WG6 Summary

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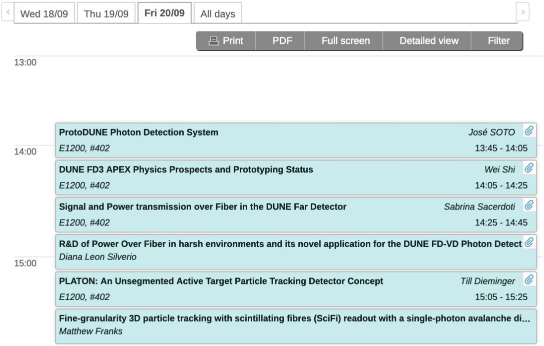
Overview

- We had a broad range of interesting topics in WG6, including various detector technologies, the status of prototyping efforts, and advanced analysis and calibration techniques



Liquid Argon TPC Prototyping

DUNE ND-LAr 2x2: Design and Status
Sindhujha Kumaran

Liquid argon Prototype Testing:

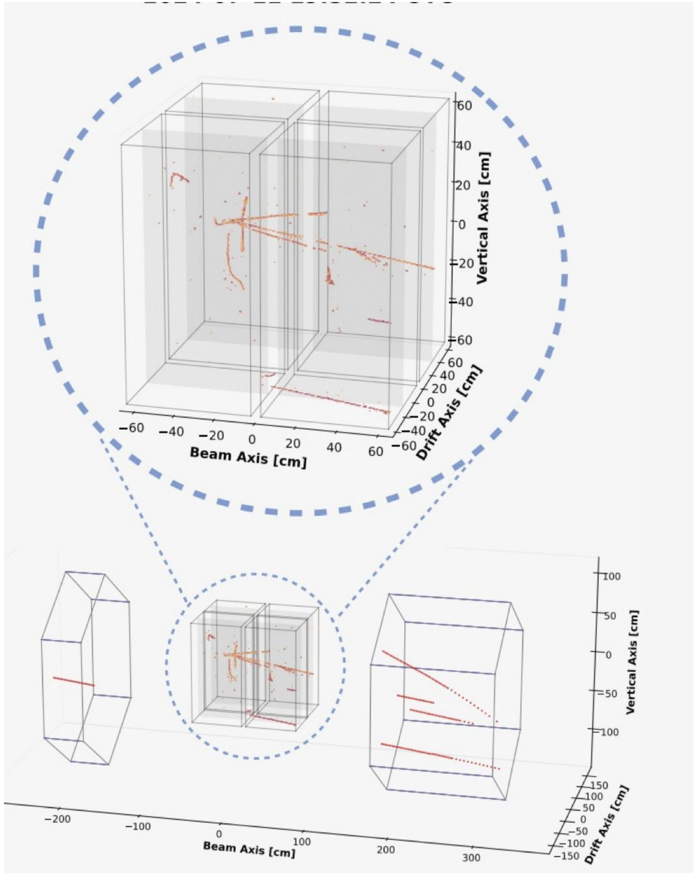
- The **2x2 prototype** is a scaled-down testbed for DUNE's liquid argon Near Detector system (ND-LAr)

Key Technologies:

- **Charge Readout**: Utilizes **pixelated readout system** with LArPix electronics.
- **Photon Detection**: Two novel SiPM-based light systems, **ArCLight** and **Light Collection Modules.**

Status:

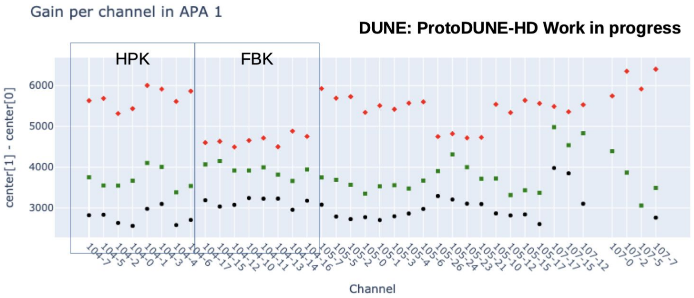
- **Prototype testing** at Fermilab's **NuMI beamline** in conjunction with the MINERvA muon tracker.
- Successful operation began in July 2024, collecting 10,000 neutrino interactions per day.

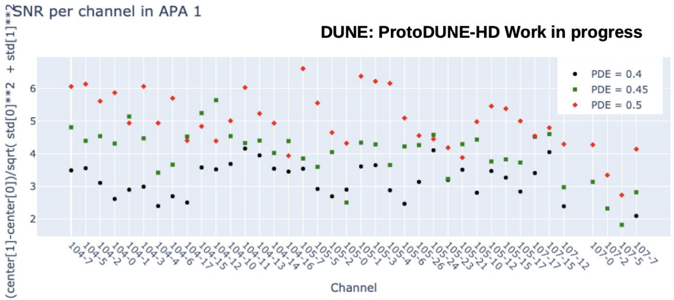


Liquid Argon TPC Prototyping

ProtoDUNE Photon Detection System
J. Soto-Oton

- **Photon Detection System (PDS)**:
  - Based on **XArapuca technology** with SiPM arrays (6x6 mm²) for light detection.
  - **Light yield requirements**: >20 PE/MeV, <100ns time resolution.
- **Detector Technologies being prototyped**:
  - **Vertical Drift (VD)**:
    - Two drift volumes of **6.5 m**.
    - 320 **XArapuca** PDS on the cathode, 352 on the cryostat walls.
  - **Horizontal Drift (HD)**:
    - Four drift volumes of **3.6 m**.
    - **Wire-based anode** with 6000 XArapuca devices.
- **Prototype Testing**:
  - **For HD: 30 million events** collected between June and September 2024, checked photon detection efficiency, voltage breakdown stability, gain calibration, light yield
  - **VD prototype** tests are on the way

