Search for the Cabibbo-suppressed decays $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ and $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$*

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K. Begzsuren[32] N. Berger[35] M. Berlowski[44] M. Bertani[28A] D. Bettoni[29A] F. Bianchi[75A,75C] E. Bianco[75A,75C]
A. Bortone[75A,75C] I. Boyko[36] R. A. Briere[5] A. Brueggemann[69] H. Cai (蔡浩)[77] M. H. Cai (蔡铭航)[38,k,l]
X. Cai (蔡啸)[1,58] A. Calcaterra[28A] G. F. Cao (曹国富)[1,64] N. Cao (曹宁)[1,64] S. A. Cetin[62A] X. Y. Chai (柴新宇)[46,h]
J. F. Chang (常劲帆)[1,58] G. R. Che (车国荣)[43] Y. Z. Che (车逾之)[1,58,64] G. Chelkov[36,b] C. Chen (陈琛)[43]
C. H. Chen (陈春卉)[9] Chao Chen (陈超)[55] G. Chen (陈刚)[1] H. S. Chen (陈和生)[1,64] H. Y. Chen (陈弘扬)[20]
M. L. Chen (陈玛丽)[1,58,64] 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)[1,64]
X. R. Chen (陈旭荣)[31,64] X. T. Chen (陈肖婷)[1,64] Y. B. Chen (陈元柏)[1,58] Y. Q. Chen[34] Z. J. Chen (陈卓俊)[25,i]
Z. K. Chen (陈梓康)[59] S. K. Choi[10] X. Chu (初晓)[12,g] G. Cibinetto[29A] F. Cossio[75C] J. J. Cui (崔佳佳)[50]
H. L. Dai (代洪亮)[1,58] J. P. Dai (代建平)[79] A. Dbeyssi[18] R. E. de Boer[3] D. Dedovich[36] C. Q. Deng (邓创旗)[73]
Z. Y. Deng (邓子艳)[1] A. Denig[35] I. Denysenko[36] M. Destefanis[75A,75C] F. De Mori[75A,75C] B. Ding (丁彪)[67,1]
X. X. Ding (丁晓萱)[46,h] Y. Ding (丁逸)[34] Y. Ding (丁勇)[40] Y. X. Ding (丁玉鑫)[30] J. Dong (董静)[1,58]
L. Y. Dong (董燎原)[1,64] M. Y. Dong (董明义)[1,58,64] X. Dong (董翔)[77] M. C. Du (杜蒙川)[1] S. X. Du (杜书先)[81]
Y. Y. Duan (段尧予)[55] Z. H. Duan (段宗欢)[42] P. Egorov[36,b] G. F. Fan (樊高峰)[42] J. J. Fan (樊俊杰)[19]
Y. H. Fan (范宇晗)[45] J. Fang (方进)[59] J. Fang (方建)[1,58] S. S. Fang (房双世)[1,64] W. X. Fang (方文兴)[1]
Y. Q. Fang (方亚泉)[1,58] R. Farinelli[29A] L. Fava[75B,75C] F. Feldbauer[3] G. Felici[28A] C. Q. Feng (封常青)[72,58]
J. H. Feng (冯俊华)[59] Y. T. Feng (冯玙潼)[72,58] M. Fritsch[3] C. D. Fu (傅成栋)[1] J. L. Fu (傅金林)[64]
Y. W. Fu (傅亦威)[1,64] H. Gao (高涵)[64] X. B. Gao (高鑫博)[41] Y. N. Gao (高语浓)[19] Y. N. Gao (高原宁)[46,h]
Y. Y. Gao (高洋洋)[30] Yang Gao (高扬)[72,58] S. Garbolino[75C] I. Garzia[29A,29B] P. T. Ge (葛潘婷)[19] Z. W. Ge (葛振武)[42]
C. Geng (耿聪)[59] E. M. Gersabeck[68] A. Gilman[70] 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[75A,75C] M. H. Gu (顾旻皓)[1,58] Y. T. Gu (顾运厅)[15] C. Y. Guan (关春懿)[1,64]
A. Q. Guo (郭爱强)[31] 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] K. L. Han (韩坤霖)[64] T. T. Han (韩婷婷)[1] F. Hanisch[3] K. D. Hao (郝科迪)[72,58]
X. Q. Hao (郝喜庆)[19] F. A. Harris[66] K. K. He (何凯凯)[55] K. L. He (何康林)[1,64] F. H. Heinsius[3] C. H. Heinz[35]
Y. K. Heng (衡月昆)[1,58,64] C. Herold[60] T. Holtmann[3] P. C. Hong (洪鹏程)[34] G. Y. Hou (侯国一)[1,64]
X. T. Hou (侯贤涛)[1,64] Y. R. Hou (侯颖锐)[64] Z. L. Hou (侯治龙)[1] B. Y. Hu (胡碧颖)[59] H. M. Hu (胡海明)[1,64]
J. F. Hu (胡继峰)[56,j] Q. P. Hu (胡启鹏)[72,58] S. L. Hu (胡圣亮)[12,g] T. Hu (胡涛)[1,58,64] Y. Hu (胡誉)[1]
Z. M. Hu (胡忠敏)[59] G. S. Huang (黄光顺)[72,58] K. X. Huang (黄凯旋)[59] L. Q. Huang (黄麟钦)[31,64] P. Huang (黄盼)[42]
X. T. Huang (黄性涛)[50] Y. P. Huang (黄燕萍)[1] Y. S. Huang (黄永盛)[59] T. Hussain[74] N. Hüsken[35]

