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# Search for the radiative decays $D^+ \rightarrow \gamma\rho^+$ and $D^+ \rightarrow \gamma K^{*+}$



## The BESIII collaboration

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ABSTRACT: We search for the radiative decays  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  using  $20.3 \text{ fb}^{-1}$  of  $e^+e^-$  annihilation data collected at the center-of-mass energy  $\sqrt{s} = 3.773 \text{ GeV}$  by the BESIII detector operating at the BEPCII collider. No significant signals are observed, and the upper limits on the branching fractions of  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  at 90% confidence level are set to be  $1.3 \times 10^{-5}$  and  $1.8 \times 10^{-5}$ , respectively.

KEYWORDS: Charm Physics,  $e^+e^-$  Experiments

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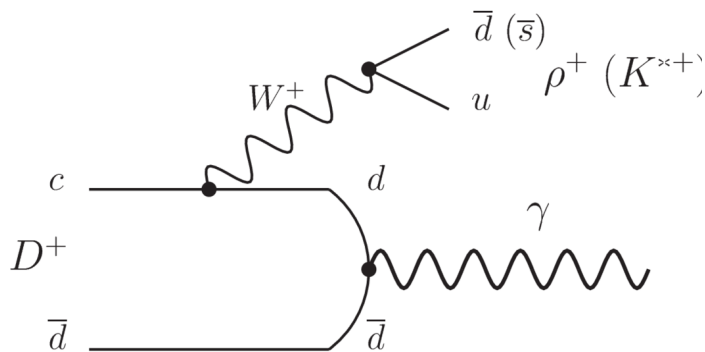
**1 Introduction**

The radiative decays  $D^+ \rightarrow \gamma\rho(770)^+$  and  $D^+ \rightarrow \gamma K^*(892)^+$  can be mediated via Feynman diagrams as shown in figure 1. The study of weak radiative decays of charged charmed mesons allows for direct observation of the dominant contributions from long-range effects that are independent of new physics, thereby testing theoretical calculations of non-perturbative QCD [1, 2]. Among charmed mesons, only the  $D^+$  mesons can be considered “pure” with respect to long-range effects, as this does not hold for neutral mesons, which are sensitive to  $c \rightarrow u$  transitions. Experimental measurements of the branching fractions of charmed meson decays are important to test QCD-based calculations of long-distance dynamics. Previously, the radiative decays of neutral charmed mesons  $D^0 \rightarrow \gamma\bar{K}^{*0}$ ,  $D^0 \rightarrow \gamma\rho^0$ ,  $D^0 \rightarrow \gamma\omega$ , and  $D^0 \rightarrow \gamma\phi$  have been measured by Belle [3, 4], BaBar [5], and CLEO II [6], respectively. However, the radiative decays  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  have not been studied yet. Throughout this paper, charge conjugations are implied.

We report the first search for the radiative decays  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  by analyzing a data sample collected in  $e^+e^-$  annihilations at the center-of-mass energy of 3.773 GeV with the BESIII detector, corresponding to an integrated luminosity of 20.3 fb<sup>-1</sup> [7]. Various theoretical approaches predict the branching fraction of the Cabibbo-suppressed process  $D^+ \rightarrow \gamma\rho^+$  [1, 8–12] up to a value of 10<sup>-5</sup>, which is accessible with the BESIII data sample. In addition, it is naively expected that the branching fraction of the doubly Cabibbo-suppressed process  $D^+ \rightarrow \gamma K^{*+}$  is one order of magnitude lower than that of  $D^+ \rightarrow \gamma\rho^+$ .

**2 Data and Monte Carlo simulation**

The BESIII detector [13] records symmetric  $e^+e^-$  collisions provided by the BEPCII storage ring [14] in the center-of-mass energy range from 1.85 to 4.95 GeV, with a peak luminosity of



**Figure 1.** Feynman diagrams for  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$ .

$1.1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  achieved at  $\sqrt{s} = 3.773 \text{ GeV}$ . BESIII has collected large data samples in this energy region [15–17]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the  $dE/dx$  resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution in the TOF barrel region is 68 ps, while that in the end cap region was 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps, which benefits 85% of the data used in this analysis [18–20].

Simulated samples have been produced with the GEANT4-based [21] Monte Carlo (MC) package. It includes the geometric description of the BESIII detector and the detector response, and is used to determine the detection efficiency and to estimate the backgrounds. The simulation includes the beam-energy spread and initial-state radiation in the  $e^+e^-$  annihilations modeled with the generator KKMC [22, 23]. 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  $J/\psi$  and  $\psi(3686)$  states, and the continuum processes. The known decay modes are modelled with EVTGEN [24, 25] using the branching fractions taken from the Particle Data Group [26], and the remaining unknown decays of the charmonium states are modeled by LUNDCHARM [27]. Final-state radiation is incorporated using the PHOTOS package [28].

The exclusive MC samples of the radiative decays  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  are generated by taking into account the helicity amplitudes, the same ones as used for the Belle and Babar measurements [4, 5].

