Search for the lepton number violating process $J/\psi \to K^{+}K^{+}e^{-}e^{-}+c.c.$*

M. Ablikim (麦迪娜)[1] M. N. Achasov[4,c] P. Adlarson[78] X. C. Ai (艾小聪)[83] R. Aliberti[37] A. Amoroso[77A,77C]
Q. An (安琪)[74,60,a] Y. Bai (白羽)[59] O. Bakina[38] Y. Ban (班勇)[48,h] H.-R. Bao (包浩然)[66] V. Batozskaya[1,46]
K. Begzsuren[34] N. Berger[37] M. Berlowski[46] M. B. Bertani[30A] D. Bettoni[31A] F. Bianchi[77A,77C] E. Bianco[77A,77C]
A. Bortone[77A,77C] I. Boyko[38] R. A. Briere[5] A. Brueggemann[71] H. Cai (蔡浩)[79] M. H. Cai (蔡铭航)[40,k,l]
X. Cai (蔡啸)[1,60] A. Calcaterra[30A] G. F. Cao (曹国富)[1,66] N. Cao (曹宁)[1,66] S. A. Cetin[64A] X. Y. Chai (柴新宇)[48,h]
J. F. Chang (常劲帆)[1,60] T. T. Chang (常甜甜)[45] G. R. Che (车国荣)[45] Y. Z. Che (车逾之)[1,60,66]
C. H. Chen (陈春卉)[9] Chao Chen (陈超)[57] G. Chen (陈刚)[1] H. S. Chen (陈和生)[1,66] H. Y. Chen (陈弘扬)[21]
M. L. Chen (陈玛丽)[1,60,66] S. J. Chen (陈申见)[44] S. L. Chen (陈思璐)[47] S. M. Chen (陈少敏)[63] T. Chen (陈通)[1,66]
X. R. Chen (陈旭荣)[33,66] X. T. Chen (陈肖婷)[1,66] X. Y. Chen (陈心宇)[12,g] Y. B. Chen (陈元柏)[1,60] Y. Q. Chen[16]
Z. Chen (陈琢)[26] Z. K. Chen (陈梓康)[61] J. C. Cheng (程捷)[47] L. N. Cheng (程利娜)[45] S. K. Choi[10]
X. Chu (初晓)[12,g] G. Cibinetto[31A] F. Cossio[77C] J. Cottee-Meldrum[65] H. L. Dai (代洪亮)[1,60] J. P. Dai (代建平)[81]
A. Dbeyssi[19] R. E. de Boer[3] D. Dedovich[38] C. Q. Deng (邓创旗)[75] Z. Y. Deng (邓子艳)[1] A. Denig[37]
I. Denisenko[38] M. Destefanis[77A,77C] F. De Mori[77A,77C] B. Ding (丁彪)[69,1] X. X. Ding (丁晓萱)[48,h] Y. Ding (丁逸)[36]
Y. Ding (丁勇)[42] Y. X. Ding (丁玉鑫)[32] J. Dong (董静)[1,60] L. Y. Dong (董燎原)[1,66] M. Y. Dong (董明义)[1,60,66]
X. Dong (董翔)[79] M. C. Du (杜蒙川)[1] S. X. Du (杜书先)[83] S. X. Du (杜少旭)[12,g] X. L. Du (杜小龙)[83]
Y. Y. Duan (段尧予)[57] Z. H. Duan (段宗欢)[44] P. Egorov[38,b] G. F. Fan (樊高峰)[44] J. J. Fan (樊俊杰)[20]
Y. H. Fan (范宇晗)[47] J. Fang (方进)[61] J. Fang (方建)[1,60] S. S. Fang (房双世)[1,66] W. X. Fang (方文兴)[1]
Y. Q. Fang (方亚泉)[1,60] R. Farinelli[31A] L. Fava[77B,77C] F. Feldbauer[3] G. Felici[30A] C. Q. Feng (封常青)[74,60]
J. H. Feng (冯俊华)[16] L. Feng (冯琳)[40,k,l] Q. X. Feng (冯千禧)[40,k,l] Y. T. Feng (冯玗潼)[74,60] M. Fritsch[3]
C. D. Fu (傅成栋)[1] J. L. Fu (傅金林)[66] Y. W. Fu (傅亦威)[1,66] H. Gao (高涵)[66] X. B. Gao (高鑫博)[43]
Y. Gao (高扬)[74,60] Y. N. Gao (高语浓)[20] Y. N. Gao (高原宁)[48,h] Y. Y. Gao (高洋洋)[32] Z. Gao (高枝)[45]
S. Garbolino[77C] I. Garzia[31A,31B] P. T. Ge (葛潘婷)[20] Z. W. Ge (葛振武)[44] C. Geng (耿聪)[61] E. M. Gersabeck[70]
A. Gilman[72] K. Goetzen[13] J. D. Gong (龚家鼎)[36] L. Gong (龚丽)[42] W. X. Gong (龚文煊)[1,60] W. Gradl[37]
S. Gramigna[31A,31B] M. Greco[77A,77C] M. H. Gu (顾旻皓)[1,60] Y. T. Gu (顾运厅)[15] C. Y. Guan (关春懿)[1,66]
A. Q. Guo (郭爱强)[33] J. N. Guo (郭嘉宁)[12,g] L. B. Guo (郭立波)[43] M. J. Guo (国梦娇)[52] R. P. Guo (郭如盼)[51]
X. Guo (郭旭)[52] Y. P. Guo (郭玉萍)[12,g] A. Guskov[38,b] J. Gutierrez[29] K. L. Han (韩坤霖)[66] T. T. Han (韩婷婷)[1]
F. Hanisch[3] K. D. Hao (郝科迪)[74,60] X. Q. Hao (郝喜庆)[20] F. A. Harris[68] K. K. He (何凯凯)[57] K. L. He (何康林)[1,66]
F. H. Heinsius[3] C. H. Heinz[37] Y. K. Heng (衡月昆)[1,60,66] C. Herold[62] P. C. Hong (洪鹏程)[36]
G. Y. Hou (侯国一)[1,66] X. T. Hou (侯贤涛)[1,66] Y. R. Hou (侯颖锐)[66] Z. L. Hou (侯治龙)[1] H. M. Hu (胡海明)[1,66]
J. F. Hu (胡继峰)[58,j] Q. P. Hu (胡启鹏)[74,60] S. L. Hu (胡圣亮)[12,g] T. Hu (胡涛)[1,60,66] Y. Hu (胡誉)[1]
Z. M. Hu (胡忠敏)[61] G. S. Huang (黄光顺)[74,60] K. X. Huang (黄凯旋)[61] L. Q. Huang (黄麟钦)[33,66] P. Huang (黄盼)[44]

