

Measurement of the branching fraction of $J/\psi \rightarrow \omega\eta\pi^+\pi^-$ and search for $J/\psi \rightarrow \omega X(1835)$, $X(1835) \rightarrow \eta\pi^+\pi^-$ decay

M. Ablikim,¹ M. N. Achasov,^{10,§} P. Adlarson,⁵⁶ S. Ahmed,¹⁵ M. Albrecht,⁴ M. Alekseev,^{55a,55c} A. Amoroso,^{55a,55c} F. F. An,¹ Q. An,^{52,42} Y. Bai,⁴¹ O. Bakina,²⁷ R. Baldini Ferroli,^{23a} Y. Ban,³⁵ K. Begzsuren,²⁵ J. V. Bennett,⁵ N. Berger,²⁶ M. Bertani,^{23a} D. Bettoni,^{24a} F. Bianchi,^{55a,55c} J. Biernat,⁵⁶ J. Bloms,⁵⁰ I. Boyko,²⁷ R. A. Briere,⁵ H. Cai,⁵⁷ X. Cai,^{1,42} A. Calcaterra,^{23a} G. F. Cao,^{1,46} N. Cao,^{1,46} S. A. Cetin,^{45b} J. Chai,^{55c} J. F. Chang,^{1,42} W. L. Chang,^{1,46} G. Chelkov,^{27,†,‡} Chen,⁶ G. Chen,¹ H. S. Chen,^{1,46} J. C. Chen,¹ M. L. Chen,^{1,42} S. J. Chen,³³ Y. B. Chen,^{1,42} W. Cheng,^{55c} G. Cibinetto,^{24a} F. Cossio,^{55c} X. F. Cui,³⁴ H. L. Dai,^{1,42} J. P. Dai,^{37,††} X. C. Dai,^{1,46} A. Dbeysi,¹⁵ D. Dedovich,²⁷ Z. Y. Deng,¹ A. Denig,²⁶ I. Denysenko,²⁷ M. Destefanis,^{55a,55c} F. De Mori,^{55a,55c} Y. Ding,³¹ C. Dong,³⁴ J. Dong,^{1,42} L. Y. Dong,^{1,46} M. Y. Dong,^{1,42,46} Z. L. Dou,³³ S. X. Du,⁶⁰ J. Z. Fan,⁴⁴ J. Fang,^{1,42} S. S. Fang,^{1,46} Y. Fang,¹ R. Farinelli,^{24a,24b} L. Fava,^{55b,55c} F. Feldbauer,⁴ G. Felici,^{23a} C. Q. Feng,^{52,42} M. Fritsch,⁴ C. D. Fu,¹ Y. Fu,¹ Q. Gao,¹ X. L. Gao,^{52,42} Y. Gao,⁵³ Y. Gao,⁴⁴ Y. G. Gao,⁶ Z. Gao,^{52,42} B. Garillon,²⁶ I. Garzia,^{24a,24b} A. Gilman,⁴⁹ K. Goetzen,¹¹ L. Gong,³⁴ W. X. Gong,^{1,42} W. Gradl,²⁶ M. Greco,^{55a,55c} L. M. Gu,³³ M. H. Gu,^{1,42} Y. T. Gu,¹³ A. Q. Guo,²² L. B. Guo,³² R. P. Guo,^{1,46} Y. P. Guo,²⁶ A. Guskov,²⁷ S. Han,⁵⁷ X. Q. Hao,¹⁶ F. A. Harris,⁴⁷ K. L. He,^{1,46} F. H. Heinsius,⁴ T. Held,⁴ Y. K. Heng,^{1,42,46} Y. R. Hou,⁴⁶ Z. L. Hou,¹ H. M. Hu,^{1,46} J. F. Hu,^{37,††} T. Hu,^{1,42,46} Y. Hu,¹ G. S. Huang,^{52,42} J. S. Huang,¹⁶ X. T. Huang,³⁶ X. Z. Huang,³³ Z. L. Huang,³¹ N. Huesken,⁵⁰ T. Hussain,⁵⁴ W. Ikegami Andersson,⁵⁶ W. Imoehl,²² M. Irshad,^{52,42} Q. Ji,¹ Q. P. Ji,¹⁶ X. B. Ji,^{1,46} X. L. Ji,^{1,42} H. L. Jiang,³⁶ X. S. Jiang,^{1,42,46} X. Y. Jiang,³⁴ J. B. Jiao,³⁶ Z. Jiao,¹⁸ D. P. Jin,^{1,42,46} S. Jin,³³ Y. Jin,⁴⁸ T. Johansson,⁵⁶ N. Kalantar-Nayestanaki,²⁹ X. S. Kang,³¹ R. Kappert,²⁹ M. Kavatsyuk,²⁹ B. C. Ke,¹ I. K. Keshk,⁴ T. Khan,^{52,42} A. Khoukaz,⁵⁰ P. Kiese,²⁶ R. Kiuchi,¹ R. Kliemt,¹¹ L. Koch,²⁸ O. B. Kolcu,^{45b,¶} B. Kopf,⁴ M. Kuemmel,⁴ M. Kuessner,⁴ A. Kupsc,⁵⁶ M. Kurth,¹ M. G. Kurth,^{1,46} W. Kühn,²⁸ J. S. Lange,²⁸ P. Larin,¹⁵ L. Lavezzi,^{55c} H. Leithoff,²⁶ T. Lenz,²⁶ C. Li,⁵⁶ Cheng Li,^{52,42} D. M. Li,⁶⁰ F. Li,^{1,42} F. Y. Li,³⁵ G. Li,¹ H. B. Li,^{1,46} H. J. Li,^{9,§§} J. C. Li,¹ J. W. Li,⁴⁰ Ke Li,¹ L. K. Li,¹ Lei Li,³ P. L. Li,^{52,42} P. R. Li,³⁰ Q. Y. Li,³⁶ W. D. Li,^{1,46} W. G. Li,¹ X. L. Li,³⁶ X. N. Li,^{1,42} X. Q. Li,³⁴ X. H. Li,^{52,42} Z. B. Li,⁴³ H. Liang,^{1,46} H. Liang,^{52,42} Y. F. Liang,³⁹ Y. T. Liang,²⁸ G. R. Liao,¹² L. Z. Liao,^{1,46} J. Libby,²¹ C. X. Lin,⁴³ D. X. Lin,¹⁵ Y. J. Lin,¹³ B. Liu,^{37,††} B. J. Liu,¹ C. X. Liu,¹ D. Liu,^{52,42} D. Y. Liu,^{37,††} F. H. Liu,³⁸ Fang Liu,¹ Feng Liu,⁶ H. B. Liu,¹³ H. M. Liu,^{1,46} Huanhuan Liu,¹ Huihui Liu,¹⁷ J. B. Liu,^{52,42} J. Y. Liu,^{1,46} K. Y. Liu,³¹ Ke Liu,⁶ Q. Liu,⁴⁶ S. B. Liu,^{52,42} T. Liu,^{1,46} X. Liu,³⁰ X. Y. Liu,^{1,46} Y. B. Liu,³⁴ Z. A. Liu,^{1,42,46} Zhiqing Liu,²⁶ Y. F. Long,³⁵ X. C. Lou,^{1,42,46} H. J. Lu,¹⁸ J. D. Lu,^{1,46} J. G. Lu,^{1,42} Y. Lu,¹ Y. P. Lu,^{1,42} C. L. Luo,³² M. X. Luo,⁵⁹ P. W. Luo,⁴³ T. Luo,^{9,§§} X. L. Luo,^{1,42} S. Lusso,^{55c} X. R. Lyu,⁴⁶ F. C. Ma,³¹ H. L. Ma,¹ L. L. Ma,³⁶ M. M. Ma,^{1,46} Q. M. Ma,¹ X. N. Ma,³⁴ X. X. Ma,^{1,46} X. Y. Ma,^{1,42} Y. M. Ma,³⁶ F. E. Maas,¹⁵ M. Maggiora,^{55a,55c} S. Maldaner,²⁶ Q. A. Malik,⁵⁴ A. Mangoni,^{23b} Y. J. Mao,³⁵ Z. P. Mao,¹ S. Marcelllo,^{55a,55c} Z. X. Meng,⁴⁸ J. G. Messchendorp,²⁹ G. Mezzadri,^{24a} J. Min,^{1,42} T. J. Min,³³ R. E. Mitchell,²² X. H. Mo,^{1,42,46} Y. J. Mo,⁶ C. Morales Morales,¹⁵ N. Yu. Muchnoi,^{10,§} H. Muramatsu,⁴⁹ A. Mustafa,⁴ S. Nakhoul,^{11,**} Y. Nefedov,²⁷ F. Nerling,^{11,**} I. B. Nikolaev,^{10,§} Z. Ning,^{1,42} S. Nisar,^{8,|||} S. L. Niu,^{1,42} S. L. Olsen,⁴⁶ Q. Ouyang,^{1,42,46} S. Pacetti,^{23b} Y. Pan,^{52,42} M. Papenbrock,⁵⁶ P. Patteri,^{23a} M. Pelizaeus,⁴ H. P. Peng,^{52,42} K. Peters,^{11,**} J. Pettersson,⁵⁶ J. L. Ping,³² R. G. Ping,^{1,46} A. Pitka,⁴ R. Poling,⁴⁹ V. Prasad,^{52,42} M. Qi,³³ T. Y. Qi,² S. Qian,^{1,42} C. F. Qiao,⁴⁶ N. Qin,⁵⁷ X. P. Qin,¹³ X. S. Qin,⁴ Z. H. Qin,^{1,42} J. F. Qiu,¹ S. Q. Qu,³⁴ K. H. Rashid,^{54,‡‡} C. F. Redmer,²⁶ M. Richter,⁴ M. Ripka,²⁶ A. Rivetti,^{55c} V. Rodin,²⁹ M. Rolo,^{55c} G. Rong,^{1,46} Ch. Rosner,¹⁵ M. Rump,⁵⁰ A. Sarantsev,^{27,||} M. Savrié,^{24b} K. Schoenning,⁵⁶ W. Shan,¹⁹ X. Y. Shan,^{52,42} M. Shao,^{52,42} C. P. Shen,² P. X. Shen,³⁴ X. Y. Shen,^{1,46} H. Y. Sheng,¹ X. Shi,^{1,42} X. D. Shi,^{52,42} J. J. Song,³⁶ Q. Q. Song,^{52,42} X. Y. Song,¹ S. Sosio,^{55a,55c} C. Sowa,⁴ S. Spataro,^{55a,55c} F. F. Sui,³⁶ G. X. Sun,¹ J. F. Sun,¹⁶ L. Sun,⁵⁷ S. S. Sun,^{1,46} X. H. Sun,¹ Y. J. Sun,^{52,42} Y. K. Sun,^{52,42} Y. Z. Sun,¹ Z. J. Sun,^{1,42} Z. T. Sun,¹ Y. T. Tan,^{52,42} C. J. Tang,³⁹ G. Y. Tang,¹ X. Tang,¹ V. Thoren,⁵⁶ B. Tsednee,²⁵ I. Uman,^{45d} B. Wang,¹ B. L. Wang,⁴⁶ C. W. Wang,³³ D. Y. Wang,³⁵ H. H. Wang,³⁶ K. Wang,^{1,42} L. L. Wang,¹ L. S. Wang,¹ M. Wang,³⁶ M. Z. Wang,³⁵ Meng Wang,^{1,46} P. L. Wang,¹ R. M. Wang,⁵⁸ W. P. Wang,^{52,42} X. Wang,³⁵ X. F. Wang,¹ X. L. Wang,^{9,¶} Y. Wang,^{52,42} Y. F. Wang,^{1,42,46} Z. Wang,^{1,42} Z. G. Wang,^{1,42} Z. Y. Wang,¹ Zongyuan Wang,^{1,46} T. Weber,⁴ D. H. Wei,¹² P. Weidenkaff,²⁶ H. W. Wen,³² S. P. Wen,¹ U. Wiedner,⁴ M. Wolke,⁵⁶ L. H. Wu,¹ L. J. Wu,^{1,46} Z. Wu,^{1,42} L. Xia,^{52,42} Y. Xia,²⁰ S. Y. Xiao,¹ Y. J. Xiao,^{1,46} Z. J. Xiao,³² Y. G. Xie,^{1,42} Y. H. Xie,⁶ T. Y. Xing,^{1,46} X. A. Xiong,^{1,46} Q. L. Xiu,^{1,42} G. F. Xu,¹ J. J. Xu,³³ L. Xu,¹ Q. J. Xu,¹⁴ W. Xu,^{1,46} X. P. Xu,⁴⁰ F. Yan,⁵³ L. Yan,^{55a,55c} W. B. Yan,^{52,42} W. C. Yan,² Y. H. Yan,²⁰ H. J. Yang,^{37,††} H. X. Yang,¹ L. Yang,⁵⁷ R. X. Yang,^{52,42} S. L. Yang,^{1,46} Y. H. Yang,³³ Y. X. Yang,¹² Yifan Yang,^{1,46} Z. Q. Yang,²⁰ M. Ye,^{1,42} M. H. Ye,⁷ J. H. Yin,¹ Z. Y. You,⁴³ B. X. Yu,^{1,42,46} C. X. Yu,³⁴ J. S. Yu,²⁰ C. Z. Yuan,^{1,46} X. Q. Yuan,³⁵ Y. Yuan,¹ A. Yuncu,^{45b,*} A. A. Zafar,⁵⁴ Y. Zeng,²⁰ B. X. Zhang,¹ B. Y. Zhang,^{1,42} C. C. Zhang,¹ D. H. Zhang,¹ H. H. Zhang,⁴³ H. Y. Zhang,^{1,42} J. Zhang,^{1,46} J. L. Zhang,⁵⁸ J. Q. Zhang,⁴ J. W. Zhang,^{1,42,46} J. Y. Zhang,¹ J. Z. Zhang,^{1,46} K. Zhang,^{1,46} L. Zhang,⁴⁴ S. F. Zhang,³³ T. J. Zhang,^{37,††} X. Y. Zhang,³⁶ Y. Zhang,^{52,42} Y. H. Zhang,^{1,42} Y. T. Zhang,^{52,42} Yang Zhang,¹ Yao Zhang,¹ Yi Zhang,^{9,§§} Yu Zhang,⁴⁶ Z. H. Zhang,⁶ Z. P. Zhang,⁵² Z. Y. Zhang,⁵⁷ G. Zhao,¹ J. W. Zhao,^{1,42} J. Y. Zhao,^{1,46}