### 3 Method

At  $\sqrt{s} = 3.773 \text{ GeV}$ , the  $D^+D^-$  pairs are produced without any accompanying hadrons, thereby offering a clean environment to investigate hadronic  $D$  decays with the double-tag (DT) method [29, 30]. The single-tag (ST)  $D^-$  candidates are selected by reconstructing a  $D^-$

in the hadronic decay modes:  $D^- \rightarrow K^+\pi^-\pi^-$ ,  $K_S^0\pi^-$ ,  $K^+\pi^-\pi^-\pi^0$ ,  $K_S^0\pi^-\pi^0$ ,  $K_S^0\pi^+\pi^-\pi^-$ , and  $K^+K^-\pi^-$ . Events in which a signal candidate is reconstructed in the presence of an ST  $D^-$  meson are referred to as DT events. The product branching fraction of the signal decay is determined by

$$\mathcal{B}_{\text{sig}} = N_{\text{DT}} / (N_{\text{ST}}^{\text{tot}} \cdot \epsilon_{\text{sig}} \cdot \mathcal{B}_{\text{sub}}), \quad (3.1)$$

where  $N_{\text{ST}}^{\text{tot}}$  and  $N_{\text{DT}}$  are the total yields of the ST and DT candidates in data, respectively. The  $N_{\text{ST}}^{\text{tot}}$  is obtained from  $\sum_i N_{\text{ST}}^i$  (the sum of ST yield for the tag modes  $i$ ). The  $\mathcal{B}_{\text{sub}}$  is the product of the subdecay branching fractions of  $\rho^+ \rightarrow \pi^+\pi^0$  (100%) or  $K^{*+} \rightarrow K^+\pi^0$  (33.3%) with  $\pi^0 \rightarrow \gamma\gamma$  ( $98.823 \pm 0.034\%$ ) [26]. The ST yield for the tag mode  $i$  is  $N_{\text{ST}}^i$ , and the efficiency  $\epsilon_{\text{sig}}$  for detecting the signal  $D^+$  decay is averaged over the tag modes  $i$ ,

$$\epsilon_{\text{sig}} = \frac{\sum_i (N_{\text{ST}}^i \cdot \epsilon_{\text{DT}}^i / \epsilon_{\text{ST}}^i)}{N_{\text{ST}}^{\text{tot}}}, \quad (3.2)$$

where  $\epsilon_{\text{ST}}^i$  is the efficiency of reconstructing the ST mode  $i$  (referred to as the ST efficiency), and  $\epsilon_{\text{DT}}^i$  is the efficiency of finding the ST mode  $i$  and the  $D^+ \rightarrow \gamma\rho^+$  or  $D^+ \rightarrow \gamma K^{*+}$  decay simultaneously (referred to as the DT efficiency).

### 3.1 Single tag selection

Charged tracks detected in the MDC (except for those used for  $K_S^0$  reconstruction) are required to originate from a region within  $|\cos\theta| < 0.93$ ,  $|V_{xy}| < 1$  cm, and  $|V_z| < 10$  cm. Here,  $\theta$  is the polar angle of the charged track with respect to the MDC axis,  $|V_{xy}|$  and  $|V_z|$  are the distances of closest approach of the charged track to the interaction point perpendicular to and along the MDC axis, respectively. Particle identification (PID) for charged tracks combines measurements of the energy deposited in the MDC ( $dE/dx$ ) and the flight time in the TOF to form likelihoods  $\mathcal{L}(h)$  ( $h = \pi, K$ ) for each hadron  $h$  hypothesis. Tracks are identified as charged kaons and pions by comparing the likelihoods for the kaon and pion hypotheses, requiring  $\mathcal{L}(K) > \mathcal{L}(\pi)$  and  $\mathcal{L}(\pi) > \mathcal{L}(K)$ .

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 within (0.487, 0.511)  $\text{GeV}/c^2$ . 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  $\chi^2$  of the vertex fits (primary and secondary vertex fit) is 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 inside a cluster is required to be within 700 ns of the event start time. The shower energy is required to be greater than 25 MeV in the barrel ( $|\cos\theta| < 0.8$ ) and 50 MeV in the end cap ( $0.86 < |\cos\theta| < 0.92$ ) region. The opening angle between the shower direction and the extrapolated position on the EMC of the closest charged track must be greater than  $10^\circ$ . The  $\pi^0$  candidates are formed from photon pairs with an invariant mass within (0.115, 0.150)  $\text{GeV}/c^2$ . To improve the resolution, a kinematic fit constraining the  $\gamma\gamma$  invariant mass to the known  $\pi^0$  mass [26] is imposed on

