Anomalous Line-Shape of Cross Sections for $e^+e^- \to$ Hadrons in the Center-of-Mass Energy Region between 3.650 and 3.872 GeV

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We observe an obvious anomalous line-shape of the $e^+e^- \to$ hadrons total cross sections in the energy region between 3.700 and 3.872 GeV from the data samples taken with the BES-II detector at the BEPC Collider. Re-analysis of the data shows that it is inconsistent with the explanation for only one simple $\psi(3770)$ resonance with a statistical significance of 7σ. The anomalous line-shape may be explained by two possible enhancements of the inclusive hadron production near the center-of-mass energies of 3.764 GeV and 3.779 GeV, indicating that either there is likely a new structure in addition to the $\psi(3770)$ resonance around 3.773 GeV, or there are some physics effects reflecting the $D\bar{D}$ production dynamics.

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In the energy range from 3.700 to 3.872 GeV, the well established ψ(3770) resonance is believed to be the only observed structure. This resonance has been identified to be a mixture of D-wave and S-wave of angular momentum eigenstates of the $c\bar{c}$ system. In addition, the ψ(3770) resonance is expected to decay into $D\bar{D}$ meson pairs with a branching fraction that is greater than 98%. However, there is a long-standing puzzle in the existing measurements of ψ(3770) production and decays. Before recent BES-II [1, 2, 3, 4, 5] and CLEO-c [6] results published, existing data indicated that about 38% of ψ(3770) does not decay to $D\bar{D}$ final states [7]. Recently, the BES Collaboration measured the branching fraction of ψ(3770) decays to $D\bar{D}$ to be $B[\psi(3770) \to D\bar{D}] = (85 \pm 5)\%$ [2, 3, 8] and directly measured the non-$D\bar{D}$ branching fraction of ψ(3770) decay to be $B[\psi(3770) \to \text{non-}D\bar{D}] = (13.4 \pm 5.0 \pm 3.6)\%$ [4] and $B[\psi(3770) \to \text{non-}D\bar{D}] = (15.1 \pm 5.6 \pm 1.8)\%$ [5] under assumption that there is only one simple ψ(3770) resonance in the energy region between 3.700 and 3.872 GeV. In the last two years, the BES and CLEO Collaborations have searched for exclusive non-$D\bar{D}$ decays of ψ(3770). However, the summed non-$D\bar{D}$ branching fraction measured by both the BES and CLEO Collaborations remains to be less than 2% [1, 6]. To understand why the measured inclusive non-$D\bar{D}$ branching fraction is substantially larger than 2%, in addition to continuing searching for more possible non-$D\bar{D}$ decay modes of ψ(3770), it is worth going back to carefully examine the previous measurements of the ψ(3770) parameters.

An examination of analyses previously reported by the BES Collaboration in Refs. [2, 9] shows that the fits to the observed hadronic cross sections or R values are rather poor for the fine-grained energy scan cross section measurements [see Fig. 4(a) in Ref. [2] and Fig. 1 in Ref. [9]] even though the branching fraction for $\psi(3770) \to$ non-$D\bar{D}$ was left as a free parameter in the fits. In this letter, we present a reanalysis of the observed inclusive hadronic cross sections to better understand the hadronic annihilation structure in the energy region between 3.700 and 3.872 GeV.

The measurements of the observed inclusive hadronic cross sections are discussed in detail in the Refs. [2, 3, 9, 10]. The observed inclusive hadronic cross sections obtained from the cross section scan data taken in March 2003 and in December 2003 are illustrated in Fig. 1 [17] by dot with error bars, where the error bars are the combined statistical and point-to-point systematic uncertainties. The systematic uncertainty includes the statistical uncertainty of the luminosity, the uncertainties of the Monte Carlo efficiencies for detections of the Bhabha scattering events and the hadronic events, as well as the uncertainty of the observed cross sections due to the reproducibility (∼ 0.1 MeV) of setting the BEPC machine energy. The c.m. (center-of-mass) energy of the BEPC

