 \pi^+) = (2.70 \pm 0.05_{\text{stat.}} \pm 0.12_{\text{sys.}}) \times 10^{-3}$ ,  $\mathcal{B}(D^0 \rightarrow K_S^0 K_S^0) = (1.67 \pm 0.11_{\text{stat.}} \pm 0.11_{\text{sys.}}) \times 10^{-4}$  and  $\mathcal{B}(D^0 \rightarrow K_S^0 K_S^0 \pi^+) = (7.21 \pm 0.33_{\text{stat.}} \pm 0.44_{\text{sys.}}) \times 10^{-4}$ , where the second one is measured for the first time and the others are measured with significantly improved precision over the previous measurements.

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## 1. Introduction

Hadronic decays of  $D$  mesons open a window to probe for the physics mechanisms in charmed meson decays, e.g., CP violation,  $D^0 \bar{D}^0$  mixing and SU(3) symmetry breaking effects. Since the discovery of  $D$  mesons in 1976, the hadronic decays of  $D$  mesons have been extensively investigated [1]. However, the existing measurements of the  $D$  hadronic decays containing at least two  $K_S^0$  mesons in the final state are still very poor due to limited statistics [1].

In this Letter, we report the measurements of the branching fractions for the hadronic decays  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$ ,  $D^+ \rightarrow K_S^0 K_S^0 K^+$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$ . Throughout this Letter, charged conjugate modes are implied. These decays have simpler event topologies and suffer less from combinatorial backgrounds than other decay modes containing two  $K_S^0$  in the final state. The comprehensive or improved measurements of three-body decays will benefit the understanding of the interplay between the weak and strong interactions in multibody decays where theoretical pre-

dictions are poorer than two-body decays. The improved measurements of two-body decays can serve to better explore the contributions of W-exchange diagrams and final-state interactions [2–5], as well as SU(3)-flavor symmetry breaking effects [6–10] in  $D$  meson decays. In addition, these measurements will also help to improve background estimations in the precision measurements of  $D$  and  $B$  meson decays.

The data sample used for this analysis, which has an integrated luminosity of  $2.93 \text{ fb}^{-1}$  [11], was taken at the  $\psi(3770)$  resonance peak with the BESIII detector [12]. The  $D^0 \bar{D}^0$  and  $D^+ D^-$  pairs produced in  $\psi(3770)$  decay provide cleaner  $D^0$  and  $D^+$  meson samples than those used in previous studies at ARGUS [13,14], CLEO [15,16] and FOCUS [17]. To optimize the precision for these measurements, we use a single-tag method, in which either a  $D$  or  $\bar{D}$  is reconstructed in an event. We combine the yields measured with previously reported values of the cross sections for  $e^+ e^- \rightarrow D^0 \bar{D}^0$  and  $D^+ D^-$  at the  $\psi(3770)$  resonance peak [18].

## 2. BESIII detector and Monte Carlo simulation

The BESIII detector is a magnetic spectrometer that operates at the BEPCII collider. It has a cylindrical geometry with a solid-angle coverage of 93% of  $4\pi$ . It consists of several main components. A 43-layer main drift chamber (MDC) surrounding the beam pipe performs precise determinations of charged particle trajectories and measures the specific ionization ( $dE/dx$ ) for charged particle identification (PID). An array of time-of-flight counters (TOF) is located outside the MDC and provides additional PID information. A CsI(Tl) electromagnetic calorimeter (EMC) surrounds the TOF and is used to measure the energies of photons and electrons. A solenoidal superconducting magnet outside the EMC provides a 1 T magnetic field in the central tracking region of the detector.

