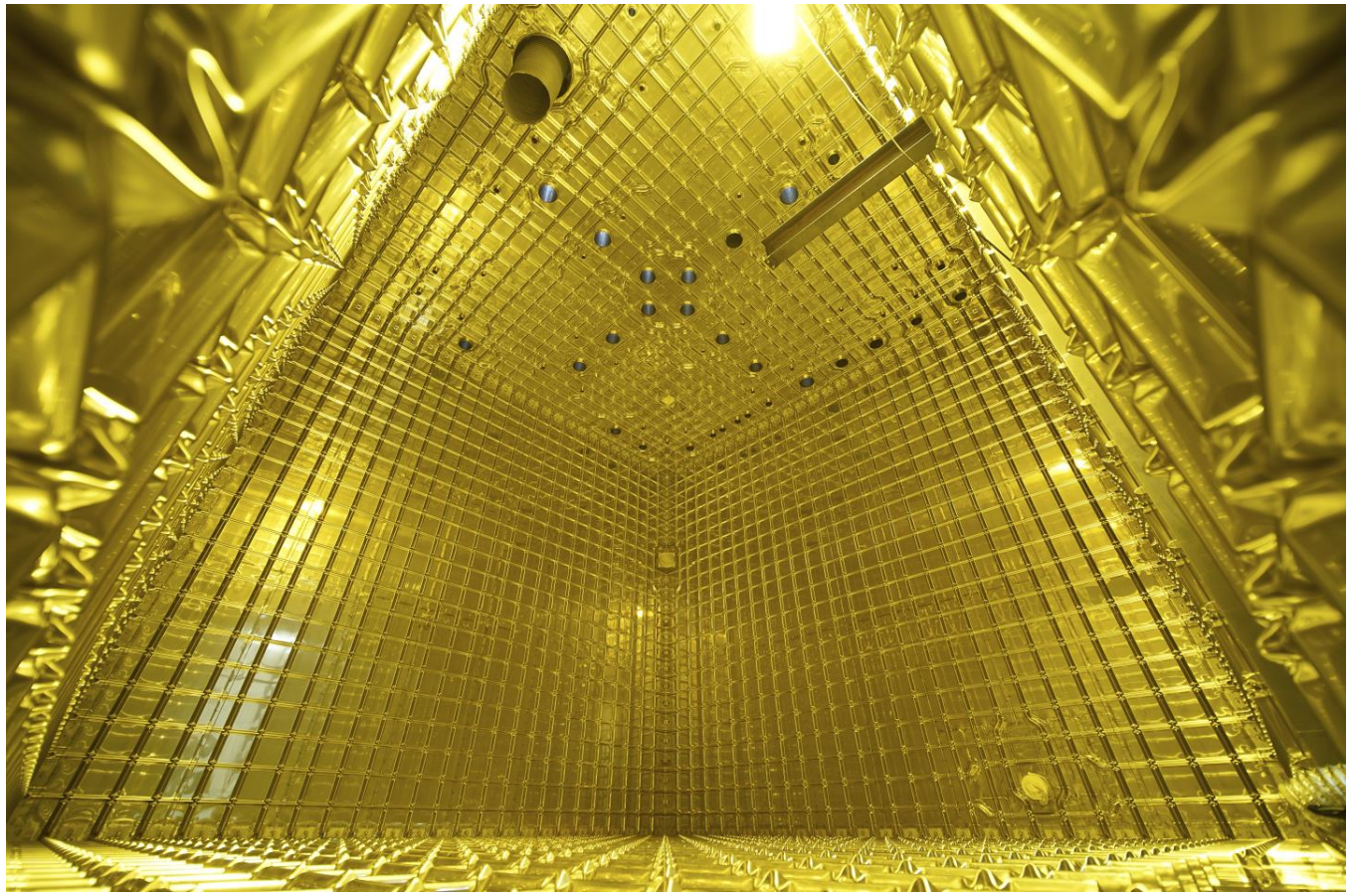
Modifying Machine Learning Algorithms For Improved Tau Neutrino Sensitivity

For The DUNE Detector

Prototype Liquid-Argon Time-Projection Chamber for the DUNE experiment. (Image: CERN)



Prince Bhaura

March 27th, 2024

Physics Research Project Oral Evaluation

Supervisors: Prof. Nikolina Ilic & William Dallaway

Physics
UNIVERSITY OF TORONTO

Contents

Physics
UNIVERSITY OF TORONTO

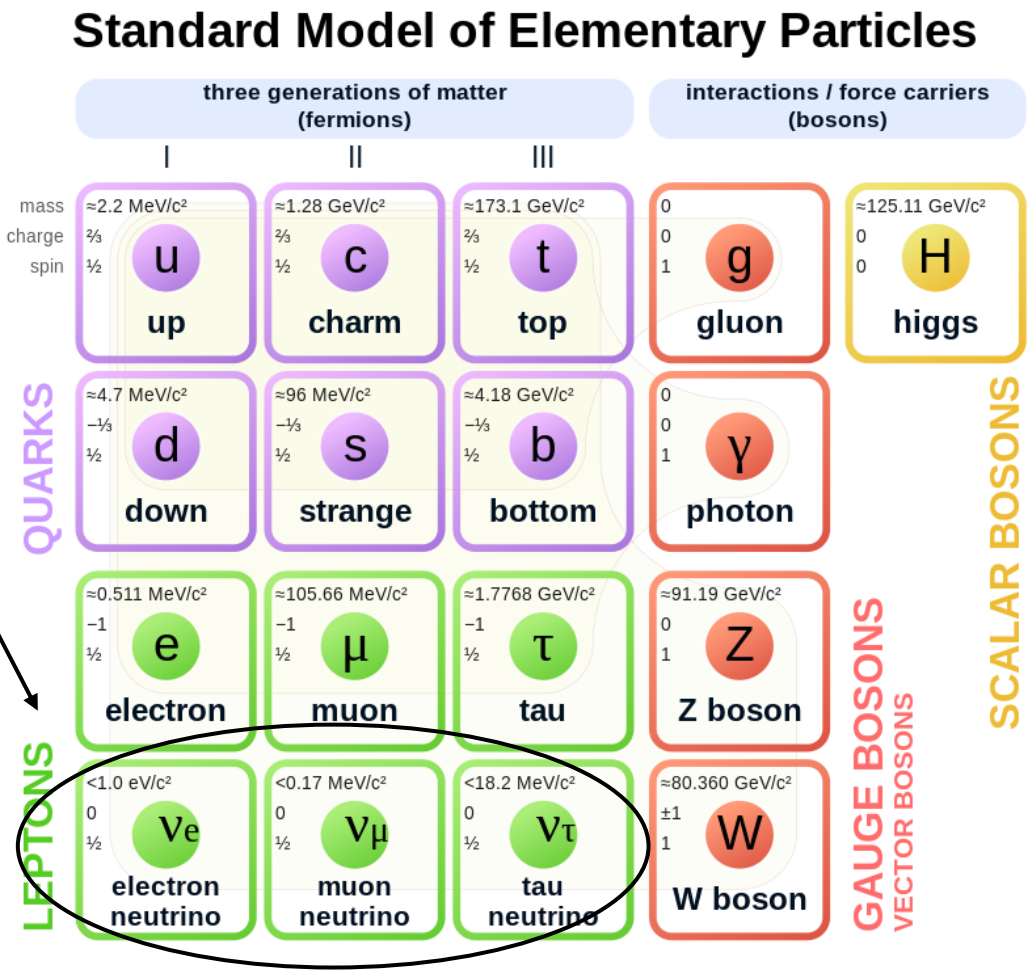
Contents

Physics
UNIVERSITY OF TORONTO

Neutrino Physics

Physics
UNIVERSITY OF TORONTO

- Neutrinos are neutral leptons, which means **we do not observe them directly**

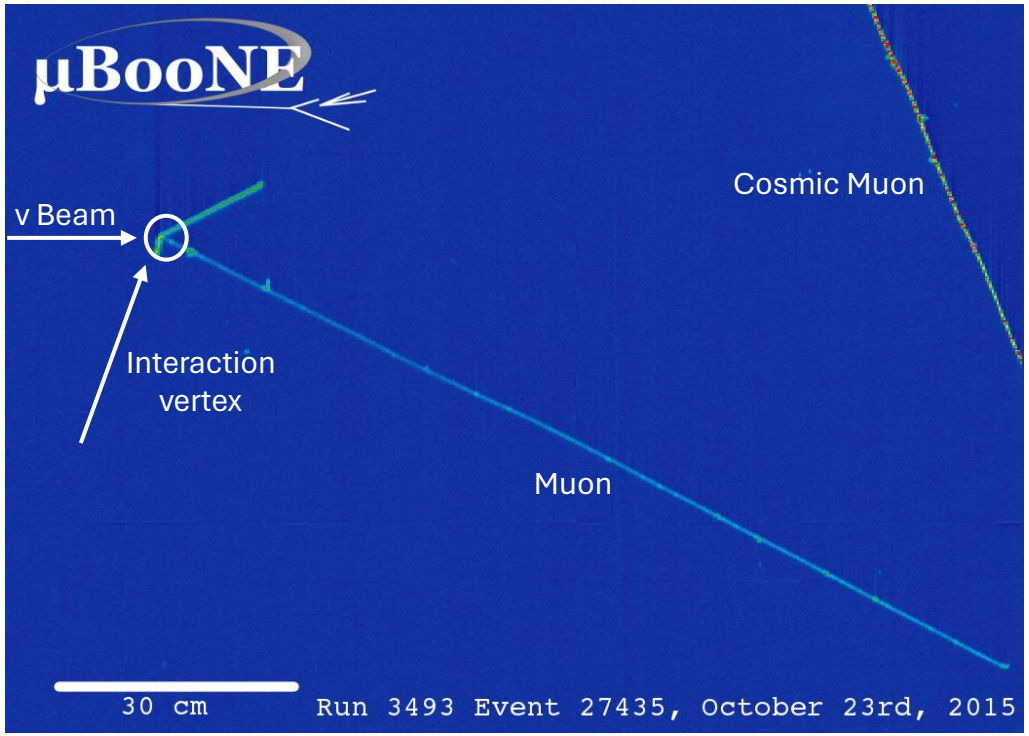


The Standard Model of Particle Physics. (Image: Wikipedia)

