Search for the lepton number violation decay $\omega\rightarrow\pi^{+}\pi^{+}e^{-}e^{-}+c.c.$*

M. Ablikim (麦迪娜)[1] M. N. Achasov[4,c] P. Adlarson[77] X. C. Ai (艾小聪)[82] R. Aliberti[36] A. Amoroso[76A,76C]
Q. An (安琪)[73,59,a] Y. Bai (白羽)[58] O. Bakina[37] Y. Ban (班勇)[47,h] H.-R. Bao (包浩然)[65] V. Batozskaya[1,45]
K. Begzsuren[33] N. Berger[36] M. Berlowski[45] M. Bertani[29A] D. Bettoni[30A] F. Bianchi[76A,76C] E. Bianco[76A,76C]
A. Bortone[76A,76C] I. Boyko[37] R. A. Briere[5] A. Brueggemann[70] H. Cai (蔡浩)[78] M. H. Cai (蔡铭航)[39,k,l]
X. Cai (蔡啸)[1,59] A. Calcaterra[29A] G. F. Cao (曹国富)[1,65] N. Cao (曹宁)[1,65] S. A. Cetin[63A] X. Y. Chai (柴新宇)[47,h]
J. F. Chang (常劲帆)[1,59] G. R. Che (车国荣)[44] Y. Z. Che (车逾之)[1,59,65] C. H. Chen (陈春卉)[9] Chao Chen (陈超)[56]
G. Chen (陈刚)[1] H. S. Chen (陈和生)[1,65] H. Y. Chen (陈弘扬)[21] M. L. Chen (陈玛丽)[1,59,65] S. J. Chen (陈申见)[43]
S. L. Chen (陈思璐)[46] S. M. Chen (陈少敏)[62] T. Chen (陈通)[1,65] X. R. Chen (陈旭荣)[32,65] X. T. Chen (陈肖婷)[1,65]
X. Y. Chen (陈心宇)[12,g] Y. B. Chen (陈元柏)[1,59] Y. Q. Chen[16] Y. Q. Chen[35] Z. Chen[25] Z. J. Chen (陈卓俊)[26,i]
Z. K. Chen (陈梓康)[60] S. K. Choi[10] X. Chu (初晓)[12,g] G. Cibinetto[30A] F. Cossio[76C] J. Cottee-Meldrum[64]
J. J. Cui (崔佳佳)[51] H. L. Dai (代洪亮)[1,59] J. P. Dai (代建平)[80] A. Dbeyssi[19] R. E. de Boer[3] D. Dedovich[37]
C. Q. Deng (邓创旗)[74] Z. Y. Deng (邓子艳)[1] A. Denig[36] I. Denysenko[37] M. Destefanis[76A,76C] F. De Mori[76A,76C]
B. Ding (丁彪)[68,1] X. X. Ding (丁晓萱)[47,h] Y. Ding (丁勇)[41] Y. Ding (丁逸)[35] Y. X. Ding (丁玉鑫)[31]
J. Dong (董静)[1,59] L. Y. Dong (董燎原)[1,65] M. Y. Dong (董明义)[1,59,65] X. Dong (董翔)[78] M. C. Du (杜蒙川)[1]
S. X. Du (杜书先)[82] S. X. Du (杜少旭)[12,g] Y. Y. Duan (段尧予)[56] Z. H. Duan (段宗欢)[43] P. Egorov[37,b]
G. F. Fan (樊高峰)[43] J. J. Fan (樊俊杰)[20] Y. H. Fan (范宇晗)[46] J. Fang (方建)[1,59] J. Fang (方进)[60]
S. S. Fang (房双世)[1,65] W. X. Fang (方文兴)[1] Y. Q. Fang (方亚泉)[1,59] R. Farinelli[30A] L. Fava[76B,76C] F. Feldbauer[3]
G. Felici[29A] C. Q. Feng (封常青)[73,59] J. H. Feng (冯俊华)[16] L. Feng (冯琳)[39,k,l] Q. X. Feng (冯千禧)[39,k,l]
Y. T. Feng (冯玙潼)[73,59] M. Fritsch[3] C. D. Fu (傅成栋)[1] J. L. Fu (傅金林)[65] Y. W. Fu (傅亦威)[1,65] H. Gao (高涵)[65]
X. B. Gao (高鑫博)[42] Y. Gao (高扬)[73,59] Y. N. Gao (高语浓)[20] Y. N. Gao (高原宁)[47,h] Y. Y. Gao (高洋洋)[31]
Z. Gao (高枝)[44] S. Garbolino[76C] I. Garzia[30A,30B] L. Ge (葛玲)[58] P. T. Ge (葛潘婷)[20] Z. W. Ge (葛振武)[43]
C. Geng (耿聪)[60] E. M. Gersabeck[69] A. Gilman[71] K. Goetzen[13] J. D. Gong (龚家鼎)[35] L. Gong (龚丽)[41]
W. X. Gong (龚文煊)[1,59] W. Gradl[36] S. Gramigna[30A,30B] M. Greco[76A,76C] M. H. Gu (顾旻皓)[1,59] Y. T. Gu (顾运厅)[15]
C. Y. Guan (关春懿)[1,65] A. Q. Guo (郭爱强)[32] L. B. Guo (郭立波)[42] M. J. Guo (国梦娇)[51] R. P. Guo (郭如盼)[50]
Y. P. Guo (郭玉萍)[12,g] A. Guskov[37,b] J. Gutierrez[28] K. L. Han (韩坤霖)[65] T. T. Han (韩婷婷)[1] F. Hanisch[3]
K. D. Hao (郝科迪)[73,59] X. Q. Hao (郝喜庆)[20] F. A. Harris[67] K. K. He (何凯凯)[56] K. L. He (何康林)[1,65]
F. H. Heinsius[3] C. H. Heinz[36] Y. K. Heng (衡月昆)[1,59,65] C. Herold[61] P. C. Hong (洪鹏程)[35] G. Y. Hou (侯国一)[1,65]
X. T. Hou (侯贤涛)[1,65] Y. R. Hou (侯颖锐)[65] Z. L. Hou (侯治龙)[1] H. M. Hu (胡海明)[1,65] J. F. Hu (胡继峰)[57,j]
Q. P. Hu (胡启鹏)[73,59] S. L. Hu (胡圣亮)[12,g] T. Hu (胡涛)[1,59,65] Y. Hu (胡誉)[1] Z. M. Hu (胡忠敏)[60]
G. S. Huang (黄光顺)[73,59] K. X. Huang (黄凯旋)[60] L. Q. Huang (黄麟钦)[32,65] P. Huang (黄盼)[43]
X. T. Huang (黄性涛)[51] Y. P. Huang (黄燕萍)[1] Y. S. Huang (黄永盛)[60] T. Hussain[75] N. Hüsken[36]

Received 30 April 2025; Accepted 27 June 2025

* This work is supported in part by National Key R&D Program of China under Contracts Nos. 2023YFA1606000, 2023YFA1606704; National Natural Science Foundation of China (NSFC) under Contracts Nos. 12035009, 11875170, 11635010, 11935015, 11935016, 11935018, 12025502, 12035013, 12061131003, 12192260, 12192261, 12192262, 12192263, 12192264, 12192265, 12221005, 12225509, 12235017, 12361141819; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; CAS under Contract No. YSBR-101; 100 Talents Program of CAS; The Institute of Nuclear and Particle Physics (INPAC) and Shanghai Key Laboratory for Particle Physics and Cosmology; Agencia Nacional de Investigación y Desarrollo de Chile (ANID), Chile under Contract No. ANID PIA/APOYO AFB230003; ERC under Contract No. 758462; German Research Foundation DFG under Contract No. FOR5327; Istituto Nazionale di Fisica Nucleare, Italy; Knut and Alice Wallenberg Foundation under Contracts Nos. 2021.0174, 2021.0299; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Research Foundation of Korea under Contract No. NRF-2022R1A2C1092335; National Science and Technology fund of Mongolia; Polish National Science Centre under Contract No. 2024/53/B/ST2/00975; STFC (United Kingdom); Swedish Research Council under Contract No. 2019.04595; U. S. Department of Energy under Contract No. DE-FG02-05ER41374

