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Discussion on Cross Section Measurement for $D\bar{D}$ Production around $\psi(3770)$ *

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We give a brief discussion on the measurement of the cross section for $D\bar{D}$ production around the $\psi(3770)$ resonance, and point out a new calculation of the cross sections based on the absolute measurements. Compared with single tag and double tag analyses, the new calculation provides us with many more opportunities to perform the cross section measurement.

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The $\psi(3770)$ resonance is produced around the center-of-mass energy of 3.773 GeV, and is believed to decay into $D\bar{D}$ pairs with a branching fraction $\sim$ 100% for a long time. In recent years, however, several measurements have been carried out by the BES-Ⅱ experiment[1] to point out and emphasize that there is a branching fraction of about 15%[2] for $\psi(3770) \to \text{non}-D\bar{D}$. On the other hand, the CLEO-c experiment stresses that the non$-D\bar{D}$ branching fraction should be very small,[3] based on its measurement of the cross section for $D\bar{D}$ production,[4] which is much larger but more precise than the results of the previous measurements. Therefore, precise measurements of the cross section for $D\bar{D}$ production are very important in understanding the $\psi(3770)$ non$-D\bar{D}$ puzzle. On the other hand, the measurement of the cross sections can also serve in the calculation of $\sigma^{\rm obs}_{D^+D^-}/\sigma^{\rm obs}_{D^0\bar{D}^0}$. This ratio around the $\psi(3770)$ resonance in e^+e^- annihilation has special significance in studies of the nature of $\psi(3770)$, the production and decay of D mesons as well as their interaction mechanism. The measurement of $\sigma^{\rm obs}_{D^+D^-}/\sigma^{\rm obs}_{D^0\bar{D}^0}$ can also serve as a probe for some unknown effects, which may be responsible for the interesting results of $\psi(3770)$ production and its decays reported in Ref. [5]. In the last year, the BES collaboration presented a measurement of the ratio $\sigma^{\rm obs}_{D^+D^-}/\sigma^{\rm obs}_{D^0\bar{D}^0}$ at a series of energy points from 3.74 to 3.80 GeV,[6] which gave the curve of energy-dependent $\sigma^{\rm obs}_{D^+D^-}/\sigma^{\rm obs}_{D^0\bar{D}^0}$ together with the line shape of $\sigma^{\rm obs}_{D^+D^-}$ and $\sigma^{\rm obs}_{D^0\bar{D}^0}$. The resulting distributions provide us with some interesting points, although they suffer from large uncertainties. Thus, the measurement of cross section for the $D\bar{D}$ production based on the largest high quality data sample collected by the BES-Ⅲ experiment is very important and interesting.

For the e^+e^- annihilation experiment around the $\psi(3770)$ peak, the D mesons are produced in pairs, that is to say, if a $\bar{D}$ meson is reconstructed in an event, which is called a singly tagged $\bar{D}$ event, there must exist a D meson in the system recoiling side against the tagged $\bar{D}$. If the pair $D\bar{D}$ is fully reconstructed in an event, the event is called a doubly tagged $D\bar{D}$ event. Traditionally, there are two methods to perform the measurement of the cross section for $D\bar{D}$ production based on singly tagged $\bar{D}$ events and doubly tagged $D\bar{D}$ events, respectively, called the single tag method and the double tag method.

In the measurement of the $D\bar{D}$ cross section based on the singly tagged $\bar{D}$ events, the number of singly tagged $\bar{D}$ mesons $N_{\bar{D}_{\rm tag}}$ and the observed cross section $\sigma^{\rm obs}_{D\bar{D}}$ are related to each other,

$$\sigma^{\rm obs}_{D\bar{D}} = \frac{N_{\bar{D}_{\rm tag}}}{2 \times \mathcal{L} \times \mathcal{B} \times \epsilon}, \tag{1}$$

