Baryon Number Violation Searches in DUNE

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Fermilab New Perspectives 2022

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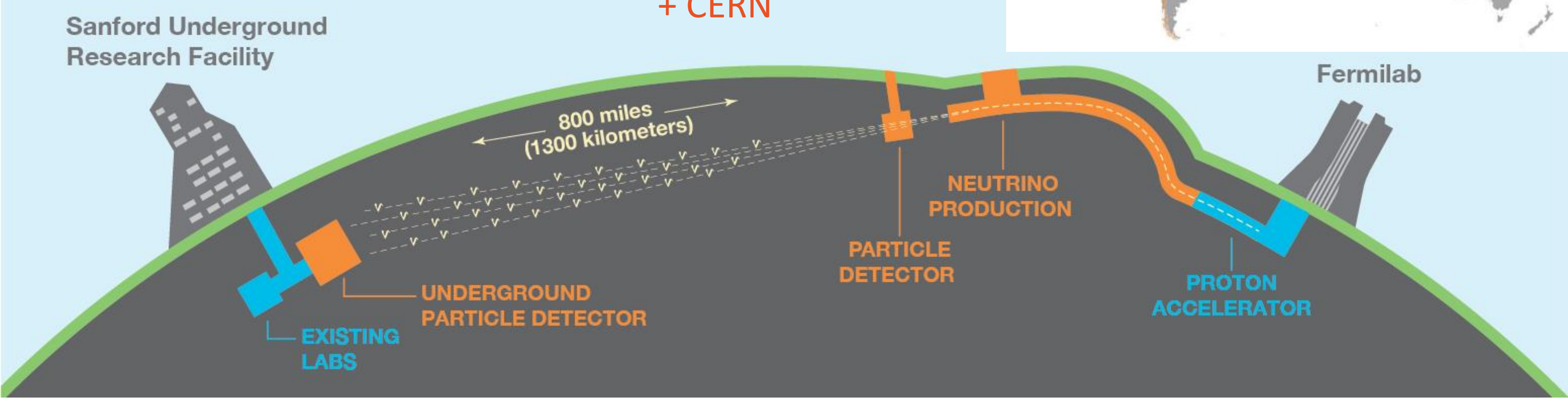
The Deep Underground Neutrino Experiment (DUNE)

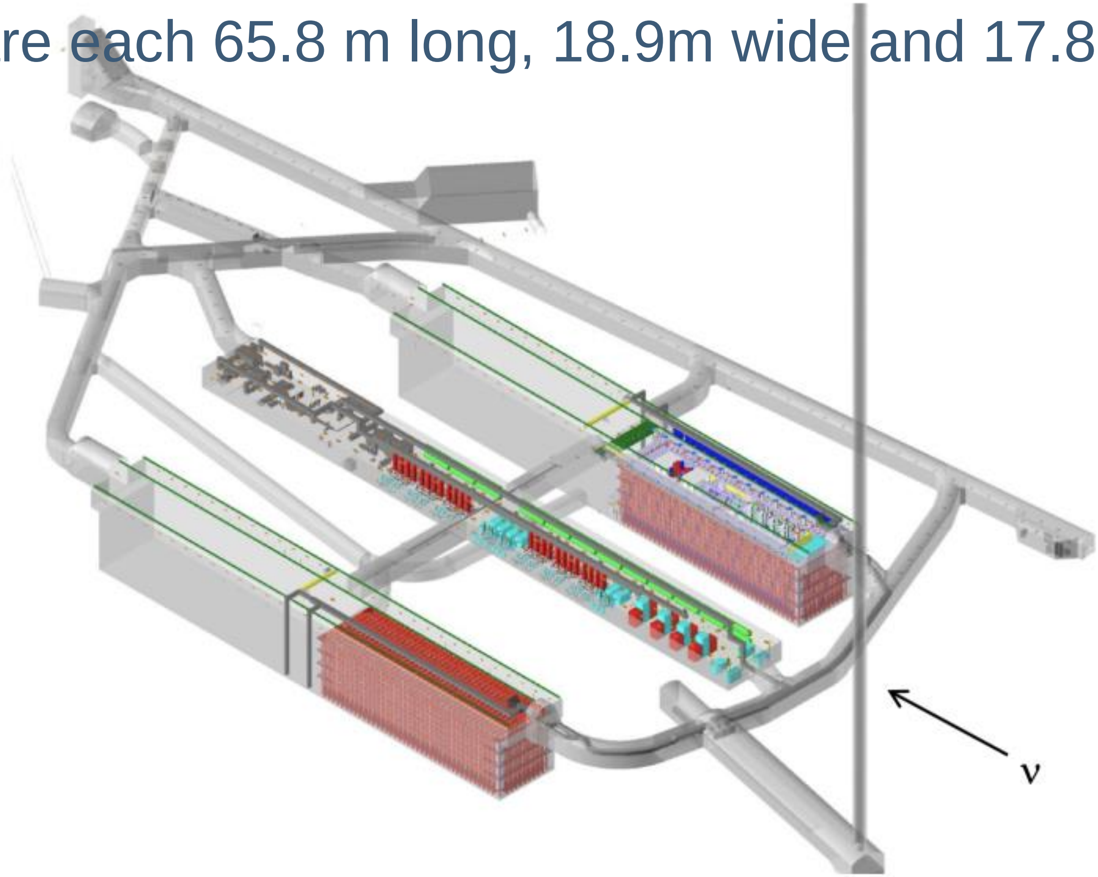
- Flagship project of Fermilab
- Will construct 1.2 MW ν beam with upgrade plans to 2.4 MW
- Near detector will utilize a suite of detectors
- Far detectors will utilize Liquid Argon Time Projection Chambers (LArTPCs)
- Total Far detector mass: 70 kt of LAr

