

Search for the radiative decays $D^0 \rightarrow \gamma \bar{K}_1(1270)^0$ and $D^+ \rightarrow \gamma K_1(1270)^+$

M. Ablikim *et al.*^{*}
(BESIII Collaboration)



(Received 25 March 2026; accepted 22 June 2026; published 29 July 2026)

A search for the radiative decays $D^0 \rightarrow \gamma \bar{K}_1(1270)^0$ and $D^+ \rightarrow \gamma K_1(1270)^+$ is conducted using 20.3 fb⁻¹ of e^+e^- annihilation data collected at the center-of-mass energy $\sqrt{s} = 3.773$ GeV by the BESIII detector operating at the BEPCII collider. No significant signals are observed, and upper limits on the branching fractions of $D^0 \rightarrow \gamma \bar{K}_1(1270)^0$ and $D^+ \rightarrow \gamma K_1(1270)^+$ at 90% confidence level are determined to be 7.8×10^{-4} and 3.9×10^{-5} , respectively. This represents the first test of the vector meson dominance mechanism in the radiative decays of charmed mesons to axial-vector mesons.

DOI: [10.1103/kpxy-tj1t](https://doi.org/10.1103/kpxy-tj1t)

I. INTRODUCTION

In the Standard Model (SM), short-distance contributions in weak radiative decays of charmed hadrons are expected to be negligible compared to long-range processes. Long-range processes or potential contributions from new physics (NP) could enhance the branching fractions (BFs) of these decays by 2 to 3 orders of magnitude relative to short-range interactions [1,2]. Examples of short-distance and long-distance vector meson dominance (VMD) processes for the decays $D^0 \rightarrow \gamma \bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$, are shown in Fig. 1. Throughout this paper, $\bar{K}_1^0$ and $\bar{K}_1^+$ denote the $\bar{K}_1(1270)^0$ and $K_1(1270)^+$ mesons, respectively. The BFs of the decays $D_s^+ \rightarrow \gamma \rho^+$, $D^+ \rightarrow \gamma \rho^+$, $D^+ \rightarrow \gamma K^{*+}$, $D^0 \rightarrow \gamma \bar{K}^{*0}$, $D^0 \rightarrow \gamma \rho^0$, $D^0 \rightarrow \gamma \omega$, and $D^0 \rightarrow \gamma \phi$ have been measured by the BESIII [3,4], Belle [5,6], BABAR [7], CLEO [8] collaborations. The BF for the $D^+ \rightarrow \gamma K_1^+$ decay mode is predicted to be $[(1.3 \pm 0.3), (1.5 \pm 0.4)] \times 10^{-5}$ [9]. There is no specific BF predicted for the D^0 channel, while its BF is constrained to be $\mathcal{O}(10^{-6}) - \mathcal{O}(10^{-4})$ [11].

Moreover, unlike these $D \rightarrow \gamma V$ decay modes, where V is vector meson, $D \rightarrow \gamma K_1$ decays can be explored via angular distribution and triple-product analyses, in which the SM contributions are strongly suppressed or have a cleaner theoretical description. This provides sensitivity for photon polarization measurements, making these processes unique and promising candidates for NP exploration [9,10].

In this paper, we report the first search for the radiative decays $D^0 \rightarrow \gamma \bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ through the analysis of e^+e^- annihilation data at the center-of-mass (c.m.) energy of 3.773 GeV with the BESIII detector corresponding to an integrated luminosity of 20.3 fb⁻¹ [11]. Charge conjugation is implied throughout this paper.

II. DATA AND MONTE CARLO

The BESIII detector [12] records symmetric e^+e^- collisions provided by the BEPCII storage ring [13] in the c.m. energy range from 1.84 to 4.95 GeV, with a peak luminosity of 1.1×10^{33} cm⁻² s⁻¹ achieved at $\sqrt{s} = 3.773$ GeV. BESIII has collected data samples corresponding to an integrated luminosity of 20.3 fb⁻¹ at the $\psi(3770)$ resonance [14–16]. 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), all enclosed within a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with muon identification modules based on resistive plate counters interleaved with steel material. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the specific energy loss (dE/dx) resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with resolutions of 2.5% and 5% at 1 GeV in the barrel and end cap regions, respectively. Before the upgrade, the TOF end cap region exhibited a time resolution of 110 ps in 2015, while the barrel region remained at 68 ps. Then, the end cap TOF system was upgraded using multigap resistive plate chamber technology, providing a time resolution of 60 ps, which benefits 85% of the data used in this analysis [17–19].

^{*}Full author list given at the end of the article.

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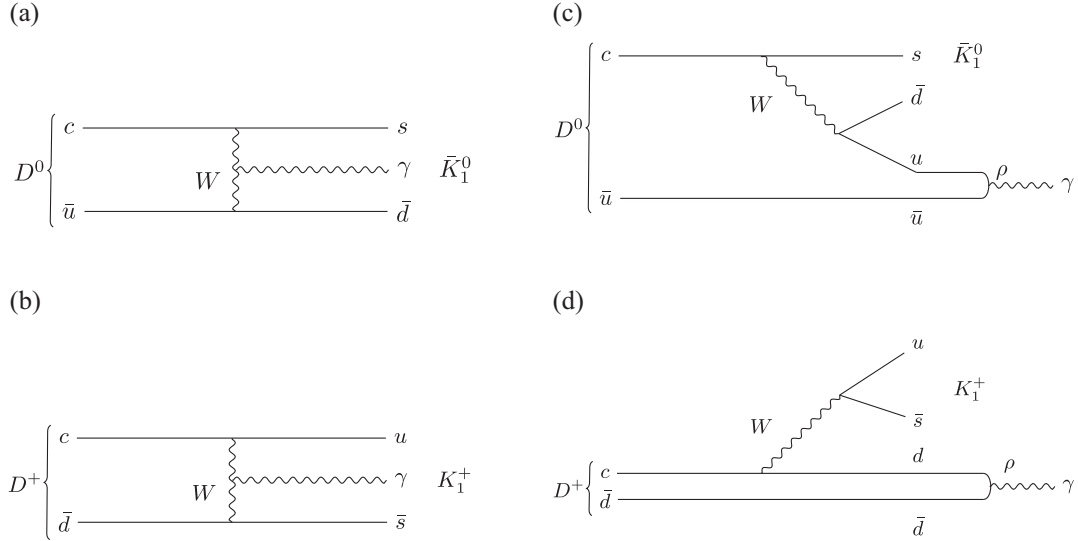


FIG. 1. Feynman diagrams for $D^0 \rightarrow \gamma \bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ decays, which are mediated via (a)(b) short-distance processes and (c)(d) long-distance VMD processes.

Monte Carlo (MC) simulated data samples have been produced with a GEANT4-based [20] software package. It includes the geometric description of the BESIII detector and the detector response, and is used to determine the detection efficiencies and estimate backgrounds. The simulation models include the beam energy (E_{beam}) spread and initial-state radiation in the e^+e^- annihilations with the generator KKMC [21,22]. The inclusive MC samples consist of the production of $D\bar{D}$ pairs, the non- $D\bar{D}$ decays of the $\psi(3770)$, the initial-state radiation production of the J/ψ and $\psi(3686)$ states and the continuum processes. All particle decays are modeled with EVTGEN [23,24] using the BFs taken from the Particle Data Group (PDG) [25], when available, or otherwise estimated with LUNDCHARM [26]. Final state radiation from charged final state particles is incorporated using PHOTOS [27].

