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M. Ablikim (麦迪娜)[1] M. N. Achasov[4,c] P. Adlarson[75] O. Afedulidis[3] X. C. Ai (艾小聪)[80] R. Aliberti[35] A. Amoroso[74A,74C] M. R. An (安美儒)[39] Q. An (安琪)[71,58,a] Y. Bai (白羽)[57] O. Bakina[36] I. Balossino[29A] Y. Ban (班勇)[46,h] H.-R. Bao (包浩然)[63] V. Batozskaya[1,44] K. Begzsuren[32] N. Berger[35] M. Berlowski[44] M. Bertani[28A] D. Bettoni[29A] F. Bianchi[74A,74C] E. Bianco[74A,74C] A. Bortone[74A,74C] I. Boyko[36] R. A. Briere[5] A. Brueggemann[68] H. Cai (蔡浩)[76] X. Cai (蔡啸)[1,58] A. Calcaterra[28A] G. F. Cao (曹国富)[1,63] N. Cao (曹宁)[1,63] S. A. Cetin[62A] J. F. Chang (常劲帆)[1,58] G. R. Che (车国荣)[43] Y. Z. Che (车逾之)[1,58,63] G. Chelkov[36,b] C. Chen (陈琛)[43] Chao Chen (陈超)[55] G. Chen (陈刚)[1] H. S. Chen (陈和生)[1,63] M. L. Chen (陈玛丽)[1,58,63] S. J. Chen (陈申见)[42] S. L. Chen (陈思璐)[45] S. M. Chen (陈少敏)[61] T. Chen (陈通)[1,63] X. R. Chen (陈旭荣)[31,63] X. T. Chen (陈肖婷)[1,63] Y. B. Chen (陈元柏)[1,58] Y. Q. Chen[34] Z. J. Chen (陈卓俊)[25,i] Z. Y. Chen (陈正元)[1,63] S. K. Choi[10] G. Cibinetto[29A] S. C. Coen[3] F. Cossio[74C] J. J. Cui (崔佳佳)[50] H. L. Dai (代洪亮)[1,58] J. P. Dai (代建平)[78] A. Dbeyssi[18] R. E. de Boer[3] D. Dedovich[36] Z. Y. Deng (邓子艳)[1] A. Denig[35] I. Denysenko[36] M. Destefanis[74A,74C] F. De Mori[74A,74C] B. Ding (丁彪)[66,1] X. X. Ding (丁晓萱)[46,h] Y. Ding (丁勇)[40] Y. Ding (丁逸)[34] J. Dong (董静)[1,58] L. Y. Dong (董燎原)[1,63] M. Y. Dong (董明义)[1,58,63] X. Dong (董翔)[76] M. C. Du (杜蒙川)[1] S. X. Du (杜书先)[80] Z. H. Duan (段宗欢)[42] P. Egorov[36,b] Y. H. Fan (范宇晗)[45] J. Fang (方建)[1,58] S. S. Fang (房双世)[1,63] W. X. Fang (方文兴)[1] Y. Fang (方易)[1] Y. Q. Fang (方亚泉)[1,58] R. Farinelli[29A] L. Fava[74B,74C] F. Feldbauer[3] G. Felici[28A] C. Q. Feng (封常青)[71,58] J. H. Feng (冯俊华)[59] K. Fischer[69] M. Fritsch[3] C. D. Fu (傅成栋)[1] J. L. Fu (傅金林)[63] Y. W. Fu (傅亦威)[1,63] H. Gao (高涵)[63] Y. N. Gao (高原宁)[46,h] Yang Gao (高扬)[71,58] S. Garbolino[74C] I. Garzia[29A,29B] L. Ge (葛玲)[80] P. T. Ge (葛潘婷)[76] Z. W. Ge (葛振武)[42] C. Geng (耿聪)[59] E. M. Gersabeck[67] A. Gilman[69] K. Goetzen[13] L. Gong (龚丽)[40] W. X. Gong (龚文煊)[1,58] W. Gradl[35] S. Gramigna[29A,29B] M. Greco[74A,74C] M. H. Gu (顾旻皓)[1,58] Y. T. Gu (顾运厅)[15] C. Y. Guan (关春懿)[1,63] A. Q. Guo (郭爱强)[31,63] L. B. Guo (郭立波)[41] M. J. Guo (国梦娇)[50] R. P. Guo (郭如盼)[49] Y. P. Guo (郭玉萍)[12,g] A. Guskov[36,b] J. Gutierrez[27] T. T. Han (韩婷婷)[1] W. Y. Han (韩文颖)[39] X. Q. Hao (郝喜庆)[19] F. A. Harris[65] K. K. He (何凯凯)[55] K. L. He (何康林)[1,63] F. H. Heinsius[3] C. H. Heinz[35] Y. K. Heng (衡月昆)[1,58,63] C. Herold[60] T. Holtmann[3] P. C. Hong (洪鹏程)[12,g] G. Y. Hou (侯国一)[1,63] X. T. Hou (侯贤涛)[1,63] Y. R. Hou (侯颖锐)[63] Z. L. Hou (侯治龙)[1] B. Y. Hu (胡碧颖)[59] H. M. Hu (胡海明)[1,63] J. F. Hu (胡继峰)[56,j] T. Hu (胡涛)[1,58,63] Y. Hu (胡誉)[1] G. S. Huang (黄光顺)[71,58] K. X. Huang (黄凯旋)[59] L. Q. Huang (黄麟钦)[31,63] X. T. Huang (黄性涛)[50] Y. P. Huang (黄燕萍)[1] T. Hussain[73] F. Hölzken[3] N. Hüsken[27,35] N. in der Wiesche[68] J. Jackson[27] S. Jaeger[3] S. Janchiv[32] Q. Ji (纪全)[1] Q. P. Ji (姬清平)[19] X. B. Ji (季晓斌)[1,63] X. L. Ji (季筱璐)[1,58] Y. Y. Ji (吉钰瑶)[50] X. Q. Jia (贾晓倩)[50] Z. K. Jia (贾泽坤)[71,58] H. B. Jiang (姜候兵)[76] P. C. Jiang (蒋沛成)[46,h] S. S. Jiang (姜赛赛)[39]

