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Observation of the semileptonic decays $D^0 \to K_S^0 \pi^- \pi^0 e^+ \nu_e$ and $D^+ \to K_S^0 \pi^+ \pi^- e^+ \nu_e$

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BESIII

ABSTRACT: By analyzing $e^+ e^-$ annihilation data corresponding to an integrated luminosity of 2.93 fb^{-1} collected at a center-of-mass energy of 3.773 GeV with the BESIII detector, the first observation of the semileptonic decays $D^0 \to K_S^0 \pi^- \pi^0 e^+ \nu_e$ and $D^+ \to K_S^0 \pi^+ \pi^- e^+ \nu_e$ is reported. With a dominant hadronic contribution from $K_1(1270)$, the branching fractions are measured to be $\mathcal{B}(D^0 \to K_1(1270)^-(\to K_S^0 \pi^- \pi^0)e^+ \nu_e) = (1.69^{+0.53}_{-0.46} \pm 0.15) \times 10^{-4}$ and $\mathcal{B}(D^+ \to \bar{K}_1(1270)^0(\to K_S^0 \pi^+ \pi^-)e^+ \nu_e) = (1.47^{+0.45}_{-0.40} \pm 0.20) \times 10^{-4}$ with statistical significance of 5.4σ and 5.6σ, respectively. When combined with measurements of the $K_1(1270) \to K^+ \pi^- \pi$ decays, the absolute branching fractions are determined to be $\mathcal{B}(D^0 \to K_1(1270)^- e^+ \nu_e) = (1.05^{+0.33}_{-0.28} \pm 0.12 \pm 0.12) \times 10^{-3}$ and $\mathcal{B}(D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e) = (1.29^{+0.40}_{-0.35} \pm 0.18 \pm 0.15) \times 10^{-3}$. The first and second uncertainties are statistical and systematic, respectively, and the third uncertainties originate from the assumed branching fractions of the $K_1(1270) \to K\pi\pi$ decays.

Contents

1   Introduction

Semileptonic charm decays induced by the $c \to se^+\nu_e$ process are dominated by pseudoscalar (K) and vector ($K^*(892)$) mesons, i.e. contain a kaon and at most one pion in the final-state hadronic systems [1, 2]. Semileptonic decays with higher multiplicity final states involving a kaon and two pions are highly suppressed and are expected to be mostly mediated by the axial-kaon system with a mixing angle θ_{K_1} [3]. Thus knowledge of θ_{K_1} is essential for theoretical calculations describing the decays of D particles into strange axial-vector mesons [4–6]. The $D \to K\pi\pi e^+\nu_e$ decays provide a unique opportunity to study $K_1(1270)$ and $K_1(1400)$ mesons in a clean environment, without any additional hadrons in the final states. Such studies can lead to a better determination of θ_{K_1} as well as of the masses and widths of the K_1 mesons, which currently all have large uncertainties [7]. By exploiting the measured properties of $D \to \bar{K}_1(1270)\ell^+\nu_\ell$ and $B \to K_1(1270)\gamma$ decays, the photon polarization in $b \to s\gamma$ can be determined without considerable theoretical ambiguity, according to Refs. [8, 9].

The BESIII collaboration, performing studies of the hadronic systems $K^-\pi^+\pi^-$ and $K^-\pi^+\pi^0$, reported the first observation of semileptonic D decays involving a $K_1(1270)$ [10, 11], and measured the branching fractions (BFs) $\mathcal{B}(D^0 \to K_1(1270)^-e^+\nu_e) = (1.09 \pm 0.13^{+0.09}_{-0.13}\pm0.12)\times10^{-3}$ and $\mathcal{B}(D^+ \to \bar{K}_1(1270)^0e^+\nu_e) = (2.30\pm0.26^{+0.18}_{-0.21}\pm0.25)\times10^{-3}$. Here the first and second uncertainties are statistical and systematic, respectively, and the third uncertainties originate from the assumed BFs of $K_1(1270)^{0,+} \to K^+\pi^-\pi^{0,+}$ [7]. The decays $D^0 \to K^0_S\pi^-\pi^0e^+\nu_e$ and $D^+ \to K^0_S\pi^+\pi^-e^+\nu_e$ have not yet been observed. In 2011, based on the $K^+\pi^+\pi^-$ system in the decay of $B^+ \to J/\psi K^+\pi^+\pi^-$, the Belle collaboration found the BFs of $K_1(1270) \to K\rho, K\omega$, and $K^*(892)\pi$ to be consistent with previous measurements, but reported the measured BF of $K_1(1270) \to K^*_0(1430)\pi$ to be significantly smaller [12]. Furthermore, measurements of the BF ratio $R_{K_1(1270)} = \frac{\mathcal{B}_{K_1(1270)\to K^*\pi}}{\mathcal{B}_{K_1(1270)\to K\rho}}$ yield different results depending on the decay channels used [13–17], whereas they are expected to be identical under the narrow width approximation for the $K_1(1270)$ meson assuming CP conservation in strong decays [18]. Measurements of the BFs of $D \to K_1(1270)(\to K^0_S\pi\pi)e^+\nu_e$ decays are desirable, as they would improve the knowledge of the relative decay rates of $K_1(1270)$ into final states with one kaon and two pions.