Neutrino Physics

Physics
UNIVERSITY OF TORONTO

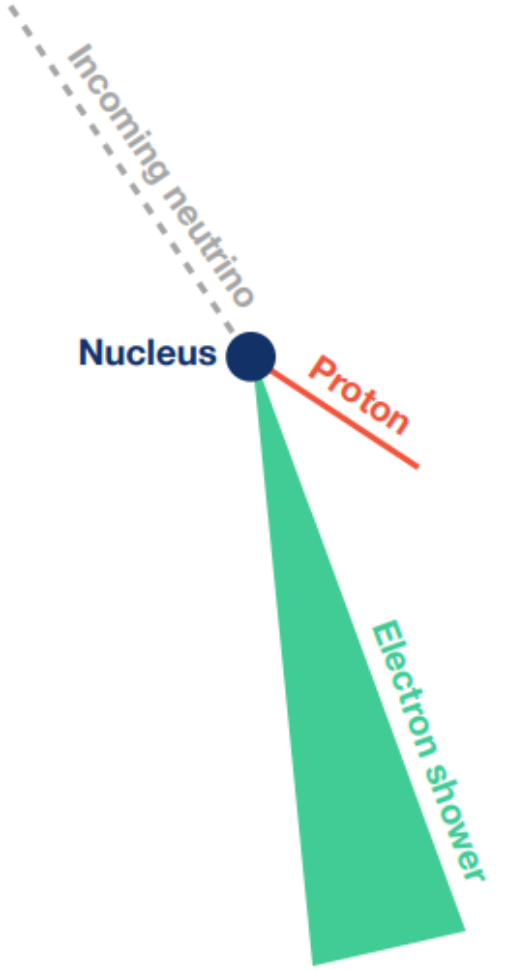
- Neutrinos are neutral leptons, which means **we do not observe them directly**
  - Instead, we search for **visible particles** that are **produced when they interact**



Neutrino Interaction Event Display from the MicroBooNE Detector. (Image: MicroBooNE)

Axes: Time vs Wire

Colour Scale: Charge



Simplified Neutrino Interaction with a Nucleus. (Image: V Hewes)

Contents

Physics
UNIVERSITY OF TORONTO

1. Neutrino Physics
2. Liquid Argon Time Projection Chambers (TPCs) – DUNE
3. Existing Neural Network (NN) Architecture
4. Modifications To Architecture
5. Result & Future Work

Liquid Argon TPCs

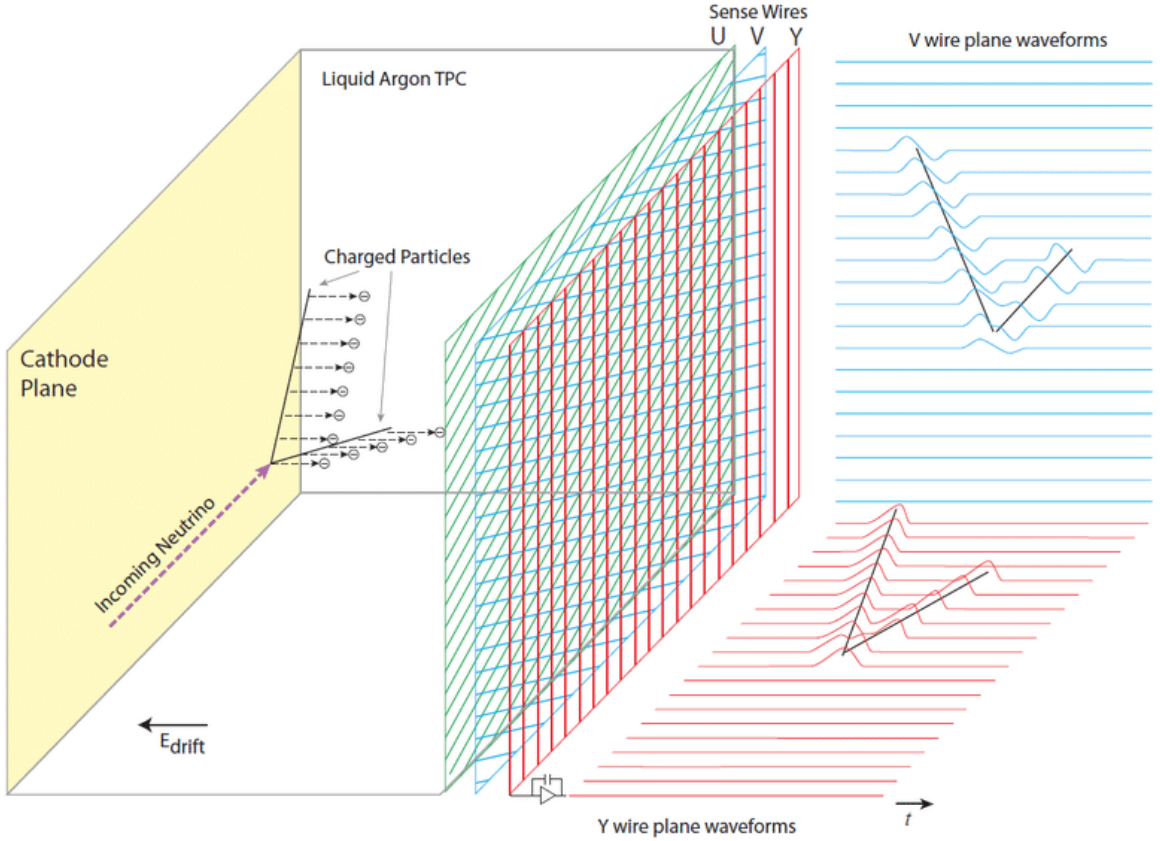
Physics
UNIVERSITY OF TORONTO

- Active Medium: Liquid Argon
  - When **charged particles traverse** through, they **ionize the argon** creating free electrons

Liquid Argon TPCs

Physics
UNIVERSITY OF TORONTO

- Active Medium: Liquid Argon
  - When **charged particles traverse** through, they **ionize the argon** creating free electrons
- Electric Field **drifts** free electrons towards wire planes

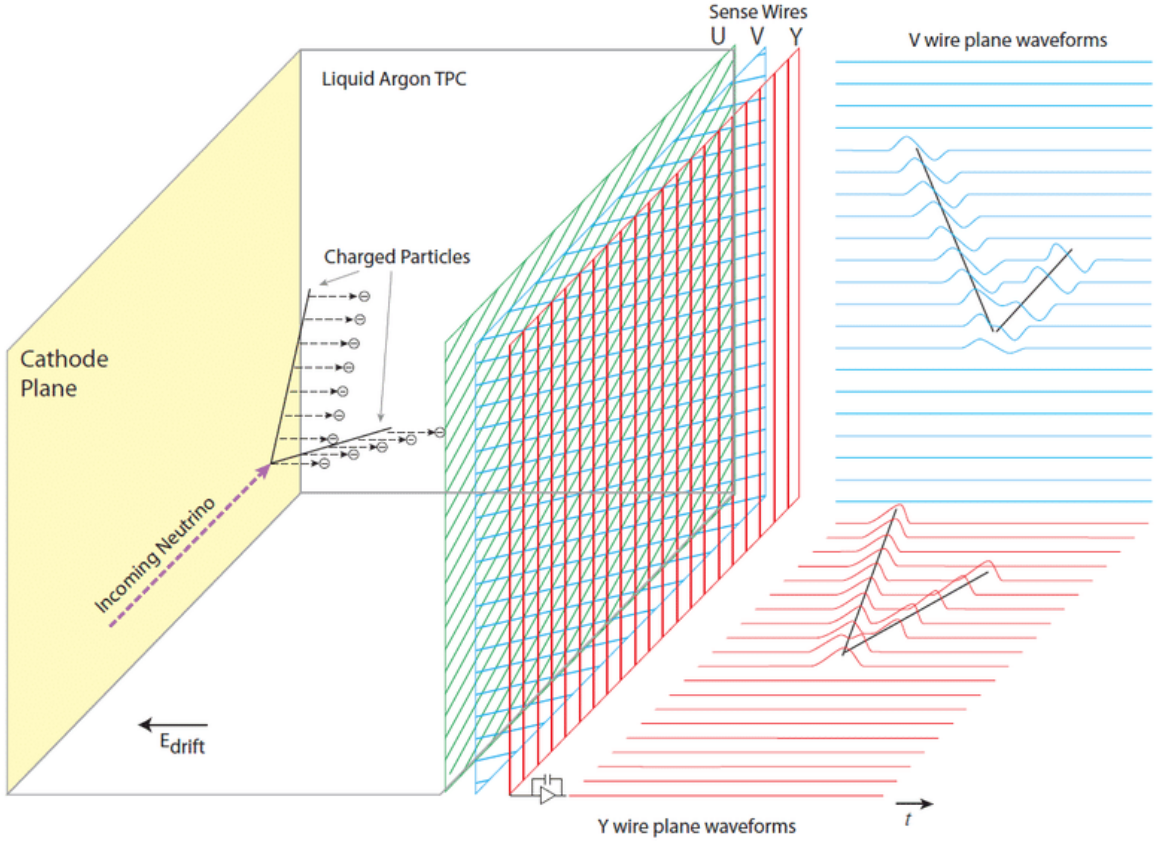


Single Phase Liquid Argon TPC Detector Setup. (Image: R. Acciarri et al 2017 JINST 12 P02017)

Liquid Argon TPCs

Physics
UNIVERSITY OF TORONTO

- Active Medium: Liquid Argon
  - When **charged particles traverse** through, they **ionize the argon** creating free electrons
- Electric Field **drifts** free electrons towards wire planes
- Free electrons **induce signal** on wires
  - Multiple wire planes allow for 3D reco.

