

Measurement of the  $CP$ -even fraction of  $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ 

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A measurement of the  $CP$ -even fraction of the decay  $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$  is performed with a quantum-correlated  $\psi(3770) \rightarrow D\bar{D}$  data sample collected by the BESIII experiment, corresponding to an integrated luminosity of  $2.93 \text{ fb}^{-1}$ . Using a combination of  $CP$  eigenstates,  $D \rightarrow \pi^+\pi^-\pi^0$  and  $D \rightarrow K_{S,L}^0\pi^+\pi^-$  as tagging modes, the  $CP$ -even fraction is measured to be  $F_+^{4\pi} = 0.735 \pm 0.015 \pm 0.005$ , where the first uncertainty is statistical and the second is systematic. This is the most precise determination of this quantity to date. It provides valuable model-independent input for the measurement of the angle  $\gamma$  of the Cabibbo-Kobayashi-Maskawa matrix with  $B^\pm \rightarrow DK^\pm$  decays, and for time-dependent studies of  $CP$  violation and mixing in the  $D^0$ - $\bar{D}^0$  system.

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## I. INTRODUCTION

Studies of  $CP$  violation in the heavy-quark sector can improve our understanding of the weak interaction and probe for new effects that cannot be accommodated within the Standard Model of particle physics. Many of these studies use neutral charm mesons, with a particular case of interest being when the charm meson decays to a  $CP$  eigenstate. Observables in the process  $B^\pm \rightarrow DK^\pm$ , where the  $D$  is a superposition of  $D^0$  and  $\bar{D}^0$  and is here reconstructed in a  $CP$  eigenstate, are sensitive to the CKM angle  $\gamma$ , and thus allow for tests of the Standard Model description of  $CP$  violation [1,2]. Furthermore, measurements of the decay time of charm mesons produced in a known flavor eigenstate and reconstructed in a  $CP$  eigenstate bring information on  $D^0 - \bar{D}^0$  oscillations [3]. These strategies can be extended to so-called quasi- $CP$  eigenstates: self-conjugate multibody decays that are not themselves  $CP$  eigenstates, but dominated by intermediate states of definite  $CP$  [4,5]. The parameter  $F_+$  quantifies the fractional  $CP$ -even content of these modes, with  $F_+ = 1$  (0) corresponding to a pure  $CP$ -even (-odd) final state. Measurements using these quasi- $CP$  eigenstates require good knowledge of  $F_+$  for interpreting the results.

$CP$ -even fractions and other parameters associated with the strong dynamics of charm-meson decays are preferentially measured from data collected at the  $\psi(3770)$  resonance. The quantum correlation between the two charm mesons produced from the decay of the  $\psi(3770)$  gives rise to interference effects that provide access to these parameters. This approach has the benefit of being model independent and is to be contrasted with alternative strategies that are based on amplitude models constructed from decays of mesons produced in incoherent environments [6,7]. Measurements of the  $CP$ -even fraction with

correlated  $D\bar{D}$  pairs have been performed with data collected by the CLEO-c experiment for a range of decay modes including  $D \rightarrow \pi^+\pi^-\pi^+\pi^-$  [4,8–10].

The decay  $D \rightarrow \pi^+\pi^-\pi^+\pi^-$  is an attractive mode for  $CP$ -violation studies on account of its reasonably high branching fraction and the good reconstruction efficiency that both LHCb and Belle II have for the fully charged final state [11–13]. This paper presents a determination of the  $CP$ -even fraction,  $F_+^{4\pi}$ , of this decay using quantum-correlated  $\psi(3770) \rightarrow D\bar{D}$  data collected by the BESIII experiment, corresponding to an integrated luminosity of  $2.93 \text{ fb}^{-1}$ . It is the first measurement of a  $CP$ -even fraction with this dataset, although BESIII has presented studies of other hadronic parameters performed with correlated  $D\bar{D}$  pairs in a variety of channels [14–18].

## II. MEASUREMENT METHOD

The strong decay  $\psi(3770) \rightarrow D\bar{D}$  conserves the negative C quantum number, leaving the charm-meson pair in an overall  $P$ -wave state. The quantum correlation between the two mesons in this antisymmetric wave function provides the opportunity to determine the  $CP$ -even fraction of  $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$  [19]. (The  $F_+$  parameter for the  $\bar{D}^0$  decay is identical.)

The method adopted in this analysis is similar to that applied in previous measurements [4,8,10], and is based on samples of “double-tag” (DT) and “single-tag” (ST) events. The DT events are those where one  $D$  meson decays to the signal final-state  $\pi^+\pi^-\pi^+\pi^-$  and the  $\bar{D}$  meson decays to a “tag mode,” as described below. The ST events are those where only one charm meson is reconstructed in its decay to a tag mode.

Various classes of tag modes are employed, the first ones being pure  $CP$  eigenstates. Several decays involving  $K_S^0$  and  $K_L^0$  mesons are included in this category, as  $CP$  violation in the kaon system can be neglected at the current level of experimental precision. The same consideration applies to  $CP$  violation associated with the charm mesons themselves [20]. For a  $CP$ -tag mode, here denoted as  $f$ , the predicted DT yield is given by

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$$M(4\pi, f) = 2N_{D\bar{D}}\mathcal{B}(4\pi)\mathcal{B}(f)\epsilon_{DT}[1 - \eta_{CP}^f(2F_+^{4\pi} - 1)], \quad (1)$$

where  $N_{D\bar{D}}$  is the number of neutral charm-meson pairs in the sample,  $\mathcal{B}(X)$  is the branching fraction of  $D \rightarrow X$ ,  $\epsilon_{DT}$  is the DT reconstruction efficiency of the event, and  $\eta_{CP}^f$  is the  $CP$  eigenvalue (+1 or -1) of the tag channel  $f$ . In this and subsequent expressions, terms of  $\mathcal{O}(y^2)$  in the charm mixing parameter  $y = (0.615_{-0.055}^{+0.056})\%$  [20] are neglected.

The predicted ST yield is given by

$$S(f) = 2N_{D\bar{D}}\mathcal{B}(f)\epsilon_{ST}[1 - \eta_{CP}^f y], \quad (2)$$

where  $\epsilon_{ST}$  is the reconstruction efficiency of the ST decay. Then  $F_+^{4\pi}$  can be accessed through

$$F_+^{4\pi} = \frac{N^+}{N^+ + N^-}, \quad (3)$$

where  $N^+$ , which measures the proportion of  $CP$ -even  $D$  mesons that decay to  $\pi^+\pi^-\pi^+\pi^-$ , is  $M(4\pi, f)[1 - \eta_{CP}^f y]/S(f)$  for a  $CP$ -odd tag, and  $N^-$  is the analogous quantity for a  $CP$ -even tag. Experimentally,  $N^+$  and  $N^-$  are determined from the corresponding ratios involving the measured DT and ST yields and are averaged over all employed tags. This calculation assumes that the DT-event efficiency can be factorized into the ST efficiency and the reconstruction efficiency of the signal decay and that any corrections to this assumption are common to all classes of DT. Possible exceptions to these assumptions are examined in the assignment of systematic uncertainties. Modifications to this procedure, described in Sec. IV, are required for certain classes of tag involving  $K_L^0$  mesons where the ST yields cannot be directly measured.