This paper presents the first observation of the semileptonic decays $D^0 \to K^0_S\pi^-\pi^0e^+\nu_e$ and $D^+ \to K^0_S\pi^+\pi^-e^+\nu_e$ and measurements of the BFs of $D^0 \to K_1(1270)^-e^+\nu_e$ and $D^+ \to \bar{K}_1(1270)^0e^+\nu_e$. The analysed data samples come from e^+e^- collisions at a center-of-mass energy of 3.773 GeV, which were collected by the BESIII detector operating at the BEPCII storage ring. These samples correspond to an integrated luminosity of 2.93 fb^{-1} accumulated at the $\psi(3770)$ resonance [19]. Throughout this paper, charge conjugate channels are always implied.

2   Detector and data sets

The BESIII detector [20] records e^+e^- collisions provided by the BEPCII storage ring [21] in the center-of-mass energy range from 2.0 to 4.95 GeV, with a peak luminosity of $1 \times$

10^{33} cm^{-2}s^{-1} achieved at $\sqrt{s} = 3.773$ GeV. BESIII has collected large data samples in this energy region [22]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive-plate-counter muon-identification modules interleaved with steel. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end-cap) region. The time resolution in the TOF barrel region is 68 ps, while that in the end-cap region is 110 ps. Details about the design and performance of the BESIII detector are given in Ref. [20].

Monte Carlo (MC) simulated data samples produced with a GEANT4-based [23] software package, which includes the geometric description of the BESIII detector and the detector response [24], are used to determine detection efficiencies and to estimate background contributions. The simulation models the beam-energy spread and initial-state radiation (ISR) in the e^+e^- annihilation with the generator KKMC [25, 26]. An 'inclusive' MC event sample includes the production of $D\bar{D}$ pairs (including quantum coherence for the neutral D channels), the non-$D\bar{D}$ decays of the $\psi(3770)$, the ISR production of the J/ψ and $\psi(3686)$ states, and the continuum processes incorporated in KKMC [25, 26]. All particle decays are modeled with EVTGEN [27, 28] using BFs either taken from the Particle Data Group (PDG) [7], when available, or otherwise estimated with LUNDCHARM [29, 30]. Final-state radiation (FSR) from charged final-state particles is incorporated using the PHOTOS package [31]. The total size of the inclusive MC samples is approximately 10 times that of the data.

The $D \to K_1(1270)e^+\nu_e$ decays are simulated with the ISGW2 model [2], and the $K_1(1270)$ is allowed to decay through all intermediate processes leading to the final state $K_S^0\pi\pi$. The $K_1(1270)$ resonance shape is parameterized by a relativistic Breit-Wigner function with a mass of (1.253 ± 0.007) GeV/c^2 and a width of (90 ± 20) MeV [7]. Using the BFs of $K_1(1270)$ measured by Belle [12] as input in the simulation gives good data/MC agreement in the kinematic distributions [11]. The $e^+e^- \to D\bar{D}$ signal MC samples, in which the D decays exclusively into signal modes while the $\bar{D}$ decays inclusively, are used to determine the detection efficiencies.

3 Measurement method and single-tag selection

At $\sqrt{s} = 3.773$ GeV, the $\psi(3770)$ resonance is produced in electron-positron annihilation, and then decays predominately into $D\bar{D}$ pairs without accompanying hadron(s), thereby offering a clean environment to investigate D decays with the double-tag (DT) method [32, 33]. In these cases, when a $\bar{D}$ meson is fully reconstructed, all of the remaining tracks and photons in the event must originate from the accompanying D meson. The fully reconstructed meson is called a single-tag (ST) $\bar{D}$. The ST $\bar{D}$ mesons are selected by reconstructing a $\bar{D}^0$ or D^- in one of the following decay modes: $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$,

$K^+\pi^-\pi^+\pi^-\pi^0$ for neutral tags, and $K^+\pi^-\pi^-$, $K_S^0\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S^0\pi^-\pi^0$, $K^+K^-\pi^-$ and $K_S^0\pi^+\pi^-\pi^-$ for charged tags. Using the ST $\bar{D}$ samples, the decays of $D \to K_S^0\pi\pi e^+\nu_e$ can be reliably identified from the recoiling tracks as DT events. The BF of the signal decay is then determined by

$$\mathcal{B}_{\mathrm{sig}} = \frac{N_{\mathrm{DT}}}{N_{\mathrm{ST}}^{\mathrm{tot}} \cdot \epsilon_{\mathrm{sig}}}, \tag{3.1}$$

where $N_{\mathrm{ST}}^{\mathrm{tot}}$ and N_{DT} are the ST and DT yields, $\epsilon_{\mathrm{sig}} = \sum_i \left[\left(\varepsilon_{\mathrm{DT}}^i N_{\mathrm{ST}}^i \right) / \left(\varepsilon_{\mathrm{ST}}^i N_{\mathrm{ST}}^{\mathrm{tot}} \right) \right]$ is the efficiency of detecting the SL decay in the presence of the ST $\bar{D}$ meson, reconstructed in any of the tag modes. Here, i denotes the tag mode, and ϵ_{ST} and ϵ_{DT} are the ST and DT efficiencies of selecting the ST and DT candidates, respectively. Using the BF of $K_1(1270) \to K_S^0\pi\pi$ given in the PDG [7], the BFs of the $D \to K_1(1270)e^+\nu_e$ decays can be obtained.

