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Search for baryon and lepton number violating decays  $D \rightarrow p\ell$ 

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We search for the baryon and lepton number violating charm decays,  $D \rightarrow p\ell$ , where  $D$  is either a  $D^0$  or a  $\bar{D}^0$  and  $\ell$  is a muon or an electron, using a data sample of  $921 \text{ fb}^{-1}$  collected by the Belle detector at the KEKB asymmetric energy  $e^+e^-$  collider. In the absence of significant signals, we set upper limits on the branching fractions in the range  $(5\text{--}8) \times 10^{-7}$  at a 90% confidence level, depending on the decay mode.

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Baryon number violation (BNV) is one of the crucial ingredients to create the matter-antimatter asymmetry as observed in the Universe [1]. The known particles and antiparticles and the interactions among them are described by the Standard Model (SM). Several grand unified theories [2–6], supersymmetry and other SM extensions [7,8] propose BNV processes of nucleons. In these models, baryon ( $B$ ) and lepton ( $L$ ) numbers are explicitly violated but the difference between these numbers is conserved i.e.,  $\Delta(B - L) = 0$ . Several attempts [9–12] have been made to search for the decays of the lightest baryon, namely the proton, but no evidence for its decay has yet been found. Searches for decays of heavy mesons to final states with

nonzero  $B$  values can provide an alternative probe for BNV decays. Various non-SM models of proton decays can be extended to predict possible decay mechanisms for  $D$  decays. For example, analogous to proton decays [13], the decays of  $D^0 \rightarrow \bar{p}\ell^+$  can be explained using leptoquark couplings. Figure 1 shows possible Feynman diagrams for  $D^0 \rightarrow \bar{p}\ell^+$  decays, where the mediators are non-SM gauge bosons. Decays of the  $D$  meson to final states containing a proton probe BNV within the first two generations. The branching fractions for  $D^0 \rightarrow \bar{p}e^+$  are predicted to be of the order of  $10^{-39}$  [14].

The  $D \rightarrow p\ell$  decays simultaneously violate  $B$  and  $L$  but conserve  $(B - L)$ . Further, leptoquarks have been proposed to explain recent anomalies reported by different experiments [15–20] and the  $D \rightarrow p\ell$  search will provide valuable input to the search for leptoquarks.

Experimentally, various BNV processes in  $D$ ,  $B$ -meson, and  $\Lambda$  decays were searched for by the CLEO [21], BABAR [22], and CLAS [23] Collaborations, respectively,

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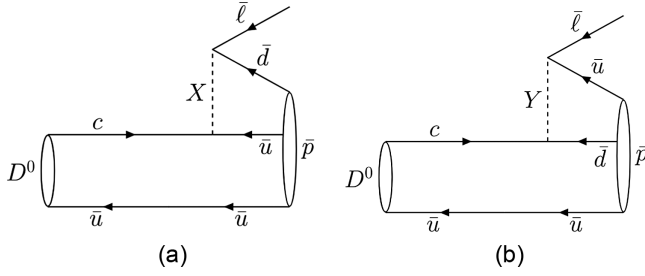


FIG. 1. Feynman diagrams of the decays  $D^0 \rightarrow \bar{p}\ell^+$  with non-SM gauge bosons (a)  $X$  and (b)  $Y$ .

but no evidence for a signal was found. The BESIII Collaboration has searched for  $D \rightarrow pe$  decay modes and set 90% confidence-level upper limits on the branching fractions of  $\mathcal{B}(D^0 \rightarrow \bar{p}e^+) < 1.2 \times 10^{-6}$  and  $\mathcal{B}(D^0 \rightarrow pe^-) < 2.2 \times 10^{-6}$  [24], and these are currently the most stringent limits. The large data sample collected by the Belle experiment provides improved sensitivity for BNV decays of charm mesons. We set limits for the  $D^0$  and  $\bar{D}^0$  decays separately for the first time. In this paper, we report a search for the  $D$  meson decay modes  $D^0 \rightarrow p\ell^-$ ,  $\bar{D}^0 \rightarrow p\ell^-$ ,  $D^0 \rightarrow \bar{p}\ell^+$ , and  $\bar{D}^0 \rightarrow \bar{p}\ell^+$ , where  $\ell$  is  $e$  or  $\mu$ , using the data collected with the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  collider [25,26] located at the High Energy Accelerator Research Organization in Japan. The data used in this analysis were collected at  $e^+e^-$  center-of-mass (c.m.) energies at and 60 MeV below the  $\Upsilon(4S)$  resonance, and at the  $\Upsilon(5S)$  resonance with integrated luminosities of  $711 \text{ fb}^{-1}$ ,  $89 \text{ fb}^{-1}$ , and  $121 \text{ fb}^{-1}$ , respectively. The total integrated luminosity is  $921 \text{ fb}^{-1}$ . Throughout this paper, charge conjugate modes are implicitly included, unless otherwise noted.

