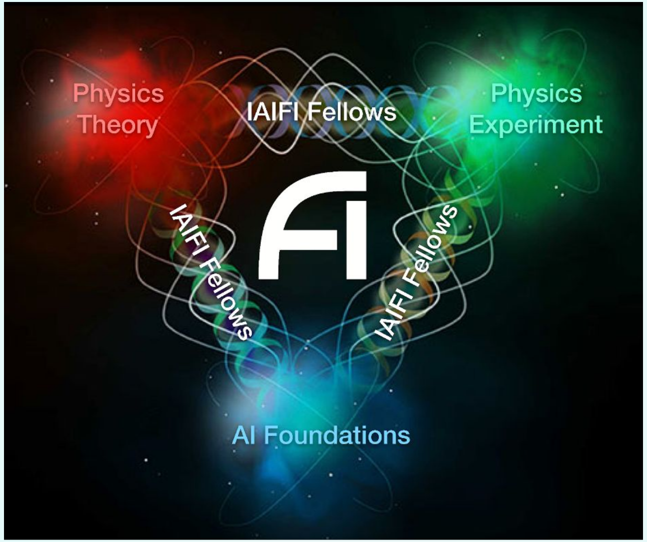
Intense Neutrino Reco: MLReco3D for DUNE's Near Detector

Jessie Micallef
on behalf of the DUNE Collaboration
IAIFI Postdoc Fellow
jessiem@mit.edu

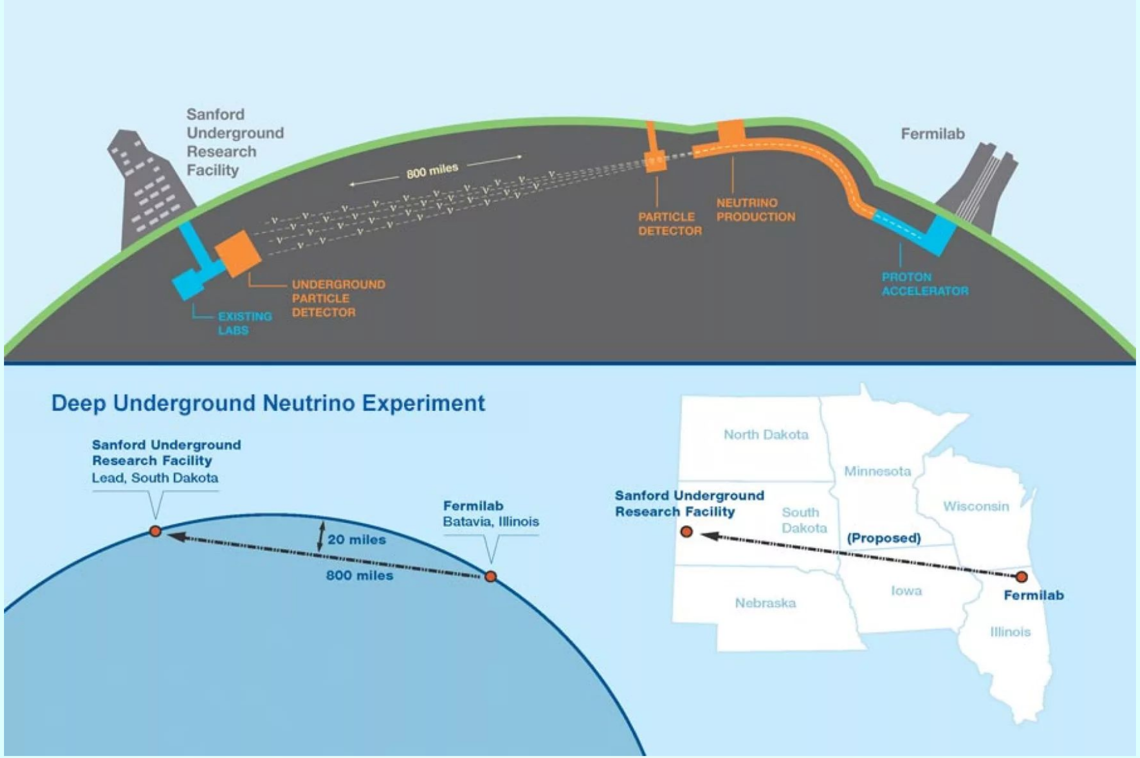
Neutrinos & Machine Learning

Institute for Artificial Intelligence and Fundamental Interactions

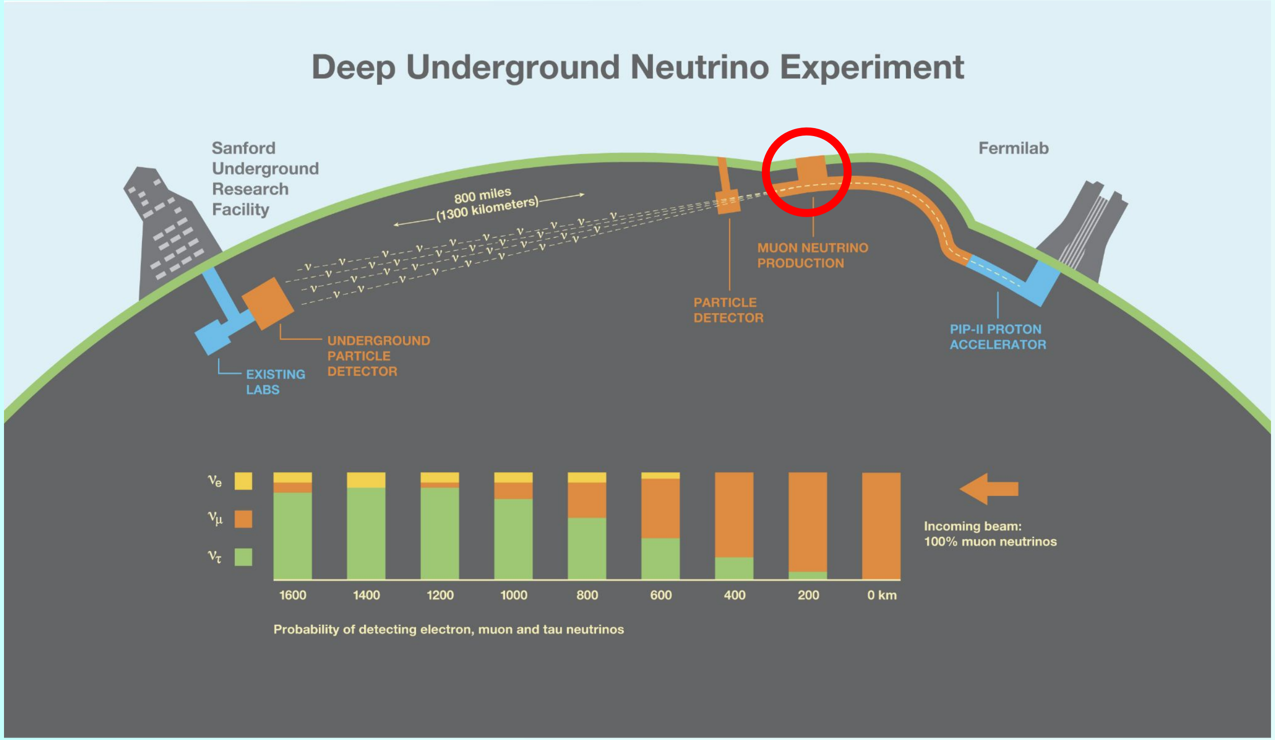


https://jessimic.github.io/tech-portfolio/

DUNE: Deep Underground Neutrino Experiment

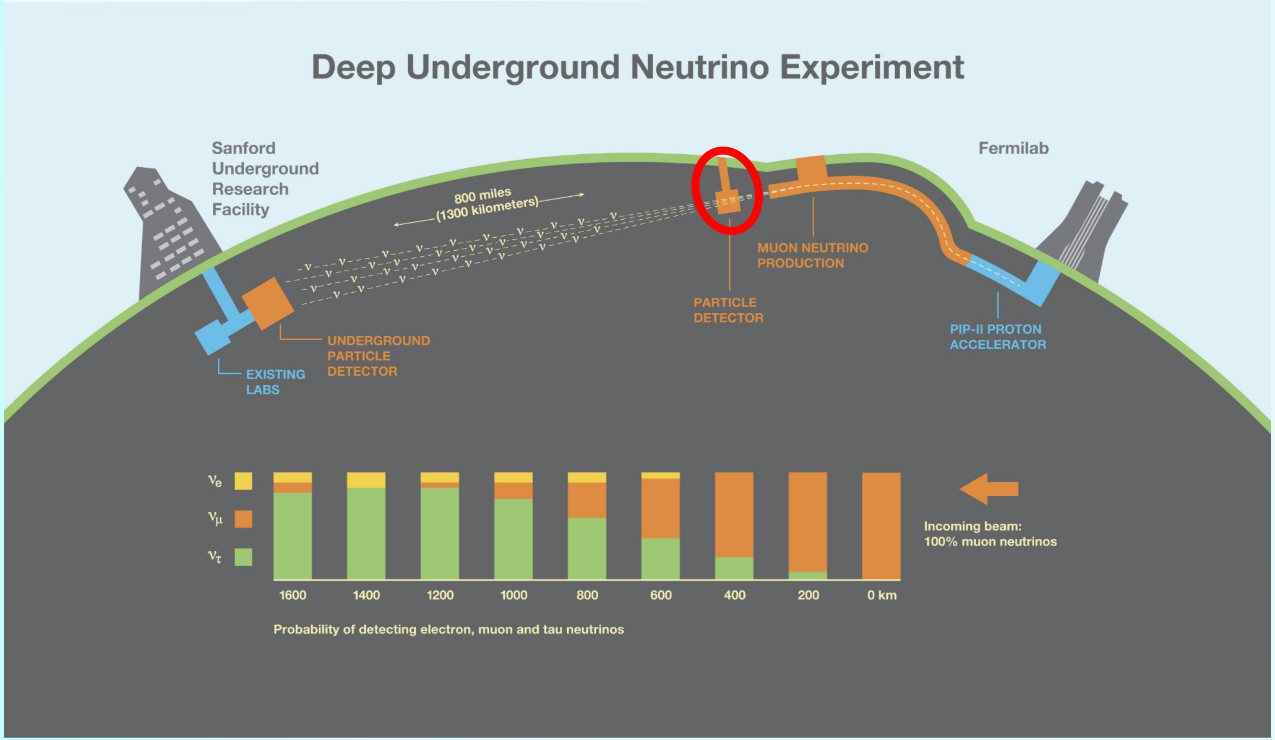


DUNE: Frontier Measurements of Neutrino Physics



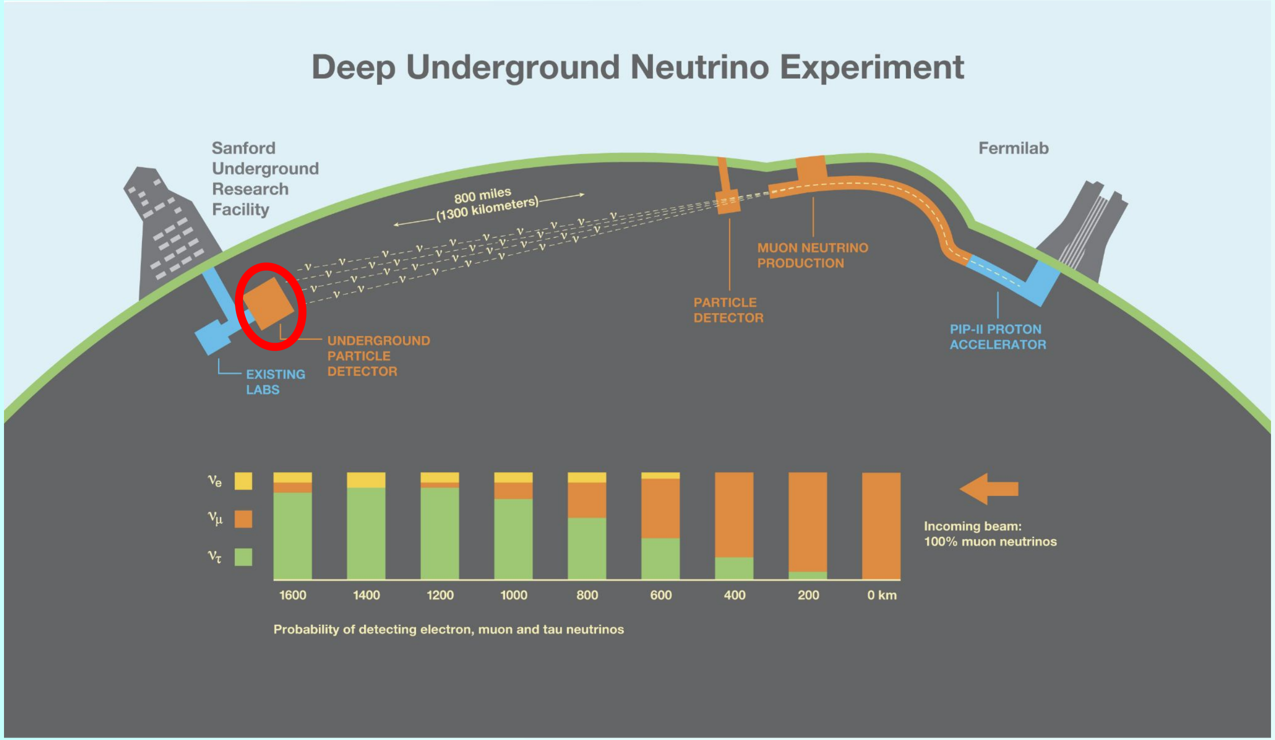
- PIP-II upgrade will lead to world's most intense neutrino beam

DUNE: Frontier Measurements of Neutrino Physics



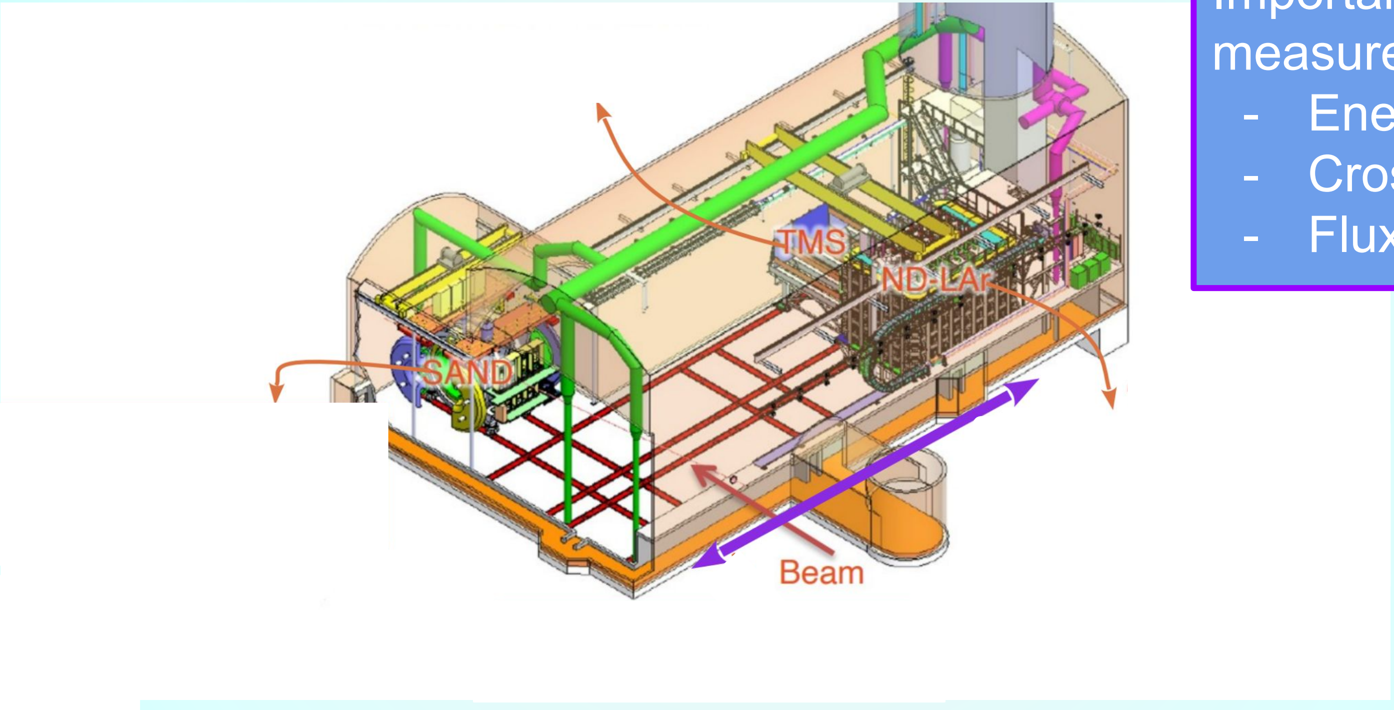
- PIP-II upgrade will lead to world's most intense neutrino beam
- Near detectors at Fermilab

DUNE: Frontier Measurements of Neutrino Physics



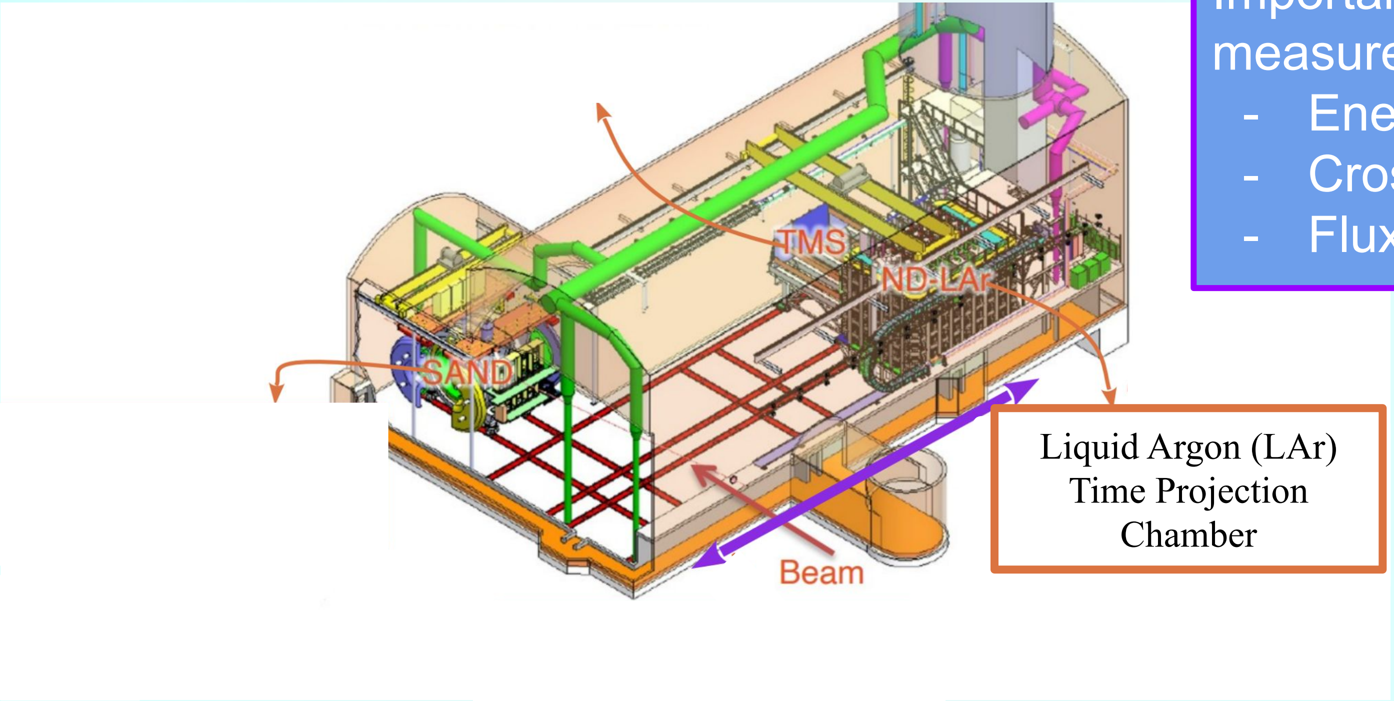
- PIP-II upgrade will lead to world's most intense neutrino beam
- Near detectors at Fermilab
- Far detector at SURF

