Nucleon Decay Searches in DUNE

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for the DUNE collaboration

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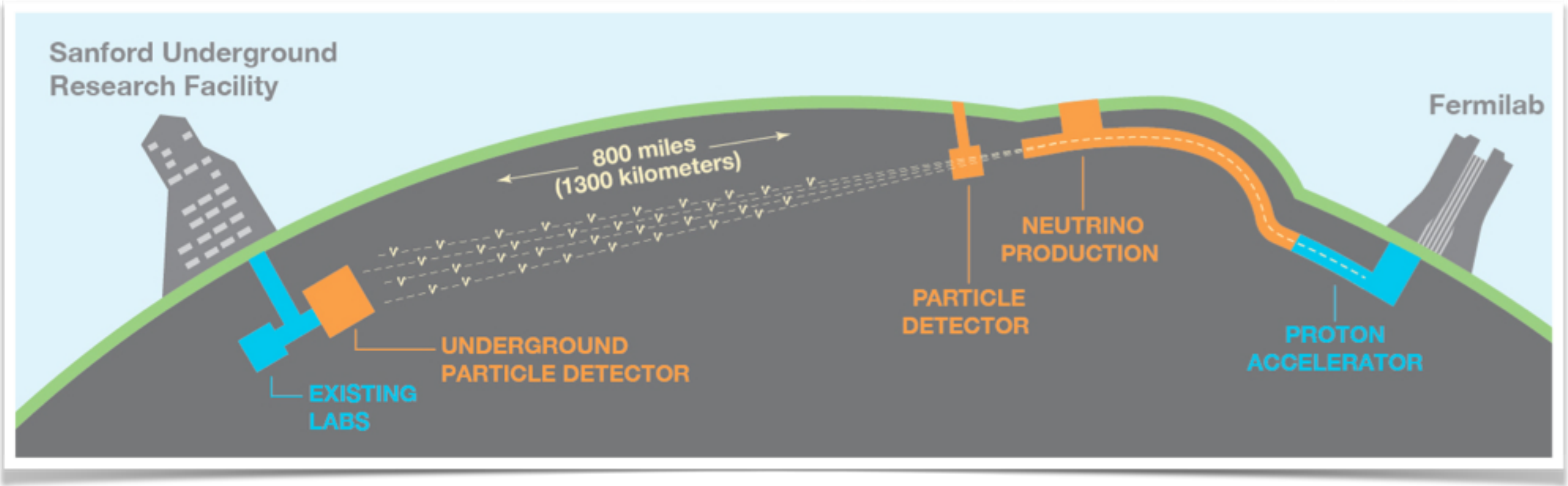
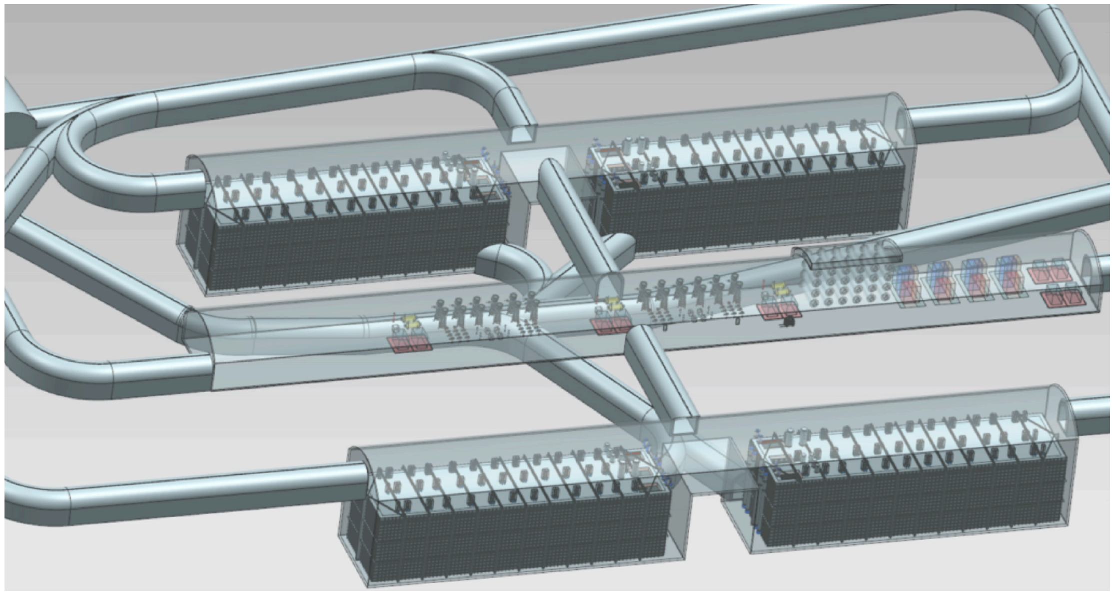
Deep Underground Neutrino Experiment (DUNE)