The Belle detector is a large solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight (TOF) scintillation counters, and a CsI(Tl) crystal based electromagnetic calorimeter (ECL); all are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return yoke placed outside the coil is instrumented with resistive plate chambers to detect  $K_L^0$  mesons and muons (KLM). A more detailed description of the detector can be found in Ref. [27].

Monte Carlo (MC) simulation samples are used to optimize the selection criteria, estimate the signal reconstruction efficiencies, and identify and model the distributions of various sources of background. The signal MC sample for each decay mode is generated using EvtGen [28] where  $e^+e^- \rightarrow q\bar{q}$  generated with PYTHIA [29] and PHOTOS [30] takes into account final state radiations. The produced particles are propagated with GEANT3 [31] to simulate a detector response. The well-established

$D^0 \rightarrow K^-\pi^+$  decay mode is used for normalization to measure the branching fractions of signal modes.

Reconstructed trajectories of charged particles (tracks) are required to originate from the interaction point (IP) and have a point of closest approach to the latter within 3.0 cm along the  $e^+$  beam axis and 1.0 cm in the transverse plane. These requirements remove tracks not originating from the IP. Additionally, the tracks are required to have at least two hits in the SVD. The final-state charged hadrons (pions, kaons, and protons) are identified based on the number of Cherenkov photons in the ACC, and TOF and  $dE/dx$  measurements. All of this information is combined to form pion, kaon, and proton likelihoods,  $\mathcal{L}_\pi$ ,  $\mathcal{L}_K$ , and  $\mathcal{L}_p$ , respectively. The selection is made on the basis of likelihood ratios,  $\mathcal{L}_{i/j} = \mathcal{L}_i/(\mathcal{L}_i + \mathcal{L}_j)$ , where  $i$  and  $j$  are  $\pi$ ,  $K$  or  $p$ . Protons are identified by requiring  $\mathcal{L}_{p/\pi} > 0.6$  and  $\mathcal{L}_{p/K} > 0.6$  with an identification efficiency of 90% while the probability of misidentifying a kaon or a pion as a proton is 3%. Kaons and pions are selected by requiring  $\mathcal{L}_{K/\pi} > 0.6$  and  $\mathcal{L}_{\pi/K} > 0.6$ , respectively. The identification efficiencies for kaons and pions are 95% and 94%, respectively. The probability of misidentifying a pion (kaon) as a kaon (pion) is 4% (5%).

The electromagnetic shower shape,  $E_{\text{ECL}}/p$  ratio, where  $E_{\text{ECL}}$  is the energy deposition in the ECL and  $p$  is the track momentum, and the position matching between track and ECL cluster are utilized for electron identification, in addition to the information used for charged hadron identification excluding that from the TOF. All this information is combined to form an electron likelihood ratio,  $\mathcal{L}_e$  and the electrons are identified requiring  $\mathcal{L}_e > 0.9$ . To recover the energy loss due to bremsstrahlung, we search for photons in a cone of 50 mrad around the initial direction of the electron momentum; if found, their momenta are added to that of the electron. Muons are identified by using the track penetration depth, hit distribution pattern in the KLM, and matching quality. This information is combined to form a muon likelihood  $\mathcal{L}_\mu$ . Muons are identified by requiring a likelihood ratio of  $\mathcal{L}_\mu/(\mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K) > 0.9$ . The electron (muon) identification efficiency for these criteria is 93% (94%) with a probability of misidentifying a pion as an electron (a muon) below 0.5% (4%). The kaon-to-electron misidentification rate is negligible, while the probability of identifying a kaon as a muon is similar to that of identifying a pion as a muon. All the quoted identification efficiencies and misidentification probabilities are averaged over the momenta of final-state particles.