where $\mathcal{L}$ is the integrated luminosity of the data sample, $\mathcal{B}$ is the branching fraction for the tag mode through which we reconstruct the $\bar{D}$ meson, and ϵ is the detection efficiency of the tag mode determined from Monte Carlo simulation. The singly tagged $\bar{D}$ mesons are observed in the invariant mass spectra of the daughter particles from the $\bar{D}$ decay. Since there are much better resolutions for neutral and charged tracks at the BES-Ⅲ than those at the BES-Ⅱ, we can apply more tag modes to obtain the number of tagged events $N_{\bar{D}_{\rm tag}}$ than those used in Ref. [7]. The $\bar{D}^0$ mesons can be reconstructed in the tag modes like $\bar{D}^0 \to K^+\pi^-$, $\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$, $\bar{D}^0 \to K^+\pi^-\pi^0$, $\bar{D}^0 \to K^+\pi^-\pi^-\pi^+\pi^0$, $\bar{D}^0 \to K^0_S\pi^+\pi^-$, $\bar{D}^0 \to K^0_S\pi^+\pi^-\pi^0$ and $\bar{D}^0 \to K^0_S\pi^0$, and the D^- mesons can be reconstructed in the tag modes of $D^- \to K^+\pi^-\pi^-$, $D^- \to K^+K^-\pi^-$, $D^- \to K^+\pi^-\pi^-\pi^0$, $D^- \to K^0_S\pi^-$, $D^- \to K^0_S\pi^+\pi^-\pi^-$ and $D^- \to K^0_S\pi^-\pi^0$. The candidate tagged events can be selected based on the method described in Ref. [8].

In the single tag method, we measure the product $\sigma^{\rm obs}_{D\bar{D}}\mathcal{B}_{\rm tag}$ instead of $\sigma^{\rm obs}_{D\bar{D}}$. Thus the extracted observed cross sections suffer from the input $\mathcal{B}_{\rm tag}$ from PDG, which will greatly enhance the systematic error of the analysis. Thus, in order to make the measure-

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ment independent of the branching fractions of the tag modes, we should employ the technique developed by the MARK-Ⅲ collaboration,[9] in which we validate a χ^2 minimization constructed as

$$\chi^2 = \Sigma_i \left(\frac{N_{\rm single}(i) - N^{\rm net}_{\rm single}(i)}{\sigma_{N^{\rm net}_{\rm single}(i)}} \right)^2 + \Sigma_{ij} \left(\frac{N_{\rm double}(i,j) - N^{\rm net}_{\rm double}(i,j)}{\sigma_{N^{\rm net}_{\rm double}(i,j)}} \right)^2, \quad (2)$$

where $N_{\rm single}(i)$ is the expected number of the singly tagged $\bar{D}$ events, $N_{\rm double}(i,j)$ is the expected number of the doubly tagged $D\bar{D}$ events, $N^{\rm net}_{\rm single}(i)$ is the observed number of the single tags after excluding background contamination, and $N^{\rm net}_{\rm double}(i,j)$ is for the double tags, $\sigma_{N^{\rm net}_{\rm single}(i)}$ and $\sigma_{N^{\rm net}_{\rm double}(i,j)}$ are statistical errors of the observed singly tagged $\bar{D}$ events and the observed doubly tagged $D\bar{D}$ events, respectively. The numbers of the singly tagged $\bar{D}$ events and the doubly tagged $D\bar{D}$ events can be expressed as

$$N_{\rm single}(i) = 2N_{D\bar{D}}\mathcal{B}(i)\epsilon(i) - \Sigma_j(2N_{D\bar{D}}\epsilon^i_{i,j}\mathcal{B}(i)\mathcal{B}(j)), \quad (3)$$

$$N_{\rm double}(i,j) = \begin{cases} N_{D\bar{D}}\mathcal{B}(i)\mathcal{B}(j)\epsilon(i,j), & (i=j), \\ 2N_{D\bar{D}}\mathcal{B}(i)\mathcal{B}(j)\epsilon(i,j), & (i\neq j), \end{cases} \quad (4)$$

