

University of Groningen

Search for the lepton number violating decay $\Sigma^- \rightarrow pe^-e^-$ and the rare inclusive decay $\Sigma^- \rightarrow \Sigma^+ X$

BESIII Collaboration; Ablikim, M.; Achasov, M.N.; Adlarson, P.; Ahmed, S.; Albrecht, M.; Aliberti, R.; Amoroso, A.; Kalantar-Nayestanaki, Nasser; Kappert, Rosa

Published in:
Physical Review D

DOI:
[10.1103/PhysRevD.103.052011](https://doi.org/10.1103/PhysRevD.103.052011)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2021

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

BESIII Collaboration, Ablikim, M., Achasov, M. N., Adlarson, P., Ahmed, S., Albrecht, M., Aliberti, R., Amoroso, A., Kalantar-Nayestanaki, N., Kappert, R., Kayatsyuk, M., Messchendorp, J., & Rođin, V. (2021). Search for the lepton number violating decay $\Sigma^- \rightarrow pe^-e^-$ and the rare inclusive decay $\Sigma^- \rightarrow \Sigma^+ X$. *Physical Review D*, 103(5), Article 052011. <https://doi.org/10.1103/PhysRevD.103.052011>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

**Search for the lepton number violating decay $\Sigma^- \rightarrow pe^- e^-$
and the rare inclusive decay $\Sigma^- \rightarrow \Sigma^+ X$**

