# Chapter 5

# Nucleon Decay Motivated by Grand Unified Theories

Baryon number conservation is an unexplained symmetry in the Universe with deep connections to both cosmology and particle physics. As one of the conditions underlying the observed matter-antimatter asymmetry of the Universe, baryon number *should* be violated. Nucleon decay, which is a manifestation of baryon number violation, is a hallmark of many Grand Unified Theories (GUTs), theories that connect quarks and leptons in ways not envisioned by the Standard Model. Observation of proton or bound-neutron decay would provide a clear experimental signature of baryon number violation.

Predicted rates for nucleon decay based on GUTs are uncertain but cover a range directly accessible with the next generation of large underground detectors. LBNE, configured with its massive, deep-underground LArTPC far detector, offers unique opportunities for the discovery of nucleon decay, with sensitivity to key decay channels an order of magnitude beyond that of the current generation of experiments.

## 5.1 LBNE and the Current Experimental Context

Current limits on nucleon decay via numerous channels are dominated by Super–Kamiokande (SK) [1], for which the most recently reported preliminary results are based on an overall exposure of 260 kt · year. Although the SK search has so far not observed nucleon decay, it has established strict limits ($90\%$ CL) on the partial lifetimes for decay modes of particular interest to GUT models such as $\tau/B(p \rightarrow e^+\pi^0) > 1.3 \times 10^{34}$ year and $\tau/B(p \rightarrow K^+\overline{\nu}) > 0.59 \times 10^{34}$ year [2]. These are significant limits on theoretical models that constrain model builders and set a high threshold for the next-generation detectors such as LBNE and Hyper-Kamiokande (Hyper-K). After more than ten years of exposure, the SK limits will improve only slowly. A much more massive detector such as Hyper-K — which will have a 560-kt fiducial mass — is required to make a significant (order-of-magnitude) improvement using the water Cherenkov technique.

The uniqueness of proton decay signatures in a LArTPC and the potential for reconstructing them with redundant information has long been recognized as a key strength of this technology. A LArTPC can reconstruct all final-state charged particles and make an accurate assessment of particle type, distinguishing between muons, pions, kaons and protons. Electromagnetic showers are readily measured, and those that originate from photons generated by $\pi^0$ decay can be distinguished to a significant degree from those that originate from $\nu_e$ charged-current (CC) interactions. Kiloton-per-kiloton, LArTPC technology is expected to outperform water Cherenkov in both detection efficiency and atmospheric-neutrino background rejection for most nucleon decay modes, although intranuclear effects, which can smear out some of the proton decay signal, are smaller for oxygen and nonexistent for hydrogen.

When mass and cost are taken into account, water Cherenkov technology is optimum for the $p \to e^+\pi^0$ final-state topology, where the signal efficiency is roughly 40% and the background rate is two events per Mt · year. The efficiency estimate for this mode [3] for a LArTPC is 45% with one event per Mt · year — not a significant enough improvement in efficiency to overcome the penalty of the higher cost per kiloton for liquid argon.

For the $p \to K^+\overline{\nu}$ channel, on the other hand, the LArTPC technology is superior based on the same criteria. In a LArTPC, the $K^+$ track is reconstructed and identified as a charged kaon. The efficiency for the $K^+\overline{\nu}$ mode in a LArTPC is estimated to be as high as 97.5% with a background rate of one event per Mt · year. In water Cherenkov detectors the efficiency for this mode is roughly 19% for a low-background search, with a background rate of four events per Mt · year. Based on these numbers and a ten-year exposure, LBNE's 34-kt LArTPC and the 560-kt Hyper-K WCD have comparable sensitivity (at 90% CL), but the estimated LArTPC background of 0.3 events is dramatically better than the 22 estimated for Hyper-K (assuming no further improvement in analysis technique past that currently executed for SK [2]).

## 5.2 Signatures for Nucleon Decay in Liquid Argon

The LBNE LArTPC's superior detection efficiencies for decay modes that produce kaons will outweigh its relatively low mass compared with multi-hundred-kiloton water Cherenkov detectors. Because the LArTPC can reconstruct protons that are below Cherenkov threshold, it can reject many atmospheric-neutrino background topologies by vetoing on the presence of a recoil proton. Due to its excellent spatial resolution, it also performs better for event topologies with displaced vertices, such as $p \to K^+\overline{\nu}$ (for multi-particle $K^+$ decay topologies) and $p \to K^0\mu^+$. The latter mode is preferred in some SUSY GUTs.

For modes with no electron in the final state, the same displaced vertex performance that underpins long-baseline neutrino oscillation measurements allows the rejection of CC interactions of atmospheric $\nu_e$'s. As will be stressed for the key mode of $p \to K^+\overline{\nu}$ described in detail below, the capability to reconstruct the charged kaon with the proper range and $dE/dx$ profile allows for a high-efficiency, background-free analysis. In general, these criteria favor all modes with a kaon, charged or neutral, in the final state. Conversely, the efficiency for decay modes to a lepton plus light meson will be limited by intranuclear reactions that plague liquid argon to a greater extent than they do $^{16}$O in a water Cherenkov detector.

