Nucleon Decay Search with DUNE

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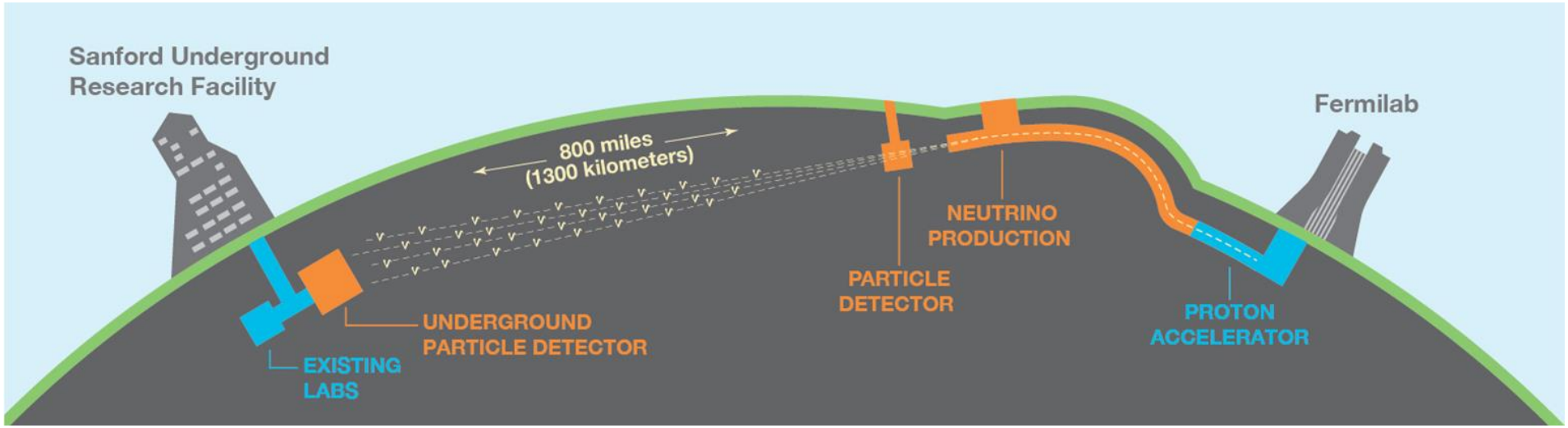
DUNE

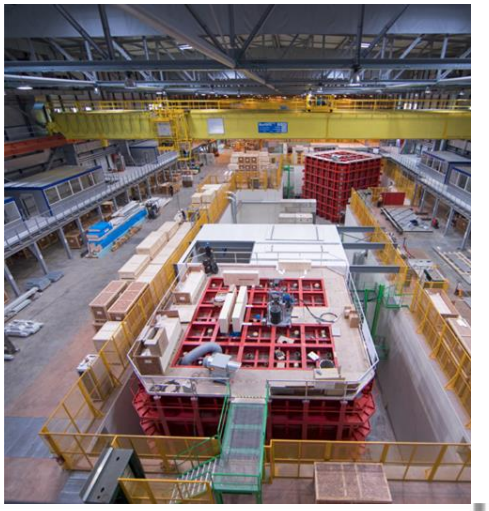
The Deep Underground Neutrino Experiment (DUNE)

