Evidence of Two Resonant Structures in e+e− → + −hc postprint

Authors: M. Ablikim[et al.]

Date: 2017-11-10T00:00:00+00:00

Abstract

The cross sections of e+e− ! + −hc at center-of-mass energies from 3.896 to 4.600 GeV are measured using data samples collected with the BESIII detector operating at the Beijing Electron Positron Collider.The cross sections are found to be of the same order of magnitude as those of e+e− ! + −J/ and e+e− ! + − (2S), but the line shape is inconsistent with the Y states observed in the latter two modes.Two structures are observed in the e+e− ! + −hc cross sections around 4.22 and 4.39 GeV/c2, which we call Y (4220) and Y (4390), respectively. A fit with a coherent sum of two Breit-Wigner functions results in a mass of (4218.4+5.5−4.5 ± 0.9) MeV/c2 and a width of (66.0+12.3−8.3 ± 0.4) MeV for the Y (4220), and a mass of (4391.5+6.3−6.8 ± 1.0) MeV/c2 and a width of (139.5+16.2−20.6 ± 0.6) MeV for the Y (4390), where the first uncertainties are statistical and the second ones systematic. The statistical significance of Y (4220) and Y (4390) is 10 over one structure assumption.

Full Text

Preamble

M. Ablikim, M. N. Achasov, S. Ahmed, X. C. Ai, O. Albayrak, M. Albrecht, D. J. Ambrose, A. Amoroso, F. F. An, Q. An, J. Z. Bai, O. Bakina, R. Baldini Ferroli, Y. Ban, D. W. Bennett, J. V. Bennett, N. Berger, M. Bertani, D. Bettoni, J. M. Bian, F. Bianchi, E. Boger, I. Boyko, R. A. Briere, H. Cai, X. Cai, O. Cakir, A. Calcaterra, G. F. Cao, S. A. Cetin, J. Chai, J. F. Chang, G. Chelkov, G. Chen, H. S. Chen, J. C. Chen, M. L. Chen, S. Chen, S. J. Chen, X. Chen, X. R. Chen, Y. B. Chen, X. K. Chu, G. Cibinetto, H. L. Dai, J. P. Dai, A. Dbeyssi, D. Dedovich, Z. Y. Deng, A. Denig, I. Denysenko, M. Destefanis, F. De Mori, Y. Ding, C. Dong, J. Dong, L. Y. Dong, M. Y. Dong, Z. L. Dou, S. X. Du, P. F. Duan, J. Z. Fan, J. Fang, S. S. Fang, X. Fang, Y. Fang, R. Farinelli, L. Fava, F. Feldbauer, G. Felici, C. Q. Feng, E. Fioravanti, M. Fritsch, C. D. Fu, Q. Gao, X. L. Gao, Y. Gao, Z. Gao, I. Garzia, K. Goetzen, L. Gong, W. X. Gong, W.

Gradl, M. Greco, M. H. Gu, Y. T. Gu, Y. H. Guan, A. Q. Guo, L. B. Guo, R. P. Guo, Y. Guo, Y. P. Guo, Z. Haddadi, A. Hafner, S. Han, X. Q. Hao, F. A. Harris, K. L. He, F. H. Heinsius, T. Held, Y. K. Heng, T. Holtmann, Z. L. Hou, C. Hu, H. M. Hu, J. F. Hu, T. Hu, Y. Hu, G. S. Huang, J. S. Huang, X. T. Huang, X. Z. Huang, Z. L. Huang, T. Hussain, W. Ikegami Andersson, Q. Ji, Q. P. Ji, X. B. Ji, X. L. Ji, L. W. Jiang, X. S. Jiang, X. Y. Jiang, J. B. Jiao, Z. Jiao, D. P. Jin, S. Jin, T. Johansson, A. Julin, N. Kalantar-Nayestanaki, X. L. Kang, X. S. Kang, M. Kavatsyuk, B. C. Ke, P. Kiese, R. Kliemt, B. Kloss, O. B. Kolcu, B. Kopf, M. Kornicer, A. Kupsc, W. Kühn, J. S. Lange, M. Lara, P. Larin, L. Lavezzi, H. Leithoff, C. Leng, C. Li, Cheng Li, D. M. Li, F. Li, F. Y. Li, G. Li, H. B. Li, H. J. Li, J. C. Li, Jin Li, K. Li, K. Li, Lei Li, P. R. Li, Q. Y. Li, T. Li, W. D. Li, W. G. Li, X. L. Li, X. N. Li, X. Q. Li, Y. B. Li, Z. B. Li, H. Liang, Y. F. Liang, Y. T. Liang, G. R. Liao, D. X. Lin, B. Liu, B. J. Liu, C. X. Liu, D. Liu, F. H. Liu, Fang Liu, Feng Liu, H. B. Liu, H. H. Liu, H. H. Liu, H. M. Liu, J. Liu, J. B. Liu, J. P. Liu, J. Y. Liu, K. Liu, K. Y. Liu, L. D. Liu, P. L. Liu, Q. Liu, S. B. Liu, X. Liu, Y. B. Liu, Y. Y. Liu, Z. A. Liu, Zhiqing Liu, H. Loehner, X. C. Lou, H. J. Lu, J. G. Lu, Y. Lu, Y. P. Lu, C. L. Luo, M. X. Luo, T. Luo, X. L. Luo, X. R. Lyu, F. C. Ma, H. L. Ma, L. L. Ma, M. M. Ma, Q. M. Ma, T. Ma, X. N. Ma, X. Y. Ma, Y. M. Ma, F. E. Maas, M. Maggiora, Q. A. Malik, Y. J. Mao, Z. P. Mao, S. Marcello, J. G. Messchendorp, G. Mezzadri, J. Min, T. J. Min, R. E. Mitchell, X. H. Mo, Y. J. Mo, C. Morales Morales, N. Yu. Muchnoi, H. Muramatsu, P. Musiol, Y. Nefedov, F. Nerling, I. B. Nikolaev, Z. Ning, S. Nisar, S. L. Niu, X. Y. Niu, S. L. Olsen, Q. Ouyang, S. Pacetti, Y. Pan, P. Patteri, M. Pelizaeus, H. P. Peng, K. Peters, J. Pettersson, J. L. Ping, R. G. Ping, R. Poling, V. Prasad, H. R. Qi, M. Qi, S. Qian, C. F. Qiao, L. Q. Qin, N. Qin, X. S. Qin, Z. H. Qin, J. F. Qiu, K. H. Rashid, C. F. Redmer, M. Ripka, G. Rong, Ch. Rosner, X. D. Ruan, A. Sarantsev, M. Savrié, C. Schnier, K. Schoenning, W. Shan, M. Shao, C. P. Shen, P. X. Shen, X. Y. Shen, H. Y. Sheng, W. M. Song, X. Y. Song, S. Sosio, S. Spataro, G. X. Sun, J. F. Sun, S. S. Sun, X. H. Sun, Y. J. Sun, Y. Z. Sun, Z. J. Sun, Z. T. Sun, C. J. Tang, X. Tang, I. Tapan, E. H. Thorndike, M. Tiemens, I. Uman, G. S. Varner, B. Wang, B. L. Wang, D. Wang, D. Y. Wang, K. Wang, L. L. Wang, L. S. Wang, M. Wang, P. Wang, P. L. Wang, W. Wang, W. P. Wang, X. F. Wang, Y. Wang, Y. D. Wang, Y. F. Wang, Y. Q. Wang, Z. Wang, Z. G. Wang, Z. H. Wang, Z. Y. Wang, Z. Y. Wang, T. Weber, D. H. Wei, P. Weidenkaff, S. P. Wen, U. Wiedner, M. Wolke, L. H. Wu, L. J. Wu, Z. Wu, L. Xia, L. G. Xia, Y. Xia, D. Xiao, H. Xiao, Z. J. Xiao, Y. G. Xie, Yuehong Xie, Q. L. Xiu, G. F. Xu, J. J. Xu, L. Xu, Q. J. Xu, Q. N. Xu, X. P. Xu, L. Yan, W. B. Yan, W. C. Yan, Y. H. Yan, H. J. Yang, H. X. Yang, L. Yang, Y. X. Yang, M. Ye, M. H. Ye, J. H. Yin, Z. Y. You, B. X. Yu, C. X. Yu, J. S. Yu, C. Z. Yuan, Y. Yuan, A. Yuncu, A. A. Zafar, Y. Zeng, Z. Zeng, B. X. Zhang, B. Y. Zhang, C. C. Zhang, D. H. Zhang, H. H. Zhang, H. Y. Zhang, J. Zhang, J. J. Zhang, J. L. Zhang, J. Q. Zhang, J. W. Zhang, J. Y. Zhang, J. Z. Zhang, K. Zhang, L. Zhang, S. Q. Zhang, X. Y. Zhang, Y. Zhang, Y. Zhang, Y. H. Zhang, Y. N. Zhang, Y. T. Zhang, Yu Zhang, Z. H. Zhang, Z. P. Zhang, Z. Y. Zhang, G. Zhao, J. W. Zhao, J. Y. Zhao, J. Z. Zhao, Lei Zhao, Ling Zhao, M. G. Zhao, Q. Zhao, Q. W. Zhao, S. J. Zhao, T. C. Zhao, Y. B.