A specific tag used in the analysis is  $D \rightarrow \pi^+\pi^-\pi^0$ , which is a quasi- $CP$  eigenstate. Here the predicted DT yield is given by

$$M(4\pi, f) = 2N_{D\bar{D}}\mathcal{B}(4\pi)\mathcal{B}(\pi\pi\pi^0)\epsilon_{DT}[1 - (2F_+^{\pi\pi\pi^0} - 1) \times (2F_+^{4\pi} - 1)], \quad (4)$$

where  $F_+^{\pi\pi\pi^0} = 0.973 \pm 0.017$  is the  $CP$ -even fraction of the tag mode [8], and the predicted ST yield is

$$S(\pi\pi\pi^0) = 2N_{D\bar{D}}\mathcal{B}(\pi\pi\pi^0)\epsilon_{ST}[1 - (2F_+^{\pi\pi\pi^0} - 1)y]. \quad (5)$$

In this case,  $F_+^{4\pi}$  can be accessed through the ratio

$$F_+^{4\pi} = \frac{N^+ F_+^{\pi\pi\pi^0}}{N^{\pi\pi\pi^0} - N^+ + 2N^+ F_+^{\pi\pi\pi^0}}, \quad (6)$$

with  $N^{\pi\pi\pi^0} = M(4\pi, \pi\pi\pi^0)[1 - (2F_+^{\pi\pi\pi^0} - 1)y]/S(\pi\pi\pi^0)$ . Experimentally,  $N^+$  and  $N^{\pi\pi\pi^0}$  are again determined from the measured DT and ST yields, with the same assumptions

concerning the factorization of the DT-event efficiency as discussed above.

The self-conjugate decays  $D \rightarrow K_S^0\pi^+\pi^-$  and  $D \rightarrow K_L^0\pi^+\pi^-$  are known to have  $CP$ -even fractions close to 0.5 [21], and hence would give poor sensitivity to  $F_+^{4\pi}$  if used as a tag of the inclusive decay in an analogous manner to  $D \rightarrow \pi^+\pi^-\pi^0$ . However, an alternative measurement may be performed where the position of the tag decay in its phase space is considered. This is possible because studies on the variation in the strong-phase difference between the  $D^0$  and  $\bar{D}^0$  amplitudes across the Dalitz plot have been performed for these modes. In particular, measurements exist of the amplitude-weighted cosine of the average strong-phase difference in binned regions of phase space [15,16,22]. The predicted DT yields in bin  $i$  are given by

$$\begin{aligned} M_i(4\pi, K_S^0\pi^+\pi^-) &= H[K_i + K_{-i} - 2\sqrt{K_i K_{-i}}c_i(2F_+^{4\pi} - 1)], \\ M'_i(4\pi, K_L^0\pi^+\pi^-) &= H'[K'_i + K'_{-i} + 2\sqrt{K'_i K'_{-i}}c'_i(2F_+^{4\pi} - 1)], \end{aligned} \quad (7)$$

where  $H$  and  $H'$  are normalization factors,  $K_i$  ( $K'_i$ ) is the fractional rate of  $D^0$  decays to  $K_S^0\pi^+\pi^-$  ( $K_L^0\pi^+\pi^-$ ) in the  $i$ th bin, and  $c_i$  ( $c'_i$ ) is the amplitude-weighted cosine of the average strong-phase difference in the  $i$ th bin. When comparing the observed distribution of events throughout the bins with the predictions, there is no need to know the overall efficiency scale. However, it is important to account for relative variations in DT efficiency bin to bin as well as migration effects brought about by bin misassignments.

### III. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [23] records symmetric  $e^+e^-$  collisions provided by the BEPCII storage ring [24], which operates with a peak luminosity of  $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  in the center-of-mass energy range from 2.0 to 4.95 GeV. BESIII has collected large data samples in this energy region [25]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multi-layer 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.

Simulated samples, which are produced with the GEANT4-based [26] Monte Carlo (MC) package that includes the description of the detector geometry and response, are used to determine the detection efficiencies and estimate the backgrounds. The beam-energy spread of 0.97 MeV and the initial-state radiation (ISR) in the  $e^+e^-$  annihilations, which is modeled with the generator KKMC [27], are included in the simulation. The inclusive MC samples for background studies consist of the production of neutral and charged charm-meson pairs from  $\psi(3770)$  decays, decays of the  $\psi(3770)$  to charmonia or light hadrons, the initial-state radiation production of the  $J/\psi$  and  $\psi(3770)$  states, continuum processes, and the QED processes  $e^+e^- \rightarrow e^+e^-$ ,  $e^+e^- \rightarrow \mu^+\mu^-$ , and  $e^+e^- \rightarrow \tau^+\tau^-$ . No attempt is made to include quantum-correlation effects in  $\psi(3770) \rightarrow D\bar{D}$  decays in the inclusive MC sample. The equivalent integrated luminosity of the inclusive MC samples is about 10 times that of the data, apart from the production of  $D\bar{D}$  events, where the equivalent integrated luminosity is about 20 times that of the data. All particle decays are modeled with EVTGEN [28] using branching fractions either taken from the Particle Data Group [29], when available, or otherwise estimated with LUNDCHARM [30,31]. The final-state radiation from the charged final-state particles is incorporated with the PHOTOS package [32].

Signal MC samples of around 200,000 events are generated separately for the different tag channels. In this generation, the  $D \rightarrow \pi^+\pi^-\pi^+\pi^-$  decay follows an isobar-based amplitude model fitted to a BESIII sample of these decays, where the flavor of the decaying meson is inferred by reconstructing the other charm meson in the event through its decay into a flavor-specific final state. The model contains the main resonant structures observed in data. The simulated DT samples involving  $D \rightarrow K_{S,L}^0\pi^+\pi^-$  tags are an order of magnitude larger in size and the tag decays are implemented with an amplitude model developed by the BABAR collaboration [33]. In all the DT samples, quantum correlations are included in the generation to ensure the best possible description of the reconstruction efficiency, especially for the different bins of phase space of the  $K_{S,L}^0\pi^+\pi^-$  tag modes.

#### IV. EVENT SELECTION AND YIELD DETERMINATION

Table I lists the tag categories that are employed in the analysis:  $CP$ -even eigenstates,  $CP$ -odd eigenstates, the quasi- $CP$ -even mode  $D \rightarrow \pi^+\pi^-\pi^0$ , and the self-conjugate decays  $D \rightarrow K_{S,L}^0\pi^+\pi^-$  of mixed  $CP$  that are analyzed in bins of phase space. The final-state resonances are reconstructed in the following channels:  $K_S^0 \rightarrow \pi^+\pi^-$ ,  $\pi^0 \rightarrow \gamma\gamma$ ,  $\eta \rightarrow \gamma\gamma$  and  $\pi^+\pi^-\pi^0$ ,  $\omega \rightarrow \pi^+\pi^-\pi^0$ , and  $\eta' \rightarrow \pi^+\pi^-\eta$  and  $\gamma\pi^+\pi^-$ .

TABLE I. Summary of tag channels.

