

Evidence of a Resonant Structure in the $e^+e^- \rightarrow \pi^+D^0D^{*-}$ Cross Section between 4.05 and 4.60 GeV

M. Ablikim,¹ M. N. Achasov,^{9,d} S. Ahmed,¹⁴ M. Albrecht,⁴ A. Amoroso,^{53a,53c} F. F. An,¹ Q. An,^{50,40} Y. Bai,³⁹ O. Bakina,²⁴ R. Baldini Ferroli,^{20a} Y. Ban,³² D. W. Bennett,¹⁹ J. V. Bennett,⁵ N. Berger,²³ M. Bertani,^{20a} D. Bettoni,^{21a} J. M. Bian,⁴⁷ F. Bianchi,^{53a,53c} E. Boger,^{24,b} I. Boyko,²⁴ R. A. Briere,⁵ H. Cai,⁵⁵ X. Cai,^{1,40} O. Cakir,^{43a} A. Calcaterra,^{20a} G. F. Cao,^{1,44} S. A. Cetin,^{43b} J. Chai,^{53c} J. F. Chang,^{1,40} G. Chelkov,^{24,b,c} G. Chen,¹ H. S. Chen,^{1,44} J. C. Chen,¹ M. L. Chen,^{1,40} P. L. Chen,⁵¹ S. J. Chen,³⁰ Y. B. Chen,^{1,40} G. Cibinetto,^{21a} H. L. Dai,^{1,40} J. P. Dai,^{35,h} A. Dbeyssi,¹⁴ D. Dedovich,²⁴ Z. Y. Deng,¹ A. Denig,²³ I. Denysenko,²⁴ M. Destefanis,^{53a,53c} F. De Mori,^{53a,53c} Y. Ding,²⁸ C. Dong,³¹ J. Dong,^{1,40} L. Y. Dong,^{1,44} M. Y. Dong,^{1,40,44} Z. L. Dou,³⁰ S. X. Du,⁵⁷ P. F. Duan,¹ J. Z. Fan,⁴² J. Fang,^{1,40} S. S. Fang,^{1,44} X. Fang,^{50,40} Y. Fang,¹ R. Farinelli,^{21a,21b} L. Fava,^{53b,53c} S. Fegan,²³ F. Feldbauer,²³ G. Felici,^{20a} C. Q. Feng,^{50,40} M. Fritsch,^{23,14} C. D. Fu,¹ Q. Gao,¹ X. L. Gao,^{50,40} Y. Gao,⁴² Y. G. Gao,⁶ Z. Gao,^{50,40} I. Garzia,^{21a} K. Goetzen,¹⁰ L. Gong,³¹ W. X. Gong,^{1,40} W. Gradl,²³ M. Greco,^{53a,53c} M. H. Gu,^{1,40} S. Gu,¹⁵ Y. T. Gu,¹² A. Q. Guo,¹ L. B. Guo,²⁹ R. P. Guo,^{1,44} Y. P. Guo,²³ Z. Haddadi,²⁶ S. Han,⁵⁵ X. Q. Hao,¹⁵ F. A. Harris,⁴⁵ K. L. He,^{1,44} F. H. Heinsius,⁴ T. Held,⁴ Y. K. Heng,^{1,40,44} T. Holtmann,⁴ Z. L. Hou,¹ C. Hu,²⁹ H. M. Hu,^{1,44} T. Hu,^{1,40,44} Y. Hu,¹ G. S. Huang,^{50,40} J. S. Huang,¹⁵ X. T. Huang,³⁴ X. Z. Huang,³⁰ Z. L. Huang,²⁸ T. Hussain,⁵² W. Ikegami Andersson,⁵⁴ Q. Ji,¹ Q. P. Ji,¹⁵ X. B. Ji,^{1,44} X. L. Ji,^{1,40} X. S. Jiang,^{1,40,44} X. Y. Jiang,³¹ J. B. Jiao,³⁴ Z. Jiao,¹⁷ D. P. Jin,^{1,40,44} S. Jin,^{1,44} Y. Jin,⁴⁶ T. Johansson,⁵⁴ A. Julin,⁴⁷ N. Kalantar-Nayestanaki,²⁶ X. L. Kang,¹ X. S. Kang,³¹ M. Kavatsyuk,²⁶ B. C. Ke,⁵ T. Khan,^{50,40} A. Khoukaz,⁴⁸ P. Kiese,²³ R. Kliemt,¹⁰ L. Koch,²⁵ O. B. Kolcu,^{43b,f} B. Kopf,⁴ M. Kornicer,⁴⁵ M. Kuemmel,⁴ M. Kuessner,⁴ M. Kuhlmann,⁴ A. Kupsc,⁵⁴ W. Kühn,²⁵ J. S. Lange,²⁵ M. Lara,¹⁹ P. Larin,¹⁴ L. Lavezzi,^{53c} S. Leiber,⁴ H. Leithoff,²³ C. Leng,^{53c} C. Li,⁵⁴ Cheng Li,^{50,40} D. M. Li,⁵⁷ F. Li,^{1,40} F. Y. Li,³² G. Li,¹ H. B. Li,^{1,44} H. J. Li,^{1,44} J. C. Li,¹ K. J. Li,⁴¹ Kang Li,¹³ Ke Li,³⁴ Lei Li,³ P. L. Li,^{50,40} P. R. Li,^{44,7} Q. Y. Li,³⁴ T. Li,³⁴ W. D. Li,^{1,44} W. G. Li,¹ X. L. Li,³⁴ X. N. Li,^{1,40} X. Q. Li,³¹ Z. B. Li,⁴¹ H. Liang,^{50,40} Y. F. Liang,³⁷ Y. T. Liang,²⁵ G. R. Liao,¹¹ D. X. Lin,¹⁴ B. Liu,^{35,h} B. J. Liu,¹ C. X. Liu,¹ D. Liu,^{50,40} F. H. Liu,³⁶ Fang Liu,¹ Feng Liu,⁶ H. B. Liu,¹² H. M. Liu,^{1,44} Huanhuan Liu,¹ Huihui Liu,¹⁶ J. B. Liu,^{50,40} J. P. Liu,⁵⁵ J. Y. Liu,^{1,44} K. Liu,⁴² K. Y. Liu,²⁸ Ke Liu,⁶ P. L. Liu,^{1,40} Q. Liu,⁴⁴ S. B. Liu,^{50,40} X. Liu,²⁷ Y. B. Liu,³¹ Z. A. Liu,^{1,40,44} Zhiqing Liu,²³ Y. F. Long,³² X. C. Lou,^{1,40,44} H. J. Lu,¹⁷ J. G. Lu,^{1,40} Y. Lu,¹ Y. P. Lu,^{1,40} C. L. Luo,²⁹ M. X. Luo,⁵⁶ X. L. Luo,^{1,40} X. R. Lyu,⁴⁴ F. C. Ma,²⁸ H. L. Ma,¹ L. L. Ma,³⁴ M. M. Ma,^{1,44} Q. M. Ma,¹ T. Ma,¹ X. N. Ma,³¹ X. Y. Ma,^{1,40} Y. M. Ma,³⁴ F. E. Maas,¹⁴ M. Maggiora,^{53a,53c} Q. A. Malik,⁵² Y. J. Mao,³² Z. P. Mao,¹ S. Marcelllo,^{53a,53c} Z. X. Meng,⁴⁶ J. G. Messchendorp,²⁶ G. Mezzadri,^{21a} J. Min,^{1,40} T. J. Min,¹ R. E. Mitchell,¹⁹ X. H. Mo,^{1,40,44} Y. J. Mo,⁶ C. Morales Morales,¹⁴ G. Morello,^{20a} N. Yu. Muchnoi,^{9,d} H. Muramatsu,⁴⁷ A. Mustafa,⁴ Y. Nefedov,²⁴ F. Nerling,^{10,g} I. B. Nikolaev,^{9,d} Z. Ning,^{1,40} S. Nisar,^{8,k} S. L. Niu,^{1,40} X. Y. Niu,^{1,44} S. L. Olsen,^{33,j} Q. Ouyang,^{1,40,44} S. Pacetti,^{20b} Y. Pan,^{50,40} M. Papenbrock,⁵⁴ P. Patteri,^{20a} M. Pelizaeus,⁴ J. Pellegrino,^{53a,53c} H. P. Peng,^{50,40} K. Peters,^{10,g} J. Pettersson,⁵⁴ J. L. Ping,²⁹ R. G. Ping,^{1,44} A. Pitka,²³ R. Poling,⁴⁷ V. Prasad,^{50,40} H. R. Qi,² M. Qi,³⁰ S. Qian,^{1,40} C. F. Qiao,⁴⁴ N. Qin,⁵⁵ X. S. Qin,⁴ Z. H. Qin,^{1,40} J. F. Qiu,¹ K. H. Rashid,^{52,i} C. F. Redmer,²³ M. Richter,⁴ M. Ripka,²³ M. Rolo,^{53c} G. Rong,^{1,44} Ch. Rosner,¹⁴ X. D. Ruan,¹² A. Sarantsev,^{24,e} M. Savrié,^{21b} C. Schnier,⁴ K. Schoenning,⁵⁴ M. Shao,^{50,40} C. P. Shen,² P. X. Shen,³¹ X. Y. Shen,^{1,44} H. Y. Sheng,¹ J. J. Song,³⁴ W. M. Song,³⁴ X. Y. Song,¹ S. Sosio,^{53a,53c} C. Sowa,⁴ S. Spataro,^{53a,53c} G. X. Sun,¹ J. F. Sun,¹⁵ L. Sun,⁵⁵ S. S. Sun,^{1,44} X. H. Sun,¹ Y. J. Sun,^{50,40} Y. K. Sun,^{50,40} Y. Z. Sun,¹ Z. J. Sun,^{1,40} Z. T. Sun,¹⁹ C. J. Tang,³⁷ G. Y. Tang,¹ X. Tang,¹ I. Tapan,^{43c} M. Tiemens,²⁶ B. Tsednee,²² I. Uman,^{43d} G. S. Varner,⁴⁵ B. Wang,^{1,*} B. L. Wang,⁴⁴ D. Y. Wang,³² Dan Wang,⁴⁴ K. Wang,^{1,40} L. L. Wang,¹ L. S. Wang,¹ M. Wang,³⁴ Meng Wang,^{1,44} P. Wang,¹ P. L. Wang,¹ W. P. Wang,^{50,40} X. F. Wang,⁴² Y. Wang,³⁸ Y. D. Wang,¹⁴ Y. F. Wang,^{1,40,44} Y. Q. Wang,²³ Z. Wang,^{1,40} Z. G. Wang,^{1,40} Z. H. Wang,^{50,40} Z. Y. Wang,¹ Zongyuan Wang,^{1,44} T. Weber,²³ D. H. Wei,¹¹ P. Weidenkaff,²³ S. P. Wen,¹ U. Wiedner,⁴ M. Wolke,⁵⁴ L. H. Wu,¹ L. J. Wu,^{1,44} Z. Wu,^{1,40} L. Xia,^{50,40} X. Xia,³⁴ Y. Xia,¹⁸ D. Xiao,¹ H. Xiao,⁵¹ Y. J. Xiao,^{1,44} Z. J. Xiao,²⁹ Y. G. Xie,^{1,40} Y. H. Xie,⁶ X. A. Xiong,^{1,44} Q. L. Xiu,^{1,40} G. F. Xu,¹ J. J. Xu,^{1,44} L. Xu,¹ Q. J. Xu,¹³ Q. N. Xu,⁴⁴ X. P. Xu,³⁸ L. Yan,^{53a,53c} W. B. Yan,^{50,40} W. C. Yan,^{50,40} W. C. Yan,² Y. H. Yan,¹⁸ H. J. Yang,^{35,h} H. X. Yang,¹ L. Yang,⁵⁵ Y. H. Yang,³⁰ Y. X. Yang,¹¹ Yifan Yang,^{1,44} M. Ye,^{1,40} M. H. Ye,⁷ J. H. Yin,¹ Z. Y. You,⁴¹ B. X. Yu,^{1,40,44} C. X. Yu,³¹ C. Z. Yuan,^{1,44} Y. Yuan,¹ A. Yuncu,^{43b,a} A. A. Zafar,⁵² A. Zallo,^{20a} Y. Zeng,¹⁸ Z. Zeng,^{50,40} B. X. Zhang,¹ B. Y. Zhang,^{1,40} C. C. Zhang,¹ D. H. Zhang,¹ H. H. Zhang,⁴¹ H. Y. Zhang,^{1,40} J. Zhang,^{1,44} J. L. Zhang,¹ J. Q. Zhang,¹ J. W. Zhang,^{1,40,44} J. Y. Zhang,¹ J. Z. Zhang,^{1,44} K. Zhang,^{1,44} L. Zhang,⁴² S. Q. Zhang,³¹ X. Y. Zhang,³⁴ Y. H. Zhang,^{1,40} Y. T. Zhang,^{50,40} Yang Zhang,¹ Yao Zhang,¹ Yu Zhang,⁴⁴ Z. H. Zhang,⁶ Z. P. Zhang,⁵⁰ Z. Y. Zhang,⁵⁵ G. Zhao,¹ J. W. Zhao,^{1,40} J. Y. Zhao,^{1,44} J. Z. Zhao,^{1,40} Lei Zhao,^{50,40}

