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Observation of a structure at 1.84 GeV/c^2 in the $3(\pi^+\pi^-)$ mass spectrum in $J/\psi \to \gamma 3(\pi^+\pi^-)$ decays

M. Ablikim,[1] M. N. Achasov,[6,*] O. Albayrak,[3] D. J. Ambrose,[39] F. F. An,[1] Q. An,[40] J. Z. Bai,[1] R. Baldini Ferroli,[17a] Y. Ban,[26] J. Becker,[2] J. V. Bennett,[16] M. Bertani,[17a] J. M. Bian,[38] E. Boger,[19,†] O. Bondarenko,[20] I. Boyko,[19] R. A. Briere,[3] V. Bytev,[19] H. Cai,[44] X. Cai,[1] O. Cakir,[34a] A. Calcaterra,[17a] G. F. Cao,[1] S. A. Cetin,[34b] J. F. Chang,[1] G. Chelkov,[19,†] G. Chen,[1] H. S. Chen,[1] J. C. Chen,[1] M. L. Chen,[1] S. J. Chen,[24] X. Chen,[26] X. R. Chen,[21] Y. B. Chen,[1] H. P. Cheng,[14] Y. P. Chu,[1] D. Cronin-Hennessy,[38] H. L. Dai,[1] J. P. Dai,[1] D. Dedovich,[19] Z. Y. Deng,[1] A. Denig,[18] I. Denysenko,[19] M. Destefanis,[43a,43c] W. M. Ding,[28] Y. Ding,[22] L. Y. Dong,[1] M. Y. Dong,[1] S. X. Du,[46] J. Fang,[1] S. S. Fang,[1] L. Fava,[43b,43c] C. Q. Feng,[40] P. Friedel,[2] C. D. Fu,[1] J. L. Fu,[24] O. Fuks,[19,†] Y. Gao,[33] C. Geng,[40] K. Goetzen,[7] W. X. Gong,[1] W. Gradl,[18] M. Greco,[43a,43c] M. H. Gu,[1] Y. T. Gu,[9] Y. H. Guan,[36] A. Q. Guo,[25] L. B. Guo,[23] T. Guo,[23] Y. P. Guo,[25] Y. L. Han,[1] F. A. Harris,[37] K. L. He,[1] M. He,[1] Z. Y. He,[25] T. Held,[2] Y. K. Heng,[1] Z. L. Hou,[1] C. Hu,[23] H. M. Hu,[1] J. F. Hu,[35] T. Hu,[1] G. M. Huang,[4] G. S. Huang,[40] J. S. Huang,[12] L. Huang,[1] X. T. Huang,[28] Y. Huang,[24] T. Hussain,[42] C. S. Ji,[40] Q. Ji,[1] Q. P. Ji,[25] X. B. Ji,[1] X. L. Ji,[1] L. L. Jiang,[1] X. S. Jiang,[1] J. B. Jiao,[28] Z. Jiao,[14] D. P. Jin,[1] S. Jin,[1] F. F. Jing,[33] N. Kalantar-Nayestanaki,[20] M. Kavatsyuk,[20] B. Kopf,[2] M. Kornicer,[37] W. Kuehn,[35] W. Lai,[1] J. S. Lange,[35] M. Lara,[16] P. Larin,[11] M. Leyhe,[2] C. H. Li,[1] Cheng Li,[40] Cui Li,[40] D. M. Li,[46] F. Li,[1] G. Li,[1] H. B. Li,[1] J. C. Li,[1] K. Li,[10] Lei Li,[1] Q. J. Li,[1] S. L. Li,[1] W. D. Li,[1] W. G. Li,[1] X. L. Li,[28] X. N. Li,[1] X. Q. Li,[25] X. R. Li,[27] Z. B. Li,[32] H. Liang,[40] Y. F. Liang,[30] Y. T. Liang,[35] G. R. Liao,[33] X. T. Liao,[1] D. 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Wen,[40] S. P. Wen,[1] M. Werner,[35] U. Wiedner,[2] L. H. Wu,[1] N. Wu,[1] S. X. Wu,[40] W. Wu,[25] Z. Wu,[1] L. G. Xia,[33] Y. X. Xia,[15] Z. J. Xiao,[23] Y. G. Xie,[1] Q. L. Xiu,[1] G. F. Xu,[1] G. M. Xu,[26] Q. J. Xu,[10] Q. N. Xu,[36] X. P. Xu,[27,31] Z. R. Xu,[40] Z. Xue,[1] L. Yan,[40] W. B. Yan,[40] Y. H. Yan,[15] H. X. Yang,[1] Y. Yang,[4] Y. X. Yang,[8] H. Ye,[1] M. Ye,[1] M. H. Ye,[5] B. X. Yu,[1] C. X. Yu,[25] H. W. Yu,[26] J. S. Yu,[21] S. P. Yu,[28] C. Z. Yuan,[1] Y. Yuan,[1] A. A. Zafar,[42] A. Zallo,[17a] S. L. Zang,[24] Y. Zeng,[15] B. X. Zhang,[1] B. Y. Zhang,[1] C. Zhang,[24] C. C. Zhang,[1] D. H. Zhang,[1] H. H. Zhang,[32] H. Y. Zhang,[1] J. Q. Zhang,[1] J. W. Zhang,[1] J. Y. Zhang,[1] J. Z. Zhang,[1] LiLi Zhang,[15] R. Zhang,[36] S. H. Zhang,[1] X. J. Zhang,[1] X. Y. Zhang,[28] Y. Zhang,[1] Y. H. Zhang,[1] Z. P. Zhang,[40] Z. Y. Zhang,[44] Zhenghao Zhang,[4] G. Zhao,[1] H. S. Zhao,[1] J. W. Zhao,[1] K. X. Zhao,[23] Lei Zhao,[40] Ling Zhao,[1] M. G. Zhao,[25] Q. Zhao,[1] S. J. Zhao,[46] T. C. Zhao,[1] X. H. Zhao,[24] Y. B. Zhao,[1] Z. G. Zhao,[40] A. Zhemchugov,[19,†] B. Zheng,[41] J. P. Zheng,[1] Y. H. Zheng,[36] B. Zhong,[23] L. Zhou,[1] X. Zhou,[44] X. K. Zhou,[36] X. R. Zhou,[40] C. Zhu,[1] K. Zhu,[1] K. J. Zhu,[1] S. H. Zhu,[1] X. L. Zhu,[33] Y. C. Zhu,[40] Y. M. Zhu,[25] Y. S. Zhu,[1] Z. A. Zhu,[1] J. Zhuang,[1] B. S. Zou,[1] and J. H. Zou[1]