Category	Decay modes
$CP$ even	$K^+K^-$ , $K_S^0\pi^0\pi^0$ , $K_L^0\pi^0$ , $K_L^0\omega$
$CP$ odd	$K_S^0\pi^0$ , $K_S^0\eta$ , $K_S^0\eta'$ , $K_S^0\omega$ , $K_L^0\pi^0\pi^0$
Quasi- $CP$ even	$\pi^+\pi^-\pi^0$
Mixed $CP$	$K_S^0\pi^+\pi^-$ , $K_L^0\pi^+\pi^-$

DT events formed of tags involving a  $K_L^0$  are partially reconstructed using a missing-mass-squared technique. All other classes of DT events are fully reconstructed, as are ST events that do not contain a  $K_L^0$  meson.

#### A. Basic event selection

Several basic requirements are imposed to ensure the quality of charged tracks in the analysis. Those tracks from  $K_S^0$  candidates must lie within 20 cm of  $e^+e^-$  interaction point (IP) along the  $z$  axis, which is the symmetry axis of the MDC. All other tracks must have a point of closest approach to the IP within  $\pm 10$  cm along the  $z$  axis and 1 cm in the transverse plane. The polar angle  $\theta$  with respect to the axis of the drift chamber must satisfy the condition  $|\cos\theta| < 0.93$ . Charged pions and kaons are distinguished by combining the information of the flight time measured from the TOF and the  $dE/dx$  measured in the MDC. The corresponding probabilities  $P_K$  ( $P_\pi$ ) for the  $K$  ( $\pi$ ) hypothesis are calculated and the track is labeled as a  $K$  ( $\pi$ ) candidate if  $P_K > P_\pi$  ( $P_K < P_\pi$ ).

The photon candidates are reconstructed from the showers in EMC, with the energy required to be larger than 25 MeV for barrel showers ( $|\cos\theta| < 0.80$ ) and 50 MeV for end cap showers ( $0.86 < |\cos\theta| < 0.92$ ). To suppress electronic noise or activity unrelated to the events, the time of the cluster measured from the EMC is required to be within 0 and 700 ns after the event start time. Furthermore, to eliminate showers originating 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 20 degrees as measured from the IP.

The  $K_S^0$  candidates are reconstructed from pairs of tracks with opposite charge on which no particle-identification requirements are imposed. A fit is applied to constrain the track pair to a common vertex. The flight significance  $L/\sigma_L$  is required to be larger than 2, where  $L$  is the flight distance and  $\sigma_L$  is the corresponding standard deviation. In addition, the invariant mass is required to be within  $[0.487, 0.511]$  GeV/ $c^2$ .

Pairs of photons are used to reconstruct  $\pi^0(\eta)$  candidates, where the invariant mass of the pair must lie within  $[0.115, 0.150]$  ( $[0.480, 0.580]$ ) GeV/ $c^2$  and at least one photon candidate is from the barrel region. In order to improve the momentum resolution, a kinematic fit is performed, where the reconstructed  $\pi^0(\eta)$  invariant mass is constrained to the known value [29] and the fitted momentum of the

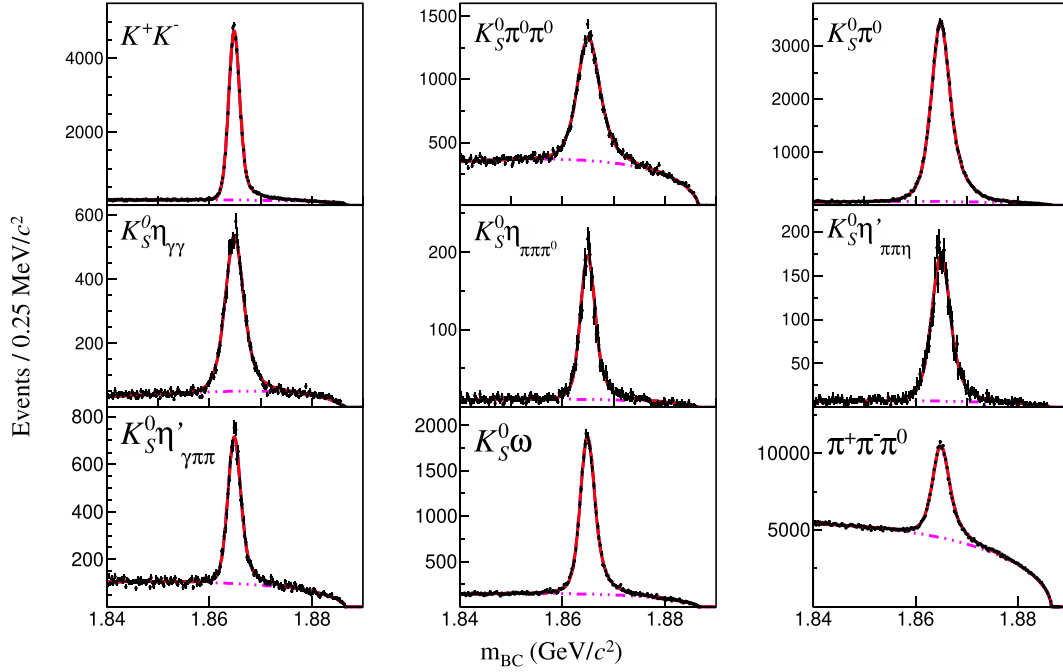


FIG. 1. Distributions of  $m_{BC}$  and fits used to determine the ST yields. In each plot the black dots with error bar are data, the total fit result is shown as the red solid line and the continuum background is shown as the pink dot-dashed line.

$\pi^0(\eta)$  is used in the subsequent stages of the analysis. When reconstructing  $\eta \rightarrow \pi^+\pi^-\pi^0$  decays, the invariant mass of the  $\eta$  candidate is required to be within  $[0.530, 0.565]$   $\text{GeV}/c^2$ . Similarly, when reconstructing  $\omega \rightarrow \pi^+\pi^-\pi^0$ ,  $\eta' \rightarrow \pi^+\pi^-\eta(\gamma\gamma)$ , and  $\eta' \rightarrow \gamma\pi^+\pi^-$ , the invariant mass is required to lie within  $[0.750, 0.820]$ ,  $[0.940, 0.976]$ , and  $[0.940, 0.970]$   $\text{GeV}/c^2$ , respectively.

## B. ST event selection and yields

ST events that do not contain a  $K_L^0$  meson are reconstructed from the charged pion, charged kaon,  $K_S^0$ , and resonance candidates. To suppress the combinatorial background, the energy difference,  $\Delta E = E_D - \sqrt{s}/2$ , is required to be within  $\pm 3\sigma_{\Delta E}$  of the  $\Delta E$  peak, where  $E_D$  is the measured energy of the  $D$ -meson candidate in the center-of-mass frame,  $\sqrt{s}$  is the center-of-mass energy, and  $\sigma_{\Delta E}$  is the resolution of the  $\Delta E$  distribution. To suppress background from cosmic and Bhabha events in the tag channel  $D \rightarrow K^+K^-$ , the two charged tracks must have a TOF time difference of less than 5 ns, and the further requirement that neither track is identified as an electron or a muon is applied. To suppress  $D \rightarrow K_S^0\pi^0$  contamination in the selection of  $D \rightarrow \pi^+\pi^-\pi^0$  decays, a  $K_S^0$  veto is applied, in which the event is rejected if the charged pion pair has a significant flight distance ( $L/\sigma_L > 2$ ) and invariant mass lying within the range  $[0.481, 0.514]$   $\text{GeV}/c^2$ . This use of flight-distance information is preferred to removing all events within the  $K_S^0$  mass window as the  $CP$ -even fraction of this mode is only known for the full phase space of the decay [8].