For the reconstruction and identification of K_S^0, $K^\pm$, $\pi^\pm$ and π^0, the same criteria are used as in Refs. [34–39]. For any selected charged track, except for those used for reconstructing K_S^0 decays, the polar angle θ with respect to the z-axis (defined as the symmetry axis of the MDC) is required to satisfy $|\cos\theta| < 0.93$, and the point of closest approach to the interaction point (IP) must be within 1 cm in the plane perpendicular to the z axis and within ± 10 cm along the z axis. Particle identification (PID) for charged tracks combines measurements of the energy deposited in the MDC ($\mathrm{d}E/\mathrm{d}x$) and the flight time measured in the TOF to form likelihoods $\mathcal{L}(h)$ ($h = K, \pi$) for each hadron hypothesis h. Charged kaons and pions are identified by comparing the likelihoods for the kaon and pion hypotheses, $\mathcal{L}(K) > \mathcal{L}(\pi)$ and $\mathcal{L}(\pi) > \mathcal{L}(K)$, respectively.

The K_S^0 candidates are selected via the $K_S^0 \to \pi^+\pi^-$ decays, and hence they are reconstructed from pairs of oppositely charged tracks. For these two tracks, the distance of closest approach to the IP is required to be less than 20 cm along the z axis. The two charged tracks are constrained to originate from a common vertex that is required to be displaced from the IP by a flight distance of at least twice the vertex resolution. The invariant mass of the $\pi^+\pi^-$ pair is required to be within $(0.486, 0.510)$ GeV/c^2.

The π^0 candidates are reconstructed via $\pi^0 \to \gamma\gamma$ decays. Photon candidates are reconstructed from isolated electromagnetic showers detected in the EMC crystals. The deposited energy is required to be greater than 25 (50) MeV in the barrel (end-cap) region. To exclude showers that originate from charged tracks, the angle subtended by the EMC shower and the position of the closest charged track at the EMC must be greater than 10 degrees as measured from the IP. To further suppress fake photon candidates due to electronic noise or beam-related background, the measured EMC time is required to be within [0, 700] ns from the event start time. The invariant mass of a photon pair is required to be within $(0.115, 0.150)$ GeV/c^2. To further improve the resolution of π^0 momentum $\vec{p}_{\pi^0}$, the invariant mass of the photon pair is constrained to the known π^0 mass [7] by applying a kinematic fit.

For the ST candidates $\bar{D}^0 \to K^+\pi^-$, the background contributions from cosmic rays and Bhabha events are rejected by using the analogue requirements as described in Ref. [40]. First, the two charged tracks used must have a TOF time difference less than 5 ns and they must not be consistent with being a muon pair or an electron-positron pair. Second, there

must be at least one EMC shower with an energy larger than 50 MeV or at least one additional charged track detected in the MDC.

The tagged $\bar{D}$ mesons are selected using two variables, the energy difference

$$\Delta E = E_{\bar{D}} - E_{\text{beam}} \tag{3.2}$$

and the beam-constrained (BC) mass

$$M_{\text{BC}} = \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}_{\bar{D}}|^2/c^2}, \tag{3.3}$$

where E_{beam} is the beam energy, and $\vec{p}_{\bar{D}}$ and $E_{\bar{D}}$ are the momentum and the energy of the $\bar{D}$ candidate in the e^+e^- rest frame. For each tag mode, if there are multiple combinations in an event, only the one giving the minimum $|\Delta E|$ is retained for further analyses. Combinatorial background contributions are suppressed with a requirement on ΔE for each tag mode as described in Refs. [10, 11]; the ΔE requirements are summarized in Table 1.

Table 1. Summary of the ΔE requirements and M_{BC} mass windows for the ten tag modes.

Tag mode	ΔE (GeV)	M_{BC} (GeV/c^2)
$\bar{D}^0 \to K^+\pi^-$	(-0.029,0.027)	(1.858,1.874)
$\bar{D}^0 \to K^+\pi^-\pi^0$	(-0.069,0.038)	(1.858,1.874)
$\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$	(-0.031,0.028)	(1.858,1.874)
$\bar{D}^0 \to K^+\pi^-\pi^+\pi^-\pi^0$	(-0.040,0.025)	(1.858,1.874)
$D^- \to K^+\pi^-\pi^-$	(-0.025,0.025)	(1.863,1.877)
$D^- \to K^+\pi^-\pi^-\pi^0$	(-0.055,0.040)	(1.863,1.877)
$D^- \to K_S^0\pi^-$	(-0.025,0.025)	(1.863,1.877)
$D^- \to K_S^0\pi^-\pi^0$	(-0.055,0.040)	(1.863,1.877)
$D^- \to K_S^0\pi^+\pi^-\pi^-$	(-0.025,0.025)	(1.863,1.877)
$D^- \to K^+K^-\pi^-$	(-0.025,0.025)	(1.863,1.877)

