Outline:

• Introduction
  • DUNE
  • Rare Event Searches
  • Zero Suppression
• Methods and Studies
  • Simulations
  • Improved Data Rates?
  • Signal Efficiency
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Introduction
• CP Violation and Neutrino Mass Hierarchy through Neutrino and Anti-Neutrino Oscillations
• Nucleon Decay and Neutron-Antineutron Oscillation
• Flavor and Spectrum of Neutrino Burst from Supernova
• **Time Projection Chamber**
  • charged particles ionize argon atoms through CC and NC interactions
  • $e^-$ ionization drifted by 500 V/cm electric field
  • $e^-$ ionization induce current on induction planes (U, V)
  • $e^-$ ionization collected on collection plane (Z)
  • PMTs collect light from Ar scintillation for $t_0$
  • creates 3D event reconstruction using charge drift and timing
  • **this study: focus on 1D wire signals**
• 2 B per sample  
• 4492 samples per channel  
• 1536000 total channels  
• 2.4 drifts per 5.4 ms readout  
• 24.9 GB per readout  
• 4.6 TB per second for continuous readout!
Why a Continuous Readout?

• If pulsed accelerator neutrino beam which only crosses detector at intermittent and predetermined times, why have continuous readout?

• What could the LArTPC detect in these off-beam times?
  • $\nu_x$ from supernova core collapse
  • Nucleon Decay
  • Neutron-Antineutron Oscillation
Neutrino Signals from Supernova

- during core collapse of a supernova, protons and electrons fuse to form neutrons due to gravitational pressure
- $\nu$ emitted to conserve lepton number
- over 99% of gravitational binding energy (10% of rest mass) emitted by low energy $\nu$
- collected $\bar{\nu}_e$ signals $O(10)$ from SN1987A confirmed basic $\nu$ models
- but many questions remain!
- flavor composition implies SN dynamics
- neutrino oscillations in dense matter

"From neutrinos.....". DK&ER, Lecture 10
LArTPC Sensitivity to Supernovas

• DUNE’s unique sensitivity O(1000) of collected signals
• most likely CC interaction:
  • $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$
• provide complement to $\nu_e$ from other scintillator experiments
• expect $\nu_e$ between O(5-50) MeV
• ~ 10 seconds for full event

Flavor composition as function of time:

Energy spectra integrated over time:

Electron flavor dominant
Allows mapping of neutronization burst, which is dominated by $\nu_e$
Challenges to Supernova Sensitivity

- ~ 10 seconds for full supernova event means ~46 TB of data
- low energy deposits throughout detector by $\nu_e$ appear similar
- radiological decay by LAr in detector
- radiological background → decay of radioactive isotopes
- must also consider noise!
solution: data reduction by zero suppression

readout from single induction plane wire

what is zero suppression?

• define condition of desired data
• if conditions met:
  keep data and surrounding samples
• else:
  set to zero

drifting e⁻ ionization pulse induced on wire

full output
Methods and Studies
simulations:

event: full readout of 4492 TDCs
default noise: RMS 2 ADCs

• From LarSoft*:
  • 1000 5-50 MeV electrons with and without noise
  • 100 noise events at varying RMS values

• From MARLEY (generated by J. Stock):
  • supernova neutrinos with full radiological background with/without noise
  • full radiological background with/without noise
  • Ar$^{39}$ background with/without noise
  • supernova neutrinos with noise, no radiologicals

* Larsorft is a simulation, reconstruction, and analysis software toolkit developed and used by the liquid argon TPC community
Study 1: Expected Data Rates with Zero Suppression

- **Data Rate Reductions**
  - What is the achieved data rate and data reduction factor as a function of zero suppression algorithm and threshold?
  - **goal:** reduce data rates

\[
data \text{ reduction factor} = \frac{\text{expected data rate from continuous stream}}{\text{zero suppression data rate}}\]
zs legacy:

- zslegacy by David Adams
- finds signal above ADC threshold
- keeps nSample buffer region on either side of region above ADC threshold
- creating Region of Interest (ROI)
- zero suppresses everything outside of these regions
- generating channel waveforms with multiple ROIs between zero suppressed regions (gaps)
Compression Factors:

\[
\text{Compression Fact.} = \frac{1}{N_{\text{channels}}} \sum_{i=0}^{N_{\text{channels}}} \frac{\text{Num. Ticks in saved ROIs for } WF_i}{\text{Num. Ticks in } WF_i} \in [0,1]
\]

mean compression factor for RMS at given threshold

- How well does zs scheme 1 reject noise?
- Will noise dominate readout?