Near Detector Hall



Important to measure ν…
- Energy
- Cross section
- Flux

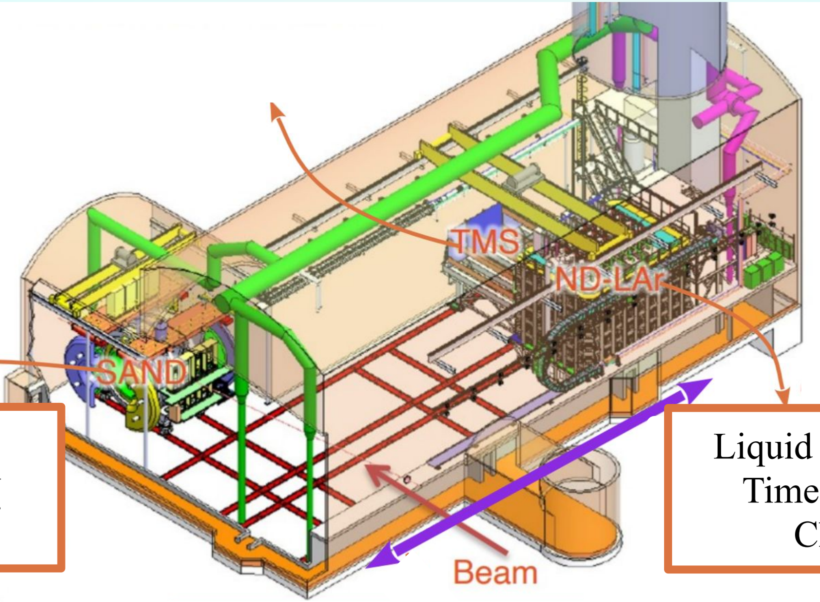
Near Detector Hall



Liquid Argon (LAr) Time Projection Chamber

Important to measure ν…
- Energy
- Cross section
- Flux

Near Detector Hall

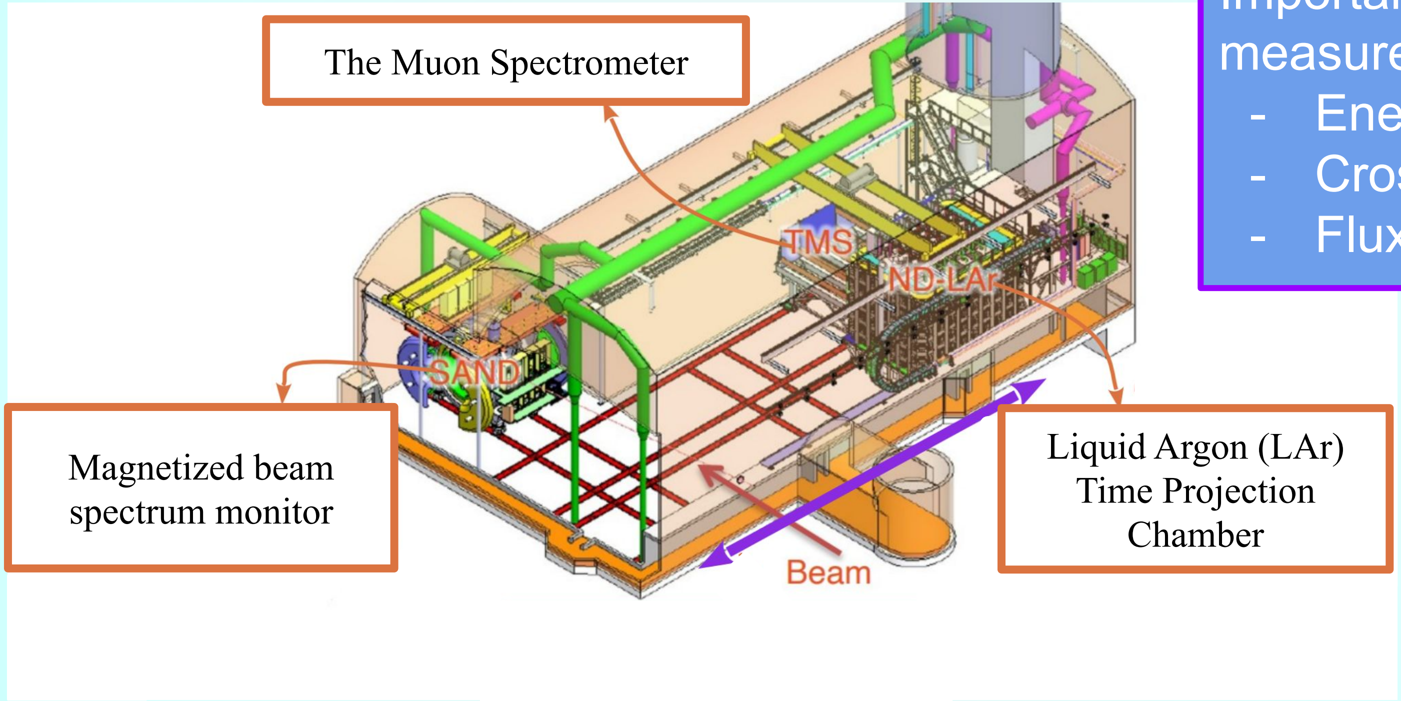


Magnetized beam spectrum monitor

Liquid Argon (LAr) Time Projection Chamber

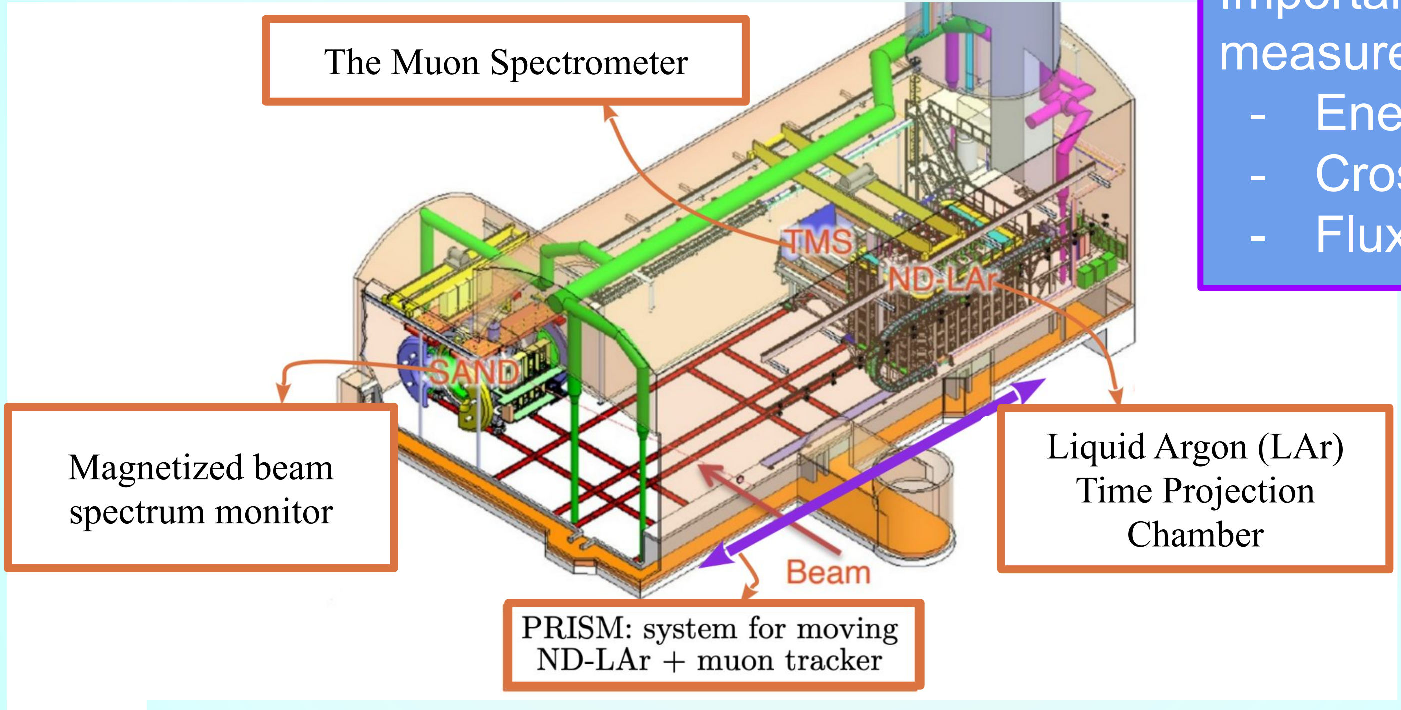
Important to measure ν…
- Energy
- Cross section
- Flux

Near Detector Hall



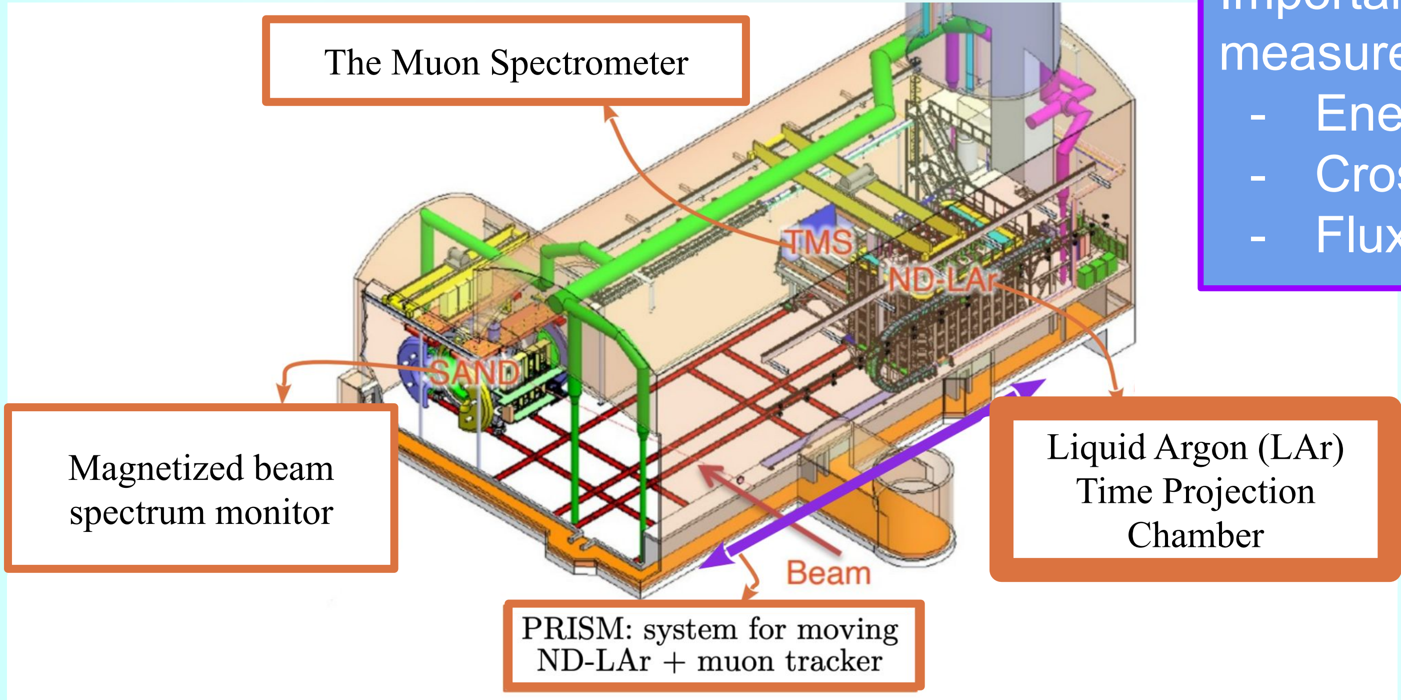
Important to measure ν…
- Energy
- Cross section
- Flux

Near Detector Hall



Important to measure ν…
- Energy
- Cross section
- Flux

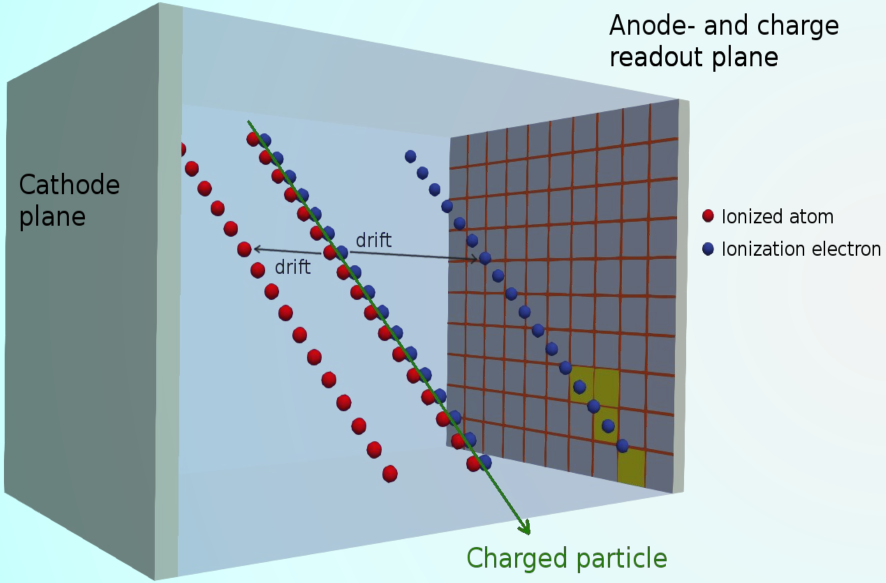
Near Detector Hall



Important to measure ν…

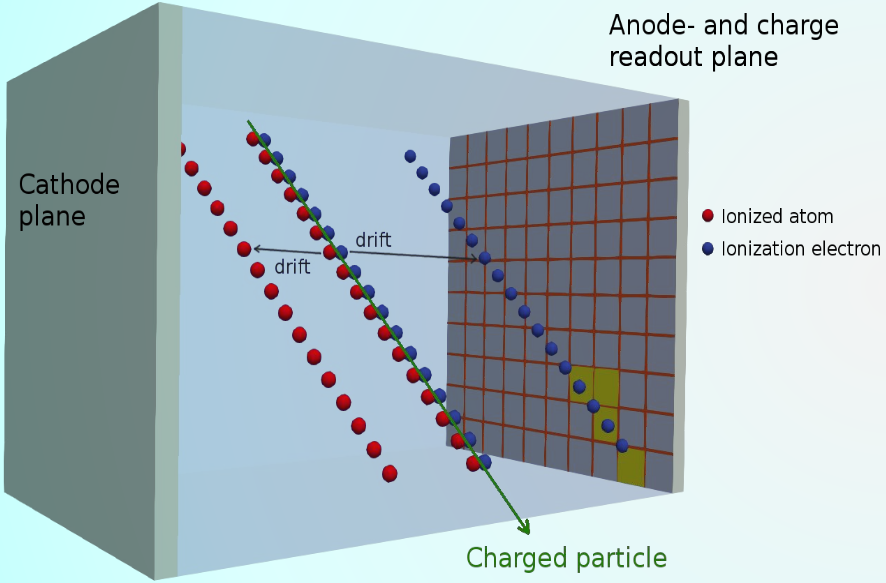
- Energy
- Cross section
- Flux

Liquid Argon (LAr) Time Projection Chamber (TPC)

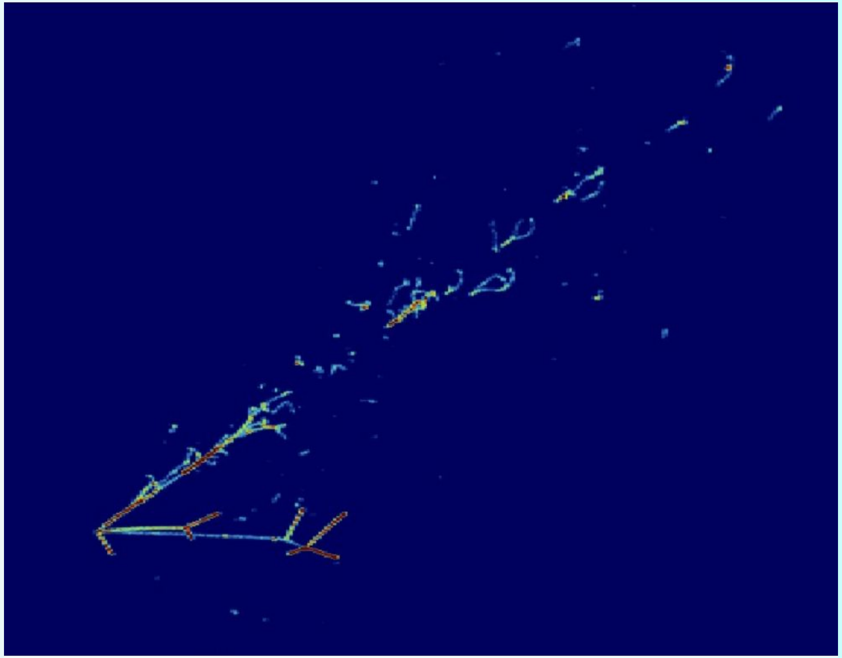


https://argoncube.org/LArTPCs.html

Liquid Argon (LAr) Time Projection Chamber (TPC)

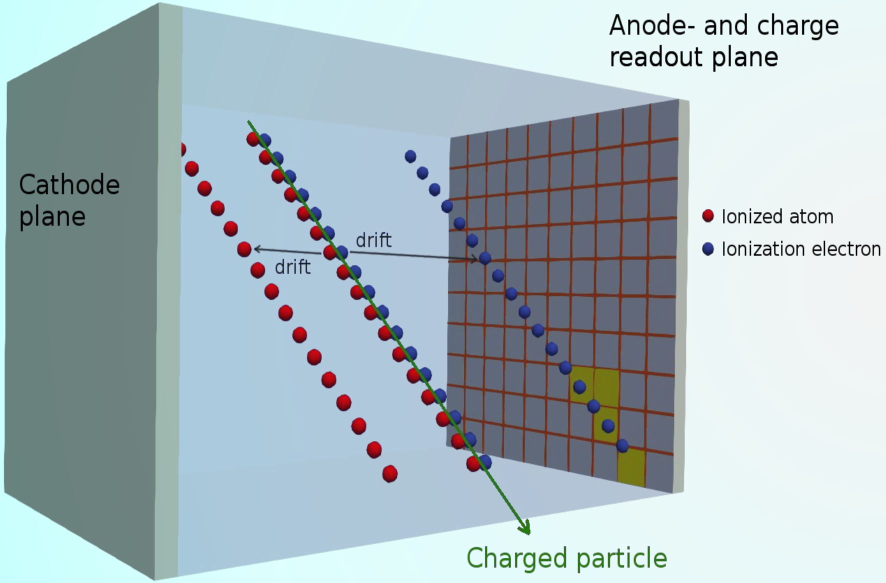


https://argoncube.org/LArTPCs.html



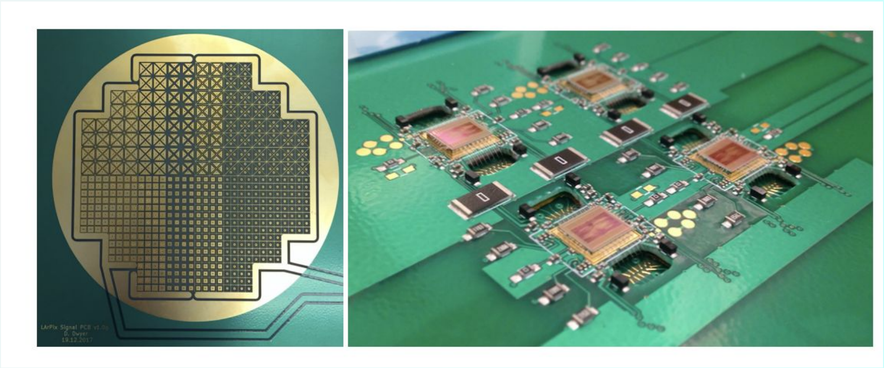
Color = charge deposition
Output: pion and two protons

Liquid Argon (LAr) Time Projection Chamber (TPC)



https://argoncube.org/LArTPCs.html

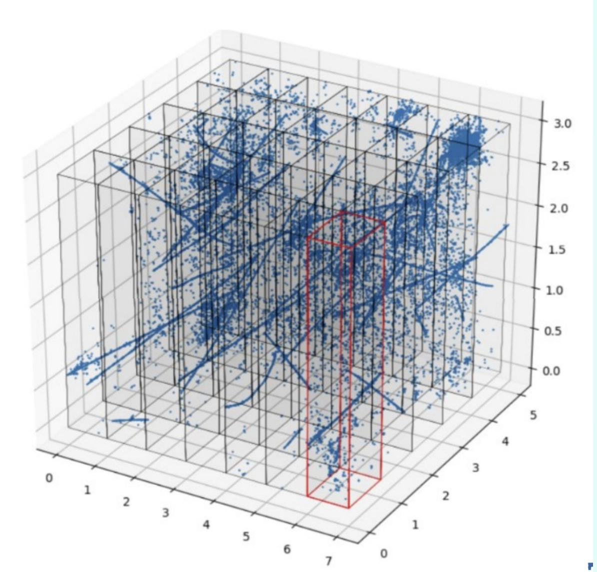
But we're using a 2D pixel plane readout! So we get a 3D image!



TPC-facing side of pixel plane with 832 pads (left) and back of plane with 4 LArPix ASICs (right).
LArPix Paper

Handling Beam Intensity

- Expect ~55 ν interactions!

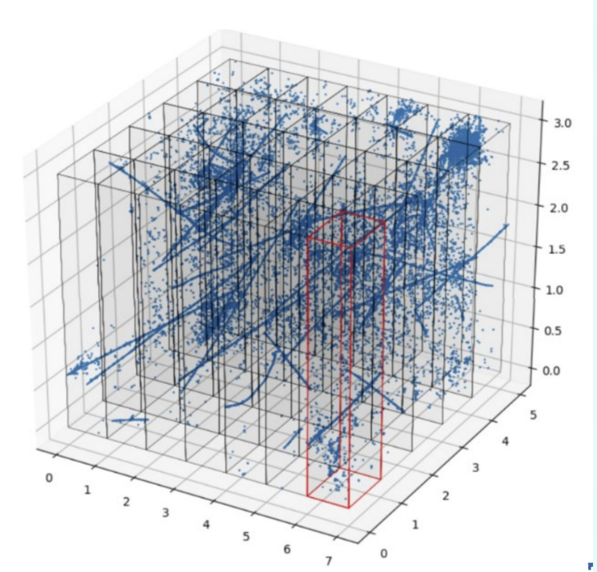


Simulation of ND LAr beam spill (10μs)

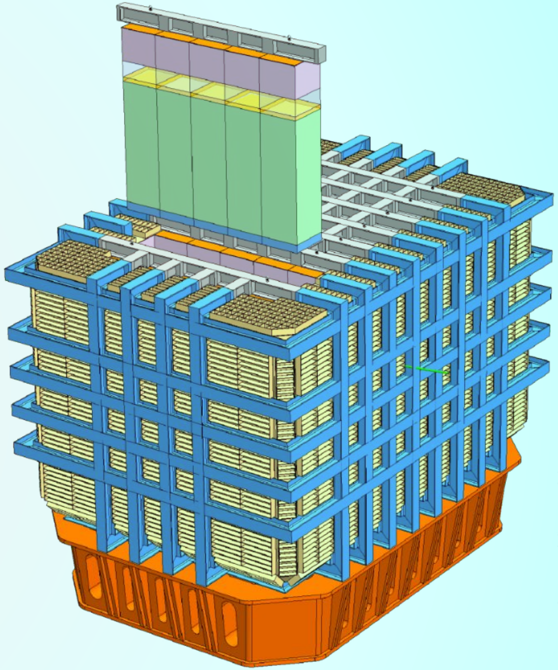
https://argoncube.org/LArTPCs.html

Handling Beam Intensity

- Expect ~55 $\boldsymbol{\nu}$ interactions!
- Need new technology:
  - Modular detector for shorter drift

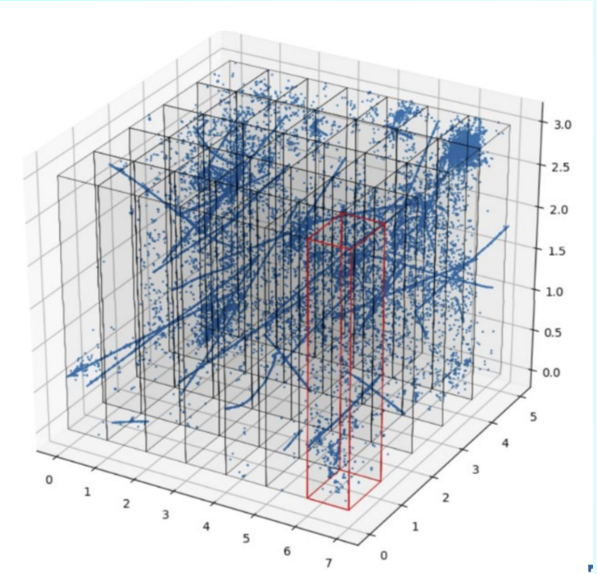


Simulation of ND LAr beam spill ($10\mu s$)