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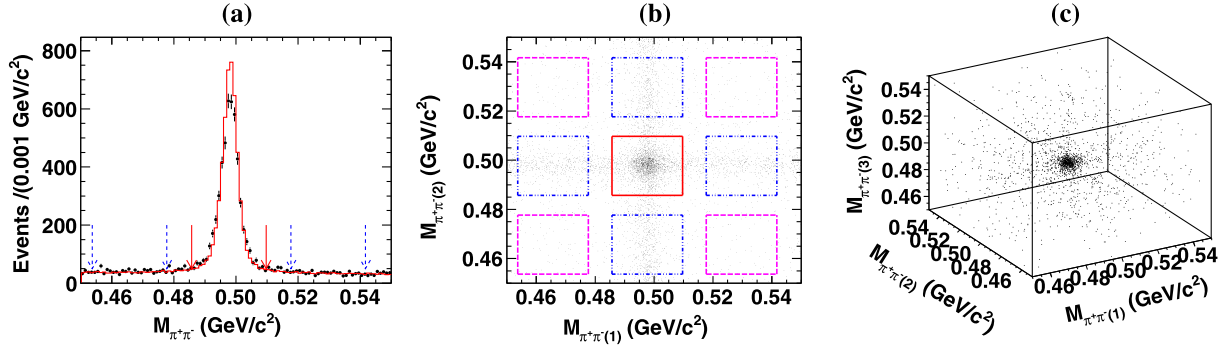
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**Fig. 1.** (a) Comparison of the  $M_{\pi^+\pi^-}$  distributions of the  $D^0 \rightarrow K_S^0 K_S^0$  candidate events between data (dots with error bars) and inclusive MC (histogram). The pairs of the solid (dashed) arrows denote the  $K_S^0$  signal (sideband) regions. (b) Distribution of  $M_{\pi^+\pi^-(1)}$  versus  $M_{\pi^+\pi^-(2)}$  for the  $D^0 \rightarrow K_S^0 K_S^0$  candidate events in data. (c) Distribution of  $M_{\pi^+\pi^-(1)}$  versus  $M_{\pi^+\pi^-(2)}$  versus  $M_{\pi^+\pi^-(3)}$  for the  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$  candidate events in data. In these figures, all selection criteria have been imposed except for the  $K_S^0$  mass requirement and  $M_{BC}$  is required to be within 5  $\text{MeV}/c^2$  around the  $D$  nominal mass [1].

The iron flux return of the magnet is instrumented with 1272  $m^2$  of resistive plate muon counters (MUC) arranged in nine layers in the barrel and eight layers in the endcaps for identification of muons with momentum greater than 0.5  $\text{GeV}/c$ . More details about the BESIII detector are described in Ref. [12].

A GEANT4-based [19] Monte Carlo (MC) simulation software package, which includes the geometric description and response of the detector, is used to determine the detection efficiency and to estimate background for each decay mode. An inclusive MC sample, which includes the  $D^0 \bar{D}^0$ ,  $D^+ D^-$  and non- $D\bar{D}$  decays of the  $\psi(3770)$ , initial-state-radiation (ISR) production of the  $\psi(3686)$  and  $J/\psi$ , the  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s$ ) continuum process, the Bhabha scattering events, the di-muon events and the di-tau events, is produced at  $\sqrt{s} = 3.773$   $\text{GeV}$ . The equivalent luminosity of the MC sample is ten times of data. The  $\psi(3770)$  decays are generated by the MC generator KKMC [20], which incorporates both ISR effects [21] and final-state-radiation (FSR) effects [22]. Known decay modes are generated using EvtGen [23] with input branching fractions from the Particle Data Group (PDG) [1]. Unmeasured decays are generated using LundCharm [24].

### 3. Data analysis

All charged tracks used in this analysis are required to be within a polar-angle ( $\theta$ ) range of  $|\cos\theta| < 0.93$ . The good charged tracks, except when used to reconstruct  $K_S^0$  mesons, are required to originate within an interaction region defined by  $V_{xy} < 1.0$   $\text{cm}$  and  $V_z < 10.0$   $\text{cm}$ , where  $V_{xy}$  and  $V_z$  are the distances of closest approach of the reconstructed track to the interaction point (IP) perpendicular to  $(xy)$  and along  $(z)$  the beam direction.