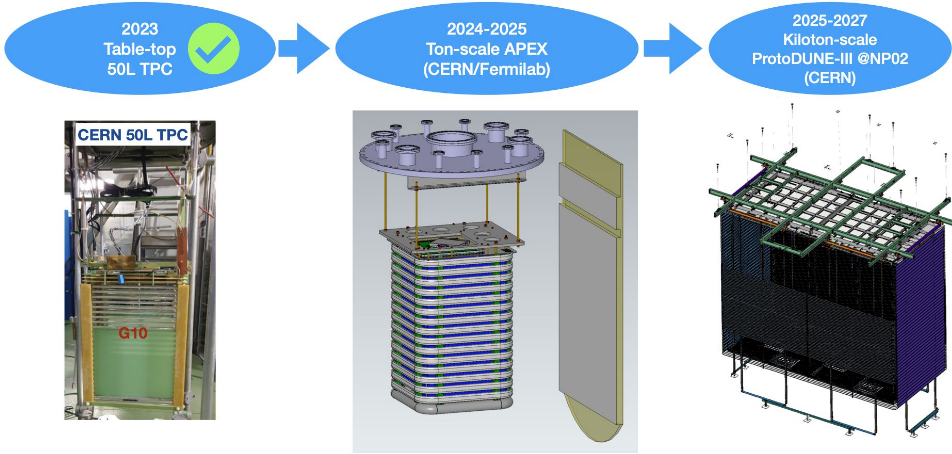




Liquid Argon TPC Prototyping

Photon Detection System for DUNE Phase II FD: Physics Prospects and Prototyping Status
Wei Shi

- DUNE Phase II will include **two additional Far Detector modules (FD3 & FD4) and a near detector upgrade to a high pressure gaseous argon TPC** to complete the core **CP violation** program of DUNE
- **FD3** will be based on Vertical Drift (VD) technology with **Aluminum Profiles with Embedded X-Arapucas (APEX)**:
  - Up to **2000% optical coverage** (10x FD2/VD coverage).
  - 7000 large photodetectors (50 cm x 50 cm), offering **avg. light yield** of **220 PE/MeV** (4x VD).
  - Utilizes **Power-over-Fiber (PoF)** technology for HV & cryogenics



- **Prototyping & Development**:
  - **APEX prototyping** is underway:
    - Table-top 50L TPC (2023), Ton-scale APEX (2024-2025 at CERN/Fermilab), & Kiloton-scale ProtoDUNE-III (2025-2027).
  - Ongoing R&D for **photon-collector, SiPM, optical coupling**, and **dual charge-light calorimetry**.
  - **Staged 2-ton APEX prototype** is being constructed at **CERN**, with initial tests in late 2024

Liquid Argon TPC Prototyping

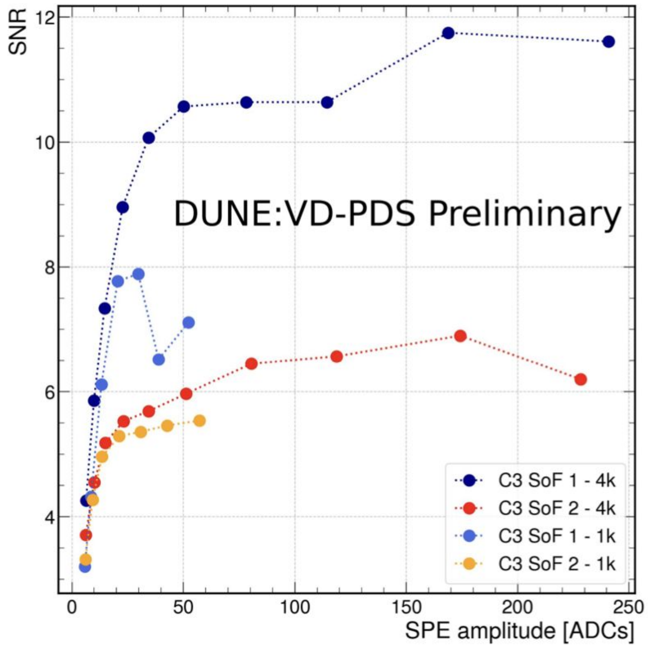
Signal and Power transmission over Fiber in the DUNE Far Detector
Sabrina Sacerdoti

Overview of Power-over-Fiber (PoF) and Signal-over-Fiber (SoF) technologies, which are used to transmit electrical power and data signals for the Photon Detection System (PDS) in FD-VD:

- Testing at the **CERN Coldbox**, real detector conditions (up to -30 kV bias)
- **Performance metrics**: achieved dynamic range of **1600-2000 PE**, with signal-to-noise ratio (SNR) ranging from 1 to 3 photoelectrons in calibration runs.

Conclusions:

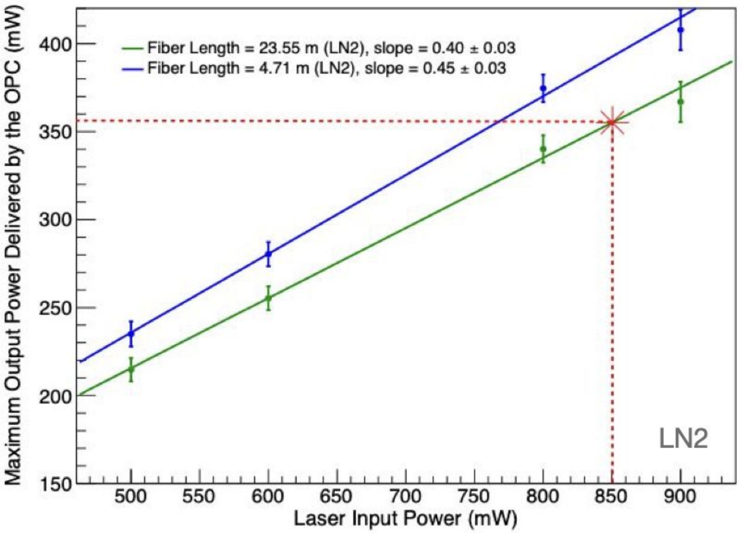
- Prototype successfully demonstrated the viability of power over fiber (**PoF) and signal over fiber (SoF) technologies in CERN cold box**
- Future improvements focus on optimizing the warm electronics stage with the **DAPHNE digitization module and testing in ProtoDUNE VD is underway**