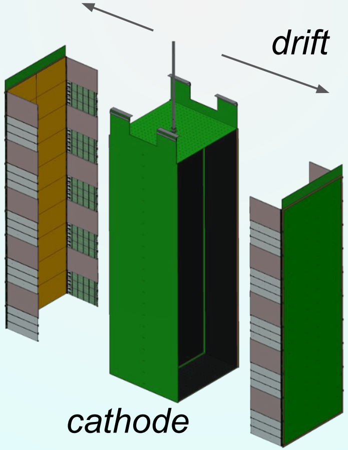
https://argoncube.org/duneND.html

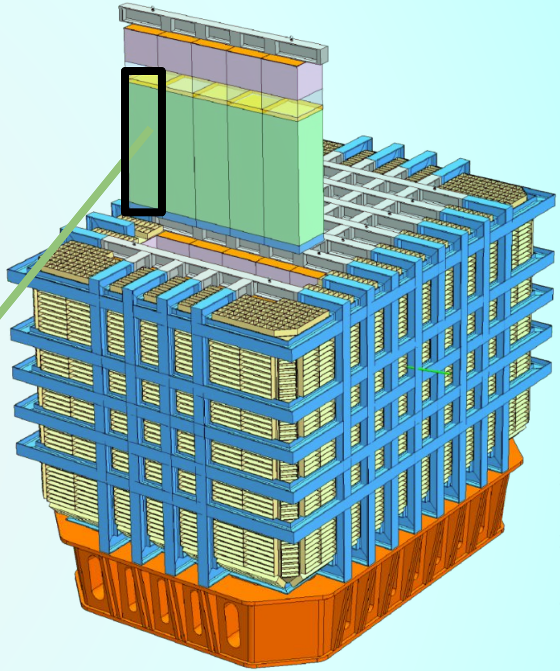
Handling Beam Intensity



Simulation of ND LAr beam spill ($10\mu s$)

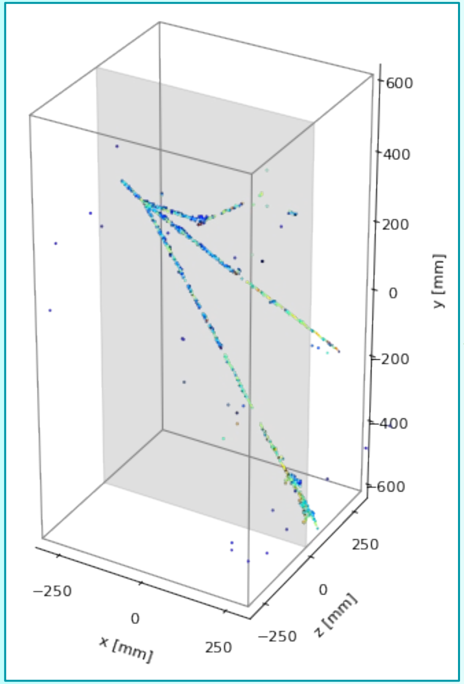
- Expect ~55 $\boldsymbol{\nu}$ interactions!
- Need new technology:
    - Modular detector for shorter drift
- TPC with central cathode





https://argoncube.org/duneND.html

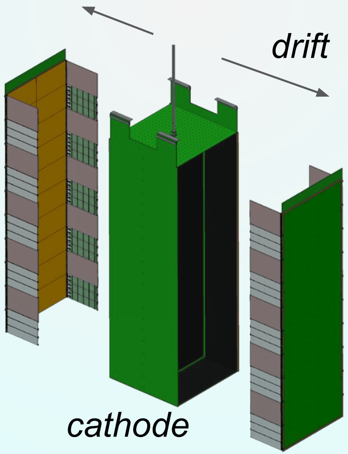
Handling Beam Intensity

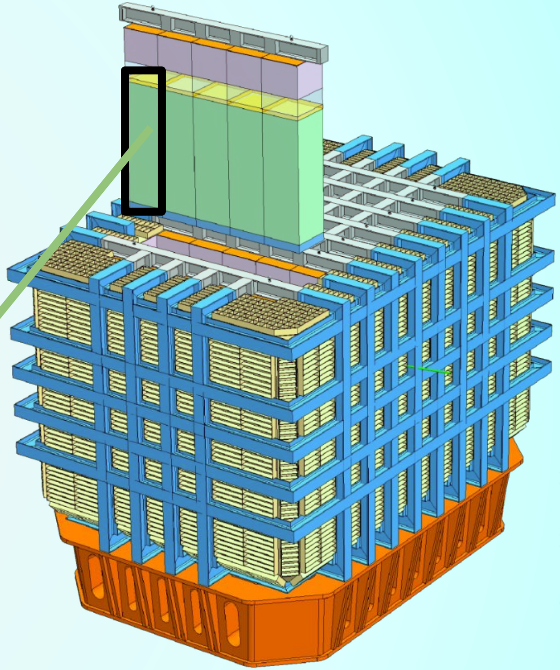


Simulation of 1 ND LAr TPC module

- Expect ~55 $\boldsymbol{\nu}$ interactions!
- Need new technology:
  - Modular detector for shorter drift
- TPC with central cathode

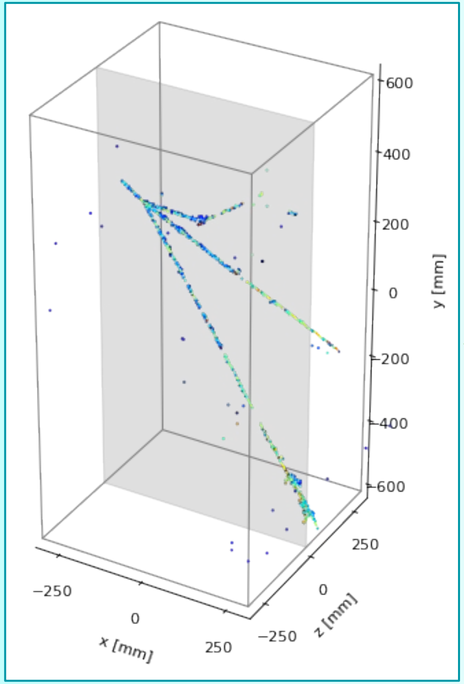
Pixel plane for 3D display





https://argoncube.org/duneND.html

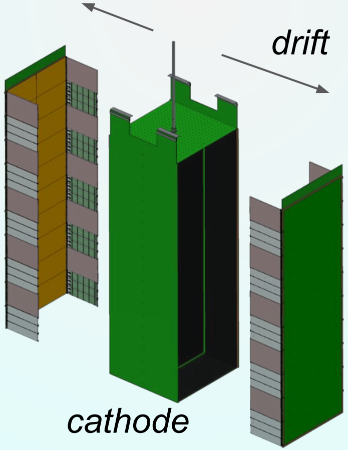
Handling Beam Intensity: 2x2 Prototype

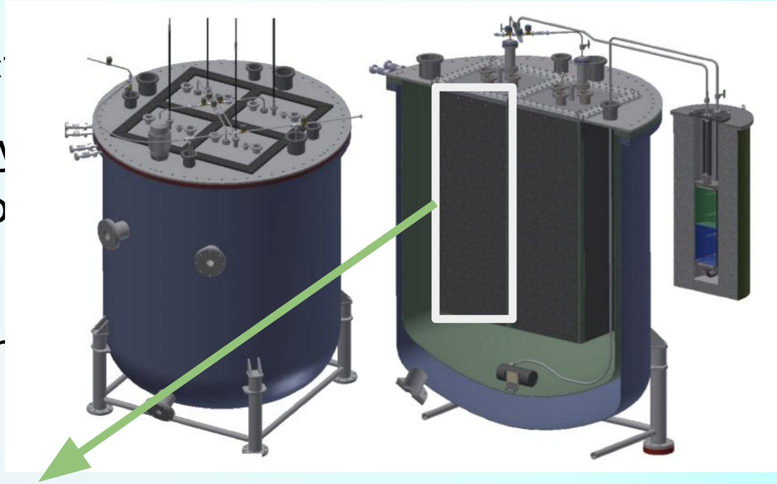


Simulation of 1 ND LAr TPC module

- Expect ~55 ν interac
- Need new technolog
  - Modular detecto shorter drift
- TPC with central cath

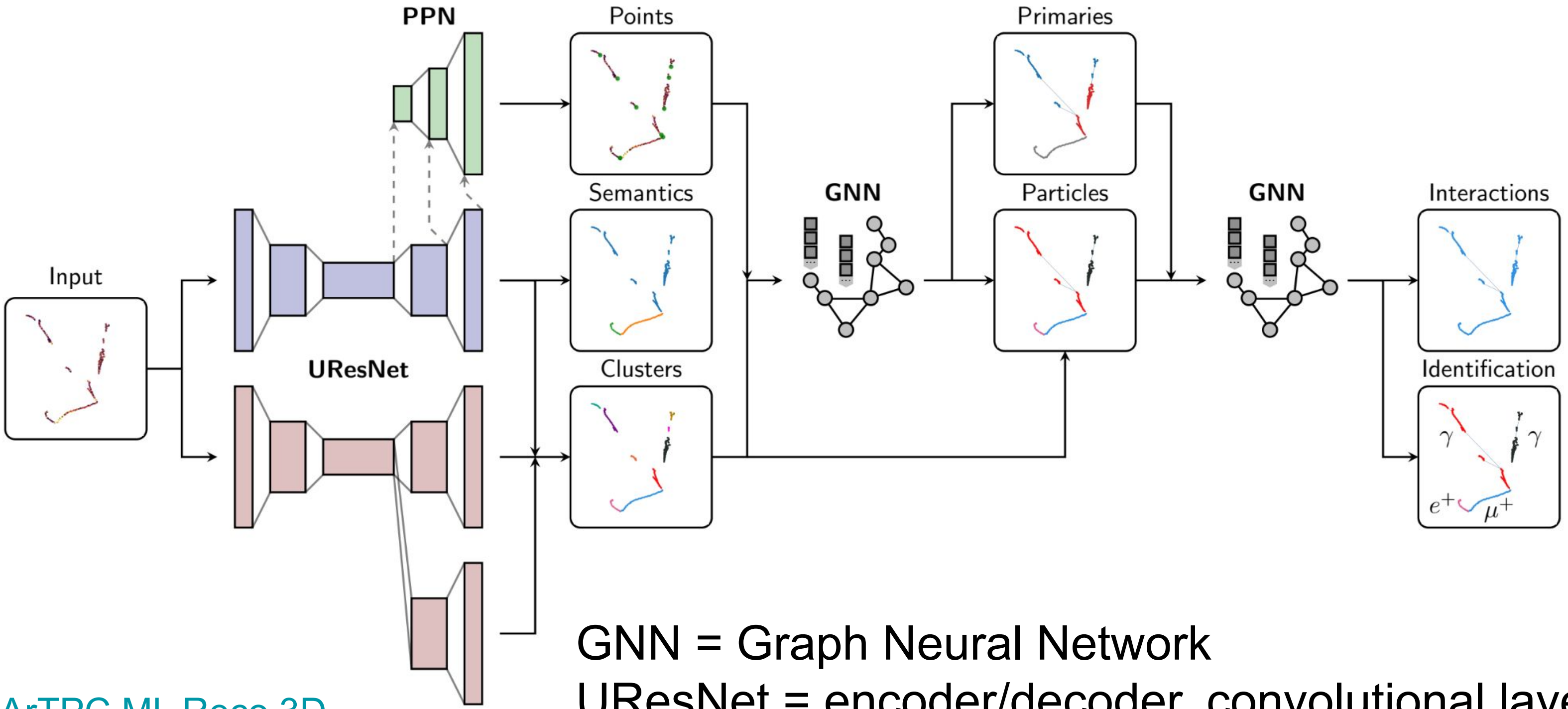
Pixel plane for 3D display





See Brooke's [ND-LAr Overview] and Richie's [2x2 Software] talks from Thursday!

3D LAr TPC: ML Reco 3D

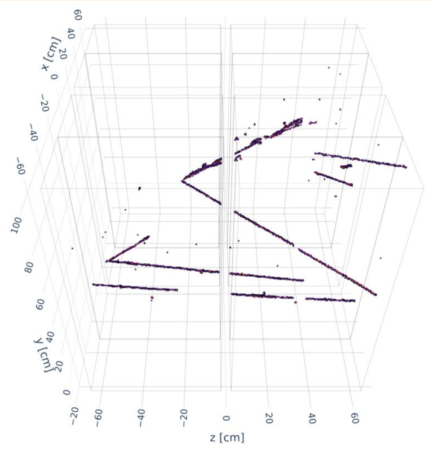


[LArTPC ML Reco 3D]

GNN = Graph Neural Network
UResNet = encoder/decoder, convolutional layers
PPN = Point Proposal Network (convolutional)

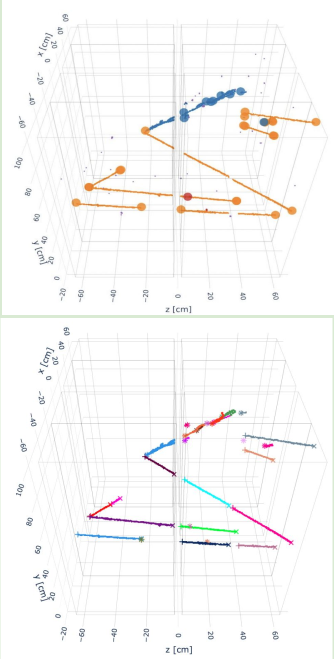
3D LAr TPC: ML Reco 3D

Input: Charge deposition

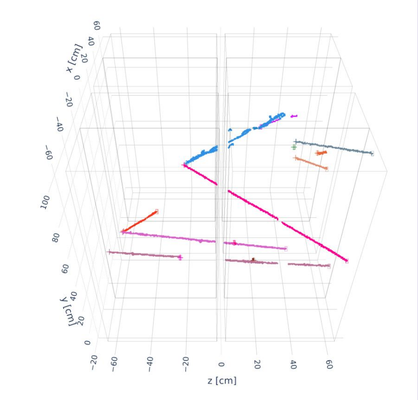


Color: energy deposition heatmap

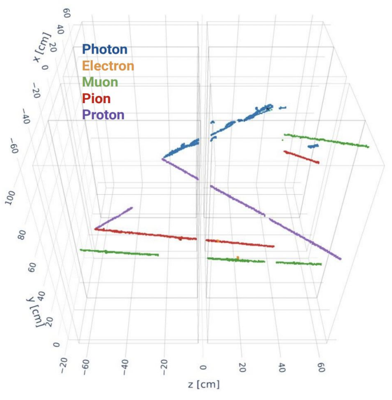
Pixel Features



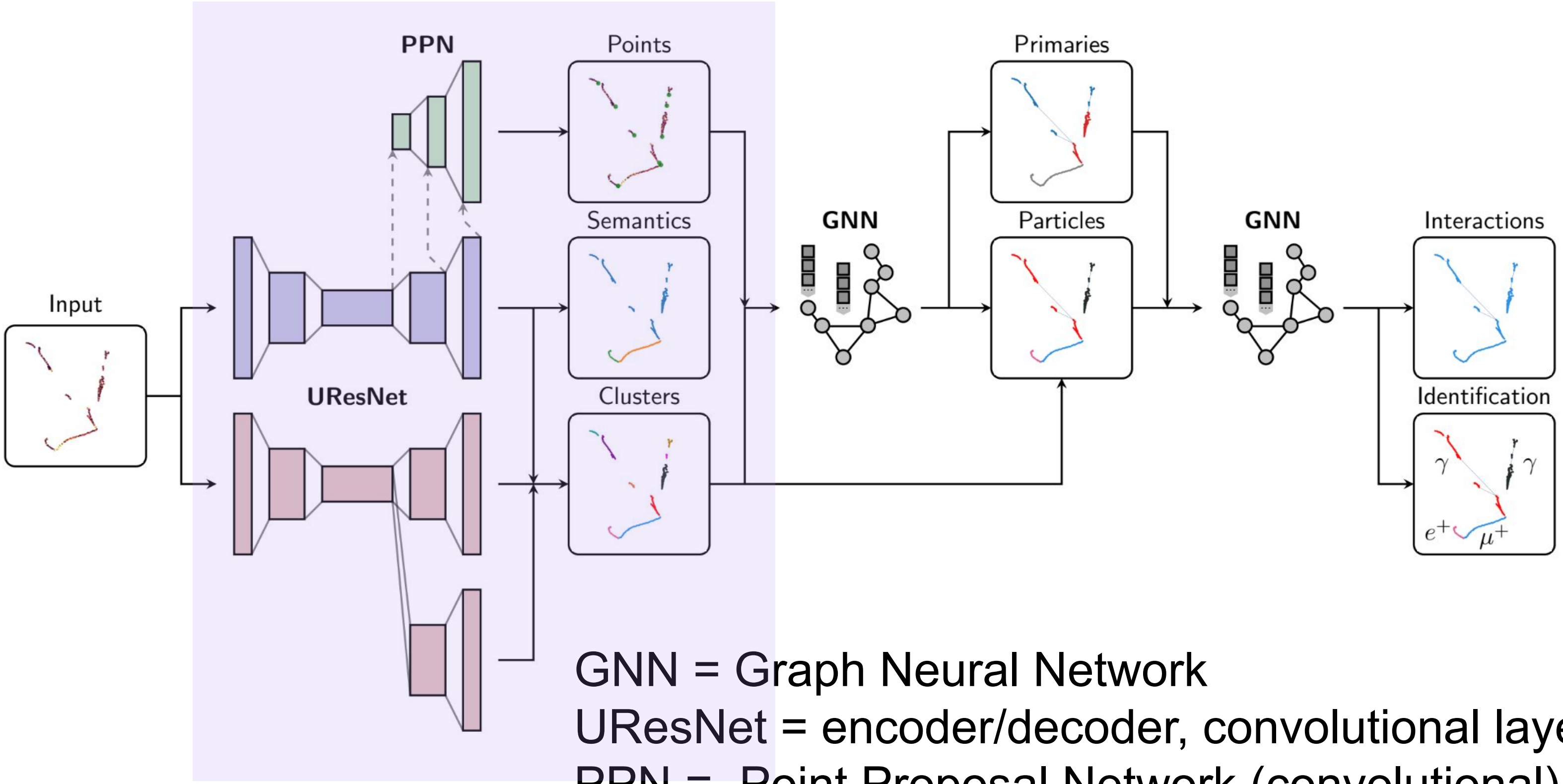
Fragment Clustering



Identification & Interactions



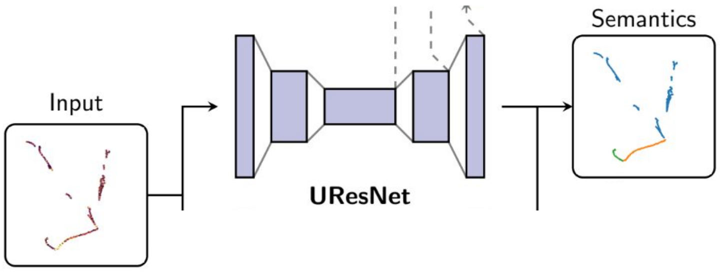
3D LAr TPC: ML Reco 3D

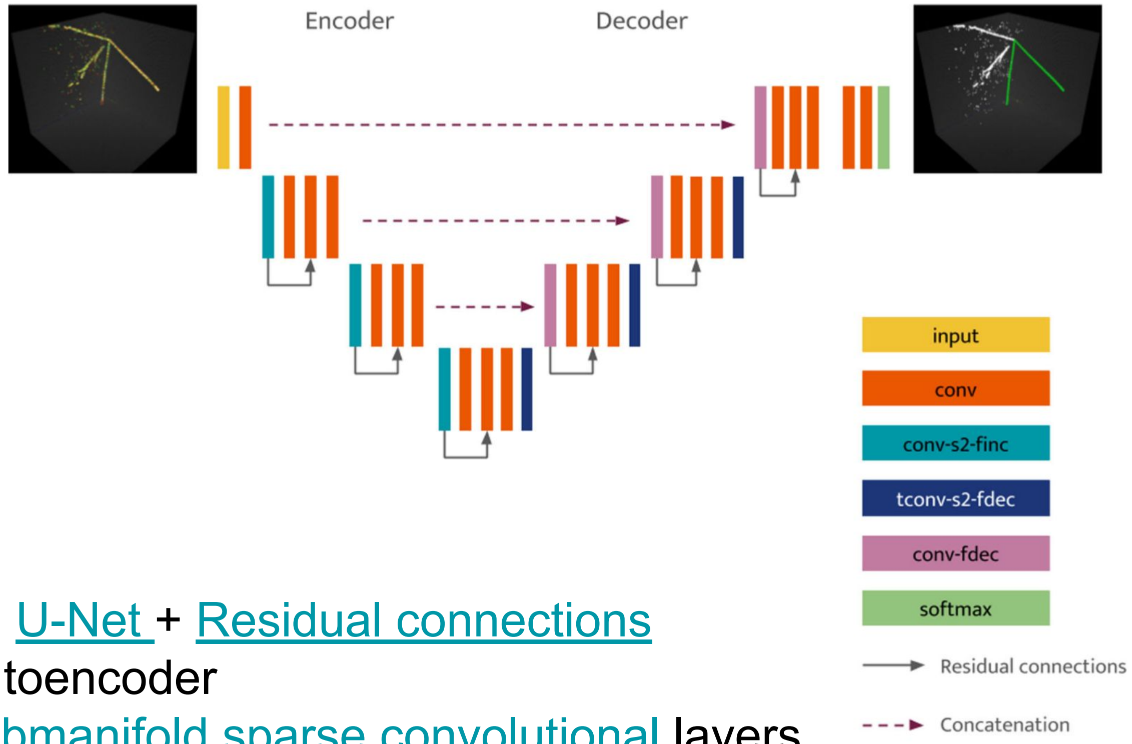


GNN = Graph Neural Network
UResNet = encoder/decoder, convolutional layers
PPN = Point Proposal Network (convolutional)

Pixel Features: Semantics

Pixel feature extraction





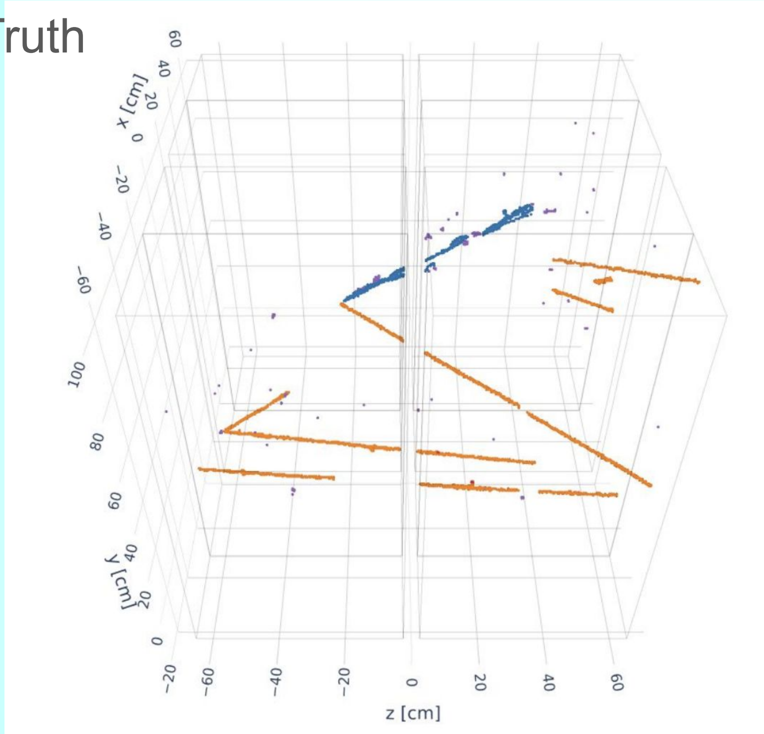
UResNet = U-Net + Residual connections
→ Uses autoencoder
→ Uses submanifold sparse convolutional layers

