Observation of $\mathcal{R}(3810)$ in $e^+e^- \to$ hadrons and Improved Measurements of the Resonance Parameters of $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$

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We report the measurement of the cross sections for $e^+e^- \to \mathrm{hadrons}$ at center-of-mass (c.m.) energies from 3.645 to 3.871 GeV. We observe a new resonance $\mathcal{R}(3810)$ in the cross sections for the first time, and observe the $\mathcal{R}(3760)$ resonance with high significance in the cross sections. The $\mathcal{R}(3810)$ has a mass of $(3804.5\pm0.9\pm0.9)$ MeV/c^2, a total width of $(5.4 \pm 3.5 \pm 3.2)$ MeV, and an electronic partial width of $(19.4 \pm 7.4 \pm 12.1)$ eV. Its significance is 7.7σ. The $\mathcal{R}(3810)$ could be interpreted as a hadro-charmonium resonance predicted by Quantum Chromodynamics (QCD). In addition, we measure the mass $(3751.9 \pm 3.8 \pm 2.8)$ MeV/c^2, the total width $(32.8 \pm 5.8 \pm 8.7)$ MeV, and the electronic partial width $(184 \pm 75 \pm 86)$ eV with improved precision for the $\mathcal{R}(3760)$. Furthermore, for the $\mathcal{R}(3780)$ we measure the mass $(3778.7 \pm 0.5 \pm 0.3)$ MeV/c^2 and total width $(20.3\pm0.8\pm1.7)$ MeV with improved precision, and the electronic partial width $(265\pm69\pm83)$ eV. The $\mathcal{R}(3780)$ can be interpreted as the 1^3D_1 state of charmonium. Its mass and total width differ significantly from the corresponding fitted values given by the Particle Data Group in 2022 by 7.1 and 3.2 times the uncertainties for $\psi(3770)$, respectively. $\psi(3770)$ has been interpreted as the 1^3D_1 state for 45 years.

The discovery of the first nonopen-charm (nOC) final state $J/\psi\pi^+\pi^-$ in the BES-II experiment [1–3] of decaying mesons above the open-charm (OC) threshold started a new era of hadron spectroscopy. These mesons are denoted by X_{aboveOC} [4] in this Letter, which encompass both heavy $c\bar{c}$ states, i.e. $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, and non-

$c\bar{c}$ states, such as four-quark states, OC-pair molecular states, hadro-charmonium states, and hybrid charmonium states, expected by QCD. Discovery of these non-$c\bar{c}$ states would be a crucial validation of QCD predictions. The resonance parameters of the $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ are fundamental quantities for understanding the nature of the two resonances. Precise measurements of the parameters can provide valuable data in testing theoretical calculations in the productions and decays of $X_{\rm aboveOC}$ states.

The charmonium model [5] predicts that more than 99% of the 1^3D_1 state of charmonium decay into OC final states. However, subsequent studies on $\psi(3770)$ decays showed that about 15% of the $\psi(3770)$ decays into nOC final states [6–9]. These indicate that there are probably some undiscovered states [10] with masses around 3.773 GeV/c^2, which decay into nOC final states with a large branching fraction. In 2008, the BES-II experiment observed an enhancement of the cross section for $e^+e^- \to$ hadrons at c.m. energies near 3.76 GeV [11] in addition to the $\psi(3770)$. This cross-section enhancement was described by a Breit-Wigner (BW) structure, and appears as one part of the full structure $\mathcal{R}s(3770)$ [11], which is composed of the $\mathcal{R}(3760)$, the $\mathcal{R}(3780)$, and additional undiscovered BW structure(s) produced in e^+e^- collisions. Reference [12] interprets the $\mathcal{R}(3760)$ as a possible molecular OC threshold resonance. It could also be interpreted as a P-wave resonance of a four-quark ($c\bar{c}q\bar{q}$) state [13]. More recently, BESIII observed the $\mathcal{R}(3760)$ in the reaction $e^+e^- \to J/\psi X$ with a significance of 5.3σ [14], hence confirming that observation and ruling out the explanations that the enhancement is due to $e^+e^- \to D\bar{D}$ continuum process (cnt$D\bar{D}$) interfering with the decay $\psi(3770) \to D\bar{D}$, or due to $\psi(3686) \to D\bar{D}$ decays at energies above the $D\bar{D}$ threshold [15].

The measurements of the $\psi(3770)$ parameters that are used in the determination of world average values (WAV) [9, 15–22] do not consider the effects of $\mathcal{R}(3760)$ decays on the $\psi(3770)$ parameters, so the WAV of $\psi(3770)$ parameters absorb the contributions from at least the $\mathcal{R}(3760)$ decays. Thus, the WAV of the $\psi(3770)$ parameters could be all under- or over-estimated. In addition, if there is more than one BW structure lying at energies around 3.81 GeV, of which there are hints in the existing data of the cross sections for $e^+e^- \to$ hadrons at energies around 3.81 GeV [11, 22, 23] measured in the BES-II experiment, the structure decaying into hadrons also affects the measured mass, and total and electronic partial widths of the $\psi(3770)$. To obtain accurate values for these quantities, it is important to measure and analyze the cross sections for $e^+e^- \to$ hadrons with high accuracy considering the inclusive hadronic decays of $X_{\rm aboveOC} \to$ hadrons.