1402 collaborators
206 institutions in 38 countries
+ CERN

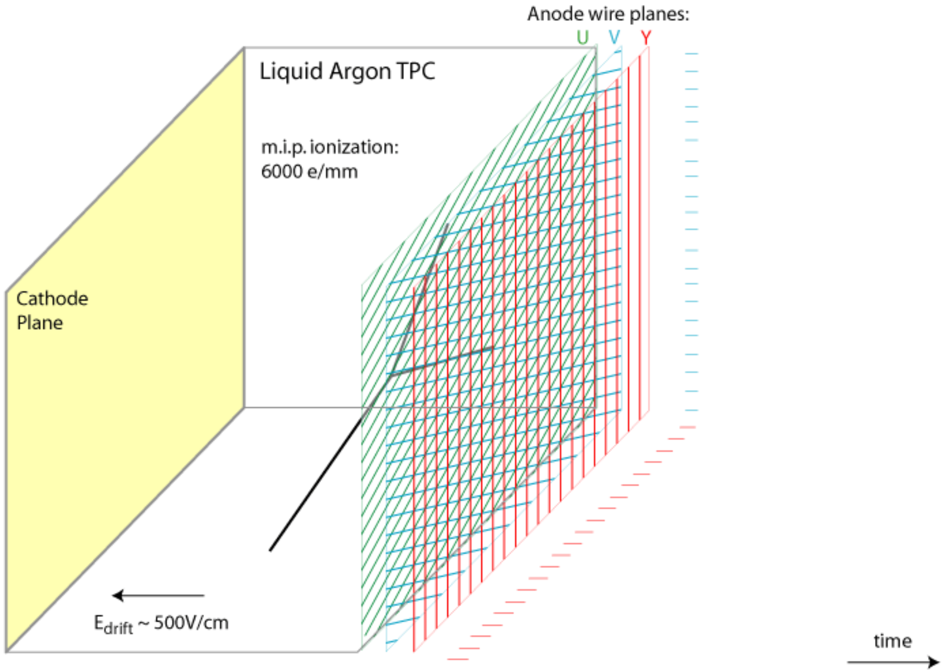


DUNE at SURF

- DUNE Far detectors will sit 1.5 km underground
- Four far detector modules each composed of 17.5 kt of LAr
  - In this talk we assume each detector has 10 kt of fiducial volume
- Cryostats are each 65.8 m long, 18.9m wide and 17.8m tall



LArTPC: How They Work



- 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
- Optical System provide t_0
- The collected charge is proportional to the energy deposition (dE/dX)

Baryon Number Violation

Nucleon Decay

Baryon Number Violation: Nucleon Decay

1. Candidate Channels Searched
   - $p \rightarrow K^{+}\bar{\nu}$
   - $p \rightarrow e^{+}\pi^{0}$
   - $n \rightarrow e^{-}K^{+}$

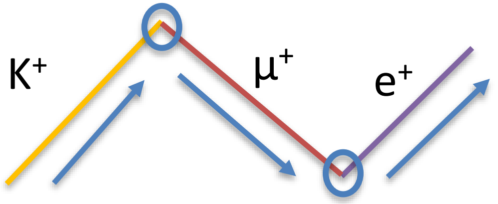
Background: atmospheric neutrino CC and NC interactions

The Golden Channel: $p \rightarrow K^{+}\bar{\nu}$

- LArTPC has an advantage with charged Kaons over Water Cherenkov detectors
- Charged kaon can be fully reconstructed in LArTPC, while in water Cherenkov it falls below the Cherenkov threshold

Key Features:

- Kaon decay daughters create a distinct signal
- Kaon Bragg peak near muon vertex