Phys Rev D (102) 012005

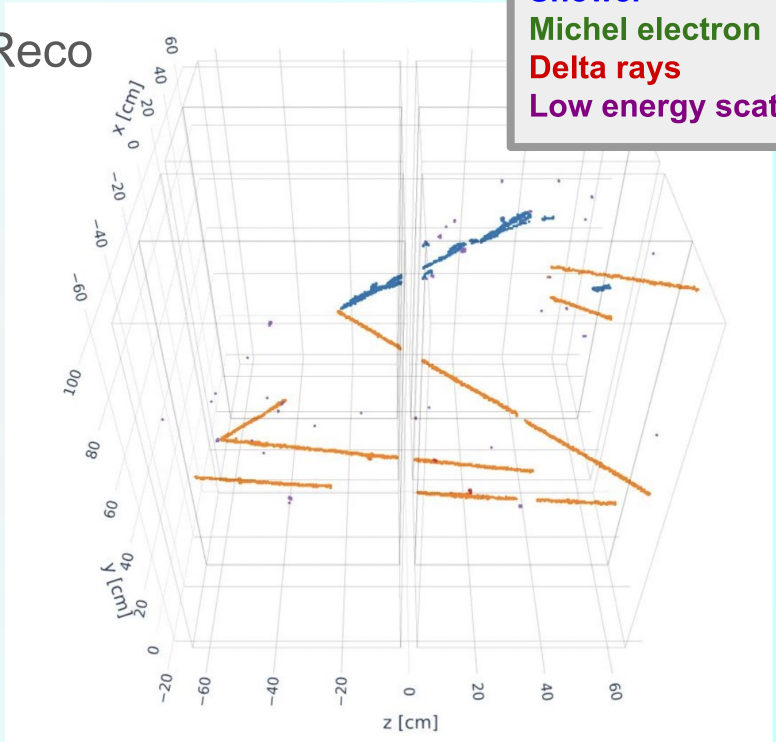
Assign Each Pixel To Label

Track
Shower
Michel electron
Delta rays
Low energy scatters

Truth

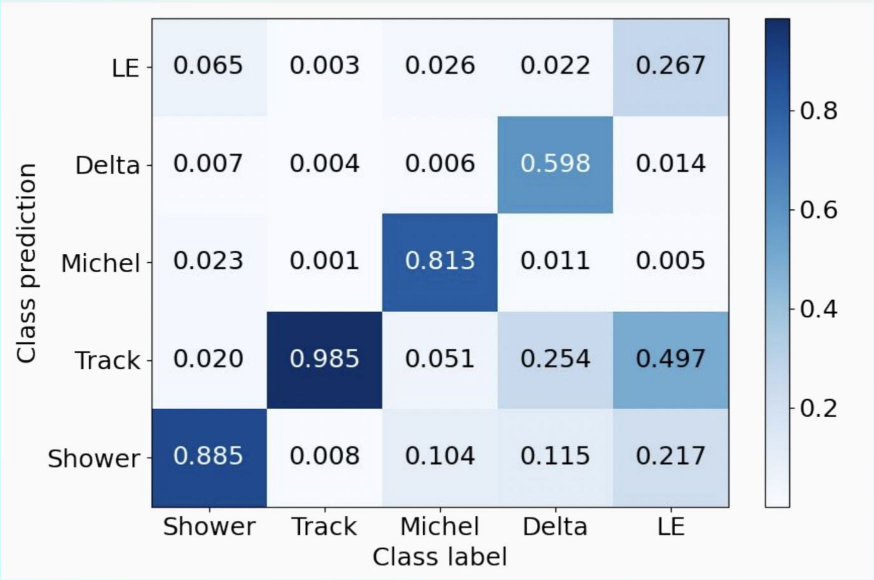


Reco

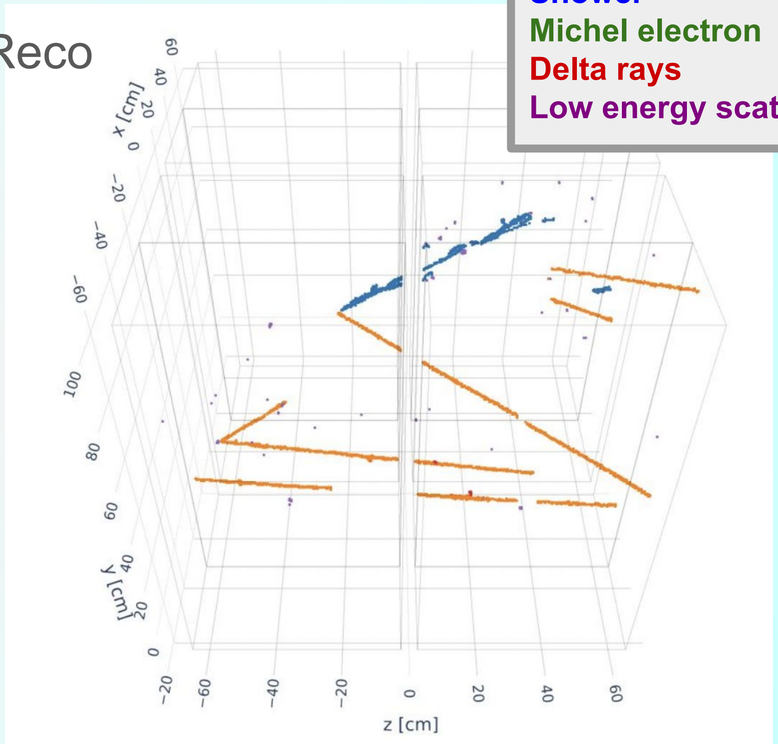


[PhysRevD (102) 012005]() & [PhysRevD (104) 032004]()

Assign Each Pixel To Label



Reco

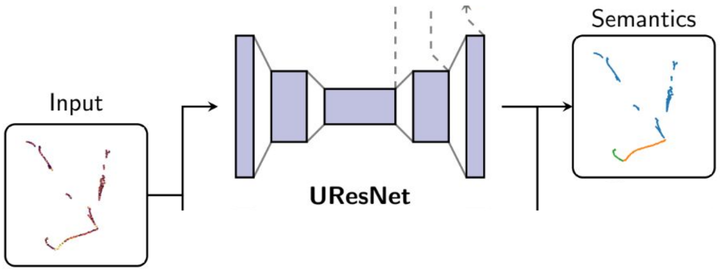


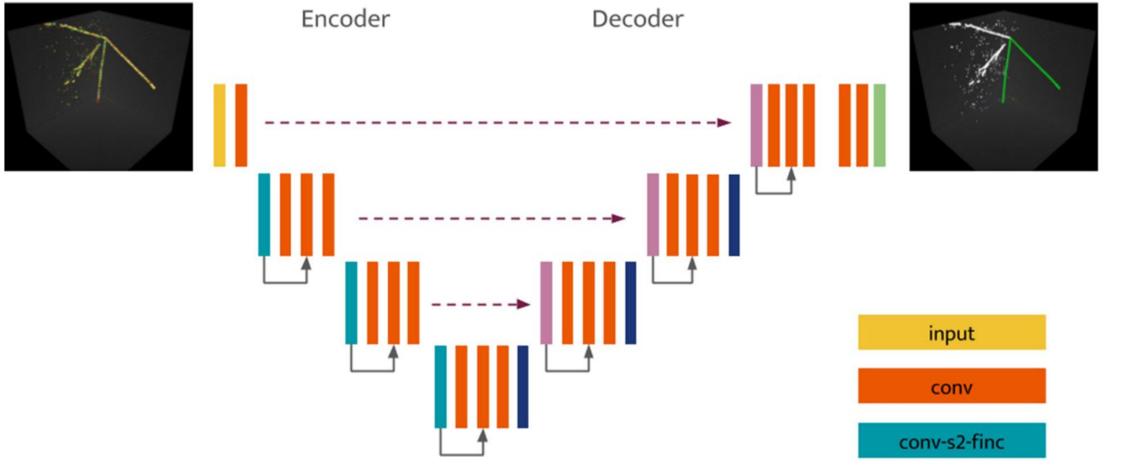
Track
Shower
Michel electron
Delta rays
Low energy scatters

PhysRevD (102) 012005 & PhysRevD (104) 032004

Pixel Features: Semantics

Pixel feature extraction



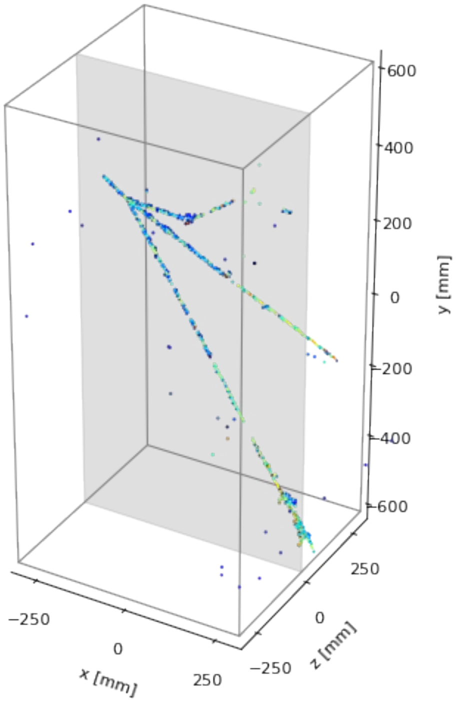


UResNet = [U-Net](#) + [Residual connections](#)
→ Uses autoencoder
→ Uses [submanifold sparse convolutional](#) layers

[Phys Rev D (102) 012005](#)

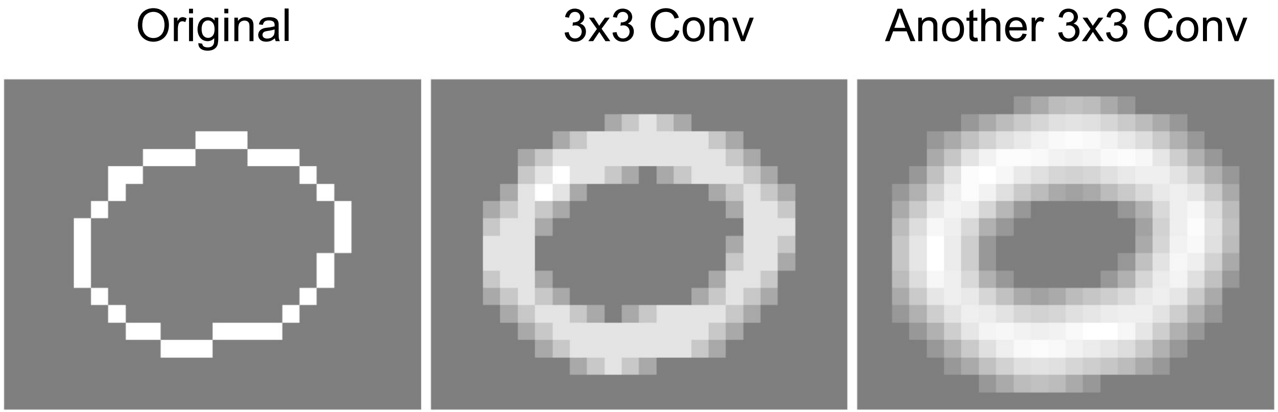
Sparse

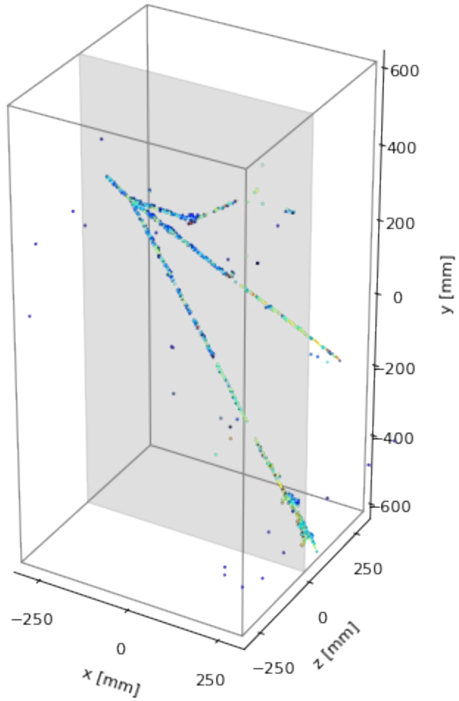
< 0.01 % of the pixels are non-zero!



Submanifold Sparse Convolutions

< 0.01 % of the pixels are non-zero!





❗ Applying regular convolutions reduces sparsity

https://arxiv.org/pdf/1706.01307.pdf

Sparse CNNs on LArTPCs

*Gives capability to train on **entire** LArTPC image, instead of multiple crops!*

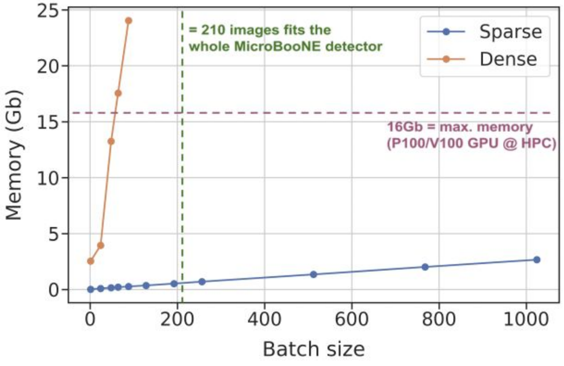


FIG. 3. GPU memory usage as a function of batch size at inference time [2D, 512px, 5-16].

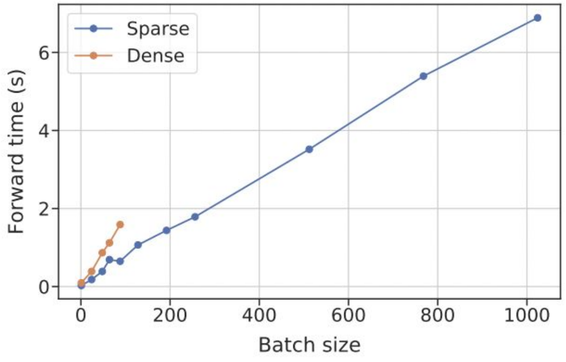


FIG. 4. Computation wall-time as a function of batch size at inference time [2D, 512px, 5-16].

Advantage of sparse conv:

✓ Classification error ~equal

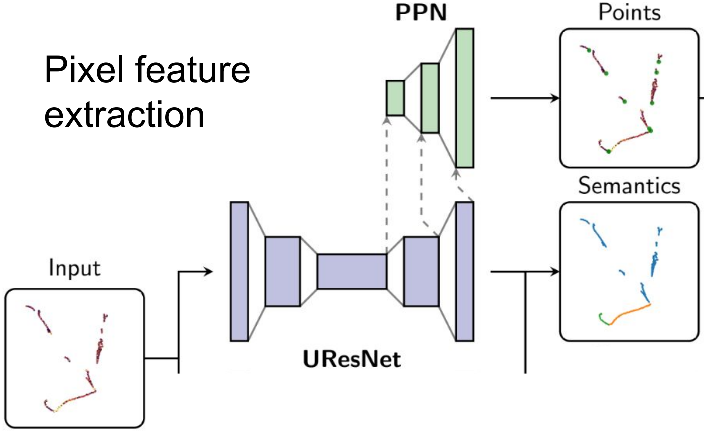
✓ Faster per batch

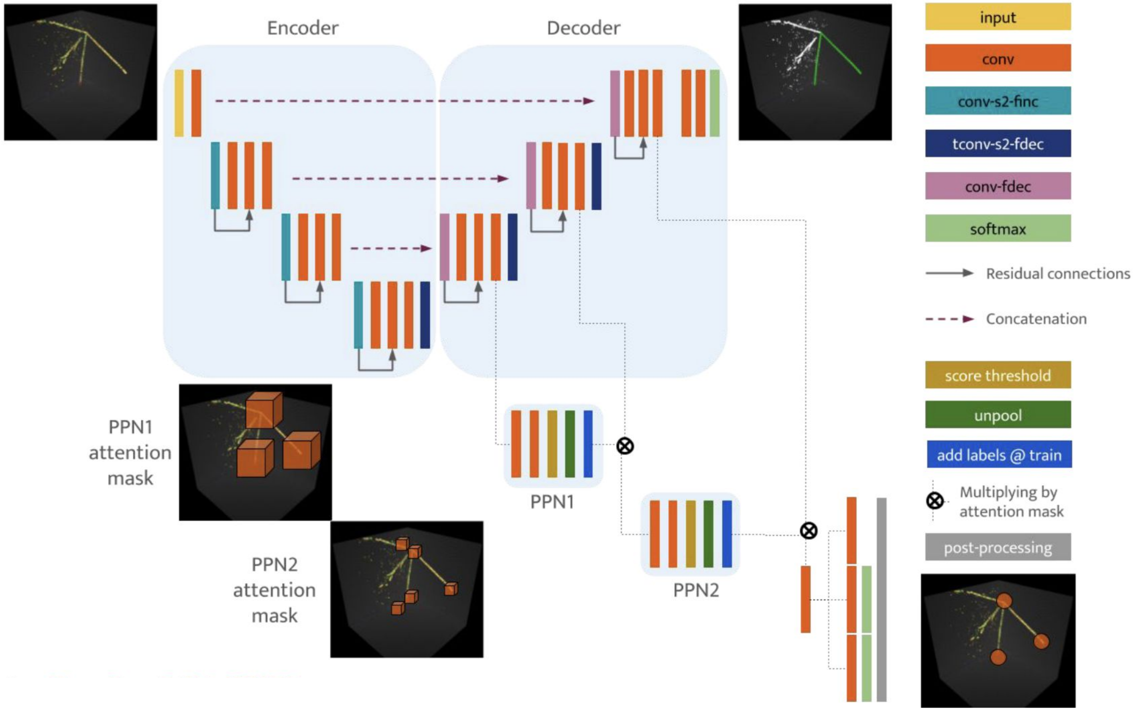
✓ Less memory for even larger batches!

Scalable CNNs for LArTPCs

Pixel Features: Points of Interest

Pixel feature extraction

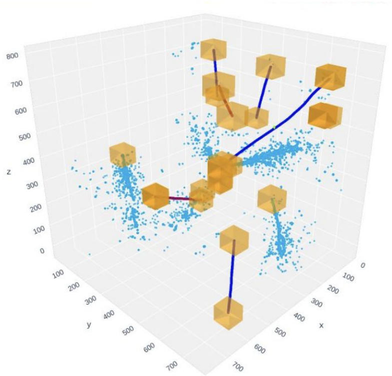


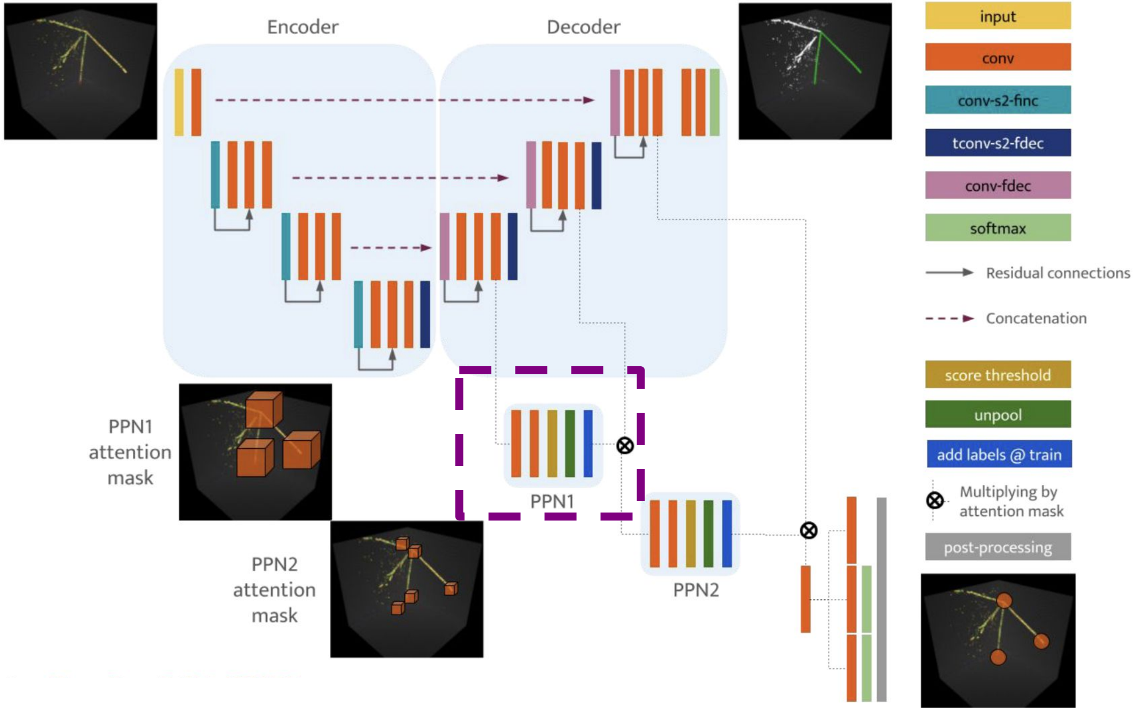


Phys Rev D (104) 032004

Pixel Features: Points of Interest

Pixel feature extraction at low resolution (PPN1)

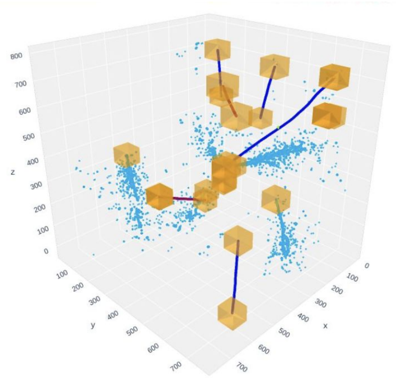




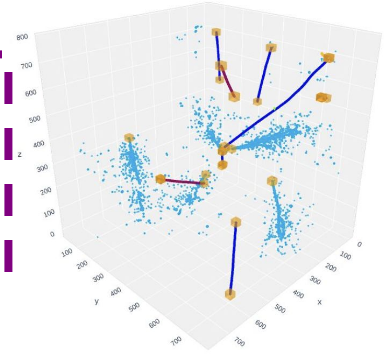
[Phys Rev D (104) 032004](#)