M. Ablikim,¹ M. N. Achasov,^{10,c} P. Adlarson,⁶⁷ S. Ahmed,¹⁵ M. Albrecht,⁴ R. Aliberti,²⁸ A. Amoroso,^{66a,66c} M. R. An,³² Q. An,^{63,49} X. H. Bai,⁵⁷ Y. Bai,⁴⁸ O. Bakina,²⁹ R. Baldini Ferroli,^{23a} I. Balossino,^{24a} Y. Ban,^{38,k} K. Begzsuren,²⁶ N. Berger,²⁸ M. Bertani,^{23a} D. Bettoni,^{24a} F. Bianchi,^{66a,66c} J. Bloms,⁶⁰ A. Bortone,^{66a,66c} I. Boyko,²⁹ R. A. Briere,⁵ H. Cai,⁶⁸ X. Cai,^{1,49} A. Calcaterra,^{23a} G. F. Cao,^{1,54} N. Cao,^{1,54} S. A. Cetin,^{53a} J. F. Chang,^{1,49} W. L. Chang,^{1,54} G. Chelkov,^{29,b} D. Y. Chen,⁶ G. Chen,¹ H. S. Chen,^{1,54} M. L. Chen,^{1,49} S. J. Chen,³⁵ X. R. Chen,²⁵ Y. B. Chen,^{1,49} Z. J. Chen,^{20,1} W. S. Cheng,^{66c} G. Cibinetto,^{24a} F. Cossio,^{66c} X. F. Cui,³⁶ H. L. Dai,^{1,49} X. C. Dai,^{1,54} A. Dbeyssi,¹⁵ R. E. de Boer,⁴ D. Dedovich,²⁹ Z. Y. Deng,¹ A. Denig,²⁸ I. Denysenko,²⁹ M. Destefanis,^{66a,66c} F. De Mori,^{66a,66c} Y. Ding,³³ C. Dong,³⁶ J. Dong,^{1,49} L. Y. Dong,^{1,54} M. Y. Dong,^{1,49,54} X. Dong,⁶⁸ S. X. Du,⁷¹ Y. L. Fan,⁶⁸ J. Fang,^{1,49} S. S. Fang,^{1,54} Y. Fang,¹ R. Farinelli,^{24a} L. Fava,^{66b,66c} F. Feldbauer,⁴ G. Felici,^{23a} C. Q. Feng,^{63,49} J. H. Feng,⁵⁰ M. Fritsch,⁴ C. D. Fu,¹ Y. Gao,^{63,49} Y. Gao,^{38,k} Y. Gao,⁶⁴ Y. G. Gao,⁶ I. Garzia,^{24a,24b} P. T. Ge,⁶⁸ C. Geng,⁵⁰ E. M. Gersabeck,⁵⁸ A. Gilman,⁶¹ K. Goetzen,¹¹ L. Gong,³³ W. X. Gong,^{1,49} W. Gradl,²⁸ M. Greco,^{66a,66c} L. M. Gu,³⁵ M. H. Gu,^{1,49} S. Gu,² Y. T. Gu,¹³ C. Y. Guan,^{1,54} A. Q. Guo,²² L. B. Guo,³⁴ R. P. Guo,⁴⁰ Y. P. Guo,^{9,h} A. Guskov,^{29,b} T. T. Han,⁴¹ W. Y. Han,³² X. Q. Hao,¹⁶ F. A. Harris,⁵⁶ K. L. He,^{1,54} F. H. Heinsius,⁴ C. H. Heinz,²⁸ T. Held,⁴ Y. K. Heng,^{1,49,54} C. Herold,⁵¹ M. Himmelreich,^{11,f} T. Holtmann,⁴ G. Y. Hou,^{1,54} Y. R. Hou,⁵⁴ Z. L. Hou,¹ H. M. Hu,^{1,54} J. F. Hu,^{47,m} T. Hu,^{1,49,54} Y. Hu,¹ G. S. Huang,^{63,49} L. Q. Huang,⁶⁴ X. T. Huang,⁴¹ Y. P. Huang,¹ Z. Huang,^{38,k} T. Hussain,⁶⁵ W. Ikegami Andersson,⁶⁷ W. Imoehl,²² M. Irshad,^{63,49} S. Jaeger,⁴ S. Janchiv,^{26,j} Q. Ji,¹ Q. P. Ji,¹⁶ X. B. Ji,^{1,54} X. L. Ji,^{1,49} Y. Y. Ji,⁴¹ H. B. Jiang,⁴¹ X. S. Jiang,^{1,49,54} J. B. Jiao,⁴¹ Z. Jiao,¹⁸ S. Jin,³⁵ Y. Jin,⁵⁷ M. Q. Jing,^{1,54} T. Johansson,⁶⁷ N. Kalantar-Nayestanaki,⁵⁵ X. S. Kang,³³ R. Kappert,⁵⁵ M. Kavatsyuk,⁵⁵ B. C. Ke,^{43,1} I. K. Keshk,⁴ A. Khoukaz,⁶⁰ P. Kiese,²⁸ R. Kiuchi,¹ R. Kliemt,¹¹ L. Koch,³⁰ O. B. Kolcu,^{53a,e} B. Kopf,⁴ M. Kuemmel,⁴ M. Kuessner,⁴ A. Kupsc,⁶⁷ M. G. Kurth,^{1,54} W. Kühn,³⁰ J. J. Lane,⁵⁸ J. S. Lange,³⁰ P. Larin,¹⁵ A. Lavanaia,²¹ L. Lavezzi,^{66a,66c} Z. H. Lei,^{63,49} H. Leithoff,²⁸ M. Lellmann,²⁸ T. Lenz,²⁸ C. Li,³⁹ C. H. Li,³² Cheng Li,^{63,49} D. M. Li,⁷¹ F. Li,^{1,49} G. Li,¹ H. Li,^{63,49} H. Li,⁴³ H. B. Li,^{1,54} H. J. Li,¹⁶ J. L. Li,⁴¹ J. Q. Li,⁴ J. S. Li,⁵⁰ Ke Li,¹ L. K. Li,¹ Lei Li,³ P. R. Li,³¹ S. Y. Li,⁵² W. D. Li,^{1,54} W. G. Li,¹ X. H. Li,^{63,49} X. L. Li,⁴¹ Xiaoyu Li,^{1,54} Z. Y. Li,⁵⁰ H. Liang,^{63,49} H. Liang,^{1,54} H. Liang,²⁷ Y. F. Liang,⁴⁵ Y. T. Liang,²⁵ G. R. Liao,¹² L. Z. Liao,^{1,54} J. Libby,²¹ C. X. Lin,⁵⁰ B. J. Liu,¹ C. X. Liu,¹ D. Liu,^{15,63} F. H. Liu,⁴⁴ Fang Liu,¹ Feng Liu,⁶ H. B. Liu,¹³ H. M. Liu,^{1,54} Huanhuan Liu,¹ Huihui Liu,¹⁷ J. B. Liu,^{63,49} J. L. Liu,⁶⁴ J. Y. Liu,^{1,54} K. Liu,¹ K. Y. Liu,³³ L. Liu,^{63,49} M. H. Liu,^{9,h} P. L. Liu,¹ Q. Liu,⁶⁸ Q. Liu,⁵⁴ S. B. Liu,^{63,49} Shuai Liu,⁴⁶ T. Liu,^{1,54} W. M. Liu,^{63,49} X. Liu,³¹ Y. Liu,³¹ Y. B. Liu,³⁶ Z. A. Liu,^{1,49,54} Z. Q. Liu,⁴¹ X. C. Lou,^{1,49,54} F. X. Lu,⁵⁰ H. J. Lu,¹⁸ J. D. Lu,^{1,54} J. G. Lu,^{1,49} X. L. Lu,¹ Y. Lu,¹ Y. P. Lu,^{1,49} C. L. Luo,³⁴ M. X. Luo,⁷⁰ P. W. Luo,⁵⁰ T. Luo,^{9,h} X. L. Luo,^{1,49} X. R. Lyu,⁵⁴ F. C. Ma,³³ H. L. Ma,¹ L. L. Ma,⁴¹ M. M. Ma,^{1,54} Q. M. Ma,¹ R. Q. Ma,^{1,54} R. T. Ma,⁵⁴ X. X. Ma,^{1,54} X. Y. Ma,^{1,49} F. E. Maas,¹⁵ M. Maggiora,^{66a,66c} S. Maldaner,⁴ S. Malde,⁶¹ Q. A. Malik,⁶⁵ A. Mangoni,^{23b} Y. J. Mao,^{38,k} Z. P. Mao,¹ S. Marcello,^{66a,66c} Z. X. Meng,⁵⁷ J. G. Messchendorp,⁵⁵ G. Mezzadri,^{24a} T. J. Min,³⁵ R. E. Mitchell,²² X. H. Mo,^{1,49,54} Y. J. Mo,⁶ N. Yu. Muchnoi,^{10,c} H. Muramatsu,⁵⁹ S. Nakhoul,^{11,f} Y. Nefedov,²⁹ F. Nerling,^{11,f} I. B. Nikolaev,^{10,c} Z. Ning,^{1,49} S. Nisar,^{8,i} S. L. Olsen,⁵⁴ Q. Ouyang,^{1,49,54} S. Pacetti,^{23b,23c} X. Pan,^{9,h} Y. Pan,⁵⁸ A. Pathak,¹ P. Patteri,^{23a} M. Pelizaeus,⁴ H. P. Peng,^{63,49} K. Peters,^{11,f} J. Pettersson,⁶⁷ J. L. Ping,³⁴ R. G. Ping,^{1,54} R. Poling,⁵⁹ V. Prasad,^{63,49} H. Qi,^{63,49} H. R. Qi,⁵² K. H. Qi,²⁵ M. Qi,³⁵ T. Y. Qi,⁹ S. Qian,^{1,49} W. B. Qian,⁵⁴ Z. Qian,⁵⁰ C. F. Qiao,⁵⁴ L. Q. Qin,¹² X. P. Qin,⁹ X. S. Qin,⁴¹ Z. H. Qin,^{1,49} J. F. Qiu,¹ S. Q. Qu,³⁶ K. H. Rashid,⁶⁵ K. Ravindran,²¹ C. F. Redmer,²⁸ A. Rivetti,^{66c} V. Rodin,⁵⁵ M. Rolo,^{66c} G. Rong,^{1,54} Ch. Rosner,¹⁵ M. Rump,⁶⁰ H. S. Sang,⁶³ A. Sarantsev,^{29,d} Y. Schelhaas,²⁸ C. Schnier,⁴ K. Schoenning,⁶⁷ M. Scodreggio,^{24a,24b} D. C. Shan,⁴⁶ W. Shan,¹⁹ X. Y. Shan,^{63,49} J. F. Shangguan,⁴⁶ M. Shao,^{63,49} C. P. Shen,⁹ H. F. Shen,^{1,54} P. X. Shen,³⁶ X. Y. Shen,^{1,54} H. C. Shi,^{63,49} R. S. Shi,^{1,54} X. Shi,^{1,49} X. D. Shi,^{63,49} J. J. Song,⁴¹ W. M. Song,^{27,1} Y. X. Song,^{38,k} S. Sosio,^{66a,66c} S. Spataro,^{66a,66c} K. X. Su,⁶⁸ P. P. Su,⁴⁶ F. F. Sui,⁴¹ G. X. Sun,¹ H. K. Sun,¹ J. F. Sun,¹⁶ L. Sun,⁶⁸ S. S. Sun,^{1,54} T. Sun,^{1,54} W. Y. Sun,²⁷ W. Y. Sun,³⁴ X. Sun,^{20,1} Y. J. Sun,^{63,49} Y. K. Sun,^{63,49} Y. Z. Sun,¹ Z. T. Sun,¹ Y. H. Tan,⁶⁸ Y. X. Tan,^{63,49} C. J. Tang,⁴⁵ G. Y. Tang,¹ J. Tang,⁵⁰ J. X. Teng,^{63,49} V. Thoren,⁶⁷ W. H. Tian,⁴³ Y. T. Tian,²⁵ I. Uman,^{53b} B. Wang,¹ C. W. Wang,³⁵ D. Y. Wang,^{38,k} H. J. Wang,³¹ H. P. Wang,^{1,54} K. Wang,^{1,49} L. L. Wang,¹ M. Wang,⁴¹ M. Z. Wang,^{38,k} Meng Wang,^{1,54} W. Wang,⁵⁰ W. H. Wang,⁶⁸ W. P. Wang,^{63,49} X. Wang,^{38,k} X. F. Wang,³¹ X. L. Wang,^{9,h} Y. Wang,⁵⁰ Y. Wang,^{63,49} Y. D. Wang,³⁷ Y. F. Wang,^{1,49,54} Y. Q. Wang,¹ Y. Y. Wang,³¹ Z. Wang,^{1,49} Z. Y. Wang,¹ Ziyi Wang,⁵⁴ Zongyuan Wang,^{1,54} D. H. Wei,¹² F. Weidner,⁶⁰ S. P. Wen,¹ D. J. White,⁵⁸ U. Wiedner,⁴ G. Wilkinson,⁶¹ M. Wolke,⁶⁷ L. Wollenberg,⁴ J. F. Wu,^{1,54} L. H. Wu,¹ L. J. Wu,^{1,54} X. Wu,^{9,h} Z. Wu,^{1,49} L. Xia,^{63,49} H. Xiao,^{9,h} S. Y. Xiao,¹ Z. J. Xiao,³⁴ X. H. Xie,^{38,k} Y. G. Xie,^{1,49} Y. H. Xie,⁶ T. Y. Xing,^{1,54} G. F. Xu,¹ Q. J. Xu,¹⁴ W. Xu,^{1,54} X. P. Xu,⁴⁶ Y. C. Xu,⁵⁴ F. Yan,^{9,h} L. Yan,^{9,h} W. B. Yan,^{63,49} W. C. Yan,⁷¹ Xu Yan,⁴⁶ H. J. Yang,^{42,g} H. X. Yang,¹ L. Yang,⁴³ S. L. Yang,⁵⁴ Y. X. Yang,¹² Yifan Yang,^{1,54} Zhi Yang,²⁵ M. Ye,^{1,49} M. H. Ye,⁷ J. H. Yin,¹ Z. Y. You,⁵⁰ B. X. Yu,^{1,49,54} C. X. Yu,³⁶ G. Yu,^{1,54} J. S. Yu,^{20,1} T. Yu,⁶⁴ C. Z. Yuan,^{1,54} L. Yuan,² X. Q. Yuan,^{38,k} Y. Yuan,¹ Z. Y. Yuan,⁵⁰ C. X. Yue,³² A. Yuncu,^{53a,a} A. A. Zafar,⁶⁵ Zeng,⁶