To extract the yields of ST $\bar{D}$ mesons for each tag mode, binned maximum-likelihood fits are performed to the M_{BC} distributions of the accepted ST candidates. The signal is modeled by the MC-simulated shape convolved with a double-Gaussian function. The combinatorial background shape is described by an ARGUS function [41]. All parameters of the double-Gaussian function and the ARGUS function are left free in the fit. The numbers of ST $\bar{D}$ mesons are obtained by integrating over the $\bar{D}$ signal shape in the mass windows [10, 11] which are listed in Table 1. The M_{BC} distributions of the accepted ST candidates in data for the ten tag modes are shown in Figure 1. The ST yield and the ST efficiency (ϵ_{ST}^i) for each tag mode are summarized in Table 2. The total ST yields of $\bar{D}^0$ and D^- candidates are $(250.5 \pm 0.4_{\text{stat.}}) \times 10^4$ and $(153.2 \pm 0.3_{\text{stat.}}) \times 10^4$, respectively.
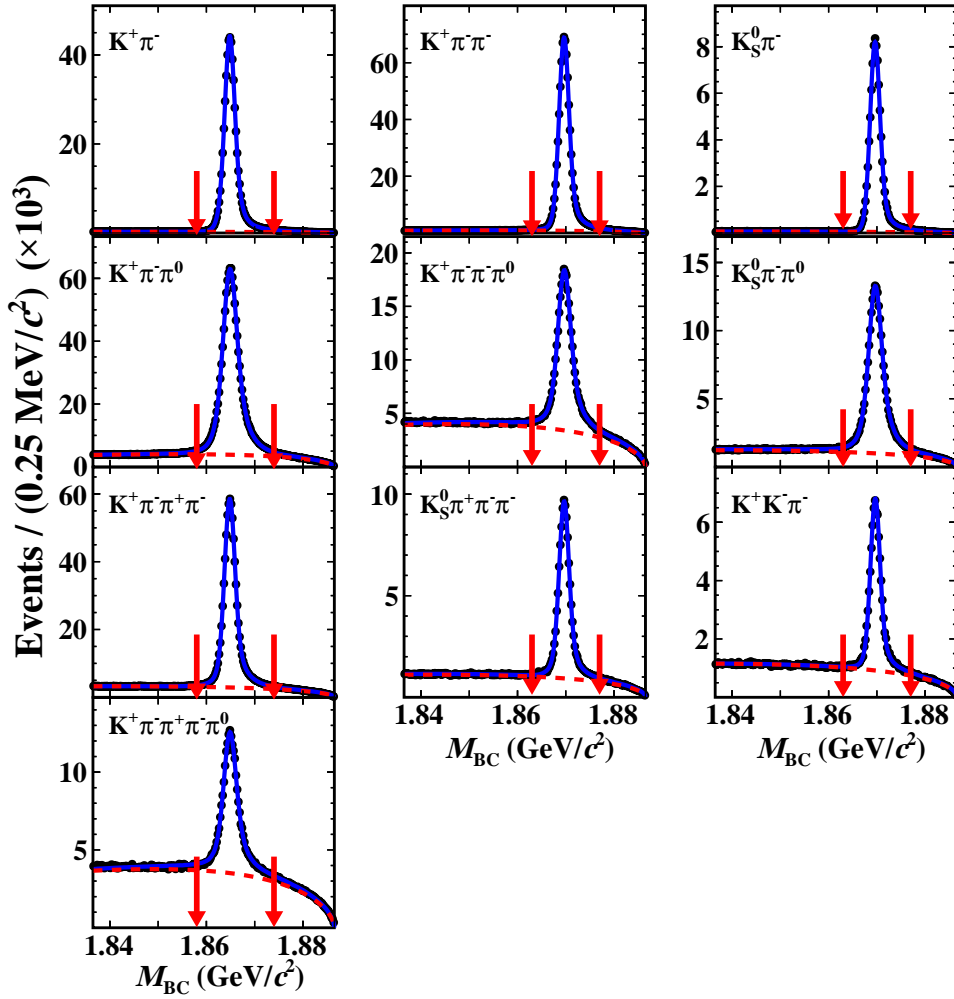
Figure 1. Fits to the M_{BC} distributions of the ST $\bar{D}$ candidates. The dots with error bars are the real data, the red dashed lines denote the background and the blue solid lines represent the overall fit. The arrows indicate the limits of the M_{BC} signal window.

4 Branching fractions

4.1 Selection of signal candidates

Candidates for the semileptonic decays $D \to K_S^0 \pi \pi e^+ \nu_e$ are reconstructed from the remaining tracks and showers that have not been used for the ST $\bar{D}$ reconstruction. The K_S^0, $\pi^\pm$ and π^0 candidates are selected with the same criteria as on the tag side. Positron PID uses the measured information in the MDC, TOF and EMC. Combined likelihoods ($\mathcal{L}'$) are calculated under the positron, pion, and kaon hypotheses. Positron candidates are required to satisfy $\mathcal{L}'(e) > 0.001$ and $\mathcal{L}'(e)/(\mathcal{L}'(e) + \mathcal{L}'(\pi) + \mathcal{L}'(K)) > 0.8$. To reduce background from hadrons, the positron candidate is further required to have a deposited energy in the EMC and momentum which satisfy $E/|\vec{p}|c > 0.18 \times \chi^2_{\mathrm{d}E/\mathrm{d}x} + 0.32$ [11], where E and $\vec{p}$ are the energy and momentum of positrons, $\chi^2_{\mathrm{d}E/\mathrm{d}x}$ is the difference between the measured

energy loss and the expectation from the Bethe-Bloch curve normalized by the resolution for positrons. To partially compensate for the energy loss due to FSR and bremsstrahlung, the four momenta of neighboring photons with an energy greater than 50 MeV and within a cone of 5 degrees around the positron direction, are added back to the four-momenta of the positron candidates (FSR recovery).