In this Letter, we report measurements of the cross sections of $e^+e^- \to \rm hadrons$ and searches for new states at c.m. energies from 3.645 to 3.871 GeV. The data samples used in the measurement were collected at 42 c.m. energies with the BESIII detector operated at the BEPCII machine in June 2010. The total integrated luminosity of the data is 75.5 pb^{-1}.

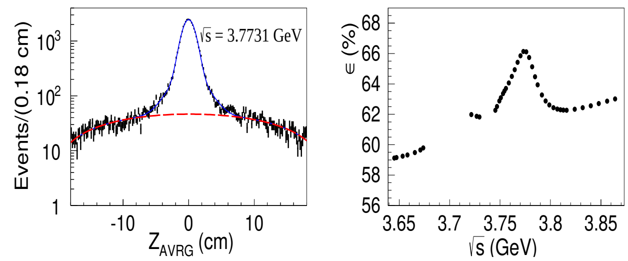

FIG. 1. Distribution of the averaged z position of charged tracks for the events selected from the data collected at $\sqrt{s} = 3.7731$ GeV, where the dots with error bars represent data, the solid line is the best fit and the dashed line is the fitted background shape (left); the efficiency ϵ for selection of the events for $e^+e^- \to \rm hadrons$ at the 42 energies (right).

The BESIII detector is described in detail in Ref. [24]. The detector response is studied using samples of Monte Carlo (MC) events which are simulated with a GEANT4-based [25] detector simulation software package. Simulated samples for all $q\bar{q}$ vector states (i.e. $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$ resonances) and their decays to $\rm hadrons$ are generated using the MC event generators KKMC [26], EVTGEN [27] and LUNDCHARM [28]. Possible background sources are estimated with MC simulated events generated using the event generator KKMC [26]. The detection efficiency is determined using six different MC simulations to describe the process $e^+e^- \to \rm hadrons$: (i) $e^+e^- \to$ light-hadrons continuum processes including lower-mass resonances (CPLMR) with masses below 2 GeV/c^2, (ii) $J/\psi \to \rm hadrons$, (iii) $\psi(3686) \to \rm hadrons$, (iv) $\psi(3770) \to D^0\bar{D}^0$, (v) $\psi(3770) \to D^+D^-$, and (vi) $\psi(3770) \to \rm nOC$. These MC events include initial/final state radiation (ISR/FSR).

Inclusive hadronic events of $e^+e^- \to \rm hadrons$ are selected from the charged and neutral track final states. In order to reject background contributions from $e^+e^- \to l^+l^-$ ($l = e, \mu, \tau$), each event is required to have more than two charged tracks in the final states [6]. These tracks are required to satisfy the selection criteria described in Ref. [29]. To separate beam-associated background events, we calculate the event vertex, i.e. the average z position of charged tracks in the beam line direction. Figure 1 (left) shows the distribution of the average z for the events selected from the data sample collected at c.m. energy $\sqrt{s} = 3.7731$ GeV. Fitting this distribution with a double-Gaussian function (using a common peak maximum) describing the signal shape and a second-order Chebychev polynomial function parameterizing the shape of the background as shown with a dashed line in Fig. 1 yields the number of candidates for hadronic events, $N^{\rm obs}_{\rm had,fit}$=35235$\pm$225. Similarly, we determine the numbers of hadronic candidate events for the data samples collected at the other energies.

The signal yield $N^{\rm obs}_{\rm had,fit}$ is still contaminated by a peaking background from several sources, e.g. $e^+e^- \to (\gamma)l^+l^-$

($l = e$, μ or τ), and $e^+e^- \to (\gamma)e^+e^-X_{\rm had}$ ($X_{\rm had}$ denotes hadrons). Using high-statistics samples of MC simulated events and the cross sections for these processes, the number of background events is estimated to be $N_{\rm b} = 1547 \pm 4$, where the uncertainty is due to the statistical uncertainty of the luminosity of the data sample. Subtracting $N_{\rm b}$ from $N^{\rm obs}_{\rm had,fit}$ yields $N^{\rm obs}_{\rm had}$=(33688 ± 225) signal events.

The efficiency ϵ for the selection of hadronic events is determined using $\epsilon = \sum_1^6 w_i\epsilon_i$, where w_i is the fraction of the number of the hadronic events selected from the i-th MC simulation component over the total number of the MC simulated hadronic events from the aforementioned six MC simulation components, while ϵ_i is the corresponding efficiency. Since the branching fraction for $\psi(3770) \to$ nOC includes all contributions from decays of the full structure $\mathcal{R}s(3770)$ [11], the efficiency includes all contributions from the decays of the BW structures contained in $\mathcal{R}s(3770)$ [11]. Figure 1 (right) shows the efficiencies for the 42 energies used in this analysis, which has the same shape as the efficiencies given in Ref. [23].

