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

M. Ablikim,[1] J. Z. Bai,[1] Y. Ban,[12] X. Cai,[1] H. F. Chen,[16] H. S. Chen,[1] H. X. Chen,[1] J. C. Chen,[1] Jin Chen,[1] Y. B. Chen,[1] Y. P. Chu,[1] Y. S. Dai,[18] L. Y. Diao,[9] Z. Y. Deng,[1] Q. F. Dong,[15] S. X. Du,[1] J. Fang,[1] S. S. Fang,[1,*] C. D. Fu,[15] C. S. Gao,[1] Y. N. Gao,[15] S. D. Gu,[1] Y. T. Gu,[4] Y. N. Guo,[1] K. L. He,[1] M. He,[13] Y. K. Heng,[1] J. Hou,[11] H. M. Hu,[1] J. H. Hu,[3] T. Hu,[1] G. S. Huang,[1,+] X. T. Huang,[13] X. B. Ji,[1] X. S. Jiang,[1] X. Y. Jiang,[5] J. B. Jiao,[13] D. P. Jin,[1] S. Jin,[1] Y. F. Lai,[1] G. Li,[1,‡] H. B. Li,[1] J. Li,[1] R. Y. Li,[1] S. M. Li,[1] W. D. Li,[1] W. G. Li,[1] X. L. Li,[1] X. N. Li,[1] X. Q. Li,[11] Y. F. Liang,[14] H. B. Liao,[1] B. J. Liu,[1] C. X. Liu,[1] F. Liu,[6] Fang Liu,[1] H. H. Liu,[1] H. M. Liu,[1] J. Liu,[12,§] J. B. Liu,[1] J. P. Liu,[17] Jian Liu,[1] Q. Liu,[1] R. G. Liu,[1] Z. A. Liu,[1] Y. C. Lou,[5] F. Lu,[1] G. R. Lu,[5] J. G. Lu,[1] C. L. Luo,[10] F. C. Ma,[9] H. L. Ma,[1] L. L. Ma,[1,∥] Q. M. Ma,[1] Z. P. Mao,[1] X. H. Mo,[1] J. Nie,[1] R. G. Ping,[1] N. D. Qi,[1] H. Qin,[1] J. F. Qiu,[1] Z. Y. Ren,[1] G. Rong,[1] X. D. Ruan,[4] L. Y. Shan,[1] L. Shang,[1] D. L. Shen,[1] X. Y. Shen,[1] H. Y. Sheng,[1] H. S. Sun,[1] S. S. Sun,[1] Y. Z. Sun,[1] Z. J. Sun,[1] X. Tang,[1] G. L. Tong,[1] D. Y. Wang,[1,¶] L. Wang,[1] L. L. Wang,[1] L. S. Wang,[1] M. Wang,[1] P. Wang,[1] P. L. Wang,[1] W. F. Wang,[1,**] Y. F. Wang,[1] Z. Wang,[1] Z. Y. Wang,[1] Zheng Wang,[1] C. L. Wei,[1] D. H. Wei,[1] Y. Weng,[1] N. Wu,[1] X. M. Xia,[1] X. X. Xie,[1] G. F. Xu,[1] X. P. Xu,[6] Y. Xu,[11] M. L. Yan,[16] H. X. Yang,[1] Y. X. Yang,[3] M. H. Ye,[2] Y. X. Ye,[16] G. W. Yu,[1] C. Z. Yuan,[1] Y. Yuan,[1] S. L. Zang,[1] Y. Zeng,[7] B. X. Zhang,[1] B. Y. Zhang,[1] C. C. Zhang,[1] D. H. Zhang,[1] H. Q. Zhang,[1] H. Y. Zhang,[1] J. W. Zhang,[1] J. Y. Zhang,[1] S. H. Zhang,[1] X. Y. Zhang,[13] Yiyun Zhang,[14] Z. X. Zhang,[12] Z. P. Zhang,[16] D. X. Zhao,[1] J. W. Zhao,[1] M. G. Zhao,[1] P. P. Zhao,[1] W. R. Zhao,[1] Z. G. Zhao,[1,++] H. Q. Zheng,[12] J. P. Zheng,[1] Z. P. Zheng,[1] L. Zhou,[1] K. J. Zhu,[1] Q. M. Zhu,[1] Y. C. Zhu,[1] Y. S. Zhu,[1] Z. A. Zhu,[1] B. A. Zhuang,[1] X. A. Zhuang,[1] and B. S. Zou[1]