Tag mode	$\Delta E_{\text{tag}}$ (MeV)	$N_{\text{ST}}^i (\times 10^3)$	$\epsilon_{\text{ST}}^i$ (%)	$\epsilon_{\text{DT}}^{i a}$ (%)	$\epsilon_{\text{DT}}^{i b}$ (%)
$D^- \rightarrow K^+ \pi^- \pi^-$	(-25, 24)	5567.2 $\pm$ 2.5	51.08 $\pm$ 0.01	9.90 $\pm$ 0.09	8.96 $\pm$ 0.09
$D^- \rightarrow K^+ \pi^- \pi^- \pi^0$	(-57, 46)	1740.2 $\pm$ 1.9	24.53 $\pm$ 0.01	4.27 $\pm$ 0.06	3.81 $\pm$ 0.06
$D^- \rightarrow K^+ K^- \pi^-$	(-24, 23)	481.4 $\pm$ 0.9	40.91 $\pm$ 0.01	7.07 $\pm$ 0.08	6.47 $\pm$ 0.08
$D^- \rightarrow K_S^0 \pi^-$	(-25, 26)	656.5 $\pm$ 0.8	51.42 $\pm$ 0.01	10.59 $\pm$ 0.10	9.55 $\pm$ 0.09
$D^- \rightarrow K_S^0 \pi^- \pi^0$	(-62, 49)	1442.4 $\pm$ 1.5	26.45 $\pm$ 0.01	5.10 $\pm$ 0.07	4.50 $\pm$ 0.07
$D^- \rightarrow K_S^0 \pi^- \pi^- \pi^+$	(-28, 27)	790.2 $\pm$ 1.1	29.68 $\pm$ 0.01	5.32 $\pm$ 0.07	4.71 $\pm$ 0.07

**Table 1.** The  $\Delta E_{\text{tag}}$  requirements, the ST  $D^-$  yields in data ( $N_{\text{ST}}^i$ ), the ST efficiencies ( $\epsilon_{\text{ST}}^i$ ), and the DT efficiencies ( $\epsilon_{\text{DT}}^i$ ) tagged  $D^+ \rightarrow \gamma \rho^+(a)$  and  $D^+ \rightarrow \gamma K^{*+}(b)$  for each tag modes. The uncertainties are statistical only.

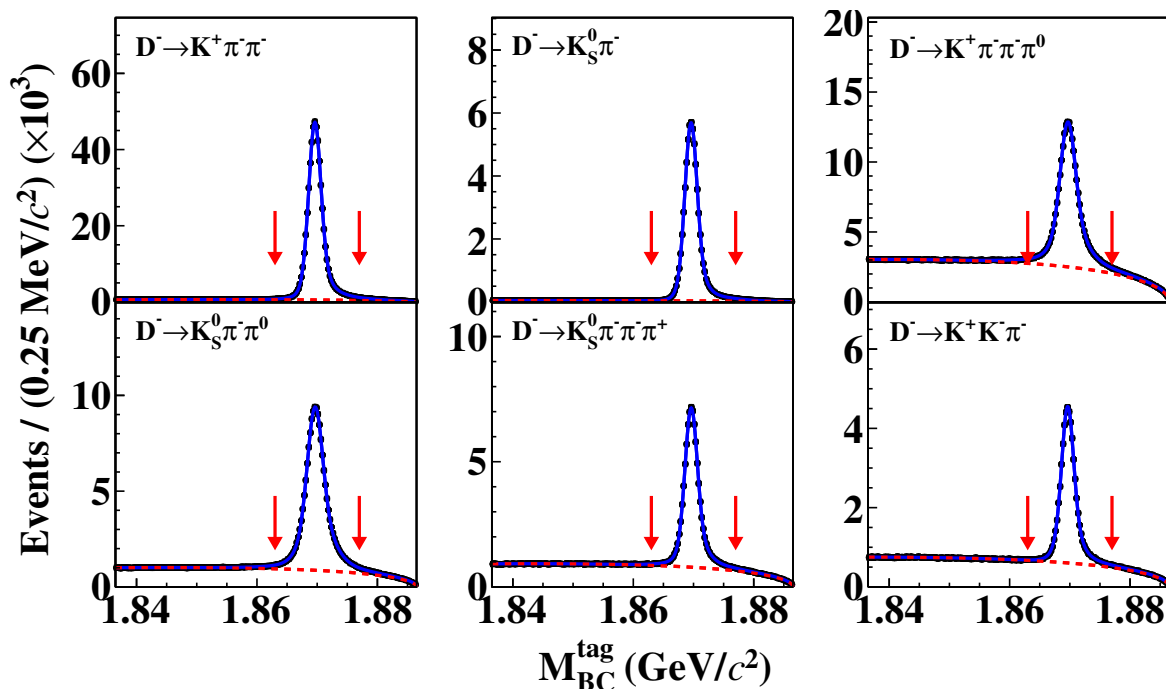
the selected photon pair. The  $\chi^2$  of the kinematic fit is required to be less than 50. The four-momentum of the  $\pi^0$  candidate updated by this kinematic fit is used for further analysis.

To separate  $D^-$  mesons from combinatorial backgrounds, the energy difference  $\Delta E_{\text{tag}}$  is defined as  $\Delta E_{\text{tag}} \equiv E_{D^-} - E_{\text{beam}}$ , where  $E_{\text{beam}}$  is the beam energy, and  $E_{D^-}$  is the total energy of the  $D^-$  candidate in the  $e^+e^-$  center-of-mass frame. If there is more than one  $D^-$  candidate in a given ST mode, the candidate with the smallest value of  $|\Delta E_{\text{tag}}|$  will be kept for the subsequent analysis. The  $\Delta E_{\text{tag}}$  requirements are listed in table 1.

