



# Analysis of BaBar, Belle, BES-II, CLEO and KEDR data on $\psi(3770)$ line shape and determination of the resonance parameters

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## ABSTRACT

The available data on the  $D\bar{D}$  and inclusive hadronic cross sections in the  $\psi(3770)$  region from the BaBar, Belle, BES-II, CLEO and KEDR experiments have been analyzed assuming that systematic uncertainties on cross sections measured by various detectors are not correlated. Four theoretical models predicting the  $\psi(3770)$  line shape were considered for the  $D\bar{D}$  channel. All of them gave satisfactory description of the data. The combined analysis of the  $D\bar{D}$  and inclusive hadronic channels was performed using the model based on the vector dominance approach and accounting for the contribution of the  $\psi(2S)$  tail to the  $D\bar{D}$  cross section. The following values of the mass, total width, electron width and decay probability to the non- $D\bar{D}$  states were obtained:

$M$ (MeV)	$\Gamma$ (MeV)	$\Gamma_{ee}$ (eV)	$\mathcal{B}_{nD\bar{D}}$
$3779.8 \pm 0.6$	$25.8 \pm 1.3$	$196 \pm 18$	$0.164 \pm 0.049$

where the errors quoted include both statistical and dominant systematic uncertainties.

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## 1. Introduction

Behavior of the hadronic cross section in the vicinity of the  $\psi(3770)$  is an object of numerous studies, both experimental and theoretical, and a subject of many discussions over the last ten years. The main topics of the discussions are the resonance line shape and the probability of decay to the non- $D\bar{D}$  states. The data on the  $D\bar{D}$  and inclusive hadronic cross section expected from BES-III should shed light on both of them. While waiting for these data, it would be useful to perform a joint analysis of all experimental data available so far, compare different theoretical models related to the  $\psi(3770)$  line shape and estimate its non- $D\bar{D}$  decay probability. Some BES-III results on the  $D\bar{D}$  channel were already presented at the workshop on charm physics [1] but have not yet been published.

A summary of the experimental data used in this study is presented in Table 1. Five types of data were involved: inclusive hadronic data in the form of the  $R$  ratio from BES and in the form of the detected cross section with a known detection efficiency

from KEDR, the  $D\bar{D}$  cross section measured by BaBar and Belle with radiative return, the  $e^+e^- \rightarrow D\bar{D}(\gamma)$  cross section by BES and CLEO, and, finally, the inclusive non- $D\bar{D}$  cross section extracted by BES using kaons of high momentum which can not appear in decays of  $D$ -mesons not too far from the production threshold. The data for the  $R$  measurement were collected by BES in December 2003, but the data set collected in March 2003 and mentioned in [2] is, unfortunately, not available.

## 2. Inclusive hadronic cross section

In the energy range from the  $\psi(2S)$  mass to the  $D\bar{D}\pi$  threshold the inclusive hadronic cross section can be parameterized as follows:

$$\begin{aligned} \sigma_{e^+e^- \rightarrow \text{hadr}(\gamma)}^{\text{visible}} &= (\varepsilon_{\psi(2S)} \sigma_{\psi(2S)}^{\text{RC}} + \varepsilon_{J/\psi} \sigma_{J/\psi}^{\text{RC}} + \varepsilon_{\tau\tau} \sigma_{\tau\tau}^{\text{RC}} + \varepsilon_{uds} \sigma_{uds}^{\text{RC}}) \\ &+ (\varepsilon_{D\bar{D}} \sigma_{D\bar{D}}^{\text{RC}} + \varepsilon_{nD\bar{D}} \mathcal{B}_{nD\bar{D}} \sigma_{\psi(3770)}^{\text{RC}}), \end{aligned} \quad (1)$$

where  $\sigma^{\text{RC}}$ 's are theoretical cross sections,  $\varepsilon$ 's are corresponding detection efficiencies. The RC superscript means that the cross section has been corrected for initial-state radiation (ISR) effects,  $nD\bar{D}$  stands for the direct  $\psi(3770)$  decay to light hadrons, the other