100 noise events
New Data Rate: zs legacy

- ~ 3.24 GB per second or 324 GB per 10 seconds of SN readout
- data reduction factor zs thresh 10 ADCs for full radiologicals: 1419

100 events for each sample

*bars indicate spread of distribution
**algorithms: zs scheme 2**

zs consecutive:
- finds signal above ADC threshold
- if next tick is also above threshold: create and save ROI

**distributions of ROI lengths: signal, signal +noise, noise**

- **ROI Length for zs thresh = 10 ADCs**
- **algorithms: zs scheme 2**
- **distributions of ROI lengths: signal, signal +noise, noise**
- **zs consecutive:**
  - finds signal above ADC threshold
  - if next tick is also above threshold: create and save ROI
- **zs thresh = 10**
- **normalized frequency**
  - **roi length (TDCs)**
  - **ADCs**
  - **TDCs**
  - **signal**
  - **noise**
New Data Rate: $zs$ consecutive

- ~ 0.925 GB per second or 92.5 GB per 10 seconds of SN readout
- data reduction factor $zs$ thresh 10 ADCs for full radiologicals: 4972

100 events for each sample

*bars indicate spread of distribution*
New Data Rate: zs consecutive

- Noise: ~ 1.3 MB per second or 130 MB per 10 seconds of SN readout

*bars indicate spread of distribution
Study 2: How is signal efficiency affected by zs?

- ionization electron signal collection efficiency
  - What is TPC signal fraction recovered (in units of ionization charge arriving at wire using known ADC gain, integrated over time ticks for collection plane) as a function of threshold?
  - **goal**: keep useful data and maintain sensitivity
signal efficiency studies:

low energy electrons (5-50 MeV):
- electrons in same energy range as expected SN $\nu_e$
- determine true deposited energy from simulation
- run through zs scheme 1 and zs scheme 2
- weight reconstructed energy by distance from APA
- compare true versus reconstructed from zs waveform
- calculate baseline and subtract baseline:
  - does signal efficiency improve?

\[
\text{efficiency} = \frac{\text{energy deposited from zs waveform (MeV)}}{\text{energy deposited without noise (MeV)}}
\]
weighting:

absolute value of x position used to weight events:

\[
\text{weighted efficiency} = \frac{\text{reconstructed efficiency at pos} \ x}{\text{true efficiency at pos} \ x}
\]

1000 low energy electrons
baseline calculation:

- subtract pedestal
- save buffer regions on either side of waveform
- pre baseline: take mean from beginning of buffer region
- post baseline: take mean from end of buffer region
zs legacy: ADC threshold

Z Plane

1000 low energy electrons
zs consecutive: 2 ADCs above threshold

1000 low energy electrons
Conclusions
Specific Study Conclusions:

• zs schemes decrease data rates by minimum factor of $O(1000)$!
• zs threshold 12 maintains signal efficiency and data rates of true sample
• zs scheme 2: lossy, but reduces noise data rate to 1.3 MB per second
• reduction of noise by zs possible, what about radiological background?
Overall Conclusions:

- barring errors in noise and event simulations, data rates effectively reduced from $\sim 5 \text{ TB/s}$ to $3.24 \text{ GB/s}$ at minimum.
- noise data reduction factor $O(10^6)$
- data reduced while quality maintained:
  - no significant impact on signal collection efficiency for lowest-energy events (i.e. SN energy regime)
Looking Ahead:

• repeat signal efficiency study on supernova $\nu_e$’s with and without background
• statistical analyses to gain confidence levels for threshold
• increase noise RMS in data, look at compression factors for zs 1 and zs 2
• is lossy zs scheme 2 worth it?
• pair with triggering schemes to reduce radiological background
• apply to other rare event searches:
  • nucleon decay
  • neutron-antineutron oscillation events
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Backups
Supernova De-excitation Photons

$^{40}\text{K}^*$ decay spectrum [ Raghavan Model ]
energy distribution of deposited electron energy for efficiency studies:
Baseline Optimization:
ADC to MeV Conversion

\[
1 \frac{ADC}{ADC} \times \frac{1 \text{mV}}{2.8 \text{ADC}} \times \frac{1 \text{fc}}{14 \text{mV}} \times \frac{6241 e^-}{1 \text{fc}} \times \frac{23.6 \text{eV} E_{\text{ion}}}{e^-} \times \frac{1 \times 10^{-6} \text{MeV}}{eV} = 3.75 \times 10^{-3} \text{MeV}
\]
zs scheme 1: ADC threshold

- Bars indicate spread of distribution.
zs scheme 2: ADC threshold

- bars indicate spread of distribution