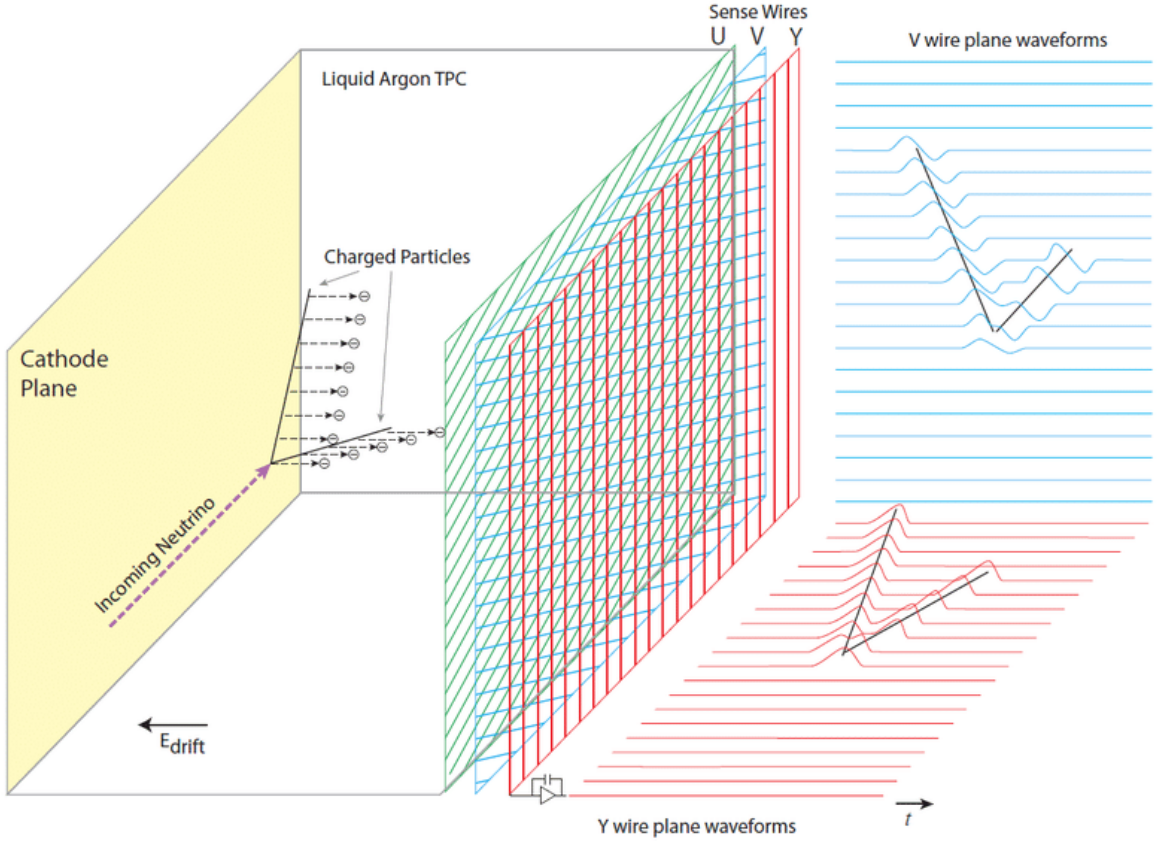


Single Phase Liquid Argon TPC Detector Setup. (Image: R. Acciarri et al 2017 JINST 12 P02017)

Liquid Argon TPCs

Physics
UNIVERSITY OF TORONTO

- Active Medium: Liquid Argon
  - When **charged particles traverse** through, they **ionize the argon** creating free electrons
- Electric Field **drifts** free electrons towards wire planes
- Free electrons **induce signal** on wires
  - Multiple wire planes allow for 3D reco.
- “Time Projection”: Time reco. for ionization events

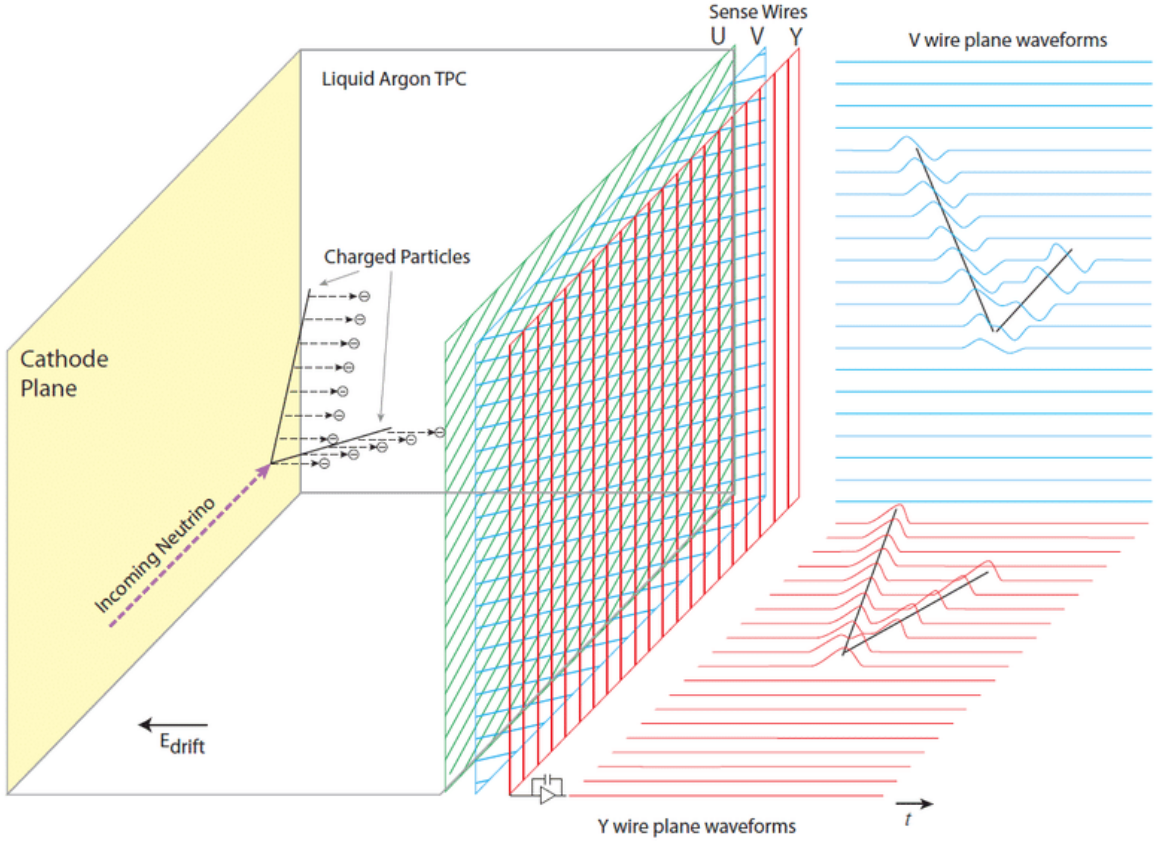


Single Phase Liquid Argon TPC Detector Setup. (Image: R. Acciarri et al 2017 JINST 12 P02017)

Liquid Argon TPCs

Physics
UNIVERSITY OF TORONTO

- Active Medium: Liquid Argon
  - When **charged particles traverse** through, they **ionize the argon** creating free electrons
- Electric Field **drifts** free electrons towards wire planes
- Free electrons **induce signal** on wires
  - Multiple wire planes allow for 3D reco.
- “Time Projection”: Time reco. for ionization events
- Excellent choice for Neutrino and DM interactions

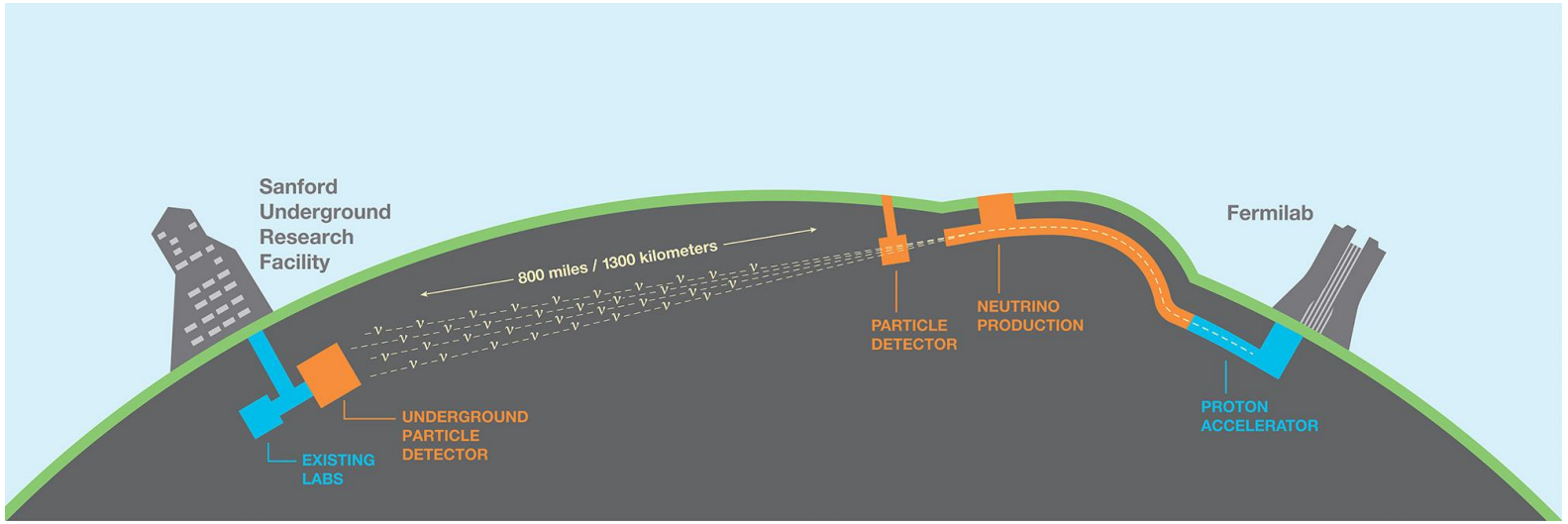


Single Phase Liquid Argon TPC Detector Setup. (Image: R. Acciarri et al 2017 JINST 12 P02017)

Liquid Argon TPCs – DUNE

Physics
UNIVERSITY OF TORONTO

- **Purpose:** Study Various Aspects of Neutrino Physics
  - Neutrino Oscillations (Neutrino Flavour Change Over Distance) ★
  - Neutrino Interactions
  - Proton Decay

