Study of decay dynamics and CP asymmetry in $D^+ \rightarrow K^0_S e^+\nu_e$ decay


(BESIII Collaboration)

1Institute of High Energy Physics, Beijing 100049, People's Republic of China
2Beihang University, Beijing 100191, People's Republic of China
3Beijing Institute of Petrochemical Technology, Beijing 102617, People's Republic of China
I. INTRODUCTION

In the Standard Model (SM), violation of the combined charge-conjugation and parity symmetries (CP) arises from a nonvanishing irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) flavor-mixing matrix [1,2]. Although, in the SM, CP violation in the charm sector is expected to be very small, $\mathcal{O}(10^{-3})$ or below [3], Ref. [4] finds that $K^0 - \bar{K}^0$ mixing will give rise to a clean CP violation signal of a magnitude of $-2\text{Re}(\epsilon) \approx -3.3 \times 10^{-3}$ in the semileptonic decays $D^+ \to K^0_L (\bar{K}^0_L) e^+ \nu_e$.

Semileptonic decays of mesons allow the determination of various important SM parameters, including elements of the CKM matrix, which in turn allows the physics of the SM to be tested at its most fundamental level. In the limit of zero electron mass, the differential decay rate for a $D$ semileptonic decay with a pseudoscalar meson $P$ is given by

$$\frac{d\Gamma(D \to Pe\nu_e)}{dq^2} = \frac{G_F^2 |V_{cs(d)}|^2}{24\pi^3} p^3 |f_+(q^2)|^2,$$

where $G_F$ is the Fermi constant, $V_{cs(d)}$ is the relevant CKM matrix element, $p$ is the momentum of the daughter meson in the rest frame of the parent $D$, $f_+(q^2)$ is the form factor, and $q^2$ is the invariant mass squared of the lepton-neutrino system.

In this paper, the first measurements of the absolute branching fraction and the CP asymmetry for the decay $D^+ \to K^0_L e^+ \nu_e$ as well as the form-factor parameters for three different theoretical models that describe the weak hadronic charged currents in $D^+ \to K^0_L e^+ \nu_e$ are presented. The paper is organized as follows. The BESIII detector and data sample are described in Sec. II. The analysis technique is introduced in Sec. III. In Secs. IV and V, the measurements of the absolute branching fraction, the CP asymmetry, and the form-factor parameters for the decay $D^+ \to K^0_L e^+ \nu_e$ are described. Finally, a summary is provided in Sec. VI.

II. BESIII DETECTOR AND DATA SAMPLE

The analysis presented in this paper is based on a data sample with an integrated luminosity of $2.92 \text{ fb}^{-1}$ [5] collected with the BESIII detector [6] at the center-of-mass energy of $\sqrt{s} = 3.773$ GeV. The BESIII detector is a general-purpose detector at the BEPCII [7] double storage rings. The detector has a geometrical acceptance of 93% of the full solid angle. We briefly describe the components of BESIII from the interaction point (IP) outward. A small-cell multilayer drift chamber (MDC), using a helium-based gas to measure momenta and specific ionization of charged particles, is surrounded by a time-of-flight (TOF) system based on plastic scintillators which determines the time of flight of charged particles. A CsI(Tl) electromagnetic calorimeter (EMC) detects electromagnetic showers. These components are all situated inside a superconducting solenoid magnet, which provides a 1.0 T magnetic field parallel to the beam direction. Finally, a multilayer resistive plate counter system installed in the iron flux return yoke of the magnet is used to track muons. The momentum resolution for charged tracks in the MDC is 0.5% for a transverse momentum of 1 GeV/$c$. The energy resolution...
for showers in the EMC is 2.5% for 1 GeV photons. More details on the features and capabilities of BESIII can be found elsewhere [6].

The performance of the BESIII detector is simulated using a GEANT4-based [8] Monte Carlo (MC) program. To develop selection criteria and test the analysis technique, several MC samples are used. For the production of ψ(3770), the KKMC [9] package is used; the beam energy spread and the effects of initial-state radiation (ISR) are included. Final-state radiation of charged tracks is taken into account with the PHOTOS package [10]. ψ(3770) → D ¯D events are generated using EVTGEN [11,12], and each D meson is allowed to decay according to the branching fractions in the Particle Data Group (PDG) [13]. We refer to this as the “generic MC.” The equivalent luminosity of the MC samples is about ten times that of the data. A sample of ψ(3770) → D ¯D events, in which the D meson decays to the signal semileptonic mode and the ¯D decays to one of the hadronic final states used in the tag reconstruction, is referred to as the “signal MC.” In both the generic and signal MC samples, the semileptonic decays are generated using the modified pole parametrization [14] (see Sec. V B).

III. EVENT SELECTION

At the ψ(3770) peak, D ¯D pairs are produced. First, we select the single-tag (ST) sample in which a D + is reconstructed in a hadronic decay mode. From the ST sample, the double-tag (DT) events of D + → K 0 S e + ν e are selected. The numbers of the ST and DT events are given by

\[ N_{ST} = N_{D^+D^-}B_{tag} \epsilon_{ST}, \quad N_{DT} = N_{D^+D^-}B_{tag}B_{sig} \epsilon_{DT}, \]

(2)

where \( N_{D^+D^-} \) is the number of D + D − pairs produced, \( N_{ST} \) and \( N_{DT} \) are the numbers of the ST and DT events, \( \epsilon_{ST} \) and \( \epsilon_{DT} \) are the corresponding efficiencies, and \( B_{tag} \) and \( B_{sig} \) are the branching fractions of the hadronic tag decay and the signal decay. In this analysis, the charge-dependent branching fractions are measured, so there is no factor of 2 in Eq. (2). From Eq. (2), we obtain

\[ B_{sig} = \frac{N_{DT}/\epsilon_{DT}}{N_{ST}/\epsilon_{ST}} = \frac{N_{DT}}{N_{ST}}, \]

(3)

where \( \epsilon = \epsilon_{DT}/\epsilon_{ST} \) is the efficiency of finding a signal candidate in the presence of a ST D, which is obtained from generic MC simulations.