When reconstructing the $D^0 \to K_S^0 \pi^- \pi^0 e^+ \nu_e$ decay, the π^0 mesons are required to have an energy greater than 0.22 GeV and a decay angle θ_{π^0} defined through $|\cos \theta_{\pi^0}| = |E_{\gamma_1} - E_{\gamma_2}|/|\vec{p}_{\pi^0}|c$, less than 0.83 to effectively veto fake π^0 candidates. Here, E_{γ_1} and E_{γ_2} are the energies of the two daughter photons of the π^0 candidate, and $\vec{p}_{\pi^0}$ is its reconstructed momentum. To suppress the background from $D^0 \to K_S^0 \pi^+ \pi^- \pi^0$ decays, $M_{K_S^0 \pi^- \pi^0 \pi_{e \to \pi}^+} <$ 1.78 GeV/c^2 is required, where $\pi_{e \to \pi}^+$ is the positron candidate reconstructed under the pion mass hypothesis.

For the $D^+ \to K_S^0 \pi^+ \pi^- e^+ \nu_e$ decay, the positron must have the opposite charge to that of the tagged D^- meson and the two charged pions must have opposite charge. To suppress the background from $D^+ \to K_S^0 \pi^+ \pi^- \pi^+$ decays, the mass $M_{K_S^0 \pi^+ \pi^- \pi_{e \to \pi}^+}$ is required to be less than 1.83 GeV/c^2. In order to reject background events from $D^+ \to K_S^0 \pi^+ \pi^0$ with the π^0 Dalitz decay $\pi^0 \to e^+ e^- \gamma$, the opening angle θ_α between e^+ and π^- is required to satisfy $\cos \theta_\alpha < 0.95$. To reject contamination from $D^+ \to K_S^0 \pi^+ \pi^- \pi^+ \pi^0$ decays, the mass $M_{K_S^0 \pi^+ \pi^- \pi_{e \to \pi}^+ \pi^0}$ is required to satisfy $M_{K_S^0 \pi^+ \pi^- \pi_{e \to \pi}^+ \pi^0} < 1.4$ GeV/c^2 when there is at least one π^0 candidate recoiling against the ST D^- meson in the event. Furthermore, the opening angle θ_β between the missing momentum (defined below) and the most energetic unused shower is required to satisfy $\cos \theta_\beta < 0.88$.

4.2 Measurement of branching fractions

To obtain information about the undetected neutrino, a kinematic quantity is defined as

$$M_{\mathrm{miss}}^2 = E_{\mathrm{miss}}^2/c^4 - |\vec{p}_{\mathrm{miss}}|^2/c^2, \tag{4.1}$$

where E_{miss} and $\vec{p}_{\mathrm{miss}}$ are the total energy and momentum of all missing particles in the event, respectively. They are calculated using $E_{\mathrm{miss}} = E_{\mathrm{beam}} - \sum_i E_i$, $\vec{p}_{\mathrm{miss}} = -\vec{p}_D - \sum_i \vec{p}_i$ where E_i and $\vec{p}_i$ are the measured energy and momentum of particle i in the $e^+ e^-$ center-of-mass frame, and i runs over K_S^0, $\pi^\pm$, π^0 and e^+ of the signal candidate. In order to improve the M_{miss}^2 resolution, a four-constraint (4-C) kinematic fit is employed. Here energy and momentum conservation is imposed, and the invariant masses of the D^0 and D^+ candidate particles are constrained to their known values. Then the momenta and energies from the kinematic fit are used to calculate M_{miss}^2.

The distributions of M_{miss}^2 versus $M_{K_S^0 \pi \pi}$ distributions of the candidate events for $D^0 \to K_S^0 \pi^- \pi^0 e^+ \nu_e$ and $D^+ \to K_S^0 \pi^+ \pi^- e^+ \nu_e$ surviving in data are shown in Figure 2 after combining all tag modes for D^0 or D^+. Signal events concentrate around zero in M_{miss}^2. They are found to cluster around the $K_1(1270)$ nominal mass in the $M_{K_S^0 \pi \pi}$ distribution. To determine the signal yield, a two-dimensional unbinned extended maximum-likelihood fit is performed on the M_{miss}^2 versus $M_{K_S^0 \pi \pi}$ distributions of the accepted $D^0 \to K_S^0 \pi^- \pi^0 e^+ \nu_e$ and $D^+ \to K_S^0 \pi^+ \pi^- e^+ \nu_e$ candidate events, respectively. The two-dimensional signal and
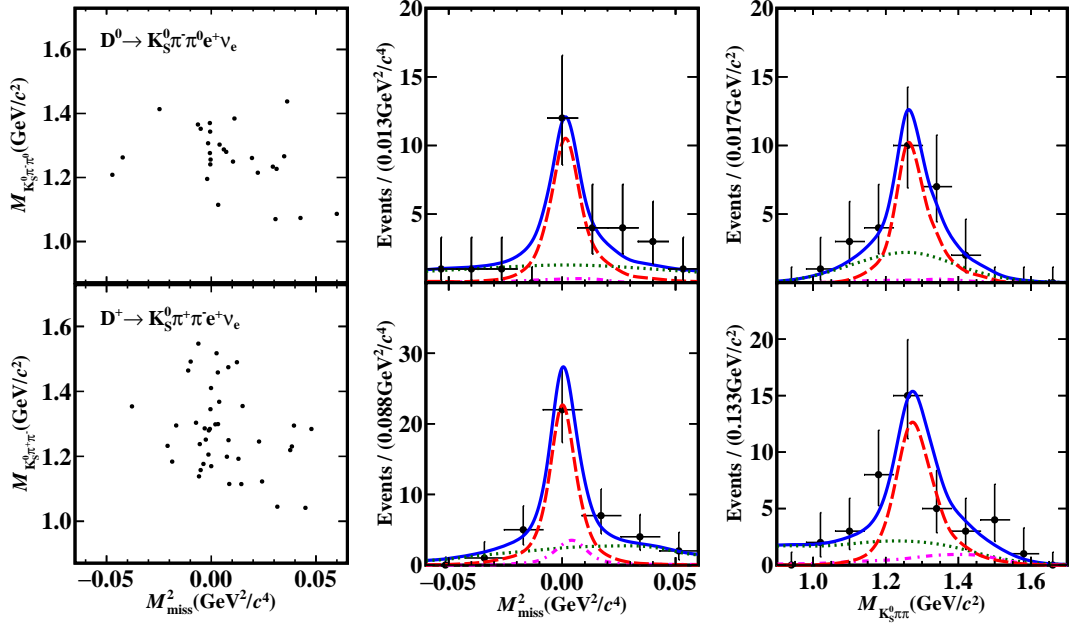
Figure 2. Distributions of M_{miss}^2 versus $M_{K_S^0\pi\pi}$ for the accepted semileptonic candidates (left column) and the projections on M_{miss}^2 (middle column) and $M_{K_S^0\pi\pi}$ (right column) of the two-dimensional fits. The top row is for $D^0 \to K_S^0\pi^-\pi^0 e^+\nu_e$ and the bottom row is for $D^+ \to K_S^0\pi^+\pi^- e^+\nu_e$. The dots with error bars are data. The blue solid line denotes the total fit. The red dashed line represents the signal. The green dotted and purple dash dotted lines represent the combinatorial background and peaking background of $D \to K_S^0\pi\pi$, respectively.