The charged kaons and pions are identified by the  $dE/dx$  and TOF measurements. The combined confidence levels for pion and kaon hypotheses ( $CL_\pi$  and  $CL_K$ ) are calculated, respectively. The charged track is identified as kaon (pion) if  $CL_K > CL_\pi$  ( $CL_\pi > CL_K$ ) is satisfied.

$K_S^0$  candidate mesons are reconstructed through the  $\pi^+\pi^-$  decay mode. Charged pions used in  $K_S^0$  candidates mesons are required to satisfy  $V_z < 20.0$   $\text{cm}$ . The two oppositely charged tracks are assumed to be a  $\pi^+\pi^-$  pair without PID requirements. To reconstruct  $K_S^0$ , the  $\pi^+\pi^-$  combination is constrained to have a common vertex. The candidate is accepted if it has an invariant mass  $M_{\pi^+\pi^-}$  within 12  $\text{MeV}/c^2$  of the  $K_S^0$  nominal mass [1] and satisfies  $L/\sigma_L > 2$ , where  $L$  is the measured flight distance and  $\sigma_L$  is its uncertainty.

To identify  $D$  candidates, we use two selection variables, the energy difference  $\Delta E \equiv E_{\text{beam}} - E_D$  and the beam-energy-constrained mass  $M_{BC} \equiv \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}_D|^2/c^2}$ , where  $E_{\text{beam}}$  is

**Table 1**

$\Delta E$  requirements (in  $\text{MeV}$ ) for data and MC samples.

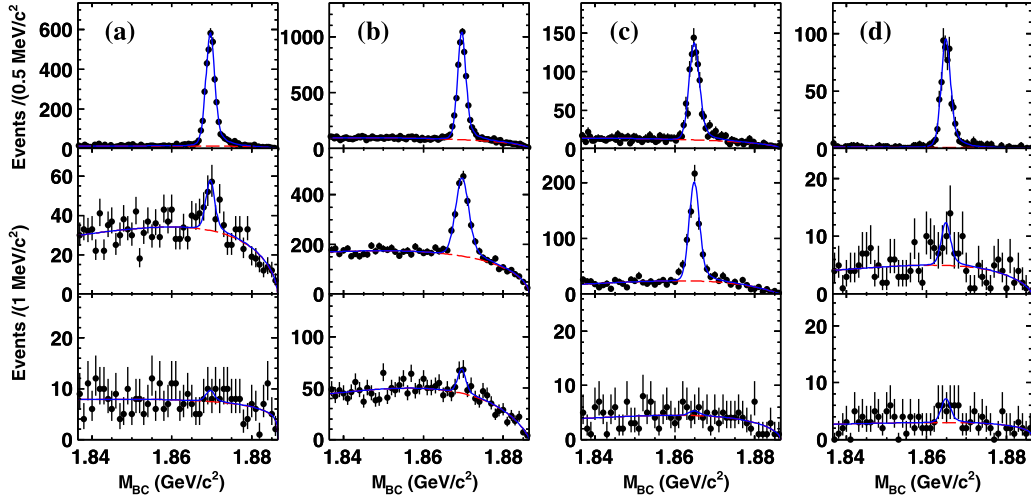
Decay modes	Data	MC
$D^+ \rightarrow K_S^0 K_S^0 K^+$	(−17, +19)	(−16, +16)
$D^+ \rightarrow K_S^0 K_S^0 \pi^+$	(−17, +17)	(−17, +16)
$D^0 \rightarrow K_S^0 K_S^0$	(−19, +17)	(−17, +14)
$D^0 \rightarrow K_S^0 K_S^0 K_S^0$	(−14, +16)	(−13, +13)

the beam energy and  $E_D$  and  $\vec{p}_D$  are the energy and momentum of the  $D$  candidate in the  $e^+e^-$  center-of-mass system. For each signal decay mode, only the combination with the minimum  $|\Delta E|$  is kept in events where more than one candidate passes the selection requirements. Mode-dependent  $\Delta E$  cuts are determined separately for data and MC based on fits to the respective  $\Delta E$  distributions. These are set at  $\pm 3\sigma$ , where  $\sigma$  is the  $\Delta E$  resolution (Table 1).

