Observation of $D^+ \to K_S^0\pi^0\mu^+\nu_\mu$, Test of Lepton Flavor Universality, and First Angular Analysis of $D^+ \to \bar{K}^*(892)^0\ell^+\nu_\ell$

M. Ablikim *et al.*[*]
(BESIII Collaboration)

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We report a study of the semileptonic decays $D^+ \to K_S^0\pi^0\ell^+\nu_\ell$ ($\ell = e, \mu$) based on 20.3 fb^{-1} of e^+e^- collision data collected at the center-of-mass energy of 3.773 GeV with the BESIII detector. The $D^+ \to K_S^0\pi^0\mu^+\nu_\mu$ decay is observed for the first time, with a branching fraction of $(0.896 \pm 0.017_{\rm stat} \pm 0.008_{\rm syst})\%$, and the branching fraction of $D^+ \to K_S^0\pi^0 e^+\nu_e$ is determined with the improved precision as $(0.943 \pm 0.012_{\rm stat} \pm 0.010_{\rm syst})\%$. From the analysis of the dynamics, we observe that the dominant $\bar{K}^*(892)^0$ component is accompanied by an S-wave contribution, which accounts for $(7.10 \pm 0.68_{\rm stat} \pm 0.41_{\rm syst})\%$ of the total decay rate of the μ^+ channel and $(6.39 \pm 0.17_{\rm stat} \pm 0.14_{\rm syst})\%$ of the e^+ channel. Assuming a single-pole dominance parametrization, the hadronic form factor ratios are extracted to be $r_V = V(0)/A_1(0) = 1.42 \pm 0.03_{\rm stat} \pm 0.02_{\rm syst}$ and $r_2 = A_2(0)/A_1(0) = 0.75 \pm 0.03_{\rm stat} \pm 0.01_{\rm syst}$. Based on the first comprehensive angular and the decay-rate CP asymmetry analysis, the full set of averaged angular and CP asymmetry observables are measured as a function of the momentum-transfer squared; they are consistent with expectations from the standard model. No evidence for violation of $\mu - e$ lepton-flavor universality is observed in either the full range or the five chosen bins of momentum-transfer squared.

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Experimental studies of semileptonic decays of heavy mesons provide important opportunities for rigorously testing the standard model (SM) and probing for potential new physics (NP). In recent years, some anomalies have been observed in semileptonic B decays mediated by the charged current $b \to c\ell\bar{\nu}_\ell$, deviating from SM predictions by 2 to 3 standard deviations [1,2], indicating possible violations of lepton flavor universality (LFU). Various NP scenarios, including W' models [3,4], leptoquark models [5], and charged Higgs models [6], proposed to resolve these tensions—can modify both branching fractions (BFs) and detailed angular distributions. Key observables therefore include BF ratios, and the full set of angular coefficients, which together constrain the relevant parameters.

By contrast, no anomalies have been observed experimentally in D mesons to date [7], yet the same NP operators invoked to explain the B anomalies [8,9] may impact the semileptonic D decays [10–15]. Some observables—such as LFU violation [16], forward-backward asymmetry [17] and lepton (hadron) polarization [18]—have been proposed as sensitive probes. In particular, experimental analysis of the BF ratios and the angular distributions in $D^+ \to \bar{K}^{*0}\ell^+\nu_\ell$ ($\ell = e, \mu$) could reveal subtle NP effects [19].

The unique mass range of charmed hadronic states allows for rich nonperturbative hadronic physics [20–22], making precision studies of heavy-to-light form factors (FFs) a key component in testing the SM. The FFs are inherently nonperturbative and describe strong interaction effects in the initial and final hadrons; theoretical predictions within the SM can only be calculated by nonperturbative approaches, such as lattice quantum chromodynamics (LQCD) [23–27], quark models [28–30], and QCD sum rules [31]. Precise experimental determination of these hadronic transition FFs and their comparison with theoretical predictions not only provides stringent tests of the SM, but also offers a means to constrain or validate NP models.

Experimental measurements of the BFs and hadronic transition FFs of $D^+ \to \bar{K}^{*0}\ell^+\nu_\ell$ ($\ell = e, \mu$) via $\bar{K}^{*0} \to K^-\pi^+$ have been reported by several experiments [32–43]. This Letter presents the first measurement of averaged angular observables and CP asymmetries in the full set of angular distributions and asymmetries in the decay rates of $D^+ \to \bar{K}^{*0}\ell^+\nu_\ell$ as well as the BF and FF measurements, via $\bar{K}^{*0} \to K_S^0\pi^0$. This $\bar{K}^{*0}$ decay mode avoids large misidentification rate between π^+ and μ^+ for $\bar{K}^{*0} \to K^-\pi^+$. In addition, we test $\mu - e$ LFU for $D^+ \to \bar{K}^{*0}\ell^+\nu_\ell$ in the full q^2 range and in five q^2 intervals.

Our measurement is based on five independent kinematic variables: the squared invariant masses of the dihadron and dilepton systems, $m^2 \equiv m^2(K_S^0\pi^0)$ and $q^2 \equiv m^2(\ell^+\nu_\ell)$,

[*]Full author list given at the end of the Letter.

and three decay angles θ_ℓ, θ_K, and χ (see Fig. 1 in Supplemental Material [44]). The decay angles are defined as follows: θ_K is the angle between the momentum of the kaon in the $K\pi$ rest frame and the direction of the $K\pi$ system in the D rest frame; θ_ℓ is the angle between the momentum of the charged lepton in the $\ell\nu_\ell$ rest frame and the direction of the $\ell\nu_\ell$ system in the D rest frame; and χ is the angle between the normals to the planes defined in the D rest frame by the $K\pi$ and $\ell\nu_\ell$ pairs, respectively [47]. When analyzing D^- decays, the sign of χ is reversed.

The five-dimensional differential decay rate for $D^+ \to K_S^0\pi^0\ell^+\nu_\ell$ can be expressed in terms of nine angular coefficients $\mathcal{I}_{1-9}$, which depend on m^2, q^2, and $\cos\theta_K$ [47–52], as

$$\frac{d^5\Gamma}{dm^2dq^2d\cos\theta_K d\cos\theta_\ell d\chi} = \frac{G_F^2|V_{cs}|^2}{(4\pi)^6 m_D^3}\lambda\beta_m\beta_\ell\Big(\mathcal{I}_1 + \mathcal{I}_2\cos 2\theta_\ell + \mathcal{I}_3\sin^2\theta_\ell\cos 2\chi + \mathcal{I}_4\sin 2\theta_\ell\cos\chi + \mathcal{I}_5\sin\theta_\ell\cos\chi + \mathcal{I}_6\cos\theta_\ell + \mathcal{I}_7\sin\theta_\ell\sin\chi + \mathcal{I}_8\sin 2\theta_\ell\sin\chi + \mathcal{I}_9\sin^2\theta_\ell\sin 2\chi\Big). \quad (1)$$

The prefactor contains Fermi coupling constant G_F, CKM matrix element V_{cs}, and the mass of D (m_D). Other parameters include $\lambda = p_{K\pi}m_D$, with $p_{K\pi}$ the $K\pi$ momentum in the D rest frame, $\beta_m = 2p^*/m$, where p^* is the kaon momentum in the $K\pi$ rest frame and m the $K\pi$ invariant mass, and β_ℓ defined analogously to β_m but for the $\ell\nu_\ell$ system.