Ling Zhao,¹ M. G. Zhao,³¹ Q. Zhao,¹ S. J. Zhao,⁵⁷ T. C. Zhao,¹ Y. B. Zhao,^{1,40} Z. G. Zhao,^{50,40} A. Zhemchugov,^{24,b}
 B. Zheng,⁵¹ J. P. Zheng,^{1,40} W. J. Zheng,³⁴ Y. H. Zheng,⁴⁴ B. Zhong,²⁹ L. Zhou,^{1,40} X. Zhou,⁵⁵ X. K. Zhou,^{50,40}
 X. R. Zhou,^{50,40} X. Y. Zhou,¹ Y. X. Zhou,¹² J. Zhu,³¹ J. Zhu,⁴¹ K. Zhu,¹ K. J. Zhu,^{1,40,44} S. Zhu,¹ S. H. Zhu,⁴⁹ X. L. Zhu,⁴²
 Y. C. Zhu,^{50,40} Y. S. Zhu,^{1,44} Z. A. Zhu,^{1,44} J. Zhuang,^{1,40} B. S. Zou,¹ and J. H. Zou¹

(BESIII Collaboration)

- ¹*Institute of High Energy Physics, Beijing 100049, People's Republic of China*
²*Beihang University, Beijing 100191, People's Republic of China*
³*Beijing Institute of Petrochemical Technology, Beijing 102617, People's Republic of China*
⁴*Bochum Ruhr-University, D-44780 Bochum, Germany*
⁵*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
⁶*Central China Normal University, Wuhan 430079, People's Republic of China*
⁷*China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China*
⁸*COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan*
⁹*G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia*
¹⁰*GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany*
¹¹*Guangxi Normal University, Guilin 541004, People's Republic of China*
¹²*Guangxi University, Nanning 530004, People's Republic of China*
¹³*Hangzhou Normal University, Hangzhou 310036, People's Republic of China*
¹⁴*Helmholtz Institute Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*
¹⁵*Henan Normal University, Xinxiang 453007, People's Republic of China*
¹⁶*Henan University of Science and Technology, Luoyang 471003, People's Republic of China*
¹⁷*Huangshan College, Huangshan 245000, People's Republic of China*
¹⁸*Human University, Changsha 410082, People's Republic of China*
¹⁹*Indiana University, Bloomington, Indiana 47405, USA*
^{20a}*INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*
^{20b}*INFN and University of Perugia, I-06100 Perugia, Italy*
^{21a}*INFN Sezione di Ferrara, I-44122 Ferrara, Italy*
^{21b}*University of Ferrara, I-44122 Ferrara, Italy*
²²*Institute of Physics and Technology, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia*
²³*Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*
²⁴*Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia*
²⁵*Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany*
²⁶*KVI-CART, University of Groningen, NL-9747 AA Groningen, Netherlands*
²⁷*Lanzhou University, Lanzhou 730000, People's Republic of China*
²⁸*Liaoning University, Shenyang 110036, People's Republic of China*
²⁹*Nanjing Normal University, Nanjing 210023, People's Republic of China*
³⁰*Nanjing University, Nanjing 210093, People's Republic of China*
³¹*Nankai University, Tianjin 300071, People's Republic of China*
³²*Peking University, Beijing 100871, People's Republic of China*
³³*Seoul National University, Seoul 151-747, Korea*
³⁴*Shandong University, Jinan 250100, People's Republic of China*
³⁵*Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*
³⁶*Shanxi University, Taiyuan 030006, People's Republic of China*
³⁷*Sichuan University, Chengdu 610064, People's Republic of China*
³⁸*Soochow University, Suzhou 215006, People's Republic of China*
³⁹*Southeast University, Nanjing 211100, People's Republic of China*
⁴⁰*State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China*
⁴¹*Sun Yat-Sen University, Guangzhou 510275, People's Republic of China*
⁴²*Tsinghua University, Beijing 100084, People's Republic of China*
^{43a}*Ankara University, 06100 Tandogan, Ankara, Turkey*
^{43b}*Istanbul Bilgi University, 34060 Eyup, Istanbul, Turkey*
^{43c}*Uludag University, 16059 Bursa, Turkey*
^{43d}*Near East University, Nicosia, North Cyprus, Mersin 10, Turkey*
⁴⁴*University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
⁴⁵*University of Hawaii, Honolulu, Hawaii 96822, USA*
⁴⁶*University of Jinan, Jinan 250022, People's Republic of China*
⁴⁷*University of Minnesota, Minneapolis, Minnesota 55455, USA*

⁴⁸University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany⁴⁹University of Science and Technology Liaoning, Anshan 114051, People's Republic of China⁵⁰University of Science and Technology of China, Hefei 230026, People's Republic of China⁵¹University of South China, Hengyang 421001, People's Republic of China⁵²University of the Punjab, Lahore 54590, Pakistan^{53a}University of Turin, I-10125 Turin, Italy^{53b}University of Eastern Piedmont, I-15121 Alessandria, Italy^{53c}INFN, I-10125 Turin, Italy⁵⁴Uppsala University, Box 516, SE-75120 Uppsala, Sweden⁵⁵Wuhan University, Wuhan 430072, People's Republic of China⁵⁶Zhejiang University, Hangzhou 310027, People's Republic of China⁵⁷Zhengzhou University, Zhengzhou 450001, People's Republic of China (Received 9 August 2018; revised manuscript received 10 February 2019; published 15 March 2019)