(BESIII Collaboration)

[1]*Institute of High Energy Physics, Beijing 100049, People's Republic of China*
[2]*Bochum Ruhr-University, D-44780 Bochum, Germany*
[3]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[4]*Central China Normal University, Wuhan 430079, People's Republic of China*

[5]China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China
[6]G. I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia
[7]GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany
[8]Guangxi Normal University, Guilin 541004, People's Republic of China
[9]GuangXi University, Nanning 530004, People's Republic of China
[10]Hangzhou Normal University, Hangzhou 310036, People's Republic of China
[11]Helmholtz Institute Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
[12]Henan Normal University, Xinxiang 453007, People's Republic of China
[13]Henan University of Science and Technology, Luoyang 471003, People's Republic of China
[14]Huangshan College, Huangshan 245000, People's Republic of China
[15]Hunan University, Changsha 410082, People's Republic of China
[16]Indiana University, Bloomington, Indiana 47405, USA
[17a]INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
[17b]INFN and University of Perugia, I-06100 Perugia, Italy
[18]Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
[19]Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
[20]KVI, University of Groningen, NL-9747 AA Groningen, Netherlands
[21]Lanzhou University, Lanzhou 730000, People's Republic of China
[22]Liaoning University, Shenyang 110036, People's Republic of China
[23]Nanjing Normal University, Nanjing 210023, People's Republic of China
[24]Nanjing University, Nanjing 210093, People's Republic of China
[25]Nankai University, Tianjin 300071, People's Republic of China
[26]Peking University, Beijing 100871, People's Republic of China
[27]Seoul National University, Seoul 151-747, Korea
[28]Shandong University, Jinan 250100, People's Republic of China
[29]Shanxi University, Taiyuan 030006, People's Republic of China
[30]Sichuan University, Chengdu 610064, People's Republic of China
[31]Soochow University, Suzhou 215006, People's Republic of China
[32]Sun Yat-Sen University, Guangzhou 510275, People's Republic of China
[33]Tsinghua University, Beijing 100084, People's Republic of China
[34a]Ankara University, Dogol Caddesi, 06100 Tandogan, Ankara, Turkey
[34b]Dogus University, 34722 Istanbul, Turkey
[34c]Uludag University, 16059 Bursa, Turkey
[35]Universitaet Giessen, D-35392 Giessen, Germany
[36]University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[37]University of Hawaii, Honolulu, Hawaii 96822, USA
[38]University of Minnesota, Minneapolis, Minnesota 55455, USA
[39]University of Rochester, Rochester, New York 14627, USA
[40]University of Science and Technology of China, Hefei 230026, People's Republic of China
[41]University of South China, Hengyang 421001, People's Republic of China
[42]University of the Punjab, Lahore 54590, Pakistan
[43a]University of Turin, I-10125 Turin, Italy
[43b]University of Eastern Piedmont, I-15121 Alessandria, Italy
[43c]INFN, I-10125 Turin, Italy
[44]Wuhan University, Wuhan 430072, People's Republic of China
[45]Zhejiang University, Hangzhou 310027, People's Republic of China
[46]Zhengzhou University, Zhengzhou 450001, People's Republic of China

