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Search for the lepton number violation decay

$$\omega \rightarrow \pi^+ \pi^+ e^- e^- + c.c. \quad *$$

To cite this article: M. Ablikim *et al* 2025 *Chinese Phys. C* **49** 103002

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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. Adlarson⁷⁷ X. C. Ai (艾小聪)⁸² R. Aliberti³⁶ A. Amoroso^{76A,76C}
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Received 30 April 2025; Accepted 27 June 2025; Published online 28 June 2025

* Supported in part by National Key R&D Program of China (2023YFA1606000, 2023YFA1606704); National Natural Science Foundation of China (NSFC) (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 (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 (ANID PIA/APOYO AFB230003); ERC (758462); German Research Foundation DFG (FOR5327); Istituto Nazionale di Fisica Nucleare, Italy; Knut and Alice Wallenberg Foundation (2021.0174, 2021.0299); Ministry of Development of Turkey (DPT2006K-120470); National Research Foundation of Korea (NRF-2022R1A2C1092335); National Science and Technology fund of Mongolia; Polish National Science Centre (2024/53/B/ST2/00975); STFC (United Kingdom); Swedish Research Council (2019.04595); U. S. Department of Energy (DE-FG02-05ER41374)



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- 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. Johansson⁷⁷ S. Kabana³⁴ N. Kalantar-Nayestanaki⁶⁶ X. L. Kang (康晓琳)⁹
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 J. B. Liu (刘建北)^{73,59} J. J. Liu (刘佳佳)²¹ K. Liu (刘凯)^{39,k,1} K. Liu (刘坤)⁷⁴ K. Y. Liu (刘魁勇)⁴¹ Ke Liu (刘珂)²³
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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}
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H. J. Wang (王泓鉴)^{39,k,1} 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,1} 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,1} Y. J. Wang (王祎军)^{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. Wei⁴⁴ F. Weidner⁷⁰ S. P. Wen (文硕频)¹
Y. R. Wen (温亚冉)⁴⁰ U. Wiedner³ G. Wilkinson⁷¹ M. Wolke⁷⁷ 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,1} 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. Xu³¹ 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. Yu¹³ J. S. Yu (俞洁晟)^{26,i} L. Q. Yu (喻丽雯)^{12,g} M. C. Yu⁴¹ T. Yu (于涛)⁷⁴ X. D. Yu (余旭东)^{47,h}
Y. C. Yu (郁焯淳)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. Zafar⁷⁵ S. H. Zeng⁶⁴ 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 Zhang⁷¹
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,1} 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,1} S. H. Zhang (张水涵)^{1,65}
Shulei Zhang (张书磊)^{26,i} X. M. Zhang (张晓梅)¹ X. Y. Zhang⁴¹ 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. Zhang²⁰ 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)

¹Institute of High Energy Physics, Beijing 100049, China²Beihang University, Beijing 100191, China³Bochum Ruhr-University, D-44780 Bochum, Germany⁴Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia⁵Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA⁶Central China Normal University, Wuhan 430079, China⁷Central South University, Changsha 410083, China⁸China Center of Advanced Science and Technology, Beijing 100190, China⁹China University of Geosciences, Wuhan 430074, China¹⁰Chung-Ang University, Seoul, 06974, Republic of Korea¹¹COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan¹²Fudan University, Shanghai 200433, China¹³GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany¹⁴Guangxi Normal University, Guilin 541004, China¹⁵Guangxi University, Nanning 530004, China¹⁶Guangxi University of Science and Technology, Liuzhou 545006, China¹⁷Hangzhou Normal University, Hangzhou 310036, China¹⁸Hebei University, Baoding 071002, China¹⁹Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany²⁰Henan Normal University, Xinxiang 453007, China²¹Henan University, Kaifeng 475004, China²²Henan University of Science and Technology, Luoyang 471003, China²³Henan University of Technology, Zhengzhou 450001, China²⁴Huangshan College, Huangshan 245000, China²⁵Hunan Normal University, Changsha 410081, China²⁶Hunan University, Changsha 410082, China²⁷Indian Institute of Technology Madras, Chennai 600036, India²⁸Indiana 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, Italy³¹Inner Mongolia University, Hohhot 010021, China³²Institute of Modern Physics, Lanzhou 730000, China³³Institute of Physics and Technology, Mongolian Academy of Sciences, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia³⁴Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile³⁵Jilin University, Changchun 130012, China³⁶Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany³⁷Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia³⁸Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany³⁹Lanzhou University, Lanzhou 730000, China⁴⁰Liaoning Normal University, Dalian 116029, China⁴¹Liaoning University, Shenyang 110036, China⁴²Nanjing Normal University, Nanjing 210023, China⁴³Nanjing University, Nanjing 210093, China⁴⁴Nankai University, Tianjin 300071, China

