

Number of J/ψ events at BESIII*

M. Ablikim(麦迪娜)¹ M. N. Achasov^{10,b} P. Adlarson⁶⁸ S. Ahmed¹⁴ M. Albrecht⁴ R. Aliberti²⁸
A. Amoroso^{67A,67C} M. R. An(安美儒)³² Q. An(安琪)^{50,64} X. H. Bai(白旭红)⁵⁸ Y. Bai(白羽)⁴⁹ O. Bakina²⁹
R. Baldini Ferroli^{23A} I. Balossino^{24A,1} Y. Ban(班勇)^{39,h} K. Begzsuren²⁶ N. Berger²⁸ M. Bertani^{23A} D. Bettoni^{24A}
F. Bianchi^{67A,67C} J. Bloms⁶¹ A. Bortone^{67A,67C} I. Boyko²⁹ R. A. Briere⁵ H. Cai(蔡浩)⁶⁹ X. Cai(蔡啸)^{1,50}
A. Calcaterra^{23A} G. F. Cao(曹国富)^{1,55} N. Cao(曹宁)^{1,55} S. A. Cetin^{54A} J. F. Chang(常劲帆)^{1,50}
W. L. Chang(常万玲)^{1,55} G. Chelkov^{29,a} G. Chen(陈刚)¹ H. S. Chen(陈和生)^{1,55} M. L. Chen(陈玛丽)^{1,50}
S. J. Chen(陈申见)³⁵ X. R. Chen(陈旭荣)²⁵ Y. B. Chen(陈元柏)^{1,50} Z. J. Chen(陈卓俊)^{20,i} W. S. Cheng(成伟帅)^{67C}
G. Cibinetto^{24A} F. Cossio^{67C} J. J. Cui(催佳佳)⁴² X. F. Cui(崔小非)³⁶ H. L. Dai(代洪亮)^{1,50} J. P. Dai(代建平)⁷¹
X. C. Dai(戴鑫琛)^{1,55} A. Dbeyssi¹⁴ R. E. de Boer⁴ D. Dedovich²⁹ Z. Y. Deng(邓子艳)¹ A. Denig²⁸
I. Denysenko²⁹ M. Destefanis^{67A,67C} F. De Mori^{67A,67C} Y. Ding(丁勇)³³ C. Dong(董超)³⁶ J. Dong(董静)^{1,50}
L. Y. Dong(董燎原)^{1,55} M. Y. Dong(董明义)¹ X. Dong(董翔)⁶⁹ S. X. Du(杜书先)⁷³ P. Egorov^{29,a}
Y. L. Fan(范玉兰)⁶⁹ J. Fang(方建)^{1,50} S. S. Fang(房双世)^{1,55} Y. Fang(方易)¹ R. Farinelli^{24A} L. Fava^{67B,67C}
F. Feldbauer⁴ G. Felici^{23A} C. Q. Feng(封常青)^{50,64} J. H. Feng(冯俊华)⁵¹ M. Fritsch⁴ C. D. Fu(傅成栋)¹
Y. Gao(高扬)^{50,64} Y. Gao(高原宁)^{39,h} I. Garzia^{24A,24B} P. T. Ge(葛潘婷)⁶⁹ C. Geng(耿聪)⁵¹ E. M. Gersabeck⁵⁹
A. Gilman⁶² K. Goetzen¹¹ L. Gong(龚丽)³³ W. X. Gong(龚文煊)^{1,50} W. Gradl²⁸ M. Greco^{67A,67C}
L. M. Gu(谷立民)³⁵ M. H. Gu(顾旻皓)^{1,50} C. Y. Guan(关春懿)^{1,55} A. Q. Guo(郭爱强)²²
A. Q. Guo(郭爱强)²⁵ L. B. Guo(郭立波)³⁴ R. P. Guo(郭如盼)⁴¹ Y. P. Guo(郭玉萍)^{9,f} A. Guskov^{29,a}
T. T. Han(韩婷婷)⁴² W. Y. Han(韩文颖)³² X. Q. Hao(郝喜庆)¹⁵ F. A. Harris⁵⁷ K. K. He(何凯凯)⁴⁷
K. L. He(何康林)^{1,55} F. H. Heinsius⁴ C. H. Heinz²⁸ Y. K. Heng(衡月昆)¹ C. Herold⁵² M. Himmelreich^{11,d}
T. Holtmann⁴ G. Y. Hou(侯国一)^{1,55} Y. R. Hou(侯锐锐)⁵⁵ Z. L. Hou(侯治龙)¹ H. M. Hu(胡海明)^{1,55}
J. F. Hu(胡继峰)^{48,j} T. Hu(胡涛)¹ Y. Hu(胡誉)¹ G. S. Huang(黄光顺)^{50,64} L. Q. Huang(黄麟钦)⁶⁵
X. T. Huang(黄性涛)⁴² Y. P. Huang(黄燕萍)¹ Z. Huang(黄震)^{39,h} T. Hussain⁶⁶ N. Hüsken^{22,28}
W. Ikegami Andersson⁶⁸ W. Imoehl²² M. Irshad^{50,64} S. Jaeger⁴ S. Janchiv²⁶ Q. Ji(纪全)¹ Q. P. Ji(姬清平)¹⁵
X. B. Ji(季晓斌)^{1,55} X. L. Ji(季筱璐)^{1,50} Y. Y. Ji(吉钰瑶)⁴² H. B. Jiang(姜侯兵)⁴² X. S. Jiang(江晓山)¹
J. B. Jiao(焦健斌)⁴² Z. Jiao(焦铮)¹⁸ S. Jin(金山)³⁵ Y. Jin(金毅)⁵⁸ M. Q. Jing(荆茂强)^{1,55} T. Johansson⁶⁸
N. Kalantar-Nayestanaki⁵⁶ X. S. Kang(康晓坤)³³ R. Kappert⁵⁶ M. Kavatsyuk⁵⁶ B. C. Ke(柯百谦)^{1,44} I. K. Keshk⁴
A. Khokaz⁶¹ P. Kiese²⁸ R. Kiuchi¹ R. Kliemt¹¹ L. Koch³⁰ O. B. Kolcu^{54A} B. Kopf⁴ M. Kuemmel⁴
M. Kuessner⁴ A. Kupsc^{37,68} M. G. Kurth^{1,55} W. Kühn³⁰ J. J. Lane⁵⁹ J. S. Lange³⁰ P. Larin¹⁴ A. Lavania²¹
L. Lavezzi^{67A,67C} Z. H. Lei(雷祚弘)^{50,64} H. Leithoff²⁸ M. Lellmann²⁸ T. Lenz²⁸ C. Li(李翠)⁴⁰
C. H. Li(李春花)³² Cheng Li(李澄)^{50,64} D. M. Li(李德民)⁷³ F. Li(李飞)^{1,50} G. Li(李刚)¹ H. Li(李慧)⁴⁴
H. Li(李贺)^{50,64} H. B. Li(李海波)^{1,55} H. J. Li(李惠静)¹⁵ H. N. Li(李衡讷)^{48,j} J. L. Li(李井文)⁴² J. Q. Li⁴