An extensive survey [3] of nucleon decay efficiency and background rates for large LArTPCs with various depth/overburden conditions, published in 2007, provides the starting point for the assessment of LBNE's capabilities. Table 5.1 lists selected modes where LArTPC technology exhibits a significant performance advantage (per kiloton) over the water Cherenkov technology. The remainder of this chapter focuses on the capabilities of LBNE for the $p \to K^+\overline{\nu}$ channel, as the most promising from theoretical and experimental considerations. Much of the discussion that follows can be applied to cover the other channels with kaons listed in the table.

**Table 5.1:** Efficiencies and background rates (events per Mt · year) for nucleon decay channels of interest for a large underground LArTPC [3], and comparison with water Cherenkov detector capabilities. The entries for the water Cherenkov capabilities are based on experience with the Super–Kamiokande detector [2].

| Decay Mode | Water Cherenkov | | Liquid Argon TPC | |
|---|---|---|---|---|
| | Efficiency | Background | Efficiency | Background |
| $p \to K^+\overline{\nu}$ | 19% | 4 | 97% | 1 |
| $p \to K^0\mu^+$ | 10% | 8 | 47% | $< 2$ |
| $p \to K^+\mu^-\pi^+$ | | | 97% | 1 |
| $n \to K^+e^-$ | 10% | 3 | 96% | $< 2$ |
| $n \to e^+\pi^-$ | 19% | 2 | 44% | 0.8 |

The key signature for $p \to K^+\overline{\nu}$ is the presence of an isolated charged kaon (which would also be monochromatic for the case of free protons, with $p = 340$ MeV). Unlike the case of $p \to e^+\pi^0$, where the maximum detection efficiency is limited to 40–45% because of inelastic intranuclear scattering of the $\pi^0$, the kaon in $p \to K^+\overline{\nu}$ emerges intact (because the kaon momentum is below threshold for inelastic reactions) from the nuclear environment of the decaying proton $\sim 97\%$ of the time. Nuclear effects come into play in other ways, however: the kaon momentum is smeared by the proton's Fermi motion and shifted downward by re-scattering [4]. The kaon emerging from this process is below Cherenkov threshold, therefore a water detector would need to detect it after it stops, via its decay products. Not all $K$ decay modes are reconstructable, however, and even for those that are, insufficient information exists to determine the initial $K$ momentum. Still, water detectors can reconstruct significant hadronic channels such as $K^+ \to \pi^+\pi^0$ decay, and the 6-MeV gamma from de-excitation of $O^{16}$ provides an added signature to help with the $K^+ \to \mu^+\nu$ channel. The overall detection efficiency in SK [2] thus approaches $20\%$.

In LArTPC detectors, the $K^+$ can be tracked, its momentum measured by range, and its identity positively resolved via detailed analysis of its energy-loss profile. Additionally, all decay modes can be cleanly reconstructed and identified, including those with neutrinos, since the decaying proton is essentially at rest. With this level of detail, it is possible for a single event to provide overwhelming evidence for the appearance of an isolated kaon of the right momentum originating from a point within the fiducial volume. The strength of this signature is clear from cosmogenic-induced kaons observed by the ICARUS Collaboration in the cosmic-ray (CR) test run of half of the T600 detector, performed at a surface installation in Pavia [5] and in high-energy neutrino interactions with the full T600 in the recent CNGS (CERN Neutrinos to Gran Sasso) run [6]. Figure 5.1 shows a sample event from the CNGS run in which the kaon is observed as a progressively heavily-ionizing track that crosses into the active liquid argon volume, stops, and decays to $\mu\nu$, producing a muon track that also stops and decays such that the Michel-electron track is also visible. The 3D reconstruction of the event is shown in Figure 5.2.

