

Search for baryon and lepton number violating decays

$$D^+ \rightarrow \bar{\Lambda}(\bar{\Sigma}^0)e^+ \text{ and } D^+ \rightarrow \Lambda(\Sigma^0)e^+$$

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Using a 2.93 fb^{-1} data sample of electron-positron collisions taken with the BESIII detector at a center-of-mass energy of 3.773 GeV , which corresponds to $(8296 \pm 31 \pm 64) \times 10^3 D^+ D^-$ pairs, we search for the baryon and lepton number violating decays $D^+ \rightarrow \bar{\Lambda}(\bar{\Sigma}^0)e^+$ and $D^+ \rightarrow \Lambda(\Sigma^0)e^+$. No obvious signals are found with the current statistics and upper limits on the branching fractions of these four decays are set at the level of 10^{-6} at 90% confidence level.

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I. INTRODUCTION

In the standard model (SM), baryon number is conserved as a consequence of the $SU(2) \times U(1)$ and $SU(3)$ gauge symmetries. However, the fact that there is an excess of baryons over antibaryons in the Universe suggests the existence of baryon number violating (BNV) processes. Thus, the search for BNV processes can shed light on the evolution of the Universe. For decades, the decay of the proton, which is the lightest baryon, has been searched for, but no evidence for its decay has yet been found. An alternative probe is to look for the BNV decays of heavy mesons. Various SM extensions with BNV processes have been proposed [1–8]. Under dimension six operators, BNV processes can happen with $\Delta(B - L) = 0$, where $\Delta(B - L)$ is the change in the difference between baryon and lepton numbers. In models including heavy gauge bosons X with charge $\frac{4}{3}$ and gauge bosons Y with charge $\frac{1}{3}$, one obtains the Feynman diagrams for BNV decays of D mesons shown in Figs. 1(a) and 1(b). Another class of BNV operators is the class of dimension seven operators where $\Delta(B - L) = 2$, as shown in the Feynman diagrams in Figs. 1(c) and 1(d). Reference [5] argues that the decay amplitudes of these two kinds of BNV processes may be comparable. A higher generation supersymmetry (SUSY) model predicts that the branching fraction (BF) of $D^+ \rightarrow \bar{\Lambda}\ell^+$ is no more than 10^{-29} [8] with the experimental limit of proton decay, where ℓ^+ represents e^+ or μ^+ . D^+ BNV decays

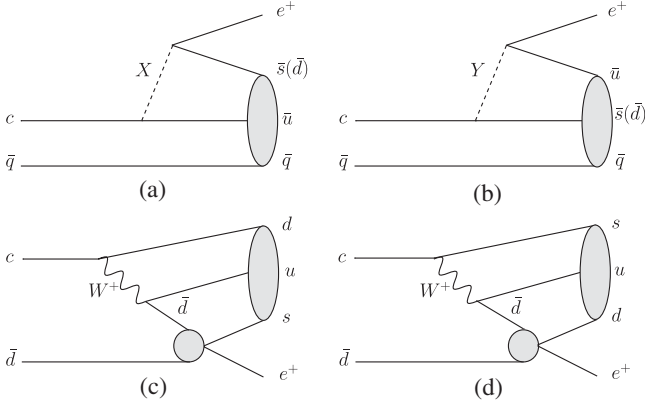


FIG. 1. Feynman diagrams for the BNV decays of D mesons with $\Delta(B-L)$ equal to 0 [(a) and (b)] and 2 [(c) and (d)].

to the $\bar{\Sigma}^0$ baryon should have a BF at similar magnitude. Nevertheless, an experimental search for these BNV decays will probe new physics effects and test theoretical models beyond the SM.

Previously, CLEO [9] and BABAR [10] searched for BNV processes in D and B decays, and recently hyperon BNV decays were searched at CLAS [11], but no evidence was found. The upper limits (ULs) at 90% confidence level were set to be at the level of 10^{-5} – 10^{-8} . In this paper, by analyzing 2.93 fb^{-1} of data taken at a center-of-mass energy of $\sqrt{s} = 3.773 \text{ GeV}$ with the BESIII detector, we report the first searches for the BNV decays $D^+ \rightarrow \bar{\Lambda} e^+$ and $D^+ \rightarrow \bar{\Sigma}^0 e^+$ with $\Delta(B-L) = 0$, as well as $D^+ \rightarrow \Lambda e^+$ and $D^+ \rightarrow \Sigma^0 e^+$ with $\Delta(B-L) = 2$. Throughout this paper, charge-conjugated channels are implied unless explicitly stated.