Liquid Argon TPC Prototyping

R&D of Power Over Fiber in harsh environments and its novel application for the DUNE FD-VD Photon Detection System
Diana Leon Silverio

- **Additional report on the successful PoF testing**
  - Long-term power stability tests showed fluctuations <3% over extended periods.
  - The power stability tested over a long period, showed fluctuations of less than **3%** relative to the input power
  - The fibers underwent rigorous testing, including **thermal cycling** in **liquid nitrogen** to simulate the extreme temperature conditions of liquid argon (LAr).
  - Precise signal-to-noise ratios of **1 to 3 photoelectrons** in calibration runs
  - Fibers also passed **light leak tests** and **bending radius tests**, demonstrating their robustness in the Coldbox environment.
  - Validated the PoF system for **23-meter fiber lengths** in liquid argon.
- **Recent integration in ProtoDUNE-VD** (which is underway) and Coldbox prototypes at CERN, mark the first use of PoF for high-voltage cryogenic applications in particle physics.



Liquid Argon TPC Prototyping

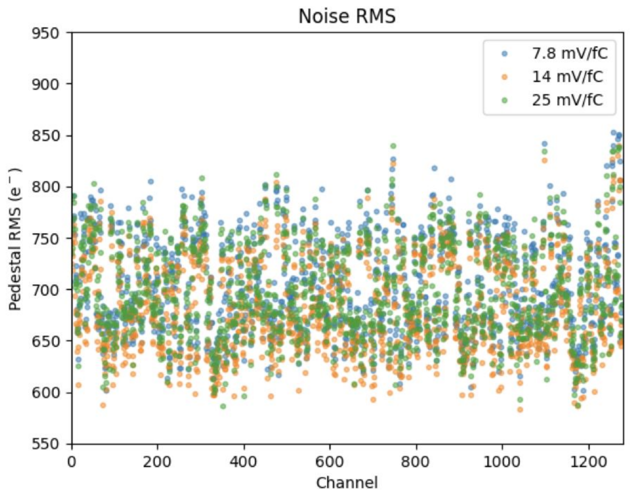
The ICEBERG Test Stand for DUNE Cold Electronics Development
Alejandro Yankelevich

Key Goals:

- Test and optimize the latest versions of DUNE's **cold electronics** (amplifiers, digitizers, and transmitters).
- Validate the **X-Arapuca photodetector** for VD under **Power-over-Fiber** mode at high voltages.
- Develop **AI-based calibration** methods using **39Ar decay** and **Michel electrons**.

Testing and Current Status::

- Successfully tested **Front-End Motherboards (FEMBs)** in **cryogenic conditions** (LN2).
- Calibration and noise data collected to optimize **signal-to-noise ratio** under various electronics settings (gain, voltage, etc.).
- **Cosmic data** and running noise and external pulse tests on-going
- Continuing development of **AI-based calibration** for real-time particle identification.
- Next testing phase planned for **Winter 2024**.



Additional Detector Technologies – JUNO

Design and status of the JUNO detector
Marco Beretta

Key Design Features:

- Central Detector: A **40 m diameter sphere** containing over **42,000 PMTs** and a 35.5 m acrylic sphere filled with **20,000 tons of liquid scintillator**.
- High optical coverage: **78%**, achieved with both large (20") and small (3") PMTs to ensure excellent energy resolution.

Construction Status:

- Stainless steel structure: **Completed**, with only 4 layers waiting for the acrylic.
- Acrylic layers: **17 out of 23** completed, with production achieving **<1 ppt U/Th/K contamination**.
- **More than 80% of PMTs installed**, and all tested and characterized.

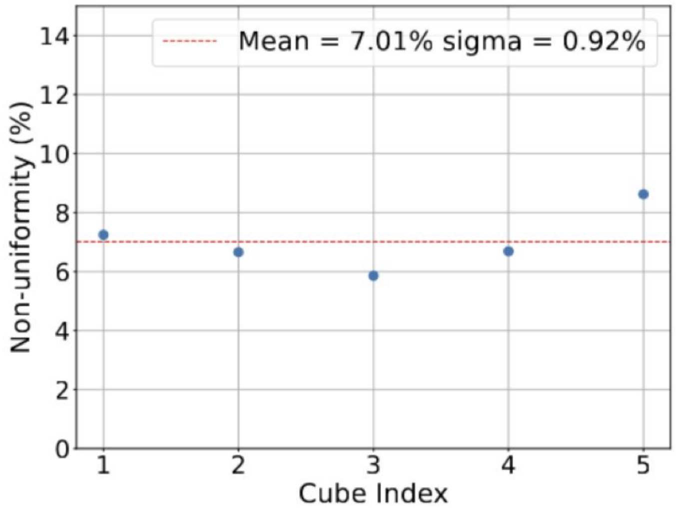
Purification and Filling:

- **Purification plants** for the liquid scintillator have been installed and commissioned.
- Water filling begins by end of 2024

Additional Detector Technologies – Manufacturing Scintillators

- **Key Developments in 3DET**:
  - **Proof of Concept**: 3D-printed polystyrene-based scintillator cubes showed high transparency and light output (~45 photoelectrons) with low cross-talk (<2%).
  - **Fused Injection Modeling (FIM)**: a novel method for injecting plastic scintillator into 3D-printed molds, achieving monolithic blocks of optically isolated cubes with embedded holes for wavelength-shifting fibers.
  - **Monolithic SuperCube**: produced with **5×5×5** scintillating cubes, showing **light yield uniformity** and confirmed performance in cosmic ray and beam tests.
- **Performance**:
  - **Crosstalk** ~ 4% and **light yield** ~ 28 p.e./cm for Minimum Ionizing Particles (MIP) detected in cosmic ray tests.
  - Successful beam tests at **CERN T9** confirmed cosmic ray data with a light yield variance of only 7% within a single cube.
- **Future Plans**:
  - Scale up the **SuperCube** to finer granularity (few-mm resolution).
  - Develop a **heat-resistant reflective filament** to further reduce light crosstalk.
  - Explore **3D printing sampling calorimeters** and optimize plastic scintillators for specific applications like neutron detection.