where $\mathcal{B}(i)$ is the branching fraction for $D \to i$; $\epsilon(i)$ is the detection efficiency for the mode $D \to i$; $\epsilon(i,j)$ is the detection efficiency for reconstruction of the double tag $D \to i$ vs. $\bar{D} \to j$; $\epsilon^i_{i,j}$ is the contaminated efficiency for misidentifying the event, which is reconstructed as the double tag $D \to i$ vs. $\bar{D} \to j$, as the single tag $D \to i$; $N_{D\bar{D}}$ is the total number of produced $D\bar{D}$ events; the second term in the expression of $N_{\rm single}(i)$ removes those events which also appear in the double tag sample, so that the single tag and double tag samples are independent. Fitting to the χ^2 function with the corresponding observed numbers of single tag and double tag events and the detection efficiencies, the values of $N_{D\bar{D}}$ and $\mathcal{B}(i)$ can be obtained simultaneously.

In the past 30 years, several experiments measured the cross sections for $D\bar{D}$ production, and these are summarized in Table 1. The superscript ^{S} means the measurements based on the single tag method, which present the product $\sigma_{D\bar{D}} \times \mathcal{B}$. For comparison with the latest single tag measurement,[7] we apply the branching fractions from Ref. [14] to derive the cross sections for $D\bar{D}$ production. The superscript ^{D} indicates the measurements based on the double tag method, which gives the absolutely measured $\sigma^{\rm obs}_{D\bar{D}}$ since the values do not depend on the branching fractions of D meson decays. In comparison with the analysis based on the single tag method, the systematic error from the double tag method is rather smaller, while the statistical error is larger, since the number of doubly tagged $D\bar{D}$ events is much smaller than that of singly tagged $\bar{D}$ events. Moreover, the double tag analysis can present an absolute measurement of the branching fractions for the tag modes, such as $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$, which play an important role in the weak interaction because they serve to normalize many D and B meson branching fractions, from which elements of the Cabibbo–Kobayashi–Maskawa (CKM) matrix are determined.

To estimate how well we can measure the cross sections for $D\bar{D}$ production with the two methods at the BES-Ⅲ experiment, we make a quantitative analysis based on Monte Carlo (MC) simulation to determine the statistical precision of the measurements. The MC events are generated as $e^+e^- \to \psi(3770) \to D\bar{D}$ at the c.m. energy $\sqrt{s} = 3.773\,{\rm GeV}$, corresponding to an integrated luminosity of $\sim 400\,{\rm pb}^{-1}$, where the D (D^0 or D^+) and $\bar{D}$ ($\bar{D}^0$ or D^-) mesons are set to decay into all possible final states with the branching fractions quoted from PDG.[2] The particle trajectories are simulated with the GEANT4[15] based Monte Carlo simulation package for the BES-Ⅲ detector.[16] The MC events are generated and reconstructed with the BES-Ⅲ offline software system (BOSS).[17] Based on this data sample, we can obtain, respectively, $\sim 0.29 \times 10^5$ tagged $\bar{D}^0$ events and $\sim 0.15 \times 10^5$ tagged D^- events in the single tag analysis. The statistical precision of the observed cross sections for $D^0\bar{D}^0$ and D^+D^- production are determined to be $\sim 0.22\%$ and $\sim 0.28\%$, respectively, while in the double tag analysis, the statistical precision of the fitted numbers of $D^0\bar{D}^0$ and D^+D^- are 0.42% and $\sim 0.54\%$, resulting in the observed cross sections for $D^0\bar{D}^0$ and D^+D^- production being $\sim 0.42\%$ and $\sim 0.54\%$, respectively.

Table 1. Measured cross sections for $D\bar{D}$ production, where the single tag measurements are based on $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and $D^+ \to K^-\pi^+\pi^+$.

