First Observation of a Three-Resonance Structure in e^+e^- → Nonopen Charm Hadrons

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We report the measurement of the inclusive cross sections for $e^+e^- \to$ nOCH (where nOCH denotes non-open charm hadrons) with improved precision at center-of-mass (c.m.) energies from 3.645 to 3.871 GeV. We observe three resonances: $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ with significances of 8.1σ, 13.7σ, and 8.8σ, respectively. The $\mathcal{R}(3810)$ state is observed for the first time, while the $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ states are observed for the first time in the nOCH cross sections. Two sets of resonance parameters describe the energy-dependent line shape of the cross sections well. In set I [set II], the $\mathcal{R}(3810)$ state has mass $(3805.7 \pm 1.1 \pm 2.7)$ $[(3805.7 \pm 1.1 \pm 2.7)]$ MeV$/c^2$, total width $(11.6 \pm 2.9 \pm 1.9)$ $[(11.5 \pm 2.8 \pm 1.9)]$ MeV, and an electronic width multiplied by the nOCH decay branching fraction of $(10.9 \pm 3.8 \pm 2.5)$ $[(11.0 \pm 3.4 \pm 2.5)]$ eV. In addition, we measure the branching fractions $\mathcal{B}[\mathcal{R}(3760) \to \text{nOCH}] = (25.2 \pm 16.1 \pm 30.4)\%[(6.4 \pm 4.8 \pm 7.7)\%]$ and $\mathcal{B}[\mathcal{R}(3780) \to \text{nOCH}] = (12.3 \pm 6.6 \pm 8.3)\%[(10.4 \pm 4.8 \pm 7.0)\%]$ for the first time. The $\mathcal{R}(3760)$ state can be interpreted as an open-charm (OC) molecular state, but containing a simple four-quark state component. The $\mathcal{R}(3810)$ state can be interpreted as a hadrocharmonium state.

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Until two decades ago, it was widely believed that hadron resonances with masses higher than the open-charm (OC) pair thresholds decay entirely to OC final states via the strong interaction. However, in July, 2003, BES reported the observation of seven events of hadron resonance(s) in this mass regime decaying to nOCH [1–4]. This discovery overturned the understanding of resonance decays and opened up a new era in hadron spectroscopy. In this Letter, we denote these resonances as X_{aboveOC} [3], which encompasses both supposed pure quark-antiquark $c\bar{c}$ states, i.e., $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, and nonpure quark-antiquark $c\bar{c}$ states (hereafter referred to as 'non-$c\bar{c}$'), such as four-quark states, OC-pair molecular states, hadrocharmonium states, and hybrid charmonium states [5–8]. Quantum chromodynamics (QCD) expects that the non-$c\bar{c}$ states exist in nature, and thus a discovery of these systems would be an important validation of the QCD predictions. The first nOCH final-state decay of a X_{aboveOC} resonance to be observed after the 2002 discoveries was $J/\psi\pi^+\pi^-$ [1,2,9], seen by BES-II. This final state can originate from a $c\bar{c}$ state, a non-$c\bar{c}$ state, or a combination of both [4]. This discovery stimulated strong interest in using $J/\psi\pi^+\pi^-$ or similar final states as golden channels to probe other nOC decays from the X_{aboveOC}, and led to the discovery of several exotic states [10–20].

Subsequent studies of the $\psi(3770)$ resonance showed that it has a branching fraction of about 15% into nOCH final states [21–24]. This fact indicates the contribution of some undiscovered states [25] with masses around 3.773 GeV$/c^2$, which predominantly decay into nOCH. In 2008, the BES-II experiment observed for the first time a double-peaked structure named $\mathcal{R}s(3770)$ in $e^+e^- \to$ hadrons at c.m. energies around 3.76 GeV [26], which is composed of two states labeled $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$. The existence of the $\mathcal{R}(3760)$ state was confirmed in $e^+e^- \to J/\psi X$ by BESIII [4]. It is seen that the study of the inclusive nOCH decays of X_{aboveOC} both helps the understanding of known states, and is a sensitive probe for undiscovered resonances, particularly non-$c\bar{c}$ states.

In this Letter, we report a measurement of the cross sections for $e^+e^- \to$ nOCH at c.m. energies from 3.645 to 3.871 GeV, studies of $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ production and decays, and a search for an additional resonant state in this energy region. The data samples used in this analysis were collected at 42 c.m. energies in 2010 and correspond to a total integrated luminosity of 75.5 pb^{-1}.

The BESIII detector [27] response is studied using Monte Carlo (MC) samples. The simulations are performed using a GEANT4-based [28] software package. Simulated samples for $q\bar{q}$ vector states (i.e. $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$) and their decays to hadrons are generated using the MC event generators KKMC [29], EVTGEN [30], and LUNDCHARM [31]. Background sources are estimated with MC samples

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generated using KKMC, and the MC event generators BABAYAGA [32] and TWOGAM [33].

We select the inclusive nOCH events from the events with charged particles or charged and neutral particles. In order to reject background contributions from $e^+e^- \to (\gamma)e^+e^-$ and $e^+e^- \to (\gamma)\mu^+\mu^-$, we require the events to have more than two charged tracks (N_{CTrk}), and impose the following selection criteria for each track: (i) the distance (R_{xy}) of the point of the closest approach to the beam pipe must satisfy the condition $R_{xy} \leq 1.0$ cm; (ii) the polar angle θ must satisfy the condition $|\cos\theta| < 0.93$; (iii) the momentum p must be less than $E_{\mathrm{b}} + 0.02E_{\mathrm{b}}\sqrt{1+E_{\mathrm{b}}^2}$, where E_{b} is the beam energy; (iv) the time-of-flight t_{TOF} must satisfy $2.0 < t_{\mathrm{TOF}} < 20.0$ ns and $|t_{\mathrm{TOF}}\text{-}t_{\mathrm{p}}| < 2.0$ ns, where t_{p} is the expected time-of-flight of protons; (v) the energy E_{EMC} deposited in the electromagnetic calorimeter (EMC) must be less than 1 GeV; (vi) the penetration depth in the muon-chamber system must be less than 30 cm.

For the selection of photons, we require the deposited energy of a neutral cluster in the EMC to be greater than 25 MeV in the barrel and 50 MeV in the end caps. We do not apply any requirements on the number of photons in the event. To suppress electronic noise and showers unrelated to the event, we impose the condition that the difference between the EMC time and the event start time be within [0,700] ns. To reduce the beam-associated events (beam interactions with gas or material), we demand that at least one charged track or photon must point into each hemisphere of $\cos\theta < 0$ and $\cos\theta > 0$. In addition, for each event, we require the total energy ($E_{\mathrm{EMC}}^{\mathrm{tot}}$) deposited in the EMC by the charged and neutral particles to be greater than $0.28E_{\mathrm{b}}$.