N. in der Wiesche[70] J. Jackson[28] Q. Ji (纪全)[1] Q. P. Ji (姬清平)[20] W. Ji (季旺)[1,65] X. B. Ji (季晓斌)[1,65]
X. L. Ji (季筱璐)[1,59] Y. Y. Ji (吉钰瑶)[51] Z. K. Jia (贾泽坤)[73,59] D. Jiang (姜地)[1,65] H. B. Jiang (姜候兵)[78]
P. C. Jiang (蒋沛成)[47,h] S. J. Jiang (蒋思婧)[9] T. J. Jiang (蒋庭俊)[17] X. S. Jiang (江晓山)[1,59,65] Y. Jiang (蒋艺)[65]
J. B. Jiao (焦健斌)[51] J. K. Jiao (焦俊坤)[35] Z. Jiao (焦铮)[24] S. Jin (金山)[43] Y. Jin (金毅)[68] M. Q. Jing (荆茂强)[1,65]
X. M. Jing (景新媚)[65] T. Johansson[77] S. Kabana[34] N. Kalantar-Nayestanaki[66] X. L. Kang (康晓琳)[9]
X. S. Kang (康晓珅)[41] M. Kavatsyuk[66] B. C. Ke (柯百谦)[82] V. Khachatryan[28] A. Khoukaz[70] R. Kiuchi[1]
O. B. Kolcu[63A] B. Kopf[3] M. Kuessner[3] X. Kui (奎贤)[1,65] N. Kumar[27] A. Kupsc[45,77] W. Kühn[38] Q. Lan (兰强)[74]
W. N. Lan (兰文宁)[20] T. T. Lei (雷天天)[73,59] M. Lellmann[36] T. Lenz[36] C. Li (李聪)[44] C. Li (李翠)[48]
C. H. Li (李春花)[40] C. K. Li (李春凯)[21] D. M. Li (李德民)[82] F. Li (李飞)[1,59] G. Li (李刚)[1] H. B. Li (李海波)[1,65]
H. J. Li (李惠静)[20] H. N. Li (李衡讷)[57,j] Hui Li (李慧)[44] J. R. Li (李嘉荣)[62] J. S. Li (李静舒)[60] K. Li (李科)[1]
K. L. Li (李凯璐)[39,k,l] K. L. Li (李凯璐)[20] L. J. Li (李林健)[1,65] Lei Li (李蕾)[49] M. H. Li (李明浩)[44]
M. R. Li (李明润)[1,65] P. L. Li (李佩莲)[65] P. R. Li (李培荣)[39,k,l] Q. M. Li (李启铭)[1,65] Q. X. Li (李起鑫)[51]
R. Li (李燃)[18,32] S. X. Li (李素娴)[12] T. Li (李腾)[51] T. Y. Li (李天佑)[44] W. D. Li (李卫东)[1,65] W. G. Li (李卫国)[1,a]
X. Li (李旭)[1,65] X. H. Li (李旭红)[73,59] X. L. Li (李晓玲)[51] X. Y. Li (李晓宇)[1,8] X. Z. Li (李绪泽)[60] Y. Li (李洋)[20]
Y. G. Li (李彦谷)[47,h] Y. P. Li (李雁鹏)[35] Z. J. Li (李志军)[60] Z. Y. Li (李紫阳)[80] C. Liang (梁畅)[43]
H. Liang (梁昊)[73,59] Y. F. Liang (梁勇飞)[55] Y. T. Liang (梁羽铁)[32,65] G. R. Liao (廖广睿)[14] L. B. Liao (廖立波)[60]
M. H. Liao (廖明华)[60] Y. P. Liao (廖一朴)[1,65] J. Libby[27] A. Limphirat[61] C. C. Lin (蔺长城)[56]
D. X. Lin (林德旭)[32,65] L. Q. Lin (邵麟筌)[40] T. Lin (林韬)[1] B. J. Liu (刘北江)[1] B. X. Liu (刘宝鑫)[78]
C. Liu (刘成)[35] C. X. Liu (刘春秀)[1] F. Liu (刘芳)[1] F. H. Liu (刘福虎)[54] Feng Liu (刘峰)[6] G. M. Liu (刘国明)[57,j]
H. Liu (刘昊)[39,k,l] H. B. Liu (刘宏邦)[15] H. H. Liu (刘欢欢)[1] H. M. Liu (刘怀民)[1,65] Huihui Liu (刘汇慧)[22]
J. B. Liu (刘建北)[73,59] J. J. Liu (刘佳佳)[21] K. Liu (刘凯)[39,k,l] K. Liu (刘坤)[74] K. Y. Liu (刘魁勇)[41] Ke Liu (刘珂)[23]
L. C. Liu (刘良辰)[44] Lu Liu (刘露)[44] M. H. Liu (刘美宏)[12,g] M. H. Liu[35] P. L. Liu (刘佩莲)[1] Q. Liu (刘倩)[65]
S. B. Liu (刘树彬)[73,59] T. Liu (刘桐)[12,g] W. K. Liu (刘维克)[44] W. M. Liu (刘卫民)[73,59] W. T. Liu (刘婉婷)[40]
X. Liu (刘鑫)[40] X. Liu (刘翔)[39,k,l] X. K. Liu (刘筱康)[39,k,l] X. L. Liu (刘兴淋)[12,g] X. Y. Liu (刘雪吟)[78]
Y. Liu (刘义)[82] Y. Liu (刘英)[39,k,l] Y. Liu (刘媛)[82] Y. B. Liu (刘玉斌)[44] Z. A. Liu (刘振安)[1,59,65] Z. D. Liu (刘宗德)[9]
Z. Q. Liu (刘智青)[51] X. C. Lou (娄辛丑)[1,59,65] F. X. Lu (卢飞翔)[60] H. J. Lu (吕海江)[24] J. G. Lu (吕军光)[1,59]
X. L. Lu (陆小玲)[16] Y. Lu (卢宇)[7] Y. H. Lu (卢泱宏)[1,65] Y. P. Lu (卢云鹏)[1,59] Z. H. Lu (卢泽辉)[1,65]
C. L. Luo (罗成林)[42] J. R. Luo (罗家瑞)[60] J. S. Luo (罗家顺)[1,65] M. X. Luo (罗民兴)[81] T. Luo (罗涛)[12,g]
X. L. Luo (罗小兰)[1,59] Z. Y. Lv (吕在裕)[23] X. R. Lyu (吕晓睿)[65,p] Y. F. Lyu (吕翌丰)[44] Y. H. Lyu (吕云鹤)[82]
F. C. Ma (马凤才)[41] H. L. Ma (马海龙)[1] Heng Ma (马衡)[26,i] J. L. Ma (马俊力)[1,65] L. L. Ma (马连良)[51]
L. R. Ma (马立瑞)[68] Q. M. Ma (马秋梅)[1] R. Q. Ma (马润秋)[1,65] R. Y. Ma (马若云)[20] T. Ma (马腾)[73,59]
X. T. Ma (马晓天)[1,65] X. Y. Ma (马骁妍)[1,59] Y. M. Ma (马玉明)[32] F. E. Maas[19] I. MacKay[71] M. Maggiora[76A,76C]
S. Malde[71] Q. A. Malik[75] H. X. Mao (毛杭翔)[39,k,l] Y. J. Mao (冒亚军)[47,h] Z. P. Mao (毛泽普)[1] S. Marcello[76A,76C]
A. Marshall[64] F. M. Melendi[30A,30B] Y. H. Meng (孟琰皓)[65] Z. X. Meng (孟召霞)[68] G. Mezzadri[30A]
H. Miao (妙晗)[1,65] T. J. Min (闵天觉)[43] R. E. Mitchell[28] X. H. Mo (莫晓虎)[1,59,65] B. Moses[28] N. Yu. Muchnoi[4,c]
J. Muskalla[36] Y. Nefedov[37] F. Nerling[19,e] L. S. Nie (聂麟苏)[21] I. B. Nikolaev[4,c] Z. Ning (宁哲)[1,59] S. Nisar[11,m]
Q. L. Niu (牛祺乐)[39,k,l] W. D. Niu (牛文迪)[12,g] C. Normand[64] S. L. Olsen[10,65] Q. Ouyang (欧阳群)[1,59,65]
S. Pacetti[29B,29C] X. Pan (潘祥)[56] Y. Pan (潘越)[58] A. Pathak[10] Y. P. Pei (裴宇鹏)[73,59] M. Pelizaeus[3]
H. P. Peng (彭海平)[73,59] X. J. Peng (彭宣嘉)[39,k,l] Y. Y. Peng (彭云翊)[39,k,l] K. Peters[13,e] K. Petridis[64]
J. L. Ping (平加伦)[42] R. G. Ping (平荣刚)[1,65] S. Plura[36] V. Prasad[35] F. Z. Qi (齐法制)[1] H. R. Qi (漆红荣)[62]
M. Qi (祁鸣)[43] S. Qian (钱森)[1,59] W. B. Qian (钱文斌)[65] C. F. Qiao (乔从丰)[65] J. H. Qiao (乔佳辉)[20]
J. J. Qin (秦佳佳)[74] J. L. Qin (覃嘉良)[56] L. Q. Qin (秦丽清)[14] L. Y. Qin (秦龙宇)[73,59] P. B. Qin (秦鹏勃)[74]
X. P. Qin (覃潇平)[12,g] X. S. Qin (秦小帅)[51] Z. H. Qin (秦中华)[1,59] J. F. Qiu (邱进发)[1] Z. H. Qu (屈子皓)[74]
J. Rademacker[64] C. F. Redmer[36] A. Rivetti[76C] M. Rolo[76C] G. Rong (荣刚)[1,65] S. S. Rong (荣少石)[1,65]
F. Rosini[29B,29C] Ch. Rosner[19] M. Q. Ruan (阮曼奇)[1,59] N. Salone[45,q] A. Sarantsev[37,d] Y. Schelhaas[36]
K. Schoenning[77] M. Scodeggio[30A] K. Y. Shan (尚科羽)[12,g] W. Shan (单葳)[25] X. Y. Shan (单心钰)[73,59]