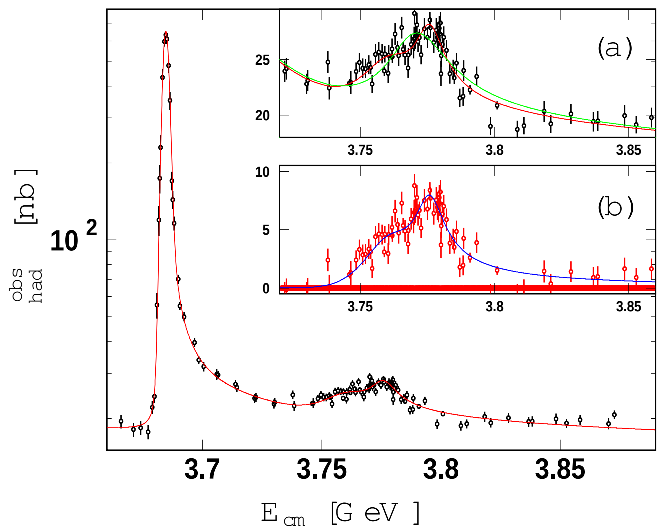

FIG. 1: The measured inclusive hadronic cross sections versus the c.m. energy for the two data sets taken in March and December 2003; the fit is done with two incoherent amplitudes (solution 1), see text for detail.

ψ(3686) and J/ψ. The measured masses of ψ(3686) and J/ψ at BEPC are obtained by analyzing 6 data sets of ψ(3686) scan and 2 data sets of J/ψ scan performed during the time periods of collecting the finer cross section scan data. The uncertainty in the calibrated energy for the combined two finer cross section scan data sets together is about ±0.5 MeV.

A close examination of the energy region (from 3.74 to 3.80 GeV) around 3.777 GeV shows that the slopes of the observed cross sections on the two sides of the peak are quite different; with the slope of the high energy side of the peak substantially larger than that of the low energy side. It conflicts with the expectations for only one resonance in this energy region, since the effects of the initial state radiation (ISR) and the $D\bar{D}$ production threshold as well as the energy dependence of the $D\bar{D}$ scattering amplitudes due to the Blatt-Weisskopt barrier [11] would all make the slope at the high energy side of the peak less steep relative to the slope on the low-energy side. This anomalous shape seen in the precision measurement indicates that one simple resonance hypothesis is quite questionable to fit the current data. Instead of the conventional definition of the ψ(3770) decay width $\Gamma(E_{cm})$, if the dynamics of $D\bar{D}$ scattering or some reasonable model describing the $D\bar{D}$ scattering can give some special form of $\Gamma(E_{cm})$ and mass shift for which the scattering amplitude gets zero or node at the rather low D meson momentum ($P_D \sim 0.4$ GeV) to adapt the unusal decline around 3.8 GeV in the cross section line shape, the anomalous line-shape of the cross sections for $e^+e^- \to$ hadrons might be understood.

However, as shown in this work, it can not be excluded to the $\psi(3770)$ resonance in the energy region between 3.700 and 3.872 GeV, which and its interference with the $\psi(3770)$ amplitude distort the line-shape of the observed cross section from that expected if there was only one resonance in the region.

To investigate whether there are some new structures in addition to the $\psi(3770)$ resonance in the energy region between 3.700 and 3.872 GeV, we fit the observed cross sections with one or two amplitudes in the energy region. The expected cross section $\sigma^{\rm expect}_{\rm had}(E_{\rm cm})$ consisting of four components can be given as

$$\sigma^{\rm expect}_{\rm had}(E_{\rm cm}) = \sigma^{\rm expect}_{Rs(3770)}(E_{\rm cm}) + \sigma^{\rm expect}_{J/\psi}(E_{\rm cm}) + \sigma^{\rm expect}_{\psi(3686)}(E_{\rm cm}) + \sigma^{\rm CTM}_{\rm had}(E_{\rm cm}); \quad (1)$$

in which $\sigma^{\rm expect}_{Rs(3770)}(E_{\rm cm})$, $\sigma^{\rm expect}_{J/\psi}(E_{\rm cm})$, $\sigma^{\rm expect}_{\psi(3686)}(E_{\rm cm})$, and $\sigma^{\rm CTM}_{\rm had}(E_{\rm cm})$ are, respectively, the expected cross sections for $Rs(3770) \to$ hadrons, $J/\psi \to$ hadrons, $\psi(3686) \to$ hadrons, and continuum light hadron production at the c.m. energy $E_{\rm cm}$, and $Rs(3770)$ denotes the full structure around 3.773 GeV. The expected cross sections are obtained from the Born order cross sections for these processes and the ISR corrections [12,13].

