

COMBINED FIT TO THE CROSS SECTIONS OF $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi$ AND $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^{**}$

JIELEI ZHANG[†], TENGJIAO ZHU

College of Physics and Electronic Engineering, Xinyang Normal University
 Xinyang 464000, People's Republic of China

(Received January 21, 2020; accepted August 12, 2020)

The cross sections of $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi$ and $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^*$ have been measured by the BESIII experiment. We try to perform a combined fit to the cross sections with one Breit–Wigner function, the fit results show the structure's mass and width $M = (4232 \pm 5) \text{ MeV}/c^2$, $\Gamma = (65 \pm 21) \text{ MeV}$. The ratio $\frac{\mathcal{B}(Z_c(3900) \rightarrow D\bar{D}^*)}{\mathcal{B}(Z_c(3900) \rightarrow \pi J/\psi)}$ is determined to be (16 ± 6) . We also try to fit the cross sections with two Breit–Wigner functions, while we cannot come to any definitive conclusions about the second structure. More measurements are desired to improve the understanding of $e^+e^- \rightarrow \pi Z_c(3900)$ line shape.

DOI:10.5506/APhysPolB.51.1921

In recent years, charmonium physics gained renewed strong interest from both the theoretical and the experimental side, due to the observation of charmonium-like states, such as $X(3872)$ [1], $Y(4260)$ [2], $Y(4360)$ [3], and $Y(4660)$ [4]. These states do not fit in the conventional charmonium spectroscopy, and could be exotic states that lie outside the quark model [5–8]. Moreover, in 2013, a charged charmonium-like state, $Z_c(3900)^\pm$, was observed by the BESIII [9] and Belle collaborations [10] in the $\pi^\pm J/\psi$ invariant mass distribution of the $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ process and confirmed using CLEO-c's data [11]. As there are at least four quarks in the structure, many theoretical interpretations of the nature and the decay dynamics of the $Z_c(3900)$ have been put forward [12, 13].

Shortly afterwards, a similar charged structure, the $Z_c(3885)^\pm$, was observed in the $(D\bar{D}^*)^\pm$ invariant mass distribution of the $e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)^\mp$ process [14, 15], with a spin parity (J^P) assignment of 1^+ favored over the

* Funded by SCOAP³ under Creative Commons License, CC-BY 4.0.

[†] Corresponding author: zhangjielei@ihep.ac.cn

1^- and 0^- hypotheses. Moreover, its mass and width are consistent with those of the $Z_c(3900)^\pm$. Recently, the spin and parity of the $Z_c(3900)^\pm$ are determined to be $J^P = 1^+$ [16]. So now $Z_c(3900)^\pm$ and $Z_c(3885)^\pm$ have been taken as one state $Z_c(3900)$ in PDG [17]. The neutral structure, $Z_c(3900)^0$, has been also observed in the $\pi^0 J/\psi$ invariant mass distribution of the $e^+e^- \rightarrow \pi^0 \pi^0 J/\psi$ process [18, 19] and $(D\bar{D}^*)^0$ invariant mass distribution of the $e^+e^- \rightarrow \pi^0 (D\bar{D}^*)^0$ process [20].

Until now, the nature of $Z_c(3900)$ is still unclear. Although the fact that $Z_c(3900)$ has charge indicates it is not conventional meson consisting of a quark–antiquark pair, its exact quark configuration is still unknown. Several models have been developed to describe its inner structure, including loosely bound hadronic molecules of two charmed mesons, compact tetraquarks, and hadro-quarkonium [12, 13]. In this paper, we try to analyze all the cross sections of $e^+e^- \rightarrow \pi Z_c(3900)$ to get the combined results about the $Z_c(3900)$. It may be useful to understand the nature of $Z_c(3900)$.

Figure 1 shows the cross sections of $e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0 \pi^0 J/\psi$, $e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^\pm (D\bar{D}^*)^\mp$ and $e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0 (D\bar{D}^*)^0$ below 4.3 GeV measured by the BESIII experiment [15, 19, 20]. Here the error bars represent the total errors. It should be noted that the cross sections rely on the model for the Z_c lineshapes used in the experiment. The cross sections of $e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- J/\psi$ in Fig. 1 are obtained by the results of cross sections of $e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0 \pi^0 J/\psi$ [19] and cross sections of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ [21] assuming the isospin conservation. We can see the line shapes are similar, the cross sections around 4.23 GeV are larger than those around 4.26 GeV, which indicates that one Breit–Wigner function with mass around 4.23 GeV can describe the cross sections. Assuming $\pi Z_c(3900)$ comes from one resonance, we perform a combined fit to the cross sections using a least χ^2 method. We fit the cross sections with one constant width relativistic Breit–Wigner function, that is,