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S. C. Yuan (苑思成)[1,63] Y. Yuan (袁野)[1,63] Z. Y. Yuan (袁朝阳)[59] C. X. Yue (岳崇兴)[39] A. A. Zafar[73]
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Y. C. Zhai (翟云聪)[50] Y. H. Zhan (詹永华)[59] A. Q. Zhang (张安庆)[1,63] B. L. Zhang (张伯伦)[1,63]
B. X. Zhang (张丙新)[1] D. H. Zhang (张丹昊)[43] G. Y. Zhang (张广义)[19] H. Zhang (张豪)[71,58]
H. C. Zhang (张航畅)[1,58,63] H. H. Zhang (张宏宏)[34] H. H. Zhang (张宏浩)[59] H. Q. Zhang (张华桥)[1,58,63]
H. Y. Zhang (章红宇)[1,58] J. Zhang (张晋)[59] J. Zhang (张进)[80] J. J. Zhang (张进军)[52] J. L. Zhang (张杰磊)[20]
J. Q. Zhang (张敬庆)[41] J. W. Zhang (张家文)[1,58,63] J. X. Zhang (张景旭)[38,k,l] J. Y. Zhang (张建勇)[1]
J. Z. Zhang (张景芝)[1,63] Jianyu Zhang (张剑宇)[63] L. M. Zhang (张黎明)[61] Lei Zhang (张雷)[42] P. Zhang (张鹏)[1,63]
Q. Y. Zhang (张秋岩)[39,80] S. H. Zhang (张水涵)[1,63] Shulei Zhang (张书磊)[25,i] X. D. Zhang (张小东)[45]
X. M. Zhang (张晓梅)[1] X. Y. Zhang (张学尧)[50] Y. Zhang (张瑶)[1] Y. Zhang (张宇)[72] Y. T. Zhang (张亚腾)[80]
Y. H. Zhang (张银鸿)[1,58] Y. X. Zhang (张雅璇)[43] Yan Zhang (张言)[71,58] Z. D. Zhang (张正德)[1]
Z. H. Zhang (张泽恒)[1] Z. L. Zhang (张兆领)[34] Z. Y. Zhang (张振宇)[76] Z. Y. Zhang (张子羽)[43] G. Zhao (赵光)[1]
J. Y. Zhao (赵静宜)[1,63] J. Z. Zhao (赵京周)[1,58] L. Zhao (赵玲)[1] Lei Zhao (赵雷)[71,58] M. G. Zhao (赵明刚)[43]
R. P. Zhao (赵若平)[63] S. J. Zhao (赵书俊)[80] Y. B. Zhao (赵豫斌)[1,58] Y. X. Zhao (赵宇翔)[31,63]
Z. G. Zhao (赵政国)[71,58] A. Zhemchugov[36,b] B. Zheng (郑波)[72] J. P. Zheng (郑建平)[1,58] W. J. Zheng (郑文静)[1,63]
Y. H. Zheng (郑阳恒)[63] B. Zhong (钟彬)[41] X. Zhong (钟鑫)[59] L. P. Zhou (周利鹏)[1,63] S. Zhou (周帅)[6]
X. Zhou (周详)[76] X. K. Zhou (周晓康)[6] X. R. Zhou (周小蓉)[71,58] X. Y. Zhou (周兴玉)[39]
Y. Z. Zhou (周祎卓)[12,g] J. Zhu (朱江)[43] K. Zhu (朱凯)[1] K. J. Zhu (朱科军)[1,58,63] L. Zhu (朱林)[34]
L. X. Zhu (朱琳萱)[63] S. H. Zhu (朱世海)[70] S. Q. Zhu (朱仕强)[42] T. J. Zhu (朱腾蛟)[12,g] Y. C. Zhu (朱莹春)[71,58]
Z. A. Zhu (朱自安)[1,63] J. H. Zou (邹佳恒)[1] J. Zu (祖健)[71,58]

(BESIII Collaboration)