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J. S. Li(李静舒)⁵¹ Ke Li(李科)¹ L. K. Li(李龙科)¹ Lei Li(李蕾)³ P. R. Li(李培荣)^{31,k,1} S. Y. Li(栗帅迎)⁵³
W. D. Li(李卫东)^{1,55} W. G. Li(李卫国)¹ X. H. Li(李旭红)^{50,64} X. L. Li(李晓玲)⁴² Xiaoyu Li(李晓宇)^{1,55}
Z. Y. Li(李紫源)⁵¹ H. Liang(梁昊)^{50,64} H. Liang(梁浩)^{1,55} H. Liang(梁浩)²⁷ Y. F. Liang(梁勇飞)⁴⁶
Y. T. Liang(梁羽铁)²⁵ G. R. Liao(廖广睿)¹² L. Z. Liao(廖龙洲)^{1,55} J. Libby²¹ A. Limphirat⁵²
C. X. Lin(林创新)⁵¹ D. X. Lin(林德旭)²⁵ T. Lin¹ B. J. Liu(刘北江)¹ C. X. Liu(刘春秀)¹ D. Liu(刘栋)^{14,64}
F. H. Liu(刘福虎)⁴⁵ Fang Liu(刘芳)¹ Feng Liu(刘峰)⁶ G. M. Liu^{48,j} H. M. Liu(刘怀民)^{1,55}
Huanhuan Liu(刘欢欢)¹ Huihui Liu(刘汇慧)¹⁶ J. B. Liu(刘建北)^{50,64} J. L. Liu(刘佳俊)⁶⁵ J. Y. Liu(刘晶译)^{1,55}
K. Liu(刘凯)¹ K. Y. Liu(刘魁勇)³³ Ke Liu(刘珂)^{17,m} L. Liu(刘亮)^{50,64} M. H. Liu(刘美宏)^{9,f} P. L. Liu(刘佩莲)¹
Q. Liu(刘倩)⁵⁵ Q. Liu(刘淇)⁶⁹ S. B. Liu(刘树彬)^{50,64} T. Liu(刘桐)^{1,55} T. Liu(刘桐)^{9,f} W. M. Liu(刘卫民)^{50,64}
X. Liu(刘翔)^{31,k,1} Y. Liu(刘英)^{31,k,1} Y. B. Liu(刘玉斌)³⁶ Z. A. Liu(刘振安)¹ Z. Q. Liu(刘智青)⁴²
X. C. Lou(娄辛丑)¹ F. X. Lu(卢飞翔)⁵¹ H. J. Lu(吕海江)¹⁸ J. D. Lu(陆嘉达)^{1,55} J. G. Lu(吕军光)^{1,50}
X. L. Lu(陆小玲)¹ Y. Lu(卢宇)¹ Y. P. Lu(卢云鹏)^{1,50} C. L. Luo(罗成林)³⁴ M. X. Luo(罗民兴)⁷²
P. W. Luo(罗朋威)⁵¹ T. Luo(罗涛)^{9,f} X. L. Luo(罗小兰)^{1,50} X. R. Lyu(吕晓睿)⁵⁵ F. C. Ma(马凤才)³³
H. L. Ma(马海龙)¹ L. L. Ma(马连良)⁴² M. M. Ma(马明明)^{1,55} Q. M. Ma(马秋梅)¹ R. Q. Ma(马润秋)^{1,55}
R. T. Ma(马瑞廷)⁵⁵ X. X. Ma(马新鑫)^{1,55} X. Y. Ma(马骁妍)^{1,50} Y. Ma(马尧)^{39,h} F. E. Maas¹⁴ M. Maggiora^{67A,67C}
S. Maldaner⁴ S. Malde⁶² Q. A. Malik⁶⁶ A. Mangoni^{23B} Y. J. Mao(冒亚军)^{39,h} Z. P. Mao(毛泽普)¹
S. Marcello^{67A,67C} Z. X. Meng(孟召霞)⁵⁸ J. G. Messchendorp⁵⁶ G. Mezzadri^{24A,1} T. J. Min(闵天觉)³⁵
R. E. Mitchell²² X. H. Mo(莫晓虎)¹ N. Yu. Muchnoi^{10,b} H. Muramatsu⁶⁰ S. Nakhoul^{11,d} Y. Nefedov²⁹
F. Nerling^{11,d} I. B. Nikolaev^{10,b} Z. Ning(宁哲)^{1,50} S. Nisar^{8,g} S. L. Olsen⁵⁵ Q. Ouyang(欧阳群)¹ S. Pacetti^{23B,23C}
X. Pan(潘祥)^{9,f} Y. Pan(潘越)⁵⁹ A. Pathak¹ A. Pathak²⁷ P. Patteri^{23A} M. Pelizaeus⁴ H. P. Peng(彭海平)^{50,64}
K. Peters^{11,d} J. Pettersson⁶⁸ J. L. Ping(平加伦)³⁴ R. G. Ping(平荣刚)^{1,55} S. Plura²⁸ S. Pogodin²⁹ R. Poling⁶⁰
V. Prasad^{50,64} H. Qi(齐航)^{50,64} H. R. Qi(漆红荣)⁵³ M. Qi(祁鸣)³⁵ T. Y. Qi(齐天钰)^{9,f} S. Qian(钱森)^{1,50}
W. B. Qian(钱文斌)⁵⁵ Z. Qian(钱圳)⁵¹ C. F. Qiao(乔从丰)⁵⁵ J. J. Qin(秦佳佳)⁶⁵ L. Q. Qin(秦丽清)¹²
X. P. Qin(覃潇平)^{9,f} X. S. Qin(秦小帅)⁴² Z. H. Qin(秦中华)^{1,50} J. F. Qiu(邱进发)¹ S. Q. Qu(屈三强)³⁶
K. H. Rashid⁶⁶ K. Ravindran²¹ C. F. Redmer²⁸ A. Rivetti^{67C} V. Rodin⁵⁶ M. Rolo^{67C} G. Rong(荣刚)^{1,55}
Ch. Rosner¹⁴ M. Rump⁶¹ H. S. Sang(桑昊榆)⁶⁴ A. Sarantsev^{29,c} Y. Schelhaas²⁸ C. Schnier⁴ K. Schoenning⁶⁸
M. Scodeggio^{24A,24B} W. Shan(单葳)¹⁹ X. Y. Shan(单心钰)^{50,64} J. F. Shangguan(上官剑锋)⁴⁷ M. Shao(邵明)^{50,64}
C. P. Shen(沈成平)^{9,f} H. F. Shen(沈宏飞)^{1,55} X. Y. Shen(沈肖雁)^{1,55} H. C. Shi(石煌超)^{50,64} R. S. Shi(师荣盛)^{1,55}
X. Shi(史欣)^{1,50} X. D. Shi(师晓东)^{50,64} J. J. Song(宋娇娇)¹⁵ W. M. Song(宋维民)^{1,27} Y. X. Song(宋尙轩)^{39,h}
S. Sosio^{67A,67C} S. Spataro^{67A,67C} F. Stieler²⁸ K. X. Su(苏可馨)⁶⁹ P. P. Su(苏彭彭)⁴⁷ G. X. Sun(孙功星)¹
H. K. Sun(孙浩凯)¹ J. F. Sun(孙俊峰)¹⁵ L. Sun(孙亮)⁶⁹ S. S. Sun(孙胜森)^{1,55} T. Sun(孙童)^{1,55}
W. Y. Sun(孙文玉)²⁷ X. Sun(孙翔)^{20,i} Y. J. Sun(孙勇杰)^{50,64} Y. Z. Sun(孙永昭)¹ Z. T. Sun(孙振田)¹
Y. H. Tan(谭英华)⁶⁹ Y. X. Tan(谭雅星)^{50,64} C. J. Tang(唐昌建)⁴⁶ G. Y. Tang(唐光毅)¹ J. Tang(唐健)⁵¹
Q. T. Tao(陶秋田)^{20,i} J. X. Teng(滕佳秀)^{50,64} V. Thoren⁶⁸ W. H. Tian(田文辉)⁴⁴ Y. T. Tian(田野)²⁵ I. Uman^{54B}
B. Wang(王斌)¹ C. W. Wang(王成伟)³⁵ D. Y. Wang(王大勇)^{39,h} H. J. Wang(王泓鉴)^{31,k,1} H. P. Wang(王宏鹏)^{1,55}
K. Wang(王科)^{1,50} L. L. Wang(王亮亮)¹ M. Wang(王萌)⁴² M. Z. Wang(王梦真)^{39,h} Meng Wang(王蒙)^{1,55}
S. Wang(王顺)^{9,f} W. Wang(王为)⁵¹ W. H. Wang(王文欢)⁶⁹ W. P. Wang(王维平)^{50,64} X. Wang(王轩)^{39,h}
X. F. Wang(王雄飞)^{31,k,1} X. L. Wang(王小龙)^{9,f} Y. Wang(王莹)⁵¹ Y. D. Wang(王雅迪)³⁸ Y. F. Wang(王贻芳)¹
Y. Q. Wang(王雨晴)¹ Y. Y. Wang(王云宇)^{31,k,1} Z. Wang(王铮)^{1,50} Z. Y. Wang(王至勇)¹ Ziyi Wang(王子一)⁵⁵
Zongyuan Wang(王宗源)^{1,55} D. H. Wei(魏代会)¹² F. Weidner⁶¹ S. P. Wen(文硕频)¹ D. J. White⁵⁹ U. Wiedner⁴
G. Wilkinson⁶² M. Wolke⁶⁸ L. Wollenberg⁴ J. F. Wu(吴金飞)^{1,55} L. H. Wu(伍灵慧)¹ L. J. Wu(吴连近)^{1,55}
X. Wu(吴潇)^{9,f} X. H. Wu(伍雄浩)²⁷ Z. Wu(吴智)^{1,50} L. Xia(夏磊)^{50,64} T. Xiang(相腾)^{39,h} H. Xiao(肖浩)^{9,f}
S. Y. Xiao(肖素玉)¹ Z. J. Xiao(肖振军)³⁴ X. H. Xie(谢昕海)^{39,h} Y. G. Xie(谢宇广)^{1,50} Y. H. Xie(谢跃红)⁶
T. Y. Xing(邢天宇)^{1,55} C. J. Xu(许创杰)⁵¹ G. F. Xu(许国发)¹ Q. J. Xu(徐庆君)¹³ W. Xu(许威)^{1,55}
X. P. Xu(徐新平)⁴⁷ Y. C. Xu(胥英超)⁵⁵ F. Yan(严芳)^{9,f} L. Yan(严亮)^{9,f} W. B. Yan(鄢文标)^{50,64}
W. C. Yan(闫文成)⁷³ H. J. Yang(杨海军)^{43,e} H. X. Yang(杨洪勋)¹ L. Yang(杨玲)⁴⁴ S. L. Yang(杨双莉)⁵⁵