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X. T. Huang (黄性涛)[52] Y. P. Huang (黄燕萍)[1] Y. S. Huang (黄永盛)[61] T. Hussain[76] N. Hüsken[37]
N. in der Wiesche[71] J. Jackson[29] Q. Ji (纪全)[1] Q. P. Ji (姬清平)[20] W. Ji (季旺)[1,66] X. B. Ji (季晓斌)[1,66]
X. L. Ji (季筱璐)[1,60] X. Q. Jia (贾晓倩)[52] Z. K. Jia (贾泽坤)[74,60] D. Jiang (姜地)[1,66] H. B. Jiang (姜候兵)[79]
P. C. Jiang (蒋沛成)[48,h] S. J. Jiang (蒋思婧)[9] X. S. Jiang (江晓山)[1,60,66] Y. Jiang (蒋艺)[66] J. B. Jiao (焦健斌)[52]
J. K. Jiao (焦俊坤)[36] Z. Jiao (焦铮)[25] S. Jin (金山)[44] Y. Jin (金毅)[69] M. Q. Jing (荆茂强)[1,66] X. M. Jing (景新媚)[66]
T. Johansson[78] S. Kabana[35] N. Kalantar-Nayestanaki[67] X. L. Kang (康晓琳)[9] X. S. Kang (康晓珅)[42]
M. Kavatsyuk[67] B. C. Ke (柯百谦)[83] V. Khachatryan[29] A. Khoukaz[71] O. B. Kolcu[64A] B. Kopf[3] M. Kuessner[3]
X. Kui (奎贤)[1,66] N. Kumar[28] A. Kupsc[46,78] W. Kühn[39] Q. Lan (兰强)[75] W. N. Lan (兰文宁)[20]
T. T. Lei (雷天天)[74,60] M. Lellmann[37] T. Lenz[37] C. Li (李翠)[49] C. Li (李聪)[45] C. H. Li (李春花)[41]
C. K. Li (李春凯)[21] D. M. Li (李德民)[83] F. Li (李飞)[1,60] G. Li (李刚)[1] H. B. Li (李海波)[1,66] H. J. Li (李惠静)[20]
H. N. Li (李衡讷)[58,j] Hui Li (李慧)[45] J. R. Li (李嘉荣)[63] J. S. Li (李静舒)[61] J. W. Li (李井文)[52] K. Li (李科)[1]
K. L. Li (李凯璐)[40,k,l] K. L. Li (李凯璐)[20] L. J. Li (李林健)[1,66] Lei Li (李蕾)[50] M. H. Li (李明浩)[45]
M. R. Li (李明润)[1,66] P. L. Li (李佩莲)[66] P. R. Li (李培荣)[40,k,l] Q. M. Li (李启铭)[1,66] Q. X. Li (李起鑫)[52]
R. Li (李燃)[18,33] S. X. Li (李素娴)[12] T. Li (李腾)[52] T. Y. Li (李天佑)[45] W. D. Li (李卫东)[1,66] W. G. Li (李卫国)[1,a]
X. Li (李旭)[1,66] X. H. Li (李旭红)[74,60] X. L. Li (李晓玲)[52] X. Y. Li (李晓宇)[1,8] X. Z. Li (李绪泽)[61] Y. Li (李洋)[20]
Y. G. Li (李彦谷)[48,h] Y. P. Li (李雁鹏)[36] Z. J. Li (李志军)[61] Z. X. Li (李振轩)[45] Z. Y. Li (李紫阳)[81]
C. Liang (梁畅)[44] H. Liang (梁昊)[74,60] Y. F. Liang (梁勇飞)[56] Y. T. Liang (梁羽铁)[33,66] G. R. Liao (廖广睿)[14]
L. B. Liao (廖立波)[61] M. H. Liao (廖明华)[61] Y. P. Liao (廖一朴)[1,66] J. Libby[28] A. Limphirat[62] C. C. Lin (蔺长城)[57]
D. X. Lin (林德旭)[33,66] L. Q. Lin (邵麟筌)[41] T. Lin (林韬)[1] B. J. Liu (刘北江)[1] B. X. Liu (刘宝鑫)[79]
C. Liu (刘成)[36] C. X. Liu (刘春秀)[1] F. Liu (刘芳)[1] F. H. Liu (刘福虎)[55] Feng Liu (刘峰)[6] G. M. Liu (刘国明)[58,j]
H. Liu (刘昊)[40,k,l] H. B. Liu (刘宏邦)[15] H. H. Liu (刘欢欢)[1] H. M. Liu (刘怀民)[1,66] Huihui Liu (刘汇慧)[22]
J. B. Liu (刘建北)[74,60] J. J. Liu (刘佳佳)[21] K. Liu (刘坤)[75] K. Liu (刘凯)[40,k,l] K. Y. Liu (刘魁勇)[42] Ke Liu (刘珂)[23]
L. C. Liu (刘良辰)[45] Lu Liu (刘露)[45] M. H. Liu[36] P. L. Liu (刘佩莲)[1] Q. Liu (刘倩)[66] S. B. Liu (刘树彬)[74,60]
