DUNE Scientific Opportunities and Capabilities for Proton Decay Searches
Outlook

• Introduction
  
  Standard Model
  
  Gran Unified Theories and Proton Decay

• LArTPCs

• DUNE Experiment

• Proton Decay Signatures at DUNE

• Proton Decay Backgrounds at DUNE

• Summary
The Standard Model of Elementary Particles

- **Strong Force**
  - Quarks
- **Electromagnetic force**
  - Quarks
  - Charged Leptons
- **Weak Force**
  - Charged Leptons
  - Neutrinos (neutral leptons)

From Wikipedia
The Standard Model of Elementary Particles

The Standard Model has been very successful

Predicted the existence of the $W$ and $Z$ bosons, and the top and charm quarks before these particles were observed

$Z$ boson mass prediction
$91.1874 \pm 0.0021 \text{ GeV/c}^2$

$Z$ boson global fit (data)
$91.1876 \pm 0.0021 \text{ GeV/c}^2$
The Standard Model of Elementary Particles

However, there are several questions remaining:

- Why are there three interactions?
- Why are there three generations?
- Why neutrinos are so light compared to other leptons?
- Why is the proton charge the opposite to the electron?
Grand Unified Theories

In order to solve those question Grand Unified Theories (GUTs) has been proposed

- Can we tested these theories? Impossible to reach this energy at the laboratory
- A GUT combined with a symmetry SU(5) or supersymmetry distinguishes themselves from other GUTs theories
- Prediction of proton decay
Grand Unified Theories

In order to solve those question Grand Unified Theories (GUTs) has been proposed

- Can we tested this theories? Impossible to reach this energy at the laboratory
- Proton decay
- Thus, proton decay is the key to unlocking the potential of these GUTs
Grand Unified Theories

- A GUTs based on SU(5) symmetry favored a proton decay channel
  \[ p \rightarrow e^+ \pi^0 \]
- The dominant channel in a SUSY GUTs
  \[ p \rightarrow K^+ \nu \]
- There are many other decays models that have been proposed I would focus on the most explored

Figs: arXiv:1512.06148
Proton Decay

- This channel has straightforward experimental signature for a water Cherenkov detector
- Where background-free high-efficiency searches are possible with large water Cherenkov detectors

- On the other hand this channel represents a challenge for water Cherenkov detectors because the kaon is below threshold
- The key signature is the presence of an isolated charged kaon

Figs: arXiv:1512.06148
Proton Decay & LArTPC

- LArTPC technology exhibits a significant performance advantage over the water Cherenkov technology.
- Charged particles ionize Ar; liberated e⁻ are drifted to wire planes where their 2D location can be reconstructed; drift time gives 3rd dimension.
- For non-beam events, obtaining the drift time relies on detecting the scintillation light (defines $t_0$).
- In a LArTPC detector the K⁺ can be tracked, then it can be possibly ID and its momentum can be measured.
Deep Underground Neutrino Experiment

An international mega-science project
- CP-violation
- Mass hierarchy
- Neutrinos from supernova
- Proton decay

- Far detector at Sanford Underground Research Facility
Deep Underground Neutrino Experiment

- LArTPC technology
- Photon detector system
- 40-kt of fiducial mass
- Being deep (1450m) underground provide an excellent shielding from cosmic rays

- 2015 New collaboration DUNE
- 2017 Start excavation at the far site (SURF)
- 2018 Two ProtoDUNE Detectors (SP & DP) operational at CERN
- 2021 Start of FD installation: 1st module
- 2023 Continue FD installation: 2nd module
- 2024 20 kt operational
- 2026 Beam operations begin at nominal power and proton energy
Deep Underground Neutrino Experiment

- No evidence has been observed so far
- Current limits are \( \sim 10^{34} \) years
- If you have 1 proton you will need to wait \( \sim 10^{34} \) years and see if it decays!