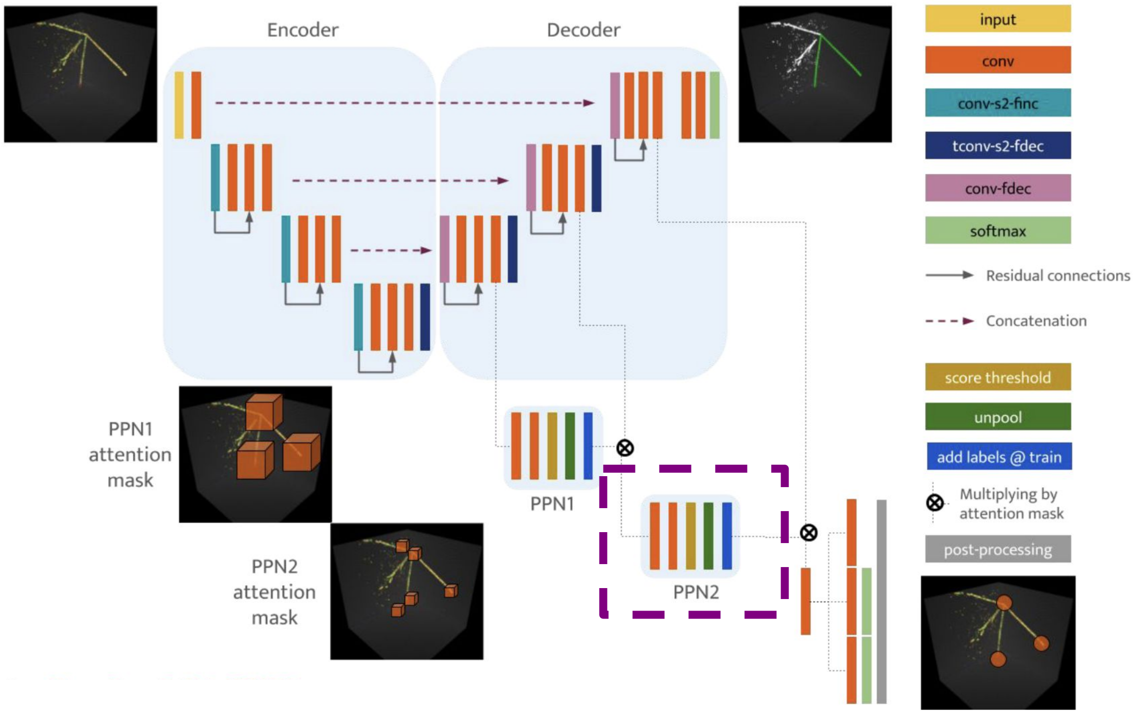
Pixel Features: Points of Interest

Pixel feature extraction at lov resolution (PPN1)



Pixel feature extraction at higher resolution (PPN2)

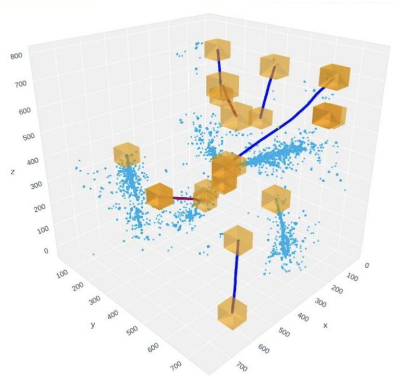




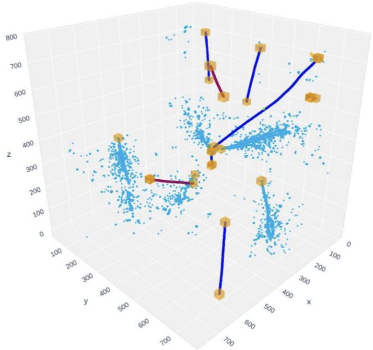
[Phys Rev D (104) 032004](#)

Pixel Features: Points of Interest

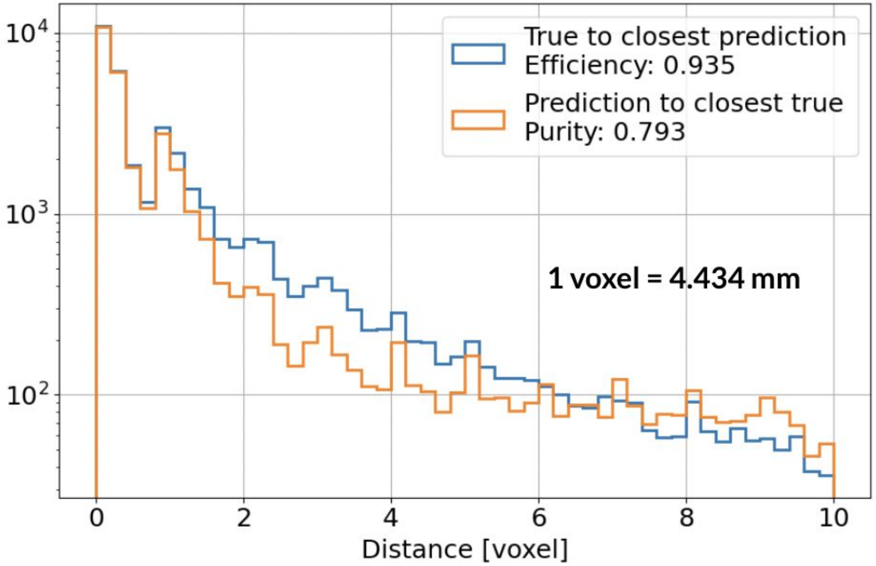
Pixel feature extraction at low resolution (PPN1)



Pixel feature extraction at higher resolution (PPN2)



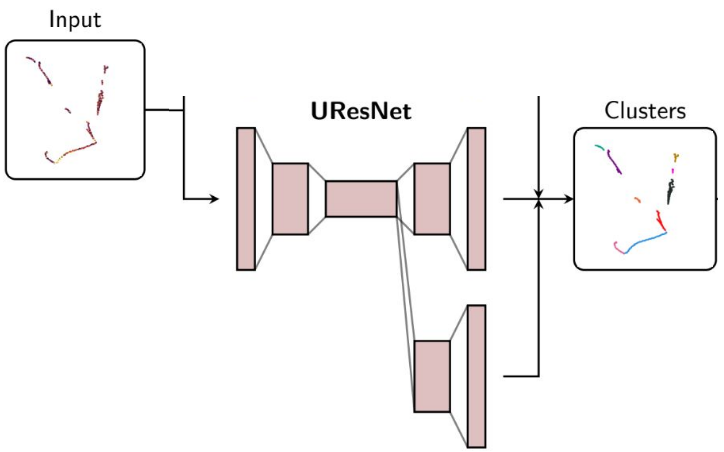
Current Performance on 2x2 Near Detector Prototype



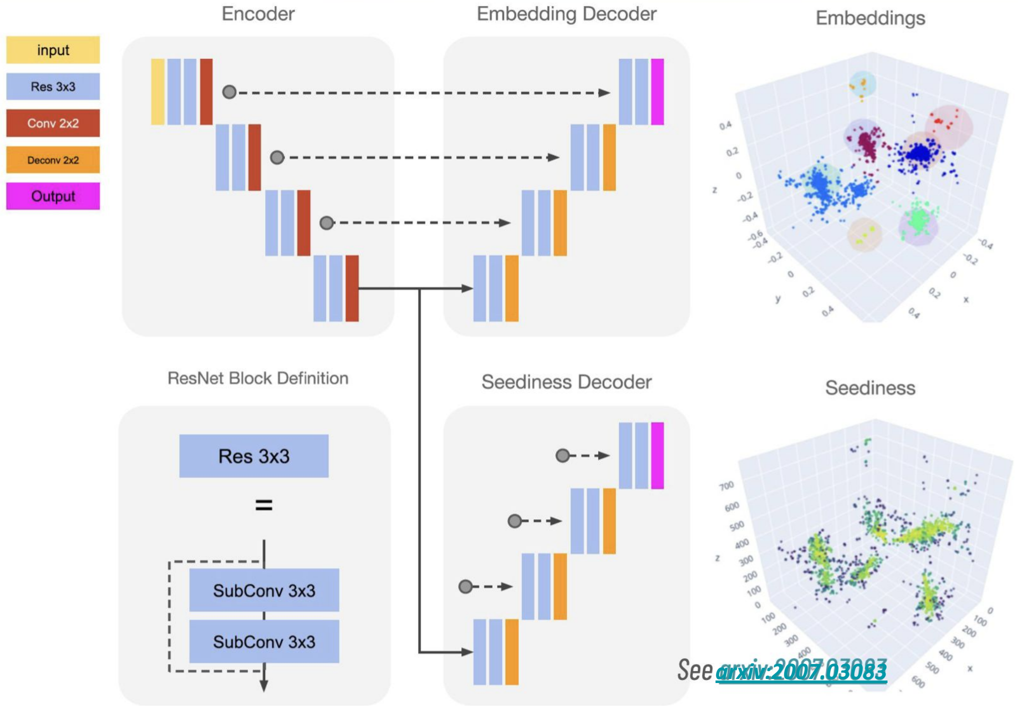
[Phys Rev D (104) 032004]()

Pixel Features: SPICE Clustering

Scalable Particle Instance Clustering using Embedding
→ Points in cluster flow normal distribution, loss uses this

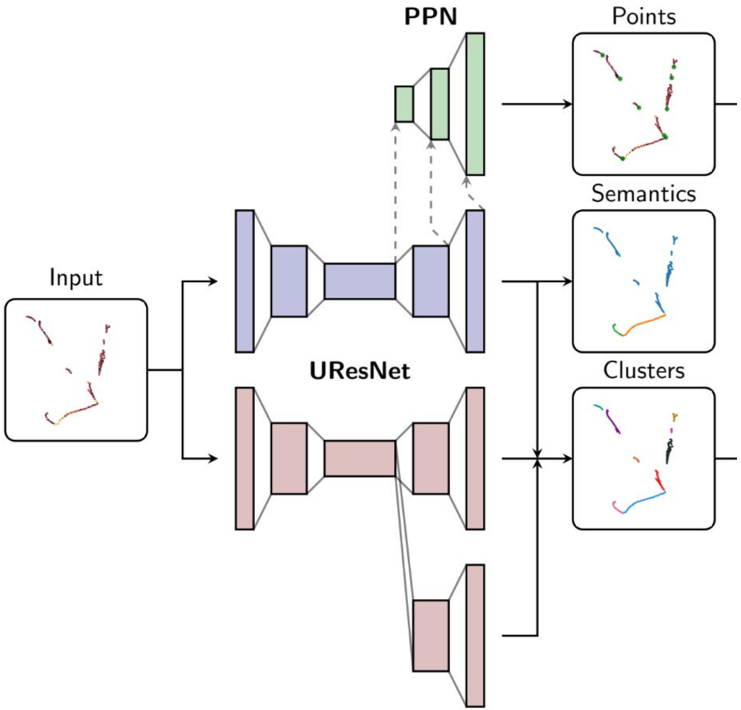


Embedding decoder	Transformation
Seediness decoder	Centroids

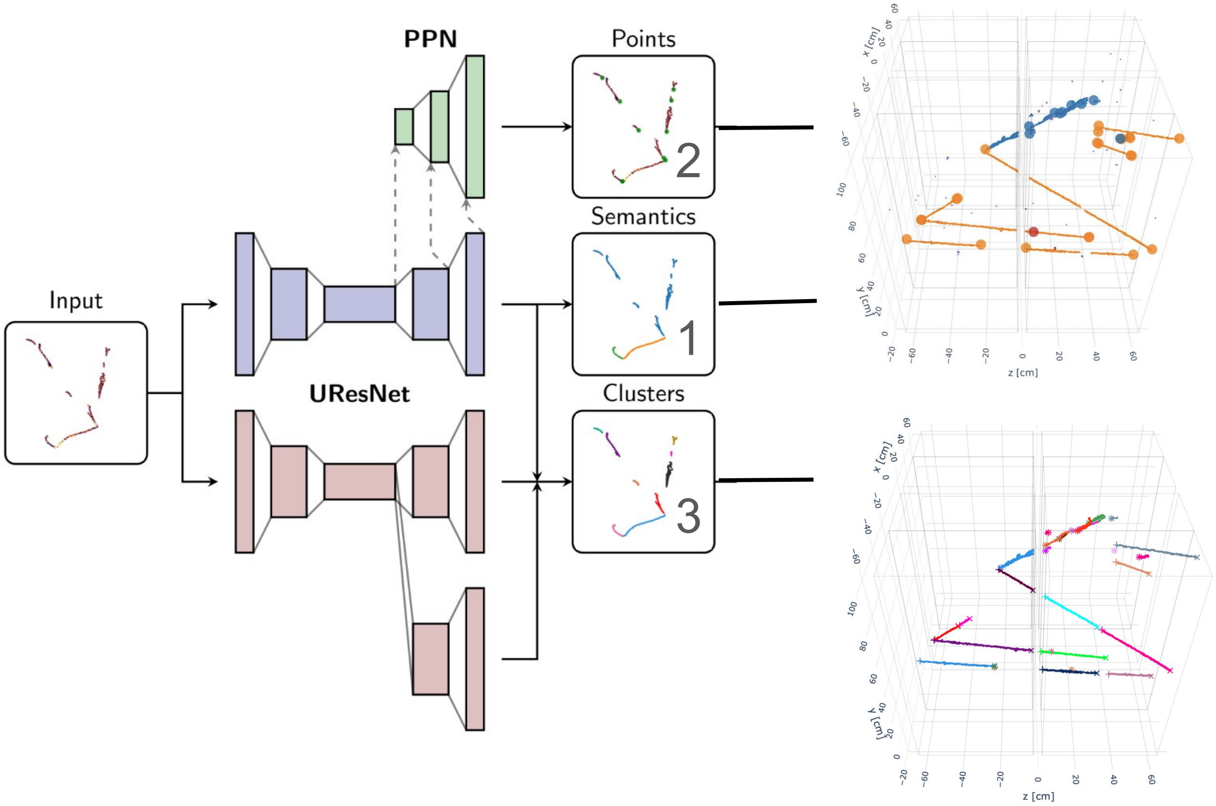


See arxiv:2007.03083

Pixel Features: Output



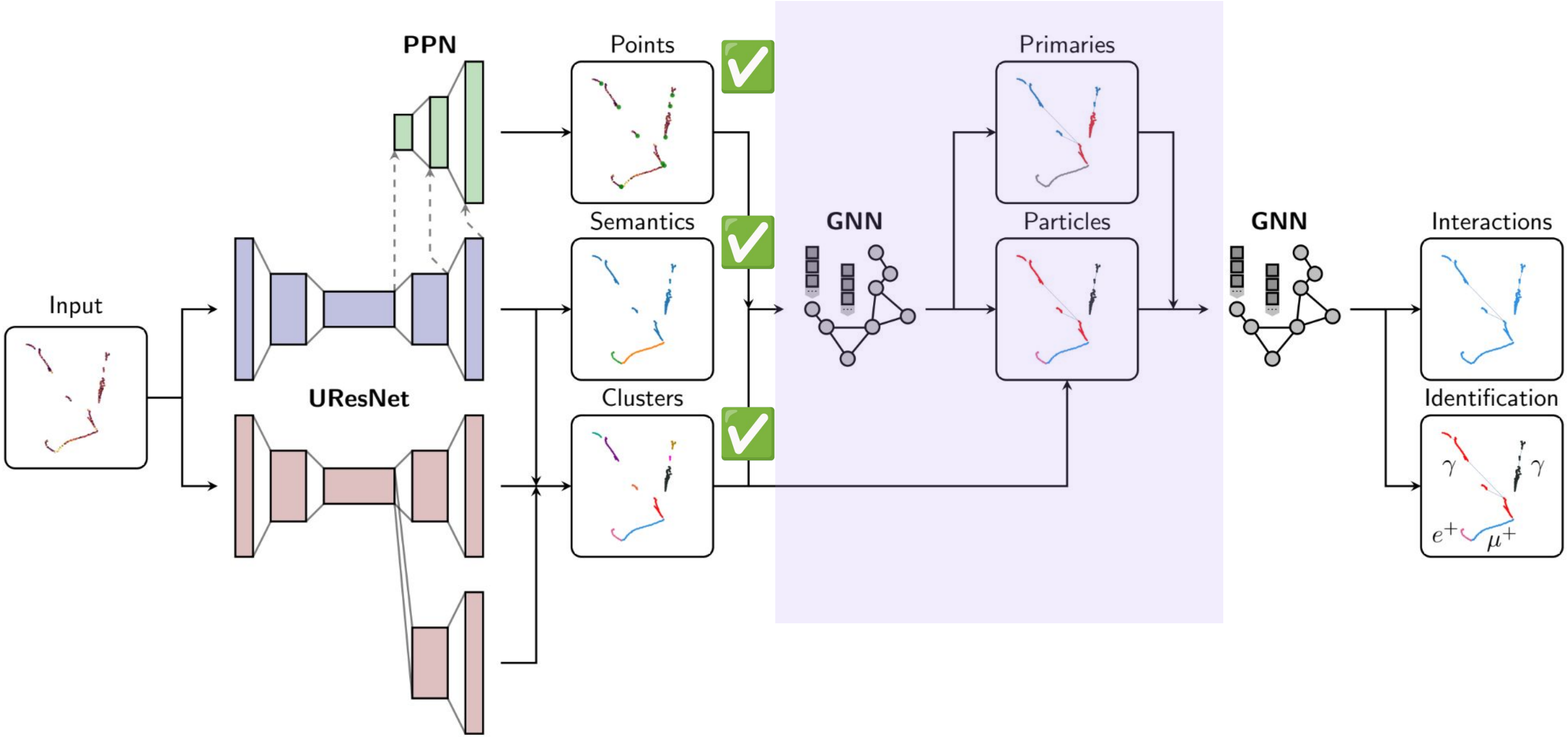
Pixel Features: Output



Track
Shower
Michel electron
Delta rays
Low energy scatters

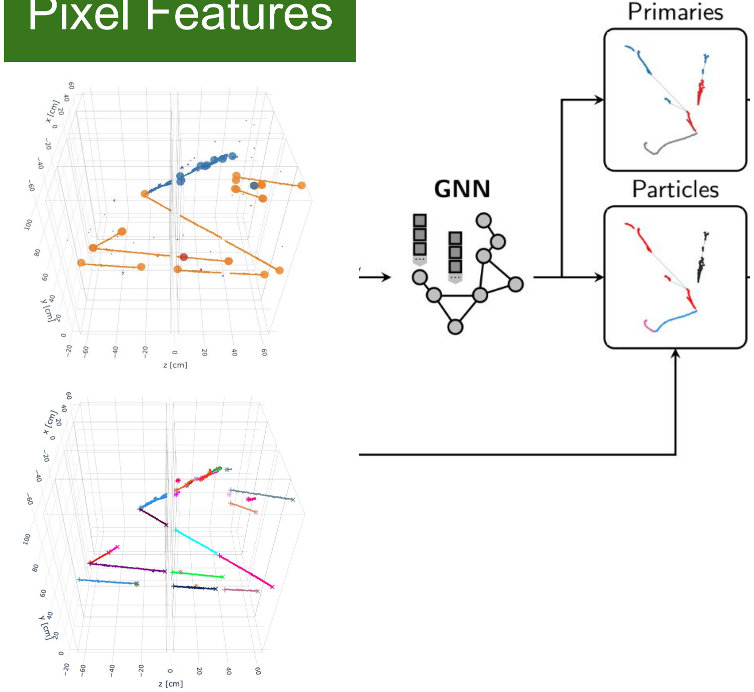
1. Pixel "signature" of particle interaction type
2. Points of interest
   a. Start of tracks & showers
   b. End track
3. Pixel clusters
   a. Including centroids

3D LAr TPC: ML Reco 3D

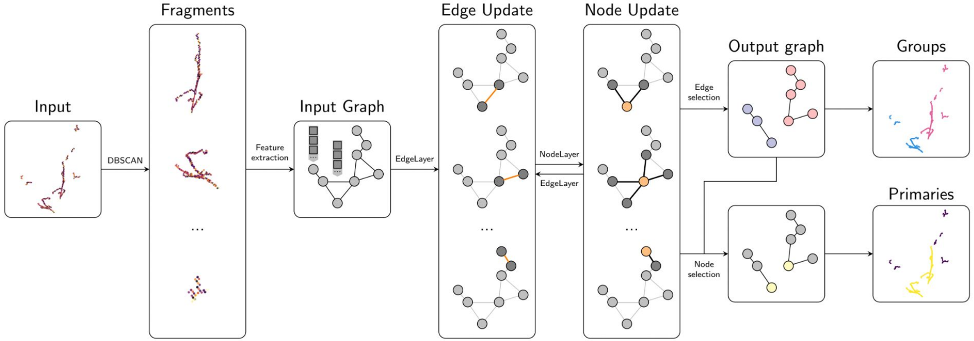


Cluster Clustering

Pixel Features



Use Graph Neural Network

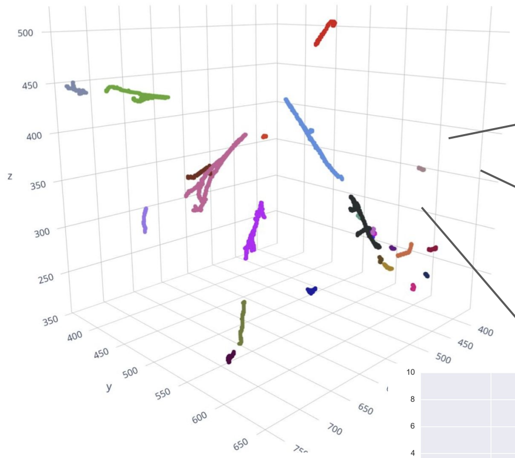


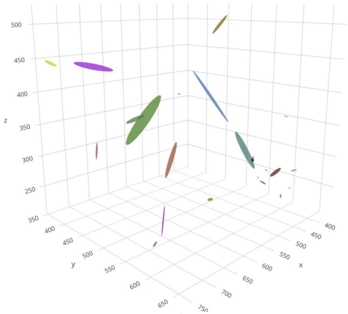
GrapPA: Graph Particle Aggregator

arxiv 2020

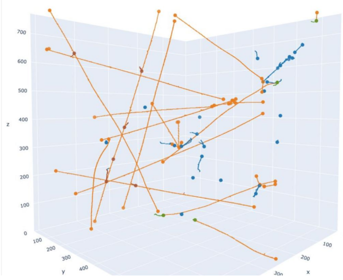
Cluster Clustering: Inputs

Input: Encode Fragments into set of node features





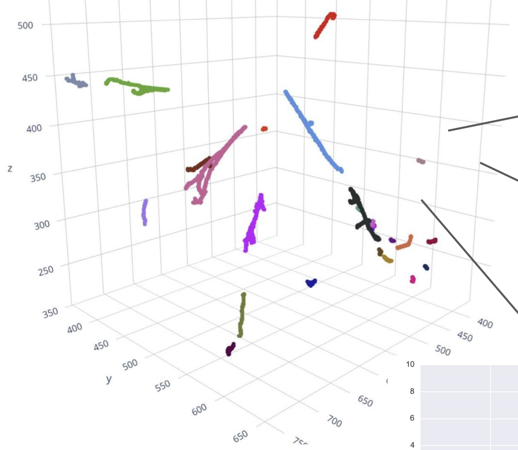
PCA (plot not related to LArTPC data)

