Observation of $\chi_{cJ} \to 4K_S^0$

M. Ablikim,[1] M. N. Achasov,[10,d] 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] D. W. Bennett,[22] J. V. Bennett,[5] N. Berger,[26] M. Bertani,[23a] D. Bettoni,[24a] F. Bianchi,[55a,55c] E. Boger,[27,b] I. Boyko,[27] R. A. Briere,[5] H. Cai,[57] X. Cai,[1,42] A. Calcaterra,[23a] G. F. Cao,[1,46] S. A. Cetin,[45b] J. Chai,[55c] J. F. Chang,[1,42] W. L. Chang,[1,46] G. Chelkov,[27,b,c] G. Chen,[1] H. S. Chen,[1,46] J. C. Chen,[1] M. L. Chen,[1,42] P. L. Chen,[53] S. J. Chen,[33] X. R. Chen,[30] Y. B. Chen,[1,42] W. Cheng,[55c] X. K. Chu,[35] G. Cibinetto,[24a] F. Cossio,[55c] H. L. Dai,[1,42] J. P. Dai,[37,h] A. Dbeyssi,[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] P. F. Duan,[1] J. Fang,[1,42] S. S. Fang,[1,46] Y. Fang,[1] R. Farinelli,[24a,24b] L. Fava,[55b,55c] S. Fegan,[26] F. Feldbauer,[4] G. Felici,[23a] C. Q. Feng,[52,42] M. Fritsch,[4] C. D. Fu,[1] Q. Gao,[1] X. L. Gao,[52,42] Y. Gao,[44] Y. G. Gao,[6] Z. Gao,[52,42] B. Garillon,[26] I. Garzia,[24a] 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,[1] L. B. Guo,[32] R. P. Guo,[1,46] Y. P. Guo,[26] A. Guskov,[27] Z. Haddadi,[29] S. Han,[57] X. Q. Hao,[16] F. A. Harris,[47] K. L. He,[1,46] X. Q. He,[51] F. H. Heinsius,[4] T. Held,[4] Y. K. Heng,[1,42,46] Z. L. Hou,[1] H. M. Hu,[1,46] J. F. Hu,[37,h] 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] T. Hussain,[54] W. Ikegami Andersson,[56] 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] A. Julin,[49] N. Kalantar-Nayestanaki,[29] X. S. Kang,[34] 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,f] B. Kopf,[4] M. Kornicer,[47] M. Kuemmel,[4] M. Kuessner,[4] A. Kupsc,[56] M. Kurth,[1] W. Kühn,[28] J. S. Lange,[28] P. Larin,[15] L. Lavezzi,[55c] S. Leiber,[4] H. Leithoff,[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,[1,46] J. C. Li,[1] J. W. Li,[40] K. J. Li,[43] Kang Li,[14] Ke Li,[1] Lei Li,[3] P. L. Li,[52,42] P. R. Li,[46,7] Q. Y. Li,[36] T. Li,[36] W. D. Li,[1,46] W. G. Li,[1] X. L. Li,[36] X. N. Li,[1,42] X. Q. Li,[34] Z. B. Li,[43] 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] B. Liu,[37,h] B. J. Liu,[1] C. X. Liu,[1] D. Liu,[52,42] D. Y. Liu,[37,h] F. H. Liu,[38] Fang Liu,[1] Feng Liu,[6] H. B. Liu,[13] H. L. Liu,[41] 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] L. D. Liu,[35] Q. Liu,[46] S. B. Liu,[52,42] X. Liu,[30] 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. 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,j] 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. 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. Marcello,[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,d] H. Muramatsu,[49] A. Mustafa,[4] S. Nakhoul,[11,g] Y. Nefedov,[27] F. Nerling,[11,g] I. B. Nikolaev,[10,d] Z. Ning,[1,42] S. Nisar,[8] S. L. Niu,[1,42] X. Y. Niu,[1,46] 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] J. Pellegrino,[55a,55c] H. P. Peng,[52,42] Z. Y. Peng,[13] K. Peters,[11,g] J. Pettersson,[56] J. L. Ping,[32] R. G. Ping,[1,46] A. Pitka,[4] R. Poling,[49] V. Prasad,[52,42] H. R. Qi,[2] M. Qi,[33] T. Y. Qi,[2] S. Qian,[1,42] C. F. Qiao,[46] N. Qin,[57] X. S. Qin,[4] Z. H. Qin,[1,42] J. F. Qiu,[1] S. Q. Qu,[34,*] K. H. Rashid,[54,i] C. F. Redmer,[26] M. Richter,[4] M. Ripka,[26] A. Rivetti,[55c] M. Rolo,[55c] G. Rong,[1,46] Ch. Rosner,[15] A. Sarantsev,[27,e] 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] J. J. Song,[36] W. M. Song,[36] 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] M. Tiemens,[29] B. Tsednee,[25] I. Uman,[45d] B. Wang,[1] B. L. Wang,[46] C. W. Wang,[33] D. Wang,[35] D. Y. Wang,[35] Dan Wang,[46] H. H. Wang,[36] K. Wang,[1,42] L. L. Wang,[1] L. S. Wang,[1] M. Wang,[36] Meng Wang,[1,46] P. Wang,[1] P. L. Wang,[1] W. P. Wang,[52,42] X. F. Wang,[1] 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] 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] X. Xia,[36] Y. Xia,[20] D. Xiao,[1] Y. J. Xiao,[1,46] Z. J. Xiao,[32] Y. G. Xie,[1,42] Y. H. Xie,[6] X. A. Xiong,[1,46] Q. L. Xiu,[1,42] G. F. Xu,[1] J. J. Xu,[1,46] L. Xu,[1] Q. J. Xu,[14] 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] 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,[30] J. S. Yu,[20] C. Z. Yuan,[1,46] Y. Yuan,[1] A. Yuncu,[45b,a] 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,h] X. Y. Zhang,[36] Y. Zhang,[52,42] Y. H. Zhang,[1,42] Y. T. Zhang,[52,42] Yang Zhang,[1] Yao Zhang,[1] 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] B. Zheng,[53] J. P. Zheng,[1,42] W. J. Zheng,[36] Y. H. Zheng,[46] B. Zhong,[32] L. Zhou,[1,42] Q. Zhou,[1,46] X. Zhou,[57] X. K. Zhou,[52,42] X. R. Zhou,[52,42] X. Y. Zhou,[1] 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. Zhu,[1] S. H. Zhu,[51] 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. Zou[1]