Some beam-associated background sources still survive this selection. These background sources are produced at random z positions [21], while genuine nOCH events are produced around $z = 0$, where z is the distance to the interaction point along the BESIII axis. To distinguish the nOCH events from the background sources, we calculate the averaged z (Z_{AVRG}) of the charged tracks in each event. Figure 1 shows the distribution of the averaged Z_{AVRG} of the accepted events from the data sample collected at $\sqrt{s} = 3.779$ GeV. Using a double-Gaussian function to describe the signal shape plus a second-order Chebychev function to parameterize the background shape, we fit the Z_{AVRG} distribution of event vertices to extract the number of nOCH candidates, $N_{\mathrm{had}}^{\mathrm{fit}}$ at each energy point.

The background to the $N_{\mathrm{had}}^{\mathrm{fit}}$ distribution comes from various sources, e.g., (i) $e^+e^- \to (\gamma)e^+e^-$, (ii) $e^+e^- \to (\gamma)\mu^+\mu^-$, (iii) $e^+e^- \to \gamma\gamma$, (iv) $e^+e^- \to (\gamma)\tau^+\tau^-$, (v) $e^+e^- \to (\gamma)e^+e^-\ell^+\ell^-$ ($\ell = e$, μ or τ), (vi) $e^+e^- \to (\gamma)e^+e^-X_{\mathrm{had}}$ (where X_{had} denotes hadrons), and (vii) $e^+e^- \to (\gamma)D\bar{D}$. The total amount of background N_{b} at each c.m. energy $\sqrt{s}$ is determined by $N_{\mathrm{b}} = \sum_{i=1}^{i=7} N_{\mathrm{b},i}$ with $N_{\mathrm{b},i} = \mathcal{L} \times \sigma_{\mathrm{b},i} \times \eta_i$, where $\mathcal{L}$ is the

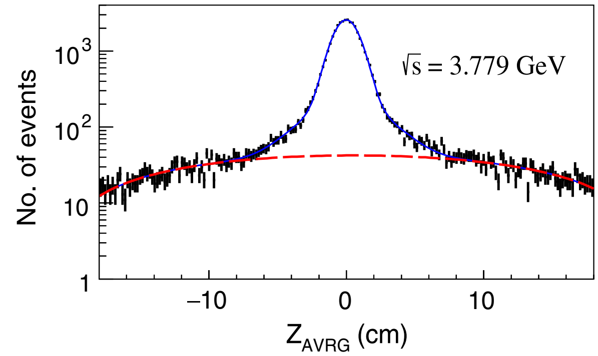

FIG. 1. Z_{AVRG} distribution of the vertices of the selected events from the data sample collected at $\sqrt{s} = 3.779$ GeV, where the dots with error bar represent data, the solid line in blue is the best fit, and the dashed line in red is the fitted background shape.

integrated luminosity of the data sample, $\sigma_{\mathrm{b},i}$ is the cross section for the ith background source and η_i is the probability of misidentifying a candidate from the ith background source as a nOCH event, which is determined by analyzing the large background MC samples. The cross sections σ_{b} for sources (i), (ii), and (iii) are taken from BABAYAGA. For source (iv), σ_{b} is calculated using the formulae given in Refs. [34,35]. The cross sections for sources (v) and (vi) are taken from TWOGAM, while that for source (vii) is taken from the observed cross sections $\sigma_{D\bar{D}}^{\mathrm{o}}(s)$ for $e^+e^- \to D\bar{D}$ determined using the same data samples. For example, at $\sqrt{s} = 3.7731$ GeV, $N_{\mathrm{had}}^{\mathrm{fit}} = (35235 \pm 225)$, $N_{\mathrm{b},\ell^+\ell^-,\gamma\gamma} = (1206 \pm 7)$, $N_{\mathrm{b},e^+e^-\ell^+\ell^-,e^+e^-\mathrm{X_{had}}} = (341 \pm 6)$, and $N_{\mathrm{b},D\bar{D}} = (9458 \pm 186)$, where the uncertainties on the first two backgrounds arise from the statistical uncertainties on $\mathcal{L}$, $\sigma_{\mathrm{b},i}$, and η_i, and that on the third is due to the statistical uncertainty on $\sigma_{D\bar{D}}^{\mathrm{o}}(s)$. To provide the most conservative signal significance for the resonance searches that are discussed below, we directly subtract N_b from $N_{\mathrm{had}}^{\mathrm{fit}}$ and allow the statistical uncertainty of $N_{\mathrm{b},D\bar{D}}$ to fully contribute to the uncertainty in the difference between $N_{\mathrm{had}}^{\mathrm{fit}}$ and N_b. This procedure yields $N_{\mathrm{nOCH}}^{\mathrm{o}} = (24230 \pm 292)$, where the uncertainty is statistical and includes the contribution from the background estimates.

We determine the detection efficiency using MC simulated events for the four components of the process $e^+e^- \to$ nOCH: (i) $e^+e^- \to$ light-hadron (LH) continuum processes including lower-mass resonances (LMRs) with masses below 2 GeV (CPLMRs), (ii) $J/\psi \to$ hadrons, (iii) $\psi(3686) \to$ hadrons, and (iv) $\mathcal{R}s(3770) \to$ nOCH [26]. We generate simulated samples for these events with the KKMC package. These events include initial-state radiation (ISR) and final-state radiation (FSR) processes. For the subsequent decays of the J/ψ, $\psi(3686)$ and $\mathcal{R}s(3770)$, we use EVTGEN to generate the known final states, given in Ref. [36], and use LUNDCHARM to generate the remaining unknown final states. The resulting selection