T. Liu (刘桐)[12,g] W. K. Liu (刘维克)[45] W. M. Liu (刘卫民)[74,60] W. T. Liu (刘婉婷)[41] X. Liu (刘翔)[40,k,l]
X. Liu (刘鑫)[41] X. K. Liu (刘筱康)[40,k,l] X. L. Liu (刘兴淋)[12,g] X. Y. Liu (刘雪吟)[79] Y. Liu (刘义)[83]
Y. Liu (刘英)[40,k,l] Y. B. Liu (刘玉斌)[45] Z. A. Liu (刘振安)[1,60,66] Z. D. Liu (刘宗德)[9] Z. Q. Liu (刘智青)[52]
X. C. Lou (娄辛丑)[1,60,66] H. J. Lu (吕海江)[25] J. G. Lu (吕军光)[1,60] X. L. Lu (陆小玲)[16] Y. Lu (卢宇)[7]
Y. H. Lu (卢泱宏)[1,66] Y. P. Lu (卢云鹏)[1,60] Z. H. Lu (卢泽辉)[1,66] C. L. Luo (罗成林)[43] J. R. Luo (罗家瑞)[61]
J. S. Luo (罗家顺)[1,66] M. X. Luo (罗民兴)[82] T. Luo (罗涛)[12,g] X. L. Luo (罗小兰)[1,60] Z. Y. Lv (吕在裕)[23]
X. R. Lyu (吕晓睿)[66,p] Y. F. Lyu (吕翌丰)[45] Y. H. Lyu (吕云鹤)[83] F. C. Ma (马凤才)[42] H. L. Ma (马海龙)[1]
Heng Ma (马衡)[27,i] J. L. Ma (马俊力)[1,66] L. L. Ma (马连良)[52] L. R. Ma (马立瑞)[69] Q. M. Ma (马秋梅)[1]
R. Q. Ma (马润秋)[1,66] R. Y. Ma (马若云)[20] T. Ma (马腾)[74,60] X. T. Ma (马晓天)[1,66] X. Y. Ma (马骁妍)[1,60]
Y. M. Ma (马玉明)[33] F. E. Maas[19] I. MacKay[72] M. Maggiora[77A,77C] S. Malde[72] Q. A. Malik[76]
H. X. Mao (毛杭翔)[40,k,l] Y. J. Mao (冒亚军)[48,h] Z. P. Mao (毛泽普)[1] S. Marcello[77A,77C] A. Marshall[65]
F. M. Melendi[31A,31B] Y. H. Meng (孟琰皓)[66] Z. X. Meng (孟召霞)[69] G. Mezzadri[31A] H. Miao (妙晗)[1,66]
T. J. Min (闵天觉)[44] R. E. Mitchell[29] X. H. Mo (莫晓虎)[1,60,66] B. Moses[29] N. Yu. Muchnoi[4,c] J. Muskalla[37]
Y. Nefedov[38] F. Nerling[19,e] Z. Ning (宁哲)[1,60] S. Nisar[11,m] Q. L. Niu (牛祺乐)[40,k,l] W. D. Niu (牛文迪)[12,g]
Y. Niu (牛艳)[52] C. Normand[65] S. L. Olsen[10,66] Q. Ouyang (欧阳群)[1,60,66] S. Pacetti[30B,30C] X. Pan (潘祥)[57]
Y. Pan (潘越)[59] A. Pathak[10] Y. P. Pei (裴宇鹏)[74,60] M. Pelizaeus[3] H. P. Peng (彭海平)[74,60] X. J. Peng (彭宣嘉)[40,k,l]
Y. Y. Peng (彭云翊)[40,k,l] K. Peters[13,e] K. Petridis[65] J. L. Ping (平加伦)[43] R. G. Ping (平荣刚)[1,66] S. Plura[37]
V. Prasad[36] F. Z. Qi (齐法制)[1] H. R. Qi (漆红荣)[63] M. Qi (祁鸣)[44] S. Qian (钱森)[1,60] W. B. Qian (钱文斌)[66]
C. F. Qiao (乔从丰)[66] J. H. Qiao (乔佳辉)[20] J. J. Qin (秦佳佳)[75] J. L. Qin (覃嘉良)[57] L. Q. Qin (秦丽清)[14]
L. Y. Qin (秦龙宇)[74,60] P. B. Qin (秦鹏勃)[75] X. P. Qin (覃潇萍)[41] X. S. Qin (秦小帅)[52] Z. H. Qin (秦中华)[1,60]
J. F. Qiu (邱进发)[1] Z. H. Qu (屈子皓)[75] J. Rademacker[65] C. F. Redmer[37] A. Rivetti[77C] M. Rolo[77C]
G. Rong (荣刚)[1,66] S. S. Rong (荣少石)[1,66] F. Rosini[30B,30C] Ch. Rosner[19] M. Q. Ruan (阮曼奇)[1,60] N. Salone[46,q]
A. Sarantsev[38,d] Y. Schelhaas[37] K. Schoenning[78] M. Scodeggio[31A] K. Y. Shan (尚科羽)[12,g] W. Shan (单葳)[26]