Y. Zeng,^{20,1} A. Q. Zhang,¹ B. X. Zhang,¹ Guangyi Zhang,¹⁶ H. Zhang,⁶³ H. H. Zhang,²⁷ H. H. Zhang,⁵⁰ H. Y. Zhang,^{1,49}
 J. J. Zhang,⁴³ J. L. Zhang,⁶⁹ J. Q. Zhang,³⁴ J. W. Zhang,^{1,49,54} J. Y. Zhang,¹ J. Z. Zhang,^{1,54} Jianyu Zhang,^{1,54}
 Jiawei Zhang,^{1,54} L. M. Zhang,⁵² L. Q. Zhang,⁵⁰ Lei Zhang,³⁵ S. Zhang,⁵⁰ S. F. Zhang,³⁵ Shulei Zhang,^{20,1} X. D. Zhang,³⁷
 X. Y. Zhang,⁴¹ Y. Zhang,⁶¹ Y. H. Zhang,^{1,49} Y. T. Zhang,^{63,49} Yan Zhang,^{63,49} Yao Zhang,¹ Yi Zhang,^{9,h} Z. H. Zhang,⁶
 Z. Y. Zhang,⁶⁸ G. Zhao,¹ J. Zhao,³² J. Y. Zhao,^{1,54} J. Z. Zhao,^{1,49} Lei Zhao,^{63,49} Ling Zhao,¹ M. G. Zhao,³⁶ Q. Zhao,¹
 S. J. Zhao,^{7,i} Y. B. Zhao,^{1,49} Y. X. Zhao,²⁵ Z. G. Zhao,^{63,49} A. Zhemchugov,^{29,b} B. Zheng,⁶⁴ J. P. Zheng,^{1,49} Y. Zheng,^{38,k}
 Y. H. Zheng,⁵⁴ B. Zhong,³⁴ C. Zhong,⁶⁴ L. P. Zhou,^{1,54} Q. Zhou,^{1,54} X. Zhou,⁶⁸ X. K. Zhou,⁵⁴ X. R. Zhou,^{63,49} X. Y. Zhou,³²
 A. N. Zhu,^{1,54} J. Zhu,³⁶ K. Zhu,¹ K. J. Zhu,^{1,49,54} S. H. Zhu,⁶² T. J. Zhu,⁶⁹ W. J. Zhu,^{9,h} W. J. Zhu,³⁶ Y. C. Zhu,^{63,49}
 Z. A. Zhu,^{1,54} B. S. Zou,¹ and J. H. Zou¹

(BESIII Collaboration)

¹*Institute of High Energy Physics, Beijing 100049, People's Republic of China*

²*Beihang University, Beijing 100191, People's Republic of China*

³*Beijing Institute of Petrochemical Technology, Beijing 102617, People's Republic of China*

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

⁵*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*

⁶*Central China Normal University, Wuhan 430079, People's Republic of China*

⁷*China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China*

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

⁹*Fudan University, Shanghai 200443, People's Republic of China*

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

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

¹²*Guangxi Normal University, Guilin 541004, People's Republic of China*

¹³*Guangxi University, Nanning 530004, People's Republic of China*

¹⁴*Hangzhou Normal University, Hangzhou 310036, People's Republic of China*

¹⁵*Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany*

¹⁶*Henan Normal University, Xixiang 453007, People's Republic of China*

¹⁷*Henan University of Science and Technology, Luoyang 471003, People's Republic of China*

¹⁸*Huangshan College, Huangshan 245000, People's Republic of China*

¹⁹*Hunan Normal University, Changsha 410081, People's Republic of China*

²⁰*Hunan University, Changsha 410082, People's Republic of China*

²¹*Indian Institute of Technology Madras, Chennai 600036, India*

²²*Indiana University, Bloomington, Indiana 47405, USA*

^{23a}*INFN Laboratori Nazionali di Frascati, INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*

^{23b}*INFN Laboratori Nazionali di Frascati, INFN Sezione di Perugia, I-06100 Perugia, Italy*

^{23c}*INFN Laboratori Nazionali di Frascati, University of Perugia, I-06100 Perugia, Italy*

^{24a}*INFN Sezione di Ferrara, INFN Sezione di Ferrara, I-44122 Ferrara, Italy*

^{24b}*INFN Sezione di Ferrara, University of Ferrara, I-44122 Ferrara, Italy*

²⁵*Institute of Modern Physics, Lanzhou 730000, People's Republic of China*

²⁶*Institute of Physics and Technology, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia*

²⁷*Jilin University, Changchun 130012, People's Republic of China*

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

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

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

³¹*Lanzhou University, Lanzhou 730000, People's Republic of China*

³²*Liaoning Normal University, Dalian 116029, People's Republic of China*

³³*Liaoning University, Shenyang 110036, People's Republic of China*

³⁴*Nanjing Normal University, Nanjing 210023, People's Republic of China*

³⁵*Nanjing University, Nanjing 210093, People's Republic of China*

³⁶*Nankai University, Tianjin 300071, People's Republic of China*

³⁷*North China Electric Power University, Beijing 102206, People's Republic of China*