The cross section of the process $e^+e^- \rightarrow \pi^+D^0D^{*-}$ for center-of-mass energies from 4.05 to 4.60 GeV is measured precisely using data samples collected with the BESIII detector operating at the BEPCII storage ring. Two enhancements are clearly visible in the cross section around 4.23 and 4.40 GeV. Using several models to describe the dressed cross section yields stable parameters for the first enhancement, which has a mass of $4228.6 \pm 4.1 \pm 6.3$ MeV/ c^2 and a width of $77.0 \pm 6.8 \pm 6.3$ MeV, where the first uncertainties are statistical and the second ones are systematic. Our resonant mass is consistent with previous observations of the $Y(4220)$ state and the theoretical prediction of a $D\bar{D}_1(2420)$ molecule. This result is the first observation of $Y(4220)$ associated with an open-charm final state. Fits with three resonance functions with additional $Y(4260)$, $Y(4320)$, $Y(4360)$, $\psi(4415)$, or a new resonance do not show significant contributions from either of these resonances. The second enhancement is not from a single known resonance. It could contain contributions from $\psi(4415)$ and other resonances, and a detailed amplitude analysis is required to better understand this enhancement.

DOI: 10.1103/PhysRevLett.122.102002

As the first observed charmoniumlike state with $J^{PC} = 1^{--}$, the $Y(4260)$ has remained a mystery. Many experimental measurements and theoretical interpretations have been proposed for this state [1], such as hybrids [2], tetraquarks [3], and hadronic molecules [4]. Since it was observed only in hidden-charm processes, while its mass is close to open-charm thresholds, studies of the open-charm production cross section in e^+e^- annihilation will provide important information on its properties. The cross section for e^+e^- annihilation into $D^{(*)}\bar{D}^{(*)}$ pairs shows a dip at the resonance mass, 4.26 GeV/ c^2 [5]. The $Y(4260)$ mass is only about 29 MeV/ c^2 below the nominal threshold for $D\bar{D}_1(2420)$, which is the first open-charm relative S -wave channel coupling to $J^{PC} = 1^{--}$. The $D\bar{D}_1(2420)$ molecule model is proposed as an interpretation of the $Y(4260)$, but it predicts a significantly smaller mass of about 4.22 GeV/ c^2 [6,7].

Recently, the precise measurement of the production cross section for $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ from the BESIII

experiment [8] indicates that the structure around 4260 MeV/ c^2 actually consists of two resonances with masses of 4222 and 4320 MeV/ c^2 . The mass of the former resonance [referred to as $Y(4220)$ hereafter] is consistent with the prediction of the $D\bar{D}_1(2420)$ molecule model. Furthermore, a $Y(4220)$ resonance has also been reported by the BESIII Collaboration in the cross-section measurements of $e^+e^- \rightarrow \omega\chi_{c0}$ [9], $e^+e^- \rightarrow \pi^+\pi^-h_c$ [10], and $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ [11]. In addition, a new resonant structure with a mass around 4.39 GeV/ c^2 , the $Y(4390)$, has been reported by BESIII in the reactions $e^+e^- \rightarrow \pi^+\pi^-h_c$ [10] and $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ [11]. The mass of the $Y(4390)$ is about 45 and 70 MeV/ c^2 higher than those of the $Y(4360)$ [12] and the second component of the $Y(4260)$ observed in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ by BESIII [8], respectively. The production of $e^+e^- \rightarrow \pi D\bar{D}^*$ is expected to be strongly enhanced above the nominal $D\bar{D}_1(2420)$ threshold and could be a key for understanding existing puzzles with these Y states [7].

The cross section of $e^+e^- \rightarrow \pi^+D^0D^{*-}$ was first measured by the Belle experiment using initial-state radiation (ISR) [13]. No evidence for charmonium(like) states was found within their statistics. In this Letter, we report improved measurements of the production cross section of $e^+e^- \rightarrow \pi^+D^0D^{*-}$ at center-of-mass energies (\sqrt{s}) from 4.05 to 4.60 GeV using data samples taken at 84 energy

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

points [14] with the BESIII detector [15]. The dataset contains five energy points ($\sqrt{s} = 4.2263, 4.2580, 4.3583, 4.4156, \text{ and } 4.5995$ GeV) with integrated luminosities larger than 500 pb^{-1} (“H-XYZ data” hereafter) and 79 energy points with integrated luminosities smaller than 200 pb^{-1} . The D^0 meson is reconstructed in the $D^0 \rightarrow K^- \pi^+$ decay channel. The bachelor π^+ produced directly in the e^+e^- annihilation process is also reconstructed, while the D^{*-} is not reconstructed directly but is inferred from energy-momentum conservation. Charge-conjugate modes are implied, unless otherwise noted.

The BESIII detector is described in detail elsewhere [15]. A Monte Carlo (MC) simulation based on GEANT4 [16] includes the geometric description of the BESIII detector and its response. For each energy point, we generate MC samples of the signal process, $e^+e^- \rightarrow \pi^+ D^0 D^{*-}$, and the isospin partner process, $e^+e^- \rightarrow \pi^+ D^- D^{*0}$, according to phase space (PHSP MC). The effect of ISR is simulated with KKMC [17] with a maximum energy for the ISR photon corresponding to the $\pi^+ D^0 D^{*-}$ mass threshold. Possible background contributions are estimated with KKMC-generated “inclusive” MC samples with integrated luminosities comparable to the H-XYZ data, where the known decay modes are simulated with EVTGEN [18] using branching fractions taken from the PDG [12], and the remaining unknown decays are simulated with the LUNDCHARM model [19].