(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 Institute of Information Technology, Lahore, 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 Avenue 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 China*
[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, Turkey*
[46]*University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[47]*University of Hawaii, Honolulu, Hawaii 96822, USA*

[48]*University of Jinan, Jinan 250022, People's Republic of China*
[49]*University of Minnesota, Minneapolis, Minnesota 55455, USA*
[50]*University of Muenster, Wilhelm-Klemm-Str. 9, 48149 Muenster, Germany*
[51]*University of Science and Technology Liaoning, Anshan 114051, People's Republic of China*
[52]*University of Science and Technology of China, Hefei 230026, People's Republic of China*
[53]*University of South China, Hengyang 421001, People's Republic of China*
[54]*University 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, Italy*
[56]*Uppsala University, Box 516, SE-75120 Uppsala, Sweden*
[57]*Wuhan University, Wuhan 430072, People's Republic of China*
[58]*Xinyang Normal University, Xinyang 464000, People's Republic of China*
[59]*Zhejiang University, Hangzhou 310027, People's Republic of China*
[60]*Zhengzhou University, Zhengzhou 450001, People's Republic of China*

(Received 24 January 2019; published 22 March 2019)

By analyzing $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector operating at the BEPCII collider, the decays of $\chi_{cJ} \to 4K_S^0$ $(J = 0, 1, 2)$ are observed for the first time with statistical significances of 26.5σ, 5.9σ and 11.4σ, respectively. The product branching fractions of $\psi(3686) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to 4K_S^0$ are presented, and the branching fractions of $\chi_{cJ} \to 4K_S^0$ decays are determined to be $\mathcal{B}_{\chi_{c0}\to 4K_S^0} = (5.76 \pm 0.34 \pm 0.38) \times 10^{-4}$, $\mathcal{B}_{\chi_{c1}\to 4K_S^0} = (0.35 \pm 0.09 \pm 0.03) \times 10^{-4}$ and $\mathcal{B}_{\chi_{c2}\to 4K_S^0} = (1.14 \pm 0.15 \pm 0.08) \times 10^{-4}$, where the first uncertainties are statistical and the second are systematic, respectively.

DOI: 10.1103/PhysRevD.99.052008

I. INTRODUCTION

In the quark model, the χ_{cJ} $(J = 0, 1, 2)$ mesons are the ^3P_J charmonium states. Since the χ_{cJ} mesons cannot be directly produced in e^+e^- collisions, according to parity conservation, their decays are experimentally and theoretically not studied as extensively as the vector charmonium states J/ψ and $\psi(3686)$. However, the χ_{cJ} mesons can be produced in radiative decays of the $\psi(3686)$ with branching fractions of about 9%, which provide a method to produce large χ_{cJ} samples in order to study χ_{cJ} decays.