Y. X. Yang(杨永刚)¹² Yifan Yang(杨翊凡)^{1,55} Zhi Yang(杨智)²⁵ M. Ye(叶梅)^{1,50} M. H. Ye(叶铭汉)⁷
 J. H. Yin(殷俊昊)¹ Z. Y. You(尤郑昀)⁵¹ B. X. Yu(俞伯祥)¹ C. X. Yu(喻纯旭)³⁶ G. Yu(余刚)^{1,55}
 J. S. Yu(俞洁晟)^{20,i} T. Yu(于涛)⁶⁵ C. Z. Yuan(苑长征)^{1,55} L. Yuan(袁丽)² Y. Yuan(袁野)¹
 Z. Y. Yuan(袁朝阳)⁵¹ C. X. Yue(岳崇兴)³² A. A. Zafar⁶⁶ X. Zeng Zeng(曾鑫)⁶ Y. Zeng(曾云)^{20,i}
 A. Q. Zhang(张安庆)¹ B. X. Zhang(张丙新)¹ G. Y. Zhang(张广义)¹⁵ H. Zhang⁶⁴ H. H. Zhang(张宏浩)⁵¹
 H. H. Zhang(张宏宏)²⁷ H. Y. Zhang(章红宇)^{1,50} J. L. Zhang(张杰磊)⁷⁰ J. Q. Zhang(张敬庆)³⁴
 J. W. Zhang(张家文)¹ J. Y. Zhang(张建勇)¹ J. Z. Zhang(张景芝)^{1,55} Jianyu Zhang(张剑宇)^{1,55}
 Jiawei Zhang(张嘉伟)^{1,55} L. M. Zhang(张黎明)⁵³ L. Q. Zhang(张丽青)⁵¹ Lei Zhang(张雷)³⁵ S. Zhang(张澍)⁵¹
 S. F. Zhang(张思凡)³⁵ Shulei Zhang(张书磊)^{20,i} X. D. Zhang³⁸ X. M. Zhang¹ X. Y. Zhang(张学尧)⁴² Y. Zhang⁶²
 Y. T. Zhang(张亚腾)⁷³ Y. H. Zhang(张银鸿)^{1,50} Yan Zhang(张言)^{50,64} Yao Zhang(张瑶)¹ Z. Y. Zhang(张振宇)⁶⁹
 G. Zhao(赵光)¹ J. Zhao(赵静)³² J. Y. Zhao(赵静宜)^{1,55} J. Z. Zhao(赵京周)^{1,50} Lei Zhao(赵雷)^{50,64}
 Ling Zhao(赵玲)¹ M. G. Zhao(赵明刚)³⁶ Q. Zhao(赵强)¹ S. J. Zhao(赵书俊)⁷³ Y. B. Zhao(赵豫斌)^{1,50}
 Y. X. Zhao(赵宇翔)²⁵ Z. G. Zhao(赵政国)^{50,64} A. Zhemchugov^{29,a} B. Zheng(郑波)⁶⁵ J. P. Zheng(郑建平)^{1,50}
 Y. H. Zheng(郑阳恒)⁵⁵ B. Zhong(钟彬)³⁴ C. Zhong(钟翠)⁶⁵ L. P. Zhou(周利鹏)^{1,55} Q. Zhou(周巧)^{1,55}
 X. Zhou(周详)⁶⁹ X. K. Zhou(周晓康)⁵⁵ X. R. Zhou(周小蓉)^{50,64} X. Y. Zhou(周兴玉)³² A. N. Zhu(朱傲男)^{1,55}
 J. Zhu(朱江)³⁶ K. Zhu(朱凯)¹ K. J. Zhu(朱科军)¹ S. H. Zhu(朱世海)⁶³ T. J. Zhu(朱腾蛟)⁷⁰ W. J. Zhu(朱文静)³⁶
 W. J. Zhu(朱文静)^{9,f} Y. C. Zhu(朱莹春)^{50,64} Z. A. Zhu(朱自安)^{1,55} B. S. Zou(邹冰松)¹ J. H. Zou(邹佳恒)¹

(BESIII Collaboration)