[1]Institute of High Energy Physics, Beijing 100049, China
[2]Beihang University, Beijing 100191, 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, China
[7]Central South University, Changsha 410083, China
[8]China Center of Advanced Science and Technology, Beijing 100190, China
[9]China University of Geosciences, Wuhan 430074, 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, China
[13]GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany
[14]Guangxi Normal University, Guilin 541004, China
[15]Guangxi University, Nanning 530004, China
[16]Hangzhou Normal University, Hangzhou 310036, China
[17]Hebei University, Baoding 071002, China
[18]Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany
[19]Henan Normal University, Xinxiang 453007, China
[20]Henan University, Kaifeng 475004, China
[21]Henan University of Science and Technology, Luoyang 471003, China
[22]Henan University of Technology, Zhengzhou 450001, China
[23]Huangshan College, Huangshan 245000, China
[24]Hunan Normal University, Changsha 410081, China
[25]Hunan University, Changsha 410082, China
[26]Indian Institute of Technology Madras, Chennai 600036, India
[27]Indiana University, Bloomington, Indiana 47405, USA
[28]INFN Laboratori Nazionali di Frascati, (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
[29]INFN Sezione di Ferrara, (A)INFN Sezione di Ferrara, I-44122, Ferrara, Italy; (B)University of Ferrara, I-44122, Ferrara, Italy
[30]Inner Mongolia University, Hohhot 010021, China
[31]Institute of Modern Physics, Lanzhou 730000, China
[32]Institute of Physics and Technology, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia
[33]Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile
[34]Jilin University, Changchun 130012, China
[35]Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
[36]Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
[37]Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany
[38]Lanzhou University, Lanzhou 730000, China
[39]Liaoning Normal University, Dalian 116029, China
[40]Liaoning University, Shenyang 110036, China
[41]Nanjing Normal University, Nanjing 210023, China
[42]Nanjing University, Nanjing 210093, China
[43]Nankai University, Tianjin 300071, China
[44]National Centre for Nuclear Research, Warsaw 02-093, Poland
[45]North China Electric Power University, Beijing 102206, China
[46]Peking University, Beijing 100871, China
[47]Qufu Normal University, Qufu 273165, China
[48]Renmin University of China, Beijing 100872, China
[49]Shandong Normal University, Jinan 250014, China
[50]Shandong University, Jinan 250100, China
[51]Shanghai Jiao Tong University, Shanghai 200240, China
[52]Shanxi Normal University, Linfen 041004, China
[53]Shanxi University, Taiyuan 030006, China
[54]Sichuan University, Chengdu 610064, China
[55]Soochow University, Suzhou 215006,
[56]South China Normal University, Guangzhou 510006, China
[57]Southeast University, Nanjing 211100, China
[58]State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, PChina
[59]Sun Yat-Sen University, Guangzhou 510275, China
[60]Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
[61]Tsinghua University, Beijing 100084, China
[62]Turkish Accelerator Center Particle Factory Group, (A)Istinye University, 34010, Istanbul, Turkey; (B)Near East University, Nicosia, North Cyprus, 99138, Mersin 10, Turkey
[63]University of Chinese Academy of Sciences, Beijing 100049, China
[64]University of Groningen, NL-9747 AA Groningen, The Netherlands
[65]University of Hawaii, Honolulu, Hawaii 96822, USA
[66]University of Jinan, Jinan 250022, China
[67]University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
[68]University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany
[69]University of Oxford, Keble Road, Oxford OX13RH, United Kingdom

[70]University of Science and Technology Liaoning, Anshan 114051, China
[71]University of Science and Technology of China, Hefei 230026, China
[72]University of South China, Hengyang 421001, China
[73]University of the Punjab, Lahore-54590, Pakistan
[74]University of Turin and INFN, (A)University of Turin, I-10125, Turin, Italy; (B)University of Eastern Piedmont, I-15121, Alessandria, Italy; (C)INFN, I-10125, Turin, Italy
[75]Uppsala University, Box 516, SE-75120 Uppsala, Sweden
[76]Wuhan University, Wuhan 430072, China
[77]Yantai University, Yantai 264005, China
[78]Yunnan University, Kunming 650500, China
[79]Zhejiang University, Hangzhou 310027, China
[80]Zhengzhou University, Zhengzhou 450001, 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, China
[g]Also at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, China
[h]Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, 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, China
[l]Also at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, 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

Abstract: Using an electron-positron collision data sample corresponding to $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected using the BESIII detector at the BEPCII collider, we firstly search for the lepton number violation decay $\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \phi\eta$. No obviously signals are found. The upper limit on the branching fraction of $\phi \to \pi^+\pi^+e^-e^-$ is set to be 1.3×10^{-5} at the 90% confidence level.

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

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I. INTRODUCTION

Matter-antimatter asymmetry [1] is a primary issue in the standard cosmology model. According to the Big Bang theory [2], matter and antimatter in the universe should be produced equally and exist in equal amounts. However, observations show that the number of baryons in the universe is $10^9 - 10^{10}$ [3] times that of antibaryons. Sakharov proposed the three conditions to understand this puzzle [4], the first of which is that the baryon number conservation must be violated. Consequently, several baryon number violation (BNV) searches have been conducted at collider experiments and specially designed non-collider experiments, such as proton decay experiments; however, no positive results have been obtained. Many theories [5, 6] pointed out that if BNV occurs, the lepton number should also be violated (LNV). This provides another perspective on exploring the asymmetry between matter and antimatter in the universe.

Conversely, neutrino oscillation experiments [7−10] show that neutrinos have tiny masses, which proves that the Standard Model (SM) cannot fully describe the neutrino sector. Some of the SM extensions believe that neutrinos may have majorana components whose particle and antiparticle are identical [11]. This may lead to LNV processes with $\Delta L = 2$, such as neutrinoless double beta decay ($0\nu2\beta$) [12]. Although hadrons comprising first generation quarks have been well explored in $0\nu2\beta$, constraints on the LNV process [13−18] suggest that searching for LNV with non-first generation quark decays at collider experiments would be necessary.