- ⁴⁵National Centre for Nuclear Research, Warsaw 02-093, Poland
⁴⁶North China Electric Power University, Beijing 102206, China
⁴⁷Peking University, Beijing 100871, China
⁴⁸Qufu Normal University, Qufu 273165, China
⁴⁹Renmin University of China, Beijing 100872, China
⁵⁰Shandong Normal University, Jinan 250014, China
⁵¹Shandong University, Jinan 250100, China
⁵²Shanghai Jiao Tong University, Shanghai 200240, China
⁵³Shanxi Normal University, Linfen 041004, China
⁵⁴Shanxi University, Taiyuan 030006, China
⁵⁵Sichuan University, Chengdu 610064, China
⁵⁶Soochow University, Suzhou 215006, China
⁵⁷South China Normal University, Guangzhou 510006, China
⁵⁸Southeast University, Nanjing 211100, China
⁵⁹State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, China
⁶⁰Sun Yat-Sen University, Guangzhou 510275, China
⁶¹Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
⁶²Tsinghua University, Beijing 100084, 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
⁶⁴University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, UK
⁶⁵University of Chinese Academy of Sciences, Beijing 100049, China
⁶⁶University of Groningen, NL-9747 AA Groningen, The Netherlands
⁶⁷University of Hawaii, Honolulu, Hawaii 96822, USA
⁶⁸University of Jinan, Jinan 250022, China
⁶⁹University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
⁷⁰University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany
⁷¹University of Oxford, Keble Road, Oxford OX13RH, United Kingdom
⁷²University of Science and Technology Liaoning, Anshan 114051, China
⁷³University of Science and Technology of China, Hefei 230026, China
⁷⁴University of South China, Hengyang 421001, China
⁷⁵University 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
⁷⁷Uppsala University, Box 516, SE-75120 Uppsala, Sweden
⁷⁸Wuhan University, Wuhan 430072, China
⁷⁹Yantai University, Yantai 264005, China
⁸⁰Yunnan University, Kunming 650500, China
⁸¹Zhejiang University, Hangzhou 310027, China
⁸²Zhengzhou University, Zhengzhou 450001, China
^aDeceased
^bAlso at the Moscow Institute of Physics and Technology, Moscow 141700, Russia
^cAlso at the Novosibirsk State University, Novosibirsk, 630090, Russia
^dAlso at the NRC "Kurchatov Institute", PNPI, 188300, Gatchina, Russia
^eAlso at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany
^fAlso 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
^gAlso at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, China
^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 MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China
^lAlso at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, China
^mAlso at the Department of Mathematical Sciences, IBA, Karachi 75270, Pakistan
ⁿAlso at Ecole Polytechnique Federale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland
^oAlso at Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany
^pAlso at Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China
^qCurrently at: Silesian University in Katowice, Chorzow, 41-500, Poland

Abstract: Lepton number violation decay $\omega \rightarrow \pi^+ \pi^+ e^- e^- + c.c.$ is searched for via $J/\psi \rightarrow \omega \eta$ using a data sample of $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected via the BESIII detector at the BEPCII collider. No significant signal is observed, and the upper limit on the branching fraction of $\omega \rightarrow \pi^+ \pi^+ e^- e^- + c.c.$ 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: 10.1088/1674-1137/ade955 **CSTR:** 32044.14.ChinesePhysicsC.49103002

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 have an extremely small mass.

If the antiparticle of a neutrino is itself, the solution to the Dirac equation can produce 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, this 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 that 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], $q\bar{q} \rightarrow l^\pm l^\pm q'\bar{q}$ and $q\gamma \rightarrow l^\pm l^\pm q''q'\bar{q}$ ($l = e, \mu$) channels by CMS [20], $X_c^+ \rightarrow h^\pm l^\mp l'^{(\prime\prime)+}$ ($X_c = D, D_s, \Lambda_c^+, h = \pi, K, p$) 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]. The 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 only negative results have been reported to date.