Recent theoretical work indicates that the color octet mechanism (COM) [1] could have large contributions to the decays of the P-wave charmonium states. However, many contradictions still exist between these theoretical calculations and experimental measurements. For instance, theoretical predictions of χ_{cJ} decays to baryon-antibaryon pairs based on the COM [2–4] are inconsistent with experimental measurements [5]. Thus, more precise experimental results are mandatory to further understand χ_{cJ} decay dynamics. Furthermore, the χ_{c0} and χ_{c2} states are expected to decay via two-gluon processes into light hadrons, giving access to the investigation of glueball dynamics. Thus, comprehensive measurements of exclusive hadronic decays of χ_{cJ} are valuable.

For the decay modes of $\chi_{cJ} \to 4K$, the branching fractions of χ_{cJ} decays into $2(K^+K^-)$ and $K^+K^-K_S^0K_S^0$ have been measured by Belle [6] and BES [7] with results

---

[*] qusq@mail.nankai.edu.cn
[†] zhaomg@nankai.edu.cn

[a] Also at Bogazici University, 34342 Istanbul, Turkey.

[b] Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.

[c] Also at the Functional Electronics Laboratory, Tomsk State University, Tomsk, 634050, Russia.

[d] Also at the Novosibirsk State University, Novosibirsk, 630090, Russia.

[e] Also at the NRC "Kurchatov Institute", PNPI, 188300, Gatchina, Russia.

[f] Also at Istanbul Arel University, 34295 Istanbul, Turkey.

[g] Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.

[h] 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.

[i] Also at Government College Women University, Sialkot—51310. Punjab, Pakistan.

[j] 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.

TABLE I. World averages on branching fractions of χ_{cJ} decays to $2(K^+K^-)$ and $K^+K^-K_S^0K_S^0$ [5–7].

Channel	Branching fraction ($\times 10^{-3}$)
$\chi_{c0} \to 2(K^+K^-)$	2.82 ± 0.29
$\chi_{c1} \to 2(K^+K^-)$	0.54 ± 0.11
$\chi_{c2} \to 2(K^+K^-)$	1.65 ± 0.20
$\chi_{c0} \to K^+K^-K_S^0K_S^0$	1.40 ± 0.50
$\chi_{c1} \to K^+K^-K_S^0K_S^0$	< 0.4
$\chi_{c2} \to K^+K^-K_S^0K_S^0$	< 0.4

summarized in Table I. Measurements of the branching fractions of their isospin-symmetrical decays, $\chi_{cJ} \to 4K_S^0$, will shed light on the understanding of isospin invariance in the $\chi_{cJ} \to 4K$ decays. In this paper, by analyzing $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events [8] collected with the BESIII detector [9], we present the first measurements of the branching fractions of χ_{cJ} decays to $4K_S^0$.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector is operated at the Beijing Electron Positron Collider II (BEPCII), which has reached a peak luminosity of 1.0×10^{33} cm^{-2} s^{-1} at a center-of-mass energy of $\sqrt{s} = 3.773$ GeV. The detector has a geometrical acceptance of 93% of the solid angle and is composed of four main components. A helium-gas-based main drift chamber (MDC) is used to track charged particles. The single wire resolution is better than 130 μm, which, together with a magnetic field of 1 T, leads to a momentum resolution of 0.5% for transverse momentum of 1 GeV$/c$. The energy loss per path length dE/dx is measured with a resolution of 6%. The MDC is surrounded by a time-of-flight system built from plastic scintillators. It provides a $2\sigma K/\pi$ separation up to 1 GeV$/c$ momentum with a time resolution of 80 (110) ps for the barrel (end caps). Particle energies are measured in the CsI(Tl) electromagnetic calorimeter (EMC), which achieves an energy resolution for electrons of 2.5% (5%) at 1 GeV$/c$ momentum and a position resolution of 6 mm (9 mm) for the barrel (end caps). Outside of the magnet coil, a muon counter composed of resistive plate chambers provides a spatial resolution of better than 2 cm. A more detailed description of the detector can be found in Ref. [9].

A GEANT4-BASED [10] Monte Carlo (MC) simulation package is used to optimize the event selections and estimate the signal efficiency and the background level. The event generator KKMC [11] simulates the electron-positron annihilation and the production of the ψ resonances. Particle decays are generated by EVTGEN [12] for the known decay modes with branching fractions from the Particle Data Group (PDG) [5] and LUNDCHARM [13] for the unknown ones. An inclusive MC sample containing 506×10^6 generic $\psi(3686)$ decays is used to study background. The $\psi(3686) \to \gamma\chi_{cJ}$ decays are generated assuming an electric-pole ($E1$) transition [14], in which the polar angle (θ) of the radiative photon is distributed with the $(1 + \cos^2\theta)$, $(1 - \frac{1}{3}\cos^2\theta)$, and $(1 + \frac{1}{13}\cos^2\theta)$ for χ_{c0}, χ_{c1}, and χ_{c2} decays [15]. The $E1$ transition width is proportional to E^3, where E is the energy of the emitted photon [16]. The $\chi_{cJ} \to 4K_S^0$ and $K_S^0 \to \pi^+\pi^-$ decays are generated in phase space (PHSP) distribution. The χ_{cJ} states are simulated using a relativistic Breit-Wigner incorporated within the helicity amplitudes in the EVTGEN package [12].