The charged tracks are reconstructed with standard selection requirements [20] and used to reconstruct D^0 meson candidates from $K^- \pi^+$ track pairs. If there is more than one D^0 candidate in an event ($\sim 0.3\%$), we choose the one whose invariant mass $M(K^- \pi^+)$ is closest to the world-average D^0 mass $m(D^0)$ [12]. The signal region is defined as $|M(K^- \pi^+) - m(D^0)| < 15 \text{ MeV}/c^2$. To select the bachelor π^+ , at least one extra charged track, which is not used in the D^0 candidate and has charge opposite to that of the reconstructed K^- , is chosen with the same selection criteria as described above. The $e^+e^- \rightarrow D^* \bar{D}^*$ background events are rejected by vetoing any $D^0 \pi^+$ candidates satisfying $M(D^0 \pi^+) < 2.03 \text{ GeV}/c^2$. After the above requirements, the presence of a D^{*-} meson is inferred by the invariant mass recoiling against the $D^0 \pi^+$ system, $RM(D^0 \pi^+)$. To improve the mass resolution, the corrected recoil mass $RM_{\text{cor}}(D^0 \pi^+) = RM(D^0 \pi^+) + M(K^- \pi^+) - m(D^0)$ is used, as shown in Fig. 1. If there is more than one bachelor π^+ in the event, the one whose $RM_{\text{cor}}(D^0 \pi^+)$ is closest to the world-average D^{*-} mass $m(D^{*-})$ is selected. A study of the inclusive MC samples shows that only the isospin partner process $e^+e^- \rightarrow \pi^+ D^- D^{*0}$ (BKG1, hereafter) has an enhancement around the D^{*-} mass region in the $RM_{\text{cor}}(D^0 \pi^+)$ distribution. The shape of this background process is different at each energy point and is taken from the MC simulation. The $RM_{\text{cor}}(D^0 \pi^+)$ distribution of the remaining background processes (BKG2, hereafter) does

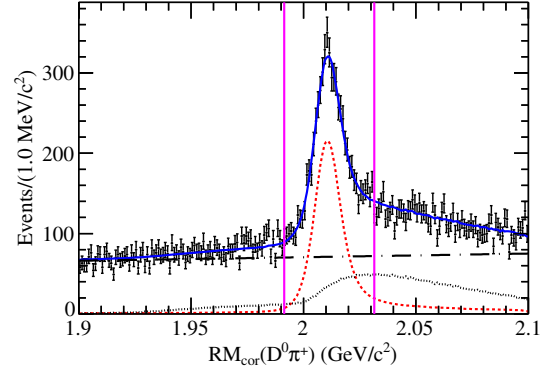


FIG. 1. Fit to the distribution of $RM_{\text{cor}}(D^0 \pi^+)$ for the data sample at $\sqrt{s} = 4.5995$ GeV. The black dots with error bars are data, the solid line (blue) describes the total fit, the dashed line (red) describes the signal shape, and the dotted and dash-dotted lines (black) describe BKG1 and BKG2, respectively. The pink vertical lines mark the signal region.

not peak and can be described by a first-order polynomial function.

An unbinned maximum likelihood fit to the $RM_{\text{cor}}(D^0 \pi^+)$ distribution is performed to determine the signal yields. The signal shape is derived from the MC shape convolved with a Gaussian function. The background shape is parametrized as a sum of the shape from the PHSP MC sample for BKG1 and a first-order polynomial function for BKG2. We perform a simultaneous fit to the $RM_{\text{cor}}(D^0 \pi^+)$ distributions for all data samples to determine the yields of the signal and background. The mean values of the Gaussian smearing function are constrained to be the same for all energy points. A center-of-mass energy-dependent width of the Gaussian function is obtained by fitting the widths of the five H-XYZ data samples with a first-order polynomial function, where these five widths are obtained by separate fits to the corresponding $RM_{\text{cor}}(D^0 \pi^+)$ distributions. The widths at $\sqrt{s} < 4.2263$ GeV are fixed to that at $\sqrt{s} = 4.2263$ GeV, since the fitted widths are close to zero. Figure 1 shows the fit result at $\sqrt{s} = 4.5995$ GeV. The signal region is defined as $|RM_{\text{cor}}(D^0 \pi^+) - \Delta M - m(D^{*-})| < 20 \text{ MeV}/c^2$, where ΔM is the mean value of the Gaussian function obtained from the fit. A sideband region, used below, is defined as $1.91 < RM_{\text{cor}}(D^0 \pi^+) < 1.95 \text{ GeV}/c^2$.

The Born cross sections (σ_{Born}) and dressed cross sections (σ_{dress}) at the individual energy points are calculated using

$$\begin{aligned} \sigma_{\text{Born}} &= \sigma_{\text{dress}} |1 - \Pi|^2 \\ &= \frac{N^{\text{obs}}}{\mathcal{L}(1 + \delta) \frac{1}{|1 - \Pi|^2} \mathcal{B}(D^0 \rightarrow K^- \pi^+) \epsilon}, \end{aligned} \quad (1)$$

where N^{obs} is the signal yield, \mathcal{L} is the integrated luminosity [21], $1 + \delta$ is the ISR correction factor [22], $[1/(|1 - \Pi|^2)]$ is

the correction factor for vacuum polarization [23], $\mathcal{B}(D^0 \rightarrow K^- \pi^+) = (3.93 \pm 0.04)\%$ [12], and ϵ is the detection efficiency. Values of all above variables are given in Supplemental Material [14]. Efficiencies at $\sqrt{s} = 4.2263, 4.2580, 4.3583, 4.4156, \text{ and } 4.5995$ GeV are calculated with MC simulated data samples [24] that are generated by the data-driven BODY3 generator based on EVTGEN [18], taking into account the influence of possible intermediate states [$Z_c(3885)^-$ in the $D^0 D^{*-}$ system [20,25] and highly excited D states in the $\pi^+ D^0$ or $\pi^+ D^{*-}$ systems]. Since the BODY3 generator requires a large selected sample obtained from events in the signal region after subtracting the background contribution (estimated with the events in the sideband region for BKG2 and MC simulation from BKG1), it is used only for the five energy points with high luminosity. Efficiencies at the other energy points are estimated with PHSP MC samples, with appropriate uncertainties included later. The obtained Born cross sections, which are consistent with and more precise than those of Belle [13], are summarized in Supplemental Material [14].

The systematic uncertainties in the cross-section measurements are listed in Table I. The uncertainty in luminosity is 1.0% at each energy point [26]. The uncertainty in $\mathcal{B}(D^0 \rightarrow K^- \pi^+)$ is 1.0% [12]. The uncertainty in the ISR correction factor is 3.0% [22]. The uncertainties associated with the detection efficiencies include the tracking and particle identification (PID) efficiencies (1.0% per track), D^0 and D^{*-} mass window requirements, and signal MC model. The uncertainties associated with the D^0 and D^{*-} mass windows are estimated by repeating the analysis with an altered mass window requirement; the relative changes in the cross sections are taken as systematic uncertainties. The uncertainties associated with the BODY3 signal MC model consist of three parts: the choice

TABLE I. Breakdown of the systematic uncertainties (%) in the measurements of the Born cross section, separately for the five energy points with high-luminosity data and the other points. Part of the systematic uncertainties is, in fact, due to the finite statistics of the data.

