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To cite this article: M. Ablikim *et al* 2017 *Chinese Phys. C* **41** 013001

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Determination of the number of J/ψ events with inclusive J/ψ decays[*]

M. Ablikim(麦迪娜)[1] M. N. Achasov[9,e] X. C. Ai(艾小聪)[1] O. Albayrak[5] M. Albrecht[4] D. J. Ambrose[44] A. Amoroso[49A,49C] F. F. An(安芬芬)[1] Q. An(安琪)[46,a] J. Z. Bai(白景芝)[1] R. Baldini Ferroli[20A] Y. Ban(班勇)[31] D. W. Bennett[19] J. V. Bennett[5] M. Bertani[20A] D. Bettoni[21A] J. M. Bian(边渐鸣)[43] F. Bianchi[49A,49C] E. Boger[23,c] I. Boyko[23] R. A. Briere[5] H. Cai(蔡浩)[51] X. Cai(蔡啸)[1,a] O. Cakir[40A] A. Calcaterra[20A] G. F. Cao(曹国富)[1] S. A. Cetin[40B] J. F. Chang(常劲帆)[1,a] G. Chelkov[23,c,d] G. Chen(陈刚)[1] H. S. Chen(陈和生)[1] H. Y. Chen(陈海云)[2] J. C. Chen(陈江川)[1] M. L. Chen(陈玛丽)[1,a] S. J. Chen(陈申见)[29] X. Chen(谌炫)[1,a] X. R. Chen(陈旭荣)[26] Y. B. Chen(陈元柏)[1,a] H. P. Cheng(程和平)[17] X. K. Chu(褚新坤)[31] G. Cibinetto[21A] H. L. Dai(代洪亮)[1,a] J. P. Dai(代建平)[34] A. Dbeyssi[14] D. Dedovich[23] Z. Y. Deng(邓子艳)[1] A. Denig[22] I. Denysenko[23] M. Destefanis[49A,49C] F. De Mori[49A,49C] Y. Ding(丁勇)[27] C. Dong(董超)[30] J. Dong(董静)[1,a] L. Y. Dong(董燎原)[1] M. Y. Dong(董明义)[1,a] Z. L. Dou(豆正磊)[29] S. X. Du(杜书先)[53] P. F. Duan(段鹏飞)[1] J. Z. Fan(范荆州)[39] J. Fang(方建)[1,a] S. S. Fang(房双世)[1] X. Fang(方馨)[46,a] Y. Fang(方易)[1] R. Farinelli[21A,21B] L. Fava[49B,49C] O. Fedorov[23] F. Feldbauer[22] G. Felici[20A] C. Q. Feng(封常青)[46,a] E. Fioravanti[21A] M. Fritsch[14,22] C. D. Fu(傅成栋)[1] Q. Gao(高清)[1] X. L. Gao(高鑫磊)[46,a] X. Y. Gao(高旭阳)[2] Y. Gao(高原宁)[39] Z. Gao(高榛)[46,a] I. Garzia[21A] K. Goetzen[10] L. Gong(龚丽)[30] W. X. Gong(龚文煊)[1,a] W. Gradl[22] M. Greco[49A,49C] M. H. Gu(顾旻皓)[1,a] Y. T. Gu(顾运厅)[12] Y. H. Guan(管颖慧)[1] A. Q. Guo(郭爱强)[1] L. B. Guo(郭立波)[28] Y. Guo(郭玥)[1]，Y. P. Guo(郭玉萍)[22] Z. Haddadi[25] A. Hafner[22] S. Han(韩爽)[51] X. Q. Hao(郝喜庆)[15] F. A. Harris[42] K. L. He(何康林)[1] T. Held[4] Y. K. Heng(衡月昆)[1,a] Z. L. Hou(侯治龙)[1] C. Hu(胡琛)[28] H. M. Hu(胡海明)[1] J. F. Hu(胡继峰)[49A,49C] T. Hu(胡涛)[1,a] Y. Hu(胡誉)[1] G. S. Huang(黄光顺)[46,a] J. S. Huang(黄金书)[15] X. T. Huang(黄性涛)[33] Y. Huang(黄勇)[29] T. Hussain[48] Q. Ji(纪全)[1] Q. P. Ji(姬清平)[30] X. B. Ji(季晓斌)[1] X. L. Ji(季筱璐)[1,a] L. W. Jiang(姜鲁文)[51] X. S. Jiang(江晓山)[1,a] X. Y. Jiang(蒋兴雨)[30] J. B. Jiao(焦健斌)[33] Z. Jiao(焦铮)[17] D. P. Jin(金大鹏)[1,a] S. Jin(金山)[1] T. Johansson[50] A. Julin[43] N. Kalantar-Nayestanaki[25] X. L. Kang(康晓琳)[1] X. S. Kang(康晓坤)[30] M. Kavatsyuk[25] B. C. Ke(柯百谦)[5] P. Kiese[22] R. Kliemt[14] B. Kloss[22] O. B. Kolcu[40B,h] B. Kopf[4] M. Kornicer[42] A. Kupsc[50] W. Kühn[24] J. S. Lange[24] M. Lara[19] P. Larin[14] C. Leng[49C] C. Li(李翠)[50] Cheng Li(李澄)[46,a] D. M. Li(李德民)[53] F. Li(李飞)[1,a] F. Y. Li(李峰云)[31] G. Li(李刚)[1] H. B. Li(李海波)[1] J. C. Li(李家才)[1] Jin Li(李瑾)[32] K. Li(李科)[33] K. Li(李康)[13] Lei Li(李蕾)[3] P. R. Li(李培荣)[41] Q. Y. Li(李启云)[33] T. Li(李腾)[33] W. D. Li(李卫东)[1] W. G. Li(李卫国)[1] X. L. Li(李晓玲)[33] X. N. Li(李小男)[1,a] X. Q. Li(李学潜)[30] Z. B. Li(李志兵)[38] H. Liang(梁昊)[46,a] Y. F. Liang(梁勇飞)[36] Y. T. Liang(梁羽铁)[24] G. R. Liao(廖广睿)[11] D. X. Lin(林德旭)[14] B. J. Liu(刘北江)[1] C. X. Liu(刘春秀)[1] D. Liu(刘栋)[46,a] F. H. Liu(刘福虎)[35] Fang Liu(刘芳)[1] Feng Liu(刘峰)[6] H. B. Liu(刘宏邦)[12] H. H. Liu(刘欢欢)[1] H. H. Liu(刘慧慧)[16] H. M. Liu(刘怀民)[1] J. Liu(刘杰)[1] J. B. Liu(刘建北)[46,a] J. P. Liu(刘觉平)[51] J. Y. Liu(刘晶译)[1] K. Liu(刘凯)[39] K. Y. Liu(刘魁勇)[27] L. D. Liu(刘兰雕)[31] P. L. Liu(刘佩莲)[1,a] Q. Liu(刘倩)[41] S. B. Liu(刘树彬)[46,a] X. Liu(刘翔)[26] Y. B. Liu(刘玉斌)[30] Z. A. Liu(刘振安)[1,a] Zhiqing Liu(刘智青)[22] H. Loehner[25] X. C. Lou(娄辛丑)[1,a,g] H. J. Lu(吕海江)[17] J. G. Lu(吕军光)[1,a] Y. Lu(卢宇)[1] Y. P. Lu(卢云鹏)[1,a] C. L. Luo(罗成林)[28] M. X. Luo(罗民兴)[52] T. Luo[42] X. L. Luo(罗小兰)[1,a] X. R. Lyu(吕晓睿)[41] F. C. Ma(马凤才)[27] H. L. Ma(马海龙)[1] L. L. Ma(马连良)[33] Q. M. Ma(马秋梅)[1] T. Ma(马天)[1] X. N. Ma(马旭宁)[30] X. Y. Ma(马骁妍)[1,a] Y. M. Ma(马玉明)[33] F. E. Maas[14] M. Maggiora[49A,49C] Y. J. Mao(冒亚军)[31] Z. P. Mao(毛泽普)[1] S. Marcello[49A,49C] J. G. Messchendorp[25] J. Min(闵建)[1,a] T. J. Min(闵天觉)[1]