background shapes are derived from the signal and inclusive MC samples, respectively. The numbers of peaking background events are fixed based on the estimation from the simulated samples, while the yields of signal and combinatorial background are free parameters. The two-dimensional probability density functions of signal and background are modeled by using RooNDKeysPdf [42].

The one-dimensional fit projections to the M_{miss}^2 and $M_{K_S^0\pi\pi}$ distributions of $D^0 \to K_S^0\pi^-\pi^0 e^+\nu_e$ and $D^+ \to K_S^0\pi^+\pi^- e^+\nu_e$ are shown in Figure 2. The fits return event yields of $16.5^{+5.1}_{-4.5}$ for the $D^0 \to K_1(1270)^- e^+\nu_e$ signal and $20.2^{+6.2}_{-5.4}$ for the $D^+ \to \bar{K}_1(1270)^0 e^+\nu_e$ signal. The DT yields and signal efficiencies are summarized in Table 2. The uncertainties in Table 2 are only statistical, and the systematic uncertainties will be discussed in Sec. 5. The statistical significance of the signal is estimated to be 5.4σ for $D^0 \to K_1(1270)^- e^+\nu_e$ and 5.6σ for $D^+ \to K_1(1270)^0 e^+\nu_e$, by comparing the likelihoods with and without the signal component, and taking the change in the number of degrees of freedom into account. The significances of $D^0 \to K_S^0\pi^-\pi^0 e^+\nu_e$ and $D^+ \to K_S^0\pi^+\pi^- e^+\nu_e$ are 4.5σ and 4.0σ, respectively, after accounting for systematic uncertainties associated with the 2D fits.

Inserting N_{DT}, $\bar{\epsilon}_{\mathrm{sig}}$, and $N_{\mathrm{ST}}^{\mathrm{tot}}$ into Eq. 3.1 yields the BF for each decay. Using the world average BFs of $\mathcal{B}(K_1(1270)^- \to K_S^0\pi^-\pi^0) = (16.15 \pm 1.74)\%$ and $\mathcal{B}(\bar{K}_1(1270)^0 \to K_S^0\pi^+ \pi^-) = (11.37 \pm 1.26)\%$[1], the absolute BFs of $D^0 \to K_1(1270)^- e^+\nu_e$ and $D^+ \to$

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[1] $\mathcal{B}_{K_1^0 \to K_S^0 \pi^+\pi^-} = \mathcal{B}_{K_1^0 \to K^0\pi^+\pi^-} \times \frac{1}{2} \times \mathcal{B}_{K_S^0 \to \pi^+\pi^-} = \frac{\mathcal{B}_{K_S^0 \to \pi^+\pi^-}}{2} \times (\frac{1}{3} \times \mathcal{B}_{K_1 \to K\rho} + \frac{4}{9} \times \mathcal{B}_{K_1 \to K^*(892)\pi} +$

Table 2. Summary of ST yields N_{ST}^i, ST efficiencies ϵ_{ST}^i (%), signal efficiencies $\epsilon_{\mathrm{sig}}^i$ of different tag modes i, where the uncertainties are statistical. The last two columns are the weighted efficiencies $\bar{\epsilon}_{\mathrm{sig}}$ and signal yields N_{DT}.