A. Selection of ST events

Each charged track is required to satisfy \(|\cos \theta| < 0.93\), where θ is the polar angle with respect to the beam axis. Charged tracks other than those from the K 0 S are required to have their points of closest approach to the beamline within 10 cm from the IP along the beam axis and within 1 cm in the plane perpendicular to the beam axis. Particle identification for charged hadrons h (h = π, K) is accomplished by combining the measured energy loss \((dE/dx)\) in the MDC and the flight time obtained from the TOF to form a likelihood \(L(h)\) for each hadron hypothesis. The K ± (π ±) candidates are required to satisfy \(L(K) > L(\pi) \) [13]

The K 0 S candidates are selected from pairs of oppositely charged tracks which satisfy a vertex-constrained fit to a common vertex. The vertices are required to be within 20 cm of the IP along the beam direction; no constraint in the transverse plane is applied. Particle identification is not required, and the two charged tracks are assumed to be pions. We require \(|M_{π±π±} - M_{K 0 S}| < 12 \text{ MeV}/c^2\), where \(M_{K 0 S}\) is the nominal K 0 S mass [13] and 12 MeV/c^2 is about 3 standard deviations of the observed K 0 S mass resolution. Lastly, the K 0 S candidate must have a decay length more than 2 standard deviations of the vertex resolution away from the IP.

Reconstructed EMC showers that are separated from the extrapolated positions of any charged tracks by more than 10° are taken as photon candidates. The energy deposited in the nearby TOF counters is included to improve the reconstruction efficiency and energy resolution. Photon candidates must have a minimum energy of 25 MeV for barrel showers \(|\cos \theta| < 0.80\) and 50 MeV for end cap showers \(0.86 < |\cos \theta| < 0.92\). The shower timing is required to be no later than 700 ns after the reconstructed event start time to suppress electronic noise and energy deposits unrelated to the event.

The π 0 candidates are reconstructed from pairs of photons, and the invariant mass \(M_{ππ}\) is required to satisfy 0.110 < \(M_{ππ}\) < 0.155 GeV/c^2. The invariant mass of two photons is constrained to the nominal π 0 mass [13] by a kinematic fit, and the \(\chi^2\) of the kinematic fit is required to be less than 20.

We form D ± candidates decaying into final hadronic states of K ± π ± π ±, K ± π ± π ± π 0, K 0 S π ± π ±, K 0 S π ± π ± π 0, K 0 S π ± π ± π ±, and K ± K − π ±. Two variables are used to identify valid ST D candidates: \(\Delta E \equiv E_D - E_{beam}\), the energy difference between the energy of the ST D (\(E_D\)) and the beam energy (\(E_{beam}\)), and the beam-constrained mass \(M_{BC} \equiv \sqrt{E_{beam}^2 - p_D^2/c^2}\), where \(p_D\) is the momentum of the D. The ST D signal should peak at the nominal D mass in the \(M_{BC}\) distribution and around zero in the \(\Delta E\) distribution. We only accept one candidate per mode; when multiple candidates are present in an event, the one with the smallest |\(\Delta E\)| is kept. Backgrounds are suppressed by the mode-dependent \(\Delta E\) requirements listed in Table I.

The ST yields of data are determined by binned maximum likelihood fits to the \(M_{BC}\) distributions. The signal MC line shape is used to describe the D signal, and an ARGUS [15] function is used to model the combinatorial backgrounds from the continuum light hadron production,
TABLE I. Requirements on $\Delta E$ for the ST $D$ candidates. The limits are set at approximately 3 standard deviations of the $\Delta E$ resolution.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Requirement (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K^+ \pi^+ \pi^+$</td>
<td>$-0.030 &lt; \Delta E &lt; 0.030$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+ \pi^+ \pi^0$</td>
<td>$-0.052 &lt; \Delta E &lt; 0.039$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+_S \pi^+ \pi^0$</td>
<td>$-0.057 &lt; \Delta E &lt; 0.040$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+_S \pi^+ \pi^0$</td>
<td>$-0.034 &lt; \Delta E &lt; 0.034$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+_S \pi^+$</td>
<td>$-0.032 &lt; \Delta E &lt; 0.032$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+ K^- \pi^+$</td>
<td>$-0.030 &lt; \Delta E &lt; 0.030$</td>
</tr>
</tbody>
</table>

$\gamma_{ISR}(3686)$, $\gamma_{ISR}J/\psi$, and nonsignal $D\bar{D}$ decays. A Gaussian function, with the standard deviation and the central value as free parameters, is convoluted with the line shape to account for imperfect modeling of the detector resolution and beam energy.

The charge-conjugated tag modes are fitted simultaneously, with the same signal and ARGUS background shapes for the tag and charge conjugated modes. The numbers of signal and background events are left free. Figures 1 and 2 show the fits to the $M_{BC}$ distributions of the ST $D^+$ and $D^-$ candidates in data, respectively. The ST yields are obtained by integrating the fitted signal function in the narrower $M_{BC}$ signal region ($1.86 < M_{BC} < 1.88$ GeV/$c^2$) and are listed in Table II.

B. Selection of DT events

After ST $D$ candidates are identified, we search for electrons and $K^0_L$ showers among the unused charged tracks and neutral showers. For electron identification, the ratio $R_{L}(e) \equiv \mathcal{L}'(e)/[\mathcal{L}'(e) + \mathcal{L}'(\pi)]$ is required to be greater than 0.8, where the likelihood $\mathcal{L}'(i)$ for the hypothesis $i = e, \pi$ or $K$ is formed by combining the EMC information with the $dE/dx$ and TOF information. The energy lost by electrons to bremsstrahlung photons is partially recovered by adding the energy of showers that are within 5$^\circ$ of the electron and are not matched to other charged particles. The selected electron is required to have the opposite charge from the ST $D$. Events that include charged tracks other than those of the ST $D$ and the electron are vetoed.