Zhao, Z. G. Zhao, A. Zhemchugov, B. Zheng, J. P. Zheng, W. J. Zheng, Y. H. Zheng, B. Zhong, L. Zhou, X. Zhou, X. K. Zhou, X. R. Zhou, X. Y. Zhou, K. Zhu, K. J. Zhu, S. Zhu, S. H. Zhu, X. L. Zhu, Y. C. Zhu, Y. S. Zhu, Z. A. Zhu, J. Zhuang, L. Zotti, B. S. Zou, J. H. Zou

Affiliations

1 Institute of High Energy Physics, Beijing 100049, People' s Republic of China (BESIII Collaboration)

7 China Center of Advanced Science and Technology, Beijing 100190, People' s Republic of China

8 COMSATS Institute of Information Technology, Lahore, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan

19 Indiana University, Bloomington, Indiana 47405, USA

20 (A)INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy; (B)INFN and University of Perugia, I-06100, Perugia, Italy

21 (A)INFN Sezione di Ferrara, I-44122, Ferrara, Italy; (B)University of Ferrara, I-44122, Ferrara, Italy

23 Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia

24 Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany

39 Tsinghua University, Beijing 100084, People' s Republic of China

40 (A)Ankara University, 06100 Tandogan, Ankara, Turkey; (B)Istanbul Bilgi University, 34060 Eyup, Istanbul, Turkey; (C)Uludag University, 16059 Bursa, Turkey; (D)Near East University, Nicosia, North Cyprus, Mersin 10, Turkey

48 University of the Punjab, Lahore-54590, Pakistan

49 (A)University of Turin, I-10125, Turin, Italy; (B)University of Eastern Piedmont, I-15121, Alessandria, Italy; (C)INFN, I-10125, Turin, Italy

53 Zhengzhou University, Zhengzhou 450001, People' s Republic of China

a Also at State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People' s Republic of China
b Also at Bogazici University, 34342 Istanbul, Turkey
c Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia
d Also at the Functional Electronics Laboratory, Tomsk State University, Tomsk, 634050, Russia
e Also at the Novosibirsk State University, Novosibirsk, 630090, Russia
f Also at the NRC "Kurchatov Institute, PNPI, 188300, Gatchina, Russia
g Also at University of Texas at Dallas, Richardson, Texas 75083, USA

h Also at Istanbul Arel University, 34295 Istanbul, Turkey
i Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany
j Also at Institute of Nuclear and Particle Physics, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai 200240, People' s Republic of China

Abstract

The cross sections of $e^+e^- \to \pi^+\pi^- h_c$ at center-of-mass energies from 3.896 to 4.600 GeV are measured using data samples collected with the BESIII detector operating at the Beijing Electron Positron Collider. The cross sections are found to be of the same order of magnitude as those of $e^+e^- \to \pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$, but the line shape is inconsistent with the Y states observed in the latter two modes.