CPC Accepted

X. Y. Shan (单心钰)[74,60] Z. J. Shang (尚子杰)[40,k,l] J. F. Shangguan (上官剑锋)[17] L. G. Shao (邵立港)[1,66]
M. Shao (邵明)[74,60] C. P. Shen (沈成平)[12,g] H. F. Shen (沈宏飞)[1,8] W. H. Shen (沈文涵)[66] X. Y. Shen (沈肖雁)[1,66]
B. A. Shi (施伯安)[66] H. Shi (史华)[74,60] J. L. Shi (石家磊)[12,g] J. Y. Shi (石京燕)[1] S. Y. Shi (史书宇)[75]
X. Shi (史欣)[1,60] H. L. Song (宋海林)[74,60] J. J. Song (宋娇娇)[20] T. Z. Song (宋天资)[61] W. M. Song (宋维民)[36]
Y. J. Song (宋宇镜)[12,g] Y. X. Song (宋昀轩)[48,h,n] Zirong Song (宋子荣)[27,i] S. Sosio[77A,77C] S. Spataro[77A,77C]
F. Stieler[37] S. S Su (苏闪闪)[42] Y. J. Su (粟杨捷)[66] G. B. Sun (孙光豹)[79] G. X. Sun (孙功星)[1] H. Sun (孙昊)[66]
H. K. Sun (孙浩凯)[1] J. F. Sun (孙俊峰)[20] K. Sun (孙开)[63] L. Sun (孙亮)[79] R. Sun (孙睿)[74] S. S. Sun (孙胜森)[1,66]
T. Sun[53,f] Y. C. Sun (孙雨长)[79] Y. H. Sun (孙益华)[32] Y. J. Sun (孙勇杰)[74,60] Y. Z. Sun (孙永昭)[1]
Z. Q. Sun (孙泽群)[1,66] Z. T. Sun (孙振田)[52] C. J. Tang (唐昌建)[56] G. Y. Tang (唐光毅)[1] J. Tang (唐健)[61]
J. J. Tang (唐嘉骏)[74,60] L. F. Tang (唐林发)[41] Y. A. Tang (唐迎澳)[79] L. Y. Tao (陶璐燕)[75] M. Tat[72]
J. X. Teng (滕佳秀)[74,60] J. Y. Tian (田济源)[74,60] W. H. Tian (田文辉)[61] Y. Tian (田野)[33] Z. F. Tian (田喆飞)[79]
I. Uman[64B] B. Wang (王斌)[1] B. Wang (王博)[61] Bo Wang (王博)[74,60] C. Wang (王程)[40,k,l] C. Wang (王超)[20]
Cong Wang (王聪)[23] D. Y. Wang (王大勇)[48,h] H. J. Wang (王泓鉴)[40,k,l] J. J. Wang (王家驹)[79] J. P. Wang (王吉鹏)[52]
K. Wang (王科)[1,60] L. L. Wang (王亮亮)[1] L. W. Wang (王璐怡)[36] M. Wang (王萌)[52] M. Wang (王咪)[74,60]
N. Y. Wang (王南洋)[66] S. Wang (王顺)[12,g] S. Wang (王石)[40,k,l] T. Wang (王婷)[12,g] T. J. Wang (王腾蛟)[45]
W. Wang (王维)[75] W. Wang (王为)[61] W. P. Wang (王维平)[37] X. Wang (王轩)[48,h] X. F. Wang (王雄飞)[40,k,l]
X. J. Wang (王希俊)[41] X. L. Wang (王小龙)[12,g] X. N. Wang (王新南)[1,66] Y. Wang (王亦)[1] Y. D. Wang (王雅迪)[47]
Y. F. Wang (王贻芳)[1,8,66] Y. H. Wang (王英豪)[40,k,l] Y. J. Wang (王祎景)[74,60] Y. L. Wang (王艺龙)[20]
Y. N. Wang (王燕宁)[79] Y. N. Wang (王亚男)[47] Y. Q. Wang (王雨晴)[1] Yaqian Wang (王亚乾)[18] Yi Wang (王义)[63]
Yuan Wang (王源)[18,33] Z. Wang (王铮)[1,60] Z. Wang (王旨)[45] Z. L. Wang (王治浪)[2] Z. L. Wang (王治浪)[75]
Z. Q. Wang (王紫祺)[12,g] Z. Y. Wang (王至勇)[1,66] Ziyi Wang (王子一)[66] D. Wei (魏栋)[45] D. H. Wei (魏代会)[14]
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Abstract: Based on $(10087\pm44)\times10^{6}$ J/ψ events collected with the BESIII detector, we search for the lepton number violating decay $J/\psi\to K^{+}K^{+}e^{-}e^{-}+c.c.$ for the first time. The upper limit on the branching fraction of this decay is set to be 2.1×10^{-9} at the 90% confidence level with a frequentist method. This is the first search for J/ψ decays with the lepton number change by two, offering valuable insights into the underlying physical processes.

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

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I. INTRODUCTION

The absence of a right-handed neutrino component in the Standard Model (SM), coupled with the imperatives of $SU(2)_L$ gauge invariance and renormalizability, results in the prediction that neutrinos should be massless. However, experimental evidence from neutrino oscillation studies [1−4] compellingly demonstrates that neutrinos possess a non-zero, albeit minute, mass. This discrepancy hints the existence of physics that extends beyond the current understanding provided by the SM.