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With a sample of 225.3×10^6 J/ψ events taken with the BESIII detector, the decay $J/\psi \to \gamma 3(\pi^+\pi^-)$ is analyzed. A structure at $1.84\ \mathrm{GeV}/c^2$ is observed in the $3(\pi^+\pi^-)$ invariant mass spectrum with a statistical significance of 7.6σ. The mass and width are measured to be $M = 1842.2 \pm 4.2^{+7.1}_{-2.6}\ \mathrm{MeV}/c^2$ and $\Gamma = 83 \pm 14 \pm 11$ MeV. The product branching fraction is

*Also at the Novosibirsk State University, Novosibirsk, 630090, Russia.
†Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.
‡Also at University of Texas at Dallas, Richardson, Texas 75083, USA.
§Also at the PNPI, Gatchina 188300, Russia.
‖Present address: Nagoya University, Nagoya 464-8601, Japan.

determined to be $B(J/\psi \to \gamma X(1840)) \times B(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36^{+0.60}_{-0.74}) \times 10^{-5}$. No η' signals are observed in the $3(\pi^+\pi^-)$ invariant mass spectrum, and the upper limit of the branching fraction for the decay $\eta' \to 3(\pi^+\pi^-)$ is set to be 3.1×10^{-5} at a 90% confidence level.

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Within the framework of quantum chromodynamics (QCD), the existence of gluon self-coupling suggests that in addition to conventional meson and baryon states, there may exist bound states such as glueballs, hybrid states and multiquark states. Experimental searches for glueballs and hybrid states have been carried out for many years, and so far no conclusive evidence has been found. The establishment of new forms of hadronic matter beyond the simple quark-antiquark system remains one of the main interests in experimental particle physics.

Decays of the J/ψ particle have always been regarded as an ideal environment in which to study light hadron spectroscopy and search for new hadrons. At BESII, important advances in light hadron spectroscopy were made using studies of J/ψ radiative decays [1–3]. Of interest is the observation of the $X(1835)$ state in $J/\psi \to \gamma\pi^+\pi^-\eta'$ decay, which was confirmed recently by BESIII [4] and CLEO-c [5]. Since the discovery of the $X(1835)$, many possible interpretations have been proposed, such as a $p\bar{p}$ bound state [6–9], a glueball [10,11], or a radial excitation of the η' meson [12,13]. In the search for the $X(1835)$ in other J/ψ hadronic decays, BESIII reported the first observation of the $X(1870)$ in $J/\psi \to \omega\pi^+\pi^-\eta$ [14]. More recently, BESIII performed spin-parity analyses of threshold structures, the $X(p\bar{p})$, observed in $J/\psi \to \gamma p\bar{p}$ [15], and the $X(1810)$, observed in $J/\psi \to \gamma\omega\phi$ [16]. The spin-parity of the $X(p\bar{p})$ is found to be 0^{-+}, and the $X(1810)$ is confirmed to be a 0^{++} state. To understand their nature, further study is strongly needed, in particular, in searching for new decay modes.