The beam-constrained mass  $M_{\text{BC}}^{\text{tag}}$  is defined as  $M_{\text{BC}}^{\text{tag}} \equiv \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}_{D^-}|^2/c^2}$  to determine the ST yield and ST efficiencies, where  $\vec{p}_{D^-}$  is the momentum of the  $D^-$  candidate in the  $e^+e^-$  center-of-mass frame. The ST yield for each ST mode is extracted by performing an unbinned maximum likelihood fit to the corresponding  $M_{\text{BC}}^{\text{tag}}$  distribution. In the fit, the signal shape is derived from the MC-simulated signal shape convolved with a double-Gaussian function to compensate for the resolution difference between data and MC simulation. The central values and resolutions of the double-Gaussian are both at MeV or sub-MeV level. The combinatorial background shape is described by the ARGUS function [31], with the end-point parameter fixed at  $E_{\text{beam}} = 1.8865 \text{ GeV}/c^2$ . Peaking backgrounds for the ST modes  $D^- \rightarrow K_S^0 \pi^-$  and  $D^- \rightarrow K_S^0 \pi^+ \pi^- \pi^-$  (with ratios of  $< 0.2\%$ ), estimated with the inclusive MC sample, have been subtracted away from the corresponding ST yields in data and ST efficiencies; while the peaking backgrounds for other four ST modes are negligible. Figure 2 shows the fits to the  $M_{\text{BC}}^{\text{tag}}$  distributions of the accepted ST candidates in data for different ST modes. The candidates with  $M_{\text{BC}}^{\text{tag}}$  within (1.863, 1.877)  $\text{GeV}/c^2$  are kept for further analyses. Summing over the tag modes, we obtain the total yield of ST  $D^-$  mesons to be  $(10638.3 \pm 3.6_{\text{stat}}) \times 10^3$  events.

### 3.2 Double tag selection

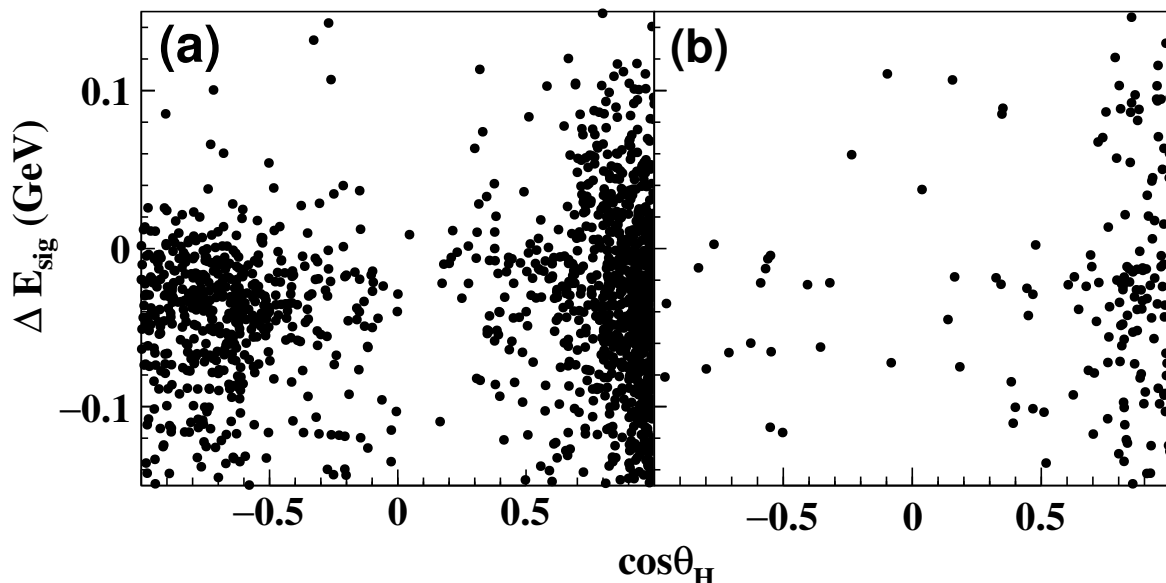
The candidates for  $D^+ \rightarrow \gamma \rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  are selected from the remaining tracks in presence of the tagged  $D^-$  candidates. The  $\rho^+$  and  $K^{*+}$  are reconstructed via  $\rho^+ \rightarrow \pi^+ \pi^0$  and  $K^{*+} \rightarrow K^+ \pi^0$ , respectively. Candidates for  $\pi^+$ ,  $K^+$ ,  $\pi^0$ , and  $\gamma$  are selected with the same criteria as those used in the tag selection. To select the candidates for  $D^+ \rightarrow \gamma \rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$ , the photon with the highest energy in a given event is selected as the radiative



**Figure 2.** Fits to the  $M_{\text{BC}}^{\text{tag}}$  distributions of the ST  $D^-$  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 red arrows indicates the signal window.