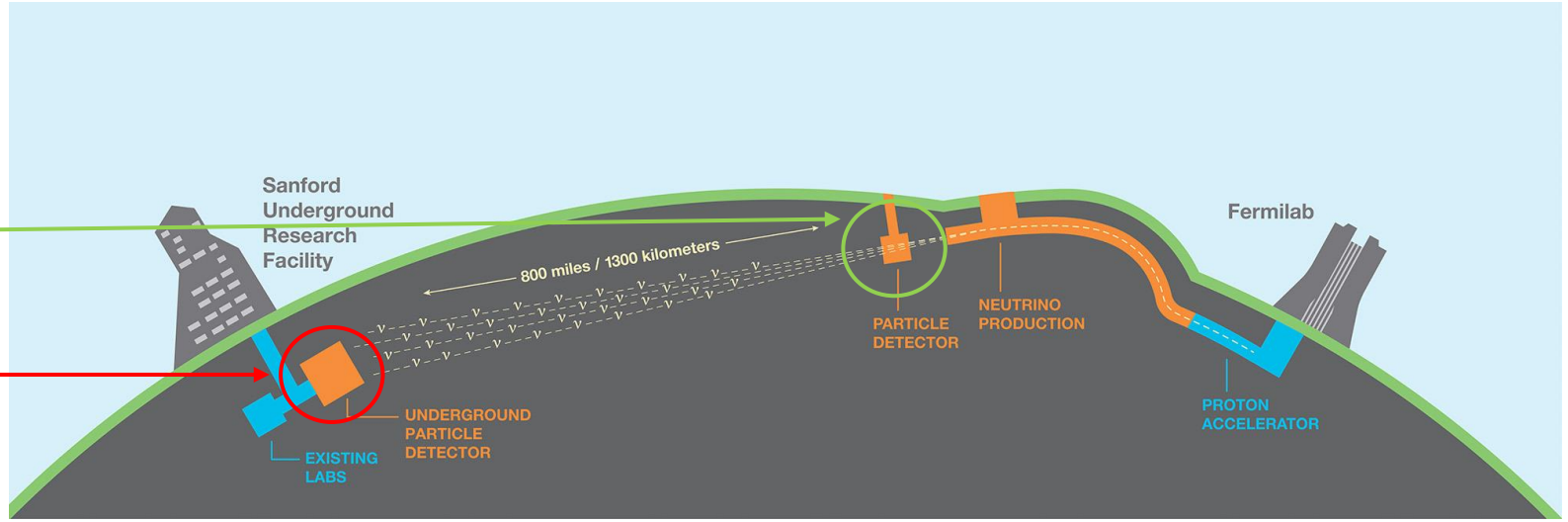


Configuration of the Long Baseline Neutrino Facility at Fermilab, and the Dune Detectors in Illinois and South Dakota. (Image: dunescience.org)

Liquid Argon TPCs – DUNE

Physics
UNIVERSITY OF TORONTO

- 3 Central Elements
  - **Far Detector**: Located 1.5km Underground at SURF, South Dakota
  - **Near Detector**: Located Just Ahead of Neutrino Source at Fermilab, Illinois
  - **Long Baseline Neutrino Facility**: Provides Beamline and Civil Construction for Both Detectors



Configuration of the Long Baseline Neutrino Facility at Fermilab, and the Dune Detectors in Illinois and South Dakota. (Image: dunescience.org)

Liquid Argon TPCs – DUNE

Physics
UNIVERSITY OF TORONTO

- 3 Central Elements
  - **Far Detector**: Located 1.5km Underground at SURF, South Dakota
  - **Near Detector**: Located Just Ahead of Neutrino Source at Fermilab, Illinois
  - **Long Baseline Neutrino Facility**: Provides Beamline and Civil Construction for Both Detectors

- Near Detector (ND) Serves as the Experiments Control (+ More)
  - Constraining Systematic Errors
  - Will Have Its Own Physics Program
  - Made Up of 3 Parts: HPgTPC, ECAL, LArTPC, and SAND

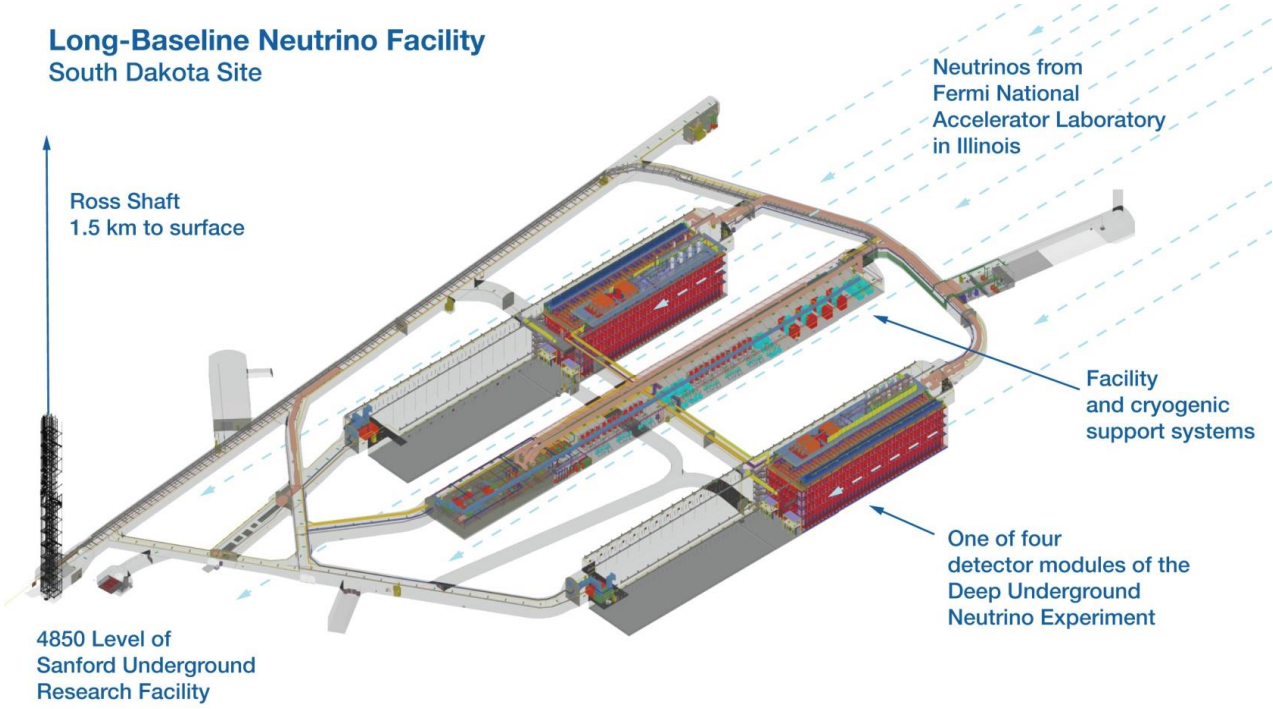
MPD

Liquid Argon TPCs – DUNE

Physics
UNIVERSITY OF TORONTO

- 3 Central Elements
  - **Far Detector**: Located 1.5km Underground at SURF, South Dakota
  - **Near Detector**: Located Just Ahead of Neutrino Source at Fermilab, Illinois
  - **Long Baseline Neutrino Facility**: Provides Beamline and Civil Construction for Both Detectors

- Far Detector (FD) are Liquid Argon TPCs



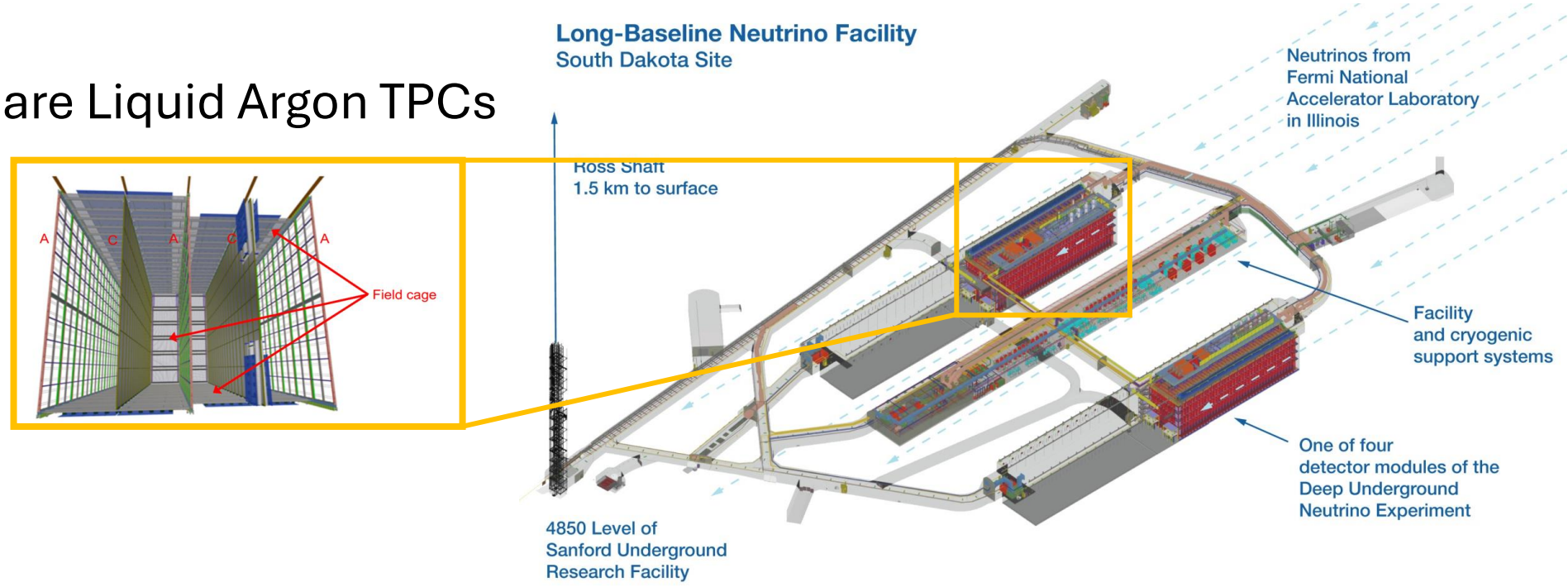
Underground Housing for the DUNE FD. (Image: dunescience.org)

Liquid Argon TPCs – DUNE

Physics
UNIVERSITY OF TORONTO

- 3 Central Elements
  - **Far Detector**: Located 1.5km Underground at SURF, South Dakota
  - **Near Detector**: Located Just Ahead of Neutrino Source at Fermilab, Illinois
  - **Long Baseline Neutrino Facility**: Provides Beamline and Civil Construction for Both Detectors

