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Nucleon decay search with DUNE

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Grand Unification and Supersymmetry are appealing theories that offer solutions to important problems of modern physics. A key prediction of both theories is the decay of protons and bound neutrons, for which no evidence has been found yet. The dominant proton decay mode in favored supersymmetric theories is $p \to \bar{\nu} K^+$ and the predicted lifetimes range between $10^{32} - 10^{35}$ years. In this report, a sensitivity study for $p \to \bar{\nu} K^+$ is presented for the Deep Underground Neutrino Experiment (DUNE). At an exposure of 400 kiloton · years, DUNE will be able to constrain the proton lifetime to $\tau / \mathrm{Br}\,(p \to \bar{\nu} K^+) > 1.3 \times 10^{34}$ years at 90 % confidence level if no proton decay is observed.

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1. Introduction

The decay of protons and bound neutrons represents the most promising test of Grand Unification, with $p \to e^+\pi^0$ being the dominant proton decay mode in most theories. The simplest Grand Unified Theory (GUT), called $SU(5)$ or Georgi-Glashow model, predicts proton lifetimes of $\tau/\mathrm{Br}\left(p \to e^+\pi^0\right) \approx 10^{31}$ years [1]. The latest results by Super-Kamiokande set a lower limit on the proton lifetime of $\tau/\mathrm{Br}\left(p \to e^+\pi^0\right) > 2.4 \cdot 10^{34}$ years [2], ruling $SU(5)$ out in favor of GUTs with supersymmetric extensions (SUSY GUTs). Supersymmetry pushes the unification scale to higher energies, resulting in predictions for $\tau/\mathrm{Br}\left(p \to e^+\pi^0\right)$ of $10^{34} - 10^{37}$ years [3] that are consistent with the observed limit. Supersymmetry also opens up additional decay channels through the exchange of supersymmetric particles, with $p \to \bar{\nu}K^+$ being the favored decay mode for most theories. The predicted lifetimes of $10^{32} - 10^{35}$ years [3] are consistent with the best limit by Super-Kamiokande of $\tau/\mathrm{Br}\left(p \to \bar{\nu}K^+\right) > 8.2 \cdot 10^{33}$ years [4] and the search for proton decay therefore remains of great interest.

The Deep Underground Neutrino Experiment will search for nucleon decay with four liquid argon time projection chambers (LAr TPCs) with a fiducial mass of 10 kilotons each, a detector technology that combines large active masses with high-resolution imaging capabilities. In this report, a sensitivity study for the decay channel $p \to \bar{\nu}K^+$ is presented for DUNE, using an experimentally tuned event generator and a full detector simulation and reconstruction. Atmospheric neutrino interactions with argon are considered as backgrounds, and a Boosted Decision Tree is trained with various reconstructed parameters to reject background events. A more complete description of the presented study can be found in reference [5].

2. Detector

The Deep Underground Neutrino Experiment will deploy four 10 kiloton LAr TPC modules within its far detector complex 1500 m underground at the Sanford Underground Research Facility. Two technologies are currently being explored for this purpose: single phase and dual phase LAr TPCs. The sensitivity study presented in this report has been carried out for a 10 kiloton single phase LAr TPC. The working principle of such a detector is shown in figure 1. Scintillation light produced by charged particles is collected by photodetectors while the ionization charge is drifted horizontally by the means of an electric field to two induction planes (U, V) and one collection plane (X) that consist of thin wires with a pitch of ~5 mm. Each plane reads a 2D projection of the event and by combining the information of multiple planes, 3D objects can be reconstructed.

3. Signal and backgrounds

Proton decay via $p \to \bar{\nu}K^+$ constitutes the signal. Since the proton decays inside an argon nucleus, the initial state of the nucleus and the intranuclear propagation of the kaon are simulated with GENIE, using the tune G18_02a_02_11a [7]. In this GENIE tune, the nucleon momentum distribution is modeled according to a global relativistic Fermi gas with Bodek-Ritchie extension [8] and the intranuclear propagation with the hA2015 model that allows only one effective interaction inside the nucleus and considers only elastic scatters for K^+. The kinetic energy distribution before