Many recent collider experiments, such as NA62 [19], E865 [20], LHCb [21], CMS [22], ATLAS [23], CLEO [24] and BESIII [25], have searched for LNV processes. Among them, references [19, 20] reported LNV with second generation quark decays in K mesons. However, no significant evidence of a possible LNV effect has been observed yet. Complementary to those measurements, the study of LNV using ϕ decays is distinctive owing to the different phase space (PHSP) it explores. In this study, we analyze the $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ data sample collected with the BESIII detector [26] operating at the

BEPCII storage ring [27] to search for the SM forbidden LNV decay of $\phi \to \pi^+\pi^+e^-e^-$. The charge conjugate channel is always implied throughout this study.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [26] records symmetric e^+e^- collisions provided by the BEPCII storage ring [27] in the center-of-mass energy range from 1.85 to 4.95 GeV, with a peak luminosity of $1.1\times10^{33}\,\mathrm{cm^{-2}s^{-1}}$ achieved at $\sqrt{s} = 3.773$ GeV. BESIII has collected large data samples in this energy region [28]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and comprises a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The magnetic field was 0.9 T in 2012, which affects 11% of the total J/ψ data. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the specific ionization energy loss (dE/dx) resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution in the TOF barrel region is 68 ps, while that in the end cap region is 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps, which benefits 87% of the data used in this analysis [29].

Simulated Monte Carlo (MC) samples produced with GEANT4-based [30] software, which includes the geometric description of the BESIII detector [31] and the detector response, are used to determine the detection efficiency and to estimate the background contributions. The simulation includes the beam-energy spread and initial-state radiation (ISR) in the e^+e^- annihilation modeled with the generator KKMC [32, 33]. The inclusive MC simulation sample includes the production of the J/ψ resonance and the continuum processes incorporated in KKMC [32, 33]. The known decay modes are modeled with EVTGEN [34, 35] using world averaged branching fraction values [36], and the remaining unknown decays from the charmonium states with LUNDCHARM [37, 38]. Final-state radiation from charged final-state particles is incorporated with PHOTOS [39].

III. DATA ANALYSIS

A. Method

In this analysis, we search for the decay $\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \phi\eta, \eta \to \gamma\gamma$. In order to avoid the large uncertainty from $\mathcal{B}(J/\psi \to \phi\eta)$ [36], which is approximately 11%, we measure the branching fraction of the signal decay $\phi \to \pi^+\pi^+e^-e^-$ relative to that of the reference channel $\phi \to K^+K^-$ via $J/\psi \to \phi\eta$.

The branching fractions of $\phi \to \pi^+\pi^+e^-e^-$ and $\phi \to K^+K^-$ can be written as

$$\mathcal{B}(\phi \to \pi^+\pi^+e^-e^-) = \frac{N^{\rm net}_{\pi^+\pi^+e^-e^-}/\varepsilon_{\pi^+\pi^+e^-e^-}}{N^{\rm tot}\times\mathcal{B}(J/\psi \to \phi\eta)\times\mathcal{B}(\eta \to \gamma\gamma)}, \quad (1)$$

and

$$\mathcal{B}(\phi \to K^+K^-) = \frac{N^{\rm net}_{K^+K^-}/\varepsilon_{K^+K^-}}{N^{\rm tot}\times\mathcal{B}(J/\psi \to \phi\eta)\times\mathcal{B}(\eta \to \gamma\gamma)}, \quad (2)$$

respectively, where $N^{\rm net}_{\pi^+\pi^+e^-e^-}$ and $N^{\rm net}_{K^+K^-}$ are the signal yields, $N^{\rm tot}$ is the total number of J/ψ events, and $\varepsilon_{\pi^+\pi^+e^-e^-}$ and $\varepsilon_{K^+K^-}$ are the detection efficiencies for the $J/\psi \to \eta\phi$, $\eta \to \gamma\gamma, \phi \to \pi^+\pi^+e^-e^-$ and $J/\psi \to \eta\phi, \eta \to \gamma\gamma, \phi \to K^+K^-$, respectively. $\mathcal{B}(J/\psi \to \phi\eta)$ and $\mathcal{B}(\eta \to \gamma\gamma)$ are the branching fractions of $J/\psi \to \phi\eta$ and $\eta \to \gamma\gamma$. Using the two equations above, the branching fraction of $\phi \to \pi^+\pi^+e^-e^-$ can be determined by

$$\mathcal{B}(\phi \to \pi^+\pi^+e^-e^-) = \mathcal{B}(\phi \to K^+K^-)\times\frac{N^{\rm net}_{\pi^+\pi^+e^-e^-}/\varepsilon_{\pi^+\pi^+e^-e^-}}{N^{\rm net}_{K^+K^-}/\varepsilon_{K^+K^-}}, \quad (3)$$

where $\mathcal{B}(\phi \to K^+K^-) = (49.2\pm0.5)\%$ [36]. The total systematic uncertainty can be reduced significantly because the uncertainty of the input $\mathcal{B}(\phi \to K^+K^-)$ is only 1.0%.

B. Analysis of $\phi \to K^+K^-$

The reference decay $J/\psi \to \phi\eta$ is reconstructed with $\eta \to \gamma\gamma$ and $\phi \to K^+K^-$. In each event, at least two charged tracks and two neutral candidates are required.

Charged tracks detected in the MDC are required to be within a polar angle (θ) range of $|\cos\theta| < 0.93$, where θ is defined with respect to the z-axis, which is the symmetry axis of the MDC. The distance of closest approach to the interaction point (IP) must be less than 10 cm along the z-axis, $|V_z|$, and less than 1 cm in the transverse plane, $|V_{xy}|$. Events with exactly two good charged tracks with zero net charge are kept for further analysis. For charged particle identification (PID), we use a combination of the dE/dx in the MDC, and the time of flight in the TOF to calculate the Confidence Level (CL) for pion and kaon hypotheses (CL_π and CL_K). For kaon candidates, they are required to satisfy $CL_K > 0.001$ and $CL_K > CL_\pi$ to avoid contamination from pions and to suppress background.