\sqrt{s} (GeV)	4.2263	4.2580	4.3583	4.4156	4.5995	Other
Luminosity	1.0	1.0	1.0	1.0	1.0	1.0
$\mathcal{B}(D^0 \rightarrow K^- \pi^+)$	1.0	1.0	1.0	1.0	1.0	1.0
$(1 + \delta)\epsilon$	3.0	3.0	3.0	3.0	3.0	3.0
Tracking	3.0	3.0	3.0	3.0	3.0	3.0
PID	3.0	3.0	3.0	3.0	3.0	3.0
D^0 mass window	0.3	0.1	0.4	0.2	0.7	0.7
D^{*-} mass window	0.2	0.1	0.2	0.3	0.3	0.3
Signal MC model	2.5	2.1	2.9	2.3	2.2	5.3
Signal shape	0.1	1.5	0.8	1.5	2.1	2.1
Background shape	0.4	0.2	0.2	0.1	0.1	0.4
Fit range	0.1	0.2	0.1	0.1	0.1	0.2
Sum in quadrature	6.0	6.0	6.2	6.1	6.2	8.0

of binning and the BKG1 and BKG2 subtractions. The uncertainty associated with the choice of binning is estimated by repeating the simulation with an altered bin size. The uncertainty associated with the BKG1 subtraction is studied by replacing the PHSP MC sample with MC samples of processes including the intermediate states $e^+ e^- \rightarrow \bar{D}_2^*(2460)^0 D^{*0}, \bar{D}_2^*(2460)^0 \rightarrow \pi^+ D^-$ and $e^+ e^- \rightarrow D_1(2460)^+ D^-, D_1(2460)^+ \rightarrow \pi^+ D^{*0}$. For the BKG2 uncertainty, we replace the sideband events with the inclusive MC sample when subtracting the background. The maximum relative changes on the detection efficiency are taken as the corresponding uncertainties. The total signal MC model uncertainty is the sum in quadrature of these three contributions. To estimate the uncertainties of the signal MC model for the low-luminosity data, we estimate the detection efficiencies for the five energy points of large luminosity with the PHSP MC samples; the resultant largest difference with respect to the nominal efficiencies, 5.3%, is assigned as the corresponding uncertainty for the low-luminosity energy points. The uncertainties associated with the signal shape, background shape, and fit range in the signal yield extraction are determined by changing the signal shape to the pure MC shape, by changing the background function from a linear polynomial function to a second-order one and by changing the fit range, respectively. Because of limited statistics, fit results at the energy points with low luminosity suffer large statistical fluctuations in such refits; thus, the largest systematic uncertainties from the five large-luminosity data samples are adopted. Assuming no significant correlations between sources, the total systematic uncertainty is obtained as the sum in quadrature.

The dressed cross section, which includes vacuum polarization effects, is shown in Fig. 2. Two enhancements around 4.23 and 4.40 GeV, denoted hereafter as R_1 and R_2 , respectively, are clearly visible. A maximum likelihood fit to the dressed cross section is performed to determine the

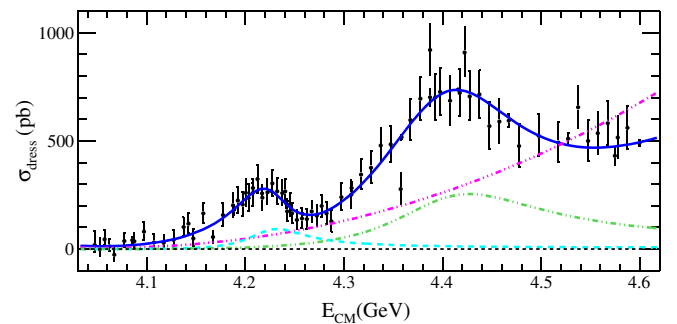


FIG. 2. Fit to the dressed cross section of $e^+ e^- \rightarrow \pi^+ D^0 D^{*-}$, where the black dots with error bars are the measured cross sections and the blue line shows the fit result. The error bars are statistical only. The pink dashed triple-dot line describes the phase-space contribution, the green dashed double-dot line describes the R_2 contribution, and the light blue dashed line describes the R_1 contribution.

parameters of these two enhancements. Since the measured cross sections have asymmetric uncertainties for the data with low statistics, the likelihood is described by an asymmetric Gaussian function as discussed in Ref. [10]. In the fit, the total amplitude is described by the coherent sum of a direct three-body phase-space term for $e^+e^- \rightarrow \pi^+D^0D^{*-}$ and two relativistic Breit-Wigner (BW) functions, representing the resonant structures R_1 and R_2 :

$$\sigma_{\text{dress}}(m) = \left| c\sqrt{P(m)} + e^{i\phi_1} B_1(m)\sqrt{P(m)/P(M_1)} + e^{i\phi_2} B_2(m)\sqrt{P(m)/P(M_2)} \right|^2, \quad (2)$$

where the three-body phase-space factor $P(m)$ [12] is modeled as a fixed fourth-order polynomial function. The factor $B_j(m) = [(\sqrt{12\pi\Gamma_j^{\text{el}}\Gamma_j})/(m^2 - M_j^2 + iM_j\Gamma_j)]$ with $j = 1$ or 2 is the BW function for a vector state, where $\Gamma_j^{\text{el}} = \Gamma_{e^+e^-} \mathcal{B}(\pi^+D^0D^{*-})_j$ is the product of the electronic partial width and the branching fraction to $\pi^+D^0D^{*-}$. Parameters c , M_j , Γ_j , Γ_j^{el} , and ϕ_j are the free parameters in the nominal fit. The beam energy spread (1.6 MeV) is considered by convolving with a Gaussian function whose width is 1.6 MeV. Only statistical uncertainties on the dressed cross sections are considered in the fit. There are four solutions with the same fit quality [27] and identical resonance parameters for R_1 and R_2 , but different c , Γ_j^{el} and ϕ_j , as listed in Table II. We also fit the dressed cross section with the coherent sum of one resonance and a phase-space term; the change of the likelihood value, $\Delta(-2\ln L)$, with respect to that of nominal fit including two resonances is 124.3. Taking into account the change in the number of degrees of freedom (4), the statistical significance of the two-resonance model over the one-resonance model is estimated to be 10.5σ .