Hadronic transition FFs are measured by performing an unbinned maximum likelihood fit to the decay rate expressed in terms of the SM helicity amplitudes [see Eqs. (6) and (7) in Supplemental Material [44]]. The amplitude analysis includes components for the $\bar{K}^{*0}$ resonance and a $(K_S^0\pi^0)_{S\text{-wave}}$ [see Eqs. (11) and (15) in Supplemental Material [44]].

The asymmetry of the total decay widths, Γ, between D^+ and D^- decays is defined as $A_{CP} \equiv \{[\Gamma(D^+ \to \bar{K}^{*0}\ell^+\nu_\ell) - \Gamma(D^- \to K^{*0}\ell^-\bar{\nu}_\ell)]/[\Gamma(D^+ \to \bar{K}^{*0}\ell^+\nu_\ell) + \Gamma(D^- \to K^{*0}\ell^-\bar{\nu}_\ell)]\}$. The eight coefficients $\mathcal{I}_{2-9}$ can be obtained by defining piecewise angular-integration ranges in χ and $\cos\theta_\ell$. For example, the unnormalized coefficient $\mathcal{I}_2$ is obtained as

$$\mathcal{I}_2 = \int_{-\pi}^{\pi} d\chi\left[\int_{-1}^{-0.5} d\cos\theta_\ell + \int_{0.5}^{1} d\cos\theta_\ell - \int_{-0.5}^{0.5} d\cos\theta_\ell\right]\frac{d^5\Gamma}{dq^2dm^2d\cos\theta_K d\cos\theta_\ell d\chi}. \quad (2)$$

Corresponding integration ranges to obtain unnormalized $\mathcal{I}_{3-9}$ are listed in Supplemental Material [44]. Since the term $\mathcal{I}_1$ has no dependence on the decay angles, it provides only a normalization factor and is not considered in this Letter. The normalized and integrated observables $\langle\mathcal{I}_i\rangle$ are defined as

$$\langle\mathcal{I}_{2,3,6,9}\rangle = \frac{1}{\Gamma}\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \int_{m^2_{\min}}^{m^2_{\max}} dm^2 \int_{-1}^{+1} d\cos\theta_K \mathcal{I}_{2,3,6,9},$$

$$\langle\mathcal{I}_{4,5,7,8}\rangle = \frac{1}{\Gamma}\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \int_{m^2_{\min}}^{m^2_{\max}} dm^2 \left[\int_{0}^{+1} d\cos\theta_K - \int_{-1}^{0} d\cos\theta_K\right]\mathcal{I}_{4,5,7,8}. \quad (3)$$

In addition to the full q^2 range, five different integration ranges (bins) in q^2 are defined. The integration in $\cos\theta_K$ is defined to optimize the sensitivity to beyond-SM effects by integrating out contributions from the dominant P-wave $\bar{K}^{*0}$ resonance in the dihadron system, the integration regions differ since $\mathcal{I}_{2,3,6,9}$ are even in $\cos\theta_K$, while $\mathcal{I}_{4,5,7,8}$ are odd. Experimentally, the observables are determined by measuring the decay-rate asymmetries in the data split according to piecewise-defined angular regions. As an example, from Eqs. (2) and (3), $\langle\mathcal{I}_2\rangle$ is measured as

$$\langle\mathcal{I}_2\rangle = \frac{1}{\Gamma}[\Gamma(|\cos\theta_\ell| > 0.5) - \Gamma(|\cos\theta_\ell| < 0.5)]. \quad (4)$$

The observables $\langle\mathcal{I}_i\rangle$, measured separately for D^+ and D^- mesons, are labeled as $\langle\mathcal{I}_i\rangle$ and $\langle\bar{\mathcal{I}}_i\rangle$, respectively. Their CP average S_i and asymmetry A_i are defined as $\langle S_i\rangle = [\langle\mathcal{I}_i\rangle + \langle\bar{\mathcal{I}}_i\rangle]$ and $\langle A_i\rangle = [\langle\mathcal{I}_i\rangle - \langle\bar{\mathcal{I}}_i\rangle]$. The well-known forward-backward asymmetry $A_{\rm FB}$ [53] and triple-product asymmetry $A_{\rm TP}$ [54] are related to $\langle S_6\rangle$ and $\langle S_9\rangle$, respectively. If only SM amplitudes contribute to the decay processes, the CP-averaged observables $\langle S_{7,8,9}\rangle$ are predicted to vanish and constitute SM null tests together with the CP asymmetries $\langle A_{2-9}\rangle$.

The BESIII detector [55,56] 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 inclusive Monte Carlo (MC) sample, described in Refs. [57–61], detailed in Supplemental Material [44], has been validated for background simulation. The signal decays $D^+ \to K_S^0\pi^0\ell^+\nu_\ell$ are generated with the helicity amplitude of $\bar{K}^{*0}$ and LASS formalism of $(K_S^0\pi^0)_{S\text{-wave}}$ [62,63], with parameters obtained in this Letter.

At $\sqrt{s} = 3.773$ GeV, the $D\bar{D}$ meson pairs are produced without accompanying particles in the final state. This property allows us to study semileptonic D decays with the double-tag (DT) method. In this method, a single-tag (ST) event is one in which a D^- meson is fully reconstructed via one of the six hadronic decay modes $K^+\pi^-\pi^-$, $K_S^0\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S^0\pi^-\pi^0$, $K_S^0\pi^+\pi^-\pi^-$, and $K^+K^-\pi^-$. A DT event is selected by reconstructing the signal-side decay $D^+ \to K_S^0\pi^0\ell^+\nu_\ell$, where $K_S^0 \to \pi^+\pi^-$, in the presence of an ST candidate. The BF of the signal decay is determined by $\mathcal{B}_{\rm sig} = (N_{\rm DT}/N_{\rm ST}^{\rm tot}\bar{\epsilon}_{\rm sig})$, where $N_{\rm ST}^{\rm tot} = \sum_j N_{\rm ST}^j$ is the total number of ST events summed over all tag modes, and $N_{\rm DT}$ is the total number of DT events; $\bar{\epsilon}_{\rm sig} = \sum_j (N_{\rm ST}^j/N_{\rm ST}^{\rm tot})(\epsilon_{\rm DT}^j/\epsilon_{\rm ST}^j)$ is the averaged signal efficiency of selecting $D^+ \to K_S^0\pi^0\ell^+\nu_\ell$ in the presence of the ST D^- meson, where $\epsilon_{\rm ST}^j$ and $\epsilon_{\rm DT}^j$ are the ST and DT efficiencies for the jth ST mode, respectively. A correction factor is applied to account for data-MC discrepancies in the signal efficiencies [44].