Z. J. Shang (尚子杰)[39,k,l] J. F. Shangguan (上官剑锋)[17] L. G. Shao (邵立港)[1,65] M. Shao (邵明)[73,59]
C. P. Shen (沈成平)[12,g] H. F. Shen (沈宏飞)[1,8] W. H. Shen (沈文涵)[65] X. Y. Shen (沈肖雁)[1,65] B. A. Shi (施伯安)[65]
H. Shi (史华)[73,59] J. L. Shi (石家磊)[12,g] J. Y. Shi (石京燕)[1] S. Y. Shi (史书宇)[74] X. Shi (史欣)[1,59]
H. L. Song (宋海林)[73,59] J. J. Song (宋娇娇)[20] T. Z. Song (宋天资)[60] W. M. Song (宋维民)[35] Y. J. Song (宋宇镜)[12,g]
Y. X. Song (宋昀轩)[47,h,n] Zirong Song (宋子荣)[26,i] S. Sosio[76A,76C] S. Spataro[76A,76C] F. Stieler[36] S. S Su (苏闪闪)[41]
Y. J. Su (粟杨捷)[65] G. B. Sun (孙光豹)[78] G. X. Sun (孙功星)[1] H. Sun (孙昊)[65] H. K. Sun (孙浩凯)[1]
J. F. Sun (孙俊峰)[20] K. Sun (孙开)[62] L. Sun (孙亮)[78] S. S. Sun (孙胜森)[1,65] T. Sun[52,f] Y. C. Sun (孙雨长)[78]
Y. H. Sun (孙益华)[31] Y. J. Sun (孙勇杰)[73,59] Y. Z. Sun (孙永昭)[1] Z. Q. Sun (孙泽群)[1,65] Z. T. Sun (孙振田)[51]
C. J. Tang (唐昌建)[55] G. Y. Tang (唐光毅)[1] J. Tang (唐健)[60] J. J. Tang (唐嘉骏)[73,59] L. F. Tang (唐林发)[40]
Y. A. Tang (唐迎澳)[78] L. Y. Tao (陶璐燕)[74] M. Tat[71] J. X. Teng (滕佳秀)[73,59] J. Y. Tian (田济源)[73,59]
W. H. Tian (田文辉)[60] Y. Tian (田野)[32] Z. F. Tian (田喆飞)[78] I. Uman[63B] B. Wang (王斌)[1] B. Wang (王博)[60]
Bo Wang (王博)[73,59] C. Wang (王程)[39,k,l] C. Wang (王超)[20] Cong Wang (王聪)[23] D. Y. Wang (王大勇)[47,h]
H. J. Wang (王泓鉴)[39,k,l] J. J. Wang (王家驹)[78] K. Wang (王科)[1,59] L. L. Wang (王亮亮)[1] L. W. Wang (王璐仪)[35]
M. Wang[73,59] M. Wang (王萌)[51] N. Y. Wang (王南洋)[65] S. Wang (王顺)[12,g] T. Wang (王婷)[12,g]
T. J. Wang (王腾蛟)[44] W. Wang (王维)[74] W. Wang (王为)[60] W. P. Wang (王维平)[36] X. Wang (王轩)[47,h]
X. F. Wang (王雄飞)[39,k,l] X. J. Wang (王希俊)[40] X. L. Wang (王小龙)[12,g] X. N. Wang (王新南)[1,65] Y. Wang (王亦)[62]
Y. D. Wang (王雅迪)[46] Y. F. Wang (王贻芳)[1,8,65] Y. H. Wang (王英豪)[39,k,l] Y. J. Wang (王祎景)[73,59]
Y. L. Wang (王艺龙)[20] Y. N. Wang (王燕宁)[78] Y. Q. Wang (王雨晴)[1] Yaqian Wang (王亚乾)[18] Yi Wang (王义)[62]
Yuan Wang (王源)[18,32] Z. Wang (王铮)[1,59] Z. L. Wang (王治浪)[74] Z. L. Wang (王治浪)[2] Z. Q. Wang (王紫祺)[12,g]
Z. Y. Wang (王至勇)[1,65] D. H. Wei (魏代会)[14] H. R. Wei[44] F. Weidner[70] S. P. Wen (文硕频)[1]
Y. R. Wen (温亚冉)[40] U. Wiedner[3] G. Wilkinson[71] M. Wolke[77] C. Wu (吴晨)[40] J. F. Wu (吴金飞)[1,8]
L. H. Wu (伍灵慧)[1] L. J. Wu (吴连近)[1,65] L. J. Wu (吴连近)[20] Lianjie Wu (武廉杰)[20] S. G. Wu (吴韶光)[1,65]
S. M. Wu (吴蜀明)[65] X. Wu (吴潇)[12,g] X. H. Wu (伍雄浩)[35] Y. J. Wu (吴英杰)[32] Z. Wu (吴智)[1,59] L. Xia (夏磊)[73,59]
X. M. Xian (咸秀梅)[40] B. H. Xiang (向本后)[1,65] D. Xiao (肖栋)[39,k,l] G. Y. Xiao (肖光延)[43] H. Xiao (肖浩)[74]
Y. L. Xiao (肖云龙)[12,g] Z. J. Xiao (肖振军)[42] C. Xie (谢陈)[43] K. J. Xie (谢凯吉)[1,65] X. H. Xie (谢昕海)[47,h]
Y. Xie (谢勇)[51] Y. G. Xie (谢宇广)[1,59] Y. H. Xie (谢跃红)[6] Z. P. Xie (谢智鹏)[73,59] T. Y. Xing (邢天宇)[1,65]
C. F. Xu[1,65] C. J. Xu (许创杰)[60] G. F. Xu (许国发)[1] H. Y. Xu (许皓月)[68,2] H. Y. Xu (许皓月)[2] M. Xu (徐明)[73,59]
Q. J. Xu (徐庆君)[17] Q. N. Xu[31] T. D. Xu (徐腾达)[74] W. Xu (许威)[1] W. L. Xu (徐万伦)[68] X. P. Xu (徐新平)[56]
Y. Xu (徐月)[12,g] Y. Xu (徐月)[41] Y. C. Xu (胥英超)[79] Z. S. Xu (许昭燊)[65] F. Yan (严芳)[12,g] H. Y. Yan (闫浩宇)[40]
L. Yan (严亮)[12,g] W. B. Yan (鄢文标)[73,59] W. C. Yan (闫文成)[82] W. H. Yan (闫文昊)[6] W. P. Yan (闫文鹏)[20]
X. Q. Yan (严薛强)[1,65] H. J. Yang (杨海军)[52,f] H. L. Yang (杨昊霖)[35] H. X. Yang (杨洪勋)[1] J. H. Yang (杨君辉)[43]
R. J. Yang (杨润佳)[20] T. Yang (杨涛)[1] Y. Yang (杨莹)[12,g] Y. F. Yang (杨艳芳)[44] Y. H. Yang (杨友华)[43]
Y. Q. Yang (杨永强)[9] Y. X. Yang (杨逸翔)[1,65] Y. Z. Yang (杨颖喆)[20] M. Ye (叶梅)[1,59] M. H. Ye (叶铭汉)[8,a]
Z. J. Ye (叶子健)[57,j] Junhao Yin (殷俊昊)[44] Z. Y. You (尤郑昀)[60] B. X. Yu (俞伯祥)[1,59,65] C. X. Yu (喻纯旭)[44]
G. Yu[13] J. S. Yu (俞洁晟)[26,i] L. Q. Yu (喻丽雯)[12,g] M. C. Yu[41] T. Yu (于涛)[74] X. D. Yu (余旭东)[47,h]
Y. C. Yu (郁烨淳)[82] C. Z. Yuan (苑长征)[1,65] H. Yuan (袁昊)[1,65] J. Yuan (袁菁)[35] J. Yuan (袁杰)[46] L. Yuan (袁丽)[2]
S. C. Yuan (苑思成)[1,65] X. Q. Yuan (袁晓庆)[1] Y. Yuan (袁野)[1,65] Z. Y. Yuan (袁朝阳)[60] C. X. Yue (岳崇兴)[40]
Ying Yue (岳颖)[20] A. A. Zafar[75] S. H. Zeng[64A,64B,64C,64D] X. Zeng (曾鑫)[12,g] Y. Zeng (曾云)[26,i]
Y. J. Zeng (曾溢嘉)[1,65] Y. J. Zeng (曾宇杰)[60] X. Y. Zhai (翟星晔)[35] Y. H. Zhan (詹永华)[60] Zhang[71]
A. Q. Zhang (张安庆)[1,65] B. L. Zhang (张伯伦)[1,65] B. X. Zhang (张丙新)[1] D. H. Zhang (张丹昊)[44]
G. Y. Zhang (张耕源)[1,65] G. Y. Zhang (张广义)[20] H. Zhang (张豪)[73,59] H. Zhang (张晗)[82] H. C. Zhang (张航畅)[1,59,65]
H. H. Zhang (张宏浩)[60] H. Q. Zhang (张华桥)[1,59,65] H. R. Zhang (张浩然)[73,59] H. Y. Zhang (章红宇)[1,59]
J. Zhang (张晋)[60] J. Zhang (张进)[82] J. J. Zhang (张进军)[53] J. L. Zhang (张杰磊)[21] J. Q. Zhang (张敬庆)[42]
J. S. Zhang (张家声)[12,g] J. W. Zhang (张家文)[1,59,65] J. X. Zhang (张景旭)[39,k,l] J. Y. Zhang (张建勇)[1]
J. Z. Zhang (张景芝)[1,65] Jianyu Zhang (张剑宇)[65] L. M. Zhang (张黎明)[62] Lei Zhang (张雷)[43] N. Zhang (张楠)[82]
P. Zhang (张鹏)[1,8] Q. Zhang (张强)[20] Q. Y. Zhang (张秋岩)[35] R. Y. Zhang (张若愚)[39,k,l] S. H. Zhang (张水涵)[1,65]