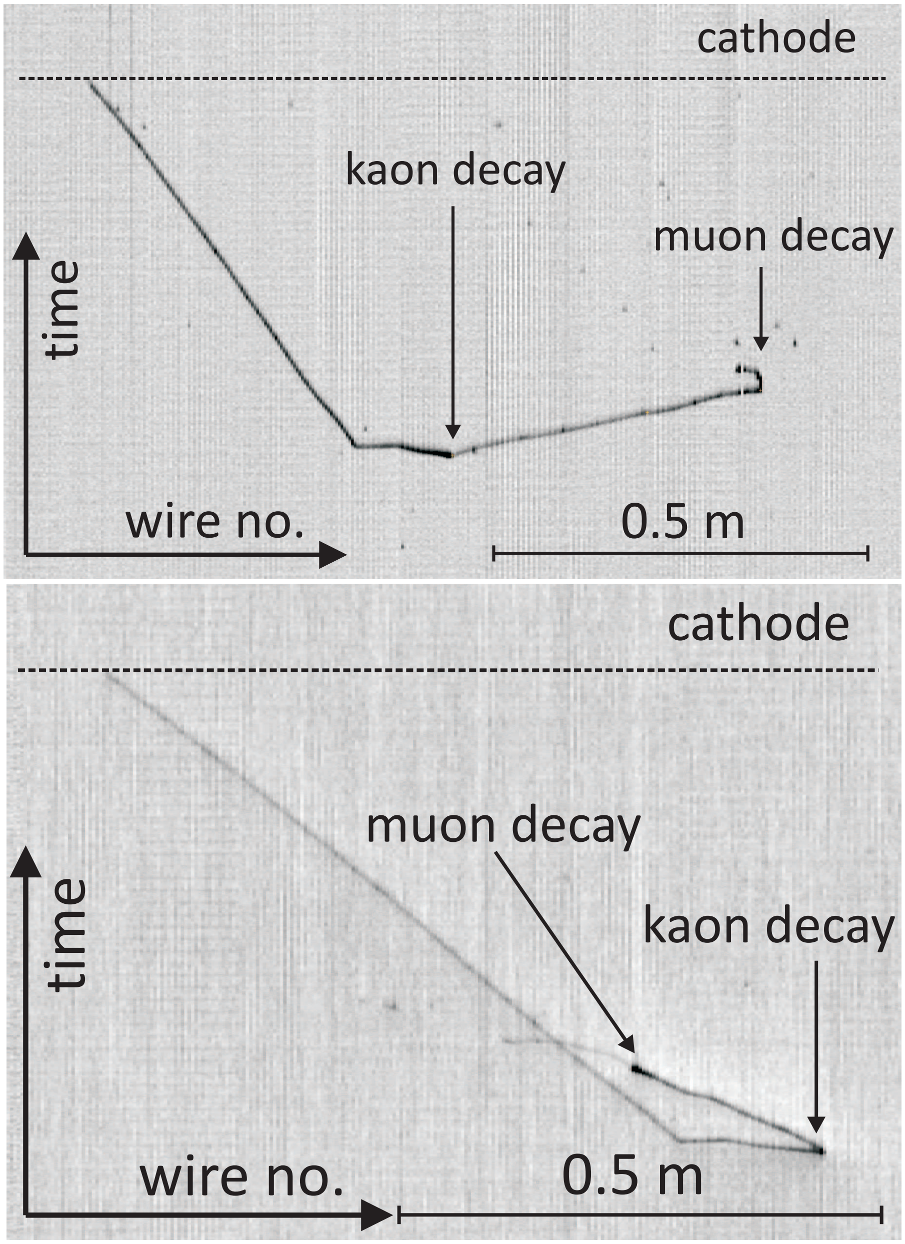

**Figure 5.1:** Event display for a decaying kaon candidate $K \rightarrow \mu\nu_\mu$ $\mu \rightarrow e\nu_e\nu_\mu$ in the ICARUS T600 detector observed in the CNGS data ($K$: 90 cm, 325 MeV; $\mu$ : 54 cm, 147 MeV; $e$ : 13 cm, 27 MeV). The top figure shows the signal on the collection plane, and the bottom figure shows the signal on the second induction plane [6].

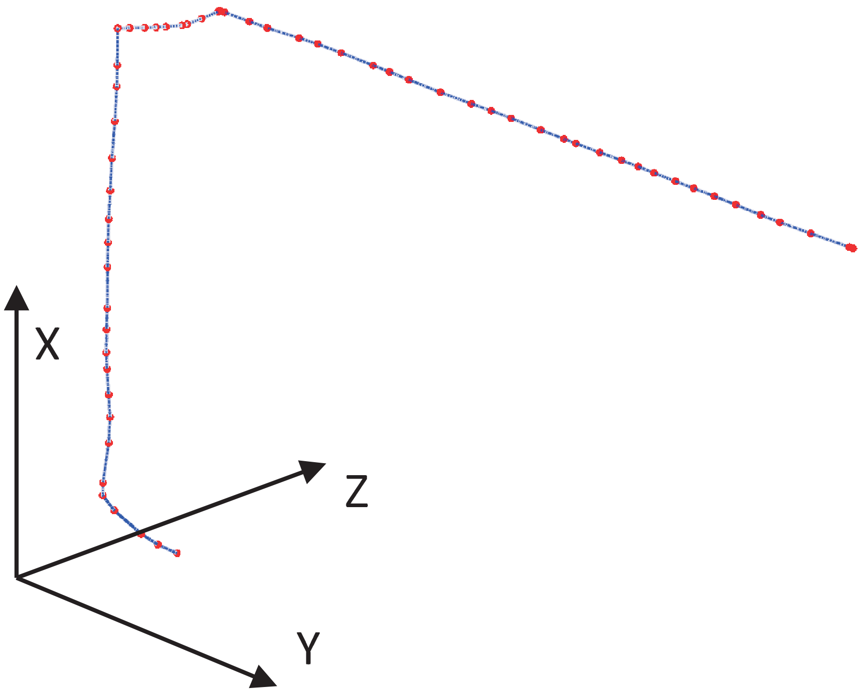

**Figure 5.2:** 3D reconstruction of the decaying kaon event observed in the ICARUS T600 detector and shown in Figure 5.1.

If it can be demonstrated that background processes mimicking this signature can be rejected at the appropriate level, a single $p \to K^+\overline{\nu}$ candidate could constitute evidence for proton decay.