The photon candidates are selected from isolated EMC clusters. The clusters are required to start within 700 ns after the event start time and fall outside a cone

angle of 20° around the nearest extrapolated good charged track to suppress electronic noise and beam related background. The minimum energy of each EMC cluster is required to be greater than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) or 50 MeV in the end-cap regions ($0.86 < |\cos\theta| < 0.92$). The η candidate is reconstructed by $\eta \to \gamma\gamma$, where the invariant mass of the $\gamma\gamma$ pair is required to satisfy $0.45\ \text{GeV}/c^2 < M_{\gamma\gamma} < 0.65\ \text{GeV}/c^2$. A kinematic fit is performed to reduce backgrounds and improve mass resolution by constraining the total four momentum (4C) to that of the initial e^+e^- beams under the hypothesis of $e^+e^- \to K^+K^-\gamma\gamma$. All good photons are looped over together with the two tracks in the kinematic fit, and the candidate with the least χ^2 is retained for further analysis.

To obtain the signal yield of $\phi \to K^+K^-$, we fit the $M_{K^+K^-}$ distribution of the accepted candidate events in the η signal region ([0.525,0.565] GeV/c^2) and in the η sideband region ([0.452,0.492] GeV/c^2 or [0.598,0.638] GeV/c^2). The signal region is determined by $[\mu-3\sigma, \mu+3\sigma]$; the sideband region is outside the signal region and the distance between the two intervals is 5σ, where μ and σ are the mean and standard deviation obtained from a Gaussian fit to the $M_{\gamma\gamma}$ distribution, as shown in Fig. 1. In the fits to the $M_{K^+K^-}$ distribution in the η signal region, the signal shape is described by a MC shape convolved with a double Gaussian function and the background shape is described by second-order polynomial function. In the fits to the $M_{K^+K^-}$ distribution in the η sideband region, the signal shape is described by a MC shape convolved with a double Gaussian function, and the background shape is described by an inverted ARGUS function [40] multiplied by a fourth-order polynomial function. The double Gaussian function and the background model parameters float in the fits. With the numbers of N_{signal} and N_{sideband} obtained from the fits in Fig. 2, the net

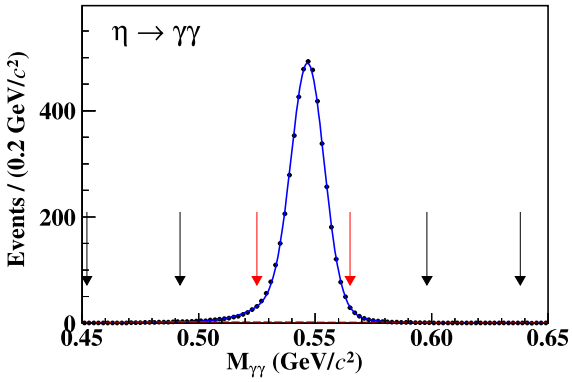

Fig. 1. (color online) Fit to the $M_{\gamma\gamma}$ distribution, where the black points represent the signal MC candidates, the blue curve is the fit result, the red dashed line is the second-order polynomial background, the red arrows show the signal region, and the black arrows show the sideband region.

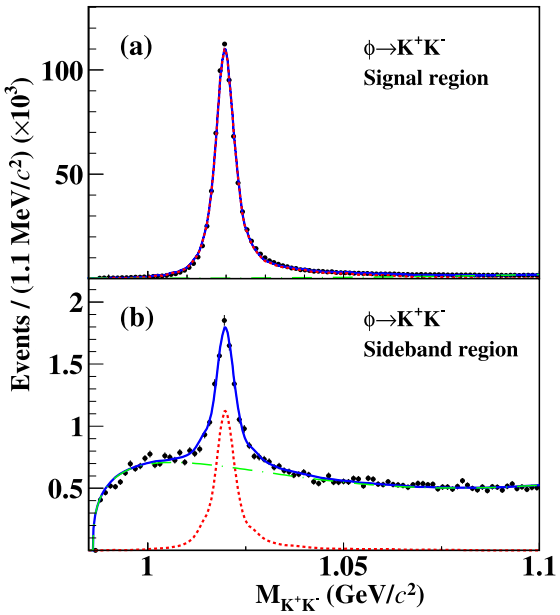

Fig. 2. (color online) Invariant mass $M_{K^+K^-}$ distributions of $J/\psi \to \phi\eta$ candidates in the (a) signal and (b) sideband region of η, with fit results overlaid. The black points represent the data, the blue curves are the fit results, the green dash-dotted curves are the fitted background shapes, and the red dotted curves are the signal shapes.

number of the $\phi \to K^+K^-$ candidate events is calculated by

$$N^{\text{net}}_{K^+K^-} = N_{\text{signal}} - \frac{1}{2} \times N_{\text{sideband}} = 823764 \pm 1023. \quad (4)$$

Here, $\frac{1}{2} \times N_{\text{sideband}}$ is the background yield under the $M_{\gamma\gamma}$ signal region, where the scale factor of 1/2 is determined under the assumption that the background is flat in the $M_{\gamma\gamma}$ distribution.