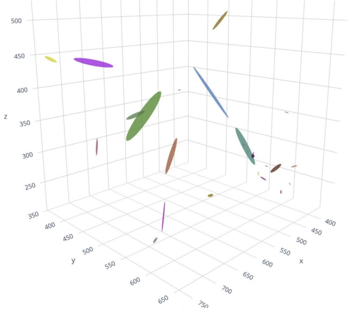


Fragment Summary	# Features
Number of voxels	1
Initial Point	3
Normalized initial direction	3
Normalized covariance matrix	9
Normalized principal axis	3
Centroid	3

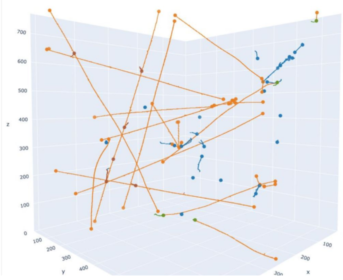
Cluster Clustering: Inputs

Input: Encode Fragments into set of node features

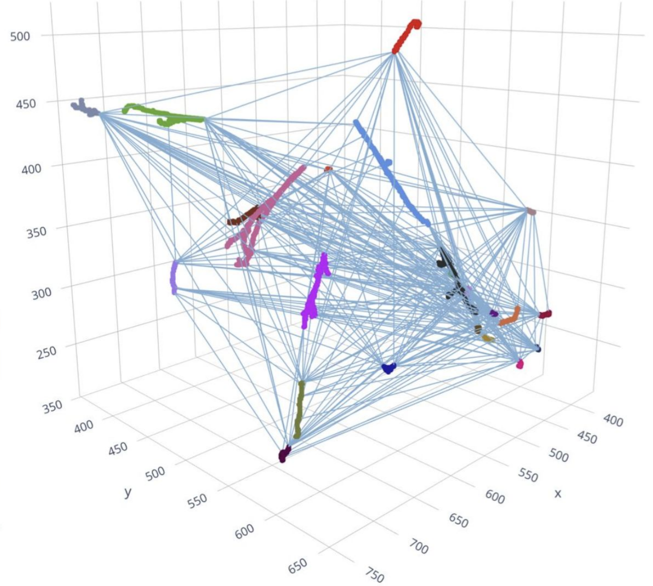




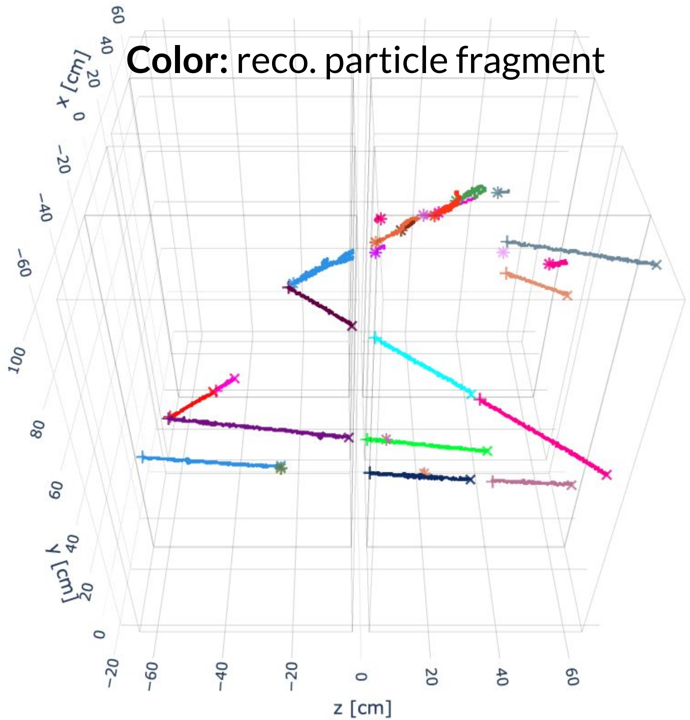
PCA (plot not related to LArTPC data)

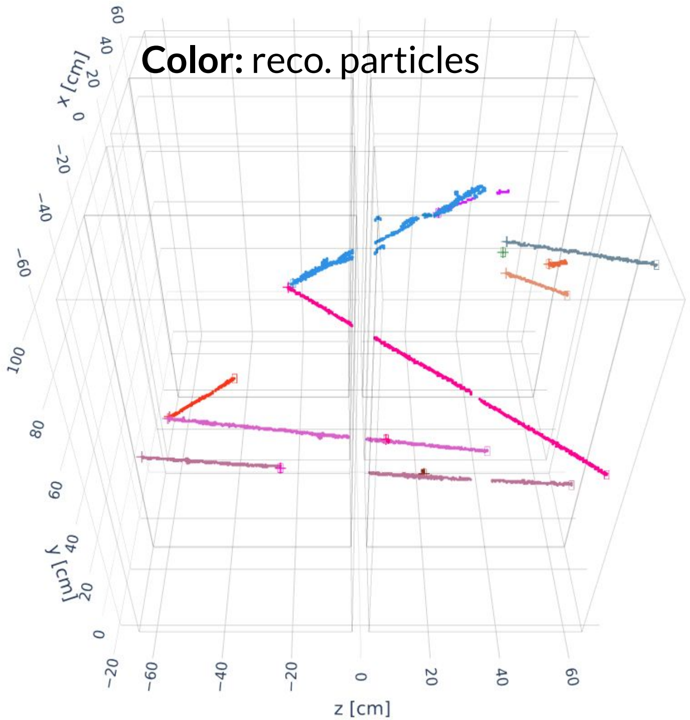


Fully connect nodes



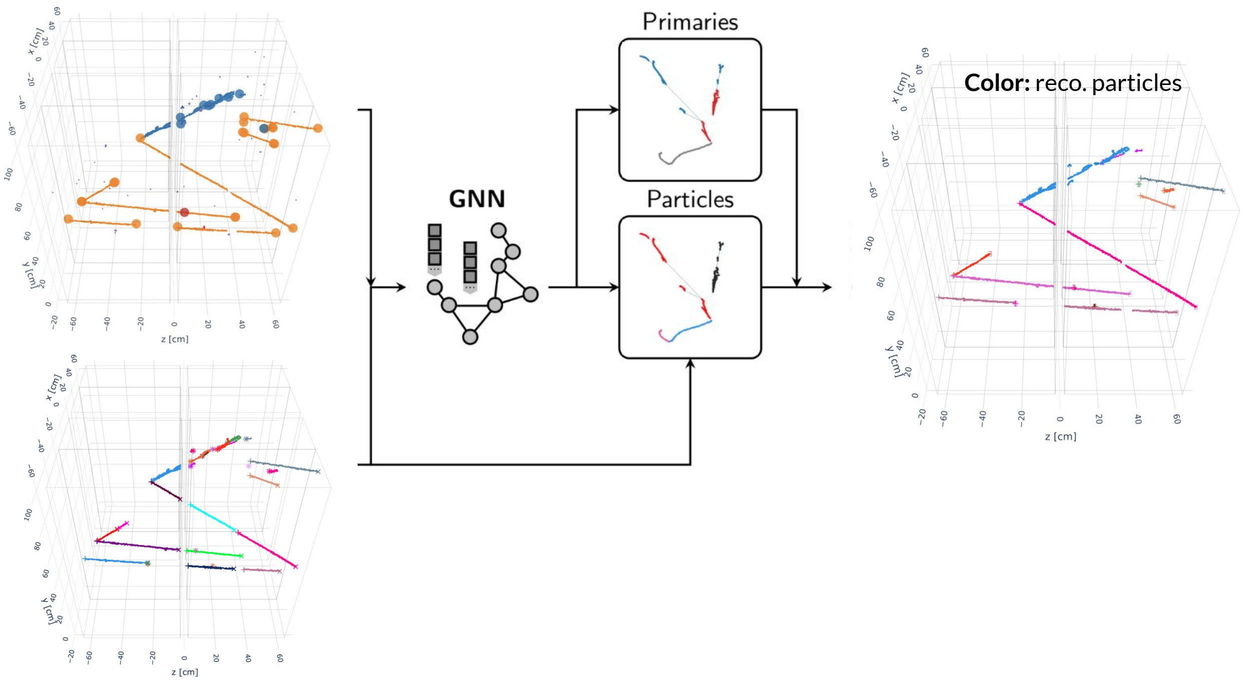
Cluster Clustering: Particle Clustering





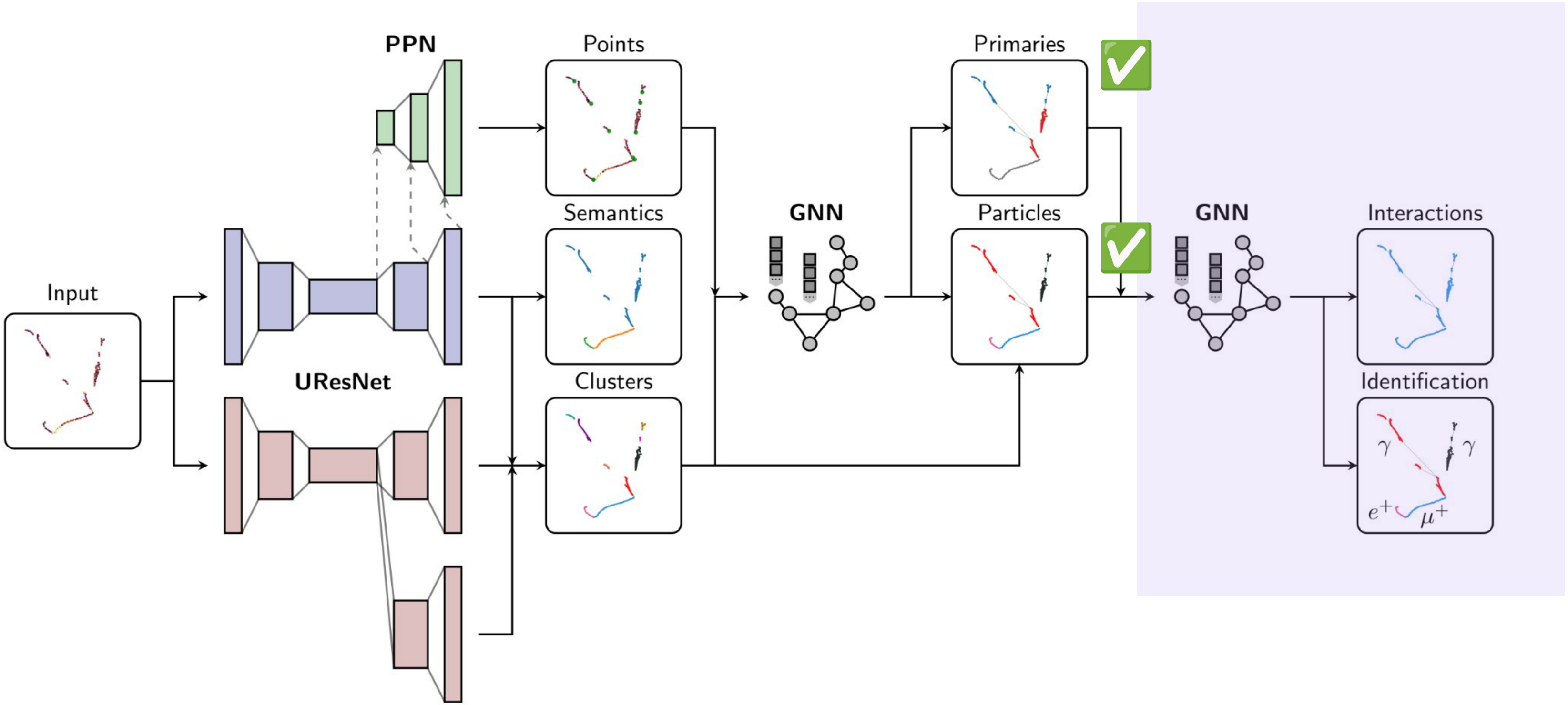
Output: Primaries & Particles

Pixel Features



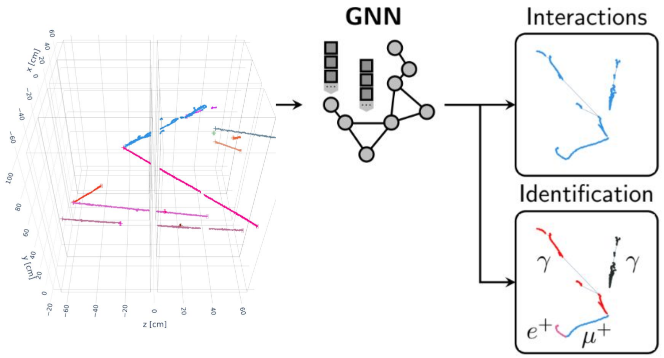
Fragment Features

3D LAr TPC: ML Reco 3D

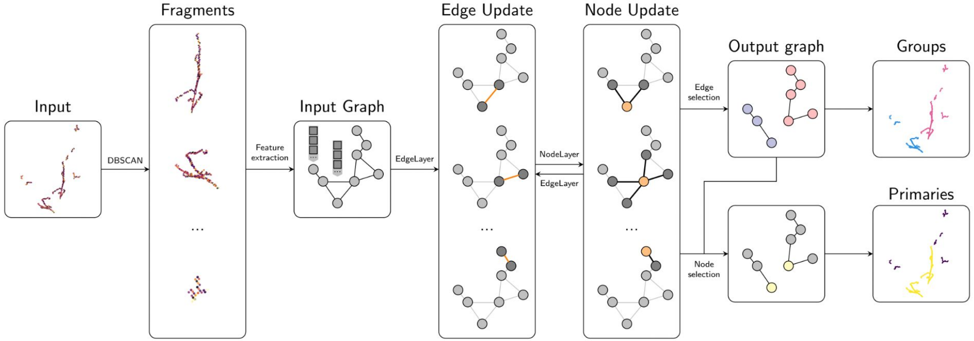


Interactions & Identification

Fragment Features



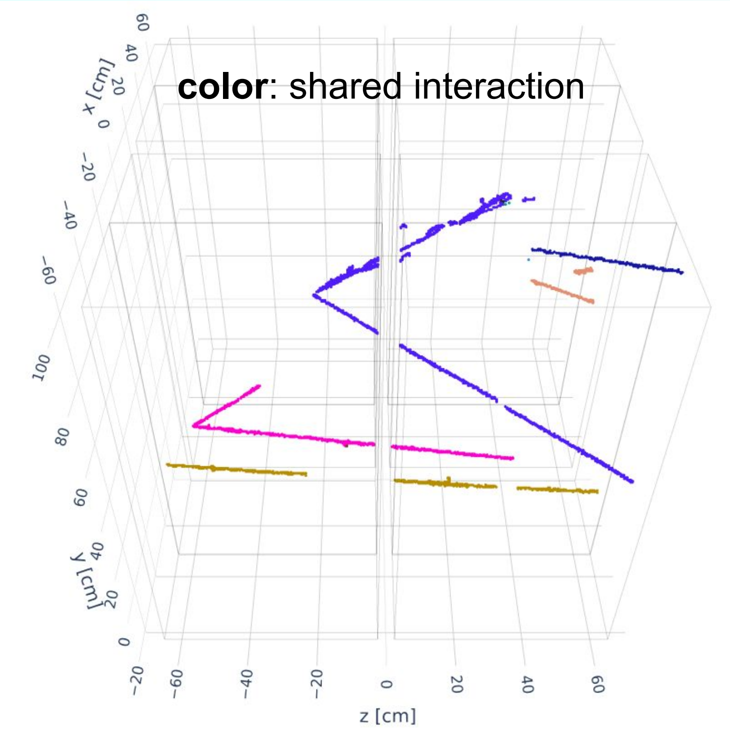
Re-use GrapPA



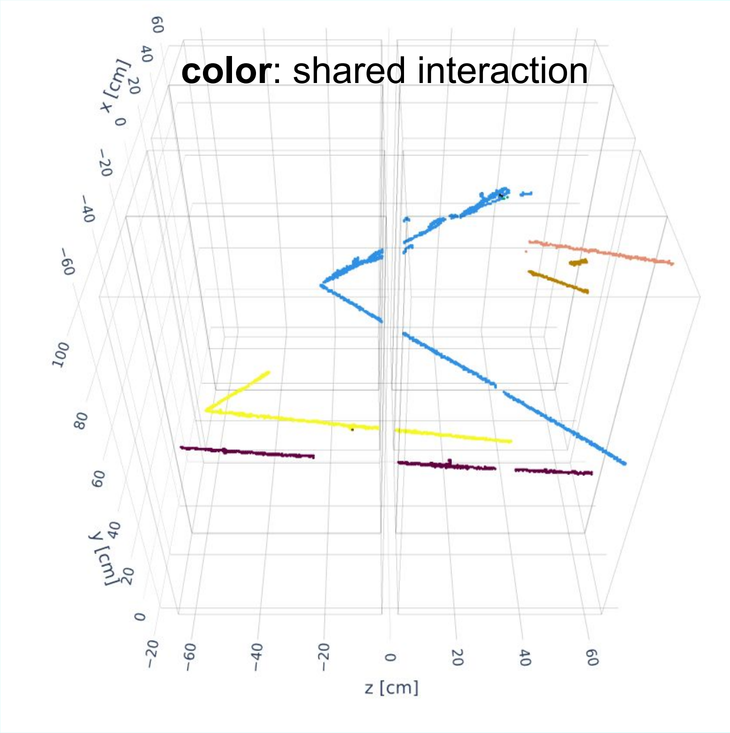
Interactions = find same neutrino source
- \+ Edges classification for interactions
- \+ Nodes classification for identification