R. E. Mitchell[19] X. H. Mo(莫晓虎)[1,a] Y. J. Mo(莫玉俊)[6] C. Morales Morales[14] N. Yu. Muchnoi[9,e] H. Muramatsu[43] Y. Nefedov[23] F. Nerling[14] I. B. Nikolaev[9,e] Z. Ning(宁哲)[1,a] S. Nisar[8] S. L. Niu(牛顺利)[1,a] X. Y. Niu(牛讯伊)[1] S. L. Olsen(马鹏)[32] Q. Ouyang(欧阳群)[1,a] S. Pacetti[20B] Y. Pan(潘越)[46,a] P. Patteri[20A] M. Pelizaeus[4] H. P. Peng(彭海平)[46,a] K. Peters[10,i] J. Pettersson[50] J. L. Ping(平加伦)[28] R. G. Ping(平荣刚)[1] R. Poling[43] V. Prasad[1] H. R. Qi(漆红荣)[2] M. Qi(祁鸣)[29] S. Qian(钱森)[1,a] C. F. Qiao(乔从丰)[41] L. Q. Qin(秦丽清)[33] N. Qin(覃拈)[51] X. S. Qin(秦小帅)[1] Z. H. Qin(秦中华)[1,a] J. F. Qiu(邱进发)[1] K. H. Rashid[48] C. F. Redmer[22] M. Ripka[22] G. Rong(荣刚)[1] Ch. Rosner[14] X. D. Ruan(阮向东)[12] V. Santoro[21A] A. Sarantsev[23,f] M. Savrié[21B] K. Schoenning[50] S. Schumann[22] W. Shan(单葳)[31] M. Shao(邵明)[46,a] C. P. Shen(沈成平)[2] P. X. Shen(沈培迅)[30] X. Y. Shen(沈肖雁)[1] H. Y. Sheng(盛华义)[1] W. M. Song(宋维民)[1] X. Y. Song(宋欣颖)[1] S. Sosio[49A,49C] S. Spataro[49A,49C] G. X. Sun(孙功星)[1] J. F. Sun(孙俊峰)[15] S. S. Sun(孙胜森)[1] Y. J. Sun(孙勇杰)[46,a] Y. Z. Sun(孙永昭)[1] Z. J. Sun(孙志嘉)[1,a] Z. T. Sun(孙振田)[19] C. J. Tang(唐昌建)[36] X. Tang(唐晓)[1] I. Tapan[40C] E. H. Thorndike[44] M. Tiemens[25] M. Ullrich[24] I. Uman[40D] G. S. Varner[42] B. Wang(王斌)[30] B. L. Wang(王滨龙)[41] D. Wang(王东)[31] D. Y. Wang(王大勇)[31] K. Wang(王科)[1,a] L. L. Wang(王亮亮)[1] L. S. Wang(王灵淑)[1] M. Wang(王萌)[33] P. Wang(王平)[1] P. L. Wang(王佩良)[1] W. Wang(王炜)[1,a] W. P. Wang(王维平)[46,a] X. F. Wang(王雄飞)[39] Y. D. Wang(王雅迪)[14] Y. F. Wang(王贻芳)[1,a] Y. Q. Wang(王亚乾)[22] Z. Wang(王铮)[1,a] Z. G. Wang(王志刚)[1,a] Z. H. Wang(王志宏)[46,a] Z. Y. Wang(王至勇)[1] T. Weber[22] D. H. Wei(魏代会)[11] P. Weidenkaff[22] S. P. Wen(文硕频)[1] U. Wiedner[4] M. Wolke[50] L. H. Wu(伍灵慧)[1] Z. Wu(吴智)[1,a] L. Xia(夏磊)[46,a] L. G. Xia(夏力钢)[39] Y. Xia(夏宇)[18] D. Xiao(肖栋)[1] H. Xiao(肖浩)[47] Z. J. Xiao(肖振军)[28] Y. G. Xie(谢宇广)[1,a] Q. L. Xiu(修青磊)[1,a] G. F. Xu(许国发)[1] L. Xu(徐雷)[1] Q. J. Xu(徐庆君)[13] Q. N. Xu(徐庆年)[41] X. P. Xu(徐新平)[37] L. Yan(严亮)[49A,49C] W. B. Yan(鄢文标)[46,a] W. C. Yan(闫文成)[46,a] Y. H. Yan(颜永红)[18] H. J. Yang(杨海军)[34,j] H. X. Yang(杨洪勋)[1] L. Yang(杨柳)[51] Y. X. Yang(杨永栩)[11] M. Ye(叶梅)[1,a] M. H. Ye(叶铭汉)[7] J. H. Yin(殷俊昊)[1] B. X. Yu(俞伯祥)[1,a] C. X. Yu(喻纯旭)[30] J. S. Yu(俞洁晟)[26] C. Z. Yuan(苑长征)[1] W. L. Yuan(袁文龙)[29] Y. Yuan(袁野)[1] A. Yuncu[40B,b] A. A. Zafar[48] A. Zallo[20A] Y. Zeng(曾云)[18] Z. Zeng(曾哲)[46,a] B. X. Zhang(张丙新)[1] B. Y. Zhang(张炳云)[1,a] C. Zhang(张驰)[29] C. C. Zhang(张长春)[1] D. H. Zhang(张达华)[1] H. H. Zhang(张宏浩)[38] H. Y. Zhang(章红宇)[1,a] J. J. Zhang(张佳佳)[1] J. L. Zhang(张杰磊)[1] J. Q. Zhang(张敬庆)[1] J. W. Zhang(张家文)[1,a] J. Y. Zhang(张建勇)[1] J. Z. Zhang(张景芝)[1] K. Zhang(张坤)[1] L. Zhang(张磊)[1] X. Y. Zhang(张学尧)[33] Y. Zhang(张瑶)[1] Y. H. Zhang(张银鸿)[1,a] Y. N. Zhang(张宇宁)[41] Y. T. Zhang(张亚腾)[46,a] Yu Zhang(张宇)[41] Z. H. Zhang(张正好)[6] Z. P. Zhang(张子平)[46] Z. Y. Zhang(张振宇)[51] G. Zhao(赵光)[1] J. W. Zhao(赵京伟)[1,a] J. Y. Zhao(赵静宜)[1] J. Z. Zhao(赵京周)[1,a] Lei Zhao(赵雷)[46,a] Ling Zhao(赵玲)[1] M. G. Zhao(赵明刚)[30] Q. Zhao(赵强)[1] Q. W. Zhao(赵庆旺)[1] S. J. Zhao(赵书俊)[53] T. C. Zhao(赵天池)[1] Y. B. Zhao(赵豫斌)[1,a] Z. G. Zhao(赵政国)[46,a] A. Zhemchugov[23,c] B. Zheng(郑波)[47] J. P. Zheng(郑建平)[1,a] W. J. Zheng(郑文静)[33] Y. H. Zheng(郑阳恒)[41] B. Zhong(钟彬)[28] L. Zhou(周莉)[1,a] X. Zhou(周详)[51] X. K. Zhou(周晓康)[46,a] X. R. Zhou(周小蓉)[46,a] X. Y. Zhou(周兴玉)[1] K. Zhu(朱凯)[1] K. J. Zhu(朱科军)[1,a] S. Zhu(朱帅)[1] S. H. Zhu(朱世海)[45] X. L. Zhu(朱相雷)[39] Y. C. Zhu(朱莹春)[46,a] Y. S. Zhu(朱永生)[1] Z. A. Zhu(朱自安)[1] J. Zhuang(庄建)[1,a] L. Zotti[49A,49C] B. S. Zou(邹冰松)[1] J. H. Zou(邹佳恒)[1]