II. THE BESIII EXPERIMENT AND DATA SAMPLE

The BESIII detector is a magnetic spectrometer [12] located at the Beijing Electron Positron Collider [13]. The cylindrical core of the BESIII detector consists of a helium-based multilayer drift chamber, 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 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 region is 68 ps, while that of the end cap is 110 ps.

Simulated samples of events produced with a GEANT4-based [14] 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^- annihilations modeled with the generator KKMC [15]. The inclusive MC samples consist of the production of $D\bar{D}$ pairs including quantum coherence for all neutral D modes, the non- $D\bar{D}$ decays of the $\psi(3770)$, the ISR production of the J/ψ and $\psi(3686)$ states, and the continuum processes incorporated in KKMC [15]. The known decay modes are modeled with EVTGEN [16,17] using BFs taken from the Particle Data Group (PDG) [18], and the remaining unknown decays of the charmonium states are simulated with LUNDCHARM [19,20]. Final state radiation from charged final state particles is incorporated with the PHOTOS [21] package.

III. EVENT SELECTION

To avoid possible bias, a blind analysis technique is followed where the data are viewed only after the analysis procedure is fixed and validated with MC simulation. The BNV decays are searched for using all tracks reconstructed within the polar angle range $|\cos\theta| < 0.93$ with respect to the beam axis. The Λ and Σ^0 baryons are reconstructed via the $\Lambda \rightarrow p\pi^-$ and $\Sigma^0 \rightarrow \gamma\Lambda$ decays, respectively. Each track used to reconstruct a Λ baryon is required to have a distance of closest approach to the interaction point (IP) along the beam axis of less than 20 cm. Particle identification (PID) is applied to the charged tracks using information from the dE/dx and TOF measurements. The confidence levels for pion, kaon, and proton hypotheses (CL_π , CL_K , and CL_p) are calculated. The proton candidates are required to satisfy $CL_p > 0.001$, $CL_p > CL_\pi$, and $CL_p > CL_K$, while no PID is required for the pion candidates. A vertex fit is performed to constrain the proton and pion tracks to a common vertex and the χ^2 of the fit is required to be less than 100. The distance between the IP and the Λ decay vertex is required to be larger than 2 standard deviations of the vertex resolution, and the invariant mass of the $p\pi^-$ combination is required to be within (1.110, 1.121) GeV/ c^2 .

Photons are selected from the isolated EMC showers whose energy lost in the TOF has been recovered. The shower must start within 700 ns of the event start time and is required to have an energy greater than 25 (50) MeV in the barrel (end-cap) region of the EMC. The minimum opening angle between the shower and any charged track has to be greater than 10° . To form a Σ^0 candidate, the invariant mass of the $\gamma p\pi^-$ combination is required to be within (1.173, 1.200) GeV/ c^2 . Figure 2 shows the invariant mass distributions of the Λ and Σ^0 candidates in the MC simulation.

The positron candidates are required to have a distance of closest approach to the IP of less than 1 cm in the transverse plane and less than 10 cm along the beam axis. Positron PID is performed using dE/dx , TOF, and EMC information, with which the confidence levels for positron, pion, kaon, and proton hypotheses (CL_e , CL_π , CL_K ,

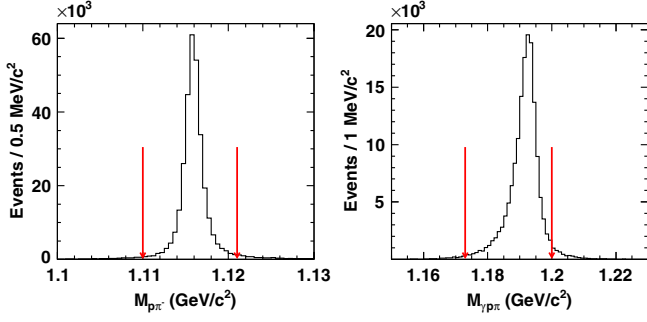


FIG. 2. The invariant mass distributions of the Λ (left) and Σ^0 (right) candidates from the generated signal MC events, where the arrows give the mass windows.