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N. in der Wiesche[69] J. Jackson[27] S. Janchiv[32] Q. Ji (纪全)[1] Q. P. Ji (姬清平)[19] W. Ji (季旺)[1,64] X. B. Ji (季晓斌)[1,64]
X. L. Ji (季筱璐)[1,58] Y. Y. Ji (吉钰瑶)[50] Z. K. Jia (贾泽坤)[72,58] D. Jiang (姜地)[1,64] H. B. Jiang (姜候兵)[77]
P. C. Jiang (蒋沛成)[46,h] S. J. Jiang (蒋思婧)[9] T. J. Jiang (蒋庭俊)[16] X. S. Jiang (江晓山)[1,58,64] Y. Jiang (蒋艺)[64]
J. B. Jiao (焦健斌)[50] J. K. Jiao (焦俊坤)[34] Z. Jiao (焦铮)[23] S. Jin (金山)[42] Y. Jin (金毅)[67] M. Q. Jing (荆茂强)[1,64]
X. M. Jing (景新媚)[64] T. Johansson[76] S. Kabana[33] N. Kalantar-Nayestanaki[65] X. L. Kang (康晓琳)[9]
X. S. Kang (康晓珅)[40] M. Kavatsyuk[65] B. C. Ke (柯百谦)[81] V. Khachatryan[27] A. Khoukaz[69] R. Kiuchi[1]
O. B. Kolcu[62A] B. Kopf[3] M. Kuessner[3] X. Kui (奎贤)[1,64] N. Kumar[26] A. Kupsc[44,76] W. Kühn[37] Q. Lan (兰强)[73]
W. N. Lan (兰文宁)[19] T. T. Lei (雷天天)[72,58] Z. H. Lei (雷祚弘)[72,58] M. Lellmann[35] T. Lenz[35] C. Li (李翠)[47]
C. Li (李聪)[43] C. H. Li (李春花)[39] C. K. Li (李春凯)[20] Cheng Li (李澄)[72,58] D. M. Li (李德民)[81] F. Li (李飞)[1,58]
G. Li (李刚)[1] H. B. Li (李海波)[1,64] H. J. Li (李惠静)[19] H. N. Li (李衡讷)[56,j] Hui Li (李慧)[43] J. R. Li (李嘉荣)[61]
J. S. Li (李静舒)[59] K. Li (李科)[1] K. L. Li (李凯璐)[19] K. L. Li (李凯璐)[38,k,l] L. J. Li (李林健)[1,64] Lei Li (李蕾)[48]
M. H. Li (李明浩)[43] M. R. Li (李明润)[1,64] P. L. Li (李佩莲)[64] P. R. Li (李培荣)[38,k,l] Q. M. Li (李启铭)[1,64]
Q. X. Li (李起鑫)[50] R. Li (李燃)[17,31] T. Li (李腾)[50] T. Y. Li (李天佑)[43] W. D. Li (李卫东)[1,64] W. G. Li (李卫国)[1,a]
X. Li (李旭)[1,64] X. H. Li (李旭红)[72,58] X. L. Li (李晓玲)[50] X. Y. Li (李晓宇)[1,8] X. Z. Li (李绪泽)[59] Y. Li (李洋)[19]
Y. G. Li (李彦谷)[46,h] Z. J. Li (李志军)[59] Z. Y. Li (李紫阳)[79] C. Liang (梁畅)[42] H. Liang (梁昊)[72,58]
Y. F. Liang (梁勇飞)[54] Y. T. Liang (梁羽铁)[31,64] G. R. Liao (廖广睿)[14] L. B. Liao (廖立波)[59] M. H. Liao (廖明华)[59]
Y. P. Liao (廖一朴)[1,64] J. Libby[26] A. Limphirat[60] C. C. Lin (蔺长城)[55] C. X. Lin (林创新)[64] D. X. Lin (林德旭)[31,64]
L. Q. Lin (邵麟筌)[39] T. Lin (林韬)[1] B. J. Liu (刘北江)[1] B. X. Liu (刘宝鑫)[77] C. Liu (刘成)[34] C. X. Liu (刘春秀)[1]
F. Liu (刘芳)[1] F. H. Liu (刘福虎)[53] Feng Liu (刘峰)[6] G. M. Liu (刘国明)[56,j] H. Liu (刘昊)[38,k,l]
H. B. Liu (刘宏邦)[15] H. H. Liu (刘欢欢)[1] H. M. Liu (刘怀民)[1,64] Huihui Liu (刘汇慧)[21] J. B. Liu (刘建北)[72,58]
J. J. Liu (刘佳佳)[20] K. Liu (刘凯)[38,k,l] K. Liu (刘坤)[73] K. Y. Liu (刘魁勇)[40] Ke Liu (刘珂)[22] L. Liu (刘亮)[72,58]
L. C. Liu (刘良辰)[43] Lu Liu (刘露)[43] M. H. Liu (刘美宏)[12,g] P. L. Liu (刘佩莲)[1] Q. Liu (刘倩)[64]
S. B. Liu (刘树彬)[72,58] T. Liu (刘桐)[12,g] W. K. Liu (刘维克)[43] W. M. Liu (刘卫民)[72,58] W. T. Liu (刘婉婷)[39]
X. Liu (刘鑫)[39] X. Liu (刘翔)[38,k,l] X. Y. Liu (刘雪吟)[77] Y. Liu (刘媛)[81] Y. Liu (刘义)[81] Y. Liu (刘英)[38,k,l]
Y. B. Liu (刘玉斌)[43] Z. A. Liu (刘振安)[1,58,64] Z. D. Liu (刘宗德)[9] Z. Q. Liu (刘智青)[50] X. C. Lou (娄辛丑)[1,58,64]
F. X. Lu (卢飞翔)[59] H. J. Lu (吕海江)[23] J. G. Lu (吕军光)[1,58] Y. Lu (卢宇)[7] Y. H. Lu (卢泱宏)[1,64]
Y. P. Lu (卢云鹏)[1,58] Z. H. Lu (卢泽辉)[1,64] C. L. Luo (罗成林)[41] J. R. Luo (罗家瑞)[59] J. S. Luo (罗家顺)[1,64]
M. X. Luo (罗民兴)[80] T. Luo (罗涛)[12,g] X. L. Luo (罗小兰)[1,58] X. R. Lyu (吕晓睿)[64,p] Y. F. Lyu (吕翌丰)[43]
Y. H. Lyu (吕云鹤)[81] F. C. Ma (马凤才)[40] H. Ma (马衡)[79] H. L. Ma (马海龙)[1] J. L. Ma (马俊力)[1,64]
L. L. Ma (马连良)[50] L. R. Ma (马立瑞)[67] Q. M. Ma (马秋梅)[1] R. Q. Ma (马润秋)[1,64] R. Y. Ma (马若云)[19]
T. Ma (马腾)[72,58] X. T. Ma (马晓天)[1,64] X. Y. Ma (马骁妍)[1,58] Y. M. Ma (马玉明)[31] F. E. Maas[18] I. MacKay[70]
M. Maggiora[75A,75C] S. Malde[70] Y. J. Mao (冒亚军)[46,h] Z. P. Mao (毛泽普)[1] S. Marcello[75A,75C]
Y. H. Meng (孟琰皓)[64] Z. X. Meng (孟召霞)[67] J. G. Messchendorp[13,65] G. Mezzadri[29A] H. Miao (妙晗)[1,64]
T. J. Min (闵天觉)[42] R. E. Mitchell[27] X. H. Mo (莫晓虎)[1,58,64] B. Moses[27] N. Yu. Muchnoi[4,c] J. Muskalla[35]
Y. Nefedov[36] F. Nerling[18,e] L. S. Nie (聂麟苏)[20] I. B. Nikolaev[4,c] Z. Ning (宁哲)[1,58] S. Nisar[11,m]
Q. L. Niu (牛祺乐)[38,k,l] S. L. Olsen[10,64] Q. Ouyang (欧阳群)[1,58,64] S. Pacetti[28B,28C] X. Pan (潘祥)[55] Y. Pan (潘越)[57]
A. Pathak[10] Y. P. Pei (裴宇鹏)[72,58] M. Pelizaeus[3] H. P. Peng (彭海平)[72,58] Y. Y. Peng (彭云翊)[38,k,l] K. Peters[13,e]
J. L. Ping (平加伦)[41] R. G. Ping (平荣刚)[1,64] S. Plura[35] V. Prasad[33] F. Z. Qi (齐法制)[1] H. R. Qi (漆红荣)[61]
M. Qi (祁鸣)[42] S. Qian (钱森)[1,58] W. B. Qian (钱文斌)[64] C. F. Qiao (乔从丰)[64] J. H. Qiao (乔佳辉)[19]
J. J. Qin (秦佳佳)[73] J. L. Qin (覃嘉良)[55] L. Q. Qin (秦丽清)[14] L. Y. Qin (秦龙宇)[72,58] P. B. Qin (秦鹏勃)[73]
X. P. Qin (覃潇平)[12,g] X. S. Qin (秦小帅)[50] Z. H. Qin (秦中华)[1,58] J. F. Qiu (邱进发)[1] Z. H. Qu (屈子皓)[73]
C. F. Redmer[35] A. Rivetti[75C] M. Rolo[75C] G. Rong (荣刚)[1,64] S. S. Rong (荣少石)[1,64] Ch. Rosner[18]
M. Q. Ruan (阮曼奇)[1,58] S. N. Ruan (阮氏宁)[43] N. Salone[44] A. Sarantsev[36,d] Y. Schelhaas[35] K. Schoenning[76]
M. Scodeggio[29A] K. Y. Shan (尚科羽)[12,g] W. Shan (单葳)[24] X. Y. Shan (单心钰)[72,58] Z. J. Shang (尚子杰)[38,k,l]
J. F. Shangguan (上官剑锋)[16] L. G. Shao (邵立港)[1,64] M. Shao (邵明)[72,58] C. P. Shen (沈成平)[12,g]
H. F. Shen (沈宏飞)[1,8] W. H. Shen (沈文涵)[64] X. Y. Shen (沈肖雁)[1,64] B. A. Shi (施伯安)[64] H. Shi (史华)[72,58]