Tracks with momentum greater than 0.6 GeV/ $c$  are used to reconstruct  $D^0$  candidates in the  $K^-\pi^+$ ,  $pe^-$ ,  $\bar{p}e^+$ ,  $p\mu^-$ , and  $\bar{p}\mu^+$  final states. The invariant mass of a  $D^0$  candidate is required to be in the range  $1.8 < M_{D^0} < 1.9 \text{ GeV}/c^2$ . We reconstruct a  $D^{*+}$  candidate by combining the  $D^0$  candidate with a slow pion ( $\pi_s^+$ ). We require all the signal  $D^0$  s to come from  $D^{*+}$ , where  $D^0$  and  $\bar{D}^0$  flavors are

determined by the  $\pi_s$  charge in  $D^{*+} \rightarrow D^0\pi_s^+$ . The mass difference,  $\Delta M = M_{D^{*+}} - M_{D^0}$ , where  $M_{D^{*+}}$  ( $M_{D^0}$ ) is the invariant mass of the  $D^{*+}$  ( $D^0$ ) candidate, is required to be less than  $0.158 \text{ GeV}/c^2$ . In order to improve the  $\Delta M$  resolution, the  $\pi_s^+$  is constrained to originate from the IP. The momentum of the  $D^{*+}$  candidate in the c.m. frame is required to be greater than  $2.5 \text{ GeV}/c$  to reduce  $B\bar{B}$  and combinatorial backgrounds. A vertex fit is performed on the selected  $D^{*+}$  candidates. After applying all the selection criteria, a small fraction (0.4%) of the selected events have more than one  $D^{*+}$  candidate. In an event with multiple  $D^{*+}$  candidates, we select the one that has the lowest  $\chi^2$  value associated with the  $D^{*+}$  vertex fit. The efficiency of such candidate selection ranges from 85% to 94% depending on the decay mode and is 83% for the normalization mode.

We study the background using simulated samples corresponding to an integrated luminosity of about 4.5 times that of the Belle data sample. In the  $\bar{D}^0 \rightarrow pe^-$  and  $D^0 \rightarrow \bar{p}e^+$  modes, background from semileptonic  $D \rightarrow K\nu_e$  decay is found to peak in the  $\Delta M$  signal region, while for the  $D^0 \rightarrow pe^-$  and  $\bar{D}^0 \rightarrow \bar{p}e^+$  decay modes, no such peaking structure is observed. Peaking background in the  $\Delta M$  distribution of the  $\bar{D}^0 \rightarrow p\mu^-$  and  $D^0 \rightarrow \bar{p}\mu^+$  modes arises from  $D \rightarrow K\rho$ ,  $K^*\pi$ ,  $KK$ , and  $K\mu\nu_\mu$  decays. In  $D^0 \rightarrow p\mu^-$ , a tiny peaking structure is observed from the  $D \rightarrow KK$  decay mode. The peaking structure in the aforementioned modes is observed owing to the misidentification of final-state particles. There is no peaking structure in  $M_{D^0}$  for any of the signal modes.

For the  $D^0 \rightarrow K^-\pi^+$  normalization mode, small background contributions originate from the correct  $D^0$  candidate's combination with a random  $\pi_s$ , as well as from partially reconstructed  $D^0$  decays. The signal purity for  $D^0 \rightarrow K^-\pi^+$  is 95% in a region around the  $M_{D^0}$  and  $\Delta M$  signal peaks that contain 78% of the  $D^0$  candidates. We reconstruct over 1.7 million events with an efficiency of 13.5%.

Signal yields are extracted with extended maximum-likelihood fits to the unbinned  $M_{D^0}$  and  $\Delta M$  distributions of each decay mode. Separate probability density functions (PDFs) are used for signal, peaking and combinatorial backgrounds. For signal events, the PDF for the  $\Delta M$  distribution is parametrized by using the sum of four Gaussians, while the  $M_{D^0}$  PDF is modeled by the sum of two Gaussians and one asymmetric Gaussian with separate parameters for each decay mode. The core Gaussian parameters for the  $D^0 \rightarrow K^-\pi^+$  decay mode are allowed to vary in the fit, while for the  $D^0 \rightarrow p\ell$  decay modes, they are fixed to the values obtained from simulated signal events calibrated with data; the calibration is determined by comparing the shape parameters between data and simulation for the  $D^0 \rightarrow K^-\pi^+$  decay. All the remaining shape parameters of signal PDF are fixed to those obtained in the fit to simulated signal events.