For the signal MC samples, we generated three million events for each of the decay channels shown in Table I. The relative fractions of all intermediate decay processes are set according to the BFs listed by the PDG [25]. The radiative decays $D \rightarrow \gamma K_1$ are simulated using the HELAMP algorithm of EVTGEN [28] to ensure the conservation of angular

momentum. The K_1 decays are simulated with the VSS_PWAVE model [28].

III. METHOD

At $\sqrt{s} = 3.773$ GeV, D^+D^- or $D^0\bar{D}^0$ pairs are produced without additional accompanying hadrons, thereby offering a clean environment to investigate hadronic decays of the D meson with a tag technique [29–31]. There are two types of samples selected with the tag technique: single-tag (ST) and double-tag (DT) methods. The ST method is employed to select a data sample with one $\bar{D}$ meson reconstructed. For the $D^- (\bar{D}^0)$ meson, the hadronic final states reconstructed are $K^+\pi^-\pi^-$, $K_S^0\pi^-$, $K^+\pi^-\pi^-\pi^0$, and $K^+K^-\pi^-$ ($K^+\pi^-$, $K^+\pi^-\pi^0$, and $K^+\pi^+\pi^-\pi^-$). The DT method is utilized to constrain the process on the opposite side to search for the signal decays, $D^+ \rightarrow \gamma K_1^+$ and $D^0 \rightarrow \gamma \bar{K}_1^0$. The BF of a signal decay is determined by

$$\mathcal{B}_{\text{sig}} = N_{\text{DT}} / (N_{\text{ST}}^{\text{tot}} \cdot \epsilon_{\text{sig}} \cdot \mathcal{B}_{\text{sub}}), \quad (1)$$

where $N_{\text{ST}}^{\text{tot}} = \sum_i N_{\text{ST}}^i$ and N_{DT} are the total yields of the ST and DT candidates in data, respectively. The $\mathcal{B}_{\text{sub}}$ is defined as the sum of the products of BFs for all intermediate decay chains from the K_1 to the final state

$$\mathcal{B}_{\text{sub}} = \sum_{\text{all chains}} \prod_i \mathcal{B}_i, \quad (2)$$

where $\mathcal{B}_i$ denotes the BF of ρ^+ , K^{*-} and $\bar{K}^{*0}$ intermediate decay for D^0 channel, ρ^0 and K^{*-} intermediate decay for D^+ channel. In addition, the BF of $\pi^0 \rightarrow \gamma\gamma$ is also incorporated into the above calculation for D^0 channel. The summation includes all K_1 decay modes listed in

TABLE I. The signal decays and their subsequent decays.

Decay	subdecay	subdecay
$D^0 \rightarrow \gamma \bar{K}_1^0$	$\bar{K}_1^0 \rightarrow \rho^+ K^-$	$\rho^+ \rightarrow \pi^+ \pi^0$
	$\bar{K}_1^0 \rightarrow K^{*-} \pi^+$	$K^{*-} \rightarrow K^- \pi^0$
	$\bar{K}_1^0 \rightarrow \bar{K}^{*0} \pi^0$	$\bar{K}^{*0} \rightarrow K^- \pi^+$
$D^+ \rightarrow \gamma K_1^+$	$K_1^+ \rightarrow K^+ \rho^0$	$\rho^0 \rightarrow \pi^+ \pi^-$
	$K_1^+ \rightarrow K^{*0} \pi^+$	$K^{*0} \rightarrow K^+ \pi^-$

Table I. The efficiency, ϵ_{sig} , for detecting the signal decay is averaged over the tag modes i ,

$$\epsilon_{\text{sig}} = \frac{\sum_i (N_{\text{ST}}^i \cdot \epsilon_{\text{DT}}^i / \epsilon_{\text{ST}}^i)}{N_{\text{ST}}^{\text{tot}}}, \quad (3)$$

where ϵ_{ST}^i is the efficiency of reconstructing the ST mode i (referred to as the ST efficiency), N_{ST}^i is the ST yield, and ϵ_{DT}^i is the efficiency of finding the tag mode i and the signal decay simultaneously.

A. Tag selection

All charged tracks detected in the MDC must satisfy $|\cos \theta| < 0.93$, where θ is defined as the polar angle with respect to the z axis, which is the symmetry axis of the MDC. For charged tracks not originating from K_S^0 decays, the distance of closest approach to the interaction point (IP) is required to be less than 1 cm in the transverse plane ($|V_{xy}|$), and less than 10 cm along the z axis ($|V_z|$). Particle identification (PID) for charged tracks combines the dE/dx measurement in the MDC with the time of flight measurement of the TOF detector to define the likelihood function $\mathcal{L}(h)$ ($h = K, \pi$) for each hadron (h) hypothesis. The 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.

Each K_S^0 candidate is reconstructed from two oppositely charged tracks satisfying $|V_z| < 20$ cm. The two charged tracks are assigned as $\pi^+\pi^-$ without imposing further PID criteria. They are constrained to originate from a common vertex and are required to have an invariant mass $M_{\pi^+\pi^-}$ such that $|M_{\pi^+\pi^-} - m_{K_S^0}| < 12$ MeV/ c^2 , where $m_{K_S^0}$ is the known K_S^0 mass [25]. The decay length of the K_S^0 candidate is required to be greater than twice the vertex resolution away from the interaction point. The χ^2 of both the primary vertex fit and second vertex fit are required to be less than 100.

Photon candidates are selected by using the information recorded by the EMC. The time information of the crystal with the largest energy deposit in a cluster is required to be within [0, 700] ns of the event start time. To exclude showers that originate from charged tracks, the opening 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.

The π^0 candidates are reconstructed from photon pairs each with an invariant mass within (0.115, 0.150) GeV/ c^2 , which corresponds to about three times the invariant mass resolution. We remove π^0 candidates where both photons are not from the barrel region of the EMC to improve the resolution. The selected π^0 candidates are constrained to the known π^0 mass [25] via a kinematic fit to improve their energy and momentum resolution.

TABLE II. Multiple candidate rates ($\mathcal{R}$) for selected tag modes, all values are given in percentage. Here, the $N = 1, 2$ means one/two combinations survived in the ST selection and $N \geq 3$ means three or more candidates survive the selection in the same event.

Tag mode	$\mathcal{R}(N = 1)$ (Data/MC)	$\mathcal{R}(N = 2)$ (Data/MC)	$\mathcal{R}(N \geq 3)$ (Data/MC)
$\bar{D}^0 \rightarrow K^+\pi^-$	99.7/99.8	0.3/0.2	0.0/0.0
$\bar{D}^0 \rightarrow K^+\pi^-\pi^0$	74.7/74.7	17.0/17.0	8.2/8.4
$\bar{D}^0 \rightarrow K^+\pi^+\pi^-\pi^-$	73.0/74.5	18.6/17.8	8.4/7.6
$D^- \rightarrow K^+\pi^-\pi^-$	94.5/94.7	5.2/5.0	0.3/0.3
$D^- \rightarrow K_S^0\pi^-$	99.2/99.3	0.8/0.7	0.0/0.0
$D^- \rightarrow K^+\pi^-\pi^-\pi^0$	65.0/64.8	21.0/20.9	13.9/14.3
$D^- \rightarrow K^+K^-\pi^-$	93.3/93.6	6.4/6.1	0.3/0.2

To separate the $D^-(\bar{D}^0)$ mesons from combinatorial backgrounds, two useful variables are defined. These are the beam-constrained mass, $M_{\text{BC}}^{\text{tag}}$, and the energy difference, ΔE_{tag} , which are defined as

$$\Delta E_{\text{tag}} = E_{\text{beam}} - E_{D^-(\bar{D}^0)},$$

$$M_{\text{BC}}^{\text{tag}} = \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}_{D^-(\bar{D}^0)}|^2/c^2}, \quad (4)$$

where $E_{D^-(\bar{D}^0)}$ and $\vec{p}_{D^-(\bar{D}^0)}$ are the total energy and momentum of the $D^-(\bar{D}^0)$ candidate in the e^+e^- c.m. frame, respectively. If there is more than one candidate in a given ST mode, the candidate with the smallest value of $|\Delta E_{\text{tag}}|$ will be kept for the subsequent analysis. Table II lists the multiple combinations rates for data and MC. The ΔE_{tag} and $M_{\text{BC}}^{\text{tag}}$ requirements are listed in Table III. The ΔE_{tag} selection requirements are determined from fits to the signal MC samples for each tag. The signal shape is modeled by a sum of three-Gaussian functions, while the background shape is described by a first-order polynomial. The ΔE_{tag} window is then defined as $(\bar{\mu} - 3.5\sigma, \bar{\mu} + 3.5\sigma)$, where $\bar{\mu}$ and σ are the average mean and standard deviation of the three Gaussian components, respectively.