J. L. Shi (石家磊)[12,g] J. Y. Shi (石京燕)[1] S. Y. Shi (史书宇)[73] X. Shi (史欣)[1,58] H. L. Song (宋海林)[72,58]
J. J. Song (宋娇娇)[19] T. Z. Song (宋天资)[59] W. M. Song (宋维民)[34,1] Y. J. Song (宋宇镜)[12,g]
Y. X. Song (宋昀轩)[46,h,n] S. Sosio[75A,75C] S. Spataro[75A,75C] F. Stieler[35] S. S Su (苏闪闪)[40] Y. J. Su (粟杨捷)[64]
G. B. Sun (孙光豹)[77] G. X. Sun (孙功星)[1] H. Sun (孙昊)[64] H. K. Sun (孙浩凯)[1] J. F. Sun (孙俊峰)[19]
K. Sun (孙开)[61] L. Sun (孙亮)[77] S. S. Sun (孙胜森)[1,64] T. Sun[51,f] Y. C. Sun (孙雨长)[77] Y. H. Sun (孙益华)[30]
Y. J. Sun (孙勇杰)[72,58] Y. Z. Sun (孙永昭)[1] Z. Q. Sun (孙泽群)[1,64] Z. T. Sun (孙振田)[50] C. J. Tang (唐昌建)[54]
G. Y. Tang (唐光毅)[1] J. Tang (唐健)[59] L. F. Tang (唐林发)[39] M. Tang (唐嘉骏)[72,58] Y. A. Tang (唐迎澳)[77]
L. Y. Tao (陶璐燕)[73] M. Tat[70] J. X. Teng (滕佳秀)[72,58] V. Thoren[76] J. Y. Tian (田济源)[72,58] W. H. Tian (田文辉)[59]
Y. Tian (田野)[31] Z. F. Tian (田喆飞)[77] I. Uman[62B] B. Wang (王斌)[1] B. Wang (王博)[59] Bo Wang (王博)[72,58]
C. Wang (王超)[19] D. Y. Wang (王大勇)[46,h] H. J. Wang (王泓鉴)[38,k,l] J. J. Wang (王家驹)[77] K. Wang (王科)[1,58]
L. L. Wang (王亮亮)[1] L. W. Wang (王璐仪)[34] M. Wang (王萌)[50] M. Wang[72,58] N. Y. Wang (王南洋)[64]
S. Wang (王石)[38,k,l] S. Wang (王顺)[12,g] T. Wang (王婷)[12,g] T. J. Wang (王腾蛟)[43] W. Wang (王维)[73]
W. Wang (王为)[59] W. P. Wang (王维平)[35,58,72,o] X. Wang (王轩)[46,h] X. F. Wang (王雄飞)[38,k,l] X. J. Wang (王希俊)[39]
X. L. Wang (王小龙)[12,g] X. N. Wang (王新南)[1] Y. Wang (王亦)[61] Y. D. Wang (王雅迪)[45] Y. F. Wang (王贻芳)[1,58,64]
Y. H. Wang (王英豪)[38,k,l] Y. L. Wang (王艺龙)[19] Y. N. Wang (王燕宁)[77] Y. Q. Wang (王雨晴)[1]
Yaqian Wang (王亚乾)[17] Yi Wang (王义)[61] Yuan Wang (王源)[17,31] Z. Wang (王铮)[1,58] Z. L. Wang (王治浪)[73]
Z. Y. Wang (王至勇)[1,64] D. H. Wei (魏代会)[14] F. Weidner[69] S. P. Wen (文硕频)[1] Y. R. Wen (温亚冉)[39]
U. Wiedner[3] G. Wilkinson[70] M. Wolke[76] C. Wu (吴晨)[39] J. F. Wu (吴金飞)[1,8] L. H. Wu (伍灵慧)[1]
L. J. Wu (吴连近)[1,64] Lianjie Wu (武廉杰)[19] S. G. Wu (吴韶光)[1,64] S. M. Wu (吴蜀明)[64] X. Wu (吴潇)[12,g]
X. H. Wu (伍雄浩)[34] Y. J. Wu (吴英杰)[31] Z. Wu (吴智)[1,58] L. Xia (夏磊)[72,58] X. M. Xian (咸秀梅)[39]
B. H. Xiang (向本后)[1,64] T. Xiang (相腾)[46,h] D. Xiao (肖栋)[38,k,l] G. Y. Xiao (肖光延)[42] H. Xiao (肖浩)[73]
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Y. Xie (谢勇)[50] Y. G. Xie (谢宇广)[1,58] Y. H. Xie (谢跃红)[6] Z. P. Xie (谢智鹏)[72,58] T. Y. Xing (邢天宇)[1,64]
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Abstract: Utilizing 4.5 fb^{-1} of e^+e^- annihilation data collected at center-of-mass energies ranging from 4599.53 MeV to 4698.82 MeV by the BESIII detector at the BEPCII collider, we search for the singly Cabibbo-suppressed hadronic decays $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ and $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$ with a single-tag method. No significant signals are observed for both decays. The upper limits on the branching fractions at the 90% confidence level are determined to be 5.0×10^{-4} for $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ and 6.5×10^{-4} for $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$.

Keywords: Charmed baryon, SCS decay, BESIII Experiment

DOI: **CSTR:**

I. INTRODUCTION

The experimental investigation of the decays of charmed baryons plays a critical role in understanding the complex dynamics of strong and weak interactions involving heavy quarks. The charmed baryon, Λ_c^+, was first observed by the Mark II experiment in 1979 [1]. However, despite the decades of research, the sum of the known Λ_c^+ decay branching fractions (BFs) is still limited to about 70%, with the remaining decays yet to be measured [2, 3]. The hadronic decay amplitudes of Λ_c^+ include both factorizable and nonfactorizable contributions [4], since its weak decays are not suppressed by color or helicity [5]. These nonfactorizable effects, such as those from W-exchange diagrams, play a crucial role in understanding the decay dynamics. In contrast, these effects are negligible in heavy meson decays [6]. To better understand the internal dynamics of charmed baryon decays, improving measurements of the BFs of Λ_c^+ decays is essential.