and CL_p) are calculated. Positron candidates are required to satisfy $CL_e > 0.001$ and

$$\frac{CL_e}{CL_e + CL_\pi + CL_K + CL_p} > 0.8. \quad (1)$$

In addition, the ratio of the energy deposited in the EMC by the positron over its momentum (E/p) is required to be within (0.8,1.2).

The BNV decays of the D^+ mesons are identified using the energy difference $\Delta E = E_D - E_{\text{beam}}$ and the beam constrained mass $M_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - p_D^2}$, where E_{beam} is the beam energy, and E_D and p_D are the energy and momentum of the D^+ candidate in the rest frame of the e^+e^- system. When multiple candidates for a specific signal mode are present, the one with ΔE nearest to 0 is retained. The D^+ candidate must satisfy $-0.023 < \Delta E < 0.022$ ($-0.028 < \Delta E < 0.024$) GeV for $D^+ \rightarrow \Lambda e^+$ and $D^+ \rightarrow \bar{\Lambda} e^+$ ($D^+ \rightarrow \Sigma^0 e^+$ and $D^+ \rightarrow \bar{\Sigma}^0 e^+$), as shown in Fig. 3.

Studies of MC samples show that there remain a few backgrounds coming from misreconstructed Λ , e.g., $D^+ \rightarrow \bar{K}^0 e^+ \nu_e$ and $D^+ \rightarrow \bar{K}^*(892)^0 e^+ \nu_e$. However, most backgrounds are from processes other than $\psi(3770) \rightarrow D\bar{D}$ where a real $\Lambda(\bar{\Lambda})$ is produced. In this case, the reconstructed positron candidates are mainly from photon conversion, decay products of pions, muons, or kaons,

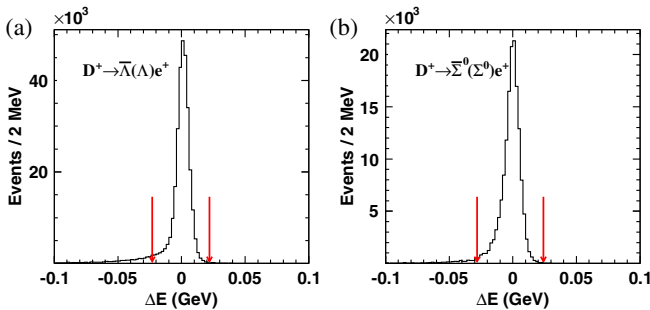


FIG. 3. The ΔE distributions from generated signal MC events for $D^+ \rightarrow \bar{\Lambda}(\Lambda)e^+$ (a) and $D^+ \rightarrow \bar{\Sigma}^0(\Sigma^0)e^+$ (b), where the arrows give the signal windows.

as well as misidentification from other kinds of particles. Backgrounds produced due to photon conversion are identified using the technique introduced in Ref. [22]. An electron-positron pair is formed by looping over all electrons in the event. The electron with minimum angle relative to the positron candidate is chosen. Three variables, the minimum signed distance between the electron and positron in the xy plane Δ_{xy} , the polar angle of the direction of the conversion photon with respect to the vector from the IP to the common vertex of the electron-positron pair θ_{eg} , and the distance between the common vertex of the electron-positron pair and the IP in the xy plane R_{xy} , are defined. Events with $-2 < \Delta_{xy} < 1$ cm, $\cos \theta_{eg} > 0.8$, and $R_{xy} > 2$ are identified as background associated with photon conversions and are rejected. To suppress backgrounds from the $e^+e^- \rightarrow q\bar{q}$ process and charmonium decays which may contain a baryon-antibaryon pair, we require that no charged particle satisfies the proton PID criteria, except the proton from the BNV decay candidate.