Since the $X(1835)$ was confirmed to be a pseudoscalar particle [4], it may have properties in common with the η_c. Six charged pions is a known decay mode of the η_c; therefore, J/ψ radiative decays to $3(\pi^+\pi^-)$ may be a favorable channel to search for the X states in the 1.8–1.9 GeV/c^2 region.

In this paper, we present results of a study of $J/\psi \to \gamma 3(\pi^+\pi^-)$ decays using a sample of $(225.3 \pm 2.8) \times 10^6$ J/ψ events [17] collected with the BESIII detector [18]. A structure at 1.84 GeV/c^2 [denoted as $X(1840)$ in this paper], is clearly observed in the mass spectrum of six charged pions. Meanwhile, in an attempt to search for η' decaying into six charged pions, no η' signals are observed. The upper limit on the decay branching fraction is set at a 90% confidence level.

The BESIII detector is a magnetic spectrometer located at BEPCII [19], a double-ring e^+e^- collider with the design peak luminosity of 10^{33} cm^{-2} s^{-1} at a center-of-mass energy of 3.773 GeV. The cylindrical core of the BESIII detector consists of a helium-based main drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The acceptance of charged particles and photons is 93% over 4π solid angle, and the charged-particle momentum resolution at 1 GeV/c is 0.5%. The EMC measures photon energies with the resolution of 2.5% (5%) at 1 GeV in the barrel (endcaps).

Monte Carlo (MC) simulations are used to estimate the backgrounds and determine the detection efficiency. Simulated events are processed using GEANT4 [20,21], where measured detector resolutions are incorporated.

Charged tracks are reconstructed using hits in the MDC and are required to pass within ± 10 cm of the interaction point in the beam direction and ± 1 cm in the plane perpendicular to the beam. The polar angle of the charged tracks should be in the region $|\cos\theta| < 0.93$. Photon candidates are selected from showers in the EMC with the energy deposit in the EMC barrel region ($|\cos\theta| < 0.8$) greater than 25 MeV and in the EMC endcap region ($0.86 < |\cos\theta| < 0.92$) greater than 50 MeV. The photon candidates should be isolated from the charged tracks by an opening angle of 10°.

Candidate events are required to have six charged tracks with zero net charge and at least one photon. All the charged tracks are assumed to be pions. The candidate events are required to successfully pass a primary vertex fit. A four-momentum-constraint (4C) kinematic fit is performed to the $J/\psi \to \gamma 3(\pi^+\pi^-)$ hypothesis, and the χ^2_{4C} is required to be less than 30. If the number of photon candidates is more than 1, the $\gamma 3(\pi^+\pi^-)$ combination with the minimum χ^2_{4C} is selected. To suppress background events with multiphotons in the final states, $P^2_{t\gamma} = 2|\vec{P}_{\rm miss}|^2(1 - \cos\theta_{\rm miss})$ is required to be less than 0.0004 GeV^2/c^2, where $\vec{P}_{\rm miss}$ is the missing momentum of the six charged tracks and $\theta_{\rm miss}$ is the angle between the missing momentum and the momentum of the radiative photon. To further reject backgrounds with additional photons in the final state, the χ^2_{4C} of the four-constraint kinematic fit in the hypothesis of $J/\psi \to \gamma 3(\pi^+\pi^-)$ is required to be less than that of the $\gamma\gamma 3(\pi^+\pi^-)$ hypothesis, and the $\gamma\gamma$ invariant mass in the $\gamma\gamma 3(\pi^+\pi^-)$ hypothesis is required to be $|M(\gamma\gamma) - M(\pi^0)| > 0.01$ GeV/c^2. To suppress background events with $K_S \to \pi^+\pi^-$ in the final

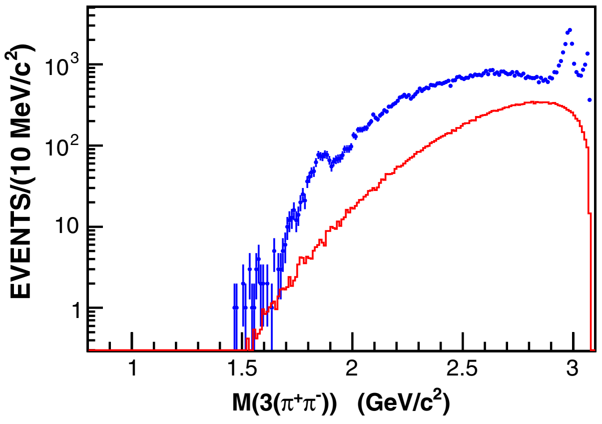

FIG. 1 (color online). Distribution of the invariant mass of $3(\pi^+\pi^-)$ from $J/\psi \to \gamma 3(\pi^+\pi^-)$ events. The dots with error bars are data; the histogram gives phase-space events with an arbitrary normalization.