Study of the three-body hadronic decays $\Lambda_c^+ \to B_n P P'$ is an important area of research, where B_n and $P(P')$ denote octet baryon and pseudoscalar meson, respectively. To date, the Cabibbo-suppressed (SCS) hadronic decay $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ has not been observed. This decay can proceed via the Feynman diagrams shown in Fig. 1. Predictions of the decay BF range from 0.8×10^{-3} to 1.2×10^{-3} with the SU(3) flavor symmetry framework [7–9], under the assumption that the PP' system is in an S-wave state. The most recent prediction, as reported in Ref. [9], considers the complete effective Hamiltonian contribution. On the other hand, Ref. [10] predicts the BF of $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ to be $(2.1\pm0.6)\times10^{-3}$ with the statistical isospin model. Experimentally, the BESIII experiment searched for this decay for the first time using a double-tag method and set an upper limit on its BF at the 90% confidence level (C.L.) to be 1.8×10^{-3} [11].

Currently, there are no theoretical predictions of the four-body hadronic decay $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$. The BaBar experiment performed the first search for this decay and reported an upper limit on the BF ratio $\frac{\mathcal{B}(\Lambda_c^+\to\Sigma^0 K^+\pi^+\pi^-)}{\mathcal{B}(\Lambda_c^+\to\Sigma^0\pi^+)} < 2.0\times10^{-2}$ at the 90% C.L. [12].

In this work, we search for the hadronic decays $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ and $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$, with subsequent decay $\Sigma^0 \to \gamma\Lambda$ and $\Lambda \to p\pi^-$, utilizing 4.5 fb^{-1} of e^+e^- annihilation data collected at center-of-mass (c.m.) energies ranging from 4599.53 MeV to 4698.82 MeV [13–15]. The results could test the theoretical models and also provide important input to them. Throughout this paper, the charge-conjugate state is always implied.

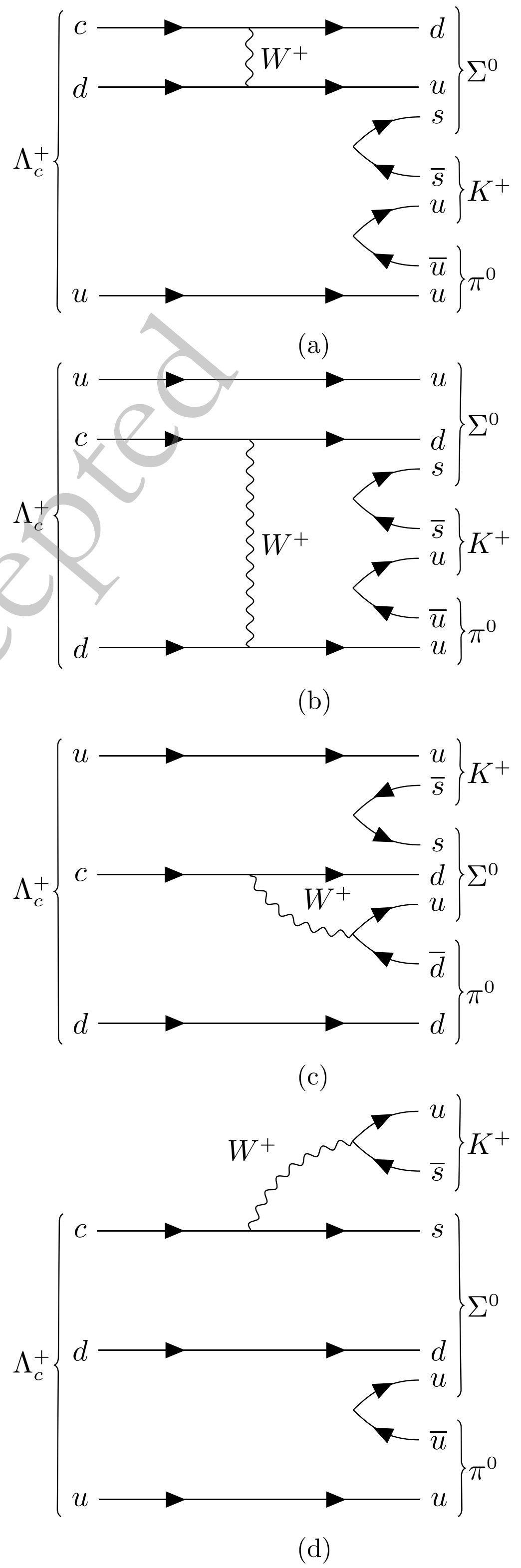

Fig. 1. The Feynman diagrams of $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$: (a) and (b) W-exchange diagrams, (c) Internal W-emission diagram, and (d) External W-emission diagram.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [16] records symmetric e^+e^- collisions provided by the BEPCII storage ring [17] in the c.m. energy range from 1.84 to 4.95 GeV, with a peak luminosity of 1.1×10^{33} cm^{-2}s^{-1} achieved at $\sqrt{s}=3.773$ GeV. BESIII has collected large data samples in this energy region [21]. 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), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. 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 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 was 110 ps. The end-cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [18–20]. About 87% of the data used in this analysis benefits from this upgrade.

Simulated samples, generated using the GEANT4-based [22] Monte Carlo (MC) package, 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^- annihilation, modeled with the generator KKMC [23]. For the ISR simulation, the Born cross section line shape of $e^+e^-\to\Lambda_c^+\bar{\Lambda}_c^-$ measured by BESIII is used [24]. Signal MC samples are generated as $\Lambda_c^+\to\Sigma^0K^+\pi^0$, $\Lambda_c^+\to\Sigma^0\pi^+\pi^0$, $\Lambda_c^+\to\Sigma^0K^+\pi^+\pi^-$, and $\Lambda_c^+\to\Sigma^0\pi^+\pi^+\pi^-$, with the $\bar{\Lambda}_c^-$ baryon decays inclusively. The signal decays are produced using the phase space (PHSP) model. To calculate the detection efficiencies, one million signal MC events are generated for each energy point, where Λ_c^+ ($\bar{\Lambda}_c^-$) decays into the signal mode, and $\bar{\Lambda}_c^-$ (Λ_c^+) decays into all possible states. Additionally, to study the peaking background, exclusive MC samples of $\Lambda_c^+\to\Xi^0K^+$ and $\Lambda_c^+\to\Lambda K^{*+}$ are generated. Inclusive MC samples consist of open-charm states, ISR production of the J/ψ and $\psi(3686)$ states, and continuum processes $e^+e^-\to q\bar{q}\,(q=u,d,s)$ are used to study backgrounds. The known decay modes of charmed hadrons and charmonium states are modeled with EVTGEN [25, 26] using BFs taken from the Particle Data Group (PDG) [2], and the remaining unknown decays are modeled with LUNDCHARM [27, 28]. Final state radiation from charged final-state particles is incorporated with the PHOTOS package [29].

III. EVENT SELECTION AND DATA ANALYSIS

Due to limited data statistics, we adopt a single-tag approach to improve signal efficiencies, where only one Λ_c^+ is reconstructed in each event, with no requirement on the recoil side. To avoid potential bias and validate the analysis procedure, a blind analysis is adopted to analyze pseudodata, such as the inclusive MC sample with equivalent size as data. The real data is unblinded after the analysis procedure has been fixed.