## 5.3 Background Levels and Rejection Capabilities

This section discusses the key background processes and their signatures, focusing on the $p \to K^+\overline{\nu}$ channel as the benchmark mode[*]. The two potential sources of background are cosmic-ray muons and atmospheric neutrinos, described separately below.

### 5.3.1 Cosmic-Ray Muon Backgrounds

Cosmic-ray (CR) muons contribute background signals when they penetrate the detector. Hence, the self-shielding feature of the LArTPC and the depth of the site are important assets for controlling the rate of signals that can mimic a proton decay event. Additionally, the energy deposition associated with spallation products is well below the hundreds-of-MeV range for depositions from proton decay final-state particles.

The most pernicious CR-muon background in liquid argon for proton decay with kaon final states

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[*] Much of this discussion applies equally well to other nucleon decay modes involving charged or neutral kaons.

thus comes from particular pathological processes. Specifically, CR muons that produce kaons via photonuclear interactions in the rock near the detector or in the liquid argon itself but outside the active volume are capable of producing signatures that mimic $p \rightarrow K^+\overline{\nu}$ and other modes with kaons. CR-induced kaon backgrounds as a function of depth have been studied for liquid argon [3,7,8].

In particular, at the 4,850-ft level, the vertical rock overburden will be approximately 4-km water equivalent, at which depth the muon rate through a 34-kt LArTPC will be approximately 0.1 $\mathrm{s}^{-1}$. This is low enough that a veto on the detection of a muon in the liquid argon volume can be applied with negligible loss of live-time. Specifically, assuming a maximum drift time of 2 ms, the probability of a muon passing through the detector in time with any candidate event (i.e., a candidate for proton decay or other signal of interest) will be $2 \times 10^{-4}$. Thus, any candidate event that coincides in time with a large energy deposition from a muon or muon-induced cascade can be rejected with a negligible signal efficiency loss of $0.02\%$. Only background from events associated with CR muons in which the muon itself does not cross the active region of the detector remain to be considered.

One class of such backgrounds involves production of a charged kaon outside the active volume, which then enters the active region. Assuming unambiguous determination of the drift time (via the scintillation-photon detection system and other cues such as detailed analysis of the $dE/dx$ profile of the kaon candidate), it will be possible to identify and reject such entering kaons with high efficiency. It should be noted that, through studies of CR muons that interact within the active volume of the detector, backgrounds of this type can be well characterized with data from the detector itself.

A potentially less tractable background for the decay mode $p^+ \rightarrow K^+\overline{\nu}$ occurs when a neutral particle (e.g., a $K^0_L$) originating in a muon-induced cascade outside the detector propagates into the detector volume and undergoes a charge-exchange reaction in the fiducial volume. To further understand the possible rate for this background at LBNE, simulations of CR muons and their secondaries at depth have been run. The rate of positive kaons produced inside the 34-kt detector by a neutral particle entering from outside (and with no muon inside) has been found to be 0.9 events per year before any other selection criteria are applied. Further studies included the following additional selection criteria:

1. No muon is in the detector active volume.
2. The $K^+$ candidate is produced inside the liquid argon active volume at a distance from the wall greater than 10 cm.
3. The energy deposition from the $K^+$ and its descendants (excluding decay products) is less than 150 MeV.

4. The total energy deposition from the $K^+$, its descendants and decay products is less than 1 GeV.

5. Energy deposition from other particles in the muon-induced cascade (i.e., excluding the energy deposition from the positive kaon, its descendants and decay products) is less than 100 MeV.

No event survived the additional selection criteria, resulting in an upper bound on the rate of this type of background event of 0.07 events per year in a 34-kt LArTPC, equivalent to two events per Mt · year. A key factor contributing to the rejection of CR backgrounds to this level is that although a large number of $K^+$'s generated by cosmic rays deposit an energy similar to that expected from proton decay, the energy depositions from $K^+$'s are not the only ones recorded for these events. Other particles from the CR-muon interaction tend also to enter the detector and deposit additional visible energy, making the rejection of background events simpler than would be expected assuming only the appearance of a kaon in the detector.

In addition to the impact of an active veto system for detectors at various depths, the studies of [3] also consider impacts of progressively restrictive fiducial volume cuts. Together, these and the above studies demonstrate that proton decay searches in the LBNE LArTPC at the 4,850-ft level can be made immune to CR-muon backgrounds, without the requirement of an external active veto system. To the extent that there are uncertainties on the rate of kaon production in CR-muon interactions, one has flexibility to suppress background from this source further by application of modest fiducial volume cuts.

### 5.3.2 Background from Atmospheric-Neutrino Interactions

Unlike the case of CR-muon backgrounds, the contamination of a nucleon decay candidate set due to interactions of atmospheric neutrinos cannot be directly controlled by changing the depth or fiducial volume definition of the LBNE detector. Furthermore the atmospheric-neutrino flux is naturally concentrated around the energy range relevant for proton decay. In the analysis of [3], a single simulated neutral-current (NC) event survived the requirement of having an isolated single kaon with no additional tracks or $\pi^0$'s, and total deposited energy below 800 MeV. This event is responsible for the estimated background rate of 1.0 per Mt · year.