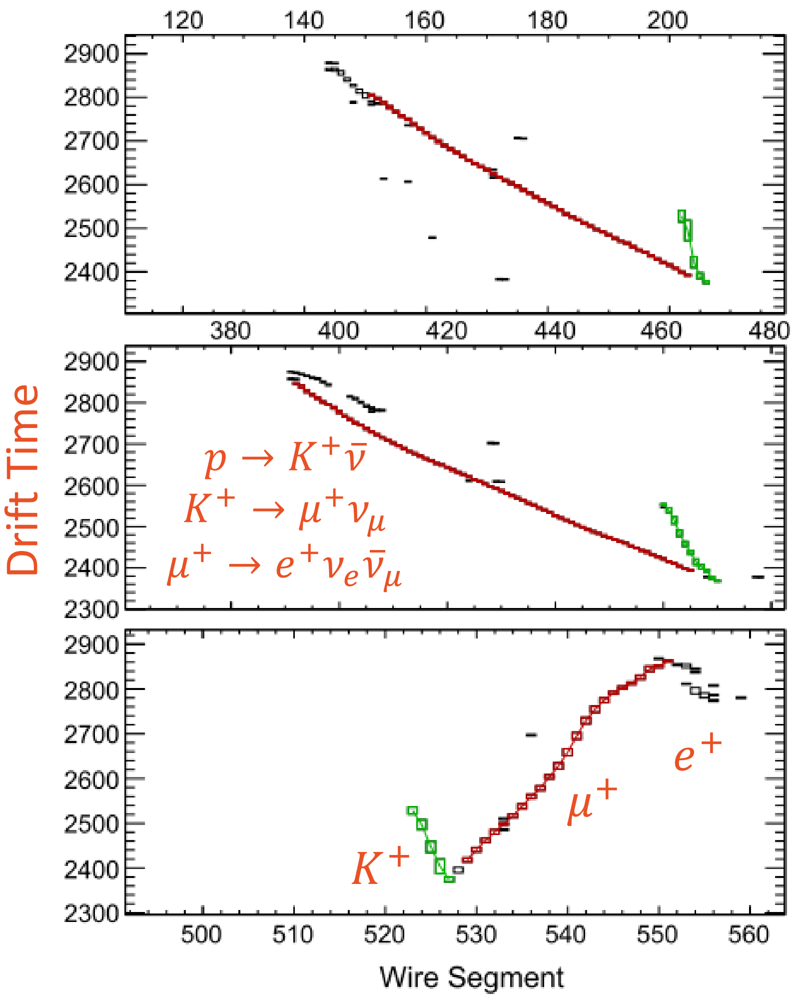


- **Key Difficulties:**
  - Decay products may undergo Final State Interactions (FSI) within Argon nucleus
  - Kaon may lose energy and become more difficult to reconstruct

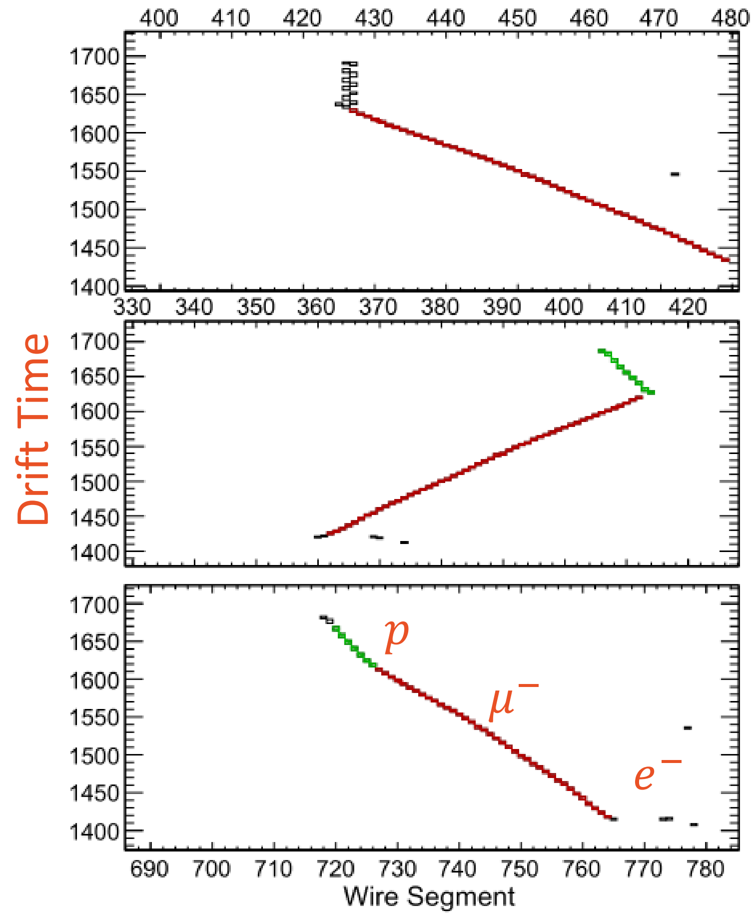
$p \rightarrow K^{+}\bar{\nu}$ Event Displays