III. EVENT SELECTION

We reconstruct events from the decay chain of the charmonium transitions $\psi(3686) \to \gamma\chi_{cJ}$ followed by the hadronic decays $\chi_{cJ} \to 4K_S^0$ and $K_S^0 \to \pi^+\pi^-$. A photon candidate is defined as a shower detected within the EMC exceeding an energy deposit of 25 MeV in the barrel region (covering the region $|\cos\theta| < 0.8$, where θ is the polar angle with respect to the positron beam direction) or of 50 MeV in the end caps ($0.86 < |\cos\theta| < 0.92$). To suppress the electronics noise and beam background, the clusters are required to start within 700 ns after the

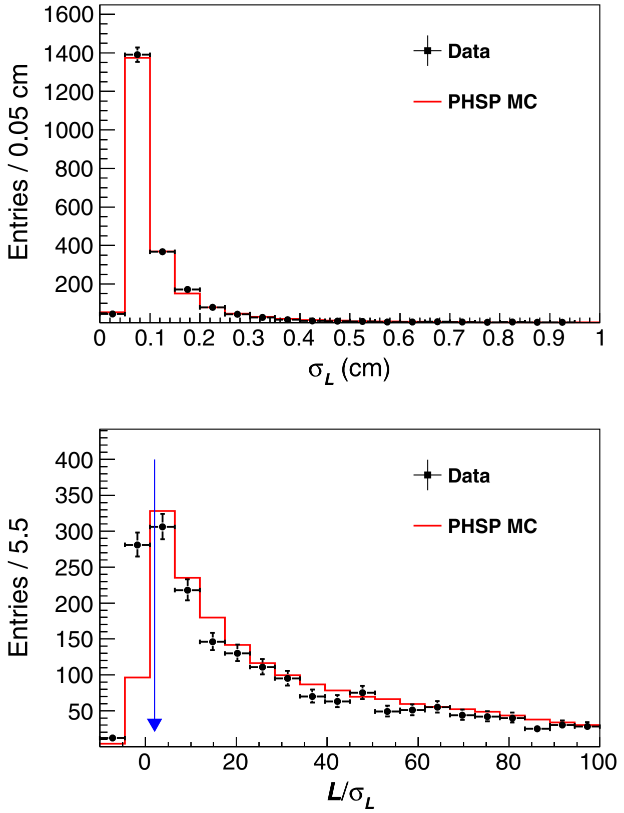

FIG. 1. The distributions of σ_L and L/σ_L for all K_S^0 candidates. The arrow indicates the selection criterion, where the dots with error bars are from data and the histogram is from the PHSP signal MC sample scaled to the amount of data events.

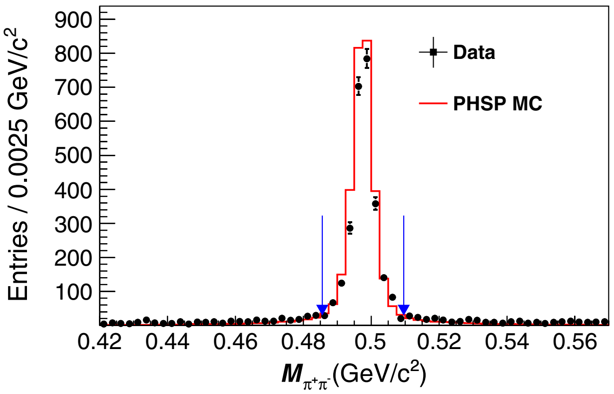

FIG. 2. The $M_{\pi^+\pi^-}$ distribution for all K_S^0 candidates. The arrows indicate the mass window of the K_S^0 signal, where the dots with error bars are from data and the histogram is from the PHSP signal MC sample scaled to the amount of data events.

estimated collision timing and fall outside a cone angle of 10° around the nearest extrapolated charged track. All charged tracks are required to originate from the interaction region defined as $|V_z| < 20$ cm and $|\cos\theta| < 0.93$, where V_z denotes the distance of the closest approach of the reconstructed track to the interaction point (IP) in the z direction. Candidate events must have eight charged tracks with zero net charge and at least one good photon. The K_S^0 candidates are reconstructed using vertex fits by looping over all oppositely charged track pairs in an event (assuming the tracks to be $\pi^\pm$ without particle identification). To suppress the $\pi^+\pi^-$ combinatorial background, the reconstructed decay lengths (L) of the K_S^0 candidates are required to be more than twice their standard deviations (σ_L). The distributions of σ_L and L/σ_L for all K_S^0 candidates are shown in Fig. 1.

