Baryon Number Violation Searches in DUNE

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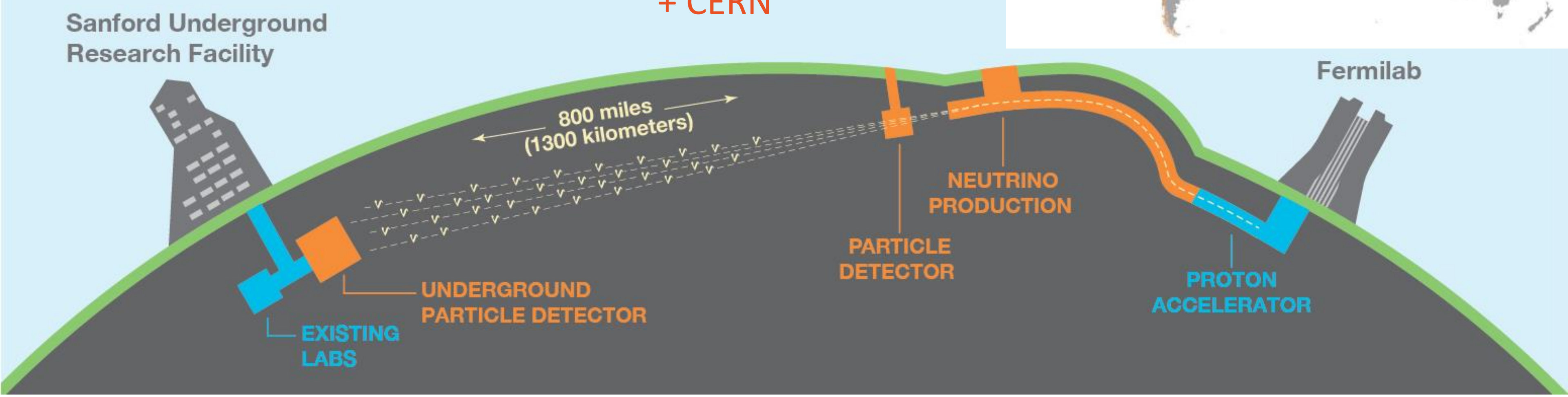
LSU | Louisiana State University

The Deep Underground Neutrino Experiment (DUNE)

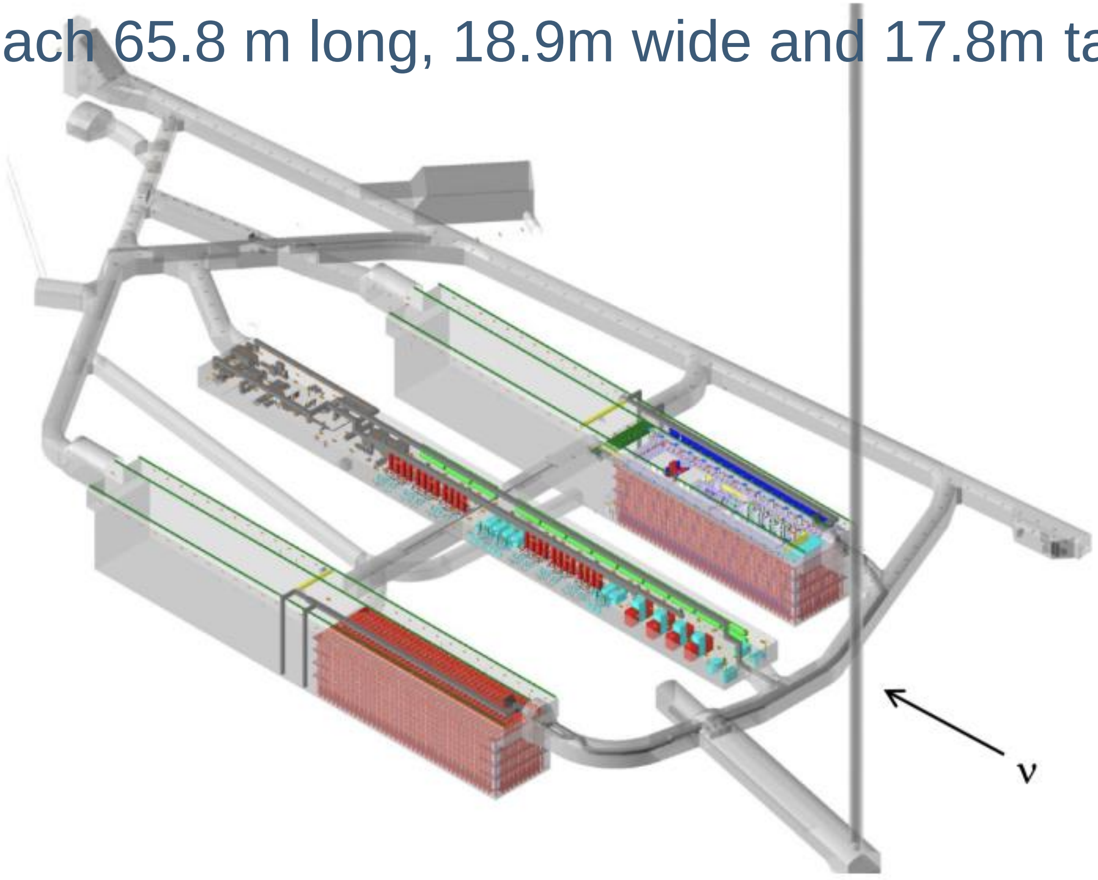
- Flagship project of Fermilab
- Will construct 1.2 MW ν beam with upgrade plans to 2.4 MW
- Near detector will utilize a suite of detectors
- Far detectors will utilize Liquid Argon Time Projection Chambers (LArTPCs)
  - Total Far detector mass: 70 kt of LAr