Because of the long $K^0_L$ lifetime, very few $K^0_L$ decay in the MDC. However, most $K^0_L$ will interact in the material of the EMC, which gives their position, and deposit part of their energy. We search for $K^0_L$ candidates by reconstructing all other particles in the event; we then loop over unused reconstructed neutral showers, taking the direction to the shower as the flight direction of the $K^0_L$. Using energy-momentum conservation and the constraint $U_{miss} = 0$, we calculate the momentum magnitude $|\vec{p}_{K^0_L}|$ of the $K^0_L$ and the four-vector of the unreconstructed neutrino in the event. The variable $U_{miss}$ is expected to peak at zero for semileptonic decay candidates and is defined as

\[
U_{miss} \approx \sum p_{\text{miss}}
\]
FIG. 2 (color online). Fits to the $M_{BC}$ distributions of the ST $D^-$ candidates for data. The dots with error bars are data, and the blue solid curves are the results of the fits. The green dashed curves are the fitted backgrounds.

<table>
<thead>
<tr>
<th>Tag mode</th>
<th>$N_{ST}$</th>
<th>$D^+ \rightarrow K^0_L \pi^+ \nu_e$</th>
<th>$D^- \rightarrow K^0_L \pi^- \bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K^+ \pi^- \pi^-$</td>
<td>410200 ± 670</td>
<td>$N_{DT}$ = 10492 ± 103</td>
<td>$f_{peak}$ (%) = 41.83 ± 0.28</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+ \pi^- \pi^0$</td>
<td>120460 ± 457</td>
<td>3324 ± 64</td>
<td>44.78 ± 0.49</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^0_S \pi^-$</td>
<td>101236 ± 378</td>
<td>2658 ± 56</td>
<td>38.93 ± 0.58</td>
</tr>
<tr>
<td>$D^- \rightarrow K^+ \pi^- \pi^-$</td>
<td>59158 ± 303</td>
<td>1459 ± 41</td>
<td>40.84 ± 0.76</td>
</tr>
<tr>
<td>$D^- \rightarrow K^+ \pi^- \pi^0$</td>
<td>47921 ± 225</td>
<td>1287 ± 36</td>
<td>38.90 ± 0.88</td>
</tr>
<tr>
<td>$D^- \rightarrow K^+ \pi^- \pi^0$</td>
<td>35349 ± 239</td>
<td>905 ± 32</td>
<td>44.64 ± 0.97</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tag mode</th>
<th>$N_{ST}$</th>
<th>$D^+ \rightarrow K^0_L \pi^- \bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^- \rightarrow K^+ \pi^- \pi^-$</td>
<td>407666 ± 668</td>
<td>$N_{DT}$ = 10354 ± 103</td>
</tr>
<tr>
<td>$D^- \rightarrow K^+ \pi^- \pi^0$</td>
<td>117555 ± 450</td>
<td>3264 ± 63</td>
</tr>
<tr>
<td>$D^- \rightarrow K^0_S \pi^-$</td>
<td>101824 ± 378</td>
<td>2642 ± 55</td>
</tr>
<tr>
<td>$D^- \rightarrow K^0_S \pi^-$</td>
<td>59460 ± 303</td>
<td>1533 ± 42</td>
</tr>
<tr>
<td>$D^- \rightarrow K^0_S \pi^-$</td>
<td>48240 ± 226</td>
<td>1217 ± 35</td>
</tr>
<tr>
<td>$D^- \rightarrow K^+ \pi^- \pi^+$</td>
<td>35742 ± 240</td>
<td>942 ± 32</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FIG. 3 (color online). Fits to the $M_{BC}$ distributions of the DT $D^+$ candidates for data. The dots with error bars are for data, and the blue solid curves are the results of the fits. The green dashed curves are the fitted combinatorial backgrounds.

$$U_{\text{miss}} \equiv E_{\text{miss}} - c|\vec{p}_{\text{miss}}|,$$

where

$$E_{\text{miss}} = E_{\text{tot}} - E_{\text{tag}} - E_{K_L^0} - E_\nu,$$

$$\vec{p}_{\text{miss}} = \vec{p}_{\text{tot}} - \vec{p}_{\text{tag}} - \vec{p}_{K_L^0} - \vec{p}_\nu;$$

$E_{\text{tot}}, E_{\text{tag}}, E_{K_L^0},$ and $E_\nu$ are the energies of the $e^+e^-$, the ST $D$, the $K_L^0$, and the electron; $\vec{p}_{\text{tot}}, \vec{p}_{\text{tag}}, \vec{p}_{K_L^0},$ and $\vec{p}_\nu$ refer to their momenta. $E_{K_L^0}$ is calculated by $E_{K_L^0} = \sqrt{|\vec{p}_{K_L^0}|^2 + m_{K_L^0}^2}$. In order to suppress background from fake photons, the energy of the $K_L^0$ shower should be greater than 0.1 GeV. We also reject photons that may come from $\pi^0$'s by rejecting $\gamma$ in any $\gamma\gamma$ combination with $0.110 < M_{\gamma\gamma} < 0.155$ GeV/$c^2$. In events with multiple $K_L^0$ shower candidates, the most energetic shower is chosen. The inferred four-momentum of the $K_L^0$ is used to determine the reconstructed $q^2$, the invariant mass squared of the $e^+\nu_e$ pair, by

$$q^2 = \frac{1}{c^4} (E_{\text{tot}} - E_{\text{tag}} - E_{K_L^0})^2 - \frac{1}{c^2} |\vec{p}_{\text{tot}} - \vec{p}_{\text{tag}} - \vec{p}_{K_L^0}|^2.$$

Similar to the determination of the ST yields, we obtain the DT yields of data from the fits to the $M_{BC}$ distributions of the corresponding ST $D$ candidates. Figures 3 and 4 show the fits to the $M_{BC}$ distributions of the DT $D^+$ and $D^-$ candidates in data, respectively. From the fits, we obtain the DT yields in the data, which are listed in the third column of Table II.

C. Estimation of backgrounds

The $K_L^0$ reconstruction efficiencies of data and MC differ, so the $K_L^0$ reconstruction efficiency of the generic MC is corrected to that of data. The correction factors of $K_L^0$ reconstruction efficiencies are determined from two control samples ($J/\psi \to K^+(892)\pm K^\mp$ with $K^+(892)\pm \to K_L^0\pi^\pm$ and $J/\psi \to \phi K_L^0 K^\mp\pi^\mp$), which are described in the Appendix. The corrected generic MC samples are used to determine the amount of peaking background and the efficiency for $D^+ \to K_L^0 e^+\nu_e$.