(BES Collaboration)

[1]*Institute of High Energy Physics, Beijing 100049, People's Republic of China*
[2]*China Center for Advanced Science and Technology, Beijing 100080, People's Republic of China*
[3]*Guangxi Normal University, Guilin 541004, People's Republic of China*
[4]*Guangxi University, Nanning 530004, People's Republic of China*
[5]*Henan Normal University, Xinxiang 453002, People's Republic of China*
[6]*Huazhong Normal University, Wuhan 430079, People's Republic of China*
[7]*Hunan University, Changsha 410082, People's Republic of China*
[8]*Jinan University, Jinan 250022, People's Republic of China*
[9]*Liaoning University, Shenyang 110036, People's Republic of China*
[10]*Nanjing Normal University, Nanjing 210097, People's Republic of China*
[11]*Nankai University, Tianjin 300071, People's Republic of China*
[12]*Peking University, Beijing 100871, People's Republic of China*
[13]*Shandong University, Jinan 250100, People's Republic of China*
[14]*Sichuan University, Chengdu 610064, People's Republic of China*
[15]*Tsinghua University, Beijing 100084, People's Republic of China*
[16]*University of Science and Technology of China, Hefei 230026, People's Republic of China*
[17]*Wuhan University, Wuhan 430072, People's Republic of China*
[18]*Zhejiang University, Hangzhou 310028, People's Republic of China*
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We observe an obvious anomalous line shape of the $e^+e^- \to$ hadions total cross sections in the energy region between 3.700 and 3.872 GeV. 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 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 $\psi(3770)$ resonance is believed to be the only observed structure. The $\psi(3770)$ 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 $\psi(3770)$ production and decays. Before recent BES-II [1–5] and CLEO-c [6] results published, existing data indicated that about 38% of $\psi(3770)$ does not decay to $D\bar{D}$ final states [7]. Recently, the BES Collaboration measured the branching fraction of

$\psi(3770)$ 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 $\psi(3770)$ 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 $\psi(3770)$ 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 $\psi(3770)$. 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 $\psi(3770)$, it is worth going back to carefully examine the previous measurements of the $\psi(3770)$ 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 $\psi(3770) \to \text{non-}D\bar{D}$ 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 [11] 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 ($\pm$ 0.1 MeV) of setting the BEPC machine energy. The c.m. (center-of-mass) energy of the BEPC machine is calibrated with the world average masses of $\psi(3686)$ and J/ψ. The measured masses of $\psi(3686)$ and J/ψ at BEPC are obtained by analyzing 6 data sets of $\psi(3686)$ 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. In Fig. 1, we combined the two independent measurements of the observed cross sections together to analyze the observed cross sections instead of the R values, since the shape of the R values is more dependence on the theoretical assumption for the structures than the one of the observed cross sections.

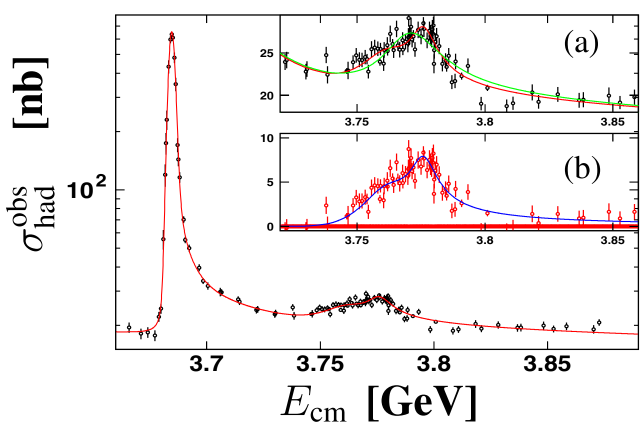

FIG. 1 (color online). [The line in the figure is given in red; the line in subfigure (b) is given in blue; the top and bottom lines at 3.8 GeV in subfigure (a) are given in green and red, respectively.] The observed inclusive hadronic cross sections versus the c.m. energy (see text).