photon. To suppress the backgrounds containing extra  $\pi^0$  mesons, we require that there are no additional combinations of two photons ( $N_{\text{extra}}^{\pi^0} = 0$ ) that satisfy the  $\pi^0$  selection criteria in the event selection. We require that there is no extra charged track ( $N_{\text{extra}}^{\text{charge}} = 0$ ) reconstructed in the signal decay. The invariant mass requirements of the vector meson ( $M_{V^+}$ , where  $V$  donates  $\rho^+$  or  $K^{*+}$ ), are optimized based on the Punzi figure-of-merit  $\epsilon/(1.5 + \sqrt{B})$  [32], where  $\epsilon$  is the signal efficiency based on the exclusive signal MC sample and  $B$  is the background yield obtained from the inclusive MC sample. According to the optimization, we require the candidates for  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  to satisfy  $M_{\pi^+\pi^0} \in (0.64, 0.89) \text{ GeV}/c^2$  and  $M_{K^+\pi^0} \in (0.84, 0.94) \text{ GeV}/c^2$ , respectively. We define the missing mass squared of the radiative photon  $M_\gamma^2 \equiv (\sqrt{s} - \sum_k E_k)^2 - |\sum_k \vec{p}_k|^2$ , in which  $E_k$  and  $\vec{p}_k$  are the energy and momentum, respectively, with  $k$  referring to the ST  $D^-$  or  $V^+$ . To remove the background from  $D^+ \rightarrow K_L^0 V^+$ , which peaks in the  $M_\gamma^2$  distribution around  $0.25 \text{ GeV}^2/c^4$  corresponding to the square of the known  $K_L^0$  mass [26], the value of  $M_\gamma^2$  is required to be less than  $0.07 \text{ GeV}^2/c^4$  based on the Punzi optimization. To extract the information of the signal side, we define two kinematic variables of  $M_{\text{BC}}^{\text{sig}}$  and  $\Delta E_{\text{sig}}$  similarly as in the tag side. After the optimization, we require the candidate events to satisfy  $M_{\text{BC}}^{\text{sig}} \in (1.865, 1.873) \text{ GeV}/c^2$ .

After applying the above requirements, the average signal efficiencies in the presence of the ST  $D^-$  mesons are  $(18.92 \pm 0.11)\%$  and  $(17.02 \pm 0.11)\%$  for  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$ , respectively.