³⁸*Peking University, Beijing 100871, People's Republic of China*

³⁹*Qufu Normal University, Qufu 273165, People's Republic of China*

⁴⁰*Shandong Normal University, Jinan 250014, People's Republic of China*

⁴¹*Shandong University, Jinan 250100, People's Republic of China*

⁴²*Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*

- ⁴³*Shanxi Normal University, Linfen 041004, People's Republic of China*
⁴⁴*Shanxi University, Taiyuan 030006, People's Republic of China*
⁴⁵*Sichuan University, Chengdu 610064, People's Republic of China*
⁴⁶*Soochow University, Suzhou 215006, People's Republic of China*
⁴⁷*South China Normal University, Guangzhou 510006, People's Republic of China*
⁴⁸*Southeast University, Nanjing 211100, People's Republic of China*
⁴⁹*State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China*
⁵⁰*Sun Yat-Sen University, Guangzhou 510275, People's Republic of China*
⁵¹*Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand*
⁵²*Tsinghua University, Beijing 100084, People's Republic of China*
^{53a}*Turkish Accelerator Center Particle Factory Group, Istanbul Bilgi University, 34060 Eyup, Istanbul, Turkey*
^{53b}*Turkish Accelerator Center Particle Factory Group, Near East University, Nicosia, North Cyprus, Mersin 10, Turkey*
⁵⁴*University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
⁵⁵*University of Groningen, NL-9747 AA Groningen, Netherlands*
⁵⁶*University of Hawaii, Honolulu, Hawaii 96822, USA*
⁵⁷*University of Jinan, Jinan 250022, People's Republic of China*
⁵⁸*University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom*
⁵⁹*University of Minnesota, Minneapolis, Minnesota 55455, USA*
⁶⁰*University of Muenster, Wilhelm-Klemm Street 9, 48149 Muenster, Germany*
⁶¹*University of Oxford, Keble Rd, Oxford OX13RH, United Kingdom*
⁶²*University of Science and Technology Liaoning, Anshan 114051, People's Republic of China*
⁶³*University of Science and Technology of China, Hefei 230026, People's Republic of China*
⁶⁴*University of South China, Hengyang 421001, People's Republic of China*
⁶⁵*University of the Punjab, Lahore-54590, Pakistan*
^{66a}*University of Turin and INFN, University of Turin, I-10125 Turin, Italy*
^{66b}*University of Turin and INFN, University of Eastern Piedmont, I-15121 Alessandria, Italy*
^{66c}*University of Turin and INFN, INFN, I-10125 Turin, Italy*
⁶⁷*Uppsala University, Box 516, SE-75120 Uppsala, Sweden*
⁶⁸*Wuhan University, Wuhan 430072, People's Republic of China*
⁶⁹*Xinyang Normal University, Xinyang 464000, People's Republic of China*
⁷⁰*Zhejiang University, Hangzhou 310027, People's Republic of China*
⁷¹*Zhengzhou University, Zhengzhou 450001, People's Republic of China*



(Received 8 December 2020; accepted 2 February 2021; published 24 March 2021)

Using a data sample of $(1310.6 \pm 7.0) \times 10^6$ J/ψ events taken with the BESIII detector at the center-of-mass energy of 3.097 GeV, we search for the first time for the lepton number violating decay $\Sigma^- \rightarrow pe^-e^-$ and the rare inclusive decay $\Sigma^- \rightarrow \Sigma^+X$, where X denotes any possible particle combination. The Σ^-

^aAlso at Bogazici University, 34342 Istanbul, Turkey.

^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 Istanbul Arel University, 34295 Istanbul, Turkey.

^fAlso at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.

^gAlso 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.

^hAlso at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, People's Republic of China.

ⁱAlso at Harvard University, Department of Physics, Cambridge, Massachusetts 02138, USA.

^jPresent address: Institute of Physics and Technology, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia.

^kAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China.

^lSchool of Physics and Electronics, Hunan University, Changsha 410082, China.

^mAlso at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China.

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

candidates are tagged in $J/\psi \rightarrow \bar{\Sigma}(1385)^+\Sigma^-$ decays. No signal candidates are found, and the upper limits on the branching fractions at the 90% confidence level are determined to be $\mathcal{B}(\Sigma^- \rightarrow pe^-e^-) < 6.7 \times 10^{-5}$ and $\mathcal{B}(\Sigma^- \rightarrow \Sigma^+X) < 1.2 \times 10^{-4}$.

DOI: 10.1103/PhysRevD.103.052011

I. INTRODUCTION

In the Standard Model (SM) [1–3] of particle physics, lepton number conservation is associated with a global $U(1)_L$ symmetry. In addition, under the postulate of massless neutrinos, $U(1)_e \times U(1)_\mu \times U(1)_\tau$ is an automatic global symmetry, which means that individual lepton-flavor numbers— e , μ , and τ number—are expected to be conserved. However, the discoveries of neutrino oscillations [4–7], the matter antimatter asymmetry of the Universe [8–11] and the existence of dark matter [12–14] require new physics theories beyond the SM. New physics models of nonzero neutrino masses predict neutrinos to be Dirac or Majorana fermions [15–18]. If neutrinos are Dirac fermions, $U(1)_L$ may remain as an exact global symmetry. However, if neutrinos are Majorana fermions, $U(1)_L$ is not a good global symmetry. Currently, we cannot distinguish whether neutrinos are Dirac fermions or Majorana fermions. Hence, it is important to investigate the validity of lepton-number conservation directly. Observation of lepton number violating (LNV) processes would explicitly point out the direction of new physics, while experimental upper limits (ULs) could translate into stringent conditions for theoretical models.

A number of experiments have searched for LNV in meson decays [19], while only a few experiments have reported searches in hyperon decays [20,21]. The LNV decay of $B_1^- \rightarrow B_2^+ l^- l^-$ (B = baryon; $l = e, \mu$) is a unique process, in which two down-type (d or s) quarks convert into two up-quarks changing the charge of the hyperons according to the $\Delta Q = \Delta L = 2$ rule, where ΔQ and ΔL are the changes of charge number and lepton number, respectively. The transition of the quarks is assumed to occur at the same space-time location, as shown in Fig. 1, and is determined by local four-quark operators [22–24]. The underlying mechanism is similar to that of neutrinoless double beta ($0\nu\beta\beta$)

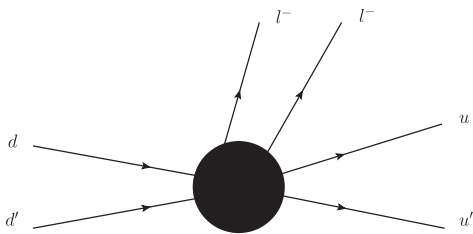


FIG. 1. Typical Feynman diagram for $B_1^- \rightarrow B_2^+ l^- l^-$ ($l = e, \mu$), in which two down type quarks convert into two up type quarks and two leptons.

nuclear decay $(A, Z) \rightarrow (A, Z + 2)e^-e^-$, which is a sensitive probe in the search for the effects of very light Majorana neutrinos [25,26]. In Refs. [22,23], based on a model where the dominant contributions are given by a loop of a virtual baryon and a Majorana neutrino, as shown in Fig. 2, the predicted branching fractions of $\Sigma^- \rightarrow pe^-e^-$ and $\Sigma^- \rightarrow \Sigma^+e^-e^-$, can reach 10^{-31} and 10^{-35} , respectively. While in Ref. [24], based on the Massachusetts Institute of Technology bag model [27,28], the branching fractions are increased by several orders of magnitude, and, for example, the branching fraction of $\Sigma^- \rightarrow pe^-e^-$ can reach 10^{-23} .

In this paper, using the process $J/\psi \rightarrow \bar{\Sigma}(1385)^+\Sigma^-$ [19] from the data sample of $(1310.6 \pm 7.0) \times 10^6$ J/ψ events [29–31] collected with the BESIII detector, we present the first search for the $\Delta Q = \Delta L = 2$ process in Σ^- decays. In the channel $\Sigma^- \rightarrow \Sigma^+e^-e^-$, due to the limited phase space ($M_{\Sigma^-} - M_{\Sigma^+} \simeq 8$ MeV/ c^2) and the small momentum of the Σ^- , the leptons have very small momenta and cannot be reconstructed in the detector. Therefore, the processes investigated in this analysis are $\Sigma^- \rightarrow pe^-e^-$ and the rare inclusive decay $\Sigma^- \rightarrow \Sigma^+X$, where X represents any particles or particle combinations, including e^-e^- . Throughout this paper, the charge conjugate channels $\bar{\Sigma}^+ \rightarrow \bar{p}e^+e^+$ and $\bar{\Sigma}^+ \rightarrow \bar{\Sigma}^-\bar{X}$ are investigated at the same time. It is important to note that the blind analysis method is used in this paper. The Monte Carlo sample is used to determine the analysis strategy. Then, with fixed strategy, the data sample is opened to obtain the final results.