Performance Shared Interaction

Truth

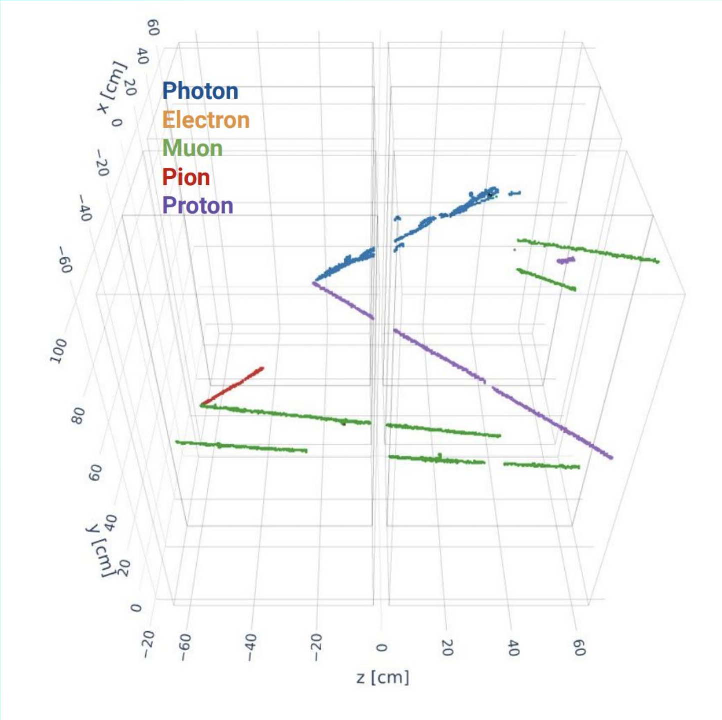


Reco

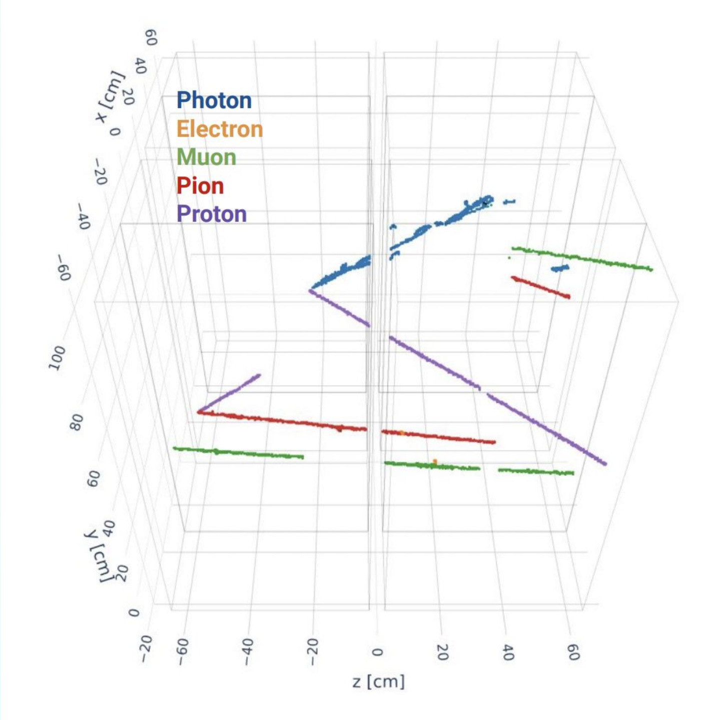


Performance: Example for Prototype ND

Truth

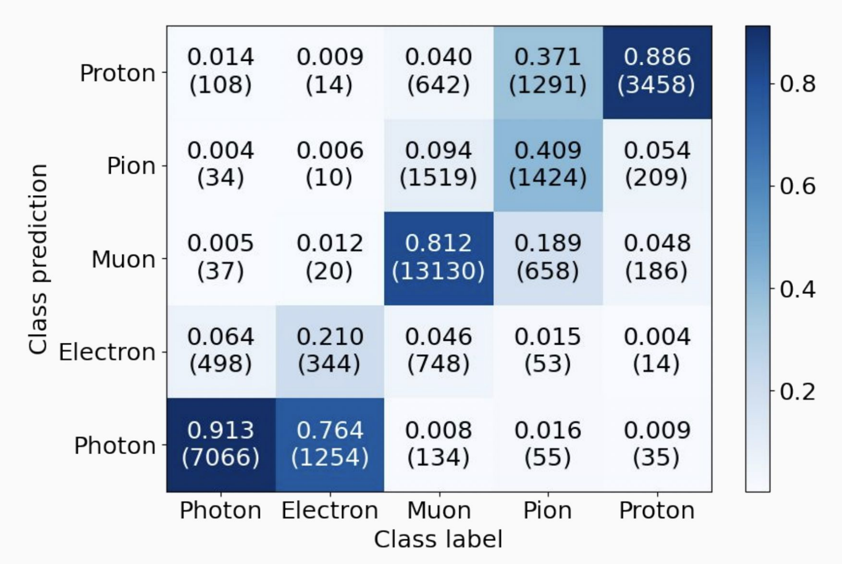


Reco

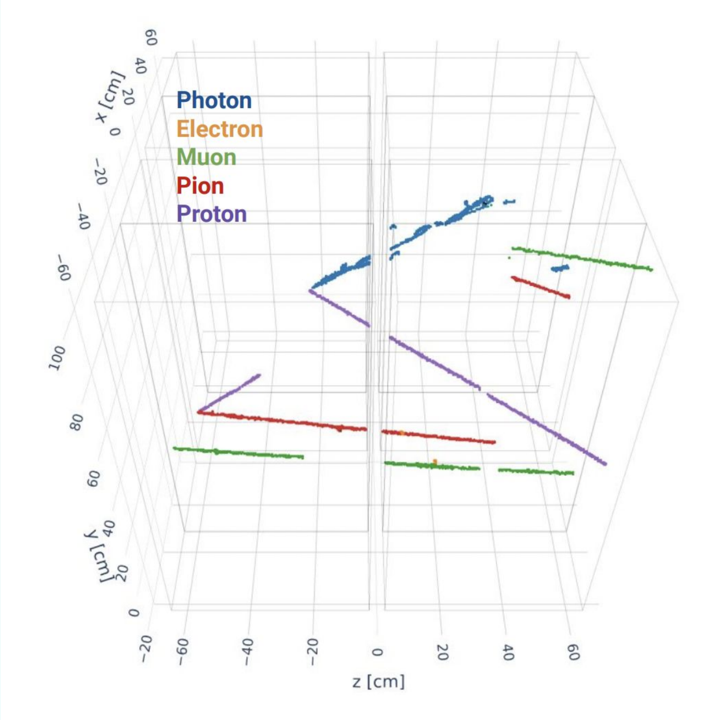


Performance: Metrics

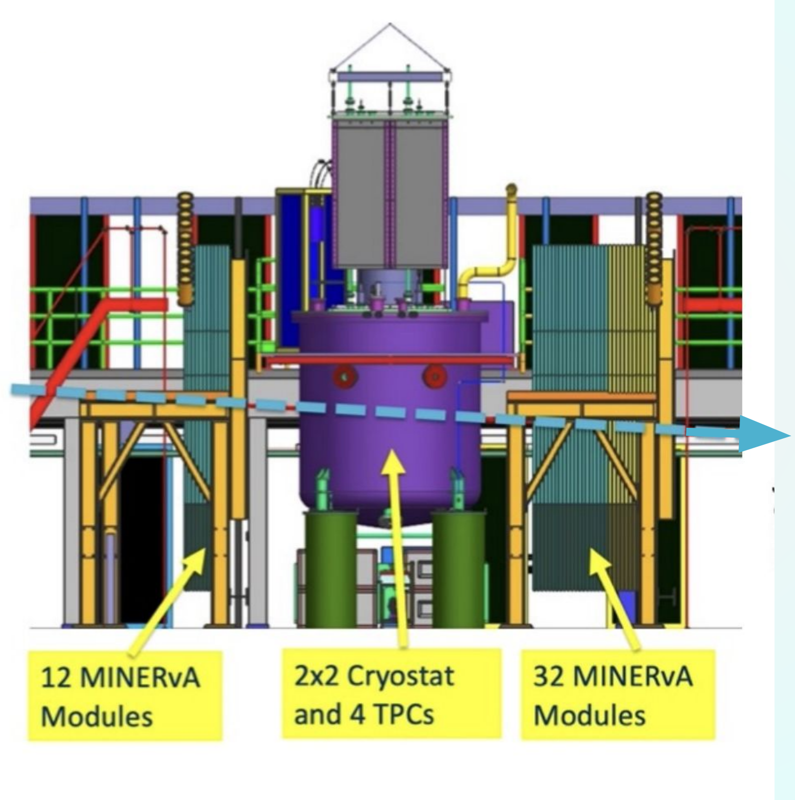
Performance



Reco

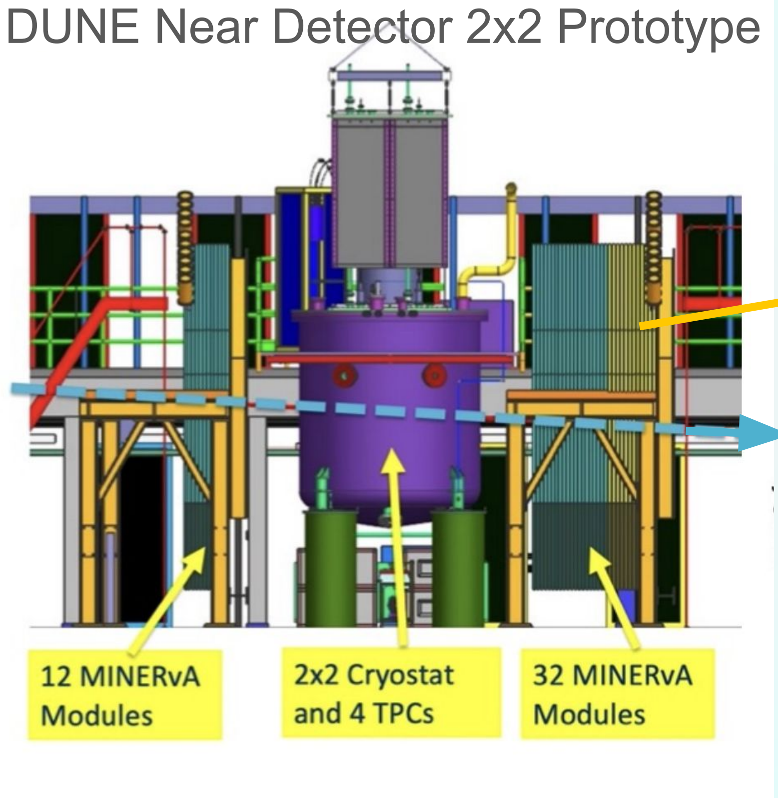


DUNE Near Detector 2x2 Prototype

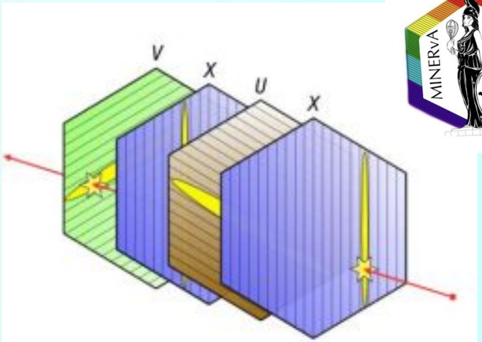


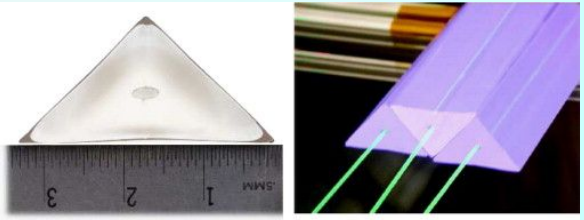
See Brooke's [ND-LAr Overview]() from Thursday afternoon!

MINERvA uses Solid Scintillator Planes



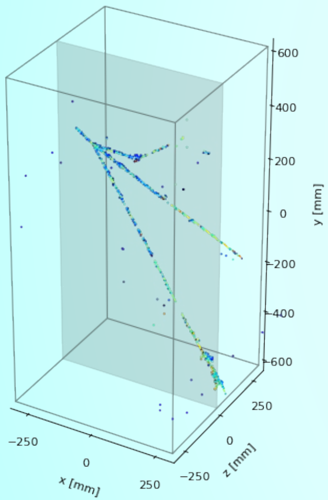
MINERvA: Solid scintillation particle detector with 3 orientations

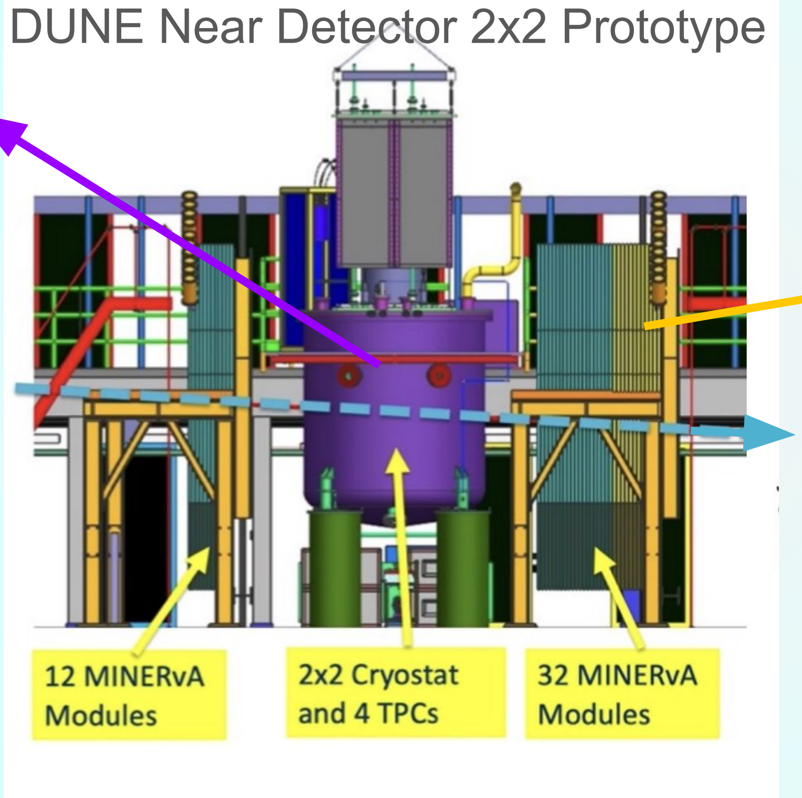




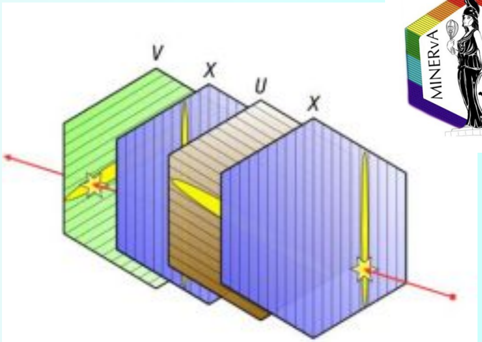
DUNE 2x2 uses Liquid Argon TPCs

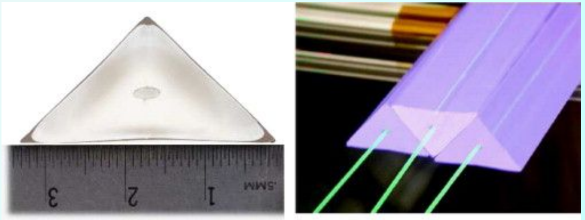
4 LArTPCs with 3D pixel readout

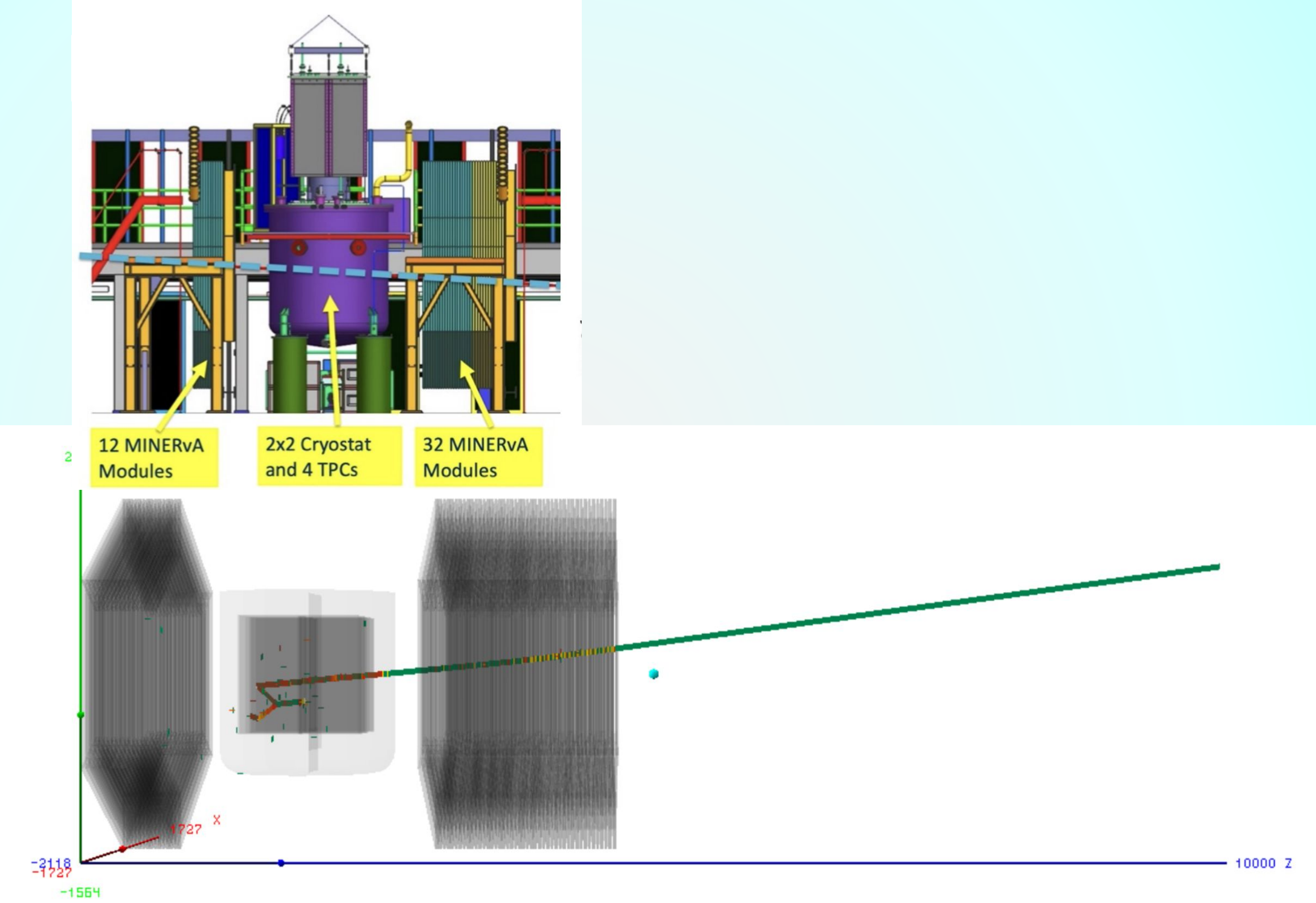




MINERvA: Solid scintillation particle detector with 3 orientations



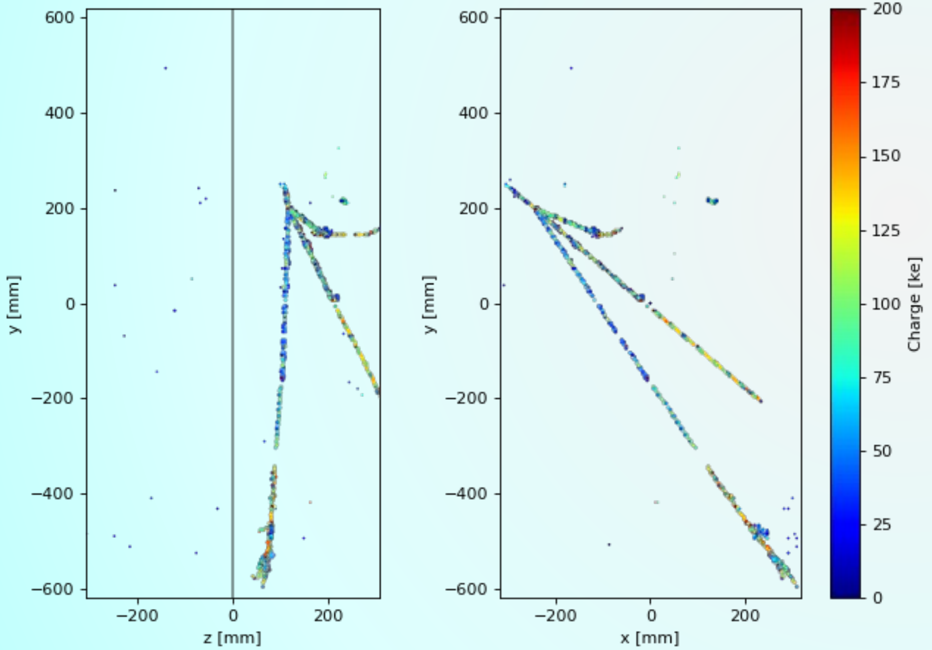



12 MINERvA Modules
2x2 Cryostat and 4 TPCs
32 MINERvA Modules
X
1727
-2118
-1727
-1564
10000 Z

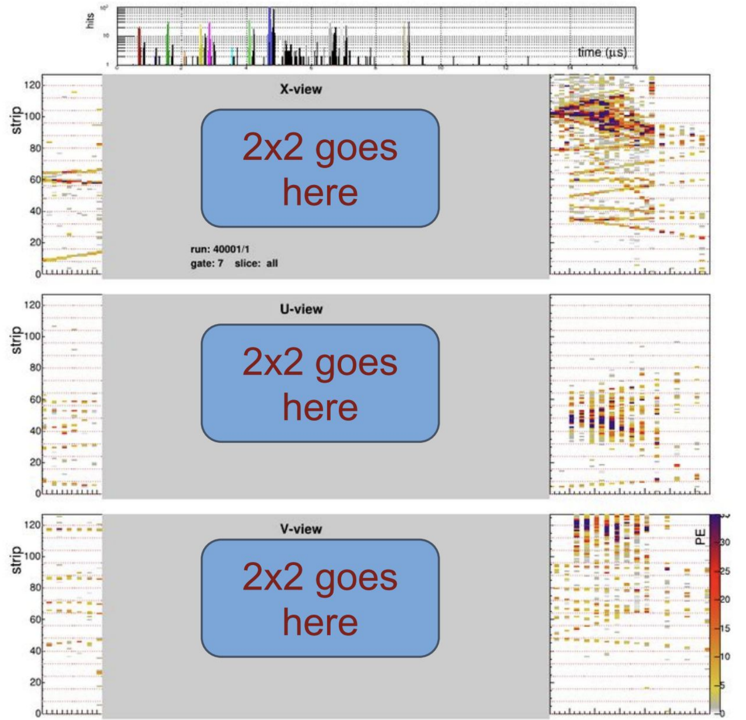
Wait! MINERvA has different detection resolution