In order to determine the ST yields for the  $CP$  eigenstate and quasi- $CP$  eigenstate tags, the beam-constrained mass,  $m_{BC} = \sqrt{(\sqrt{s}/2)^2 - |\mathbf{p}_D|^2}$ , is used to identify the signal, where  $\mathbf{p}_D$  is the three-momentum vector of the  $D$  candidate in the center-of-mass frame. Binned maximum-likelihood fits are performed on the  $m_{BC}$  distributions, as shown in Fig. 1, where the signal is described by the shape found in the MC simulation convolved with a Gaussian function, to account for differences in resolution between the MC simulation and data, and the combinatorial background is described by an ARGUS function with an end point fixed to  $\sqrt{s}/2$  [34]. The peaking-background contributions from other charm decays are estimated from the MC simulation and then subtracted from the fitted ST yields. In the case of  $D \rightarrow K_S^0\omega$ ,  $K_S^0\eta_{\pi\pi\pi^0}$ , and  $K_S^0\eta'_{\gamma\pi\pi}$ , the peaking-background fractions are 11.5%, 9.7%, and 3.9%, respectively, and arise mainly from  $D \rightarrow K_S^0\pi^+\pi^-\pi^0$  decays. The peaking-background fraction in the  $D \rightarrow \pi^+\pi^-\pi^0$  sample is 5%, mainly from  $D \rightarrow K_S^0\pi^0$  decays. The contamination in the  $D \rightarrow K_S^0\pi^0(\pi^0)$  selection mainly comes from  $D \rightarrow \pi^+\pi^-\pi^0(\pi^0)$  decays and constitutes 0.3% (3.1%) of the sample. For the other three channels, the peaking-background are not significant. The ST yields after background subtraction,  $N_{ST}$ , are summarized in Table II, together with the  $\Delta E$  window imposed for each channel.

The difficulty of reconstructing  $K_L^0$  mesons means that it is impractical to select ST samples for the modes  $D \rightarrow K_L^0 X$  ( $X = \omega, \pi^0$ , or  $\pi^0\pi^0$ ). However, effective ST yields can be determined through the relation

TABLE II. Summary of  $\Delta E$  requirements, ST yields ( $N_{\text{ST}}$ ), and DT yields ( $N_{\text{DT}}$ ) for each tag mode, grouped by tag category. The uncertainties are statistical. The entry “/” indicates that the information is not defined ( $\Delta E$  for  $K_L^0 X$  modes) or not required for the analysis (ST yields for  $K_{S,L}^0 \pi^+ \pi^-$ ).

Mode	$\Delta E$ (GeV)	$N_{\text{ST}}$	$N_{\text{DT}}$
$K^+ K^-$	[-0.021, 0.020]	$56668 \pm 262$	$115.4 \pm 14.4$
$K_S^0 \pi^0 \pi^0$	[-0.072, 0.053]	$73176 \pm 299$	$36.4 \pm 10.3$
$K_L^0 \pi^0$	/	$79689 \pm 5631$	$130.9 \pm 18.8$
$K_L^0 \omega$	/	$29128 \pm 1962$	$61.5 \pm 13.8$
$K_S^0 \pi^0$	[-0.071, 0.051]	$73176 \pm 299$	$326.0 \pm 19.2$
$K_S^0 \eta \gamma \gamma$	[-0.038, 0.036]	$10071 \pm 123$	$57.7 \pm 7.7$
$K_S^0 \eta_{\pi\pi\pi^0}$	[-0.035, 0.028]	$2775 \pm 65$	$16.5 \pm 4.2$
$K_S^0 \eta'_{\pi\pi\eta}$	[-0.035, 0.031]	$3449 \pm 67$	$11.6 \pm 3.5$
$K_S^0 \eta'_{\gamma\pi\pi}$	[-0.031, 0.025]	$8691 \pm 126$	$41.1 \pm 7.5$
$K_S^0 \omega$	[-0.042, 0.033]	$26220 \pm 215$	$128.7 \pm 13.8$
$K_L^0 \pi^0 \pi^0$	/	$25772 \pm 2184$	$178.5 \pm 23.9$
$\pi^+ \pi^- \pi^0$	[-0.062, 0.051]	$115556 \pm 682$	$190.7 \pm 24.6$
$K_S^0 \pi^+ \pi^-$	[-0.026, 0.023]	/	$539.7 \pm 26.0$
$K_L^0 \pi^+ \pi^-$	/	/	$1374.6 \pm 50.4$

$$N_{\text{ST}}(K_L^0 X) = 2N_{D\bar{D}} \mathcal{B}(K_L^0 X) \epsilon'_{\text{ST}}(K_L^0 X), \quad (8)$$

where  $N_{\text{ST}}(K_L^0 X)$  is the effective ST yield for mode  $D \rightarrow K_L^0 X$ ,  $N_{D\bar{D}} = (10597 \pm 28 \pm 98) \times 10^3$  is the number of neutral charm-meson pairs in the sample [35] and  $\mathcal{B}(K_L^0 X)$  is the branching fraction of the  $D \rightarrow K_L^0 X$  mode [36]. The effective efficiency  $\epsilon'_{\text{ST}}(K_L^0 X)$  is defined as the ratio of the efficiency for reconstructing  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  versus  $D \rightarrow K_L^0 X$  DT events with the partial-reconstruction technique, as discussed below, and the reconstruction efficiency for  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ . The effective ST yields are included in Table II.

### C. DT event selection and yields

DT samples are selected for all tags not involving a  $K_L^0$  by attempting to reconstruct the  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  signal decay from the remaining tracks in the ST samples. Only events with four extra charged tracks are considered. All four charged tracks must be identified as pions and their net charge is required to be zero. A tight  $K_S^0$  veto is applied to suppress background from  $D \rightarrow K_S^0 \pi^+ \pi^-$  decays: if the invariant mass of any of the  $\pi^+ \pi^-$  pairs lies within [0.481, 0.514] GeV/ $c^2$ , then the event is rejected. As this requirement removes a specific region of phase space, rejecting around 13% of the signal, it has the potential to bias the  $CP$ -even fraction of the sample. This effect is considered in the assignment of systematic uncertainties. The energy difference  $\Delta E$  of the signal decay is required to lie within [-26, 23] MeV.

For each fully reconstructed DT channel, the DT yield is determined by an unbinned maximum-likelihood fit to the  $m_{\text{BC}}$  distribution of the signal  $D$  candidate. The  $m_{\text{BC}}$  distributions and the fits for the  $CP$ -eigenstate and quasi- $CP$ -eigenstate tags are presented in Fig. 2. In these fits, the signal is described by the MC-simulated shape convolved with a Gaussian function, and the combinatorial background is described by an ARGUS function. The fitted signal yield includes contamination from peaking-background contributions. The most significant source of peaking background is the residual contamination from  $D \rightarrow K_S^0 \pi^+ \pi^-$  decays in the selection of the signal channel. The size of this background is determined from data by performing fits to the invariant-mass distribution of  $\pi^+ \pi^-$  pairs associated with the signal candidate without any  $K_S^0$  veto in place. The results are then scaled by the suppression factor of the veto on the background mode, as determined from the MC simulation. This background is found to vary from 2% to 5%, depending on the tag mode. The size of the other peaking backgrounds, such as  $D \rightarrow K_S^0 \pi^0$  in the  $D \rightarrow \pi^+ \pi^- \pi^0$  tag, are estimated from MC simulation. Where necessary, corrections are applied to account for the quantum-correlated enhancements or suppressions that are not simulated in the inclusive simulation, according to the  $CP$  content of the background. The DT yields after background subtraction are summarized in Table II.