Two structures are observed in the $e^+e^- \to \pi^+\pi^- h_c$ cross sections around 4.22 and 4.39 GeV/c^2, which we call $Y(4220)$ and $Y(4390)$, respectively. A fit with a coherent sum of two Breit-Wigner functions results in a mass of $(4218.4^{+5.5}_{-4.5} \pm 0.4)$ MeV/c^2 and a width of $(66.0^{+12.3}_{-8.3} \pm 1.0)$ MeV for the $Y(4220)$, and a mass of $(4391.5^{+6.3}_{-8.3} \pm 0.6)$ MeV/c^2 and a width of $(139.5^{+16.2}_{-20.6} \pm 1.0)$ MeV for the $Y(4390)$, where the first uncertainties are statistical and the second ones systematic. The statistical significance of $Y(4220)$ and $Y(4390)$ is 10σ over the one structure assumption. The product of the electronic partial width and branching fraction $(\Gamma_{ee}\mathcal{B})_1 = (4.6^{+2.9}_{-1.4} \pm 0.9)$ eV for $Y(4220)$ and $(\Gamma_{ee}\mathcal{B})_2 = (11.6^{+5.0}_{-4.4} \pm 0.6)$ eV for $Y(4390)$.

PACS numbers: 14.40.Rt, 14.40.Pq, 13.66.Bc, 13.25.Gv

Introduction

In the last decade, a series of charmonium-like states have been observed at e^+e^- colliders. These states challenge the understanding of charmonium spectroscopy as well as QCD calculations [?, ?]. According to potential models, there are five vector charmonium states between the 1D state $\psi(3770)$ and 4.7 GeV/c^2, namely the 3S, 2D, 4S, 3D, and 5S states [?]. From experimental studies, besides the three well-established structures observed in the inclusive hadronic cross section [?], i.e., $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, five Y states, i.e., $Y(4008)$, $Y(4230)$, $Y(4260)$, $Y(4360)$, and $Y(4660)$ have been reported in initial state radiation (ISR) processes $e^+e^- \to \gamma_{\mathrm{ISR}}\pi^+\pi^-\psi(2S)$ at the B factories [?, ?, ?, ?, ?, ?, ?, ?] or in the direct production processes at the CLEO and BESIII experiments [?, ?]. The overpopulation of structures in this region and the mismatch of the properties between the potential model prediction and experimental measurements make them good candidates for exotic states. Various scenarios have been proposed, which interpret one or some of them as hybrid states, tetraquark states, or molecular states [?].

The study of charmonium-like states in different production processes supplies useful information on their properties. The process $e^+e^- \to \pi^+\pi^- h_c$ was first studied by CLEO [?] at center-of-mass (c.m.) energies $\sqrt{s}$ from 4.000 to 4.260 GeV. A 10σ signal at 4.170 GeV and a hint of a rising cross section at 4.260 GeV were observed. Using data samples taken at 13 c.m. energies from 3.900 to 4.420 GeV [?], BESIII reported the measurement of the cross section of $e^+e^- \to \pi^+\pi^-h_c$ [?]. Unlike the line shape of the process $e^+e^- \to \pi^+\pi^-J/\psi$, there is a broad structure in the high energy region with a possible local maximum at around 4.23 GeV in $e^+e^- \to \pi^+\pi^-h_c$. Based on the CLEO measurement at $\sqrt{s} = 4.170$ GeV and the BESIII measurement, two assumptions were made to describe the cross section in Ref. [?]. In both assumptions, a narrow structure exists at around 4.23 GeV, while the situation in the high energy region is unclear due to the lack of experimental data.

In this Letter, we present a follow-up study of $e^+e^- \to \pi^+\pi^-h_c$ at c.m. energies from 3.896 to 4.600 GeV using data samples taken at 79 energy points [?] with the BESIII detector [?]. Two resonant structures are observed at $\sqrt{s} = 4.22$ and 4.39 GeV [hereafter referred to as $Y(4220)$ and $Y(4390)$]. The integrated luminosity at each energy point is measured with an uncertainty of 1.0% using large-angle Bhabha events [?, ?]. There are 17 energy points where the integrated luminosities are larger than 40 pb^{-1} (referred to as "XYZ data sample" hereafter), while the integrated luminosities for the other energy points are smaller than 20 pb^{-1} (referred to as "R-scan data sample" hereafter).

The c.m. energies for the XYZ data sample are measured with $e^+e^- \to \gamma_{\text{ISR/FSR}}\mu^+\mu^-$ events with an uncertainty of 0.8 MeV [?], which is dominated by the systematic uncertainty. A similar method is used for the R-scan data sample with multihadron final states [?].

Event Selection and Reconstruction

In this study, the h_c is reconstructed via its electric-dipole transition $h_c \to \gamma\eta_c$ with $\eta_c \to X_i$, where X_i is one of 16 exclusive hadronic final states: $2(\pi^+\pi^-)$, $2(K^+K^-)$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-\bar{p}p$, $3(\pi^+\pi^-)$, $K_S^0K^\pm\pi^\mp\pi^+\pi^-$, $K^+K^-\pi^0$, $2(\pi^+\pi^-)K^+K^-$, $K_S^0\bar{p}p\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-\pi^0\pi^0$, and $2(\pi^+\pi^-\pi^0)$. Here, the K_S^0 is reconstructed using its decay to $\pi^+\pi^-$, and the π^0 and η from the $\gamma\gamma$ final state.

Monte Carlo (MC) simulated events are used to optimize the selection criteria, determine the detection efficiency, and estimate the possible backgrounds. The simulation of the BESIII detector is based on GEANT4 [?] and includes the geometric description of the BESIII detector and the detector response. For the signal process, we use an MC sample for $e^+e^- \to \pi^+\pi^-h_c$ generated according to phase space. ISR is simulated with KKMC [?] with a maximum energy for the ISR photon corresponding to the $\pi^+\pi^-h_c$ mass threshold.