- Far Detector (FD) are Liquid Argon TPCs



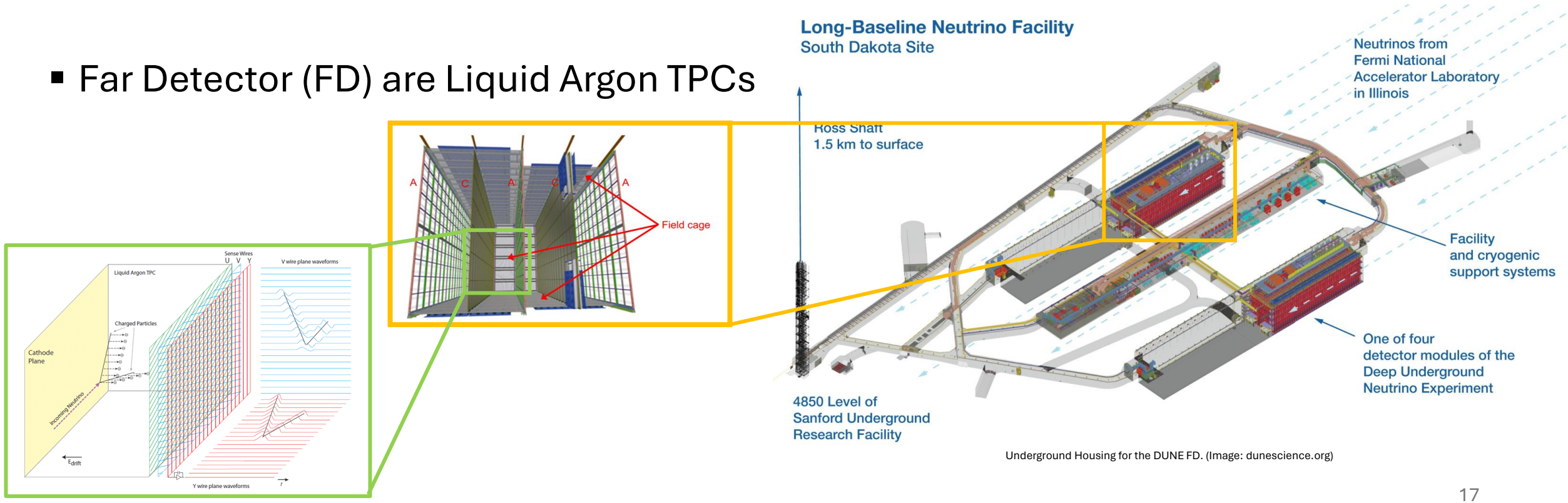
Underground Housing for the DUNE FD. (Image: dunescience.org)

Liquid Argon TPCs – DUNE

Physics
UNIVERSITY OF TORONTO

- 3 Central Elements
  - **Far Detector**: Located 1.5km Underground at SURF, South Dakota
  - **Near Detector**: Located Just Ahead of Neutrino Source at Fermilab, Illinois
  - **Long Baseline Neutrino Facility**: Provides Beamline and Civil Construction for Both Detectors

- Far Detector (FD) are Liquid Argon TPCs



Underground Housing for the DUNE FD. (Image: dunescience.org)

Contents

Physics
UNIVERSITY OF TORONTO

Main Idea

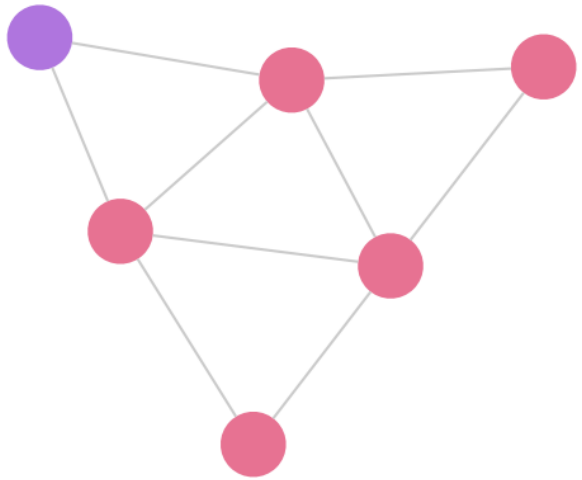
Physics
UNIVERSITY OF TORONTO

- Liquid Argon TPC **Hits** Can Be Connected in a **Graph**

Main Idea

Physics
UNIVERSITY OF TORONTO

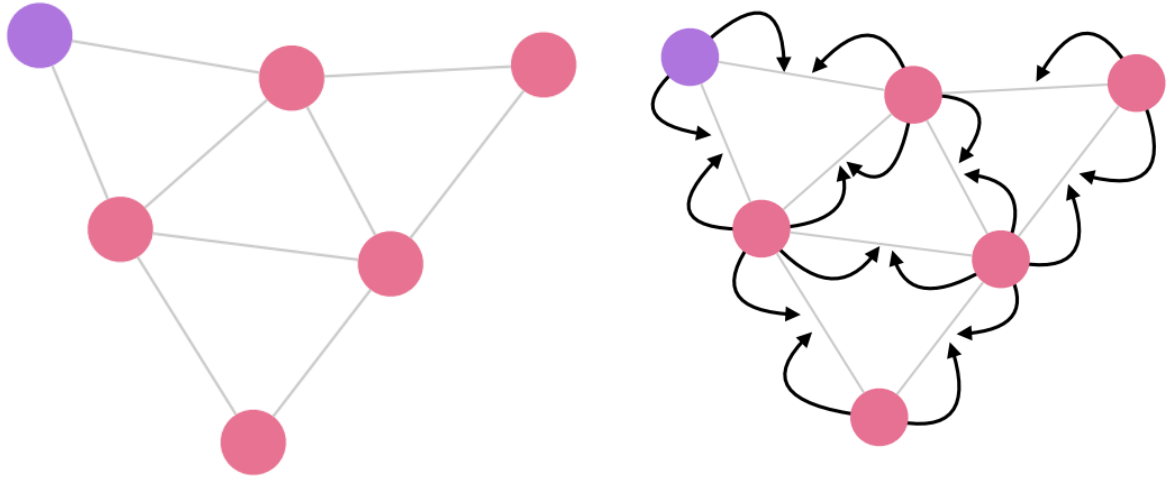
- Liquid Argon TPC **Hits** Can Be Connected in a **Graph**
  - Construct **Graph** Where Each **Node** is a **Detector Hit**



Main Idea

Physics
UNIVERSITY OF TORONTO

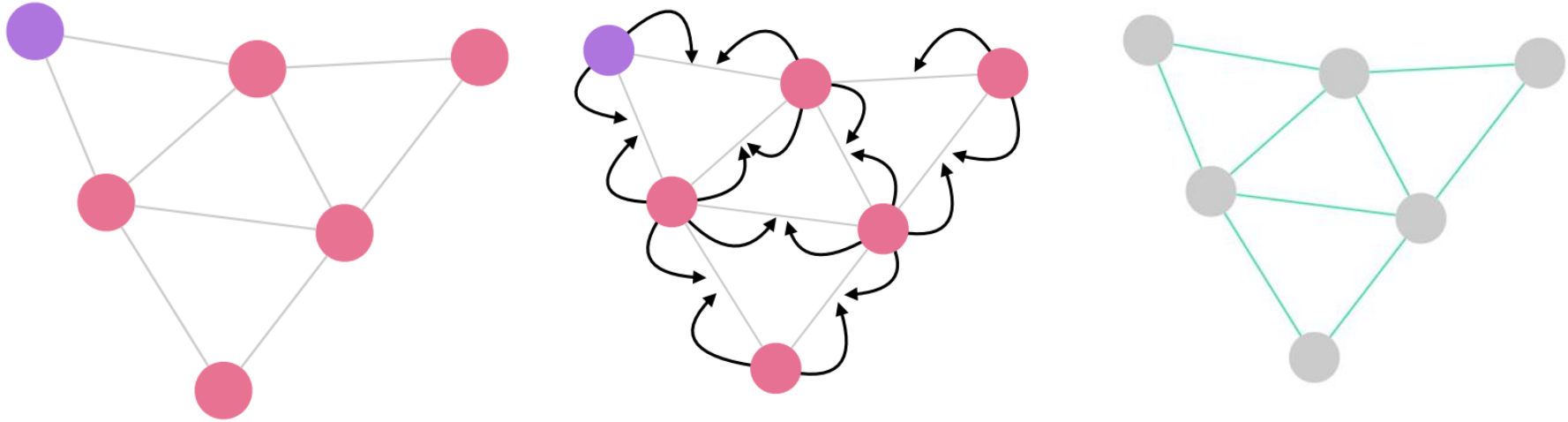
- Liquid Argon TPC **Hits** Can Be Connected in a **Graph**
  - Construct **Graph** Where Each **Node** is a **Detector Hit**
  - Form **Edge Features** By Pulling in Features from Incoming and Outgoing **Nodes**



Main Idea

Physics
UNIVERSITY OF TORONTO

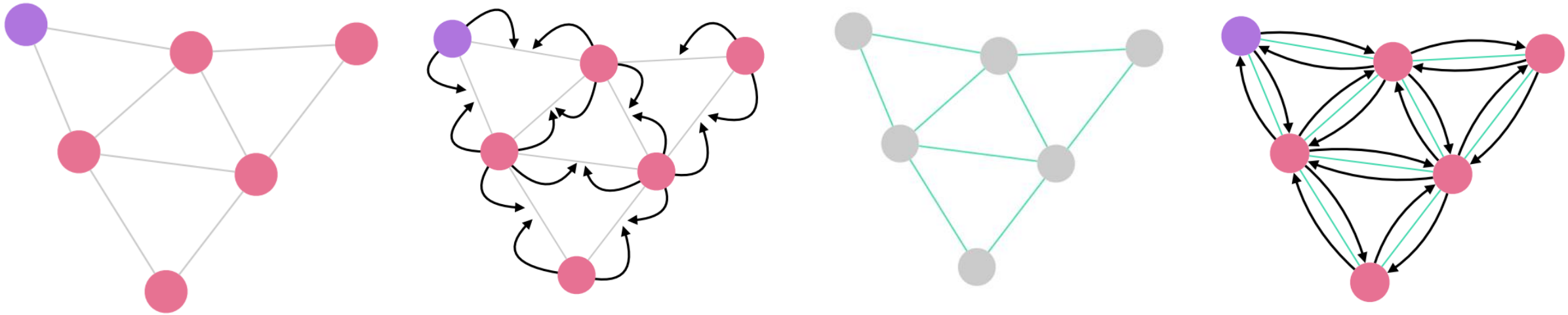
- Liquid Argon TPC **Hits** Can Be Connected in a **Graph**
  - Construct **Graph** Where Each **Node** is a **Detector Hit**
  - Form **Edge Features** By Pulling in Features from Incoming and Outgoing **Nodes**
  - Perform Convolutions on **Edge Scores** to Form a Set of **Class-Wise Probabilities**