All charged tracks are required to have a polar angle (θ) range within $|\cos\theta|<0.93$, where θ is defined with respect to the z axis, which is the symmetry axis of the MDC. For the charged tracks not originating from Λ decays, 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}. Particle identification (PID) for charged tracks combines measurements of the energy deposited in the MDC (dE/dx) and the flight time in the TOF to form likelihoods $\mathcal{L}(h)$ ($h=p,K,\pi$) for each hadron h hypothesis. Tracks are identified as protons when the proton hypothesis has the greatest likelihood ($\mathcal{L}(p)>\mathcal{L}(K)$ and $\mathcal{L}(p)>\mathcal{L}(\pi)$), while charged kaons and pions are identified by comparing the likelihoods for the kaon and pion hypotheses, $\mathcal{L}(K)>\mathcal{L}(\pi)$ and $\mathcal{L}(\pi)>\mathcal{L}(K)$, respectively.

The Λ particles are reconstructed from a pair of oppositely charged proton and pion candidates satisfying $|V_z|<$ 20 cm. The same PID requirements as mentioned before are imposed to select the proton candidates. Other charged tracks are assigned to be π candidate without any PID requirements. These charged tracks are constrained to originate from the common decay vertex by requiring the χ^2 of the vertex fit to be less than 100, and the decay length is required to be greater than twice the vertex resolution away from the IP. To ensure reconstruction reliability, the Λ candidates are required to have an invariant mass within $1.111<M(p\pi^-)<1.121$ GeV/c^2, which corresponds to three times of the mass resolution around the known Λ mass [2].

Photon candidates are identified using isolated showers in the EMC. The deposited energy of each shower must be more than 25 MeV in the barrel region ($|\cos\theta|<0.80$) and more than 50 MeV in the end cap region ($0.86<|\cos\theta|<0.92$). To exclude showers that originate from charged tracks, the angle subtended by the EMC shower and the position of the closest charged track at the EMC must be greater than 10° as measured from the IP. To suppress electronic noise and showers unrelated to the event, the difference between the EMC time and the event start time is required to be within [0, 700] ns. The π^0 candidates are reconstructed from photon pairs with an invariant mass within $0.115<M(\gamma\gamma)<0.150$ GeV/c^2. To improve momentum resolution, a one-constraint kinematic fit is utilized to constrain the $M(\gamma\gamma)$ to the known π^0 mass [2]. Only combinations that satisfy $\chi^2<200$ are retained, and the refined momenta are then employed for subsequent analysis. Then, the Σ^0 candidates are reconstructed from the $\Lambda\gamma$ final states, with an invariant mass in the range $1.179 < M(\Lambda\gamma) < 1.203$ GeV/c^2.

To reduce the effect from the noise produced by $\bar{p}$ in the EMC, the opening angle between photon and antiproton is required to be greater than 20°, which is obtained by optimizing the figure-of-merit defined as Punzi FOM $= \frac{\varepsilon}{2.5+\sqrt{B}}$ [30]. Here, ε is the signal efficiency and B denotes the background yield from the inclusive MC samples. By utilizing the generic event-type analysis tool TopoAna [31], the study of inclusive MC samples shows that the peaking backgrounds for $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ are from the $\Lambda_c^+ \to \Xi^0 K^+$ and $\Lambda_c^+ \to \Lambda K^{*+}$ decays. These backgrounds involve one less photon in the final state than the signal process. To suppress these backgrounds, we define the energy difference $\Delta E_{p\pi^- K^+\gamma\gamma} \equiv E_p + E_{\pi^-} + E_{K^+} + E_{\gamma 1} + E_{\gamma 2} - E_{\rm beam}$, where E_p, E_{π^-}, E_{K^+}, and $E_{\gamma 1/2}$ are the energies of the proton, pion, kaon, and two photons(come from π^0), respectively while $E_{\rm beam}$ representing the beam energy. Candidate events for $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ are required to satisfy $-160 < \Delta E_{p\pi^- K^+\gamma\gamma} < -30$ MeV; while candidate events for $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$ are required to satisfy $\Delta E_{p\pi^- K^+\pi^+\pi^-} < -40$ MeV. The distributions of $\Delta E_{p\pi^- K^+\gamma\gamma}(\Delta E_{p\pi^- K^+\pi^+\pi^-})$ are shown in Fig. 2.

After applying the above requirements, The Σ^0, K^+ and $\pi^0(\pi^\pm)$ candidates are combined to reconstruct the Λ_c^+. Kinematic variables, including energy difference ΔE, defined as $\Delta E \equiv E_{{\rm rec}-\Lambda_c^+} - E_{\rm beam}$, and the beam-constrained mass $M_{\rm BC}$, defined as $M_{\rm BC} \equiv \sqrt{E_{\rm beam}^2/c^4 - |\vec{p}|^2/c^2}$, are utilized to identify Λ_c^+ candidates. Here, $E_{{\rm rec}-\Lambda_c^+}$ and $\vec{p}$ are the energy and momentum of Λ_c^+ candidate, respectively. If there are multiple combinations satisfying these requirements in an event, the one with the minimum $|\Delta E|$ is retained. Candidate events for $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ and $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$ are required to satisfy $\Delta E \in [-27, 6]$ MeV and $\Delta E \in [-21, 7]$ MeV respectively, with the ranges optimized according to the Punzi FOM. The signal efficiency and background yield are obtained within the $M_{\rm BC}$ signal region of $M_{\rm BC} \in [2.282, 2.291]$ GeV/c^2. To obtain a pure signal, we have employed the truth-match method [32]. This method involves comparing two photons in the π^0, one photon in the Σ^0, and the charged tracks $K^\pm$ and $\pi^\pm$ with their corresponding truth information. The angle $\theta_{\rm truth}$ is defined as the opening angle between each reconstructed tracks (showers) and its corresponding simulated tracks (showers). The signal shape is derived from events where $\theta_{\rm truth}$ is less than 20° for all tracks (showers).

Table 1 lists the signal efficiencies obtained at different energy points. Figure 3 and Figure 5 show the $M_{\rm BC}$ distributions of the simultaneous fit performed between different energy points for each of the signal decays, where no clear Λ_c^+ signals are observed. A likelihood scan method is employed after incorporating the systematic uncertainties, as discussed in the next section, to estimate the upper limits.

The absolute BF of the signal decay is determined by

$$\mathcal{B}^{\rm sig} \equiv \frac{N^{\rm sig}}{2 \cdot N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathcal{B}^{\rm inter} \cdot \varepsilon^{\rm sig}}, \tag{1}$$

where $N_{\Lambda_c^+\bar{\Lambda}_c^-}$ is the total number of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs, $\varepsilon^{\rm sig}$ is the single-tag efficiency, and $\mathcal{B}^{\rm inter}$ is the product BFs of the intermediate states Σ^0, Λ and π^0.