1347 collaborators
204 institutions in 33 countries
+ CERN

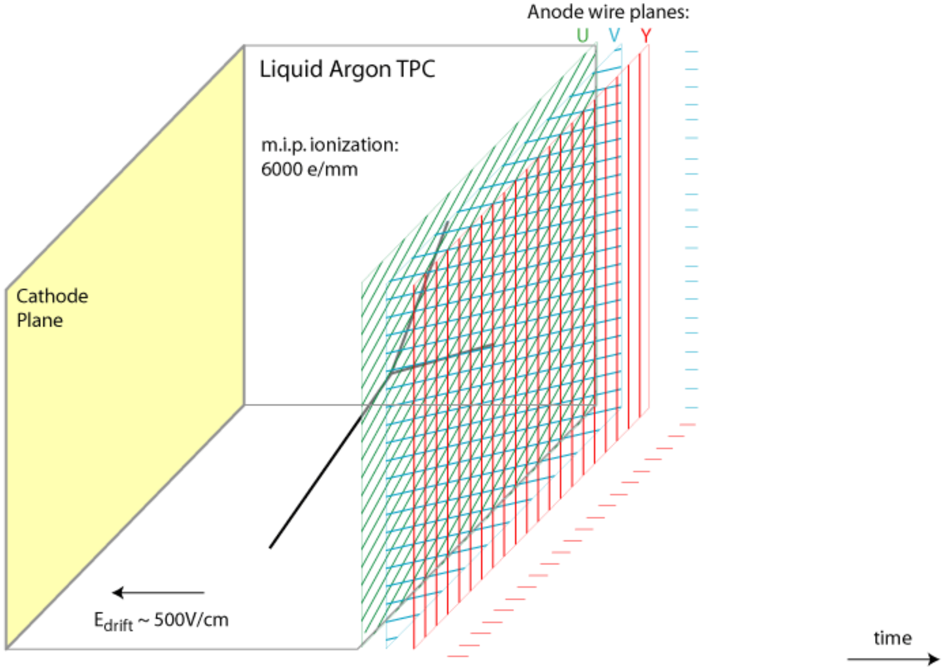


DUNE At SURF

- 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

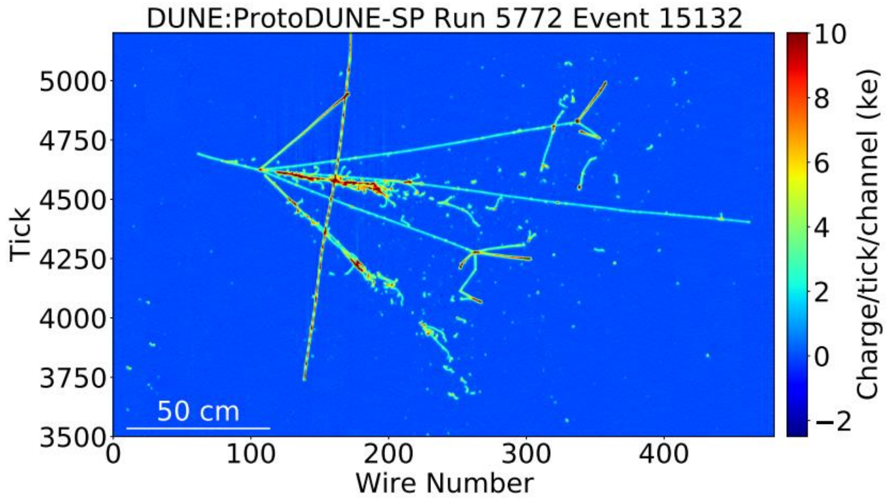


- A large uniform liquid argon volume
- Electric field applied across drift volume
- ionizing particles create free charge
    - Electrons drift towards anode planes
- 3 wire planes each yield 2D images of wire coordinate and drift coordinate
- Optical System provide t_0
- The collected charge is proportional to the energy deposition (dE/dX)