We examine the topologies of the corrected generic MC samples to study the composition of the DT samples. In the $M_{BC}$ signal region, the DT $D$ candidates can be divided into the following categories:

1. Signal: Tag side and signal side correctly matched.

2. Background:
   (a) Tag-side mismatched events (Bkg I).
   (b) Tag-side matched but signal-side mismatched signal events (Bkg II).
   (c) Tag-side matched but $D \to Xe\nu_e$ no-signal events on the signal side (Bkg III).
   (d) Tag-side matched but $D \to X\mu\nu_\mu$ events on the signal side (Bkg IV).
events varies from 49% to 58% according to the specific hadronic tag mode. Bkg I comes from $D\bar{D}$ decays in which the hadronic tag $D$ is misreconstructed and non-$D\bar{D}$ processes and varies from 1% to 12% according to the specific hadronic tag mode. Bkg II (~10%) consists of $D^+ \to K^0 L e^+\nu_e$ events of which the $K^0 L$ shower is misreconstructed. The dominant background in the DT sample is Bkg III (~24%), which is from $D^+ \to K^*(892)^0 e^-\nu_e$ (41.9%), $D^+ \to K^0 e^+\nu_e$ (41.2%), $D^+ \to \pi^0 e^+\nu_e$ (10.2%), $D^+ \to \eta e^+\nu_e$ (6.0%), and $D^+ \to \omega e^+\nu_e$ (0.7%). Bkg IV (~3%) consists of $D^+ \to K^0 L \mu^+\nu_\mu$ (65.2%), $D^+ \to K^*(892)^0 \mu^+\nu_\mu$ (23.3%), and $D^+ \to K^0 L \mu^+\nu_\mu$ (11.5%). Bkg V (~3%) consists of $D^+ \to K^0 \pi^+\pi^0$ (78%) and $D^+ \to K^0 K^*(892)^+$ (22%).

### IV. BRANCHING FRACTION AND CP ASYMMETRY

The branching fraction for $D^+ \to K^0 e^+\nu_e$ ($B_{\text{sig}}$) is determined by

$$B_{\text{sig}} = \frac{N_{\text{DT}}(1 - f_{\text{peak}}^{\text{bkg}})}{e N_{\text{ST}}} ,$$

where $N_{\text{DT}}, N_{\text{ST}}$ are the DT and ST yields, $f_{\text{peak}}^{\text{bkg}}$ is the proportion of peaking backgrounds in the DT candidates (from Bkg II to Bkg V), and $e$ is the efficiency for finding $D^+ \to K^0 e^+\nu_e$ in the presence of ST. $f_{\text{peak}}^{\text{bkg}}$ and $e$ are obtained from the $K^0 L$ efficiency corrected generic MC samples. The $D^+ \to K^0 e^+\nu_e$ branching fractions for different ST modes are listed in Table II. We obtain $B(D^+ \to K^0 e^+\nu_e) = (4.454 \pm 0.038 \pm 0.102)\%$ and $B(D^- \to K^0 e^-\bar{\nu}_e) = (4.507 \pm 0.038 \pm 0.104)\%$, which are the weighted averages of the six ST modes for $D^+$ and $D^-$ separately. Combining these branching fractions, we obtain the averaged branching fraction $B(D^+ \to K^0 e^+\nu_e) = (4.481 \pm 0.027 \pm 0.103)\%$, which agrees well with the measurement of $B(D^+ \to K^0 e^+\nu_e)$ of CLEO-c [16]. The CP asymmetry of $D^+ \to K^0 e^+\nu_e$ is

$$A_{CP} = \frac{B(D^+ \to K^0 e^+\nu_e) - B(D^- \to K^0 e^-\bar{\nu}_e)}{B(D^+ \to K^0 e^+\nu_e) + B(D^- \to K^0 e^-\bar{\nu}_e)} = (-0.59 \pm 0.60 \pm 1.48)\%.$$  

This result is consistent with the theoretical prediction in Ref. [4] ($-3.3 \times 10^{-3}$).

Table III summarizes the systematic uncertainties in the measurements of absolute branching fractions and the CP asymmetry of $D^+ \to K^0 e^+\nu_e$. A brief description of each systematic uncertainty is provided below.
TABLE III. Systematic uncertainties in the measurements of the absolute branching fraction and the \( CP \) asymmetry of \( D^+ \to K_L^0 e^+\bar{\nu}_e \).

<table>
<thead>
<tr>
<th>Source</th>
<th>( D^+ \to K_L^0 e^+\bar{\nu}_e )(%)</th>
<th>( D^- \to K_L^0 e^-\bar{\nu}_e )(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron tracking</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Electron ID</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>( K_L^0 ) efficiency correction</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Extra ( \chi^2 ) cut for ( K_L^0 ) efficiency correction</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Peaking backgrounds in DT</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>( M_{BC} ) fit</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Total (branching fraction)</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Total (( CP ) asymmetry)</td>
<td>2.1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

A. Electron (positron) track-finding and identification efficiency

Uncertainties of electron (positron) track-finding and identification (ID) efficiency are obtained by comparing the track-finding and ID efficiencies for the electrons (positrons) from radiative Bhabha processes in the data and MC. Considering both the \( \cos \theta \), where \( \theta \) is the polar angle of the positron, and momentum distributions of the electrons (positrons) of the signal events, we obtain the two-dimensional weighted uncertainty of electron (positron) track finding to be 0.5% and the averaged uncertainties of positron and electron ID efficiency to be 0.03% and 0.10%, respectively.

B. \( K_L^0 \) Efficiency correction

We take the relative statistical uncertainty of the \( K_L^0 \) efficiency difference between data and MC as a function of momentum (as shown in Fig. 7 in the Appendix) as the uncertainty of the \( K_L^0 \) efficiency correction. Weighting these uncertainties by the \( K_L^0 \) momentum distribution in \( D^+ \to K_L^0 e^+\bar{\nu}_e \) and \( K_L^0 \) efficiency corrections to both be 1.2%.