Since there are different distributions of background and signal events at each energy point, a simultaneous fit is performed on individual $M_{\rm BC}$ distributions. The BF of each signal decay is constrained to be the same value through a maximum likelihood simultaneous fit to individual $M_{\rm BC}$ distributions across seven energy points. In the fit, the signal shapes are derived from MC simulations convolved with Gaussian functions to account for the potential difference between data the MC simulations, due to imperfect modeling in MC simulation and the beam-energy spread. The control samples of $\Lambda_c^+ \to \Sigma^0 \pi^+ \pi^0$ and $\Lambda_c^+ \to \Sigma^0 \pi^+ \pi^+ \pi^-$ are used to evaluate the

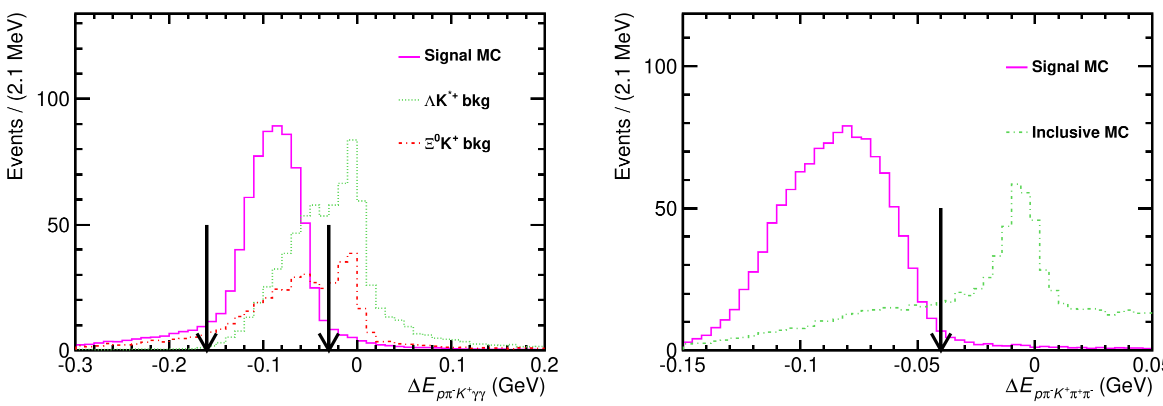

Fig. 2. (color online) The distributions of $\Delta E_{p\pi^- K^+\gamma\gamma}(\Delta E_{p\pi^- K^+\pi^+\pi^-})$ for $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0 (\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-)$. The histograms of the signal MC are normalized to make the distribution more intuitive when compared to the inclusive MC.

Table 1. Single-tag efficiencies (%) for $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$ and $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$ at different energy points, where the uncertainties are statistical only.

$\sqrt{s}$(MeV)	$\varepsilon_{\Lambda_c^+ \to \Sigma^0 K^+\pi^0}$	$\varepsilon_{\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-}$
4599.53	5.17±0.04	3.44±0.03
4611.86	4.89±0.03	3.10±0.03
4628.00	4.76±0.03	3.14±0.03
4640.91	4.76±0.03	3.21±0.03
4661.24	4.71±0.03	3.32±0.03
4681.92	4.68±0.03	3.43±0.03
4698.82	4.65±0.03	3.44±0.03

resolution, which have similar topologies as our signal decays. The combinatorial backgrounds are well described by the ARGUS function [33] with c.m. energy dependent endpoint fixed at $E_{\rm beam}$. The remaining peaking backgrounds, $\Lambda_c^+ \to \Xi^0 K^+$ and $\Lambda_c^+ \to \Lambda K^{*+}$ for $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$, are described using exclusive MC simulations with yields determined by the known BFs and the simulated misidentification rates as listed in Table 2. For $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$, there is no significant peaking background. Unmatched events, studied through the signal MC samples, exhibit a non-flat distribution. In the simultaneous fit, the yields associated with the unmatched events are determined by evaluating the ratio between the matched signal yields and the unmatched background yields, with the ratio obtained from MC simulation.

IV. SYSTEMATIC UNCERTAINTY

The systematic uncertainties in the determinations of the upper limits on the BFs are classified into two categories: additive terms and multiplicative terms.

The additive terms include the uncertainties introduced by the chosen signal and background shapes. The uncertainty associated with the signal shape is estimated by changing the parameters of the convolved Gaussian functions within their uncertainties. The largest deviation of the individual changes is taken as the uncertainty. The background shape of the non-peaking components is changed from the ARGUS function to be the shape extracted from the inclusive MC samples. The uncertainty due to the fixed contribution of the peaking background yields in the fit is investigated by varying the fixed yields within $\pm 1\sigma$ of the PDG BFs of individual background sources. Among all the above terms, the case yielding the largest upper limit is chosen for further analysis. The additive uncertainty for $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$ is dominated by the signal shape uncertainty, while the $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$ is mainly influenced by the background shape uncertainty.

The sources of multiplicative systematic uncertainties include tracking and PID of charged particles, π^0 reconstruction, Λ reconstruction, photon reconstruction, ΔE requirement, $\mathcal{B}^{\rm inter}$(Quoted BF), MC model, truth matching, MC statistics, $N_{\Lambda_c^+\bar{\Lambda}_c^-}$, ΔE_Λ($\Delta E_{p\pi^- K^+\gamma\gamma}$ and $\Delta E_{p\pi^- K^+\pi^+\pi^-}$) and $\theta_{\bar{p}\gamma}$ requirement. The total multiplicative systematic uncertainties are summarized in Table 3 and discussed in details below.

(**a**) Tracking and PID: The uncertainties of either PID or tracking of the charged tracks are quoted as 1.0% per track based on studies of the control sample of $e^+e^- \to K^+K^-\pi^+\pi^-$ [34].

(**b**) π^0 reconstruction: The π^0 reconstruction efficiency is studied with the control samples of

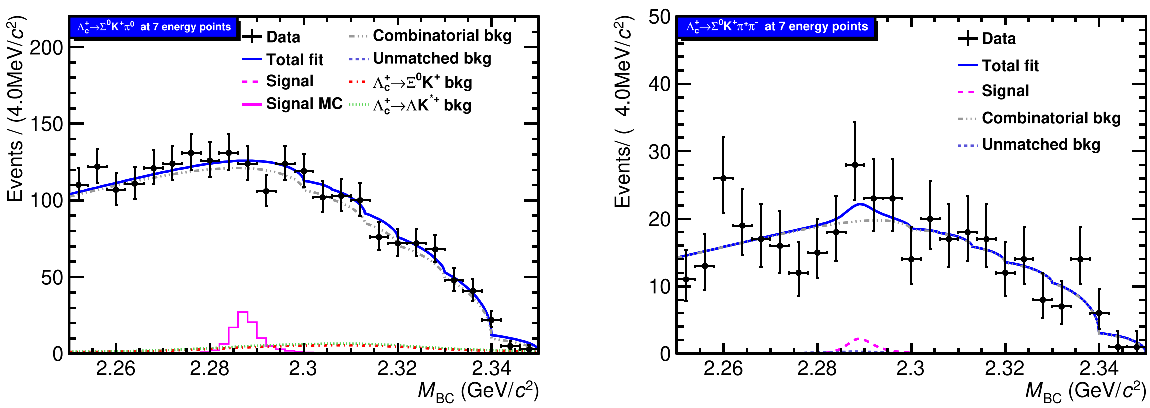

Fig. 3. (color online) The fit to the $M_{\rm BC}$ distributions of $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$(left) and $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$(right) of the combined data. For $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$, the violet histograms are the signal MC samples normalized with a product BF of 1.2 $\times 10^{-3}$ [7]. The ARGUS function includes seven sub-ARGUS functions, the black point with the error bar is data, the blue solid line represents the total fit function, the gray dashed line shows the combinatorial background, the violet dash line is the signal function, the navy blue dashed line is the unmatched component, cyan dashed line is the background shape extract from $\Lambda_c^+ \to \Lambda K^{*+}$ MC samples, and red dashed line is the background shape extract from $\Lambda_c^+ \to \Xi^0 K^+$ MC samples.

Table 2. The contamination rates (%) after including the BFs of the secondary decays at each energy point, where the uncertainties are statistical only.