The ST yields are extracted by performing a binned maximum likelihood fit to the corresponding $M_{\text{BC}}^{\text{tag}}$ distribution. The signal shape is modeled by an MC-simulated shape convolved with a double-Gaussian function describing the resolution difference between data and MC simulation. All parameters of the double-Gaussian function are floated in the fit, as well as the signal yield and background normalization. The background shape is described by the ARGUS function [32]

$$f_{\text{ARGUS}} = m \cdot \left(1 - \frac{m^2}{e^2}\right)^p \cdot \exp \left[c \cdot \left(1 - \frac{m^2}{e^2}\right) \right], \quad (5)$$

where $m = M_{\text{BC}}^{\text{tag}}$, e is the end point parameter, c is a shape parameter, and p is an exponent. The end point parameter

TABLE III. The ΔE_{tag} requirements, the $M_{\text{BC}}^{\text{tag}}$ requirements, the ST D meson yields in data (N_{ST}^i), the ST efficiencies (ϵ_{ST}^i), and the DT efficiencies (ϵ_{DT}^i) for each tag mode. The uncertainties are statistical only.

Tag mode	ΔE_{tag} (MeV)	$M_{\text{BC}}^{\text{tag}}$ (GeV/ c^2)	N_{tag}^i ($\times 10^3$)	ϵ_{ST}^i (%)	ϵ_{DT}^i (%)
$\bar{D}^0 \rightarrow K^+\pi^-$	(-0.27, 0.27)	(1.859, 1.873)	3725.7 ± 2.0	65.10 ± 0.01	6.10 ± 0.02
$\bar{D}^0 \rightarrow K^+\pi^-\pi^0$	(-0.62, 0.49)		7422.3 ± 3.2	35.60 ± 0.01	2.81 ± 0.01
$\bar{D}^0 \rightarrow K^+\pi^+\pi^-\pi^-$	(-0.26, 0.24)		4987.5 ± 2.5	40.94 ± 0.01	3.18 ± 0.01
$D^- \rightarrow K^+\pi^-\pi^-$	(-0.25, 0.24)	(1.863, 1.877)	5552.8 ± 2.5	51.10 ± 0.01	8.46 ± 0.01
$D^- \rightarrow K_S^0\pi^-$	(-0.25, 0.26)		656.5 ± 0.8	51.42 ± 0.01	8.71 ± 0.04
$D^- \rightarrow K^+\pi^-\pi^-\pi^0$	(-0.57, 0.46)		1723.7 ± 1.8	24.40 ± 0.01	3.28 ± 0.01
$D^- \rightarrow K^+K^-\pi^-$	(-0.24, 0.23)		481.4 ± 0.9	40.91 ± 0.01	6.14 ± 0.04

$e = 1.8865$ GeV is fixed to the E_{beam} . The parameter p is floated for $\bar{D}^0 \rightarrow K^-\pi^+$, and fixed at 0.5 for other tags. The parameter c is floated for all tags.

Figure 2 shows the results of the fits to the $M_{\text{BC}}^{\text{tag}}$ distributions of the accepted ST candidates for different tag modes in data. The candidates with $M_{\text{BC}}^{\text{tag}}$ within (1.859, 1.873) GeV/ c^2 and (1.863, 1.877) GeV/ c^2 are kept for the double-tag analysis for the $\bar{D}^0$ and D^- channels, respectively.

B. Signal selection

In the ST samples, candidates for $D^0 \rightarrow \gamma\bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ are selected from the remaining good tracks and showers not used in the tag side reconstruction. The $\bar{K}_1^0$ and K_1^+ mesons are reconstructed via $\bar{K}_1^0 \rightarrow K^-\pi^+\pi^0$ and $K_1^+ \rightarrow K^+\pi^+\pi^-$, respectively. The $\pi^\pm$, $K^\pm$, π^0 , and γ candidates are selected with the same criteria as those used in the ST selection. The photon with the highest energy in the signal side is selected as the radiative photon. If there is more than one candidate, the candidate with the smallest value of $|\Delta E_{\text{sig}}|$ will be kept for the subsequent analysis. To suppress combinatorial backgrounds and backgrounds containing a π^0 meson, we require that there is no additional pair of photons ($N_{\text{extra}}^{\pi^0}$) satisfying the π^0 selection criteria, and no extra charged track ($N_{\text{extra}}^{\text{charge}}$) present in the event. Here, the charged track definition is identical to that described of Sec. III A. The invariant mass requirements of the K_1 candidates, $M_{K^-\pi^+\pi^0}$ and $M_{K^+\pi^+\pi^-}$, are optimized using the Punzi method [33] with the figure-of-merit (FoM) $\epsilon/(1.5 + \sqrt{B})$, where ϵ is the signal efficiency determined from the signal MC sample and B is the background yield estimated from the inclusive MC sample. Based on optimizations, we require the signal candidates to satisfy $M_{K^-\pi^+\pi^0}$ within (1.20, 1.37) GeV/ c^2 and $M_{K^+\pi^+\pi^-}$ within (1.22, 1.37) GeV/ c^2 for $D^0 \rightarrow \gamma\bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$, respectively. Background from $D^0(D^+) \rightarrow K_1^0(K_1^+)\pi^0$ decays is suppressed through the use of the variable $M_{\gamma\gamma_{\text{extra}}}$, which is the invariant mass of the radiative γ and an extra γ not used in the reconstruction of

the tag and signal sides. Events that satisfy $M_{\gamma\gamma_{\text{extra}}} < 0.115$ GeV/ c^2 or $M_{\gamma\gamma_{\text{extra}}} > 0.15$ GeV/ c^2 are kept for further analysis. With this π^0 veto requirement, the $D^0 \rightarrow K_1^0\pi^0$ background is suppressed by 52.8%, and the