The invariant mass of $\pi^+\pi^-$ ($M_{\pi^+\pi^-}$) must be within the K_S^0 signal region, defined as 12 MeV$/c^2$ around the K_S^0 nominal mass [5]. The $M_{\pi^+\pi^-}$ distribution for all K_S^0 candidates is shown in Fig. 2. To further suppress combinatorial background, a four-momentum conservation constraint (4C) is applied to the events. The $\chi^2_{4\mathrm{C}}$ of the kinematic fit is required to be less than 200. To reduce the difference of the distributions of χ^2 of the 4C kinematic fit ($\chi^2_{4\mathrm{C}}$) between data and MC simulation, we correct the track helix parameters of MC simulation in the 4C kinematic fit.

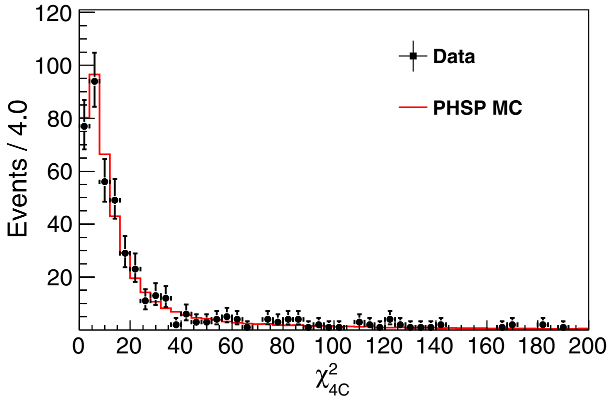

FIG. 3. The $\chi^2_{4\mathrm{C}}$ distribution after corrections, where the dots with error bars are from data and the histogram is from the PHSP signal MC sample scaled to the amount of data events.

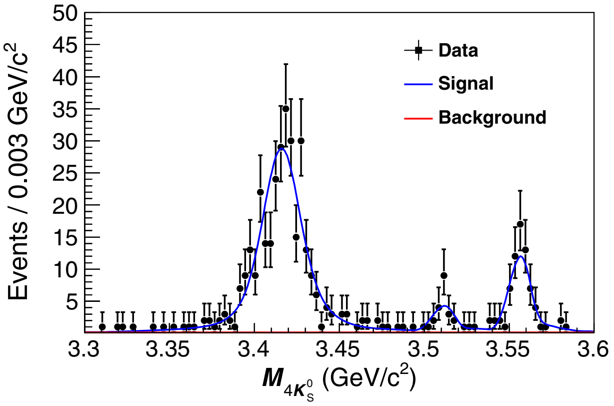

FIG. 4. Fit to the $M_{4K_S^0}$ distribution of the candidate events of $\psi(3686) \to \chi_{cJ}, \chi_{cJ} \to 4K_S^0$. The points with error bars are data, the blue curve is the overall fit, and the red curve is the fitted background.

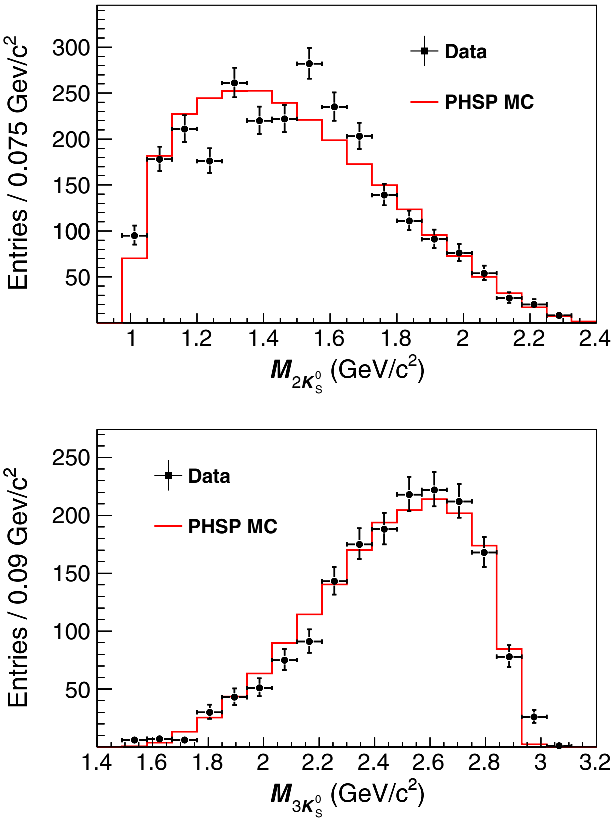

FIG. 5. The $M_{2K_S^0}$ and $M_{3K_S^0}$ distributions for all $2K_S^0$ and $3K_S^0$ combinations, where the dots with error bars are from data and the histogram is from the PHSP signal MC sample scaled to the amount of data events.

