Sensitivity study for proton decay via $p \rightarrow K^+ \bar{\nu}$ in the Deep Underground Neutrino Experiment

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Outline

1. Theoretical motivation

2. The Deep Underground Neutrino Experiment

3. Simulation and reconstruction

4. Analysis
1. Theoretical motivation
Theory: equal amounts of matter and antimatter produced during Big Bang

Observation: dominance of baryons over antibaryons in today’s universe

→ Baryogenesis under Sakharov conditions can solve this problem, e.g. through proton decay

Grand Unified Theory (GUT) predicts proton decay

Supersymmetric (SUSY) extension of GUT opens new proton decay channels and pushes up the proton lifetime:

→ \( p \rightarrow K^+ \bar{\nu} \) with \( \tau \approx 10^{35} \) yrs

Proton decay searches test Baryogenesis, GUT and SUSY
2. The Deep Underground Neutrino Experiment (DUNE)
Physics program: accelerator $\nu$’s ($\delta_{CP}$ & mass hierarchy), nucleon decay, supernova $\nu$’s

DUNE far detector:
- 4 (DP) LAr TPC’s
- $\sim 40$ kton active mass
- 1500 m underground
- R&D program: $3 \times 1 \times 1$ m$^3$, protoDUNE
Dual Phase Liquid Argon Time Projection Chamber

- Ionization charge drifted upwards, extracted and amplified in argon gas
- Two perpendicular readout views
- Readout pitch: 3 mm
- Sampling time: 400 ns

→ High spatial and calorimetric resolution
- Scintillation light collected by PMTs for trigger
3. Simulation and reconstruction
Signal and background simulation and reconstruction

- **Signal:** \( p \rightarrow K^+ \bar{\nu}, \quad K^+ \rightarrow \mu^+ \nu_\mu \) \((E_{\text{vis}} \approx 200 - 400 \text{ MeV})\)
- **Background:** HONDA atmospheric \( \nu \) flux + NEUT \( \chi \)-sections
- **Full detector simulation:** GEANT4, drift and amplification

**Diagram:**

**Hit finding and hit to true particle matching**

**3D track reconstruction**

→ Detector simulation and reco validated with 3x1x1 \( m^3 \)
4. Analysis
**Goal:** determine lower proton lifetime limit per branching ratio $\tau_{\text{Br}}$ if no proton decay is observed

$\tau_{\text{Br}} = \text{Signal selection efficiency} \times \text{Exposure} \times \frac{1}{S}$

Background $B$: $B = 0 \rightarrow S = 2.3 \quad B = 5 \rightarrow S = 5.1$

→ Background rejection strategy: find the single kaon

**Reconstructed 3D tracks: kaon identification**

- Preselection & $\langle dE/ds \rangle$ vs. $E_{\text{kin}}$ with neural network

**Kaons:**

**Protons:**
Signal selection and background rejection

For 2 Mton x years:

<table>
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<th>Cut</th>
<th>Signal selection efficiency</th>
<th>Background events</th>
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**Cut 1:** One reconstructed kaon

**Cut 2:** Three reconstructed particles

**Cut 3:** $500 \, \text{fC} \leq \text{total reconstructed charge} \leq 2000 \, \text{fC}$

**Cut 4:** Reconstructed particle with $40 \, \text{cm} \leq L \leq 60 \, \text{cm}$ that starts less than 5 cm from kaon end point ($K^+ \rightarrow \mu^+\nu_\mu$)
Proton decay sensitivity at 90% C.L. for $p \rightarrow K^+ \bar{\nu}$

- **Super-K**: $\tau_{Br} = 5.9 \cdot 10^{33}$ years at 260 kton x years (https://arxiv.org/abs/1408.1195)

- **Hyper-K**: $\tau_{Br} = 5 \cdot 10^{34}$ years, after 20 years with one module (https://arxiv.org/abs/1805.04163)
Conclusion and outlook

- Sensitivity study of $p \rightarrow K^+ \bar{\nu}$ in DUNE dual phase with validated simulation and reconstruction with aided pattern recognition
- LAr TPC superior over Water Cherenkov for $p \rightarrow K^+ \bar{\nu}$
- DUNE: $\tau_{Br} \approx 8 \cdot 10^{34}$ years at an exposure of 1 Mton x years (prediction SUSY GUT: $\tau \approx 10^{35}$ years)
- To do: study systematic uncertainties
Thank you!
Atmospheric neutrino background energy spectrum normalized to 2 Mton x years

\[ \frac{dN_{\nu}}{dE} \text{ [GeV]^{-1}} \]

- $\nu_\mu$
- $\nu_e$
- $\bar{\nu}_\mu$
- $\bar{\nu}_e$

\[ E_\nu \text{ [GeV]} \]
Kaon ID performance

Particle selection efficiency

Number of particles

- Reconstructed
- Preselection cuts
- $<dE/ds>$ vs. $E_{\text{kin}}$

Nuclei

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