- **Location**
  - **1.5 km** underground @ **SURF**, Lead, South Dakota,
  - **1300 km** from the neutrino source
- **Neutrino source**
  - powerful new beam of neutrinos @ Fermilab, Chicago, Illinois
- Planned to start with 1st module in 2026, remaining 3 modules will be added sequentially

Experimental Halls at SURF



- 4 modules, 17.5 kt/10 kt fiducial LAr each
- Modules
  - cryostats 18.9 m (W)×17.8 m (H)×65.8 m (L)
  - instrumented with TPC (currently 2 technologies designed, single phase and dual phase LArTPC)

DUNE Physics Programme

Primary

- Neutrino oscillation (CP violation and mass hierarchy, mixing parameters)
- Proton decay ← this talk
- Supernova neutrinos

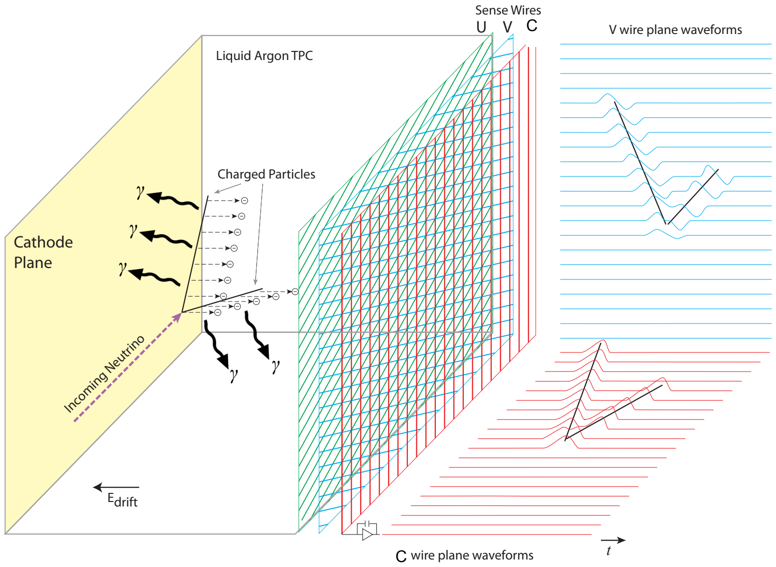
Ancillary

- BSM physics
- Atmospheric neutrinos
- $n\bar{n}$ oscillations ← this talk
- dark matter

Liquid Argon Time Projection Chamber — LArTPC

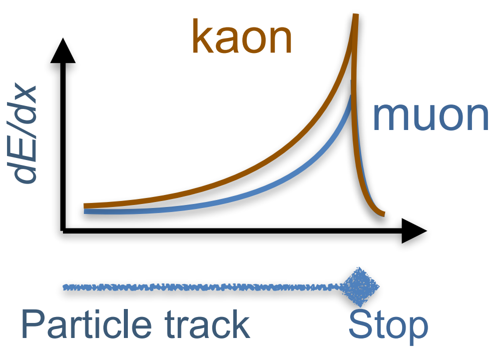
Principle of operation

- ionisation charge drifts in electric field towards readout plane
- 3D reconstruction:
  - measured drift time (X)
  - location on readout planes (YZ)
- signal proportional to deposited energy → ***dE/dx* measurement — particle ID**



Anode planes — readout

- induction plane wires — electrons pass through
- collection plane wires — last plane, all ionisation electrons collected
- each plane constitute a 2D view: drift time—wire



DUNE — 3 readout planes

- collection plane (C) wires vertical
- induction plane (U,V) wires 37.5° from vertical
- wire pitch 5 mm