The selection criteria of $\pi^\pm, K^\pm, K_S^0, \gamma$, and π^0 candidates are widely used in our previous works [64,65], and details are provided in Supplemental Material [44]. Two kinematic variables, the energy difference $\Delta E \equiv E_{D^-} - E_{\rm beam}$ and the beam-constrained mass $M_{\rm BC} \equiv \sqrt{E_{\rm beam}^2/c^4 - |\vec{p}_{D^-}|^2/c^2}$, are used to distinguish the ST D^- mesons from combinatorial backgrounds, where $E_{\rm beam}$ is the beam energy and $(E_{D^-}, \vec{p}_{D^-})$ is the four-momentum of the ST D^- in the e^+e^- rest frame. The combination with the smallest $|\Delta E|$ is chosen if multiple combinations are in an event.

The ST candidates are required to satisfy mode-dependent requirements on ΔE corresponding to $\pm 3.5\sigma$ around the fitted peaks. The ST yields in data for each ST mode are extracted by fitting individual $M_{\rm BC}$ distributions. Candidates with $M_{\rm BC} \in [1.863, 1.877]$ GeV$/c^2$ are retained for further analysis. The ΔE requirements, the ST yields in data, and the ST efficiencies for different ST modes are listed in Supplemental Material [44]. Summing over all ST modes yields a total of $N_{\rm ST}^{\rm tot} = (10646.9 \pm 4.0) \times 10^3$ ST candidates.

In the presence of the ST D^-, candidates for $D^+ \to K_S^0\pi^0\ell^+\nu_\ell$ are selected from the remaining tracks and showers. The selection criteria of K_S^0, and π^0 candidates are the same as ST selection. The ℓ^+ candidates are selected by performing PID with the specific ionization energy loss in the MDC dE/dx, time of flight, EMC information, based on which likelihoods for positron, muon, pion, and kaon hypotheses $\mathcal{L}_{e,\mu,\pi,K}$ are calculated. The e^+ is identified with $\mathcal{L}_e > 0.8(\mathcal{L}_K + \mathcal{L}_e + \mathcal{L}_\pi)$ and $\mathcal{L}(e) > 0.001$, while the μ^+ candidate must satisfy $\mathcal{L}(\mu) > \mathcal{L}(e), \mathcal{L}(\mu) > \mathcal{L}(K), \mathcal{L}(\mu) > \mathcal{L}(\pi)$, and $\mathcal{L}(\mu) > 0.001$. To further distinguish ℓ^+ candidates from hadronic backgrounds, the requirements $E_{\rm EMC}^\mu < 0.3$ GeV and $E_{\rm EMC}^e/(p \cdot c) \in (0.4, 1.4)$ are imposed on μ^+ and e^+ candidates, respectively where $E_{\rm EMC}$ is the energy deposited in the EMC and p is the MDC momentum. Furthermore, the maximum energy of the extra photon, $E_\gamma^{\rm max}$, is required to be less than 0.2 GeV for the μ^+ channel and 0.5 GeV for the e^+ channel.

Since the neutrino cannot be directly detected, its four-momentum $(E_{\rm miss}, \vec{p}_{\rm miss})$ is obtained by calculating the missing energy and momentum, defined as $E_{\rm miss} \equiv E_{\rm beam} - \sum_k E_k$ and $\vec{p}_{\rm miss} \equiv \vec{p}_{D^-} - \sum_k \vec{p}_k$. Here, the index k sums over the K_S^0, π^0 and ℓ^+ of the signal candidate and $(E_k, \vec{p}_k)$ is the four-momentum of the kth particle. A kinematic variable $U_{\rm miss} \equiv E_{\rm miss} - |\vec{p}_{\rm miss}|c$ is defined to extract the signal yield. To further improve the resolution of the missing momentum, the D^- momentum is constrained as $\vec{p}_{D^-} = -\hat{p}_{D^-}\sqrt{E_{\rm beam}^2/c^2 - m_{D^-}^2 c^2}$, where $\hat{p}_{D^-}$ is the unit vector in the momentum direction of the ST D^- meson, and m_{D^-} is the nominal mass of the D^- meson [66].

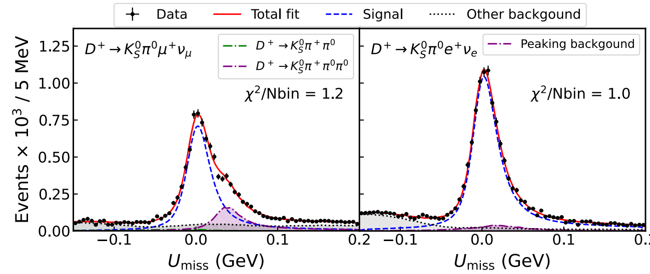

FIG. 1. Fits to the $U_{\rm miss}$ distributions of the accepted candidates.

The potential background from $D^+ \to K_S^0\pi^+\pi^0$ is suppressed by requiring the $K_S^0\pi^0\ell^+$ invariant mass to satisfy $M_{K_S^0\pi^0\ell^+} < 1.6(1.8)$ GeV$/c^2$ for the μ^+ (e^+) channel.

The signal yields of $D^+ \to K_S^0\pi^0\mu^+\nu_\mu$ and $D^+ \to K_S^0\pi^0 e^+\nu_e$ are determined to be $6767 \pm 126_{\rm stat}$ and $11095 \pm 137_{\rm stat}$, from an unbinned maximum-likelihood fit on the $U_{\rm miss}$ distributions of the accepted candidates, as shown in Fig. 1. In the fit, the signal shape is modeled using the MC simulation, convolved with a Gaussian resolution function with free parameters, and the background shape is derived from the inclusive MC sample. For the μ^+ channel, the yield of peaking background $D^+ \to K_S^0\pi^+\pi^0$ is fixed according to MC simulation, while the yields of both the $D^+ \to K_S^0\pi^+\pi^0\pi^0$ peaking background and other flatter backgrounds are separately floating. For the e^+ channel, the yields of peaking backgrounds $D^+ \to K_S^0\pi^+\pi^0$, $D^+ \to K_S^0\pi^0\mu^+\nu_\mu$, and $D^0 \to K_S^0\pi^- e^+\nu_e$ are fixed according to MC simulation, while the remaining background yield is floated. The first two are due to the misidentification of leptons, while the last one is due to particle exchange between tag and signal sides. The signal efficiencies are estimated to be $(10.44 \pm 0.04_{\rm stat})\%$ and $(17.09 \pm 0.05_{\rm stat})\%$ for the μ^+ and e^+ channels, based on signal MC samples generated according to our amplitude analysis results for the helicity amplitudes of $\bar{K}^{*0}$ and the LASS formalism for the $(K_S^0\pi^0)_{S\text{-wave}}$. The BFs of $D^+ \to K_S^0\pi^0\mu^+\nu_\mu$ and $D^+ \to K_S^0\pi^0 e^+\nu_e$ are determined to be $0.896 \pm 0.017_{\rm stat} \pm 0.008_{\rm syst}$ and $0.943 \pm 0.012_{\rm stat} \pm 0.010_{\rm syst}$, respectively.