Additive Manufacturing of
3D-Segmented Plastic Scintillators
Umut KOSE



Additional Detector Technologies – T2K SuperFGD

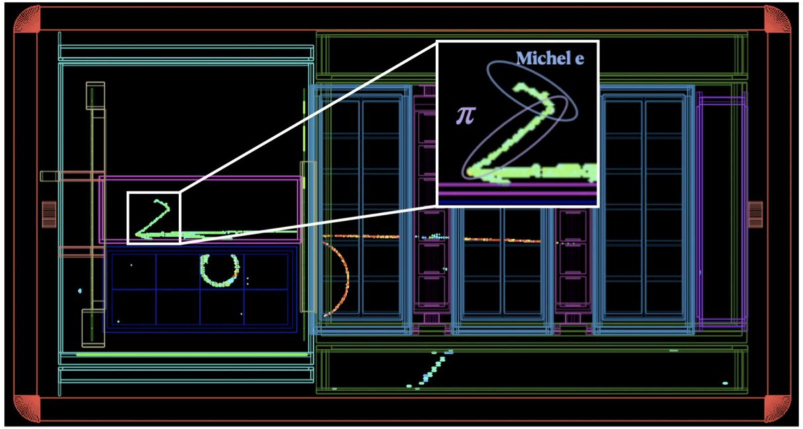
The SuperFGD for the T2K experiment
Tristan Doyle

SuperFGD Structure:

- Composed of **2 million 1 cm^3 scintillator cubes**, each connected by three orthogonal **wavelength-shifting fibers**.
- Each fiber is coupled to a **Multi-Pixel Photon Counter (MPPC)**, providing precise 3D tracking with high spatial resolution.

Prototype Performance:

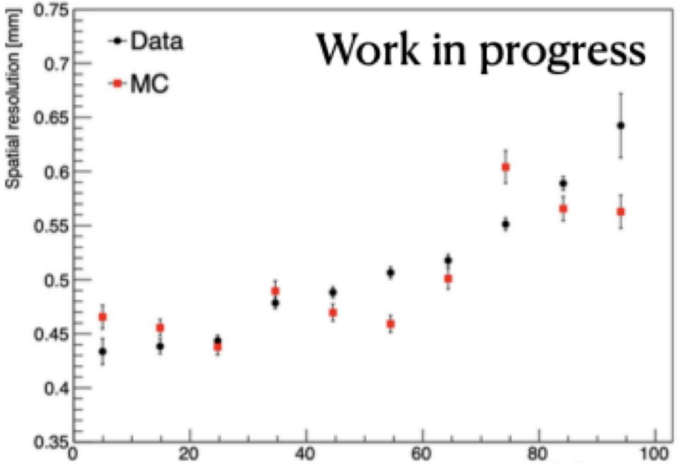
- **48×24×8 cm^3 prototype** exposed to particle beams at **CERN**:
  - Light yield: **58 photoelectrons (PE) per Minimum Ionizing Particle (MIP)**.
  - Time resolution: **1.1 ns per channel**.
  - **3% cross-talk**, confirming good isolation between channels.
- **LANL Neutron Beam Test**:
  - SuperFGD demonstrated its capability to measure **neutron kinematics**.
- **Current Status:**
  - Cubes were assembled into **56 layers** using fishing lines, a labor-intensive process that took **~20 months**.
  - Final assembly at **J-PARC** included fiber insertion, MPPCs, and the installation of the **LED calibration system**.



Additional Detector Technologies – T2K High Angle TPCs

- **Key Features**:
  - **High Angle Time Projection Chamber (HATPC)** to extend the angular acceptance for neutrino events
  - **Atmospheric pressure TPC** with a drift length of 1 meter.
    - Uses resistive MicroMegas (ERAM) sensors for charge readout.
    - **Charge Readout**: ERAM sensors provide high spatial resolution (~400 μm) and prevent charge build-up, reducing the risk of sparks.
- **Production and Testing**:
  - **Field Cage Construction**: Precision-built at NEXUS (Barcelona) and assembled/tested at CERN.
  - **ERAM Production**: Approximately 50 detectors produced and characterized, with detailed response models developed through X-ray testing.
  - **Performance**: Achieved momentum resolution of <9% at 1 GeV/c, with a spatial resolution of ~500 μm for 3D tracking.
- **Current Status**:
  - First HATPC installed and tested with cosmic rays, commissioning with neutrino beam at **J-PARC** ongoing in 2024.
  - Final design and improvements for field cages and resistive layers are set for stable and efficient operations.

Technical challenges for the new T2K High Angle TPCs
Samira Hassani



Additional Detector Technologies – PLATON

Key Features:

- Uses **scintillation photons** and **stereoscopic imaging** to reconstruct particle tracks.
- Prototype: First SPAD-based plenoptic camera developed by **SwissSPAD2** with **Raytrix software** for image reconstruction.