C. Extra \( \chi^2 \) cut for \( K_L^0 \) efficiency correction

As described in the Appendix, in the determination of the correction factor of the \( K_L^0 \) efficiency, we apply a \( \chi^2 \) cut which brings an extra uncertainty. The uncertainty of the \( \chi^2 \) cut is obtained by comparing the cut efficiency between data and MC using two control samples \( [J/\psi \to K^+\bar{K}^0 (892)^+K^+\bar{K}^0]^\pm \) with \( K^+\bar{K}^0 (892)^+K^+\bar{K}^0 \) and \( J/\psi \to \phi K^0\bar{K}^0 K^+\bar{K}^0 \). Weighting by the momentum distribution of the \( K_L^0 \) of signal events, the uncertainty of the extra \( \chi^2 \) cut \( (\chi^2 < 100) \) is 0.8%.

D. Peaking backgrounds in DT

For Bkg II, from Eq. (7), the ratio of misreconstructed \( K_L^0 \) will not affect the measured branching fraction, since the numerator and the denominator share the common factor. The uncertainties of the peaking backgrounds of misreconstructed \( K_L^0 \) can be safely ignored. For Bkg III, Bkg IV, and Bkg V, we determine the change of the number of DT events by varying the branching fractions of peaking background channels by \( 1\sigma \), and the uncertainty of peaking backgrounds in DT events is 1.6%.

E. \( M_{BC} \) fit

To evaluate the systematic uncertainty from the \( M_{BC} \) fit, we determine the changes of the DT yields divided by the ST yields when varying the standard deviation of the convoluted Gaussian function by \( \pm 1\sigma \) deviation for each tag mode. We find that they are negligible.

The total systematic uncertainties of the branching fractions for \( D^+ \to K_L^0 e^+\bar{\nu}_e \) and \( D^- \to K_L^0 e^-\bar{\nu}_e \) are determined to be 2.3% and 2.3%, respectively, by adding all contributions in quadrature. In the determination of the \( CP \) asymmetry, the corresponding systematic uncertainties of branching fractions for \( D^+ \to K_L^0 e^+\bar{\nu}_e \) and \( D^- \to K_L^0 e^-\bar{\nu}_e \) are obtained in a similar fashion, except that the contribution of the extra \( \chi^2 \) cut of the \( K_L^0 \) efficiency correction is not used since it cancels. The systematic uncertainties entering the \( CP \) asymmetry are found to be 2.1% and 2.1%, respectively.

V. HADRONIC FORM FACTOR

A. Method of extraction of form factor

The number of produced signal events for each tag mode from the whole \( q^2 \) range can be written as

\[
n = 2N_{D^+} \frac{B_{\text{tag}} B_{\text{sig}}}{\Gamma_{D^+}} = N_{\text{sig}} \frac{\Gamma_{\text{sig}}}{\Gamma_{D^+}},
\]

where \( \Gamma_{\text{sig}} \) is the partial decay width of \( D^+ \to K_L^0 e^+\bar{\nu}_e \) while \( \Gamma_{D^+} \) is the total decay width of \( D^+ \). So we obtain

\[
dn = \frac{N_{\text{tag}}}{\Gamma_{D^+}} d\tau_{\text{sig}} = N_{\text{tag}} \frac{\Gamma_{\text{sig}}}{\Gamma_{D^+}} d\tau_{\text{sig}},
\]

where \( \tau_{D^+} = 1/\Gamma_{D^+} \) is the \( D^+ \) lifetime and \( d\tau_{\text{sig}} \) is the differential decay width of the signal.
Substituting Eq. (10) into Eq. (1), Eq. (1) can be rewritten as

$$\frac{dn}{dq^2} = AN_\text{tag} p^3 |f_+(q^2)|^2,$$

where $A = \frac{1}{2} \frac{G^2_F V_{ts}}{4\pi^2} 2D_s$, and the number of observed semileptonic signal events as a function of $q^2$ is given by

$$\frac{dn_{\text{observed}}}{dq^2} = AN_\text{tag} \left[p^3 (q^2)|f_+(q^2)|^2 \epsilon(q^2)\right] \otimes \sigma(q^2, q^2),$$

where $q^2$ refers to the true value and $q^2$ refers to the measured value, $p(q^2)$ is the momentum of $K^0_s$ in the rest frame of the parent $D$, $\epsilon(q^2)$ is the detection efficiency, and $\sigma(q^2, q^2)$ is the detector resolution. To account for detector effects, we use the theoretical function convoluted with a Gaussian detector resolution to describe the observed signal curve.

### B. Form-factor parametrizations

The goal of any particular parametrization $f_+(q^2)$ of the semileptonic form factors is to provide an accurate, and physically meaningful, expression of the strong dynamics in the decays. One possible way to achieve this goal is to express the form factors in terms of a dispersion relation. This approach of using dispersion relations and dispersive bounds in the description of form factors has been well established in the literature. In general, the dispersive representation is derived from the evaluation of the two point function [17,18] and can be written as

$$f_+(q^2) = \frac{f_+(0)}{(1-\alpha)} \frac{1}{1 - \frac{q^2}{m_\text{pole}^2}} + \frac{1}{\pi} \int_{(m_D + m_p)^2}^{\infty} \frac{\text{Im}f_+(t)}{t - q^2 - i\epsilon} dt,$$

where $m_D$ and $m_p$ are the masses of the $D$ meson and pseudoscalar meson, respectively, while $m_\text{pole}$ is the mass of the lowest-lying $c\bar{q}$ vector meson, with $c \rightarrow q$ the quark transition of the semileptonic decay. For the charm semileptonic decays, we have $m_\text{pole} = m_D$; for $D \rightarrow K e\nu$ decays. The parameter $\alpha$ expresses the size of the vector meson pole contribution to $f_+(0)$. It is common to write the contribution from the continuum integral as a sum of effective poles

$$f_+(q^2) = \frac{f_+(0)}{(1-\alpha)} \frac{1}{1 - \frac{q^2}{m_\text{pole}^2}} + \sum_{k=1}^{N} \frac{\rho_k}{1 - \frac{q^2}{t_k m_\text{pole}^2}},$$

where $\rho_k$ and $t_k$ are expansion parameters.