The peaking background PDF in  $\Delta M$  is modeled by the sum of two asymmetric Gaussians for the  $\bar{D}^0 \rightarrow pe^-$  and  $D^0 \rightarrow \bar{p}e^+$  modes. The sum of the  $D \rightarrow K\mu\nu_\mu$ ,  $D \rightarrow K\rho$  and  $D \rightarrow K^*\pi$  components is modeled by the sum of two asymmetric Gaussians for the  $\bar{D}^0 \rightarrow p\mu^-$  and  $D^0 \rightarrow \bar{p}\mu^+$  modes. The  $D \rightarrow KK$  component is parametrized by the sum of two Gaussians for the  $D^0 \rightarrow p\mu^-$  decay mode. The background components in  $M_{D^0}$  are modeled by a first-order polynomial for all the decay modes. For the normalization mode, the background from random  $\pi_s$  in  $\Delta M$  is parametrized by a threshold function, defined as

$$f(\Delta M) = (\Delta M - m_\pi)^a e^{-b(\Delta M - m_\pi)}, \quad (1)$$

where  $m_\pi$  is the known charged pion mass [32] and  $a$ ,  $b$  are the shape parameters. The background from partially reconstructed  $D$  decays is parametrized by a Gaussian in  $\Delta M$ . The aforementioned two backgrounds are parametrized by a Gaussian function and a second-order polynomial, respectively, in  $M_{D^0}$ .

For the combinatorial background for each decay mode, the PDF for  $\Delta M$  is parametrized by the threshold function. The combinatorial background PDF for  $M_{D^0}$  is modeled by a first- and second-order polynomial for the signal and normalization decay mode, respectively. The parameters of the combinatorial background PDF for signal modes are fixed except for  $D^0 \rightarrow pe^-$ ,  $\bar{D}^0 \rightarrow \bar{p}e^+$ ,  $D^0 \rightarrow p\mu^-$ , and  $\bar{D}^0 \rightarrow \bar{p}\mu^+$  decay modes in which cases they are floated. The parameters of the combinatorial background PDF for the normalization mode,  $D^0 \rightarrow K^-\pi^+$ , are floated. The fit projections for the  $M_{D^0}$  and  $\Delta M$  distributions are shown in Figs. 2–4 for the  $D^0 \rightarrow K^-\pi^+$ ,  $D \rightarrow pe$ , and  $D \rightarrow p\mu$  decay modes, respectively. The obtained signal yields are listed in Table I.

The branching fractions ( $\mathcal{B}$ ) for  $D^0 \rightarrow p\ell$  decay modes are measured using

$$\mathcal{B}(D \rightarrow p\ell) = \frac{N_{p\ell} \epsilon_{K\pi}}{N_{K\pi} \epsilon_{p\ell}} \mathcal{B}(D^0 \rightarrow K^-\pi^+), \quad (2)$$

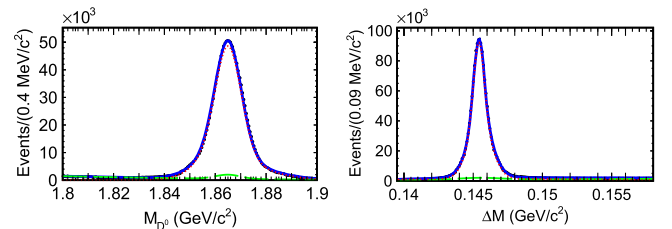


FIG. 2. Fit projections for the  $M_{D^0}$  (left) and  $\Delta M$  (right) distributions for the  $D^0 \rightarrow K^-\pi^+$  normalization mode. The red dotted curves show the fit function for the signal, the green dashed curves show the fit function for the total background, and the blue solid curves show the sum of the fit functions.