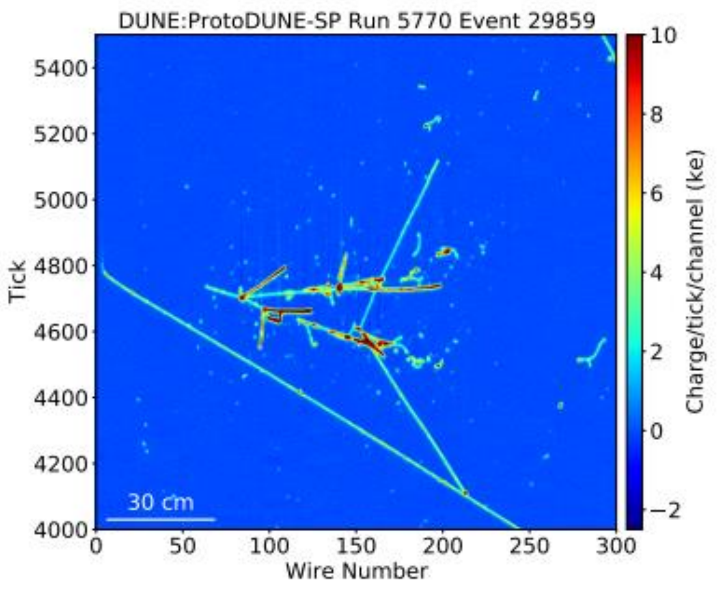
LArTPC Excellence

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

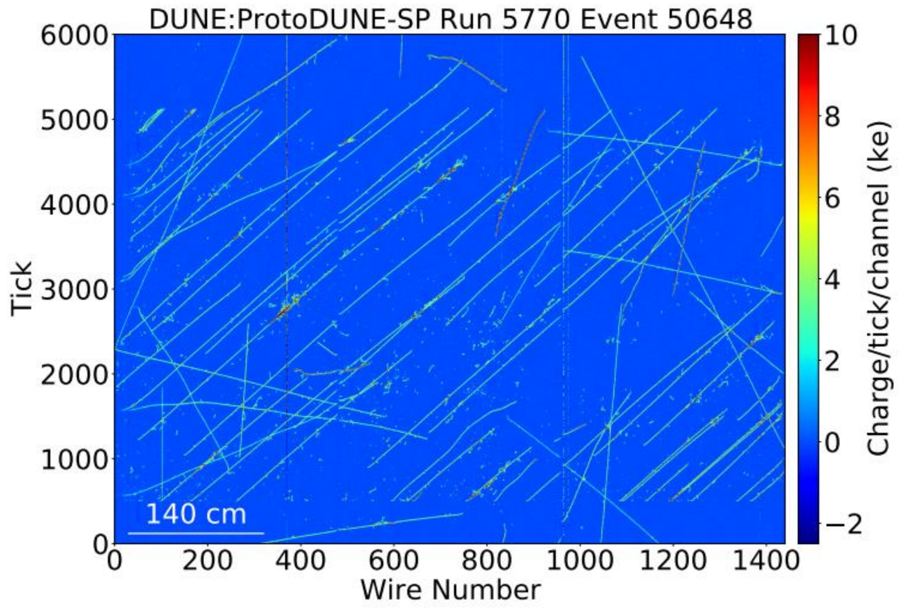
- 3D Bubble Chamber-like images
- Can classify complex topologies
- Can reconstruct $K^{\pm}$ from nucleon decay events
- Example data events from Prototype DUNE Detector



A 6 GeV/c Pion candidate



6 GeV/c Kaon candidate



Cosmic air shower candidate

Baryon Number Violation

Nucleon Decay

Baryon Number Violation: Nucleon Decay

1. Leading Candidate Channels

- $p \rightarrow K^{+}\bar{\nu}$
- $p \rightarrow e^{+}\pi^{0}$
- $n \rightarrow e^{-}K^{+}$