At $\sqrt{s} = 3.7731$ GeV, the efficiency is 66.13%. The integrated luminosity of the data collected at $\sqrt{s} = 3.7731$ GeV is $\mathcal{L} = (1831.63 \pm 4.49)$ nb^{-1}. The number $N^{\rm obs}_{\rm had}$=(33688 ± 225) divided by both the luminosity and efficiency yields the observed cross section $\sigma^{\rm obs}_{\rm had} = (27.813 \pm 0.198)$ nb, which is in very good agreement with the value $\sigma^{\rm obs}_{\rm had} = 27.680 \pm 0.272$ nb (given in Table 4 of Ref. [6]) measured by the BES Collaboration, where the errors are the uncertainty of statistical origin (number of observed events, MC event statistics and statistical uncertainty of the luminosity measurement). Similarly, we determine the cross sections $\sigma^{\rm obs}_{\rm had}(s)$ at the other energies. The systematic uncertainty on the cross section arises from the track and event selection criteria, which cause a total systematic uncertainty of 2.89% for all cross sections [29].

To investigate the potential existence of a further BW structure $\mathcal{R}$ beyond $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ within the full structure $\mathcal{R}s(3770)$ [11], we perform a least-χ^2 fit to the cross sections. The observed (O) cross section used in the fit is modeled by

$$\sigma^{\rm O}_{\rm had}(s) = f_{\rm c}\sigma^{\rm B}_{\mu^+\mu^-}(s) + \int_0^{1-\frac{4m_\pi^2}{s}} dx\sigma^{\rm D}_{J/\psi}(s')\mathcal{F}(x,s) + \int_0^\infty dw\mathcal{G}(s,w)\int_0^{1-\frac{4m_\pi^2}{s}} dx\, \sigma^{\rm D}_{\mathcal{V}_{\rm up3680}}(s')\mathcal{F}(x,s). \quad (1)$$

In Eq. (1), the first term gives the observed cross section for CPLMR, where $\sigma^{\rm B}_{\mu^+\mu^-}(s)$ is the Born cross section for the $e^+e^- \to \mu^+\mu^-$ continuum process and $f_{\rm c}$ is a free parameter; the second term gives the observed cross section of $J/\psi \to {\rm hadrons}$ including the ISR correction, where $\sigma^{\rm D}_{J/\psi}(s')$ is the dressed cross section for $J/\psi \to {\rm hadrons}$, s'=$s(1-x)$, x is a parameter relating to the total energy of the emitted ISR photons [30], $\mathcal{F}(x,s)$ is the sampling function [30], and m_π is the mass of pion; the third term describes the observed cross sections for the hadronic decays of $\mathcal{V}_{\rm up3680}$ states or structures with masses above 3.680 GeV, $\sigma^{\rm D}_{\mathcal{V}_{\rm up3680}}(s') = \sigma^{\rm D}_{\psi(3686)}(s') + \sigma^{\rm D}_{X_{\rm aboveOC+cntD\bar{D}}}(s')$, in which $\sigma^{\rm D}_{\psi(3686)}(s')$ is the dressed cross section for $\psi(3686) \to$ hadrons, $\sigma^{\rm D}_{X_{\rm aboveOC+cntD\bar{D}}}(s')$ is the total dressed cross section for $X_{\rm aboveOC} \to$ hadrons and the cnt$D\bar{D}$, $\mathcal{G}(s,w)$ is a Gaussian function describing the beam energy spread (1.355 MeV), and w integrates over the energy. The dressed cross sections for J/ψ and $\psi(3686)$ decaying into hadrons are determined by $\sigma^{\rm D}_{J/\psi}(s') = |A_{J/\psi}(s')|^2$ and $\sigma^{\rm D}_{\psi(3686)}(s') = |A_{\psi(3686)}(s')|^2$, where $A_{J/\psi}(s')$ and $A_{\psi(3686)}(s')$ are parameterized by a relativistic BW function

$$\mathcal{A}_{\mathcal{S}} = \sqrt{12\pi\Gamma^{ee}_{\mathcal{S}}\mathcal{B}\Gamma^{\rm tot}_{\mathcal{S}}}/[(s'-M^2_{\mathcal{S}}) + i\Gamma^{\rm tot}_{\mathcal{S}}M_{\mathcal{S}}], \quad (2)$$

where $\mathcal{S}$ indicates J/ψ and $\psi(3686)$, $M_{\mathcal{S}}$, $\Gamma^{ee}_{\mathcal{S}}$, and $\Gamma^{\rm tot}_{\mathcal{S}}$ are its mass, electronic width, and total width, respectively, and $\mathcal{B}$ is the branching fraction for $\mathcal{S} \to {\rm hadrons}$. The dressed cross section for $X_{\rm aboveOC+cntD\bar{D}} \to {\rm hadrons}$ is modeled by

$$\sigma^{\rm D}_{X_{\rm aboveOC+cntD\bar{D}}}(s') = |A_{{\rm cnt}D\bar{D}}(s') + A_{\mathcal{G}(3900)}(s')e^{i\phi_0} + A_{\mathcal{R}(3760)}(s')e^{i\phi_1} + A_{\mathcal{R}(3780)}(s')e^{i\phi_2} + A_{\mathcal{R}}(s')e^{i\phi_3}|^2. \quad (3)$$