The combinatorial  $\pi^+\pi^-|_{\text{non-}K_S^0}$  pairs with invariant mass in  $K_S^0$  signal region may also satisfy the  $K_S^0$  selection criteria and contribute peaking background around the  $D$  mass in the  $M_{BC}$  distribution. This peaking background is estimated with events in the  $K_S^0$  sideband region, defined as  $0.020 < |M_{\pi^+\pi^-} - M_{K_S^0}| < 0.044$   $\text{GeV}/c^2$ . Fig. 1(a) shows the comparison of the  $M_{\pi^+\pi^-}$  distribution for  $D^0 \rightarrow K_S^0 K_S^0$  candidates in data with the corresponding distribution for the inclusive MC. In the figure, the solid (dashed) arrows delineate the  $K_S^0$  signal (sideband) regions.

In the analyses of the  $D^0 \rightarrow K_S^0 K_S^0$ ,  $D^+ \rightarrow K_S^0 K_S^0 K^+$  and  $K_S^0 K_S^0 \pi^+$  decays, two-dimensional (2D) signal and sideband regions are defined. Fig. 1(b) shows the distribution of  $M_{\pi^+\pi^-(1)}$  versus  $M_{\pi^+\pi^-(2)}$  for the  $D^0 \rightarrow K_S^0 K_S^0$  candidate events in data. The solid box, in which both of the  $\pi^+\pi^-$  combinations lie in the  $K_S^0$  signal regions, denotes the 2D signal region. The dot-dashed (dashed) boxes indicate the 2D sideband 1 (2) regions, in which one (two) of the  $\pi^+\pi^-$  combinations lie in the  $K_S^0$  sideband regions and the others are in the  $K_S^0$  signal region. For the  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$  decay,  $M_{\pi^+\pi^-(1)}$  versus  $M_{\pi^+\pi^-(2)}$  versus  $M_{\pi^+\pi^-(3)}$  of the candidate events in data is shown in Fig. 1(c). The region in which all three  $\pi^+\pi^-$  combinations lie in the  $K_S^0$  signal regions is taken as the three-dimensional (3D) signal region. The 3D sideband  $i$  ( $i = 1, 2, 3$ ) regions denote those in which  $i$  of the three  $\pi^+\pi^-$  pairs lie in the  $K_S^0$  sideband regions and the rest are located in the  $K_S^0$  signal regions.

The resulting  $M_{BC}$  distributions of the accepted candidate events in the 2D or 3D signal region, sideband 1 region and sideband 2 region are shown in the sub-figures of the first, second and third rows of Fig. 2, respectively. By fitting these  $M_{BC}$  distri-



**Fig. 2.** Fits to the  $M_{BC}$  distributions of the (a)  $D^+ \rightarrow K_S^0 K_S^0 K^+$ , (b)  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ , (c)  $D^0 \rightarrow K_S^0 K_S^0$  and (d)  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$  candidate events. The dots with error bars are data, the solid curves are the total fits, and the dashed curves are the fitted backgrounds. The first, second and third rows correspond to the fits to the candidate events in the 2D or 3D signal region, sideband 1 region and sideband 2 region, respectively.

**Table 2**

Input quantities and results for the determination of the branching fractions as described in the text. The uncertainties are statistical only.