II. BESIII DETECTOR AND MONTE CARLO SIMULATIONS

The BESIII detector is a magnetic spectrometer [32] located at the Beijing Electron Positron Collider (BEPCII) [33]. The cylindrical core of the BESIII detector consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed

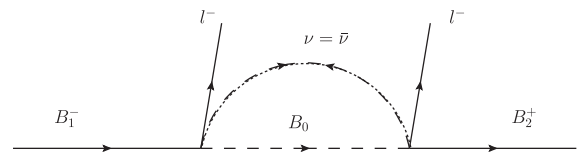


FIG. 2. Feynman diagram for $B_1^- \rightarrow B_2^+ l^- l^-$ ($l = e, \mu$), where a loop of a virtual baryon, B_0 , and a Majorana neutrino, ν , is introduced.

in a superconducting solenoidal magnet providing a 1.0 T (0.9 T in 2012) magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The acceptance of charged particles and photons is 93% over 4π solid angle. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for the 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 of the TOF barrel part is 68 ps, while that of the end cap part is 110 ps.

Simulated samples produced with the GEANT4-based [34] Monte Carlo (MC) software, which includes the geometric description of the BESIII detector and the detector response, are used to determine the detection efficiency and to estimate the backgrounds. The simulation includes the beam energy spread and initial state radiation (ISR) in the e^+e^- annihilations modeled with the generator KKMC [35,36].

The inclusive MC sample consists of the production of the J/ψ resonance, and the continuum processes ($e^+e^- \rightarrow q\bar{q}$) incorporated in KKMC [35,36]. The known decay modes of J/ψ are modeled with EvtGen [37,38] using branching fractions taken from the Particle Data Group [19], and the remaining unknown decays from the charmonium states with LundCharm [39,40]. The final state radiation from charged final state particles are incorporated with the PHOTOS [41] package.

III. EVENT SELECTION

In this paper, the Σ^- data sample is obtained through the process $J/\psi \rightarrow \bar{\Sigma}(1385)^+\Sigma^-$. A double-tag method, which was developed by the MARK-III experiment [42], is employed to determine the absolute branching fraction and reduce the systematic uncertainties. First, we reconstruct $\bar{\Sigma}(1385)^+$ via the decay $\bar{\Sigma}(1385)^+ \rightarrow \bar{\Lambda}\pi^+$ and then determine the number of Σ^- events in the recoil mass spectrum of the $\bar{\Sigma}(1385)^+$, which is defined in Eq. (2). These events are referred to as ‘‘single tag’’ (ST) events. Next, we search for signal candidates in the selected Σ^- sample by looking directly for their decay products. Events with signal candidates are called ‘‘double tag’’ (DT) events. The absolute branching fraction is calculated by

$$\mathcal{B}_{\text{sig}} = \frac{N_{\text{DT}}^{\text{obs}}}{N_{\text{ST}}^{\text{obs}} \epsilon_{\text{DT}} / \epsilon_{\text{ST}}}, \quad (1)$$

where $N_{\text{ST}}^{\text{obs}}$ is the ST yield, $N_{\text{DT}}^{\text{obs}}$ is the DT yield, ϵ_{ST} and ϵ_{DT} are the ST and the DT efficiencies.

A. ST event selection

In the selection of ST events, $\bar{\Sigma}(1385)^+$ is reconstructed via the $\bar{\Sigma}(1385)^+ \rightarrow \bar{\Lambda}\pi^+$ decay. All charged tracks are

required to have a polar angle within $|\cos\theta| < 0.93$. The $\bar{\Lambda}$ is reconstructed via $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ decay. Each track used to reconstruct $\bar{\Lambda}$ is required to have a distance of closest approach to the interaction point (IP) along the beam direction less than 20 cm, while the bachelor pion candidates are required to have a distance of closest approach to the IP less than 1 cm in the plane perpendicular to the beam and less than 10 cm along the beam direction. The values of 20 cm, 1 cm and 10 cm are based on track performance study.

We perform particle identification (PID) on the charged tracks with the information of dE/dx measured in the MDC and the time of flight measured by the TOF. The confidence levels (CLs) for the pion, kaon, and proton hypotheses (CL_π , CL_K , and CL_p) are calculated. The anti-proton candidates are required to satisfy $CL_p > 0.001$, $CL_p > CL_\pi$, and $CL_p > CL_K$. The bachelor pion candidates are required to satisfy $CL_\pi > 0.001$ and $CL_\pi > CL_K$, while there is no PID requirement for the pion from $\bar{\Lambda}$ decay.

The two charged tracks used to reconstruct $\bar{\Lambda}$ are constrained to originate from a common decay vertex by performing a primary vertex fit on the two tracks. The χ^2_1 , which represents the goodness of the primary vertex fit, is required to be less than 100. A secondary vertex fit is also performed on the same daughter tracks of $\bar{\Lambda}$ candidates, imposing the additional constraint that the momentum of the candidate points back to the IP. The χ^2_2 of the secondary vertex fit is required to be less than 100. The two values of χ^2 requirements result in high quality vertex fits. To further suppress non- $\bar{\Lambda}$ background, the decay length of $\bar{\Lambda}$, which is the distance between the IP and the secondary vertex, is required to be larger than 2 standard deviations of the decay length. The fitted four-momentum of the $\bar{p}\pi^+$ combination is used in further analysis, and the invariant mass of the $\bar{p}\pi^+$ combination is required to be within (1.112, 1.120) GeV/c².

The recoil mass of $\bar{\Sigma}(1385)^+$ is defined as

$$M_{\text{recoil}} = \sqrt{(E_{J/\psi} - E_{\bar{\Lambda}} - E_{\pi^+})^2 - (\vec{\mathbf{p}}_{J/\psi} - \vec{\mathbf{p}}_{\bar{\Lambda}} - \vec{\mathbf{p}}_{\pi^+})^2}, \quad (2)$$

where, $E_{J/\psi}(\vec{\mathbf{p}}_{J/\psi})$, $E_{\bar{\Lambda}}(\vec{\mathbf{p}}_{\bar{\Lambda}})$ and $E_{\pi^+}(\vec{\mathbf{p}}_{\pi^+})$ are the energies (momenta) of J/ψ , $\bar{\Lambda}$ and π^+ in the J/ψ 's center-of-mass frame. To suppress backgrounds, such as $J/\psi \rightarrow \bar{\Sigma}(1385)^+\Sigma(1385)^-$, the sum of $E_{\bar{\Lambda}}$ and E_{π^+} is required to be within (1.59, 1.70) GeV.