J. Z. Zhao,^{1,42} Lei Zhao,^{52,42} Ling Zhao,¹ M. G. Zhao,³⁴ Q. Zhao,¹ S. J. Zhao,⁶⁰ T. C. Zhao,¹ Y. B. Zhao,^{1,42} Z. G. Zhao,^{52,42}
 A. Zhemchugov,^{27,†} B. Zheng,⁵³ J. P. Zheng,^{1,42} Y. Zheng,³⁵ Y. H. Zheng,⁴⁶ B. Zhong,³² L. Zhou,^{1,42} L. P. Zhou,^{1,46}
 Q. Zhou,^{1,46} X. Zhou,⁵⁷ X. K. Zhou,⁴⁶ X. R. Zhou,^{52,42} Xiaoyu Zhou,²⁰ Xu Zhou,²⁰ A. N. Zhu,^{1,46}
 J. Zhu,³⁴ J. Zhu,⁴³ K. Zhu,¹ K. J. Zhu,^{1,42,46} S. H. Zhu,⁵¹ W. J. Zhu,³⁴ X. L. Zhu,⁴⁴ Y. C. Zhu,^{52,42} Y. S. Zhu,^{1,46}
 Z. A. Zhu,^{1,46} J. Zhuang,^{1,42} 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*Fudan University, Shanghai 200443, People's Republic of China*
¹⁰*G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia*
¹¹*GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany*
¹²*Guangxi Normal University, Guilin 541004, People's Republic of China*
¹³*Guangxi University, Nanning 530004, People's Republic of China*
¹⁴*Hangzhou Normal University, Hangzhou 310036, People's Republic of China*
¹⁵*Helmholtz Institute Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*
¹⁶*Henan Normal University, Xinxiang 453007, People's Republic of China*
¹⁷*Henan University of Science and Technology, Luoyang 471003, People's Republic of China*
¹⁸*Huangshan College, Huangshan 245000, People's Republic of China*
¹⁹*Hunan Normal University, Changsha 410081, People's Republic of China*
²⁰*Hunan University, Changsha 410082, People's Republic of China*
²¹*Indian Institute of Technology Madras, Chennai 600036, India*
²²*Indiana University, Bloomington, Indiana 47405, USA*
^{23a}*INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy*
^{23b}*INFN and University of Perugia, I-06100, Perugia, Italy*
^{24a}*INFN Sezione di Ferrara, I-44122, Ferrara, Italy*
^{24b}*University of Ferrara, I-44122, Ferrara, Italy*
²⁵*Institute of Physics and Technology, Peace Ave. 54B, Ulaanbaatar 13330, Mongolia*
²⁶*Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*
²⁷*Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia*
²⁸*Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany*
²⁹*KVI-CART, University of Groningen, NL-9747 AA Groningen, The Netherlands*
³⁰*Lanzhou University, Lanzhou 730000, People's Republic of China*
³¹*Liaoning University, Shenyang 110036, People's Republic of China*
³²*Nanjing Normal University, Nanjing 210023, People's Republic of China*
³³*Nanjing University, Nanjing 210093, People's Republic of China*
³⁴*Nankai University, Tianjin 300071, People's Republic of China*
³⁵*Peking University, Beijing 100871, People's Republic of China*
³⁶*Shandong University, Jinan 250100, People's Republic of China*
³⁷*Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*
³⁸*Shanxi University, Taiyuan 030006, People's Republic of China*
³⁹*Sichuan University, Chengdu 610064, People's Republic of China*
⁴⁰*Soochow University, Suzhou 215006, People's Republic of China*
⁴¹*Southeast University, Nanjing 211100, People's Republic of China*
⁴²*State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China*
⁴³*Sun Yat-Sen University, Guangzhou 510275, People's Republic of China*
⁴⁴*Tsinghua University, Beijing 100084, People's Republic of Cxuhina*
^{45a}*Ankara University, 06100 Tandogan, Ankara, Turkey*
^{45b}*Istanbul Bilgi University, 34060 Eyup, Istanbul, Turkey*