In 1937, Majorana proposed that neutrinos might be their own antiparticles, a scenario in which the neutrino and the antineutrino are indistinguishable [5]. This possibility raises an unresolved question: are neutrinos Dirac particles, distinct from their antiparticles, or Majorana particles, which are not? The ``see-saw'' mechanism [6−8] is a popular model for generating light neutrino masses, requiring a heavy Majorana neutrino with a mass ranging from a few hundred MeV/c^2 to a few GeV/c^2. If neutrino masses arise from this mechanism, there could be processes that violate lepton number by two units ($\Delta L=2$), revealing the Majorana nature of neutrinos. Thus, search for lepton number violation (LNV) is crucial to confirm whether neutrinos are Majorana particles. In 1939, based on Majorana's theory, Furry [9] studied the neutrinoless double beta ($0\nu2\beta$) decay [10], which is an LNV process. Since then, various theories concerning LNV processes have been proposed, and numerous experiments have been carried out to explore these processes.

In addition, the observed matter-antimatter asymmetry in the Universe presents a significant challenge to our understanding of nature. The Big Bang theory, which is the prevailing cosmological model for the Universe's evolution, predicts equal amounts of baryons and anti-baryons in the early Universe. However, the observed amount of baryons exceeds that of the anti-baryons by a factor currently estimated at $10^{9}-10^{10}$ [11]. To give a reasonable interpretation of the baryon-antibaryon asymmetry, Sakharov proposed three principles [12], the first of which is that baryon number conservation must be violated. Many theories believe that if there is baryon number violation, there will also be LNV[13]. Consequently, experimental searches for the LNV $\Delta L=2$ processes are of great interest.

Apart from the $0\nu2\beta$ decay experiments, which could search for Majorana neutrinos, several collider experiments have explored related processes. For example, the LHCb experiment investigated the $B^{-}\to\pi^{+}\mu^{-}\mu^{-}$ decays [14], the CMS experiment studied the $p\bar{p}\to e^{+}e^{+}X$ process [15], the BaBar experiment analyzed the $D_s^{+}\to\pi^{+}l^{+}l^{+}$ decays [16], and the ATLAS experiment searched for right-handed W bosons and heavy right-handed Majorana or Dirac neutrinos, using final state containing a pair of charged leptons and two jets [17]. The Gerda experiment searched for the rare $0\nu2\beta$ decay process in ^{76}Ge [18]. In addition, the CLEO experiment investigated the $D\to\pi(K)e^{+}e^{+}$ decays [19] and the FOCUS experiment searched for the decays of D^{+} and D_s^{+} containing the same-sign di-muons [20]. In recent years, the BESIII experiment searched for the LNV decays of charmed mesons, including $D\to K\pi e^{+}e^{+}$ [21], $D^{0}\to\bar{p}e^{+}(pe^{-})$ [22], $D^{+}\to\bar{\Lambda}(\bar{\Sigma}^{0}e^{+})$ [23], and $D^{+}(D^{-})\to ne^{+}(\bar{n}e^{-})$ [24]. In all above searches, no evidence has been found.

In the τ-charm energy region, the huge data set of charmonia (such as J/ψ) can be analyzed to search for various LNV processes, and it is feasible to search for $J/\psi\to K^{+}K^{+}e^{-}e^{-}$ (throughout this paper, charge conjugation is implied) and other LNV processes in the decay products of $\phi,\omega,K^{0},\eta/\eta'$, and so on. Fig. 1 shows Feynman diagram of $J/\psi\to K^{+}K^{+}e^{-}e^{-}+c.c$ through possible high dimension operator [25]. Search for this process would provide hints for new physics, as they are expected to be suppressed due to higher-order processes in the SM.

In this paper, by analyzing $(10087\pm44)\times10^{6}$ J/ψ [26] events collected with the BESIII detector [27] operating at the BEPCII storage ring, we search for the LNV decay $J/\psi\to K^{+}K^{+}e^{-}e^{-}$ for the first time. Furthermore, we explore the upper limits on the branching fractions of this decay under different Majorana neutrino mass hypo-

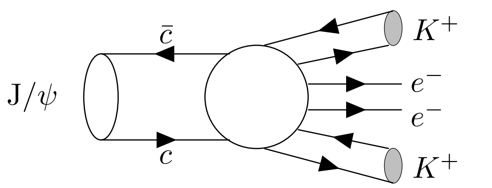

Fig. 1. Possible Feynman diagram of $J/\psi\to K^{+}K^{+}e^{-}e^{-}$.

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theses. To avoid possible bias, a blind analysis technique is employed, where the data are analyzed only after the analysis procedure has been finalized and validated with MC simulation.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector is located at the south collision point of the BEPCII [28] storage ring, which operates at a center-of-mass energy range of $\sqrt{s}$ = 1.84 to 4.95 GeV, with a maximum luminosity of 1.1×10^{33} cm^{-2}s^{-1} at 3.773 GeV.

The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC). These components are enclosed within a superconducting solenoidal magnet that provides a 1.0 T magnetic field (0.9 T in 2012). The solenoid is supported by an octagonal flux-return yoke, with resistive plate counter muon identifier modules interleaved with steel. The BESIII coordinate system is defined such that the z-axis aligns with the beam direction, the x-axis is horizontal and points outward from the interaction point, and the y-axis is vertical, forming a right-handed coordinate system.

At a momentum of 1 GeV/c, the charged particle momentum resolution is 0.5%, and the specific ionization energy loss (dE/dx) resolution is 6% for electrons from Bhabha scattering. The EMC has a photon energy 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 in the end-cap region it is 110 ps. In 2015, the end-cap TOF system was upgraded using multigap resistive plate chamber technology, improving the time resolution to 60 ps [29]. Approximately 87% of the data used in this analysis benefit from this upgrade.