For the $Rs(3770)$ resonance(s), we use one or two pure P-wave Breit-Wigner amplitude(s) with energy-dependent total widths [2, 3, 9] to fit the observed hadronic cross sections. The two amplitudes are expected as

$$A_j(E_{\rm cm}) = \frac{\sqrt{12\pi\Gamma^{ee}_j\Gamma^{had}_j}}{(E^2_{\rm cm} - M^2_j) + i\Gamma^{tot}_j(E_{\rm cm})M_j} \quad (j = 1;2); \quad (2)$$

where M_j, Γ^{ee}_j, Γ^{had}_j, and $\Gamma^{tot}_j(s)$ are the masses, leptonic widths, hadronic widths, and the total widths of the two resonances, respectively. $\Gamma^{tot}_j(E_{\rm cm})$ is chosen to be energy dependent [2,3,9]. For two amplitude hypothesis, concerning the possible interference between the two amplitudes, we use two extreme schemes to see if we can get better description for the anomalous line shape. In the first scheme, we ignore the possible interference; and in the second, we assume the complete interference between the two amplitudes. These two schemes give the Solution 1 and Solution 2, respectively. The Born order cross section for $Rs(3770)$ production in Solution 1 and Solution 2 can, respectively, be written as

$$\sigma_{Rs(3770)}(E_{\rm cm}) = |A_1(E_{\rm cm})|^2 + |A_2(E_{\rm cm})|^2 \quad (3)$$

and

$$\sigma_{Rs(3770)}(E_{\rm cm}) = |A_1(E_{\rm cm}) + e^{i\phi}A_2(E_{\rm cm})|^2; \quad (4)$$

where the ϕ is the relative phase difference between the two amplitudes.

The non-resonant background shape is taken as

with

$$\sigma^{\rm CTM}_{DD}(E_{\rm cm}) = f\,[(\frac{p_{D^0}}{E_{D^0}})^3\theta_{00} + (\frac{p_{D^+}}{E_{D^+}})^3\theta_{+-}]\,\sigma^{B}_{\mu^+\mu^-}(E_{\rm cm}); \quad (6)$$

where $\sigma^{\rm CTM}_{\rm LtHd}(E_{\rm cm})$ is the observed cross section for light hadronic event production given in Refs. [2,9], $\sigma^{B}_{\mu^+\mu^-}(s)$ is the Born cross section for $e^+e^- \to \mu^+\mu^-$, p_{D^0} and p_{D^+} (E_{D^0} and E_{D^+}) are the momenta (energies) of D^0 and D^+ mesons produced at the nominal energy $\sqrt{s}$, θ_{00} and θ_{+-} are the step functions to account for the thresholds of the $D^0\bar{D}^0$ and D^+D^- meson pair production, respectively; f is a parameter to be fitted. The effect of energy spread on the observed cross sections is also considered in the analysis.

In the following, ignoring the tiny difference of the detection efficiencies determined from the different schemes as described above, we fit the observed cross sections presented in Fig. 1 and in Fig. 2, respectively, with the expected cross sections given in Eq. (1) in two schemes. In the first case, it is defined in Eq. (3) and the fits give the results of the Solution 1. In the second case, it is defined in the Eq.(4) and the fit gives the results of the Solution 2. As a comparison we also fit the cross sections with the conventional one Briet-Wigner form of $\psi(3770)$ resonance as the definition of the $R_s(3770)$ for the one resonance hypothesis. In the fits, we fix $r = 1.5$ fm (r is the interaction radius of the $c\bar{c}$ system) [2, 3, 9] and fix the J/ψ parameters at the values given in PDG07 [8]; the $\psi(3686)$ and $Rs(3770)$ resonance parameters are left free, R_{uds} and f [2,9] are also left free.

As shown in Fig. 1 and in Fig. 2, the circles with error bars show the observed cross sections. The red lines in both of the figures and in the sub-figures (a) inserted in Fig. 1 and Fig. 2 represent the fitted values of the cross sections of Solution 1 and Solution 2. The green lines in the sub-figures (a) show the fit to the observed cross sections for the one amplitude hypothesis. The circles with error bars in red as shown in the sub-guares (b) inserted in Fig. 1 and Fig. 2 show the measured net cross sections, which are obtained by subtracting the contributions from J/ψ and $\psi(3686)$ decays to hadrons, the continuum hadron production and the interference term of the two amplitudes in $Rs(3770)$ definition for the Solution 2; the blue lines show the fit to the net cross sections from the two resonances for both of the Solution 1 and Solution 2, respectively.

The 2nd, the 3rd and the 4th columns of Table I summarize, respectively, the results of the fits for the Solution 1 and the Solution 2 of the two amplitude hypothesis, and for the one amplitude hypothesis, where the first errors are from the fit and the second systematic. For the measured masses, the second errors mainly arise from the uncertainty of the BEPC machine energy calibration for the combined two data sets together. For the one res-

TABLE I: The tted results for the data taken in March 2003 and December 2003.