- A BDT multivariate analysis is used to classify events

A high scoring signal MC event

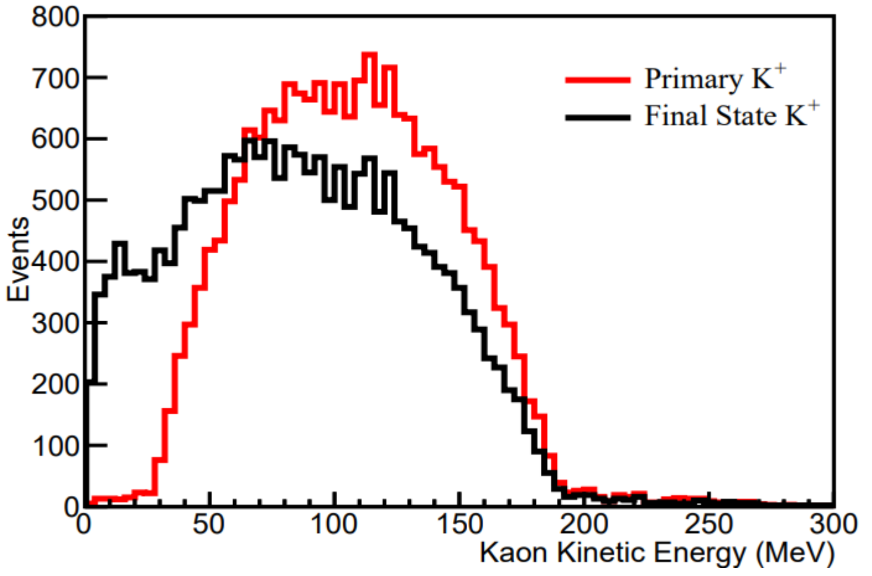


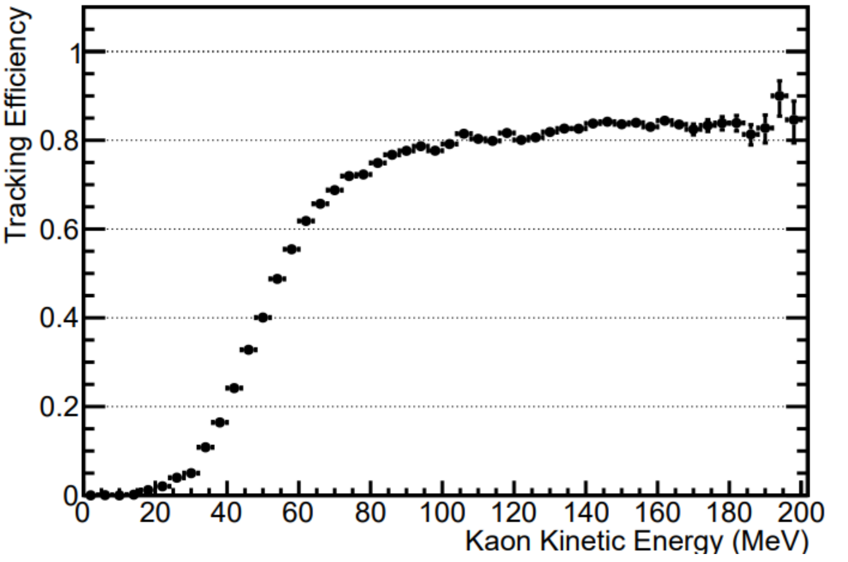
A high scoring atmospheric MC event



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

Kaon FSI Effects





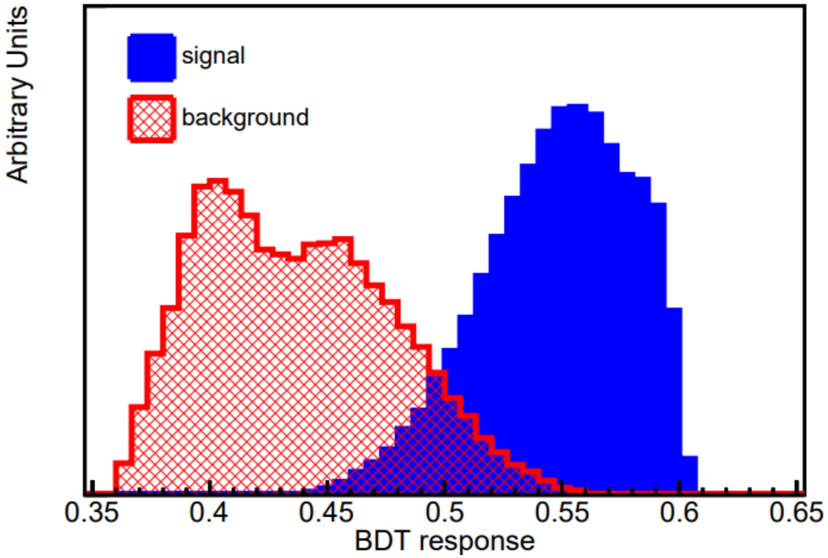
- Top Left: Kaon kinetic energy without and with FSI
- Top Right: Kaon tracking efficiency
- Ongoing work for improving low energy Kaon reconstruction

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

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

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

- Kaon tracking efficiency: 58%
  - With improved reconstruction this can be greatly improved
- 30% signal efficiency
  - Main limiting factor in signal efficiency is K/p separation
- 3×10^{-6} background suppression
  - 1 background per Mton-year or 25 years of data
- Systematics:
  - 2% on signal from FSI uncertainties
  - 20% on background from neutrino flux and cross-section uncertainties



Expected Sensitivity

400 kt-year exposure with no observed events → a limit of 1.3×10^{34} years

Current Limit by SK

5.9×10^{33} years

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.90.072005

Other Channels

$$n \rightarrow e^{-}K^{+}$$

- Similar analysis to $\mathbf{p} \rightarrow \mathbf{K}^{+}\bar{\boldsymbol{\nu}}$
- Additional electron shower
- Invariant mass ~1 GeV
- Background: atmospheric neutrinos
- Signal efficiency: 47%
- 400 kt-year exposure → A limit of $1.1\text{x}10^{34}$ years

Current Limit by Fréjus

$3.2\text{x}10^{31}$ years

https://www.sciencedirect.com/science/article/pii/037026939191479F

$$p \rightarrow e^{+}\pi^{0}$$

- Signature: 3 EM showers
- Invariant mass ~1 GeV
- Background: atmospheric neutrinos
- Preliminary analysis based on MC Truth
- Reconstruction only approximated
- 400 kt-year exposure → A limit of $8.17\text{x}10^{33}$ years to $1.1\text{x}10^{34}$ years
  - Depending upon reconstruction
- Can reach SK limit by doubling exposure

Current Limit by SK

$2.4\text{x}10^{34}$ years

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.102.112011

Baryon Number Violation

Neutron-antineutron Transformations ($n \rightarrow \bar{n}$)

Baryon Number Violation: $\mathbf{n} \to \bar{\mathbf{n}}$

- We know neutral particles are capable of oscillation
  - $K^0 \leftrightarrow \bar{K}^0, B^0 \leftrightarrow \bar{B}^0, D^0 \leftrightarrow \bar{D}^0$
- Neutrons are predicted to also oscillate by several BSM theories
- Neutrons bound in a nucleus can oscillate as well as free neutrons
- Their oscillation times can be related with a suppression factor