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**Table 1**

Analysis	Comments
BES [3] inclusive hadrons	68 points of $R(W)$
BaBar [4] $D\bar{D}$	36 points, $\int_{W-\Delta W/2}^{W+\Delta W/2} \sigma_{e^+e^- \rightarrow D\bar{D}}(W') dW' / \Delta W$ , $\Delta W = 5$ MeV
BES [5] + [6] inclusive hadrons, non- $D\bar{D}$	1 + 1 point, $\sigma_{e^+e^- \rightarrow \text{hadr}(\psi)}(W)$ , $\sigma_{e^+e^- \rightarrow \text{non-}D\bar{D}(\psi)}(W)$ , $W = 3773$ MeV
BES [7] $D\bar{D}$	14 points, $\sigma_{e^+e^- \rightarrow D\bar{D}(\psi)}(W)$
Belle [8] $D\bar{D}$	9 points, $\int_{W-\Delta W/2}^{W+\Delta W/2} \sigma_{e^+e^- \rightarrow D\bar{D}}(W') dW' / \Delta W$ , $\Delta W = 20$ MeV
CLEO [9] + [10] inclusive hadrons, $D\bar{D}$	1 + 1 point, $\sigma_{e^+e^- \rightarrow \text{hadr}(\psi)}(W)$ , $\sigma_{e^+e^- \rightarrow D\bar{D}(\psi)}(W)$ , $W = 3774 \pm 1$ MeV
KEDR [11] inclusive hadrons	17 + 21 + 38 points in 3 scans $\sigma_{e^+e^- \rightarrow \text{hadr}(\psi)}(W)$

(super/sub)scripts seem self-explanatory. The detection efficiencies depend on energy weakly and monotonously.

In this work Eq. (1) was used for analysis of KEDR data in the approximation of Ref. [11]. Only the latter parenthesis in (1) is essential for  $\psi(3770)$  characteristics, the former one represents the background which is subtracted by introducing additional parameters in the fit.

The multihadron cross section by BES was published in terms of  $R$ . That simplifies the background subtraction but complicates a study of the  $D\bar{D}$  signal and inclusive non- $D\bar{D}$  decays of  $\psi(3770)$ . Indeed, the calculation of  $R$  requires weighting of different detection efficiencies entering in (1) and the evaluation of ISR corrections for the  $D\bar{D}$  cross section, which can not be done without assumptions about the  $\sigma_{D\bar{D}}(W)$  behavior and  $\psi(3770)$  parameters. To facilitate this problem,  $R$  was transformed to the excess of the observable cross section due to  $D\bar{D}$  production and non- $D\bar{D}$  decays of  $\psi(3770)$ :

$$\delta\sigma_{\text{hadr}(\psi)} = \sigma_{D\bar{D}}^{\text{RC}} + (\varepsilon_{nD\bar{D}}/\varepsilon_{D\bar{D}}) \mathcal{B}_{nD\bar{D}} \sigma_{\psi(3770)}^{\text{RC}}. \quad (2)$$

The required information on the detection efficiency and on the account for radiative corrections was taken from Refs. [3,12]. Some details on the transformation can be found in Appendix A. Since the properties of the non- $D\bar{D}$  decay are not known well, it was assumed that  $\varepsilon_{nD\bar{D}}/\varepsilon_{D\bar{D}} = 1$ .

### 3. $D\bar{D}$ cross section

The  $D\bar{D}$  cross sections can be presented in the form

$$\sigma_{D\bar{D}}(W) = \frac{\pi\alpha^2}{3W^2} \beta_D^3 |F_D(W)|^2, \quad \beta_D = \sqrt{1 - 4m_D^2/W^2}, \quad (3)$$

where  $\beta_D$  is the meson velocity in the c.m. frame and  $F_D$  is a  $D$  meson form factor. For determination of the  $\psi(3770)$  parameters in the usual way it should be split into independent parts

$$F_D(W) = F^{\psi(3770)}(W) e^{i\phi} + F^{\text{N.R.}}(W), \quad (4)$$

where  $F^{\psi}(W)$  is a P-wave Breit-Wigner amplitude with energy-dependent total width  $\Gamma(W)$ ,  $F^{\text{N.R.}}(W)$  is a non-resonant (with respect to  $\psi(3770)$ ) part of the form factor and  $\phi$  is a relative phase shift.