DT channels involving a  $D \rightarrow K_L^0 X$  tag mode cannot be fully reconstructed. Nonetheless, a partial reconstruction is performed, accounting for all other charged and neutral particles in the event, and the yield is determined using a missing-mass-squared technique. In this procedure the  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  candidate is first reconstructed with the same criteria as used previously, and then the standard selections are imposed to select the remaining charged and neutral tracks in the event. Candidates for the tag modes  $D \rightarrow K_L^0 \pi^0$ ,  $D \rightarrow K_L^0 \pi^0 \pi^0$ ,  $D \rightarrow K_L^0 \omega$ , and  $D \rightarrow K_L^0 \pi^+ \pi^-$  are selected from the charged tracks and  $\pi^0$  candidates in the event. Any events with surplus charged tracks, surplus  $\pi^0$  candidates, or an  $\eta \rightarrow \gamma \gamma$  candidate are rejected. In the case of  $D \rightarrow K_L^0 \omega$ , events containing more than one  $\omega$  candidate are discarded.

The signal yields in the partially reconstructed DTs are determined by performing unbinned maximum-likelihood fits to the squared missing-mass  $M_{\text{miss}}^2 = (\sqrt{s}/2 - E_X)^2 - |\mathbf{p}_X + \hat{\mathbf{p}}_{4\pi} \sqrt{s/4 - M_D^2}|^2$ , which is calculated in the center-of-mass frame. Here  $E_X$  and  $\mathbf{p}_X$  are the energy and three-momentum, respectively, of the reconstructed particles in the event not associated with the signal candidate,  $\hat{\mathbf{p}}_{4\pi}$  is the direction of the signal candidate, and  $M_D$  is the known  $D^0$  mass [29]. The  $M_{\text{miss}}^2$  distributions and fits for the  $CP$  eigenstate tags are included in Fig. 2. The resulting signal yields can be found in Table II. In these fits, the signal distribution is described by the shape found in the MC simulation convolved with a Gaussian function whose



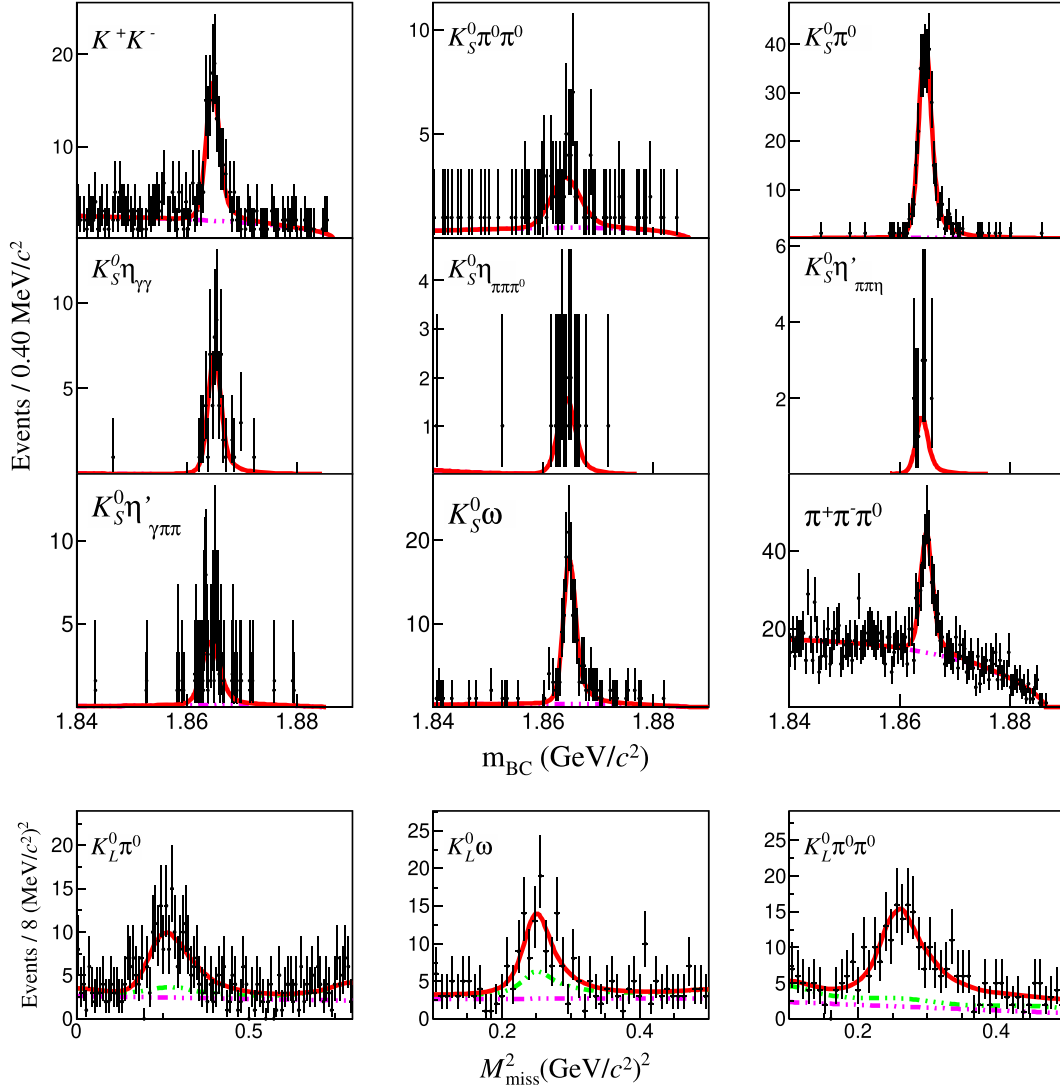


FIG. 2. Distributions and fits used to determine the DT yields. These distributions are of  $m_{BC}$  in the fully reconstructed case, and of  $M_{\text{miss}}^2$  for the partially reconstructed case involving  $K_L^0$  mesons. In each plot the black dots with the error bar are data, the total fit result is shown as the red solid line, the continuum background is shown as the pink dot-dashed line, and sum of the continuum and the peaking background for the  $K_L^0 X$  DTs is shown as the green dashed line.

width is a free parameter. Fixed contributions from MC simulation are included for peaking backgrounds, and the continuum background is modeled with a first-order Chebychev polynomial, whose parameters are determined in the fit. Peaking backgrounds arise mainly from  $D \rightarrow K_S^0 \pi^+ \pi^-$  decays that are misreconstructed as  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ , or decays involving an unreconstructed  $K_S^0$  meson that contaminate the tag candidates. These backgrounds constitute 28%, 16%, and 7% of the  $D \rightarrow K_L^0 \omega$ ,  $K_L^0 \pi^0$ , and  $K_L^0 \pi^0 \pi^0$  samples, respectively.