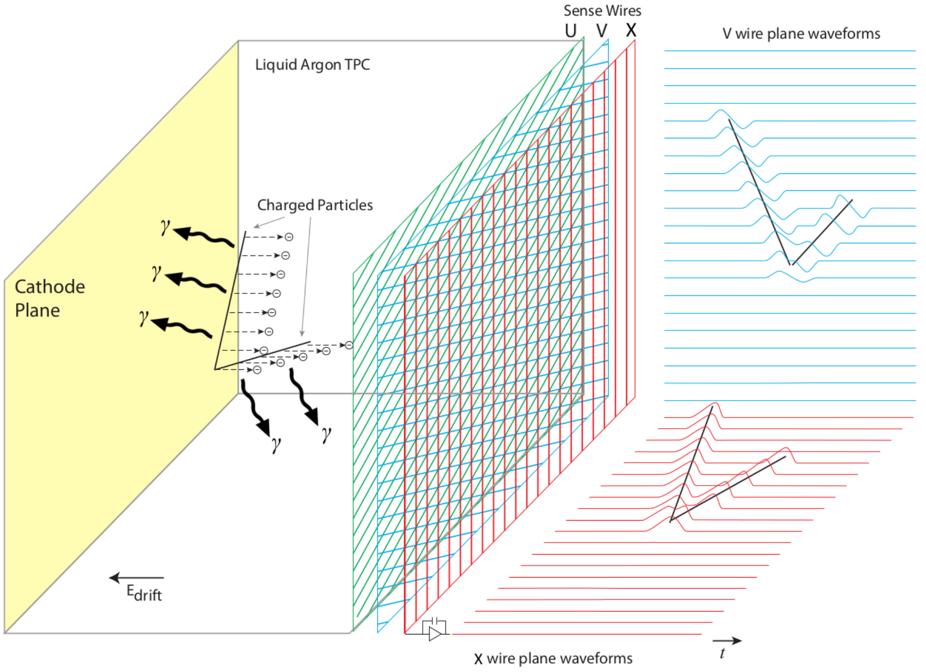
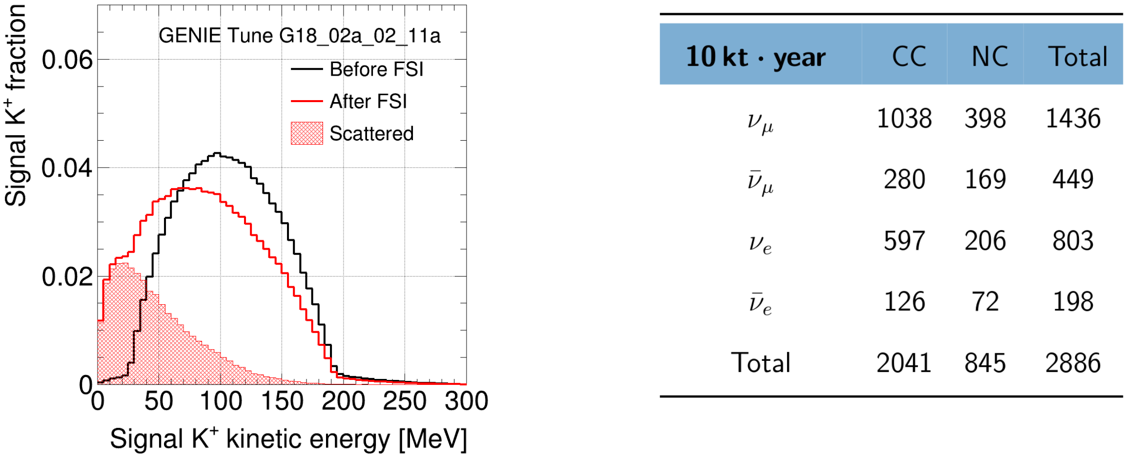


Figure 1: Working principle of a single phase LAr TPC. The scintillation light produced by charged particles is collected by photodetectors and the ionization charge is drifted horizontally by the means of an electric field to two induction planes (U, V) and one collection plane (X). Figure is taken from reference [6].



10 kt · year	CC	NC	Total
ν_μ	1038	398	1436
$\bar{\nu}_\mu$	280	169	449
ν_e	597	206	803
$\bar{\nu}_e$	126	72	198
Total	2041	845	2886

Figure 2: Left: Kinetic energy distribution of K^+ in the signal sample before and after final state interactions. Kaons that scattered off a nucleon typically lose a large amount of their kinetic energy. Right: Number of expected neutrino-argon interactions for an exposure of 10 kiloton · years according to the Bartol atmospheric neutrino flux [9] and GENIE cross-sections in tune G18_02a_02_11a, taken from reference [5].

and after intranuclear propagation, a process also referred to as final state interactions (FSI), is shown in figure 2. An example event display for $p \to \bar{\nu} K^+$ is shown in figure 3.

