

# Nucleon Decay Searches in DUNE

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for the DUNE collaboration

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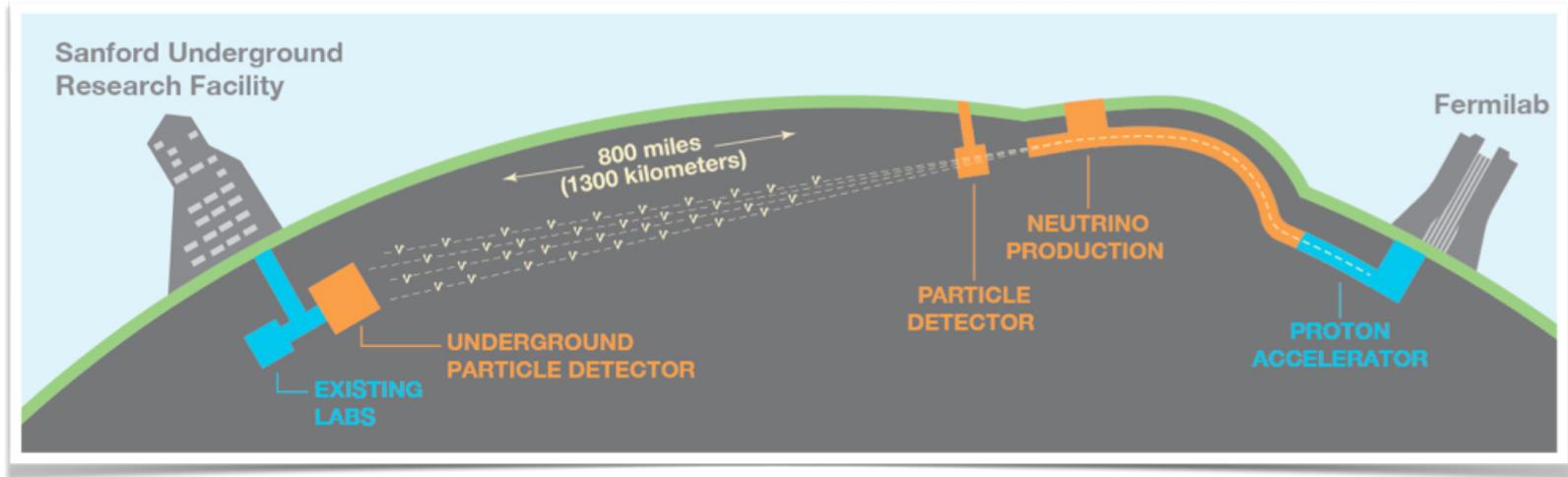
October 22nd, 2019



The  
University  
Of  
Sheffield.



# Deep Underground Neutrino Experiment (DUNE)



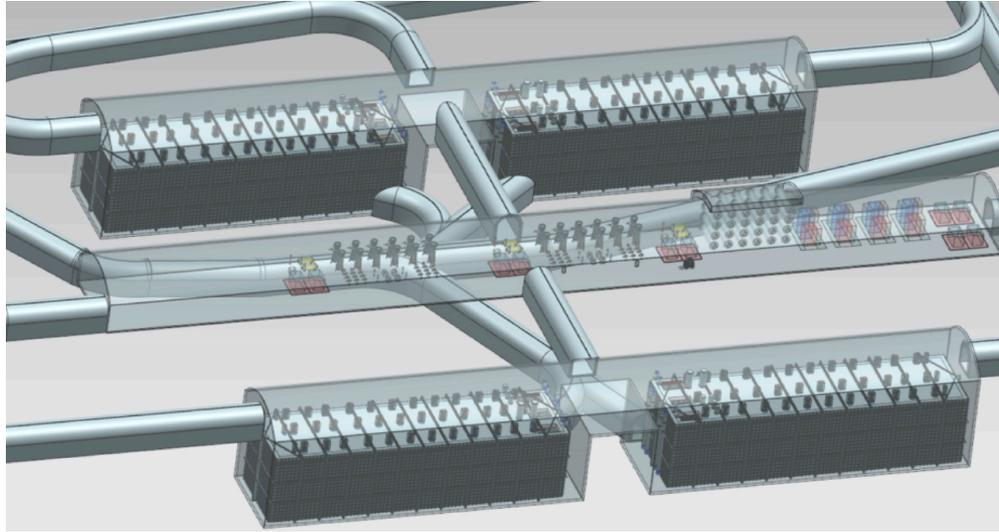
- **Location**

- 1.5 km underground @ **SURF**, Lead, South Dakota,
- 1300 km from the neutrino source

- **Neutrino source**

- powerful new beam of neutrinos @ Fermilab, Chicago, Illinois

# 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)
- Planned to start with 1st module in 2026, remaining 3 modules will be added sequentially

# 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

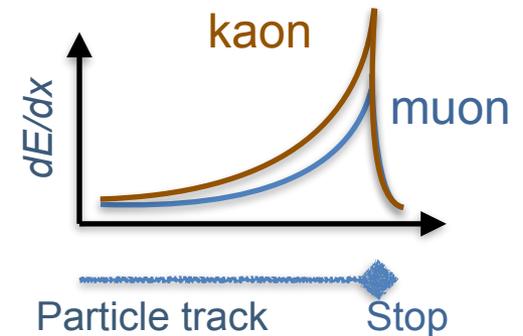
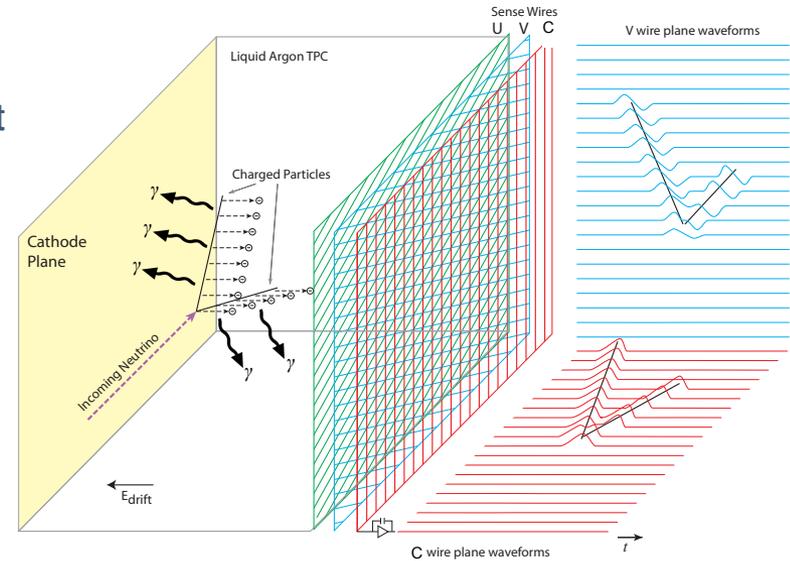
- ionisation charge drifts in electric field towards readout plane
- 3D reconstruction:
  - measured drift time (X)
  - location on readout planes (YZ)
- signal proportional to deposited energy →  $dE/dx$  measurement — particle ID