state, K_S candidates are reconstructed from secondary vertex fits to all oppositely charged track pairs. The invariant mass $M(\pi^+\pi^-)$ must be within the range $|M(\pi^+\pi^-) - M(K_S)| < 0.005\ \mathrm{GeV}/c^2$, where $M(K_S)$ is the nominal K_S mass [22]. The number of K_S candidates is required to be less than 2.

Figure 1 shows the $3(\pi^+\pi^-)$ invariant mass spectrum for events that survive the above selection criteria, where a clear η_c peak is observed around $2.98\ \mathrm{GeV}/c^2$, no evident η' signal is observed, and a distinct enhancement is seen around $1.84\ \mathrm{GeV}/c^2$. In Fig. 2, the $M(3(\pi^+\pi^-))$ distribution is plotted in the range $[1.55, 2.15]\ \mathrm{GeV}/c^2$.

To investigate possible backgrounds, we use a MC sample of 225×10^6 simulated J/ψ decays, in which the decays with known branching fractions [22] are generated by BESEVTGEN [23] and unmeasured J/ψ decays are generated by the Lundcharm model [24]. With the same selection criteria, we find no evident structure at $1.84\ \mathrm{GeV}/c^2$. The background resulting from other, incorrectly reconstructed event topologies is mainly from $J/\psi \to \pi^0 3(\pi^+\pi^-)$, which shows no structure at $1.84\ \mathrm{GeV}/c^2$ in the $3(\pi^+\pi^-)$ mass spectrum. To estimate this contribution, we reconstruct the $J/\psi \to \pi^0 3(\pi^+\pi^-)$ decay from data and then reweight the $3(\pi^+\pi^-)$ invariant mass spectrum by a multiplicative weighting factor $\varepsilon_1/\varepsilon_2$, where ε_1 and ε_2 are the efficiencies for $J/\psi \to \pi^0 3(\pi^+\pi^-)$ MC events to pass the $J/\psi \to \gamma 3(\pi^+\pi^-)$ and $J/\psi \to \pi^0 3(\pi^+\pi^-)$ selection criteria, respectively. The selection criteria for $J/\psi \to \pi^0 3(\pi^+\pi^-)$ are similar to those applied to $J/\psi \to \gamma 3(\pi^+\pi^-)$, except for the requirement of an additional photon. The background analysis shows that the structure at $1.84\ \mathrm{GeV}/c^2$ in the $3(\pi^+\pi^-)$ mass spectrum does not come from background events.

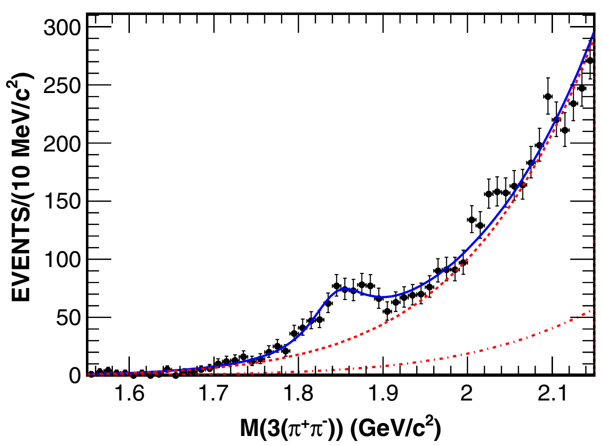

FIG. 2 (color online). The fit of the mass spectrum of $3(\pi^+\pi^-)$. The dots with error bars are data; the solid line is the fit result. The dashed line represents all the backgrounds, including the background events from $J/\psi \to \pi^0 3(\pi^+\pi^-)$ (represented by the dash-dotted line, fixed in the fit) and a third-order polynomial representing other backgrounds.