^{45c}Uludag University, 16059 Bursa, Turkey^{45d}Near East University, Nicosia, North Cyprus, Mersin 10, Turkey⁴⁶University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China⁴⁷University of Hawaii, Honolulu, Hawaii 96822, USA⁴⁸University of Jinan, Jinan 250022, People's Republic of China⁴⁹University of Minnesota, Minneapolis, Minnesota 55455, USA⁵⁰University of Muenster, Wilhelm-Klemm-Str. 9, 48149 Muenster, Germany⁵¹University of Science and Technology Liaoning, Anshan 114051, People's Republic of China⁵²University of Science and Technology of China, Hefei 230026, People's Republic of China⁵³University of South China, Hengyang 421001, People's Republic of China⁵⁴University of the Punjab, Lahore-54590, Pakistan^{55a}University of Turin, I-10125, Turin, Italy^{55b}University of Eastern Piedmont, I-15121, Alessandria, Italy^{55c}INFN, I-10125, Turin, Italy⁵⁶Uppsala University, Box 516, SE-75120 Uppsala, Sweden⁵⁷Wuhan University, Wuhan 430072, People's Republic of China⁵⁸Xinyang Normal University, Xinyang 464000, People's Republic of China⁵⁹Zhejiang University, Hangzhou 310027, People's Republic of China⁶⁰Zhengzhou University, Zhengzhou 450001, People's Republic of China

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Using a sample of 1.31×10^9 J/ψ events collected by the BESIII detector at BEPCII during 2009 and 2012, we study the $J/\psi \rightarrow \omega\eta'\pi^+\pi^-$ hadronic process. For the first time, we measure the branching ratio $\mathcal{B}(J/\psi \rightarrow \omega\eta'\pi^+\pi^-) = (1.12 \pm 0.02 \pm 0.13) \times 10^{-3}$. We search for the $X(1835)$ state in the $\eta'\pi^+\pi^-$ invariant mass spectra. No evidence is found and we estimate the upper limit on the branching fraction at 90% confidence level to be $\mathcal{B}(J/\psi \rightarrow \omega X(1835), X(1835) \rightarrow \eta'\pi^+\pi^-) < 6.2 \times 10^{-5}$.

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* Also at the Novosibirsk State University, Novosibirsk, 630090, Russia.

† Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.

‡ Also at the Functional Electronics Laboratory, Tomsk State University, Tomsk, 634050, Russia.

§ Also 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.

|| Also at Istanbul Arel University, 34295 Istanbul, Turkey.

¶ Also at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, People's Republic of China.

** Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.

†† Also at Harvard University, Department of Physics, Cambridge, Massachusetts, 02138, USA.

‡‡ Also at Government College Women University, Sialkot-51310, Punjab, Pakistan.

§§ Also at the NRC "Kurchatov Institute", PNPI, 188300, Gatchina, Russia.

||| Also at Bogazici University, 34342 Istanbul, Turkey.

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One of the main topics of the BESIII physics program is the search for unconventional hadronic states. Among the light hadrons, the $X(1835)$ state has caught the attention both from an experimental and a theoretical point of view. It was observed first in the $\eta'\pi^+\pi^-$ invariant mass spectra at BES in the $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$ radiative decay [1], and confirmed later with much higher statistics by BESIII [2]. Its mass and width were measured to be $M = 1836.5 \pm 3.0^{+5.6}_{-2.1}$ MeV/ c^2 and $\Gamma = 190 \pm 9^{+38}_{-36}$ MeV, with the product of branching fractions $\mathcal{B}(J/\psi \rightarrow \gamma X(1835)) \cdot \mathcal{B}(X(1835) \rightarrow \eta'\pi^+\pi^-) = (2.87 \pm 0.09^{+0.49}_{-0.52}) \times 10^{-4}$ [2]. The $X(1835)$ state was also seen in the process $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$ [3]; its mass and width were found to be in agreement with those measured in Ref. [2], and the quantum numbers J^{PC} were determined to be 0^{-+} from a partial wave analysis.

Just a few years before the observation of the $X(1835)$ state, an anomalous enhancement close to the $p\bar{p}$ mass threshold, called $X(1860)$, has been observed by BES in the $J/\psi \rightarrow \gamma p\bar{p}$ decay [4], and confirmed by BESIII [5] and CLEO [6], while no evidence has been seen in other channels, such as $J/\psi \rightarrow \omega p\bar{p}$ [7,8] or $J/\psi \rightarrow \phi p\bar{p}$ [9]. A partial wave analysis of the $p\bar{p}$ mass-threshold enhancement was performed [10], and the J^{PC} quantum number were determined to be the same as for the $X(1835)$. The discovery of these new states has stimulated many

theoretical speculations on their nature, such as a $p\bar{p}$ bound state [11–14], a pseudoscalar glueball [15–17], a radial excitation of the η' meson [18], etc. Thanks to the world's largest $e^+e^- \rightarrow J/\psi$ dataset collected by BESIII, it has been possible to study in detail the significant abrupt change in the line shape of the $X(1835) \rightarrow \eta'\pi^+\pi^-$ in correspondence of the $p\bar{p}$ mass threshold [19], which could be originated from the opening of the $p\bar{p}$ additional decay channel (threshold effect) or by the interference between two different resonances. However, none of the hypotheses could be excluded and no final conclusion has been made. In order to extract additional information about the states around $1.85 \text{ GeV}/c^2$ with the present BESIII statistics, additional decay modes must be investigated.