While this rate is acceptable for LBNE, it is natural to ask to what extent simulations are capable of providing reliable estimates for such rare processes. What if the actual rate for single-kaon atmospheric-neutrino events is higher by a factor of ten or more? Is that even conceivable? To set the scale, it is useful to recall that the atmospheric-neutrino sample size in LBNE is expected to be of order $10^5$ per Mt · year of exposure (Table 4.11). Hence, "rare-but-not-negligible" in this context denotes a process that occurs at a level of no less than $10^{-6}$.

Super–Kamiokande has given considerable attention to atmospheric-neutrino backgrounds in its nucleon decay searches (e.g., [9]). In the SK analyses, data obtained with relaxed cuts have been studied to validate the atmospheric-neutrino flux and interaction models employed. Consequently, the atmospheric-neutrino backgrounds for nucleon decay searches are well established at the level required for the water Cherenkov detector approach to this physics.

For the case of LBNE, however, with a different detector technology, and with a goal of being sufficiently background-free to enable a discovery based on observation of a single candidate event, one would like to go further to understand at a detailed level what the rates for the specific background processes are. The first question to ask is what are the physical processes that could produce the exact signature of a $p \to K^+\overline{\nu}$ event? Some possibilities are discussed below.

**Strange particle production in $\Delta S = 0$ processes:** An identified source of background events for SK [9] involves associated production of a pair of strange hadrons, nominally in the strong decay of a nucleonic resonance excited via an inelastic NC neutrino-nucleon interaction. This could be in the form of a kaon accompanying a $\Lambda$ baryon. Again, conservation of strangeness holds that the baryon cannot be absorbed, and thus a weak decay of the strange quark is guaranteed. For water Cherenkov detectors the strange baryon is produced with a small enough momentum that its decay products are typically below Cherenkov threshold. For a liquid argon detector, these final state particles should be detectable, leaving distinctive signatures that can be reconstructed. Thus in principle, this source of background can be suppressed with appropriate event reconstruction and analysis tools. To understand this prospect in quantitative terms, the range of kinematic distributions are currently under investigation.

It is possible to imagine yet more contrived scenarios, for example where the meson produced is a $K^0_L$ that escapes detection, while a charged kaon ($K^-$ in this case) results from the decay of an excited $\Lambda$ or $\Sigma$ baryon produced in association. However, one would expect such processes to be even more rare than those described above. Thus if the rates for (say) the $K^+\Lambda$ production channel described above can be constrained as being sufficiently small, it can be argued that the more contrived scenarios can be ignored.

**Strange particle production in $\Delta S = 1$ processes:** A potentially challenging source of background is production of a single charged kaon (in this case a $K^-$) in a $\Delta S = 1$ process. In the simplest case, one could think of it as the Cabibbo-suppressed version of single $\pi$ production in a CC antineutrino interaction. In contrast to the $\Delta S = 0$ processes described above, no strange baryon is produced in association, and so there are no other hadrons to detect. (Similarly, one could imagine the kaon originating in the decay of a strange baryon resonance produced in a Cabibbo-suppressed neutrino interaction, accompanied by a neutron that goes undetected.) On the other hand, such processes can only occur in CC interactions, and thus a charged lepton will accompany the kaon. This therefore constitutes a background only for cases where the charged lepton is missed, which should be rare. The combination of probabilities associated with (1) Cabibbo-suppression, (2) single hadron production, and (3) circumstances causing the charged lepton to be missed, lead to an overall suppression of this source of background. Thus it should be possible to rule it out as a source of concern for LBNE on the basis of these features alone.

**Misidentification of pions in atmospheric neutrino events:** While misidentification of leading pions as kaons in atmospheric-neutrino scattering events is a potential problem, it can be argued that the rate for such misidentification events can be controlled. Key signatures for the kaon are found in the distinctive residual-range dependence of its energy deposition near the end of its trajectory (nominally 14 cm) as well as in the explicit reconstruction of its decay products. Similarly, tails in the measurement of $dE/dx$ would be a concern if they led a pion track to mimic a kaon, however the momentum (30 MeV) and hence range of the muon produced in the decay of a stopping pion would not match that of the corresponding muon (236 MeV) in a $K^+ \to \mu^+\nu$ decay. Thus, it should be possible to control this background experimentally.