¹Institute of High Energy Physics, Beijing 100049, China

²Beihang University, Beijing 100191, China

³Beijing Institute of Petrochemical Technology, Beijing 102617, China

⁴Bochum Ruhr-University, D-44780 Bochum, Germany

⁵Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

⁶Central China Normal University, Wuhan 430079, China

⁷China Center of Advanced Science and Technology, Beijing 100190, China

⁸COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan

⁹Fudan University, Shanghai 200443, China

¹⁰G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia

¹¹GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany

¹²Guangxi Normal University, Guilin 541004, China

¹³Hangzhou Normal University, Hangzhou 310036, China

¹⁴Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany

¹⁵Henan Normal University, Xinxing 453007, China

¹⁶Henan University of Science and Technology, Luoyang 471003, China

¹⁷Henan University of Technology, Zhengzhou 450001, China

¹⁸Huangshan College, Huangshan 245000, China

¹⁹Hunan Normal University, Changsha 410081, China

²⁰Hunan University, Changsha 410082, China

²¹Indian Institute of Technology Madras, Chennai 600036, India

²²Indiana University, Bloomington, Indiana 47405, USA

²³(A)INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy; (B)INFN Sezione di Perugia, I-06100, Perugia, Italy; (C)University of Perugia, I-06100, Perugia, Italy

²⁴(A)University of Ferrara, I-44122, Ferrara, Italy; (B)University of Ferrara, I-44122, Ferrara, Italy

²⁵Institute of Modern Physics, Lanzhou 730000, China

²⁶Institute of Physics and Technology, Peace Ave. 54B, Ulaanbaatar 13330, Mongolia

²⁷Jilin University, Changchun 130012, China

²⁸Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany

²⁹Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia

³⁰Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany

³¹Lanzhou University, Lanzhou 730000, China

³²Liaoning Normal University, Dalian 116029, China

³³Liaoning University, Shenyang 110036, China

³⁴Nanjing Normal University, Nanjing 210023, China

³⁵Nanjing University, Nanjing 210093, China

³⁶Nankai University, Tianjin 300071, China

³⁷National Centre for Nuclear Research, Warsaw 02-093, Poland

³⁸North China Electric Power University, Beijing 102206, China

³⁹Peking University, Beijing 100871, China

⁴⁰Qufu Normal University, Qufu 273165, China

⁴¹Shandong Normal University, Jinan 250014, China

- ⁴²Shandong University, Jinan 250100, China
⁴³Shanghai Jiao Tong University, Shanghai 200240, China
⁴⁴Shanxi Normal University, Linfen 041004, China
⁴⁵Shanxi University, Taiyuan 030006, China
⁴⁶Sichuan University, Chengdu 610064, China
⁴⁷Soochow University, Suzhou 215006, China
⁴⁸South China Normal University, Guangzhou 510006, China
⁴⁹Southeast University, Nanjing 211100, China
⁵⁰State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, China
⁵¹Sun Yat-Sen University, Guangzhou 510275, China
⁵²Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
⁵³Tsinghua University, Beijing 100084, China
⁵⁴(A)Istinye University, 34010, Istanbul, Turkey; (B)Near East University, Nicosia, North Cyprus, Mersin 10, Turkey
⁵⁵University of Chinese Academy of Sciences, Beijing 100049, China
⁵⁶University of Groningen, NL-9747 AA Groningen, The Netherlands
⁵⁷University of Hawaii, Honolulu, Hawaii 96822, USA
⁵⁸University of Jinan, Jinan 250022, China
⁵⁹University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
⁶⁰University of Minnesota, Minneapolis, Minnesota 55455, USA
⁶¹University of Muenster, Wilhelm-Klemm-Str. 9, 48149 Muenster, Germany
⁶²University of Oxford, Keble Rd, Oxford, UK OX13RH
⁶³University of Science and Technology Liaoning, Anshan 114051, China
⁶⁴University of Science and Technology of China, Hefei 230026, China
⁶⁵University of South China, Hengyang 421001, China
⁶⁶University of the Punjab, Lahore-54590, Pakistan
⁶⁷(A)University of Turin, I-10125, Turin, Italy; (B)University of Eastern Piedmont, I-15121, Alessandria, Italy; (C)INFN, I-10125, Turin, Italy
⁶⁸Uppsala University, Box 516, SE-75120 Uppsala, Sweden
⁶⁹Wuhan University, Wuhan 430072, China
⁷⁰Xinyang Normal University, Xinyang 464000, China
⁷¹Yunnan University, Kunming 650500, China
⁷²Zhejiang University, Hangzhou 310027, China
⁷³Zhengzhou University, Zhengzhou 450001, China
^aAlso at the Moscow Institute of Physics and Technology, Moscow 141700, Russia
^bAlso at the Novosibirsk State University, Novosibirsk, 630090, Russia
^cAlso at the NRC "Kurchatov Institute", PNPI, 188300, Gatchina, Russia
^dAlso at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany
^eAlso 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, China
^fAlso at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, China
^gAlso at Harvard University, Department of Physics, Cambridge, MA, 02138, USA
^hAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
ⁱAlso at School of Physics and Electronics, Hunan University, Changsha 410082, China
^jAlso at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China
^kAlso at Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China
^lAlso at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, China
^mHenan University of Technology, Zhengzhou 450001, China

Abstract: Using inclusive decays of J/ψ , a precise determination of the number of J/ψ events collected with the BESIII detector was performed. For the two data sets taken in 2009 and 2012, the numbers of J/ψ events were recalculated to be $(224.0 \pm 1.3) \times 10^6$ and $(1088.5 \pm 4.4) \times 10^6$, respectively; these numbers are in good agreement with the previous measurements. For the J/ψ sample taken in 2017–2019, the number of events was determined to be $(8774.0 \pm 39.4) \times 10^6$. The total number of J/ψ events collected with the BESIII detector was determined to be $(10087 \pm 44) \times 10^6$, where the uncertainty is dominated by systematic effects, and the statistical uncertainty is negligible.

Keywords: number of J/ψ events, BESIII detector, inclusive J/ψ decays

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I. INTRODUCTION

As a charmonium ground state, the J/ψ offers a

unique laboratory for studying light hadron spectroscopy. In particular, J/ψ decays can be used to search for exotic hadrons composed of light quarks and gluons, which are

key to a more comprehensive understanding of the nature of the strong interaction.

Many important results in light hadron spectroscopy [1] have been reported based on $(1310.6 \pm 7.0) \times 10^6$ J/ψ events collected by the BESIII experiment [2] in 2009 and 2012. An additional large sample of J/ψ events was collected by BESIII during 2017–2019 to improve the precision of the measurements and search for new processes. The three data samples of J/ψ events collected at BESIII are summarized in Table 1.

This paper reports a precise determination of the total number of J/ψ events. The number of J/ψ events for the new samples collected in 2017–2019 was determined with an inclusive method as the one used in the previous measurements [3, 4]. In addition, in this analysis we also recalculate the number of J/ψ events for the two data samples taken in 2009 and 2012, reconstructed using the latest BESIII software [5, 6]. The number of J/ψ events, $N_{J/\psi}$, was calculated as

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

where N_{sel} is the number of inclusive J/ψ decays selected from the J/ψ data; N_{bg} is the number of background events estimated with continuum data taken at $\sqrt{s} = 3.08$ 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 $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$. 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 $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$. f_{cor} is expected to be approximately unity and is determined by the Monte Carlo (MC) simula-

tion sample with

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

where $\epsilon_{\text{MC}}^{J/\psi}$ 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 $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$. For the number of J/ψ events determined with Eq. (1), only f_{cor} depends on MC simulation. According to Eq. (2), the uncertainties related to MC simulation (including generator, detector response, etc.) almost cancel out because they impact both the numerator and denominator, which improves the precision of the number of J/ψ events. In the MC simulation, the production of J/ψ and $\psi(3686)$ resonances was simulated with a GEANT4-based [7] MC software, which includes the geometric description of the BESIII detector and the detector response. The simulation models the beam energy spread and initial state radiation (ISR) in the e^+e^- annihilations with the generator KKMC [8]. The known decay modes were modeled with EVTGEN [9, 10] using branching fractions taken from the Particle Data Group [11], and the remaining unknown charmonium decays were modeled with LUNDCHARM [12, 13].