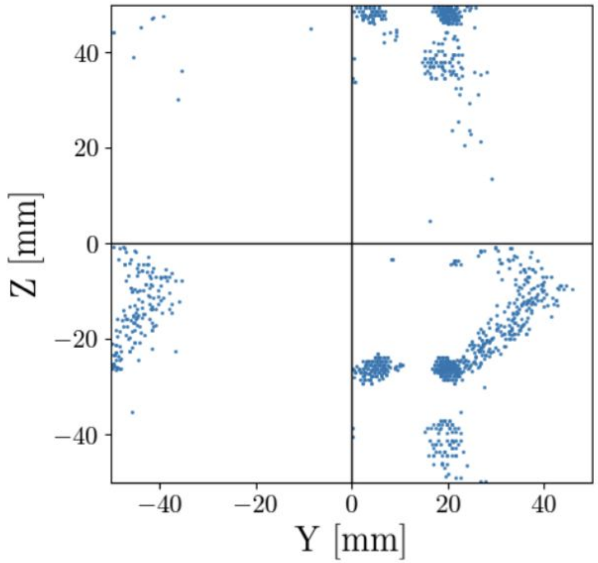
Performance:

- Achieved lateral resolution of **~100 µm** and **3 mm depth** resolution in tests using a 5-axis stage.
- **Simulations** using **NEUT neutrino generator** and **Geant4** for particle propagation.
- Data-driven reconstruction using **neural networks**, achieving sub-mm particle tracking.

Future Developments:

- **Single Photon Avalanche Diode (SPAD) array optimization** for higher **Photon Detection Efficiency (PDE)** and lower noise.
- Development of custom **SPAD chips** in collaboration with EPFL for improved performance in neutrino detection.

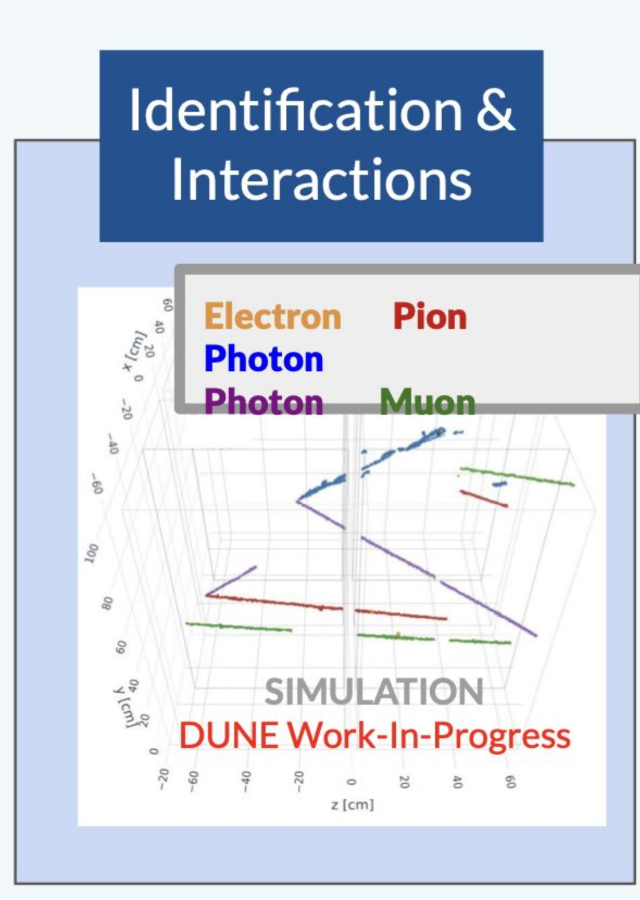
PLATON: An unsegmented active target tracking detector
Till Dieminger



Analysis Techniques – Mitigating Pile up

Machine Learning Reconstruction for DUNE's Near Detector Prototype: Handling Multi-Detector Input to Identify 3D Particle Signatures
Jessie Micallef

- **Machine learning in Liquid argon TPCs:**
  - **Benefits the future near detector (ND-LAr) in DUNE** which includes 2D pixel planes for **3D event reconstruction**
  - Utilizes **GrapPA** (Graph Neural Network) and **UResNet** architectures for 3D pixel readouts.
  - SPINE extracts **pixel-level features** such as **charge deposition**, **track start/end points**, and particle types (e.g., muons, electrons, showers).
  - Handles high beam intensity (~55 neutrino interactions/spill) with ns-scale time resolution and **optically segmented TPCs** & mitigates pileup
  - Tests of the algorithm to be carried out on the ND-LAr 2x2 prototype data



Analysis Techniques – Insights into Cosmic Variation Data

Cosmic muons are a significant background in neutrino experiments, and seasonal variations in cosmic muon flux expected to be influenced by atmospheric temperature.

Previous Studies: Experiments like MACRO, IceCube, and MINOS showed seasonal variation in muon flux. MINOS specifically showed maximum rate in winter and minimum rate in summer. NOvA verified and expanded on MINOS' findings.

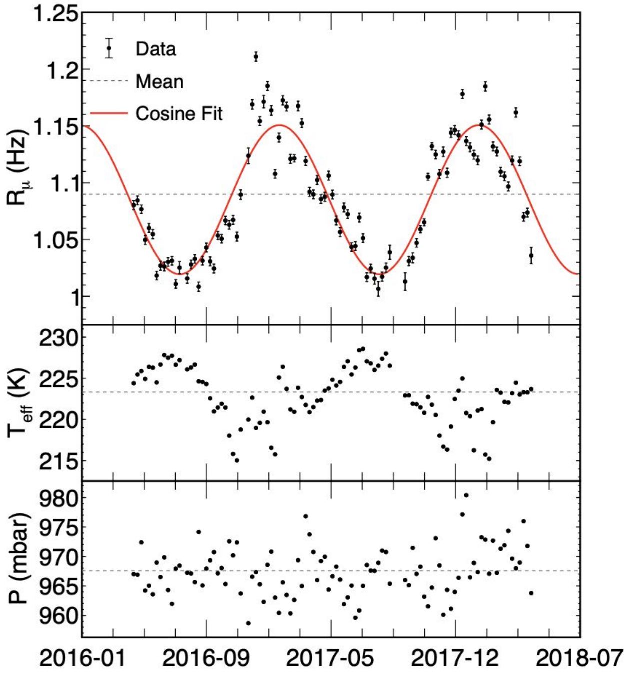
NOvA Detectors:

- **Near Detector (ND):** 100m underground, measures cosmic rays and neutrino oscillations.
- **Far Detector (FD):** Surface detector with a high muon detection rate.

