FERMILAB-SLIDES-23-387-STUDENT

Measurement of Rayleigh Scattering in Liquid Argon at Vacuum Ultraviolet Wavelengths

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SULI Oral Presentation

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Introduction

DUNE Experiment

Physics Objectives

- Long Baseline Neutrino Oscillation Measurements
  - Answer neutrino questions
    - Neutrino Mass Order
    - Presence of Leptonic CP Violation
    - Possible Unitary Neutrino Mixing Matrix
- Observe Galactic Supernovae Neutrinos
  - Rare opportunity to study astroparticle physics in extreme environments
  - Measurable impact of neutrino-neutrino interactions?
- Potentially discover nucleon decay
  - Major potential discovery and inform Beyond the Standard Model (BSM) Physics)

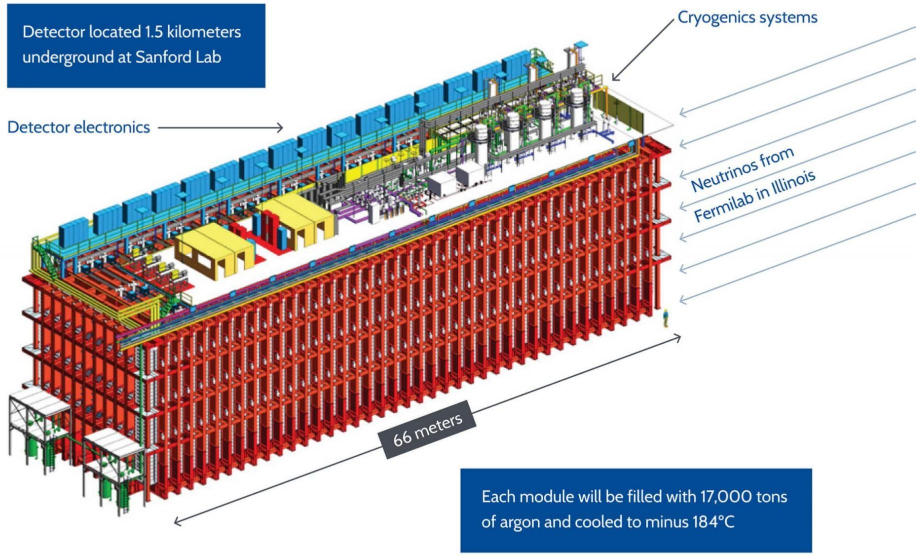
Introduction

DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE

Design

- Long Baseline Neutrino Facility (LBNF)
  - Located at Fermilab
  - Generates high-intensity neutrino beam
- Near Detector (ND)
  - Located at Fermilab
  - Measures initial neutrino beam composition produced by LBNF
- Far Detector
  - Located at Sanford Underground Research Facility, South Dakota
  - 4 time projection chambers (TPCs), 40 ktons of liquid argon total
  - Measures neutrino beam spectrum after oscillations
  - Detects potential supernova neutrinos
  - Detects potential nucleon decays