II. INCLUSIVE J/ψ SELECTION CRITERIA

Candidate events must contain two or more charged tracks that must have a momentum less than 2.0 GeV/c and to be within a polar angle (θ) range of $|\cos\theta| < 0.93$, where θ is defined with respect to the axis of the Main Drift Chamber (MDC). The distance of closest approach

Table 1. Data samples used in the determination of the number of J/ψ events. $\psi(3686)$ and QED samples (continuum data samples at $\sqrt{s} = 3.08$ GeV) are taken in close chronological order to each J/ψ sample with only different c.m. energies to make sure the efficiency and background estimation reliable.

Data set	$\sqrt{s}$	$\mathcal{L}_{\text{online}}$	Date (duration) (YYYY-MM-DD)
J/ψ	3.097 GeV	2678 pb ⁻¹	2017-08-12 – 2019-06-02
QED1	3.08 GeV	48 pb ⁻¹	2018-04-12 – 2018-04-14
QED2	3.08 GeV	88 pb ⁻¹	2019-02-07 – 2019-02-11
$\psi(3686)$	3.686 GeV	25 pb ⁻¹	2018-05-20
J/ψ	3.097 GeV	323 pb ⁻¹	2012-04-10 – 2012-05-22
QED1	3.08 GeV	13 pb ⁻¹	2012-04-08
QED2	3.08 GeV	17 pb ⁻¹	2012-05-23 – 2012-05-24
$\psi(3686)$	3.686 GeV	7.5 pb ⁻¹	2012-05-26
J/ψ	3.097 GeV	82 pb ⁻¹	2009-06-12 – 2009-07-28
QED	3.08 GeV	0.3 pb ⁻¹	2009-06-19
$\psi(3686)$	3.686 GeV	150 pb ⁻¹	2009-03-07 – 2009-04-14

to the interaction point (IP) must be less than 15 cm along the z -axis, $|V_z|$, and less than 1 cm in the transverse plane, V_r . Photon candidates were identified using isolated showers in the electromagnetic calorimeter (EMC). The deposited energy of each shower must be more than 25 MeV in the barrel region ($|\cos\theta| < 0.83$) and more than 50 MeV in the end cap region ($0.86 < |\cos\theta| < 0.93$). To suppress electronic noise and showers unrelated to the event, the difference between the EMC time and the event start time is required to be within $[0, 700]$ ns.

To suppress events from Quantum Electrodynamics (QED) processes (*i.e.*, Bhabha and dimuon events), from cosmic rays, beam-induced backgrounds, and electronic noise, a series of selection criteria were applied to the candidate events.

The sum of charged particle energies computed from the track momenta assuming a pion mass and the neutral shower energies deposited in the EMC, E_{vis} , is required to be greater than 1.0 GeV. Fig. 1 shows 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. The requirement $E_{\text{vis}} > 1.0$ GeV removes one third of the background events while retaining 99.5% of the signal events.

For events with only two charged tracks, the momentum of each track is required to be less than 1.5 GeV/c to exclude Bhabha and dimuon events. Fig. 2 shows a scatter plot of the momenta of the two charged tracks, and the solid lines depict the momentum requirement. Fig. 3 displays the distribution of energy deposited by the charged particles in the EMC; a significant peak around 1.5 GeV is from Bhabha events, which can be rejected by requiring the energy deposited in the EMC to be less than 1 GeV for each charged track.

After the above requirements, $N_{\text{sel}} = (6912.03 \pm$

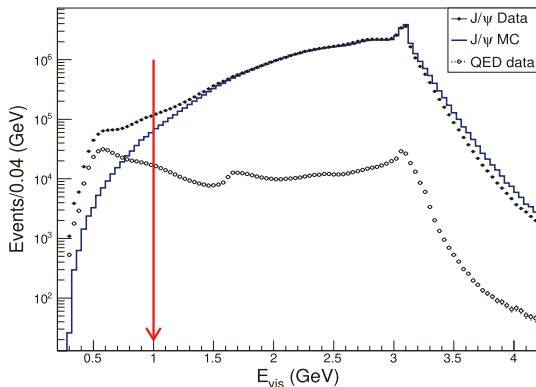


Fig. 1. (color online) Distributions of the visible energy E_{vis} for J/ψ data (dots with error bars), continuum data at $\sqrt{s} = 3.08$ GeV (open circles with error bars, normalized to the integrated luminosity of J/ψ data) and MC simulation of inclusive J/ψ events (blue solid line). The arrow indicates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

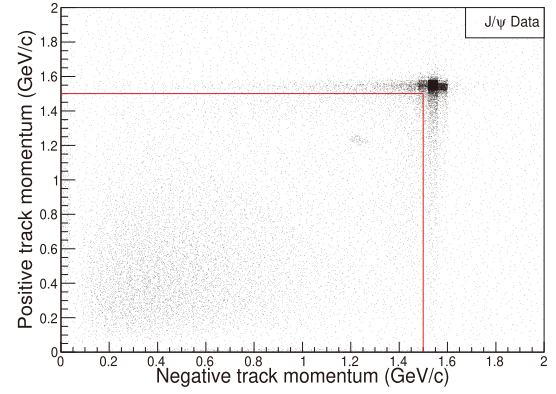


Fig. 2. (color online) Distribution of the momenta of the charged tracks for 2-prong events in data. The cluster around 1.55 GeV/c corresponds to the contribution from lepton pairs, and the cluster at 1.23 GeV/c comes from $J/\psi \rightarrow p\bar{p}$. Most of lepton pairs are removed with the requirements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

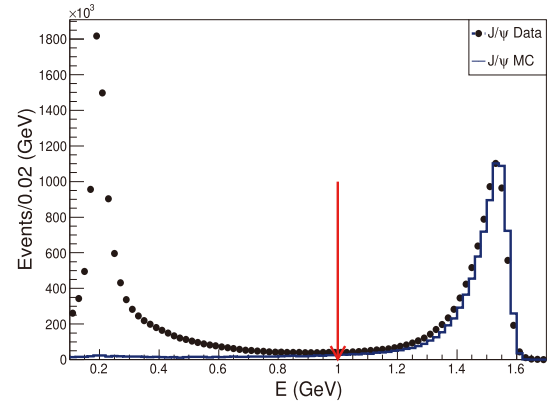


Fig. 3. (color online) Distributions of deposited energy in the EMC for the charged tracks of 2-prong events for J/ψ data (dots with error bars) and for the combined, normalized MC simulations of $e^+e^- \rightarrow e^+e^-(\gamma)$ and $J/\psi \rightarrow e^+e^-(\gamma)$ (blue solid line).