Tag mode	N_{ST}^i ($\times 10^3$)	ϵ_{ST}^i (%)	$\epsilon_{\mathrm{sig}}^i$ (%)	$\bar{\epsilon}_{\mathrm{sig}}$ (%)	N_{DT}
$\bar{D}^0 \to K^+\pi^-$	540.7±0.8	66.57 ± 0.09	4.86±0.05		
$\bar{D}^0 \to K^+\pi^-\pi^0$	1066.8±1.2	34.76 ± 0.04	4.10±0.03	3.89±0.03	$16.5^{+5.1}_{-4.5}$
$\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$	736.3±1.2	41.22 ± 0.05	3.30±0.04		
$\bar{D}^0 \to K^+\pi^-\pi^+\pi^-\pi^0$	162.0±0.4	15.94 ± 0.05	2.02±0.04		
$D^- \to K^+\pi^-\pi^-$	800.6±1.0	51.10 ± 0.06	9.99±0.11		
$D^- \to K^+\pi^-\pi^-\pi^0$	253.0±0.6	24.54 ± 0.06	7.83±0.17		
$D^- \to K_S^0\pi^-$	93.3±0.3	50.90 ± 0.17	9.99±0.33	8.96±0.09	$20.2^{+6.2}_{-5.4}$
$D^- \to K_S^0\pi^-\pi^0$	208.9±0.5	25.15 ± 0.06	7.88±0.21		
$D^- \to K_S^0\pi^-\pi^-\pi^+$	107.5±0.4	29.47 ± 0.09	5.23±0.22		
$D^- \to K^+K^-\pi^-$	68.9±0.3	41.23 ± 0.18	9.00±0.35		

$\bar{K}_1(1270)^0e^+\nu_e$ are also determined. The obtained BFs $\mathcal{B}_{\mathrm{sig}}$ are summarized in Table 3, and are in agreement with those obtained from measurements with a charged kaon in the final state [10, 11]. Therefore the two sets of the results are combined to yield the values $\mathcal{B}_{\mathrm{com}}$, which are also given in Table 3.

Table 3. Summary of measured BFs $\mathcal{B}_{\mathrm{sig}}$ for different decays and combined BFs $\mathcal{B}_{\mathrm{com}}$ for $D \to K_1(1270)e^+\nu_e$ decays. The first and second uncertainties are statistical and systematic, respectively. For $D \to K_1(1270)e^+\nu_e$ modes, the third uncertainty originates from the assumed BFs of $K_1(1270)$ decays [7].

Decay mode	$\mathcal{B}_{\mathrm{sig}}$ ($\times 10^{-4}$)	$\mathcal{B}_{\mathrm{com}}$ ($\times 10^{-4}$)
$D^0 \to K_S^0\pi^-\pi^0 e^+\nu_e$	$(1.69^{+0.53}_{-0.46} \pm 0.18)$	/
$D^+ \to K_S^0\pi^+\pi^- e^+\nu_e$	$(1.47^{+0.45}_{-0.40} \pm 0.20)$	/
$D^0 \to K_1(1270)^- e^+\nu_e$	$(10.5^{+3.3}_{-2.8} \pm 1.2 \pm 1.2)$	$(10.8^{+1.3+0.8}_{-1.2-1.1} \pm 1.2)$
$D^+ \to \bar{K}_1(1270)^0 e^+\nu_e$	$(12.9^{+4.0}_{-3.5} \pm 1.8 \pm 1.5)$	$(18.6^{+2.3}_{-2.2} \pm 1.3 \pm 2.1)$

5 Systematic uncertainties

While in the BF determination using Eq. 3.1 the uncertainties associated with the ST candidate selection cancel, the following sources of systematic uncertainties must be considered.

- The uncertainty in the total yield of ST $\bar{D}$ mesons is assigned to be 0.5% [10, 11].

$\frac{4}{9} \times \mathcal{B}_{K_1 \to K_0^*(1430)\pi} \times \mathcal{B}_{K_0^*(1430)\to K\pi} + \mathcal{B}_{K_1 \to K^+\omega} \times \mathcal{B}_{\omega\to\pi^+\pi^-})$, $\mathcal{B}_{K_1^- \to K_S^0\pi^-\pi^0} = \mathcal{B}_{K_1^- \to K^0\pi^-\pi^0} \times$ $\frac{1}{2} \times \mathcal{B}_{K_S^0\to\pi^+\pi^-} = \frac{\mathcal{B}_{K_S^0\to\pi^+\pi^-}}{2} \times (\frac{2}{3} \times \mathcal{B}_{K_1 \to K\rho} + \frac{4}{9} \times \mathcal{B}_{K_1 \to K^*(892)\pi} + \frac{4}{9} \times \mathcal{B}_{K_1 \to K_0^*(1430)\pi} \times$ $\mathcal{B}_{K_0^*(1430)\to K\pi})$, where K_1 denotes $K_1(1270)$ and K_S^0 is reconstructed via $K_S^0 \to \pi^+\pi^-$

- $\pi^{\pm}$ tracking and PID efficiencies. The data/MC differences of $\pi^{\pm}$ tracking and PID efficiencies are re-weighted by the corresponding $\pi^{\pm}$ momentum spectra of signal MC events. The systematic uncertainty of tracking (PID) efficiency is assigned to be 0.2% (0.3%) per $\pi^{\pm}$, based on the residual statistical uncertainties of the measured data/MC differences.

- $e^{\pm}$ tracking and PID efficiencies. The systematic uncertainties originating from e^{+} tracking and PID efficiencies are studied by using a control sample of $e^{+}e^{-} \to \gamma e^{+}e^{-}$ events. The tracking and PID efficiencies of MC are also re-weighted in momentum and $\cos\theta$ to match the $D \to K_S^0 \pi\pi e^{+}\nu_e$ data. The systematic uncertainty of tracking (PID) efficiency is assigned to be 0.3%(0.3%) per $e^{\pm}$.