## 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  $37.5^\circ$  from vertical
- wire pitch 5 mm



# Advantage of LArTPC

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



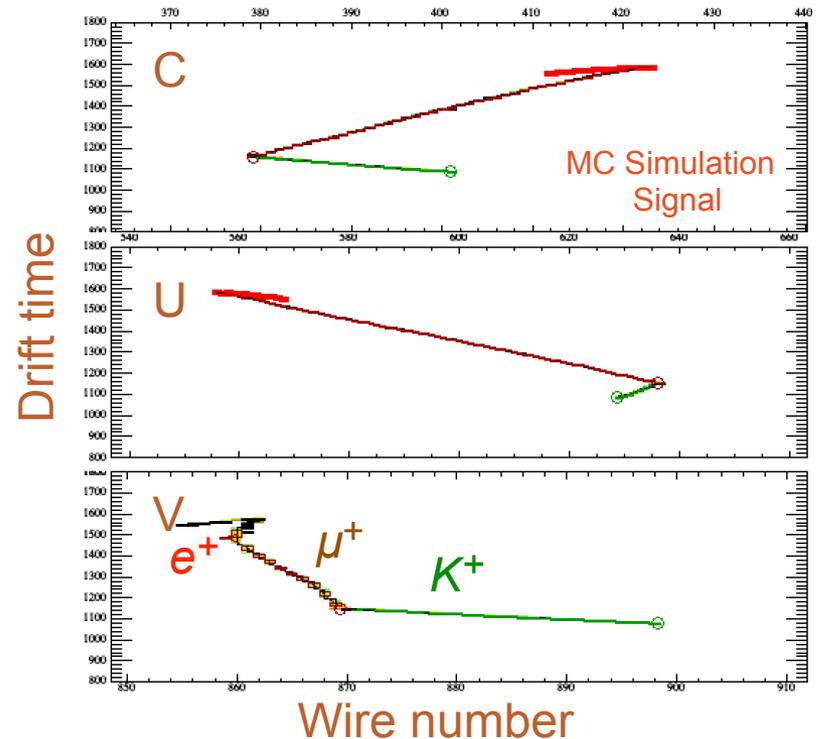
- Can identify  $K$  in nucleon-to- $K$  decays
- Can classify different event topologies
- Can discriminate gammas and electrons

- 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:
  - $p \rightarrow K^+\bar{\nu}, n \rightarrow e^-K^+, p \rightarrow e^+\pi^0$
- More nucleon decay modes will be studied in the future
- Backgrounds:
  - atmospheric neutrino CC interactions dominant
  - cosmogenic found sub-dominant



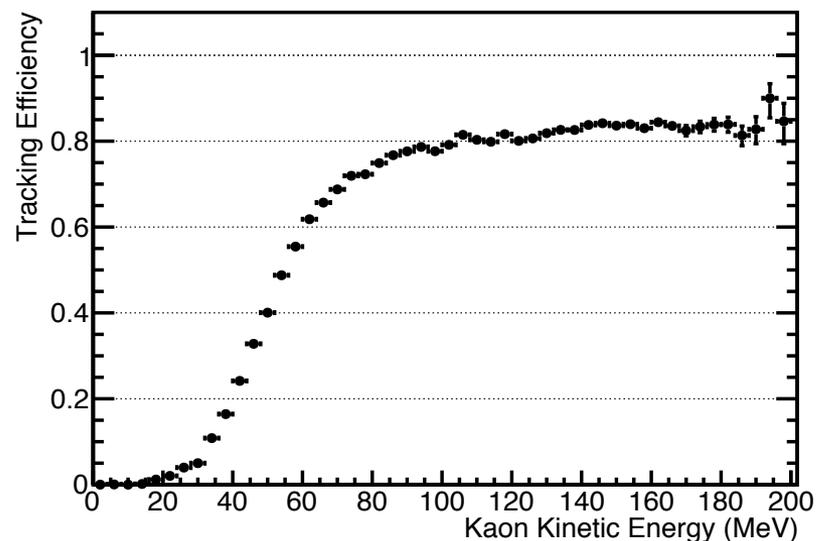
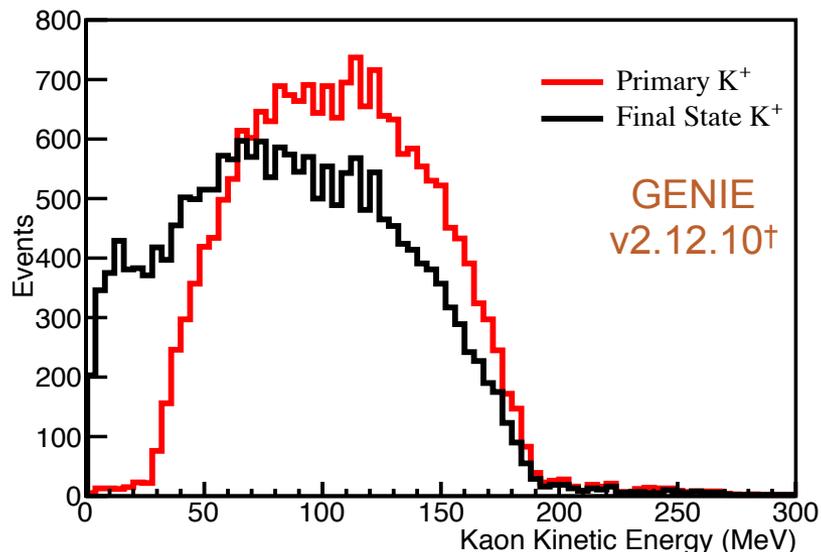
## Key features