(BESIII Collaboration)

[1] Institute of High Energy Physics, Beijing 100049, China
[2] Beihang University, Beijing 100191, China
[3] Beijing Institute of Petrochemical Technology, Beijing 102617, China
[4] Bochum Ruhr-University, D-44780 Bochum, Germany
[5] Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
[6] Central China Normal University, Wuhan 430079, China
[7] China Center of Advanced Science and Technology, Beijing 100190, China
[8] COMSATS Institute of Information Technology, Lahore, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan
[9] G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia
[10] GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany
[11] Guangxi Normal University, Guilin 541004, China
[12] Guangxi University, Nanning 530004, China
[13] Hangzhou Normal University, Hangzhou 310036, China
[14] Helmholtz Institute Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
[15] Henan Normal University, Xinxiang 453007, China
[16] Henan University of Science and Technology, Luoyang 471003, China
[17] Huangshan College, Huangshan 245000, China
[18] Hunan University, Changsha 410082, China
[19] Indiana University, Bloomington, Indiana 47405, USA
[20] (A)INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy; (B)INFN and University of Perugia, I-06100, Perugia, Italy
[21] (A)INFN Sezione di Ferrara, I-44122, Ferrara, Italy; (B)University of Ferrara, I-44122, Ferrara, Italy
[22] Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
[23] Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
[24] Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany

^{25} KVI-CART, University of Groningen, NL-9747 AA Groningen, The Netherlands

^{26} Lanzhou University, Lanzhou 730000, China

^{27} Liaoning University, Shenyang 110036, China

^{28} Nanjing Normal University, Nanjing 210023, China

^{29} Nanjing University, Nanjing 210093, China

^{30} Nankai University, Tianjin 300071, China

^{31} Peking University, Beijing 100871, China

^{32} Seoul National University, Seoul, 151-747 Korea

^{33} Shandong University, Jinan 250100, China

^{34} Shanghai Jiao Tong University, Shanghai 200240, China

^{35} Shanxi University, Taiyuan 030006, China

^{36} Sichuan University, Chengdu 610064, China

^{37} Soochow University, Suzhou 215006, China

^{38} Sun Yat-Sen University, Guangzhou 510275, China

^{39} Tsinghua University, Beijing 100084, China

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

^{41} University of Chinese Academy of Sciences, Beijing 100049, China

^{42} University of Hawaii, Honolulu, Hawaii 96822, USA

^{43} University of Minnesota, Minneapolis, Minnesota 55455, USA

^{44} University of Rochester, Rochester, New York 14627, USA

^{45} University of Science and Technology Liaoning, Anshan 114051, China

^{46} University of Science and Technology of China, Hefei 230026, China

^{47} University of South China, Hengyang 421001, China

^{48} University of the Punjab, Lahore-54590, Pakistan

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

^{50} Uppsala University, Box 516, SE-75120 Uppsala, Sweden

^{51} Wuhan University, Wuhan 430072, China

^{52} Zhejiang University, Hangzhou 310027, China

^{53} Zhengzhou University, Zhengzhou 450001, China

^{a} Also at State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, China

^{b} Also at Bogazici University, 34342 Istanbul, Turkey

^{c} Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia

^{d} Also at the Functional Electronics Laboratory, Tomsk State University, Tomsk, 634050, Russia

^{e} Also at the Novosibirsk State University, Novosibirsk, 630090, Russia

^{f} Also at the NRC "Kurchatov Institute, PNPI, 188300, Gatchina, Russia

^{g} Also at University of Texas at Dallas, Richardson, Texas 75083, USA

^{h} Also at Istanbul Arel University, 34295 Istanbul, Turkey

^{i} Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany

^{j} Also at Institute of Nuclear and Particle Physics, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai 200240, China

Abstract: A measurement of the number of J/ψ events collected with the BESIII detector in 2009 and 2012 is performed using inclusive decays of the J/ψ. The number of J/ψ events taken in 2009 is recalculated to be $(223.7 \pm 1.4) \times 10^6$, which is in good agreement with the previous measurement, but with significantly improved precision due to improvements in the BESIII software. The number of J/ψ events taken in 2012 is determined to be $(1086.9 \pm 6.0) \times 10^6$. In total, the number of J/ψ events collected with the BESIII detector is measured to be $(1310.6 \pm 7.0) \times 10^6$, where the uncertainty is dominated by systematic effects and the statistical uncertainty is negligible.