Advantage of LArTPC

- Can reconstruct tracks
- Sees *dE/dx* profile

→

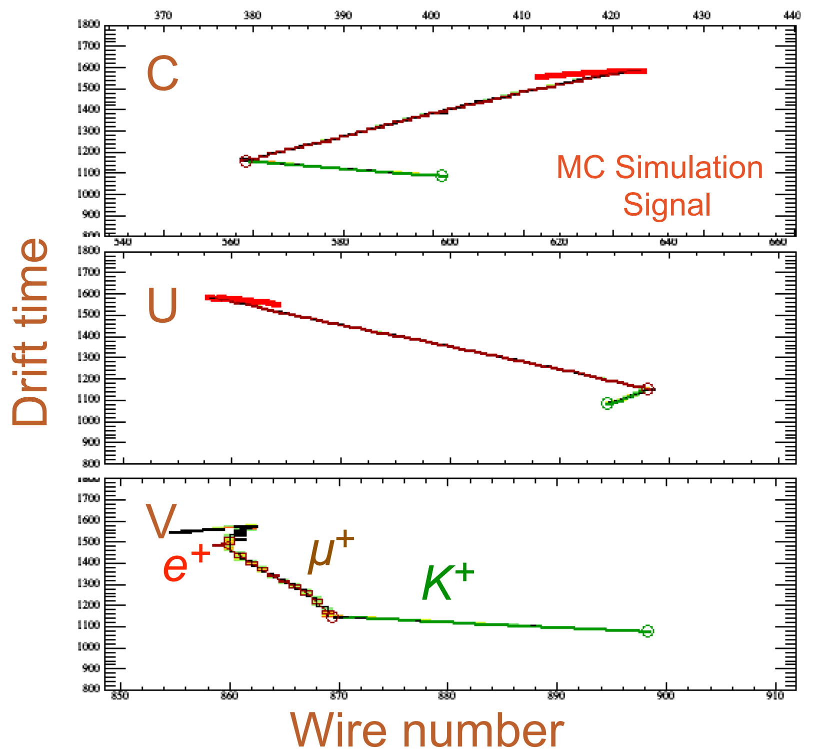
- Can identify *K* in nucleon-to-*K* decays
- Can classify different event topologies

- Example of crisp proton-decay event display
- in 3 wire views

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

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



Nucleon Decays

- Potential of DUNE for some nucleon decays investigated:
  - $p \to K^+\bar{\nu}, n \to e^-K^+, p \to e^+\pi^0$
- More nucleon decay modes will be studied in the future
- Backgrounds:
  - atmospheric neutrino CC and NC interactions
  - cosmogenic found sub-dominant

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

Key features

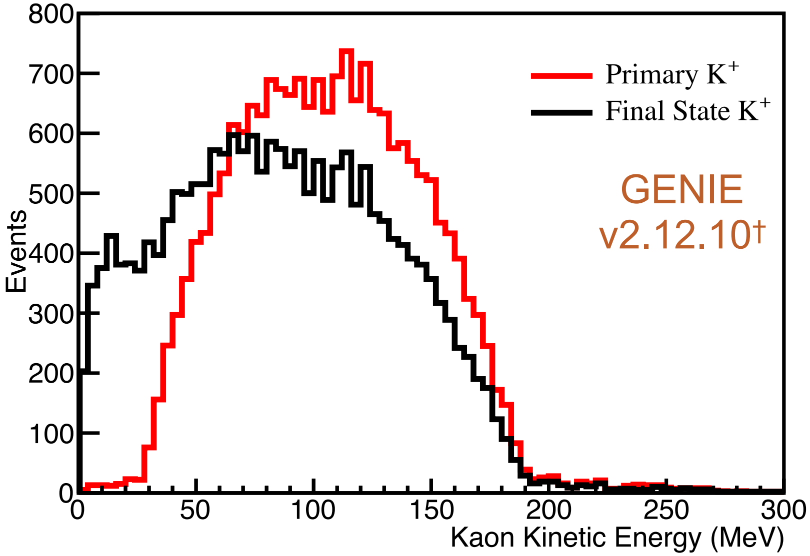
- identifiable *K* track
  - *dE/*dx near the end of the track → ID and direction
- golden channel: $K^+ \to \mu^+\nu$ (64%) – mono-energetic muon track
- next best: $K^+ \to \pi^+\pi^0$ (21%) mono-energetic π^+ track + 2 π^0 gamma showers