In Eq. (3), the first term is the amplitude of cnt$D\bar{D}$,

$$A_{{\rm cnt}D\bar{D}}(s') = \left[f_{D\bar{D}}\left(\beta_0^3\theta_{\rm n} + \beta_+^3\theta_{\rm c}\right)\sigma^B_{\mu^+\mu^-}(s')\right]^{\frac{1}{2}}, \quad (4)$$

where $\theta_{\rm n}$ and $\theta_{\rm c}$ are step functions to account for the thresholds of $D^0\bar{D}^0$ and D^+D^- production, respectively, β_0 and β_+ are the velocities [9] of the D^0 and D^+ mesons, and $f_{D\bar{D}}$ is a free parameter; the second term is the decay amplitude for the structure predicted by the charmonium model [5] and observed as a Gaussian structure $\mathcal{G}(3900)$ by BaBar [19] in $e^+e^- \to D\bar{D}$ cross sections in 2007, we take $A_{\mathcal{G}(3900)}(s') = (\mathcal{C}e^{-(\sqrt{s'}-M_{\mathcal{G}})^2/(2\sigma^2_{\mathcal{G}})})^{1/2}$ as the amplitude, where $\mathcal{C}$ is a free parameter, $M_{\mathcal{G}}$ and $\sigma_{\mathcal{G}}$ are the peak position and standard deviation of the $\mathcal{G}(3900)$ structure, respectively; the remaining terms: $A_{\mathcal{R}(3760)}(s')$, $A_{\mathcal{R}(3780)}(s')$, and $A_{\mathcal{R}}(s')$ are the amplitudes for $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}$ decaying into hadrons, respectively, which are described by Eq. (2). ϕ_0, ϕ_1, ϕ_2 and ϕ_3 in Eq. (3) are the phases with respect to $A_{{\rm cnt}D\bar{D}}(s')$. For the $\mathcal{R}(3780)$ state, the energy dependent total width [9] is used in its decay amplitude.

The sum of the dressed-resonance cross sections and the observed-continuum-J/ψ (DROCJ) cross section is given by

$$\sigma^{\rm D}_{\rm had}(s) = f_{\rm c}\sigma^{\rm B}_{\mu^+\mu^-}(s) + \sigma^{\rm O}_{J/\psi}(s) + \sigma^{\rm D}_{\mathcal{V}}(s), \quad (5)$$

where $\sigma^{\rm O}_{J/\psi}(s) = \int_0^{1-4m_\pi^2/s} dx\sigma^{\rm D}_{J/\psi}(s')\mathcal{F}(x,s)$. For study of the decays of $X_{\rm aboveOC}$ states it is not necessary to do radiative corrections for the first and second terms in Eq. (5).

In the fit, the BW parameters of the J/ψ and $\psi(3686)$ states are fixed to the central values given by the 2022 Particle Data Group (PDG) [31], the $M_{\mathcal{G}}$, the $\sigma_{\mathcal{G}}$, and the $\mathcal{C}$ are fixed to the central values of $(3873.6 \pm 4.7 \pm 0.1)$ MeV/c^2, $(53.3 \pm 6.3 \pm 0.1)$ MeV, and $(1.07 \pm 0.29 \pm 0.03)$ nb, respectively, the $f_{D\bar{D}}$ is fixed to the central value of $(0.212 \pm 0.177 \pm 0.006)$ nb$^{\frac{1}{2}}$, and the ϕ_0 is fixed to zero degree. These values are determined by fitting the cross sections of $e^+e^- \to D\bar{D}$ at energies from 3.74 to 3.99 GeV, measured using the BESIII data. In this fit, we do not observe $\mathcal{R}(3810)$. The first uncertainties of these parameters are from the fits to the cross sections, and the second ones are due to the uncertainties of both the cross section measurements and the branching fraction for $\mathcal{R}(3760) \to D\bar{D}$ and $\mathcal{R}(3780) \to D\bar{D}$. In the fit, these branching fractions are fixed to $(85 \pm 6)\%$ [8], determined by fitting cross sections for $e^+e^- \to$non-$D\bar{D}$ at over 150 energy points from 3.65 to 3.87 GeV. We assume that the branching fractions for $\mathcal{R}(3760) \to$ hadrons, $\mathcal{R}(3780) \to$ hadrons, and $\mathcal{R}(3810) \to$ hadrons are all 100% in the fit. The other parameters are left free in the fit. Using $\sigma^{\rm O}_{\rm had}(s)$ given in Eq. (1), we fit the $\sigma^{\rm obs}_{\rm had}(s)$ to obtain the parameter values.