1   Introduction

Studies of J/ψ decays have provided a wealth of information since the discovery of the J/ψ in 1974 [1, 2]. Decays of the J/ψ offer a clean laboratory for light hadron spectroscopy, provide an insight into decay mechanisms and help in distinguishing between conventional hadronic states and exotic states.

A lot of important progress in light hadron spectroscopy has been achieved based on a sample of $(225.3 \pm 2.8) \times 10^6$ J/ψ events collected by the BESIII experiment [3] in 2009. To further comprehensively study the J/ψ decay mechanism, investigate the light hadron spectrum, and search for exotic states, e.g. glueballs, hybrids and multi-quark states, an additional, larger J/ψ sam-

ple was collected in 2012. A precise determination of the number of J/ψ events is essential for analyses based on these data samples. With improvements in the BESIII software, particularly in Monte Carlo (MC) simulations and the reconstruction of tracks in the main drift chamber (MDC), it is possible to perform a more precise measurement of the number of J/ψ events taken in 2009 and 2012. The relevant data samples used in this analysis are listed in Table 1.

Table 1. Data samples used in the determination of the number of J/ψ events collected in 2009 and 2012.

data set	$\sqrt{s}$	$\mathcal{L}_{\text{online}}$	date(duration) (MM/DD/YYYY)
J/ψ	3.097 GeV	323pb^{-1}	4/10/2012–5/22/2012
QED1	3.08 GeV	13pb^{-1}	4/8/2012
QED2	3.08 GeV	17pb^{-1}	5/23/2012–5/24/2012
ψ(3686)	3.686 GeV	7.5pb^{-1}	5/26/2012
J/ψ	3.097 GeV	82pb^{-1}	6/12/2009–7/28/2009
QED	3.08 GeV	0.3pb^{-1}	6/19/2009
ψ(3686)	3.686 GeV	150pb^{-1}	3/7/2009–4/14/2009

We implement the same method as that used in the previous study [4] to determine the number of J/ψ events. The advantage of this approach is that the detection efficiency of inclusive J/ψ decays can be extracted directly from the data sample taken at the peak of the ψ(3686). This is useful because the correction factor of the detection efficiency is less dependent on the MC model for the inclusive J/ψ decay and therefore the systematic uncertainty can be reduced significantly. The number of J/ψ events, $N_{\text{J/ψ}}$, is calculated as

$$N_{\text{J/ψ}} = \frac{N_{\text{sel}} - N_{\text{bg}}}{\epsilon_{\text{trig}} \times \epsilon_{\text{data}}^{\psi(3686)} \times f_{\text{cor}}}, \qquad (1)$$

where N_{sel} is the number of inclusive J/ψ events selected from the J/ψ data; N_{bg} is the number of background events estimated with continuum data taken at $\sqrt{s} = 3.08\,\text{GeV}$; ϵ_{trig} is the trigger efficiency; $\epsilon_{\text{data}}^{\psi(3686)}$ is the inclusive J/ψ detection efficiency determined experimentally using the J/ψ sample from the reaction $\psi(3686) \to \pi^+\pi^- \text{J/ψ}$. f_{cor} is a correction factor that accounts for the difference in the detection efficiency between the J/ψ events produced at rest and those produced in $\psi(3686) \to \pi^+\pi^- \text{J/ψ}$. f_{cor} is expected to be approximately unity, and is determined by the MC simulation sample with

$$f_{\text{cor}} = \frac{\epsilon_{\text{MC}}^{\text{J/ψ}}}{\epsilon_{\text{MC}}^{\psi(3686)}}, \qquad (2)$$

where $\epsilon_{\text{MC}}^{\text{J/ψ}}$ is the detection efficiency of inclusive J/ψ events determined from the MC sample of J/ψ events

produced directly in electron-positron collisions, and $\epsilon_{\text{MC}}^{\psi(3686)}$ is that from the MC sample of $\psi(3686) \to \pi^+\pi^- \text{J/ψ}$ (J/ψ → inclusive) events. In MC simulation, the J/ψ and ψ(3686) resonances are simulated with KKMC [5]. The known decay modes of the J/ψ and ψ(3686) are generated by EVTGEN [6, 7] with branching fractions taken from the Review of Particle Physics [8], while the remaining decays are generated according to the LUNDCHARM model [9, 10]. All of the MC events are fed into a GEANT4-based [11] simulation package, which takes into account the detector geometry and response.

2 Inclusive J/ψ selection criteria

To distinguish the inclusive J/ψ decays from Quantum Electrodynamics (QED) processes (i.e. Bhabha and dimuon events) and background events from cosmic rays and beam-gas interactions, a series of selection criteria are applied to the candidate events. The charged tracks are required to be detected in the MDC within a polar angle range of $|\cos\theta| < 0.93$, and to have a momentum of $p < 2.0\,\text{GeV}/c$. Each track is required to originate from the interaction region by restricting the distance of closest approach to the run-dependent interaction point in the radial direction, $V_r < 1$ cm, and in the beam direction, $|V_z| < 15$ cm. For photon clusters in the electromagnetic calorimeter (EMC), the deposited energy is required to be greater than 25 (50) MeV for the barrel (endcap) region of $|\cos\theta| < 0.83$ ($0.86 < |\cos\theta| < 0.93$). In addition, the EMC cluster timing T must satisfy $0 < T \leqslant 700$ ns, which is used to suppress electronics noise and energy deposits unrelated to the event.
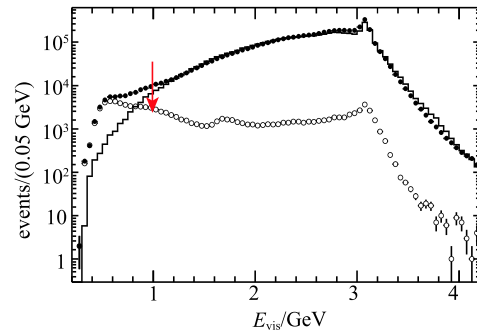

Fig. 1. Distributions of the visible energy E_{vis} for J/ψ data (dots with error bars), continuum data at $\sqrt{s} = 3.08$ GeV (open circles with error bars) and MC simulation of inclusive J/ψ events (histogram). The arrow indicates the minimum E_{vis} required to select inclusive events.