The χ^2_{4C} distribution after corrections is shown in Fig. 3, in which the consistency between data and MC simulation is reasonable. The spectrum of the invariant mass of the $4K_S^0$ ($M_{4K_S^0}$) of the accepted candidate events is shown in Fig. 4. Clear χ_{c0}, χ_{c1} and χ_{c2} signals are observed.

We further examine the possible substructures in the $\chi_{cJ} \to 4K_S^0$. Figure 5 shows the distribution of invariant masses of $2K_S^0$ ($M_{2K_S^0}$) and $3K_S^0$ ($M_{3K_S^0}$). No obvious structure is found.

IV. BACKGROUND STUDIES

The continuum data taken at $\sqrt{s} = 3.65$ GeV, corresponding to an integrated luminosity of 44.45 pb^{-1} [17], are used to estimate the QED background. No events within this sample satisfy the same selection criteria applied to the main data sample. Studies of the signal MC events of $\psi(3686) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to 4K_S^0$ decays show that the signals containing misformed K_S^0 can be ignored safely. In addition, the inclusive MC sample is used to study all potential backgrounds from $\psi(3686)$ decays. Only two background events of $\psi(3686) \to \bar{K}^{*0}(892)K_S^0 f_2'(1525)$ and $\bar{K}^{*0}(892)K_S^0 f_0(1710)$ survive. Further studies with large exclusive MC samples show that the two background sources only form a uniform distribution across the fit range. Thus, all peaking background components are negligible in this analysis.

V. BRANCHING FRACTIONS

The signal yields N^J_{obs} are obtained by fitting to the $M_{4K_S^0}$ distribution. The $M_{4K_S^0}$ distribution is fitted using an unbinned maximum likelihood fit. In the fit, each χ_{cJ} signal is described with the MC simulated shape, which is the probability density function translated by utilizing the RooHistPDF class [18] in RooFit [19], convolved with a Gaussian function with free parameters to take into account the resolution difference between data and MC simulation. Since the background level is very low, as discussed in Sec. IV, the background shape is assumed to be flat. The signal yields of χ_{c0}, χ_{c1} and χ_{c2} are fitted to be 319.4 ± 19.0, 21.6 ± 5.2 and 68.0 ± 8.7, respectively. The statistical significances are estimated to be 26.5σ, 5.9σ and 11.4σ for χ_{c0}, χ_{c1} and χ_{c2} individually, which are determined by comparing the fit likelihood values with and without each χ_{cJ} signal separately. The obtained corrected efficiencies for $\chi_{cJ} \to 4K_S^0$ are $(5.51 \pm 0.03)\%$, $(6.19 \pm 0.04)\%$ and $(6.08 \pm 0.04)\%$, respectively, including detector acceptance as well as reconstruction and selection efficiencies.

The branching fraction is calculated with

$$\mathcal{B}_{\chi_{cJ} \to 4K_S^0} = \frac{N^J_{\mathrm{obs}}}{N_{\psi(3686)} \cdot \mathcal{B}_{\psi(3686) \to \gamma\chi_{cJ}} \cdot \mathcal{B}^4_{K_S^0 \to \pi^+\pi^-} \cdot \epsilon}, \quad (1)$$

where ϵ is the efficiency, $N_{\psi(3686)}$ is the number of $\psi(3686)$ events, $\mathcal{B}_{\psi(3686) \to \gamma\chi_{cJ}}$ and $\mathcal{B}_{K_S^0 \to \pi^+\pi^-}$ are the branching fractions of the PDG fit of $\psi(3686) \to \gamma\chi_{cJ}$ decays and $K_S^0 \to \pi^+\pi^-$ decay [5].

VI. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the measurements of $\mathcal{B}_{\chi_{cJ} \to 4K_S^0}$ originate from several sources, as summarized in Table II. They are estimated and described below.

The number of $\psi(3686)$ events has been measured to be $N_{\psi(3686)} = (448.1 \pm 2.9) \times 10^6$ with the inclusive hadronic data sample, as described in Ref. [8]. The uncertainty of the total number is 0.6%.

The systematic uncertainty due to the photon detection is assumed to be 1.0% per photon with the control sample $J/\psi \to \rho^0\pi^0$ [20].