In the spirit of the Vector Dominance Model (VDM) one can assume that the form factor is saturated by contributions of nearest vector mesons. Below 3.9 GeV it can be reduced to

$$F^{\text{N.R.}}(W) = F^{\psi(2S)}(W) + F_0, \quad (5)$$

where  $F_0$  is a real constant representing contributions of  $\psi(4040)$  and higher  $\psi$ 's. Such an approach was used for determination of  $\psi(3770)$  parameters in Ref. [11] and was employed in this work. In BES-III report [1] it is considered as one of two options.

Alternatively, the form factors following from the works [14–16] were implemented in the analysis procedure. In these cases the form factor can not be split according to Eq. (4), thus the resonance mass and widths can not be compared with those obtained in the VDM approach.

The  $D\bar{D}$  cross sections published by BaBar and Belle can be directly matched with the theoretical cross section in Eq. (3). The  $D\bar{D}(\psi)$  cross sections published by BES and CLEO correspond to  $\sigma_{D\bar{D}}^{\text{RC}}(W)$  in Eq. (1):

$$\sigma_{D\bar{D}}^{\text{RC}}(W) = \int \sigma_{D\bar{D}}(W' \sqrt{1-x}) \mathcal{F}(x, W'^2) G(W, W') dW' dx, \quad (6)$$

where  $\mathcal{F}(x, s)$  is the radiative correction kernel depending on the fraction of  $s$  lost in the initial-state radiation [17] and  $G(W, W')$  describes a distribution of the total collision energy. The latter is assumed to be Gaussian with the standard deviation  $\sigma_W$  which is about 1.3 and 2 MeV for BES and CLEO, respectively [18].

### 4. Data analysis

A sum of likelihood functions for independent experiments is minimized with

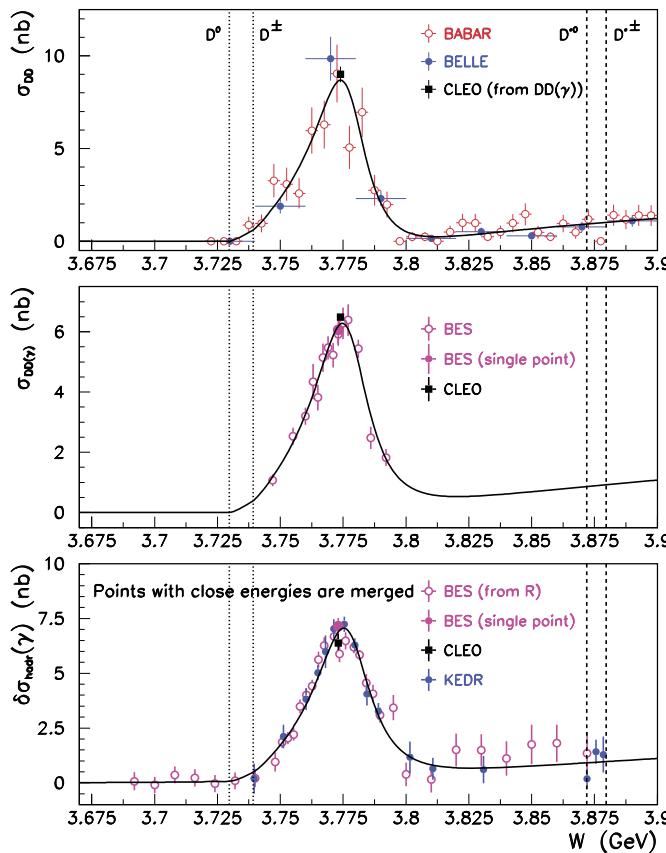
$$\mathcal{L}^{\text{exp}} = \mathcal{L}_{\text{data}}(f_N, \Delta_W) + \mathcal{L}_{\text{syst}}(f_N, \Delta_W), \quad (7)$$

where  $\mathcal{L}_{\text{data}}$  is the Poisson likelihood function multiplied by two when the number of observed events is known or just  $\chi^2$  when only the cross section and its error are known. The integration of the theoretical cross section to match BaBar and Belle data is performed numerically with an energy step of 0.5 MeV.

Expected values in the likelihood are calculated with the additional free parameters  $f_N$  and  $\Delta_W$  specific for each experiment. They account for systematic uncertainties of the experiment in the cross section normalization and in the energy scale, respectively. Their variations are limited by the term  $\mathcal{L}_{\text{syst}} = (f_N - 1)^2/\sigma_N^2 + \Delta_W^2/\delta_W^2$  with the  $\sigma_N$  and  $\delta_W$  values taken from the appropriate publication. Thus, the uncertainty estimates returned by the fit reflect a statistical error as well as dominant systematic uncertainties.