The candidate event must contain at least two charged tracks. The visible energy E_{vis}, defined as the sum of charged particle energies computed from the track momenta by assuming a pion mass and from the neutral

shower energies deposited in the EMC, is required to be greater than 1.0 GeV. A comparison of the E_{vis} distribution between the J/ψ data, the data taken at $\sqrt{s} = 3.08$ GeV, and the inclusive J/ψ MC sample is illustrated in Fig. 1. The requirement $E_{\text{vis}} > 1.0$ GeV removes one third of the background events while retaining 99.4% of the signal events.
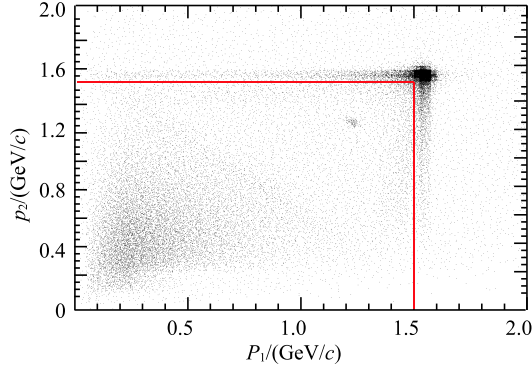

Fig. 2.   Scatter plot of the momenta of the charged tracks for 2-prong events in data. The cluster around 1.55 GeV/c corresponds to the contribution from lepton pairs and the cluster at 1.23 GeV/c comes from J/ψ → p$\bar{\text{p}}$. Most of lepton pairs are removed with the requirements on the two charged tracks, $p_1 < 1.5$ GeV/c and $p_2 < 1.5$ GeV/c, as indicated by the solid lines.
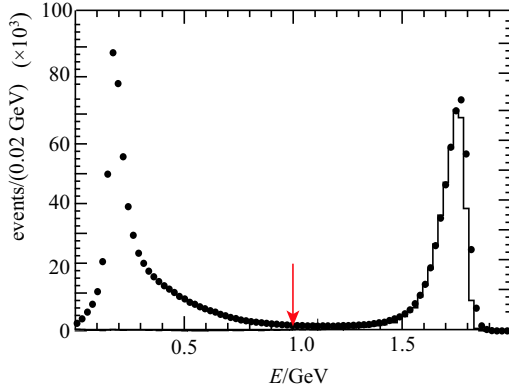

Fig. 3.   Distributions of deposited energy in the EMC for the charged tracks of 2-prong events for J/ψ data (dots with error bars) and for the combined, normalized MC simulations of $e^+e^- \rightarrow e^+e^-(\gamma)$ and J/ψ $\rightarrow e^+e^-(\gamma)$ (histogram).

Since Bhabha ($e^+e^- \rightarrow e^+e^-$) and dimuon ($e^+e^- \rightarrow \mu^+\mu^-$) events are two-body decays, each charged track carries the same energy, close to half of the center-of-mass energy. Therefore, for events with only two charged tracks, we require that the momentum of each charged track is less than 1.5 GeV/c in order to remove Bhabha and dimuon events. This requirement is depicted by the solid lines in the scatter plot of the momenta of the two charged tracks (Fig. 2). The Bhabha events are characterized by a significant peak around 1.5 GeV in the

distribution of energy deposited in the EMC, shown in Fig. 3. Hence an additional requirement that the energy deposited in the EMC for each charged track is less than 1 GeV is applied to further reject the Bhabha events.
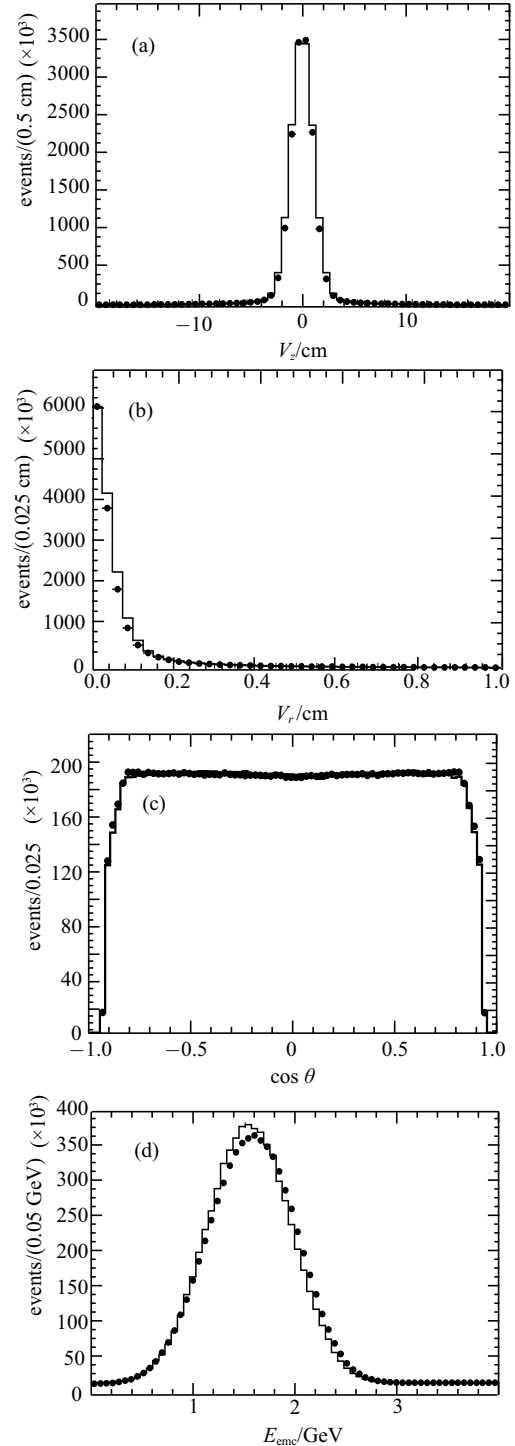

Fig. 4.   Comparison of distributions between J/ψ data (dots with error bars) and MC simulation of inclusive J/ψ (histogram): (a) V_z, (b) V_r, (c) $\cos\theta$ of charged tracks, (d) total energy deposited in the EMC.

After the above requirements, $N_{\text{sel}} = (854.60 \pm 0.03) \times 10^6$ candidate events are selected from the J/ψ data taken in 2012. The distributions of the track parameters of closest approach in the beam line and radial directions (V_z and V_r), the polar angle ($\cos\theta$), and the total energy deposited in the EMC (E_{EMC}) after subtracting background events estimated with the continuum data taken at $\sqrt{s} = 3.08$ GeV (see Sec. 3 for details) are shown in Fig. 4. Reasonable agreement between the data and MC samples is observed. The multiplicity of charged tracks (N_{good}) is shown in Fig. 5, where the MC sample generated according to the LUNDCHARM model agrees very well with the data while the MC sample generated without the LUNDCHARM model deviates from the data. The effect of this discrepancy on the determination of the number of J/ψ events is small, as described in Sec. 6.
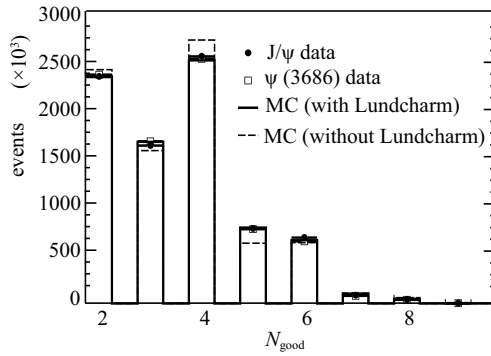

Fig. 5. Distributions of the reconstructed charged track multiplicity of inclusive J/ψ events for J/ψ data (dots with error bars) and ψ(3686) data (squares with error bars) and MC simulation generated with and without the LUND-CHARM model (solid and dashed histograms, respectively).