The systematic uncertainties in the BF measurement are discussed below. The uncertainties of $\mu^+(e^+)$ tracking, 0.2% (0.2%), PID, 0.3% (0.2%), K_S^0 reconstruction, 0.2% (0.2%), and π^0 reconstruction, 0.2% (0.2%), are estimated

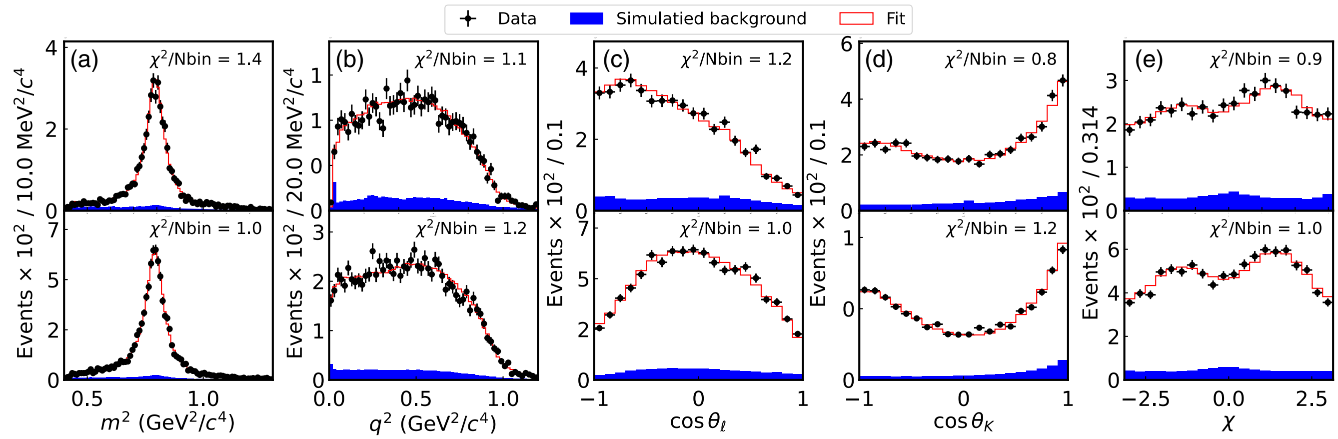

FIG. 2. Projections of the data and amplitude analysis fits for the (top) μ^+ and (bottom) e^+ channels.

using $e^+e^- \to \gamma\mu^+\mu^-$ events, $e^+e^- \to \gamma e^+e^-$ events and DT D^-D^+ hadronic events, respectively. The uncertainties associated with the $E_\gamma^{\rm max}$, $N_{\rm extra}^{\rm track}$, and $N_{\rm extra}^{\pi^0}$ requirements and $M_{K_S^0\pi^0\ell^+}$ requirements are estimated to be 0.6% (0.6%) with a control sample of $D^+ \to K_S^0\pi^+\pi^0(\pi^0)$. The uncertainty associated with the fit to the $U_{\rm miss}$ distribution is estimated to be 0.3% (0.7%) by varying the shapes and fixed normalizations. The common uncertainty in the ST D^- yield is due to the fit to the $M_{\rm BC}$ distributions assigned as 0.3% by varying the signal and background shapes. The uncertainty related to the signal MC model is taken as 0.2% (0.2%), which is the change of the DT efficiencies via varying the input parameters by $\pm1\sigma$. Common uncertainties due to the limited MC statistics, 0.2%, and the quoted BF of $K_S^0 \to \pi^+\pi^-$, 0.1%, are also included. The total systematic uncertainties are 0.9% and 1.1% for the μ^+ and e^+ channels, respectively.

Using the SM helicity-amplitude expansion, we perform an unbinned maximum-likelihood fit to extract the hadronic transition FFs. To select high-purity samples, a strict requirement $|U_{\rm miss}| < 0.02(0.05)$ GeV is used for the μ^+ (e^+) channel. After selection, 4170 μ^+ and 8929 e^+ candidate events survive with background fractions of $(13.3 \pm 0.3)\%$ and $(9.1 \pm 0.2)\%$, respectively. The helicity FFs are expressed in terms of two axial-vector FFs, $A_1(q^2)$ and $A_2(q^2)$, and one vector FF, $V(q^2)$. The FFs are all described with a simple pole form $A_{1,2}(q^2) = A_{1,2}(0)/(1 - q^2/M_A^2)$ and $V(q^2) = V(0)/(1 - q^2/M_V^2)$, with pole masses $M_V = 1.81$ GeV$/c^2$ and $M_A = 2.61$ GeV$/c^2$ fixed according to Ref. [42]. The FF ratios, $r_V = V(0)/A_1(0)$ and $r_2 = A_2(0)/A_1(0)$, are determined from the fit. The S-wave amplitude parameterization is taken from Refs. [41,42], in which the scattering length, $a_{\rm S,BG}^{1/2}$, and the relative intensity, r_S, are determined by the fit. The dimensionless coefficient, $r_S^{(1)}$, and the effective range, $b_{\rm S,BG}^{1/2}$, are fixed to 0.08 and -0.81 (GeV$/c)^{-1}$ [42]. The background shape is modeled with the inclusive MC sample using the XGBoost algorithm [67]. Simultaneous fits are performed to the μ^+ and e^+ channels by minimizing the sum of their negative log-likelihood functions. Figure 2 shows the projections of the nominal fit result. The fitted parameters and the fit fractions are summarized in Table I.

The systematic uncertainties are evaluated as the difference between the nominal fit results and those obtained after changing a variable or a condition by an amount corresponding to the estimated uncertainty of that quantity. The detailed fitting systematic studies are discussed in Supplemental Material [44].

Each angular observable, and A_{CP}, is determined from the partial decay rate $d\Gamma_i/dq_i^2$(Tag), where "Tag" refers to the angular and flavor tags defined by the piecewise integration from Eqs. (2) and (3). The partial decay rate depends on the yield in each Tag and q^2 bin, and the yields are measured independently through the same fit methods used for the BF measurement but with the candidates split by Tag and q^2 region. The fits use the same modeling described earlier, including the same treatment of floating components, but with shapes determined independently in each Tag and q^2 region. The results for $\langle A_i\rangle$, $\langle S_i\rangle$, and A_{CP}, including both statistical and systematic uncertainties

TABLE I. The fitted parameters for the amplitude analysis, where the first and second uncertainties are statistical and systematic, respectively.