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.*, $\omega \rightarrow \pi^+\pi^+l^-l^-$. To avoid backgrounds from pion-muon misidentification and utilize a larger phase space, we focus on the $\pi^+\pi^+e^-e^-$ final states in this work. Figure 1 shows two possible Feyn-

man diagrams for $\omega \rightarrow \pi^+\pi^+e^-e^-$ in the Majorana neutrino scenario, analogous to those in Ref. [30], with suppression owing to the large mass of the W^\pm bosons. The LNV decay of the ω meson in the process $\omega \rightarrow \pi^+\pi^+e^-e^-$ has a unique phase space coverage compared with 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 $\omega \rightarrow \pi^+\pi^+e^-e^-$ via $J/\psi \rightarrow \omega\eta$ decay based on $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events [31] collected by the BESIII [32] detector at the Beijing Electron-Positron Collider II (BEPCII) [33]. The charge-conjugated decay mode $\omega \rightarrow \pi^-\pi^-e^+e^+$ is included and implicitly assumed throughout.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

BESIII [32] is a symmetric cylindrical particle detector located around the interaction point of BEPCII [33], which is an e^+e^- collider employing a double storage ring. The center-of-mass collision luminosity of BEPCII reached a peak of $1.1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ at 3.773 GeV. The BESIII detector consists of four detector sub-components [32]: a helium-based multilayer drift chamber (MDC), plastic scintillator time-of-flight counter (TOF), CsI(Tl) electromagnetic calorimeter (EMC), and 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 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

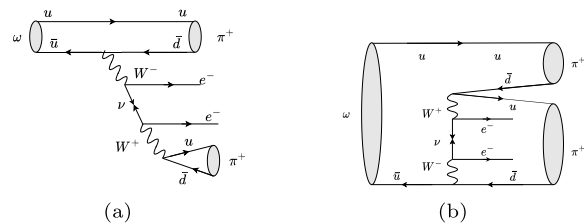


Fig. 1. Two possible Feynman diagrams for $\omega \rightarrow \pi^+\pi^+e^-e^-$.

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

III. DATA ANALYSIS

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

$$\mathcal{B}(\omega \rightarrow \pi^+\pi^-e^+e^-) = \mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0) \times \mathcal{B}(\pi^0 \rightarrow \gamma\gamma) \times \frac{N_{\pi^+\pi^-e^+e^-}^{\text{sig}} / \epsilon_{\pi^+\pi^-e^+e^-}}{N_{\pi^+\pi^-\pi^0}^{\text{ref}} / \epsilon_{\pi^+\pi^-\pi^0}}, \quad (1)$$

where $\mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0)$ and $\mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$ are the branching fractions of $\omega \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0 \rightarrow \gamma\gamma$, respectively. $N_{\pi^+\pi^-e^+e^-}^{\text{sig}}$ and $N_{\pi^+\pi^-\pi^0}^{\text{ref}}$ 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 utilize 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 $\text{CL}_\pi > 0.001$ and $\text{CL}_\pi > \text{CL}_K$, whereas electron candidates are required to satisfy

$\text{CL}_e > 0.001$ and $\text{CL}_e / (\text{CL}_e + \text{CL}_K + \text{CL}_\pi) > 0.8$.

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 must 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 must be larger than 10 degrees.

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

For the reference channel $J/\psi \rightarrow \omega\eta$, with $\eta \rightarrow \gamma\gamma$, $\omega \rightarrow \pi^+\pi^-\pi^0$, and $\pi^0 \rightarrow \gamma\gamma$, 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 $\Delta m_{2\gamma}^2 = \frac{(M_{\gamma\gamma} - M_{\pi^0})^2}{\sigma_{\pi^0}^2} + \frac{(M_{\gamma\gamma} - M_\eta)^2}{\sigma_\eta^2}$ 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 the MC simulation. The π^0 and η candidates with the smallest $\Delta m_{2\gamma}^2$ are kept for further analysis.