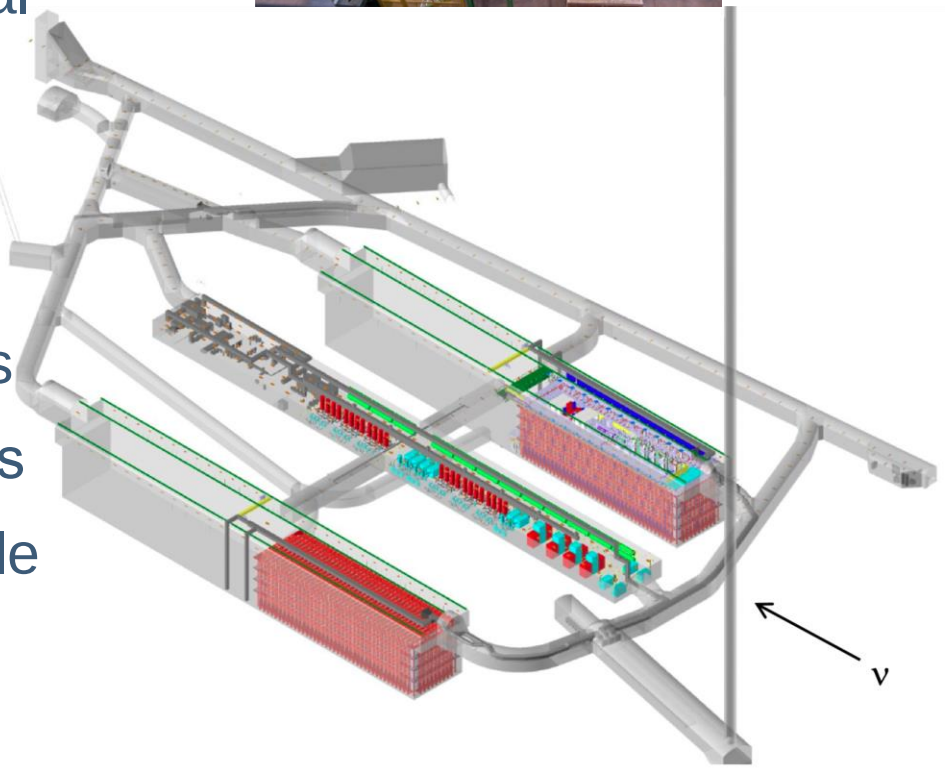
- Long-baseline neutrino oscillations, including discovery sensitivity to CP violation and neutrino mass ordering
- MeV-scale neutrino physics, including supernova burst astrophysics and solar neutrinos
- Broad program of physics searches beyond the Standard Model, including baryon number violation, non-standard oscillations, dark matter



DUNE Far Detector

- Deep underground cavern (1.5 km) at SURF
- Four 17-kiloton Liquid argon TPC (LArTPC) modules (70-kiloton total mass)
  - Each cryostat is 65.8 m long, 18.9 m wide and 17.8 m tall
- Photon Detection System system to provide t_0 for non-beam physics
- Expect FD to turn on in late 2020's
- Successful operation of large-scale DUNE prototypes at CERN (ProtoDUNE)



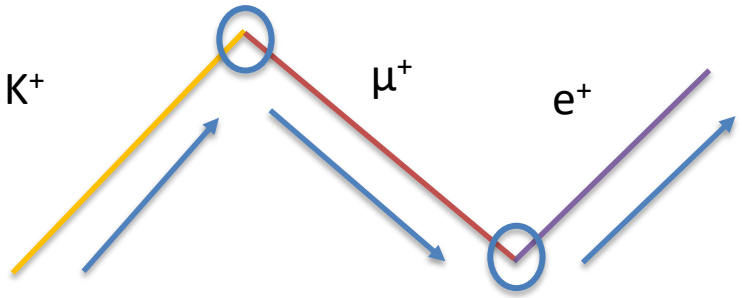


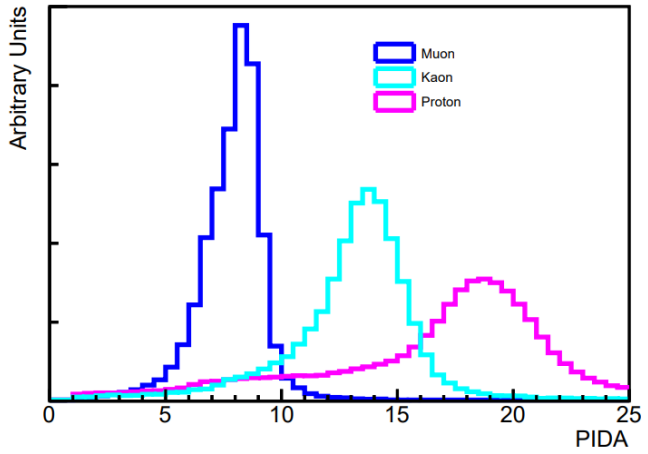
Nucleon Decay

- Observation of baryon number violating processes such as nucleon decay and neutron-antineutron oscillation would provide evidence of physics beyond the Standard Model
  - Benchmark proton decay modes from grand unified theories:
    - $p \rightarrow e^{+}\pi^{0}$
    - $p \rightarrow K^{+}\bar{\nu}$
- Large mass, deep underground location, and excellent imaging and particle ID capabilities in LArTPCs make the DUNE FD ideal for nucleon decay searches
- The most stringent limits in most decay channels are set by the Super-Kamiokande experiment (water Cherenkov detector, 50 kiloton total mass, in operation for more than 25 years)
  - Improvements on these limits will require long exposure times coupled with larger sensitive mass and/or improved efficiency and background rejection
- Two other large detectors will be operating in the DUNE era: Hyper-Kamiokande (water Cherenkov) and JUNO (liquid scintillator)
  - Highly complementary searches