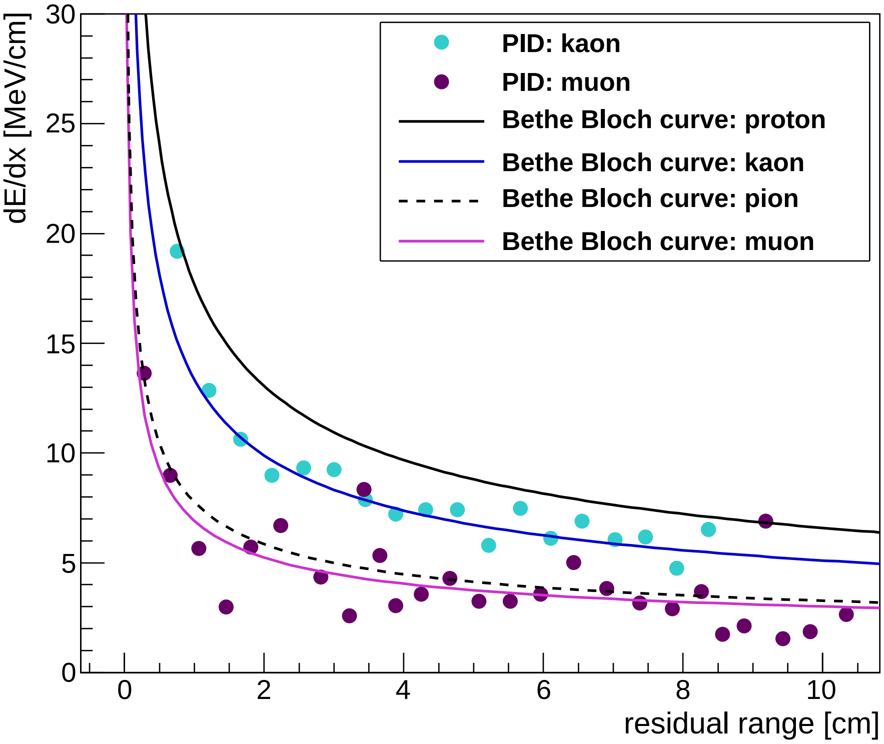

**Figure 5.3:** Measurements of $dE/dx$ versus residual range for signals associated with the kaon track in Figure 5.1 (cyan points) and the decay muon (magenta points). Overlaid are the expected $dE/dx$ profiles for the two particle identities [6].

One variant of this background source occurs for the case where the pion decays in flight. Two experimental handles on this background can be immediately identified. First is the deviation from the expected $dE/dx$ profile for a kaon, which will be more dramatic than in the case of the stopping pion. Second is the correlation of the direction of the decay muon with that of the pion, which is absent in the decay of a particle at rest. Assessment of the cumulative impact of event rejection based on these features is under study. However, the decaying kaon observed in the ICARUS CNGS run displayed in Figure 5.1 can be used to give a sense of the $\pi/K$ discrimination possible in a LArTPC via $dE/dx$. In Figure 5.3, the measurements of $dE/dx$ versus residual range for the anode wires registering signals from the kaon and muon tracks in this event are plotted against the expected $dE/dx$ profiles [6]. The data from the kaon track (cyan points) agree very well with the expected $dE/dx$ profile (blue curve) and are quite distinguishable from the expected pion profile (dashed curve).

**Event reconstruction pathologies:** While consideration of rare event topologies in atmospheric-neutrino interactions is important, it will be equally important to understand ways in which more typical events might be misreconstructed so as to mimic nucleon decay processes. For example, a quasi-elastic $\nu_\mu$-CC interaction will produce a muon and a recoil proton from a common vertex. However, it may be possible to interpret the vertex as the kink associated with the decay of a stopping kaon, where the proton track is confused with a kaon traveling in the opposite direction. Tools are still under development to be able to understand the degree to which this possibility poses a potential background. Naively, the $dE/dx$ profile of the proton as a function of residual range will not match the time-reversed version of this for a kaon, and distributions of kinematic quantities will be distinct. Additionally, such a background will only affect the portion of the $p \to K^+\overline{\nu}$ analysis focused on $K^+ \to \mu^+\nu$; other $K^+$ decays will be immune to this pathology.

The point of this example is to illustrate that although the exquisite performance characteristics of the LArTPC technique enables unambiguous identification of nucleon decay signatures, an extensive program of detailed analysis will be required to fully exploit these capabilities.

**Conclusions on atmospheric-neutrino backgrounds:** The above examples suggest that it will be possible to demonstrate the desired level of suppression of atmospheric-neutrino background without undue reliance on simulations via a combination of arguments based on existing experimental data (from SK proton decay searches, as well as data from various sources on exclusive and inclusive neutrino-interaction processes that yield rare topologies), physics considerations, and detailed analysis of anticipated detector response. For the latter, ongoing LBNE event-reconstruction efforts will play a role with simulated atmospheric-neutrino samples. Additionally, useful input is expected to come in over the short/intermediate term from analyses of LArTPC data from ArgoNeuT, MicroBooNE and the proposed LArIAT. Finally, while the state of neutrino flux and interaction models is already quite advanced, vigorous theoretical work is ongoing to improve these further, exploiting existing data from neutrino and electron-scattering experiments. In particular, kaon production in neutrino interactions in relevant energy ranges is receiving renewed attention [10].

## 5.4 Summary of Expected Sensitivity to Key Nucleon Decay Modes

Based on the expected signal efficiency and the upper limit on the background rates estimated in Section 5.3, the expected limit on the proton lifetime as a function of running time in LBNE for $p \to K^+\overline{\nu}$ is shown in Figure 5.4.