Variable	$D^+ \to K_S^0\pi^0 e^+\nu_e$	$D^+ \to K_S^0\pi^0\mu^+\nu_\mu$
$m_{\bar{K}^{*0}}$ (MeV$/c^2$)	$897.3 \pm 0.3 \pm 2.2$	
$\Gamma_{\bar{K}^{*0}}$ (MeV$/c^2$)	$45.2 \pm 0.6 \pm 0.5$	
r_V	$1.42 \pm 0.03 \pm 0.02$	
r_2	$0.75 \pm 0.03 \pm 0.01$	
$a_{\rm S,BG}^{1/2}$ (GeV$/c)^{-1}$	$2.32 \pm 0.11 \pm 0.25$	$1.47 \pm 0.25 \pm 0.22$
r_S (GeV)$^{-1}$	$-8.44 \pm 0.13 \pm 0.37$	$-9.59 \pm 0.46 \pm 0.58$
$f_{S\text{-wave}}$	$6.39 \pm 0.17 \pm 0.14$	$7.10 \pm 0.68 \pm 0.41$
$f_{\bar{K}^{*0}}$	$93.50 \pm 0.18 \pm 0.28$	$92.81 \pm 0.67 \pm 0.47$

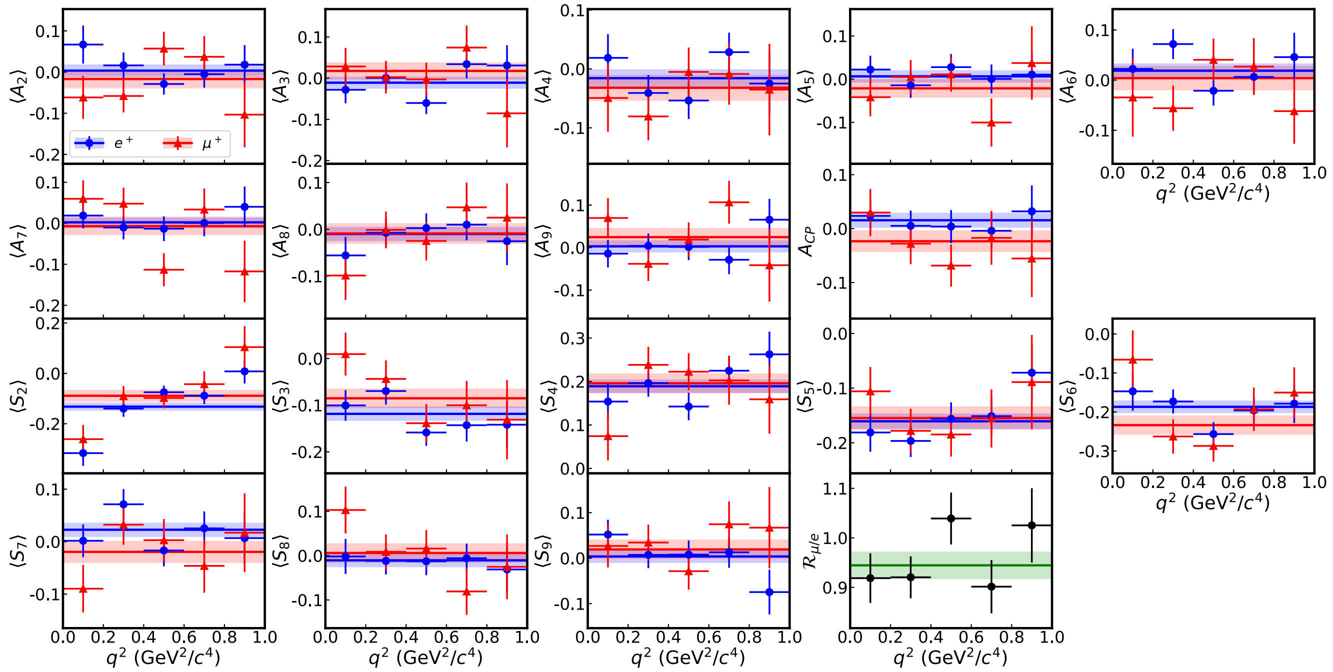

FIG. 3. Measured observables $\langle A_i \rangle$, $\langle S_i \rangle$, $\mathcal{R}_{\mu/e}$ and the CP asymmetry for $D^+ \to \bar{K}^{*0}\ell^+\nu_\ell$ in different q^2 regions with $0.8 < m_{\bar{K}^{*0}} < 1.0$ GeV$^2/c^4$. The e^+ (μ^+) results are shown in blue (red). The horizontal lines and shaded bands represent the mean value and 1 standard deviation across full q^2 range.

added in quadrature, are shown in Fig. 3. A tabulated version is given in Supplemental Material [44]. In general, the null-test observables show agreement with the SM predictions of zero.

The systematic uncertainties typically range from negligible to 50% of the statistical uncertainty, depending on the observable and the q^2 region. These arise from the following sources: the model used in the $U_{\rm miss}$ fits, the D^- ST yield, the input D^+ lifetime, the estimation of the efficiency correction, and the limited size of the MC simulation sample. The leading systematic uncertainties are from the $U_{\rm miss}$ fits; these are evaluated by repeating the analysis after either changing the simulation shape or fixed yield, the largest contribution from the background shape, or the fixed peaking background yield.

The ratio of the BFs between $D^+ \to K_S^0\pi^0\mu^+\nu_\mu$ and $D^+ \to K_S^0\pi^0 e^+\nu_e$ is determined to be $\mathcal{R}_{\mu/e} = 0.94 \pm 0.02_{\rm stat} \pm 0.01_{\rm syst}$, which is consistent with the SM predictions from 0.92 to 0.95 [18]. The values of $\mathcal{R}_{\mu/e}$ in different q^2 intervals are shown in Fig. 3. Here, the correlated systematic uncertainties associated with the reconstruction of K_S^0 and π^0, $E_\gamma^{\rm max}, N_{\rm extra}^{\rm track}, N_{\rm extra}^{\pi^0}$, and $K_S^0\pi^0\ell^+$ requirements, as well as the quoted BF and MC model, largely cancel out. The results in q^2 bins are all consistent with the SM predictions.

In summary, using 20.3 fb^{-1} [68] of e^+e^- collision data taken at $\sqrt{s} = 3.773$ GeV with the BESIII detector, the first measurement of full set of CP asymmetries and averaged angular observables with A_{CP} in the decays $D^+ \to \bar{K}^{*0}\ell^+\nu_\ell$ via $\bar{K}^{*0} \to K_S^0\pi^0$ is reported. All measured null-test observables A_{CP}, $\langle S_{7-9} \rangle$ and $\langle A_{2-9} \rangle$ are in agreement with the SM predictions, with the largest deviation being 1.7σ. These results help constrain the parameters of physics models extending the SM. In addition, the absolute BF of $D^+ \to K_S^0\pi^0\mu^+\nu_\mu$ is measured for the first time, and the absolute BF of $D^+ \to K_S^0\pi^0 e^+\nu_e$ is measured with improved precision. By analyzing the $D^+ \to K_S^0\pi^0\ell^+\nu_\ell$ decay dynamics, the fraction of the P-wave component and the hadronic FF ratios of $D^+ \to \bar{K}^{*0}$ are presented. We have also tested LFU with $D^+ \to \bar{K}^{*0}\ell^+\nu_\ell$ integrated over q^2 as well as in five q^2 intervals, and no LFU violation is observed.