$p \rightarrow K^+ \bar{\nu}$

- DUNE's initial focus is on proton decay modes producing charged kaons
  - Kaon is typically below threshold in a water Cherenkov detector, but can be identified by dE/dx and decay in a LArTPC
- Signature: single kaon with origin in the fiducial volume followed by decay products
  - 64% branching fraction for decay to muon
- Background due to cosmic-ray muons can be controlled by requiring no activity close to the edges of the TPCs
- Atmospheric neutrinos make up the dominant background
  - Most significant background is not neutrino-induced kaon production, but charged-current quasi-elastic events where the proton is misID-ed as a kaon
  - Look for kaon Bragg peak near muon vertex



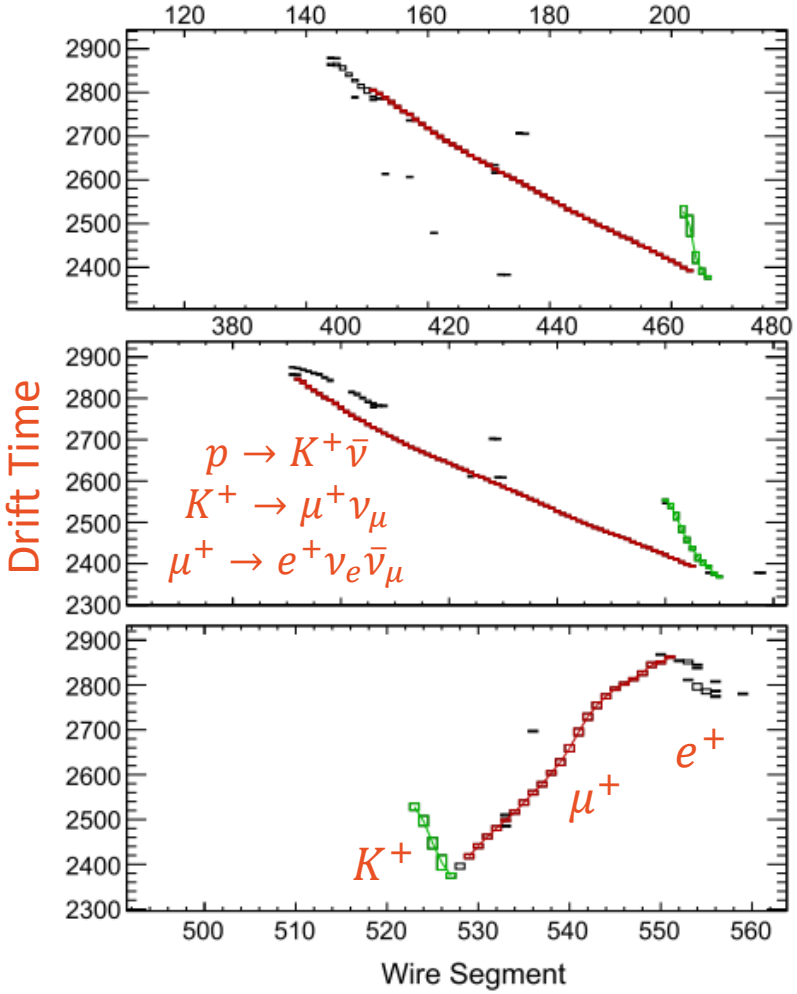


Analysis:

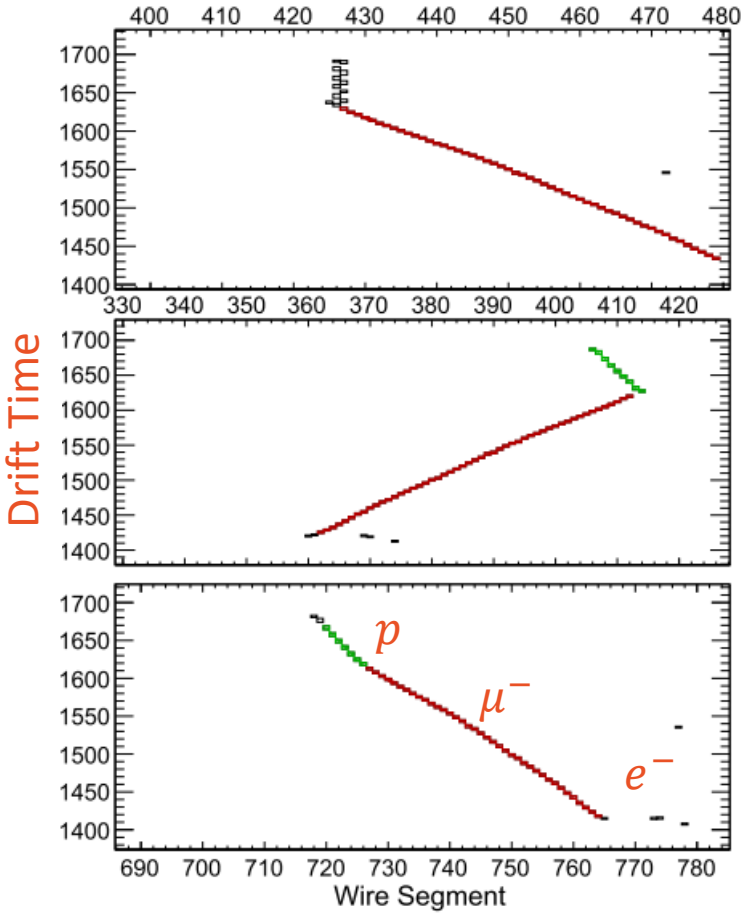
- At least two tracks (kaon + decay product, usual muon), longest track <100 cm (removes background from high-energy nus)
- Boosted Decision Tree identifier with 14 input variables

$p \rightarrow K^+\bar{\nu}$ Event Displays

A high scoring signal MC event



A high scoring atmospheric MC event



https://link.springer.com/article/10.1140/epjc/s10052-021-09007-w

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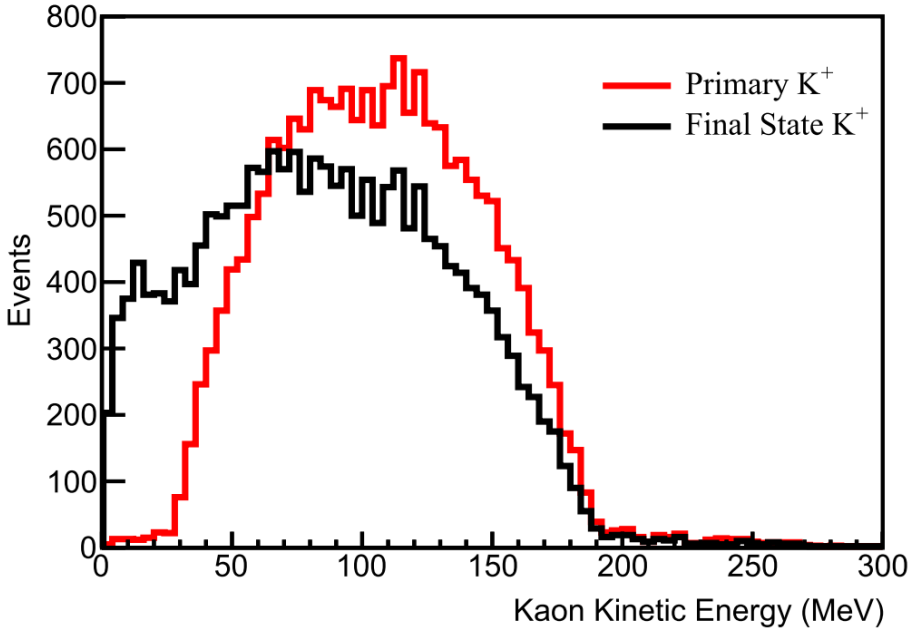
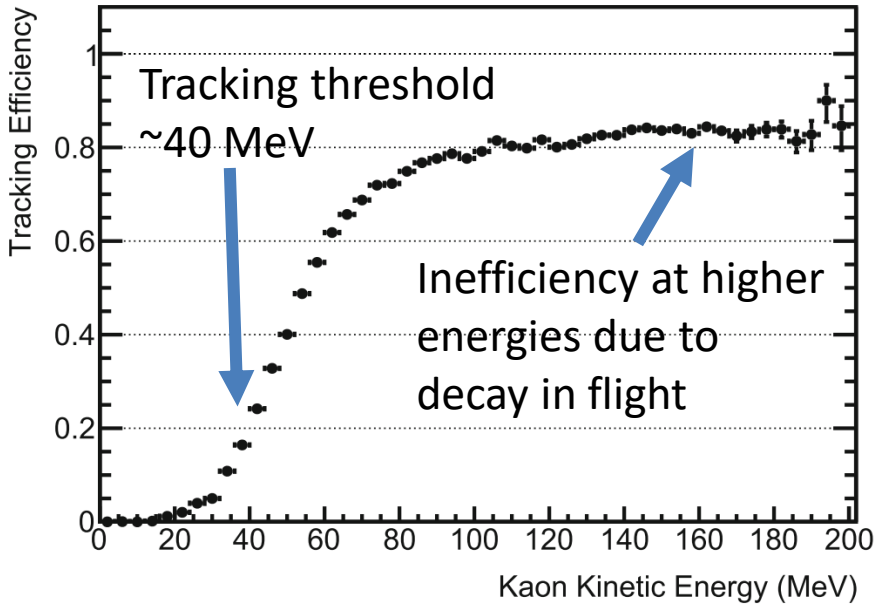
Effect of Final State Interactions