Atmospheric neutrino interactions with argon are considered as background and are simulated with the Bartol atmospheric neutrino flux [9] and various neutrino-argon cross-section models

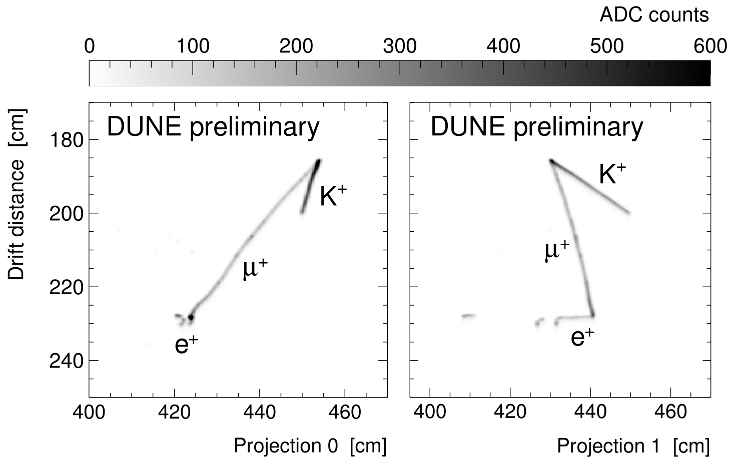


Figure 3: Event display of a simulated proton decay via $p \to \bar{\nu} K^+$ in which the kaon decays into a μ^+. For this example event display, the angle between the orientation of the two shown readout planes is 90 °.

implemented within GENIE tune G18_02a_02_11a. The expected numbers of interactions for an exposure of 10 kiloton · years are summarized in figure 2.

4. Reconstruction and analysis

Hits are reconstructed in each readout wire that has recorded ionization charge, and a pattern recognition algorithm determines groups of hits that are thought to originate from the same particle in each readout plane independently. Hit groups are matched between the readout planes based on their starting and stopping time and charge content to obtain 3D tracks and showers. Since kaons are rarely produced in neutrino interactions and always accompanied by other detectable particles, the general analysis strategy is to identify the kaon and its decay products based on their reconstructed 3D objects. For this purpose, a particle identification score $PIDA$ is calculated for each track:

$$PIDA = \left\langle \left(\frac{dE}{ds}\right)_{\text{Hit}} \cdot R_{\text{Hit}}^{0.42} \right\rangle \tag{1}$$

where $(dE/ds)_{\text{Hit}}$ is the reconstructed local linear stopping power at a given hit and R_{Hit} is the reconstructed range between a given hit and the particle's stopping point. The kaon tracking efficiency in the signal sample and the $PIDA$ distributions for kaons in the signal sample and muons and protons in the background sample are shown in figure 4.

Since some proton and muon tracks in the background are misidentified as kaons, a forward-backward-likelihood is calculated for pairs of identified kaons and connected tracks to determine whether the end point (forward) or start point (backward) of the identified kaon is connected to another track. This makes use of the fact that the kaon is typically only connected to its decay products in proton decay events while multiple particles share a vertex in background events.

After preselecting events with at least two reconstructed tracks and without tracks longer than 100 cm, a Boosted Decision Tree (BDT) is trained with the $PIDA$, the forward-backward-likelihood, a convolutional neural network score of the event display that directly distinguishes