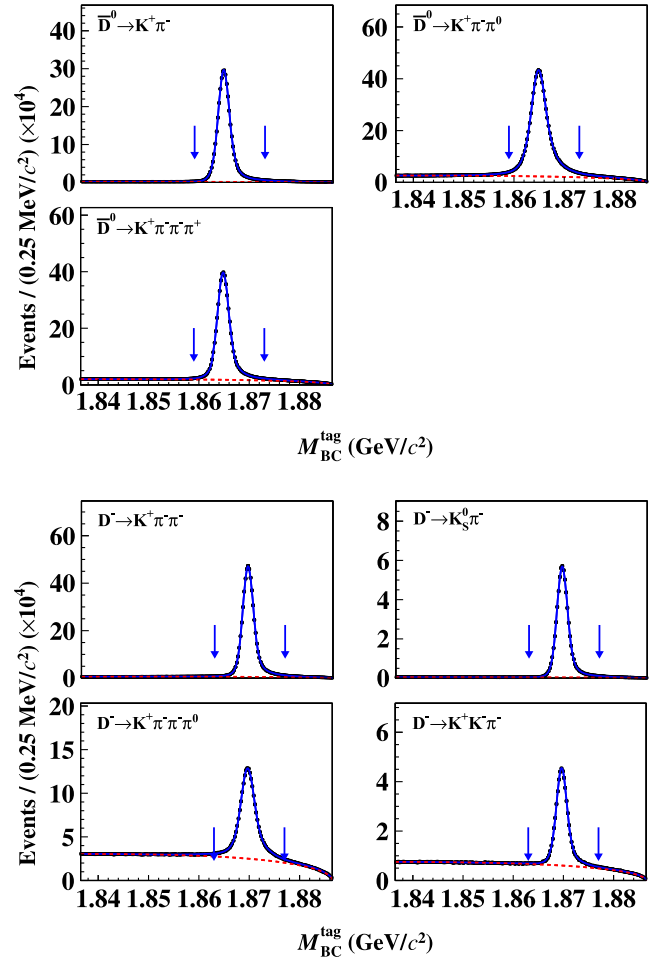


FIG. 2. Fits to the $M_{\text{BC}}^{\text{tag}}$ distributions of the ST candidates for different tag modes. In each plot, the points with error bars are data, the blue curves are the best fits, and the red dashed curves describe the fitted combinatorial background shapes. The pair of blue arrows indicate the signal window.

$D^+ \rightarrow K_1^+ \pi^0$ background is reduced by 32.7%. To remove the background contamination from the decay $D^0 \rightarrow K^- \omega \pi^+$ in $D^0 \rightarrow \gamma K_1^0$ decays and $D^+ \rightarrow K_S^0 K^+ \pi^0$ reconstructed as the $D^+ \rightarrow \gamma K_1^+$ decay, we veto events with a recoil mass of $K^- \pi^+$ around the known ω mass ($0.75 < M_{K^- \pi^+}^{\text{rec}} < 0.815 \text{ GeV}/c^2$) and events with $\pi^+ \pi^-$ invariant mass around the known K_S^0 mass ($0.4677 < M_{\pi^+ \pi^-} < 0.5277 \text{ GeV}/c^2$), respectively. For the signal side, we also define the ΔE_{sig} and $M_{\text{BC}}^{\text{sig}}$ in an analogous way to the tag side as in Eq. (4). After FoM optimization [33], we require the candidate events to satisfy $M_{\text{BC}}^{\text{sig}}$ within (1.862, 1.869) GeV/c^2 for the $D^0 \rightarrow \gamma \bar{K}_1^0$ channel and $M_{\text{BC}}^{\text{sig}}$ within (1.867, 1.874) GeV/c^2 for the $D^+ \rightarrow \gamma K_1^+$ channel.

IV. BRANCHING FRACTIONS

To further study combinatorial backgrounds and determine the signal yields, we define the K_1 helicity angle θ_H [34], which is the angle between the normal to the K_1 decay plane, in the $K\pi\pi$ final state rest frame and the direction of flight of the K_1 meson in the D meson rest frame. The signal yields are extracted from a two-dimensional (2D) unbinned-maximum-likelihood fit to the ΔE_{sig} versus $\cos \theta_H$ distribution for the $D^0 \rightarrow \gamma \bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ decays. The ΔE_{sig} ensures the property of a D meson and $\cos \theta_H$ reveals that of $D \rightarrow \gamma K_1$. The dominant backgrounds for the $D^0 \rightarrow \gamma \bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ decays are listed in Table IV. Even with the aforementioned π^0 veto applied, the $D \rightarrow K\pi\pi\pi^0$ decay remains the dominant background contribution.

In the fits, the signal shapes are derived from the signal MC samples, and the background shapes are derived from the inclusive MC samples with a kernel density estimation technique [35]. The signal and background shapes are fixed in the fit, while only their yields are set as free parameters. The expected background yields are 6085 for the $D^0 \rightarrow \gamma \bar{K}_1^0$ decay and 99 for the $D^+ \rightarrow \gamma K_1^+$ decay, respectively. Figure 3 shows the fit projections for the $D^0 \rightarrow \gamma \bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ decay channels. The signal yields are measured

TABLE IV. The dominant backgrounds for the $D^0 \rightarrow \gamma \bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ decay channels.

Dominant backgrounds	%
$D^0 \rightarrow K^- \pi^+ \pi^0 \pi^0$	84
$D^0 \rightarrow K^- \pi^+ \eta$	3
$D^0 \rightarrow K^- \pi^+ \omega$	3
$D^+ \rightarrow K^+ \pi^- \pi^+ \pi^0$	65
$e^+ e^- \rightarrow q \bar{q}$	5
$D^+ \rightarrow K_S^0 \pi^+$	5
$D^+ \rightarrow K^+ K_S^0 \pi^0$	3

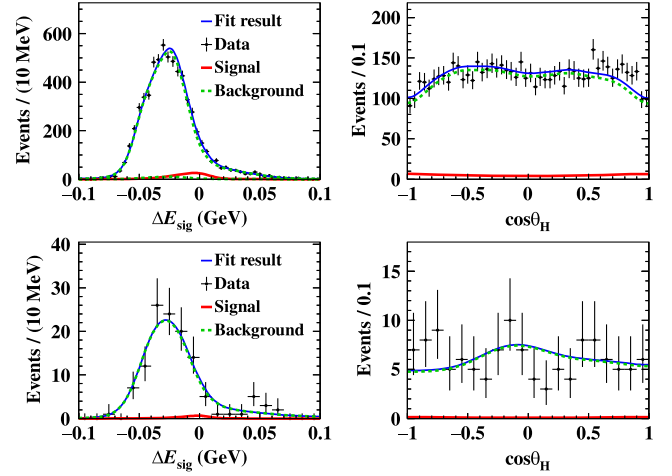


FIG. 3. One-dimensional projections of the 2D fits to the ΔE versus $\cos \theta_H$ distributions for the DT candidate events for $D^0 \rightarrow \gamma \bar{K}_1^0$ (up) and $D^+ \rightarrow \gamma K_1^+$ (bottom). The dots with error bars are data, the blue solid curves are the fit results, the red solid curves are the signal shapes, and the green dashed curves are total background shapes.

to be 199_{-68}^{+69} for the $D^0 \rightarrow \gamma \bar{K}_1^0$ decay and 2_{-7}^{+8} for the $D^+ \rightarrow \gamma K_1^+$ decay. To further illustrate the separation between signal and background components, we present the signal-enhanced projections of $\cos \theta_H$ for both decay modes shown in Fig. 4. These projections are derived from the 2D fit results within the $\pm 2\sigma$ signal region defined by $-0.048 < \Delta E_{\text{sig}} < 0.028 \text{ GeV}$.

Since no significant signal is found in either channel, we set upper limits on the BF by using the frequentist approach [36,37]. Finally, upper limits on the BFs of $D^0 \rightarrow \gamma \bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ are set to be 7.8×10^{-4} and 3.9×10^{-5} at the 90% confidence level, after considering the systematic uncertainties discussed later, respectively.

V. SYSTEMATIC UNCERTAINTY

The sources of systematic uncertainties on the BF measurement are categorized into two classes: additive (independent of the measured BF central value) and multiplicative (proportional to the BF).