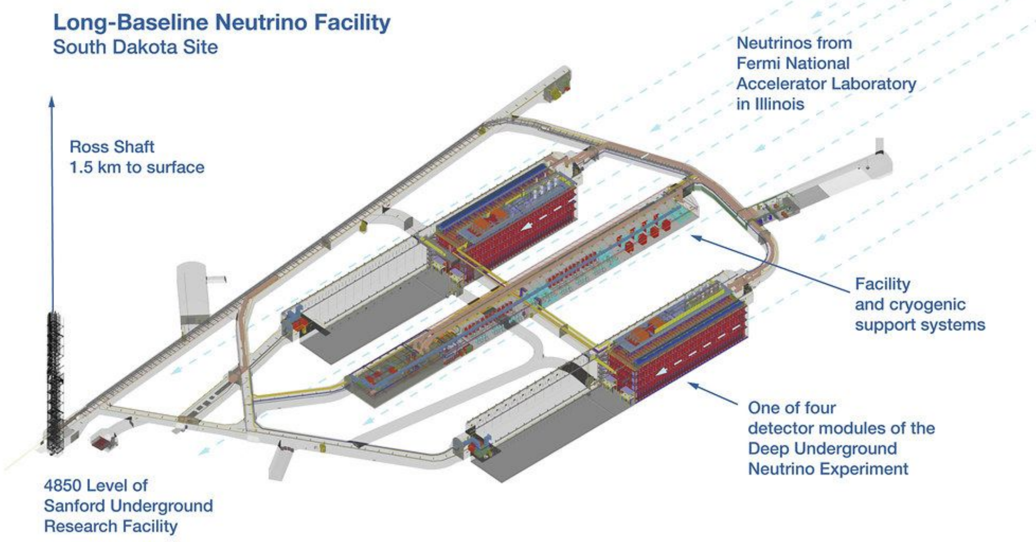
Far Detector Module
Image Credits: DUNE

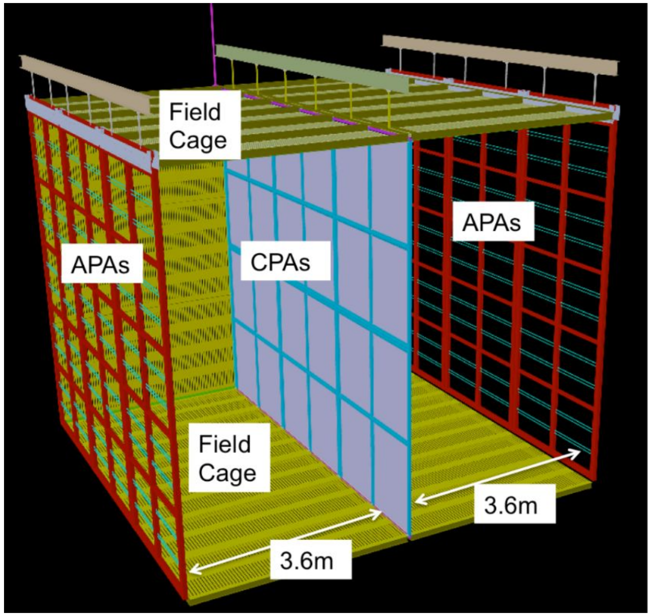
Introduction

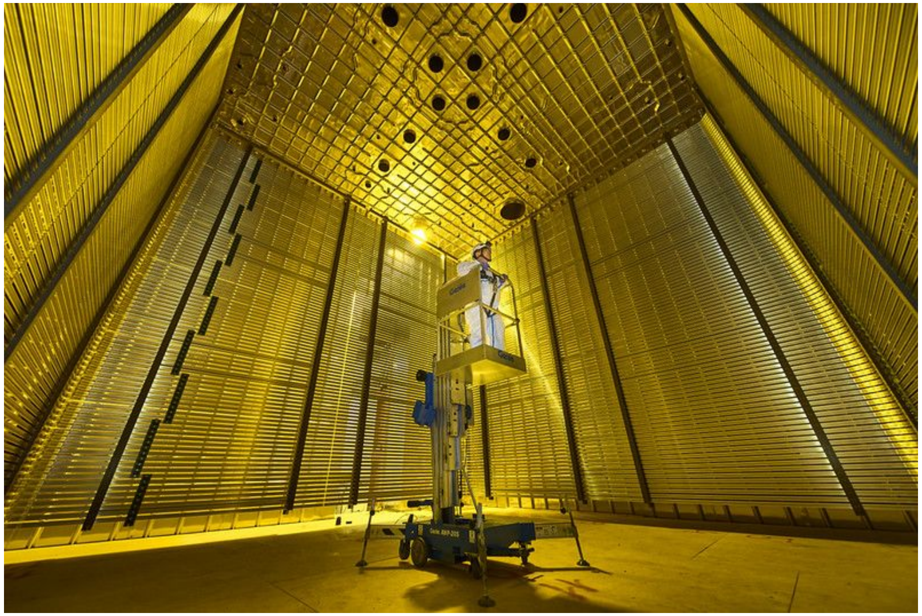
Top Right: LBNF Facility (Credits: DUNE)