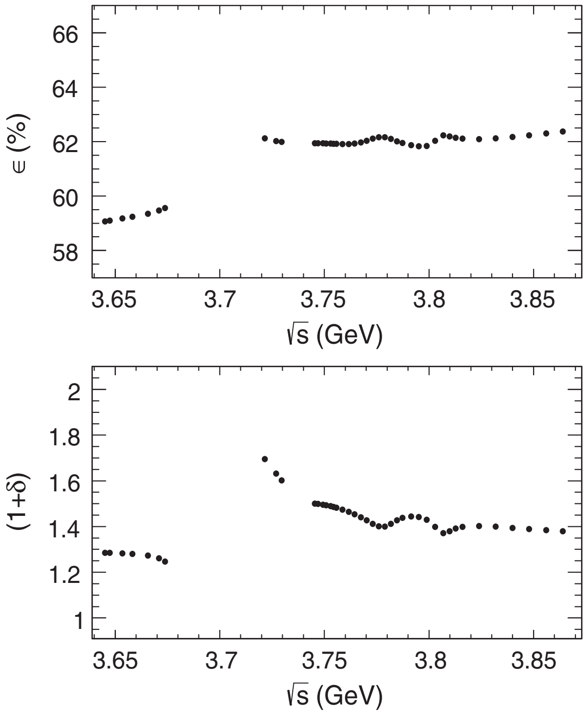

FIG. 2. The efficiency ϵ (top) versus the c.m. energy; the ISR correction factor $[1+\delta(s)]$ (bottom) versus the c.m. energy.

efficiency is determined using $\epsilon = \sum_1^4 w_i \epsilon_i$, where w_i is the number of nOCH events simulated for the ith component over the total number of MC simulated nOCH events for all four components, and ϵ_i is the corresponding efficiency for selection of the nOCH events from the ith component. Figure 2 (top) shows the efficiencies determined at the 42 energy points.

At $\sqrt{s} = 3.7731$ GeV, the efficiency is $\epsilon = 62.11\%$. The integrated luminosity corresponding to the data collected at this energy is $\mathcal{L} = (1831.63 \pm 4.49)\ \mathrm{nb}^{-1}$. Dividing the number $N^{\mathrm{o}}_{\mathrm{nOCH}} = (24230 \pm 292)$ by both the integrated luminosity and the efficiency yields the observed nOCH cross section $\sigma^{\mathrm{o}}_{\mathrm{nOCH}} = (21.299 \pm 0.262)$ nb, where the uncertainty arises from the statistical uncertainty on the $N^{\mathrm{o}}_{\mathrm{OCH}}$, the size of the MC samples, and the statistical uncertainty of the luminosity measurement. Similarly, we measure $\sigma^{\mathrm{o}}_{\mathrm{nOCH}}(s)$ at the remaining 41 energy points.

Table I summarizes the systematic uncertainties assigned to the $\sigma^{\mathrm{o}}_{\mathrm{nOCH}}(s)$ measurements. To determine the systematic uncertainties due to the choice of the selection criteria, we vary each criterion from its baseline value to an alternative setting, as given in Table I, and assign the resulting change in $\sigma^{\mathrm{o}}_{\mathrm{nOCH}}(s)$ as the systematic uncertainty. Removing the requirement that tracks must point into different hemispheres in z changes $\sigma^{\mathrm{o}}_{\mathrm{nOCH}}(s)$ by 0.80%, which is taken as the corresponding uncertainty associated with this possible source of bias. To estimate the uncertainty associated with the fit to the Z_{AVRG} distribution, we reperform the fit changing the background shape from a second-order to third-order, and then from a third-order to fourth-order Chebychev function. These result in 0.83% change in the cross sections, which is assigned as the corresponding systematic uncertainty. The uncertainty on the number of background sources is dominated by the estimation of the two-photon contribution, which induces a 0.75% uncertainty of the $\sigma^{\mathrm{o}}_{\mathrm{nOCH}}(s)$.

TABLE I. Systematic uncertainties on $\sigma^{\mathrm{o}}_{\mathrm{nOCH}}(s)$.

Source	Variation range	Uncertainty (%)
R_{xy} cut	[0.9, 1.1]	0.20
$\cos\theta$ cut	[0.875, 0.930]	0.40
$p < E_{\mathrm{b}} + 0.02E_{\mathrm{b}}\sqrt{1+E_{\mathrm{b}}}$	[nominal value, ∞]	0.01
t_{TOF} cut and t_{TOF}-t_{p}	$[0,\infty]$ and $[2,\infty]$	0.09
E_{EMC} cut	$[1,\infty]$	0.39
Penetration depth	$[30,\infty]$	0.04
$E^{\mathrm{tot}}_{\mathrm{EMC}}$ cut	[0,0.28]	0.34
N_{CTrk} cut	[2,3]	1.45
Different hemisphere in z		0.80
Fitting Z_{AVRG} distribution		0.83
N_{b}		0.75
MC signal model		1.70
Integrated luminosity		1.00
Total		2.89

The choice of the MC generator for $e^+e^- \to$ nOCH impacts the selection efficiency. We recalculate the efficiency with different MC packages and take the 1.70% variation observed as the associated uncertainty. There is an uncertainty on $\sigma^{\mathrm{o}}_{\mathrm{nOCH}}(s)$ of 1.00% arising from the corresponding uncertainty on the luminosity. Adding these contributions in quadrature yields a total systematic uncertainty of 2.89% on $\sigma^{\mathrm{o}}_{\mathrm{nOCH}}(s)$. This total does not include an energy-dependent uncertainty on $\sigma^{\mathrm{o}}_{\mathrm{nOCH}}(s)$, caused by the 1.43% uncertainty on the $\sigma^{\mathrm{o}}_{D\bar{D}}(s)$ shape, which is accounted for when considering the systematic uncertainties on the fitted parameter values, as discussed below.

To investigate whether the $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ states decay to nOCH and if a new resonance $\mathcal{R}$ exists in this energy region, we perform a least-χ^2 fit to the nOCH cross sections. The dressed nOCH cross section is modeled by

$$\sigma^{\mathrm{D}}_{\mathrm{nOCH}}(s') = \sigma^{\mathrm{D}}_{\mathrm{LH}}(s') + \sigma^{\mathrm{D}}_{J/\psi}(s') + \sigma^{\mathrm{D}}_{\mathcal{R}_{\mathcal{S}\mathrm{up}3680}}(s'), \quad (1)$$