$\sqrt{s}$(MeV)	$\varepsilon_{\Lambda_c^+\to\Xi^0K^+}$	$\varepsilon_{\Lambda_c^+\to\Lambda K^{*+}}$
4599.53	2.34±0.03	2.63±0.02
4611.86	1.97±0.03	2.59±0.02
4628.00	2.10±0.03	2.58±0.02
4640.91	2.06±0.03	2.58±0.02
4661.24	2.10±0.03	2.57±0.02
4681.92	2.14±0.03	2.56±0.02
4698.82	2.25±0.03	2.46±0.02

Table 3. Multiplicative systematic uncertainties in unit of % for the BF measurement.

Source	$\Lambda_c^+\to\Sigma^0K^+\pi^0$	$\Lambda_c^+\to\Sigma^0K^+\pi^+\pi^-$
Tracking	1.0	3.0
PID	1.0	3.0
π^0 reconstruction	3.1	-
Λ reconstruction	2.5	2.5
Photon detection	0.5	0.5
ΔE requirement	2.0	3.7
MC model	5.5	18.5
$\mathcal{B}^{\rm inter}$	0.8	0.8
Truth matching	5.5	4.9
$N_{\Lambda_c^+\bar{\Lambda}_c^-}$	0.9	0.9
MC statistics	0.5	0.3
ΔE_Λ requirement	0.4	0.3
$\theta_{\bar{p}\gamma}$ requirement	0.1	-
Total	9.2	20.1

$\psi(3686)\to J/\psi\pi^0\pi^0$ and $e^+e^-\to\omega\pi^0$. The associated systematic uncertainty is assigned to be 3.1% for each π^0.

(**c**) Λ reconstruction: The systematic uncertainty of Λ reconstruction is assigned to be 2.5% by referring to the study of $\Lambda_c^+\to\Lambda\pi^+$ in Ref. [35], which includes the systematics associated with reconstructing the daughter particles proton and pion.

(**d**) Photon reconstruction: The systematic uncertainty due to the photon reconstruction is estimated to be 0.5% for photon by analyzing the ISR process $e^+e^-\to\gamma\mu^+\mu^-$.

(**e**) ΔE requirements: Potential differences in the ΔE distributions between data and MC simulation are studied with the control samples of $\Lambda_c^+\to\Sigma^0\pi^+\pi^0$ and $\Lambda_c^+\to\Sigma^0\pi^+\pi^+\pi^-$. The differences between the nominal and alternative acceptance efficiencies, 2.0% and 3.7%, are taken as the systematic uncertainties for $\Lambda_c^+\to\Sigma^0K^+\pi^0$ and $\Lambda_c^+\to\Sigma^0K^+\pi^+\pi^-$, respectively.

(**f**) MC model: The systematic uncertainties associated with the MC model are evaluated with alternative signal MC samples for $\Lambda_c^+\to\Sigma^0K^+\pi^0$ and $\Lambda_c^+\to\Sigma^0K^+\pi^+\pi^-$. These samples are generated as $\Lambda_c^+\to\Lambda(1405)K^+$, with $\Lambda(1405)\to\Sigma^0\pi^0$ via the PHSP model, and $\Lambda_c^+\to\Sigma^0\pi^+K^*$, with $K^*\to K^+\pi^-$ also simulated in the PHSP model. The differences between the efficiencies of these alternative models and the nominal model are taken as the systematic uncertainties, which are 5.5% for $\Lambda_c^+\to\Sigma^0K^+\pi^0$ and 18.5% for $\Lambda_c^+\to\Sigma^0K^+\pi^+\pi^-$, respectively.

(**g**) $\mathcal{B}^{\rm inter}$: The BFs of $\Sigma^0\to\Lambda\gamma$, $\Lambda\to p\pi^-$ and $\pi^0\to\gamma\gamma$, are quoted from the PDG [2]. The uncertainties of these known BFs add up to a total uncertainty of 0.8%.

(**h**) Truth matching: To estimate the uncertainty caused by the angle cut in deriving the signal MC shape, we loosen the cut by 5° for each angle. The differences between the nominal and new efficiencies are taken as the systematic uncertainties, which are 5.5% for $\Lambda_c^+\to\Sigma^0K^+\pi^0$ and 4.9% for $\Lambda_c^+\to\Sigma^0K^+\pi^+\pi^-$.

(**i**) $N_{\Lambda_c^+\bar{\Lambda}_c^-}$: The uncertainty of $N_{\Lambda_c^+\bar{\Lambda}_c^-}$ is quoted from Refs. [13, 15]. Its effect on the BF measurement, 0.9%, is assigned as the systematic uncertainty for both decays.

(**j**) MC statistics: The uncertainties due to limited MC statistics are 0.5% for $\Lambda_c^+\to\Sigma^0K^+\pi^0$ and 0.3% for $\Lambda_c^+\to\Sigma^0K^+\pi^+\pi^-$.

(**k**) ΔE_Λ requirement: The uncertainty due to the ΔE_Λ requirement is estimated with the control samples of $\Lambda_c^+\to\Sigma^0\pi^+\pi^0$ and $\Lambda_c^+\to\Sigma^0\pi^+\pi^+\pi^-$. The maximum changes of the acceptance efficiencies between data and MC simulation by varying the ΔE_Λ requirement by ±0.05 GeV are taken as the systematic uncertainties, which are 0.4% and 0.3% for $\Lambda_c^+\to\Sigma^0K^+\pi^0$ and $\Lambda_c^+\to\Sigma^0K^+\pi^+\pi^-$, respectively.

(**l**) $\theta_{\bar{p}\gamma}$ requirement: The systematic uncertainty from the $\theta_{\bar{p}\gamma}$ requirement for $\Lambda_c^+\to\Sigma^0K^+\pi^0$ is estimated with the control sample of $\Lambda_c^+\to\Sigma^0\pi^+\pi^0$. The maximum change of the acceptance efficiencies between data and MC simulation after varying the $\theta_{\bar{p}\gamma}$ requirement by ±5°, 0.1%, is assigned as the systematic uncertainty.

V. RESULTS

The fit result is consistent with a background-only hypothesis of $\Lambda_c^+\to\Sigma^0K^+\pi^0$ and $\Lambda_c^+\to\Sigma^0K^+\pi^+\pi^-$, and the upper limits on their BFs are determined. The distributions of raw likelihoods versus individual BFs are shown as the blue dashed curves in Fig. 4. Each curve is then convolved with a Gaussian function with zero mean and width set as the corresponding multiplicative systematic uncertainty, according to Refs. [36, 37]. The updated likelihood distributions are shown as the red solid lines in Fig. 4. By integrating the red solid curves from zero to

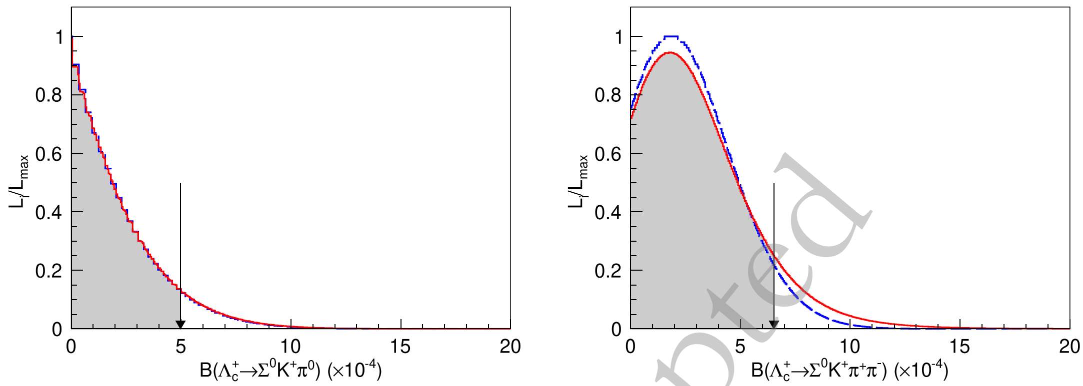

Fig. 4. (color online) The distributions of the likelihoods versus the BFs of $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ (top) and $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$ (bottom). The results obtained with and without incorporating the systematic uncertainties are shown in the red solid and blue dashed curves, respectively. The black arrows shows the results corresponding to the 90% C.L..