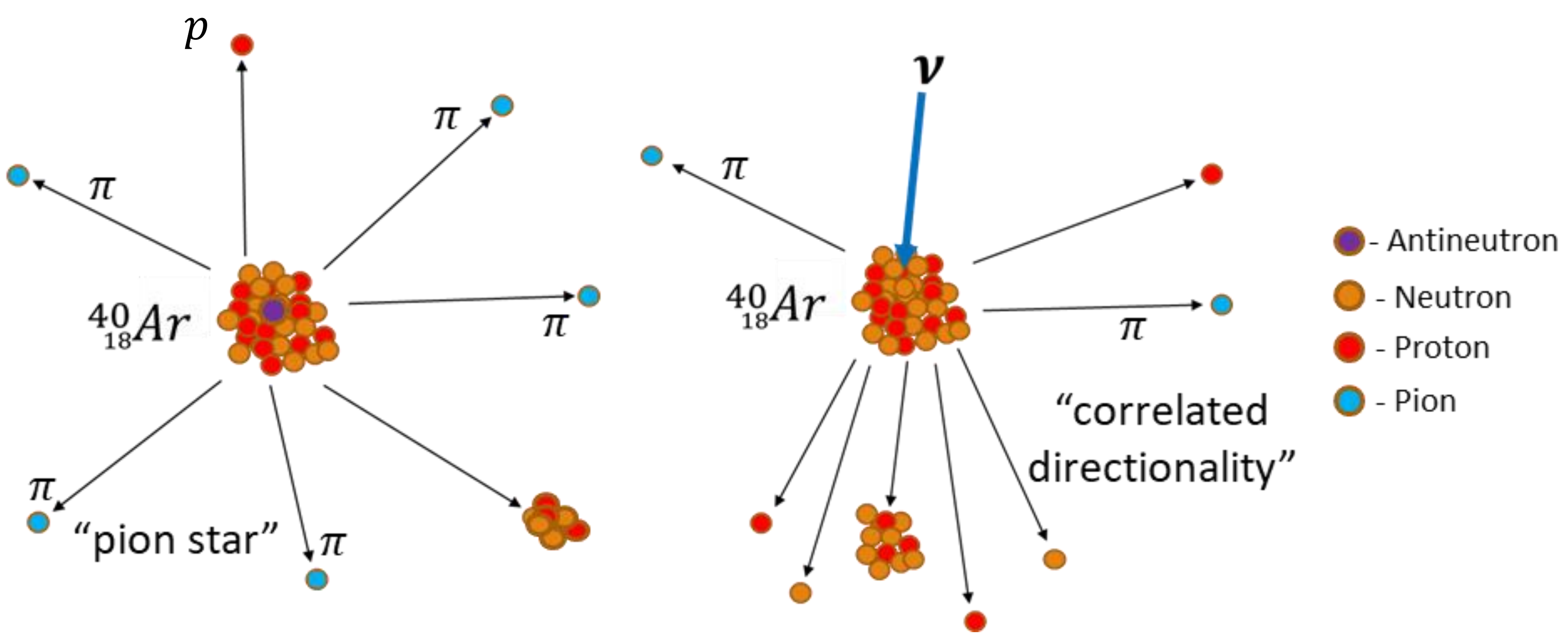
$$\tau_{\text{bound}} = \text{R} \cdot \tau_{\text{free}}^2$$

- R varies for different nuclei
- $R \sim 6.66 \times 10^{22} s^{-1}$ for ${}^{56}_{26}\text{Fe}$ is used for this analysis
- Future works will use the newly calculated: $R \sim 5.6 \times 10^{22} s^{-1}$ for ${}^{40}_{18}\text{Ar}$

Phys. Rev. D 101, 036008 (2020) https://journals.aps.org/prd/abstract/10.1103/PhysRevD.78.016002

$n \rightarrow \bar{n}$ Expected Topologies

- Annihilation produces multiple pions
  - So called "pion star"
- FSI can yield nucleon knock outs
- Main background are NC atmospheric events



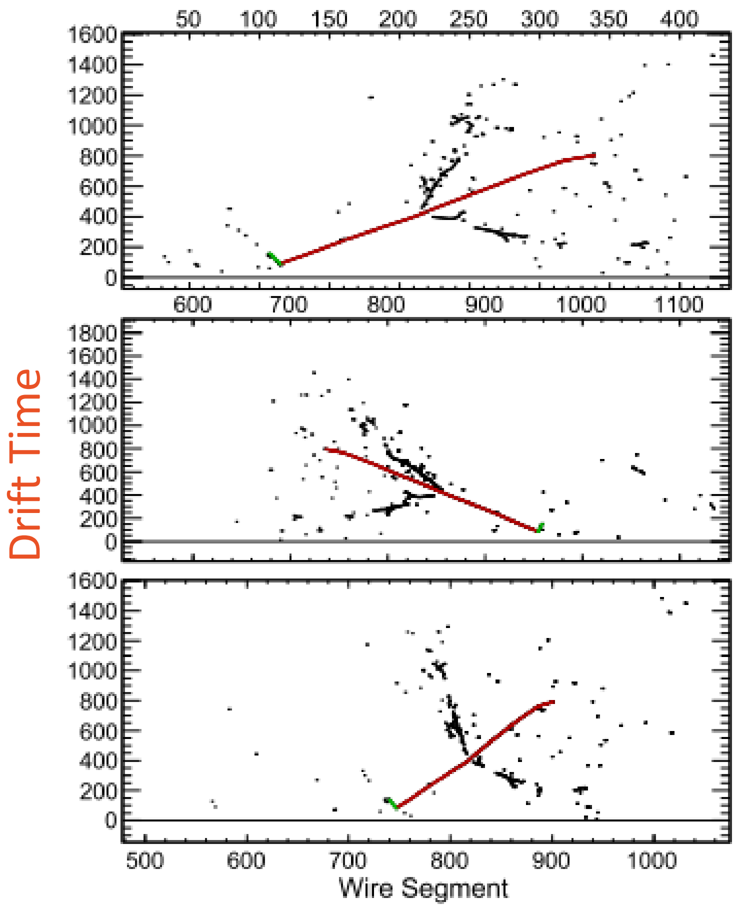
https://indico.fnal.gov/event/44472/contributions/192778/