$$\sigma(\sqrt{s}) = \left| \text{BW}(\sqrt{s}) \sqrt{\frac{\text{PS}(\sqrt{s})}{\text{PS}(M)}} \right|^2, \quad (1)$$

where $\text{PS}(\sqrt{s})$ is the two-body phase space factor that increases smoothly from the mass threshold with the \sqrt{s} [17], $\text{BW}(\sqrt{s}) = \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}(\pi Z_c(3900))}\Gamma}{s-M^2+iM\Gamma}$ is the Breit–Wigner function for a vector state, with mass M , total width Γ , electron partial width Γ_{ee} , and the branching fraction to $\pi Z_c(3900)$, $\mathcal{B}(\pi Z_c(3900))$. From the fit, the Γ_{ee} and $\mathcal{B}(\pi Z_c(3900))$ cannot be obtained separately, we can only extract the product $\Gamma_{ee}\mathcal{B}(\pi Z_c(3900))$.

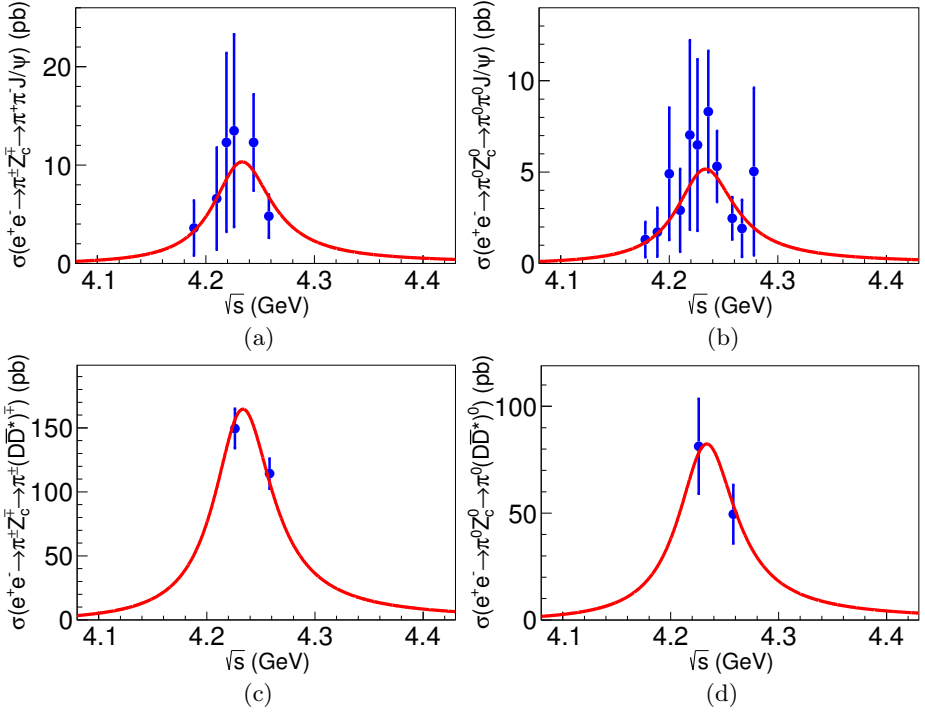


Fig. 1. (Color online) The results of the combined fit to the cross sections of $e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- J/\psi$ (a), $e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0\pi^0 J/\psi$ (b), $e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^\pm (D\bar{D}^*)^\mp$ (c), and $e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0 (D\bar{D}^*)^0$ (d) using one Breit–Wigner function. The solid red curves show the best fits.

In the combined fit, we fix the ratio $\frac{\mathcal{B}(\pi^+ Z_c(3900)^-)+\mathcal{B}(\pi^- Z_c(3900)^+)}{\mathcal{B}(\pi^0 Z_c(3900)^0)}$ to be 2 assuming the isospin conservation. The χ^2 is minimized to obtain the best estimation of the resonant parameters, and the uncertainties are obtained when χ^2 value changes 1 compared to the minimum value. Figure 1 shows the fit results. The fits indicate the existence of one resonance (called Y) with mass and width $M = (4232 \pm 5) \text{ MeV}/c^2$ and $\Gamma = (65 \pm 21) \text{ MeV}$. The goodness of the fit is $\chi^2/\text{n.d.f.} = 5.3/17$, where n.d.f. is the number of degrees of freedom. The all fitted parameters of the cross sections are listed in Table I.