In this paper, we report on the search for $X(1835)$ in the $J/\psi \rightarrow \omega\eta'\pi^+\pi^-$ process. The comparison of the production rates between $J/\psi \rightarrow \omega X(1835)$ and $J/\psi \rightarrow \gamma X(1835)$ could also help to get information on the $q\bar{q}$ or gluon component of $X(1835)$ [13,15], i.e., if $X(1835)$ contains substantial $q\bar{q}$ components, like the η' meson, it should be observed in $J/\psi \rightarrow \omega X(1835)$. Using the branching fraction of $J/\psi \rightarrow \omega(\phi)\eta'$, the branching fraction of $J/\psi \rightarrow \omega(\phi)X(1835)$ is estimated to be in the order of 10^{-5} [15]. On the other hand, a very small branching fraction is expected for larger gluon component. Another estimation was done in Ref. [13], where $\mathcal{B}(J/\psi \rightarrow \omega X(1835))$ is expected to be two orders of magnitude less than that of $J/\psi \rightarrow \gamma X(1835)$ decay.

This analysis is based on 1.31×10^9 J/ψ events collected by BESIII during 2009 and 2012. The BESIII detector [20] is a magnetic spectrometer operating at BEPCII, a double-ring e^+e^- collider with center-of-mass energies ranging from 2.0 to 4.6 GeV. The geometrical acceptance covered is 93% of a 4π solid angle. From the inner to the outer side, it consists of a helium-based main drift chamber (MDC), a time-of-flight system (TOF) and a CsI(Tl) electromagnetic calorimeter (EMC), all enclosed in a superconducting solenoidal magnet providing a magnetic field of 1 T (0.9 T in 2012). The solenoid is surrounded by an octagonal flux-return yoke with resistive plate chambers interleaved with steel.

A GEANT4-based Monte Carlo (MC) simulation package [21] is used to optimize selection criteria, estimate background processes, and determine detection efficiency. The production of the J/ψ resonance is simulated with KKMC event generator [22,23], while the decays are generated with EVTGEN [24,25]. Simulated inclusive J/ψ events of approximately the equivalent luminosity of data are used to study background processes. The known decays of J/ψ are modeled with branching fractions being set to the world average values from Particle Data Group (PDG) [26], while the remaining decays are generated with LUNDCHARM [27]. We simulate 700,000 MC events using phase space model for the processes $J/\psi \rightarrow \omega\eta'\pi^+\pi^-$ and $J/\psi \rightarrow \omega X(1835)$, $X(1835) \rightarrow \eta'\pi^+\pi^-$, which are used to optimize the event

selection and to determine the selection efficiency. For the $J/\psi \rightarrow \omega X(1835)$ signal simulation we also take into account the $J^{PC} = 0^{-+}$ quantum numbers.

For each candidate event, we select charged tracks well reconstructed in the MDC detector with the polar angle θ satisfying the condition $|\cos\theta| < 0.93$. The tracks are required to pass the interaction point within ± 10 cm along the beam direction and within 1 cm in the plane perpendicular to the beams. Photon candidates are reconstructed using clusters of energy deposited in the EMC. The energy deposited in the TOF is also included in EMC measurements in order to improve the reconstruction efficiency and the energy resolution. Good photon candidates are required to have a deposited energy larger than 25 MeV in the barrel region ($|\cos\theta| < 0.8$) and 50 MeV in the end caps ($0.86 < |\cos\theta| < 0.92$). To eliminate those clusters associated with charged tracks, the angle between the direction of any charged track and the photon candidate must be larger than 5° . Clusters due to the electronic noise and energy deposit unrelated to the event are suppressed by requiring the shower time to be within 700 ns of the event start time. Events with six charged tracks, net charge equal to zero, and at least four photon candidates that satisfy the above requirements are retained for further studies.

In the reconstruction of $J/\psi \rightarrow \omega\eta'\pi^+\pi^-$, the ω meson is reconstructed in its dominant $\pi^+\pi^-\pi^0$ decay mode and η' via $\eta' \rightarrow \eta\pi^+\pi^-$, while both η and π^0 are reconstructed from $\gamma\gamma$ pairs after applying the corresponding mass constrained kinematic fit. To improve momentum resolution, for each $\pi^0\eta\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ combination a four constraints (4C) energy-momentum kinematic fit is performed. We select only events with $\chi^2_{4C} < 60$. In order to determine the $\pi^+\pi^-$ pairs produced in ω/η' decays, we select the combination which minimizes the quantity

$\sqrt{(M_{\pi^+\pi^-\pi^0} - m_\omega)^2 + (M_{\eta\pi^+\pi^-} - m_{\eta'})^2}$, where m_ω and $m_{\eta'}$ are the nominal masses of ω and η' [26], respectively, while $M_{\pi^+\pi^-\pi^0}$ ($M_{\eta\pi^+\pi^-}$) is the $\pi^+\pi^-\pi^0$ ($\eta\pi^+\pi^-$) invariant mass. Then, we require $M_{\pi^+\pi^-\pi^0}$ and $M_{\eta\pi^+\pi^-}$ to be within $22 \text{ MeV}/c^2$ and $12 \text{ MeV}/c^2$ of the nominal mass, respectively. Figure 1 shows the $\eta'\pi^+\pi^-$ invariant mass distribution ($M_{\eta'\pi^+\pi^-}$) from data sample for those events that satisfy the selection criteria. No clear enhancement is visible.