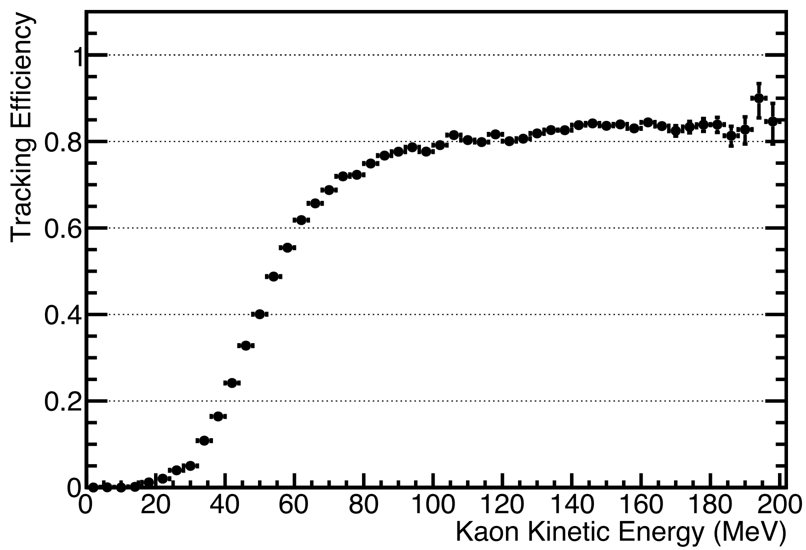
Difficulty

- proton decays in Ar → some *K* will undergo Final State Interactions (FSI) inside the nucleus

➡ *K* loses energy and it is more difficult to reconstruct its track

Effect of FSI on K Track





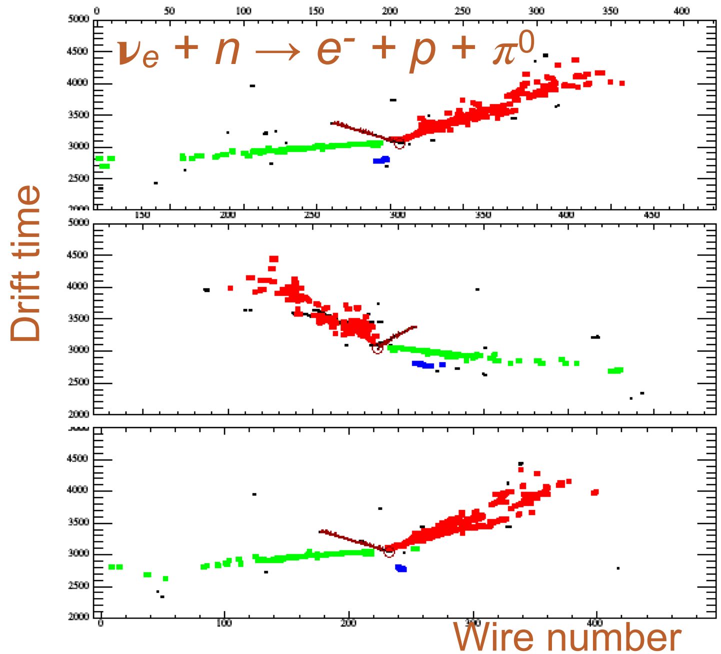
- Left: kinetic energies of kaons leaving Ar nucleus without and with FSI
- Right: current tracking efficiency of kaons: reconstruction switches on only at about 40 MeV
- Visual scanning of events improvement in kaon tracking efficiency possible
  - current 58% ➞ 80% achievable
- Improvements in reconstructions are being investigated

† GENIE v2.12.10: Nuclear model: relativistic Fermi gas with Bodek-Ritchie tail; FSI: hA2015

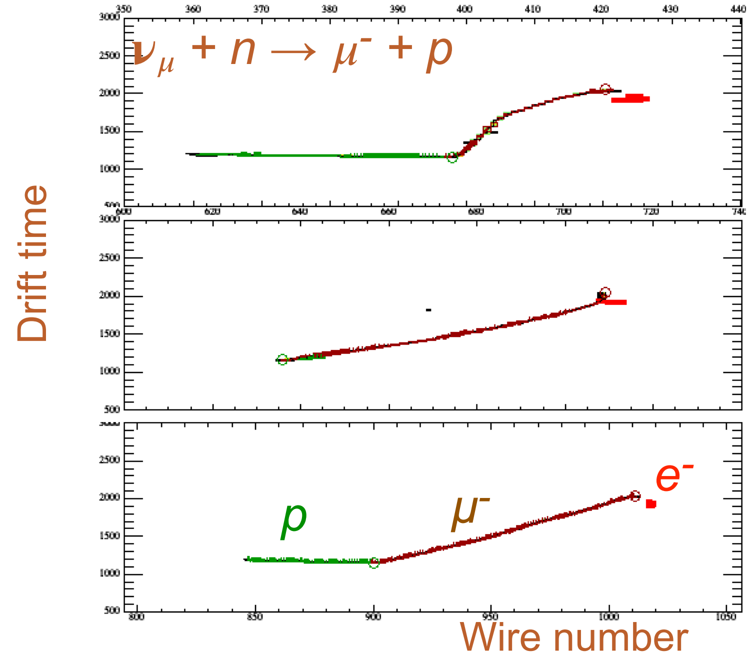
$p \rightarrow K\bar{\nu}$ Background Events