From Table I, the ratio $\frac{\mathcal{B}(Z_c(3900) \rightarrow D\bar{D}^*)}{\mathcal{B}(Z_c(3900) \rightarrow \pi J/\psi)}$ is determined to be (16 ± 6) , which shows the branching fraction of $Z_c(3900)$ decays into open charm final states is about an order of magnitude larger than that of $Z_c(3900)$ decays into hidden charm final states. It indicates that $Z_c(3900)$ has stronger coupling with open charm channel, which is important to understand the nature of $Z_c(3900)$.

TABLE I

The fitted parameters from the combined fit to the cross sections of $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi$ and $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^*$ using one Breit–Wigner function. Here, $\mathcal{B}(Y \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi)$ means the sum of $\mathcal{B}(Y \rightarrow \pi^+ Z_c(3900)^- \rightarrow \pi^+ \pi^- J/\psi)$, $\mathcal{B}(Y \rightarrow \pi^- Z_c(3900)^+ \rightarrow \pi^+ \pi^- J/\psi)$ and $\mathcal{B}(Y \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0 \pi^0 J/\psi)$, and the same definition is for $\mathcal{B}(Y \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^*)$.

Parameter	Solution
M [MeV/ c^2]	4232 ± 5
Γ [MeV]	65 ± 21
$\Gamma_{ee} \mathcal{B}(Y \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi)$ [eV]	1.2 ± 0.3
$\Gamma_{ee} \mathcal{B}(Y \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^*)$ [eV]	19.6 ± 4.5

Figure 2 shows the cross sections with some points above 4.3 GeV added [18]. As shown by the fit results in Ref. [21], we also try to use coherent sum of two Breit–Wigner functions (called Y_1 and Y_2) to fit the cross sections assuming the isospin conservation. In the fit, $\mathcal{B}(Y_2 \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^*)$ is fixed to be $\frac{\mathcal{B}(Y_1 \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^*) \mathcal{B}(Y_2 \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi)}{\mathcal{B}(Y_1 \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi)}$. Figure 2 shows the fit results. The two structures' mass and width are $M_1 = (4239 \pm 10)$ MeV/ c^2 , $\Gamma_1 = (60 \pm 21)$ MeV and $M_2 = (4325 \pm 16)$ MeV/ c^2 , $\Gamma_2 = (8 \pm 26)$ MeV. Two solutions are found with the same fit quality, the all fitted parameters of the cross sections are listed in Table II. The ratio $\frac{\mathcal{B}(Z_c(3900) \rightarrow D\bar{D}^*)}{\mathcal{B}(Z_c(3900) \rightarrow \pi J/\psi)}$ is determined to be (16 ± 11) or (16 ± 7) , which is consistent with the results of using one Breit–Wigner function to fit. Since the measured cross-section points between 4.3 GeV and 4.4 GeV are very scarce, we cannot come to some definitive conclusions about Y_2 . It is clear that the result on the second peak in Fig. 2 cannot be trusted, since the fit prefers a narrow structure in a region where no data sit. However, the results of Y_1 are consistent with the above results of fitting with one Breit–Wigner function.

In summary, we perform a combined fit to the cross sections of $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi$ and $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^*$ with one Breit–Wigner function. The fit results show $\pi Z_c(3900)$ may be from a structure with mass and width are $M = (4232 \pm 5)$ MeV/ c^2 , $\Gamma = (65 \pm 21)$ MeV. The ratio $\frac{\mathcal{B}(Z_c(3900) \rightarrow D\bar{D}^*)}{\mathcal{B}(Z_c(3900) \rightarrow \pi J/\psi)}$ is determined to be (16 ± 6) . We also try to use two Breit–Wigner functions to fit the cross sections, the first structure results are consistent with the results of fitting with one Breit–Wigner function. Due to the fact that measured cross-section points between 4.3 GeV and 4.4 GeV are very scarce, we cannot come to some definitive conclusions about the second structure. So the two resonances fit is nonphysical, and