where $s' = s(1-x)$, x is the radiative-photon energy fraction, $\sigma^{\mathrm{D}}_{\mathrm{LH}}(s')$, $\sigma^{\mathrm{D}}_{J/\psi}(s')$ and $\sigma^{\mathrm{D}}_{\mathcal{R}_{\mathcal{S}\mathrm{up}3680}}(s')$ are the cross sections of $e^+e^- \to$ LH, $J/\psi \to$ hadrons, and $\mathcal{R}_{\mathcal{S}\mathrm{up}3680} \to$ nOCH, respectively. Here $\mathcal{R}_{\mathcal{S}\mathrm{up}3680}$ indicates the states with masses above $3.680\ \mathrm{GeV}/c^2$. The cross sections for CPLMRs are taken to be $\sigma^{\mathrm{D}}_{\mathrm{LH}}(s') = f\sigma^{\mathrm{B}}_{\mu^+\mu^-}(s') + \sigma^{\mathrm{D}}_{\mathrm{LMRs}}(s')$, where $\sigma^{\mathrm{B}}_{\mu^+\mu^-}(s')$ is the Born cross section for continuum $e^+e^- \to \mu^+\mu^-$ production, f is a free parameter, $f\sigma^{\mathrm{B}}_{\mu^+\mu^-}(s')$ gives the cross section for continuum $e^+e^- \to$ hadrons production [24], and $\sigma^{\rm D}_{\rm LMRs}(s')$ is the cross section for the production of LMRs decaying into LH, which is determined using the zeroth-order cross sections [36] multiplied by the vacuum-polarization correction factor $(1/|1-\Pi(s)|^2)$ [37,38] at energies below 2 GeV. The cross sections for J/ψ and $\mathcal{R}_{\mathcal{S}{\rm up}3680}$ decaying into nOCH are, respectively, taken as $\sigma^{\rm D}_{J/\psi}(s') = |A_{J/\psi}(s')|^2$ and $\sigma^{\rm D}_{\mathcal{R}_{\mathcal{S}{\rm up}3680}}(s') = |A_{\psi(3686)}(s') + \sum_1^3 A_k e^{i\phi_k}(s')|^2$, where $k = 1, 2, 3$ are for the $\mathcal{R}(3760)$ state, $\mathcal{R}(3780)$ state, and $\mathcal{R}$, respectively, and ϕ_k are relative phases.

In the above formulations, $A_{\mathcal{S}}$ are the generic decay amplitudes for these states, which are parameterized by $A_{\mathcal{S}}(s') = \sqrt{12\pi\Gamma^{ee}_{\mathcal{S}}\Gamma^{\rm tot}_{\mathcal{S}}\mathcal{B}(\mathcal{S}\to{\rm nOCH})}/[(s'-M^2_{\mathcal{S}}) + i(\Gamma^{\rm tot}_{\mathcal{S}}M_{\mathcal{S}})]$, in which $\mathcal{S}$ stands for the J/ψ, $\psi(3686)$, $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ states, as well as resonance $\mathcal{R}$; $M_{\mathcal{S}}$, $\Gamma^{\rm tot}_{\mathcal{S}}$, and $\Gamma^{ee}_{\mathcal{S}}$ are, respectively, the mass, total, and electronic widths of the $\mathcal{S}$, and $\mathcal{B}(\mathcal{S}\to{\rm nOCH})$ is the decay branching fraction of the $\mathcal{S}$. For the $\mathcal{R}(3780)$ state, the total width is set to be energy dependent, as in Ref. [24].

In the fit, the masses, the total widths, the electronic widths, and the hadronic decay branching fractions of J/ψ and $\psi(3686)$ resonances are fixed to those given in Ref. [36]. The $\mathcal{R}(3780)$ mass and total width are fixed to $(3781.0\pm1.3\pm0.5)\,{\rm MeV}/c^2$ and $(19.3\pm3.1\pm0.1)\,{\rm MeV}$ [26], respectively. The remaining parameters are left as free parameters in the fit.

The observed cross section is described by $\sigma^{\rm O}_{\rm nOCH}(s) = \int_0^{1-(4m_\pi^2/s)} dx\, \sigma^{\rm D}_{\rm nOCH}[s(1-x)]\mathcal{F}(x,s)$, where $\mathcal{F}(x,s)$ is the sampling function [24,37], and m_π is the pion mass. The cross section as a function of energy is determined by a fit to $\sigma^{\rm o}_{\rm nOCH}(s)$ at the 42 energy points. Using $\sigma^{\rm D}_{\rm nOCH}(s)$ obtained from the parameter values, we determine the ISR correction factors $[1+\delta(s)] = \sigma^{\rm O}_{\rm nOCH}(s)/\sigma^{\rm D}_{\rm nOCH}(s)$ at the 42 energy points, which are shown in Fig. 2 (bottom). Dividing the observed nOCH cross section $\sigma^{\rm o}_{\rm nOCH}(s)$ by $[1+\delta(s)]$ yields the observed dressed nOCH cross section $\sigma^{\rm d}_{\rm nOCH}(s)$, where the lower case superscripts are used to distinguish the measured from the predicted (upper case superscripts) quantities.

The circles with error bars in Fig. 3 show the $\sigma^{\rm d}_{\rm nOCH}(s)$ measurements, where the uncertainties are statistical. Using the same fit procedure described above, we fit $\sigma^{\rm d}_{\rm nOCH}(s)$ with the function $\sigma^{\rm D}_{\rm nOCH}(s)$ given in Eq. (1), with x fixed to zero. The fit converges at two sets of acceptable parameter values. We denote these as Result I and Result II. Table II summarizes the parameter values, where the first uncertainties are from the fit to the $\sigma^{\rm d}_{\rm nOCH}(s)$, and the second are systematic. The two sets of results have the fit quality of $\chi^2/{\rm ndof}$ of 22.1/31, and 22.0/31, respectively. As the mass of the fitted resonance is close to 3810 MeV, we denote it as $\mathcal{R}(3810)$. The cross section described by Result I is superimposed on the fit results in Fig. 3. Also shown are the fit results including one contribution to $\sigma^{\rm D}_{\mathcal{R}_{\mathcal{S}{\rm up}3680}}(s)$ included at a time. The measured mass and total width of the $\mathcal{R}(3760)$ state are consistent within 1.8σ and 0.9σ, respectively, with those measured by the BES-II experiment [26].

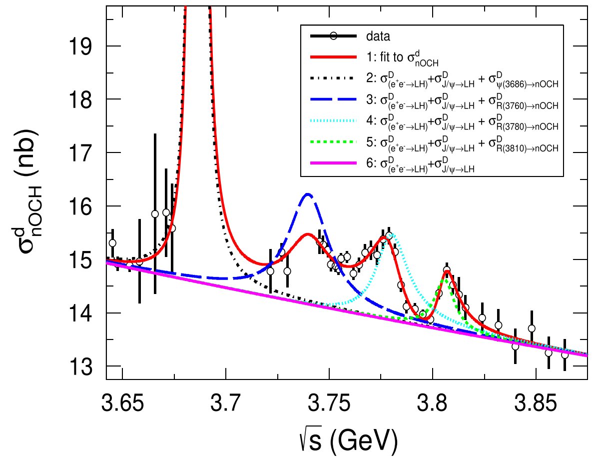

FIG. 3. The dressed cross sections for $e^+e^-\to{\rm nOCH}$, showing also the Result-I fit (line 1) and the contributions to this fit including separate contributions to $\sigma^{\rm D}_{\mathcal{R}_{\mathcal{S}{\rm up}3680}}(s)$ (lines 2–6).