Shulei Zhang (张书磊)[26,i] X. M. Zhang (张晓梅)[1] X. Y Zhang[41] X. Y. Zhang (张学尧)[51] Y. Zhang (张宇)[74]
Y. Zhang (张瑶)[1] Y. T. Zhang (张亚腾)[82] Y. H. Zhang (张银鸿)[1,59] Y. M. Zhang (张悦明)[40]
Y. P. Zhang (张越鹏)[73,59] Z. D. Zhang (张正德)[1] Z. H. Zhang (张泽恒)[1] Z. L. Zhang (张志龙)[56]
Z. L. Zhang (张兆领)[35] Z. X. Zhang (张泽祥)[20] Z. Y. Zhang (张子羽)[44] Z. Y. Zhang (张振宇)[78]
Z. Z. Zhang (张子扬)[46] Zh. Zh. Zhang[20] G. Zhao (赵光)[1] J. Y. Zhao (赵静宜)[1,65] J. Z. Zhao (赵京周)[1,59]
L. Zhao (赵玲)[1] L. Zhao (赵雷)[73,59] M. G. Zhao (赵明刚)[44] N. Zhao (赵宁)[80] R. P. Zhao (赵若平)[65]
S. J. Zhao (赵书俊)[82] Y. B. Zhao (赵豫斌)[1,59] Y. L. Zhao (赵艳琳)[56] Y. X. Zhao (赵宇翔)[32,65]
Z. G. Zhao (赵政国)[73,59] A. Zhemchugov[37,b] B. Zheng (郑波)[74] B. M. Zheng (郑变敏)[35] J. P. Zheng (郑建平)[1,59]
W. J. Zheng (郑文静)[1,65] X. R. Zheng (郑心如)[20] Y. H. Zheng (郑阳恒)[65,p] B. Zhong (钟彬)[42] C. Zhong (钟翠)[20]
H. Zhou (周航)[36,51,o] J. Q. Zhou (周嘉奇)[35] J. Y. Zhou (周佳莹)[35] S. Zhou (周帅)[6] X. Zhou (周详)[78]
X. K. Zhou (周晓康)[6] X. R. Zhou (周小蓉)[73,59] X. Y. Zhou (周兴玉)[40] Y. X. Zhou (周亦雄)[79]
Y. Z. Zhou (周祎卓)[12,g] A. N. Zhu (朱傲男)[65] J. Zhu (朱江)[44] K. Zhu (朱凯)[1] K. J. Zhu (朱科军)[1,59,65]
K. S. Zhu (朱康帅)[12,g] L. Zhu (朱林)[35] L. X. Zhu (朱琳萱)[65] S. H. Zhu (朱世海)[72] T. J. Zhu (朱腾蛟)[12,g]
W. D. Zhu (朱稳定)[42] W. D. Zhu (朱稳定)[12,g] W. J. Zhu (朱文静)[1] W. Z. Zhu (朱文卓)[20] Y. C. Zhu (朱莹春)[73,59]
Z. A. Zhu (朱自安)[1,65] X. Y. Zhuang (庄新宇)[44] J. H. Zou (邹佳恒)[1] J. Zu (祖健)[73,59]
(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]Bochum Ruhr-University, D-44780 Bochum, Germany
[4]Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia
[5]Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
[6]Central China Normal University, Wuhan 430079, People's Republic of China
[7]Central South University, Changsha 410083, People's Republic of China
[8]China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China
[9]China University of Geosciences, Wuhan 430074, People's Republic of China
[10]Chung-Ang University, Seoul, 06974, Republic of Korea
[11]COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan
[12]Fudan University, Shanghai 200433, People's Republic of China
[13]GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany
[14]Guangxi Normal University, Guilin 541004, People's Republic of China
[15]Guangxi University, Nanning 530004, People's Republic of China
[16]Guangxi University of Science and Technology, Liuzhou 545006, People's Republic of China
[17]Hangzhou Normal University, Hangzhou 310036, People's Republic of China
[18]Hebei University, Baoding 071002, People's Republic of China
[19]Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany
[20]Henan Normal University, Xinxiang 453007, People's Republic of China
[21]Henan University, Kaifeng 475004, People's Republic of China
[22]Henan University of Science and Technology, Luoyang 471003, People's Republic of China
[23]Henan University of Technology, Zhengzhou 450001, People's Republic of China
[24]Huangshan College, Huangshan 245000, People's Republic of China
[25]Hunan Normal University, Changsha 410081, People's Republic of China
[26]Hunan University, Changsha 410082, People's Republic of China
[27]Indian Institute of Technology Madras, Chennai 600036, India
[28]Indiana University, Bloomington, Indiana 47405, USA
[29A]INFN Laboratori Nazionali di Frascati, INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy
[29B]INFN Laboratori Nazionali di Frascati, INFN Sezione di Perugia, I-06100, Perugia, Italy
[29C]INFN Laboratori Nazionali di Frascati, University of Perugia, I-06100, Perugia, Italy
[30A]INFN Sezione di Ferrara, INFN Sezione di Ferrara, I-44122, Ferrara, Italy
[30B]INFN Sezione di Ferrara, University of Ferrara, I-44122, Ferrara, Italy
[31]Inner Mongolia University, Hohhot 010021, People's Republic of China
[32]Institute of Modern Physics, Lanzhou 730000, People's Republic of China
[33]Institute of Physics and Technology, Mongolian Academy of Sciences, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia
[34]Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile
[35]Jilin University, Changchun 130012, People's Republic of China
[36]Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
[37]Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
[38]Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany
[39]Lanzhou University, Lanzhou 730000, People's Republic of China
[40]Liaoning Normal University, Dalian 116029, People's Republic of China
[41]Liaoning University, Shenyang 110036, People's Republic of China
[42]Nanjing Normal University, Nanjing 210023, People's Republic of China

