Nucleon Decay and Atmospheric Neutrino Reconstruction in DUNE

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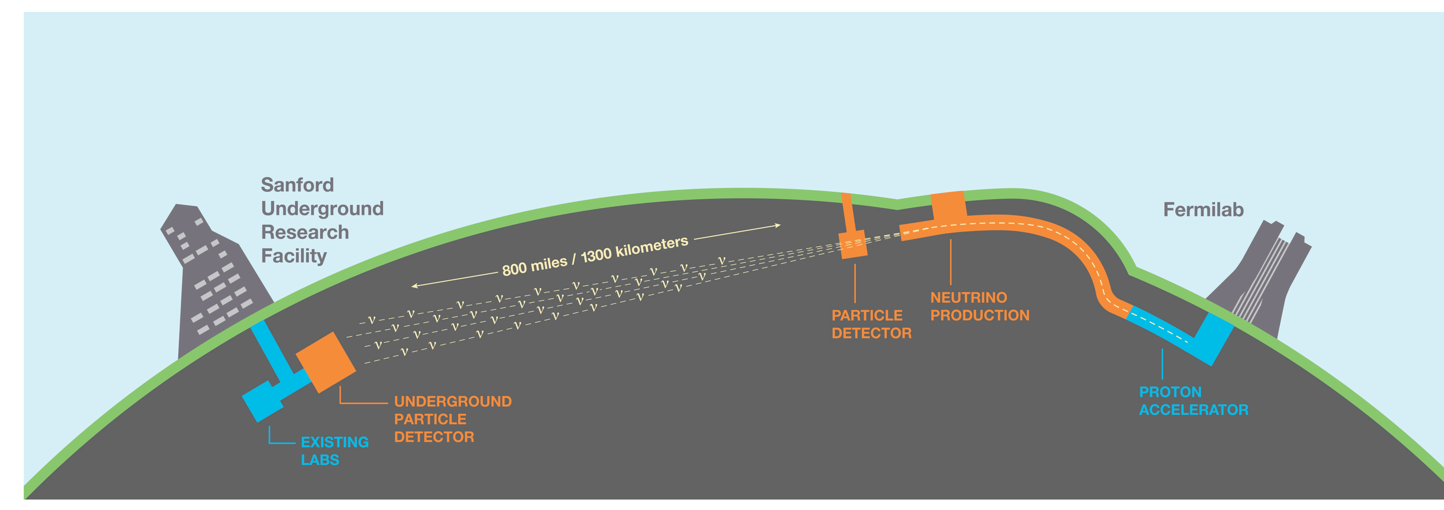
The Deep Underground Neutrino Experiment

An international collaboration of more than 750 scientists, hosted by Fermilab IL, has come together to develop the **D**eep **U**nderground **N**eutrino **E**xperiment. The DUNE collaboration and the **L**ong-**B**aseline **N**eutrino **F**acility will construct the neutrino beam line and the near and far detectors.

The DUNE far detector modules will be located deep underground at the Sanford Lab, SD. With 40 kton liquid Argon cryostats, 1,475 m underneath the surface, DUNE will be able to study atmospheric neutrino oscillations and perform low background searches of nucleon decay. Being particularly sensitive to the important modes with kaons in the final state.



An experimental program in neutrinos, nucleon decay and astroparticle physics enabled by the Fermilab Long-Baseline Neutrino Facility.

Motivation

Initial DUNE sensitivity results have been based on simplified studies of different detector performances. In particular, atmospheric neutrino and nucleon decay events have used estimates for hadron (lepton) direction and energy resolutions, signal efficiency, background rates and nu/nubar separation.

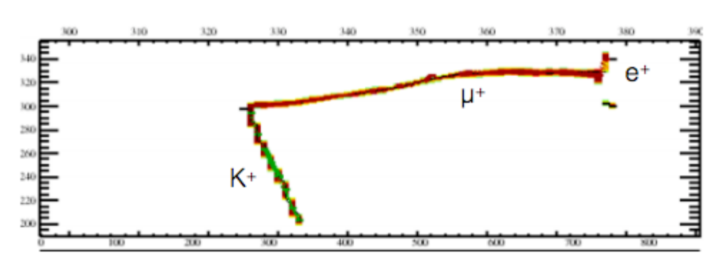
Angular Resolution	Electron	1 deg
	Muon	1 deg
	Hadronic System	10 deg
Energy resolution	Stopping muon	3%
	Exiting muon	15%
	Electron	1%/√E + 1%
	Hadronic system	30%/√E
Signal Acceptance	Electrons	90%
	Muons	100%
Background rejection	e-like (π^0, γ)	95%
	μ-like (π^+, π^-)	99%

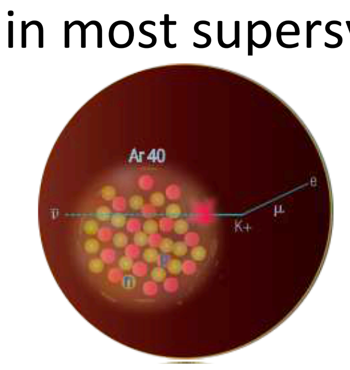
This work aims to validate these previous assumptions. Recent efforts use fully simulated/reconstructed Monte Carlo to evaluate signal efficiencies and background rejection power.