$0.08) \times 10^6$ candidate events were selected from the J/ψ data taken in 2017–2019. The distributions of the track parameters of closest approach along the beam line and in radial direction (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. III for details) are illustrated in Fig. 4. The multiplicity of charged tracks (N_{good}) is shown in Fig. 5, where the MC sample generated according to the standard MC model agrees very well with the data while the MC sample generated with an ‘incomplete’ MC model deviates from the data. The standard MC model includes the known decay processes listed in the PDG and the unknown ones modeled with LUNDCHARM [12, 13], while the incomplete MC model only includes the known decay modes listed in the

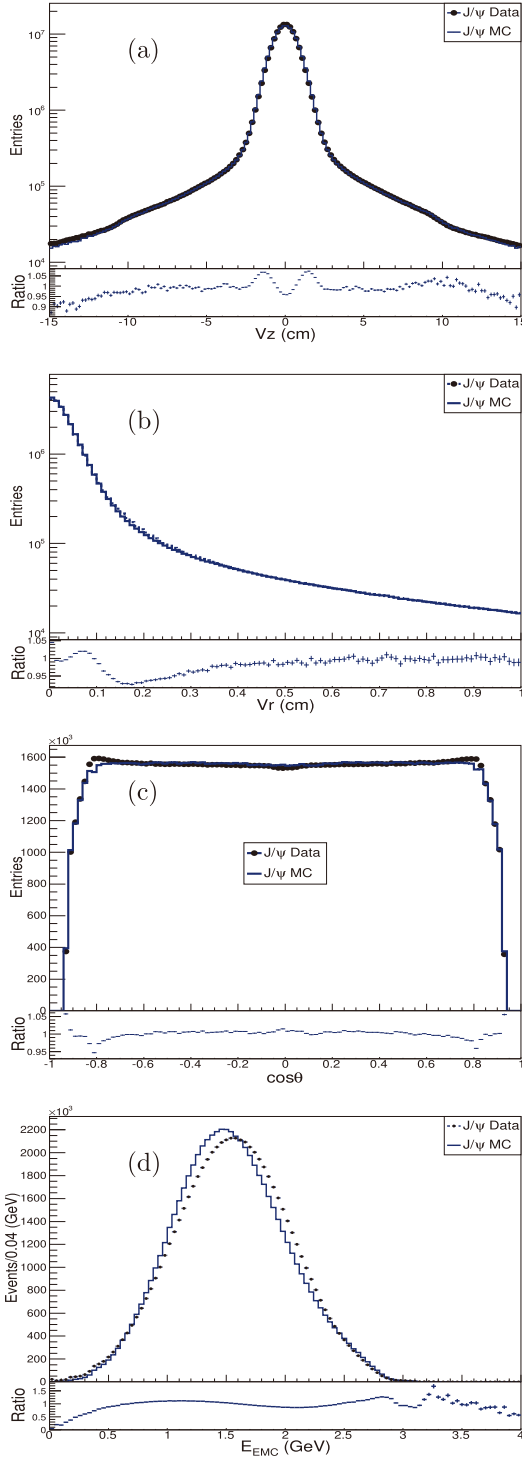


Fig. 4. (color online) Comparison of distributions between J/ψ data (dots with error bars) and MC simulation of inclusive J/ψ (blue solid line): (a) V_z , (b) V_r , (c) $\cos\theta$ of charged tracks, (d) total energy deposited in the EMC.

PDG. The MC sample generated with the incomplete MC model was used to test the effect of this discrepancy on the determination of the number of J/ψ events, which is small as described in Sec. VI.

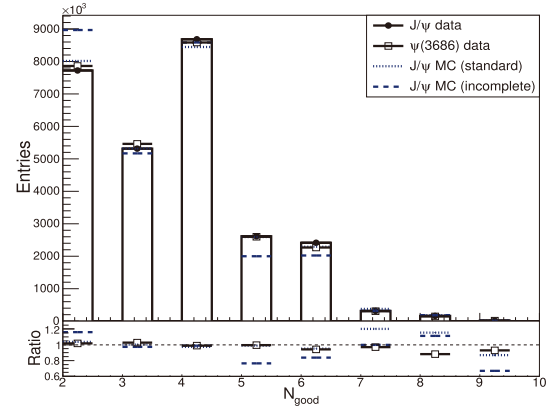


Fig. 5. (color online) Distributions of the reconstructed charged track multiplicity in inclusive J/ψ events for J/ψ data (dots with error bars) and $\psi(3686)$ data (squares with error bars) and MC simulation generated using standard and incomplete MC model (short-dashed and long-dashed lines, respectively).

III. BACKGROUND ANALYSIS

In this analysis, the potential background sources include QED processes, beam-induced background, cosmic rays, and electronic noise. The continuum data samples at $\sqrt{s} = 3.08$ GeV were taken in close chronological order to each J/ψ sample to estimate these backgrounds.

The integrated luminosity was determined using the process $e^+e^- \rightarrow \gamma\gamma$. The candidate events were selected by requiring at least two showers in the EMC within $|\cos\theta| < 0.8$ and with the energy of the second most energetic shower between 1.2 and 1.6 GeV. The number of signal events was determined from the number of events in the signal region $|\Delta\phi| < 2.5^\circ$, and the background was estimated from those in the side-band region $2.5^\circ < |\Delta\phi| < 5^\circ$, where $\Delta\phi = |\phi_{\gamma 1} - \phi_{\gamma 2}| - 180^\circ$ and $\phi_{\gamma 1/2}$ are the azimuthal angles of the two photon candidates. 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 in 2017–2019 were determined to be $(2568.07 \pm 0.40) \text{ pb}^{-1}$ and $(136.22 \pm 0.09) \text{ pb}^{-1}$, respectively, where the errors are statistical only.

After applying the same selection criteria as for the J/ψ data, $N_{3.08} = 6,363,941 \pm 2,523$ events were 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} , was estimated to be

$$N_{\text{bg}} = N_{3.08} \times \frac{\mathcal{L}_{J/\psi}}{\mathcal{L}_{3.08}} \times \frac{s_{3.08}}{s_{J/\psi}} = (118.66 \pm 0.05) \times 10^6, \quad (3)$$

where $\mathcal{L}_{J/\psi}$ 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, and $s_{J/\psi}$ and $s_{3.08}$ are the corresponding squares of the center-of-mass energies. The background was calculated to be $(1.717 \pm 0.002)\%$ of the number of selected inclusive J/ψ events taken in 2017–2019.

IV. DETERMINATION OF THE DETECTION EFFICIENCY AND CORRECTION FACTOR

In this analysis, the detection efficiency was determined experimentally using a sample of J/ψ events from the reaction $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ to reduce the uncertainty related to any discrepancies between the MC simulation and the data. To ensure that the beam conditions and detector status are similar to those of the sample collected at the J/ψ peak, a dedicated $\psi(3686)$ sample taken on May 20, 2018 was used for this study.

For a candidate $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ event, there must be at least two soft pions with opposite charge detected in the MDC with $|\cos\theta| < 0.93$. Each candidate pion is required to have a momentum less than 0.4 GeV/c, and the distance of closest approach to the IP must satisfy $|V_z| < 15$ cm and $V_r < 1$ cm. 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 prominent peak around 3.1 GeV/c², corresponding to the decay of $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ is observed over a smooth background. The number of inclusive J/ψ events, $N_{\text{inc}} = (3538.5 \pm 3.6) \times 10^3$, was 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.

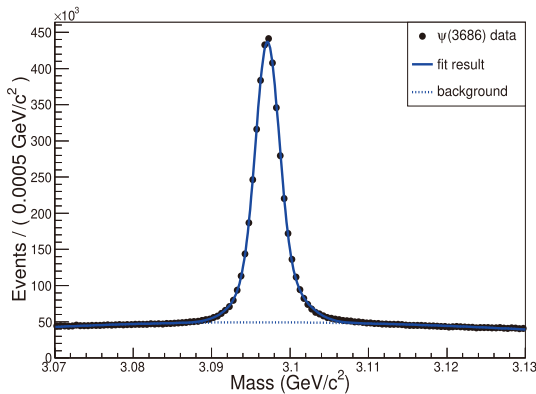


Fig. 6. (color online) Invariant mass recoiling against selected $\pi^+\pi^-$ pairs for the (3686) data sample. The curves are the results of the fit described in the text.