[43]Nanjing University, Nanjing 210093, People's Republic of China
[44]Nankai University, Tianjin 300071, People's Republic of China
[45]National Centre for Nuclear Research, Warsaw 02-093, Poland
[46]North China Electric Power University, Beijing 102206, People's Republic of China
[47]Peking University, Beijing 100871, People's Republic of China
[48]Qufu Normal University, Qufu 273165, People's Republic of China
[49]Renmin University of China, Beijing 100872, People's Republic of China
[50]Shandong Normal University, Jinan 250014, People's Republic of China
[51]Shandong University, Jinan 250100, People's Republic of China
[52]Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
[53]Shanxi Normal University, Linfen 041004, People's Republic of China
[54]Shanxi University, Taiyuan 030006, People's Republic of China
[55]Sichuan University, Chengdu 610064, People's Republic of China
[56]Soochow University, Suzhou 215006, People's Republic of China
[57]South China Normal University, Guangzhou 510006, People's Republic of China
[58]Southeast University, Nanjing 211100, People's Republic of China
[59]State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China
[60]Sun Yat-Sen University, Guangzhou 510275, People's Republic of China
[61]Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
[62]Tsinghua University, Beijing 100084, People's Republic of China
[63A]Turkish Accelerator Center Particle Factory Group, Istinye University, 34010, Istanbul, Turkey
[63B]Turkish Accelerator Center Particle Factory Group, Near East University, Nicosia, North Cyprus, 99138, Mersin 10, Turkey
[64]University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, UK
[65]University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[66]University of Groningen, NL-9747 AA Groningen, The Netherlands
[67]University of Hawaii, Honolulu, Hawaii 96822, USA
[68]University of Jinan, Jinan 250022, People's Republic of China
[69]University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
[70]University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany
[71]University of Oxford, Keble Road, Oxford OX13RH, United Kingdom
[72]University of Science and Technology Liaoning, Anshan 114051, People's Republic of China
[73]University of Science and Technology of China, Hefei 230026, People's Republic of China
[74]University of South China, Hengyang 421001, People's Republic of China
[75]University of the Punjab, Lahore-54590, Pakistan
[76A]University of Turin and INFN, University of Turin, I-10125, Turin, Italy
[76B]University of Turin and INFN, University of Eastern Piedmont, I-15121, Alessandria, Italy
[76C]University of Turin and INFN, INFN, I-10125, Turin, Italy
[77]Uppsala University, Box 516, SE-75120 Uppsala, Sweden
[78]Wuhan University, Wuhan 430072, People's Republic of China
[79]Yantai University, Yantai 264005, People's Republic of China
[80]Yunnan University, Kunming 650500, People's Republic of China
[81]Zhejiang University, Hangzhou 310027, People's Republic of China
[82]Zhengzhou University, Zhengzhou 450001, People's Republic of China
[a]Deceased
[b]Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia
[c]Also at the Novosibirsk State University, Novosibirsk, 630090, Russia
[d]Also at the NRC "Kurchatov Institute", PNPI, 188300, Gatchina, Russia
[e]Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany
[f]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
[g]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
[h]Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China
[i]Also at School of Physics and Electronics, Hunan University, Changsha 410082, China
[j]Also at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China
[k]Also at MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, People's Republic of China
[l]Also at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, People's Republic of China
[m]Also at the Department of Mathematical Sciences, IBA, Karachi 75270, Pakistan
[n]Also at Ecole Polytechnique Federale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland
[o]Also at Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany
[p]Also at Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China
[q]Currently at: Silesian University in Katowice, Chorzow, 41-500, Poland

Abstract: The lepton number violation decay $\omega\to\pi^+\pi^+e^-e^-+c.c.$ is searched for via $J/\psi\to\omega\eta$ using a data sample of $(1.0087\pm0.0044)\times10^{10}$ J/ψ events collected by the BESIII detector at the BEPCII collider. No significant signal is observed, and the upper limit on the branching fraction of $\omega\to\pi^+\pi^+e^-e^-+c.c.$ at the 90% confidence level is determined for the first time to be 2.8×10^{-6}.

Keywords: Lepton number violation, matter anti-matter asymmetry, neutrinoless double beta decay

DOI: **CSTR:**

I. INTRODUCTION

Neutrinos, described by the Dirac equation and considered as $SU(2)_L$ gauge invariant fields, were accepted in the Standard Model (SM) as massless left-handed Dirac fermions after the experimental measurement of neutrino helicity as -1 in 1958 [1]. However, the Solar Neutrino Experiment, Sudbury Neutrino Observatory, and Super-Kamioka Neutrino Detection Experiment have observed neutrino oscillation [2–5], indicating that neutrinos possess a tiny mass.

If the antiparticle of a neutrino is itself, the solution to the Dirac equation can give rise to a Majorana particle. In the theory of Majorana [6], neutrinos can potentially possess mass. Some theories, such as the seesaw mechanism [7, 8], provide a natural framework for generating a small Majorana mass. If neutrinos are indeed Majorana fermions, it would lead to a violation of lepton number conservation by two units. Hence, the discovery of lepton number violating processes might be relevant to the properties of neutrinos. Furthermore, Baryon Number Violation (BNV) is a key aspect of some Grand Unified Theories (GUTs) and is essential for understanding the early Universe. The connection between BNV and Lepton Number Violation (LNV) in various theories and models [9–12] suggests the search for the LNV decay is one of the important approaches to establish a theory beyond the SM.

Various LNV signals have been sought after, and the search for neutrinoless double-beta ($0\nu\beta\beta$) decay [13–16], which was first proposed by Furry [17] in 1939, is considered to be the most sensitive. Many collider experiments have searched for LNV decays, such as B^- decays by LHCb [18, 19], $q\bar{q}\to l^{\pm}l'^{\pm}q'\bar{q}$ and $q\gamma\to l^{\pm}l^{\pm}q''q'\bar{q}$ $(l=e,\mu)$ channels by CMS [20], $X_c^+\to h^{\pm}l^{\mp}l^{(\prime)+}$ $(X_c=D,D_s,\Lambda_c^+,h=\pi,K,p)$ decays by BaBar [21], decays with final states consisting of two charged leptons and two jets by ATLAS [22], decays of charm and charmed-strange mesons to final states $h^{\pm}e^{\mp}e^{+}$ $(h=\pi,K)$ by CLEO [23], 3-body di-muon decays of D^+,D_s^+ by FOCUS [24], and D meson LNV decays by BESIII [25, 26]. E865 [27], NA62 [28], and BESIII [29] experiments also searched for LNV with non-first generation quark decays in K and ϕ meson decays, but so far have reported negative results only.

The world's largest J/ψ dataset taken at BESIII offers a good opportunity to search for possible LNV decays of various light hadrons, e.g., $\omega\to\pi^+\pi^+l^-l^-$. To avoid backgrounds from pion-muon misidentification and take advantage of larger phase space, we focus on the $\pi^+\pi^+e^-e^-$ final states in this work. Figure 1 shows two possible Feynman diagrams for $\omega\to\pi^+\pi^+e^-e^-$ in the Majorana neutrino scenario, analogous to those in Ref. [33], with suppression due to the large mass of the $W^{\pm}$ bosons. The LNV decay of the ω meson in the process $\omega\to\pi^+\pi^+e^-e^-$ has a unique phase space coverage compared to other measurements and low background contamination. Its discovery will indicate the existence of new physics.

In this paper, we present the first search for the LNV decay $\omega\to\pi^+\pi^+e^-e^-$ via $J/\psi\to\omega\eta$ decay based on $(1.0087\pm0.0044)\times10^{10}$ J/ψ events [30] collected by the BESIII [31] detector at the Beijing Electron-Positron Collider II (BEPCII) [32]. The charge-conjugated decay mode $\omega\to\pi^-\pi^-e^+e^+$ is included and implicitly assumed throughout.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

BESIII [31] is a symmetric cylindrical particle detector located around the interaction point of BEPCII [32], which is an e^+e^- collider employing a double storage ring. The center-of-mass collision luminosity of BEPCII reached a peak of 1.1×10^{33} cm^{-2}s^{-1} at 3.773 GeV. The BESIII detector consists of four detector sub-components [31]: a helium-based multilayer drift chamber (MDC), a plastic scintillator Time-Of-Flight counter (TOF), a CsI(Tl) Electromagnetic Calorimeter (EMC), and a muon counter, providing a coverage of 93% of the total solid angle. The superconducting solenoid supported by an octagonal flux-return yoke provides a magnetic field of 1.0 T for the MDC for most of the J/ψ data. The magnetic field was 0.9 T in 2012, which affects 11% of the total J/ψ data. The momentum resolution of the MDC for charged particles at 1 GeV/c is 0.5%, and the ionization energy loss (dE/dx) resolution for electrons from Bhabha scattering is 6%. The time resolution of the TOF barrel region is 68 ps, and the time resolution of the end

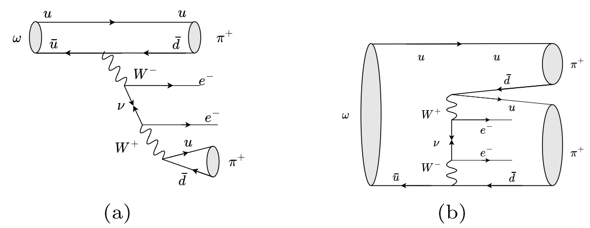

Fig. 1. Two possible Feynman diagrams for $\omega\to\pi^+\pi^+e^-e^-$.

cap region was 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [34], which benefits 87% of the data used in this analysis. The EMC achieves an energy resolution of 2.5% at 1 GeV.