To estimate the systematic uncertainties of the fitted parameter in Table II, we vary the values of the $\sigma^{\rm d}_{\rm nOCH}(s)$, the values of the $\sigma^{\rm o}_{D\bar{D}}(s)$, and the fixed parameters by $\pm1\sigma$, refit the $\sigma^{\rm d}_{\rm nOCH}(s)$, and take the difference between the refitted parameter value and the baseline fit result as the corresponding systematic uncertainty. The estimation of the

TABLE II. Results of the fit to the cross sections for $e^+e^-\to$ nOCH showing the values of the mass M_k [MeV/c^2], total width $\Gamma^{\rm tot}_k$ [MeV], the product of electronic width (Γ^{ee}_k) and nOCH branching fraction ($\mathcal{B}_k$) $\Gamma^{ee}_k\mathcal{B}_k$ [eV], and relative phase ϕ_k [degree], where k represents $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$. $\mathcal{B}_k$ is the branching fractions [%] for $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ decays into nOCH and OC.

Parameters	Result I	Result II
$M_{\mathcal{R}(3760)}$	$3739.9\pm4.2\pm2.6$	$3739.7\pm3.9\pm2.6$
$\Gamma^{\rm tot}_{\mathcal{R}(3760)}$	$23.9\pm8.2\pm4.8$	$22.5\pm8.3\pm4.5$
$\Gamma^{ee}_{\mathcal{R}(3760)}\mathcal{B}_{\mathcal{R}(3760)}$	$46.8\pm29.9\pm25.1$	$11.9\pm9.0\pm6.4$
$\phi_{\mathcal{R}(3760)}$	$228\pm52\pm58$	$113\pm51\pm29$
$\Gamma^{ee}_{\mathcal{R}(3780)}\mathcal{B}_{\mathcal{R}(3780)}$	$29.9\pm16.1\pm3.7$	$25.3\pm11.6\pm3.1$
$\phi_{\mathcal{R}(3780)}$	$82\pm126\pm17$	$250\pm119\pm52$
${\rm M}_{\mathcal{R}(3810)}$	$3805.7\pm1.1\pm2.7$	$3805.7\pm1.1\pm2.7$
$\Gamma^{\rm tot}_{\mathcal{R}(3810)}$	$11.6\pm2.9\pm1.9$	$11.5\pm2.8\pm1.9$
$\Gamma^{ee}_{\mathcal{R}(3810)}\mathcal{B}_{\mathcal{R}(3810)}$	$10.9\pm3.8\pm2.5$	$11.0\pm3.4\pm2.5$
$\phi_{\mathcal{R}(3810)}$	$52\pm149\pm25$	$215\pm148\pm103$
f	$2.28\pm0.01\pm0.07$	$2.28\pm0.01\pm0.07$
$\mathcal{B}[\mathcal{R}(3760)\to{\rm nOCH}]$	$25.2\pm16.1\pm30.4$	$6.4\pm4.8\pm7.7$
$\mathcal{B}[\mathcal{R}(3780)\to{\rm nOCH}]$	$12.3\pm6.6\pm8.3$	$10.4\pm4.8\pm7.0$
$\mathcal{B}[\mathcal{R}(3760)\to{\rm OC}]$	$74.8\pm16.1\pm30.4$	$93.6\pm4.8\pm7.7$
$\mathcal{B}[\mathcal{R}(3780)\to{\rm OC}]$	$87.7\pm6.6\pm8.3$	$89.6\pm4.8\pm7.0$

systematic uncertainty due to the uncertainty of the c.m. energies is similar to that described in Ref. [4]. Adding these uncertainties in quadrature yields the total systematic uncertainty.

Dividing the measured values for $\Gamma^{ee}_{\mathcal{R}(3760)}\mathcal{B}_{\mathcal{R}(3760)}$ and $\Gamma^{ee}_{\mathcal{R}(3780)}\mathcal{B}_{\mathcal{R}(3780)}$ in Table II by $\Gamma^{ee}_{\mathcal{R}(3760)} = (186 \pm 201 \pm 8)$ eV [26] and $\Gamma^{ee}_{\mathcal{R}(3780)} = (243 \pm 160 \pm 9)$ eV [26], respectively, yields the nOCH branching fractions for the decays $\mathcal{R}(3760) \to$ nOCH and $\mathcal{R}(3780) \to$ nOCH, which are shown in Table II. Their corresponding OC branching fractions are also presented in Table II. These nOCH branching fractions of $\mathcal{R}(3780)$ decays are in good agreement with $\mathcal{B}[\psi(3770) \to \text{non-}D\bar{D}] = (15.1 \pm 5.6 \pm 1.8)\%$ [21–24] measured by the BES-II experiment.

By removing the $\mathcal{R}(3810)$ from the $\sigma^{\mathrm{D}}_{\mathcal{R}_{\mathcal{S}\mathrm{up}3680}}(s)$ as discussed above, the χ^2/ndof of the fit changes from 22.1/31 to 116.1/36, indicating that the significance of the $\mathcal{R}(3810)$ signal is 8.8σ. Similarly, the significance of the $\mathcal{R}(3760)$ signal is determined to be 8.1σ by comparing the difference of χ^2/ndof relative to the number degrees of freedom with and without including the $\mathcal{R}(3760)$ component in the fit. A similar procedure is applied to determine the $\mathcal{R}(3780)$ significance, which is 13.7σ. These significances include the systematic uncertainties.