Main Idea

Physics
UNIVERSITY OF TORONTO

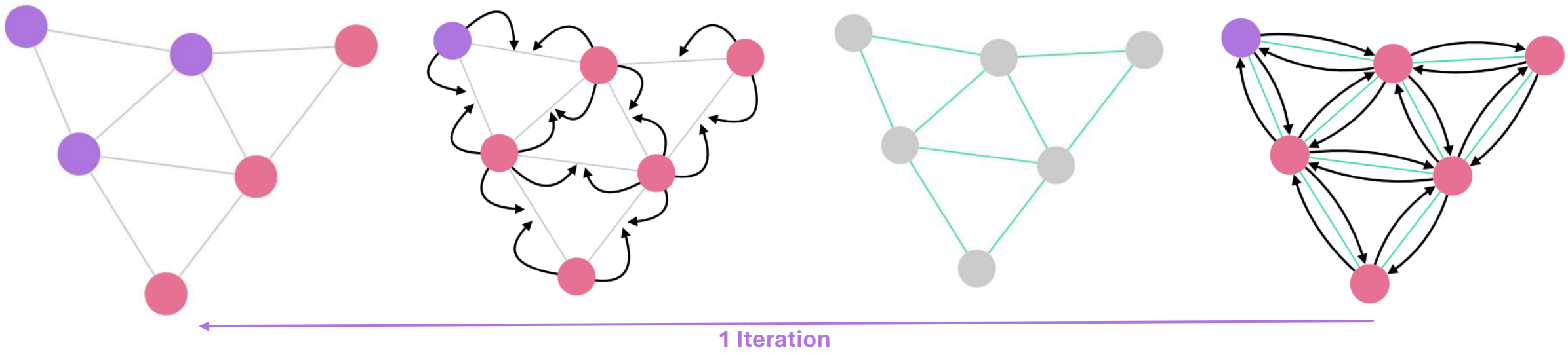
- Liquid Argon TPC **Hits** Can Be Connected in a **Graph**
  - Construct **Graph** Where Each **Node** is a **Detector Hit**
  - Form **Edge Features** By Pulling in Features from Incoming and Outgoing **Nodes**
  - Perform Convolutions on **Edge Scores** to Form a Set of **Class-Wise Probabilities**
  - Propagate **Node Features** Across **Edges**, Weighting by **Edge Scores**



Main Idea

Physics
UNIVERSITY OF TORONTO

- Liquid Argon TPC **Hits** Can Be Connected in a **Graph**
  - Construct **Graph** Where Each **Node** is a **Detector Hit**
  - Form **Edge Features** By Pulling in Features from Incoming and Outgoing **Nodes**
  - Perform Convolutions on **Edge Scores** to Form a Set of **Class-Wise Probabilities**
  - Propagate **Node Features** Across **Edges**, Weighting by **Edge Scores**
  - Perform Convolutions on **Nodes** to **Update Node Features**



NuGraph2

Physics
UNIVERSITY OF TORONTO

- NuGraph2 is a Second-Generation Graph Neural Network
  - Designed for Reconstructing Particle Interactions in Neutrino Physics Detector Environments

NuGraph2

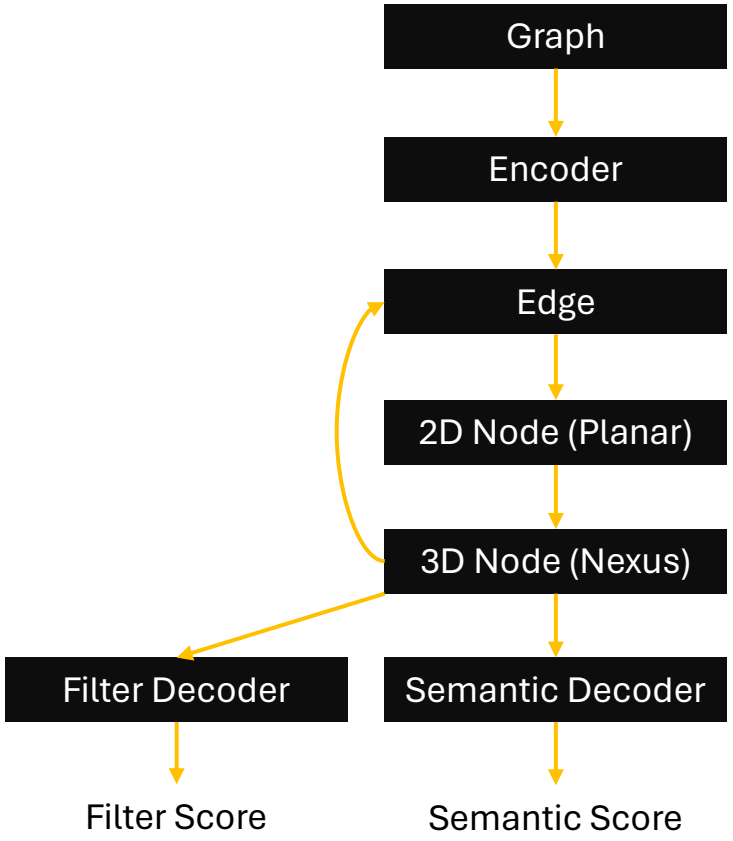
Physics
UNIVERSITY OF TORONTO

- NuGraph2 is a Second-Generation Graph Neural Network
  - Designed for Reconstructing Particle Interactions in Neutrino Physics Detector Environments

- Primary Goal: **Classify Each Detector Hit According to Particle Type**
- Use 5 Semantic Categories:
  - **MIP: Minimum Ionizing Particles (Muons, Pions, etc.)**
  - **HIP: Highly Ionizing Particles (Protons)**
  - **EM Showers (Electrons, Photons)**
  - **Michel Electrons (Electrons Produced from Muon Decay)**
  - **Diffuse Activity (Compton Scatters, Neutrons, etc.)**
- Also, Neutrino Event Type

NuGraph2 Architecture

Physics
UNIVERSITY OF TORONTO



Graph node features include **plane, wire, and time coordinates** in both local and global coordinate system, **ID of the TPC** in which the hit occurred – as well as **integral and RMS width** of each hit

Initial encoding step generates a learned embedding for each graph node. Currently two-layer sequential network with one linear and one non-linear layer: $\boldsymbol{z} = \mathbf{tanh}(\boldsymbol{W}\boldsymbol{x} + \boldsymbol{b})$ where W, b are learned parameters

Pass messages **internally** in each TPC plane

Pass messages **externally** to mix information between detector planes

Semantic Decoder: Trained to classify each neutrino-induced hit according to particle type
Filter Decoder: Trained to separate neutrino induced hit from noise or cosmic-induced hits

Performance Metrics: **Recall** (efficiency), **Precision** (purity), **Loss** (accuracy between prediction and truth)

Contents

Physics
UNIVERSITY OF TORONTO

NuGraph2 Modifications – Why?

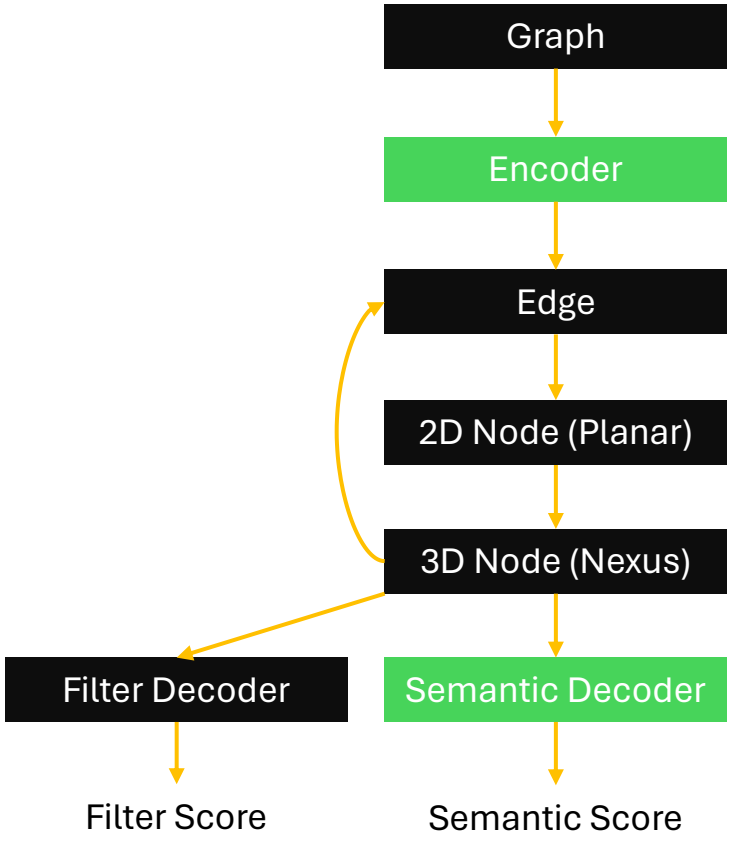
Physics
UNIVERSITY OF TORONTO

- Overall: Study All Flavours, But Emphasis on Tau Neutrinos
  - Least Understood

- Goal: Network **Can** Be Better at Classifying Tau Neutrino Events
  - Modifications Can Be Made to Multiple Areas
  - We Focus on **Two** Areas Which We Believe Have the Most Impact

NuGraph2 Modifications

Physics
UNIVERSITY OF TORONTO



Initial encoding step generates a learned embedding for each graph node. Add additional layer to create four-layer sequential network with same linear and non-linear layer: $\boldsymbol{z = \tanh(W_2 \tanh(W_1 x + b_1) + b_2)}$ where again W_i, b_i are learned parameters

Semantic Decoder: Trained to classify each neutrino-induced hit according to particle type
Filter Decoder: Trained to separate neutrino induced hit from noise or cosmic-induced hits

Performance Metrics: **Recall** (efficiency), **Precision** (purity), **Loss** (accuracy between prediction and truth)