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 [12] would all make the slope at the high-energy side of the peak less steep relative to the slope on the low-energy side. It indicates that one simple resonance hypothesis is quite questionable to fit the current data. Instead of the conventional definition of the $\psi(3770)$ decay width $\Gamma(E_{\rm c.m.})$, if the dynamics of $D\bar{D}$ scattering or some reasonable model describing the $D\bar{D}$ scattering can give some special form of $\Gamma(E_{\rm c.m.})$ 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 unusual 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 may not be excluded neither that there can be some new structure in addition 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 $\sigma_{\rm had}^{\rm exp}(E_{\rm c.m.})$ can be given as

$$\sigma_{\rm had}^{\rm exp}(s) = \sigma_{Rs(3770)}^{\rm exp}(s) + \sigma_{J/\psi}^{\rm exp}(s) + \sigma_{\psi(3686)}^{\rm exp}(s) + \sigma_h^C(s), \quad (1)$$

with $s = E^2_{\rm c.m.}$, where $\sigma^{\rm exp}_{Rs(3770)}(s)$, $\sigma^{\rm exp}_{J/\psi}(s)$, $\sigma^{\rm exp}_{\psi(3686)}(s)$, and $\sigma^C_h(s)$ 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 $E_{\rm c.m.}$, 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 [13,14].

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. 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.

The nonresonant background shape is taken as

$$\sigma^C_h(s) = \sigma^C_{\rm LH}(s) + f\bigg[\bigg(\frac{p_{D^0}}{E_{D^0}}\bigg)^3\theta_{00} + \bigg(\frac{p_{D^+}}{E_{D^+}}\bigg)^3\theta_{+-}\bigg]\sigma^B_{\mu^+\mu^-}(s), \quad (2)$$

where $\sigma^C_{\rm LH}(s)$ 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. In the first and second cases, the fits give the results of the Solution 1 and Solution 2, respectively. 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 $Rs(3770)$ 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, $R_{\rm uds}$ and f [2,9] are also left free.

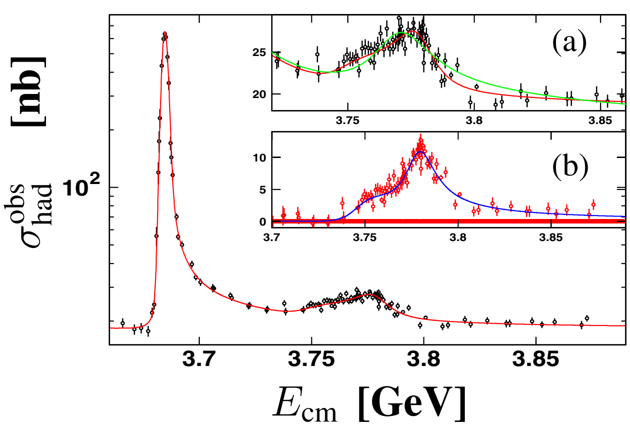

FIG. 2 (color online). [The line in the figure is given in red; the line in subfigure (b) is given in blue; the top and bottom lines at 3.8 GeV in subfigure (a) are given in green and red, respectively.] The observed inclusive hadronic cross sections versus the nominal c.m. energies for solution 2.

As shown in Figs. 1 and 2, the circles with error bars show the observed cross sections. The red lines (please refer to the captions of Figs. 1 and 2 for the color lines) in both of the figures and in the subfigures (a) inserted in Figs. 1 and 2 represent the fitted values of the cross sections of Solution 1 and Solution 2. The green lines in the subfigures (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 subfigures (b) inserted in Figs. 1 and 2 show the measured net cross sections, corresponding to the two amplitudes themselves in $Rs(3770)$ definition for the two solutions; the blue lines show the fits to the net cross sections from the two resonances for both of the Solution 1 and Solution 2, respectively.