To extract the number of signal events associated with the peaking structure, an unbinned maximum-likelihood fit is applied to the six-pion mass spectrum. The fit includes three components: a signal shape; shapes for the $J/\psi \to \pi^0 3(\pi^+\pi^-)$ background; and other backgrounds, which have the same final states, but do not contribute to the structure around $1.84\ \mathrm{GeV}/c^2$. The signal shape is described with a Breit-Wigner function modified by the effects of the phase-space factor and the detection efficiency, which is determined by a phase-space MC simulation of $J/\psi \to \gamma 3(\pi^+\pi^-)$. The Breit-Wigner function is convolved with a Gaussian function to account for the detector resolution ($5.1\ \mathrm{MeV}/c^2$, determined from MC simulation). For the background shape, the contribution from the $J/\psi \to \pi^0 3(\pi^+\pi^-)$ background, which is fixed in the fit and shown by the dash-dotted line in Fig. 2, is represented by the reweighted $3(\pi^+\pi^-)$ invariant mass spectrum, while other contributions are represented by a third-order polynomial. The total background is shown as the dashed line in Fig. 2.

The fit yields 632 ± 93 events in the peak at $1842.2 \pm 4.2\ \mathrm{MeV}/c^2$ and a width of $\Gamma = 83 \pm 14$ MeV. The statistical significance of the signal is determined from the change in log likelihood and the change in the number of degrees of freedom (d.o.f.) in the fit with and without the structure $X(1840)$. Different possibilities have been studied by varying the fit range and the background shapes, and by removing the phase-space factor. Among all possibilities, the smallest statistical significance was 7.6σ, corresponding to $-2\Delta \ln L = 67$ and Δd.o.f. $= 3$. With the detection efficiency, $(11.5 \pm 0.1)\%$, obtained from the phase-space MC simulation, the product branching fraction is measured to be $B(J/\psi \to \gamma X(1840)) \times B(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36) \times 10^{-5}$, where the error is statistical only.

No η' events are observed in the $3(\pi^+\pi^-)$ mass spectrum. The upper limit at the 90% confidence level is 2.44 events with the confidence intervals suggested in Ref. [25]. The detection

TABLE I. Summary of the systematic uncertainties in the branching fractions (in percent).

Sources	$X(1840)$	η'
MDC tracking	12	12
Photon detection	1	1
$P^2_{t\gamma}$ cut	2.0	2.0
Kinematic fit	4.3	5.1
Background uncertainty	17.1	$\cdots$
Mass spectrum fit	$^{+10.3}_{-20.3}$	$\cdots$
Detection efficiency	6.1	$\cdots$
MC statistics	0.9	1.3
$B(J/\psi \to \gamma\eta')$	$\cdots$	2.9
Number of J/ψ events	1.2	1.2
Total	$^{+24.6}_{-30.2}$	13.7

efficiency in the mass region $[0.928, 0.988]\,\mathrm{GeV}/c^2$ is determined to be $(7.8 \pm 0.1)\%$ from the MC simulation. Since only the statistical error is considered when we obtain the 90% upper limit of the number of events, the upper limit of the number of events is shifted up by 1σ of the total systematic uncertainty shown in Table I. With the number of J/ψ events and the measured $B(J/\psi \to \gamma\eta') = (5.16 \pm 0.15) \times 10^{-3}$ [22], the upper limit of the branching fraction is obtained to be $B(\eta' \to 3(\pi^+\pi^-)) < 3.1 \times 10^{-5}$.

Sources of systematic errors and their corresponding contributions to the measurement of the branching fractions are summarized in Table I. The uncertainties in tracking and photon detection have been studied [26], and the difference between data and MC is about 2% per charged track and 1% per photon, which is taken as the systematic error. Uncertainty associated with the 4C kinematic fit comes from the inconsistency between data and MC simulation of the fit; this difference is reduced by correcting the track helix parameters of the MC simulation, as described in detail in Ref. [27]. In this analysis, we take the efficiency with correction as the nominal value, and we take the difference between the efficiencies with and without correction as the systematic uncertainty from the kinematic fit. The background uncertainty is determined by changing the background functions and the fit range. The uncertainties from the mass spectrum fit include contributions from the variation of the phase-space factor and the possible impact of other resonances [e.g. $f_2(2010)$]. The systematic error for the $P^2_{t\gamma}$ selection criterion is estimated with the sample of $J/\psi \to \pi^0 3(\pi^+\pi^-)$ by comparing the efficiency of this requirement between MC and data. For the detection efficiency uncertainty due to the unknown spin-parity of the structure, we use the difference between phase space and a pseudoscalar meson hypothesis. The uncertainties from MC statistics, the branching fraction of $J/\psi \to \gamma\eta'$ [22], and the flux of J/ψ events [17] are also considered. We assume all of these sources are independent and take the total systematic error to be their sum in quadrature.