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

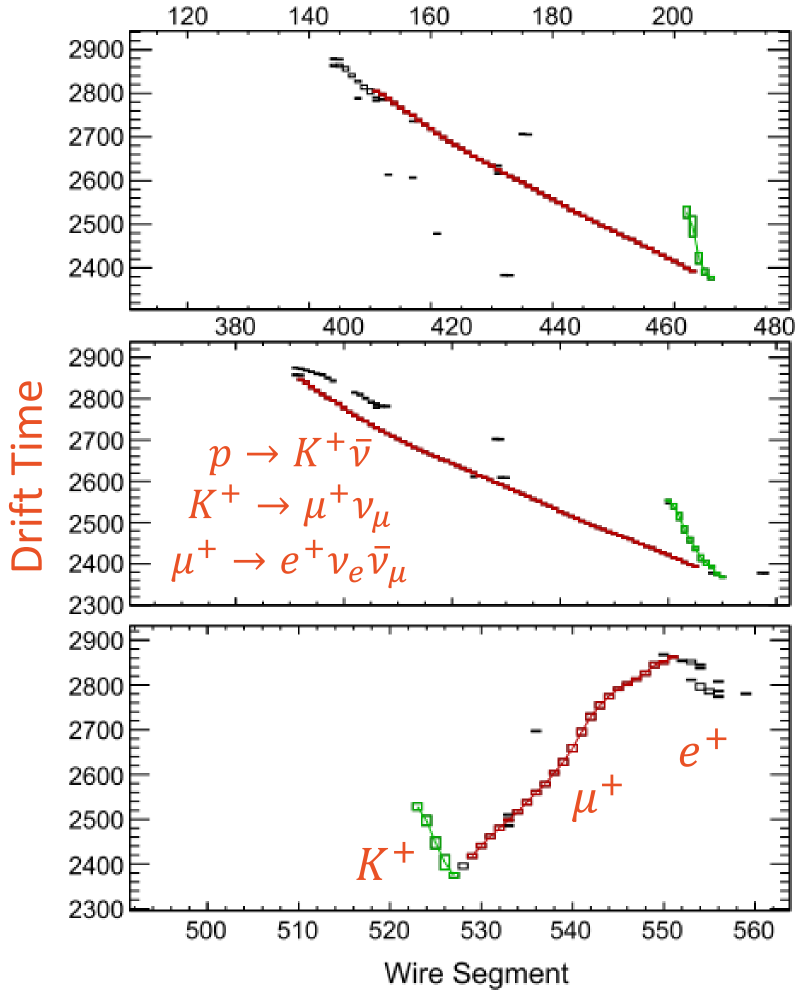
- **Key Difficulties:**

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

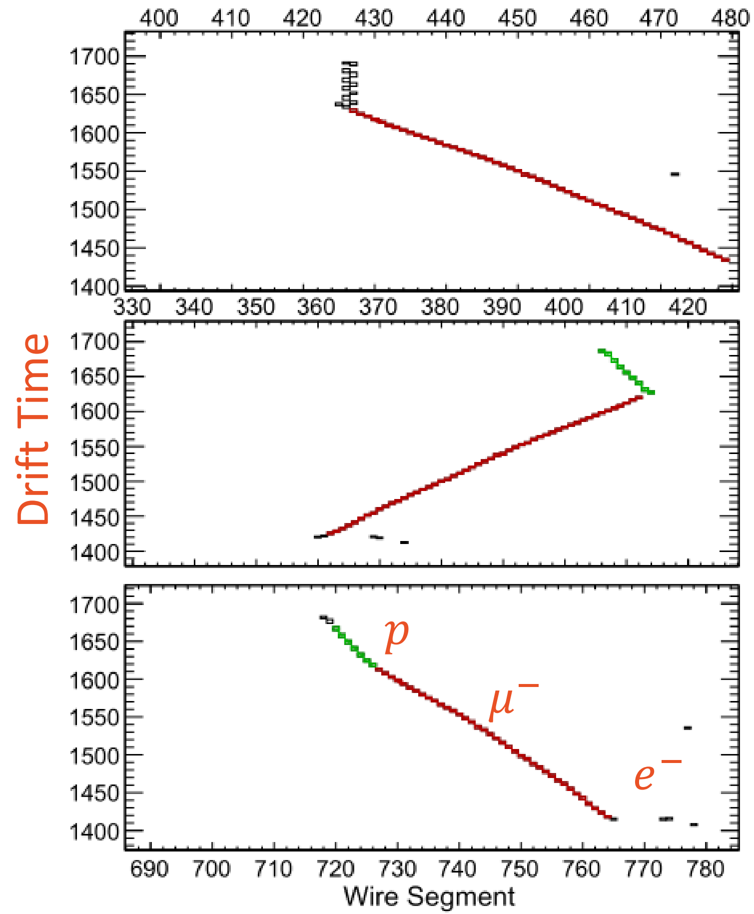
$p \rightarrow K^+\bar{\nu}$ Event Displays