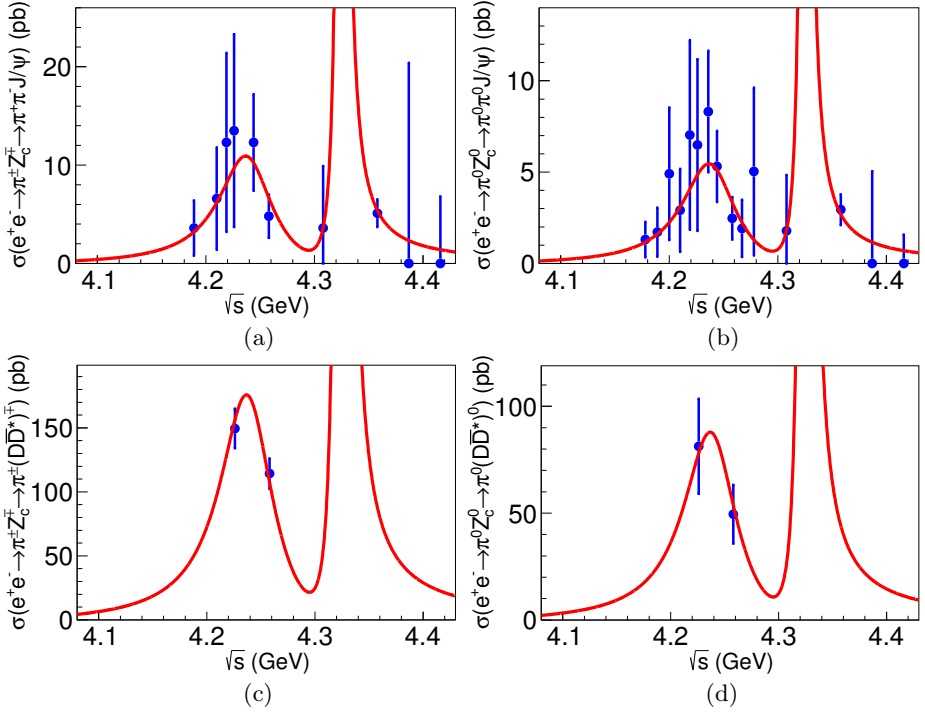


Fig. 2. (Color online) The results of the combined fit to the cross sections of $e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- J/\psi$ (a), $e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0\pi^0 J/\psi$ (b), $e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^\pm (D\bar{D}^*)^\mp$ (c), and $e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0 (D\bar{D}^*)^0$ (d) using two Breit–Wigner functions. The solid red curves show the best fits.

TABLE II

The fitted parameters from the combined fit to the cross sections of $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi$ and $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^*$ using two Breit–Wigner functions.

Parameter	Solution I	Solution II
M_1 [MeV/ c^2]	4239 ± 10	
Γ_1 [MeV]	60 ± 21	
M_2 [MeV/ c^2]	4325 ± 16	
Γ_2 [MeV]	8 ± 26	
$\Gamma_{ee}\mathcal{B}(Y_1 \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi)$ [eV]	1.1 ± 0.5	1.6 ± 0.5
$\Gamma_{ee}\mathcal{B}(Y_1 \rightarrow \pi Z_c(3900) \rightarrow \pi D\bar{D}^*)$ [eV]	18.0 ± 9.1	26.0 ± 7.0
$\Gamma_{ee}\mathcal{B}(Y_2 \rightarrow \pi Z_c(3900) \rightarrow \pi\pi J/\psi)$ [eV]	2.1 ± 5.3	2.6 ± 6.3
ϕ [rad]	0.1 ± 1.5	-1.3 ± 1.2

the one resonance fit should be taken as the result of the paper. At present, the number of data points in $e^+e^- \rightarrow \pi Z_c(3900)$ line shape is relatively small and the errors are large, so more accurate measurements are needed to provide more constraint on the $e^+e^- \rightarrow \pi Z_c(3900)$ line shape. It will help to understand where $Z_c(3900)$ comes from, and further reveal the nature of $Z_c(3900)$. These measurements can be achieved by BESIII and BelleII experiments in the future.

This work is supported by the National Natural Science Foundation of China (NSFC) under contract No. 11905179, Foundation of Henan Educational Committee (No. 19A140015), and Nanhu Scholars Program for Young Scholars of Xinyang Normal University.