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

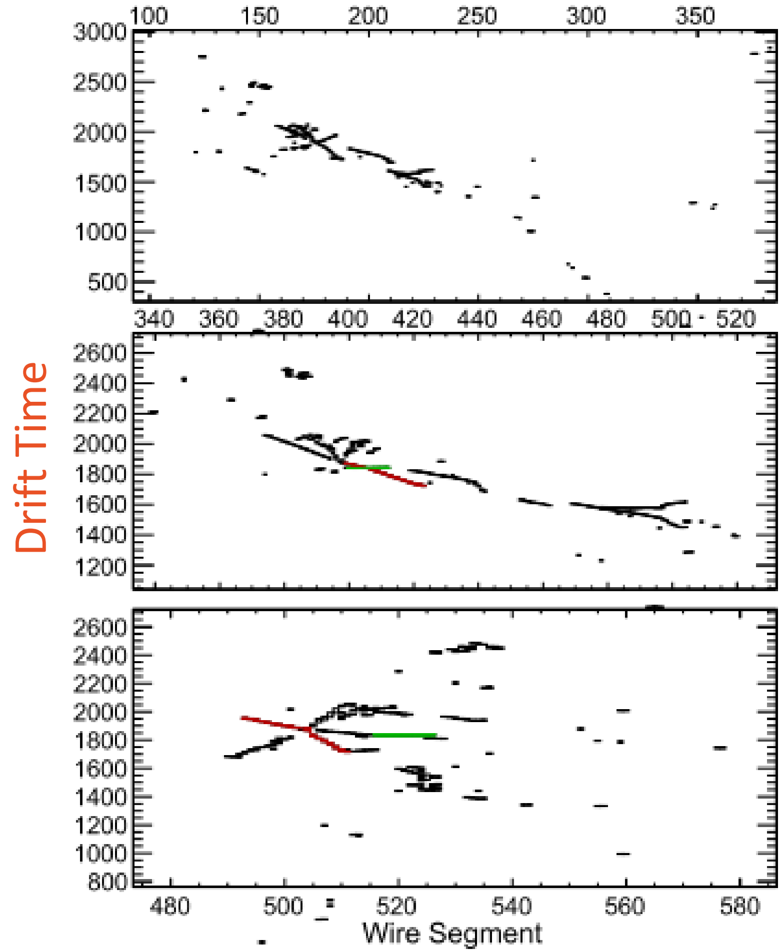
- A BDT multivariate analysis is used to classify events

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

A high scoring signal MC event



A high scoring atmospheric MC event



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

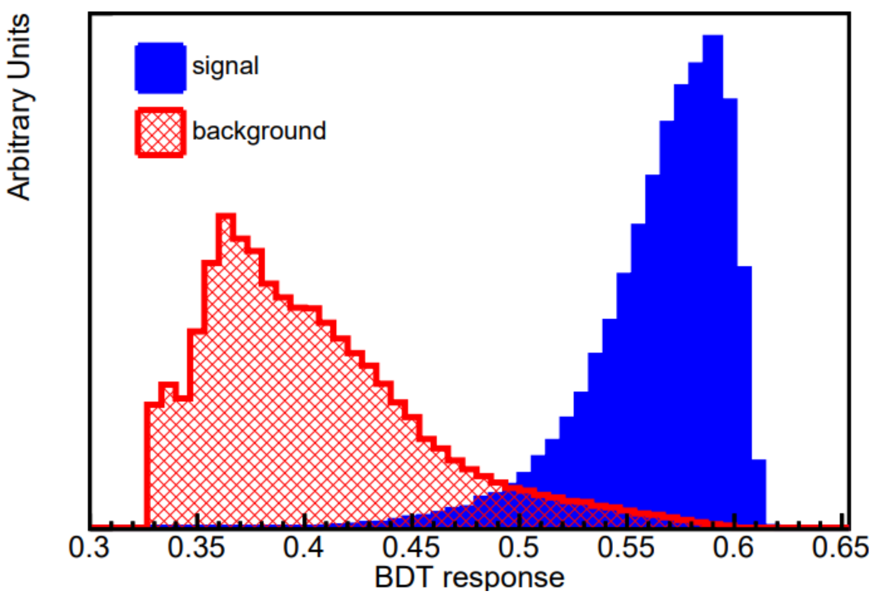
$n \rightarrow \bar{n}$ Oscillation Limits

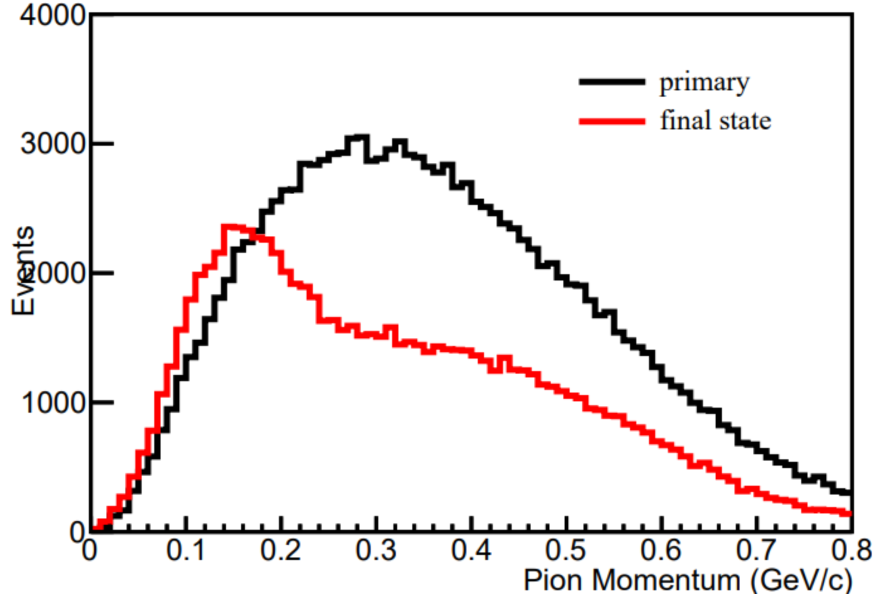
- Similar multi-variate approach as in the nucleon decay studies
- Bound neutron limit: 6.45×10^{32} years
  - @ 90% CL with 400 kt-year exposure
- Free neutron oscillation limit: 5.53×10^{8} s
- ~2x improvement over current best limit