The characteristic value of the normalization uncertainty  $\sigma_N$  is about 10% for the  $D\bar{D}$  cross section measurements and about 3% for the inclusive hadronic cross section. The typical energy uncertainty is about 1–2 MeV for all experiments but KEDR, which has a high-precision system of beam energy determination.

Due to the second term of Eq. (7), introduction of parameters  $f_N$  and  $\Delta_W$  does not reduce the number of degrees of freedom. Up to nine additional free parameters were used to subtract the background and exclude systematic uncertainties related to calculations of the  $\psi(2S)$  radiative tail. The subtraction of the background in the KEDR data is described in Ref. [11]. For the BES hadronic data two parameters were introduced,  $\Delta R_{uds}$  and  $\Delta \Gamma_{ee}^{\psi(2S)} / \Gamma_{ee}^{\psi(2S)}$ . The former corrects the  $uds$ -background level, the latter gives the relative correction to the value of the  $\psi(2S)$  leptonic width used in Ref. [3] for the radiative correction calculation.



**Fig. 1.** The fit of data in the  $e^+e^- \rightarrow D\bar{D}$ ,  $e^+e^- \rightarrow D\bar{D}(\gamma)$  and  $e^+e^- \rightarrow \text{hadrons}(\gamma)$  channels. For the latter only the excess of the cross section associated with the  $D\bar{D}$  threshold is shown. The dotted and dashed lines mark  $D^0$ ,  $D^\pm$  and  $D^*$ 's thresholds.

## 5. VDM fit results

The results of the combined fit of all data in the VDM ansatz are presented in Fig. 1. The fit gives  $\chi^2 = 230$  for 192 degrees of freedom which corresponds to the  $\chi^2$  probability of about 3.2%. Such a value of  $P(\chi^2)$  can be considered as satisfactory due to outliers existing in some data sets. After a few points are removed,  $P(\chi^2)$  reaches 17%.

The fit gives the following values of the parameters  $f_N$  and  $\Delta_W$  for  $D\bar{D}$  channels:

Experiment	$f_N - 1$ (%)	$\Delta_W$ (MeV)
Belle	$-6.02 \pm 6.55$	$-1.23 \pm 1.16$
BaBar	$0.17 \pm 5.99$	$2.90 \pm 1.00$
BES	$4.99 \pm 3.97$	$0.40 \pm 0.19$

They demonstrate that the experiments agree within the errors quoted. The parameters  $f_N$  were fixed at unity for the data obtained by BES, CLEO and KEDR in the inclusive hadronic channel. The corrections for the  $R_{uds}$  and  $\Gamma_{ee}^{\psi(2S)}$  values used in the BES hadronic data analysis are small,  $\Delta R_{uds} = 0.015 \pm 0.022$ ,  $\Delta \Gamma_{ee}^{\psi(2S)} / \Gamma_{ee}^{\psi(2S)} = 0.022 \pm 0.014$ .

As discussed in [11], for the form factor in Eq. (4) the likelihood function has two local minima with very close values of  $\chi^2$  at two values of the relative phase  $\phi$ . This corresponds to two possible solutions for the  $\psi(3770)$  parameters:

	$M$ (MeV)	$\Gamma$ (MeV)	$\mathcal{B}_{nD\bar{D}}$	$\Gamma_{ee}$ (eV)	$\phi$ (deg)
1:	$3779.8 \pm 0.6$	$25.8 \pm 1.3$	$0.164 \pm 0.049$	$196 \pm 18$	$187 \pm 5$
2:	$3779.9 \pm 0.6$	$25.9 \pm 1.3$	$0.099 \pm 0.030$	$328 \pm 18$	$227 \pm 3$

The unitarity condition gives some arguments that the interference phase  $\phi$  should be close either to zero or 180 degrees. For this reason the first solution looks preferable.