In Fig. 1, the $\eta'\pi^+\pi^-$ invariant mass spectrum from inclusive MC sample is also reported. Since there are some discrepancies between the two distributions, more pronounced for $M_{\eta'\pi^+\pi^-} > 1.9 \text{ GeV}/c^2$, we cannot use the inclusive MC sample to model the background contribution. As an alternative, a two-dimensional fit to the $\pi^+\pi^-\pi^0$ and $\eta\pi^+\pi^-$ distributions will be used to get the number of $J/\psi \rightarrow \omega\eta'\pi^+\pi^-$ signal events. The scatter plot of $M_{\eta\pi^+\pi^-}$ as a function of $M_{\pi^+\pi^-\pi^0}$ is reported in Fig. 2. The ω signal is parametrized by a Breit-Wigner (BW) function convolved with a double Gaussian and the η' signal by a double

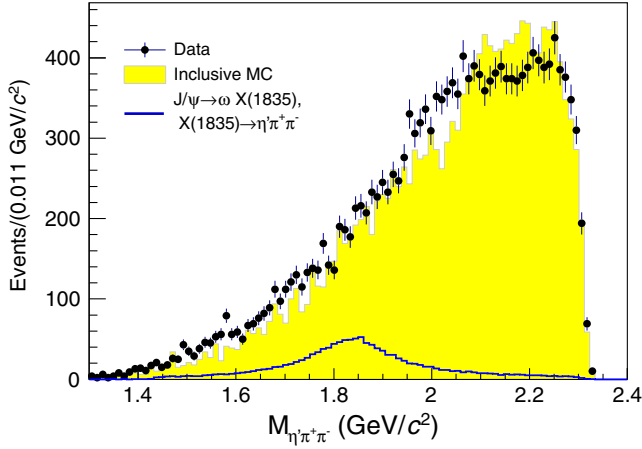


FIG. 1. $\eta' \pi^+ \pi^-$ invariant mass distribution for data (black points), inclusive MC sample (yellow histogram) and $J/\psi \rightarrow \omega X(1835)$, $X(1835) \rightarrow \eta' \pi^+ \pi^-$ signal MC sample with an arbitrary normalization (blue line).

Gaussian function, while third-order polynomial functions are used for both ω and η' backgrounds. All the parameters are treated as free with the exception of the ω width, which is fixed to the world average value [26].

The one-dimensional projections of the fit result are shown in Fig. 3. The branching fraction of the $J/\psi \rightarrow \omega \eta' \pi^+ \pi^-$ process is calculated with

$$\mathcal{B}(J/\psi \rightarrow \omega \eta' \pi^+ \pi^-) = \frac{N_{\text{sig}}}{N_{J/\psi} \cdot \epsilon \cdot \mathcal{B}_{\text{int}}}, \quad (1)$$

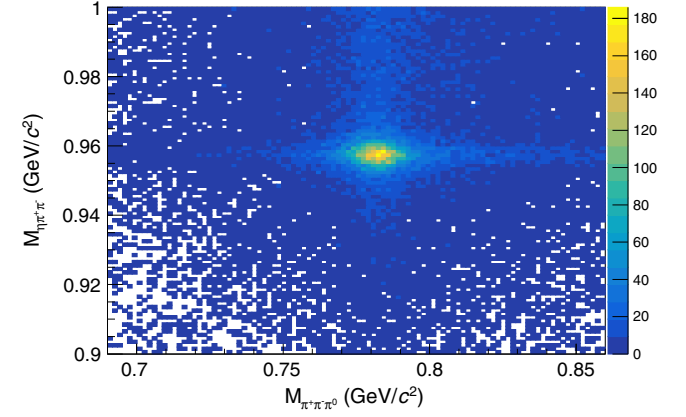
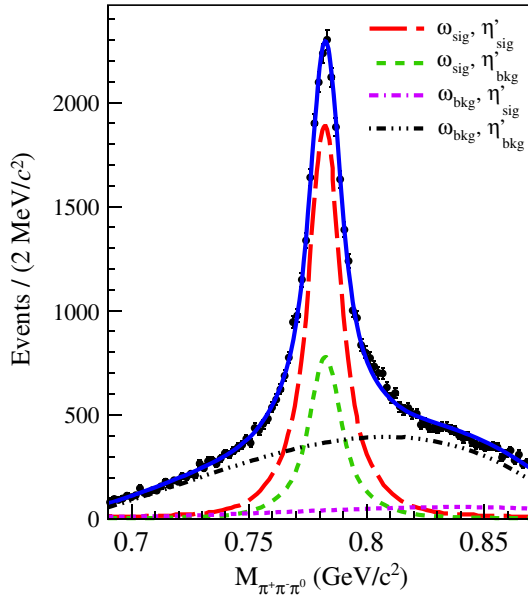


FIG. 2. Scatter plot of $\eta \pi^+ \pi^-$ invariant mass as a function of $\pi^+ \pi^- \pi^0$ invariant mass distribution.

where $N_{\text{sig}} = 14151 \pm 287$ is the number of $J/\psi \rightarrow \omega \eta' \pi^+ \pi^-$ signal events from the fit to the data sample, $N_{J/\psi}$ the number of J/ψ events [28], $\epsilon = 6.48\%$ the detection efficiency calculated from signal simulation, and \mathcal{B}_{int} the product of the decay branching fractions for the $\omega \rightarrow \pi^+ \pi^- \pi^0$, $\pi^0 \rightarrow \gamma \gamma$, $\eta' \rightarrow \eta \pi^+ \pi^-$, and $\eta \rightarrow \gamma \gamma$ intermediate states quoted from PDG [26]. The branching fraction is then determined to be $\mathcal{B}(J/\psi \rightarrow \omega \eta' \pi^+ \pi^-) = (1.12 \pm 0.02) \times 10^{-3}$, where the uncertainty is statistical only.