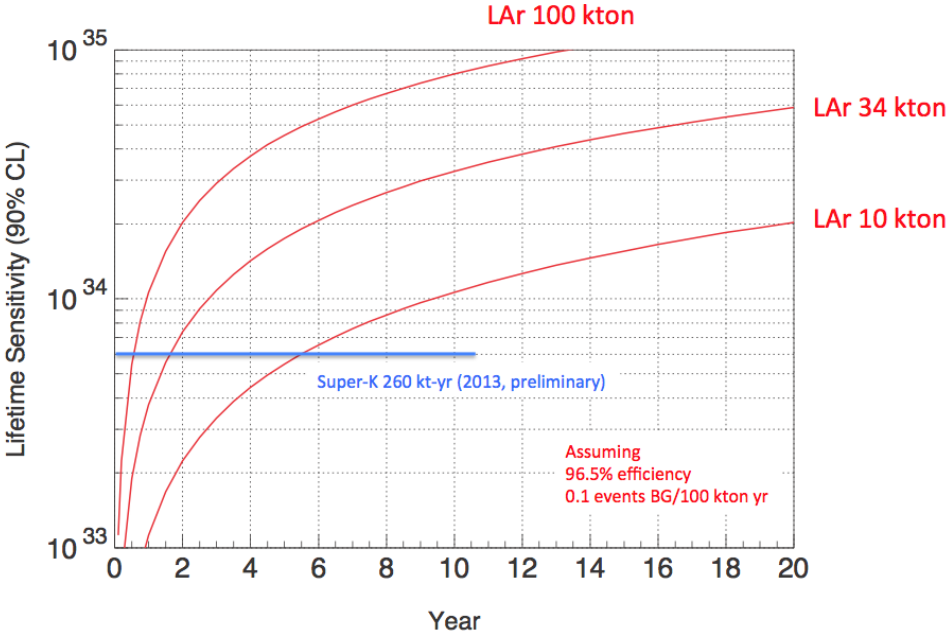

**Figure 5.4:** Proton decay lifetime limit for $p \to K^+\overline{\nu}$ as a function of time for underground LArTPCs of fiducial masses 10, 34 and 100 kt. For comparison, the current limit from SK is also shown. The limits are at 90% C.L., calculated for a Poisson process including background, assuming that the detected events equal the expected background.

Figure 5.4 demonstrates that to improve the current limits on the $p \to \overline{\nu}K^+$, set by Super–Kamiokande, significantly beyond that experiment's sensitivity, a LArTPC detector of at least 10 kt, installed deep underground, is needed. A 34-kt detector will improve the current limits by an order of magnitude after running for two decades. Clearly a larger detector mass would improve the limits even more in that span of time.

While the background rates are thought to be no higher than those assumed in generating the above sensitivity projections, it is possible to estimate the impact of higher rates. For $p \to K^+\overline{\nu}$, Table 5.2 shows a comparison of the $90\%$ CL lower bounds on proton lifetime for an exposure of 340 kt · year assuming the nominal 1.0 per Mt · year background rate with the corresponding bounds for a rate that is ten times higher, as well as for a fully background-free experiment. While a factor of ten increase in the background would hurt the sensitivity, useful limits can still be obtained. As stated above, however, there is good reason to believe such a case is highly unlikely.

**Table 5.2:** The impact of different assumed background rates on the expected 90% CL lower bound for the partial proton lifetime for the $p \to K^+\overline{\nu}$ channel, for a 34-kt detector operating for ten years. The expected background rate is one event per Mt · year. Systematic uncertainties are not included in these evaluations.

| Background Rate | Expected Partial Lifetime Limit |
|---|---|
| 0 events/Mt · year | $3.8 \times 10^{34}$ years |
| 1 events/Mt · year | $3.3 \times 10^{34}$ years |
| 10 events/Mt · year | $2.0 \times 10^{34}$ years |

Sensitivities have been computed for some of the other decay channels listed in Table 5.1. The limits that could be obtained from an LBNE 34-kt detector in ten years of running as compared to other proposed future experiments and theoretical expectations are shown in Figure 5.5.