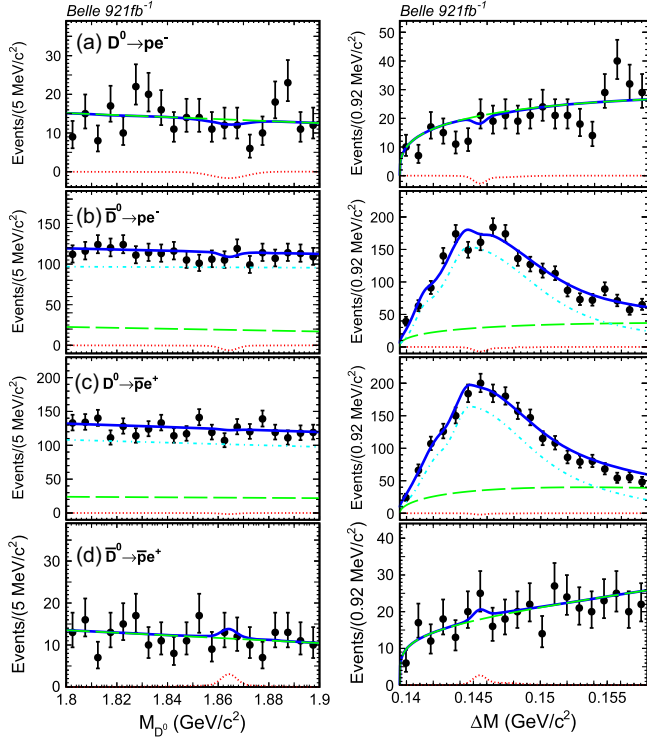


FIG. 3. Fit projections for the  $M_{D^0}$  (left) and  $\Delta M$  (right) distributions for the (a)  $D^0 \rightarrow pe^-$ , (b)  $\bar{D}^0 \rightarrow pe^-$ , (c)  $D^0 \rightarrow \bar{p}e^+$ , and (d)  $\bar{D}^0 \rightarrow \bar{p}e^+$  decay modes. The red dotted curves show the fit function for the signal, the green dashed curves show the fit function for the combinatorial background, the cyan dashed-dotted curves show the fit function for the peaking background, and the blue solid curves show the sum of the fit functions.

where  $N_{p\ell}$  ( $N_{K\pi}$ ) and  $\epsilon_{p\ell}$  ( $\epsilon_{K\pi}$ ) are the number of  $D^0$  mesons and the efficiency for the signal (normalization) mode, respectively. The obtained signal yields, reconstruction efficiencies, upper limits on the signal yield and branching fractions for  $D^0 \rightarrow p\ell$  decay modes are summarized in Table I.

The statistical significance ( $\mathcal{S}$ ) of the signal yield is evaluated using the likelihood ratio,  $\mathcal{S} = \sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\max})}$ , where  $\mathcal{L}_{\max}$  ( $\mathcal{L}_0$ ) is the likelihood of the nominal fit (null hypothesis). The signal significances obtained for the  $D^0 \rightarrow p\ell$  decay modes are summarized in Table I, after taking into account the systematic uncertainties. In the absence of a significant signal, an upper limit is calculated for each signal yield at 90% confidence level using a frequentist technique [33]. We generate toy experiments using the shape and background yield from the fitted PDF and vary the input signal yield. For each input value, we calculate the fraction of the ensemble that gives a fitted signal yield less than or equal to what is obtained in the data. The upper limit on the signal yield is given at 90% confidence level. The upper limit on the branching fraction is calculated using Eq. (2) with  $N_{p\ell}$  replaced