- A BDT multivariate analysis is used to classify events

A high scoring signal MC event

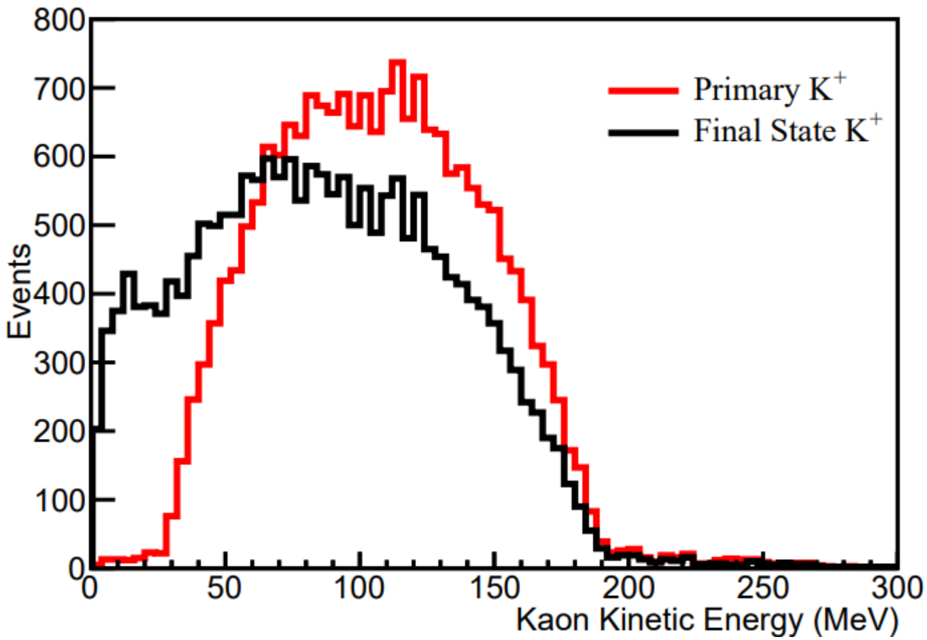


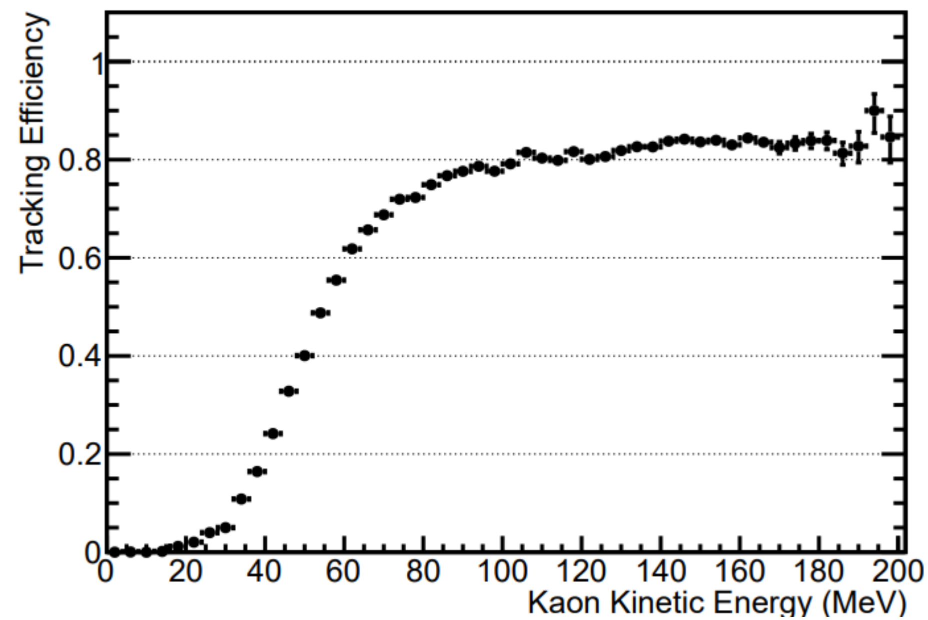
A high scoring atmospheric MC event



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

Kaon FSI Effects





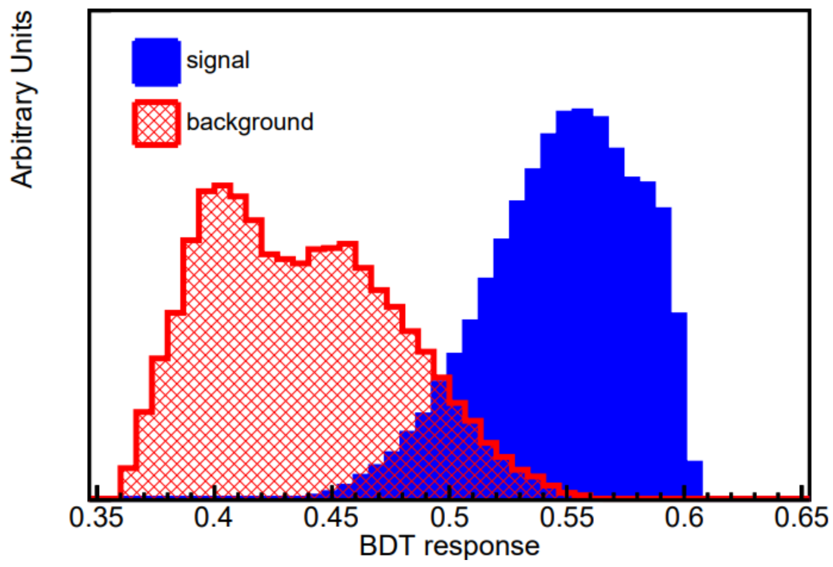
- Top Left: Kaon kinetic energy without and with FSI
- Top Right: Kaon tracking efficiency
- Ongoing work for improving low energy Kaon reconstruction

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
- $3\text{x}10^{-6}$ 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 $1.3\text{x}10^{34}$ years

Current Limit by SK

$5.9\text{x}10^{33}$ years

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

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

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

Current Limit by Fréjus

3.2×10^{31} years

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

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

- 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 8.17×10^{33} years to 1.1×10^{34} years
  - Depending upon reconstruction
- Can reach SK limit by doubling exposure

Current Limit by SK

2.4×10^{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: $\mathrm{n} \rightarrow \bar{\mathrm{n}}$

- 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
- Inside nucleus oscillated neutrons would quickly annihilate
- Their oscillation times can be related with a suppression factor

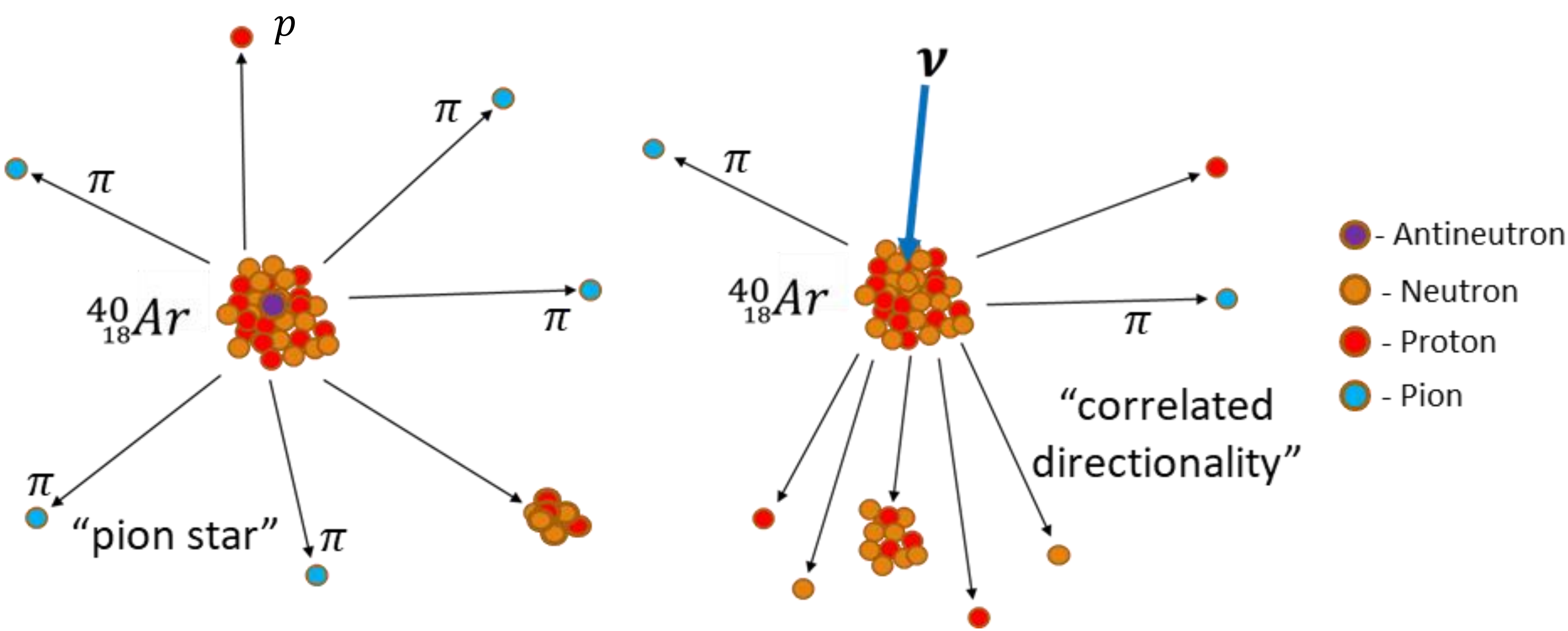
$$\tau_{\mathrm{bound}} = \mathrm{R} \cdot \tau_{\mathrm{free}}^2$$

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

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



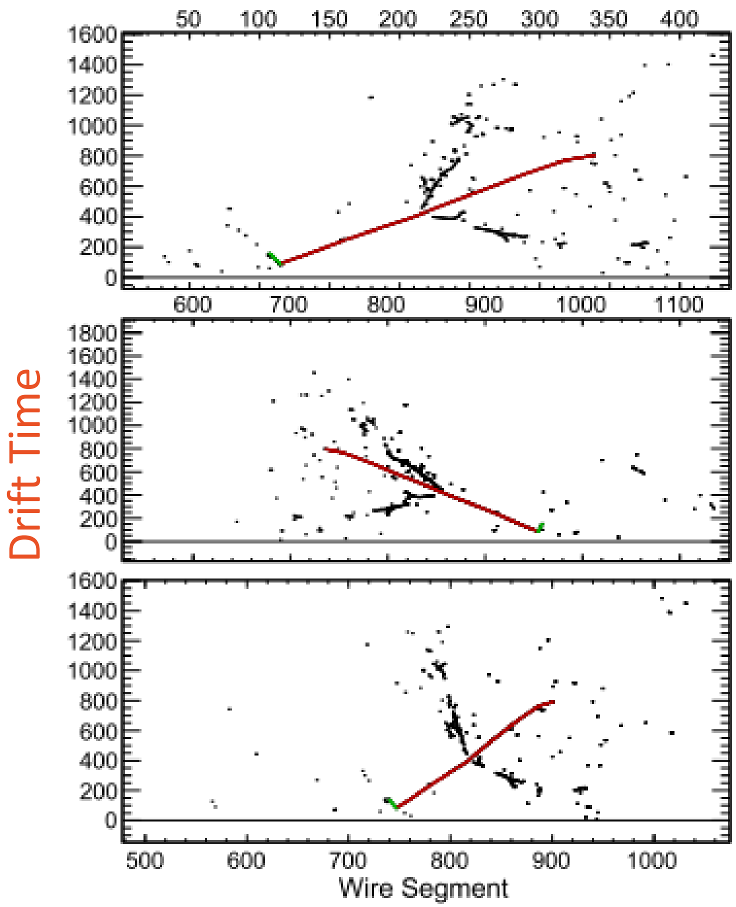
https://indico.fnal.gov/event/44472/contributions/192778/

n → n̄ Event Displays

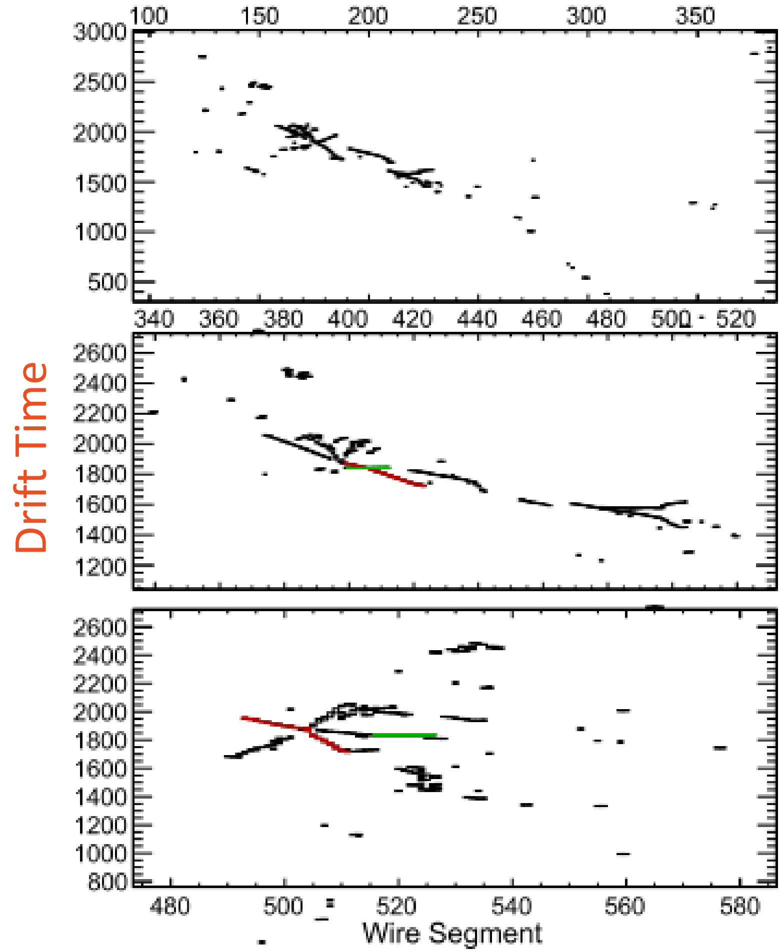
- A BDT multivariate analysis is used to classify events

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

A high scoring signal MC event



A high scoring atmospheric MC event



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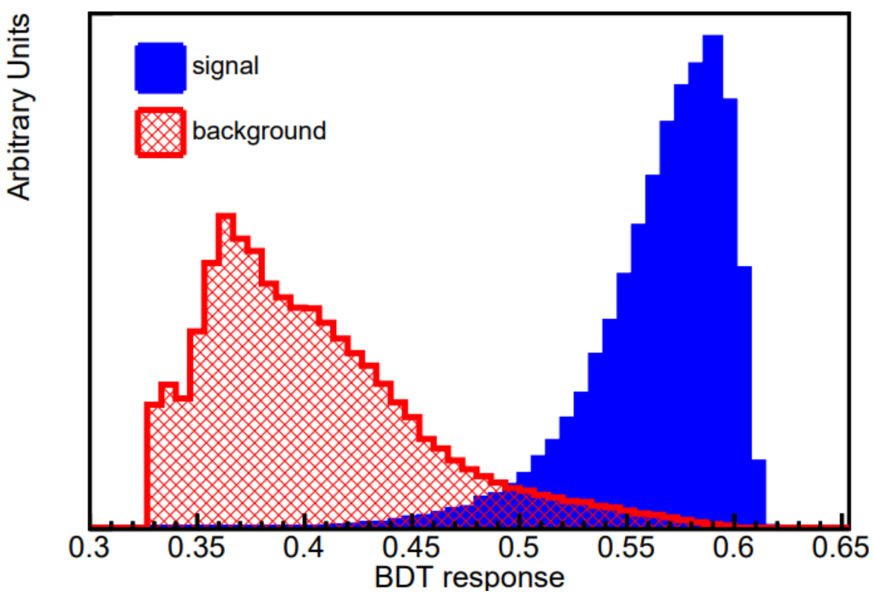
$n \rightarrow \bar{n}$ Oscillation Limits

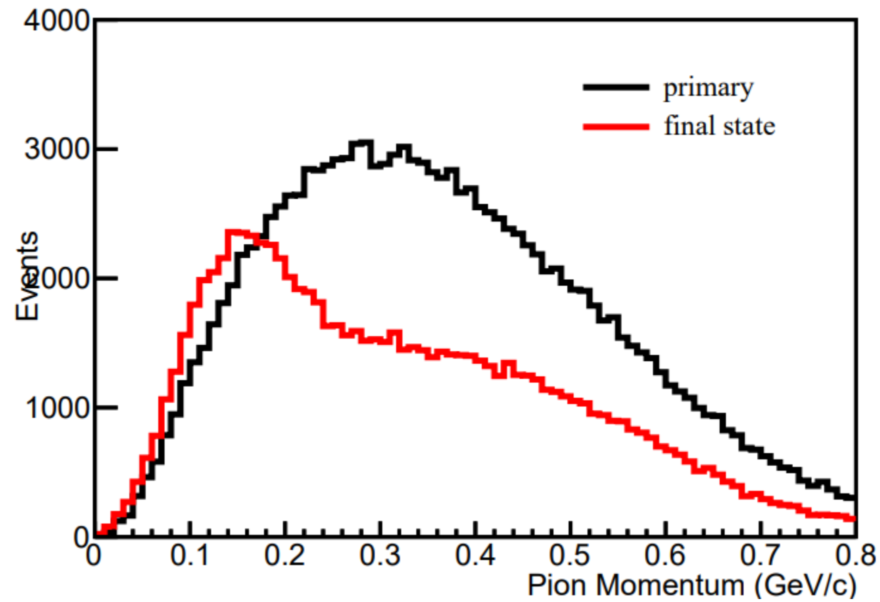
- Similar multi-variate approach as in the nucleon decay studies
- Bound neutron limit: 6.45×10^{32} years
  - @ 90% CL with 400 kt-year exposure
- Free neutron oscillation limit: 5.53×10^{8} s
- ~2x improvement over current best limit

Current Limit by SK

3.6×10^{32} years

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





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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?