To determine the detection efficiency, the $J/\psi \to \phi\eta\,(\phi \to K^+K^-, \eta \to \gamma\gamma)$ decays are simulated, where the decays of $J/\psi \to \phi\eta$, $\phi \to K^+K^-$, and $\eta \to \gamma\gamma$ are modeled by a helicity amplitude generator HELAMP, a VSS model (decay of a vector particle to a pair of scalars), and a PHSP generator, respectively [41]. After applying all the selection criteria, we fit the invariant mass of the K^+K^- combination ($M_{K^+K^-}$) for the survived signal MC events in the signal and sideband regions, respectively. In the fits, the signal shape is modeled by a MC shape convolved with a double Gaussian function and the background is described by a second-order polynomial function. The number of observed signal events is obtained to be $N^{\text{MC}}_{\text{obs}} = N^{\text{signal}}_{\phi\to K^+K^-} - \frac{1}{2} \times N^{\text{sideband}}_{\phi\to K^+K^-}$, where $N^{\text{signal}}_{\phi\to K^+K^-}$ and $N^{\text{sideband}}_{\phi\to K^+K^-}$ are the observed numbers in the η signal and sideband regions, respectively. Dividing it by the number of total signal MC events $N^{\text{MC}}_{\text{total}}$, the efficiency of detecting the decays of $\phi \to K^+K^-$ is

$$\varepsilon_{KK} = \frac{N^{\rm MC}_{\rm obs}}{N^{\rm MC}_{\rm total}} = \frac{471297}{1000000} = (47.1 \pm 0.1)\%. \quad (5)$$

C. Analysis of $\phi \to \pi^+\pi^+e^-e^-$

The LNV decay of $\phi \to \pi^+\pi^+e^-e^-$ is searched through $J/\psi \to \phi\eta$, where the η candidate is reconstructed through $\eta \to \gamma\gamma$. In each event, at least four charged tracks and two neutral candidates are required.

The good charged tracks are selected using the same criteria as those used in the reference mode. For charged PID, we use a combination of the dE/dx in the MDC, the time of flight in the TOF, and the energy and shape of clusters in the EMC to calculate the CL for the electron, pion, and kaon hypotheses (CL_e, CL_π, and CL_K). The electron candidates are required to satisfy $CL_e > 0.001$ and $CL_e/(CL_e+CL_K+CL_\pi) > 0.8$. Furthermore, to suppress background from pions, electrons must satisfy an additional requirement $E/p > 0.8$ for tracks with $p_e \geq 0.5$ GeV/c, where E and p represent the energy deposited in the EMC and the momentum reconstructed in the MDC, respectively. Pion candidates are required to satisfy $CL_\pi > 0$ and $CL_\pi > CL_K$. The good photons are selected in the same way as in the reference mode.

A kinematic fit is performed to reduce backgrounds and improve the mass resolution by constraining the total four momentum (4C) to that of the initial e^+e^- beams. All the good photons are looped over together with the four tracks in the kinematic fit. To suppress the combinatorial background, the χ^2 of the 4C kinematic fit is required to be less than 30, determined via the Punzi significance method [42] using the formula $\frac{\varepsilon}{1.5+\sqrt{B}}$, where ε is the detection efficiency and B is the number of background events from the inclusive MC sample. If more than one combination is obtained, the combination with the minimum χ^2 is retained.

We perform 4C kinematic fits under six different hypotheses of $J/\psi \to \pi^+\pi^+e^-e^-\gamma\gamma$, $K^+K^-K^+K^-\gamma\gamma$, $K^+K^-p\bar{p}\gamma\gamma$, $K^+K^-\pi^+\pi^-\gamma\gamma$, $\pi^+\pi^-\pi^+\pi^-\gamma\gamma$, and $\pi^+\pi^-p\bar{p}\gamma\gamma$ to suppress the contamination of the final states with four charged tracks from mis-identification. If the kinematic fit for the $\pi^+\pi^+e^-e^-\gamma\gamma$ hypotheses is successful and gives the minimum χ^2 among these six assignments, the event is then accepted for further analysis.

To further suppress possible background from γ-conversion, the opening angle $\theta_{\pi e}$ between any pions (possibly mis-identified from real positrons) and electrons are required to be greater than 8°.

Based on a fit with a double Gaussian function and a Chebychev polynomial to model the signal and background shapes of the simulated $M_{\pi^+\pi^+e^-e^-}$ and $M_{\gamma\gamma}$ distributions, the signal region is determined to be [0.99, 1.04] GeV/c^2 for $M_{\pi^+\pi^+e^-e^-}$ and [0.52, 0.57] GeV/c^2 for $M_{\gamma\gamma}$. This corresponds to a range of ±3 times the mass resolution around their known masses [36]. The detection efficiency is determined to be 4.40% with simulated $J/\psi \to \phi\eta \to (\pi^+\pi^+e^-e^-)(\gamma\gamma)$ events, where the J/ψ decay is modeled by a helicity amplitude generator HELAMP [41] and the ϕ/η decays are modeled by a phase space (PHSP) generator.

Using TopoAna, an event type analysis tool [43], the backgrounds from J/ψ decays are investigated using an inclusive MC simulation sample, which has the same size as the J/ψ data sample. Only 39 events from 14 different decay channels remain. The distribution of $M_{\pi^+\pi^+e^-e^-}$ for the background events from the inclusive MC simulation sample is shown in Fig. 3, where the red arrows show the signal region. No background event is observed in the signal region.