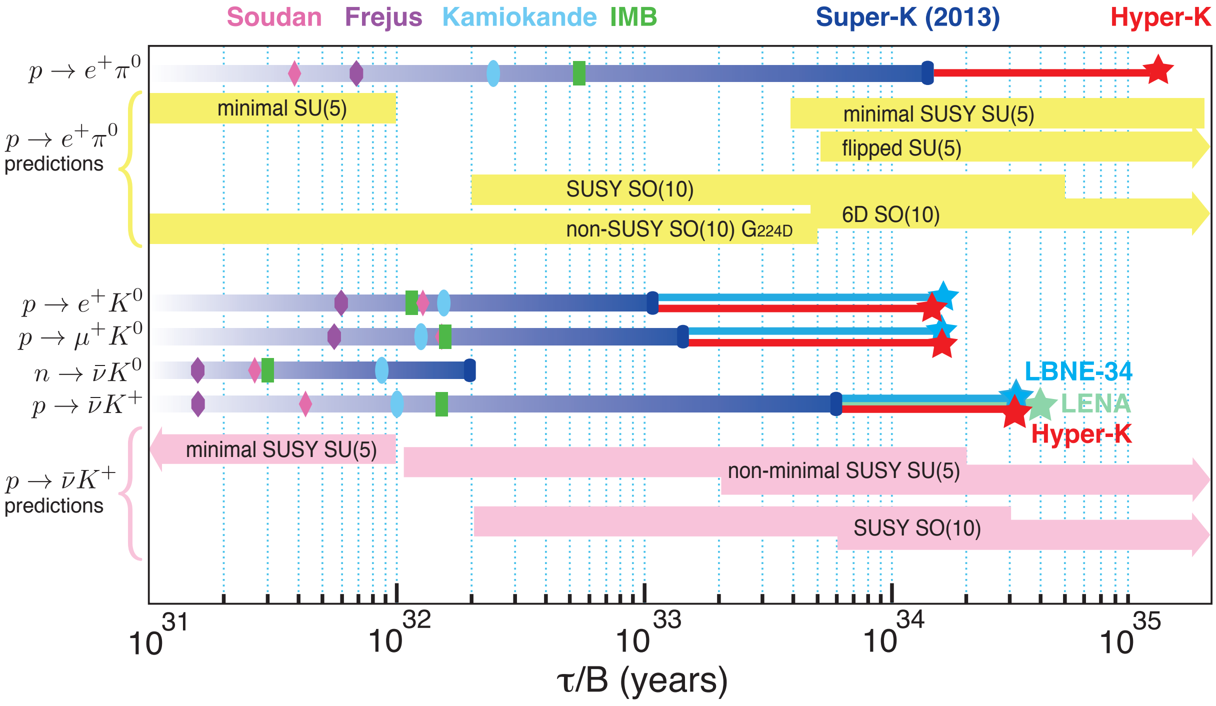

**Figure 5.5:** Proton decay lifetime limits that can be achieved by the LBNE 34-kt detector compared to other proposed future experiments. The limits are at 90% C.L., calculated for a Poisson process including background, assuming that the detected events equal the expected background.

# References

1. J. L. Raaf, **Super-Kamiokande Collaboration** , “Recent Nucleon Decay Results from Super-Kamiokande,” *Nucl.Phys.Proc.Suppl.* **229-232** (2012) 559. Cited in Section 5.1 (pg.139).
2. E. Kearns, “Future Experiments for Proton Decay. Presentation at ISOUPS (International Symposium: Opportunities in Underground Physics for Snowmass), Asilomar, May 2013,” 2013. Cited in Sections 5.1 (pg.139), 5.1 (pg.140), and 5.2 (pg.141).
3. A. Bueno, Z. Dai, Y. Ge, M. Laffranchi, A. Melgarejo, *et al.*, “Nucleon decay searches with large liquid argon TPC detectors at shallow depths: Atmospheric neutrinos and cosmogenic backgrounds,” *JHEP* **0704** (2007) 041, `arXiv:hep-ph/0701101 [hep-ph]`. Cited in Sections 5.1 (pg.140), 5.2 (pg.140), 5.3.1 (pg.144), 5.3.1 (pg.145), and 5.3.2 (pg.145).
4. D. Stefan and A. M. Ankowski, “Nuclear effects in proton decay,” *Acta Phys.Polon.* **B40** (2009) 671–674, `arXiv:0811.1892 [nucl-th]`. Cited in Section 5.2 (pg.141).
5. S. Amerio *et al.*, **ICARUS Collaboration** , “Design, construction and tests of the ICARUS T600 detector,” *Nucl.Instrum.Meth.* **A527** (2004) 329–410. Cited in Section 5.2 (pg.141).
6. M. Antonello, B. Baibussinov, P. Benetti, E. Calligarich, N. Canci, *et al.*, “Precise 3D track reconstruction algorithm for the ICARUS T600 liquid argon time projection chamber detector,” *Adv.High Energy Phys.* **2013** (2013) 260820, `arXiv:1210.5089 [physics.ins-det]`. Cited in Sections 5.2 (pg.142) and 5.3.2 (pg.148).
7. A. Bernstein, M. Bishai, E. Blucher, D. B. Cline, M. V. Diwan, *et al.*, “Report on the Depth Requirements for a Massive Detector at Homestake,” FERMILAB-TM-2424-E, BNL-81896-2008-IR, LBNL-1348E, `arXiv:0907.4183 [hep-ex]`, 2009. Cited in Section 5.3.1 (pg.144).
8. V. Kudryavtsev *et al.*, “Cosmic rays and cosmogenics. report to the lbne collaboration.,” `LBNE-doc-5904`, 2012. Cited in Section 5.3.1 (pg.144).
9. K. Kobayashi *et al.*, **Super-Kamiokande Collaboration** , “Search for nucleon decay via modes favored by supersymmetric grand unification models in Super-Kamiokande-I,” *Phys.Rev.* **D72** (2005) 052007, `arXiv:hep-ex/0502026 [hep-ex]`. Cited in Section 5.3.2 (pg.146).
10. H. Gallagher, “Private communication.”. Cited in Section 5.3.2 (pg.148).