To measure the detection efficiency of inclusive J/ψ events, the same selection criteria as described in Sec. II were applied to the remaining charged tracks and showers. The number of selected inclusive J/ψ events, $N_{\text{inc}}^{\text{sel}}$, was determined to be $(2717.6 \pm 3.4) \times 10^3$ using a fit to the recoil mass distribution of the selected events with the same function as described above. The detection efficiency of inclusive J/ψ events, $\epsilon_{\text{data}}^{\psi(3686)} = (76.80 \pm 0.05)\%$, was calculated from the ratio of the number of inclusive J/ψ events with and without the inclusive J/ψ event selection criteria applied.

To account for the efficiency difference between the J/ψ produced at rest and the J/ψ from the decay $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$, a correction factor, defined in Eq. (2), was used. Two large statistics MC samples, inclusive $\psi(3686)$ and inclusive J/ψ events, were produced and subjected to the same selection criteria as the data samples. The detection efficiencies of inclusive J/ψ events were determined to be $\epsilon_{\text{MC}}^{\psi(3686)} = (76.93 \pm 0.02)\%$ and $\epsilon_{\text{MC}}^{J/\psi} = (77.56 \pm 0.01)\%$ for the two inclusive MC samples, respectively. The correction factor f_{cor} for the detection efficiency was therefore taken as

$$f_{\text{cor}} = \frac{\epsilon_{\text{MC}}^{J/\psi}}{\epsilon_{\text{MC}}^{\psi(3686)}} = 1.0082 \pm 0.0007, \quad (4)$$

where the error is statistical only.

V. NUMBER OF J/ψ EVENTS

With Eq. (1) and the corresponding parameter values summarized in Table 2, the number of J/ψ events collected in 2017–2019 was determined to be $(8774.0 \pm 0.2) \times 10^6$. The trigger efficiency of the BESIII detector was taken to be 100%, based on a study of various reactions [14]. With the same procedure, the numbers of J/ψ events taken in 2012 and 2009 were recalculated to be $(1088.5 \pm 0.1) \times 10^6$ and $(224.0 \pm 0.1) \times 10^6$, respectively, where the uncertainties are statistical only. The statistical uncertainties of N_{bg} were taken into account as part of the systematic uncertainty (see Sec. VI.D). The systematic uncertainties from different sources are discussed in detail in Sec. VI.

VI. SYSTEMATIC UNCERTAINTY

The sources of systematic uncertainties, including the MC model, track reconstruction efficiency, fit to the J/ψ peak, background estimation, random trigger mixing and the efficiency of selecting the two soft pions recoiling against J/ψ , are investigated in detail below, and the corresponding contributions are summarized in Table 3.

Table 2. The values used in the calculation, and the resulting number of J/ψ events, where the uncertainties are statistical.

Item	2017–2019	2012	2009
$N_{\text{sel}}(\times 10^6)$	6912.03 ± 0.08	860.59 ± 0.03	180.84 ± 0.01
ϵ_{trig}	1.00	1.00	1.00
$N_{\text{QED}}(\times 10^3)$	6363.9 ± 2.5	1616.6 ± 1.3	24.6 ± 0.2
$N_{\text{bg}}(\times 10^6)$	118.66 ± 0.05	15.32 ± 0.02	6.89 ± 0.04
$\epsilon_{\text{data}}^{\psi(3686)}$	$\frac{(2717.6 \pm 3.4) \times 10^3}{(3538.5 \pm 3.6) \times 10^3} = 0.7680 \pm 0.0005$	$\frac{(981.6 \pm 2.0) \times 10^3}{(1274.9 \pm 2.1) \times 10^3} = 0.7699 \pm 0.0005$	$\frac{(17048.6 \pm 8.9) \times 10^3}{(22120.0 \pm 9.4) \times 10^3} = 0.7707 \pm 0.0001$
$\epsilon_{\text{MC}}^{\psi(3686)}$	$\frac{(4450.2 \pm 3.2) \times 10^3}{(5784.7 \pm 3.5) \times 10^3} = 0.7693 \pm 0.0002$	$\frac{(4668.8 \pm 3.1) \times 10^3}{(6056.3 \pm 3.4) \times 10^3} = 0.7709 \pm 0.0002$	$\frac{(4626.8 \pm 3.3) \times 10^3}{(5991.4 \pm 3.4) \times 10^3} = 0.7723 \pm 0.0002$
$\epsilon_{\text{MC}}^{J/\psi}$	$\frac{(6747.59 \pm 0.04) \times 10^6}{8700 \times 10^6} = 0.7756 \pm 0.0001$	$\frac{(7775.5 \pm 1.4) \times 10^3}{10^7} = 0.7776 \pm 0.0001$	$\frac{(174.26 \pm 0.02) \times 10^6}{224 \times 10^6} = 0.7780 \pm 0.0001$
f_{cor}	1.0082 ± 0.0007	1.0086 ± 0.0008	1.0074 ± 0.0003
$N_{J/\psi}(\times 10^6)$	8774.0 ± 0.2	1088.5 ± 0.1	224.0 ± 0.1

Table 3. Sources of systematic uncertainties and the corresponding contributions to the number of J/ψ events, where the superscript * indicates that the error is common for the same item in different data samples.

Sources	2017–2019(%)	2012 (%)	2009(%)
MC model uncertainty	0.18*	0.18*	0.27*
Tracking efficiency	0.02*	0.03*	0.31
Fit to J/ψ peak	0.10	0.21	0.09
Background uncertainty	0.04	0.10	0.14
Noise mixing	0.06	0.02	0.12
$\epsilon_{\pi^+\pi^-}$ uncertainty	0.40*	0.27*	0.32*
Total	0.45	0.40	0.56

A. MC model uncertainty

There are some differences between experimental data and MC simulation as shown in Figs. 1, 3, 4 because only half of the J/ψ inclusive decays were measured, and the MC model cannot describe the J/ψ inclusive decays exactly. In the measurement of the number of J/ψ events, only the efficiency correction factor, f_{cor} , depends on the MC simulation. To evaluate the uncertainty due to the MC model, MC samples were generated with the incomplete MC model, and the correction factor based on these samples was compared to its nominal value. As shown in Fig. 5, the charged track multiplicity distribution of the incomplete MC sample significantly deviates from the experimental data, indicating that this method will overestimate the systematic uncertainty. To be conservative, the change in the correction factor, 0.18%, was taken as the systematic uncertainty due to the MC model on the number of J/ψ events collected in 2017–2019 (0.18% for 2012 and 0.27% for 2009).

B. Track reconstruction efficiency

The charged track reconstruction efficiencies in MC simulation and experimental data were studied, and the disagreement between them was less than 1% for each charged track. In the analysis, the detection efficiency for inclusive J/ψ decays was obtained using the $\psi(3686)$ data sample. The consistency of charged track reconstruction efficiency between the MC and data samples in $\psi(3686)$ decays was assumed to be the same as that in J/ψ decays since the $\psi(3686)$ data was taken in close chronological proximity to the J/ψ sample. To evaluate the effect of a possible difference, the track reconstruction efficiencies in both J/ψ and $\psi(3686)$ MC samples were varied by -1% to determine the uncertainty due to the MDC tracking. As expected, the change in the correction factor was very small at 0.02%, and this value was taken as a systematic uncertainty (0.03% for 2012).