The 2nd, 3rd, and 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 resonance hypothesis, the fit yields $\psi(3770)$ and $\psi(3686)$ 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 [8,15] and with the earlier BES measurements [2,3] obtained by analyzing the two data samples separately. The fit gives the mass difference between the $\psi(3770)$ and $\psi(3686)$ resonances to be $\Delta M = 87.8 \pm 0.5$ MeV. However, the large χ^2/ndof in the 4th column of Table I gives the fit 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 χ^2 changes for the two hypotheses are 57 and 70 in Solution 1 and in Solution 2 with the reduction of 3 and 4 degrees of freedom, indicating that the signal significance for the new structure are 7.0σ and 7.6σ, respectively.

However, it is noted that the fitted value $f = 5.2 \pm 2.5 \pm 0.6$ in the Solution 2 would lead to a huge $D\bar{D}$ production cross section at higher energy region and there exists an evident dip of the inclusive hadronic cross section around $E_{\rm c.m.} = 3.80$ GeV. These indicate that, instead of only the continuum $D\bar{D}$ production, there might be a broad structure whose peak is at higher energy than 3.83 GeV and it interferes with $Rs(3770)$. Recently,

TABLE I. The fitted results, where M, Γ^{tot} and Γ^{ee} are the mass, total, and leptonic widths of resonance(s), σ_G is standard deviation of $G(3900)$, ϕ is the phase difference between the two amplitudes and AM stands for amplitude(s). ndof denotes number of degrees of freedom.

Quantity	two AM (Solution 1)	two AM (Solution 2)	one AM	$\psi(3770)$ and $G(3900)$ AM (Solution 3)
$\chi^2/(\mathrm{ndof})$	$125/103 = 1.21$	$112/102 = 1.10$	$182/106 = 1.72$	$170/104 = 1.63$
$M_{\psi(3686)}$ [MeV]	$3685.5 \pm 0.0 \pm 0.5$	$3685.5 \pm 0.0 \pm 0.5$	$3685.5 \pm 0.0 \pm 0.5$	$3685.5 \pm 0.0 \pm 0.5$
$\Gamma^{tot}_{\psi(3686)}$ [keV]	$312 \pm 34 \pm 1$	$311 \pm 38 \pm 1$	$304 \pm 36 \pm 1$	$293 \pm 36 \pm 1$
$\Gamma^{ee}_{\psi(3686)}$ [keV]	$2.24 \pm 0.04 \pm 0.11$	$2.23 \pm 0.04 \pm 0.11$	$2.24 \pm 0.04 \pm 0.11$	$2.23 \pm 0.04 \pm 0.11$
M_1 [MeV]	$3765.0 \pm 2.4 \pm 0.5$	$3762.6 \pm 11.8 \pm 0.5$	$3773.3 \pm 0.5 \pm 0.5$	$3774.4 \pm 0.5 \pm 0.5$
Γ^{tot}_1	$28.5 \pm 4.6 \pm 0.1$	$49.9 \pm 32.1 \pm 0.1$	$28.2 \pm 2.1 \pm 0.1$	$28.6 \pm 2.3 \pm 0.1$
Γ^{ee}_1 [eV]	$155 \pm 34 \pm 8$	$186 \pm 201 \pm 8$	$260 \pm 21 \pm 8$	$264 \pm 23 \pm 8$
M_2 [MeV]	$3777.0 \pm 0.6 \pm 0.5$	$3781.0 \pm 1.3 \pm 0.5$	$\cdots$	3943.0 (fixed)
Γ^{tot}_2 [MeV]	$12.3 \pm 2.4 \pm 0.1$	$19.3 \pm 3.1 \pm 0.1$	$\cdots$	$\cdots$
or σ_G [MeV]	$\cdots$	$\cdots$		54 (fixed)
Γ^{ee}_2 [eV]	$93 \pm 26 \pm 9$	$243 \pm 160 \pm 9$	$\cdots$	$\cdots$
or C	$\cdots$	$\cdots$	$\cdots$	0.243 (fixed)
ϕ [deg]	$\cdots$	$(158 \pm 334 \pm 5)$	$\cdots$	$(150 \pm 23 \pm 5)$
f	$0.4 \pm 5.6 \pm 0.6$	$5.2 \pm 2.5 \pm 0.6$	$0.0 \pm 0.5 \pm 0.6$	$0.0 \pm 1.2 \pm 0.6$