MC Simulation
Atm.neutrinos

Low scoring



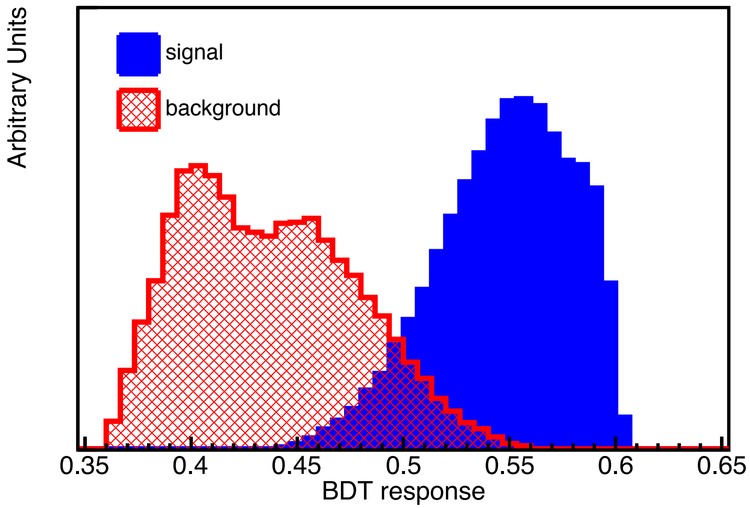
High scoring



- Example of potential background events — atmospheric neutrino CC interaction
- Boosted Decision Tree multi-variate analysis used to classify events:
  - Left: well discriminated by the classifier (low score)
  - Right: poorly discriminated (high score)

Sensitivity to $p \rightarrow K\bar{\nu}$

- With current reconstruction:
  - signal efficiency 15% with background suppression of 3×10^{-6} (~0.4 bg event per 400 kt-year / 10 years of data taking)
- With improved reconstruction:
  - signal efficiency 30%



Systematics:

- 50% variation in FSI contribution → 2% uncertainty on signal efficiency
- atmospheric neutrino flux and cross-section uncertainties → 20% uncertainty in backgrounds

Sensitivity:

- limit of **1.3×10^{34} years (90%CL)**
  - if no signal observed in 10 years, in full 40 kt configuration
  - 30% efficiency assumed

Other Nucleon Decay Modes Investigated

$n \rightarrow e^- K^+$

- Similar analysis to $p \rightarrow K\bar{\nu}$ decay
- Additional electron shower
- Limit **1.1×10^{34} years** (90%CL) in 400 kt-year exposure with signal efficiency expected 47% and with 6 background events (after optimised reconstruction)
- → >2 orders of magnitude improvement of the current limit

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

- Signature: 3 EM showers
- Preliminary analysis based on MC truth
- Reconstruction only approximated
- 8.7×10^{33} years to 1.1×10^{34} for exposure of 400 kt-year (90%CL)
  - dependent on approximated detector effects (energy smearing)
- Doubling the exposure would allow reaching current SK limit

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$n\bar{n}$ Oscillation

- Were $n\bar{n}$ oscillations possible, neutrons would transform into antineutron and quickly annihilate with surrounding nucleons
- Oscillation time heavily suppressed for neutrons bound in nucleus
- Effective conversion time $T_{n-\bar{n}}$ relates to free neutron oscillation time $\tau_{n-\bar{n}}$:

$$\tau^2_{n-\bar{n}} = \frac{T_{n-\bar{n}}}{R}$$

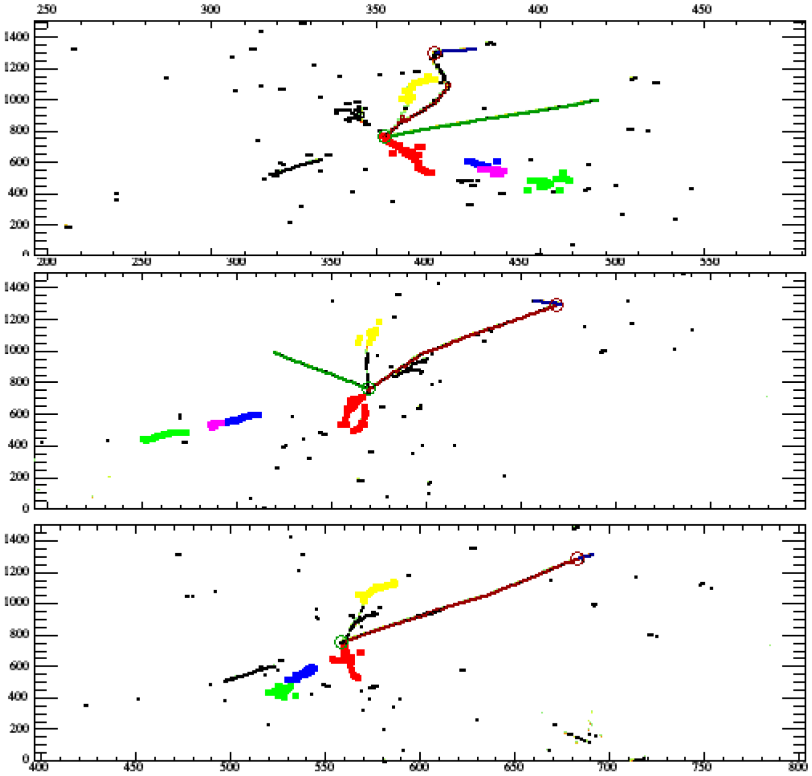
- Used suppression factor calculated for iron [1] $R = 6.66 \times 10^{22} s^{-1}$
- A new calculation exists for suppression factor in argon [2], see details in Josh Barrow's poster: $R = 5.6 \times 10^{22}$