- Limiting factor in kaon identification is the kaon tracking efficiency
- Kaons from proton decay are ~100 MeV and strongly affected by final state interactions (FSI)
  - After FSI, ~25% of kaons have kinetic energy <50 MeV
  - FSI can also cause nucleons to be emitted; presence of these nucleons can also affect kaon reco





$p \rightarrow K^+ \bar{\nu}$ Sensitivity

- Assumed a 30% signal efficiency (including expected tracking improvements)
- Applied same cuts to atmospheric neutrino events to get an expected background of one event per megaton-year (3×10^{-6} background suppression)
- Systematics: 2% on signal (FSI uncertainty); 20% on background (flux and cross section uncertainty)
- DUNE sensitivity (90% CL lower limit on proton lifetime in this channel):
  - 1.3×10^{34} years (400 kiloton-year exposure)
  - Current published limit from Super-K: 5.9×10^{33} years (260 kiloton-year exposure)

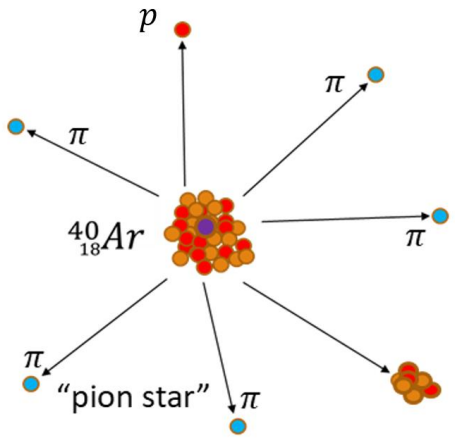
Other Nucleon Decay Channels

- $n \rightarrow e^{-}K^{+}$
- Applied similar analysis techniques as $p \rightarrow K^{+}\bar{\nu}$ analysis, with requirement of electron shower in addition to kaon ID
- Signal efficiency: 47%
- DUNE sensitivity:
  - 1.1×10^{34} years (400 kiloton-year exposure)
  - Current published limit (Frejus experiment): 3.2×10^{31} years

- $p \rightarrow e^{+}\pi^{0}$
- Preliminary analysis based on Monte Carlo truth variables (approximated reconstruction)
- Must identify 3 electromagnetic showers
- DUNE sensitivity:
  - 8.7×10^{33} – 1.1×10^{34} years depending on reconstruction performance (400 kiloton-year exposure)
  - Current published limit from Super-K: 2.4×10^{34} years (450 kiloton-year exposure)