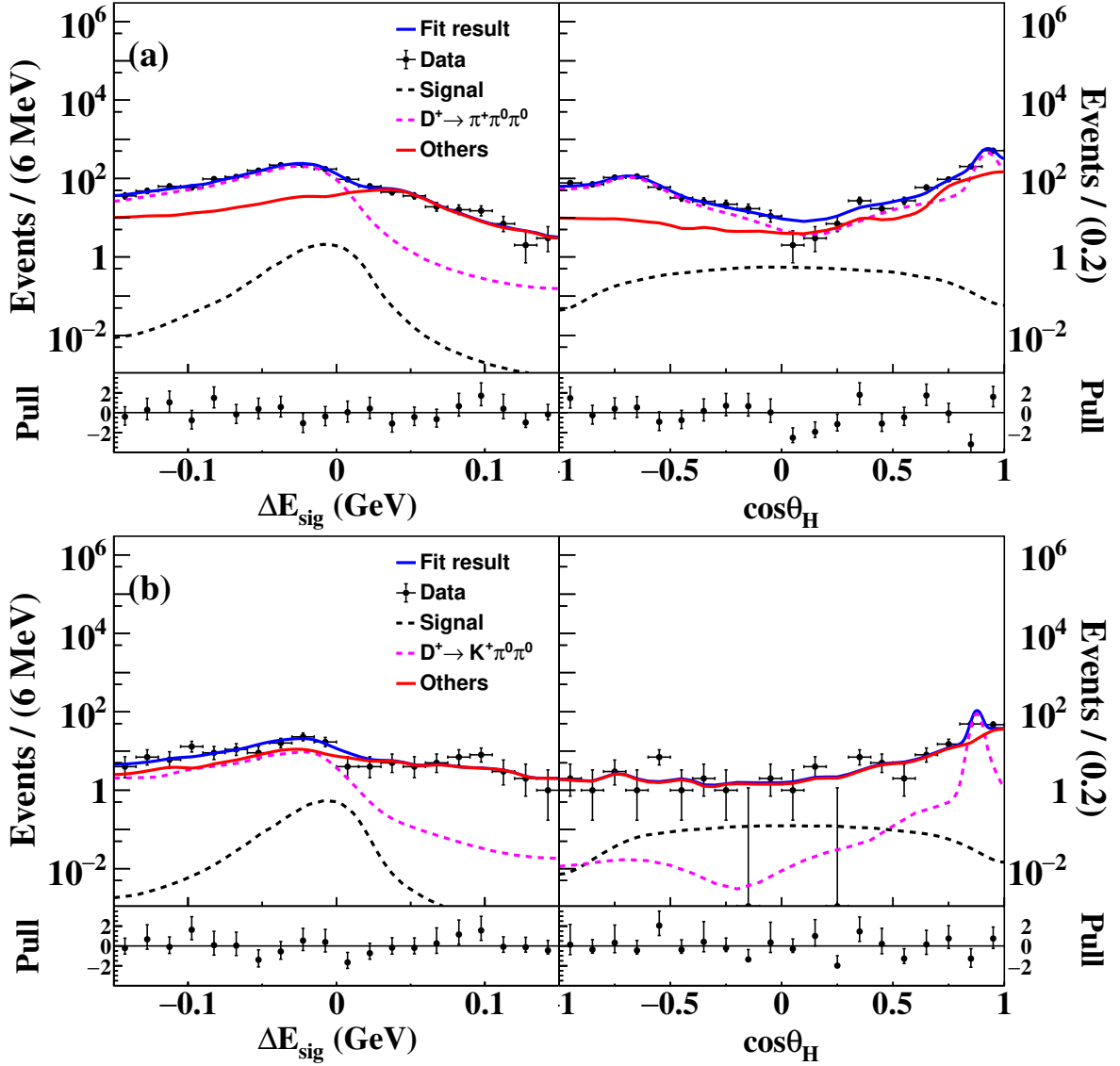


**Figure 3.** Distributions of  $\Delta E_{\text{sig}}$  versus  $\cos\theta_H$  of the DT candidate events for  $D^+ \rightarrow \gamma\rho^+$  (a) and  $D^+ \rightarrow \gamma K^{*+}$  (b) in data.

## 4 Results

To further study combinatorial backgrounds and extract the signal yields, we define the helicity angle  $\theta_H$  of  $\pi^+(K^+)$ , which is the angle between the  $\pi^+(K^+)$  momentum in the  $\rho^+(K^{*+})$  rest frame and  $\rho^+(K^{*+})$  momentum in the  $D^+$  rest frame. The  $\Delta E_{\text{sig}}$  and  $M_{\text{BC}}^{\text{sig}}$  ensure the property of a  $D$  meson,  $\cos\theta_H$  reveals that of the  $D \rightarrow \gamma V$  decay. The two-dimensional distributions of the  $\Delta E_{\text{sig}}$  versus  $\cos\theta_H$  of  $\pi^+(K^+)$  in data are shown in figure 3. The signal shape in the  $\cos\theta_H$  distribution is arched, while the corresponding background shape is concave, as shown in figure 4.

Detailed study of the inclusive MC sample shows that the background  $D^+ \rightarrow \pi^+\pi^0\pi^0$  in the  $D^+ \rightarrow \gamma\rho^+$  channel and the background  $D^+ \rightarrow K^+\pi^0\pi^0$  in the  $D^+ \rightarrow \gamma K^{*+}$  channel exhibit the largest relative contributions and are referred to as the dominant backgrounds, and the remaining components are called ‘‘Others’’ backgrounds. The signal yields are extracted from a 2D unbinned maximum likelihood fit to the  $\Delta E_{\text{sig}}$  versus  $\cos\theta_H$  distribution for  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$ , respectively. In the fits, the signal shapes are derived from the signal MC sample, and the background shapes are derived from the inclusive MC sample with the RooKeysPDF tool [33]. The signal and background yields are both allowed to float in the fit. The yields of the dominant background,  $D^+ \rightarrow \pi^+\pi^0\pi^0$  or  $D^+ \rightarrow K^+\pi^0\pi^0$ , are fixed by the mis-identification and the branching fractions. Figure 4 shows the fitted results for  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$ . The signal yields are  $6.8_{-11.2}^{+12.4}$  for  $D^+ \rightarrow \gamma\rho^+$  and  $1.8_{-4.3}^{+5.2}$  for  $D^+ \rightarrow \gamma K^{*+}$ . After inserting the numbers into eq. 3.1, the  $\mathcal{B}_{D^+ \rightarrow \gamma\rho^+}$  and  $\mathcal{B}_{D^+ \rightarrow \gamma K^{*+}}$  are determined to be  $(0.34_{-0.55}^{+0.61} \pm 0.01) \times 10^{-5}$  and  $(0.30_{-0.71}^{+0.86} \pm 0.01) \times 10^{-5}$ , respectively, where the first uncertainties statistical and the second systematic. Since no significant signal is found, we set the upper limits as shown in figure 5 by using the Bayesian approach [34–37] after considering the systematic uncertainties discussed later. Finally, the upper limits on