Decay modes	$N_{K_S^0 \text{sig}}$	$N_{\text{sb1}}$	$N_{\text{sb2}}$	$N_{\text{sb3}}$	$N_{\text{other}}^b$	$N_{\text{net}}$	$\epsilon$ (%)	$\mathcal{B}$ ( $\times 10^{-4}$ )
$D^+ \rightarrow K_S^0 K_S^0 K^+$	$3616 \pm 66$	$97 \pm 19$	$6 \pm 8$	–	$18 \pm 2$	$3551 \pm 67$	$8.27 \pm 0.04$	$25.4 \pm 0.5$
$D^+ \rightarrow K_S^0 K_S^0 \pi^+$	$5643 \pm 88$	$1464 \pm 68$	$69 \pm 19$	–	$31 \pm 3$	$4897 \pm 94$	$10.72 \pm 0.04$	$27.0 \pm 0.5$
$D^0 \rightarrow K_S^0 K_S^0$	$888 \pm 36$	$626 \pm 31$	$3 \pm 6$	–	0	$576 \pm 39$	$16.28 \pm 0.30$	$1.67 \pm 0.11$
$D^0 \rightarrow K_S^0 K_S^0 K_S^0$	$622 \pm 27$	$24 \pm 8$	$14 \pm 6$	0	$16 \pm 3$	$597 \pm 27$	$3.92 \pm 0.05$	$7.21 \pm 0.33$

contributions as shown in Fig. 2, we obtain the fitted yields of  $D$  signal in the 2D or 3D signal region, sideband 1 region and sideband 2 region,  $N_{K_S^0 \text{sig}}$ ,  $N_{\text{sb1}}$ ,  $N_{\text{sb2}}$ , which are given in Table 2. In the fits, the  $D$  signal is modeled by a MC-simulated shape convoluted with a Gaussian function with free parameters accounting for the difference of detector resolution between data and MC. The combinatorial backgrounds are described by an ARGUS function [25] with an endpoint of 1.8865  $\text{GeV}/c^2$ . In the  $M_{BC}$  fits for the 2D or 3D sideband events, the parameters of the convoluted Gaussian function are fixed at the values determined for the signal region. For the  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$  decays, the peaking backgrounds from sideband 3 region are negligible since few events survive.

In this analysis, the combinatorial background in the  $M_{\pi^+\pi^-}$  distribution is assumed to be flat, which implies that the ratio of background yields between the  $K_S^0$  signal and sideband regions is 0.5. Thus, the net numbers of the  $D^0 \rightarrow K_S^0 K_S^0$ ,  $D^+ \rightarrow K_S^0 K_S^0 K^+$  and  $K_S^0 K_S^0 \pi^+$  decays can be calculated by

$$N_{\text{net}} = N_{K_S^0 \text{sig}} - \frac{1}{2}N_{\text{sb1}} + \frac{1}{4}N_{\text{sb2}} - N_{\text{other}}^b, \quad (1)$$

and the net number of the  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$  decays can be calculated by

$$N_{\text{net}} = N_{K_S^0 \text{sig}} - \frac{1}{2}N_{\text{sb1}} + \frac{1}{4}N_{\text{sb2}} - \frac{1}{8}N_{\text{sb3}} - N_{\text{other}}^b, \quad (2)$$

where  $N_{K_S^0 \text{sig}}$  and  $N_{\text{sbi}}$  are  $D$  signal yields from the fit in the 2D or 3D signal regions and sideband  $i$  regions, respectively.  $N_{\text{other}}^b$  is the normalized number of residual peaking background. For the  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$  decays, the residual peaking background is mainly from the events of  $D^+ \rightarrow K_S^0 K_L^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_L^0 \pi^+$  and  $D^0 \rightarrow K_S^0 K_L^0 K_S^0$  versus  $D^-(\bar{D}^0) \rightarrow K_S^0 X$  ( $X =$  any possible particle combination). This kind of background peaks

around the nominal  $D$  mass [1] when the  $K_S^0$  from a  $D^-(\bar{D}^0)$  decay has momentum similar to that of a  $K_L^0$  produced in  $D^+(D^0)$  decay. These peaking backgrounds cannot be modeled by the events from the 2D or 3D sideband region and are estimated by analyzing the inclusive MC sample. The measured values of  $N_{\text{other}}^b$  and  $N_{\text{net}}$  are given in Table 2.