Bottom Left: ProtoDUNE Diagram (Credits: Alex Himmel)

Bottom Right: ProtoDUNE Interior (Credits: DUNE)







Introduction

DUNE Detector Operation

- LArTPCs - charged particles ionize argon atoms and produce scintillation light
- Ionization Charge
  - ~40% of deposited energy
  - Electric field → charge drifts toward anode, measured by wires or planes
    - Records charge signal in two dimensions, third dimension measured from relative arrival time
- Scintillation Light
  - ~60% of deposited energy
  - Characteristic spectrum emitted after excitation by ionizing radiation (argon peak at 128 nm)
  - Detected by photon sensors (e.g. photomultiplier tube (PMT) or silicon photomultiplier (SiPM))
  - Determines the absolute time (arrival difference between scintillation light and charge)
    - Compare scintillation light time (ns scintillation production+speed of light propagation) to drift charge time (<~6000 μs from emission to detection) to calculate third dimension
- Reconstruction of event position needed to define fiducial volumes for exclusion of background and correction of charge signal attenuation

Motivation

SULI Project Objectives

- Potential for photon detector system to advance DUNE physics objectives by enabling a second calorimetric measurement of event energy
  - Second energy measurement improves analysis outcomes
    - Improves overall energy resolution since light and charge energy measurement resolution have different limitations
    - Provides in-situ cross-comparison of the TPC energy measurement, reducing systematic uncertainty of the energy measurement
- Scintillation light role currently limited by ability to reconstruct photon signals due to Rayleigh scattering
- Measuring the Rayleigh scattering length of scintillation wavelengths in LAr is first step to developing additional photon system analysis capabilities
  - Previous measurements and calculations claim wide ranges of values from 55 cm to >130 cm for the Rayleigh scattering length of 128 nm light in liquid argon

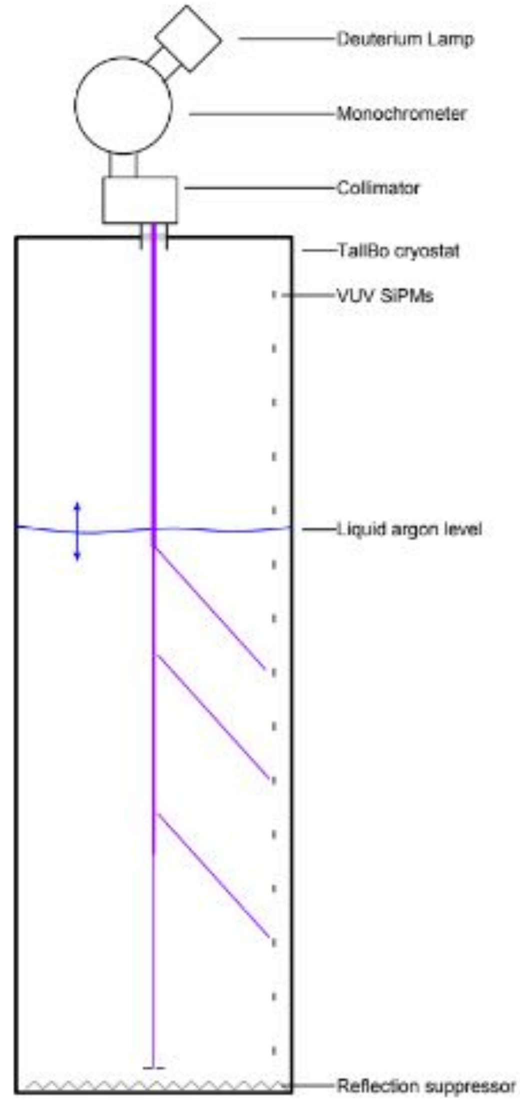
Measurement

TallBo Cryostat Setup

- Deuterium Lamp: produces UV light spectrum
- Monochromator: selects single UV wavelengths
- Collimator: reduces beam dispersion
- TallBo Cryostat: designed for liquid argon optics tests
- VUV SiPMs: detects photons
- Reflection Suppressor: absorbs incident light, prevents reflections