The systematic uncertainty associated with K_S^0 reconstruction is determined to be 1.5% per K_S^0 with the control samples of $J/\psi \to K^{*\pm}(892)K^{\mp}$, $K^{*\pm}(892) \to K_S^0\pi^{\pm}$ and $J/\psi \to \phi K_S^0 K^{\mp}\pi^{\pm}$ in Ref. [21].

To estimate the systematic uncertainties of the MC model for the $\chi_{cJ} \to 4K_S^0$ decay, we compare our nominal efficiency with that determined from the signal MC events after mixing some possible sub-resonant decays, including $\chi_{cJ} \to f_0(1500)f_0(1500)$, $\chi_{cJ} \to K_S^0K_S^0f_0(1500)$, $\chi_{cJ} \to K_S^0K_S^0f_2'(1525)$, $\chi_{cJ} \to f_0(1500)f_2'(1525)$, $\chi_{cJ} \to f_0(1500)f_0(1710)$, $\chi_{cJ} \to f_0(1500)f_2(1565)$ and $\chi_{cJ} \to f_2'(1525)f_2(1565)$. The systematic uncertainties are estimated as the relative changes of efficiencies, which are 0.4%, 0.2% and 0.2% for χ_{c0}, χ_{c1} and χ_{c2} decays, respectively.

We correct the track helix parameters for MC simulation in the 4C kinematic fit. The change in detection efficiency is not more than 1.0% when varying the correction factors within one standard deviation around the nominal value. We, therefore, assume 1.0% as the systematic uncertainty of the 4C kinematic fit.

TABLE II. Summary of the systematic uncertainties (%).

Source	χ_{c0}	χ_{c1}	χ_{c2}
Number of $\psi(3686)$ events	0.6	0.6	0.6
γ detection	1.0	1.0	1.0
K_S^0 reconstruction	6.0	6.0	6.0
MC model	0.4	0.2	0.2
4C kinematic fit	1.0	1.0	1.0
Angular distribution	0.7	0.5	0.7
Fit range	0.6	1.5	0.9
Signal shape	0.4	2.8	1.7
MC statistics	0.6	0.5	0.6
Quoted branching fractions	2.0	2.5	2.1
Total	6.6	7.4	6.9

To estimate the systematic uncertainties in the polar-angle distribution of single K_S^0, we use a reweighting method. New signal MC events are obtained by reweighting the polar-angle distribution of single K_S^0 in the signal MC events to data. The changes to the detection efficiencies are taken as the systematic uncertainties, which are 0.7%, 0.5% and 0.7% for χ_{c0}, χ_{c1} and χ_{c2} decays, respectively.

The systematic uncertainties due to the fit range are estimated by a series of fits with alternative intervals. The standard deviations of the resulting branching fractions are assigned as the systematic uncertainties, which are 0.6%, 1.5% and 0.9% for χ_{c0}, χ_{c1} and χ_{c2} decays, respectively.

To estimate the systematic uncertainties due to the signal shape, we use alternative signal shapes, a Breit Wigner function smeared with a double Gaussian and a MC simulated shape ignoring the effect of the χ_{cJ} width on PHSP convolved with a Gaussian function, to describe each χ_{cJ} signal. The maximum deviations of the resulting branching fractions are assigned as the relevant systematic uncertainties, which are 0.4%, 2.8% and 1.7% for χ_{c0}, χ_{c1} and χ_{c2} decays, respectively.

The systematic uncertainties due to the statistics of the MC samples are 0.6%, 0.5%, and 0.6% for χ_{c0}, χ_{c1} and χ_{c2} decays, respectively.

The systematic uncertainties from the branching fractions of $\psi(3686) \to \gamma\chi_{cJ}$ and $K_S^0 \to \pi^+\pi^-$ decays quoted from the PDG [5] are 2.0%, 2.5% and 2.1% for χ_{c0}, χ_{c1} and χ_{c2} decays and 0.07% for K_S^0, respectively.

We assume that all systematic uncertainties are independent and add them in quadrature to obtain the total systematic uncertainty for each decay.