The charmonium model [39] predicts only the 1^3D_1 state existing in the c.m. energy range from 3.733 to 3.870 GeV, which is generally assumed to be the $\psi(3770)$, and so the $\mathcal{R}(3760)$ and $\mathcal{R}(3810)$ states are presumably two non-$c\bar{c}$ states. The $\mathcal{R}(3760)$ state can be explained as a p-wave resonance of a four-quark ($c\bar{c}q\bar{q}$) state [40,41]. It can be thought of either as an OC molecular state, or as a four-quark bound state [41]. Reference [42] interprets $\mathcal{R}(3760)$ as a possible molecular OC threshold resonance. The most salient features of the $\mathcal{R}(3760)$ state is that its mass, which is $(3739.9 \pm 4.2 \pm 2.6)$ MeV$/c^2$ for Result I [$(3739.7 \pm 3.9 \pm 2.6)$ MeV$/c^2$ for Result II], is just at the D^+D^- threshold (3739.3 ± 0.1) MeV$/c^2$, and its branching fraction is $\mathcal{B}[\mathcal{R}(3760) \to \text{OC}] = (74.8 \pm 16.1 \pm 30.4)\%$ [$\mathcal{B}\{\mathcal{R}(3760) \to \text{OC}\} = (93.6 \pm 4.8 \pm 7.7)\%$]. These experimental facts can lead one naturally to interpret the $\mathcal{R}(3760)$ state as an OC pair molecular state, but containing a simple four-quark state component. As no signal for the decay $\mathcal{R}(3810) \to D\bar{D}$ is observed in the cross sections for $e^+e^- \to D\bar{D}$ at c.m. energies around 3.810 GeV [43,44], and the $\mathcal{R}(3810)$ mass $(3805.7 \pm 1.1 \pm 2.7)$ MeV$/c^2$ for Result I [$(3805.7 \pm 1.1 \pm 2.7)$ MeV$/c^2$ for Result II] is exactly at the $h_c\pi^+\pi^-$ threshold (3804.5 ± 0.1) MeV$/c^2$, the $\mathcal{R}(3810)$ state can be interpreted as a hadrocharmonium resonance [8].

In summary, we have measured the inclusive nOCH cross sections of $e^+e^- \to$ nOCH with improved precision at c.m. energies from 3.645 to 3.871 GeV. We observe three resonances: $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ in the energy-dependent line shape of the nOCH cross sections with significances of 8.1σ, 13.7σ, and 8.8σ, respectively. The $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ states are observed for the first time in the nOCH cross sections, while the $\mathcal{R}(3810)$ state is observed for the first time with mass $(3805.7 \pm 1.1 \pm 2.7)$ [$(3805.7 \pm 1.1 \pm 2.7)$] MeV$/c^2$, total width $(11.6 \pm 2.9 \pm 1.9)$ [$(11.5 \pm 2.8 \pm 1.9)$] MeV, and the product of the electronic width and the nOCH decay branching fraction $(10.9 \pm 3.8 \pm 2.5)$ [$(11.0 \pm 3.4 \pm 2.5)$] eV for Result I [Result II]. In addition, for the first time, we measure $\mathcal{B}[\mathcal{R}(3760) \to \text{nOCH}] = (25.2 \pm 16.1 \pm 30.4)\%$[$(6.4 \pm 4.8 \pm 7.7)\%$] and $\mathcal{B}[\mathcal{R}(3780) \to \text{nOCH}] = (12.3 \pm 6.6 \pm 8.3)\%$ [$(10.4 \pm 4.8 \pm 7.0)\%$]. The $\mathcal{R}(3760)$ state can be interpreted as an OC pair molecular state, but containing a simple four-quark state component. The $\mathcal{R}(3810)$ state can be interpreted as a hadrocharmonium state [8].

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[1] J. Z. Bai *et al.* (BES Collaboration), arXiv:hep-ex/0307028v1; W. G. Li, G. Rong, and D. G. Cassel, in *Proceedings of Tenth International Conference on Hadron Spectroscopy, Aschaffenburg, Germany, 2003*, pp. 495, 592, 937; J. Z. Bai *et al.* (BES Collaboration), High Energy Physics and Nuclear Physics **28**, 325 (2004).
[2] G. Rong, in *Proceedings of the Symposium of 30 Years of BES Physics, Beijing, China, 2019* (World Scientific, Singapore, 2019), p. 48.
[3] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **102**, 112009 (2020).
[4] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **127**, 082002 (2021).
[5] F. E. Close and P. R. Page, Phys. Lett. B **578**, 119 (2004).
[6] M. B. Voloshin and L. B. Okun, JETP Lett. **23**, 369 (1976).
[7] N. Brambilla *et al.*, Eur. Phys. J. C **71**, 1534 (2011).
[8] S. Dubynskiy and M. B. Voloshin, Phys. Lett. B **666**, 344 (2008).
[9] J. Z. Bai *et al.* (BES Collaboration), Phys. Lett. B **605**, 63 (2005).
[10] S. K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
[11] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **95**, 142001 (2005).
[12] Q. He *et al.* (CELO Collaboration), Phys. Rev. D **74**, 091104(R) (2006).
[13] T. E. Coan *et al.* (CLEO Collaboration), Phys. Rev. Lett. **96**, 162003 (2006).
[14] M. Ablikim *et al.* (BESIII Collabration), Phys. Rev. Lett. **110**, 252001 (2013).
[15] M. Ablikim *et al.* (BESIII Collabration), Phys. Rev. Lett. **112**, 092001 (2014).
[16] M. Ablikim *et al.* (BESIII Collabration), Phys. Rev. Lett. **111**, 242001 (2013).
[17] X. L. Wang *et al.* (Belle Collaboration), Phys. Rev. Lett. **99**, 142002 (2007).
[18] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **98**, 212001 (2007).
[19] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **118**, 092001 (2017).
[20] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **118**, 092002 (2017).
[21] M. Ablikim *et al.* (BES Collaboration), Phys. Lett. B **641**, 145 (2006).
[22] M. Ablikim *et al.* (BES Collaboration), Phys. Rev. D **76**, 122002 (2007).
[23] M. Ablikim *et al.* (BES Collaboration), Phys. Lett. B **659**, 74 (2008).
[24] M. Ablikim *et al.* (BES Collaboration), Phys. Rev. Lett. **97**, 121801 (2006).
[25] G. Rong, Chin. Phys. C **34**, 788 (2010).
[26] M. Ablikim *et al.* (BES Collaboration), Phys. Rev. Lett. **101**, 102004 (2008).
[27] M. Ablikim *et al.* (BESIII Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **614**, 345 (2010).
[28] S. Agostinelli *et al.* (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[29] S. Jadach, B. F. L. Ward, and Z. Was, Comput. Phys. Commun. **130**, 260 (2000).
[30] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001); R. G. Ping, Chin. Phys. C **32**, 599 (2008).
[31] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, Phys. Rev. D **62**, 034003 (2000).
[32] G. Balossini, C. M. Carloni Calame, G. Montagna, O. Nicrosini, and F. Piccinini, Nucl. Phys. **B758**, 227 (2006); G. Balossini, C. Bignamini, C. M. C. Calame, G. Montagna, O. Nicrosini, and F. Piccinini, Phys. Lett. B **663**, 209 (2008).
[33] S. Nova, A. Olchevski, and T. Todorov, TWOGAM, a Monte Carlo event generator for two photon physics, DELPHI Note 90-35 PROG 152.
[34] J. Z. Bai *et al.* (BES Collaboration), Phys. Rev. D **53**, 20 (1996).
[35] H. Burkhardt and B. Pietrzyk, Phys. Lett. B **513**, 46 (2001).
[36] R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).
[37] E. A. Kuraev and V. S. Fadin, Yad. Fiz. **41**, 733 (1985); Sov. J. Nucl. Phys. **41**, 466 (1985).
[38] D. Zhang, G. Rong, and J. C. Chen, Phys. Rev. D **74**, 054012 (2006).
[39] E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, and T.-M. Yan, Phys. Rev. D **17**, 3090 (1978); E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, and T. M. Yan, Phys. Rev. D **21**, 203 (1980).
[40] A. De Rujula, Howard Georgi, and S. L. Glashow, Phys. Rev. Lett. **38**, 317 (1977).
[41] Rafe Hyam Schindler, Stanford Linear Accelerator Center, Stanford University, Stanford, California, Report No. 219, p. 98, May 1979.
[42] S. Dubynskiy and M. B. Voloshin, Phys. Rev. D **78**, 116014 (2008).
[43] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **76**, 111105(R) (2007).
[44] G. Pakhlova *et al.* (Belle Collaboration), Phys. Rev. D **77**, 011103(R) (2008).