Inserting these parameter values into Eq. (1) and Eq. (5) yields the expectant observed cross sections $\sigma^{\rm O}_{\rm had}(s)$ and expectant DROCJ cross sections $\sigma^{\rm D}_{\rm had}(s)$, with which we determine the ISR correction factors $f_{\rm ISR}(s) = \sigma^{\rm O}_{\rm had}(s)/\sigma^{\rm D}_{\rm had}(s)$. Dividing the observed cross sections $\sigma^{\rm obs}_{\rm had}(s)$ by $f_{\rm ISR}(s)$ yields the DROCJ cross section $\sigma^{\rm DROCJ}_{\rm had}(s)$. The circles with error bars in Fig. 2 show $\sigma^{\rm DROCJ}_{\rm had}(s)$.

Using Eq. (5) we fit these $\sigma^{\rm DROCJ}_{\rm had}(s)$ and obtain the values for these parameters. The nominal fit returns six solutions with fit χ^2 less than 26. For four of the six solutions, the $\mathcal{R}(3780)$ electronic widths are less than 120 eV or larger than 415 eV, which are not consistent with $\psi(3770)$ electronic width of 262 eV [31], hence these are not possible physical solutions. Table I presents the values of the parameters for the remained two solutions, where the first uncertainties are statistical, and the second systematic. The two solutions have fitted χ^2 values of 25.5 and 25.6 for 29 degrees of freedom. Both solutions include a result for a new structure with mass close to 3810 MeV/c^2, and we denote it as $\mathcal{R}(3810)$. Since the electronic width of the $\mathcal{R}(3810)$ in solution II is closer to the product $\Gamma^{ee}_{\mathcal{R}(3810)}\mathcal{B}_{\mathcal{R}(3810)} = 11.0 \pm 2.9 \pm 2.4$ eV [29] ($\mathcal{B}_{\mathcal{R}(3810)} \sim 100\%$ since no $\mathcal{R}(3810)$ is observed in $e^+e^- \to D\bar{D}$), we choose solution II as the nominal result.

The systematic uncertainties on the values of the parameters given in Table I originate from three sources: (i) the systematic uncertainties on the observed cross sections, (ii) the uncertainties of the fixed parameters, and (iii) the uncertainties on the c.m. energies. Estimations of these uncertainties are similar to those described in Ref. [29]. Adding these uncertainties in quadrature yields the total systematic uncertainty for each parameter value given in Table I.

Figure 2 also shows the fit to $\sigma^{\rm DROCJ}_{\rm had}(s)$, where the solid line is the fit to the cross sections and the dashed line in yellow is the summed cross sections over the observed cross sections of the CPLMR and the observed cross sections of $J/\psi \to$ hadrons, the dashed lines in black, green, blue, green-blue, and pink are the dressed cross sections for $\psi(3686) \to$ hadrons, $\mathcal{R}(3760) \to$ hadrons, $\mathcal{R}(3780) \to$ hadrons, $\mathcal{R}(3810) \to$ hadrons, and $\mathcal{G}(3900) \to$ hadrons, respectively. To clearly see each of these contributions, we enlarge the partial cross-section data at energies from 3.790 to 3.848 GeV, as shown in the inset figures, where the dashed line in red in the bottom figure is the cross section for cnt-$D\bar{D}$. This fit provides a very good description of the DROCJ cross-section data. The small peak around 3.810 GeV is due to the decays of $\mathcal{R}(3810) \to$ hadrons. Table II shows a comparison of the measurements of the resonance parameters to that measured in the BES-II, which are in good agreement.

TABLE I. Results from the fit to the $e^+e^- \to$ hadrons cross section showing the values of the mass M_i [in MeV/c^2], total width $\Gamma^{\rm tot}_i$ [in MeV], electronic partial width Γ^{ee}_i [in eV], relative phase ϕ_i [in degree], and f_c, where i represents $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$.