VII. CONCLUSION

By analyzing $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events with the BESIII detector, the product branching fractions are determined to be $\mathcal{B}_{\psi(3686)\to\gamma\chi_{c0}} \times \mathcal{B}_{\chi_{c0}\to 4K_S^0} = (0.564 \pm 0.033 \pm 0.037) \times 10^{-4}$, $\mathcal{B}_{\psi(3686)\to\gamma\chi_{c1}} \times \mathcal{B}_{\chi_{c1}\to 4K_S^0} = (0.034 \pm 0.009 \pm 0.003) \times 10^{-4}$ and $\mathcal{B}_{\psi(3686)\to\gamma\chi_{c2}} \times \mathcal{B}_{\chi_{c2}\to 4K_S^0} = (0.108 \pm 0.015 \pm 0.008) \times 10^{-4}$, where the first and second uncertainties are statistical and systematic, respectively. We measure for the first time the branching fractions of $\chi_{cJ} \to 4K_S^0$ decays to be $\mathcal{B}_{\chi_{c0}\to 4K_S^0} = (5.76 \pm 0.34 \pm 0.38) \times 10^{-4}$, $\mathcal{B}_{\chi_{c1}\to 4K_S^0} = (0.35 \pm 0.09 \pm 0.03) \times 10^{-4}$, $\mathcal{B}_{\chi_{c2}\to 4K_S^0} = (1.14 \pm 0.15 \pm 0.08) \times 10^{-4}$, where the first and second uncertainties are statistical and systematic, respectively. Combining the world averages of the branching fractions of the $\chi_{cJ} \to 2(K^+K^-)$ decays, we obtain the branching fraction ratios $\mathcal{B}_{\chi_{c0}\to 4K_S^0}/\mathcal{B}_{\chi_{c0}\to 2(K^+K^-)} = 0.204 \pm 0.028$, $\mathcal{B}_{\chi_{c1}\to 4K_S^0}/\mathcal{B}_{\chi_{c1}\to 2(K^+K^-)} = 0.064 \pm 0.023$, and $\mathcal{B}_{\chi_{c2}\to 4K_S^0}/\mathcal{B}_{\chi_{c2}\to 2(K^+K^-)} = 0.069 \pm 0.013$. Our results provide valuable data to explore isospin symmetry in $\chi_{cJ} \to 4K$ decays.

ACKNOWLEDGMENTS

The BESIII Collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key Basic Research Program of China under Contract No. 2015CB856700; National Natural Science Foundation of China (NSFC) under Contracts No. 11475090, No. 11875170, No. 11335008, No. 11425524, No. 11625523, No. 11635010, and No. 11735014; 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. U1832207, No. U1532257, No. U1532258, and No. U1732263; CAS Key Research Program of Frontier Sciences under Contracts No. QYZDJ-SSW-SLH003 and No. QYZDJ-SSW-SLH040; 100 Talents Program of CAS; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under Contracts No. Collaborative Research Center CRC 1044 and No. 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.

---

[1] G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D **51**, 1125 (1995); H. W. Huang and K. T. Chao, Phys. Rev. D **54**, 6850 (1996); A. Petrelli, Phys. Lett. B **380**, 159 (1996); J. Bolz, P. Kroll, and G. A. Schuler, Eur. Phys. J. C **2**, 705 (1998); S. H. M. Wong, Eur. Phys. J. C **14**, 643 (2000).

[2] R. G. Ping, B. S. Zou, and H. C. Chiang, Eur. Phys. J. A **23**, 129 (2005).

[3] X. H. Liu and Q. Zhao, J. Phys. G **38**, 035007 (2011).

[4] S. M. H. Wong, Eur. Phys. J. B **14**, 643 (2000).

[5] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

[6] S. Uehara *et al.* (Belle Collaboration), Eur. Phys. J. C **53**, 1 (2007).

[7] M. Ablikim *et al.* (BESIII Collaboration), Phys. Lett. B **630**, 21 (2005).

[8] M. Ablikim *et al.* (BESIII Collaboration), Chin. Phys. C **42**, 023001 (2018).

[9] M. Ablikim *et al.* (BESIII Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **614**, 345 (2010).

[10] S. Agostinelli *et al.* (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).

[11] S. Jadach, B. F. L. Ward, and Z. Was, Phys. Rev. D **63**, 113009 (2001).

[12] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001); R. G. Ping, Chin. Phys. C **32**, 599 (2008).

[13] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, Phys. Rev. D **62**, 034003 (2000).

[14] E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, and T. M. Yan, Phys. Rev. D **21**, 203 (1980).

[15] W. M. Tanenbaum *et al.*, Phys. Rev. D **17**, 1731 (1978); G. R. Liao, R. G. Ping, and Y. X. Yang, Chin. Phys. Lett. **26**, 051101 (2009).

[16] Y. B. Ding, D. H. Qin, and K. T. Chao, Phys. Rev. D **44**, 3562 (1991).

[17] M. Ablikim *et al.* (BESIII Collaboration), Chin. Phys. C **37**, 123001 (2013).

[18] https://root.cern/doc/master/classRooHistPdf.html.

[19] W. Verkerke and D. Kirkby, eConf **C0303241**, MOLT007 (2003).

[20] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **86**, 052011 (2012).

[21] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **92**, 112008 (2015).