Findings:

- NOvA data supports seasonal muon rate variation, confirming earlier MINOS results.

Seasonal Variation in Cosmic Muon Rate at the NOvA Experiment
Amit Pal



Analysis Techniques – Improving Energy Estimation

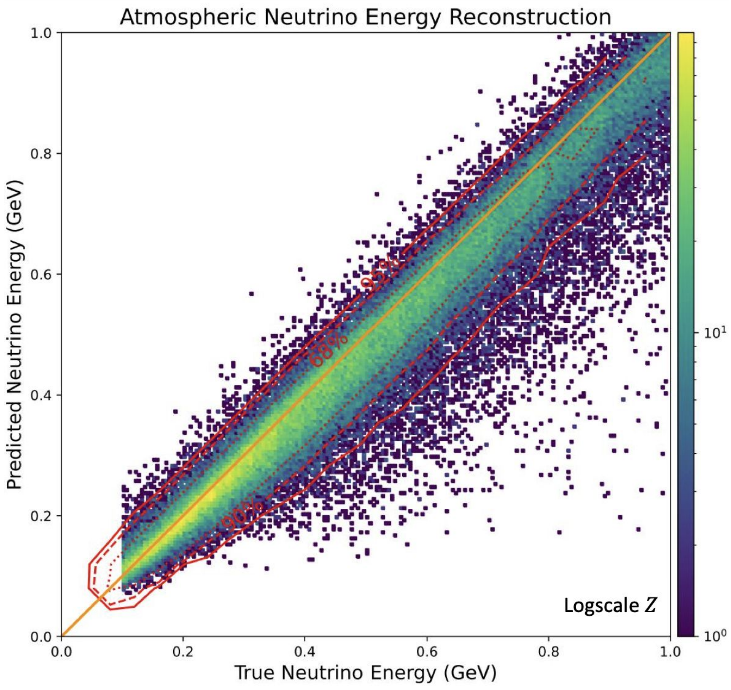
Enforcing Self-Consistent Kinematic Constraints in Neutrino Energy Estimators Using GENIE Atmospheric Events
J. L. Barrow

Key Insights:

- Traditional energy estimators often focus on reconstructing energy without considering kinematic/angular constraints.
- By enforcing consistency between energy and angle predictions, can reduce error and improve event reconstruction.

Method:

- Utilize composite, multivariate loss functions for machine learning (ML) estimators, optimizing both energy and angular variables
- Implement **Physics-Informed Machine Learning (PIML)**, ensuring that the ML models account for physical principles such as momentum conservation.
- Initial training shows promising results, with improved energy estimation and reduced angular inconsistency.
- Experiments using **GENIE atmospheric neutrino samples** have demonstrated successful application of these techniques.



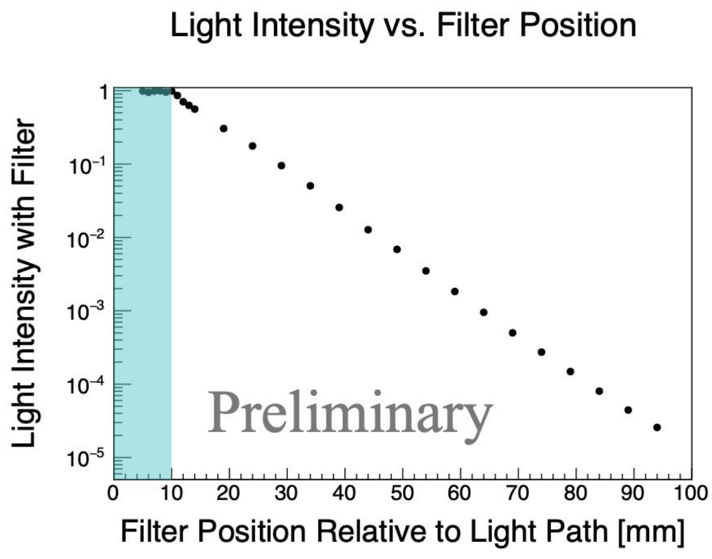
Calibration Techniques – JUNO Calibration

Detector calibration in the JUNO experiment
Akira Takenaka

- **Gamma-ray sources** are deployed to correct the non-linearity of the liquid scintillator.
- **Cosmogenic products** cover the higher energy regions for calibration.

Calibration Systems:

- **Automatic Calibration Unit (ACU)**: Covers the central axis.
- **Cable Loop System (CLS)**: Covers the off-axis region in a two-dimensional plane.
- **Guide Tube Calibration System (GTCS)**: Deploys sources along the outer surface of the acrylic sphere.
- **Remotely Operated Vehicle (ROV)**: Provides 3D calibration across the LS volume.
- **UV laser device** delivers photons into the LS, with a diffuser ball placed by the ACU.
- The system allows for tuning light intensity over a range of **4 orders of magnitude**, calibrating the 20-inch PMTs.