All $\bar{\Sigma}(1385)^+$ candidates in an event are retained. We then fit the M_{recoil} distribution to obtain the ST yield. Figure 3 shows the fit to the M_{recoil} distribution of data. In the fit, the background is described by a second order Chebychev polynomial function, and the signal shape is modeled by MC simulated shape convolved with a Gaussian function to

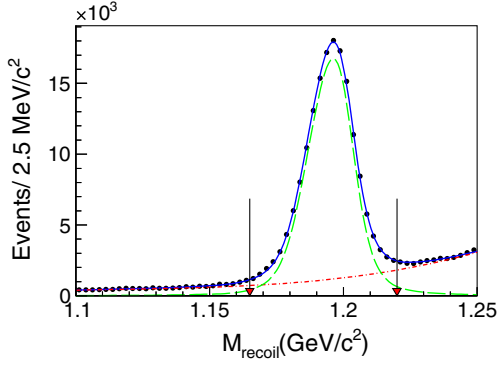


FIG. 3. Fit to the M_{recoil} distribution of ST events in data. Points with error bars represent data. The solid blue line is the total fit, the green line is the signal shape and the red line is the background component. The arrows denote the M_{recoil} signal region.

account for the resolution difference between data and MC simulation. The mean and the width of the Gaussian function are additional free parameters in the fit. The ST efficiency obtained from MC simulations is $(31.59 \pm 0.09)\%$. With the ST yield returned by the fit, $N_{\text{ST}} = 147743 \pm 563$, we obtain $\mathcal{B}(J/\psi \rightarrow \bar{\Sigma}(1385)^+\Sigma^-) = (3.21 \pm 0.07) \times 10^{-4}$, where the uncertainty is statistical only. This branching fraction is compatible with the world average value taken from the PDG [19], $(3.1 \pm 0.5) \times 10^{-4}$, within the large uncertainties of the world average.

B. DT event selection

In the recoil side of the selected ST events, we search for the LNV process $\Sigma^- \rightarrow pe^-e^-$ and the rare inclusive decay $\Sigma^- \rightarrow \Sigma^+X$, using the charged tracks and electromagnetic showers not used previously. Each charged track is also required to have a polar angle within $|\cos\theta| < 0.93$ and a distance of closest approach to the interaction IP along the beam direction less than 20 cm. The momentum of the Σ^- is small and the phase space in $\Sigma^- \rightarrow \Sigma^+X$ is extremely small like that in $\Sigma^- \rightarrow \Sigma^+e^-e^-$ due to the small difference in the Σ^\pm masses. Therefore the momenta of particles in the $\Sigma^- \rightarrow \Sigma^+X$ decay, except for Σ^+ reconstructed via $\Sigma^+ \rightarrow p\pi^0$, are too small to reach the MDC and other detectors. So only three charged tracks are required for $\Sigma^- \rightarrow pe^-e^-$ and one charged track for $\Sigma^- \rightarrow \Sigma^+X$.

Proton PID is performed as above. Electron PID is performed using the dE/dx , TOF, and EMC information, with which the CLs for electron, pion and kaon hypotheses (CL_e , CL_π , and CL_K) are calculated. Electron candidates are required to satisfy $CL_e > 0.001$ and $CL_e/(CL_e + CL_\pi + CL_K) > 0.8$.

Electromagnetic showers are reconstructed from clusters of energy deposited in the EMC. The photon candidate showers must have a minimum energy of 25 MeV in the barrel region ($|\cos\theta| < 0.80$) or 50 MeV in the end cap regions ($0.86 < |\cos\theta| < 0.92$). To suppress electronic

noise and energy deposits unrelated to the event, timing information from the EMC for the photon candidates must be in coincidence with collision events, with a requirement of $0 \leq t \leq 700$ ns. The π^0 candidates are reconstructed from pairs of photon candidates. Due to the worse resolution in the end cap regions of the EMC, π^0 candidates reconstructed with both photons in the end caps of the EMC are rejected. The invariant mass of two photons is required to be within $(0.115, 0.150)$ GeV/c^2 for π^0 candidates. To improve the overall kinematic resolution, a mass-constraint kinematic fit is performed by constraining the $\gamma\gamma$ invariant mass to the nominal π^0 mass [19]. When multiple π^0 candidates are reconstructed, we retain the one with the smallest χ^2 of the mass-constraint kinematic fit.

Furthermore, we require the pe^-e^- invariant mass to be within $(1.169, 1.209)$ GeV/c^2 and the $p\pi^0$ invariant mass to be within $(1.167, 1.201)$ GeV/c^2 . For the $\Sigma^- \rightarrow \Sigma^+X$ channel, to further suppress background, one additional kinematic variable is defined as

$$\vec{\mathbf{p}}_{\text{miss}} = \vec{\mathbf{p}}_{J/\psi} - \vec{\mathbf{p}}_{\bar{\Lambda}} - \vec{\mathbf{p}}_{\pi^+} - \vec{\mathbf{p}}_{\Sigma^+}, \quad (3)$$

where $\vec{\mathbf{p}}$ are the corresponding momenta in the J/ψ 's center-of-mass system, and $|\vec{\mathbf{p}}_{\text{miss}}|$ is required to be less than 0.1 GeV/c .

Since the X particles are not detected, the DT efficiency of $\Sigma^- \rightarrow \Sigma^+X$ is only affected by the reconstruction of the p and π^0 from the Σ^+ decays. Simulation studies show that due to the limited phase space and small Σ^- momentum, the momenta and the angular distributions of p and π^0 are almost the same when X represents different final states. Therefore, we use the MC samples of $\Sigma^- \rightarrow \Sigma^+e^-e^-$ to estimate the efficiency of $\Sigma^- \rightarrow \Sigma^+X$.

To determine the DT yield, we search for candidates in the M_{recoil} distributions for $\Sigma^- \rightarrow pe^-e^-$ and $\Sigma^- \rightarrow \Sigma^+X$ in data, shown in Fig. 4. The signal region is defined as $[1.165, 1.220]$ GeV/c^2 , which covers more than 99.7% of all signal events. The DT efficiencies obtained from MC simulations are 9.02% and 11.08%, respectively. No event is observed in the signal region for either channel.

C. Background study

Potential background candidates come from the continuum process and from other J/ψ decays. To estimate the first kind, we study the continuum process with data samples collected at $\sqrt{s} = 3.08, 3.65, 3.773$ GeV , where the integrated luminosity values are about 150 pb^{-1} , 50 pb^{-1} , and 2.93 fb^{-1} , respectively. There is no ST peaking background, and no event passes the DT selection.

We use the inclusive MC sample to estimate backgrounds from J/ψ decays. The ST peaking background component is from $J/\psi \rightarrow \Sigma(1385)^0\bar{\Lambda} + \text{c.c.}$, and the number of events scaled to data accounts for about 0.07% of the total ST yield, so it is ignored. The smooth

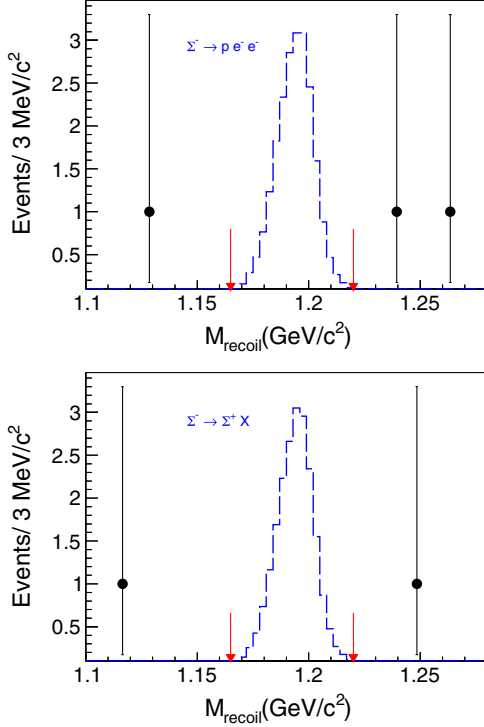


FIG. 4. M_{recoil} distributions of (top) $\Sigma^- \rightarrow pe^-e^-$ and (bottom) $\Sigma^- \rightarrow \Sigma^+X$. Points with error bars are data, and dashed histograms are signal MC simulations with arbitrary normalization. The arrows show the signal region.