#### 4. Branching fractions

The branching fraction for the hadronic decay  $D^{+(0)} \rightarrow f$  is determined by

$$\mathcal{B}(D^{+(0)} \rightarrow f) = \frac{N_{\text{net}}}{2 \cdot \sigma_{D^+D^-} (D^0\bar{D}^0) \cdot \mathcal{L} \cdot \epsilon}, \quad (3)$$

where  $N_{\text{net}}$  is the net number of  $D^{+(0)} \rightarrow f$  decays in data,  $\epsilon$  is the detection efficiency including the branching fraction of  $K_S^0 \rightarrow \pi^+\pi^-$ ,  $\mathcal{L}$  is the integrated luminosity of data [11] and  $\sigma_{D^+D^-} (D^0\bar{D}^0)$  is the  $D^+D^-$  ( $D^0\bar{D}^0$ ) cross section at the  $\psi(3770)$  resonance peak.

The detection efficiencies are determined by analyzing the inclusive MC sample. In this sample, the signal MC events for  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$  are produced as a mixed sample containing 90% of the  $D^+ \rightarrow K_S^0 K^*(892)^+$ ,  $K^*(892)^+ \rightarrow K_S^0 \pi^+$  decays and 10% of the direct three-body decay in phase space  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ . The signal MC events for  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $K_S^0 K_S^0 K_S^0$  are produced using a phase-space model. Detailed studies show that the momentum and polar-angle distributions of the daughter particles in data are well modeled by the MC simulation for each decay mode. By analyzing the inclusive MC sample with the same analysis procedure applied to the data (including the  $M_{BC}$  fits and the calculation of the net signal yields), we obtain the net number of  $D$  mesons observed for each decay. The detection efficiency  $\epsilon$  is

**Table 3**  
Systematic uncertainties (%) in the branching fraction measurements.

Sources	$D^+ \rightarrow K_S^0 K_S^0 K^+$	$D^+ \rightarrow K_S^0 K_S^0 \pi^+$	$D^0 \rightarrow K_S^0 K_S^0$	$D^0 \rightarrow K_S^0 K_S^0 K_S^0$
MC statistics	0.5	0.4	1.8	1.3
Luminosity of data	0.5	0.5	0.5	0.5
$D\bar{D}$ cross section	1.6	1.6	1.6	1.6
$\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)$	0.2	0.2	0.2	0.3
$K_S^0$ reconstruction	3.0	3.0	3.0	4.5
Tracking for $K^+(\pi^+)$	0.5	0.5	–	–
PID for $K^+(\pi^+)$	0.5	0.5	–	–
$M_{BC}$ fit	2.1	1.0	4.2	2.7
$\Delta E$ requirement	2.0	1.5	2.0	1.5
PBKG normalization	0.5	1.4	2.4	0.8
$K_S^0$ sideband	0.5	0.5	2.0	1.0
MC modeling	1.0	1.0	–	1.0
Total	4.7	4.4	6.8	6.1

obtained by dividing the net  $D$  signal by the total number of signal events, taking into account the efficiency correction discussed in Sect. 5.

Inserting the numbers of  $N_{\text{net}}$ ,  $\epsilon$ ,  $\mathcal{L}$ , as well as  $\sigma_{D^+D^-} = (2.882 \pm 0.018_{\text{stat.}} \pm 0.042_{\text{sys.}})$  nb or  $\sigma_{D^0\bar{D}^0} = (3.607 \pm 0.017_{\text{stat.}} \pm 0.056_{\text{sys.}})$  nb quoted from Ref. [18] into Eq. (3), we obtain the branching fraction for each decay, as listed in Table 2, where the uncertainties are statistical only.

## 5. Systematic uncertainty

Table 3 shows the systematic uncertainties in the branching fraction measurements. Each of them, estimated relative to the measured branching fraction, is discussed below.