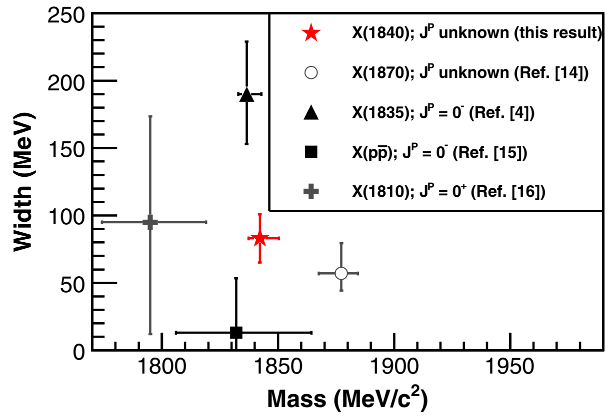

FIG. 3 (color online). Comparisons of observations at BESIII. The error bars include statistical, systematic, and, where applicable, model uncertainties.

The systematic uncertainties on mass and width are estimated from the mass scale, background shape, fitting range, mass spectrum fit, and possible biases due to the fitting procedure. The uncertainty from the detector resolution is checked by using a double Gaussian function as the resolution function, and the change is found to be negligible. The uncertainty from the mass scale is estimated by fitting the η_c resonance in the $M(3(\pi^+\pi^-))$ spectrum. Uncertainties from the background shape and fitting range are estimated by varying the functional form used to represent the background and the fitting range. Uncertainties from the mass spectrum fit include contributions from the variation of the phase-space factor and the possible impact of other resonances [e.g. $f_2(2010)$]. Possible biases due to the fitting procedure are estimated from differences between the input and output of the mass and width values from MC studies. Adding these sources in quadrature, the total systematic error on the mass is $^{+7.1}_{-2.6}$ MeV/c^2, and the total systematic error on the width is ± 11 MeV.

In summary, we studied the decay $J/\psi \to \gamma 3(\pi^+\pi^-)$ with a sample of 225.3×10^6 J/ψ events [17] accumulated at the BESIII detector. A structure at 1.84 GeV/c^2 is observed in the $3(\pi^+\pi^-)$ mass spectrum with a statistical significance of 7.6σ. Fitting the structure $X(1840)$ with a modified Breit-Wigner function yields $M = 1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV/c^2 and $\Gamma = 83 \pm 14 \pm 11$ MeV. The product branching fraction is determined to be $B(J/\psi \to \gamma X(1840)) \times B(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36^{+0.60}_{-0.74}) \times 10^{-5}$. The comparison to the BESIII results of the masses and widths of the $X(1835)$ [4], $X(p\bar{p})$ [15], $X(1870)$ [14], and $X(1810)$ [16] are displayed in Fig. 3, where the mass of $X(1840)$ is in agreement with those of $X(1835)$ and $X(p\bar{p})$, while its width is significantly different from either of them. However, we do not include the BESII result in Fig. 3, as a more precise study of the $X(1835)$ in BESIII [4] indicates that one must consider the presence of additional resonances above 2 GeV/c^2 that were not apparent in the BESII analysis in order to obtain an accurate determination of the width of the $X(1835)$. Therefore, based on these data, one cannot determine whether $X(1840)$ is a new state or the signal of a $3(\pi^+\pi^-)$ decay mode of an existing state. Further study, including an amplitude analysis to determine the spin and parity of the $X(1840)$, is needed to establish the relationship between different experimental observations in this mass region and determine the nature of the underlying resonance or resonances.

A search for $\eta' \to 3(\pi^+\pi^-)$ is also performed, but no η' signal is observed. The upper limit on the branching fraction for the decay at the 90% confidence level is $B(\eta' \to 3(\pi^+\pi^-)) < 3.1 \times 10^{-5}$, which is improved by 1 order of magnitude compared to the previous measurement [28].

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