The simplest parametrization, known as the simple pole model, assumes that the sum in Eq. (14) is dominated by a single pole,

$$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{m_\text{pole}^2}},$$

where the value of $m_\text{pole}$ is predicted to be $m_D$. In experiments, $m_\text{pole}$ is left as a free fit parameter to improve the fit quality.

Another parametrization is known as the modified pole model, or Becirevic-Kaidelov parametrization [14]. The idea is to add the first term in the effective pole expansion, while making simplifications such that the form factor can be determined with only two parameters: the intercept $f_+(0)$ and an additional shape parameter $\alpha$. The simplified one-term expansion is usually written in the form

$$f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{m_\text{pole}^2})(1 - \alpha q^2/m_\text{pole})}. $$

A third parametrization is known as the series expansion [19]. Exploiting the analytic properties of $f_+(q^2)$, a transformation of variables is made that maps the cut in the $q^2$ plane onto a unit circle $|z| < 1$, where

$$z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}},$$

$$(t_\pm = m_D \pm m_P)^2$$, and $t_0$ is any real number less than $t_+$. This transformation amounts to expanding the form factor about $q^2 = t_0$, with the expanded form factor given by

$$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2, t_0)} \sum_{k=0}^{\infty} a_k(t_0)|z(q^2, t_0)|^k.$$

where $a_k$ are real coefficients, $P(q^2) = z(q^2, M^2_{D_s})$ for kaon final states, $P(q^2) = 1$ for pion final states, and $\phi(q^2, t_0)$ is any function that is analytic outside a cut in the complex $q^2$ plane that lies along the axis from $t_+$ to $\infty$. This expansion has improved convergence properties over Eq. (14) due to the smallness of $z$, for example, taking the traditional choice of $t_0 = t_+(1 - (1 - t_+/t_+)^{1/2})$, which minimizes the maximum value of $z(q^2, t_0)$. Further, taking the standard choice of $\phi$

$$\phi(q^2, t_0) = \sqrt{\frac{\pi m_2^2}{3}} \left(\frac{z(q^2, t_0)}{q^2 - q^2}\right)^{5/2} \left(\frac{z(q^2, t_0) - t_0}{t_+ - t_0}\right)^{-1/2} \times \left(\frac{z(q^2, t_-)}{t_- - q^2}\right)^{-3/4} \frac{t_+ - q^2}{(t_+ - t_0)^{1/4}}. $$
where $m_c$ is the mass of charm quark and it can be shown that the sum over all $k$ of $a_k^2$ is of order unity.

In practical use of the series expansion form factor, one often takes $k = 1$ and $k = 2$ in Eq. (18), which gives following two forms of the form factor.

(i) 2 parameter series expansion of the form factor is given by

$$f_+ (q^2) = \frac{1}{P(q^2)\phi(q^2, t_0)} a_0(t_0)(1 + r_1(t_0)[z(q^2, t_0)]).$$

(20)

It can be rewritten as

$$f_+ (q^2) = \frac{1}{P(q^2)\phi(q^2, t_0)} f_+(0)P(0)\phi(0, t_0) \times (1 + r_1(t_0)[z(q^2, t_0)]) \times (1 + r_2(t_0)[z(q^2, t_0)]^2).$$

(21)

where $r_1 = a_1/a_0$.

(ii) 3 parameter series expansion of the form factor is given by

$$f_+ (q^2) = \frac{1}{P(q^2)\phi(q^2, t_0)} a_0(t_0) \times (1 + r_1(t_0)[z(q^2, t_0)] + r_2(t_0)[z(q^2, t_0)]^2).$$

(22)

It can be rewritten as

$$f_+ (q^2) = \frac{1}{P(q^2)\phi(q^2, t_0)} f_+(0)P(0)\phi(0, t_0) \times (1 + r_1(t_0)[z(q^2, t_0)] + r_2(t_0)[z(q^2, t_0)]^2.\tag{23}$$

where $r_1 = a_1/a_0$, $r_2 = a_2/a_0$.

C. Determination of $f_±^K(0)|V_{cs}|$

We perform simultaneous fits to the distributions of observed DT candidates as a function of $q^2$ for the six ST modes to determine $f_±^K(0)|V_{cs}|$. In the fits, we treat $D^+$ and $D^-$ DT candidates together. The detection efficiency $e(q^2)$ and detector resolution $\sigma(q^2, q^2)$ are obtained from the $K_L^0$ efficiency corrected signal MC simulations. For each ST mode, $e(q^2)$ is described by a fourth-order polynomial; the $(q_2 - q_2^2)$ distribution is described by a Gaussian function. As an example, Fig. 5 shows the fits to $e(q^2)$ for signal events tagged by $D^± \to K^±\pi^±\pi^±$.

Simultaneous fits are made with one or two common parameters related to the form-factor shape to the data for the simple pole model ($m_{pole}$), the modified pole model ($a$), two-parameter series expansion ($r_1$) and three-parameter series expansion ($r_1, r_2$). As an example, Fig. 6 shows the simultaneous fit results using the two-parameter series expansion model. The signal Probability Density Function is constructed in the form of Eq. (12). For the background shape, as mentioned in Sec. III C, the shape and the number of Bkg I events are fixed according to the side-band region of the $M_{BC}$ distribution ($1.83 < M_{BC} < 1.85$ GeV/c$^2$) from data; for Bkgs from II to V, the shape is determined from the $K_L^0$ efficiency corrected generic MC samples. We also fix the relative proportion of $N_{sig}$, $N_{BkgII}$, and $N_{BkgIII} + N_{BkgIV}$ events, to the result from the $K_L^0$ efficiency corrected generic MC. Here, $N_{sig}$, $N_{BkgII}$, $N_{BkgIII}$, and $N_{BkgIV}$ represent the numbers of the signal, Bkg II, Bkg III, and Bkg IV events, respectively.