The results obtained confirm the conclusions of the work [11] by the KEDR collaboration. Namely, the exotic assumptions are not necessary for the description of the  $D\bar{D}$  line shape and the value of the  $\psi(3770)$  mass is almost 7 MeV higher than the result of the PDG fit [18] performed using measurements which do not account for effects of the resonance-continuum interference. Similar results on the mass and total width were presented by BES-III [1]:  $M = 3781.5 \pm 0.3$ ,  $\Gamma = 25.2 \pm 0.7$  MeV (statistical errors only) although the value of the relative phase differs:  $\phi = 208 \pm 4$  degrees. It should be noted that in [1] it was not specified which of possible solutions was chosen.

The fit gives a large probability of the non- $D\bar{D}$  decays  $0.164 \pm 0.049$  in agreement with the results by the BES collaboration obtained using ‘inclusive non- $D\bar{D}$  selection’ [6]:

$$\mathcal{B}_{nD\bar{D}} = 0.151 \pm 0.056 \pm 0.018.$$

The formal statistical significance of the result is about  $3.3\sigma$ , however, the total error of 0.049 is dominated by systematic uncertainties in the  $D\bar{D}$  normalization scale and can be underestimated. The exclusion of BES data on  $e^+e^- \rightarrow D\bar{D}(\gamma)$  [7] reduces the result to  $0.126 \pm 0.056$  ( $2.2\sigma$ ).

The results presented above were obtained without the correction of the  $R$  values by BES to the detection efficiency dependence on the assumption on  $\psi(3770)$  shape and parameters which were used in the analysis [3]. To check the corresponding systematic uncertainties this correction was applied as described in Appendix A. The following variations of the main  $\psi(3770)$  parameters were obtained:  $\delta M = -0.3$  MeV,  $\delta \Gamma = 0.4$  MeV,  $\delta \Gamma_{ee} = 4.2$  eV,  $\delta \mathcal{B}_{nD\bar{D}} = 0.007$ . They are not large compared to the total errors of corresponding parameters.

## 6. Alternative $D\bar{D}$ cross section models

Recently a few theoretical works appeared that discussed the  $\psi(3770)$  line shape in the  $D\bar{D}$  decay channel, their comprehensive list can be found elsewhere [13]. Here we consider three works: N.N. Achasov and G.N. Shestakov [14] suggested a model of the  $D$  meson form factor which meets the elastic unitarity requirement; G.-Y. Chen and Q. Zhao [15] studied the line shape of the  $D\bar{D}$  cross section within an effective field theory, while X. Cao and H. Lenske [16] accounted for the interactions between  $\psi(3770)$  and the  $D\bar{D}$  continuum in the approach suggested by U. Fano [19]. The number of free parameters in these models is equal to six.

In all three cases the predictions for the inclusive hadronic cross section for the non-negligible  $\mathcal{B}_{nD\bar{D}}$  are absent. For this reason the models were employed to fit the  $D\bar{D}$  cross section measured by BaBar, Belle, BES and CLEO and compare the fit quality with that for the VDM inspired model. The following values of  $\chi^2$  for the fits in the two energy regions were obtained:

Model	$\chi^2/N_{\text{Dof}}$	$P(\chi^2)\%$	$\chi^2/N_{\text{Dof}}$	$P(\chi^2)\%$
VDM (this work)	68.1/54	9.4	40.4/34	20.8
A-S [14]	75.4/54	2.9	43.9/34	11.9
C-Z [15]	75.6/54	2.8	43.9/34	11.9
C-L [16]	75.5/54	2.8	44.9/34	10.0
$W$	$< 3.9$ GeV		$< 3.82$ GeV	

The alternative models do not improve the description of available  $D\bar{D}$  data.

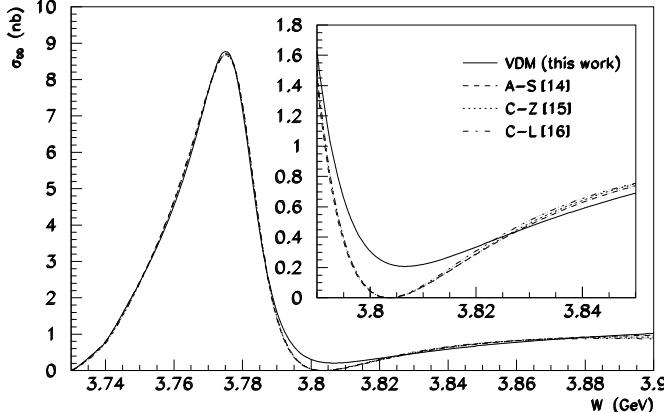


Fig. 2. Comparison of  $\psi(3770)$  line shapes for the models considered.