3 Background analysis

In this analysis, the data samples taken at $\sqrt{s} = 3.08$ GeV and in close chronological order to the J/ψ sample are used to estimate the background due to QED processes, beam-gas interactions and cosmic rays. To normalize the selected background events to the J/ψ data, the integrated luminosity for the data samples taken at the J/ψ peak and at $\sqrt{s} = 3.08$ GeV is determined using the precess $e^+e^- \rightarrow \gamma\gamma$, respectively.

To determine the integrated luminosity, the candidate events $e^+e^- \rightarrow \gamma\gamma$ are selected by requiring at least two showers in the EMC. It is further required that the energy of the second most energetic shower is between 1.2 and 1.6 GeV and that the polar angles of the two showers are in the range $|\cos\theta| < 0.8$. The number of signal events is determined from the number of events in the signal region $|\Delta\phi| < 2.5°$ and the background is estimated from those in the sideband region $2.5° < |\Delta\phi| < 5°$,

where $\Delta\phi = |\phi_{\gamma 1} - \phi_{\gamma 2}| - 180°$ and $\phi_{\gamma 1/2}$ is the azimuthal angle of the photon. Taking into account the detector efficiency obtained from the MC simulation and the cross section of the QED process $e^+e^- \rightarrow \gamma\gamma$, the integrated luminosities of the J/ψ data sample and the sample taken at $\sqrt{s} = 3.08$ GeV taken in 2012 are determined to be $(315.02 \pm 0.14)\, \text{pb}^{-1}$ and $(30.84 \pm 0.04)\, \text{pb}^{-1}$, respectively, where the errors are statistical only.

After applying the same selection criteria as for the J/ψ data, $N_{3.08} = 1,440,376 \pm 1,200$ events are selected from the continuum data taken at $\sqrt{s} = 3.08$ GeV. Assuming the same detection efficiency at $\sqrt{s} = 3.08$ GeV as for the J/ψ peak and taking into account the energy-dependent cross section of the QED processes, the number of background events for the J/ψ sample, N_{bg}, is estimated to be

$$N_{\text{bg}} = N_{3.08} \times \frac{\mathcal{L}_{\text{J/ψ}}}{\mathcal{L}_{3.08}} \times \frac{s_{3.08}}{s_{\text{J/ψ}}} = (14.55 \pm 0.02) \times 10^6, \quad (3)$$

where $\mathcal{L}_{\text{J/ψ}}$ and $\mathcal{L}_{3.08}$ are the integrated luminosities for the J/ψ data sample and the data sample taken at $\sqrt{s} = 3.08$ GeV, respectively, and $s_{\text{J/ψ}}$ and $s_{3.08}$ are the corresponding squares of the center-of-mass energies. The background is calculated to be 1.7% of the number of selected inclusive J/ψ events taken in 2012.

According to the studies of the MC sample and the V_z distribution, the QED background fraction is found to be about 1.5% of the total data. $J/ψ \rightarrow \mu^+\mu^-$ events are selected and those MDC hits away from $\mu^+\mu^-$ tracks come from beam related background, electronic noise etc. The result indicates the beam conditions for the data taken in 2009 were worse, the corresponding noise level was higher and the background was much higher than for the 2012 sample. With the same method, the total background (including the QED contribution) for the 2009 sample is estimated to be 3.7%.

4 Determination of the detection efficiency and correction factor

In the previous study, the detection efficiency was determined using a MC simulation of the reaction J/ψ → inclusive, assuming that both the physics process of the inclusive J/ψ decay and the detector response were simulated well. In this analysis, to reduce the uncertainty related to the discrepancy between the MC simulation and the data, the detection efficiency is determined experimentally using a sample of J/ψ events from the reaction $\psi(3686) \rightarrow \pi^+\pi^- J/ψ$. To ensure that the beam conditions and detector status are similar to those of the sample collected at the J/ψ peak, a dedicated ψ(3686) sample taken on May 26, 2012 is used for this study.

To select $\psi(3686) \rightarrow \pi^+\pi^- J/ψ$ events, there must be at least two soft pions with opposite charge in the

MDC within the polar angle range $|\cos\theta| < 0.93$, having $V_r < 1$ cm and $|V_z| < 15$ cm, and momenta less than 0.4 GeV/c. No further selection criteria on the remaining charged tracks or showers are required. The distribution of the invariant mass recoiling against all possible soft $\pi^+\pi^-$ pairs is shown in Fig. 6 (a). A prominent peak around 3.1 GeV/c^2, corresponding to the decay of $\psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to$ inclusive, is observed over a smooth background. The total number of inclusive J/ψ events, $N_{\rm inc} = (1147.8\pm1.9)\times10^3$, is obtained by fitting a double-Gaussian function for the J/ψ signal plus a second-order Chebychev polynomial for the background to the $\pi^+\pi^-$ recoil mass spectrum.
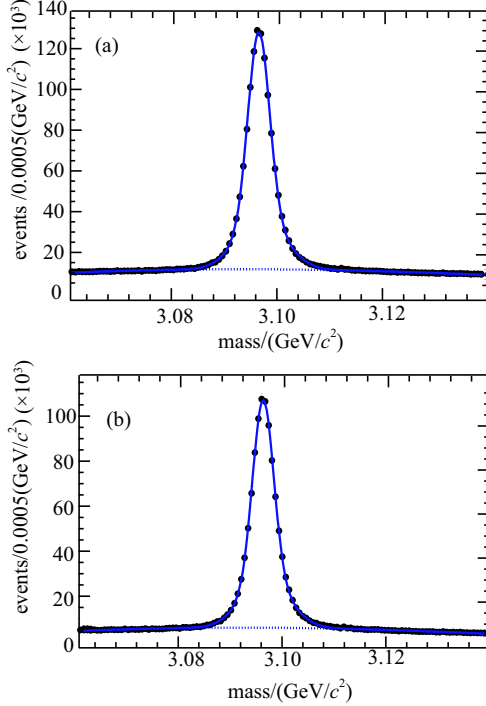

Fig. 6.   Invariant mass recoiling against selected $\pi^+\pi^-$ pairs for the $\psi(3686)$ data sample. The curves are the results of the fit described in the text: (a) for the sample with soft pion selection criteria applied, and (b) for the sample with the addition of the inclusive J/ψ event selection criteria applied.