Monte Carlo (MC) samples are used to analyze backgrounds and determine the detection efficiency. The detector response, geometric description [35, 36], and the signal digitization models are simulated by GEANT4 [37] software. For the inclusive MC sample, the known J/ψ decay modes are generated by EVTGEN [38] with average branching fractions taken from the Particle Data Group (PDG) [39], while the remaining unknown decays modes from the charmonium states are generated by LUNDCHARM [40]. The J/ψ resonance is produced via e^+e^- annihilations by KKMC [41], which includes the effects of beam energy spread and initial state radiation. Final state radiation from charged final-state particles is incorporated with PHOTOS [42]. Signal MC events of $J/\psi\to\omega\eta$, with $\eta\to\gamma\gamma$ and $\omega\to\pi^+\pi^-\pi^0$ or $\omega\to\pi^+\pi^+e^-e^-$, are also generated. The $J/\psi\to\omega\eta$ decays are modeled by a helicity amplitude model [38], and the $\omega\to\pi^+\pi^-\pi^0$ decays are modeled by an ω Dalitz model [43]. Other decays are modeled by a phase space model.

III. DATA ANALYSIS

To avoid the large uncertainty (11.5%) [39] from the world average value of $\mathcal{B}(J/\psi\to\omega\eta)$, we measure the branching fraction of the decay $\omega\to\pi^+\pi^+e^-e^-$ relative to the reference decay $\omega\to\pi^+\pi^-\pi^0$

$$\mathcal{B}(\omega\to\pi^+\pi^+e^-e^-)=\mathcal{B}(\omega\to\pi^+\pi^-\pi^0)\times\mathcal{B}(\pi^0\to\gamma\gamma)\times\frac{N^{\rm sig}_{\pi^+\pi^+e^-e^-}/\epsilon_{\pi^+\pi^+e^-e^-}}{N^{\rm ref}_{\pi^+\pi^-\pi^0}/\epsilon_{\pi^+\pi^-\pi^0}},\qquad(1)$$

where $\mathcal{B}(\omega\to\pi^+\pi^-\pi^0)$ and $\mathcal{B}(\pi^0\to\gamma\gamma)$ are the branching fractions of $\omega\to\pi^+\pi^-\pi^0$ and $\pi^0\to\gamma\gamma$, respectively. $N^{\rm sig}_{\pi^+\pi^+e^-e^-}$ and $N^{\rm ref}_{\pi^+\pi^-\pi^0}$ are the numbers of signal and reference channel events, respectively. $\epsilon_{\pi^+\pi^+e^-e^-}$ and $\epsilon_{\pi^+\pi^-\pi^0}$ are the detection efficiencies of signal and reference decays, respectively.

All charged tracks are reconstructed in the detector acceptance region of the MDC. Their polar angles θ are required to satisfy $|\cos\theta|<0.93$, where θ is measured relative to the z-axis, the symmetry axis of the MDC. The distances of closest approach to the interaction point of the charged tracks, along the z direction and in the plane perpendicular to the z-axis, $|V_z|$ and $|V_{xy}|$, are required to be less than 10 cm and 1 cm, respectively.

For charged particle identification (PID), we make use of a combination of dE/dx in the MDC, the time of flight in the TOF and the information of clusters in the EMC to calculate the confidence level (CL) for the pion, kaon and electron hypotheses (CL_π, CL_K, CL_e). Pion candidates are required to satisfy $\mathrm{CL}_\pi>0.001$ and $\mathrm{CL}_\pi>\mathrm{CL}_K$, while electron candidates are required to satisfy $\mathrm{CL}_e>0.001$ and $\mathrm{CL}_e/(\mathrm{CL}_e+\mathrm{CL}_K+\mathrm{CL}_\pi)>0.8$.

Photons are reconstructed using isolated clusters in the EMC. The deposited energies in the barrel region ($|\cos\theta|<0.8$) and endcap region ($0.86<|\cos\theta|<0.92$) are required to be larger than 25 MeV and 50 MeV, respectively. To suppress electronic noise and unrelated encodings, the EMC timing of the photon candidate is required to be within 700 ns after the event start time. To eliminate photons emanating from charged tracks, the opening angle between the photon and the nearest charged track is required to be larger than 10 degrees.

A. Analysis of $\omega\to\pi^+\pi^-\pi^0$

For the reference channel $J/\psi\to\omega\eta$, with $\eta\to\gamma\gamma$, $\omega\to\pi^+\pi^-\pi^0$ and $\pi^0\to\gamma\gamma$, at least four reconstructed photons and two reconstructed charged tracks with zero net charge are required. To select the photons of the π^0 and η candidates, we calculate the value of $\Delta m^2_{2\gamma}=\frac{(M_{\gamma\gamma}-M_{\pi^0})^2}{\sigma^2_{\pi^0}}+\frac{(M_{\gamma\gamma}-M_\eta)^2}{\sigma^2_\eta}$ for all possible sets of four photons, where $M_{\gamma\gamma}$ is the $\gamma\gamma$ invariant mass, M_{π^0} and M_η are the known π^0 and η masses [39], and σ_{π^0} and σ_η are the corresponding mass resolutions determined from MC simulation. The π^0 and η candidates with the smallest $\Delta m^2_{2\gamma}$ are kept for further analysis.

In order to reduce backgrounds and improve the mass resolution, a five-constraint (5C) kinematic fit [44] is performed to all the tracks enforcing energy and momentum conservation and constraining $M_{\gamma\gamma}$ to M_{π^0}. The $\chi^2_{5\rm C}$ from the kinematic fit is required to be less than 20, which is determined by optimizing the figure-of-merit $\frac{S}{\sqrt{S+B}}$, where S is the number of signal events and B is the number of background events from the inclusive MC sample. The requirement vetoes 84% of background contributions and retains 67% of the reference channel.

Backgrounds are investigated using the 1.0011×10^{10} inclusive J/ψ MC events. Backgrounds with peaks in the invariant mass distributions of both $\pi^+\pi^-\pi^0$ ($M_{3\pi}$) and $M_{\gamma\gamma}$ are negligible. The remaining backgrounds includes non-peaking backgrounds (BKGI) and those with peaks in either the $M_{3\pi}$ or $M_{\gamma\gamma}$ distributions (BKGII). The contributions of these backgrounds are determined by performing a two-dimensional (2D) fit to the invariant mass distributions of $M_{3\pi}$ and $M_{\gamma\gamma}$.

We use the sum of the two Crystal Ball (CB) functions ($F^\omega_{\rm sig}$) with the same σ and μ values but different tail parameters to describe the signal of $M_{3\pi}$ and a signal MC shape convolved with a Gaussian function ($F^\eta_{\rm sig}$) to describe $M_{\gamma\gamma}$. The non-peaking background contributions in the $M_{3\pi}$ and $M_{\gamma\gamma}$ distributions are described by a reversed ARGUS function [45] ($F^\omega_{\rm bkg}$ and $F^\eta_{\rm bkg}$). Consequently, the total signal shape is described by $F^\omega_{\rm sig}\otimes F^\eta_{\rm sig}$, the backgrounds like $\pi^+\pi^-\pi^0\eta$ and $\pi^0\pi^0\omega$ (BKGII) are described by $F^{\omega}_{\rm bkg}\otimes F^{\eta}_{\rm sig}$ and $F^{\eta}_{\rm bkg}\otimes F^{\omega}_{\rm sig}$, and the non-peaking background (BKGI) is described by $F^{\omega}_{\rm bkg}\otimes F^{\eta}_{\rm bkg}$.The fit range is chosen to be [0.70, 0.86] GeV/c^2 for $M_{3\pi}$, and [0.45, 0.65] GeV/c^2 for $M_{\gamma\gamma}$. We float the parameters of probability density functions (PDFs) during the fit and the signal yield is determined to be $N^{\rm ref}_{\pi^+\pi^-\pi^0} = 941,336\pm 1,352$, where the uncertainty is statistical. The projections of the 2D fit to the $M_{3\pi}$ and $M_{\gamma\gamma}$ distributions are shown in Fig. 2. The detection efficiency of the reference channel is determined by the dedicated MC sample to be $\epsilon_{\pi^+\pi^-\pi^0} = (12.80\pm 0.03)\%$. By taking into account the signal yield $N^{\rm ref}_{\pi^+\pi^-\pi^0}$, the detection efficiency $\epsilon_{\pi^+\pi^-\pi^0}$, and the decay branching fractions of $\omega\to\pi^+\pi^-\pi^0$ and $\pi^0\to\gamma\gamma$ from the PDG [39], the branching fraction of $J/\psi\to\omega\eta$ is measured to be consistent with its world average value quoted from the PDG [39] within one standard deviation.