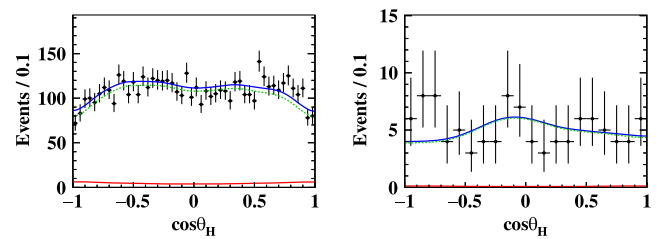


FIG. 4. Signal-enhanced projections of $\cos \theta_H$ for $D^0 \rightarrow \gamma \bar{K}_1^0$ (left) and $D^+ \rightarrow \gamma K_1^+$ (right) decays. The distributions are 2D fit results obtained from the ΔE_{sig} signal region.

Additive uncertainties affect the signal yield determination, which are dominated by the imperfect background shape description. These uncertainties are studied by altering the nominal MC background shape with two methods. First, alternative MC samples are used to derive the background shape. Since the $D^0 \rightarrow K^-\pi^+\pi^0\pi^0$ and $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ decays are the major background contributions for $D^0 \rightarrow \gamma\bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$, and $D^0 \rightarrow K^-\pi^+\omega$ is the peaking background for D^0 channel, we alter the MC shapes by varying the relative fractions of the background according to the PDG uncertainties [25]. The largest change is taken as the corresponding systematic uncertainty. Second, to account for the additive systematic uncertainty used to determine the background shape systematic uncertainties related to the fits, the smoothing parameter in RooKeysPDF from RooFit [38,39] used to implement the KDE is varied between 0 and 2. Among the results of these fits, the largest upper limit on the BF is chosen.

The multiplicative systematic uncertainties considered are described below. The uncertainty associated with the ST yield $N_{\text{ST}}^{\text{tot}}$, is assigned as 0.3% after varying the signal and background shapes and floating the parameters of double Gaussian function in the fits [40]. Following previous BESIII studies [4], the tracking efficiency systematic uncertainty is assigned as 1.0% per charged track, and the PID efficiency uncertainty is 1.0% per charged $K^\pm$ or $\pi^\pm$ meson in the final state. The systematic uncertainty due to the selection criteria of the γ is studied with the $J/\psi \rightarrow \pi^+\pi^-\pi^0$ decay [41]. The systematic uncertainty due to π^0 selection is examined through the DT hadronic $D\bar{D}$ events, as documented in Ref. [42]. These uncertainties are assigned as 1.0% per photon and 2.0% per π^0 , respectively. The differences in the $M_{\text{BC}}^{\text{sig}}$ resolution between data and MC simulation are obtained from the DT control samples of $D^0 \rightarrow K^-\pi^+\pi^0\pi^0$ and $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ decays, reconstructed against the same tag modes used in the baseline analysis. The discrepancies in efficiencies between data and MC simulation, 0.1% and 1.2%, are taken as the systematic uncertainties. The combined systematic uncertainty from the $N_{\text{extra}}^{\pi^0}$ and $N_{\text{extra}}^{\text{charge}}$ requirements are estimated to be 1.3% and 0.4%, which is also assigned by analyzing the control sample of $D^0 \rightarrow K^-\pi^+\pi^0\pi^0$ and $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ decays, respectively. The BFs of the intermediate decays $K_1^0 \rightarrow K^-\pi^+\pi^0$ and $K_1^+ \rightarrow K^+\pi^-\pi^+$ are taken from the PDG world averages [25], with central values of $(46.2 \pm 9.3)\%$ and $(33.6 \pm 6.5)\%$, corresponding to relative uncertainties of 20.2% and 19.3%, respectively. The systematic uncertainties associated with the MC model are estimated by changing the BFs of the known decay modes as well as the masses and widths of the $\bar{K}_1^0$ and K_1^+ mesons. Their uncertainties are 1.0% and 0.6%, respectively.

The total multiplicative systematic uncertainty is obtained by adding the individual components in

TABLE V. Relative multiplicative systematic uncertainties (%) in the BF measurements.

Source	$D^0 \rightarrow \gamma\bar{K}_1^0$	$D^+ \rightarrow \gamma K_1^+$
$N_{\text{ST}}^{\text{tot}}$	0.3	0.3
Tracking	2.0	3.0
PID	2.0	3.0
γ and π^0 selection	3.0	1.0
$M_{K\pi\pi}$ requirement	0.2	0.2
M_{BC} requirement	0.1	1.2
$N_{\text{extra}}^{\text{charge}\&\pi^0}$ requirements	1.3	0.4
Quoted BFs	20.2	19.3
MC model	1.0	0.6
Total multiplicative uncertainty	20.7	19.8
Source	$D^0 \rightarrow \gamma\bar{K}_1^0$	$D^+ \rightarrow \gamma K_1^+$
$D^0 \rightarrow K^-\pi^+\pi^0\pi^0$ shape	6.6	...
$D^0 \rightarrow K^-\pi^+\omega$ shape	1.2	...
$D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ shape	...	2.3
Total additive uncertainty	6.7	2.3

quadrature. Table V summarizes the sources of the systematic uncertainties in the BF measurements. The total systematic uncertainties is 21.8% and 19.9% $D^0 \rightarrow \gamma\bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$, respectively.

VI. SUMMARY

By analyzing a data sample corresponding to an integrated luminosity of 20.3 fb^{-1} collected in e^+e^- annihilations at $\sqrt{s} = 3.773 \text{ GeV}$, the radiative decays $D^0 \rightarrow \gamma\bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ are searched for the first time. No significant signal is observed. The upper limits on the BFs of the $D^0 \rightarrow \gamma\bar{K}_1^0$ and $D^+ \rightarrow \gamma K_1^+$ decays at the 90% confidence level are set to be 7.8×10^{-4} and 3.9×10^{-5} , respectively. These results are consistent with SM theoretical expectations. Notably, the signal yields are 199_{-68}^{+69} (D^0) and 2_{-7}^{+8} (D^+), with systematic uncertainties of 21.8% and 19.9%, respectively. For the D^0 channel, the statistical uncertainty ($\sim 34.7\%$) is moderately larger than the systematic uncertainty, while for the D^+ channel the statistical uncertainty ($\sim 400\%$) is overwhelmingly dominant compared with the systematic uncertainty. In both decay modes, the statistical uncertainty constitutes the main component of the total uncertainty and governs the size of the BF upper limits.

ACKNOWLEDGMENTS

The BESIII Collaboration thanks the staff of BEPCII ([43]) and the IHEP computing center for their strong support. This work is supported in part by National Key R&D Program of China under Contracts

No. 2023YFA1606000, No. 2023YFA1606704; National Natural Science Foundation of China (NSFC) under Contracts No. 12405094, No. 12275067, No. 11635010, No. 11935015, No. 11935016, No. 11935018, No. 12025502, No. 12035009, No. 12035013, No. 12061131003, No. 12192260, No. 12192261, No. 12192262, No. 12192263, No. 12192264, No. 12192265, No. 12221005, No. 12225509, No. 12235017, No. 12361141819; Joint Large-Scale Scientific Facility Fund of the NSFC and the Chinese Academy of Sciences under Contract No. U2032104; the Excellent Youth Foundation of Henan Scientific Committee under Contract No. 242300421044; Science and Technology R&D Program Joint Fund Project of Henan Province (Grant No. 225200810030); Science and Technology Innovation Leading Talent Support Program of Henan Province; Outstanding Young Talent Support Program of Henan Province; Program of Science and Technology Development Plan of Jilin Province of China under Contract No. 20230101021JC; The Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the Strategic Priority Research Program of Chinese Academy of Sciences under Contract No. XDA0480600; CAS under Contract No. YSBR-101; 100 Talents Program of CAS; The