Quantity	two amplitudes (without interference) Solution 1	two amplitudes (interference) Solution 2	one amplitude	(3770) and G(3900) amplitudes (interference) Solution 3
^{2}=ndof	125=103 = 1:21	112=102 = 1:10	182=106 = 1:72	170=104 = 1:63
$M_{(3686)}$ [MeV]	3685:5 0:0 0:5	3685:5 0:0 0:5	3685:5 0:0 0:5	3685:5 0:0 0:5
$^{tot}_{(3686)}$ [keV]	312 34 1	311 38 1	304 36 1	293 36 1
$^{ee}_{(3686)}$ [keV]	2:24 0:04 0:11	2:23 0:04 0:11	2:24 0:04 0:11	2:23 0:04 0:11
M_1 [MeV]	3765:0 2:4 0:5	3762:6 11:8 0:5	3773:3 0:5 0:5	3774:4 0:5 0:5
$^{tot}_{1}$ [MeV]	28:5 4:6 0:1	49:9 32:1 0:1	28:2 2:1 0:1	28:6 2:3 0:1
$^{ee}_{1}$ [eV]	155 34 8	186 201 8	260 21 8	264 23 8
M_2 [MeV]	3777:0 0:6 0:5	3781:0 1:3 0:5	—	3943:0 (xed)
$^{tot}_{2}$ [MeV]	12:3 2:4 0:1	19:3 3:1 0:1	—	—
or $_G$ [MeV]	—	—	—	54 (xed)
$^{ee}_{2}$ [eV]	93 26 9	243 160 9	—	—
or C	—	—	—	0:243 (xed)
[°]	—	(158 334 5)	—	(150 23 5)
f	0:4 5:6 0:6	5:2 2:5 0:6	0:0 0:5 0:6	0:0 1:2 0:6

parameters as listed in the 4th column of Table I. These measured values of the resonance parameters are consistent within error with the world averages [14] [18] and with the earlier BES measurements [2] [3] obtained by analyzing the two data samples separately. The t gives the mass di erence between the (3770) and (3686) resonances to be $_M$ = 87:8 0:5 MeV. However, the large ^{2}=ndof in the 4th column of Table I gives the t probability of less than 7 10^{6}, meaning that the one resonance hypothesis is strongly incomparable with the present precision measurement data. On the contrary, the ^{2} change for the two hypotheses in Solution 1 is (182 125) = 57 with a reduction of 3 degrees of freedom. This indicates that the signal signi cance for the new structure is 7:0 . The ^{2} change for the two hypotheses in the Solution 2 is 70 with a reduction of 4 degrees of freedom. This indicates that the statistical signi cance of the new structure is 7:6 . Comparing the ts for the Solution 1 and Solution 2, we nd that the ^{2} change of 13 with a reduction of 1 degree of freedom. The signi cance of the interference between the two Breit-Wigner amplitudes is 3:6 , which indicates that the two amplitudes likely interfere somehow with each other. The actual situation of the interference would be somewhere between the two cases. It depends on what are the exact nal states of the possible new structure decays.

However, it is noted that the tted value f = 5:2 2:5 0:6 in the Solution 2 would lead to a huge D D production cross section at higher energy region and there exists an evident dip of the inclusive hadronic cross section around E_{cm} = 3.80 GeV. These indicate that, instead of only the continuum D D production, there might be a broad structure whose peak is at higher energy than 3.83 GeV and

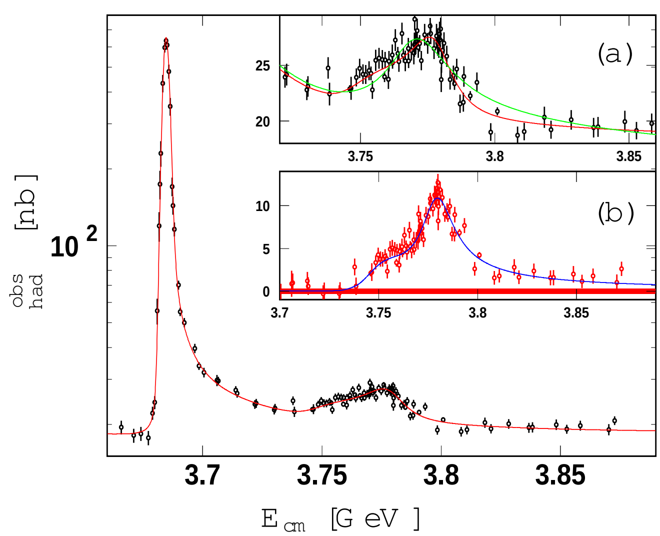

FIG. 2: The observed inclusive hadronic cross sections versus the nominal c.m. energies for the combined data sets taken in March and December 2003; the t was done with two coherent amplitudes for R s(3770) (Solution 2).