As can be seen from Fig. 1, no significant $X(1835)$ signal is observed in the $\eta' \pi^+ \pi^-$ invariant mass spectrum, and hence we extract the upper limit (UL) on the number of $X(1835)$ signal events. As stated before, we cannot use

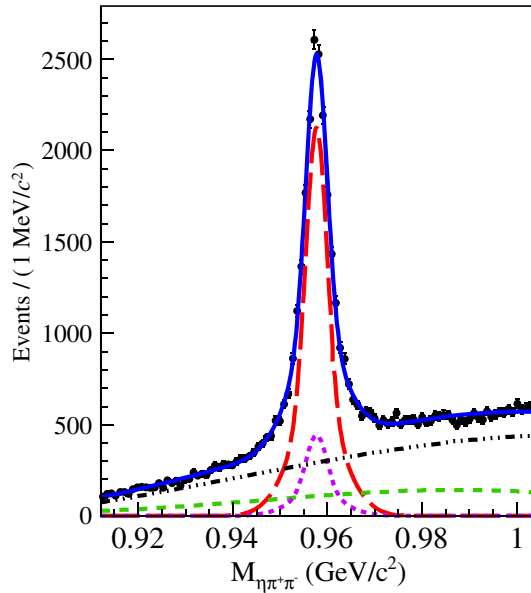


FIG. 3. One-dimensional projections of two dimensional fit results to the $\pi^+ \pi^- \pi^0$ (left) and $\eta \pi^+ \pi^-$ (right) invariant mass distributions. Blue curves refer to the final fit result, while the other fit components are represented by colored dashed curves: red for ω and η' signals, green for ω signal and η' background, magenta for ω background and η' signal, and black for both ω and η' backgrounds.

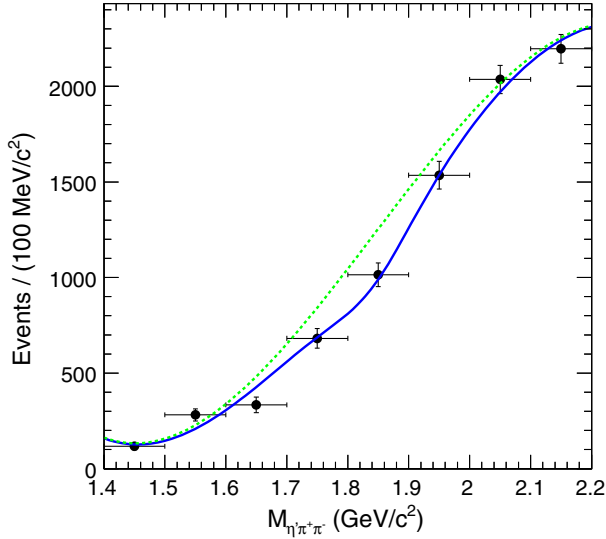


FIG. 4. χ^2 -fit result (blue curve) to the background subtracted $\eta'\pi^+\pi^-$ invariant mass spectrum (black dots) extracted as described in the text. Dashed green curve shows the background contribution which is parametrized by means of a third-order polynomial function, while for the signal component we use an efficiency-weighted BW function.

inclusive FMz sample to parametrize the background shape. Also a polynomial function may not be appropriate to describe a large background component under a very small signal fraction of a broad resonance. As an alternative in order to extract the background-corrected distribution, the two-dimensional fit to the $\pi^+\pi^-\pi^0$ and $\eta\pi^+\pi^-$ invariant mass spectra is performed in eight slices of $\eta'\pi^+\pi^-$ mass spectrum from 1.4 GeV/c^2 to 2.2 GeV/c^2 . The background-subtracted $\eta'\pi^+\pi^-$ invariant mass is shown in Fig. 4. The UL on the number of $X(1835)$ signal events is extracted by means of a χ^2 -fit. In this fit, all processes other than $J/\psi \rightarrow \omega X(1835)$ are considered as background, and we assume there is no interference between $X(1835)$ and non- $X(1835)$ components. Both the $X(1835)$ signal and background yields are fitted as free parameters, and we associate to the signal yield a Gaussian distribution with mean and width equal to the number of signal events and the corresponding uncertainty resulting from the χ^2 -fit. Then, the UL at 90% confidence level (C.L.) is obtained by finding the point where the cumulative probability of this Gaussian distribution is equal to 0.9.

In the χ^2 -fit, two different signal functions are taken into account: a BW function with $X(1835)$ mass and width fixed to values from Ref. [2], and a Flatté function with fixed parameters from Ref. [19], both weighted by the efficiency, while a third-order polynomial function is used for the background. Systematic effects are evaluated by changing the $\eta'\pi^+\pi^-$ fit range and the bin size, as well as by varying the fit parameters within one standard deviation. Since the $\eta'\pi^+\pi^-$ background-corrected distribution is

extracted from a two-dimensional fit to the $\pi^+\pi^-\pi^0$ and $\eta\pi^+\pi^-$ invariant mass spectra, we need to evaluate its systematic contribution. On this purpose, three different signal functions are used to parametrize the ω and η' signal: (1) a BW convolved with a double Gaussian for ω and a double Gaussian for η' , (2) the ω and η' MC shapes, and (3) the convolution of the ω and η' MC shapes with a double Gaussian. The resulting $\eta'\pi^+\pi^-$ background-corrected distribution are then fitted using a χ^2 -fit, as described before. The fit that gives the largest result is then used to extract the UL on the number of $X(1835)$ signal events at 90% C.L., which amounts to $N^{UL} = 582$. The corresponding UL on the branching fraction of the $J/\psi \rightarrow \omega X(1835)$, $X(1835) \rightarrow \eta'\pi^+\pi^-$ decay at 90% C.L. is calculated as

$$\mathcal{B}(J/\psi \rightarrow \omega X(1835), X(1835) \rightarrow \eta'\pi^+\pi^-) < \frac{N^{UL}}{N_{J/\psi} \cdot \epsilon' \cdot \mathcal{B}_{\text{int}} \cdot (1 - \sigma_{\text{sys}})} = 6.2 \times 10^{-5}, \quad (2)$$

where $\epsilon' = 5.26\%$ is the $X(1835)$ selection efficiency in the $\omega - \eta'$ signal region, and σ_{sys} is the total systematic uncertainty reported in Table I and discussed below.