## V. $CP$ -EVEN FRACTION MEASUREMENT

The  $CP$ -even fraction is determined using the ST and DT yields of the  $CP$ -eigenstate and quasi- $CP$ -eigenstate tags,

and the distribution of decays in tag phase space of the  $D \rightarrow K_{S,L}^0 \pi^+ \pi^-$  DT events. The analysis follows the procedure outlined in Sec. II.

### A. $CP$ -eigenstate tags

The  $N^+$  and  $N^-$  parameters are determined for each tag channel, and systematic uncertainties are assigned as discussed in Sec. VD. The results are displayed in Fig. 3. A least-squares fit, which takes account of the correlations between the systematic uncertainties, returns

$$\langle N^+ \rangle = (4.73 \pm 0.20 \pm 0.09) \times 10^{-3},$$

$$\langle N^- \rangle = (1.83 \pm 0.16 \pm 0.04) \times 10^{-3},$$

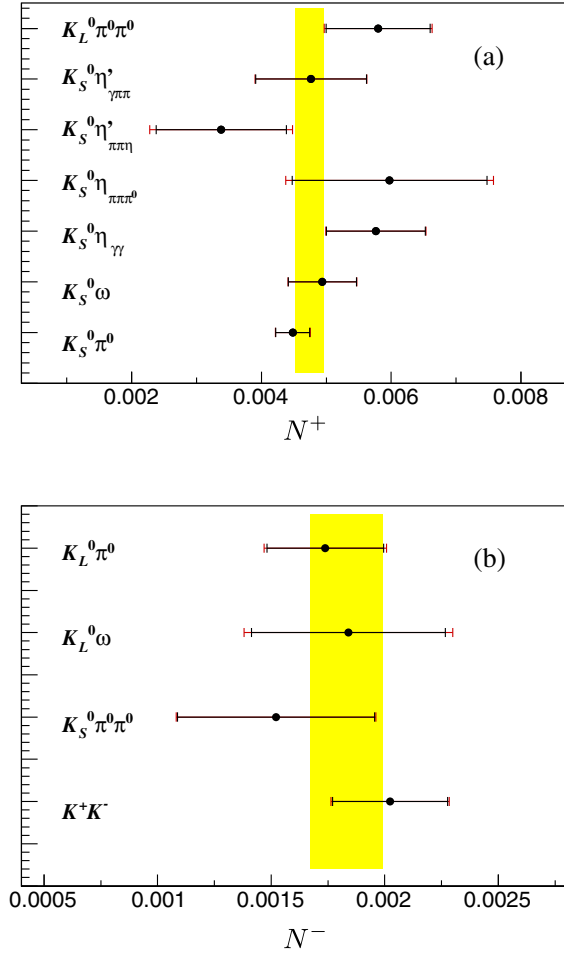


FIG. 3. The results for  $N^+$  (a) and  $N^-$  (b). The wide red error bars show the total uncertainties, and the inner black error bars the statistical uncertainties. The yellow bands correspond to the one- $\sigma$  regions around the mean values.

where, here and for all subsequent results, the first uncertainty is statistical and the second is systematic. The  $\chi^2$  per number of degrees of freedom for the  $N_+$  and  $N_-$  fits are 6.68/6 and 1.21/3, respectively. It follows from Eq. (3) that

$$F_+^{4\pi} = 0.721 \pm 0.019 \pm 0.007,$$

indicating that the decay  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  is predominantly  $CP$  even.

### B. $D \rightarrow \pi^+ \pi^- \pi^0$ tag

A second determination of  $F_+^{4\pi}$  is made using the quasi- $CP$ -even eigenstate  $D \rightarrow \pi^+ \pi^- \pi^0$ . From the ST and DT yields it follows that

$$N^{\pi\pi\pi^0} = (1.64 \pm 0.21 \pm 0.06) \times 10^{-3},$$

which, as expected, lies very close to the result for  $\langle N^- \rangle$ . Using Eq. (6) and the measured value of  $F_+^{\pi\pi\pi^0}$  [8] it is found that

$$F_+^{4\pi} = 0.753 \pm 0.028 \pm 0.010,$$

together with a correlation coefficient of 0.15 with the measurement performed with the  $CP$ -eigenstate tags, mainly arising from the common use of  $\langle N^+ \rangle$  in the two determinations.

### C. $D \rightarrow K_{S,L}^0 \pi^+ \pi^-$ tags

The DT events tagged with  $D \rightarrow K_{S,L}^0 \pi^+ \pi^-$  decays are analyzed in phase-space bins of the tag channel. The Dalitz plots of these decays have axes corresponding to the squared invariant masses  $m_-^2 = m(K_{S,L}^0 \pi^-)^2$  and  $m_+^2 = m(K_{S,L}^0 \pi^+)^2$ . Eight pairs of bins are defined symmetrically about the line  $m_-^2 = m_+^2$  with a positive bin number in the region  $m_+^2 > m_-^2$  and a negative one on the other side of the line of equality. Bin boundaries have been defined according to the “equal  $\Delta\delta_D$  scheme” of Ref. [22], such that the strong-phase difference between symmetric points in the Dalitz plot spans an equal range in each bin, according to the expectations of an amplitude model [37]. For  $D \rightarrow K_S^0 \pi^+ \pi^-$ , both the CLEO and BESIII collaborations have made measurements of  $c_i$ , the cosine of the average strong-phase difference weighted by the  $D^0$  decay amplitude in each bin, and  $c'_i$ , the analogous quantity for  $D \rightarrow K_L^0 \pi^+ \pi^-$  decays [15,16,22]. The current analysis uses the averaged BESIII and CLEO results for  $c_i$  and  $c'_i$ , together with the BESIII results for  $K_i$  and  $K'_i$ , which are the probabilities of the  $D^0$  decay occurring in bin  $i$ . All of these inputs are reported in Ref. [16].

As is clear from Eq. (7), the expected yields  $M_i^{(\prime)}$  are symmetric under the exchange  $i \leftrightarrow -i$  and so the yields in these pairs of bins are aggregated in the analysis, giving eight effective bins, labeled 1 through to 8, for each tag mode. The DT yields are determined from independent fits to the events in each effective bin following the procedure already described in Sec. IV. In some regions, the sample sizes are low and it is necessary to fix the parameters of the convolving Gaussian function to those determined from a fit to the whole of phase space. The fitted yields include contamination from peaking background, which is estimated from MC simulation to be at the level of 2.3% and 9.5% for  $D \rightarrow K_S^0 \pi^+ \pi^-$  and  $D \rightarrow K_L^0 \pi^+ \pi^-$ , respectively.

To improve the resolution of the location of the decay in the Dalitz plot, and thereby ensure the most reliable assignment of the phase-space bin, the tag decay is refitted with the  $D$  mass constrained to the known mass of the  $D^0$  meson [29]. Even with this constraint in place, there are occasional bin misassignments. These misassignments, and the variations in relative efficiency between bins, are accounted for by an  $8 \times 8$  efficiency matrix  $\epsilon_{ij}$ , which is determined from the MC simulation:

$$\epsilon_{ij} = \frac{N_{ij}^{\text{rec}}}{N_i^{\text{gen}}}, \quad (9)$$

where  $N_{ij}^{\text{rec}}$  is the number of signal MC events generated in the  $i$ th bin and reconstructed in the  $j$ th bin, and  $N_i^{\text{gen}}$  is the number of the signal MC events generated in the  $i$ th bin. The probability of misassignment varies from 5% to 20% depending on the bin and tag channel. The relative variation in efficiency between bins is within 20%. Separate efficiency matrices  $\epsilon_{ij}^{K_S^0\pi\pi}$  and  $\epsilon_{ij}^{K_L^0\pi\pi}$  are determined for each tag mode. The full efficiency matrices can be found in the Appendix.