- *MC statistics*: The uncertainties due to the limited MC statistics are 0.5%, 0.4%, 1.8% and 1.3% for  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$ , respectively.
- *Luminosity of data*: The uncertainty in the quoted integrated luminosity of data is 0.5% [11].
- *$D\bar{D}$  cross section*: The uncertainties of the quoted  $D^+D^-$  and  $D^0\bar{D}^0$  cross sections are 1.6% [18].
- $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)$ : The uncertainty of the quoted branching fraction for  $K_S^0 \rightarrow \pi^+ \pi^-$  is 0.1% [1].
- *$K_S^0$  reconstruction*: The  $K_S^0$  reconstruction efficiency has been studied as a function of momentum by using the control samples  $J/\psi \rightarrow K^*(892)^\mp K^\pm$  and  $J/\psi \rightarrow \phi K_S^0 K^\pm \pi^\mp$ . Small data-MC efficiency differences are found and presented in Ref. [26]. To correct the  $K_S^0$  reconstruction efficiency, a piecewise fit to these differences as a function of  $K_S^0$  momentum is performed. For the efficiencies of detecting the decays  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$ , the momentum weighted differences associated with  $K_S^0$  reconstruction between data and MC are determined to be  $(+3.9 \pm 1.9)\%$ ,  $(+3.0 \pm 1.4)\%$ ,  $(+1.8 \pm 0.8)\%$  and  $(+5.9 \pm 2.8)\%$ , respectively, where the uncertainties are statistical. These corrections are applied to the detection efficiencies, after which only the statistical uncertainties of the differences are retained. On average, the residual uncertainty for each  $K_S^0$  is no more than 1.0%. Furthermore, the difference of the momentum-weighted efficiencies between data and MC from the different fits, which is 1.0% per  $K_S^0$ , is included as an additional uncertainty. Finally, we assign 1.5% per  $K_S^0$  as the systematic uncertainty for the reconstruction efficiency.
- *Tracking [PID] for  $K^+(\pi^+)$* : The tracking [PID] efficiencies for  $K^+$  and  $\pi^+$  are investigated using doubly tagged  $D\bar{D}$  hadronic events. The difference of momentum weighted efficiencies between data and MC of the tracking [PID] are determined to

be  $(+2.1 \pm 0.4)\%$  [ $(-0.3 \pm 0.1)\%$ ] for the  $K^+$  in the  $D^+ \rightarrow K_S^0 K_S^0 K^+$  decay and  $(+0.4 \pm 0.3)\%$  [ $(-0.3 \pm 0.1)\%$ ] for the  $\pi^+$  in the  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$  decay, where the uncertainties are statistical. After correcting the detection efficiencies by these differences, we take 0.5% [0.5%] as the systematic uncertainties in tracking [PID] for the  $K^+$  and  $\pi^+$ , respectively.

- *$M_{BC}$  fit*: In order to estimate the systematic uncertainty associated with the  $M_{BC}$  fit, we repeat the measurements by varying the fit range  $((1.8415, 1.8865) \text{ GeV}/c^2)$ , signal shape (with different MC matching requirements) and endpoint of the ARGUS function ( $\pm 0.2 \text{ MeV}/c^2$ ). Quadratically summing the changes of the branching fractions yields 2.1%, 1.0%, 4.2% and 2.7% for  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$ , which are assigned as the relevant systematic uncertainties.
- *$\Delta E$  requirement*: To investigate the systematic uncertainty associated with the  $\Delta E$  requirement, we repeat the measurements using alternative  $\Delta E$  requirements of  $\pm(4, 5, 6)$  times the resolution around the  $\Delta E$  peaks. The maximum changes of the branching fractions, 2.0%, 1.5%, 2.0% and 1.5% for  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$ , are taken as the associated systematic uncertainties.
- *Normalization of peaking backgrounds*: In the nominal analysis, the normalization factor for the peaking backgrounds, which is the ratio of background yields between the  $K_S^0$  signal and sideband regions, has been assumed to be 0.5. The branching fractions are recalculated with alternative normalization factors determined by MC simulation. The corresponding changes on the branching fractions, 0.5%, 1.4%, 2.4% and 0.7% for  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$ , are assigned as the systematic uncertainties associated with the peaking background (PBKG) normalization. On the other hand, the uncertainties of the residual peaking backgrounds are dominated by the uncertainties of the input branching fractions for  $D^-(\bar{D}^0) \rightarrow K_S^0 X$ , which contribute additional uncertainties of 0.1%, 0.1% and 0.4% for the measured branching fractions for  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$ , respectively.
- *$K_S^0$  sideband*: To evaluate the systematic uncertainty due to the choice of  $K_S^0$  sideband region, we remeasure the branching fractions after shifting the  $K_S^0$  sideband by  $\pm 2 \text{ MeV}/c^2$ . The corresponding maximum changes in the branching fraction, which are 0.5%, 0.5%, 2.0% and 1.0% for  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$ , respectively, are taken as the systematic uncertainties.
- *MC modeling*: For the three-body decays, we examine the reweighted detection efficiencies by including the possible sub-resonances  $a_0(980)$  and  $f_0(980)$  in the signal MC samples.