We select signal candidates with the same method as that described in Ref. [?]. Figure 1 [Figure 1: see original paper] shows the scatter plot of the invariant mass of the η_c candidate versus the one of the h_c candidate and the invariant mass distribution of $\gamma\eta_c$ in the η_c signal region for the data sample at $\sqrt{s} = 4.416$

GeV. A clear $h_c \to \gamma\eta_c$ signal is observed. The η_c signal region is defined by a mass window around the nominal η_c mass [?], which is within 50 MeV/c^2 with efficiency about 84% (45 MeV/c^2 with efficiency about 80%) from MC simulation for final states with only charged or K_S^0 particles (for those including π^0 or η).

We determine the number of $\pi^+\pi^-h_c$ signal events ($n_{\rm obs}$) from the $\gamma\eta_c$ invariant mass distribution. For the XYZ data sample, the $\gamma\eta_c$ mass spectrum is fitted with the MC simulated signal shape convolved with a Gaussian function to reflect the mass resolution difference between the data and MC simulation, together with a linear background. The fit to the data sample at $\sqrt{s} = 4.416$ GeV is shown in Fig. 1. The tail on the high mass side is due to events with ISR (ISR photon undetected); this is simulated with KKMC in MC simulation, and its fraction is fixed in the fit. For the data samples with large statistics ($\sqrt{s} = 4.226$, 4.258, 4.358, and 4.416 GeV), the fit is applied to the 16 η_c decay modes simultaneously with the number of signal events in each decay mode constrained by the corresponding branching fraction [?]. For the data samples at the other energy points, we fit the mass spectrum summed over all η_c decay modes. For the R-scan data sample, the number of signal events is calculated by counting the entries in the h_c signal region $[3.515, 3.535]$ GeV/c^2 ($n_{\rm sig}$) and the entries in the h_c sideband regions $[3.475, 3.495]$ GeV/c^2 and $[3.555, 3.575]$ GeV/c^2 ($n_{\rm side}$) using the formula $n_{\rm obs} = n_{\rm sig} - f \cdot n_{\rm side}$. Here, the scale factor $f = 0.5$ is the ratio of the size of the signal region and the background region, and the background is assumed to be distributed linearly in the region.

Cross Section Calculation

The Born cross section is calculated from

$$\sigma_B = \frac{n_{\rm obs}}{\mathcal{L}(1+\delta)(1+\Pi)\sum_{i=1}^{16}\epsilon_i\mathcal{B}_i}$$

where $n_{\rm obs}$ is the number of observed signal events, $\mathcal{L}$ is the integrated luminosity, $(1+\delta)$ is the ISR correction factor, $1+\Pi$ is the correction factor for vacuum polarization [?], ϵ_i and $\mathcal{B}_i$ are the detection efficiency and branching fraction for the ith η_c decay mode [?], respectively. The ISR correction factor is obtained using the QED calculation as described in Ref. [?] and taking the formula used to fit the cross section measured in this analysis after two iterations as input. The Born cross sections are summarized in the Supplemental Material [?] together with all numbers used in the calculation of the Born cross sections. The dressed cross sections (including vacuum polarization effects) are shown in Fig. 2 [Figure 2: see original paper] with dots and squares for the R-scan and XYZ data sample, respectively. The cross sections are of the same order of magnitude as those of the $\pi^+\pi^-\psi(2S)$ [?, ?, ?, ?, ?, ?, ?, ?, ?], but follow a different line shape. The cross section drops in the high energy region, but more slowly than for the $e^+e^- \to \pi^+\pi^-J/\psi$ process.

Systematic uncertainties in the cross section measurement mainly come from the luminosity measurement, the branching fraction of $h_c \to \gamma\eta_c$, the detection efficiency, the ISR correction factor, and the fit. The uncertainty due to the vacuum polarization is negligible. The uncertainty in the integrated luminosity is 1% at each energy point. The uncertainty sources for the detection efficiency include systematic uncertainties in tracking efficiency (1% per track), photon reconstruction (1% per photon), and K_S^0 reconstruction (1.2% per K_S^0). Further uncertainties arise from the π^0/η mass window requirement (1% per π^0/η), the χ^2 4C requirement, η_c parameters and line shape, possible intermediate states in the $\pi^\pm h_c$ and $\pi^+\pi^-$ mass spectra, intermediate states in η_c decays (included in the uncertainty from the branching fraction of $\eta_c \to X_i$), and the limited statistics of the MC simulation.

The uncertainty due to the χ^2 4C requirement is estimated by correcting the helix parameters of the simulated charged tracks to match the resolution found in data, and repeating the analysis [**?**]. Uncertainties due to the η_c parameters and line shape are estimated by varying them in the MC simulation. When producing MC events for the $e^+e^- \to \pi^+\pi^-h_c$ process through the intermediate states $Z_c(3900)$ or $Z_c(4020)$, the parameters of the $Z_c(3900)$ and $Z_c(4020)$ are fixed to the average values from the published measurements [**?**, **?**, **?**, **?**, **?**]. The quantum numbers of both $Z_c(3900)$ and $Z_c(4020)$ are assumed to be $J^P = 1^+$. The differences in the efficiency obtained from phase space MC samples and those with intermediate Z_c states are taken as the uncertainties from possible intermediate states in the $\pi^\pm h_c$ system. The uncertainty from intermediate states in the $\pi^+\pi^-$ system is estimated by reweighting the $\pi^+\pi^-$ mass distribution in the phase space MC sample according to the data, and the resulting difference in the efficiency is considered as uncertainty. The uncertainties due to data and MC differences in the detection efficiency are determined to be between 5.5% and 10.8%, depending on the η_c decay modes and the c.m. energy. Combining the uncertainties for the branching fractions of η_c decays [**?**], the uncertainties for the average efficiency $\sum_{i=1}^{16} \epsilon_i \mathcal{B}_i$ are between 6.4% and 9.1% depending on the c.m. energy.

The uncertainty in the ISR correction is estimated as described in Ref. [**?**]. Uncertainties due to the choice of the signal shape, the background shape, the mass resolution, and fit range are estimated by changing the h_c and η_c resonant parameters and line shapes in the MC simulation, changing the background function from a linear to a second-order polynomial, changing the mass resolution difference between the data and the MC simulation by 1 standard deviation, and by extending or shrinking the fit range.