Figure 4 shows the M_{BC} distributions of the accepted candidate events in data and inclusive MC samples. A maximum likelihood fit to the M_{BC} distribution is performed on each distribution of data to extract the number of signal events in each signal decay mode. In the fit, the signal is modeled by an MC-simulated shape convolved with a Gaussian to account for the resolution difference between data and MC simulation and the background is modeled by an ARGUS function [23], which has been found to be in agreement with inclusive MC samples. The end point of the ARGUS function is fixed at the beam energy and other parameters are determined from the fit. The data/MC difference in M_{BC} resolution is estimated using the topologically similar decays $D^+ \rightarrow K_S^0 \pi^+$ and $D^+ \rightarrow K_S^0 \pi^+ \pi^0$ for signal channels involving Λ and Σ^0 ,

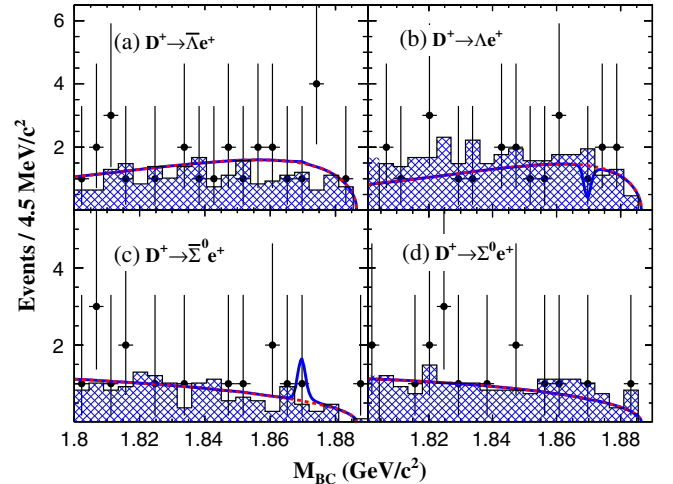


FIG. 4. Fits to the M_{BC} distributions of the accepted candidate events in data, where the dots with error bars are data, the solid curves are the best fits, and the red dashed curves are the background shapes. The blue hatched histograms are the MC-simulated backgrounds scaled to data according to the luminosity.

respectively. The efficiencies of reconstructing the four signal decay modes are estimated using the signal MC samples, in which signal events are generated with unpolarized particles.

IV. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the searches for these BNV decays excluding those involved in the M_{BC} fit are summarized in Table I. The total number of D^+D^- pairs in the data set was previously measured in Ref. [24] with an uncertainty of 0.9%. The uncertainties in the tracking and PID efficiencies of the positron are studied using $e^+e^- \rightarrow \gamma e^+e^-$ events. To account for the difference in kinematics between the positrons in the control sample and the signal decays, the tracking and PID efficiencies are estimated by weighting the efficiencies extracted from the control sample in two-dimensional (momentum and $\cos\theta$) distributions. The differences of the weighted efficiencies between data and MC simulation, which are 0.3% for tracking and 1.0% for PID, are taken as the associated systematic uncertainties. The uncertainty in the reconstruction efficiency of $\Lambda(\bar{\Lambda})$ was previously studied in Ref. [25] using $J/\psi \rightarrow \Lambda\bar{\Lambda}\pi^+\pi^-$ events. The momentum-weighted difference of $\Lambda(\bar{\Lambda})$ reconstruction efficiencies between data and MC simulation is 1.5%, which is assigned as an uncertainty of the $\Lambda(\bar{\Lambda})$ reconstruction. This includes the uncertainties in the tracking efficiencies of the pion and proton, the PID efficiency of the proton, the decay length requirement, and the mass window. For decays involving the $\Sigma^0(\bar{\Sigma}^0)$ baryon, the uncertainty in the photon reconstruction efficiency is taken to be 1.0% according to the previous study using $J/\psi \rightarrow \pi^+\pi^-\pi^0$ events [26]. The uncertainty in the requirement of the mass window of the $\Sigma^0(\bar{\Sigma}^0)$ baryon is studied with $J/\psi \rightarrow pK^-\bar{\Sigma}^0 + c.c.$ events, and is found to be negligible. The uncertainties in the ΔE requirement are estimated by smearing the MC simulated ΔE distributions with Gaussian functions accounting for the resolution difference between data

TABLE I. The systematic uncertainties excluding those involved in the M_{BC} fit (in %) for the four signal channels.