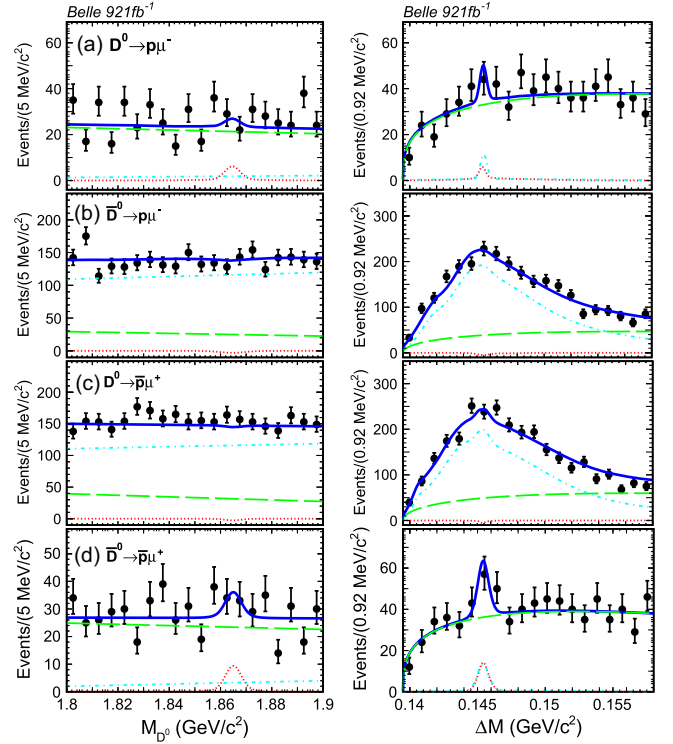


FIG. 4. Fit projection for the  $M_{D^0}$  (left) and  $\Delta M$  (right) distributions for the (a)  $D^0 \rightarrow p\mu^-$ , (b)  $\bar{D}^0 \rightarrow p\mu^-$ , (c)  $D^0 \rightarrow \bar{p}\mu^+$ , and (d)  $\bar{D}^0 \rightarrow \bar{p}\mu^+$  decay modes. The red dotted curves show the fit function for the signal, the green dashed curves show the fit function for the combinatorial background, the cyan dashed-dotted curves show the fit function for the peaking background, and the blue solid curves show the sum of the fit functions.

by  $N_{p\ell}^{UL}$ . Systematic uncertainties are included in the upper limit calculations by smearing the signal yield with the systematic uncertainty. The resulting upper limits on the signal yields and branching fractions are listed in Table I.

Table II summarizes the systematic uncertainties in the measured branching fractions from various sources.

TABLE I. Reconstruction efficiency ( $\epsilon$ ), signal yield ( $N_S$ ), signal significance ( $\mathcal{S}$ ), upper limit on the signal yield ( $N_{p\ell}^{UL}$ ), and branching fraction ( $\mathcal{B}$ ) at 90% confidence level for each decay mode.

| Decay mode                           | $\epsilon$ (%) | $N_S$            | $\mathcal{S}$ ( $\sigma$ ) | $N_{p\ell}^{UL}$ | $\mathcal{B} \times 10^{-7}$ |
|--------------------------------------|----------------|------------------|----------------------------|------------------|------------------------------|
| $D^0 \rightarrow pe^-$               | 10.2           | $-6.4 \pm 8.5$   |                            | 17.5             | $< 5.5$                      |
| $\bar{D}^0 \rightarrow pe^-$         | 10.2           | $-18.4 \pm 23.0$ |                            | 22.0             | $< 6.9$                      |
| $D^0 \rightarrow \bar{p}e^+$         | 09.7           | $-4.7 \pm 23.0$  |                            | 22.0             | $< 7.2$                      |
| $\bar{D}^0 \rightarrow \bar{p}e^+$   | 09.6           | $7.1 \pm 9.0$    | 0.6                        | 23.0             | $< 7.6$                      |
| $D^0 \rightarrow p\mu^-$             | 10.7           | $11.0 \pm 23.0$  | 0.9                        | 17.1             | $< 5.1$                      |
| $\bar{D}^0 \rightarrow p\mu^-$       | 10.7           | $-10.8 \pm 27.0$ |                            | 21.8             | $< 6.5$                      |
| $D^0 \rightarrow \bar{p}\mu^+$       | 10.5           | $-4.5 \pm 14.0$  |                            | 21.1             | $< 6.3$                      |
| $\bar{D}^0 \rightarrow \bar{p}\mu^+$ | 10.4           | $16.7 \pm 8.8$   | 1.6                        | 21.4             | $< 6.5$                      |

TABLE II. Summary of systematic uncertainties (%) due to normalization mode  $D^0 \rightarrow K^- \pi^+$  (Norm), proton ( $p$ ) and lepton ( $\ell$ ) identification, PDF used for signal extraction, fit bias from toy study (“...” denotes negligible bias) and tracking for  $D^0 \rightarrow p\ell$  decay modes.