Parameters	Solution I	Solution II
$M_{\mathcal{R}(3760)}$	$3752.6 \pm 4.2 \pm 2.8$	$3751.9 \pm 3.8 \pm 2.8$
$\Gamma^{\rm tot}_{\mathcal{R}(3760)}$	$31.7 \pm 5.7 \pm 8.4$	$32.8 \pm 5.8 \pm 8.7$
$\Gamma^{ee}_{\mathcal{R}(3760)}$	$206 \pm 83 \pm 96$	$184 \pm 75 \pm 86$
ϕ_1	$-70 \pm 23 \pm 39$	$-49 \pm 29 \pm 27$
$M_{\mathcal{R}(3780)}$	$3778.6 \pm 0.5 \pm 0.3$	$3778.7 \pm 0.5 \pm 0.3$
$\Gamma^{\rm tot}_{\mathcal{R}(3780)}$	$20.3 \pm 0.8 \pm 1.7$	$20.3 \pm 0.8 \pm 1.7$
$\Gamma^{ee}_{\mathcal{R}(3780)}$	$243 \pm 61 \pm 76$	$265 \pm 69 \pm 83$
ϕ_2	$131 \pm 16 \pm 15$	$151 \pm 23 \pm 17$
$M_{\mathcal{R}(3810)}$	$3804.5 \pm 0.9 \pm 0.9$	$3804.5 \pm 0.9 \pm 0.9$
$\Gamma^{\rm tot}_{\mathcal{R}(3810)}$	$5.6 \pm 3.6 \pm 3.4$	$5.4 \pm 3.5 \pm 3.2$
$\Gamma^{ee}_{\mathcal{R}(3810)}$	$2.3 \pm 0.7 \pm 1.4$	$19.4 \pm 7.4 \pm 12.1$
ϕ_3	$81 \pm 22 \pm 18$	$-11 \pm 20 \pm 2$
$f_{\rm c}$	$2.743 \pm 0.019 \pm 0.081$	$2.741 \pm 0.019 \pm 0.081$

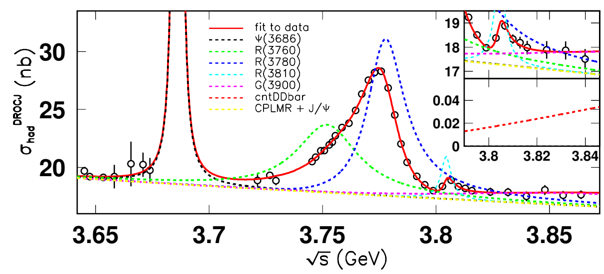

FIG. 2. Measured DROCJ cross sections for $e^+e^- \to$ hadrons with the fit superimposed (see text for details).

TABLE II. Comparison of measurements at the BESIII and BES-II.

Parameter	This work	BES-II measurement [11]
$M_{\mathcal{R}(3760)}$ [MeV/c^2]	$3751.9 \pm 3.8 \pm 2.8$	$3762.6 \pm 11.8 \pm 0.5$
$\Gamma^{\rm tot}_{\mathcal{R}(3760)}$ [MeV]	$32.8 \pm 5.8 \pm 8.7$	$49.9 \pm 32.1 \pm 0.1$
$\Gamma^{ee}_{\mathcal{R}(3760)}$ [eV]	$184 \pm 75 \pm 86$	$186 \pm 201 \pm 8$
$M_{\mathcal{R}(3780)}$ [MeV/c^2]	$3778.7 \pm 0.5 \pm 0.3$	$3781.0 \pm 1.3 \pm 0.5$
$\Gamma^{\rm tot}_{\mathcal{R}(3780)}$ [MeV]	$20.3 \pm 0.8 \pm 1.7$	$19.3 \pm 3.1 \pm 0.1$
$\Gamma^{ee}_{\mathcal{R}(3780)}$ [eV]	$265 \pm 69 \pm 83$	$243 \pm 160 \pm 9$

To evaluate the significance of $\mathcal{R}(3810)$, we re-fit the $\sigma_{\rm had}^{\rm DROCJ}(s)$ with the $\mathcal{R}(3760)$ mass and total width fixed to $(3739.7 \pm 3.9 \pm 2.6)$ MeV/c^2 [29] and $(23.2 \pm 7.2 \pm 4.5)$ MeV [29], respectively. The fit (fit-A) including the $\mathcal{R}(3810)$ returns $\chi^2 = 52.8$ for 31 degrees of freedom, while the fit (fit-B) excluding the $\mathcal{R}(3810)$ returns $\chi^2 = 124.3$ for 35 degrees of freedom. Comparing the two fits, reducing the degrees of freedom in the fit-B by 4 causes a change of χ^2 of 71.6, indicating a significance for the $\mathcal{R}(3810)$ of 7.7σ including systematic uncertainty. Alternatively, we re-fit the $\sigma_{\rm had}^{\rm DROCJ}(s)$ with the $\mathcal{R}(3810)$ mass and total width fixed to $(3805.8 \pm 1.1 \pm 2.7)$ MeV/c^2 [29] and $(10.8 \pm 3.2 \pm 2.3)$ MeV [29], respectively. The fit (fit-C) including the $\mathcal{R}(3760)$ returns $\chi^2 = 31.6$ for 31 degrees of freedom, while the fit (fit-D) excluding the $\mathcal{R}(3760)$ returns $\chi^2 = 294.8$ for 35 degrees of freedom. Comparing the two fits, we get a significance for the $\mathcal{R}(3760)$ of 15.7σ including systematic uncertainty.