Several sources of systematic uncertainties are considered: uncertainty due to the total number of J/ψ events [28], intermediate branching fractions [26], data-MC differences in tracking efficiency, photon detection efficiency, selection efficiencies, angular distributions, kinematic fit, signal and background functions and fit range. Uncertainties due to the tracking efficiency for charged tracks are determined using control samples of $J/\psi \rightarrow \pi^+\pi^-p\bar{p}$ and $J/\psi \rightarrow K_s^0 K^\pm \pi^\mp$. The difference between the tracking efficiency in data and MC simulations is 1% for each charged track. However, since we have six charged

TABLE I. Summary of systematic uncertainties. Those items marked with “-” have been taken into account in obtaining the UL on the number of $X(1835)$ signal events.

Sources	$\mathcal{B}(J/\psi \rightarrow \omega\eta'\pi^+\pi^-)$ (%)	UL (%)
Number of J/ψ	0.5	0.5
$\mathcal{B}_{\text{int}}(\omega \rightarrow \pi^0\pi^+\pi^-)$	0.78	0.78
$\mathcal{B}_{\text{int}}(\pi^0 \rightarrow \gamma\gamma)$	0.03	0.03
$\mathcal{B}_{\text{int}}(\eta' \rightarrow \eta\pi^+\pi^-)$	1.63	1.63
$\mathcal{B}_{\text{int}}(\eta \rightarrow \gamma\gamma)$	0.51	0.51
Tracking efficiency	6	6
Photon detection	4	4
Selection efficiency	3.2	Negligible
Angular distribution	1.0	...
Kinematic fit	5	5
ω/η' signal function	4.8	...
Fit range	2.6	...
Background shape	4.3	...
Total	11.8	9.0

pions in the final state, and hence pions with very low momentum, we check for possible tracking efficiency underestimation. We correct our MC simulations according to the data, also taking into account possible difference in the polar angle distributions, and we find a tracking efficiency consistent with 6%. For the neutral candidates, control samples of $J/\psi \rightarrow \rho\pi^0$ and $e^+e^- \rightarrow \gamma\gamma$ are used to study the photon detection efficiency, which amount to 1% for each photon candidate.

The systematic contributions related to the selection efficiency used to calculate both branching fraction and upper limit are evaluated by means of additional MC samples, in which also different intermediate states are considered. However, since no obvious structures are observed in the different combinations of two- or three-particles invariant mass distributions, we simulate a MC sample, without intermediate resonances, taking into account the spin-parity of the initial and final states, and the difference in the efficiency is taken as systematic contribution. Additional contribution can arise from differences between the angular distribution of data and simulation in the $J/\psi \rightarrow \omega\eta'\pi^+\pi^-$ process. We simulate a new MC sample following the same angular dependence as in the data. The difference in the efficiency amount to 1%, which is taken as systematic uncertainty.

A control sample of $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow \pi^+\pi^-\pi^0\eta'$, $\eta' \rightarrow \eta\pi^+\pi^-$ is used to determine the systematic uncertainty related to the kinematic fit. We perform a 2-dimensional fit to the J/ψ and η' invariant mass spectra in order to extract the number of signal events and calculate the efficiency as a function of χ_{4C}^2 . The difference between data and MC in correspondence of the χ_{4C}^2 cut used in this analysis is taken as systematic uncertainty.

Systematic contributions associated only with the branching fraction are those related to the two-dimensional fit of the $\pi^+\pi^-\pi^0$ and $\eta\pi^+\pi^-$ invariant masses. In particular, the systematic related to the signal functions are evaluated by means of MC shape distributions for both the ω and η' invariant mass spectra. For the background, instead, we change the order of the polynomial function. In both cases, the difference in the number of signal events is taken as systematic uncertainty. We also change the fit range by a step of 5 MeV/ c^2 , and the difference in the signal yield is taken as systematic uncertainty.

Table I summarizes all sources of systematic uncertainties, for which the total contribution is obtained as sum of them in quadrature.

Using a sample of 1.31×10^9 J/ψ events collected with the BESIII detector, we measure for the first time the branching fraction for the decay $J/\psi \rightarrow \omega\eta'\pi^+\pi^-$ to be

$(1.12 \pm 0.02 \pm 0.13) \times 10^{-3}$, where the first uncertainty is statistical and the second systematic. We also search for the $X(1835)$ state in the hadronic J/ψ decay $J/\psi \rightarrow \omega X(1835)$, with $X(1835) \rightarrow \eta'\pi^+\pi^-$. No significant signal is observed and the upper limit at 90% C.L. on the branching fraction is determined to be $\mathcal{B}(J/\psi \rightarrow \omega X(1835), X(1835) \rightarrow \eta'\pi^+\pi^-) < 6.2 \times 10^{-5}$. Since the $X(1835)$ state is observed only in radiative J/ψ decays and the branching fraction is measured to be of the order of 10^{-4} [2,3,19], the authors of Ref. [15] suggest that a smaller branching fraction measured in hadronic J/ψ decays could be an indication of a large gluon component. The authors of Ref. [13] treat $X(1835)$ as a baryonium with sizable gluon content, and estimate a branching ratio of the order of 10^{-6} . Unfortunately, our upper limit result is too large to confirm or distinguish among several theoretical interpretations, but it provides the first search for the $X(1835)$ state in J/ψ hadronic decays, which can be further investigated by studying additional hadronic decay modes.

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