Massive LArTPC Far Detector

- Four 10-kt (fiducial) modules
- \( 10^{33} \) protons!!
- Size, location, and technology make this a suitable tool for proton decay search
Proton Decay Signatures at DUNE

Simulation of proton decay at DUNE LArTPC

\[ p \rightarrow K^+ \bar{\nu} \]

- GENIE v2.12.0
- Proton decay from Ar nucleus
- Simulation of nuclear effects
  - Fermi motion
  - Final state interaction

\[ p \rightarrow K^+ \bar{\nu} \]

\[ K^+ \rightarrow \mu^+ \bar{\nu}_\mu \]

\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]
Proton Decay Signatures at DUNE

Simulation of proton decay at DUNE LArTPC

\[ p \rightarrow K^+ \bar{\nu} \]

- We have developed an end-to-end simulation and reconstruction chain
- Enabling track reconstruction and PID

Simulated event with tracks and PIDA (dE/dx) distribution:

- Positive tracks: e^+, K^+, \mu^+

Data analysis work in progress.
Proton Decay Signatures at DUNE

Simulation of proton decay at DUNE LArTPC  \( p \rightarrow K^+\bar{\nu} \)

- The key signature for proton decay search for an isolated charged kaon (kaon ID)
- Another quantity that is particularly useful is the muon’s momentum from the kaon decay (95% decays-at-rest)
Proton Decay Backgrounds

- Atmospheric neutrinos ($\nu_\mu$ CCQE) where a proton is misidentified as kaon
- Another potential is cosmogenic-induced kaons, these kaons are produced when cosmic muons interact with the rock and produce a neutral kaon that enters the detector before undergoing charge exchange

- Most kaons in muon-induced events are accompanied by a non-negligible energy deposition quite far from the kaon vertex
Proton Decay Backgrounds

- $^{39}$Ar beta decay produces light inside the LArTPC which the DUNE FD photon detector system is sensitive to.

- Should this light be reconstructed within the drift window of a cosmogenic background and confused for $t_0$, the track can seemingly be pulled into the fiducial volume.

- Monte Carlo simulation of $^{39}$Ar activity indicates setting a threshold of ~10PE on reconstructed light would eliminate the potential background.
DUNE Sensitivities

- Given the current reconstruction and analysis tools a preliminary evaluation of signal efficiency and background rate allows to calculate the partial lifetime sensitivity at 90% C.L for a 400 kton-year exposure.
Summary

- Using LArTPC technology the $K^+$ can be tracked. This is in sharp contrast with water detectors, in which the $K^+$ momentum is below Cherenkov threshold.

- DUNE’s massive LArTPC far detector offers a great opportunity to search for proton decay and other baryon number violating processes.

- The current status of the automated reconstruction allows to have a preliminary estimation of DUNE’s sensitivity.

- DUNE has a rich program from neutrino oscillation physics to proton decay and more… so stay tuned for exiting news!!
The End

Thanks for listening

DUNE Collaboration, CERN, January 2017
Backups
Challenges of Tracking Kaons

- Final state interaction tends to softer the kaon spectrum
- Additional nucleons from FSI may overlap with kaon tracks
- The current tracking threshold is ~30 MeV (~15 mm on LAr)
Other Decays Modes

- Other decay modes where DUNE will have potential of improve on the current limits

<table>
<thead>
<tr>
<th>Mode</th>
<th>PDG ID</th>
<th>Current Limit (10^{33} yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n \rightarrow e^+ K^-$</td>
<td>13</td>
<td>$&gt; 0.017$</td>
</tr>
<tr>
<td>$p \rightarrow e^+ K^0$</td>
<td>13</td>
<td>$&gt; 1.0$</td>
</tr>
<tr>
<td>$n \rightarrow \mu^+ K^-$</td>
<td>16</td>
<td>$&gt; 0.026$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ K^0$</td>
<td>16</td>
<td>$&gt; 1.6$</td>
</tr>
<tr>
<td>$p \rightarrow e^+ K^{*0}$</td>
<td>21</td>
<td>$&gt; 0.084$</td>
</tr>
<tr>
<td>$n \rightarrow e^- K^+$</td>
<td>34</td>
<td>$&gt; 0.032$</td>
</tr>
<tr>
<td>$n \rightarrow \mu^- K^+$</td>
<td>35</td>
<td>$&gt; 0.057$</td>
</tr>
<tr>
<td>$p \rightarrow e^- \pi^+ K^+$</td>
<td>40</td>
<td>$&gt; 0.075$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^- \pi^+ K^+$</td>
<td>41</td>
<td>$&gt; 0.245$</td>
</tr>
</tbody>
</table>

see [http://pdg.lbl.gov](http://pdg.lbl.gov) for a full list of potential decay modes