Source	$\bar{\Lambda}e^+$	Λe^+	$\bar{\Sigma}^0 e^+$	$\Sigma^0 e^+$
$N_{D^+D^-}^{\text{tot}}$	0.9	0.9	0.9	0.9
ΔE cut	0.6	0.6	0.9	0.9
$\Lambda(\bar{\Lambda})$ reconstruction	1.5	1.5	1.5	1.5
$\Sigma^0(\bar{\Sigma}^0)$ mass window			<0.1	<0.1
e^+ tracking	0.3	0.3	0.3	0.3
e^+ PID	1.0	1.0	1.0	1.0
γ reconstruction			1.0	1.0
MC statistics	0.3	0.4	0.4	0.4
No extra (anti-)proton	0.3	0.3	0.3	0.3
Photon conversion veto	0.5	0.5	0.5	0.5
Quoted BF(s)	0.8	0.8	0.9	0.9
Total	2.4	2.4	2.7	2.7

and MC simulation. The efficiency changes after smearing are taken to be the associated systematic uncertainties, which are 0.6%, 0.6%, 0.9%, and 0.9% for $D^+ \rightarrow \bar{\Lambda}e^+$, $D^+ \rightarrow \Lambda e^+$, $D^+ \rightarrow \bar{\Sigma}^0 e^+$, and $D^+ \rightarrow \Sigma^0 e^+$, respectively. To study the uncertainty in the photon conversion veto, we separately examine the data-MC difference in finding an extra electron in the system recoiling against the D^+ meson and that for the R_{xy} , Δ_{xy} and $\cos\theta_{eg}$ requirement. The former is studied using the selected $D^+ \rightarrow K_S^0\pi^+$ vs $D^- \rightarrow \text{anything}$ sample, and the latter with $J/\psi \rightarrow \pi^+\pi^-\pi^0$, $\pi^0 \rightarrow \gamma e^+e^-$ events. Combining these two studies, we assign 0.5% for the uncertainty in the photon conversion veto for the four signal decay modes. The uncertainty in the requirement of no extra proton (antiproton) is studied using the selected $D^+ \rightarrow K_S^0\pi^+$ vs $D^- \rightarrow \text{anything}$ sample. The difference of the acceptance rates of no additional proton (antiproton) between data and MC simulation, 0.3%, is assigned as the associated uncertainty. We take 0.8% as the uncertainty in the BF of $\Lambda \rightarrow p\pi^-$ quoted from the PDG [18] and 0.5% for $\Sigma^0 \rightarrow \gamma\Lambda$ by referring to a theoretical value of the BF of $\Sigma^0 \rightarrow \Lambda e^+e^-$ [27]. In total, the uncertainties of the quoted BFs are 0.8% for $D^+ \rightarrow \bar{\Lambda}(\Lambda)e^+$ and 0.9% for $D^+ \rightarrow \bar{\Sigma}^0(\Sigma^0)e^+$. The limited MC statistics is also taken into account as a source of systematic uncertainty. The total systematic uncertainties are obtained by adding these uncertainties in quadrature.

V. UPPER LIMIT ESTIMATION

Since no significant signals are observed, we set the ULs on the BFs at 90% confidence level for the four signal decay modes. This is done by scanning the ratio of the likelihood value given the number of signal events and the maximum likelihood value [$\lambda(N_{\text{sig}})$] in the M_{BC} fit. The likelihood ratio distribution is then convoluted with a Gaussian function with corresponding width to incorporate the systematic