Experiment	$E_{\rm c.m.}$ (GeV)	Luminosity (pb^{-1})	$\sigma^{\rm obs}_{D^0\bar{D}^0}$ (nb)	$\sigma^{\rm obs}_{D^+D^-}$ (nb)	$\sigma^{\rm obs}_{D\bar{D}}$ (nb)
BES-Ⅱ^S[7]	3.773	17.3	$3.58 \pm 0.09 \pm 0.31$	$2.56 \pm 0.08 \pm 0.26$	$6.14 \pm 0.12 \pm 0.50$
MARK-Ⅱ^S[10]	3.771	2.9	$3.86 \pm 0.24 \pm 0.31$	$2.09 \pm 0.14 \pm 0.23$	$5.95 \pm 0.28 \pm 0.38$
MARK-I^S[11]	3.774	1.3	$2.85 \pm 0.33 \pm 0.33$	$1.98 \pm 0.26 \pm 0.20$	$4.83 \pm 0.42 \pm 0.39$
CLEO-c^D[12]	3.774	281.0	$3.66 \pm 0.03 \pm 0.06$	$2.91 \pm 0.03 \pm 0.05$	$6.57 \pm 0.04 \pm 0.10$
CLEO-c^D[4]	3.773	55.8	$3.60 \pm 0.07^{+0.07}_{-0.05}$	$2.79 \pm 0.07^{+0.10}_{-0.04}$	$6.39 \pm 0.10^{+0.17}_{-0.08}$
BES-Ⅱ^D[13]	3.773	17.3	$3.47 \pm 0.32 \pm 0.21$	$2.46 \pm 0.33 \pm 0.20$	$5.93 \pm 0.46 \pm 0.35$
MARK-Ⅲ^D[9]	3.768	9.6	$2.90 \pm 0.25 \pm 0.30$	$2.10 \pm 0.30 \pm 0.15$	$5.00 \pm 0.39 \pm 0.34$

Besides the two methods, in fact, the cross sections can also be derived from the absolute measurement of the branching fractions of D meson decay. For example, in the measurement of the branching fraction for inclusive electron decay, the measured branching fraction can be calculated by

$$\mathcal{B}_{D\to e^+X} = \frac{N^{\rm obs}_{D\to e^+X}}{\epsilon_{D\to e^+X} N_{\bar{D}_{\rm tag}}}, \tag{5}$$

where $N^{\rm obs}_{D\to e^+X}$, $\mathcal{B}_{D\to e^+X}$, and $\epsilon_{D\to e^+X}$ are the observed number of events, branching fraction, and the detection efficiency for inclusive electron decay of the D meson.[18] Usually, we introduce $N^{\rm obs}_{D\to e^+X}$, $\epsilon_{D\to e^+X}$, and $N_{\bar{D}_{\rm tag}}$ to obtain $\mathcal{B}_{D\to e^+X}$. However, since the number of the singly tagged $\bar{D}$ events can be expected as

$$N_{\bar{D}_{\rm tag}} = 2\mathcal{L}\sigma^{\rm obs}_{D\bar{D}}\Sigma_i\mathcal{B}(i)\epsilon(i), \tag{6}$$

where $\mathcal{L}$ is the luminosity of the data sample, $\mathcal{B}(i)$ is the branching fraction[2] for the tag mode and $\epsilon(i)$ is the corresponding detection efficiency, consequently, the observed cross section for $D\bar{D}$ production can be calculated by

$$\sigma^{\rm obs}_{D\bar{D}} = \frac{N^{\rm obs}_{D\to e^+X}}{2\mathcal{L}\mathcal{B}_{D\to e^+X}\epsilon_{D\to e^+X}\Sigma_i\mathcal{B}(i)\epsilon(i)}. \tag{7}$$