[1] Phys. Rev. D78 (2008) 016002
[2] arXiv:1906.02833

$n\bar{n}$ Oscillation Signal

- Annihilation produces **multiple pions**
- FSI can yield nucleons
- Typical **star-like** signal
- Invariant mass **~2 GeV**
- **Vanishing total momentum**

MC Simulation Signal



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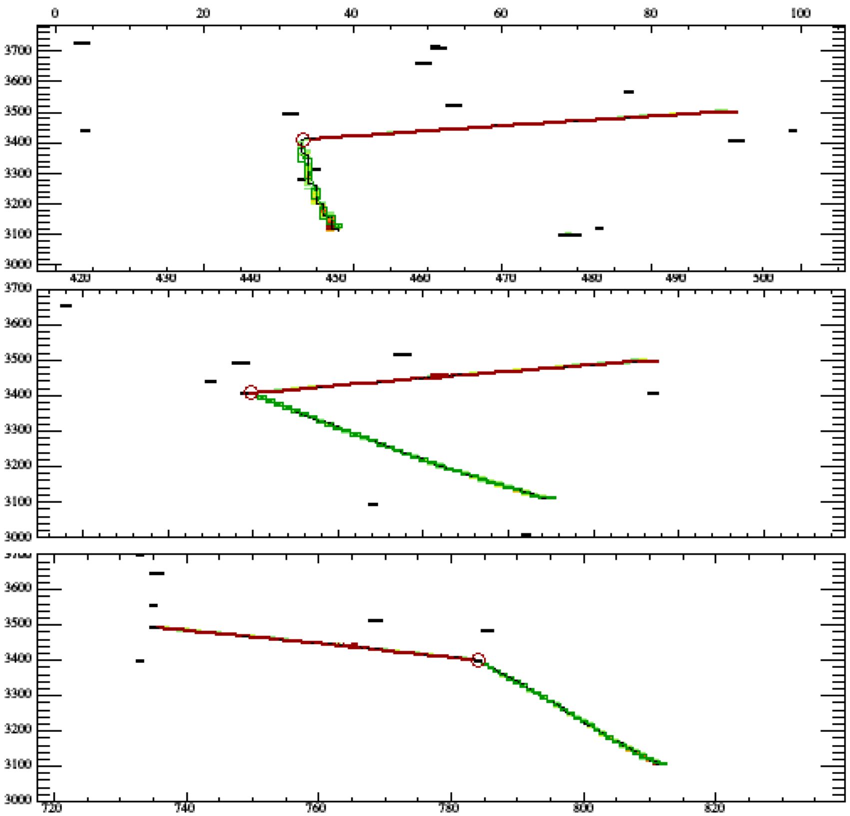
$n\bar{n}$ Backgrounds