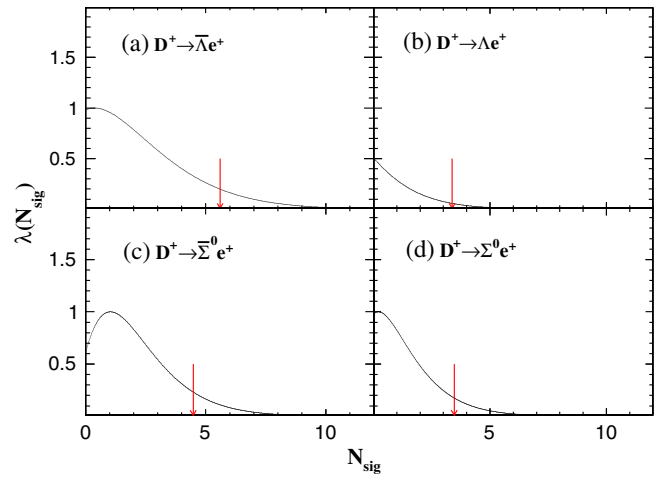


FIG. 5. The likelihood ratio distributions with respect to the number of signal events, where the red arrows give the upper limits at 90% confidence level.

TABLE II. The ULs on the number of signal events at 90% confidence level, the detection efficiencies not including the BFs of the secondary decays, and the corresponding ULs on the BFs for the four signal decay modes, where the systematic uncertainties have been included.

Mode	$N_{\text{sig}}^{\text{UL}}$	ϵ (%)	\mathcal{B}^{UL}
Λe^+	5.6	31.11 ± 0.14	1.1×10^{-6}
$\bar{\Lambda} e^+$	3.4	31.18 ± 0.10	6.5×10^{-7}
$\Sigma^0 e^+$	4.5	16.31 ± 0.07	1.7×10^{-6}
$\bar{\Sigma}^0 e^+$	3.5	16.40 ± 0.07	1.3×10^{-6}

uncertainties. The ULs on the number of signal events at 90% confidence level ($N_{\text{sig}}^{\text{UL}}$) are extracted by integrating over the physics region and finding the solution of

$$\int_0^{N_{\text{sig}}^{\text{UL}}} N_{\text{sample}} dN_{\text{sig}} / \int_0^{\infty} N_{\text{sample}} dN_{\text{sig}} = 90\%, \quad (2)$$

where $N_{\text{sample}} dN_{\text{sig}}$ is the number of samples with the signal events between N_{sig} and $N_{\text{sig}} + dN_{\text{sig}}$. In addition, to account for the uncertainties introduced in the fitting method, we vary the signal shape, background shape and fitting range and keep the maximum $N_{\text{sig}}^{\text{UL}}$ given for each signal decay. To be specific, the signal shape is varied by changing the width of the convoluted Gaussian according to its uncertainty; the end point of the ARGUS function is altered from 1.8865 GeV/ c^2 to 1.8864 and 1.8866 GeV/ c^2 ; and the fit is performed within three different regions: (1.80,1.89), (1.81,1.89), and (1.82, 1.89) GeV/ c^2 . Figure 5 shows the likelihood ratio distributions with respect to the number of signal events for the four signal decays. For each signal decay mode, the UL on the BF is calculated as

$$\mathcal{B}^{\text{UL}} = N_{\text{sig}}^{\text{UL}} / (2 \times N_{D^+D^-}^{\text{tot}} \times \epsilon \times \mathcal{B}_{\Lambda, \Sigma^0}), \quad (3)$$

where $N_{D^+D^-}^{\text{tot}}$ is the total number of D^+D^- pairs which was measured to be $(8296 \pm 31 \pm 64) \times 10^3$ [24], ϵ is the signal efficiency and $\mathcal{B}_{\Lambda, \Sigma^0}$ represents the BFs of the secondary decays used to reconstruct Λ and Σ^0 . Table II summarizes the ULs on the numbers of signal events in data, the signal efficiencies and the corresponding ULs on the BFs for the four signal decay modes.

VI. SUMMARY

In summary, using 2.93 fb $^{-1}$ of data taken at $\sqrt{s} = 3.773$ GeV with the BESIII detector, we have searched for the BNV decays $D^+ \rightarrow \bar{\Lambda} e^+$, $D^+ \rightarrow \bar{\Sigma}^0 e^+$, $D^+ \rightarrow \Lambda e^+$, and $D^+ \rightarrow \Sigma^0 e^+$ for the first time with the assumption of no preferred polarization of the final products. No obvious signals are found, and the ULs on the BFs of these decays are set at 90% confidence level, as shown in Table II. Our limits are far above the prediction of the higher generation model [8].

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