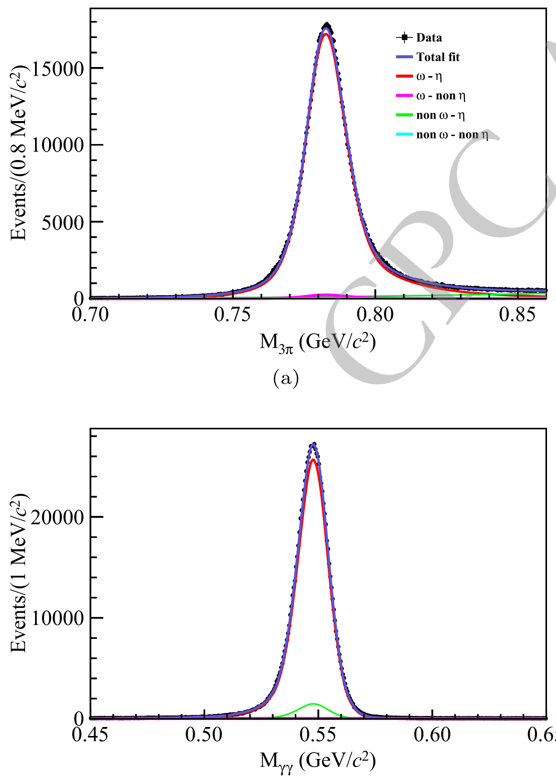

Fig. 2. (color online) The projections of the 2D fit of the (a) $M_{3\pi}$ and (b) $M_{\gamma\gamma}$ distributions, where the total PDF is shown by a blue solid curve. The signal PDF is shown by a red solid curve and labeled by $\omega-\eta$. The non-peaking background distribution is shown by a cyan solid curve and labeled by non-ω – non-η. The peaking background in $M_{3\pi}$ is shown by a pink solid curve and labeled by ω – non-η. The peaking background in $M_{\gamma\gamma}$ is shown by a green solid line and labeled by non-$\omega-\eta$.

B. Analysis of $\omega\to\pi^+\pi^+e^-e^-$

For the signal channel $J/\psi\to\omega\eta$ with $\eta\to\gamma\gamma$ and $\omega\to\pi^+\pi^+e^-e^-$, at least two reconstructed photons and four reconstructed charged tracks with zero net charge are required. The selection criteria of charged and neutral tracks that are consistent with those used in the reference channel.

In order to reduce backgrounds and improve the mass resolution, a four-constraint (4C) kinematic fit [44] is performed by constraining the energy and momentum of the four charged tracks ($\pi^+\pi^+e^-e^-$) and two photons to those of the initial state. If there are more than two photons, we keep the candidate with the lowest χ^2_{4C} for further analysis. To further suppress backgrounds, the χ^2_{4C} is required to be less than 10, which is determined by the Punzi figure-of-merit method [46], with the figure of merit $\frac{\epsilon}{1.5+\sqrt{B}}$, where ϵ is the detection efficiency and B is the number of background events. This selection criterion can remove 99% of background events while retaining 56% of the signal events. To further suppress misidentification from processes with four charged tracks, we re-calculate the χ^2 of the 4C kinematic fit with different mass assignments ($\chi^2_{\rm re}$): $\pi^+\pi^-\pi^+\pi^-\gamma\gamma$, $K^+K^-K^+K^-\gamma\gamma$, $\pi^+\pi^-K^+K^-\gamma\gamma$, and $\pi^+\pi^-p\bar{p}\gamma\gamma$. If any of the $\chi^2_{\rm re}$s is less than χ^2_{4C}, the event is considered as background and rejected.

The signal region is determined by fitting the $M_{\pi^+\pi^+e^-e^-}$ and $M_{\gamma\gamma}$ distributions of signal MC samples, where the signal shape is modeled by a double Gaussian function and the background shape a second-order polynomial function. The fitted regions are determined as $[0.72, 0.84]$ GeV$/c^2$ for $M_{\pi^+\pi^+e^-e^-}$ and $[0.51, 0.59]$ GeV$/c^2$ for $M_{\gamma\gamma}$. These intervals correspond to $\pm 5\sigma$ ranges centered on the composite mean position of the double Gaussian function, where σ is the effective resolution parameter derived from the fit. The detection efficiency is $\epsilon_{\pi^+\pi^+e^-e^-} = (11.52\pm 0.03)\%$ based on the simulated signal MC samples.

Figure 3 shows the 2D scatter plot of $M_{\gamma\gamma}$ versus $M_{\pi^+\pi^+e^-e^-}$ for the candidate events from J/ψ data. In the scatterplot no candidates are found inside the defined signal region. Thus, the number of observed events is $N^{\rm obs}_{\pi^+\pi^+e^-e^-} = 0$. To study the possible backgrounds, 1.0011×10^{10} inclusive J/ψ MC events are analyzed. We find there is no event located near the signal region, and the number of background events is determined to be $N^{\rm bkg}_{\pi^+\pi^+e^-e^-} = 0$.

C. Systematic uncertainty

The systematic uncertainties for the signal and reference decays include the uncertainties in the MDC tracking, PID, π^0 reconstruction, kinematic fit and χ^2 requirement, signal window, 2D fit, MC modeling, $N^{\rm ref}_{\pi^+\pi^-\pi^0}$ determination, and input branching fractions. The systematic uncertainties of the η reconstruction with $\mathcal{B}(J/\psi\to\omega\eta)$

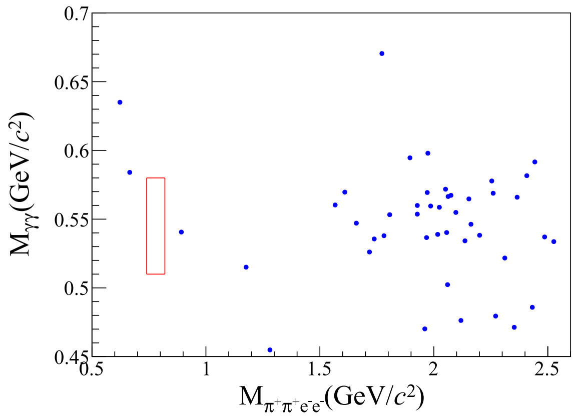

Fig. 3. (color online) The 2D distribution of $M_{\gamma\gamma}$ versus $M_{\pi^+\pi^+e^-e^-}$ of the candidate events from the J/ψ data, where the red box shows the signal region.

Table 1. Relative systematic uncertainties.

Source	Uncertainty (%)
MDC tracking	4.5
PID	4.5
π^0 reconstruction	1.0
Kinematic fit and χ^2 requirement	2.7
Signal window	0.2
2D fit	3.5
MC modeling	0.3
$N^{\rm ref}_{\pi^+\pi^-\pi^0}$ determination	0.2
MC statistics	0.3
$\mathcal{B}(\omega\to\pi^+\pi^-\pi^0,\pi^0\to\gamma\gamma)$	0.8
Total	7.9

and $\mathcal{B}(\eta\to\gamma\gamma)$ cancel due to calculating the relative branching fraction ratio.

The systematic uncertainties of MDC tracking and PID for charged pions and electrons are 1.0% [47, 48] per charged track. Since there are two charged tracks for the reference channel and four charged tracks for the LNV channel, the systematic uncertainties are assigned to be 2.0% and 4.0%, respectively. The individual systematic uncertainties for both MDC tracking and PID of charged tracks are calculated to be $\sqrt{(2.0\%)^2+(4.0\%)^2}=4.5\%$ each.

The systematic uncertainty of π^0 reconstruction is 1.0% [49]. The systematic uncertainty in the kinematic fit and the χ^2 requirement of the signal (reference) decay is estimated with the control sample $J/\psi\to\pi^+\pi^-\pi^+\pi^-\eta,\eta\to\gamma\gamma$ ($J/\psi\to\omega\pi^0,\omega\to\pi^+\pi^-\pi^0$). The relative difference of the selection efficiencies between data and MC simulation is taken as the uncertainty. The systematic uncertainties due to the kinematic fit are 2.7% for the LNV channel and 0.1% for the reference channel. The uncertainty of the kinematic fit is calculated to be 2.7%. The systematic uncertainty of signal window is studied by changing the ranges to $\pm4.9\sigma$, $\pm5.1\sigma$, etc. The maximum relative difference 0.2% is taken as the systematic uncertainty.