- K_S^0 reconstruction. The systematic uncertainty associated with K_S^0 reconstruction is studied with control samples of the decays $J/\psi \to K^{*\pm}K^{\mp}$ and $J/\psi \to \phi K_S^0 K^{\pm}\pi^{\mp}$ [43]. The systematic uncertainty for each K_S^0 is assigned as 1.5%.

- π^0 reconstruction. The systematic uncertainty of π^0 reconstruction is assigned as 2.0% per π^0 from studies of the DT $D^0\bar{D}^0$ hadronic decay samples [34].

- Two-dimensional fit. To estimate the uncertainty arising from the signal shape used in the fit, the mass and width of $K_1(1270)$ are varied by $\pm 1\sigma$. To take into account the potential resolution difference between data and MC simulation in the fit, a convolution of a Gaussian function is considered for M^2_{miss} and $M_{K_S^0\pi\pi}$. The peaking background yields are varied by 20.0% after considering their statistical fluctuations. The uncertainties of combinatorial background shapes are estimated by varying the smoothing parameters [42]. Potential non-resonant decays are also considered and the uncertainty associated with this component is assigned as the change of the fitted DT yield by fixing its contribution (14.2%) [11, 12] in the two-dimensional fit. The associated systematic uncertainties are summarized in Table 4.

- Signal generator. To estimate the systematic uncertainty associated with the signal generator, alternative signal MC events are generated using a phase-space model. The changes in the measured BFs using this alternative MC simulation are 6.5% for $\mathcal{B}(D^0 \to K_S^0\pi^-\pi^0 e^{+}\nu_e)$ and 4.0% for $\mathcal{B}(D^+ \to K_S^0\pi^+\pi^- e^{+}\nu_e)$.

- $K_1(1270)$ subdecays. The uncertainties in the ratios of $K_1(1270)$ subdecays are assigned by remeasuring the BFs based on PDG models [7]. A systematic uncertainty of 2.0% is assigned both for $\mathcal{B}(D^0 \to K_S^0\pi^-\pi^0 e^{+}\nu_e)$ and $\mathcal{B}(D^+ \to K_S^0\pi^+\pi^- e^{+}\nu_e)$.

- MC sample size. The systematic uncertainty due to the limited size of the MC sample is assigned to be 1.0% by $\sqrt{\sum_i (f_i \frac{\sigma_{\epsilon_i}}{\epsilon_i})^2}$, where f_i is the tag yield fraction, and ϵ_i and σ_{ϵ_i} are signal efficiency and the corresponding uncertainty of tag mode i, respectively.

- FSR recovery. The uncertainty from FSR recovery is assigned to be 0.3% following Ref. [44].

Table 4. Systematic uncertainties from the 2D fits.

Uncertainty (%)	$K_S^0\pi^-\pi^0 e^+\nu_e$	$K_S^0\pi^+\pi^- e^+\nu_e$
Signal shape	3.0	5.0
Resolution	2.4	3.3
Peaking background	1.3	2.1
Combinatorial background	1.0	3.8
Non-resonant decays	7.0	10.7
Total	8.2	13.0

Table 5. Relative systematic uncertainties in the BF measurements.

Uncertainty (%)	$K_S^0\pi^-\pi^0 e^+\nu_e$	$K_S^0\pi^+\pi^- e^+\nu_e$
N_{ST}	0.5	0.5
$\pi^\pm, e^\pm$ tracking	0.5	0.7
$\pi^\pm, e^\pm$ PID	0.6	0.9
K_S^0 reconstruction	1.5	1.5
π^0 reconstruction	2.0	/
Two-dimensional simultaneous fit	8.2	13.0
Signal generator	6.5	4.0
$K_1(1270)$ subdecays	2.0	2.0
MC sample size	1.0	1.0
FSR recovery	0.3	0.3
Total	11.0	14.0

The total systematic uncertainty is estimated by adding all the individual contributions in quadrature. The sources of the systematic uncertainties in the BF measurements are summarized in Table 5. They are assigned relatively to the measured BFs.

6 Summary

By analyzing a data sample corresponding to an integrated luminosity of 2.93 fb^{-1} collected at $\sqrt{s} = 3.773$ GeV with the BESIII detector, the first observations of the semileptonic decays $D^0 \to K_S^0\pi^-\pi^0 e^+\nu_e$ and $D^+ \to K_S^0\pi^+\pi^- e^+\nu_e$ are obtained with statistical significances of 5.3σ and 5.6σ, respectively. The resulting BFs are summarized in Table 3. The measured BFs of $D \to \bar{K}_1(1270)e^+\nu_e$ decays are consistent with previous measurements using $\bar{K}_1(1270) \to K^-\pi^+\pi^{(-,0)}$ [10, 11]. The combined BFs of $D \to \bar{K}_1(1270)e^+\nu_e$ agree with the CLFQM and LCSR predictions when $\theta_{K_1} \approx 33°$ or $57°$ [4, 5] and contradict the predictions reported in Ref. [6] when setting the value of θ_{K_1} negative.

With approximately six times more data coming from BESIII at $\sqrt{s} = 3.773$ GeV in the foreseen future [22], a thorough investigation with the enlarged data samples in the four

K_1 channels $\left(K^-\pi^+\pi^+, K_S^0\pi^0\pi^+, K_S^0\pi^+\pi^-, K^-\pi^+\pi^0\right)$ will be possible to further elucidate the knowledge on $K_1(1270)$ and $K_1(1400)$ meson in a systematic fashion.

Acknowledgments

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