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

## Difficulty

- proton decays in Ar  $\rightarrow$  some  $K$  will undergo Final State Interactions (FSI) inside the nucleus
  - $\rightarrow$   $K$  loses energy and it is more difficult to reconstruct its track

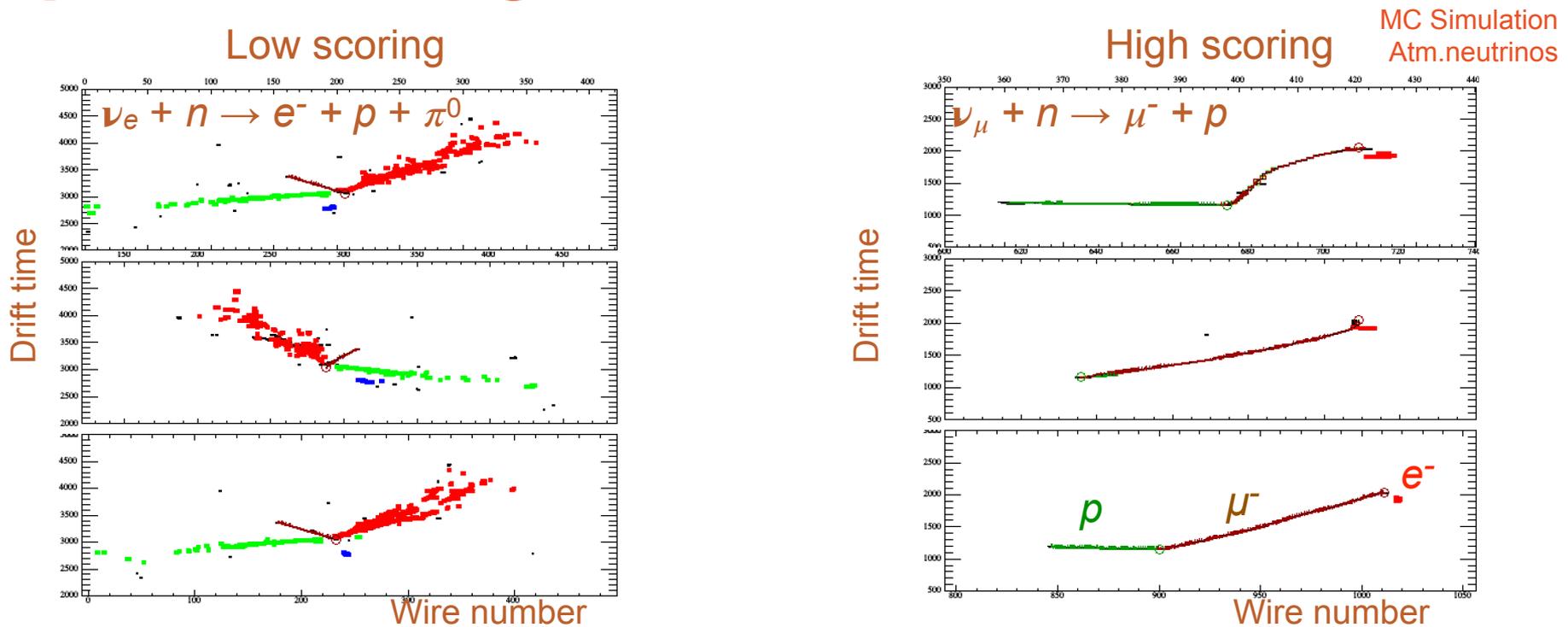
# Effect of FSI on K Track



- 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 shows 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



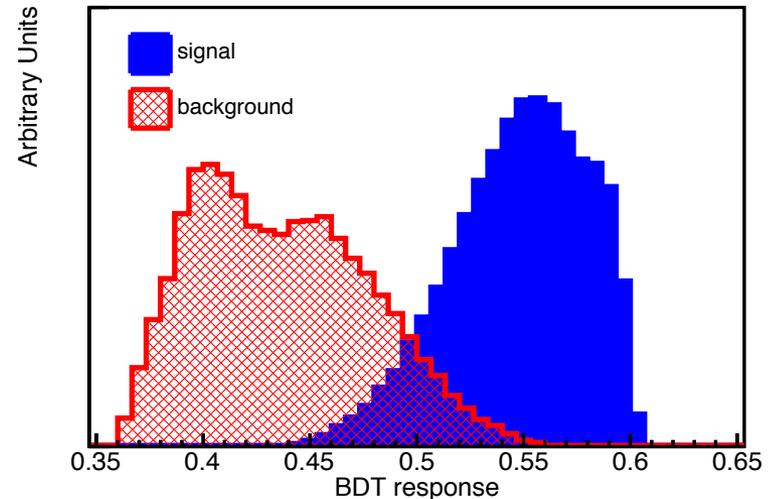
- Example of potential background events — atmospheric neutrino CC interaction
- Boosted Decision Tree multi-variate analysis used to classify events:
  - Left: well discriminated by the classifier (low score)
  - Right: poorly discriminated (high score)

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

- With current reconstruction:
  - signal efficiency 15% with background suppression of  $3 \times 10^{-6}$  (~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  $\rightarrow$  2% uncertainty on signal efficiency
- atmospheric neutrino flux and cross-section uncertainties  $\rightarrow$  20% uncertainty in backgrounds