Current Limit by SK

$3.6\text{x}10^{32}$ years

https://www.sciencedirect.com/science/article/pii/037026939191479F





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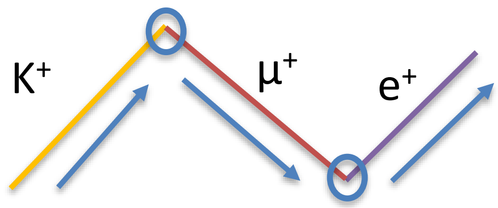
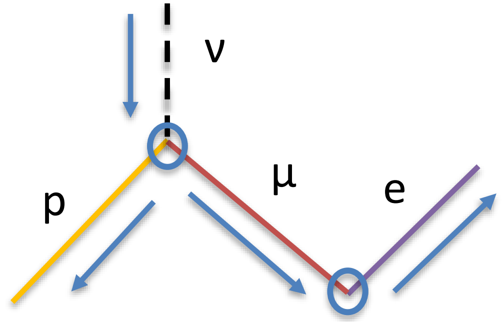
Ongoing Work & Improvements

- Particle identification and vertex identification are key for PDK





- Work has been ongoing to improve both
  - 75% improvement in atmospheric vertexing (reco – true) with Pandora
  - New machine learning methods to improve PID
- Exploration of different nuclear models and nuclear cascade models

Summary

- LArTPC technology offers unique advantages in nucleon decay searches
- At full scale (400 kt-year exposure) DUNE will be competitive with large water Cherenkov experiments in rare process searches
- $\mathbf{p \rightarrow K^{+}\bar{\nu}}$: Improvement on current limits with more potential as reconstruction and particle identification improve
- $\mathbf{n \rightarrow e^{-}K^{+}}$: $\gtrsim 2$ order of magnitude improvement over current limits
- $\mathbf{p \rightarrow e^{+}\pi^{0}}$: preliminary study suggests current limits reachable after double exposure
- $\mathbf{n \rightarrow \bar{n}}$: $\gtrsim 2$ factor improvement expected over current limits

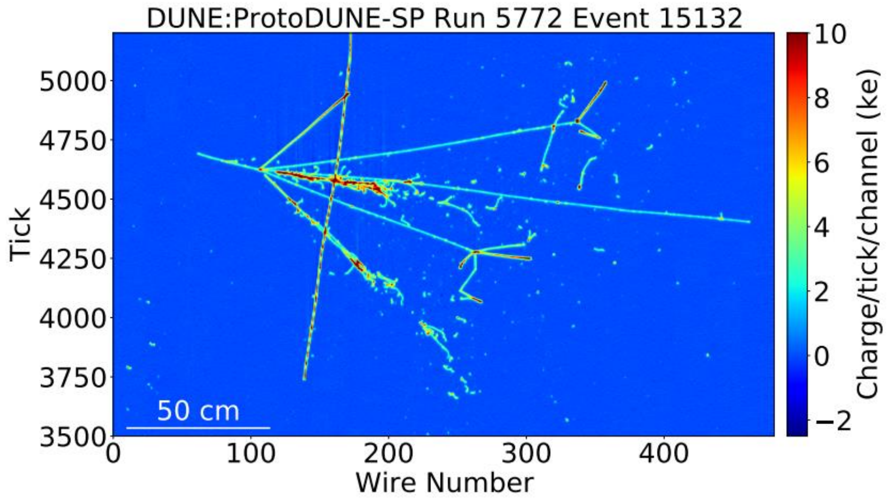
Thank you for time!

Questions?