Institute of Nuclear and Particle Physics (INPAC) and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; German Research Foundation DFG under Contract No. FOR5327; Istituto Nazionale di Fisica Nucleare, Italy; Knut and Alice Wallenberg Foundation under Contracts No. 2021.0174, No. 2021.0299; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Research Foundation of Korea under Contract No. NRF-2022R1A2C1092335; National Science and Technology fund of Mongolia; Polish National Science Centre under Contract No. 2024/53/B/ST2/00975; STFC (United Kingdom); Swedish Research Council under Contract No. 2019.04595; U.S. Department of Energy under Contract No. DE-FG02-05ER41374.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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Feng Liu⁶, G. M. Liu^{61,k}, H. Liu^{42,l,m}, H. B. Liu¹⁵, H. M. Liu^{1,70}, Huihui Liu²², J. B. Liu^{77,64}, J. J. Liu²¹, K. Liu^{42,l,m}, K. Liu⁷⁸, K. Y. Liu⁴⁴, Ke Liu²³, L. Liu⁴², L. C. Liu⁴⁷, Lu Liu⁴⁷, M. H. Liu³⁸, P. L. Liu¹, Q. Liu⁷⁰, S. B. Liu^{77,64}, W. M. Liu^{77,64}, W. T. Liu⁴³, X. Liu^{42,l,m}, X. K. Liu^{42,l,m}, X. L. Liu^{12,h}, X. Y. Liu⁸², Y. Liu^{42,l,m}, Y. Liu⁸⁶, Y. B. Liu⁴⁷, Z. A. Liu^{1,64,70}, Z. D. Liu¹⁰, Z. Q. Liu⁵⁴, Z. Y. Liu⁴², X. C. Lou^{1,64,70}, H. J. Lu²⁵, J. G. Lu^{1,64}, X. L. Lu¹⁶, Y. Lu⁷, Y. H. Lu^{1,70}, Y. P. Lu^{1,64}, Z. H. Lu^{1,70}, C. L. Luo⁴⁵, J. R. Luo⁶⁵, J. S. Luo^{1,70}, M. X. Luo⁸⁵, T. Luo^{12,h}, X. L. Luo^{1,64}, Z. Y. Lv²³, X. R. Lyu^{70,p}, Y. F. Lyu⁴⁷, Y. H. Lyu⁸⁶, F. C. Ma⁴⁴, H. L. Ma¹, Heng Ma^{27,j}, J. L. Ma^{1,70}, L. L. Ma⁵⁴, L. R. Ma⁷², Q. M. Ma¹, R. Q. Ma^{1,70}, R. Y. Ma²⁰, T. Ma^{77,64}, X. T. Ma^{1,70}, X. Y. Ma^{1,64}, Y. M. Ma³⁴, F. E. Maas¹⁹, I. MacKay⁷⁵, M. Maggiora^{80a,80c}, S. Malde⁷⁵, Q. A. Malik⁷⁹, H. X. Mao^{42,l,m}, Y. J. Mao^{50,i}, Z. P. Mao¹, S. Marcello^{80a,80c}, A. Marshall⁶⁹, F. M. Melendi^{31a,31b}, Y. H. Meng⁷⁰, Z. X. Meng⁷², G. Mezzadri^{31a}, H. Miao^{1,70}, T. J. Min⁴⁶, R. E. Mitchell²⁹, X. H. Mo^{1,64,70}, B. Moses²⁹, N. Yu. Muchnoi^{4,d}, J. Muskalla³⁹, Y. Nefedov⁴⁰, F. Nerling^{19,f}, H. Neuwirth⁷⁴, Z. Ning^{1,64}, S. Nisar^{33,b}, Q. L. Niu^{42,l,m}, W. D. Niu^{12,h}, Y. Niu⁵⁴, C. Normand⁶⁹, S. L. Olsen^{11,70}, Q. Ouyang^{1,64,70}, S. Pacetti^{30b,30c}, X. Pan⁶⁰, Y. Pan⁶², A. Pathak¹¹, Y. P. Pei^{77,64}, M. Pelizaeus³, H. P. Peng^{77,64}, X. J. Peng^{42,l,m}, Y. Y. Peng^{42,l,m}, K. Peters^{13,f}, K. Petridis⁶⁹, J. L. Ping⁴⁵, R. G. Ping^{1,70}, S. Plura³⁹, V. Prasad³⁸, F. Z. Qi¹, H. R. Qi⁶⁷, M. Qi⁴⁶, S. Qian^{1,64}, W. B. Qian⁷⁰, C. F. Qiao⁷⁰, J. H. Qiao²⁰, J. J. Qin⁷⁸, J. L. Qin⁶⁰, L. Q. Qin¹⁴, L. Y. Qin^{77,64}, P. B. Qin⁷⁸, X. P. Qin⁴³, X. S. Qin⁵⁴, Z. H. Qin^{1,64}, J. F. Qiu¹, Z. H. Qu⁷⁸, J. Rademacker⁶⁹, C. F. Redmer³⁹, A. Rivetti^{80c}, M. Rolo^{80c}, G. Rong^{1,70}, S. S. Rong^{1,70}, F. Rosini^{30b,30c}, Ch. Rosner¹⁹, M. Q. Ruan^{1,64}, N. Salone^{48,q}, A. Sarantsev^{40,e}, Y. Schelhaas³⁹, K. Schoenning⁸¹, M. Scodeggio^{31a}, W. Shan²⁶, X. Y. Shan^{77,64}, Z. J. Shang^{42,l,m}, J. F. Shangguan¹⁷, L. G. Shao^{1,70}, M. Shao^{77,64}, C. P. Shen^{12,h}, H. F. Shen^{1,9}, W. H. Shen⁷⁰, X. Y. Shen^{1,70}, B. A. Shi⁷⁰, H. Shi^{77,64}, J. L. Shi^{8,r}, J. Y. Shi¹, S. Y. Shi⁷⁸, X. Shi^{1,64}, H. L. Song^{77,64}, J. J. Song²⁰, M. H. Song⁴², T. Z. Song⁶⁵, W. M. Song³⁸, Y. X. Song^{50,i,n}, Zirong Song^{27,j}, S. Sosio^{80a,80c}, S. Spataro^{80a,80c}, S. Stanslaus⁷⁵, F. Stieler³⁹, S. S. Su⁴⁴, G. B. Sun⁸², G. X. Sun¹, H. Sun⁷⁰, H. K. Sun¹, J. F. Sun²⁰, K. Sun⁶⁷, L. Sun⁸², R. Sun⁷⁷, S. S. Sun^{1,70}, T. Sun^{56,g}, W. Y. Sun⁵⁵, Y. C. Sun⁸², Y. H. Sun³², Y. J. Sun^{77,64}, Y. Z. Sun¹, Z. Q. Sun^{1,70}, Z. T. Sun⁵⁴, C. J. Tang⁵⁹, G. Y. Tang¹, J. Tang⁶⁵, J. J. Tang^{77,64}, L. F. Tang⁴³, Y. A. Tang⁸², L. Y. Tao⁷⁸, M. Tat⁷⁵, J. X. Teng^{77,64}, J. Y. Tian^{77,64}, W. H. Tian⁶⁵, Y. Tian³⁴, Z. F. Tian⁸², I. Uman^{68b}, B. Wang¹, B. Wang⁶⁵, Bo Wang^{77,64}, C. Wang^{42,l,m}, C. Wang²⁰, Cong Wang²³, D. Y. Wang^{50,i}, H. J. Wang^{42,l,m}, H. R. Wang⁸³, J. Wang¹⁰, J. J. Wang⁸², J. P. Wang³⁷, K. Wang^{1,64}, L. L. Wang¹, L. W. Wang³⁸, M. Wang⁵⁴, M. Wang^{77,64}, N. Y. Wang⁷⁰, S. Wang^{42,l,m}, Shun Wang⁶³, T. Wang^{12,h}, T. J. Wang⁴⁷, W. Wang⁶⁵, W. P. Wang³⁹, X. Wang^{50,i}, X. F. Wang^{42,l,m}, X. L. Wang^{12,h}, X. N. Wang^{1,70}, Xin Wang^{27,j}, Y. Wang¹, Y. D. Wang⁴⁹, Y. F. Wang^{1,9,70}, Y. H. Wang^{42,l,m}, Y. J. Wang^{77,64}, Y. L. Wang²⁰, Y. N. Wang⁴⁹, Y. N. Wang⁸², Yaqian Wang¹⁸, Yi Wang⁶⁷, Yuan Wang^{18,34}, Z. Wang^{1,64}, Z. Wang⁴⁷, Z. L. Wang², Z. Q. Wang^{12,h}, Z. Y. Wang^{1,70}, Ziyi Wang⁷⁰, D. Wei⁴⁷, D. H. Wei¹⁴, H. R. Wei⁴⁷, F. Weidner⁷⁴, S. P. Wen¹, U. Wiedner³, G. Wilkinson⁷⁵, M. Wolke⁸¹, J. F. Wu^{1,9}, L. H. Wu¹, L. J. Wu²⁰, Lianjie Wu²⁰, S. G. Wu^{1,70}, S. M. Wu⁷⁰, X. W. Wu⁷⁸, Y. J. Wu³⁴, Z. Wu^{1,64}, L. Xia^{77,64}, B. H. Xiang^{1,70}, D. Xiao^{42,l,m}, G. Y. Xiao⁴⁶, H. Xiao⁷⁸, Y. L. Xiao^{12,h}, Z. J. Xiao⁴⁵, C. Xie⁴⁶, K. J. Xie^{1,70}, Y. Xie⁵⁴, Y. G. Xie^{1,64}, Y. H. Xie⁶, Z. P. Xie^{77,64}, T. Y. Xing^{1,70}, C. J. Xu⁶⁵, G. F. Xu¹, H. Y. Xu², M. Xu^{77,64}, Q. J. Xu¹⁷, Q. N. Xu³², T. D. Xu⁷⁸, X. P. Xu⁶⁰, Y. Xu^{12,h}, Y. C. Xu⁸³, Z. S. Xu⁷⁰, F. Yan²⁴, L. Yan^{12,h}, Q. Yan³⁸, W. B. Yan^{77,64}, W. C. Yan⁸⁶, W. H. Yan⁶, W. P. Yan²⁰, X. Q. Yan^{12,h}, Y. Y. Yan⁶⁶, H. J. Yang^{56,g}, H. L. Yang³⁸, H. X. Yang¹, J. H. Yang⁴⁶, R. J. Yang²⁰, Y. Yang^{12,h}, Y. H. Yang⁴⁶, Y. Q. Yang¹⁰, Y. Z. Yang²⁰, Z. P. Yao⁵⁴, M. Ye^{1,64}, M. H. Ye^{9,a}, Z. J. Ye^{61,k}, Junhao Yin⁴⁷, Z. Y. You⁶⁵, B. X. Yu^{1,64,70}, C. X. Yu⁴⁷, G. Yu¹³, J. S. Yu^{27,j}, L. W. Yu^{12,h}, T. Yu⁷⁸, X. D. Yu^{50,i}, Y. C. Yu⁸⁶, Y. C. Yu⁴², C. Z. Yuan^{1,70}, H. Yuan^{1,70}, J. Yuan³⁸, J. Yuan⁴⁹, L. Yuan², M. K. Yuan^{12,h}, S. H. Yuan⁷⁸, Y. Yuan^{1,70}, C. X. Yue⁴³, Ying Yue²⁰, A. A. Zafar⁷⁹, F. R. Zeng⁵⁴, S. H. Zeng⁶⁹, X. Zeng^{12,h}, Yujie Zeng⁶⁵, Y. J. Zeng^{1,70}, Y. C. Zhai⁵⁴, Y. H. Zhan⁶⁵, Shunan Zhang⁷⁵, B. L. Zhang^{1,70}, B. X. Zhang^{1,a}, D. H. Zhang⁴⁷, G. Y. Zhang²⁰, G. Y. Zhang^{1,70}, H. Zhang^{77,64}, H. Zhang⁸⁶, H. C. Zhang^{1,64,70}, H. H. Zhang⁶⁵, H. Q. Zhang^{1,64,70}, H. R. Zhang^{77,64}, H. Y. Zhang^{1,64}, J. Zhang⁶⁵, J. J. Zhang⁵⁷, J. L. Zhang²¹, J. Q. Zhang⁴⁵, J. S. Zhang^{12,h}, J. W. Zhang^{1,64,70}, J. X. Zhang^{42,l,m}, J. Y. Zhang¹, J. Z. Zhang^{1,70}, Jianyu Zhang⁷⁰, L. M. Zhang⁶⁷, Lei Zhang⁴⁶, N. Zhang³⁸, P. Zhang^{1,9}, Q. Zhang²⁰, Q. Y. Zhang³⁸, R. Y. Zhang^{42,l,m}, S. H. Zhang^{1,70}, Shulei Zhang^{27,j}, X. M. Zhang¹, X. Y. Zhang⁵⁴, Y. Zhang¹, Y. Zhang⁷⁸, Y. T. Zhang⁸⁶, Y. H. Zhang^{1,64}, Y. P. Zhang^{77,64}, Z. D. Zhang¹, Z. H. Zhang¹, Z. L. Zhang³⁸