Simulated samples produced with the GEANT4-based [30] Monte Carlo (MC) program which includes the geometric description [31, 32] of the BESIII detector and the detector response, are used to determine the detection efficiency and estimate the backgrounds. The simulation includes the beam energy spread and initial state radiation in the e^+e^- annihilations modeled with the generator KKMC [33]. The inclusive MC sample includes both the production of the J/ψ resonance and the continuum processes incorporated in KKMC [33]. All particle decays are modelled with EVTGEN [34] using branching fractions either taken from the Particle Data Group [35], when available, or otherwise estimated with LUNDCHARM [36]. Final state radiation (FSR) from charged final state particles is incorporated using the PHOTOS package [37]. In this work, a sample of 100,000 phase space (PHSP) MC events are generated to study the detection efficiencies for the LNV decay, with equal contributions from each conjugate channel. For background analysis, 10 billion inclusive MC events are used. The continuum background is estimated using off-resonance data samples at $\sqrt{s}=3.650$, 3.682 and 3.080 GeV [38], with integrated luminosities of 410 pb^{-1}, 404 pb^{-1} and 167 pb^{-1}, respectively.

III. DATA ANALYSIS

All charged tracks are required to satisfy a geometrical acceptance of $|\cos\theta|<0.93$, where θ is the polar angle of the charged track, defined with respect to the z-axis, which is the symmetry axis of the MDC. Each track must originate from the interaction region, defined as $R_{xy}<1.0$ cm and $|R_z|<10.0$ cm, where R_{xy} and R_z are the distances of the closest approach to the interaction point of the track in the transverse plane and z-axis, respectively. Events with at least four charged tracks with zero net charge are retained for further analysis.

Particle identification (PID) for charged tracks combines measurements of the energy deposited in the MDC (dE/dx), the flight time in the TOF, and the energy and shape of clusters in the EMC to calculate the confidence level (CL) for electron, pion, kaon hypotheses (CL$_e$, CL$_\pi$, CL$_K$). Electron candidates must have CL$_e$ greater than 0.001, and the ratio of CL$_e$ to the sum of CLs for electrons, kaons, and pions (CL$_e$ + CL$_K$ + CL$_\pi$) should be greater than 0.8. In addition, the ratio of energy deposited in the EMC(E) to the momentum measured in the MDC(p) must lie between 0.8c and 1.2c. For kaon candidates, the criteria include CL$_K>0$ and CL$_K>$ CL$_\pi$. To further reduce the misidentification(mis-PID) between electrons and kaons, an additional requirement of E/p less than 0.8c is applied [39]. The charges of the two selected kaons must be identical and opposite to the charges of the two selected electrons, which are also required to be the same. The minimum number of kaons and electrons are two. If there are multiple candidates in an event, the combination with the smallest $\chi^2_{4\rm C}$ is retained for further analysis, where the $\chi^2_{4\rm C}$ is from a kinematic fit [40] enforcing four-momentum conservation (4C).

To suppress potential contamination from mis-PID in processes with the same charged multiplicity, we perform an additional 4C kinematic fit with the hypotheses of $e^+e^-\to K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$ and $\pi^+\pi^-\pi^+\pi^-$. By requiring that the $\chi^2_{4\rm C}$ of the $K^+K^+e^-e^-$ mass assignment is the smallest one among all possible assignments, such backgrounds can be effectively suppressed and only events with $\chi^2_{K^+K^+e^-e^-,4\rm C}<20$ are kept for further analysis. This requirement has been optimized with the Punzi significance [41] using the formula $\frac{\varepsilon}{1.5+\sqrt{b}}$, where ε is the detection efficiency from the signal MC simulation and b is the number of background events from the inclusive MC sample. Furthermore, the selected $K^+K^-e^+e^-$ and

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$\pi^+\pi^-e^+e^-$ combinations will be rejected if the e^+e^- pair comes from gamma conversions in the beam pipe.

The J/ψ signal region is defined as [3.07, 3.12] GeV/c^2, which corresponds to a range of three times of the mass resolution around the J/ψ mass [35]. The detection efficiency is determined to be 15.68% based on the simulated $J/\psi \to K^+K^+e^-e^-$ events.

With all above selections applied, only one event from data is left in the signal region as shown in Fig. 2, while no event survives from the inclusive MC sample. To investigate the potential contamination from continuum processes, we analyze the off-resonance data samples taken at $\sqrt{s} = 3.650$ GeV, 3.682 GeV and 3.080 GeV [38]. After considering the differences in integrated luminosities, cross sections, particle momenta, and center-of-mass energies, no event survives in the signal region, $N^{\rm continuum} = 0$. Thus, the total number of background events is calculated as $N^{\rm bkg} = N^{\rm inc} + N^{\rm continuum} = 0$.

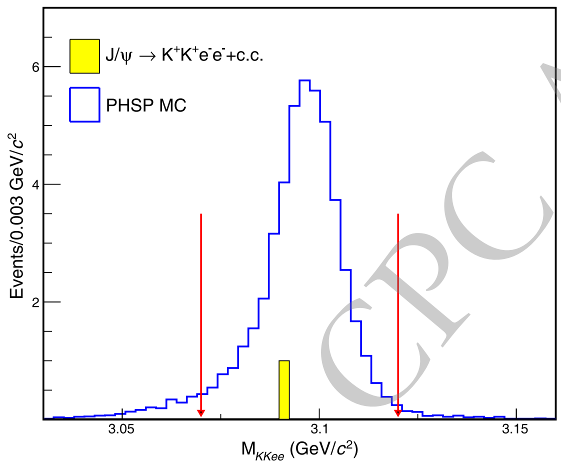

Fig. 2. (color online) The distribution of $M_{K^+K^+e^-e^-+c.c.}$, where the blue histogram represents the simulated shape of signal, the yellow filled histogram represents data, and the red arrows indicate the signal region.