Calibration Techniques – Liquid Argon TPC MeV-capability

Tagging Neutron Capture on Argon for Light Calorimetry Calibration and MeV Physics
Wei Shi

Neutron Capture for Calibration:

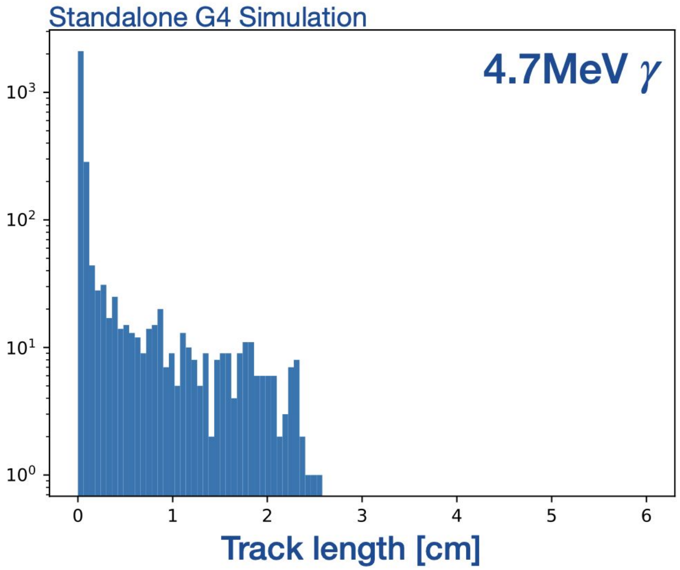
- Neutron capture on **argon-40 (40Ar)** provides a reliable **calibration source** due to its fixed **6.1 MeV energy cascade**.
- Calibration of the DUNE **Photon Detection System (PDS)** helps create a light yield map for **MeV energy reconstruction**.

Calibration Approach:

- **Pulsed Neutron Source (PNS)**: Used in the **CERN ColdBox** to demonstrate light calibration with **neutron capture**.
- **Light Yield Map** developed through neutron capture events
- Simulations show **sub-millimeter particle tracking** and improved energy resolution.

Results and Future Work:

- Successful first physics run of PNS at **VD ColdBox**, ongoing **charge-light matching** expected to further improve background rejection.



Calibration Techniques – Liquid Argon TPC MeV-capability

New MeV-scale capabilities in the MicroBooNE liquid argon time projection chamber
Will Foreman

MeV-Scale Sensitivity Explored in MicroBooNE:

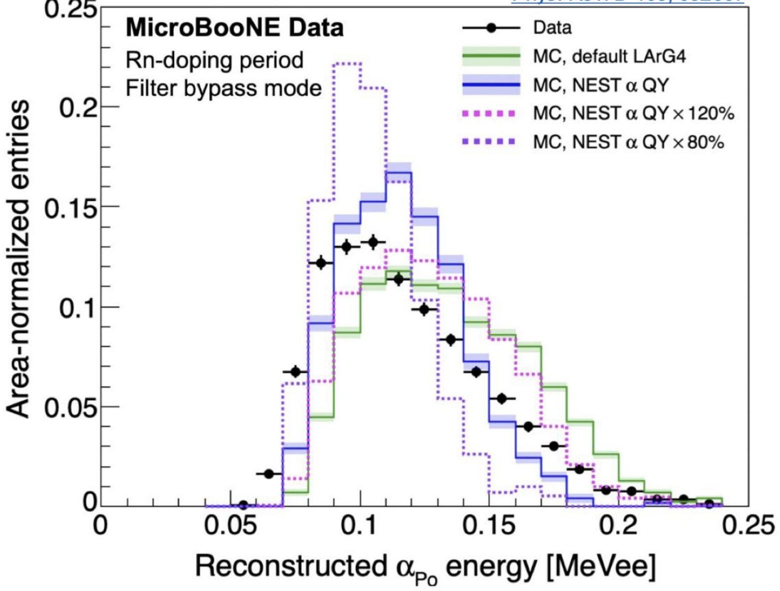
- **Blip detection** (0.1–1 MeV) important for capturing information from **Compton-scattered gamma rays** and **neutron inelastic collisions**, often missed by high-energy reconstruction algorithms.
- Important for sensitivity to **neutron kinematics** and better event identification at the **MeV scale**.

Calibration with Radon:

- A special R&D run introduced **radon into the LAr circulation**, allowing for the tagging of **214Bi → 214Po decays**.
- Enhanced detection algorithms able identify the corresponding **MeV blips** and isolate them from background noise.

MicroBooNE's MeV-scale sensitivity improvements will aid future LArTPC experiments (e.g., DUNE) in better handling **low-energy neutrino interactions** and rare signal searches.

Phys. Rev. D 109, 052007



Calibration Techniques – Mean Excitation Energy in LAr

Motivation:

- Accurate mean excitation energy (I-value) measurements crucial for optimizing simulations of energy loss in **LArTPCs**, directly impacting particle tracking, calorimetry, and event reconstruction in large-scale liquid argon neutrino detectors.

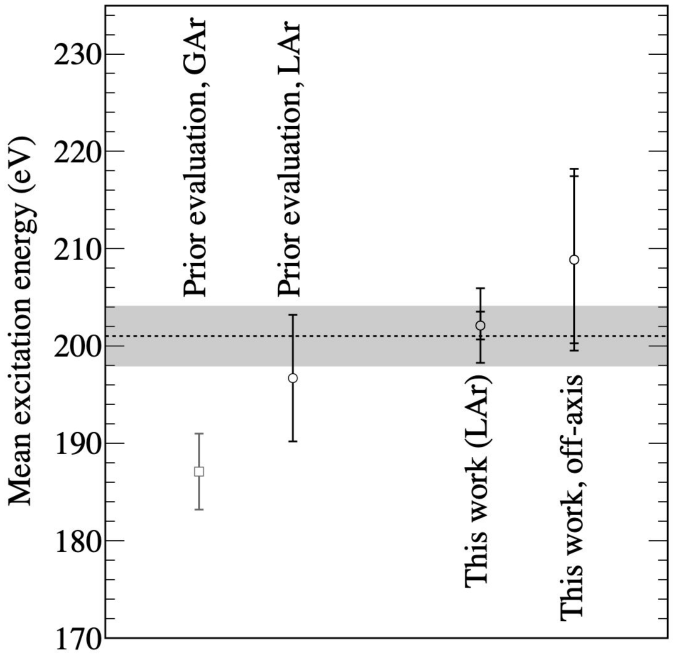
Key Findings:

- **Measured I-value**, set up was in Irradiation Test Area at Fermilab: 187 eV for liquid argon, consistent with prior evaluations (e.g., ICRU 90).
- **Comparisons**: Results align with theoretical models (Bethe, Andersen-Ziegler) with slight deviations observed in comparisons to gaseous argon data.
- **Reduced uncertainties**: Achieved improved precision in I-value measurements.