| Decay mode                           | Norm | $p$ | $\ell$ | PDF  | Fit bias | Tracking | Total  |
|--------------------------------------|------|-----|--------|--|----------|----------|--|
| $D^0 \rightarrow pe^-$               | 1.8  | 0.3 | 1.6    | $\begin{smallmatrix} -1.1 \\ +4.7 \end{smallmatrix}$   | ...      | 0.7      | $\begin{smallmatrix} +5.3 \\ -2.8 \end{smallmatrix}$   |
| $\bar{D}^0 \rightarrow pe^-$         | 1.8  | 0.3 | 1.6    | $\begin{smallmatrix} +8.2 \\ -9.2 \end{smallmatrix}$   | ...      | 0.7      | $\begin{smallmatrix} +8.6 \\ -9.5 \end{smallmatrix}$   |
| $D^0 \rightarrow \bar{p}e^+$         | 1.8  | 0.3 | 1.6    | $\begin{smallmatrix} +11.1 \\ -8.1 \end{smallmatrix}$  | ...      | 0.7      | $\begin{smallmatrix} +11.4 \\ -8.5 \end{smallmatrix}$  |
| $\bar{D}^0 \rightarrow \bar{p}e^+$   | 1.8  | 0.3 | 1.6    | $\begin{smallmatrix} +6.4 \\ -2.0 \end{smallmatrix}$   | 1.7      | 0.7      | $\begin{smallmatrix} +7.1 \\ -3.6 \end{smallmatrix}$   |
| $D^0 \rightarrow p\mu^-$             | 1.8  | 0.4 | 1.8    | $\begin{smallmatrix} +3.7 \\ -7.8 \end{smallmatrix}$   | 2.2      | 0.7      | $\begin{smallmatrix} +5.1 \\ -8.5 \end{smallmatrix}$   |
| $\bar{D}^0 \rightarrow p\mu^-$       | 1.8  | 0.3 | 2.0    | $\begin{smallmatrix} +21.3 \\ -12.3 \end{smallmatrix}$ | ...      | 0.7      | $\begin{smallmatrix} +21.5 \\ -12.6 \end{smallmatrix}$ |
| $D^0 \rightarrow \bar{p}\mu^+$       | 1.8  | 0.3 | 1.5    | $\begin{smallmatrix} +21.7 \\ -18.2 \end{smallmatrix}$ | ...      | 0.7      | $\begin{smallmatrix} +21.8 \\ -18.4 \end{smallmatrix}$ |
| $\bar{D}^0 \rightarrow \bar{p}\mu^+$ | 1.8  | 0.3 | 1.6    | 6.0  | 2.4      | 0.7      | 6.9  |

The uncertainty on the track-finding efficiency is obtained using a control sample  $D^{*+} \rightarrow D^0 \pi_s^+$ ,  $D^0 \rightarrow \pi^+ \pi^- K_S^0$ ,  $K_S^0 \rightarrow \pi^+ \pi^-$  and is found to be 0.35% per track. For the particle identification efficiencies, calibration factors are obtained using  $D^{*+} \rightarrow D^0 \pi_s^+$  ( $D^0 \rightarrow K^- \pi^+$ ),  $\gamma\gamma \rightarrow \ell\ell$ , and  $\Lambda \rightarrow p\pi^-$  control samples for pion, leptons, and protons, respectively, to account for the differences between data and simulation. The resulting systematic uncertainties on the proton, pion, electron, and muon identification efficiencies lie within the range (0.3–0.4)%, (0.2–1.0)%, 1.6%, and (1.6–2.0)%, respectively, depending on the decay mode. The largest source of systematic uncertainty is the modeling of the  $M_{D^0}$  and  $\Delta M$  PDFs. The uncertainties on the PDF shapes are obtained by varying each of the fixed parameters by  $\pm 1\sigma$  and the ratio of the differences in obtained and nominal signal yield to the latter is added in quadrature to calculate the total systematic uncertainty from PDF modeling. The fit procedures are validated in simulated MC samples. Small observed biases of (1–2)% are taken as systematic uncertainties. The uncertainties due to pion and kaon identification are 1.1% and 0.8%, respectively, for the normalization mode  $D^0 \rightarrow K^- \pi^+$ . The uncertainty on  $\mathcal{B}(D^0 \rightarrow K^- \pi^+)$  is 0.03%. These uncertainties are taken into account to determine the upper limit on the branching fraction. The uncertainty on the  $\pi_s$  efficiency cancels between the signal and normalization mode. All systematic uncertainties are added in quadrature to obtain the total systematic uncertainty.

In summary, we have searched for the baryon and lepton number violating decays  $D^0 \rightarrow pe^-$ ,  $\bar{D}^0 \rightarrow pe^-$ ,  $D^0 \rightarrow \bar{p}e^+$ ,  $\bar{D}^0 \rightarrow \bar{p}e^+$ ,  $D^0 \rightarrow p\mu^-$ ,  $\bar{D}^0 \rightarrow p\mu^-$ ,  $D^0 \rightarrow \bar{p}\mu^+$ , and  $\bar{D}^0 \rightarrow \bar{p}\mu^+$  by analyzing 921 fb $^{-1}$  data collected at and 60 MeV below the  $\Upsilon(4S)$  resonance, and at the  $\Upsilon(5S)$  resonance by the Belle detector at KEKB. In the absence of any significant signal, we set an upper limit at 90% confidence level for each signal decay mode. The corresponding limits on the branching fractions are determined to be

(5–8)  $\times 10^{-7}$ . The obtained upper limits are the most stringent to date. The limits on the  $D \rightarrow p\mu$  modes are the first such results.