Neutron-Antineutron Oscillations

- Another baryon number violating process predicted by some theories ($|\Delta B|=2$)
- Detector via antineutron annihilation with a nucleon
- Roughly spherical signature of a vertex with several emitted light hadrons ("pion star"), total energy of twice the nucleon mass, roughly zero net momentum
- FSI: decrease pion energy, decrease pion multiplicity, knockout nucleons

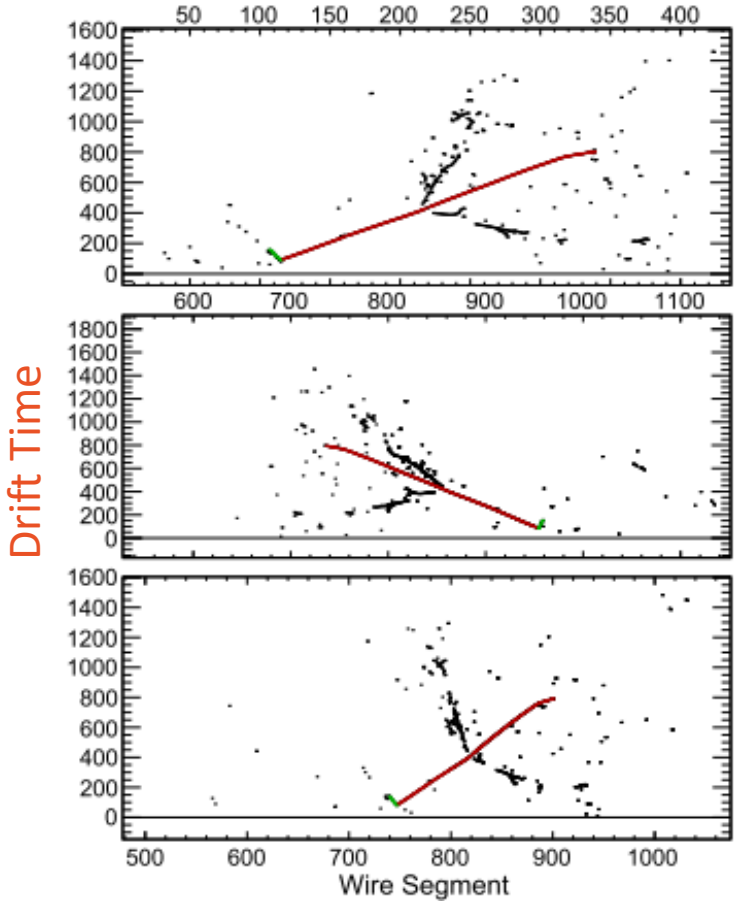


- Analysis techniques similar to $p \rightarrow K^{+}\bar{\nu}$
- DUNE sensitivity for free neutron oscillation time (400 kiloton-year exposure): 5.53×10^{8} s
- Current published limit from Super-K (370 kiloton-year exposure): 4.7×10^{8} s