BABAR [16] and BELLE Collaborations [17] observed $G(3900)$. To consider the effect of the $G(3900)$ on the observed cross sections, instead of the first two solutions for the two structure hypotheses one may adopt the third approach by including the new component of $D\bar{D}$ production amplitude of $G(3900)$. The fitting procedure is analogous to Solution 2. The mass and σ_G of $G(3900)$ are fixed at the measured values [16] and a constant C is fixed at 0.243 corresponding to the $D\bar{D}$ cross section as the one measured by *BABAR* at 3.943 GeV. The red line (please refer to the caption of Fig. 3 for the color lines) in Fig. 3(a) represents the fitted values of the cross sections, which is obtained from the fit under assumption that the $\psi(3770)$ and $G(3900)$ amplitudes interfere with each other; the fitted value from the hypotheses for only $\psi(3770)$ 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. 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 including two amplitudes for $Rs(3770)$ and one amplitudes for $G(3900)$ in the fit, 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. Figure 3(b) shows the ratio of the residual between the observed cross section and the fitted value for the one $\psi(3770)$ amplitude hypothesis to the error of the observed cross section. The variation of the ratio with $E_{\mathrm{c.m.}}$ indicates that there is more likely some new structure additional to the $\psi(3770)$ resonance.

In summary, by 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 hypothesis that only one simple $\psi(3770)$ 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-Weigner shape of the cross sections, the analysis shows that the fit is inconsistent with the explanation for only one simple $\psi(3770)$ resonance there at 7σ statistical significance, indicating that there might be evidence for a new structure additional to the single $\psi(3770)$ resonance. However, if there are some dynamics effects distorting the pure D-wave Breit-Weigner 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 $\psi(3770)$ resonance, one has to consider these effects in the measurements of the resonance parameters of

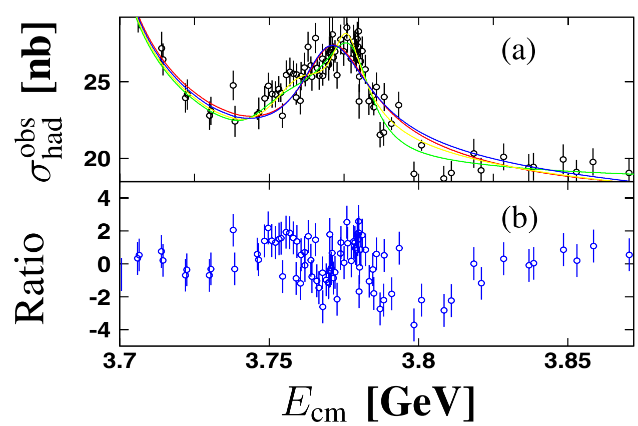

FIG. 3 (color online). (a) [The first, second, third, and fourth lines from the bottom to top at 3.8 GeV in (a) are given in green, yellow, red, and blue, respectively.] The observed inclusive hadronic cross section versus the nominal c.m. energy; (b) ratio of residual to error of observed cross section (see text).

$\psi(3770)$, since these effects would definitely shift the measured values of the resonance parameters. Anyway, the large non-$D\bar{D}$ branching fraction of the $\psi(3770)$ decays measured previously [2,3] may partially be due to the assumption that there is only one simple resonance in the energy region in the previous measurements of the $\psi(3770)$ parameters. Analyzing the combined two independent measurements of the observed cross sections makes the two possible enhancements observed more clearly than that some evidence is seen around 3.80 GeV in the R values reported previously [9].

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*Current address: DESY, D-22607, Hamburg, Germany.

†Current address: University of OK, Norman, OK 73019, USA.

‡Current address: Universite Paris XI, LAL-Bat. 208-BP34, 91898- ORSAY Cedex, France.

§Current address: Max-Plank-Institut fuer Physik, Foehringer Ring 6, 80805 Munich, Germany.

∥Current address: University of Toronto, Toronto M5S 1A7, Canada.

¶Current address: CERN, CH-1211 Geneva 23, Switzerland.

**Current address: Laboratoire de l'Accéelerateur Liǹeaire, Orsay, F-91898, France.

††Current address: University of Michigan, Ann Arbor, MI 48109, USA.

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