Belle has observed the $\psi(4415)$ in $\psi(4415) \rightarrow D\bar{D}_2^*(2460)$ [28] which can also decay to the final state considered in this analysis. Considering the observations of other charmonium(like) states, models fixing the mass and width of R_2 to those of $Y(4260)$, $Y(4320)$, $Y(4360)$, or

$\psi(4415)$ are also investigated and ruled out with a confidence level equivalent to more than 5.0σ . Models including one additional known resonance, either $Y(4260)$, $Y(4320)$, $Y(4360)$, or $\psi(4415)$, in which the masses and widths of these resonances are fixed to the world-average values [12], can improve the fit quality. However, the statistical significances of the additional resonances are only 0.4σ , 0.4σ , 1.4σ , and 1.0σ , respectively. The statistical significance of an additional unknown resonance is only 0.8σ , accounting for the two extra free parameters of mass and width. The high-mass enhancement has a more complicated underlying structure, the understanding of which requires a detailed amplitude analysis that is beyond the scope of this Letter.

All above models yield a stable set of parameters for R_1 but wildly varying parameters for R_2 , so we only estimate the systematic uncertainties of parameters of R_1 , which are mainly from the uncertainties of the absolute center-of-mass energy measurements, the cross-section measurements, and the parametrization of the three-body phase-space factor. The uncertainty of the energy measurement (0.8 MeV) is propagated to the masses of the resonances. The uncertainty associated with the cross-section measurements consists of two parts. The first is from the common uncertainties of the measured cross sections [tracking, PID, luminosity, and $\mathcal{B}(D^0 \rightarrow K^-\pi^+)$] for all energy points (4.5%); we shift up or down all measured cross sections by 4.5% simultaneously and repeat the fit on the measured cross sections. The differences, $0.1 \text{ MeV}/c^2$ for the mass and 0.1 MeV for the width, are taken as systematic uncertainties for the R_1 resonance. The second part includes all the other uncertainties of the measured cross sections. We add these uncertainties into the statistical ones in quadrature and repeat the fit. The resulting differences in resonance parameters, $4.9 \text{ MeV}/c^2$ for the mass and 2.7 MeV for the width of R_1 , are taken as systematic uncertainties. The uncertainty associated with the three-body phase-space factor is determined by changing the parametrization function from a fourth-order polynomial function to a third-order one. The resulting differences, $3.8 \text{ MeV}/c^2$ for the mass and 5.7 MeV for the width, are

TABLE II. The fitted parameters of the cross sections of $e^+e^- \rightarrow \pi^+D^0D^{*-}$. The uncertainties are statistical only.

Parameter	Solution I	Solution II	Solution III	Solution IV
c ($\text{MeV}^{-3/2}$)		$(6.2 \pm 0.5) \times 10^{-4}$		
M_1 (MeV/c^2)		4228.6 ± 4.1		
Γ_1 (MeV)		77.0 ± 6.8		
M_2 (MeV/c^2)		4404.7 ± 7.4		
Γ_2 (MeV)		191.9 ± 13.0		
Γ_1^{el} (eV)	77.4 ± 10.1	8.6 ± 1.6	99.5 ± 14.6	11.1 ± 2.3
Γ_2^{el} (eV)	100.4 ± 13.3	64.2 ± 8.0	664.2 ± 80.0	423.0 ± 47.0
ϕ_1 (rad)	-2.0 ± 0.1	3.0 ± 0.2	-0.9 ± 0.1	-2.2 ± 0.1
ϕ_2 (rad)	2.1 ± 0.2	2.5 ± 0.2	-2.3 ± 0.1	-1.9 ± 0.1

taken as the corresponding uncertainties for R_1 . Assuming the individual systematic uncertainties are uncorrelated, the total systematic uncertainty is obtained by summing the individual values in quadrature, yielding $6.3 \text{ MeV}/c^2$ for the mass and 6.3 MeV for the width of R_1 .

In summary, the Born cross section for the process $e^+e^- \rightarrow \pi^+D^0D^{*-}$ is precisely measured using the data samples collected at 84 energy points from 4.05 to 4.60 GeV with the BESIII detector. Two enhancements are observed in the dressed cross sections around 4.23 and 4.40 GeV. Using many models to describe the dressed cross section, we obtain a stable resonant structure around 4.23 GeV, the parameters of which are measured to be $M(R_1) = (4228.6 \pm 4.1 \pm 6.3) \text{ MeV}/c^2$ and $\Gamma(R_1) = (77.0 \pm 6.8 \pm 6.3) \text{ MeV}$, where the first uncertainties are statistical and the second ones systematic. The resonance parameters for the enhancement around 4.40 GeV are strongly dependent on the model assumptions, necessitating further studies.

The statistical significance of the two-resonance model over a one-resonance model is estimated to be 10.5σ . This is the first experimental evidence for open-charm production associated with the Y states. The mass of R_1 is consistent with the mass of the resonance observed in the hidden-charm processes by the BESIII experiment as well as the theoretical prediction of the $D\bar{D}_1(2420)$ molecule interpretation [6]. The width of R_1 is consistent with that of $e^+e^- \rightarrow \pi^+\pi^-h_c$ [10] and $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ [11], but it is about 39 and 33 MeV/c^2 higher than that seen in $e^+e^- \rightarrow \omega\chi_{c0}$ [9] and $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ [8], respectively. The minimum and maximum of the branching ratio, $\{\mathcal{B}[Y(4220) \rightarrow \pi D\bar{D}^*]/\mathcal{B}[Y(4220) \rightarrow \pi\pi J/\psi]\}$ ($\{\mathcal{B}[Y(4220) \rightarrow \pi D\bar{D}^*]/\mathcal{B}[Y(4220) \rightarrow \pi\pi h_c]\}$), are calculated to be 1.3 ± 0.3 and 124.3 ± 36.1 ($3.7^{+2.5}_{-1.5}$ and $43.3^{+29.0}_{-16.4}$) by assuming isospin symmetry, respectively. The measured Born cross section of $e^+e^- \rightarrow \pi^+D^0D^{*-}$ at the $Y(4220)$ peak is higher than the sum of the known hidden-charm channels. Since no other open-charm production associated with this Y state has yet been reported, the $\pi^+D^0D^{*-}$ final state may be the dominant decay mode of the $Y(4220)$ state, as predicted by the $D\bar{D}_1(2420)$ molecule interpretation [6]. No significant contributions from a third resonance are observed using three-resonance models with additional $Y(4260)$, $Y(4320)$, $Y(4360)$, $\psi(4415)$, or a new resonance, while $Y(4320)$ and $\psi(4415)$ are observed in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ [8] and $\psi(4415) \rightarrow D\bar{D}_2^*(2460)$ [28], respectively. The amplitude studies of this final state and more studies on other open-charm production modes will shed additional light on the nature of these charmonium(like) states.