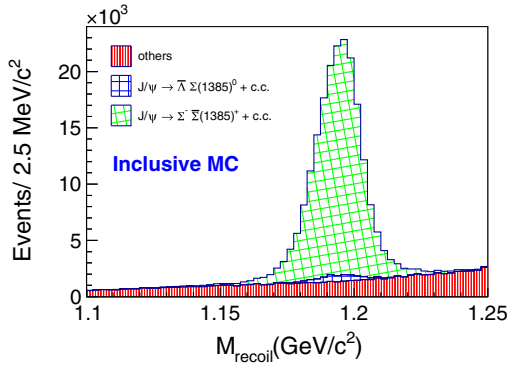


FIG. 5. M_{recoil} distribution of the inclusive Monte Carlo sample.

background components can be described by a second order Chebychev polynomial. Figure 5 shows the different components from the inclusive MC sample. For the DT selection, only 4 and 3 background events survive in the signal regions of the $\Sigma^- \rightarrow pe^-e^-$ and $\Sigma^- \rightarrow \Sigma^+X$ channels, respectively, corresponding to normalized numbers of 0.3 and 0.6 background events.

IV. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the measurements, summarized in Table I, mainly originate from differences

TABLE I. The relative systematic uncertainties (in %) on the branching fraction measurements.

Source	$\Sigma^- \rightarrow pe^-e^-$	$\Sigma^- \rightarrow \Sigma^+X$
Tracking of proton	1.0	1.0
PID of proton	0.4	0.3
Tracking of electron	3.6	...
PID of electron	2.8	...
Photon detection	...	2.0
π^0 reconstruction	...	1.0
Σ^- mass window	0.5	...
Σ^+ mass window	...	0.6
Tag bias	1.3	1.3
MC model	1.0	0.9
Quoted branching ratios	...	0.6
Total	5.0	3.1

between data and simulation in the tracking and PID efficiency, the tag bias, the MC model, and the cited branching fractions.

The systematic uncertainty due to the proton tracking efficiency is determined to be 1.0% for each track by studying the two control samples of $J/\psi \rightarrow pK^-\bar{\Lambda} + \text{c.c.}$ and $J/\psi \rightarrow \Lambda\bar{\Lambda}$ [43]. The uncertainty arising from the proton PID efficiency is determined with the control sample $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$. We bin events in the sample in $\cos\theta$ (i) and $|\vec{p}|$ (j) of the proton [44] and add differences between data and MC samples together with the following formula

$$\Delta\epsilon^{\text{PID}} = \sum_{i,j} (\Delta\epsilon_{ij}^{\text{PID}} \times w_{ij}^{\text{PID}}), \quad (4)$$

where $\Delta\epsilon_{ij}^{\text{PID}}$ is the difference of PID efficiency and w_{ij}^{PID} is the weight factor. The weight factor is defined as the ratio of the number of events in the ij bin to the total number of events of the sample. We use the total differences as the uncertainties in $\Sigma^- \rightarrow pe^-e^-$ and $\Sigma^- \rightarrow \Sigma^+X$, which are 0.4% and 0.3%, respectively.

The uncertainties due to the tracking and PID efficiencies of the electron are studied with the control sample $e^+e^- \rightarrow \gamma e^+e^-$ (at $\sqrt{s} = 3.097$ GeV). Similar as above, we bin events in the sample by $\cos\theta$ and $|\vec{p}_t|$ ($|\vec{p}|$) for tracking (PID). The uncertainties of the tracking efficiency for the high-momentum and low-momentum electrons are 0.5% and 3.1%, respectively, and the uncertainties of the PID efficiency are 0.6% and 2.2%, respectively. The total differences for tracking and PID for $\Sigma^- \rightarrow pe^-e^-$ are 3.6% and 2.8%, respectively. The uncertainties associated with photon detection and π^0 reconstruction are obtained from the control sample $J/\psi \rightarrow \pi^+\pi^-\pi^0$ [45]. The differences between data and MC samples are 1.0% per photon and 1.0% per π^0 , respectively.

The systematic uncertainty due to the $\Sigma^+(p\pi^0)$ mass window is determined to be 0.6% using a control sample of

$J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ decays [46]. Since we do not have a sample of $\Sigma^- \rightarrow pe^-e^-$, we change the limits to those obtained from the mass distribution of Σ^- whose decay is determined by a phase space model. The relative change of the DT efficiency, 0.5%, is taken as the uncertainty of $\Sigma^-(pe^-e^-)$ mass window.

The main uncertainties in the ST selection, including the total number of J/ψ events, the reconstruction of $\bar{\Lambda}$, and the bachelor π^+ , cancel in the double tag method. The tag bias is related with the MC sample used to obtain the ST efficiency. We change the sample with the decay chain $J/\psi \rightarrow \bar{\Sigma}(1385)^+\Sigma^-(\Sigma^- \rightarrow X)$ to the sample with the decay chain $J/\psi \rightarrow \bar{\Sigma}(1385)^+\Sigma^-(\Sigma^- \rightarrow pe^-e^-)$ and $J/\psi \rightarrow \bar{\Sigma}(1385)^+\Sigma^-(\Sigma^- \rightarrow \Sigma^+e^-e^-)$. The average relative change of the ST efficiency is taken as the associated uncertainty, which is 1.3%. The statistical uncertainty of the tag yields is 0.38%, and it is taken into account together with the statistical uncertainties of efficiencies when calculating the ULs.

To estimate the uncertainty of the MC model for the signal, we change the values of parameters in the model that describes the q^2 -dependent differential decay width of $B_1^- \rightarrow B_2^+ l^- l^-$ [24]. We take the relative changes of the DT efficiencies as the associated uncertainties for $\Sigma^- \rightarrow pe^-e^-$ and $\Sigma^- \rightarrow \Sigma^+X$, which are 1.0% and 0.9%, respectively.

Since the limit for $|\vec{p}_{\text{miss}}|$ (0.1 GeV/ c) is much larger than the kinematic limit, the uncertainty of the requirement on $|\vec{p}_{\text{miss}}|$ is negligible. The relative uncertainties for branching fractions of $\pi^0 \rightarrow \gamma\gamma$ and $\Sigma^+ \rightarrow p\pi^0$ are taken from the PDG [19], and are 0.034% and 0.6%, respectively. The uncertainty for the π^0 is so small that it can be ignored. The total systematic uncertainties are obtained by adding all uncertainties above in quadrature.