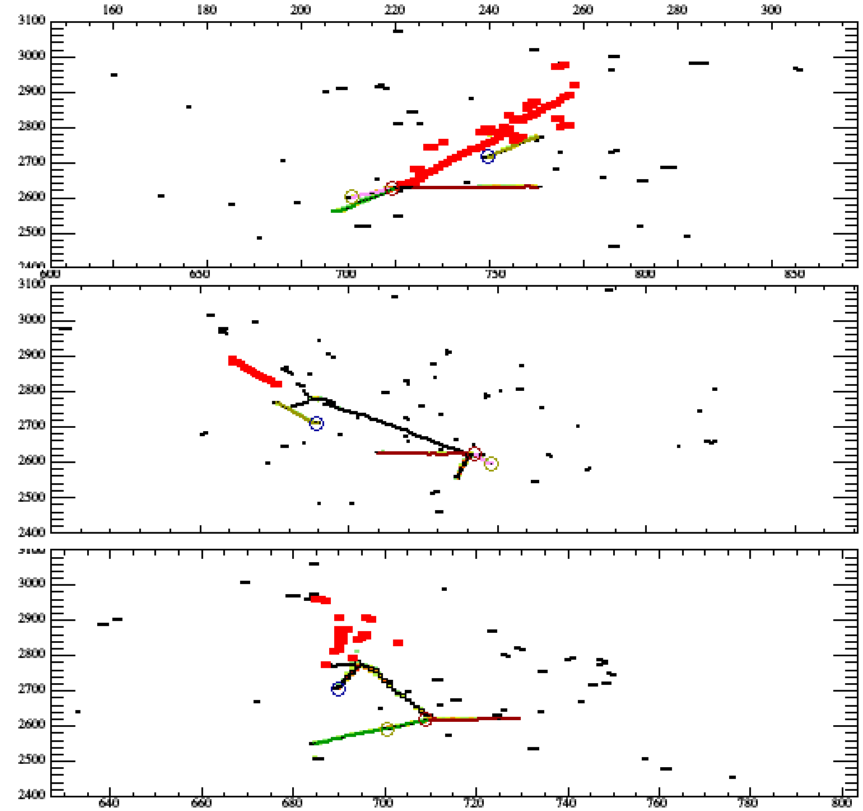
- Atmospheric neutrino NC interactions

MC Simulation
Atm.neutrinos

Low scoring



High scoring



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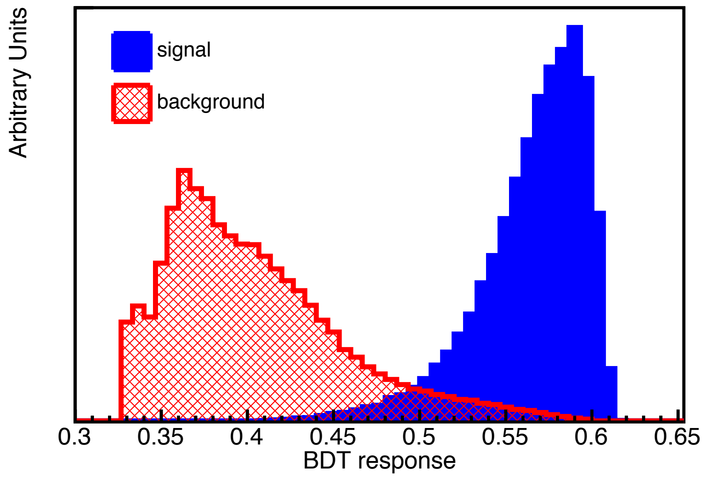
$n\bar{n}$ Oscillation Time Limits

- Analysis uses similar multi-variate methods to nucleon decay searches
- **Bound neutron**:
  - 8% signal efficiency and expected background of 23 events (current reconstruction)

  ➡ **6.45×10^{32} years** (90%CL) limit with 400 kt-year exposure (~10 years in full configuration)
- **Free neutron** oscillation time limit (using suppression factor for iron):
  - **5.53×10^{8} s**
- 2× improvement over the current limits



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Summary

- LArTPC new technology for nucleon decay searches
- DUNE will be the largest LArTPC with sensitivities complementary to large water Cherenkov detectors
- Three nucleon decay modes were investigated so far and complementary and improved lifetime limits are achievable
- $n\bar{n}$ — factor 2 improvement on free neutron oscillation time expected
- Observation of 1 event in some decay modes can constitute compelling evidence

Backups

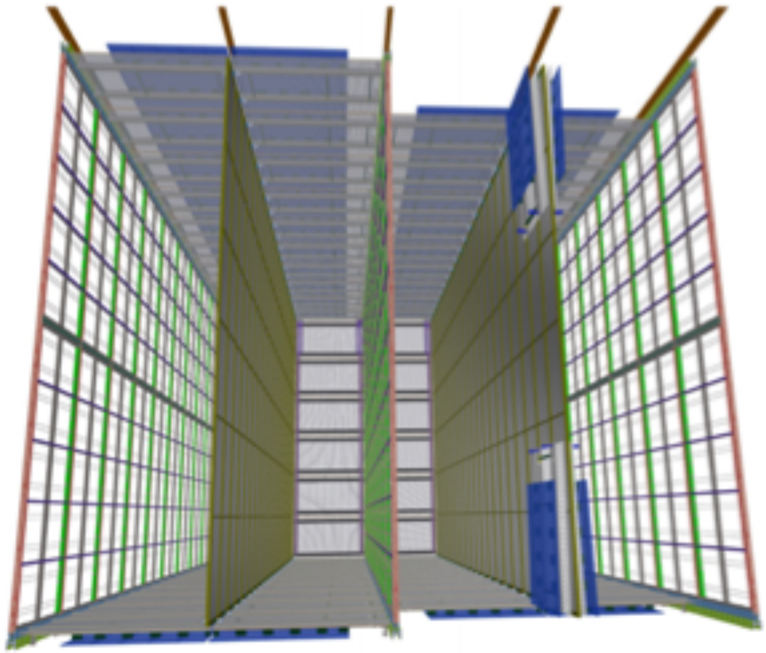
Comparison of Current Limits and Sensitivity of DUNE