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 No. 11521505, No. 11075174, No. 11121092, No. 11235011, No. 11335008, No. 11405046, No. 11425524, No. 11475185, No. 11575077, No. 11605042, No. 11625523, and No. 11635010; Chinese Academy of Science Focused Science Grant; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts No. U1332201, No. U1532257, No. U1504112, No. U1532258, and No. U1632109; CAS under Contracts No. KJCX2-YW-N29 and No. KJCX2-YW-N45; CAS Key Research Program of Frontier Sciences under Contracts No. QYZDJ-SSW-SLH003 and No. QYZDJ-SSW-SLH040; 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 Collaborative Research Center CRC 1044, FOR 2359; Istituto Nazionale di Fisica Nucleare, Italy; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) under Contract No. 530-4CDP03; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Science and Technology fund; The Swedish Research Council; U.S. Department of Energy under Contracts No. DE-FG02-05ER41374, No. DE-SC-0010118, No. DE-SC-0010504, and No. DE-SC-0012069; 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; and China Postdoctoral Science Foundation.

*Corresponding author.
wangbin@ihep.ac.cn

^aAlso at Bogazici University, 34342 Istanbul, Turkey.

^bAlso at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.

^cAlso at the Functional Electronics Laboratory, Tomsk State University, Tomsk 634050, Russia.

^dAlso at the Novosibirsk State University, Novosibirsk 630090, Russia.

^eAlso at the NRC ‘‘Kurchatov Institute,’’ PNPI, Gatchina 188300, Russia.

^fAlso at Istanbul Arel University, 34295 Istanbul, Turkey.

^gAlso at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.

^hAlso at Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology; Institute of Nuclear and Particle Physics, Shanghai 200240, People’s Republic of China.

ⁱAlso at Government College Women University, Sialkot—51310 Punjab, Pakistan.

^jPresent address: Center for Underground Physics, Institute for Basic Science, Daejeon 34126, Korea.

^kAlso at Harvard University, Department of Physics, Cambridge, Massachusetts 02138, USA.

- [1] H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, *Phys. Rep.* **639**, 1 (2016).
- [2] S. L. Zhu, *Phys. Lett. B* **625**, 212 (2005); F. E. Close and P. R. Page, *Phys. Lett. B* **628**, 215 (2005); E. Kou and O. Pene, *Phys. Lett. B* **631**, 164 (2005).
- [3] L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, *Phys. Rev. D* **72**, 031502(R) (2005).
- [4] X. Liu, X. Q. Zeng, and X. Q. Li, *Phys. Rev. D* **72**, 054023(R) (2005); F. K. Guo, C. Hanhart, Ulf-G. Meißner, Q. Wang, Q. Zhao, and B. S. Zou, *Rev. Mod. Phys.* **90**, 015004 (2018).
- [5] D. Cronin-Hennessy *et al.* (CLEO Collaboration), *Phys. Rev. D* **80**, 072001 (2009).
- [6] M. Cleven, Q. Wang, F.-K. Guo, C. Hanhart, Ulf-G. Meißner, and Q. Zhao, *Phys. Rev. D* **90**, 074039 (2014).
- [7] Q. Wang, C. Hanhart, and Q. Zhao, *Phys. Rev. Lett.* **111**, 132003 (2013); W. Qin, S. R. Xue, and Q. Zhao, *Phys. Rev. D* **94**, 054035 (2016).
- [8] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **118**, 092001 (2017).
- [9] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **114**, 092003 (2015).
- [10] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **118**, 092002 (2017).
- [11] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **96**, 032004 (2017).
- [12] C. Patrignani *et al.* (Particle Data Group), *Chin. Phys. C* **40**, 100001 (2016).
- [13] G. Pakhlova *et al.* (Belle Collaboration), *Phys. Rev. D* **80**, 091101(R) (2009).
- [14] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.122.102002> for a summary of the number of signal events, integrated luminosity, and Born cross section at each energy point.
- [15] M. Ablikim *et al.* (BESIII Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **614**, 345 (2010).
- [16] S. Agostinelli *et al.* (GEANT4 Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [17] S. Jadach, B. F. L. Ward, and Z. Was, *Comput. Phys. Commun.* **130**, 260 (2000); *Phys. Rev. D* **63**, 113009 (2001).
- [18] R. G. Ping, *Chin. Phys. C* **32**, 599 (2008); D. J. Lange, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [19] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, *Phys. Rev. D* **62**, 034003 (2000).
- [20] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **92**, 092006 (2015).
- [21] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **40**, 063001 (2016).
- [22] E. A. Kuraev and V. S. Fadin, *Yad. Fiz.* **41**, 733 (1985) [*Sov. J. Nucl. Phys.* **41**, 466 (1985)]. Since the efficiency and the ISR correction depend on the line shape of cross sections, the measured cross sections are used as input, and we iterate the procedure until the value of $(1 + \delta)e$ becomes stable. The largest variation in $(1 + \delta)e$ during the last two iterations, 3.0%, is taken as the systematic uncertainty.
- [23] S. Actis *et al.*, *Eur. Phys. J. C* **66**, 585 (2010).
- [24] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **89**, 112006 (2014).
- [25] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **112**, 022001 (2014).
- [26] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **39**, 093001 (2015).
- [27] K. Zhu, X. H. Mo, C. Z. Yuan, and P. Wang, *Int. J. Mod. Phys. A* **26**, 4511 (2011); A. D. Bukin, [arXiv:0710.5627](https://arxiv.org/abs/0710.5627).
- [28] G. Pakhlova *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **100**, 062001 (2008).