To avoid the influence of statistical fluctuation, large exclusive MC simulation samples for the three main background channels, (1) $J/\psi \to \pi^+\pi^-\eta\gamma^F, \eta \to e^+e^-\gamma^F$ (γ^F is the γ from final state radiation), (2) $J/\psi \to \eta'$, $\eta' \to \pi^+\pi^-\eta$, $\eta \to e^+e^-$, and (3) $J/\psi \to \pi^+\eta b_1^-$, $\eta \to \gamma\gamma$, $b_1^- \to \pi^-\omega$, $\omega \to e^+e^-$, are produced. Furthermore, the possibility of background from other ϕ decays, such as $J/\psi \to \phi\eta$, $\phi \to e^+e^-\eta$, $\eta \to \gamma\gamma$, is also investigated. No background event is found near the signal region under the current MC sample statistics. Figure 4 shows the two dimensional distribution of $M_{\gamma\gamma}$ versus $M_{\pi^+\pi^+e^-e^-}$ of the accepted $\phi \to \pi^+\pi^+e^-e^-$ candidate events in the data. No event is observed in the signal region.

IV. SYSTEMATIC UNCERTAINTY

The sources of systematic uncertainties for the product branching fractions include MDC tracking, charged PID, 4C kinematic fit, χ^2 requirement, $\theta_{\pi e}$ requirement, signal window, fitting procedure, MC modeling, $N^{\rm net}_{K^+K^-}$ determination, and $\mathcal{B}(\phi \to K^+K^-)$. All the sys-

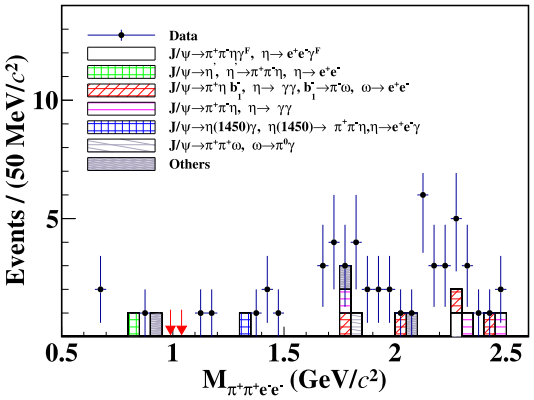

Fig. 3. (color online) The distribution of $M_{\pi^+\pi^+e^-e^-}$ for events in the range of $M_{\gamma\gamma} \in (0.52, 0.57)$ GeV/c^2, where the points with error bars are data, the histogram in different styles represent different sources of background modes shown in the legends. The red arrows show the signal region.

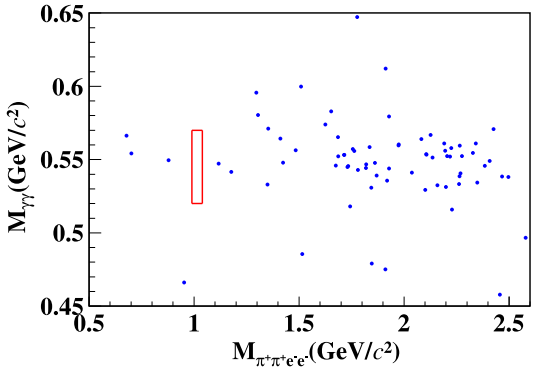

Fig. 4. (color online) The distribution of $M_{\gamma\gamma}$ versus $M_{\pi^+\pi^+e^-e^-}$ of the accepted $\phi \to \pi^+\pi^+e^-e^-$ candidate events in data. The red box indicates the signal region defined as $[0.99, 1.04]$ GeV/c^2 for $M_{\pi^+\pi^+e^-e^-}$ and $[0.52, 0.57]$ GeV/c^2 for $M_{\gamma\gamma}$.

Table 1. Relative systematic uncertainties in the branching fraction measurement.

Source	Uncertainty (%)
MDC tracking	2.6
PID	6.2
4C kinematic fit for $\phi \to K^+K^-$	0.2
4C kinematic fit for $\phi \to \pi^+\pi^-e^+e^-$	2.3
$\theta_{\pi e}$ selection requirement	4.1
Signal window	0.2
Yield of $\phi \to K^+K^-$	1.1
MC modeling	1.9
$\mathcal{B}(\phi \to K^+K^-)$	1.0
Total	8.6

tematic uncertainties are summarized in Table 1, and the total uncertainty is obtained by adding the individual components in quadrature.

The systematic uncertainties of photon detection and quoted branching fractions ($\mathcal{B}(J/\psi \to \phi\eta)$ and $\mathcal{B}(\eta \to \gamma\gamma)$) are canceled based Eq. (3).

The uncertainties in tracking efficiency are estimated using the control samples $J/\psi \to \pi^+\pi^-\pi^0$, $J/\psi \to e^+e^-$ ($\gamma_{\rm FSR}$) ($\gamma_{\rm FSR}$ is the FSR photon), and $J/\psi \to \pi^0K^+K^-$, and are determined to be 0.3% per pion, 0.7% per electron, and 0.3% per kaon, considering the efficiency differences between the data and MC simulations, respectively. Similarly, the uncertainties of PID are 1.0%, 1.0%, and 1.1% for each charged electron, pion, and kaon, respectively. After adding the systematic uncertainties of each track linearly, the total systematic uncertainties in tracking efficiency and PID efficiency are obtained to be 2.6% and 6.2%, respectively.