BELLE collaborations [16] observed G(3900). To consider the e ect of the G(3900) on the observed cross sections, instead of the rst two solutions for the two structure hypotheses one may adopt the third approach by including the new component of D D production amplitude of G(3900). The tting procedure is analogous to Solution 2. However, the amplitude $A_2(E_{cm})$ in Eq. (4) is replaced by a square root product of a parameter C and a Gaussian function G. The mass and the standard deviation of G are xed at the measured valing to the $D\bar{D}$ cross section as the one measured by BABAR at 3.943 GeV. The red line in Fig. 3(a) represents the fitted values of the cross sections, which is obtained from the fit under assumption that the (3770) and G(3900) amplitudes interfere with each other; the fitted value from the hypotheses for only (3770) amplitude (blue line), from Solution 1 (yellow line) and from Solution 2 (green line) are also illustrated in Fig. 3(a). The 5th column of Table I summarizes the results (Solution 3) of the fit including G(3900). The fit gives a rather poor fit probability of less than 5×10^{-5}, which does not significantly improve the fit from the one resonance hypothesis. If we consider three coherent amplitudes in the fit by replacing $|A_1(E_{cm}) + e^{i\phi} A_2(E_{cm})|^2$ with $|A_1(E_{cm}) + e^{i\phi_1} A_2(E_{cm}) + e^{i\phi_2} G(E_{cm})|^2$ in Eq. (4), where G is the G(3900) structure, we obtain almost the same results as these shown in Solution 2 in Table I instead of $f = 5.2 \pm 2.5 \pm 0.6$. This fit gives $f = 2.7 \pm 6.4 \pm 0.6$, which is comparable with the inclusive hadronic cross section measurements at the higher energy region. Fig. 3(b) shows the ratio of the residual between the observed cross section and the fitted value for the one (3770) amplitude hypothesis to the error of the observed cross section. The variation of the ratio with E_{cm} indicates that there is more likely some new structure additional to (3770) resonance.

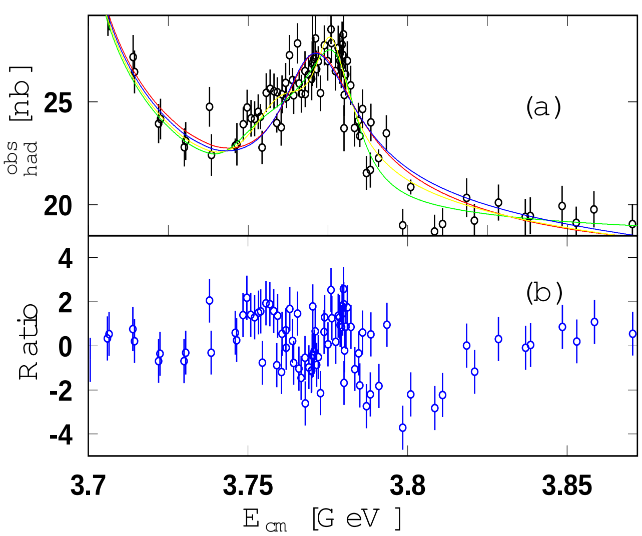

FIG. 3: (a) the observed inclusive hadronic cross section versus the nominal c.m. energy; (b) ratio of residual to error of observed cross section; (see text).

In summary, by re-analyzing the line-shape of the cross sections for $e^+e^- \to$ hadrons, we find that it does not describe the cross section shape well with the hypothese that only one simple (3770) resonance exists in the energy region from 3.700 to 3.872 GeV. If there are no other dynamics effects which distort the pure D-wave Breit-Wigner shape of the cross sections, the analysis shows one simple (3770) resonance there at 7 statistical significance, indicating that there might be evidence for a new structure additional to the single (3770) resonance. However, if there are some dynamics effects distorting the pure D-wave Breit-Wigner shape of the cross sections, such as the rescattering of $D\bar{D}$ leading to the significant energy dependence of the wave function in the $D\bar{D}$ decays of the (3770) resonance, one has to consider those effects in the measurements of the resonance parameters of (3770), since these effects would definitely shift the measured values of the resonance parameters. Anyway, the large non-$D\bar{D}$ branching fraction of (3770) decays measured previously [2, 3] may partially be due to the assumption that there is only one simple resonance in the energy region between 3.700 and 3.872 GeV in the previous measurements of the (3770) parameters.

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[17] The observed cross sections from the two data sets are corrected with the measured R_{uds} values before combining them together.

[18] We compare our results with PDG06 world average, since PDG06 did not include BES results on the measurements