→ ***CNN would be affected by this***

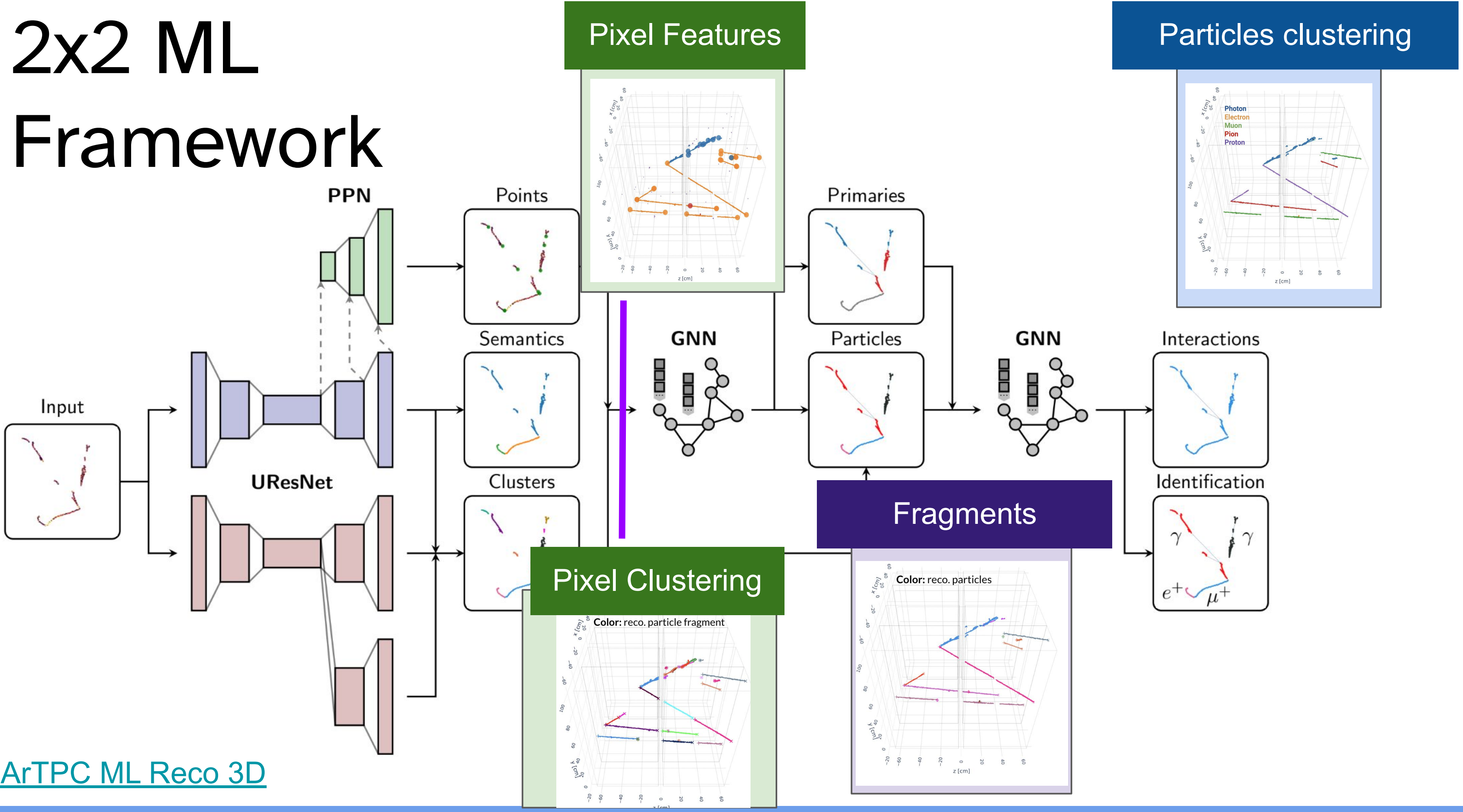
2x2 in 2D projection simulation



Preliminary
DUNE ND-LAr 2x2 MINERvA data

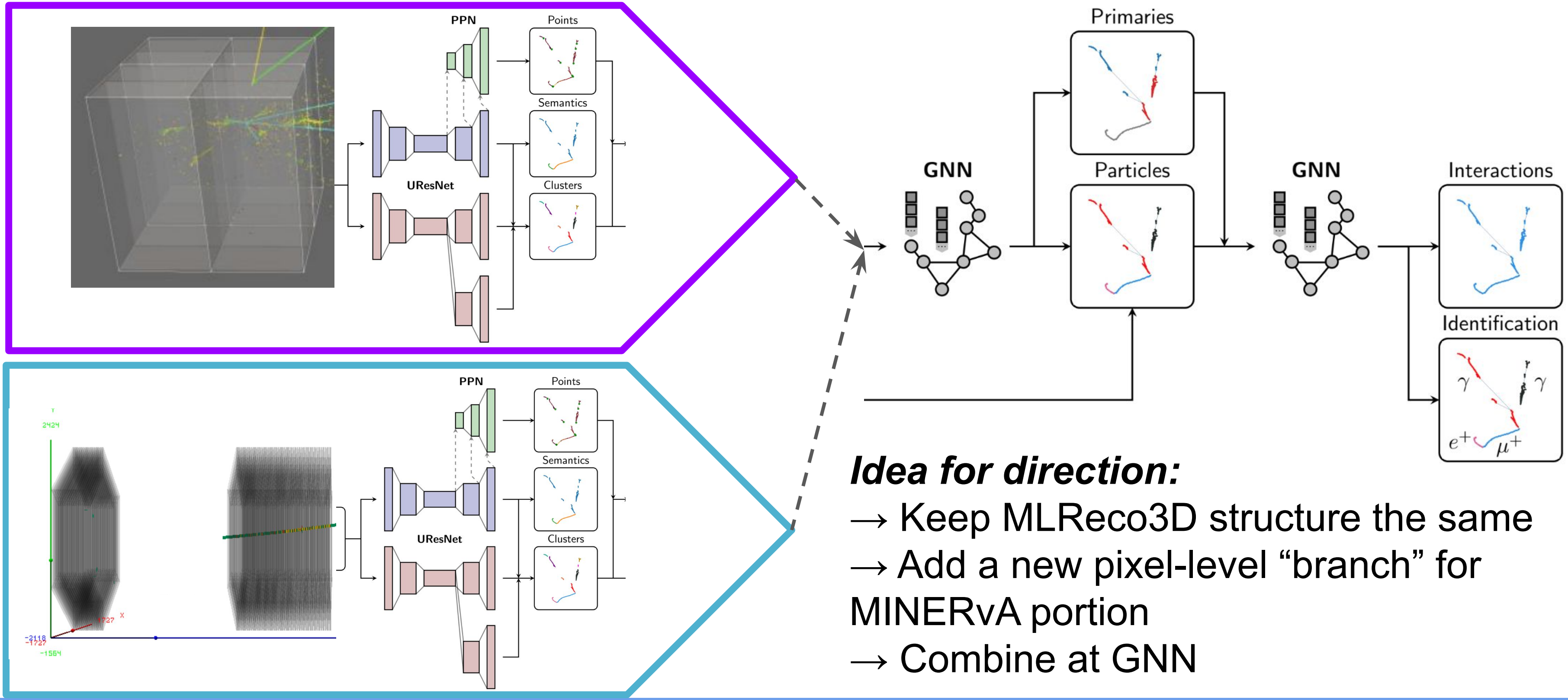


2x2 ML Framework



[LArTPC ML Reco 3D]

ML Reco 3D: Adding MINERvA



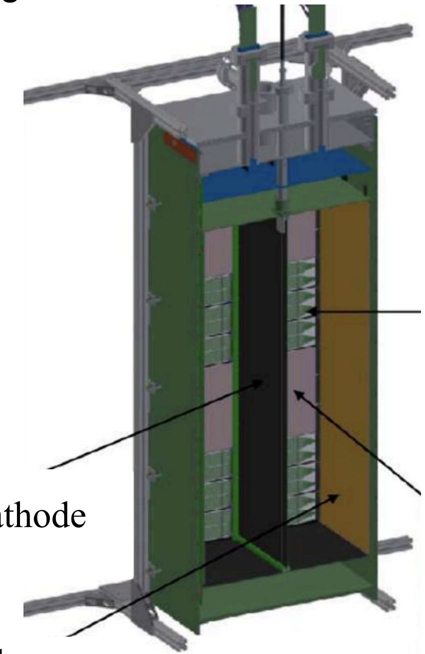
Idea for direction:

→ Keep MLReco3D structure the same
→ Add a new pixel-level “branch” for MINERvA portion
→ Combine at GNN

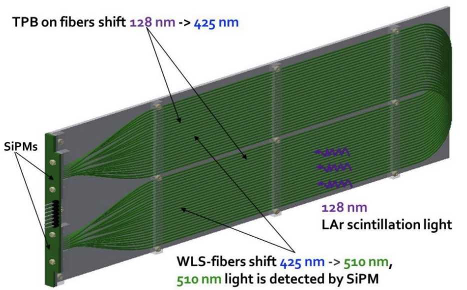
Future Applications

- Integrating detection from multiple detectors into single network
  - Light & Charge

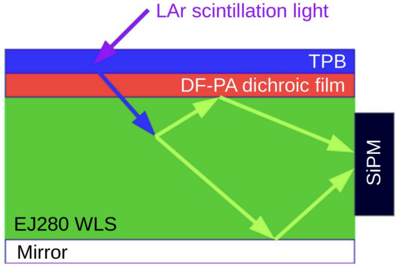
Single ND-LAr Module



Light Collection Module



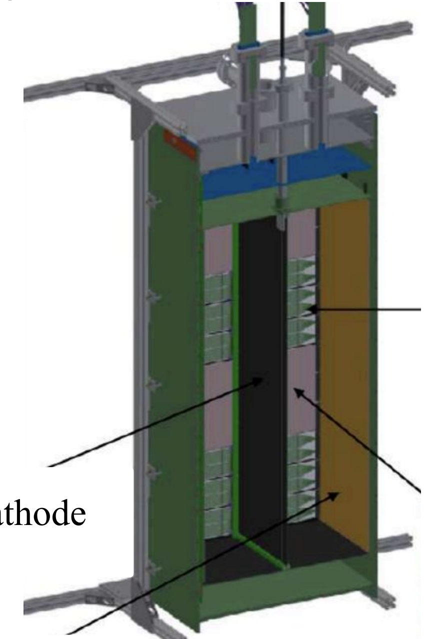
ArCLight



Future Applications

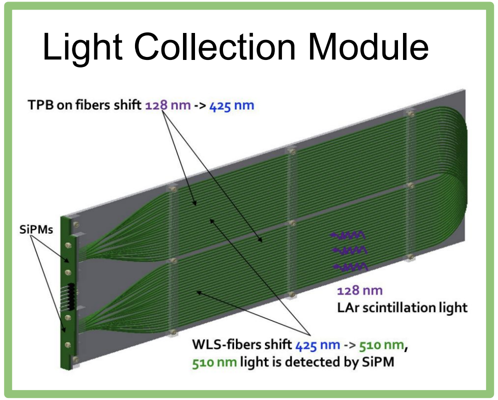
- Integrating detection from multiple detectors into single network
  - Light & Charge
  - ND-LAr & TMS

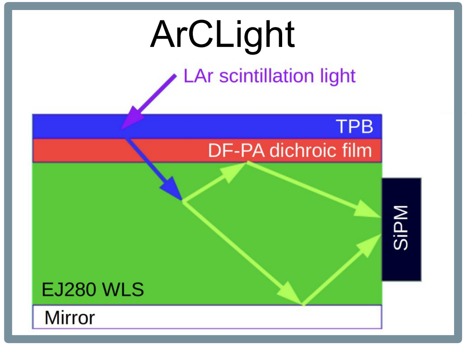
Single ND-LAr Module

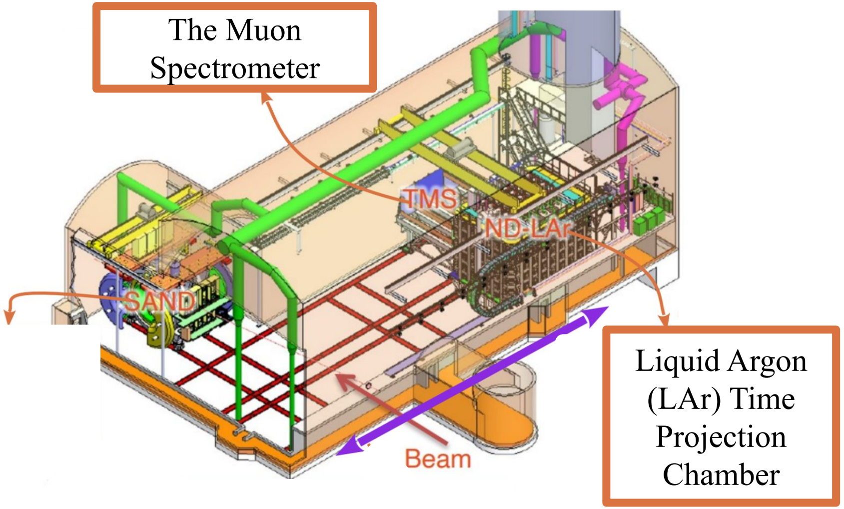


Cathode

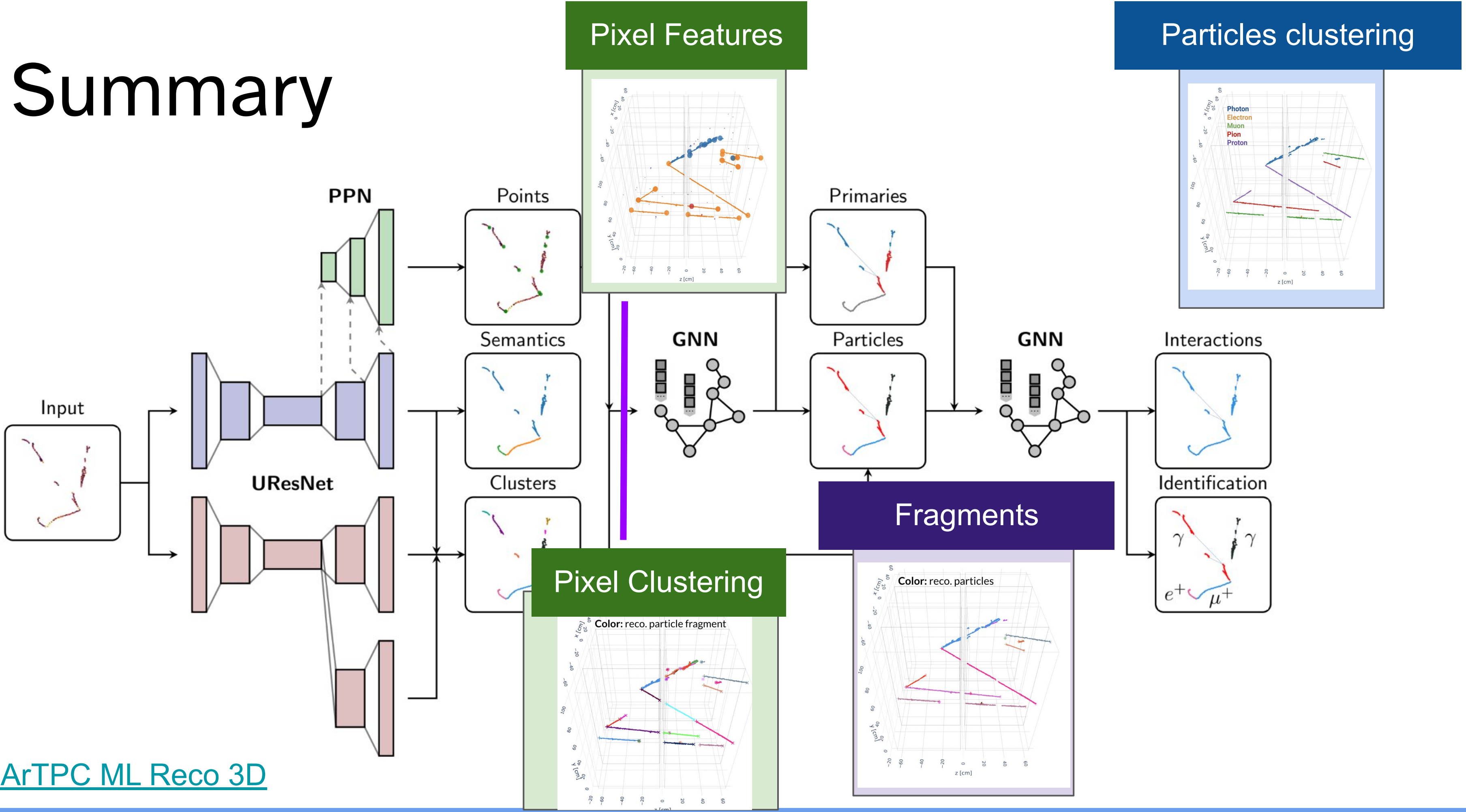
Charge readout







Summary



[LArTPC ML Reco 3D]

Thank you for your attention!

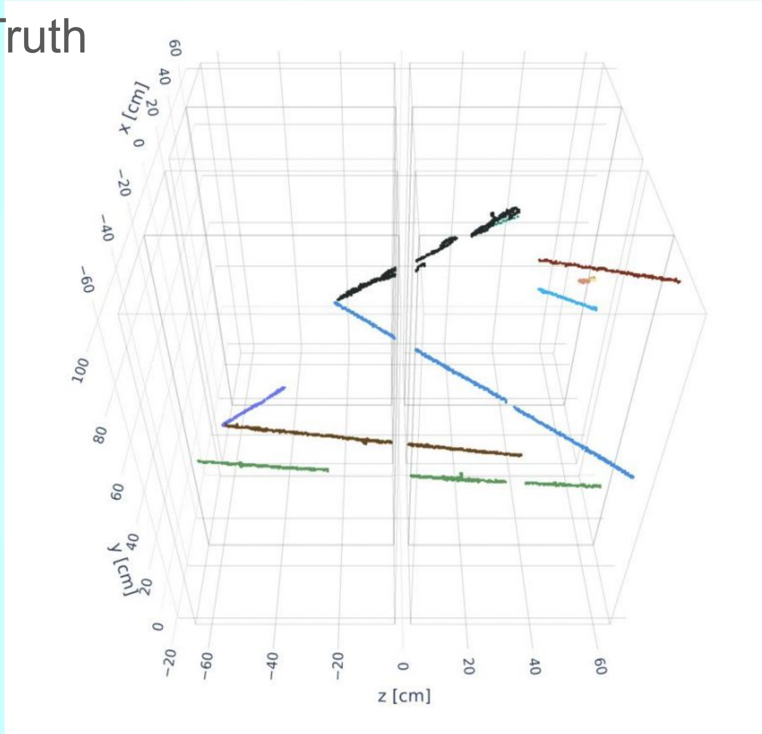
U.S. DEPARTMENT OF ENERGY | Office of Science

2x2 Analysis Workshop May 2023

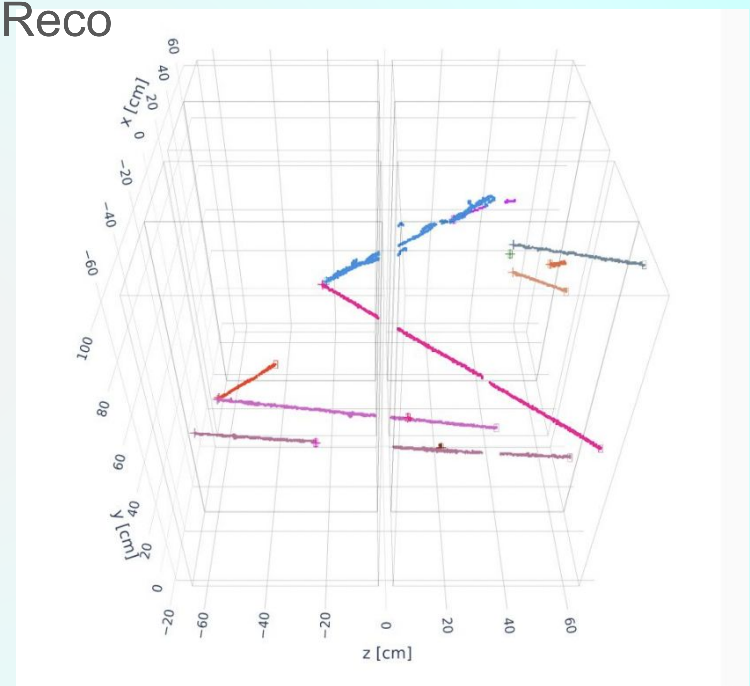
Backup

Pixel Features: Output

Truth

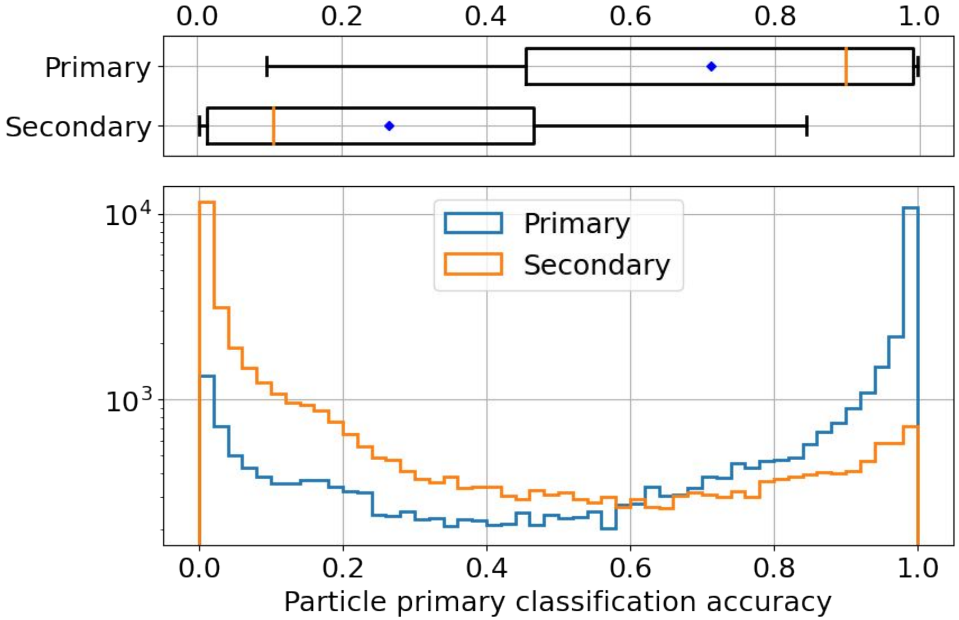


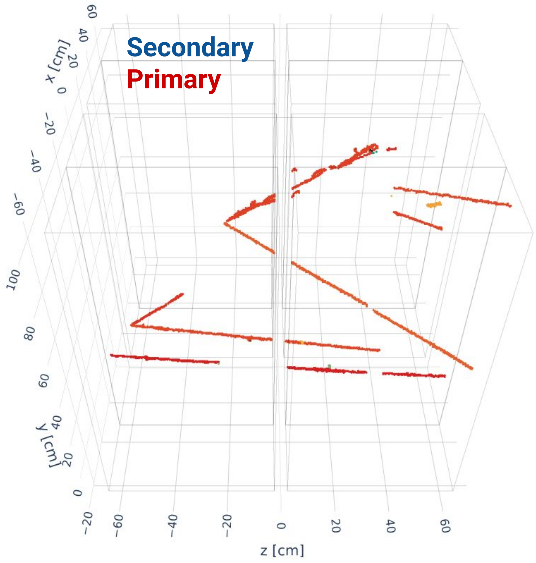
Reco



[Phys Rev D (102) 012005]

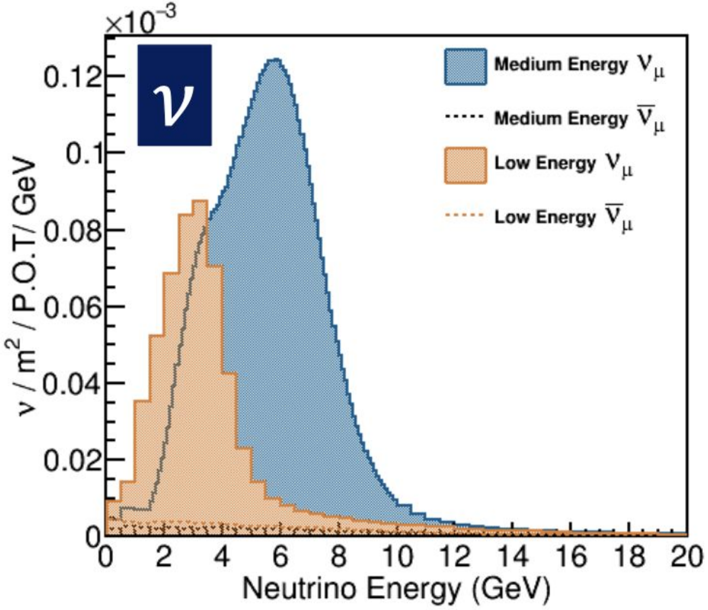
Cluster Clustering: Primary Classification





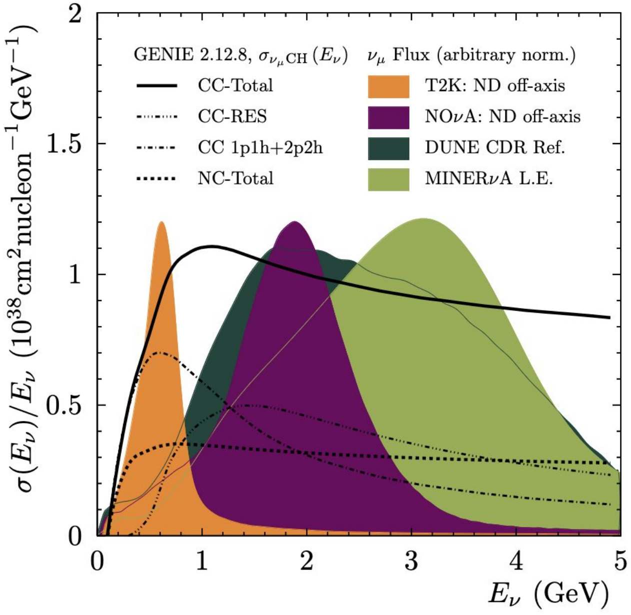
2x2 Prototype Beam vs DUNE Beam

NuMI



https://indico.cern.ch/event/881216/contributions/5048756/attachments/2534229/4361050/Klustova_MINERvAFlux_NuINT22.pdf

DUNE (dark green)



https://arxiv.org/pdf/1803.08848.pdf