Compared with the former two methods, the systematic error in this calculation is the largest one, since it depends on more input values with large errors, and the statistical precision is different in different absolute measurements. For example, through the simulation with the Monte Carlo sample generated above, we can get the statistical error of the unfolded number $N^{\rm obs}_{D^0\to e^+X}$ to be about 0.96% based on 10 $\bar{D}^0$ tag modes, resulting a statistical precision $\sim 0.96\%$ for the calculated $\sigma^{\rm obs}_{D^0\bar{D}^0}$. However, if we make use of the measurement of inclusive K^- decay of the D^0 meson, we can get the statistical error of $N^{\rm obs}_{D^0\to K^-X}$ to be about 0.33%, leading to a statistical precision of about 0.33% for $\sigma^{\rm obs}_{D^0\bar{D}^0}$. The advantage of the calculation is that we can examine the value of $\sigma^{\rm obs}_{D\bar{D}}$, usually measured by the single tag or double tag methods, in any absolute measurements of D decay branching fractions. It provides us with opportunities to obtain the $\sigma^{\rm obs}_{D\bar{D}}$ from many different measurements, and helps us to understand the nature of $\psi(3770)$ and its non$-D\bar{D}$ decay puzzle, in the coming BES-Ⅲ experiment.

In summary, we have introduced three methods in calculation of the observed cross section for $D\bar{D}$ production, and discussed the advantage and shortcoming of each method in the measurement. Compared with single tag and double tag analysis, the new calculation method can be carried out in any absolute branching fraction measurements for D meson decay.

References

[1] Ablikim M et al (BES Collaboration) 2006 *Phys. Lett.* B **641** 145
Ablikim M et al (BES Collaboration) 2006 *Phys. Rev. Lett.* **97** 121801
Ablikim M et al (BES Collaboration) 2007 *Phys. Rev.* **D 76** 122002
Ablikim M et al (BES Collaboration) 2008 *Phys. Lett.* B **659** 74

[2] Amsler C et al (Particle Data Group) 2008 *Phys. Lett.* B **667** 1

[3] Besson D et al (CLEO Collaboration) 2006 *Phys. Rev. Lett.* **96** 092002

[4] He Q et al (CLEO Collaboration) 2005 *Phys. Rev. Lett.* **95** 121801

[5] Ablikim M et al (BES Collaboration) 2008 *Phys. Rev. Lett.* **101** 102004

[6] Ablikim M et al (BES Collaboration) 2008 *Phys. Lett.* B **668** 263

[7] Ablikim M et al (BES Collaboration) 2004 *Phys. Lett.* B **603** 130

[8] Zhao M G, Yu C X and Li X Q 2009 *Chin. Phys. Lett.* **26** 121401

[9] Baltrusaitis R M et al (MARK III Collaboration) 1986 *Phys. Rev. Lett.* **56** 2140
Adler J et al 1988 *Phys. Rev. Lett.* **60** 89

[10] Schindler R H et al 1981 *Phys. Rev.* D **24** 78

[11] Peruzzi I et al 1977 *Phys. Rev. Lett.* **39** 1301
Scharre D L et al 1978 *Phys. Rev. Lett.* **40** 74

[12] Dobbs S et al (CLEO Collaboration) 2007 *Phys. Rev.* D **76** 112001

[13] Ablikim M et al (BES Collaboration) 2005 *Nucl. Phys.* B **727** 395

[14] Hagiwara K et al (Particle Data Group) 2002 *Phys. Rev.* D **66** 010001

[15] Agostinelli S et al (Geant4 Collaboration) 2003 *Nucl. Instrum. Methods* A **506** 250

[16] Deng Z Y et al 2006 *High Energy Phys. Nucl. Phys.* **30** 371 (in Chinese)

[17] Li W D, Liu H M et al 2006 *The Offine Software for the BES Experiment, Proceeding of CHEP06* (Mumbai, India 13–17 February 2006)

[18] Adam N E et al (CLEO Collaboration) 2006 *Phys. Rev. Lett.* **97** 251801