Measurement Theory

- Measure photon rate of SiPM directly below light source at multiple liquid argon depths
- Lower liquid argon volume results in less scattering and a greater photon rate
- Curve fitting the photon rate versus liquid argon depth gives the Rayleigh scattering length



TallBo Cryostat
(diagram by Alex Himmel)

Measurement

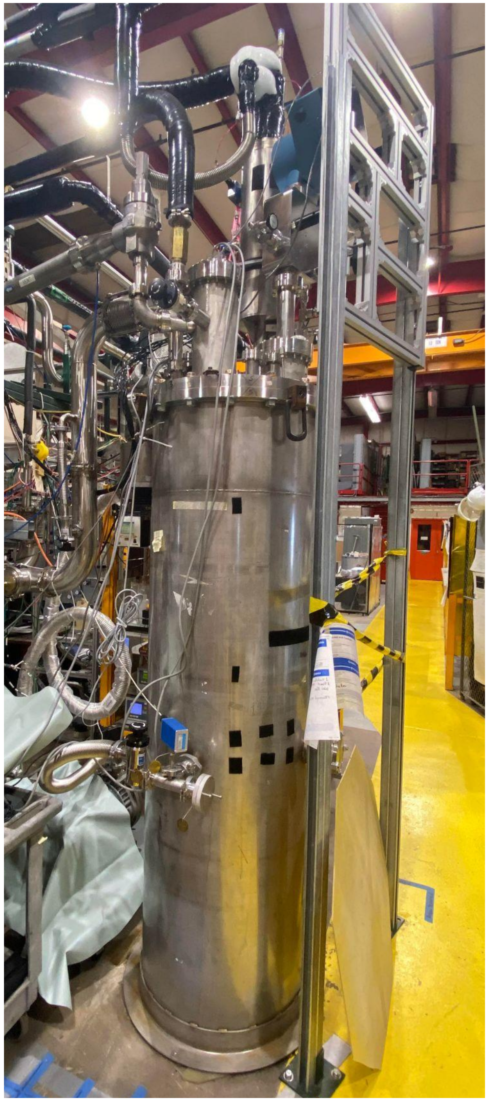
Run Procedure

- Fill cryostat to maximum liquid argon level
- Measure background rate and lamp on rate of wavelengths from 124 to 180 nm
  - SiPM response is temperature dependent → only consider submerged SiPMs
- Lower level and repeat measurement

Analysis Procedures

- Check 1 SiPM trigger event waveform corresponds to 1 photon
- Confirm the shallowest submerged SiPM has greater signal rate than deepest submerged SiPMs
- Plot bottom SiPM trigger rate versus depth
- Curve fit rate vs depth plot to exponential decay function for Rayleigh scattering length l