Assuming all of the sources are independent, the total systematic uncertainty in the $\pi^+\pi^-h_c$ cross section measurement is determined to be 9.4%-13.6% depending on the c.m. energy. The uncertainty in $\mathcal{B}(h_c \to \gamma\eta_c)$ is 11.8% [**?**], common to all energy points, and quoted separately in the cross section measurement. Altogether, the quadratic sum of the common systematic errors at each energy point accounts for about 95% of the total systematic error.

Resonance Fit and Results

A maximum likelihood method is used to fit the dressed cross sections to determine the parameters of the resonant structures. The likelihood is constructed taking the fluctuations of the number of signal and background events into account (the definition is described in the Supplemental Material [?]). Assuming that the $\pi^+\pi^- h_c$ signal comes from two resonances, the cross section is parametrized as the coherent sum of two constant width relativistic Breit-Wigner functions, i.e.,

$$\sigma(m) = \left| \sqrt{\mathcal{P}(m)} \left[\frac{\sqrt{(\Gamma_{ee}\mathcal{B})_1 \Gamma_1}}{m^2 - M_1^2 + iM_1\Gamma_1} + e^{i\phi} \frac{\sqrt{(\Gamma_{ee}\mathcal{B})_2 \Gamma_2}}{m^2 - M_2^2 + iM_2\Gamma_2} \right] \right|^2 \mathcal{P}(m)$$

where M_j, Γ_j, and $(\Gamma_{ee}\mathcal{B})_j$ $(j = 1, 2)$ are the mass, total width, and product of the electronic partial width and the branching fraction to $\pi^+\pi^- h_c$ for the two resonances, respectively; ϕ is the relative phase between the two Breit-Wigner functions. The masses M_j, the total widths Γ_j, the products $(\Gamma_{ee}\mathcal{B})_j$, and the relative phase ϕ are free parameters in the fit. Only the statistical uncertainty is considered in the fit. There are two solutions from the fit, one of which is shown in Fig. 2. The second solution is very close to the one shown here. This can be proved analytically using Eq.(9) in Ref. [?], which relates the two solutions from the fit when a sum of two coherent Breit-Wigner functions is used.

The parameters determined from the fit are $M_1 = (4218.4^{+5.5}_{-4.5} \pm 0.4)$ MeV/c^2, $\Gamma_1 = (66.0^{+12.3}_{-8.3} \pm 1.0)$ MeV, and $(\Gamma_{ee}\mathcal{B})_1 = (4.6^{+2.9}_{-1.4} \pm 0.9)$ eV for $Y(4220)$, and $M_2 = (4391.5^{+6.3}_{-8.3} \pm 0.6)$ MeV/c^2, $\Gamma_2 = (139.5^{+16.2}_{-20.6} \pm 1.0)$ MeV, and $(\Gamma_{ee}\mathcal{B})_2 = (11.6^{+5.0}_{-4.4} \pm 0.6)$ eV for $Y(4390)$. The relative phase ϕ is $(3.1^{+0.7}_{-0.9})$ rad. The correlation matrix of the fit parameters shows large correlation between the $(\Gamma_{ee}\mathcal{B})_j$ and ϕ (see Supplemental Material [?]).

The likelihood contours in the mass and width planes for $Y(4220)$ and $Y(4390)$ are shown in Fig. 3 [Figure 3: see original paper], together with the positions of $Y(4230)$, $Y(4260)$, $Y(4360)$, and $\psi(4415)$ with the parameters taken from the latest PDG average [?]. The low-lying resonance from the study of $e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII [?], marked as $Y(4260)_{\text{BESIII}}$ in the plot, is also compared. $Y(4260)$, $Y(4360)$, and $\psi(4415)$ are located outside the 3σ contours, while $Y(4230)$ and $Y(4260)_{\text{BESIII}}$ are overlapped with the 3σ contour of $Y(4220)$.

Fitting the dressed cross section with only one resonance yields a worse result; the change of the likelihood value from two resonances to one resonance is $\Delta(2\ln\mathcal{L}) = 113.5$. Taking the change in the number of degrees of freedom (4) into account, the significance for the assumption of two resonant structures over the assumption of one resonant structure is 10σ. The fit with the coherent sum of one Breit-Wigner function and a phase space term gives a worse result as well; the change of the likelihood value is $\Delta(2\ln\mathcal{L}) = 66.8$. We also fit the cross section with the coherent sum of three Breit-Wigner functions, or the coherent sum of two Breit-Wigner functions and a phase space term. Both assumptions improve the fit quality, but the significances of the third resonance and the phase space term are only 2.6σ and 2.9σ, respectively.

Systematic Uncertainties

The systematic uncertainties in the resonance parameters mainly come from the absolute c.m. energy measurement, the c.m. energy spread, and the systematic uncertainty on the cross section measurement. The uncertainty from the c.m. energy measurement includes the uncertainty of the c.m. energy and the assumption made in the measurement for the R-scan data sample. Because of the low statistics at each energy point in the R-scan data sample, we approximate the difference between the requested and the actual c.m. energy by a common constant. To assess the systematic uncertainty connected with this assumption, we replace the constant by a c.m. energy-dependent second-order polynomial. The systematic uncertainty of the c.m. energy is common for all the energy points in the two data samples and will propagate to the mass measurement (0.8 MeV). The changes on the parameters are taken as uncertainty. The uncertainty from c.m. energy spread is estimated by convoluting the fit formula with a Gaussian function with a width of 1.6 MeV, which is the beam spread measured by the Beam Energy Measurement System [**?**].

The uncertainty from the cross section measurement is divided into two parts. The first one is uncorrelated among the different c.m. energy points and comes mainly from the fit to the $\gamma\eta_c$ invariant mass spectrum to determine the signal yields. The corresponding uncertainty is estimated by including the uncertainty in the fit to the cross section, and taking the differences on the parameters as uncertainties. The second part includes all the other sources, is common for all data points (14.8%), and only affects the $\Gamma_{ee}\mathcal{B}$ measurement. Table I summarizes the systematic uncertainty in the resonance parameters.