Significance:

- Results enhance models for **ionization energy loss** in LAr detectors.
- Direct applications for improved particle identification and tracking in neutrino experiments.
- Supports design optimization in detectors for future neutrino and rare event searches.

Measurement of the Mean Excitation Energy of Liquid Argon
Matthew Strait



Calibration Techniques – Improving Energy Estimation in LAr

Ensure accurate energy reconstruction for neutrino events in the **DUNE Far Detector (FD)** using **Liquid Argon Time Projection Chambers (LArTPCs)**.

Energy reconstruction and calibration techniques of the DUNE LArTPC
Praveen Kumar

Key Calibration Sources:

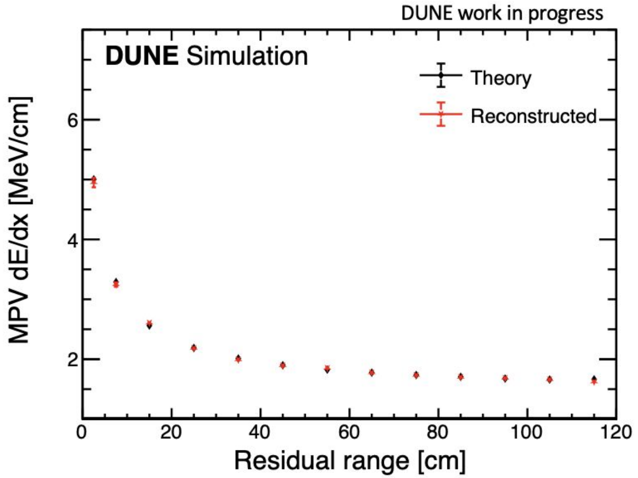
- **Cosmic muons**: ~90 stopping muons per day per module, used to calibrate energy deposition (dE/dx).
- **Neutrino beam events**: For calibrating energy response over a wide range of energy scales.
- **Radioactive sources**: Provide precise, standardized energy deposition for calibration.

Calibration Methods:

- **Stopping muons**: Used as a standard for measuring energy deposition with low uncertainty, leveraging the **Landau-Vavilov theory**.
- **dE/dx calibration**: Converts ionization charge (dQ/dx) to energy deposition (dE/dx) using models like the **modified box model** and **absolute energy scale**.

Results:

- Good agreement between **theoretical predictions** and **reconstructed dE/dx** for stopping muons, pions, and protons, especially in high residual range.



Calibration Techniques – NOvA Test Beam

Electromagnetic Response Studies in the NOvA Test Beam
Dalton Myers

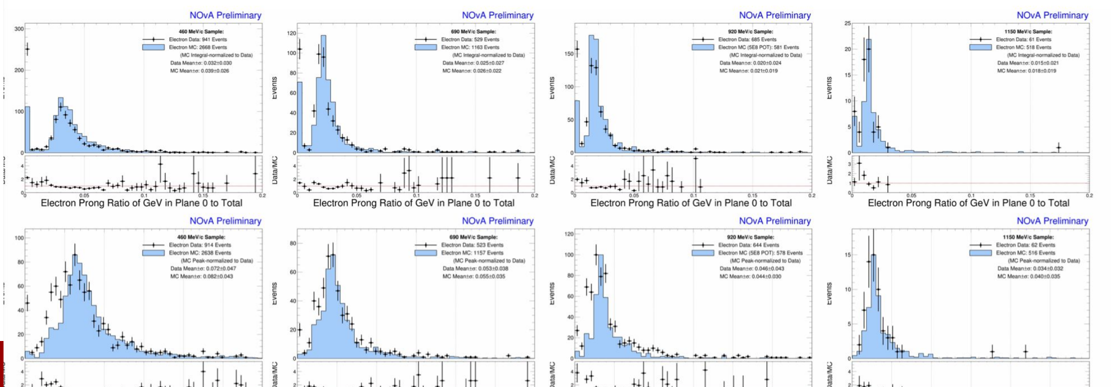
Improve understanding of systematic uncertainties and detector calibration for the **NOvA Near and Far Detectors** with Fermilab Test Beam Facility using (p, K±, e±, μ±, π±) in the **0.2–2 GeV** range

Electromagnetic Energy Response:

- Calorimetric response of the NOvA hardware associated with beamline momentum measurements.
- Studied using different magnet current settings (500A, 750A, 1000A, 1250A) to reconstruct the electron energy spectrum.

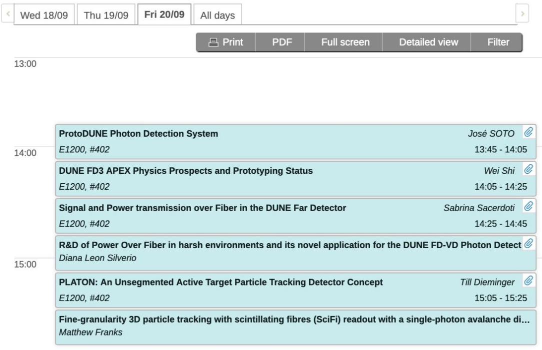
Beamline Energy Loss:

- Simulations showed electrons lose energy via **matter interactions**, primarily radiative losses in **ToF modules**.
- Classified events based on energy loss for further analysis.
- Investigated topological event properties (e.g., prong length, number of hits) to improve event selection.



In Summary

- We had a broad range of interesting topics in WG6, including various detector technologies, the status of prototyping efforts, and advanced analysis and calibration techniques – **many thanks to NuFact24 organizing committee for making this possible!**
- Please feel free to check out the link to the four sessions and the slides of all the speakers: https://indico.fnal.gov/event/63406/sessions/25383/#20240918



Thank you!