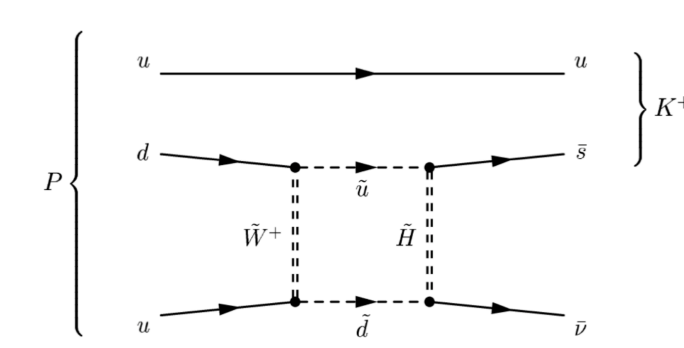
Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8

Nucleon Decay

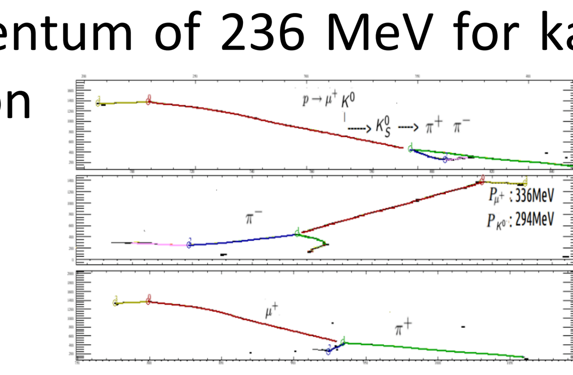
Grand **U**nified **T**heories predict the decay of protons and bound neutrons. The dominant proton decay mode in most supersymmetric GUTs is $p \to \bar{\nu} K^+$.





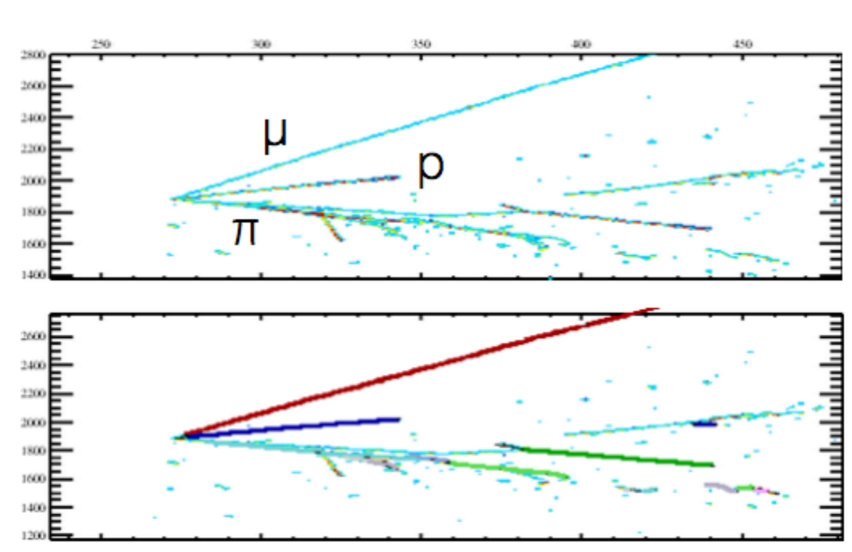


Most of the time, the kaon decays into an anti-muon and a neutrino, leaving a very clean signal in the detector (DUNE golden mode). The mono-energetic kaon has its momentum smeared by Fermi momenta of the nucleus, but the mono-energetic muon has a well defined momentum of 236 MeV for kaons decaying at rest. Due to the high spatial resolution of the detector, DUNE can also identify neutral kaons through their displaced vertices (lepton plus neutral kaon modes).



Atmospheric Neutrinos

With energies spanning multiple decades and travel lengths from tens to thousands of km, atmospheric neutrinos are a unique tool to study neutrino oscillations. Such a unique probe will also help to understand matter effects, the neutrino mass-hierarchy and measure the leptonic CP violating phase.



The liquid-Ar DUNE far detector will offer great energy and angular resolutions together with particle ID. As for nucleon decay, the rock overburden will provide a shield against cosmic-rays and its large mass will deliver high event rate.