IV. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in the measurement arise from the total number of J/ψ events, tracking, PID, kinematic fit, MC modeling, and signal region.

- The uncertainty in the total number of J/ψ events, determined using inclusive hadronic events, is 0.5% [26].

- The uncertainty in the MDC tracking is estimated by comparing efficiency between data and MC control samples of $J/\psi \to e^+e^-(\gamma_{\rm FSR})$ and $J/\psi \to \pi^0K^+K^-$. The resulting uncertainties are 0.7% per electron and 0.3% per kaon. Consequently, the total systematic uncertainty in the MDC tracking is 2.0%.

- The uncertainty in the PID is evaluated using the same high-purity control samples of electrons and kaons as mentioned above. The uncertainties are found to be 0.5% per electron and 0.6% per kaon, resulting in a total PID uncertainty of 2.2%.

- The systematic uncertainty from the 4C kinematic fit and the $\chi^2_{4C} < 20$ requirement is studied using a control sample of $J/\psi \to p\bar{p}\pi^+\pi^-$. The relative difference in efficiencies between data and MC simulation is found to be 6.2%, which is taken as the systematic uncertainty from this source.

- The systematic uncertainty associated with the signal region is also calculated using the control sample of $J/\psi \to p\bar{p}\pi^+\pi^-$. The relative difference in efficiencies, 0.4%, is taken as the uncertainty.

- The uncertainty due to the signal MC sample size is 0.9%.

- To obtain the systematic uncertainty from the MC modeling, we compare the difference of the detection efficiency between the PHSP generator and two alternative MC models, i.e., $J/\psi \to \nu_M K^+e^- \to (K^+e^-)K^+e^-$ and $J/\psi \to \nu_M\nu_M \to (K^+e^-)(K^+e^-)$, where the Majorana neutrino ν_M decays into K^+e^- with different Majorana masses and corresponding detection efficiencies. Possible Feynman diagrams are shown in Fig. 3. The Majorana neutrino mass is varied from the Ke mass threshold to the maximum phase space allowed by the J/ψ decay, approximately from 0.575 GeV/c^2 to 1.525 GeV/c^2, with an interval of 0.025 GeV/c^2. The largest efficiency difference, 1.0%, is taken as the systematic uncertainty.

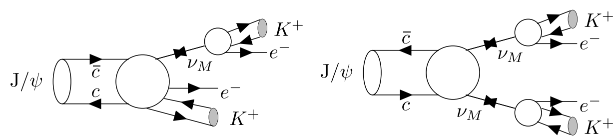

Fig. 3. A possible Feynman diagram for the decay process of $J/\psi \to \nu_M\nu_M \to (K^+e^-)(K^+e^-)$(left), and for the decay process of $J/\psi \to \nu_M K^+e^- \to (K^+e^-)K^+e^-$(right).

All the uncertainties are summarized in Table 1, and the total systematic uncertainty ($\Delta^{\rm sys}$) is obtained by adding the individual effects in quadrature.

V. RESULTS

A. Upper limit on $J/\psi \to K^+K^+e^-e^-$

One candidate event ($N^{\rm obs}$) is observed in the signal region, while zero background event ($N^{\rm bkg}$) is expected.

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Table 1. Summary of the systematic uncertainties.

Source	Uncertainty (%)
$N_{J/\psi}$	0.5
MDC tracking	2.0
PID	2.2
4C kinematic fit and χ^2 cut	6.2
signal region	0.4
MC statistics	0.9
MC modeling	1.0
Total $\Delta^{\rm sys}$	7.0

The efficiency-corrected upper limit (UL) on the signal yield $N^{\rm up}_{K^+K^+e^-e^-}$ is estimated to be 23.2 at the 90% CL using a frequentist method [42]. This estimation employs an unbounded profile likelihood approach to account for systematic uncertainties ($\Delta^{sys} = 7.0\%$), where both observed events ($N^{\rm obs} = 1$) and background events ($N^{bkg} = 0$) modeled by a Poisson distribution, the detection efficiency ($\varepsilon_{K^+K^+e^-e^-} = 15.83\%$) following a Gaussian distribution and the systematic uncertainty is taken as its standard deviation. The UL of the branching fraction (BF) of $J/\psi \to K^+K^+e^-e^-$ at the 90% CL is determined by

$$\mathcal{B}(J/\psi \to K^+K^+e^-e^-) < \mathcal{B}^{\rm UL}(J/\psi \to K^+K^+e^-e^-) = \frac{N^{\rm up}_{K^+K^+e^-e^-}}{N^{\rm tot}_{J/\psi}} = 2.1\times 10^{-9}, \quad (1)$$

where $N^{\rm tot}_{J/\psi} = (10087 \pm 44)\times 10^6$ is the total number of J/ψ events in data.