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Jiang,[1,59,65] Y. Jiang,[65] J. B. Jiao,[51] J. K. Jiao,[35] Z. Jiao,[24] S. Jin,[43] Y. Jin,[68] M. Q. Jing,[1,65] X. M. Jing,[65] T. Johansson,[77] S. Kabana,[34] N. Kalantar-Nayestanaki,[66] X. L. Kang,[9] X. S. Kang,[41] M. Kavatsyuk,[66] B. C. Ke,[82] V. Khachatryan,[28] A. Khoukaz,[70] R. Kiuchi,[1] O. B. Kolcu,[63a] B. Kopf,[3] M. Kuessner,[3] X. Kui,[1,65] N. Kumar,[27] A. Kupsc,[45,77] W. Kühn,[38] Q. Lan,[74] W. N. Lan,[20] T. T. Lei,[73,59] M. Lellmann,[36] T. Lenz,[36] C. Li,[48] C. Li,[73,59] C. Li,[44] C. H. Li,[40] C. K. Li,[21] D. M. Li,[82] F. Li,[1,59] G. Li,[1] H. B. Li,[1,65] H. J. Li,[20] H. N. Li,[57,j] Hui Li,[44] J. R. Li,[62] J. S. Li,[60] K. Li,[1] K. L. Li,[20] K. L. Li,[39,k,l] L. J. Li,[1,65] Lei Li,[49] M. H. Li,[44] M. R. Li,[1,65] P. L. Li,[65] P. R. Li,[39,k,l] Q. M. Li,[1,65] Q. X. Li,[51] R. Li,[18,32] S. X. Li,[12] T. Li,[51] T. Y. Li,[44] W. D. Li,[1,65] W. G. Li,[1,a] X. Li,[1,65] X. H. Li,[73,59] X. L. Li,[51] X. Y. Li,[1,8] X. Z. Li,[60] Y. Li,[20] Y. G. Li,[47,h] Y. P. Li,[35] Z. J. Li,[60] Z. Y. Li,[80] H. Liang,[73,59] Y. F. Liang,[55] Y. T. Liang,[32,65] G. R. Liao,[14] L. B. Liao,[60] M. H. Liao,[60] Y. P. Liao,[1,65] J. Libby,[27] A. Limphirat,[61] C. C. Lin,[56] D. X. Lin,[32,65] L. Q. Lin,[40] T. Lin,[1] B. J. Liu,[1] B. X. Liu,[78] C. Liu,[35] C. X. Liu,[1] F. Liu,[1] F. H. Liu,[54] Feng Liu,[6] G. M. Liu,[57,j] H. Liu,[39,k,l] H. B. Liu,[15] H. H. Liu,[1] H. M. Liu,[1,65] Huihui Liu,[22] J. B. Liu,[73,59] J. J. Liu,[21] K. Liu,[39,k,l] K. Liu,[74] K. Y. Liu,[41] Ke Liu,[23] L. C. Liu,[44] Lu Liu,[44] M. H. Liu,[12,g] P. L. Liu,[1] Q. Liu,[65] S. B. Liu,[73,59] T. Liu,[12,g] W. K. Liu,[44] W. M. Liu,[73,59] W. T. Liu,[40] X. Liu,[39,k,l] X. Liu,[40] X. K. Liu,[39,k,l] X. Y. Liu,[78] Y. Liu,[82] Y. Liu,[39,k,l] Y. Liu,[82] Y. B. Liu,[44] Z. A. Liu,[1,59,65] Z. D. Liu,[9] Z. Q. Liu,[51] X. C. Lou,[1,59,65] F. X. Lu,[60] H. J. Lu,[24] J. G. Lu,[1,59] X. L. Lu,[16] Y. Lu,[7] Y. H. Lu,[1,65] Y. P. Lu,[1,59] Z. H. Lu,[1,65] C. L. Luo,[42] J. R. Luo,[60] J. S. Luo,[1,65] M. X. Luo,[81] T. Luo,[12,g] X. L. Luo,[1,59] Z. Y. Lv,[23] X. R. Lyu,[65,p] Y. F. Lyu,[44] Y. H. Lyu,[82] F. C. Ma,[41] H. L. Ma,[1] J. L. Ma,[1,65] L. L. Ma,[51] L. R. Ma,[68] Q. M. Ma,[1] R. Q. Ma,[1,65] R. Y. Ma,[20] T. Ma,[73,59] X. T. Ma,[1,65] X. Y. Ma,[1,59] Y. M. Ma,[32] F. E. Maas,[19] I. MacKay,[71] M. Maggiora,[76a,76c] S. Malde,[71] Q. A. Malik,[75] H. X. Mao,[39,k,l] Y. J. Mao,[47,h] Z. P. Mao,[1] S. Marcello,[76a,76c] A. Marshall,[64] F. M. Melendi,[30a,30b] Y. H. Meng,[65] Z. X. Meng,[68] G. Mezzadri,[30a] H. Miao,[1,65] T. J. Min,[43] R. E. Mitchell,[28] X. H. Mo,[1,59,65] B. Moses,[28] N. Yu. Muchnoi,[4,c] J. Muskalla,[36] Y. Nefedov,[37] F. Nerling,[19,e] L. S. Nie,[21] I. B. Nikolaev,[4,c] Z. Ning,[1,59] S. Nisar,[11,m] Q. L. Niu,[39,k,l] W. D. Niu,[12,g] C. Normand,[64] S. L. Olsen,[10,65] Q. Ouyang,[1,59,65] S. Pacetti,[29b,29c] X. Pan,[56] Y. Pan,[58] A. Pathak,[10] Y. P. Pei,[73,59] M. Pelizaeus,[3] H. P. Peng,[73,59] X. J. Peng,[39,k,l] Y. Y. Peng,[39,k,l] K. Peters,[13,e] K. Petridis,[64] J. L. Ping,[42] R. G. Ping,[1,65] S. Plura,[36] V. Prasad,[35] F. Z. Qi,[1] H. R. Qi,[62] M. Qi,[43] S. Qian,[1,59] W. B. Qian,[65] C. F. Qiao,[65] J. H. Qiao,[20] J. J. Qin,[74] J. L. Qin,[56] L. Q. Qin,[14] L. Y. Qin,[73,59] P. B. Qin,[74] X. P. Qin,[12,g] X. S. Qin,[51] Z. H. Qin,[1,59] J. F. Qiu,[1] Z. H. Qu,[74] J. Rademacker,[64] C. F. Redmer,[36] A. Rivetti,[76c] M. Rolo,[76c] G. Rong,[1,65] S. S. Rong,[1,65] F. Rosini,[29b,29c] Ch. Rosner,[19] M. Q. Ruan,[1,59] N. Salone,[45] A. Sarantsev,[37,d] Y. Schelhaas,[36] K. Schoenning,[77] M. Scodeggio,[30a] K. Y. Shan,[12,g] W. Shan,[25] X. Y. Shan,[73,59] Z. J. Shang,[39,k,l] J. F. Shangguan,[17] L. G. Shao,[1,65] M. Shao,[73,59] C. P. Shen,[12,g] H. F. Shen,[1,8] W. H. Shen,[65]