To measure the detection efficiency of inclusive J/ψ events, the same selection criteria as described in Sec. 2 are applied to the remaining charged tracks and showers at the event level. The distribution of the invariant mass recoiling against $\pi^+\pi^-$ for the remaining events is shown in Fig. 6 (b); it is fitted with the same function as described above. The number of selected inclusive J/ψ events, $N_{\rm inc}^{\rm sel}$, is determined to be $(877.6\pm1.7)\times10^3$. The detection efficiency of inclusive J/ψ events, $\epsilon_{\rm data}^{\psi(3686)} = (76.46\pm0.07)\%$, is calculated from the ratio of the number of inclusive J/ψ events with and without the inclusive J/ψ event selection criteria applied.

Since the J/ψ particle in the decay $\psi(3686) \to \pi^+\pi^- J/\psi$ is not at rest, a correction factor, defined in Eq. (2), is used to take into account the kinematical effect on the detection efficiency of the inclusive J/ψ event selection. Two large statistics, inclusive $\psi(3686)$ and J/ψ MC samples are produced and are subjected to the same selection criteria as the data samples. The detection efficiencies of inclusive J/ψ events are determined to be $\epsilon_{\rm MC}^{\psi(3686)} = (75.76\pm0.06)\%$, and $\epsilon_{\rm MC}^{J/\psi} = (76.58\pm0.04)\%$ for the two inclusive MC samples, respectively. The correction factor $f_{\rm cor}$ for the detection efficiency is therefore taken as

$$f_{\rm cor} = \frac{\epsilon_{\rm MC}^{J/\psi}}{\epsilon_{\rm MC}^{\psi(3686)}} = 1.0109 \pm 0.0009. \qquad (4)$$

5   The number of J/ψ events

Using Eq. (1), the number of J/ψ events collected in 2012 is calculated to be $(1086.90\pm0.04)\times10^6$. The values used in this calculation are summarized in Table 2. The trigger efficiency of the BESIII detector is 100%, based on the study of various reactions [12]. With the same procedure, the number of J/ψ events taken in 2009 is determined to be $(223.72\pm0.01)\times10^6$. Here, the statistical uncertainty is from the number of J/ψ events only, while the statistical fluctuation of $N_{\rm bg}$ is taken into account as part of the systematic uncertainty (see Sec. 6.4). The systematic uncertainties from different sources are discussed in detail in Sec. 6.

Table 2.   Summary of the values used in the calculation and the resulting number of J/ψ events.

item	2012	2009
$N_{\rm sel}$	$(854.60\pm0.03)\times10^6$	$(179.63\pm0.01)\times10^6$
$N_{\rm bg}$	$(14.55\pm0.02)\times10^6$	$(6.58\pm0.04)\times10^6$
$\epsilon_{\rm trig}$	1.00	1.00
$\epsilon_{\rm data}^{\psi(3686)}$	0.7646 ± 0.0007	0.7655 ± 0.0001
$\epsilon_{\rm MC}^{\psi(3686)}$	0.7576 ± 0.0006	0.7581 ± 0.0005
$\epsilon_{\rm MC}^{J/\psi}$	0.7658 ± 0.0004	0.7660 ± 0.0004
$f_{\rm cor}$	1.0109 ± 0.0009	1.0105 ± 0.0009
$N_{J/\psi}$	$(1086.90\pm0.04)\times10^6$	$(223.72\pm0.01)\times10^6$

6   Systematic uncertainty

The sources of systematic uncertainty and their corresponding contributions are summarized in Table 3, and are discussed in detail below.

6.1   MC model uncertainty

In the measurement of the number of J/ψ events, only the efficiency correction factor, $f_{\rm cor}$, is dependent

on the MC simulation. To evaluate the uncertainty due to the MC model, we generate a set of MC samples without the LUNDCHARM model and compare the correction factor determined using these samples to its nominal value. According to the distributions of the charged track multiplicity shown in Fig. 5, the MC simulation without the LUNDCHARM model poorly describes the data, which means this method will overestimate the systematic uncertainty. The studies show that the correction factor has a slight dependence on the MC mode of inclusive J/ψ decays. To be conservative, the change in the correction factor, 0.42% (0.36%), is taken as the systematic uncertainty due to the MC model on the number of J/ψ events taken in 2012 (2009).

6.2   Track reconstruction efficiency

According to studies of the track reconstruction efficiency, the difference in track reconstruction efficiencies between the MC and data samples of J/ψ decays is less than 1% for each charged track.

In the analysis, the ψ(3686) data sample used to determine the detection efficiency is taken in close chronological order to the J/ψ sample. The consistency of track reconstruction efficiency between the MC and data samples in ψ(3686) decays is assumed to be exactly the same as that in J/ψ decays. Therefore the track reconstruction efficiencies in both J/ψ and ψ(3686) MC samples are varied by −1% to evaluate the uncertainty due to the MDC tracking. As expected, the change in the correction factor is very small, 0.03%, and this value is taken as a systematic uncertainty.

In the determination of the number of J/ψ events taken in 2009, the J/ψ and ψ(3686) data samples were collected at different times, which may lead to slight differences in the tracking efficiency between the two data sets due to the imperfect description of detector performance and response in the MC simulation. To estimate the corresponding systematic uncertainty, we adjust the track reconstruction efficiency by −0.5% in the J/ψ MC sample, keeping it unchanged for the ψ(3686) MC sample. The resulting change in the correction factor, 0.30%, is taken as a systematic uncertainty on the number of J/ψ events in 2009.

6.3   Fit to the J/ψ peak

In this measurement, the selection efficiency of inclusive J/ψ events is estimated experimentally with the ψ(3686) data sample (ψ(3686) → π⁺π⁻J/ψ), and the yield of J/ψ events used in the efficiency calculation is determined by a fit to the invariant mass spectra recoiling against π⁺π⁻. The following systematic uncertainties of the fit are considered: (a) the fit: we propagate the statistical uncertainties of the J/ψ signal yield from the fit to the selection efficiency, and the resulting un-

certainties, 0.09% and 0.08% for $\epsilon_{\text{data}}^{\psi(3686)}$ and $\epsilon_{\text{MC}}^{\psi(3686)}$, respectively, are considered to be the uncertainty from the fit itself. (b) the fit range: we change the fit range on the π⁺π⁻ recoiling mass from [3.07, 3.13] GeV/c^2 to [3.08, 3.12] GeV/c^2, and the resulting difference, 0.08% is taken as a systematic uncertainty. (c) the signal shape: we perform an alternative fit by describing the J/ψ signal with a histogram obtained from the recoil mass spectrum of π⁺π⁻ in ψ(3686) → π⁺π⁻J/ψ, J/ψ → μ⁺μ⁻, and the resulting change, 0.12%, is considered to be the associated systematic uncertainty. (d) the background shape: the uncertainty due to the background shape, 0.02%, is estimated by replacing the second-order Chebychev polynomial with a first-order Chebychev polynomial. By assuming that all of the sources of systematic uncertainty are independent, the fit uncertainty for the 2012 J/ψ sample, 0.19%, is obtained by adding all of the above effects in quadrature.