Z. L. Zhang⁶⁰, Z. X. Zhang²⁰, Z. Y. Zhang⁸², Z. Y. Zhang⁴⁷, Z. Y. Zhang⁴⁹, Zh. Zh. Zhang²⁰, G. Zhao¹,
 J. Y. Zhao^{1,70}, J. Z. Zhao^{1,64}, L. Zhao¹, L. Zhao^{77,64}, M. G. Zhao⁴⁷, S. J. Zhao⁸⁶, Y. B. Zhao^{1,64}, Y. L. Zhao⁶⁰,
 Y. P. Zhao⁴⁹, Y. X. Zhao^{34,70}, Z. G. Zhao^{77,64}, A. Zhemchugov^{40,c}, B. Zheng⁷⁸, B. M. Zheng³⁸, J. P. Zheng^{1,64},
 W. J. Zheng^{1,70}, X. R. Zheng²⁰, Y. H. Zheng^{70,p}, B. Zhong⁴⁵, C. Zhong²⁰, H. Zhou^{39,54,o}, J. Q. Zhou³⁸,
 S. Zhou⁶, X. Zhou⁸², X. K. Zhou⁶, X. R. Zhou^{77,64}, X. Y. Zhou⁴³, Y. X. Zhou⁸³, Y. Z. Zhou^{12,h}, A. N. Zhu⁷⁰,
 J. Zhu⁴⁷, K. Zhu¹, K. J. Zhu^{1,64,70}, K. S. Zhu^{12,h}, L. X. Zhu⁷⁰, Lin Zhu²⁰, S. H. Zhu⁷⁶, T. J. Zhu^{12,h},
 W. D. Zhu^{12,h}, W. J. Zhu¹, W. Z. Zhu²⁰, Y. C. Zhu^{77,64}, Z. A. Zhu^{1,70}, X. Y. Zhuang⁴⁷ and J. H. Zou¹