M. Ablikim,[1] M. N. Achasov,[5,b] P. Adlarson,[75] X. C. Ai,[81] R. Aliberti,[36] A. Amoroso,[74a,74c] M. R. An,[40] Q. An,[71,58] Y. Bai,[57] O. Bakina,[37] I. Balossino,[30a] Y. Ban,[47,g] V. Batozskaya,[1,45] K. Begzsuren,[33] N. Berger,[36] M. Berlowski,[45] M. Bertani,[29a] D. Bettoni,[30a] F. Bianchi,[74a,74c] E. Bianco,[74a,74c] A. Bortone,[74a,74c] I. Boyko,[37] R. A. Briere,[6] A. Brueggemann,[68] H. Cai,[76]

X. Cai,[1,58] A. Calcaterra,[29a] G. F. Cao,[1,63] N. Cao,[1,63] S. A. Cetin,[62a] J. F. Chang,[1,58] T. T. Chang,[77] W. L. Chang,[1,63] G. R. Che,[44] G. Chelkov,[37,a] C. Chen,[44] Chao Chen,[55] G. Chen,[1] H. S. Chen,[1,63] M. L. Chen,[1,58,63] S. J. Chen,[43] S. M. Chen,[61] T. Chen,[1,63] X. R. Chen,[32,63] X. T. Chen,[1,63] Y. B. Chen,[1,58] Y. Q. Chen,[35] Z. J. Chen,[26,h] W. S. Cheng,[74c] S. K. Choi,[11] X. Chu,[44] G. Cibinetto,[30a] S. C. Coen,[4] F. Cossio,[74c] J. J. Cui,[50] H. L. Dai,[1,58] J. P. Dai,[79] A. Dbeyssi,[19] R. E. de Boer,[4] D. Dedovich,[37] Z. Y. Deng,[1] A. Denig,[36] I. Denysenko,[37] M. Destefanis,[74a,74c] F. De Mori,[74a,74c] B. Ding,[66,1] X. X. Ding,[47,g] Y. Ding,[41] Y. Ding,[35] J. Dong,[1,58] L. Y. Dong,[1,63] M. Y. Dong,[1,58,63] X. Dong,[76] M. C. Du,[1] S. X. Du,[81] Z. H. Duan,[43] P. Egorov,[37,a] Y. L. Fan,[76] J. Fang,[1,58] S. S. Fang,[1,63] W. X. Fang,[1] Y. Fang,[1] R. Farinelli,[30a] L. Fava,[74b,74c] F. Feldbauer,[4] G. Felici,[29a] C. Q. Feng,[71,58] J. H. Feng,[59] K. Fischer,[69] M. Fritsch,[4] C. Fritzsch,[68] C. D. Fu,[1] J. L. Fu,[63] Y. W. Fu,[1] H. Gao,[63] Y. N. Gao,[47,g] Yang Gao,[71,58] S. Garbolino,[74c] I. Garzia,[30a,30b] P. T. Ge,[76] Z. W. Ge,[43] C. Geng,[59] E. M. Gersabeck,[67] A. Gilman,[69] K. Goetzen,[14] L. Gong,[41] W. X. Gong,[1,58] W. Gradl,[36] S. Gramigna,[30a,30b] M. Greco,[74a,74c] M. H. Gu,[1,58] Y. T. Gu,[16] C. Y. Guan,[1,63] Z. L. Guan,[23] A. Q. Guo,[32,63] L. B. Guo,[42] M. J. Guo,[50] R. P. Guo,[49] Y. P. Guo,[13,f] A. Guskov,[37,a] T. T. Han,[50] W. Y. Han,[40] X. Q. Hao,[20] F. A. Harris,[65] K. K. He,[55] K. L. He,[1,63] F. H. H. Heinsius,[4] C. H. Heinz,[36] Y. K. Heng,[1,58,63] C. Herold,[60] T. Holtmann,[4] P. C. Hong,[13,f] G. Y. Hou,[1,63] X. T. Hou,[1,63] Y. R. Hou,[63] Z. L. Hou,[1] H. M. Hu,[1,63] J. F. Hu,[56,i] T. Hu,[1,58,63] Y. Hu,[1] G. S. Huang,[71,58] K. X. Huang,[59] L. Q. Huang,[32,63] X. T. Huang,[50] Y. P. Huang,[1] T. Hussain,[73] N. Hüsken,[28,36] W. Imoehl,[28] M. Irshad,[71,58] J. Jackson,[28] S. Jaeger,[4] S. Janchiv,[33] J. H. Jeong,[11] Q. Ji,[1] Q. P. Ji,[20] X. B. Ji,[1,63] X. L. Ji,[1,58] Y. Y. Ji,[50] X. Q. Jia,[50] Z. K. Jia,[71,58] H. J. Jiang,[76] L. L. Jiang,[1] P. C. Jiang,[47,g] S. S. Jiang,[40] T. J. Jiang,[17] X. S. Jiang,[1,58,63] Y. Jiang,[63] J. B. Jiao,[50] Z. Jiao,[24] S. Jin,[43] Y. Jin,[66] M. Q. Jing,[1,63] T. Johansson,[75] X. Kui,[1] S. Kabana,[34] N. Kalantar-Nayestanaki,[64] X. L. Kang,[10] X. S. Kang,[41] R. Kappert,[64] M. Kavatsyuk,[64] B. C. Ke,[81] A. Khoukaz,[68] R. Kiuchi,[1] R. Kliemt,[14] O. B. Kolcu,[62a] B. Kopf,[4] M. K. Kuessner,[4] A. Kupsc,[45,75] W. Kühn,[38] J. J. Lane,[67] P. Larin,[19] A. Lavania,[27] L. Lavezzi,[74a,74c] T. T. Lei,[71,k] Z. H. Lei,[71,58] H. Leithoff,[36] M. Lellmann,[36] T. Lenz,[36] C. Li,[44] C. Li,[48] C. H. Li,[40] Cheng