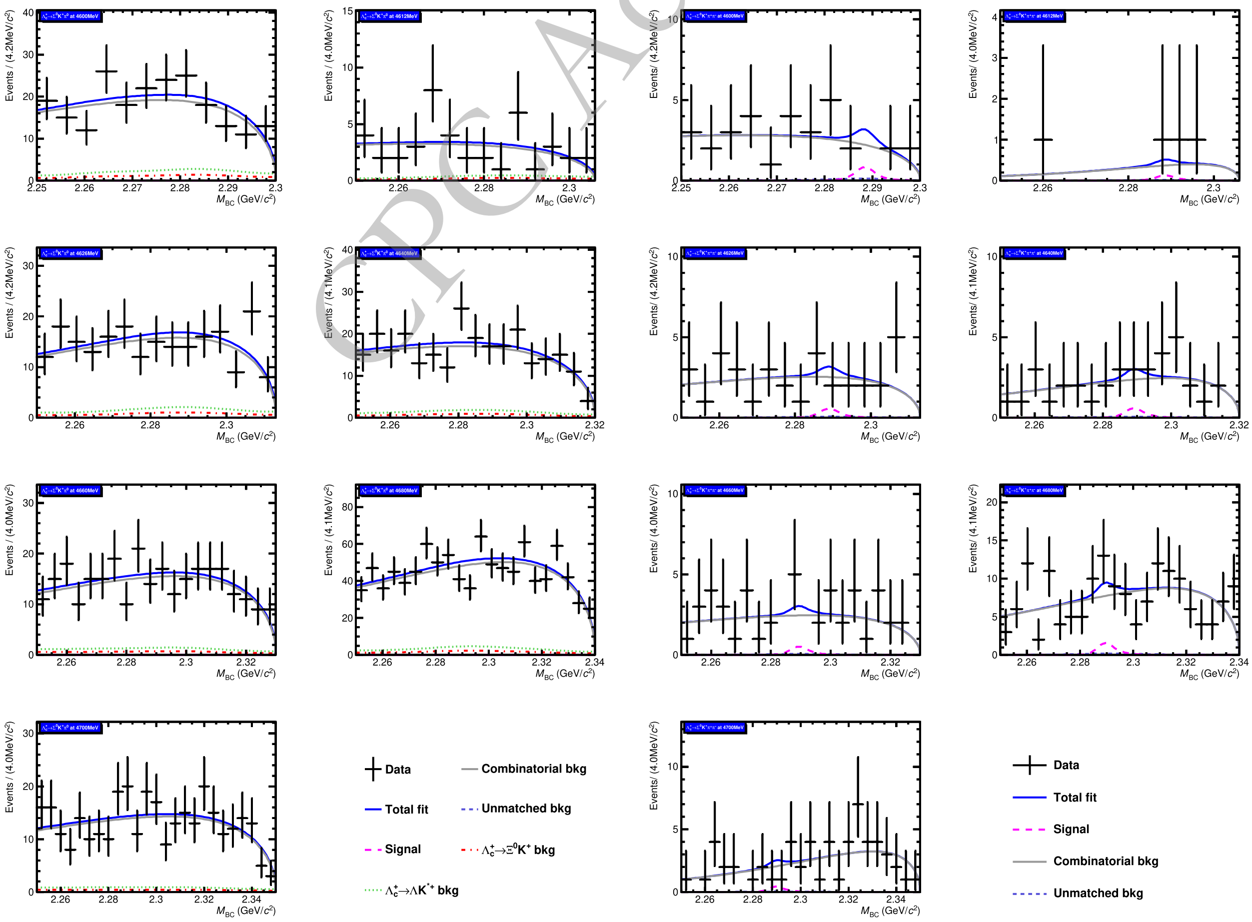

Fig. 5. (color online) The fit to the $M_{\rm BC}$ distributions of $\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$ (left) and $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$ (right) at different energy points. The black point with the error bar is data, the blue solid line represents the total fit function, the gray dashed line shows the combinatorial background, the violet dash line is the signal function, the navy blue dashed line is the un-matched component, cyan dashed line is the background shape extract from $\Lambda_c^+ \to \Lambda K^{*+}$ MC samples, and red dashed line is the background shape extract from $\Lambda_c^+ \to \Xi^0 K^+$ MC samples.

90% of the physical region, the upper limits on the BFs at the 90% C.L. are set to be

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+\pi^0) < 5.0\times10^{-4},$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-) < 6.5\times10^{-4}.$$

VI. SUMMARY

Based on 4.5 fb^{-1} of e^+e^- annihilation data collected at c.m. energies between 4599.53 MeV and 4698.82 MeV with the BESIII detector at the BEPCII collider, we present the studies of the singly Cabibbo-suppressed hadronic decays $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$ and $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$ using a single-tag method. The upper limits on their BFs at the 90% C.L. are set to be 5.0×10^{-4} for $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$ and 6.5×10^{-4} for $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$. The upper limit of the BF of $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$ is more stringent than the previous BESIII measurement using a double-tag method [11]. The predictions based on $SU(3)$ flavor symmetry exceed our upper limit by 2.4σ [7], 1.7σ [8], and 2.0σ [9], respectively. These discrepancies can be further investigated through fits to increasingly precise experimental measurements. And predictions from the statistical isospin model [10] differs from our result by 2.9σ, which indicates that the assumption of $\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K^+\pi^-)$= $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+\pi^0)$ is very rough, as shown in Table 4. For $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$, the upper limit is less stringent than the BaBar result [12]. These results provide valuable information for understanding the dynamics of charmed baryon decays and important input to theoretical models. The sensitivities to these two decays could be further improved with a larger data sample at BESIII [38] in the near future.

Table 4. Comparison of the experimental measurements of $\Lambda_c^+ \to \Sigma^0 K^+\pi^0$ and $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$ obtained in this work, and those of BaBar and BESIII (single-tag) as well as theoretical predictions.

Decay mode	$\Lambda_c^+ \to \Sigma^0 K^+\pi^0$	$\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$
M.Gronau *et al.* [10]	$(2.1\pm0.6)\times10^{-3}$	-
C.Q.Geng *et al.* [7]	$(1.2\pm0.3)\times10^{-3}$	-
J.Y.Cen *et al.* [8]	$(7.8\pm2.3)\times10^{-4}$	-
C.Q.Geng *et al.* [9]	$(8.2\pm1.4)\times10^{-4}$	-
BESIII (double-tag) [11]	$<1.8\times10^{-3}$	-
BaBar experiment [12]	-	$<2.5\times10^{-4}$
BESIII (single-tag)	$<5.0\times10^{-4}$	$<6.5\times10^{-4}$

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