The product $f_±^K(0)|V_{cs}|$ is obtained from

$$f_±^K(0)|V_{cs}| = \sqrt{\frac{48\pi^3}{G_F^2}} N_{sig} \frac{1}{\tau_{D^±}} I,$$

(24)

where $I = \int [p^3(q^2)|f_±^K(q^2)|^2 e(q^2)] \otimes \sigma(q^2, q^2) dq^2$.

Since the $q^2$ distribution of the signal events is smooth, the form-factor fit is insensitive to the detector resolution. For each tag mode, we use the full width at half maximum (FWHM) of the $(q_2 - q_2^2)$ distribution to estimate $\sigma(q^2, q^2)$ and obtain $\text{FWHM} = 0.0360$ GeV$^2/c^4$ and the corresponding resolution $\sigma = \text{FWHM}/2\sqrt{2\ln 2} = 0.0153$ GeV$^2/c^4$. The distributions of DT candidates as a function of $q^2$ are fit again by different models with the detector resolution $\sigma = 0.0153$ GeV$^2/c^4$. Compared to the previous results, the form-factor parameters and the signal yields are almost unchanged. So the uncertainty of the detector resolution can be ignored in the form-factor fit.

Systematic uncertainties of the form-factor parameters are more sensitive to the distribution of backgrounds in this analysis. We use a different side-band region of the $M_{BC}$
distribution \((1.835 < M_{\text{BC}} < 1.855 \text{ GeV}/c^2)\) and ISGW2 model to simulate the main possible semileptonic backgrounds. We simultaneously fit the distributions of observed DT candidates as a function \(q^2\) again. The differences between the form-factor parameters obtained from the two determinations are taken as the systematic uncertainties of the form-factor parameters.

Systematic uncertainties associated with the product \(f^K_S(0)|V_{cs}|\) are one-half of the systematic uncertainties in the branching fraction measurements, presented in Sec. IV, combined in quadrature with the uncertainties associated with the \(D^+\) lifetime \((0.67\%)\) \cite{4} and the integration \(I\), which are obtained by varying the form-factor parameters by \(\pm 1\sigma\). The systematic uncertainties of \(f^K_S(0)|V_{cs}|\) are

![Graphs showing fits to DT candidates](image)

**TABLE IV.** Comparison of results of \(f^K_S(0)|V_{cs}|\) and shape parameters \((m_{\text{pole}}, \alpha, r_1, \text{and } r_2)\) to previous corresponding results determined by \(D^+ \rightarrow K_S^0 e^+ \nu_e\) from CLEO-c \cite{16}. The first uncertainties are statistical, and the second are systematic.

| Decay mode         | \(f^K_S(0)|V_{cs}|\)  | \(m_{\text{pole}}\) (GeV/c^2) |
|--------------------|----------------------|-------------------------------|
| \(D^+ \rightarrow K_S^0 e^+ \nu_e\) | 0.729 ± 0.006 ± 0.010 | 1.953 ± 0.044 ± 0.036       |
| \(D^+ \rightarrow K_S^0 e^+ \nu_e\) | 0.720 ± 0.006 ± 0.009 | 1.95 ± 0.03 ± 0.01          |

| Decay mode         | \(f^K_S(0)|V_{cs}|\)  | \(\alpha\)                      |
|--------------------|----------------------|----------------------------------|
| \(D^+ \rightarrow K_S^0 e^+ \nu_e\) | 0.727 ± 0.006 ± 0.011 | 0.239 ± 0.077 ± 0.065            |
| \(D^+ \rightarrow K_S^0 e^+ \nu_e\) | 0.715 ± 0.007 ± 0.009 | 0.28 ± 0.06 ± 0.02               |

**Two-parameter series expansion**

| Decay mode         | \(f^K_S(0)|V_{cs}|\)  | \(r_1\)                        |
|--------------------|----------------------|---------------------------------|
| \(D^+ \rightarrow K_S^0 e^+ \nu_e\) | 0.728 ± 0.006 ± 0.011 | −1.91 ± 0.33 ± 0.28             |
| \(D^+ \rightarrow K_S^0 e^+ \nu_e\) | 0.716 ± 0.007 ± 0.009 | −2.10 ± 0.25 ± 0.08             |

**Three-parameter series expansion**

| Decay mode         | \(f^K_S(0)|V_{cs}|\)  | \(r_1\) | \(r_2\)          |
|--------------------|----------------------|---------|------------------|
| \(D^+ \rightarrow K_S^0 e^+ \nu_e\) | 0.737 ± 0.006 ± 0.009 | −2.23 ± 0.42 ± 0.53 | 11.3 ± 8.5 ± 8.7 |
| \(D^+ \rightarrow K_S^0 e^+ \nu_e\) | 0.707 ± 0.010 ± 0.009 | −1.66 ± 0.44 ± 0.10 | −14 ± 11 ± 1     |
obtained for the simple pole model, modified pole model, two-parameter series expansion, and three-parameter series expansion to be 1.4%, 1.5%, 1.5%, and 1.2%, respectively.

The fit results are given in Table IV. As a comparison, Table IV also lists the corresponding form-factor results determined for \( D^+ \rightarrow K^0_S e^+\nu_e \) from CLEO-c [16]. Our results are consistent with those from CLEO-c within uncertainties except for three-parameter series expansion model due to heavy backgrounds in this analysis. In general, as long as the normalization and at least one shape parameter are allowed to float, all models describe the data well. We choose the two-parameter series fit to determine \( f_+^K(0) \) and \( |V_{cs}| \).

The BESIII experiment has recently reported the most precise value of \( f_+^K(0)|V_{cs}| \) using the two-parameter series expansion for \( D^0 \rightarrow K^-e^+\nu_e \) [20]. It is in agreement with the results reported here.