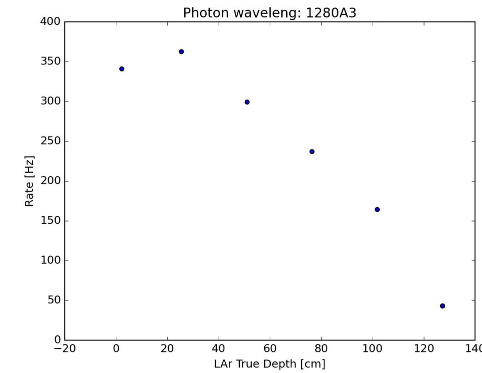
$$rate = ae^{-z/l} + b$$

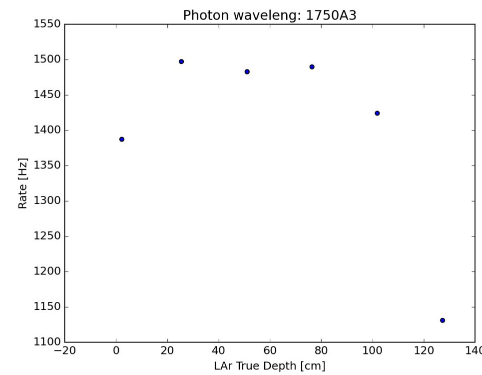


TallBo Cryostat

SULI Summer Summary

- Setup experiment equipment, develop hardware operation procedures
  - Grounding issues with Arduino (timing control) and monochromator motor power supply
  - Issues with performance of some SiPMs
  - Data collection, transmission rate limitations
- Conduct analysis to understand SiPM signal waveforms
- Create procedures for measurement run 1
- Run 1:
  - Results unexpected
    - Turn over effect when comparing background subtracted rate versus depth at different wavelengths
    - Background division plot is better fit to expected exponential behavior than background subtraction
    - Future tests focus on understanding sources of behavior and solutions to remove additional effects

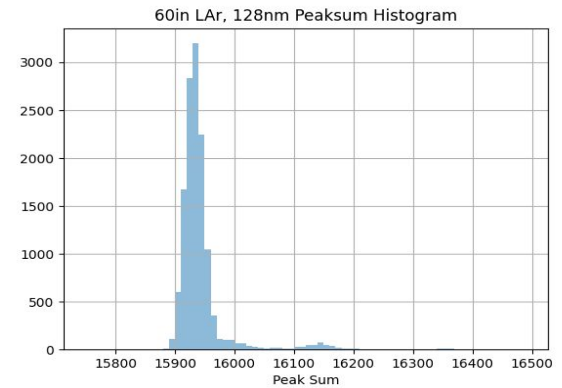


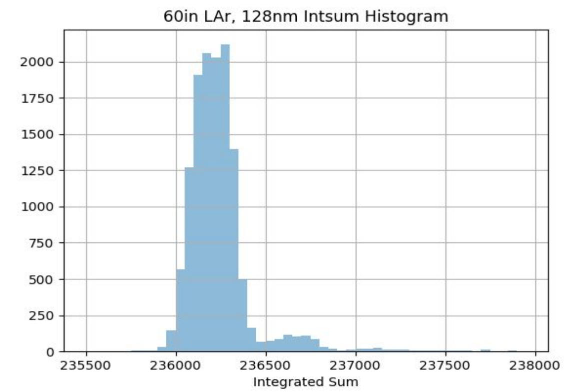


Bottom SiPM Rate vs Depth (Background Subtraction)

SiPM Waveforms

- SiPM Waveform Signals
  - Data transfer rate is limited, so only save SSP calculated data (no raw waveform values)
  - Plots of energy spectrum (waveform signal peak integral) are consistent with combination of
    - Single photon signals
    - SiPM crosstalk between pixels (single photon appears to be two photons)
    - background contribution from radiation, SiPM dark count
- Background
  - Argon-39 radioactive decay scintillation signals
    - Contributes to change in background rate at different liquid depths
      - Eliminated through background subtraction
  - Cosmic Ray Scintillation
  - SiPM Dark Count

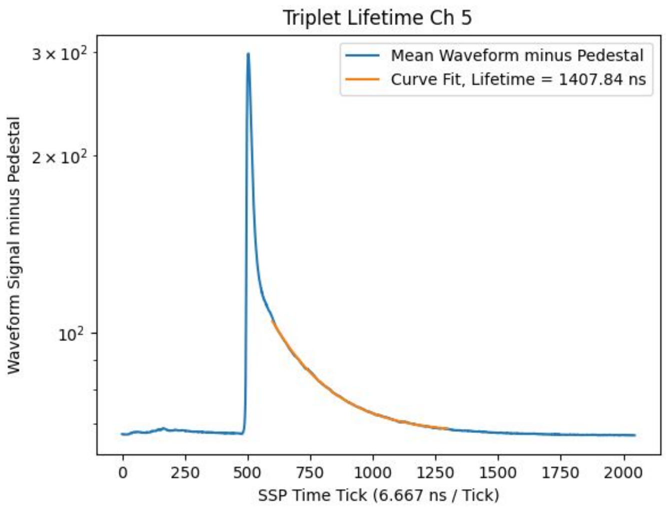




Peak Sum (Initial Peak), Integrated Sum (Peak+Tail)