ProtoDUNE

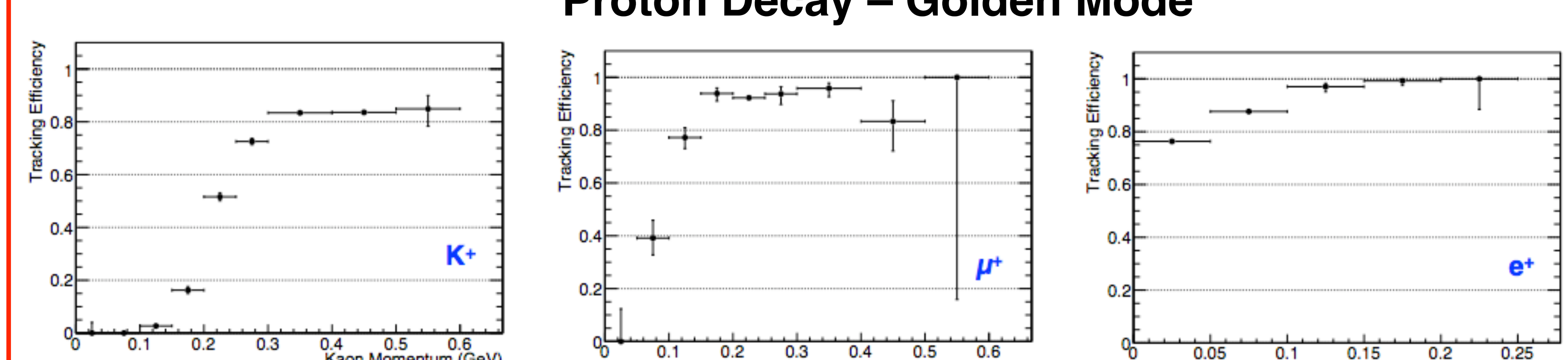
The protoDUNE experimental program will test and validate technologies and designs of the DUNE far detector. The detectors will be placed in a dedicated charged-particle beam line at CERN.

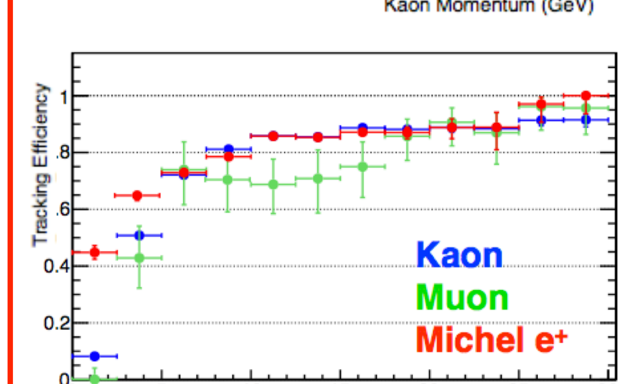
ProtoDUNE will be crucial for understanding nucleon decay and atmospheric neutrino events. Namely, the program will provide:

- Particle ID performance:
  Full e/μ/π/K/p separation
- Track/Shower reconstruction performance:
  Single particle reconstruction efficiency
  Displaced vertex reconstruction
- Charged pions and kaons cross sections in Argon:
  Low kinetic energies (~100 MeV)

Efficiencies and Conclusions

Proton Decay – Golden Mode

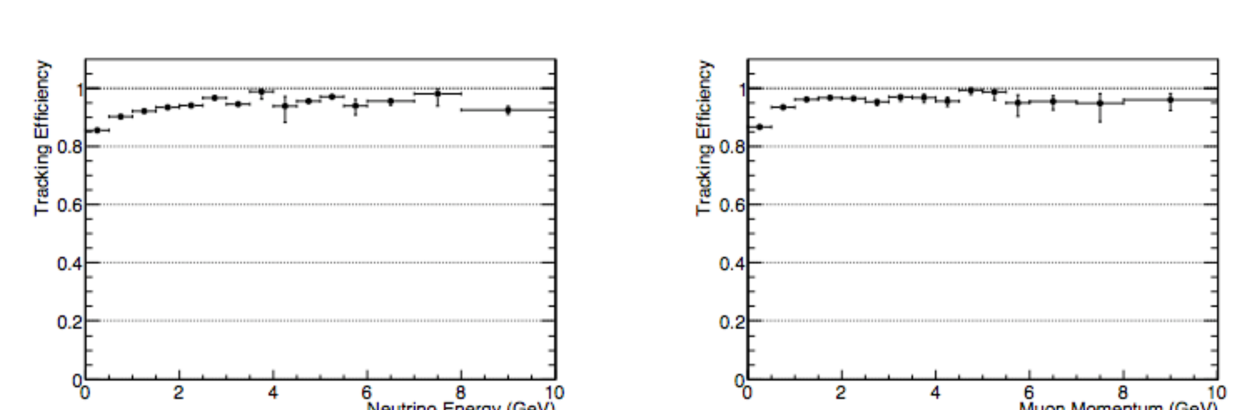




Reconstruction efficiencies as a function of true momenta and track length for the golden mode.

For higher energies, the present reconstruction is able to achieve high efficiencies similar to the one used in preliminary lifetime sensitivity studies for the golden mode (97%): $p \to \bar{\nu} K^+$.

Atmospheric Neutrinos



Track reconstruction efficiencies as a function of true neutrino and muon energies. Previous studies estimated ~100% efficiency for numu events.

Conclusions

DUNE recently started to fully simulate and reconstruct nucleon decay and atmospheric neutrino MC events in the far detector. Without any reconstruction optimization done for these events, results show that for higher energies the efficiencies are already similar to the ones used in previous studies. Ongoing efforts to optimize reconstruction at lower energies.