X. Y. Shen,[1,65] B. A. Shi,[65] H. Shi,[73,59] J. L. Shi,[12,g] J. Y. Shi,[1] S. Y. Shi,[74] X. Shi,[1,59] H. L. Song,[73,59] J. J. Song,[20] T. Z. Song,[60] W. M. Song,[35] Y. J. Song,[12,g] Y. X. Song,[47,h,n] S. Sosio,[76a,76c] S. Spataro,[76a,76c] F. Stieler,[36] S. S. Su,[41] Y. J. Su,[65] G. B. Sun,[78] G. X. Sun,[1] H. Sun,[65] H. K. Sun,[1] J. F. Sun,[20] K. Sun,[62] L. Sun,[78] S. S. Sun,[1,65] T. Sun,[52,f] Y. C. Sun,[78] Y. H. Sun,[31] Y. J. Sun,[73,59] Y. Z. Sun,[1] Z. Q. Sun,[1,65] Z. T. Sun,[51] C. J. Tang,[55] G. Y. Tang,[1] J. Tang,[60] J. J. Tang,[73,59] L. F. Tang,[40] Y. A. Tang,[78] L. Y. Tao,[74] M. Tat,[71] J. X. Teng,[73,59] J. Y. Tian,[73,59] W. H. Tian,[60] Y. Tian,[32] Z. F. Tian,[78] I. Uman,[63b] B. Wang,[60] B. Wang,[1] Bo Wang,[73,59] C. Wang,[39,k,l] C. Wang,[20] Cong Wang,[23] D. Y. Wang,[47,h] H. J. Wang,[39,k,l] J. J. Wang,[78] K. Wang,[1,59] L. L. Wang,[1] L. W. Wang,[35] M. Wang,[73,59] M. Wang,[51] N. Y. Wang,[65] S. Wang,[12,g] T. Wang,[12,g] T. J. Wang,[44] W. Wang,[60] W. Wang,[74] W. P. Wang,[36,59,73,o] X. Wang,[47,h] X. F. Wang,[39,k,l] X. J. Wang,[40] X. L. Wang,[12,g] X. N. Wang,[1] Y. Wang,[62] Y. D. Wang,[46] Y. F. Wang,[1,8,65] Y. H. Wang,[39,k,l] Y. J. Wang,[73,59] Y. L. Wang,[20] Y. N. Wang,[78] Y. Q. Wang,[1] Yaqian Wang,[18] Yi Wang,[62] Yuan Wang,[18,32] Z. Wang,[1,59] Z. L. Wang,[2] Z. L. Wang,[74] Z. Q. Wang,[12,g] Z. Y. Wang,[1,65] D. H. Wei,[14] H. R. Wei,[44] F. Weidner,[70] S. P. Wen,[1] Y. R. Wen,[40] U. Wiedner,[3] G. Wilkinson,[71] M. Wolke,[77] C. Wu,[40] J. F. Wu,[1,8] L. H. Wu,[1] L. J. Wu,[1,65] L. J. Wu,[20] Lianjie Wu,[20] S. G. Wu,[1,65] S. M. Wu,[65] X. Wu,[12,g] X. H. Wu,[35] Y. J. Wu,[32] Z. Wu,[1,59] L. Xia,[73,59] X. M. Xian,[40] B. H. Xiang,[1,65] D. Xiao,[39,k,l] G. Y. Xiao,[43] H. Xiao,[74] Y. L. Xiao,[12,g] Z. J. Xiao,[42] C. Xie,[43] K. J. Xie,[1,65] X. H. Xie,[47,h] Y. Xie,[51] Y. G. Xie,[1,59] Y. H. Xie,[6] Z. P. Xie,[73,59] T. Y. Xing,[1,65] C. F. Xu,[1,65] C. J. Xu,[60] G. F. Xu,[1] H. Y. Xu,[68,2] H. Y. Xu,[2] M. Xu,[73,59] Q. J. Xu,[17] Q. N. Xu,[31] T. D. Xu,[74] W. Xu,[1] W. L. Xu,[68] X. P. Xu,[56] Y. Xu,[41] Y. Xu,[12,g] Y. C. Xu,[79] Z. S. Xu,[65] F. Yan,[12,g] H. Y. Yan,[40] L. Yan,[12,g] W. B. Yan,[73,59] W. C. Yan,[82] W. H. Yan,[6] W. P. Yan,[20] X. Q. Yan,[1,65] H. J. Yang,[52,f] H. L. Yang,[35] H. X. Yang,[1] J. H. Yang,[43] R. J. Yang,[20] T. Yang,[1] Y. Yang,[12,g] Y. F. Yang,[44] Y. H. Yang,[43] Y. Q. Yang,[9] Y. X. Yang,[1,65] Y. Z. Yang,[20] M. Ye,[1,59] M. H. Ye,[8,a] Z. J. Ye,[57,j] Junhao Yin,[44] Z. Y. You,[60] B. X. Yu,[1,59,65] C. X. Yu,[44] G. Yu,[13] J. S. Yu,[26,i] L. Q. Yu,[12,g] M. C. Yu,[41] T. Yu,[74] X. D. Yu,[47,h] Y. C. Yu,[82] C. Z. Yuan,[1,65] H. Yuan,[1,65] J. Yuan,[35] J. Yuan,[46] L. Yuan,[2] S. C. Yuan,[1,65] X. Q. Yuan,[1] Y. Yuan,[1,65] Z. Y. Yuan,[60] C. X. Yue,[40] Ying Yue,[20] A. A. Zafar,[75] S. H. Zeng,[64] X. Zeng,[12,g] Y. Zeng,[26,i] Y. J. Zeng,[60] Y. J. Zeng,[1,65] X. Y. Zhai,[35] Y. H. Zhan,[60] A. Q. Zhang,[1,65] B. L. Zhang,[1,65] B. X. Zhang,[1] D. H. Zhang,[44] G. Y. Zhang,[1,65] G. Y. Zhang,[20] H. Zhang,[73,59] H. Zhang,[82] H. C. Zhang,[1,59,65] H. H. Zhang,[60] H. Q. Zhang,[1,59,65] H. R. Zhang,[73,59] H. Y. Zhang,[1,59] J. Zhang,[60] J. Zhang,[82] J. J. Zhang,[53] J. L. Zhang,[21] J. Q. Zhang,[42] J. S. Zhang,[12,g] J. W. Zhang,[1,59,65] J. X. Zhang,[39,k,l] J. Y. Zhang,[1] J. Z. Zhang,[1,65] Jianyu Zhang,[65] L. M. Zhang,[62] Lei Zhang,[43] N. Zhang,[82] P. Zhang,[1,8] Q. Zhang,[20] Q. Y. Zhang,[35] R. Y. Zhang,[39,k,l] S. H. Zhang,[1,65] Shulei Zhang,[26,i] X. M. Zhang,[1] X. Y. Zhang,[41] X. Y. Zhang,[51] Y. Zhang,[74] Y. Zhang,[1] Y. T. Zhang,[82] Y. H. Zhang,[1,59] Y. M. Zhang,[40] Y. P. Zhang,[73,59] Z. D. Zhang,[1] Z. H. Zhang,[1] Z. L. Zhang,[35] Z. L. Zhang,[56] Z. X. Zhang,[20] Z. Y. Zhang,[78] Z. Y. Zhang,[44] Z. Z. Zhang,[46] Zh. Zh. Zhang,[20] G. Zhao,[1] J. Y. Zhao,[1,65] J. Z. Zhao,[1,59] L. Zhao,[73,59] L. Zhao,[1] M. G. Zhao,[44] N. Zhao,[80] R. P. Zhao,[65] S. J. Zhao,[82] Y. B. Zhao,[1,59] Y. L. Zhao,[56] Y. X. Zhao,[32,65] Z. G. Zhao,[73,59] A. Zhemchugov,[37,b] B. Zheng,[74] B. M. Zheng,[35] J. P. Zheng,[1,59] W. J. Zheng,[1,65] X. R. Zheng,[20] Y. H. Zheng,[65,p] B. Zhong,[42] C. Zhong,[20] H. Zhou,[36,51,o] J. Q. Zhou,[35] J. Y. Zhou,[35] S. Zhou,[6] X. Zhou,[78] X. K. Zhou,[6] X. R. Zhou,[73,59] X. Y. Zhou,[40] Y. X. Zhou,[79] Y. Z. Zhou,[12,g] A. N. Zhu,[65] J. Zhu,[44] K. Zhu,[1] K. J. Zhu,[1,59,65] K. S. Zhu,[12,g] L. Zhu,[35] L. X. Zhu,[65] S. H. Zhu,[72] T. J. Zhu,[12,g] W. D. Zhu,[12,g] W. D. Zhu,[42] W. J. Zhu,[1] W. Z. Zhu,[20] Y. C. Zhu,[73,59] Z. A. Zhu,[1,65] X. Y. Zhuang,[44] J. H. Zou,[1] and J. Zu[73,59]