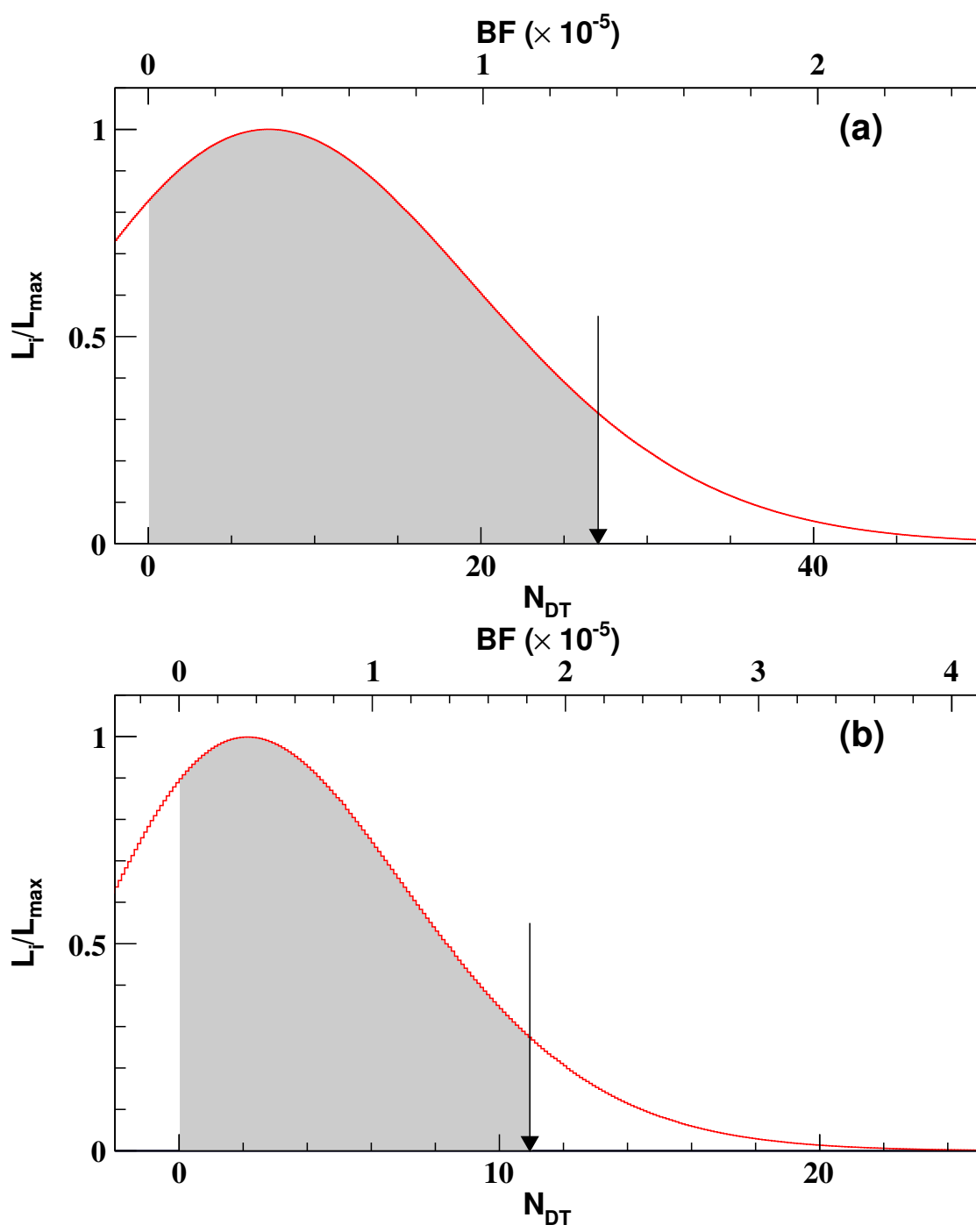


**Figure 4.** One-dimensional projections of the two-dimensional fit to the  $\Delta E_{\text{sig}}$  versus  $\cos\theta_H$  distributions for the DT candidate events of  $D^+ \rightarrow \gamma\rho^+$  (a) and  $D^+ \rightarrow \gamma K^{*+}$  (b). The dots with error bars correspond to data. The blue solid curves correspond to the fit results. The black dashed lines correspond to the fitted signal, the pink dashed curves correspond to the dominant background contributions, and the red solid curves correspond to other background contributions.

the branching fractions of  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  at 90% confidence level are set to be  $1.3 \times 10^{-5}$  and  $1.8 \times 10^{-5}$ , respectively.

### 5 Systematic uncertainty

With the DT method, many systematic uncertainties associated with the ST selection cancel and do not affect the branching fraction measurement. This concerns tracking, PID, subdecay branching fractions, and the  $\Delta E$  requirements in the ST selection.



**Figure 5.** Distributions of normalized likelihood versus the signal yield  $N_{DT}$  or normalized branching fraction of  $D^+ \rightarrow \gamma \rho^+$ (a) and  $D^+ \rightarrow \gamma K^{*+}$ (b). The results obtained with the systematic uncertainties incorporated are shown by the red curves. The black arrow shows the result corresponding to 90% confidence level.

To account for the additive systematic uncertainties related to the fits, alternative fits involve different RooKeysPDF smooth parameters by varying  $\pm 0.5$  from the default value of 1.0. Among the results of these fits, the largest upper limit on the branching fraction is chosen. The multiplicative systematic uncertainties are discussed below.

The uncertainty associated with the ST yield  $N_{\text{ST}}^{\text{tot}}$  is assigned as 0.1% after varying the signal and background shapes and floating the parameters of one Gaussian in the fit. The tracking and PID efficiencies of  $K^\pm$  and  $\pi^\pm$  are studied by analyzing DT  $D^0\bar{D}^0(D^+D^-)$  events, where the control samples comprise hadronic decays of  $D^0 \rightarrow K^-\pi^+$ ,  $D^0 \rightarrow K^-\pi^+\pi^0$ ,  $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$  versus  $D^0 \rightarrow K^+\pi^-$ ,  $D^0 \rightarrow K^+\pi^-\pi^0$ ,  $D^0 \rightarrow K^+\pi^-\pi^-\pi^+$  as well as  $D^+ \rightarrow K^-\pi^+\pi^+$  versus  $D^+ \rightarrow K^+\pi^-\pi^-$ . The systematic uncertainty due to tracking efficiencies is assigned as 1.0% for both  $K^\pm$  and  $\pi^\pm$ ; the systematic uncertainty due to PID is assigned as 1.0% for  $K^\pm$  and  $\pi^\pm$ . The systematic uncertainty related to the  $\gamma$  selection is studied with the  $J/\psi \rightarrow \pi^+\pi^-\pi^0$  decay [38], while the systematic uncertainty on the  $\pi^0$  selection is examined through the DT hadronic  $D\bar{D}$  events, as in ref. [39]. These uncertainties are assigned as 1.0% per photon and 2.0% per  $\pi^0$ .