To reduce backgrounds and improve the mass resolution, we perform a five-constraint (5C) kinematic fit [44] to all the tracks enforcing energy and momentum conservation and constraining $M_{\gamma\gamma}$ to M_{π^0} . χ_{5C}^2 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 include 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_{sig}^ω) 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_{sig}^η) 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_{bkg}^ω and F_{bkg}^η). Consequently, the total signal shape is described by $F_{\text{sig}}^\omega \otimes F_{\text{sig}}^\eta$, backgrounds such as $\pi^+\pi^-\pi^0\eta$ and $\pi^0\pi^0\omega$ (BKGII) are described by $F_{\text{bkg}}^\omega \otimes F_{\text{sig}}^\eta$ and $F_{\text{bkg}}^\eta \otimes F_{\text{sig}}^\omega$, and the BKGI is de-

scribed by $F_{\text{bkg}}^\omega \otimes F_{\text{bkg}}^\eta$. The fit range is selected 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 $N_{\pi^+\pi^-\pi^0}^{\text{ref}} = 941,336 \pm 1,352$, 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 considering the signal yield $N_{\pi^+\pi^-\pi^0}^{\text{ref}}$, detection efficiency $\epsilon_{\pi^+\pi^-\pi^0}$, and decay branching fractions of $\omega \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0 \rightarrow \gamma\gamma$ from the PDG [39], we measure the branching fraction of $J/\psi \rightarrow \omega\eta$ to be consistent with its world average value quoted from the PDG [39] within two standard deviation.

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

For the signal channel $J/\psi \rightarrow \omega\eta$ with $\eta \rightarrow \gamma\gamma$ and $\omega \rightarrow \pi^+\pi^+e^-e^-$, at least two reconstructed photons and

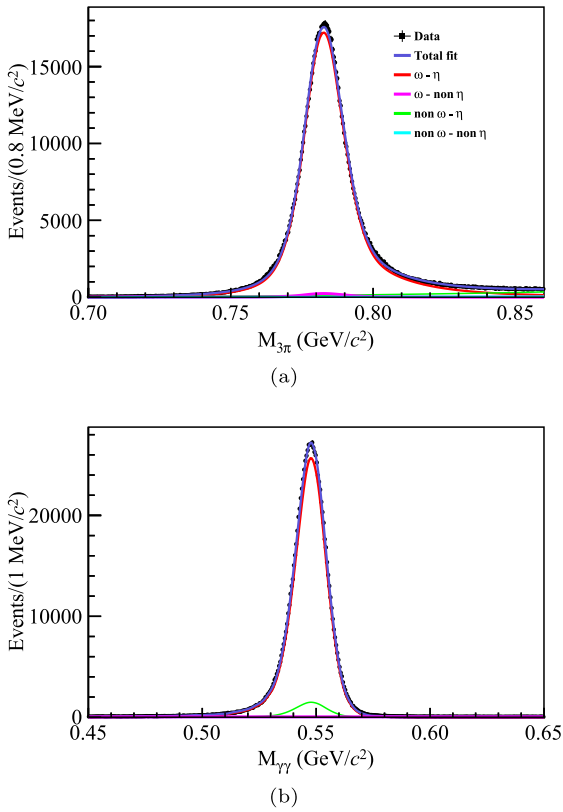


Fig. 2. (color online) Projections of the 2D fit of the (a) $M_{3\pi}$ and (b) $M_{\gamma\gamma}$ distributions, where the total PDF is shown by a blue solid curve. The signal PDF is shown by a red solid curve and labeled as $\omega-\eta$. The non-peaking background distribution is shown by a cyan solid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

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.

To reduce backgrounds and improve the mass resolution, we perform a four-constraint (4C) kinematic fit [44] 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 more than two photons exist, we keep the candidate with the lowest χ_{4C}^2 for further analysis. To further suppress backgrounds, χ_{4C}^2 must 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 (χ_{re}^2): $\pi^+\pi^-\pi^+\pi^-\gamma\gamma$, $K^+K^-K^+K^-\gamma\gamma$, $\pi^+\pi^-K^+K^-\gamma\gamma$, and $\pi^+\pi^-p\bar{p}\gamma\gamma$. If any of the χ_{re}^2 s is less than χ_{4C}^2 , 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 by 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 scatter plot, no candidates are found inside the defined signal region. Thus, the number of observed events is $N_{\pi^+\pi^+e^-e^-}^{\text{obs}} = 0$. To study the possible backgrounds, we analyze 1.0011×10^{10} inclusive J/ψ MC events. We find that no event is located near the signal region, and the number of background events is determined to be $N_{\pi^+\pi^+e^-e^-}^{\text{bkg}} = 0$.