To investigate whether the parameterizations for the cnt$D\bar{D}$ amplitudes could cause the cross-section enhancement around 3.76 GeV shown in Fig. 2, we remove both the $\mathcal{R}(3760)$ and $\mathcal{R}(3810)$ amplitudes and replace $\sqrt{f_{D\bar{D}}}$ in Eq. (4) with an exponential factor $f_{\rm NR}e^{-(p_{D^0}+p_{D^+})^2/\lambda^2}$ [32] in the fit (fit-E), or use a threshold function $(\sqrt{s} - 2m_{D^0})^d e^{-h\sqrt{s}-ts}$ [19] to replace $A_{{\rm cnt}D\bar{D}}(s')$ in Eq. (3) in the fit (fit-F), where p_{D^0} (p_{D^+}) and m_{D^0} (m_{D^+}) are the momentum and mass of the D^0 (D^+) meson, respectively; $f_{\rm NR}$, λ, d, h and t are parameters describing the cnt$D\bar{D}$ cross-section shape. In the fits, the values for these parameters are fixed to those determined by analyzing the cross sections for $e^+e^- \to D\bar{D}$ using the function given in Eq. (3). Fit-E and fit-F return $\chi^2 = 119.1$ (PV $\leq 2 \times 10^{-10}$) and $\chi^2 = 225.8$ (PV $\leq 1 \times 10^{-28}$) for 37 degrees of freedom, respectively, indicating that fit-E and fit-D are strongly incompatible with the precision measurements in data.

The Vector Dominance Model (VDM) assumes that the $\psi(3686)$ could decay into $D\bar{D}$ at energies above the $D\bar{D}$ production threshold [33]. To check the validity of the VDM approach, we remove the amplitude $A_{\mathcal{R}}(s')$, and replace the amplitude $A_{\mathcal{R}(3760)}(s')$ in Eq. (3) with $\mathcal{A}_{\psi'}(s') = \sqrt{12\pi\Gamma_{\psi'}^{ee}\Gamma_{\psi'}^{D\bar{D}}}/[(s' - M_{\psi'}^2) + i\Gamma_{\psi'}^{\rm tot\ abovD\bar{D}}M_{\psi'}(s')]$ [15] in the fit (fit-G), where ψ' is $\psi(3686)$, while $\Gamma_{\psi'}^{\rm tot\ aboveD\bar{D}}$ and $\Gamma_{\psi'}^{D\bar{D}}$ are the total and $D\bar{D}$ partial widths of $\psi(3686)$, respectively. $\Gamma_{\psi'}^{\rm tot\ aboveD\bar{D}}$ is chosen to be energy-dependent and defined as that for $\psi(3770)$ [9, 22] with branching fractions $\mathcal{B}_{00}(\psi(3686) \to D^0\bar{D}^0)$ and $\mathcal{B}_{+-}(\psi(3686) \to D^+D^-)$ fixed to 56% and 44%, respectively. In fit-G, the values for $\Gamma_{\psi'}^{\rm tot\ aboveD\bar{D}}$, $\Gamma_{\psi(3686)}^{D\bar{D}}$ and ϕ_1 are fixed to those determined by analyzing the cross sections for $e^+e^- \to D\bar{D}$ using the function given in Eq. (3). Fit-G returns $\chi^2 = 139.4$ (PV $\leq 9 \times 10^{-14}$) for 37 degrees of freedom. This means that the VDM approach is also strongly incompatible with the present precision measurements in data.

None of the three approaches performed in fit-E, fit-F and fit-G describe the data, indicating that large fractions of the $\mathcal{R}(3760)$, $\mathcal{R}(3780)$ and $\mathcal{R}(3810)$ decays are to nOC hadrons, which are significantly observed in Ref. [29].

The charmonium model [5] predicts that only the 1^3D_1 state of charmonium can be produced in e^+e^- annihilation at energies from 3.73 to 3.87 GeV. While "A New Spectroscopy" model [13] proposes that a P-wave resonance of a four-quark ($c\bar{c}q\bar{q}$) state can be produced in e^+e^- annihilation at energies above 3.73 GeV. This four-quark state can be either a simple four-quark bound state or an OC molecular state. Since the $\mathcal{R}(3760)$ mass $(3751.9 \pm 3.8 \pm 2.8)$ MeV/c^2 is (12.6 ± 4.7) MeV higher than the D^+D^- production threshold (3739.3 ± 0.1) MeV and its total width is $(32.8 \pm 5.8 \pm 8.7)$ MeV, these experimental facts could naturally let one interpret the $\mathcal{R}(3760)$ as an OC pair molecular state [12]. As the $\mathcal{R}(3760)$ is also observed in nOC hadron final states with a resonance peak at (3739.7 ± 4.7) MeV/c^2 [29], the $\mathcal{R}(3760)$ could also contain a component of the simple four-quark state. This feature is consistent with the four-quark state production and decays [13]. Since no $\mathcal{R}(3810)$ is observed in the cross sections of $e^+e^- \to D\bar{D}$, and its mass $(3804.5{\pm}0.9{\pm}0.9)$ MeV/c^2 is just at the $h_c\pi^+\pi^-$ threshold (3804.5 ± 0.1) MeV/c^2, the $\mathcal{R}(3810)$ could be interpreted as a hadro-charmonium state [34]. The $\mathcal{R}(3780)$ total width $(20.3{\pm}0.8{\pm}1.7)$ MeV is consistent with the values from 10 to 26 MeV predicted by the potential models [35–37] for the 1^3D_1 state, hence it can be interpreted as the 1^3D_1 state.