D. Determination of \( f_+^K(0) \) and \( |V_{cs}| \)

Using the \( f_+^K(0)|V_{cs}| \) value from the two-parameter series expansion fit and \( |V_{cs}| = 0.97343 \pm 0.00015 \) from PDG fits assuming CKM unitarity [13] or \( f_+^K(0) = 0.747 \pm 0.019 \) from the unquenched LQCD calculation [21] as input, we obtain

\[
f_+^K(0) = 0.748 \pm 0.007 \pm 0.012 \quad (25)
\]

and

\[
|V_{cs}| = 0.975 \pm 0.008 \pm 0.015 \pm 0.025, \quad (26)
\]

where the uncertainties are statistical, systematic, and external [in Eq. (26)]. For Eq. (25), the external error is negligible (0.0002) compared to our measurement. The measured \( f_+^K(0) \) is consistent with the one measured with \( D^+ \rightarrow K^0_S e^+\nu_e \) at CLEO-c [16]; it is also in good agreement with LQCD predictions, although the currently available LQCD results have relatively large uncertainties. The measured \( |V_{cs}| \) is in agreement with that reported by the PDG.

VI. SUMMARY

In this paper, we present the first measurement of the absolute branching fraction \( B(D^+ \rightarrow K^0_S e^+\nu_e) = (4.841 \pm 0.027 \text{(stat)} \pm 0.103 \text{(sys)}) \% \), which is in excellent agreement with \( B(D^+ \rightarrow K^0_S e^+\nu_e) \) measured by CLEO-c [16]. The \( CP \) asymmetry \( A_{CP}^{D^+\rightarrow K^0_S e^+\nu_e} = (-0.59 \pm 0.60 \text{(stat)} \pm 1.48 \text{(sys)}) \% \), which agrees with the theoretical prediction on \( CP \) violation in the \( K^0 \) system within the statistical error, is also determined. By fitting the distributions of the observed DT events as a function of \( q^2, f_+^K(0)|V_{cs}| \) and the corresponding parameters for three different theoretical form-factor models are determined. Taking \( f_+^K(0)|V_{cs}| \) from the two-parameter series expansion parametrization, \( f_+^K(0)|V_{cs}| = 0.728 \pm 0.006 \text{(stat)} \pm 0.011 \text{(sys)} \), and using \( |V_{cs}| \) from the SM constraint fit, we find \( f_+^K(0) = 0.748 \pm 0.007 \text{(stat)} \pm 0.012 \text{(sys)} \). By using an unquenched LQCD prediction for \( f_+^K(0) \), \( |V_{cs}| = 0.975 \pm 0.008 \text{(stat)} \pm 0.015 \text{(sys)} \pm 0.025 \text{(LQCD)} \).

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APPENDIX: SYSTEMATIC UNCERTAINTY IN \( K^0_L \) RECONSTRUCTION EFFICIENCY

To determine the systematic uncertainty in the \( K^0_L \) reconstruction efficiency, we measure the \( K^0_L \) efficiency in data and MC using a partial reconstruction technique. We then determine the efficiency difference between data and MC, \( \epsilon_{data}/\epsilon_{MC} - 1 \), of the \( K^0_L \) reconstruction efficiency, where \( \epsilon_{MC} \) is the efficiency for MC and \( \epsilon_{data} \) is the efficiency for data. Based on 1.3 B J/ψ events collected by the BESIII detector in the years 2009 and 2012, we use two control samples to measure \( K^0_L \) reconstruction efficiency. One sample is \( J/\psi \rightarrow K^*(892)^\pm K^\mp \) with \( K^*(892)^\pm \rightarrow K^0_L \pi^\pm \),
and the other is $J/\psi \to \phi K^0_L K^\pm \pi^\mp$. We reconstruct all the particles in the event except the $K^0_L$ of which the efficiency we wish to measure. The number of $K^0_L(K^0)$ is denoted by $N_1$. Then, by applying $K^0_L$ selection requirements mentioned in Sec. III B, we obtain the number of $K^0_L(K^0)$ denoted by $N_2$. Here, in order to select $K^0_L$ control samples with a low level of backgrounds, we perform the kinematic fit to select the $K^0_L$ candidate with the minimal $\chi^2$ and require $\chi^2 < 100$.

The $K^0_L(K^0)$ reconstruction efficiency is calculated by $e = N_2/N_1$. For data, $N_1, N_2$ are determined by fitting the missing mass squared distribution of $K^0_L$. Each fit includes a signal line shape function which is determined from MC samples smeared with a Gaussian resolution, and the background shape is determined from MC samples as well. With respect to MC samples, $N_1, N_2$ are obtained from MC truth directly. The fits are performed in separate momentum bins. In each fit, $N_1(N_2)$ consists of the number of $K^0_L$ and $K^0$. The ratio of $K^0_L$ to $K^0_S$ is estimated from MC simulations. Due to the effect of the difference in nuclear interactions of $K^0$ and $K^0$ mesons, we consider $K^0 \to K^+_L$ and $\bar{K}^0 \to K^0_L$ separately. We use the charge of the kaon to tag $K^0$ or $\bar{K}^0$ in the control sample, which means if we find a $K^+$ in the process, the corresponding $K^0_L$ must be derived from $\bar{K}^0$.

Figure 7 shows the distributions of $K^0_L$ reconstruction efficiency differences between data and MC in 19 momentum bins for the processes of $K^0 \to K^+_L$ and $\bar{K}^0 \to K^0_L$. The probability of an inelastic interaction of a neutral kaon in the detector depends on the strangeness of the kaon at any point along its path, which is due to oscillations in kaon strangeness and different nuclear cross sections for $K^0$ and $\bar{K}^0$. Hence, the total efficiency to observe a final state $K^0_L(K^0_S)$ differs from that expected for either $K^0$ or $\bar{K}^0$. This effect is related to the coherent regeneration of neutral kaons [22]. However, the detector-simulation program GEANT4 does not take into account this effect. The time-dependent $K^0 - \bar{K}^0$ oscillations are thereby ignored in GEANT4. Considering the massive detector materials in the outer of the MDC, the TOF counter and the EMC, it results in an obvious discrepancy (>10%) of the $K^0_L$ shower-finding efficiency in the EMC between the data and MC. On the other hand, we take the same method to study the $K^0_S$ reconstruction efficiency difference between the data and MC for the processes of $K^0 \to K^0_S$ and $\bar{K}^0 \to K^0_S$ by a 224 M $J/\psi$ control sample, as shown in Fig. 8. We find that the $K^0_S$ reconstruction efficiency of the data is a little higher than that of MC, which gives another hint of the absence of the coherent regeneration of neutral kaons by GEANT4.