B. Majorana mass dependent upper limits

In addition to the overall UL, assuming the LNV signal from Majorana neutrino, we also investigate the ULs on the branching fractions of $J/\psi \to 2\nu_M \to (K^+e^-)(K^+e^-)$ with different Majorana masses. Full kinematic ranges of the Ke invariant mass (m_{Ke}) from the threshold to the largest phase space allowed in the J/ψ decay,

$$m_K + m_e \le m_{\nu_M} \le \frac{m_{J/\psi}}{2}, \quad (2)$$

is considered. We take the Majorana neutrino mass m_{ν_M} from 0.575 GeV/c^2 to 1.500 GeV/c^2 and divide this mass range into uniform intervals, with a width of 0.025 GeV/c^2. In each interval, the Majorana mass is taken as the center value. Due to extremely small phase space, the first three (0.500 GeV/c^2, 0.525GeV/c^2, and 0.550 GeV/c^2) are not selected as mass possibilities.

The values of the mass dependent detection efficiencies, the signal event counts, the background event counts, the total systematic uncertainties, and the ULs on the BFs at the 90% CL are reported in Table 2, for each m_{Ke} bin. The mass dependent ULs are calculated to be from [2.04, 0.92]×10^{-9} with the same method, and the results are shown in Fig. 4.

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Table 2. The mass dependent detection efficiencies(ϵ_i), the signal event counts($N_i^{\rm sig}$), the background event counts($N_i^{\rm bkg}$), the total systematic uncertainties ($\Delta_i^{\rm sys}$), and the ULs on the BFs at the 90% CL($\mathcal{B}^{\rm UL}$) for different Majorana mass hypotheses from 0.575 GeV/c^2 to 1.525 GeV/c^2 with an interval of 0.025 GeV/c^2.

m_{ν_M} (GeV/c^2)	$\varepsilon_{2\nu_M}$ (%)	$N_i^{\rm sig}$	$N_i^{\rm bkg}$	$\Delta_i^{\rm sys}$ (%)	$\mathcal{B}^{\rm UL}$ (10^{-9})
0.575	8.97	0	0	26.8	2.04
0.600	12.34	0	0	25.8	1.48
0.625	13.69	0	0	26.4	1.34
0.650	13.60	0	0	22.9	1.35
0.675	13.79	0	0	19.3	1.33
0.700	14.15	0	0	16.9	1.29
0.725	14.56	0	0	15.5	1.26
0.750	15.32	0	0	14.1	1.19
0.775	15.87	0	0	12.1	1.15
0.800	16.14	0	0	11.3	1.13
0.825	16.18	0	0	8.4	1.13
0.850	16.67	0	0	11.2	1.10
0.875	16.57	0	0	9.0	1.11
0.900	16.26	0	0	7.0	1.11

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Table 2-continued from previous page

m_{ν_M} (GeV/c^2)	$\varepsilon_{2\nu_M}$ (%)	$N_i^{\rm sig}$	$N_i^{\rm bkg}$	$\Delta_i^{\rm sys}$ (%)	$\mathcal{B}^{\rm UL}$ (10^{-9})
0.925	16.55	0	0	7.0	1.11
0.950	16.55	0	0	7.0	1.09
0.975	16.72	0	0	7.0	1.09
1.000	16.74	0	0	7.0	1.08
1.025	16.94	0	0	7.1	1.08
1.050	16.96	0	0	7.0	1.07
1.075	17.16	0	0	7.2	1.08
1.100	16.96	0	0	7.5	1.08
1.125	17.01	0	0	7.8	1.06
1.150	17.28	0	0	7.0	1.05
1.175	17.36	0	0	7.4	1.05
1.200	17.47	1	0	7.2	1.93
1.225	17.94	0	0	7.0	1.02
1.250	17.16	0	0	7.0	1.01
1.275	18.30	0	0	7.5	1.00
1.300	18.55	0	0	7.3	0.99
1.325	18.51	0	0	7.6	0.99
1.350	18.75	0	0	8.5	0.98
1.375	18.80	0	0	8.9	0.97
1.400	19.12	0	0	9.4	0.96
1.425	18.82	0	0	8.7	0.97
1.450	19.31	0	0	11.5	0.95
1.475	19.38	0	0	11.1	0.95
1.500	20.00	0	0	12.8	0.92
1.525	20.28	0	0	16.2	0.90

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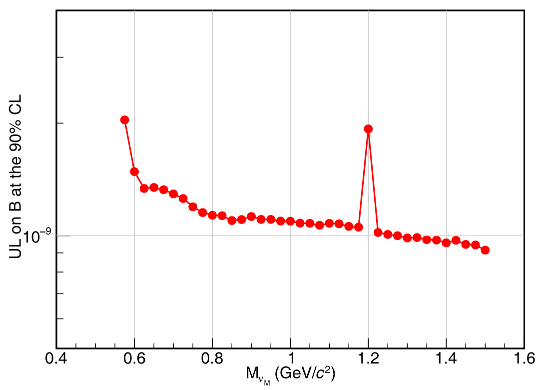

Fig. 4. The ULs at the 90% CL for the data sample as a function of m_{ν_M} for the decay $J/\psi \to 2\nu_M\ (\to K^+e^-)$.

VI. SUMMARY

In summary, by using $(10087\pm44)\times10^6$ J/ψ events collected by the BESIII detector, we search for the LNV decay $J/\psi \to K^+K^+e^-e^- + c.c.$ for the first time. One event survives in the signal region and the UL on the decay branching fraction of $J/\psi \to K^+K^+e^-e^- + c.c.$ is determined to be 2.1×10^{-9} at the 90% CL. The Majorana mass dependent ULs on the branching fractions at the 90% CL are estimated, varying within the range of [0.92, 2.04]$\times10^{-9}$. By utilizing these results, constraints on the mixed matrix element $|V_{e\nu_M}|^2$ between the Majorana neutrino and electron can be derived within the theoretical models.

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