Li,[71,58] D. M. Li,[81] F. Li,[1,58] G. Li,[1] H. Li,[71,58] H. B. Li,[1,63] H. J. Li,[20] H. N. Li,[56,i] Hui Li,[44] J. R. Li,[61] J. S. Li,[59] J. W. Li,[50] K. L. Li,[20] Ke Li,[1] L. J. Li,[1,63] L. K. Li,[1] Lei Li,[3] M. H. Li,[44] P. R. Li,[39,j,k] Q. X. Li,[50] S. X. Li,[13] T. Li,[50] W. D. Li,[1,63] W. G. Li,[1] X. H. Li,[71,58] X. L. Li,[50] Xiaoyu Li,[1,63] Y. G. Li,[47,g] Z. J. Li,[59] Z. X. Li,[16] C. Liang,[43] H. Liang,[35] H. Liang,[1,63] H. Liang,[71,58] Y. F. Liang,[54] Y. T. Liang,[32,63] G. R. Liao,[15] L. Z. Liao,[50] Y. P. Liao,[1,63] J. Libby,[27] A. Limphirat,[60] D. X. Lin,[32,63] T. Lin,[1] B. J. Liu,[1] B. X. Liu,[76] C. Liu,[35] C. X. Liu,[1] F. H. Liu,[53] Fang Liu,[1] Feng Liu,[7] G. M. Liu,[56,i] H. Liu,[39,j,k] H. B. Liu,[16] H. M. Liu,[1,63] Huanhuan Liu,[1] Huihui Liu,[22] J. B. Liu,[71,58] J. L. Liu,[72] J. Y. Liu,[1,63] K. Liu,[1] K. Y. Liu,[41] Ke Liu,[23] L. Liu,[71,58] L. C. Liu,[44] Lu Liu,[44] M. H. Liu,[13,f] P. L. Liu,[1] Q. Liu,[63] S. B. Liu,[71,58] T. Liu,[13,f] W. K. Liu,[44] W. M. Liu,[71,58] X. Liu,[39,j,k] Y. Liu,[39,j,k] Y. Liu,[81] Y. B. Liu,[44] Z. A. Liu,[1,58,63] Z. Q. Liu,[50] X. C. Lou,[1,58,63] F. X. Lu,[59] H. J. Lu,[24] J. G. Lu,[1,58] X. L. Lu,[1] Y. Lu,[8] Y. P. Lu,[1,58] Z. H. Lu,[1,63] C. L. Luo,[42] M. X. Luo,[80] T. Luo,[13,f] X. L. Luo,[1,58] X. R. Lyu,[63] Y. F. Lyu,[44] F. C. Ma,[41] H. L. Ma,[1] J. L. Ma,[1,63] L. L. Ma,[50] M. M. Ma,[1,63] Q. M. Ma,[1] R. Q. Ma,[1,63] R. T. Ma,[63] X. Y. Ma,[1,58] Y. Ma,[47,g] Y. M. Ma,[32] F. E. Maas,[19] M. Maggiora,[74a,74c] S. Malde,[69] Q. A. Malik,[73] A. Mangoni,[29b] Y. J. Mao,[47,g] Z. P. Mao,[1] S. Marcello,[74a,74c] Z. X. Meng,[66] J. G. Messchendorp,[14,64] G. Mezzadri,[30a] H. Miao,[1,63] T. J. Min,[43] R. E. Mitchell,[28] X. H. Mo,[1,58,63] N. Yu. Muchnoi,[5,b] Y. Nefedov,[37] F. Nerling,[19,d] I. B. Nikolaev,[5,b] Z. Ning,[1,58] S. Nisar,[12,l] Y. Niu,[50] S. L. Olsen,[63] Q. Ouyang,[1,58,63] S. Pacetti,[29b,29c] X. Pan,[55] Y. Pan,[57] A. Pathak,[35] P. Patteri,[29a] Y. P. Pei,[71,58] M. Pelizaeus,[4] H. P. Peng,[71,58] K. Peters,[14,d] J. L. Ping,[42] R. G. Ping,[1,63] S. Plura,[36] S. Pogodin,[37] V. Prasad,[34] F. Z. Qi,[1] H. Qi,[71,58] H. R. Qi,[61] M. Qi,[43] T. Y. Qi,[13,f] S. Qian,[1,58] W. B. Qian,[63] C. F. Qiao,[63] J. J. Qin,[72] L. Q. Qin,[15] X. P. Qin,[13,f] X. S. Qin,[50] Z. H. Qin,[1,58] J. F. Qiu,[1] S. Q. Qu,[61] C. F. Redmer,[36] K. J. Ren,[40] A. Rivetti,[74c] V. Rodin,[64] M. Rolo,[74c] G. Rong,[1,63] Ch. Rosner,[19] S. N. Ruan,[44] N. Salone,[45] A. Sarantsev,[37,c] Y. Schelhaas,[36] K. Schoenning,[75] M. Scodeggio,[30a,30b] K. Y. Shan,[13,f] W. Shan,[25] X. Y. Shan,[71,58] J. F. Shangguan,[55] L. G. Shao,[1,63] M. Shao,[71,58] C. P. Shen,[13,f] H. F. Shen,[1,63] W. H. Shen,[63] X. Y. Shen,[1,63] B. A. Shi,[63] H. C. Shi,[71,58] J. L. Shi,[13] J. Y. Shi,[1] Q. Q. Shi,[55] R. S. Shi,[1,63] X. Shi,[1,58] J. J. Song,[20] T. Z. Song,[59] W. M. Song,[35,1] Y. J. Song,[13] Y. X. Song,[47,g] S. Sosio,[74a,74c] S. Spataro,[74a,74c] F. Stieler,[36] Y. J. Su,[63] G. B. Sun,[76] G. X. Sun,[1] H. Sun,[63] H. K. Sun,[1] J. F. 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