REFERENCES

- [1] Belle Collaboration (S.K. Choi *et al.*), «Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ Decays», *Phys. Rev. Lett.* **91**, 262001 (2003).
- [2] BaBar Collaboration (B. Aubert *et al.*), «Observation of a Broad Structure in the $\pi^+ \pi^- J/\psi$ Mass Spectrum around 4.26 GeV/ c^2 », *Phys. Rev. Lett.* **95**, 142001 (2005).
- [3] BaBar Collaboration (B. Aubert *et al.*), «Evidence of a Broad Structure at an Invariant Mass of 4.32 GeV/ c^2 in the Reaction $e^+e^- \rightarrow \pi^+ \pi^- \psi(2S)$ Measured at BABAR», *Phys. Rev. Lett.* **98**, 212001 (2007).
- [4] Belle Collaboration (X.L. Wang *et al.*), «Observation of Two Resonant Structures in $e^+e^- \rightarrow \pi^+ \pi^- \psi(2S)$ via Initial-State Radiation at Belle», *Phys. Rev. Lett.* **99**, 142002 (2007).
- [5] N. Brambilla *et al.*, «Heavy quarkonium: progress, puzzles, and opportunities», *Eur. Phys. J. C* **71**, 1534 (2011).
- [6] A. Esposito, A. Pilloni, A. Polosa, «Multiquark resonances», *Phys. Rep.* **668**, 1 (2017).
- [7] M. Cleven *et al.*, « $Y(4260)$ as the first S -wave open charm vector molecular state?», *Phys. Rev. D* **90**, 074039 (2014).
- [8] P. Guo *et al.*, «Charmonium meson and hybrid radiative transitions», *Phys. Rev. D* **89**, 116005 (2014).
- [9] BESIII Collaboration (M. Ablikim *et al.*), «Observation of a Charged Charmoniumlike Structure in $e^+e^- \rightarrow \pi^+ \pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV», *Phys. Rev. Lett.* **110**, 252001 (2013).
- [10] Belle Collaboration (Z.Q. Liu *et al.*), «Study of $e^+e^- \rightarrow \pi^+ \pi^- J/\psi$ and Observation of a Charged Charmoniumlike State at Belle», *Phys. Rev. Lett.* **110**, 252002 (2013).

- [11] T. Xiao, S. Dobbs, A. Tomaradze, K.K. Seth, «Observation of the Charged Hadron $Z_c^\pm(3900)$ and Evidence for the Neutral $Z_c^0(3900)$ in $e^+e^- \rightarrow \pi\pi J/\psi$ at $\sqrt{s} = 4170$ MeV», *Phys. Lett. B* **727**, 366 (2013).
- [12] H.X. Chen, W. Chen, X. Liu, S.L. Zhu, «The hidden-charm pentaquark and tetraquark states», *Phys. Rep.* **639**, 1 (2016).
- [13] Y.R. Liu *et al.*, «Pentaquark and Tetraquark States», *Prog. Part. Nucl. Phys.* **107**, 237 (2019).
- [14] BESIII Collaboration (M. Ablikim *et al.*), «Observation of a Charged $(D\bar{D}^*)^\pm$ Mass Peak in $e^+e^- \rightarrow \pi D\bar{D}^*$ at $\sqrt{s} = 4.26$ GeV», *Phys. Rev. Lett.* **112**, 022001 (2014).
- [15] BESIII Collaboration (M. Ablikim *et al.*), «Confirmation of a charged charmoniumlike state $Z_c(3885)^\mp$ in $e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)^\mp$ with double D tag», *Phys. Rev. D* **92**, 092006 (2015).
- [16] BESIII Collaboration (M. Ablikim *et al.*), «Determination of the Spin and Parity of the $Z_c(3900)$ », *Phys. Rev. Lett.* **119**, 072001 (2017).
- [17] Particle Data Group (M. Tanabashi *et al.*), «Review of Particle Physics», *Phys. Rev. D* **98**, 030001 (2018).
- [18] BESIII Collaboration (M. Ablikim *et al.*), «Observation of $Z_c(3900)^0$ in $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$ », *Phys. Rev. Lett.* **115**, 112003 (2015).
- [19] M. Ablikim *et al.*, «Study of the process $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$ and neutral charmoniumlike state $Z_c(3900)^0$ », *Phys. Rev. D* **102**, 012009 (2020), [arXiv:2004.13788 \[hep-ex\]](https://arxiv.org/abs/2004.13788).
- [20] BESIII Collaboration (M. Ablikim *et al.*), «Observation of a Neutral Structure near the $D\bar{D}^*$ Mass Threshold in $e^+e^- \rightarrow (D\bar{D}^*)^0\pi^0$ at $\sqrt{s} = 4.226$ and 4.257 GeV», *Phys. Rev. Lett.* **115**, 222002 (2015).
- [21] BESIII Collaboration (M. Ablikim *et al.*), «Precise Measurement of the $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ Cross Section at Center-of-Mass Energies from 3.77 to 4.60 GeV», *Phys. Rev. Lett.* **118**, 092001 (2017).