## Sensitivity:

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

# Other Nucleon Decay Modes Investigated



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



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

# $n\bar{n}$ 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  $\tau_{n-\bar{n}}$ :

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

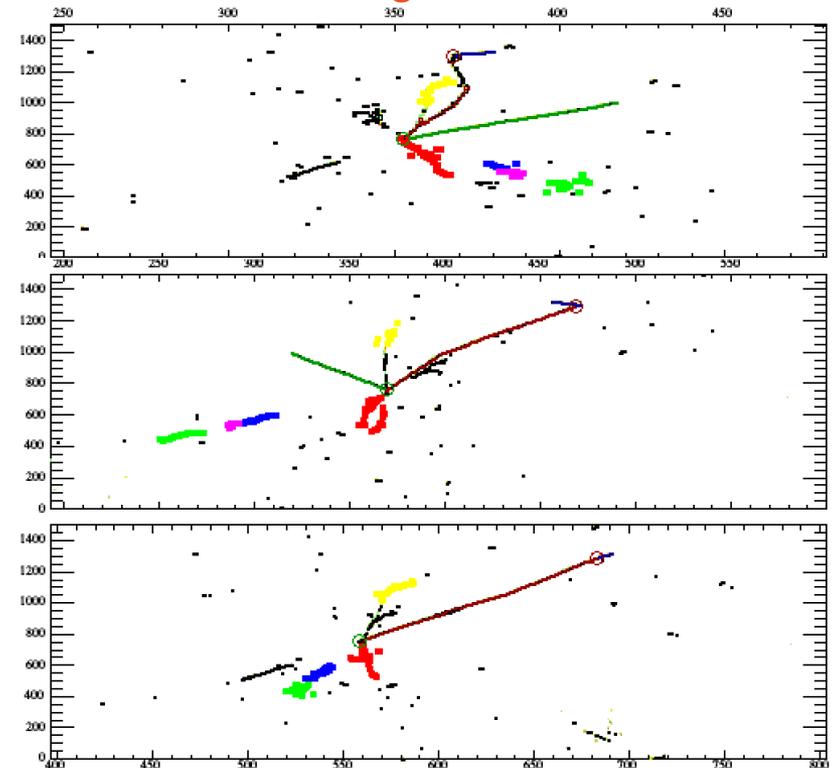
- Used suppression factor calculated for iron [1]  $R = 6.66 \times 10^{22} s^{-1}$
- A new calculation exists for suppression factor in argon [2]:  $R = 5.6 \times 10^{22}$ ; Josh Barrow can give more details, go see him by his poster

[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  **$\sim 2$  GeV**
- **Vanishing total momentum**