	DUNE estimated sensitivity [years] @ 90% CL, after 400 kt-year exposure	Current limit, all 90% CL	Notes
$p \rightarrow K^+\overline{\nu}$	1.3×10^{34}	5.9×10^{33} [1] 8.2×10^{33} [2]	[1] SK, PysRev D90, 072005 (2014); 260 kt-year [2] SK, TAUP2019, preliminary; 365 kt-year
$n \rightarrow e^- K^+$	1.1×10^{34}	3.2×10^{31} [3]	[3] FREJUS, PhysLett B269, 227 (1991); 2 kt-year
$p \rightarrow e^+\pi^0$	8.7×10^{33} – 1.1×10^{34}	1.6×10^{34} [4] 2.0×10^{34} [5]	[4] SK, PhysRev D95, 012004 (2017); 306 kt-year [5] SK, TAUP2019, preliminary; 365 kt-year
$n\overline{n}$ oscillation [s] note: used nuclear suppression factor for Fe	5.53×10^8	8.6×10^7 [6] 2.7×10^8 [7]	[6] free $n\overline{n}$ @ ILL, ZPhys C63, 409 (1994) [7] SK, PhysRev D91, 072006 (2015); 200 kt-year

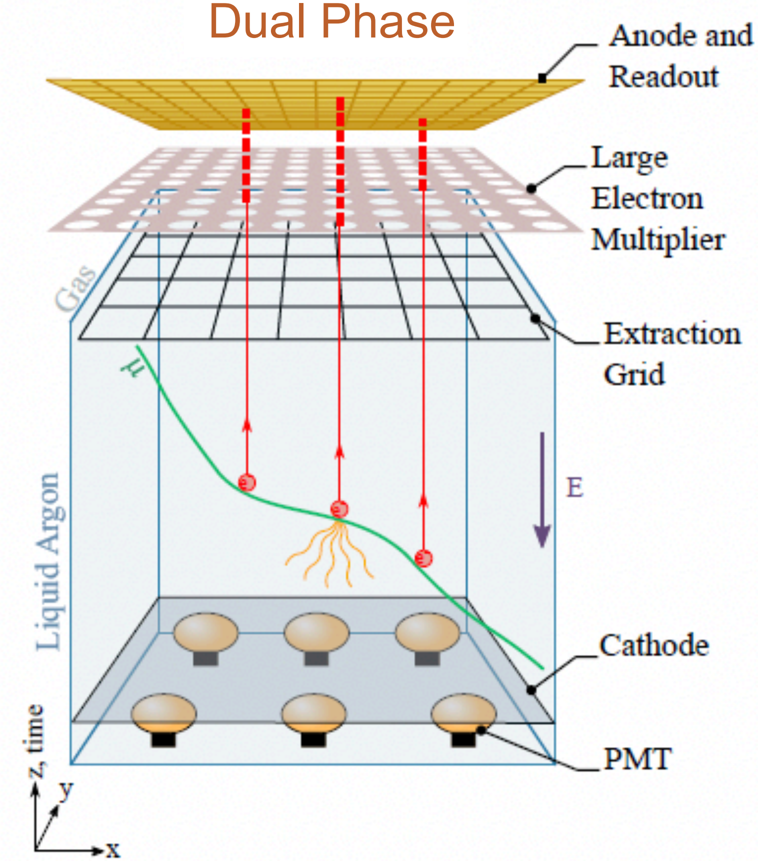
- All limits are on lifetime/branching ratio
- 400 kt-year exposure is equivalent to 10 year running in full 4-module configuration

Single vs Dual Phase LArTPC

Single Phase



Dual Phase



- Horisontal drift, all in LAr
- Vertical drift, charge multiplied in gaseous Ar above LAr

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