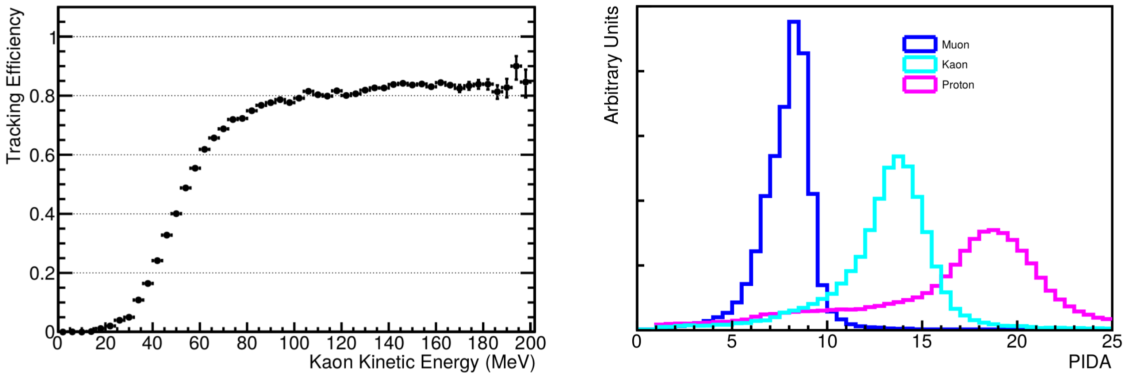


Figure 4: Left: kaon tracking efficiency as a function of true kaon kinetic energy in the signal sample, c.f. figure 2. The tracking efficiency is defined as ratio of kaons with a reconstructed track over the total number of kaons. Right: *PIDA* score for kaons in the signal sample and muons and protons in the background sample. The overlap between the distributions leads to the misidentification of some muons and protons as kaons. Both figures are taken from reference [5].

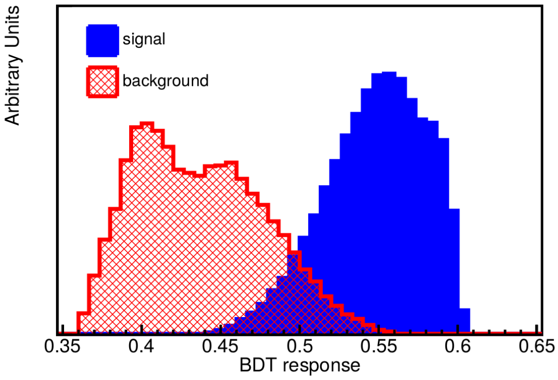


Figure 5: Boosted Decision Tree response for signal and background events, taken from reference [5].

between signal and background events [5], the visible energy of the event, the number of tracks, and other reconstructed variables to distinguish between proton decay and atmospheric neutrino interactions. The BDT response is shown in figure 5 and the cut is chosen so that only one background event is left for an exposure of 1 megaton · year, yielding a signal efficiency of $\epsilon = 15\,\%$. Since the reconstruction has not been fully tuned and significant improvements are expected especially for the tracking efficiency of low-energy kaons (c.f. figure 4), an eye scan of signal and background event displays has been performed and a signal efficiency of $\epsilon = 30\,\%$ was established as realistic goal at the same background level. The sensitivity, which is the lower lifetime limit that can be determined if no proton decay is observed, can be calculated with:

$$\tau/\mathrm{Br}\left(p \longrightarrow \bar{\nu}K^{+}\right) > \epsilon \cdot \mathrm{Exposure} \cdot \frac{1}{S} \tag{2}$$

where S is the constrained number of signal events at 90 % confidence level. For $\epsilon = 30\,\%$ and an exposure of 400 kiloton · years with 0.4 expected background events, this analysis yields $\tau/\mathrm{Br}\,(p \longrightarrow \bar{\nu}K^{+}) > 1.3 \times 10^{34}$ years. A similar study has been carried out for the bound neutron decay channel $n \rightarrow e^- K^+$, yielding $\tau/\mathrm{Br}\,(n \rightarrow e^- K^+) > 1.1 \times 10^{34}$ years at 400 kiloton · years. A Monte Carlo truth study with energy smearing for the decay channel $p \rightarrow e^+\pi^0$ results in $\tau/\mathrm{Br}\,(p \rightarrow e^+\pi^0) > 0.9 - 1.1 \times 10^{34}$ years at the same exposure.

5. Conclusions

DUNE will be able to test Grand Unification and Supersymmetry by searching for different nucleon decay modes. In this report, the sensitivity of a 10 kiloton single phase LAr TPC module in the DUNE far detector complex for the benchmark channel $p \rightarrow \bar{\nu} K^+$ was determined to $\tau/\mathrm{Br}\,(p \rightarrow \bar{\nu} K^+) > 1.3 \times 10^{34}$ years at an exposure of 400 kiloton · years and 90 % confidence level, reaching the proton lifetime predictions of favored supersymmetric theories of $10^{32} - 10^{35}$ years. A similar performance has been obtained for $n \rightarrow e^- K^+$ and $p \rightarrow e^+\pi^0$. Thanks to its high-resolution imaging capabilities and concomitant strong background rejection, DUNE will be competitive to the larger Hyper-Kamiokande water Cherenkov detector [10] and enable discoveries at the few events level in quasi-background-free conditions for many nucleon decay channels.

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