MC Simulation  
Signal

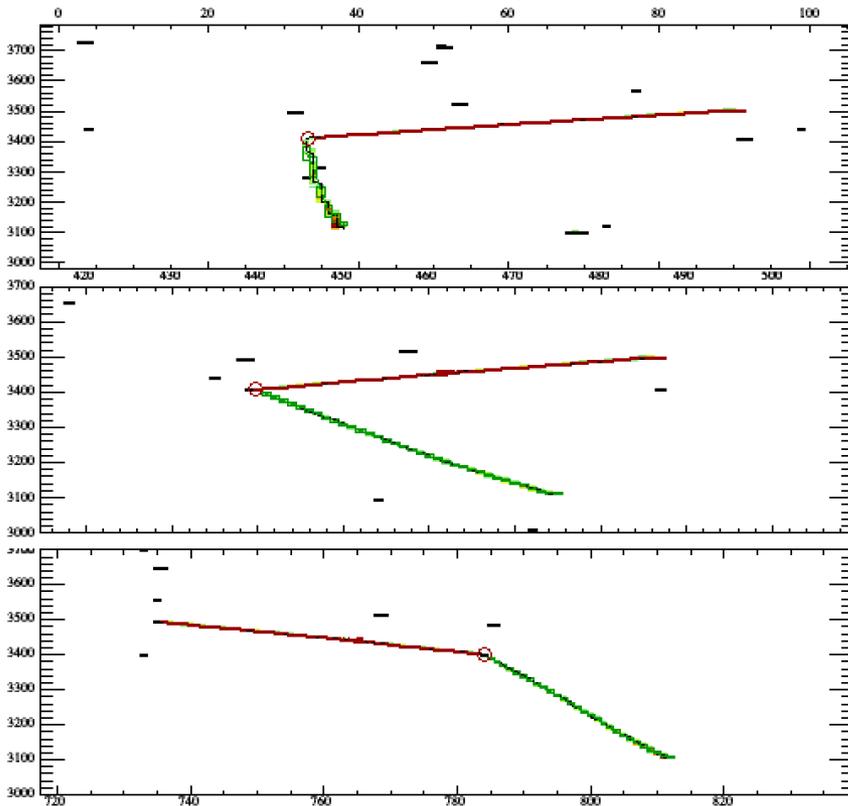


# $n\bar{n}$ Backgrounds

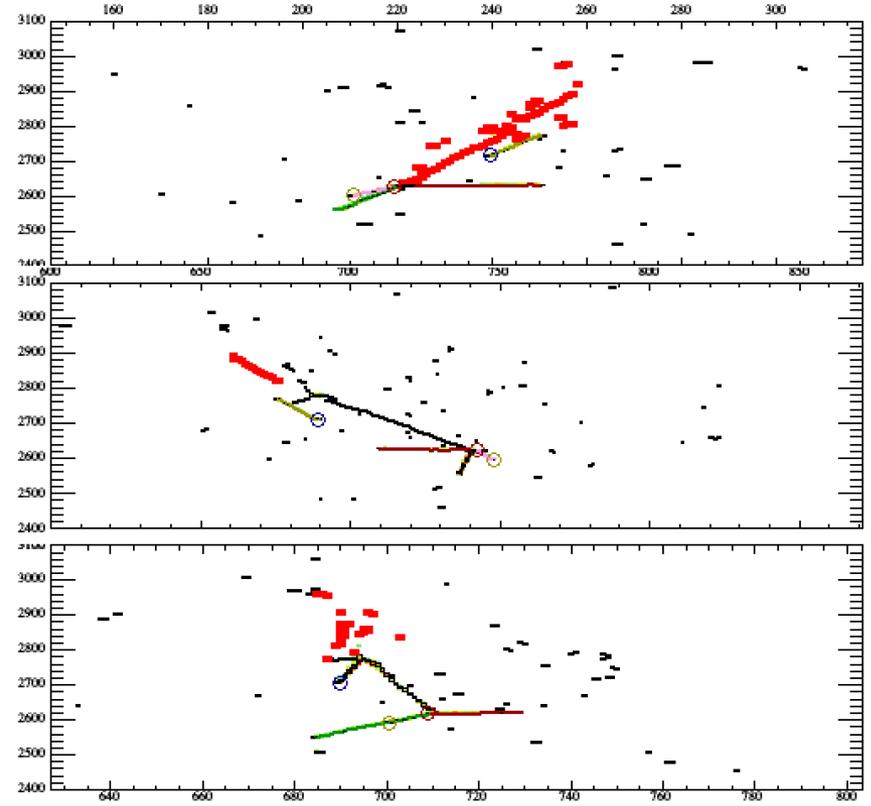
- Atmospheric neutrino NC interactions

MC Simulation  
Atm. neutrinos

Low scoring

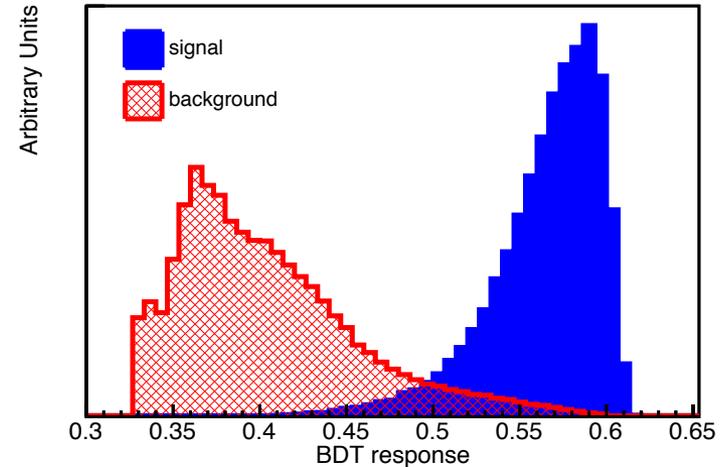


High scoring



# $n\bar{n}$ 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)
  - ➔  **$6.45 \times 10^{32}$  years** (90%CL) limit with 400 kt-year exposure ( $\sim 10$  years in full configuration)
- **Free neutron** oscillation time limit (using suppression factor for iron):
  - **$5.53 \times 10^8$  s**
- $\sim 2\times$  improvement over the current limits