In summary, the most precise measurement of the cross sections for $e^+e^- \to$ hadrons at c.m. energies from 3.645 to 3.871 GeV is performed. We observe, for the first time, a resonance $\mathcal{R}(3810)$ in the total inclusive hadronic cross sections with a significance of 7.7σ. We measure its mass, total width, and electronic width to be $(3804.5{\pm}0.9{\pm}0.9)$ MeV/c^2, $(5.4{\pm}3.5{\pm}3.2)$ MeV, $(19.4{\pm}7.4{\pm}12.1)$ eV, respectively. The $\mathcal{R}(3810)$ could be interpreted as a hadro-charmonium state. In addition, we observe $\mathcal{R}(3760)$ with a significance of 15.7σ, and precisely measure its mass $(3751.9 \pm 3.8 \pm 2.8)$ MeV/c^2, total width $(32.8 \pm 5.8 \pm 8.7)$ MeV, and electronic partial width $(184 \pm 75 \pm 86)$ eV. The $\mathcal{R}(3760)$ could be interpreted as an OC-pair molecular state, but it may also contain a component of a four-quark state. Moreover, by combining the $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, $\mathcal{R}(3810)$, cnt$D\bar{D}$ and $\mathcal{G}(3900)$ line shape including the interference among these amplitudes, we measure the mass, the total width, and electronic partial width of the $\mathcal{R}(3780)$ to be $(3778.7 \pm 0.5 \pm 0.3)$ MeV/c^2 and $(20.3 \pm 0.8 \pm 1.7)$ MeV with improved precision, and $(265 \pm 69 \pm 83)$ eV, respectively. The $\mathcal{R}(3780)$ can be interpreted as the 1^3D_1 state. These observations and measurements again rule out explanations that the enhancement of the cross sections of $e^+e^- \to$ hadrons at energies around 3.76 GeV is due to the cnt$D\bar{D}$ interfering with the decay $\psi(3770) \to D\bar{D}$, or due to $\psi(3686) \to D\bar{D}$ decays at energies above the $D\bar{D}$ threshold [15]. These reveal that $\psi(3770)$ is actually a complex $\mathcal{R}s(3770)$ [11] composed of the $\mathcal{R}(3760)$ [11], $\mathcal{R}(3780)$ [11], and $\mathcal{R}(3810)$ [38]. In addition, these measurements provide important data to validate QCD predictions for the production and decays of non-$c\bar{c}$ states.

The BESIII Collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key R&D Program of China under Contracts Nos. 2009CB825204; 2020YFA0406300, 2020YFA0406400; National Natural Science Foundation of China (NSFC) under Contracts Nos. 10935007,11635010, 11735014, 11835012, 11935015, 11935016, 11935018, 11961141012, 12022510, 12025502, 12035009, 12035013, 12061131003, 12192260, 12192261, 12192262, 12192263, 12192264, 12192265, 12221005, 12225509, 12235017; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); CAS Key Research Program of Frontier Sciences under Contracts Nos. QYZDJ-SSW-SLH003, QYZDJ-SSW-SLH040; 100 Talents Program of CAS; the CAS Research Program under Code No. Y41G1010Y1; the CAS Other Research Program under Code No. Y129360; The Institute of Nuclear and Particle Physics (INPAC) and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; European Union's Horizon 2020 research and innovation programme under Marie Sklodowska-Curie grant agreement under Contract No. 894790; German Research Foundation DFG under Contracts Nos. 443159800, 455635585, Collaborative Research Center CRC 1044, FOR5327, GRK 2149; Istituto Nazionale di Fisica Nucleare, Italy; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Research Foundation of Korea under Contract No. NRF-2022R1A2C1092335; National Science and Technology fund of Mongolia; National Science Research and Innovation Fund (NSRF) via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation of Thailand under Contract No. B16F640076; Polish National Science Centre under Contract No. 2019/35/O/ST2/02907; The Swedish Research Council; U. S. Department of Energy under Contract No. DE-FG02-05ER41374

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3.87 GeV, but the fits do not describe the data. While the nominal fit is performed under assumption of three resonances existing at these energies, and the fit describe the data vary well. These reveal that the $\psi(3770)$ resonance [16, 17], discovered by the MARK-I Collaboration [16] and interpreted as the 1^3D_1 state of charmonium by the MARK-I and DELO [17] Collaborations, is actually a complex $\mathcal{R}s(3770)$ [11] composed of the $\mathcal{R}(3760)$ [11] , $\mathcal{R}(3780)$ [11], and $\mathcal{R}(3810)$ resonances.