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- [1] A. D. Sakharov, *Pis'ma Zh. Eksp. Teor. Fiz.* **5**, 32 (1967) [*JETP Lett.* **5**, 24 (1967)]; *Usp. Fiz. Nauk* **161**, 61 (1991) [*Sov. Phys. Usp.* **34**, 392 (1991)].
- [2] J. C. Pati and A. Salam, *Phys. Rev. D* **8**, 1240 (1973).
- [3] H. Georgi and S. L. Glashow, *Phys. Rev. Lett.* **32**, 438 (1974).
- [4] S. Raby, [arXiv:hep-ph/0608183](https://arxiv.org/abs/hep-ph/0608183).
- [5] A. Davidson, *Phys. Rev. D* **20**, 776 (1979).
- [6] R. E. Marshak and R. N. Mohapatra, *Phys. Lett.* **91B**, 222 (1980).
- [7] S. Lola and G. G. Ross, *Phys. Lett. B* **314**, 336 (1993).
- [8] N. Polonsky, *Supersymmetry: Structure and Phenomena Extensions of the Standard Model* (Springer, Berlin, Heidelberg, 2001).
- [9] H. Nishino *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. Lett.* **102**, 141801 (2009).
- [10] M. Shiozawa *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. Lett.* **81**, 3319 (1998).
- [11] Y. Hayato *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. Lett.* **83**, 1529 (1999).
- [12] A. Bueno, A. J. Melgarejo, S. Navas, Z. Dai, Y. Ge, M. Laffranchi, A. Merzaglia, and A. Rubbia, *J. High Energy Phys.* **04** (2007) 041.
- [13] K. Biswal, L. Maharana, and S. P. Misra, *Phys. Rev. D* **25**, 266 (1982).
- [14] W. Hou, M. Nagashima, and A. Soddu, *Phys. Rev. D* **72**, 095001 (2005).
- [15] T. Aaltonen *et al.* (CDF Collaboration), *Science* **376**, 170 (2022).
- [16] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. Lett.* **128**, 191803 (2022).
- [17] S. Choudhury *et al.* (Belle Collaboration), *J. High Energy Phys.* **03** (2021) 105.
- [18] J. P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **109**, 101802 (2012).
- [19] J. P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. D* **88**, 072012 (2013).
- [20] B. Abi *et al.* (Muon  $g - 2$  Collaboration), *Phys. Rev. Lett.* **126**, 141801 (2021).
- [21] P. Rubin *et al.* (CLEO Collaboration), *Phys. Rev. D* **79**, 097101 (2009).
- [22] P. del Amo Sanchez *et al.* (BABAR Collaboration), *Phys. Rev. D* **83**, 091101 (2011).
- [23] M. E. McCracken *et al.* (CLAS Collaboration), *Phys. Rev. D* **92**, 072002 (2015).
- [24] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **105**, 032006 (2022).
- [25] S. Kurokawa and E. Kikutani, *Nucl. Instrum. Methods Phys. Res., Sect. A* **499**, 1 (2003).
- [26] T. Abe *et al.*, *Prog. Theor. Exp. Phys.* **2013**, 03A001 (2013).
- [27] A. Abashian *et al.* (Belle Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **479**, 117 (2002); also see Section II in J. Brodzicka *et al.*, *Prog. Theor. Exp. Phys.* **2012**, 04D001 (2012).
- [28] D. J. Lange, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [29] T. Sjöstrand, S. Mrenna, and P. Z. Skands, *Comput. Phys. Commun.* **178**, 852 (2008).
- [30] E. Barberio and Z. Was, *Comput. Phys. Commun.* **79**, 291 (1994); P. Golonka and Z. Was, *Eur. Phys. J. C* **45**, 97 (2006); **50**, 53 (2007).
- [31] R. Brun *et al.*, GEANT3.21, CERN Report No. DD/EE/84-1, 1984.
- [32] R. L. Workman *et al.* (Particle Data Group), *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
- [33] T. Junk, *Nucl. Instrum. Methods Phys. Res., Sect. A* **434**, 435 (1999).