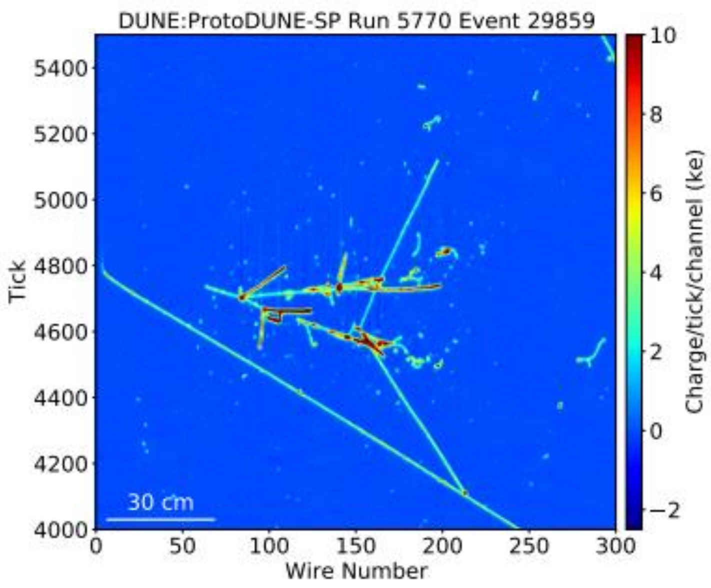
LArTPC Excellence

https://iopscience.iop.org/article/10.1088/1748-0221/15/12/P12004

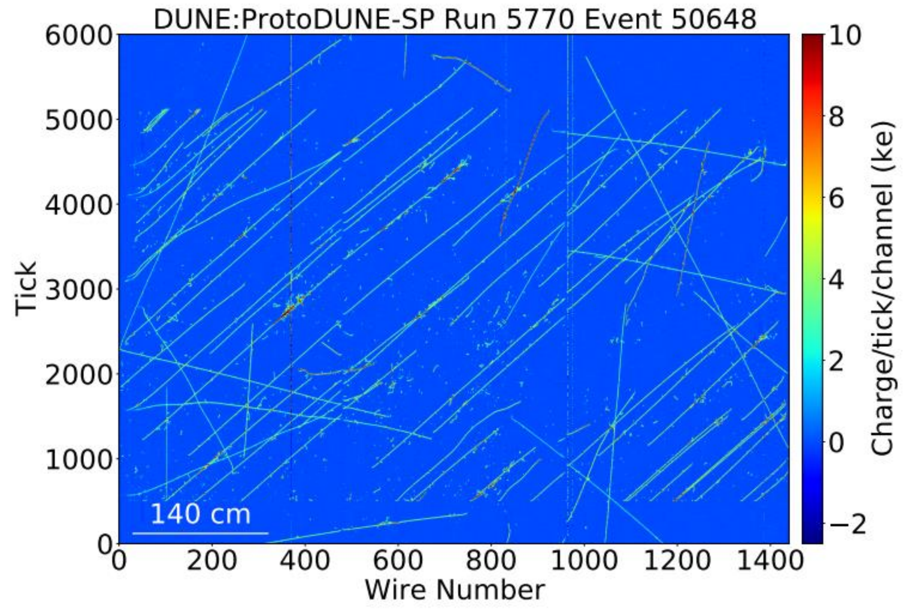
- 3D Bubble Chamber-like images
- Can classify complex topologies
- Can reconstruct $K^{\pm}$ from nucleon decay events
- Example data events from Prototype DUNE Detector



A 6 GeV/c Pion candidate



6 GeV/c Kaon candidate



Cosmic air shower candidate

Available Nuclear Models

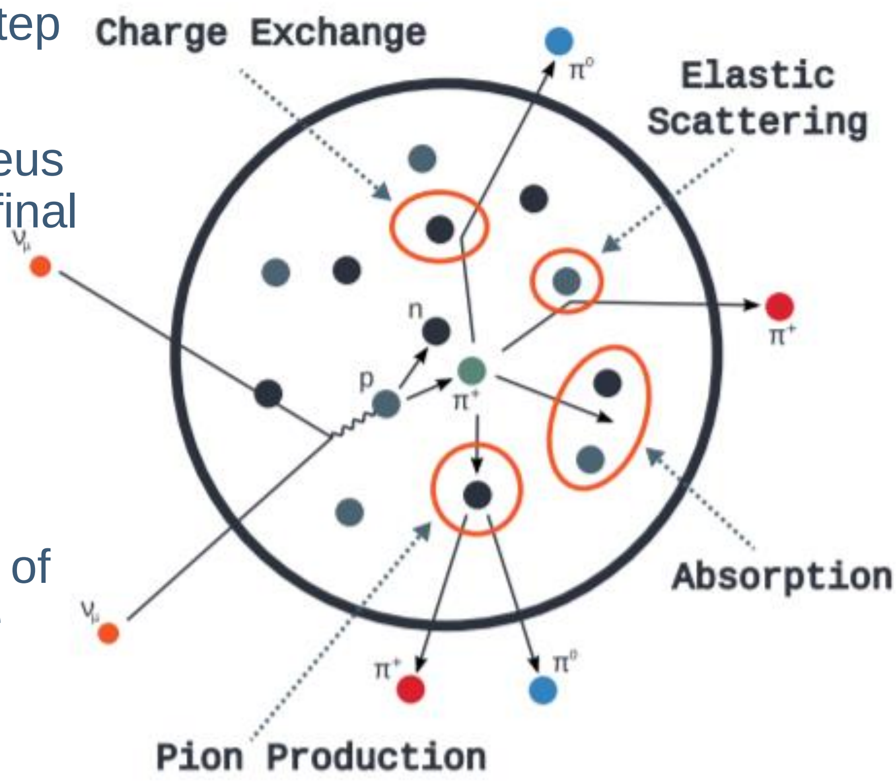
- In GENIE v3.0.6, there are three main nuclear models of Fermi motion *currently* available:
  1. Bodek-Ritchie (relativistic) *nonlocal* Fermi gas
  2. *Local* (nonrelativistic) Fermi Gas
  3. Effective Spectral Function (*nonlocal*)
- There are two main intranuclear cascades available:
  1. hA2018 (single effective interaction)
  2. hN2018 (full intranuclear cascade model)

Final State Interactions

Used in the TDR Analysis

The two main intranuclear cascades:

1. hA2018 (single effective interaction)
    - Does not model the cascade of hadronic interactions step by step
    - Relies on a single effective interaction where hadron+nucleus data is used to determine the final state



2. hN2018 (full intranuclear cascade model)
    - Models the stochastic cascade of hadronic interactions within the nucleus

Figure from: Tomasz Golan
https://indico.fnal.gov/event/15286/contributions/30851/attachments/19320/24158/nustec_mc_02.pdf