The uncertainties from the background (signal) shapes in the 2D fit are estimated by changing the reverse ARGUS function (sum of two CB function) to a second-order polynomial function (sum of a CB function and the signal MC shape obtained from MC simulation). The maximum differences of 3.3% and 1.1% between the signal yields are taken as the uncertainties due to background and signal shapes. So the total uncertainty for 2D fit is calculated to be 3.5%.

The systematic uncertainty of the MC modeling is studied by generating events with a Majorana intermediate state in two different modes: one with two Majorana neutrinos ($\omega\to\nu_M\nu_M,\nu_M\to\pi^+e^-$), and the other with one Majorana neutrino ($\omega\to\nu_M\pi^+e^-,\nu_M\to\pi^+e^-$), where the mass of the Majorana neutrino can range from the πe mass threshold to the largest phase space of ω decay. The largest difference between the average detection efficiencies in the nominal analysis and in these two modes, 0.3%, is taken as the systematic uncertainty.

The statistical uncertainty in $N^{\rm ref}_{\pi^+\pi^-\pi^0}$ determination is calculated to be 0.2%. The uncertainty due to MC statistics is given by $\sqrt{\frac{1-\epsilon}{\epsilon N^{\rm MC}_{\rm total}}}$, where ϵ is detection efficiency of $\omega\to\pi^+\pi^+e^-e^-$, and $N^{\rm MC}_{\rm total}$ is the total number of produced signal MC events. It is determined to be 0.3%. The uncertainty of the input branching fraction $\mathcal{B}(\omega\to\pi^+\pi^-\pi^0,\pi^0\to\gamma\gamma)$ is 0.8% [39].

Table 1 summarizes the systematic uncertainties. The total systematic uncertainty ($\Delta_{\rm sys}$) is calculated by adding the individual contributions in quadrature.

IV. RESULT

Since we do not observe any signal or background events, we set an upper limit on the signal yield at the 90% confidence level (C.L.) using Feldman-Cousins intervals [50]. Both the number of observed events and the background yield are assumed to follow Poisson distributions, and the upper limit on the signal yield is calculated to be 2.44 at the 90% C.L. Since the Feldman-Cousins method does not take into account the systematic uncertainty ($\Delta_{\rm sys}=7.9\%$), the upper limit is shifted up to $2.44/(1-\Delta_{\rm sys})=2.65$. Thus, the upper limit on the branching fraction of $\omega\to\pi^+\pi^+e^-e^-$ at the 90% C.L. is calculated by Eq. (1) to be

$$\mathcal{B}(\omega\to\pi^+\pi^+e^-e^-)<2.8\times10^{-6}.$$

V. SUMMARY

In this paper, we search for the LNV decay $\omega \to \pi^+\pi^+e^-e^-$ for the first time by analyzing 1.0087×10^{10} J/ψ events collected with the BESIII detector. No signal is observed, and the upper limit on its decay branching fraction is set to be $\mathcal{B}(\omega \to \pi^+\pi^+e^-e^- + c.c.) < 2.8\times10^{-6}$ at the 90% C.L. This is the first experimental constraint on the LNV decay of the ω meson. Our result enriches the searches for $0\nu\beta\beta$ decay in the collider experiments which are complimentary to the specially designed $0\nu\beta\beta$ searching experiments. The upper limit may be further improved with other advanced methodology, such as the partial reconstruction strategy which is based on inclusive ω signal finding, which will introduce a higher background but can also yield higher statistics. In the future, the constraint can be further improved with an expected increase of over 100 times J/ψ events from the super τ-charm facility [51].

ACKNOWLEDGEMENTS

The BESIII Collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support.

References

[1] M. Goldhaber *et al.*, Phys. Rev. **109**, 1015 (1958)
[2] Y. Fukuda *et al.* (Super-Kamiokande Collaboration), Phys. Rev. Lett. **81**, 1562 (1998)
[3] Q. R. Ahmad *et al.* (SNO Collaboration), Phys. Rev. Lett. **89**, 011301 (2002)
[4] K. Eguchi *et al.* (KamLAND Collaboration), Phys. Rev. Lett. **90**, 021802 (2003)
[5] F. P. An *et al.* (DAYA-BAY Collaboration), Phys. Rev. Lett. **108**, 171803 (2012)
[6] E. Majorana, Nuovo Cimento **14**, 171 (1937)
[7] P. Minkowski, Phys. Lett. B **421**, 67 (1977)
[8] W. Konetschny and W. Kummer, Phys. Lett. B **433**, 70 (1977)
[9] M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986)
[10] S. Yu. Khlebnikov and M. E. Shaposhnikov, Nucl. Phys. B **308**, 885 (1988)
[11] S. Davidson, E. Nardi, and Y. Nir, Phys. Rep. **466**, 105 (2008)
[12] B. Dasgupta and J. Kopp, Phys. Rept. **928**, 1 (2021)
[13] F. T. Avignone, S. R. Elliott, and J. Engel, Rev. Mod. Phys. **80**, 481 (2008)
[14] P. Novella *et al.* (NEXT Collaboration), JHEP **09**, 190 (2023)
[15] I. J. Arnquist *et al.* (MAJORNANA Collaboration), Phys. Rev. Lett. **131**, 152501 (2023)
[16] B. T. Zhang *et al.* (CDEX Collaboration), Chin. Phys. C **48**, 101001 (2024)
[17] W. H. Furry, Phys. Rev. **56**, 1184 (1939)
[18] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D **85**, 112004 (2012)
[19] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **112**, 131802 (2014)
[20] A. M. Sirunyan *et al.* (CMS Collaboration), JHEP **01**, 122 (2019)
[21] J. P. Lees *et al.* (BaBar Collaboration), Phys. Rev. D **84**, 072006 (2011)
[22] M. Aaboud *et al.* (ATLAS Collaboration), JHEP **01**, 016 (2019)
[23] P. Rubin *et al.* (CLEO Collaboration), Phys. Rev. D **82**, 092007 (2010)
[24] J. M. Link *et al.* (FOCUS Collaboration), Phys. Lett. B **572**, 21 (2003)
[25] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **99**, 112002 (2019)
[26] M. Ablikim *et al.* (BESIII Collaboration), arXiv: 2403.11597 (2024).
[27] R. Appel *et al.*, (E865 Collaboration), Phys. Rev. Lett. **85**, 2877 (2000)
[28] R. Aliberti *et al.*, (NA62 Collaboration), Phys. Rev. Lett. **127**, 131802 (2021)
[29] M. Ablikim *et al.* (BESIII Collaboration), Chin. Phys. C **49**, 043001 (2025)
[30] M. Ablikim *et al.* (BESIII Collaboration), Chin. Phys. C **46**, 074001 (2022)
[31] M. Ablikim *et al.* (BESIII Collaboration), Nucl. Instrum. Meth. A **614**, 345 (2010)
[32] C. H. Yu *et al.*, Proceedings of IPAC 2016, Busan, Korea (2016).
[33] H. Yuan, T. H. Wang, G. L. Wang, W. L. Ju, and J. M. Zhang, JHEP **08**, 066 (2013)
[34] P. Cao *et al.*, Nucl. Instrum. Meth. A **53**, 163053 (2020)
[35] Z. J. Li, Y. X. Song, Y. G. Li, and J. S. Li, Front. Phys. **19**, 64201 (2024)
[36] K. X. Huang, Z. J. Li, Z. Qian, J. Zhu, and H. Y. Li, Nucl. Sci. Tech. **33**, 11142 (2022)
[37] S. Agostuneli *et al.* (GEANT4 Collaboration), Nucl. Instrum. Meth. A **506**, 250 (2003)
[38] D. J. Lange, Chin. Phys. C **32**, 599 (2008)
[39] M. Tanabashi *et al.*, Phys. Rev. D **110**, 030001 (2024)
[40] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, Phys. Rev. D **62**, 034003 (2000)
[41] S. Jadach, B. F. L. Ward, and Z. Was, Comp. Phys. Commu. **130**, 260 (2000)
[42] E. Richter-Was, Phys. Lett. B **303**, 163 (1993)
[43] P. Adlarson *et al.* (WASA-at-COSY), Phys. Lett. B **770**, 418 (2017)
[44] L. Yan, R. L. He, W. G. Li, J. M. Bian, and C. D. Fu, Chin. Phys. C **34**, 204 (2010)
[45] H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **241**, 278 (1990)
[46] G. Punzi, arXiv: 2011.11770 (2020).
[47] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **104**, 052008 (2021)
[48] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **99**, 072006 (2019)
[49] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **101**, 052009 (2020)
[50] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998). Nucl. Instrum. Meth. A **551**, 493 (2005).
[51] M. Achasov, X. C. Ai, L. P. An, *et al.*, Front. Phys. **19**, 14701 (2024)