V. RESULTS

The ULs for the signal yields are calculated using a frequentist method with an unbounded profile likelihood treatment of systematic uncertainties, which is implemented by the class `TRolke` in the ROOT framework [47]. The number of the signal and background events are assumed to follow a Poisson distribution, the detection efficiency is assumed to follow a Gaussian distribution, and the systematic uncertainty is considered as the standard deviation of the efficiency. The resulting UL for the branching fraction is determined by

$$\mathcal{B}_{\text{sig}}^{\text{up}} < \frac{s_{90}^{\text{obs}}}{N_{\text{tag}}^{\text{obs}} \epsilon_{\text{DT}} / \epsilon_{\text{ST}}}, \quad (5)$$

where s_{90}^{obs} is the upper limit on the number of signal events determined at the 90% CL. The ULs for branching fractions are

$$\mathcal{B}(\Sigma^- \rightarrow pe^-e^-) < 6.7 \times 10^{-5},$$

$$\mathcal{B}(\Sigma^- \rightarrow \Sigma^+X) < 1.2 \times 10^{-4}.$$

VI. SUMMARY

To summarize, with the data sample of $(1310.6 \pm 7.0) \times 10^6$ J/ψ events collected by BESIII detector, a search for the LNV decay $\Sigma^- \rightarrow pe^-e^-$ and the rare inclusive decay $\Sigma^- \rightarrow \Sigma^+X$ is performed for the first time. No signal event is observed, and the upper limits on the branching fractions of $\Sigma^- \rightarrow pe^-e^-$ and $\Sigma^- \rightarrow \Sigma^+X$ at the 90% CL are 6.7×10^{-5} and 1.2×10^{-4} , respectively. Our results are well above the prediction in references [22–24].

ACKNOWLEDGMENTS

The BESIII collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Natural Science Foundation of China (NSFC) under Contracts No. 11625523, No. 11635010, No. 11735014, No. 11822506, No. 11835012, No. 11935015, No. 11935016, No. 11935018, No. 11961141012, and No. 12035009; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts No. U1532257, No. U1732263, and No. U1832207; CAS Key Research Program of Frontier Sciences under Contracts No. QYZDJ-SSW-SLH003 and No. QYZDJ-SSW-SLH040; 100 Talents Program of CAS; Institute of Nuclear and Particle Physics and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; German Research Foundation DFG under Contract No. 443159800, Collaborative Research Center CRC 1044, FOR 2359, FOR 2359, GRK 214; Istituto Nazionale di Fisica Nucleare, Italy; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Science and Technology fund; Olle Engkvist Foundation under Contract No. 200-0605; STFC (United Kingdom); The Knut and Alice Wallenberg Foundation (Sweden) under Contract No. 2016.0157; The Royal Society, U.K. under Contracts No. DH140054 and No. DH160214; The Swedish Research Council; U.S. Department of Energy under Contracts No. DE-FG02-05ER41374 and No. DE-SC-0012069.

- [1] S. L. Glashow, *Nucl. Phys.* **22**, 579 (1961).
- [2] A. Salam and J. C. Ward, *Phys. Lett.* **13**, 168 (1964).
- [3] S. Weinberg, *Phys. Rev. Lett.* **19**, 1264 (1967).
- [4] Y. Fukuda *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. Lett.* **81**, 1158 (1998).
- [5] Y. Fukuda *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. Lett.* **81**, 1562 (1998).
- [6] Q. R. Ahmad *et al.* (SNO Collaboration), *Phys. Rev. Lett.* **89**, 011301 (2002).
- [7] K. Eguchi *et al.* (KamLAND Collaboration), *Phys. Rev. Lett.* **90**, 021802 (2003).
- [8] M. Trodden, *Rev. Mod. Phys.* **71**, 1463 (1999).
- [9] M. Dine and A. Kusenko, *Rev. Mod. Phys.* **76**, 1 (2004).
- [10] P. Di Bari, A. Masiero, and R. Mohapatra, *New J. Phys.* **15**, 035030 (2013).
- [11] A. D. Sakharov, *Sov. Phys. Usp.* **34**, 392 (1991).
- [12] S. D. M. White, G. Efstathiou, and C. S. Frenk, *Mon. Not. R. Astron. Soc.* **262**, 1023 (1993).
- [13] S. W. Allen, A. E. Evrard, and A. B. Mantz, *Annu. Rev. Astron. Astrophys.* **49**, 409 (2011).
- [14] P. Salucci, *Astron. Astrophys. Rev.* **27**, 2 (2019).
- [15] R. N. Mohapatra and G. Senjanovic, *Phys. Rev. Lett.* **44**, 912 (1980).
- [16] J. Schechter and J. W. F. Valle, *Phys. Rev. D* **22**, 2227 (1980).
- [17] T. P. Cheng and L. F. Li, *Phys. Rev. D* **22**, 2860 (1980).
- [18] E. Ma, *Phys. Rev. Lett.* **81**, 1171 (1998).
- [19] P. A. Zyla *et al.* (Particle Data Group), *Prog. Theor. Exp. Phys.* (**2020**), 083C01.
- [20] L. S. Littenberg and R. E. Shrock, *Phys. Rev. D* **46**, R892 (1992).
- [21] D. Rajaram, R. A. Burnstein, A. Chakravorty, A. Chan, Y. C. Chen, W. S. Choong *et al.* (HyperCP Collaboration), *Phys. Rev. Lett.* **94**, 181801 (2005).
- [22] C. Barbero, G. Lopez Castro, and A. Mariano, *Phys. Lett. B* **566**, 98 (2003).
- [23] C. Barbero, L. F. Li, G. Lopez Castro, and A. Mariano, *Phys. Rev. D* **76**, 116008 (2007).
- [24] C. Barbero, L. F. Li, G. Lopez Castro, and A. Mariano, *Phys. Rev. D* **87**, 036010 (2013).
- [25] W. Rodejohann, *Int. J. Mod. Phys. E* **20**, 1833 (2011).
- [26] M. J. Dolinski, A. W. P. Poon, and W. Rodejohann, *Annu. Rev. Nucl. Part. Sci.* **69**, 219 (2019).
- [27] A. Chodos, R. L. Jaffe, K. Johnson, C. B. Thorn, and V. F. Weisskopf, *Phys. Rev. D* **9**, 3471 (1974).
- [28] A. Chodos, R. L. Jaffe, K. Johnson, and C. B. Thorn, *Phys. Rev. D* **10**, 2599 (1974).
- [29] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **36**, 915 (2012).
- [30] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **41**, 013001 (2017).
- [31] H. B. Li, *Front. Phys. (Beijing)* **12**, 121301 (2017); **14**, 64001(E) (2019).
- [32] M. Ablikim *et al.* (BESIII Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **614**, 345 (2010).
- [33] C. Yu *et al.*, *Proceedings of IPAC2016, Busan, Korea (JACoW, Geneva, 2016)*, <https://doi.org/10.18429/JACoW-IPAC2016-TUYA01>.
- [34] S. Agostinelli *et al.* (GEANT4 Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [35] S. Jadach, B. F. L. Ward, and Z. Was, *Comput. Phys. Commun.* **130**, 260 (2000).
- [36] S. Jadach, B. F. L. Ward, and Z. Was, *Phys. Rev. D* **63**, 113009 (2001).
- [37] D. J. Lange, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [38] R. G. Ping, *Chin. Phys. C* **32**, 243 (2008).
- [39] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, *Phys. Rev. D* **62**, 034003 (2000).
- [40] R. L. Yang, R. G. Ping, and H. Chen, *Chin. Phys. Lett.* **31**, 061301 (2014).
- [41] E. Richter-Was, *Phys. Lett. B* **303**, 163 (1993).
- [42] R. M. Baltrusaitis *et al.* (MARK-III Collaboration), *Phys. Rev. Lett.* **56**, 2140 (1986).
- [43] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **86**, 032008 (2012).
- [44] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **99**, 072006 (2019).
- [45] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **81**, 052005 (2010).
- [46] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **87**, 012003 (2013).
- [47] W. A. Rolke, A. M. Lopez, and J. Conrad, *Nucl. Instrum. Methods Phys. Res., Sect. A* **551**, 493 (2005).