Liquid Argon Purity Diagnostics

- Vacuum Ultraviolet light is extremely susceptible to absorption from contaminants (Water, N2, O2, etc.)
  - Constant contaminant level is important to ensure stable light flux entering liquid argon
  - Test by measuring liquid argon triplet lifetime
    - Take high peak waveform data of background radiation
    - Calculate average value of each point in waveform, curve fit to find triplet lifetime
    - Measured lifetime of 1.4 microseconds, consistent with known value of 1.3 microseconds



Triplet Lifetime Plot, Curve Fit

Fermilab

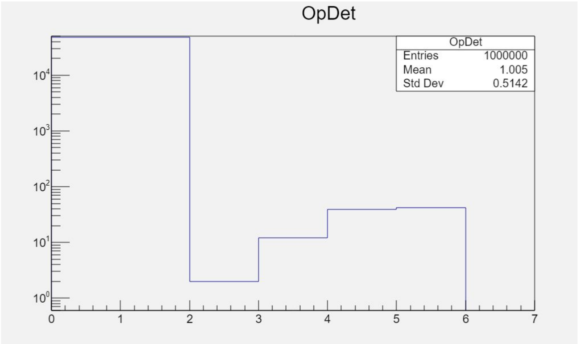
Simulation Comparison

Geant4 Simulations on DUNE computers

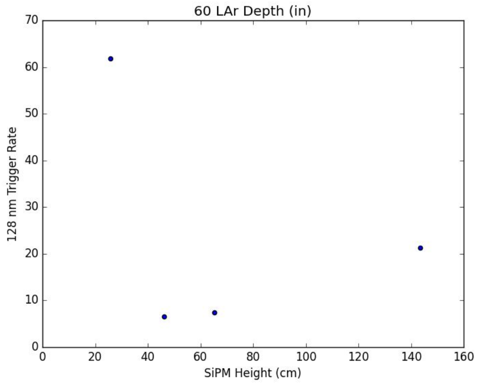
- Create cryostat, detector geometry
- Add photons using particle gun function
- Check detector geometry and photon beam tracks using OpenGL visualization
- Plot shows photon number is greater on shallower submerged side SiPMs compared to deeper submerged side SiPMs
  - Light flux greatest at light beam point of entry at liquid surface
  - As light travels through liquid argon, more light is attenuated and the beam intensity decreases
  - Less scattered photons at deeper liquid argon depths

Measurement

- Qualitatively agrees with simulation
  - SiPMs closer to liquid surface observe more photons



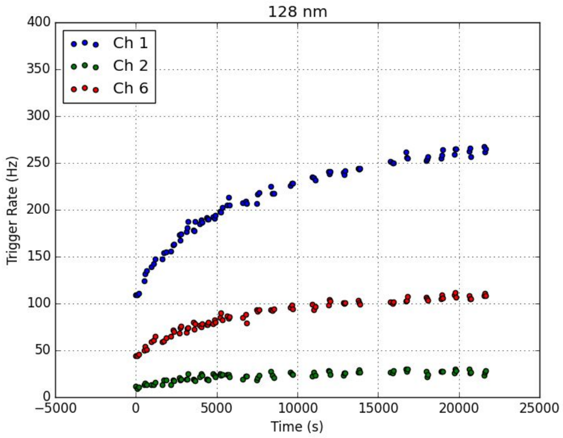
Geant4 Simulation Detected Photons per SiPM (log scale)