Summary

In summary, we measure the $e^+e^- \to \pi^+\pi^- h_c$ Born cross section using data at 79 c.m. energy points from 3.896 to 4.600 GeV. Assuming the $\pi^+\pi^- h_c$ events come from two resonances, we obtain $M = (4218.4^{+5.5}_{-4.5} \pm 0.4)$ MeV/c^2, $\Gamma = (66.0^{+12.3}_{-8.3} \pm 0.9)$ MeV, and $(\Gamma_{ee}\mathcal{B}) = (4.6^{+2.9}_{-1.4} \pm 0.8)$ eV for $Y(4220)$, and $M = (4391.5^{+6.3}_{-8.3} \pm 0.6)$ MeV/c^2, $\Gamma = (139.5^{+16.2}_{-20.6} \pm 1.0)$ MeV, and $(\Gamma_{ee}\mathcal{B}) = (11.6^{+5.0}_{-4.4} \pm 1.9)$ eV for $Y(4390)$, with a relative phase of $\phi = (3.1^{+0.7}_{-0.9} \pm 0.2)$ rad. The first errors are statistical and the second are systematic.

The parameters of these structures are different from those of $Y(4260)$, $Y(4360)$, and $\psi(4415)$ [**?**]$. The resonance parameters of $Y(4220)$ are consistent with those of the resonance observed in $e^+e^- \to \omega\chi_{c0}$ [**?**].

The two resonances observed in the $e^+e^- \to \pi^+\pi^- h_c$ process are located in the mass region between 4.2 and 4.4 GeV/c^2, where the vector charmonium hybrid states are predicted from various QCD calculations [?, ?, ?]. The mass of $Y(4220)$ is lower than that of $Y(4260)$ observed in the $e^+e^- \to \pi^+\pi^- J/\psi$ process. The smaller mass is consistent with some of the theoretical calculations for the mass of $Y(4260)$ when explaining it as a $D_1\bar{D}$ molecule [?, ?].

Acknowledgments

The BESIII Collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key Basic Research Program of China under Contract No. 2015CB856700; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11235011, 11322544, 11335008, 11425524; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); the Collaborative Innovation Center for Particles and Interactions (CICPI); Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts Nos. U1232201, U1332201; CAS under Contracts Nos. KJCX2-YW-N29, KJCX2-YW-N45; 100 Talents Program of CAS; National 1000 Talents Program of China; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under Contracts Nos. Collaborative Research Center CRC 1044, FOR 2359; Istituto Nazionale di Fisica Nucleare, Italy; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U1532257; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U1532258; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) under Contract No. 530-4CDP03; Ministry of Development of Turkey under Contract No. DPT2006K-120470; NSFC under Contract No. 11275266; The Swedish Research Council; U. S. Department of Energy under Contracts Nos. DE-FG02-05ER41374, DE-SC-0010504, DE-SC0012069, DESC0010118; U.S. National Science Foundation; University of Groningen (RuG) and the Helmholtzzentrum fuer Schwerionenforschung GmbH (GSI), Darmstadt; WCU Program of National Research Foundation of Korea under Contract No. R32-2008-000-10155-0.

References

[1] For a recent review, see N. Brambilla et al., Eur. Phys. J. C 71, 1534 (2011).
[2] R. A. Briceno et al., Chin. Phys. C 40(4), 042001 (2016).
[3] K. A. Olive et al. (Particle Data Group), Chin. Phys. C 38(9), 090001 (2014); C. Patrignani et al. (Particle Data Group), Chin. Phys. C 40(10), 100001 (2016).
[4] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 95, 142001 (2005).
[5] C. Z. Yuan et al. (Belle Collaboration), Phys. Rev. Lett. 99, 182004 (2007).
[6] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 98, 212001 (2007).
[7] X. L. Wang et al. (Belle Collaboration), Phys. Rev. Lett. 99, 142002 (2007).
[8] J. P. Lees et al. (BaBar Collaboration), Phys. Rev. D 89, 111103 (2014).
[9] X. L. Wang et al. (Belle Collaboration), Phys. Rev. D 91, 112007 (2015).
[10] J. P. Lees et al. (BaBar Collaboration), Phys. Rev. D 86, 051102(R) (2012).

[11] Z. Q. Liu et al. (Belle Collaboration), Phys. Rev. Lett. 110, 252002 (2013).
[12] T. E. Coan et al. (CLEO Collaboration), Phys. Rev. Lett. 96, 162003 (2006).
[13] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 114, 092003 (2015).
[14] H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Phys. Rep. 639, 1 (2016).
[15] T. K. Pedlar et al. (CLEO Collaboration), Phys. Rev. Lett. 107, 041803 (2011).
[16] The data samples are the same as those used in this study except at 4.420 GeV. At 4.420 GeV, more data has been collected and analysed. Besides, the CM energies at all energy points have been remeasured using $e^+e^- \to \gamma_{\mathrm{ISR/FSR}}\mu^+\mu^-$ events, and found to be a few MeV smaller.
[17] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 111, 242001 (2013).
[18] C. Z. Yuan, Chin. Phys. C 38(4), 043001 (2014).
[19] See supplemental material at [URL will be inserted by publisher] for a summary of number of signal events, luminosity, and Born cross section at each energy point, the definition of the likelihood used in the fit to the dressed cross section, and the correlation matrix of the fit parameters from the fit.
[20] M. Ablikim et al. (BESIII Collaboration), Nucl. Instrum. Meth. A 614, 345 (2010).
[21] M. Ablikim et al. (BESIII Collaboration), Chin. Phys. C 39(9), 093001 (2015).
[22] M. Ablikim et al. (BESIII Collaboration), arXiv:1702.04977.
[23] M. Ablikim et al. (BESIII Collaboration), Chin. Phys. C 40(6), 063001 (2016).
[24] M. Ablikim et al. (BESIII Collaboration), "Measurement of the center-of-mass energies for R scan experiment" , paper in preparation.
[25] S. Agostinelli et al. (GEANT4 Collaboration), Nucl. Instrum. Meth. A 506, 250 (2003).
[26] S. Jadach, B. F. L. Ward and Z. Was, Comp. Phys. Commun. 130, 260 (2000); Phys. Rev. D 63, 113009 (2001).
[27] M. Ablikim et al., (BESIII Collaboration), Phys. Rev. D 86, 092009 (2012).
[28] S. Actis et al., Eur. Phys. J. C 66, 585 (2010).
[29] E. A. Kuraev and V. S. Fadin, Sov. J. Nucl. Phys. 41, 466 (1985) [Yad. Fiz. 41, 733 (1985).]
[30] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 87, 012002 (2013).
[31] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 110, 252001 (2013).
[32] T. Xiao, S. Dobbs, A. Tomaradze and K. K. Seth, Phys. Lett. B 727, 366 (2013).
[33] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 112, 022001 (2014).
[34] K. Zhu, X. H. Mo, C. Z. Yuan and P. Wang, Int. J. Mod. Phys. A 26, 4511 (2011).
[35] M. Ablikim et al. (BESIII Collaboration), arXiv:1611.01317[hep-ex].

[36] E. V. Abakumova et al., Nucl. Instrum. Meth. A 659, 21 (2011).
[37] L. Liu et al. (Hadron Spectrum Collaboration), J. High Energy Phys. 07, 126 (2012).
[38] T. Barnes, F. E. Close, and E. S. Swanson, Phys. Rev. D 52, 5242 (1995); P. Guo, A. P. Szczepaniak, G. Galata, A. Vassallo and E. Santopinto, Phys. Rev. D 78, 056003 (2008); Yu. S. Kalashnikova and A. V. Nefediev, Phys. Rev. D 77, 054025 (2008).
[39] Y. Chen, W. F. Chiu, M. Gong, L. C. Gui, and Z. F. Liu, Chin. Phys. C 40(8), 081002 (2016).
[40] M. Cleven, Q. Wang, F. K. Guo, C. Hanhart, U. G. Meißner, and Q. Zhao, Phys. Rev. D 90, 074039 (2014).
[41] T. W. Chiu and T. H. Hsieh (TWQCD Collaboration), Phys. Rev. D 73, 094510 (2006).

Appendices

Cross section of $e^+e^- \to \pi^+\pi^- h_c$

The number of signal events n_{obs}, the luminosity $\mathcal{L}$, the product of the initial state radiation correction factor and average efficiency $(1+\delta)\sum_{i=1}^{16}\epsilon_i\mathcal{B}_i$, and the Born cross section σ_B for XYZ data sample and R-scan data sample are summarized in Table II and Table III. The average efficiency is smaller for the R-scan data sample than for the XYZ data sample due to the different methods used in determining the number of signal events.

TABLE II. $e^+e^- \to \pi^+\pi^- h_c$ **cross sections from XYZ data sample**

The first errors are statistical, the second ones systematic uncertainty except the uncertainty in $\mathcal{B}(h_c \to \gamma\eta_c)$, and the third errors are from the uncertainty in $\mathcal{B}(h_c \to \gamma\eta_c)$.

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$(1+\delta)\sum_{i=1}^{16}\epsilon_i\mathcal{B}_i$ (%)	σ_B (pb)
3.896	52.0	$1.5^{+1.9}_{-1.0}$	$6.8^{+8.4}_{-3.7} \pm$ 2.0
4.008	52.0	$1.0^{+2.4}_{-1.0}$	$+2.0_{-1.3}\pm$ 3.1
4.090	52.0	$0.5^{+2.6}_{-0.5}$	$+8.0_{-2.9}\pm$ 16.6
4.170	52.0	$1.0^{+2.8}_{-1.0}$	$+12.5_{-6.8}\pm$ 40.7
4.190	52.0	$1.5^{+3.6}_{-1.5}$	$+12.3_{-8.0}\pm$ 43.2
4.210	52.0	$1.5^{+2.9}_{-1.5}$	$+13.2_{-8.9}\pm$ 39.9

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$(1+\delta)\sum_{i=1}^{16}\epsilon_i\mathcal{B}_i$ (%)	σ_B (pb)
4.220	52.0	$2.0^{+2.7}_{-2.0}$	$+12.5_{-8.6}\pm$ 65.0
4.226	52.0	$0.5^{+2.6}_{-0.5}$	$+15.6_{-10.9}\pm$ 45.5
4.240	52.0	$0.5^{+3.1}_{-0.5}$	$+12.9_{-9.0}\pm$ 19.3
4.258	52.0	$1.0^{+2.8}_{-1.0}$	$+6.9_{-5.1}\pm$ 0.9
4.308	52.0	$1.5^{+1.9}_{-1.5}$	$+5.3_{-3.5}\pm$ 15.1
4.358	52.0	$2.0^{+3.5}_{-2.0}$	$+11.2_{-7.1}\pm$ 7.2
4.416	566.9	$6.5^{+4.2}_{-6.5}$	$+2.3_{-2.0}\pm$ 23.6
4.600	52.0	$1.0^{+2.8}_{-1.0}$	$+7.2_{-5.7}\pm$ 25.3

TABLE III. $e^+e^- \to \pi^+\pi^- h_c$ **cross sections in R-scan data sample**

The errors are statistical only. The systematic uncertainty is 18.0%, and common for all energy points.

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	n_{sig}	n_{side}	$(1+\delta)\sum_{i=1}^{16}\epsilon_i\mathcal{B}_i$ (%)	σ_B (pb)
3.900	52.0	$1.5^{+1.9}_{-1.5}$	$1.0^{+2.4}_{-1.0}$	$0.5^{+2.6}_{-0.5}$	$28.0^{+34.6}_{-15.3}$
4.000	52.0	$1.0^{+2.4}_{-1.0}$	$0.5^{+2.6}_{-0.5}$	$1.0^{+2.8}_{-1.0}$	$18.9^{+44.7}_{-15.6}$
4.050	52.0	$0.5^{+2.6}_{-0.5}$	$1.0^{+2.8}_{-1.0}$	$1.5^{+3.6}_{-1.5}$	$8.8^{+45.1}_{-16.3}$
4.100	52.0	$1.0^{+2.8}_{-1.0}$	$1.5^{+3.6}_{-1.5}$	$1.5^{+2.9}_{-1.5}$	$18.5^{+51.5}_{-23.4}$
4.150	52.0	$1.5^{+3.6}_{-1.5}$	$1.5^{+2.9}_{-1.5}$	$2.0^{+2.7}_{-2.0}$	$27.2^{+65.0}_{-39.9}$
4.200	52.0	$1.5^{+2.9}_{-1.5}$	$2.0^{+2.7}_{-2.0}$	$0.5^{+2.6}_{-0.5}$	$25.3^{+48.1}_{-22.9}$
4.250	52.0	$2.0^{+2.7}_{-2.0}$	$0.5^{+2.6}_{-0.5}$	$0.5^{+3.1}_{-0.5}$	$34.0^{+45.8}_{-21.9}$
4.300	52.0	$0.5^{+2.6}_{-0.5}$	$0.5^{+3.1}_{-0.5}$	$1.0^{+2.8}_{-1.0}$	$8.1^{+41.5}_{-14.9}$
4.350	52.0	$0.5^{+3.1}_{-0.5}$	$1.0^{+2.8}_{-1.0}$	$1.5^{+1.9}_{-1.5}$	$3.5^{+22.2}_{-11.9}$
4.400	52.0	$1.0^{+2.8}_{-1.0}$	$1.5^{+1.9}_{-1.5}$	$2.0^{+3.5}_{-2.0}$	$17.5^{+48.8}_{-22.2}$
4.450	52.0	$1.5^{+1.9}_{-1.5}$	$2.0^{+3.5}_{-2.0}$	$6.5^{+4.2}_{-6.5}$	$25.5^{+31.5}_{-13.9}$
4.500	52.0	$2.0^{+3.5}_{-2.0}$	$6.5^{+4.2}_{-6.5}$	$1.0^{+2.8}_{-1.0}$	$34.2^{+60.3}_{-36.6}$
4.550	52.0	$6.5^{+4.2}_{-6.5}$	$1.0^{+2.8}_{-1.0}$	$0.5^{+3.0}_{-0.5}$	$109.4^{+70.7}_{-48.6}$
4.600	52.0	$1.0^{+2.8}_{-1.0}$	$0.5^{+3.0}_{-0.5}$	$2.5^{+3.8}_{-2.5}$	$18.7^{+52.0}_{-23.6}$

Definition of likelihood function

In the maximum likelihood fit to the dressed cross sections of $e^+e^- \to \pi^+\pi^- h_c$, the likelihood is defined as:

$$\mathcal{L}(\mu_{\text{sig}}; p) = \prod_i L_i(\mu_{\text{sig}}; p_i) \prod_j L_j(\mu_{\text{sig}}; p_j),$$

where μ_{sig} is the expected number of signal events, p_i and p_j are the parameters in the likelihood functions. L_i and L_j are the likelihood functions for the XYZ and R-scan data samples, respectively.

The likelihood functions for the XYZ and R-scan data samples are defined differently due to the different statistics of the samples. For the XYZ data sample, where the statistics is large, the likelihood function is described by an asymmetric Gaussian function

$$L_i = G(\mu_{\text{sig}}; m_i, \sigma_{\text{left}}, \sigma_{\text{right}}) = \begin{cases} \frac{2}{\sqrt{2\pi}(\sigma_{\text{left}}+\sigma_{\text{right}})} \exp\left[-\frac{(\mu_{\text{sig}}-m_i)^2}{2\sigma_{\text{left}}^2}\right], & \mu_{\text{sig}} < m_i; \\ \frac{2}{\sqrt{2\pi}(\sigma_{\text{left}}+\sigma_{\text{right}})} \exp\left[-\frac{(\mu_{\text{sig}}-m_i)^2}{2\sigma_{\text{right}}^2}\right], & \mu_{\text{sig}} \geq m_i. \end{cases}$$

By scanning the number of h_c signal events in the fit to the $\gamma\eta_c$ invariant mass spectrum, the likelihood value as a function of expected signal events μ_{sig} is obtained. The parameters of the Gaussian function are determined from a fit to the likelihood distribution.

For the R-scan data sample, the likelihood is defined as:

$$L_j(\mu_{\text{sig}}; N_{\text{sig}}, N_{\text{side}}) = \int P(N_{\text{sig}}; \mu_{\text{sig}} + \mu_{\text{bkg}}) P(N_{\text{side}}; \mu_{\text{bkg}}) d\mu_{\text{bkg}}$$

where $P(N;\mu) = \frac{1}{N!}\mu^N e^{-\mu}$ is the Poisson distribution, μ_{sig} and μ_{bkg} are the expected number of signal and background events, respectively.

Correlation matrix from the fit to the cross section

The correlation matrix of the fit parameters from the fit to the dressed cross sections of $e^+e^- \to \pi^+\pi^- h_c$ is:

Parameter	M_1	Γ_1	$(\Gamma_{ee}\mathcal{B})_1$	M_2	Γ_2	$(\Gamma_{ee}\mathcal{B})_2$	ϕ
M_1	1.00	-0.12	-0.08	0.05	-0.03	-0.02	0.04
Γ_1	-0.12	1.00	0.85	-0.04	0.03	0.02	-0.05
$(\Gamma_{ee}\mathcal{B})_1$	-0.08	0.85	1.00	-0.03	0.02	0.01	-0.78

Parameter	M_1	Γ_1	$(\Gamma_{ee}\mathcal{B})_1$	M_2	Γ_2	$(\Gamma_{ee}\mathcal{B})_2$	ϕ
M_2	0.05	-0.04	-0.03	1.00	-0.15	-0.10	0.06
Γ_2	-0.03	0.03	0.02	-0.15	1.00	0.88	-0.07
$(\Gamma_{ee}\mathcal{B})_2$	-0.02	0.02	0.01	-0.10	0.88	1.00	-0.82
ϕ	0.04	-0.05	-0.78	0.06	-0.07	-0.82	1.00

where M_j, Γ_j, and $(\Gamma_{ee}\mathcal{B})_j$ $(j = 1, 2)$ are the mass, the total width, and the product of the electronic partial and the branching fraction to $\pi^+\pi^-h_c$ for the two resonances, respectively; ϕ is the relative phase between two Breit-Wigner functions.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.