(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]*China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China*
[9]*China University of Geosciences, Wuhan 430074, People's Republic of China*
[10]*Chung-Ang University, Seoul, 06974, Republic of Korea*
[11]*COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan*
[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]Huangshan College, Huangshan 245000, People's Republic of China
[25]Hunan Normal University, Changsha 410081, People's Republic of China
[26]Hunan University, Changsha 410082, People's Republic of China
[27]Indian Institute of Technology Madras, Chennai 600036, India
[28]Indiana University, Bloomington, Indiana 47405, USA
[29a]INFN Laboratori Nazionali di Frascati, INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy
[29b]INFN Sezione di Perugia, I-06100, Perugia, Italy
[29c]University of Perugia, I-06100, Perugia, Italy
[30a]INFN Sezione di Ferrara, INFN Sezione di Ferrara, I-44122, Ferrara, Italy
[30b]University of Ferrara, I-44122, Ferrara, Italy
[31]Inner Mongolia University, Hohhot 010021, People's Republic of China
[32]Institute of Modern Physics, Lanzhou 730000, People's Republic of China
[33]Institute of Physics and Technology, Mongolian Academy of Sciences, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia
[34]Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile
[35]Jilin University, Changchun 130012, People's Republic of China
[36]Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
[37]Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
[38]Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany
[39]Lanzhou University, Lanzhou 730000, People's Republic of China
[40]Liaoning Normal University, Dalian 116029, People's Republic of China
[41]Liaoning University, Shenyang 110036, People's Republic of China
[42]Nanjing Normal University, Nanjing 210023, People's Republic of China
[43]Nanjing University, Nanjing 210093, People's Republic of China
[44]Nankai University, Tianjin 300071, People's Republic of China
[45]National Centre for Nuclear Research, Warsaw 02-093, Poland
[46]North China Electric Power University, Beijing 102206, People's Republic of China
[47]Peking University, Beijing 100871, People's Republic of China
[48]Qufu Normal University, Qufu 273165, People's Republic of China
[49]Renmin University of China, Beijing 100872, People's Republic of China
[50]Shandong Normal University, Jinan 250014, People's Republic of China
[51]Shandong University, Jinan 250100, People's Republic of China
[52]Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
[53]Shanxi Normal University, Linfen 041004, People's Republic of China
[54]Shanxi University, Taiyuan 030006, People's Republic of China
[55]Sichuan University, Chengdu 610064, People's Republic of China
[56]Soochow University, Suzhou 215006, People's Republic of China
[57]South China Normal University, Guangzhou 510006, People's Republic of China
[58]Southeast University, Nanjing 211100, People's Republic of China
[59]State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China
[60]Sun Yat-Sen University, Guangzhou 510275, People's Republic of China
[61]Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
[62]Tsinghua University, Beijing 100084, People's Republic of China
[63a]Turkish Accelerator Center Particle Factory Group, Istinye University, 34010, Istanbul, Turkey
[63b]Near East University, Nicosia, North Cyprus, 99138, Mersin 10, Turkey
[64]University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom
[65]University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[66]University of Groningen, NL-9747 AA Groningen, The Netherlands
[67]University of Hawaii, Honolulu, Hawaii 96822, USA
[68]University of Jinan, Jinan 250022, People's Republic of China
[69]University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
[70]University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany

[71]*University of Oxford, Keble Road, Oxford OX13RH, United Kingdom*
[72]*University of Science and Technology Liaoning, Anshan 114051, People's Republic of China*
[73]*University of Science and Technology of China, Hefei 230026, People's Republic of China*
[74]*University of South China, Hengyang 421001, People's Republic of China*
[75]*University of the Punjab, Lahore-54590, Pakistan*
[76a]*University of Turin and INFN, University of Turin, I-10125, Turin, Italy*
[76b]*University of Eastern Piedmont, I-15121, Alessandria, Italy*
[76c]*INFN, I-10125, Turin, Italy*
[77]*Uppsala University, Box 516, SE-75120 Uppsala, Sweden*
[78]*Wuhan University, Wuhan 430072, People's Republic of China*
[79]*Yantai University, Yantai 264005, People's Republic of China*
[80]*Yunnan University, Kunming 650500, People's Republic of China*
[81]*Zhejiang University, Hangzhou 310027, People's Republic of China*
[82]*Zhengzhou University, Zhengzhou 450001, People's Republic of China*

[a]Deceased.
[b]Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.
[c]Also at the Novosibirsk State University, Novosibirsk, 630090, Russia.
[d]Also at the NRC "Kurchatov Institute", PNPI, 188300, Gatchina, Russia.
[e]Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.
[f]Also 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.
[g]Also 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.
[h]Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China.
[i]Also at School of Physics and Electronics, Hunan University, Changsha 410082, China.
[j]Also at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China.
[k]Also at MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, People's Republic of China.
[l]Also at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, People's Republic of China.
[m]Also at the Department of Mathematical Sciences, IBA, Karachi 75270, Pakistan.
[n]Also at Ecole Polytechnique Federale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland.
[o]Also at Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany.
[p]Also at Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China.