# 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

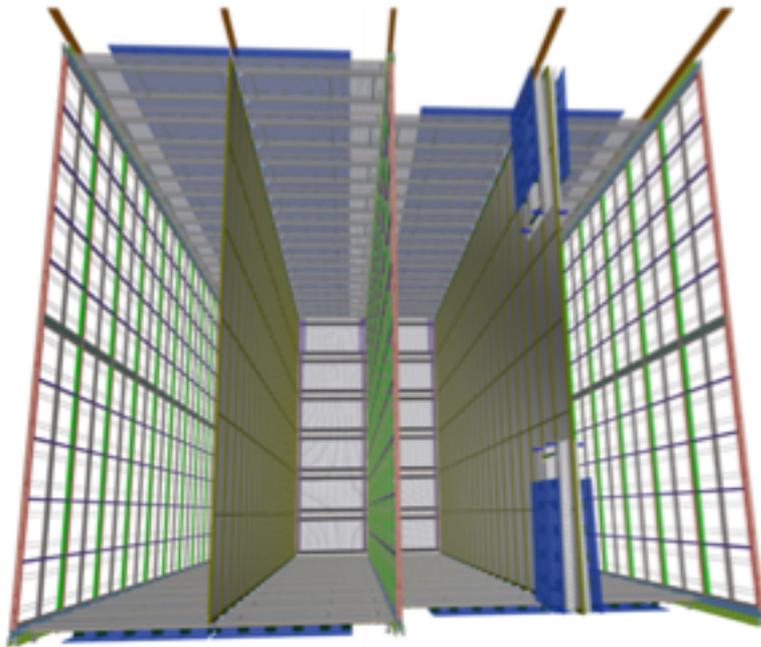
# Comparison of Current Limits and Sensitivity of DUNE

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

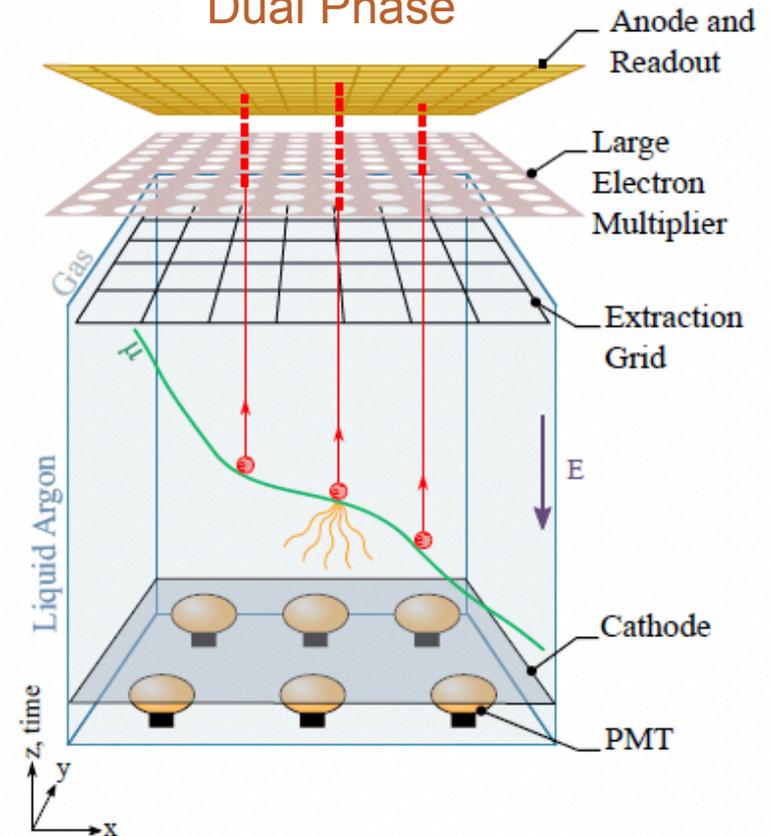
# Single vs Dual Phase LArTPC

Single Phase



- Horizontal drift, all in LAr

Dual Phase



- Vertical drift, charge multiplied in gaseous Ar above LAr