The systematic uncertainties due to the  $\rho^+$  and  $K^{*+}$  mass windows are estimated by using the DT samples of  $\bar{D}^0 \rightarrow K^+\pi^-$ ,  $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$ ,  $\bar{D}^0 \rightarrow K^+\pi^-\pi^-\pi^+$  versus  $D^0 \rightarrow \pi^-\pi^0e^+\nu_e$  and  $D^0 \rightarrow K^-\pi^0e^+\nu_e$ , respectively. The selection criteria of candidates are the same as in ref. [40]. The differences of the acceptance efficiencies between data and MC simulation, 0.5% and 0.1%, are assigned as the systematic uncertainties for  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$ , respectively.

The differences in the  $M_{\text{BC}}^{\text{sig}}$  resolution between data and MC simulation are obtained from the DT events of  $D^+ \rightarrow \pi^+\pi^0\pi^0$  reconstructed versus the same tag modes used in the baseline analysis. The discrepancy in acceptance efficiencies between data and MC simulation of 0.1% is taken as the related systematic uncertainty.

The combined systematic uncertainty from the  $N_{\text{extra}}^{\pi^0}$  and  $N_{\text{extra}}^{\text{charge}}$  requirements is estimated to be 0.7%, which is also assigned by analyzing the control sample of  $D^+ \rightarrow \pi^+\pi^0\pi^0$ .

The systematic uncertainty from the  $M_\gamma^2$  requirement is estimated to be 0.6%, with the control sample of  $D^+ \rightarrow \pi^+\pi^0\pi^0$  by missing a  $\gamma$  in the final state.

The uncertainties due to the limited size of MC samples are 0.6% and 0.7% for  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$ , respectively.

The uncertainties of the branching fractions of  $\rho^+ \rightarrow \pi^+\pi^0$ ,  $K^{*+} \rightarrow K^+\pi^0$  and  $\pi^0 \rightarrow \gamma\gamma$  are negligible with respect to the other systematic contributions [26].

The total multiplicative systematic uncertainty is obtained by adding the individual components in quadrature. Table 2 summarizes the sources of the systematic uncertainties in the branching fraction measurements.

## 6 Summary

By analyzing a data sample corresponding to an integrated luminosity of  $20.3 \text{ fb}^{-1}$  collected in  $e^+e^-$  annihilations recorded at  $\sqrt{s} = 3.773 \text{ GeV}$ , we search for the radiative decays  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$ . No significant signals are observed. The upper limits on the branching fractions of  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  at 90% confidence level are set to be  $1.3 \times 10^{-5}$  and  $1.8 \times 10^{-5}$ , respectively. Table 3 summarizes the different theoretically

Source	$D^+ \rightarrow \gamma\rho^+$ (%)	$D^+ \rightarrow \gamma K^{*+}$ (%)
$N_{ST}$	0.1	0.1
Tracking	1.0	1.0
PID	1.0	1.0
$\gamma$ and $\pi^0$ selection	3.0	3.0
$M_{V^+}$ requirement	0.5	0.1
$M_{BC}^{sig}$ requirement	0.1	0.1
$N_{extra}^{charge}$ & $N_{extra}^{\pi^0}$ requirement	0.7	0.7
$M_\gamma^2$ requirement	0.6	0.6
MC statistics	0.6	0.7
Total	3.6	3.5

**Table 2.** Relative multiplicative systematic uncertainties in the branching fraction measurements.

Result	$D^+ \rightarrow \gamma\rho^+$ ( $\times 10^{-5}$ )	$D^+ \rightarrow \gamma K^{*+}$ ( $\times 10^{-5}$ )
PoleDiagram and VMD [1]	2 – 6	0.1 – 0.3
SM [8]	$5.0 \pm 0.9$	—
QCD SM [9]	0.46	—
Hybrid [10]	0.017 – 2.33	0.048 – 0.76
FS [11]	1.8 – 4.1	0.25 – 0.5
Factorization [12]	0.4 – 6.3	0.03 – 0.44
This work	$< 1.3$	$< 1.8$

**Table 3.** The predicted branching fractions of  $D^+ \rightarrow \gamma\rho^+$  and  $D^+ \rightarrow \gamma K^{*+}$  from various theories, and the upper limits in this work.

predicted branching fractions and our measured upper limits. The results obtained in this analysis are compatible with theoretical calculations, except that the upper limit on the branching fraction of  $D^+ \rightarrow \gamma\rho^+$  deviates with theoretical calculation in the SM [8] by about  $3.6\sigma$ . The larger data sample at the Super Tau-Charm Facility [41] will offer an opportunity to further enhance the sensitivity of the search for these radiative decays.

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