The efficiency matrices are used to adjust the idealized expressions of Eq. (7), giving expected DT signal yields in bin  $i$  of

$$\begin{aligned}
 M_i(4\pi, K_S^0\pi^+\pi^-) &= H \sum_j^8 \epsilon_{ij}^{K_S^0\pi\pi} [K_j + K_{-j} \\
 &\quad - 2\sqrt{K_j K_{-j}} c_j (2F_+^{4\pi} - 1)], \\
 M_i'(4\pi, K_L^0\pi^+\pi^-) &= H' \sum_j^8 \epsilon_{ij}^{K_L^0\pi\pi} [K'_j + K'_{-j} \\
 &\quad + 2\sqrt{K'_j K'_{-j}} c'_j (2F_+^{4\pi} - 1)]. \quad (10)
 \end{aligned}$$

The  $CP$ -even fraction is then determined by minimizing the negative log-likelihood

$$\begin{aligned}
 -2 \log \mathcal{L} &= -2 \log G(M_i^{\text{obs}}; M_i^{\text{exp}}, \sigma_{M_i}) \\
 &\quad - 2 \log G(M_i'^{\text{obs}}; M_i'^{\text{exp}}, \sigma_{M_i'}), \quad (11)
 \end{aligned}$$

where  $G$  is a Gaussian function,  $M_i^{(r)\text{obs}}$  and  $M_i^{(r)\text{exp}}$  are the observed and predicted DT yields in bin  $i$ , respectively (here including peaking background contributions), and  $\sigma_{M_i^{(r)}}$  is the uncertainty on  $M_i^{(r)\text{obs}}$ . This fit yields

$$F_+^{4\pi} = 0.754 \pm 0.031 \pm 0.009.$$

Separate fits to the  $D \rightarrow K_S^0\pi^+\pi^-$  and  $D \rightarrow K_L^0\pi^+\pi^-$  samples give the results  $0.813 \pm 0.045$  and  $0.712 \pm 0.038$ , respectively, with purely statistical uncertainties. These fits are shown in Fig. 4.

#### D. Assignment of systematic uncertainties

There are several sources of potential systematic bias on the three determinations of  $F_+^{4\pi}$ , some of which are correlated between two or all of the measurements. The assigned uncertainties are summarized in Table III and are discussed below.

There are systematic uncertainties on  $N_{\text{ST}}$  and  $N_{\text{DT}}$  for each tag mode that lead to corresponding uncertainties in the values of  $\langle N^+ \rangle$ ,  $\langle N^- \rangle$ , and  $N^{\pi\pi\pi^0}$ . There are various components contributing to these uncertainties. To assess any bias associated with the fit procedure, alternative fits

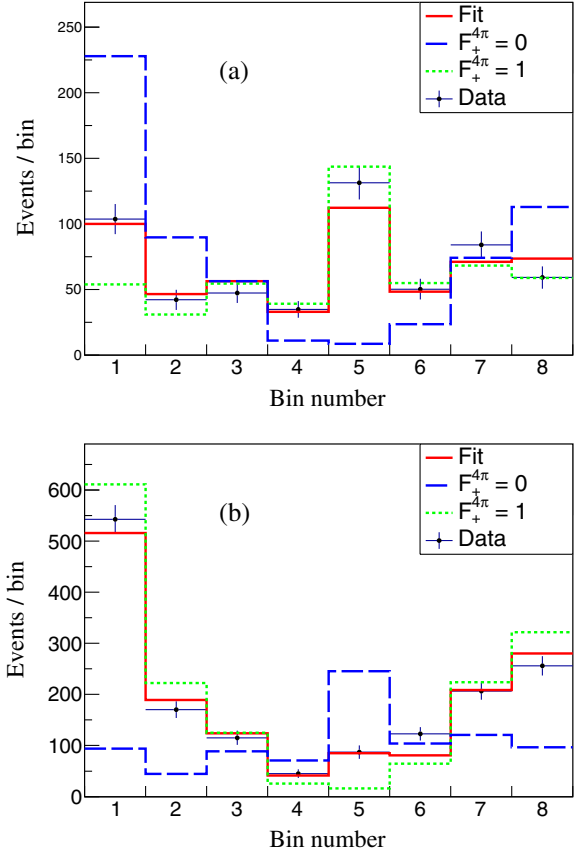


FIG. 4. Fit results for  $D \rightarrow K_S^0\pi^+\pi^-$  (a) and  $D \rightarrow K_L^0\pi^+\pi^-$  (b) channels. Also shown are the expected distributions in the limiting cases  $F_+^{4\pi} = 0$  and  $F_+^{4\pi} = 1$ .

are performed to the  $m_{\text{BC}}$  distributions for the ST samples and fully reconstructed DT samples, with variations of  $\pm 0.5$  MeV applied to the end point of the ARGUS function. The contributions of the peaking backgrounds in all samples are varied according to the uncertainties of their branching fractions [29]. The variation in results is taken as the uncertainty associated with these sources. The

TABLE III. Summary of systematic contributions for the  $F_+^{4\pi}$  measurement performed with  $CP$ -eigenstate,  $D \rightarrow \pi^+\pi^-\pi^0$ , and  $D \rightarrow K_{S,L}^0\pi^+\pi^-$  tags. The entry “/” indicates that there is no possible bias from the listed source.

Source	$CP$	$\pi^+\pi^-\pi^0$	$K_{S,L}^0\pi^+\pi^-$
ST and DT yields	0.005	0.003	/
Efficiency factorization	0.003	0.006	/
$F_+^{\pi\pi\pi^0}$	/	0.007	/
$K_i^{(r)}$	/	/	0.005
$c_i^{(r)}$	/	/	0.004
Bin misassignment	/	/	0.003
$K_{S,L}^0\pi^+\pi^-$ backgrounds	/	/	0.003
$K_S^0$ veto	0.003	0.003	0.003
Total	0.007	0.010	0.009

effective ST yields for the  $D \rightarrow K_L^0 X$  tags have a small uncertainty associated with the total size of the charm-meson sample [35]. The uncertainties arising from the knowledge of the  $D \rightarrow K_L^0 X$  branching fractions are also small, as those contributions to these uncertainties associated with the reconstruction efficiencies [36] are common to the  $\epsilon_{\text{ST}}(K_L^0 X)$  efficiencies in Eq. (8), and so cancel in the measurement of the effective ST yields. The determinations of  $N^{\text{ST}}$  and  $N^{\text{DT}}$  are the dominant source of systematic uncertainty for the  $CP$ -eigenstate tags. The common use of  $\langle N^- \rangle$  means that this uncertainty is correlated between the  $CP$ -eigenstate measurement and that made with  $D \rightarrow \pi^+ \pi^- \pi^0$  tags.