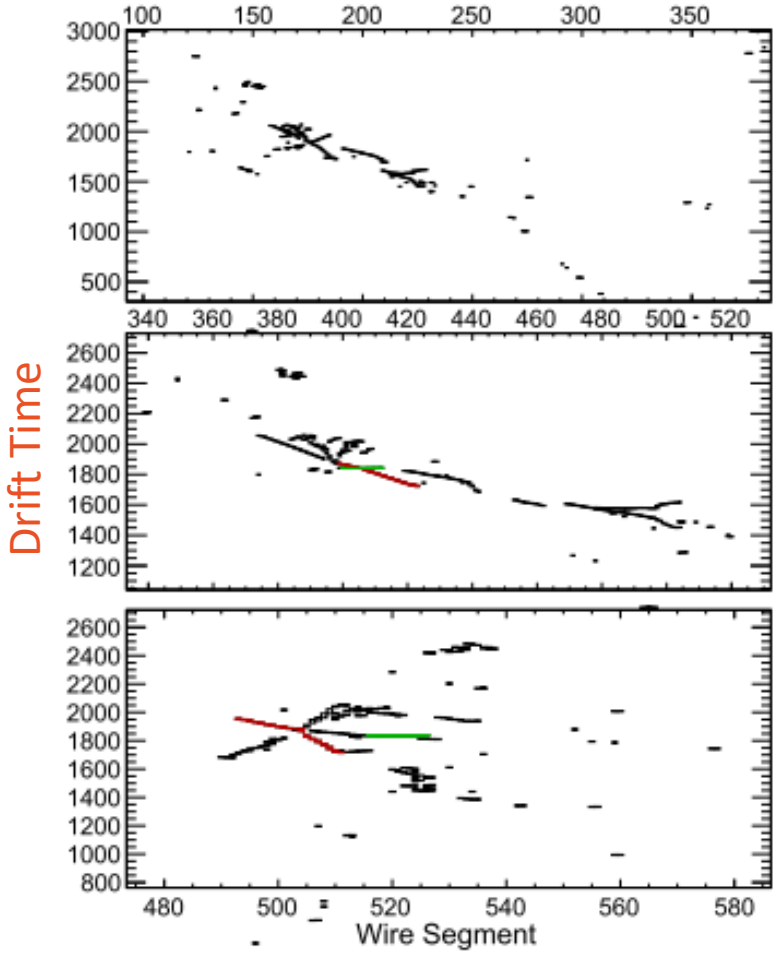
$n \to \bar{n}$ Event Displays

$$n\bar{n} \to n\pi^0\pi^0\pi^+\pi^-$$

A high scoring signal MC event



A high scoring atmospheric MC event



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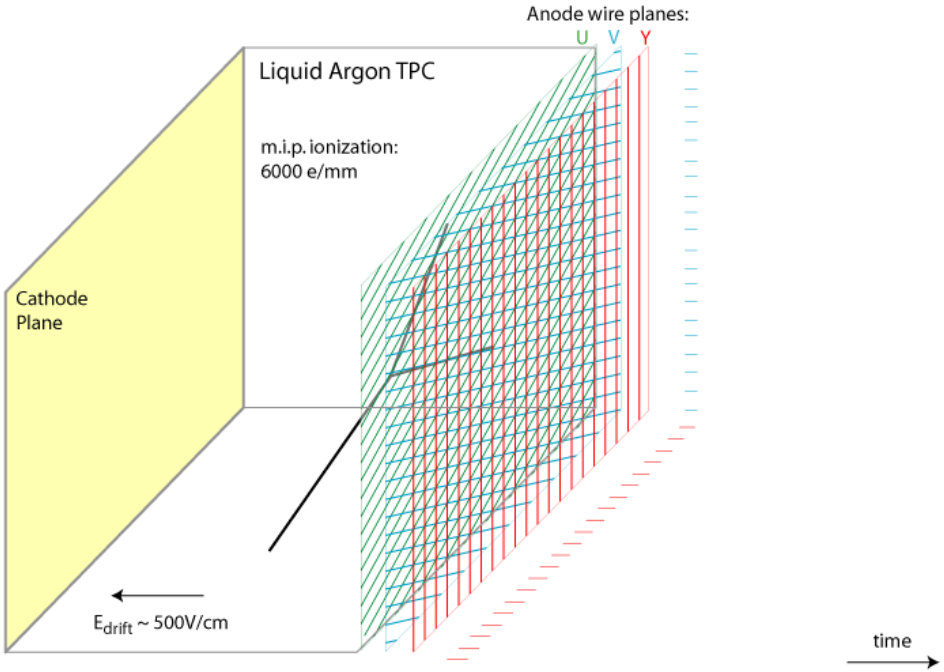
Summary and Future Outlook

- DUNE has conducted initial investigations into nucleon decay and neutron-antineutron oscillation sensitivity with full simulation and reconstruction
  - LArTPC technology offers unique advantages in certain nucleon decay channels
  - We've investigated only a few channels so far, but ultimately DUNE will conduct searches in many different channels
- Highly complementary searches with other large underground detectors that will be operating concurrently
  - Should a signal be observed by any one experiment, confirmation by the others using different detector technologies would be powerful evidence
- Future outlook
  - Improvements in track/vertex reconstruction
  - Investigations of impact of different FSI models
  - Additional nucleon decay modes

Backup

Liquid Argon TPCs



- A large uniform liquid argon volume
- Electric field applied across drift volume
- Ionizing particles create free charge; Electrons drift towards anode planes
- 3 wire planes each yield 2D images of wire coordinate and drift coordinate
- The collected charge is proportional to the energy deposition (dE/dX)