(BESIII Collaboration)

¹*Institute of High Energy Physics, Beijing 100049, People's Republic of China*

²*Beihang University, Beijing 100191, People's Republic of China*

³*Bochum Ruhr-University, D-44780 Bochum, Germany*

⁴*Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia*

⁵*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*

⁶*Central China Normal University, Wuhan 430079, People's Republic of China*

⁷*Central South University, Changsha 410083, People's Republic of China*

⁸*Chengdu University of Technology, Chengdu 610059, People's Republic of China*

⁹*China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China*

¹⁰*China University of Geosciences, Wuhan 430074, People's Republic of China*

¹¹*Chung-Ang University, Seoul, 06974, Republic of Korea*

¹²*Fudan University, Shanghai 200433, People's Republic of China*

¹³*GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany*

¹⁴*Guangxi Normal University, Guilin 541004, People's Republic of China*

¹⁵*Guangxi University, Nanning 530004, People's Republic of China*

¹⁶*Guangxi University of Science and Technology, Liuzhou 545006, People's Republic of China*

¹⁷*Hangzhou Normal University, Hangzhou 310036, People's Republic of China*

¹⁸*Hebei University, Baoding 071002, People's Republic of China*

¹⁹*Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany*

²⁰*Henan Normal University, Xinxiang 453007, People's Republic of China*

²¹*Henan University, Kaifeng 475004, People's Republic of China*

²²*Henan University of Science and Technology, Luoyang 471003, People's Republic of China*

²³*Henan University of Technology, Zhengzhou 450001, People's Republic of China*

²⁴*Hengyang Normal University, Hengyang 421001, People's Republic of China*

²⁵*Huangshan College, Huangshan 245000, People's Republic of China*

²⁶*Hunan Normal University, Changsha 410081, People's Republic of China*

²⁷*Hunan University, Changsha 410082, People's Republic of China*

²⁸*Indian Institute of Technology Madras, Chennai 600036, India*

²⁹*Indiana University, Bloomington, Indiana 47405, USA*

^{30a}*INFN Laboratori Nazionali di Frascati, INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy;*

^{30b}*INFN Sezione di Perugia, I-06100, Perugia, Italy;*

^{30c}*University of Perugia, I-06100, Perugia, Italy*

^{31a}*INFN Sezione di Ferrara, INFN Sezione di Ferrara, I-44122, Ferrara, Italy;*

^{31b}*University of Ferrara, I-44122, Ferrara, Italy*

³²*Inner Mongolia University, Hohhot 010021, People's Republic of China*

³³*Institute of Business Administration, Karachi,*

³⁴*Institute of Modern Physics, Lanzhou 730000, People's Republic of China*

³⁵*Institute of Physics and Technology, Mongolian Academy of Sciences,*

Peace Avenue 54B, Ulaanbaatar 13330, Mongolia

³⁶*Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile*

³⁷*Jiangsu Ocean University, Lianyungang 222000, People's Republic of China*

³⁸*Jilin University, Changchun 130012, People's Republic of China*

³⁹*Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*

⁴⁰*Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia*

⁴¹*Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut,*

Heinrich-Buff-Ring 16, D-35392 Giessen, Germany

⁴²*Lanzhou University, Lanzhou 730000, People's Republic of China*

- ⁴³Liaoning Normal University, Dalian 116029, People's Republic of China
⁴⁴Liaoning University, Shenyang 110036, People's Republic of China
⁴⁵Nanjing Normal University, Nanjing 210023, People's Republic of China
⁴⁶Nanjing University, Nanjing 210093, People's Republic of China
⁴⁷Nankai University, Tianjin 300071, People's Republic of China
⁴⁸National Centre for Nuclear Research, Warsaw 02-093, Poland
⁴⁹North China Electric Power University, Beijing 102206, People's Republic of China
⁵⁰Peking University, Beijing 100871, People's Republic of China
⁵¹Qufu Normal University, Qufu 273165, People's Republic of China
⁵²Renmin University of China, Beijing 100872, People's Republic of China
⁵³Shandong Normal University, Jinan 250014, People's Republic of China
⁵⁴Shandong University, Jinan 250100, People's Republic of China
⁵⁵Shandong University of Technology, Zibo 255000, People's Republic of China
⁵⁶Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
⁵⁷Shanxi Normal University, Linfen 041004, People's Republic of China
⁵⁸Shanxi University, Taiyuan 030006, People's Republic of China
⁵⁹Sichuan University, Chengdu 610064, People's Republic of China
⁶⁰Soochow University, Suzhou 215006, People's Republic of China
⁶¹South China Normal University, Guangzhou 510006, People's Republic of China
⁶²Southeast University, Nanjing 211100, People's Republic of China
⁶³Southwest University of Science and Technology, Mianyang 621010, People's Republic of China
⁶⁴State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China
⁶⁵Sun Yat-Sen University, Guangzhou 510275, People's Republic of China
⁶⁶Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
⁶⁷Tsinghua University, Beijing 100084, People's Republic of China
^{68a}Turkish Accelerator Center Particle Factory Group, Istinye University, 34010, Istanbul, Turkey;
^{68b}Near East University, Nicosia, North Cyprus, 99138, Mersin 10, Turkey
⁶⁹University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom
⁷⁰University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
⁷¹University of Hawaii, Honolulu, Hawaii 96822, USA
⁷²University of Jinan, Jinan 250022, People's Republic of China
⁷³University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
⁷⁴University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany
⁷⁵University of Oxford, Keble Road, Oxford OX13RH, United Kingdom
⁷⁶University of Science and Technology Liaoning, Anshan 114051, People's Republic of China
⁷⁷University of Science and Technology of China, Hefei 230026, People's Republic of China
⁷⁸University of South China, Hengyang 421001, People's Republic of China
⁷⁹University of the Punjab, Lahore-54590, Pakistan
^{80a}University of Turin and INFN, University of Turin, I-10125, Turin, Italy;
^{80b}University of Eastern Piedmont, I-15121, Alessandria, Italy;
^{80c}INFN, I-10125, Turin, Italy
⁸¹Uppsala University, Box 516, SE-75120 Uppsala, Sweden
⁸²Wuhan University, Wuhan 430072, People's Republic of China
⁸³Yantai University, Yantai 264005, People's Republic of China
⁸⁴Yunnan University, Kunming 650500, People's Republic of China
⁸⁵Zhejiang University, Hangzhou 310027, People's Republic of China
⁸⁶Zhengzhou University, Zhengzhou 450001, People's Republic of China

^aDeceased.^bAlso at Bogazici University, 34342 Istanbul, Turkey.^cAlso at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.^dAlso at the Novosibirsk State University, Novosibirsk, 630090, Russia.^eAlso at the NRC "Kurchatov Institute," PNPI, 188300, Gatchina, Russia.^fAlso at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.^gAlso at Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology; Institute of Nuclear and Particle Physics, Shanghai 200240, People's Republic of China.^hAlso at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, People's Republic of China.ⁱAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China.

^jAlso at School of Physics and Electronics, Hunan University, Changsha 410082, China.

^kAlso at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China.

^lAlso at MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, People's Republic of China.

^mAlso at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, People's Republic of China.

ⁿAlso at Ecole Polytechnique Federale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland.

^oAlso at Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany.

^pAlso at Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China.

^qCurrently at Silesian University in Katowice, Chorzow, 41-500, Poland.

^rAlso at Applied Nuclear Technology in Geosciences Key Laboratory of Sichuan Province, Chengdu University of Technology, Chengdu 610059, People's Republic of China.