The same sources of systematic uncertainty are considered for the J/ψ sample taken in 2009. The fit has an uncertainty of 0.02% for $\epsilon_{\text{data}}^{\psi(3686)}$ and 0.07% for $\epsilon_{\text{MC}}^{\psi(3686)}$. The uncertainties from the fit range, signal function and background shape are 0.02%, 0.15% and 0.02%, respectively. The total uncertainty from the fit for the 2009 data is 0.17%.

6.4   Background uncertainty

In the measurement of the number of J/ψ events, the number of background events from QED processes, cosmic rays, and beam-gas interactions is estimated by normalizing the number of events in the continuum data sample taken at $\sqrt{s}$ = 3.08 GeV according to Eq. (3). Therefore the background uncertainty mainly comes from the normalization method, the statistics of the sample taken at $\sqrt{s}$ = 3.08 GeV, the statistical uncertainty of the integrated luminosity and the uncertainty due to beam associated backgrounds.

In practice, Eq. (3) is improper for the normalization of the background of cosmic rays and beam-gas. The number of cosmic rays is proportional to the time of data taking, while beam-gas interaction backgrounds are related to the vacuum status and beam current during data taking in addition to the time of data taking. Assuming a stable beam and vacuum status, the backgrounds of cosmic rays and beam-gas interactions are proportional to the integrated luminosity. Therefore, the difference in the estimated number of backgrounds between that with and without the energy-dependent factor in Eq. (3) is considered to be the associated systematic uncertainty.

In 2012, two data samples with $\sqrt{s}$ = 3.08 GeV were taken at the beginning and end of the J/ψ data taking. To estimate the uncertainty of the background related with the stability of the beam and vacuum status, we es-

timated the background with Eq. (3) for the two continuum data samples, individually. The maximum change in the nominal results, 0.05%, is taken as the associated systematic uncertainty. In the background estimation for data taken in 2009, only one continuum data sample was taken. The corresponding uncertainty is estimated by comparing the selected background events from the continuum sample to those from the J/ψ data, which is described in detail in Ref. [4].

After considering the above effects, the uncertainties on the number of J/ψ events related to the background are 0.06% and 0.13% for the data taken in 2012 and 2009, respectively. The uncertainties are determined from the quadratic sum of the above individual uncertainties, assuming all of them to be independent.

6.5 Noise mixing

In the BESIII simulation software, the detector noise and machine background are included in the MC simulation by mixing the simulated events with events recorded by a random trigger. To determine the systematic uncertainty associated with the noise realization in the MC simulation, the $\psi(3686)$ MC sample is reconstructed by mixing the noise sample accompanying the J/ψ data taking. The change of the correction factor for the detection efficiency, 0.09%, is taken as the systematic uncertainty due to noise mixing for the number of J/ψ events taken in 2012.

In the determination of the number of J/ψ events collected in 2009, 106 million of $\psi(3686)$ events taken in 2009 are used to determine the detection efficiency, and the corresponding uncertainty related to the noise realization is estimated to be 0.10% with the same method. However, the noise level was not entirely stable during the time of the $\psi(3686)$ data taking. To check the effect on the detection efficiency related to the different noise levels, the $\psi(3686)$ data and the MC samples are divided into three sub-samples, and the detection efficiency and the correction factor are determined for the three sub-samples individually. The resulting maximum change in the number of J/ψ events, 0.06%, is taken as an additional systematic uncertainty associated with the noise realization. The total systematic uncertainty due to the noise is estimated to be 0.12% for the J/ψ events taken in 2009.

6.6 Uncertainty of selection efficiency of two soft pions

According to the MC study, the selection efficiency of soft pions, $\epsilon_{\pi^+\pi^-}$, recoiling against the J/ψ in $\psi(3686) \to$ $\pi^+\pi^- J/\psi$ is found to depend on the multiplicity of the J/ψ decays. Differences between the data and MC samples may lead to a change in the number of J/ψ events. We compare the multiplicity distribution of J/ψ decays in the $\psi(3686) \to \pi^+\pi^- J/\psi$ data sample to that of the J/ψ data at rest to obtain the dependence of $\epsilon_{\pi^+\pi^-}$ in the data. The efficiency determined from the $\psi(3686) \to \pi^+\pi^- J/\psi(J/\psi \to$ inclusive) MC sample, $\epsilon_{\text{MC}}^{\psi(3686)}$ in Eq. (2), is reweighted with the dependence of $\epsilon_{\pi^+\pi^-}$ from the data sample. The resulting change in the number of J/ψ events, 0.28% (0.34%) is taken as the uncertainty for the data taken in 2012 (2009).

The systematic uncertainties from the different sources studied above are summarized in Table 3. The total systematic uncertainty for the number of J/ψ in 2012 (2009), 0.55% (0.63%), is the quadratic sum of the individual uncertainties.

Table 3. Summary of systematic sources and the corresponding contributions to the number of J/ψ events, where the superscript∗ means the error is common for the data samples taken in 2009 and 2012.

sources	2012 (%)	2009(%)
∗MC model uncertainty	0.42	0.36
track reconstruction efficiency	0.03	0.30
fit to J/ψ peak	0.19	0.17
background uncertainty	0.06	0.13
noise mixing	0.09	0.12
∗$\epsilon_{\pi^+\pi^-}$ uncertainty	0.28	0.34
total	0.55	0.63

7 Summary

Using inclusive J/ψ events, the number of J/ψ events collected with the BESIII detector in 2012 is determined to be $N_{J/\psi 2012} = (1086.9 \pm 6.0) \times 10^6$, where the uncertainty is systematic only and the statistical uncertainty is negligible. The number of J/ψ events taken in 2009 is recalculated to be $N_{J/\psi 2009} = (223.7 \pm 1.4) \times 10^6$, which is consistent with the previous measurement [4], but with improved precision.

In summary, the total number of J/ψ events taken with BESIII detector is determined to be $N_{J/\psi} = (1310.6 \pm 7.0) \times 10^6$. Here, the total uncertainty is determined by adding the common uncertainties directly and the independent ones in quadrature.

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