The line shapes with parameters of models obtained in the fit are presented in Fig. 2. The resulting line shapes for the models [14–16] are surprisingly similar. All of them predict a zero  $D\bar{D}$  cross section slightly above 3.8 GeV. The cross section can not drop to zero in the model in which the amplitude is a sum of Breit–Wigner shapes. The value of  $\chi^2$  for six data points in the energy range from 3.795 to 3.82 GeV is about 5.86 for the VDM assumptions and about 8.1 for the alternative models, thus vanishing of the cross section can not be either excluded or confirmed.

## 7. Conclusion

A joint analysis of all data on cross sections for hadron production in  $e^+e^-$  annihilation around the  $\psi(3770)$  resonance published so far leads, in our opinion, to the following conclusions:

- Account of the resonance-continuum interference in any reasonable way solves the problem of the  $\psi(3770)$  line shape. The existing data do not allow a selection of the best model among those considered.
- The  $\psi(3770)$  parameters obtained ignoring the resonance-continuum interference are not accurate and should not be used. In particular, it concerns various results on the difference of the  $\psi(3770)$  and  $\psi(2S)$  masses presented in Ref. [18].
- The  $\psi(3770)$  cross section measured in the  $D\bar{D}$  channel is less than the total one by a factor of  $0.836 \pm 0.049$ , thus the problem of the non- $D\bar{D}$  decays is still pending.

The data on the  $D\bar{D}$  cross section and the inclusive hadronic cross section from BES-III are eagerly awaited.

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## Appendix A

The  $R$  data by BES was transformed to the cross section as follows:

$$\delta\sigma_{\text{hadr}(\gamma)}(W) = F^{\text{RC}}(W) \left( R \varepsilon_h(W)/\varepsilon'_h(W) - R_{uds} \right) \sigma_{\mu\mu}^{\text{B}}(W), \quad (8)$$

where  $\sigma_{\mu\mu}^{\text{B}}(W) = 4\pi\alpha^2/3W^2$  is the Born cross section of the dimuon production,  $R_{uds} = 2.141$  is the light quark contribution in  $R$  according to [3],  $\varepsilon_h(W)$  is the net hadronic detection efficiency used for the  $R$  calculation in Ref. [3],  $\varepsilon'_h(W)$  is the hadronic detection efficiency reweighted for the current assumption on the  $\psi(3770)$  shape and parameters.

The radiative correction factor  $F^{\text{RC}}(W)$  for  $\psi(3770)$  production was calculated as in Ref. [3] using the values of the mass  $M = 3772.2$  MeV and the total width  $\Gamma = 26.9$  MeV [12].

The correction for the detection efficiency variation was applied iteratively. In terms of Eq. (1) the net detection efficiency for hadronic events can be defined as follows:

$$\varepsilon_h = \sigma_{e^+e^- \rightarrow \text{hadr}(\gamma)}^{\text{visible}} / \sigma_{\text{hadr}}^{\text{RC}}, \quad (9)$$

where  $\sigma_{\text{hadr}}^{\text{RC}}$  is the sum of hadronic cross sections. The  $\varepsilon_h(W)$  dependence presented in Fig. 2 of Ref. [3] was fitted to extract the values of  $\varepsilon_{uds}$ ,  $\varepsilon_{J/\psi}$ ,  $\varepsilon_{\psi(2S)}$  and  $\varepsilon_{D\bar{D}}$  entering in Eq. (1). The contribution of the  $\tau$  pair production was neglected. The parameters and assumptions required for the calculation of  $\sigma_{\text{hadr}}^{\text{RC}}$  were the same as in Ref. [3]. At the first iteration the fit of cross sections was performed with  $\varepsilon_h/\varepsilon'_h = 1$  which allowed to calculate the net efficiency  $\varepsilon'_h(W)$  for the second iteration using Eqs. (9) and (1).

At the first approximation the values of  $\delta\sigma_{\text{hadr}(\gamma)}$  obtained as described above do not depend on assumptions on the  $\psi(3770)$  shape and parameters. Since  $\varepsilon_h(W)$  was taken from the plot, the correction for the efficiency variation is not accurate. We used it only for the check of the systematic uncertainty.

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