The measurements performed with the  $CP$ -eigenstate and the  $D \rightarrow \pi^+ \pi^- \pi^0$  tags assume that the DT-event efficiency can be factorized into the reconstruction efficiencies of the two decay modes in a universal manner for all tags. Studies with MC simulations show that this is not exactly true, and so small correction factors obtained from the simulation are applied to each class of DT in the measurement. Shifts of  $0.06 \times 10^{-3}$  and  $0.01 \times 10^{-3}$  are observed in the values of  $\langle N^+ \rangle$  and  $\langle N^- \rangle$ , respectively, and of  $0.05 \times 10^{-3}$  for  $N^{\pi\pi\pi^0}$ , which are assigned as systematic uncertainties that when propagated to  $F_+^{4\pi}$  give the uncertainties listed in Table III.

The quasi- $CP$ -eigenstate measurement carries an uncertainty from the imperfect knowledge of the  $CP$ -even fraction of  $D \rightarrow \pi^+ \pi^- \pi^0$  [8]. This is the dominant systematic uncertainty for the determination of  $F_+^{4\pi}$  using this tag channel.

The measurement performed with  $D \rightarrow K_{S,L}^0 \pi^+ \pi^-$  tags has uncertainties associated with the knowledge of the external parameters  $K_i^{(j)}$  and  $c_i^{(j)}$ . To evaluate the size of these contributions, the measurement is reperformed 1000 times for each set of inputs with the values of the parameters smeared in a manner that corresponds to the covariance matrices reported in Ref. [16]. The spread on the resulting distribution for  $F_+^{4\pi}$  over the ensemble of measurements is assigned as the uncertainty of the result from these sources. The efficiency matrix, used to describe bin misassignment and relative bin-to-bin efficiencies, has uncertainties arising from the finite size of the MC sample from which its elements are determined. The effect of these uncertainties, which are most important for bin misassignments, are determined by reperforming the fit 1000 times with smeared inputs. The branching fractions of the peaking backgrounds in these samples are varied within their measured uncertainties to determine the size of the potential bias from this source [29].

A final uncertainty is assigned, common to all three measurements, to account for the possibility that the  $K_S^0$  veto in the DT selection leads to a sample with a different  $CP$ -even fraction to that of the unbiased decay. The size of the effect is estimated to be  $3 \times 10^{-3}$  and is determined

TABLE IV. Summary of  $F_+^{4\pi}$  results from the different tag channels and the combination of these results, where the first uncertainty is statistical and the second is systematic.

Tag modes	$F_+^{4\pi}$
$CP$ eigenstates	$0.721 \pm 0.019 \pm 0.007$
$D \rightarrow \pi^+ \pi^- \pi^0$	$0.753 \pm 0.028 \pm 0.010$
$D \rightarrow K_{S,L}^0 \pi^+ \pi^-$	$0.754 \pm 0.031 \pm 0.009$
Combination	$0.735 \pm 0.015 \pm 0.005$

from the amplitude model by computing  $F_+^{4\pi}$  with and without the relevant region of phase space included.

### E. Combination of results

The results of the three separate measurements of  $F_+^{4\pi}$  are summarized in Table IV. It can be seen that these results are consistent with each other. A combination is made of these measurements, taking account of the correlation coefficient of 0.15 between the  $CP$ -eigenstate and  $D \rightarrow \pi^+ \pi^- \pi^0$  tags, that yields the result presented in Table IV. This result is consistent with the CLEO-c result of  $0.737 \pm 0.028$  from a measurement that employs a similar analysis strategy and is around twice as precise [8]. It is also compatible with a CLEO-c determination that is based on localized measurements in phase space and has around a 30% smaller uncertainty [9].

## VI. SUMMARY

In summary, a measurement has been made of  $F_+^{4\pi}$ , the  $CP$ -even fraction of the decay  $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ , using  $2.93 \text{ fb}^{-1}$  of  $e^+ e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$  data collected by the BESIII experiment. The measurement is the combination of three separate, but consistent, determinations of this parameter made with  $CP$ -eigenstate tags, the quasi- $CP$ -eigenstate tag  $D \rightarrow \pi^+ \pi^- \pi^0$  and a study of the distributions in phase space of  $D \rightarrow K_{S,L}^0 \pi^+ \pi^-$  tags. The  $CP$ -even fraction is determined to be

$$F_+^{4\pi} = 0.735 \pm 0.015 \pm 0.005,$$

where the first uncertainty is statistical and the second is systematic. This result is compatible with previous measurements [8,9], but has a higher precision, and provides valuable input to measurements of the CKM angle  $\gamma$  and charm-mixing studies performed at LHCb and Belle II.

The dataset can be further exploited to study the  $CP$  content and related parameters in localized regions of phase space, as was demonstrated in Ref. [9]. Such measurements, and improved determinations of  $F_+^{4\pi}$ , will be particularly interesting with the substantially larger samples that will be collected at BESIII over the coming years [25].

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## APPENDIX: EFFICIENCY MATRICES

The efficiency matrices for  $\pi^+\pi^-\pi^+\pi^-$  vs  $K_{S,L}^0\pi^+\pi^-$  giving the efficiency in each bin and migration probabilities between bins are shown in Table V.

TABLE V. Efficiency matrix  $\epsilon_{ij}$  (%) for  $\pi^+\pi^-\pi^+\pi^-$  vs  $K_{S,L}^0\pi^+\pi^-$ . The column gives the true bin  $i$ , while the row gives the reconstructed bin  $j$ .

Bins	1	2	3	4	5	6	7	8
$\epsilon_{ij}$ for $\pi^+\pi^-\pi^+\pi^-$ vs $K_{S,L}^0\pi^+\pi^-$								
1	0.2928	0.0103	0.0014	0.0005	0.0012	0.0009	0.0013	0.0139
2	0.0219	0.2965	0.0121	0.0003	0.0012	0.0006	0.0015	0.0026
3	0.0029	0.0089	0.3424	0.0062	0.0023	0.0010	0.0008	0.0009
4	0.0015	0.0005	0.0110	0.3394	0.0080	0.0015	0.0008	0.0011
5	0.0020	0.0004	0.0011	0.0035	0.3070	0.0074	0.0010	0.0013
6	0.0023	0.0005	0.0013	0.0008	0.0156	0.2810	0.0176	0.0020
7	0.0028	0.0010	0.0009	0.0006	0.0016	0.0134	0.2698	0.0186
8	0.0252	0.0019	0.0010	0.0004	0.0010	0.0012	0.0188	0.2701
$\epsilon_{ij}$ for $\pi^+\pi^-\pi^+\pi^-$ vs $K_L^0\pi^+\pi^-$								
1	0.4216	0.0167	0.0010	0.0002	0.0005	0.0008	0.0028	0.0276
2	0.0399	0.4139	0.0150	0.0005	0.0008	0.0012	0.0024	0.0046
3	0.0026	0.0177	0.4366	0.0073	0.0018	0.0009	0.0030	0.0023
4	0.0015	0.0026	0.0196	0.4497	0.0107	0.0026	0.0030	0.0007
5	0.0002	0.0003	0.0009	0.0060	0.4164	0.0150	0.0016	0.0009
6	0.0039	0.0015	0.0011	0.0013	0.0174	0.3653	0.0371	0.0045
7	0.0071	0.0016	0.0006	0.0004	0.0010	0.0164	0.3753	0.0415
8	0.0476	0.0039	0.0006	0.0001	0.0005	0.0013	0.0364	0.3683

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