Contents

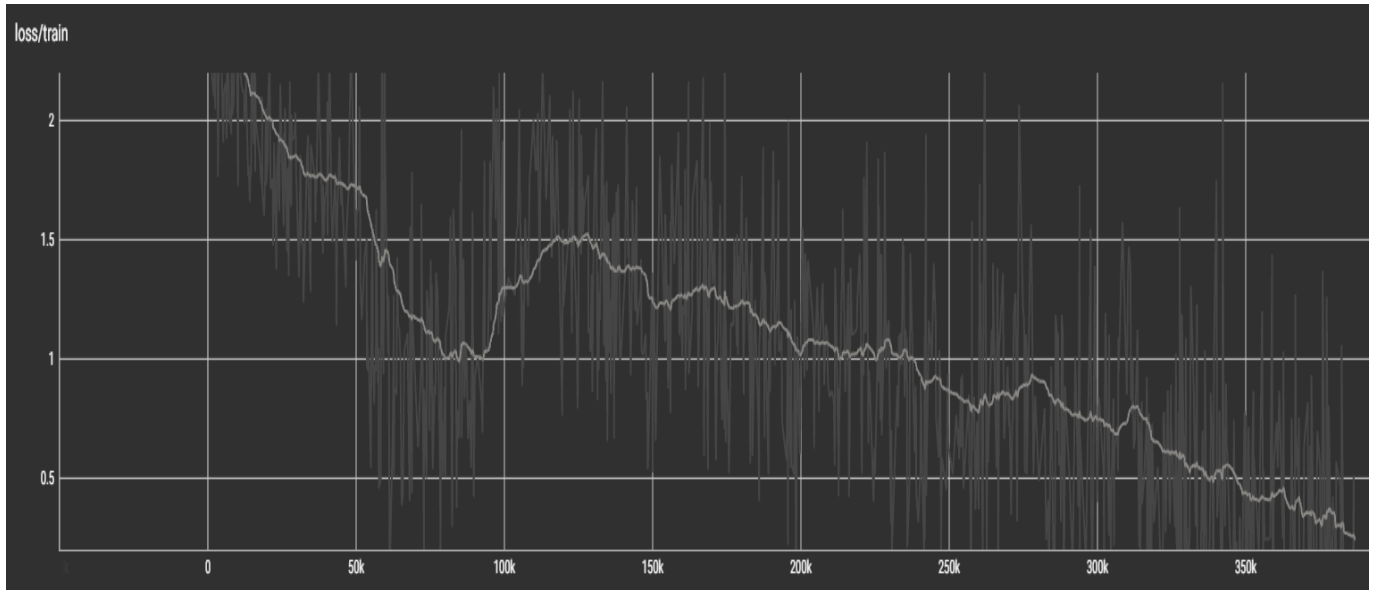
Physics
UNIVERSITY OF TORONTO

Result - Loss

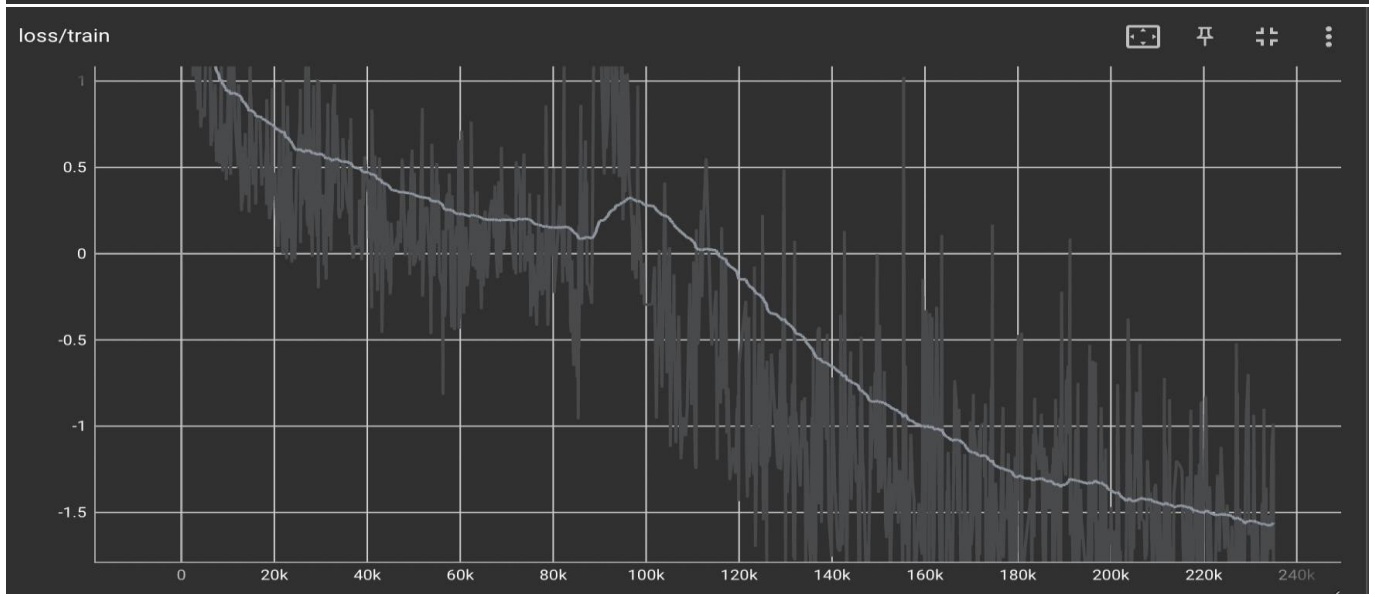
Physics
UNIVERSITY OF TORONTO

- Loss Function: A measurement of how good the model is in terms of predicting the expected outcome
  - Directly related to the predictions of the model
  - If loss function value is low, model will provide good results
  - Needs to be minimized to improve model's performance
  - Cross Entropy Loss: $L = -\frac{1}{m}\sum_{i=1}^{m} y_i \cdot \log(\grave{y}_i)$, value between 0 and 1

Result - Loss



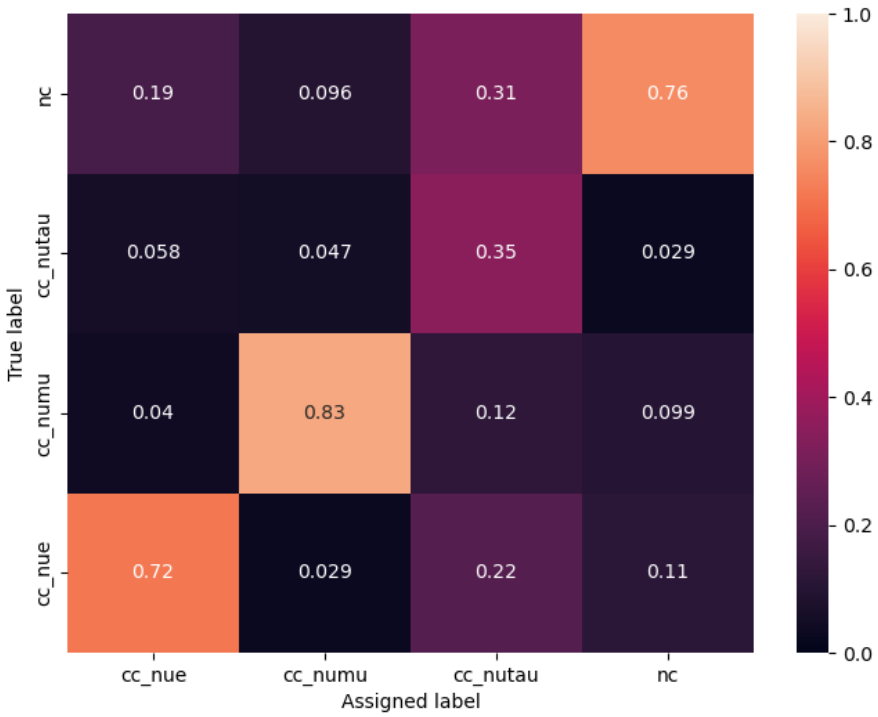
Old (Standard Cross Entropy)



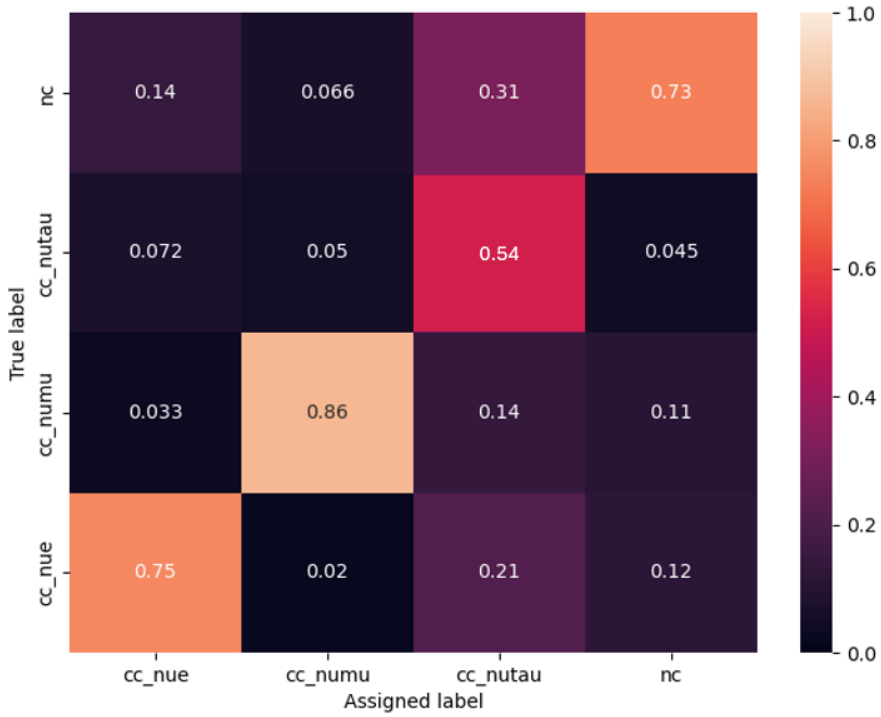
New (Cross Entropy Weighted)
~ Half the Run Time

Result – Event Type

Physics
UNIVERSITY OF TORONTO



Old



New (Additional Layer)