In 2009, the J/ψ and $\psi(3686)$ data samples were collected in different time periods, and there may be slight differences in the tracking efficiencies between the two data sets. Here, the difference between the MC/data consistencies in the J/ψ and $\psi(3686)$ samples was assumed to be 0.5%, half of the data/MC inconsistency, 1%. To estimate the corresponding systematic uncertainty, we modify the track reconstruction efficiency by -0.5% in the J/ψ MC sample, keeping it unchanged for the $\psi(3686)$ MC sample. The resulting change in the correction factor, 0.31%, was taken as a systematic uncertainty on the number of J/ψ events in 2009.

C. Fit to the J/ψ peak

The $\psi(3686)$ data sample was used to measure the selection efficiency of inclusive J/ψ events. The yield of J/ψ events in $\psi(3686)$ decays was determined by fitting the J/ψ peak in the mass spectrum recoiling against $\pi^+\pi^-$. The uncertainties due to the fit were investigated.

(a) *The fit*: we propagated the statistical uncertainties of the J/ψ signal yield from the fit to the selection efficiency, and the resulting uncertainties, 0.07% and 0.03% for $\epsilon_{data}^{\psi(3686)}$ and $\epsilon_{MC}^{\psi(3686)}$, respectively, are considered to be the uncertainties from the fit itself. (b) *The fit range*: the fit range on the $\pi^+\pi^-$ recoil mass was changed from [3.07, 3.13] GeV/ c^2 to [3.08, 3.12] GeV/ c^2 , and the change of the result, 0.07%, was taken as the corresponding systematic uncertainty. (c) *The signal description*: we performed an alternative fit by describing the J/ψ signal with a histogram (convolved with a Gaussian function) obtained from the recoil mass spectrum of $\pi^+\pi^-$ in $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \mu^+\mu^-$, and the resulting change, 0.01%, was considered to be the associated systematic uncertainty. (d) *The background shape*: the uncertainty due to the background shape, 0.03%, was estimated by replacing the second-order Chebychev polynomial with a first-order or third-order Chebychev polynomial. By assuming that all of the sources of systematic uncertainty are independent, the fit uncertainty for the 2017–2019 J/ψ sample, 0.10%, was obtained by adding all of the above effects in quadrature.

The same sources of systematic uncertainty were considered for the J/ψ sample taken in 2012 (2009). The fit has an uncertainty of 0.07% (0.02%) for $\epsilon_{data}^{\psi(3686)}$ and 0.03% (0.03%) for $\epsilon_{MC}^{\psi(3686)}$. The uncertainties from the fit range, signal function, and background shape are 0.08% (0.03%), 0.15% (0.06%), and 0.10% (0.04%), respectively. The total uncertainty from the fit for the 2012 (2009) data is 0.21% (0.09%).

D. Background uncertainty

In this analysis, the events selected from the experimental data sample include the J/ψ events and background: QED processes, cosmic rays, beam-induced backgrounds, and electronic noise. The contribution of the background was estimated by normalizing the number of events in the continuum data sample taken at $\sqrt{s} = 3.08$ GeV according to Eq. (3). The uncertainty due to the background estimation mainly comes from the normalization method, the statistics of the continuum sample, the statistical uncertainty of the integrated luminosity, and the uncertainty due to beam associated backgrounds.

The cosmic ray background, beam associated backgrounds and electronic noise can not be normalized properly with Eq. (3), since the number of cosmic rays is proportional to the time of data taking, while beam-associated backgrounds depend on the vacuum status and beam currents during data taking in addition to the time of data taking; the electronic noise also depends on the detector status. To estimate the associated systematic uncertainty, the difference in the estimated number of background events with and without the energy-dependent factor in Eq. (3) was used.

During 2017–2019, two data samples at $\sqrt{s} = 3.08$ GeV were taken at different times during the J/ψ data taking. They were compared to each other to estimate the uncertainty of the background related with the stability of the beam and vacuum status. Each of the two continuum data samples was used to estimate the background with Eq. (3), and the maximum difference to the nominal result, 0.03%, was taken as the related systematic uncertainty. The corresponding systematic uncertainty for the 2012 sample is 0.09%. Only one continuum data sample was taken for J/ψ data in 2009. The selected background events from the continuum sample were compared to those from the J/ψ data to estimate the corresponding uncertainty, as described in detail in Ref. [3].

Assuming that all the above effects are independent, their contributions were added quadratically. The resulting uncertainties on the number of J/ψ events due to the background estimation were determined to be 0.04%, 0.10%, and 0.14% for the data taken in 2017–2019, 2012, and 2009, respectively.

E. Random Trigger mixing

In the MC simulation, events recorded by a random trigger were mixed into the MC events to simulate the electronic noise and beam-induced background. In the $\psi(3686)$ MC sample, the random trigger events from the $\psi(3686)$ data taking were replaced by the random trigger events from the J/ψ data taking to estimate the effect of the different background levels. The change of the correction factor for the detection efficiency, 0.06%, was taken as the systematic uncertainty due to random trigger mixing for the number of J/ψ events taken in 2017–2019. The corresponding uncertainties for the 2012 and 2009 samples are 0.02% and 0.12%, respectively.

F. Uncertainty of selection efficiency of two soft pions

Study of the MC sample shows that the selection efficiency of soft pions, $\epsilon_{\pi^+\pi^-}$, recoiling against the J/ψ in $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ depends on the multiplicity of charged tracks in the J/ψ decays. Differences between the data and MC samples may lead to a change in the number of J/ψ events. The dependence of $\epsilon_{\pi^+\pi^-}$ in the data is obtained by comparing the multiplicity distribution of J/ψ decays in the $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ data sample to that of the J/ψ data at rest. Then the efficiency of J/ψ in the $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ ($J/\psi \rightarrow$ inclusive) MC sample, $\epsilon_{MC}^{\psi(3686)}$ in Eq. (2), can be reweighted with the dependence of $\epsilon_{\pi^+\pi^-}$ from the data sample. The resulting changes in the number of J/ψ events, 0.40%, 0.27%, and 0.32%, are taken as the uncertainties for the data taken in 2017–2019, 2012, and 2009, respectively.

G. Summary of systematic uncertainties

The systematic uncertainties from the different

sources studied above are summarized in Table 3. The total systematic uncertainty for the number of J/ψ events in 2017–2019, 0.45%, is the quadratic sum of the individual uncertainties. Correspondingly, the uncertainties for 2012 and 2009 are 0.40% and 0.56%, respectively.

VII. SUMMARY

Using the inclusive J/ψ decays, the number of J/ψ events collected with the BESIII detector in 2017–2019 was determined to be $(8774.0 \pm 39.4) \times 10^6$, where the uncertainty is completely dominated by systematics, and the statistical uncertainty is negligible. The numbers of J/ψ events taken in 2009 and 2012 were recalculated to be

$(224.0 \pm 1.3) \times 10^6$ and $(1088.5 \pm 4.4) \times 10^6$, which are consistent with the previous measurements [4] but with improved precision.

The total number of J/ψ events taken with BESIII detector was determined to be $N_{J/\psi} = (10087 \pm 44) \times 10^6$. Here, the total uncertainty was determined by adding the common uncertainties linearly and the independent ones in quadrature.

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