**Table 4**

Comparisons of the branching fractions (in  $10^{-4}$ ) measured in this work with the PDG values [1].

Decay modes	This work	PDG
$D^+ \rightarrow K_S^0 K_S^0 K^+$	$25.4 \pm 0.5 \pm 1.2$	$45 \pm 20$
$D^+ \rightarrow K_S^0 K_S^0 \pi^+$	$27.0 \pm 0.5 \pm 1.2$	–
$D^0 \rightarrow K_S^0 K_S^0$	$1.67 \pm 0.11 \pm 0.11$	$1.7 \pm 0.4$
$D^0 \rightarrow K_S^0 K_S^0 K_S^0$	$7.21 \pm 0.33 \pm 0.44$	$9.1 \pm 1.3$

The maximum change of the reweighted detection efficiencies, 1.0%, is taken as the systematic uncertainty in MC modeling.

Adding all of above systematic uncertainties in quadrature, we obtain the total systematic uncertainties of 4.7%, 4.4%, 6.8% and 6.1% for  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$ , respectively.

## 6. Summary

In summary, by analyzing  $2.93 \text{ fb}^{-1}$  of data collected at  $\sqrt{s} = 3.773 \text{ GeV}$  with the BESIII detector, we measure the branching fractions for the hadronic decays  $D^+ \rightarrow K_S^0 K_S^0 K^+$ ,  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$ ,  $D^0 \rightarrow K_S^0 K_S^0$  and  $D^0 \rightarrow K_S^0 K_S^0 K_S^0$  using a single-tag method. Table 4 presents the comparisons of the measured branching fractions with the PDG values [1]. The branching fraction for  $D^+ \rightarrow K_S^0 K_S^0 \pi^+$  is measured for the first time and the others are consistent with previous measurements, but with much improved precision. We also determine the branching fraction ratios  $\mathcal{B}(D^+ \rightarrow K_S^0 K_S^0 K^+)/\mathcal{B}(D^+ \rightarrow K_S^0 K_S^0 \pi^+) = 0.941 \pm 0.025_{\text{stat.}} \pm 0.040_{\text{sys.}}$  and  $\mathcal{B}(D^0 \rightarrow K_S^0 K_S^0)/\mathcal{B}(D^0 \rightarrow K_S^0 K_S^0 K_S^0) = 0.232 \pm 0.019_{\text{stat.}} \pm 0.016_{\text{sys.}}$ , in which the systematic uncertainties in the  $D^+ D^-$  (or  $D^0 \bar{D}^0$ ) cross section, the integrated luminosity of data, as well as the reconstruction efficiencies and the branching fractions of the two  $K_S^0$  mesons cancel. The results in this analysis provide helpful experimental data to probe for the interplay between the weak and strong interactions in charmed meson decay [2–5]. In addition, the measured branching fraction for the two-body decay  $D^0 \rightarrow K_S^0 K_S^0$  can also help to understand SU(3)-flavor symmetry breaking effects in  $D$  meson decays [6–10].

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