The systematic uncertainty due to the 4C kinematic fit for $J/\psi \to \phi\eta \to K^+K^-\eta\,(\eta \to \gamma\gamma)$ is studied by using the control sample of the $J/\psi \to K^+K^-\pi^0\,(\pi^0 \to \gamma\gamma)$ decay mode. The corresponding uncertainty is estimated to be 0.2% by comparing the efficiency differences between the data and MC simulation. Similarly, the systematic uncertainty due to the 4C kinematic fit and $\chi^2 < 30$ for $J/\psi \to \phi\eta \to \pi^+\pi^-e^+e^-\eta\,(\eta \to \gamma\gamma)$ is studied using the control sample of the $J/\psi \to \pi^+\pi^-\pi^+\pi^-\eta\,(\eta \to \gamma\gamma)$ decay mode. The corresponding uncertainty is assigned to be 2.3%.

The uncertainty of the $\theta_{\pi e}$ requirement is estimated by varying the optimized requirement $\theta_{\pi e} > 8°$ with alternative $\theta_{\pi e}$ requirements, i.e., $\theta_{\pi e} > 3°$, $\theta_{\pi e} > 4°$,..., $\theta_{\pi e} > 12°$, $\theta_{\pi e} > 13°$. The largest standard deviation on the detection efficiency, 4.1%, is taken as the corresponding systematic uncertainty.

We use different signal window ranges, such as $\pm 3.1\sigma$, $\pm 3.2\sigma$, and $\pm 2.8\sigma$, to investigate the systematic uncertainty due to the selected η signal window. The standard deviation on a detection efficiency of 0.2% is taken as the uncertainty.

The systematic uncertainty of the yield of the reference decay $J/\psi \to \phi\eta, \phi \to K^+K^-$ includes the fit range, signal shape, and background shape. The uncertainty due to the fit range of M_{KK} is estimated by changing the fit from (0.99,1.10) GeV/c^2 to (0.99,1.09) GeV/c^2 and (0.98,1.10) GeV/c^2. The uncertainty due to the background shape is estimated by changing the second-order polynomial function to a first-order polynomial function. We use alternative signal shapes (an MC shape convolved with a Gaussian function) to estimate the systematic uncertainty due to signal shape. The relative difference between the signal yield and the detection efficiency is taken as the corresponding systematic uncertainty. Consequently, the systematic uncertainties are determined to be 1.0%, 0.1%, and 0.3% for fit range, background shape, and signal shape, respectively. After adding them in quadrature, the total systematic uncertainty associated with the fit procedure is obtained as 1.1%.

An intermediate majorana neutrino ν_N is assumed to decay into $\pi^+e^-$to estimate the uncertainty related to the MC simulation model. However, the mass of ν_N remains unknown and can range from the πe mass threshold to the largest available phase space of ϕ decay, which needs to satisfy $m_e + m_\pi \le m_{\nu_N} \le \frac{m_\phi}{2}$. We divide the mass range (0.150,0.50) GeV into 14 equidistant intervals, with a step of 0.025 GeV, i.e., 0.175 GeV, 0.200 GeV,..., 0.500 GeV. The detection efficiency is averaged to be $(4.32 \pm 0.09)\%$. The difference between this value and the detection efficiency obtained by the PHSP model of 1.9% is taken as the associated systematic uncertainty.

The uncertainty of the quoted branching fraction $\mathcal{B}(\phi \to K^+K^-)$ is 1.0% [36].

V. RESULT

Because no event is observed in the signal region, the signal yield ($N^{\rm sig}$) and background yield ($N^{\rm bkg}$) are determined to be 0. The upper limit on the signal yield $N^{\rm up}_{\pi^+\pi^+e^-e^-}$ is estimated to be 45.4 at the 90% CL by utilizing a frequentist method [44] with unbounded profile likelihood treatment of systematic uncertainties, where the background fluctuation is assumed to follow a Poisson distribution, the detection efficiency ($\varepsilon_{\pi^+\pi^+e^-e^-}$ = 4.40%) is assumed to follow a Gaussian distribution, and the systematic uncertainty ($\Delta_{\rm sys} = 8.6\%$) is considered as the standard deviation of the efficiency.

The upper limit on the branching fraction of $\phi \to \pi^+\pi^+e^-e^-$ is determined by

$$\mathcal{B}(\phi \to \pi^+\pi^+e^-e^-) < \mathcal{B}(\phi \to K^+K^-) \times \frac{N^{\rm up}_{\pi^+\pi^+e^-e^-}}{N^{\rm net}_{K^+K^-}/\varepsilon_{K^+K^-}},$$

where $\varepsilon_{K^+K^-} = 47.1\%$, $N^{\rm net}_{K^+K^-} = 823764 \pm 1023$, $\mathcal{B}(\phi \to K^+K^-) = (49.2 \pm 0.5)\%$ [34] and $N^{\rm up}_{\pi^+\pi^+e^-e^-} = 45.4$. Thus, the upper limit on the branching fraction is set to be

$$\mathcal{B}(\phi \to \pi^+\pi^+e^-e^-) < 1.3 \times 10^{-5}.$$

VI. SUMMARY

In summary, by analyzing $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected using the BESIII detector at the BEPCII collider, we conduct a novel search for the LNV decay $\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \phi\eta$. No obvious signal event is observed and the upper limit on the branching fraction of this decay is set to be 1.3×10^{-5} at the 90% CL. This is the first LNV signal constraint in ϕ meson decays. Our study findings improve the experimental knowledge of LNV decay for hadrons composed of second generation quarks.

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