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, $N_{\pi^+\pi^-\pi^0}^{\text{ref}}$ determination, and input branching fractions. The systematic uncertainties of the η reconstruction with $\mathcal{B}(J/\psi \rightarrow \omega\eta)$ and $\mathcal{B}(\eta \rightarrow \gamma\gamma)$ cancel when calculating the relative branching fraction ratio.

The systematic uncertainties of MDC tracking and

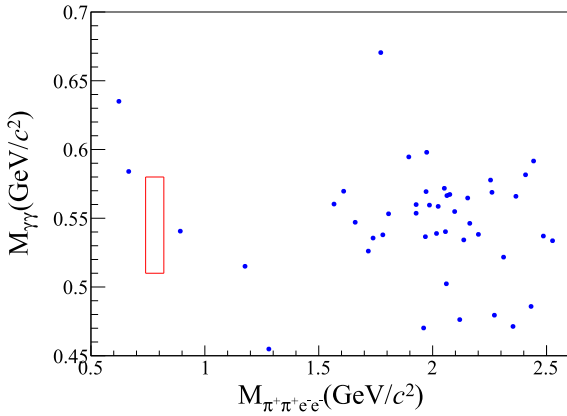


Fig. 3. (color online) 2D distribution of $M_{\gamma\gamma}$ versus $M_{\pi^+\pi^+e^-e^-}$ of the candidate events from the J/ψ data, where the red box shows the signal region.

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

The systematic uncertainty of π^0 reconstruction is 1.0% [49]. The systematic uncertainty in the kinematic fit and χ^2 requirement of the signal (reference) decay is estimated with the control sample $J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\eta, \eta \rightarrow \gamma\gamma$ ($J/\psi \rightarrow \omega\pi^0, \omega \rightarrow \pi^+\pi^-\pi^0$). 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 $\pm 4.9\sigma, \pm 5.1\sigma$, 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 the 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, respectively. Therefore, 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 ($\omega \rightarrow \nu_M \nu_M, \nu_M \rightarrow \pi^+ e^-$), and the other with one Majorana neutrino ($\omega \rightarrow \nu_M \pi^+ e^-, \nu_M \rightarrow \pi^+ e^-$), where the mass of the Majorana neutrino can range from the πe mass threshold to the largest phase space of ω decay. The

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
$N_{\pi^+\pi^-\pi^0}^{\text{ref}}$ determination	0.2
MC statistics	0.3
$\mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma)$	0.8
Total	7.9

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

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

IV. RESULT

Because we do not observe any signal or background events, we set an upper limit on the signal yield at the 90% CL using Feldman-Cousins intervals [50]. Both the number of observed events and 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% CL. Because the Feldman-Cousins method does not consider the systematic uncertainty ($\Delta_{\text{sys}} = 7.9\%$), the upper limit is shifted up to $2.44/(1-\Delta_{\text{sys}}) = 2.65$. Thus, the upper limit on the branching fraction of $\omega \rightarrow \pi^+\pi^+e^-e^-$ at the 90% CL is calculated using Eq. (1) to be

$$\mathcal{B}(\omega \rightarrow \pi^+\pi^+e^-e^-) < 2.8 \times 10^{-6}.$$

V. SUMMARY

In this paper, we search for the LNV decay $\omega \rightarrow \pi^+\pi^+e^-e^-$ for the first time by analyzing 1.0087×10^{10} J/ψ events collected using the BESIII detector. No

signal is observed, and the upper limit on its decay branching fraction is set to be $\mathcal{B}(\omega \rightarrow \pi^+\pi^+e^-e^- + c.c.) < 2.8 \times 10^{-6}$ at the 90% CL. 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 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 methodologies, such as the partial reconstruction strategy, which is based

on inclusive ω signal finding; it introduces 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.

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