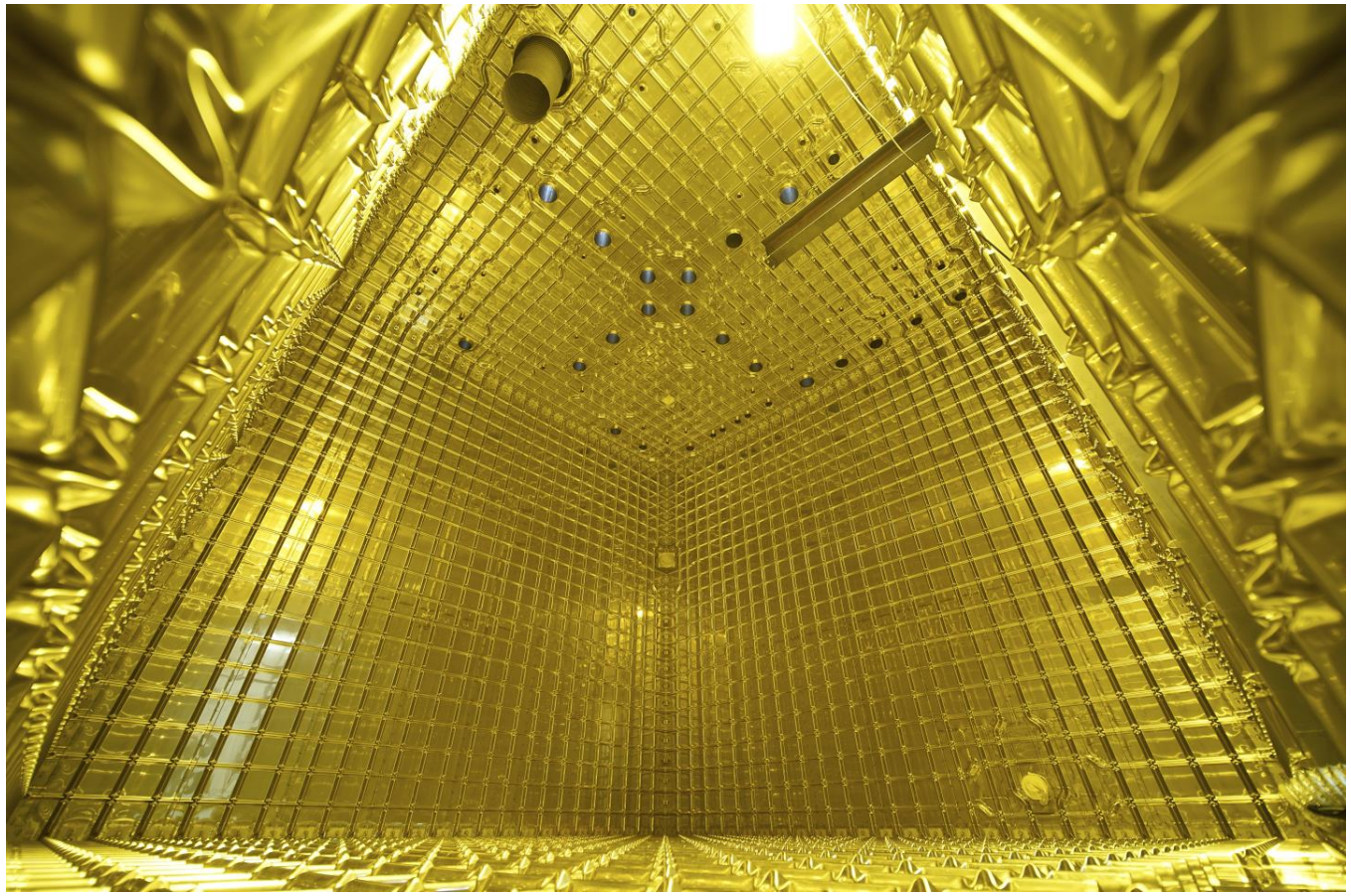
Future Work

Physics
UNIVERSITY OF TORONTO

- Longer Run Time = Better Results (Training Can Take Several Weeks)
- Negative Loss Function Fix
- Further Modifications are Possible
- NuGraph3?

Backup Slides

Prototype Liquid-Argon Time-Projection Chamber for the DUNE experiment. (Image: CERN)



Physics
UNIVERSITY OF TORONTO

Prince Bhaura

March 27th, 2024

Physics Research Project Oral Evaluation

Supervisors: Prof. Nikolina Ilic & William Dallaway

Liquid Argon as Target

Physics
UNIVERSITY OF TORONTO

- Density
  - High Density Increases the Likelihood of Particle Interactions Making it More Sensitive to Rare Events (Neutrinos or Dark Matter)
- Interaction Cross Section
  - Sizable Interaction Cross Section with Various Particles, Including Charged Particles Like Electrons and Ions
  - Increases the Likelihood of a Signal
- Scintillation Light & Large Scintillation Yield
  - Charged Particles Passing Through Create Scintillation Light Which Can be Detected in Addition to Ionization Signals

Liquid Argon as Target

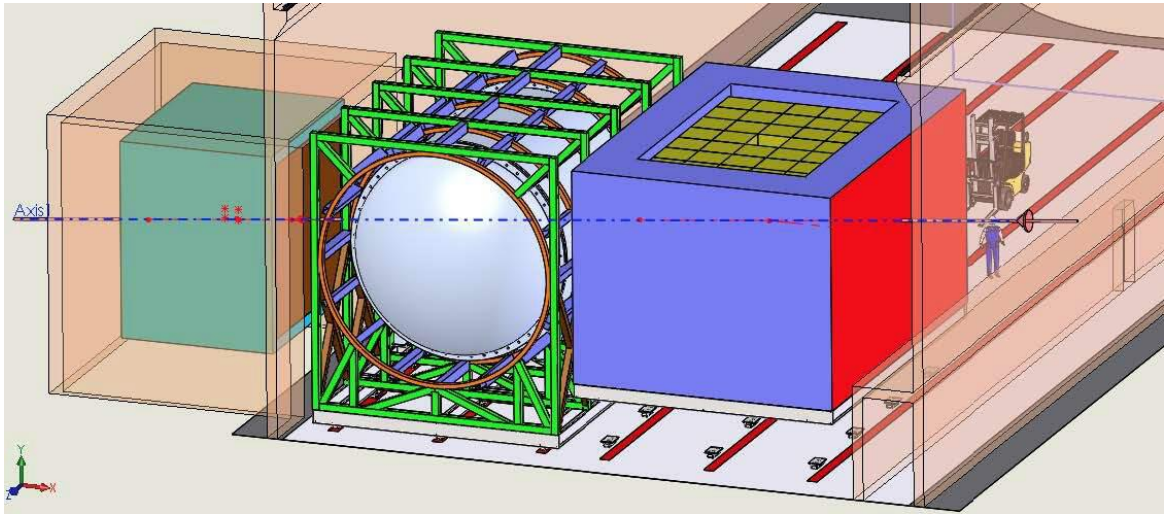
Physics
UNIVERSITY OF TORONTO

- Purity
  - Liquid Argon can be Purified to Extreme Levels
  - Electronegative Contaminants that Could Capture Drifting Electrons can be Removed
- Noble Element
  - Chemically Inert Property Prevents Unwanted Chemical Reactions
- Readily Available
  - Argon is Abundant and Relatively Easy to Obtain

Near Detector

Physics
UNIVERSITY OF TORONTO

- Experiments Control
  - Constraining Systematic Errors
  - Measuring Unaltered Neutrino Energy Spectra (Before Any Oscillations Occur)
  - Measures Initial Neutrino-Argon Interactions Which Further Mitigates Systematic Uncertainties

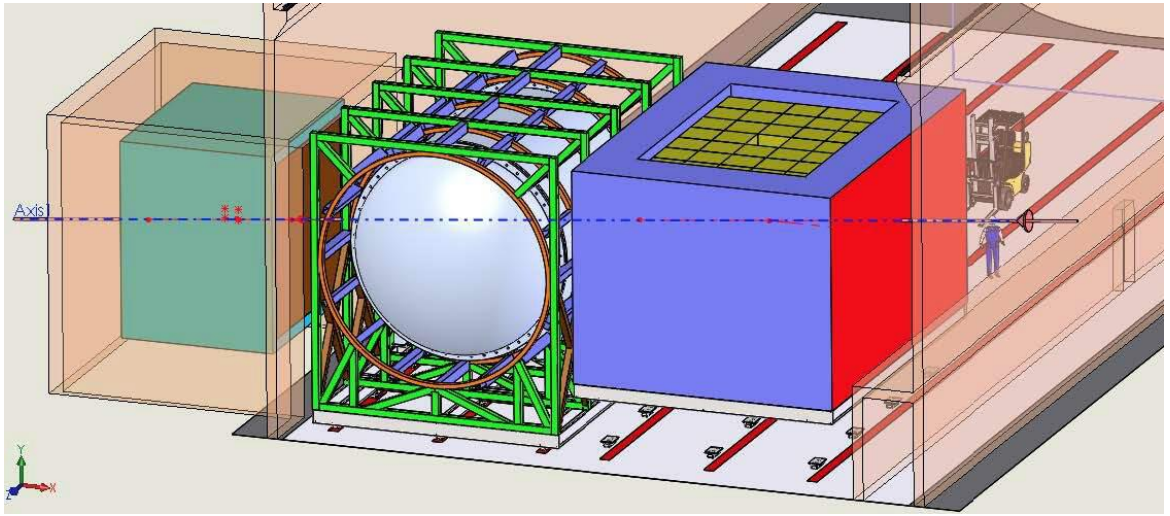


Setup of the DUNE ND. Beam is Shown Entering from the Right. Neutrinos First Encounter the LArTPC (right), MPD (center), and then the On-Axis Beam Monitor (left) (Image: dunescience.org)

Near Detector

Physics
UNIVERSITY OF TORONTO

- Own Physics Program
  - Will Measure Neutrino Interactions
  - Explorations Beyond Standard Model Seeking Sterile Neutrinos, Dark Photons, and Other Exotics
  - Comprised of: LArTPC (Right), High-Pressure Gaseous TPC + Electromagnet Calorimeter → MPD (Middle), and a On-Axis Beam Monitor called System for On-Axis Neutrino Detection (Left)
    → SAND



Setup of the DUNE ND. Beam is Shown Entering from the Right. Neutrinos First Encounter the LArTPC (right), MPD (center), and then the On-Axis Beam Monitor (left) (Image: dunescience.org)

Input Data

Physics
UNIVERSITY OF TORONTO