Run 3 Measured Rate vs SiPM Height

Run 2

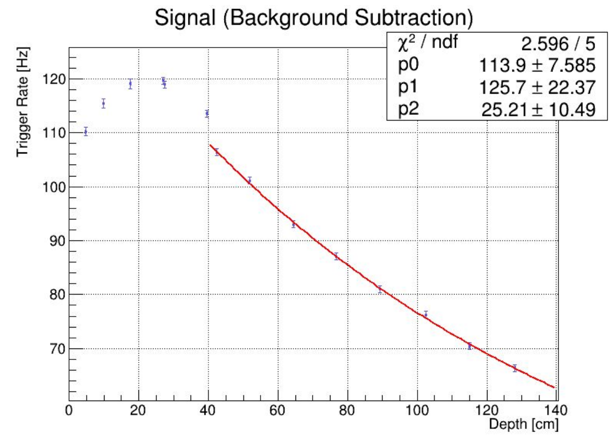
- Understand major issue - light intensity entering cryostat is not constant
  - Deuterium lamp requires warm-up (~30 min) to stabilize after powered on
  - The gaseous argon purge procedure caused varying levels of contaminants over time inside the monochromator
    - Lowering contaminant level lowers VUV wavelength light absorption
    - Resulted in lamp intensity increasing over 8+ hours as contaminants are constantly removed
  - Curve fitting and subtracting warm up effect is inconsistent (depends on purge rate) + results in greater error
- Solution: change setup to allow constant gaseous argon purge (previously required turn off overnight for safety), and leave lamp on
  - Resulted in constant lamp intensity versus time



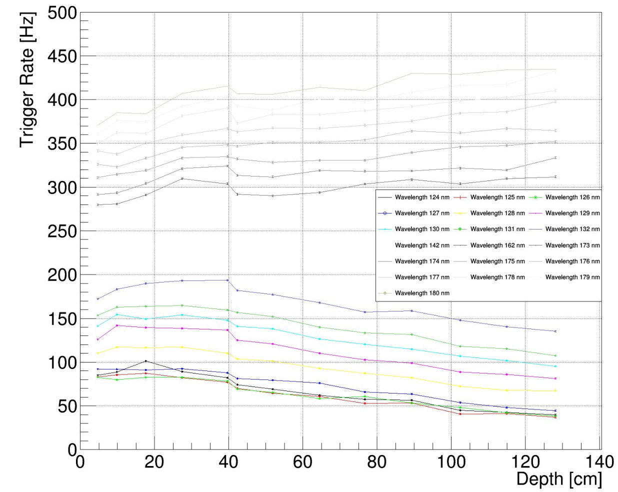
SiPM Signal Rate vs Time (Background Subtraction)

Run 3

- Analysis results are significantly improved due to lamp intensity stability, but still factors to be solved
- Incident due to pressure rupture disk failure overnight during run
  - No pressure control, forced cryostat to be opened to atmosphere
  - Pressure levels different from before incident, leading to possibly unusable data for lower LAr depths
    - Further investigation found impact of incident on data is likely small
  - Plot still displays turnover effect
    - Liquid argon temperature gradient → inconsistent SiPM gain
- Longer wavelengths follows positive (incorrect) slope
  - Scattering length may be too long to measure for setup, but that implies 0 slope and does not explain a positive correlation
    - Possible additional rate dependence on liquid level to understand and correct



128 nm Bottom SiPM Signal Rate vs Time



Bottom SiPM Signal Rate vs Time

Conclusions

- Waveform Measurement
  - Single trigger consistent with single photon detection
- Triplet Lifetime Measurement
  - Triplet lifetime consistent with high purity liquid argon
- Run 1
  - Initial measurement, understand behavior of unexpected effects
- Run 2
  - Implement new procedures to stabilize incident light intensity
- Run 3
  - Preliminary Rayleigh scattering length of 125.7+/- 22.37 cm for 128 nm wavelength

Future Work

- Exhaust other data analysis possibilities for data set
- Correct for SiPM gain difference between SiPM Channels

Acknowledgements

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DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT