# Identifying Particles and Neutrino Final States with Convolutional Neural Networks in MicroBooNE

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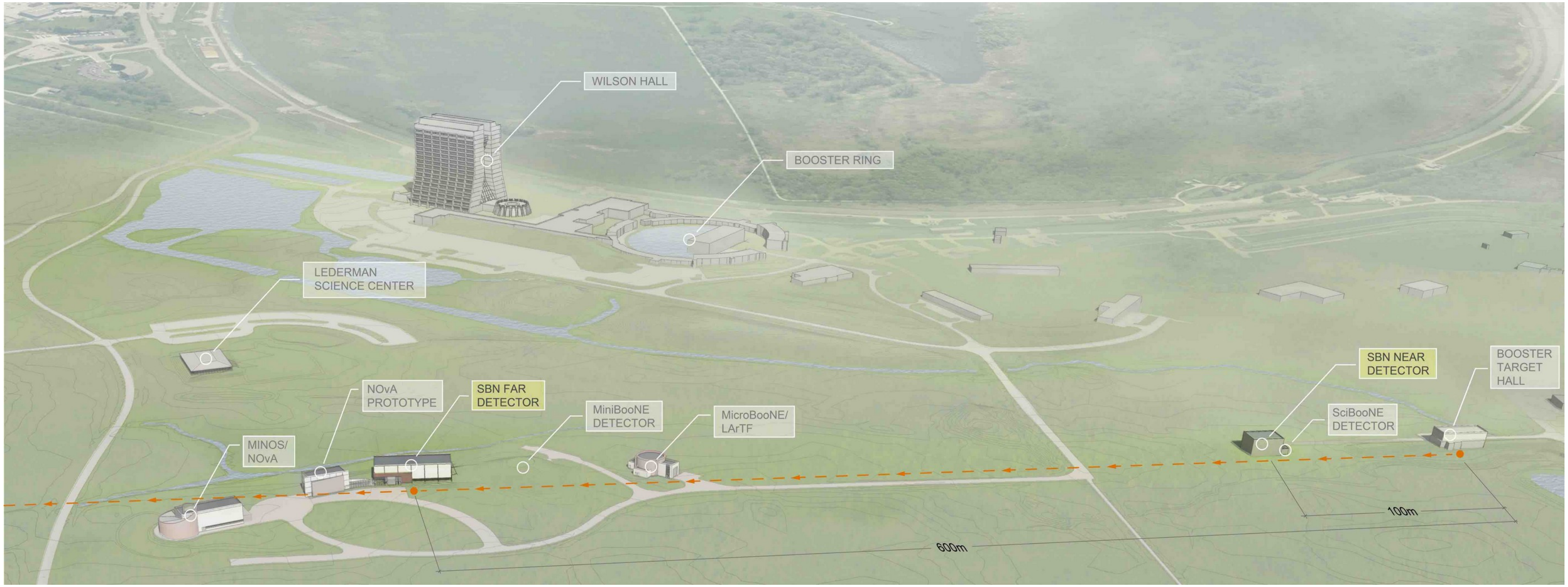
# Overview

- A brief overview of:
  - The MicroBooNE detector
  - The motivation for new deep-learning-based reconstruction tools
  - LArMatch: a new U-NET CNN developed by Taritree Wongjirad to reconstruct 3D points from 2D LArTPC images
- Main focus: LArPID, a new CNN to classify 3D tracks and showers produced in the LArMatch-based MicroBooNE reconstruction
  - Development / training
  - Performance
  - Preliminary studies on interpreting the model
  - Utility in identifying neutrino final states in MicroBooNE
    - Initial results for an inclusive CC $\nu_e$ selection
- Applicability in other reconstruction frameworks and LArTPC detectors

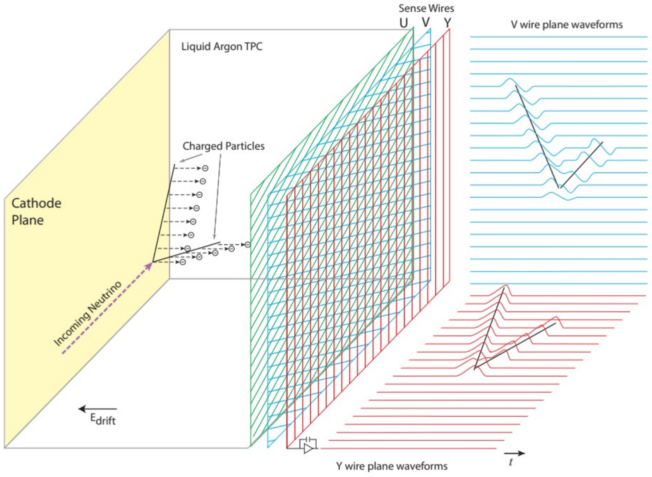
# The MicroBooNE Detector

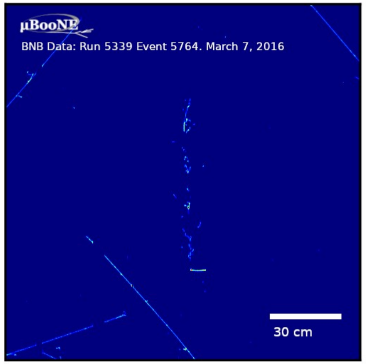
- A LArTPC located in the Booster Neutrino Beam at Fermilab
  - Designed with a primary aim of studying the MiniBooNE low-energy excess

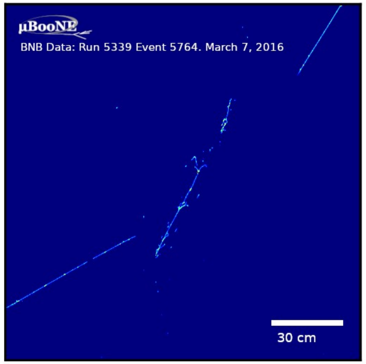


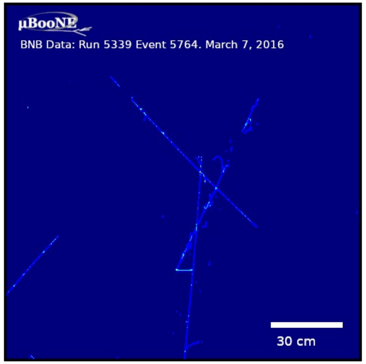
# The MicroBooNE Detector

- A LArTPC located in the Booster Neutrino Beam at Fermilab
  - Provides the capability to image neutrino interactions with mm-scale precision
    - This allows for the use of powerful computer vision techniques to reconstruct neutrino interactions



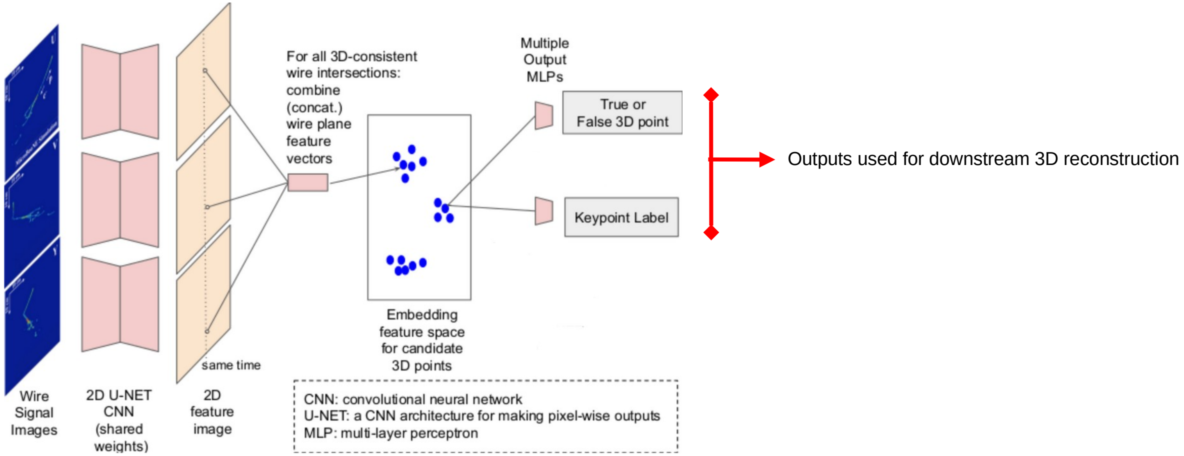



# A New Deep-Learning-Based Reconstruction Framework

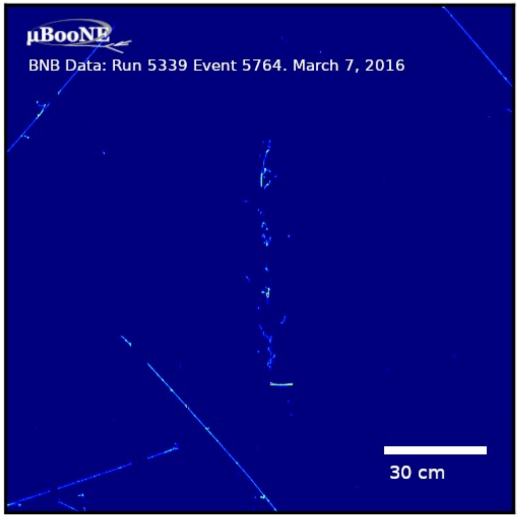
- A previous DL-based reconstruction directly searched (in 2D) for “v-shaped” 1e1p vertices from quasi-elastic CC $\nu_e$ events
  - P. Abratenko et al. (MicroBooNE), Phys. Rev. D **105**, 112003 (2022)
  - Designed to test hypothesis that MiniBooNE excess was produced by quasi-elastic CC $\nu_e$ interactions
- A new, more general reconstruction paradigm:
  - Use LArMatch, a U-NET CNN developed by Taritree Wongjirad, to find 3D energy-deposition points from 2D images

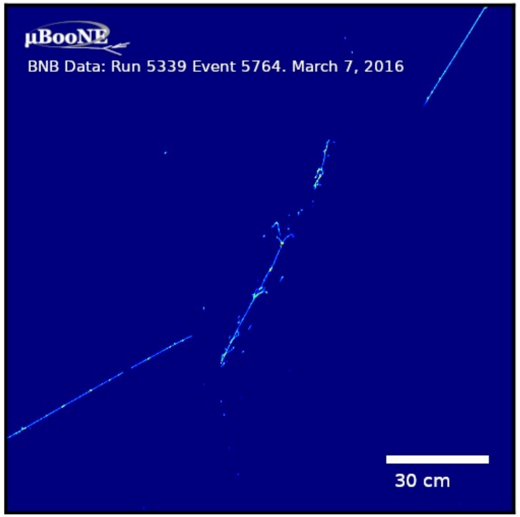


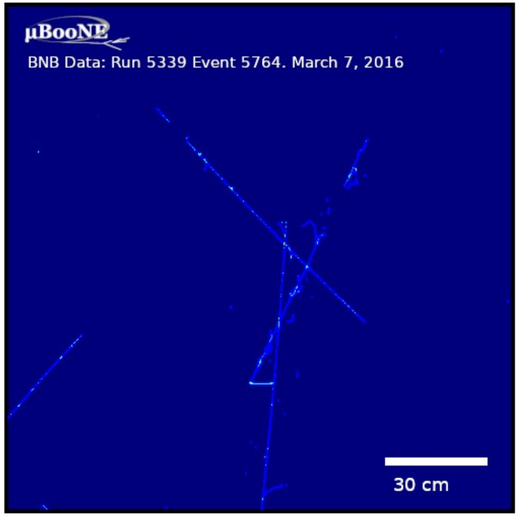

  - Cluster tracks and showers (prongs) in 3D
  - Use LArPID, a new CNN, to attach particle labels to 3D prongs by analyzing associated pixels in 2D images
    - Much more on this later

# Reconstruction Example: LArMatch Input

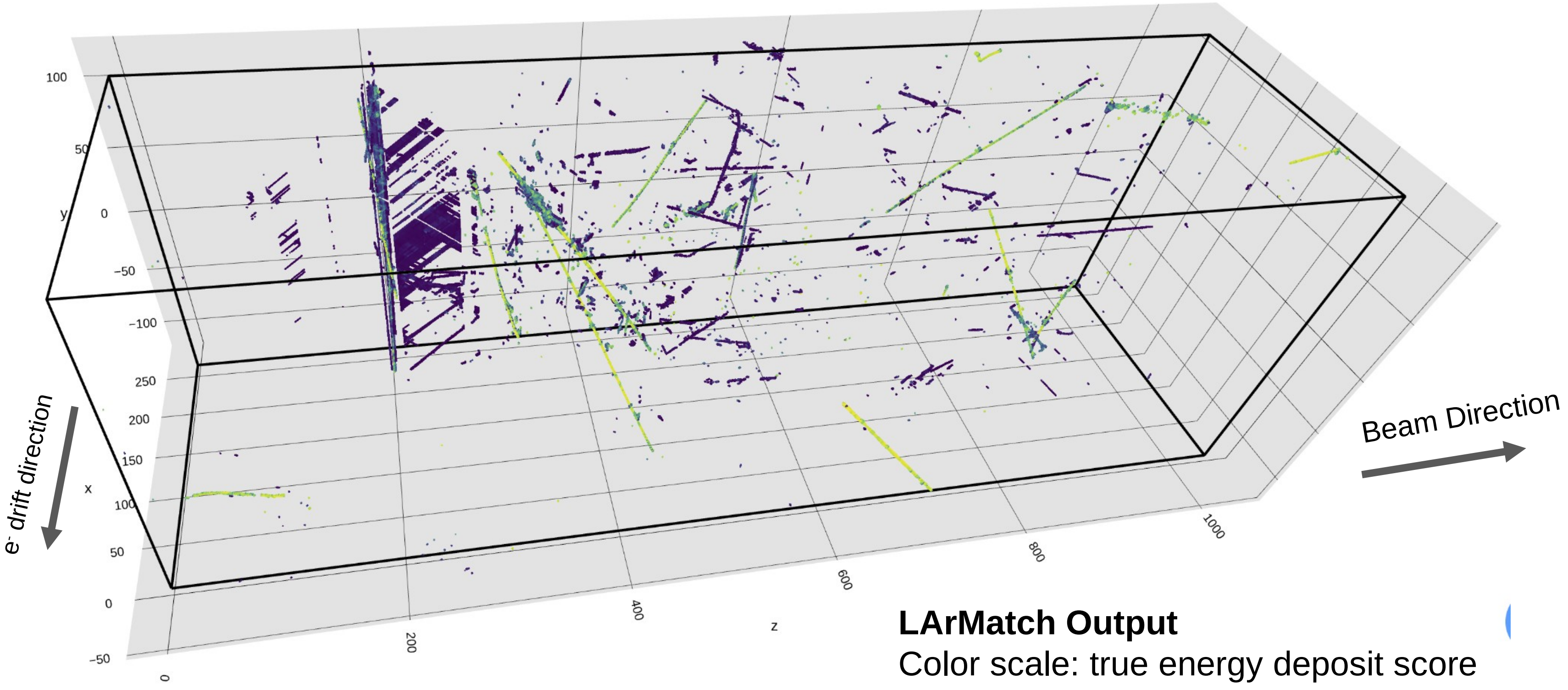
Zoomed in view of probable CC $\nu_e$ interaction from open data:



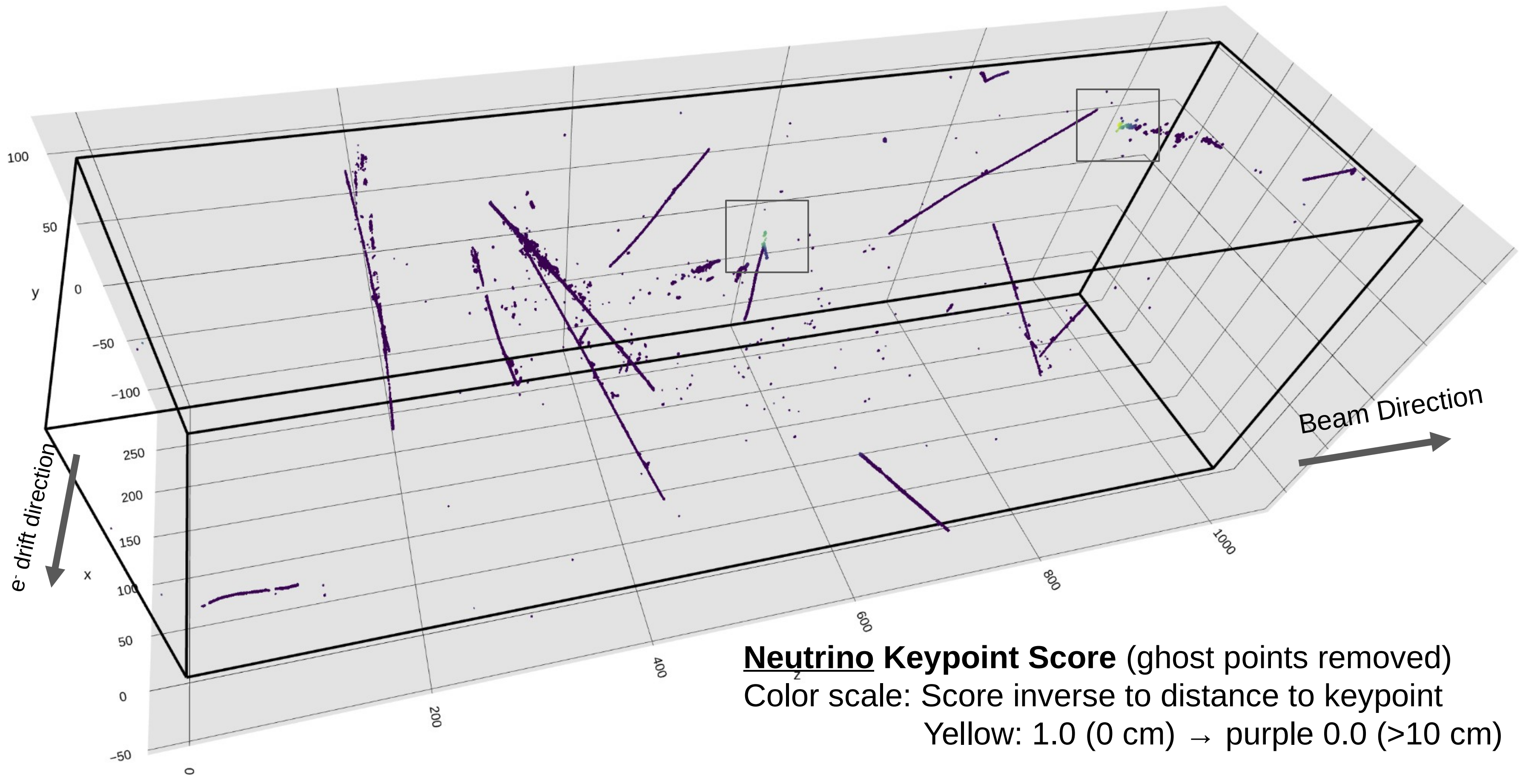



# Reconstruction Example: LArMatch True Energy Deposit Output




**LArMatch Output**
Color scale: true energy deposit score
Purple:0.0 → Yellow: 1.0

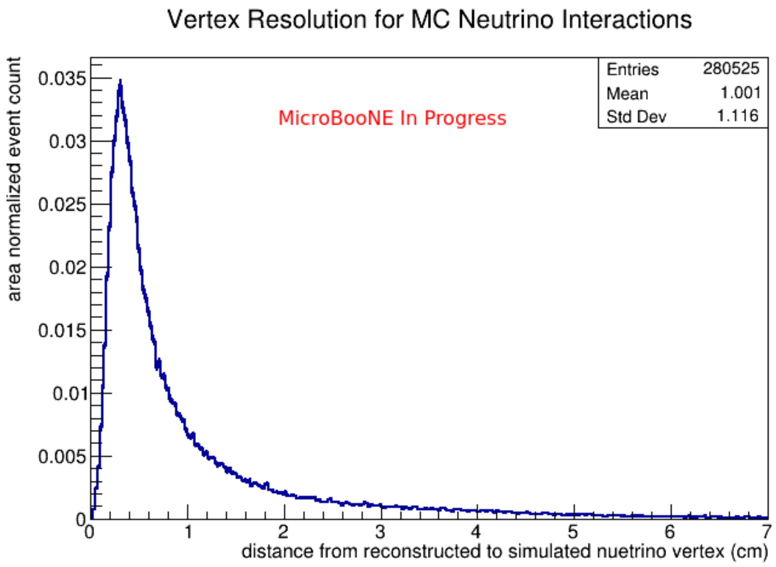
# Reconstruction Example: LArMatch Neutrino Keypoint Score Output



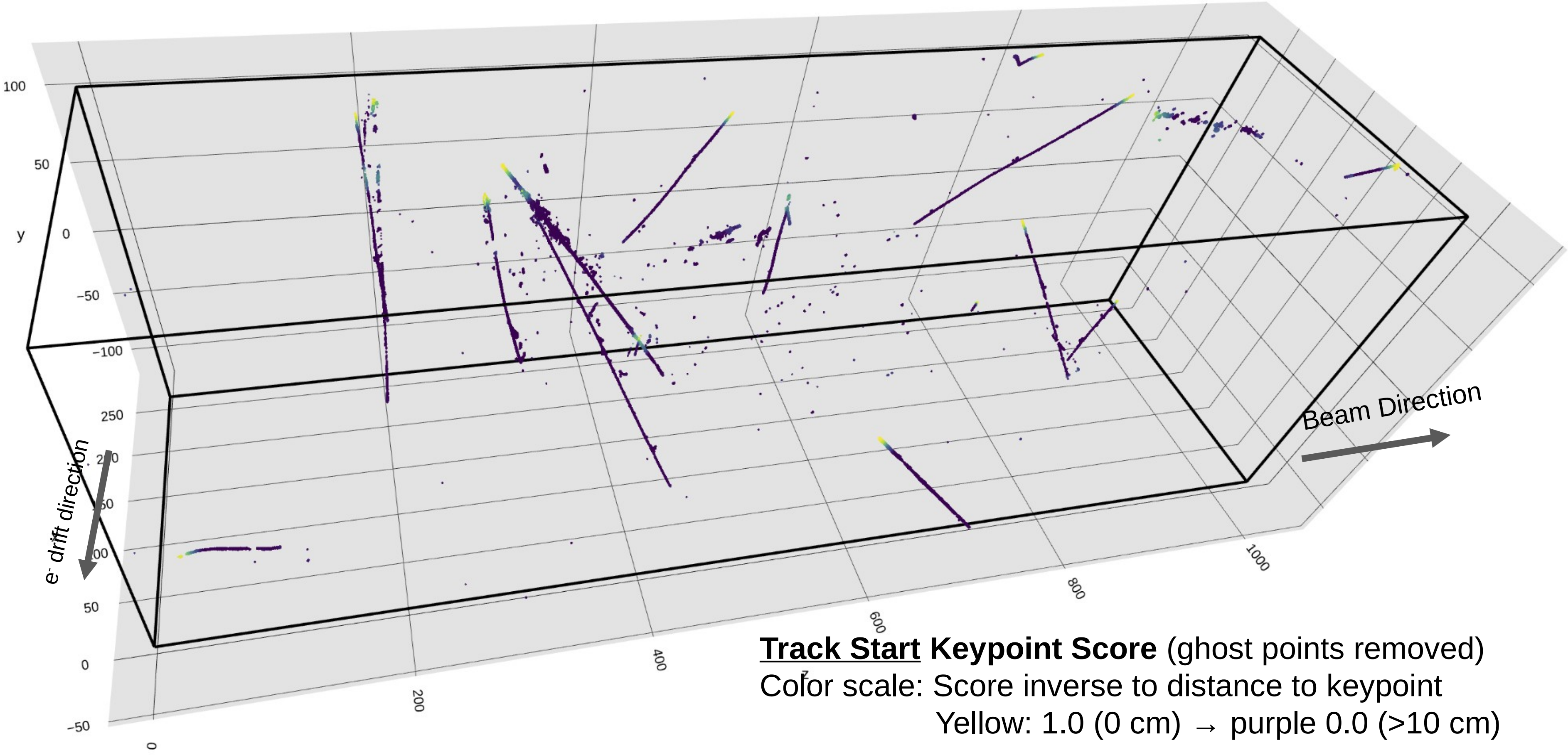

**Neutrino Keypoint Score** (ghost points removed)
Color scale: Score inverse to distance to keypoint
Yellow: 1.0 (0 cm) → purple 0.0 (>10 cm)

# LArMatch Neutrino Vertex Resolution

- In MC, 68% of reconstructed neutrino vertices are within 9.2mm of simulated interaction position
  - Wire spacing is 3mm, so this is within 3 wires, which is quite good

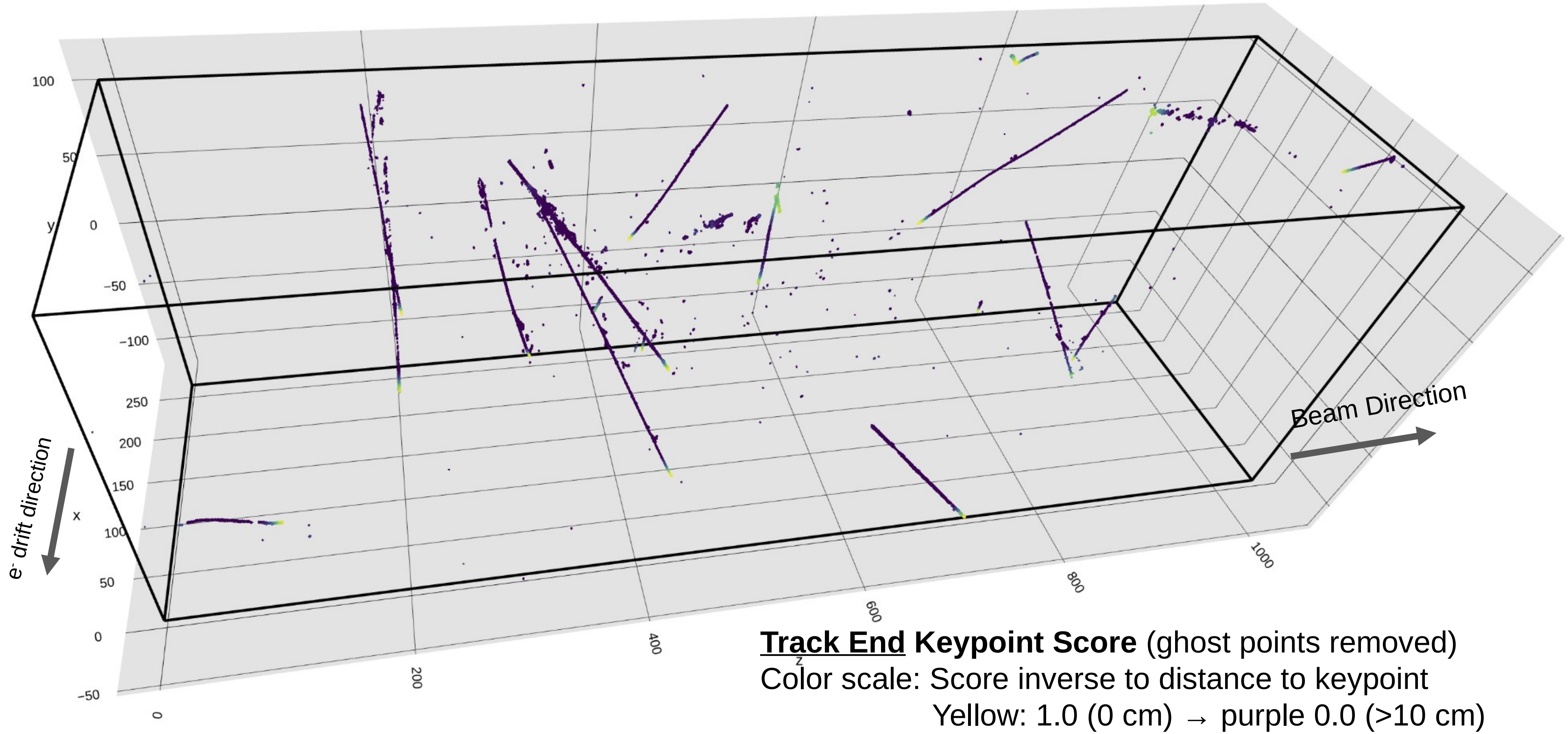


# Reconstruction Example: LArMatch Track Start Score Output



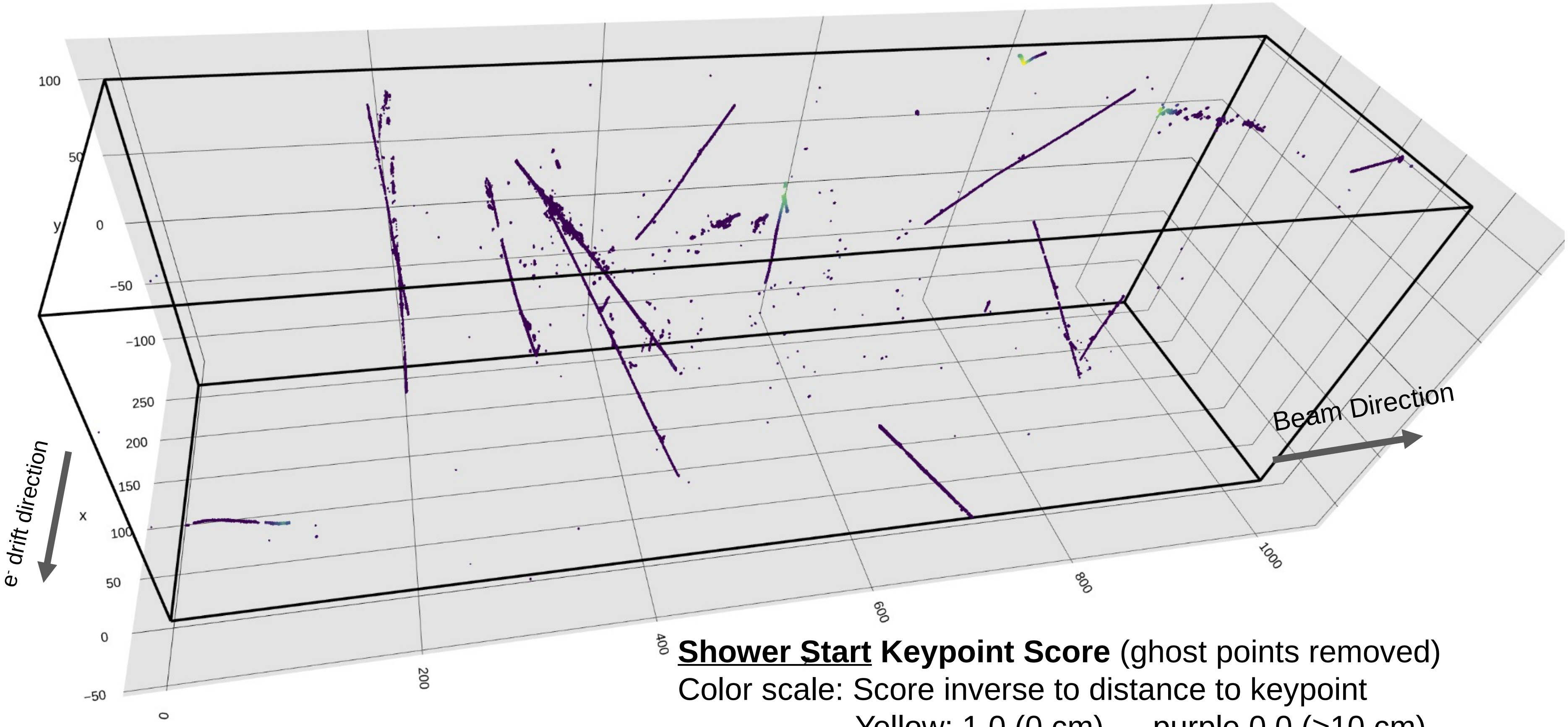

**Track Start Keypoint Score** (ghost points removed)
Color scale: Score inverse to distance to keypoint
Yellow: 1.0 (0 cm) → purple 0.0 (>10 cm)

# Reconstruction Example: LArMatch Track End Score Output




**<u>Track End</u> Keypoint Score** (ghost points removed)
Color scale: Score inverse to distance to keypoint
Yellow: 1.0 (0 cm) → purple 0.0 (>10 cm)

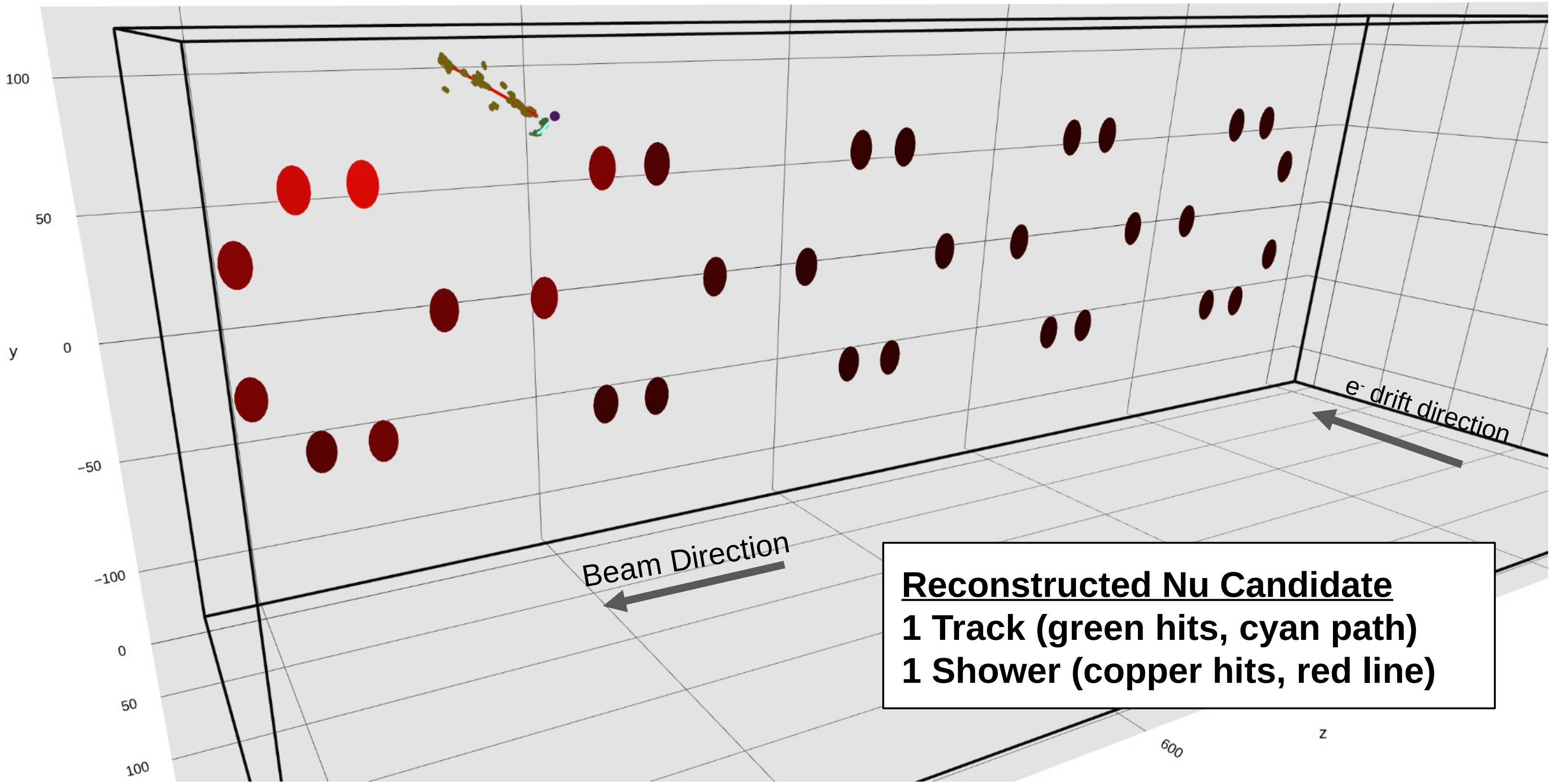
# Reconstruction Example: LArMatch Shower Start Score Output




**<u>Shower Start</u> Keypoint Score** (ghost points removed)
Color scale: Score inverse to distance to keypoint
Yellow: 1.0 (0 cm) → purple 0.0 (>10 cm)

# Reconstruction Example:
# Vertexing & Track/Shower Clustering

Shower trunk obscured in both U and V plane → leads to missing shower trunk in 3d hits, but seen by 2D CNN in Y plane



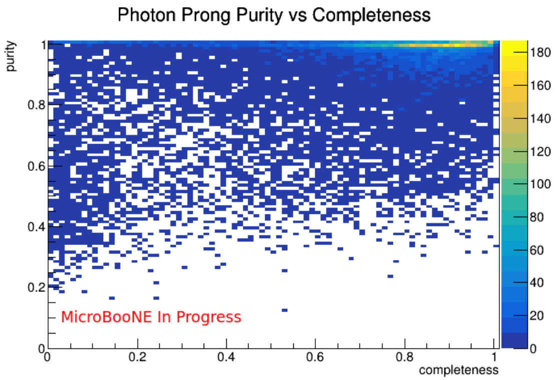

**Reconstructed Nu Candidate**
**1 Track (green hits, cyan path)**
**1 Shower (copper hits, red line)**

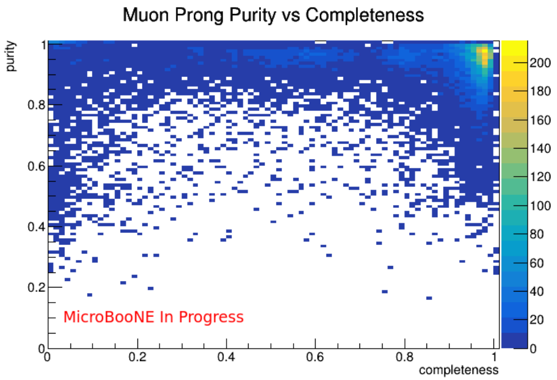
# The LArPID Network

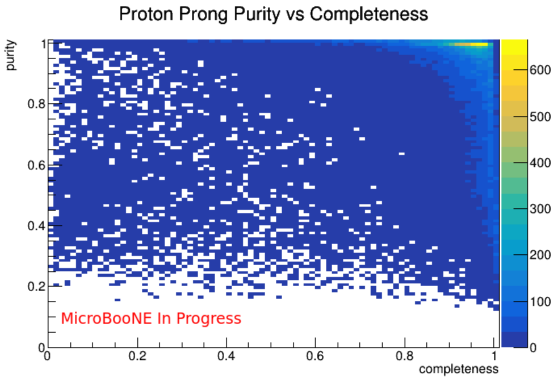
- A CNN to classify reconstructed 3D tracks and showers
  - Similar to work by NOvA: PhysRevD.100.073005
- Does particle identification (PID)
  - Outputs five score indicating how likely that the input is a muon, pion, proton, photon, or electron
- Outputs reconstruction quality metrics
  - Completeness prediction: fraction of true particle reconstructed in input track/shower
  - Purity prediction: fraction of reconstructed track/shower that was created from true particle

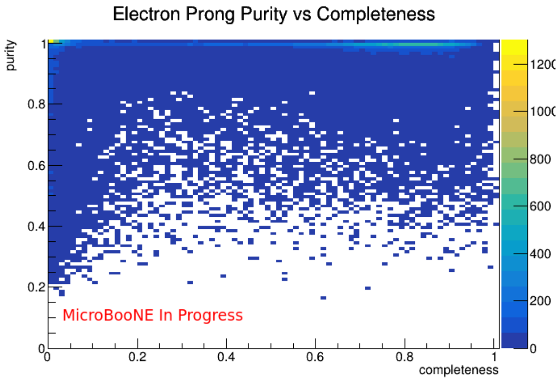
# LArPID: Training Sample

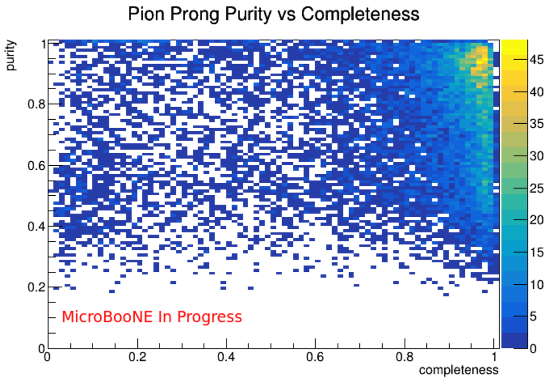
- Trained on reconstructed tracks and showers attached to LArMatch-identified neutrino vertices from MicroBooNE neutrino Monte Carlo simulations



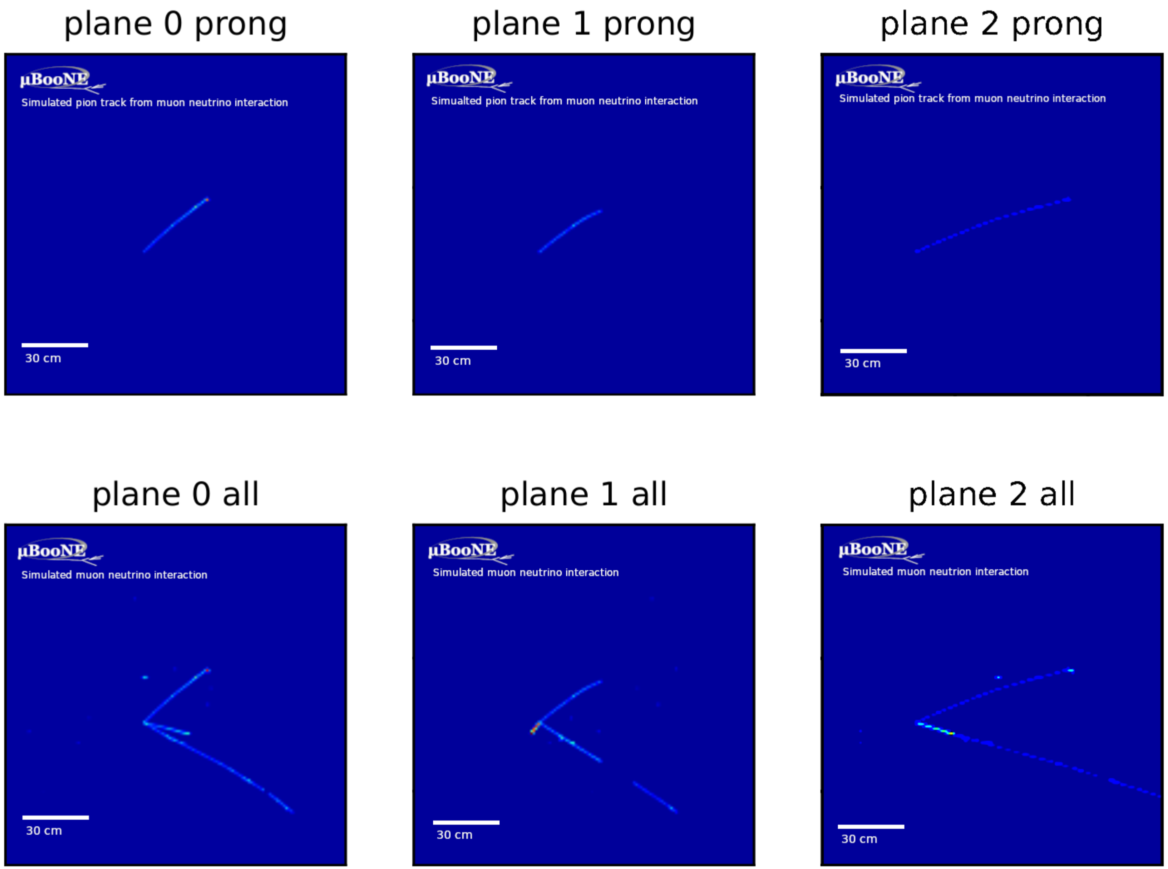



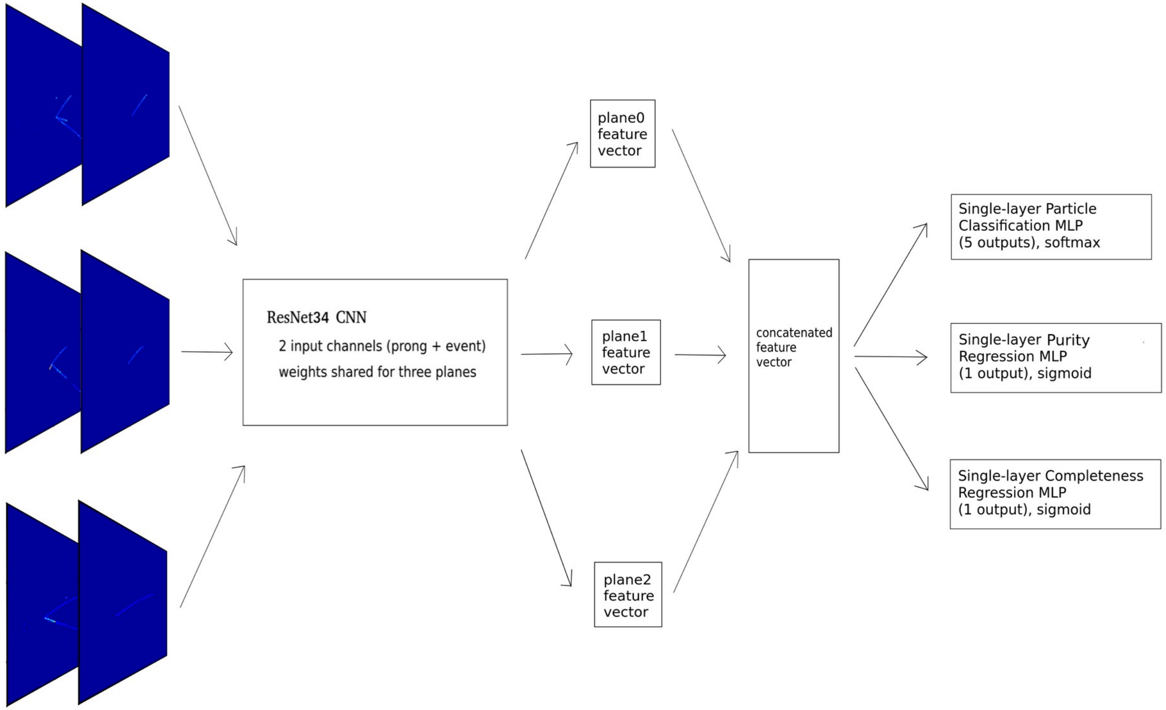
# LArPID: Image Preprocessing

- In 2D images, select all pixels included in 3D prong hits
- Crop to 512 x 512 window. Center prong in image if it fits, otherwise crop around prong end point (if it’s a track) or start point (if it’s a shower)
- Normalize pixel values (subtract mean, divide by standard deviation)
- Provide full event images (with cosmics removed) along with prong images



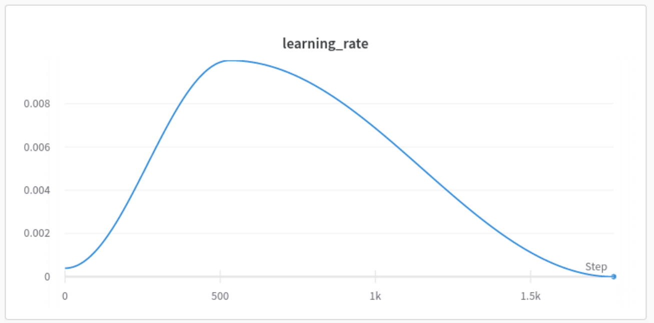
# LArPID: Network Architecture

- Use tried and tested ResNet architecture (arXiv:1512.03385)
- Limit CNN depth to 34 layers due to computational constraints



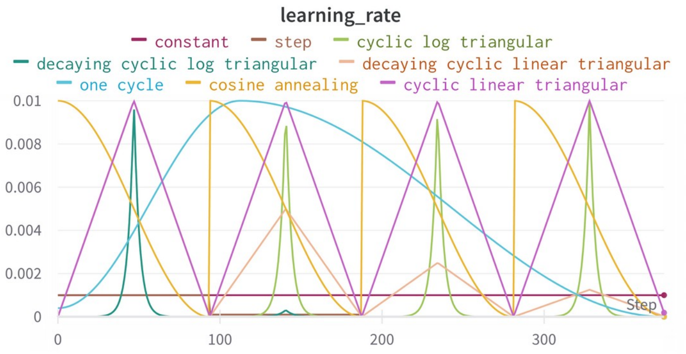
# LArPID: Training

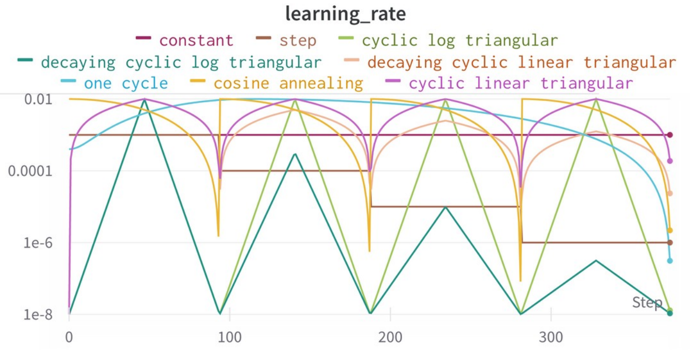
- Use learned weights to combine losses from three tasks (arXiv:1705.07115)
  - Loss = $\exp(-s_{cr})L_{cr} + \exp(-s_{pr})L_{pr} + 2\exp(-s_{pc})L_{pc} + s_{cr} + s_{pr} + s_{pc}$
    - $L_{cr}$ = mean square error **c**ompleteness **r**egression loss
    - $L_{pr}$ = mean square error **p**urity **r**egression loss
    - $L_{pc}$ = cross entropy **p**article **c**lassification loss
- Training sample: on the order of 100k prongs (tracks/showers) of each particle type (electrons, photons, muons, pions, and protons)
  - Weight $L_{pc}$ contributions to account for class imbalance
- Validation sample:
  - 10k prongs, 2k per particle type
- Training
  - Data augmentation: randomly flip input images
  - Trained for 20 epochs with a variable learning rate scheduler:



# LArPID: Training/Development Lessons Learned

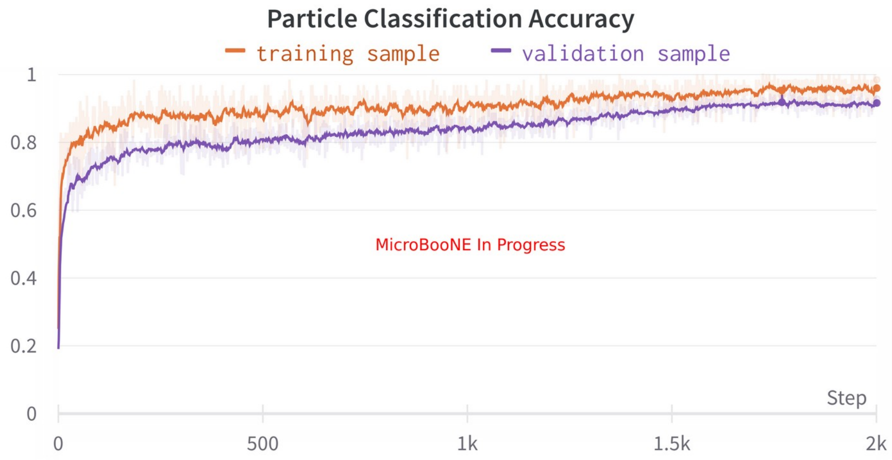
- Model wouldn't learn with batch normalization, used instance normalization instead
  - I suspect this has to do with the sparsity of LArTPC images, and the difficulty this presents in calculating representative running averages in batch normalization layers
- Using learned loss weights in multi-task loss provides better performance than adding loss functions with hard-coded weights, regardless of choice of weight values
- Adding completeness and purity regression tasks neither hurt nor helped particle classification performance
- Including small, low-purity tracks/showers in training did not make model's performance on larger, better reconstructed particles any worse
- Increasing depth of final classification/regression MLPs made it much more difficult for the model to learn and did not provide any boost in performance
- The "single cycle cosine annealing" learning rate scheduler is a good choice for this task, outperformed other learning rate choices:



# LArPID: Particle Classification Results

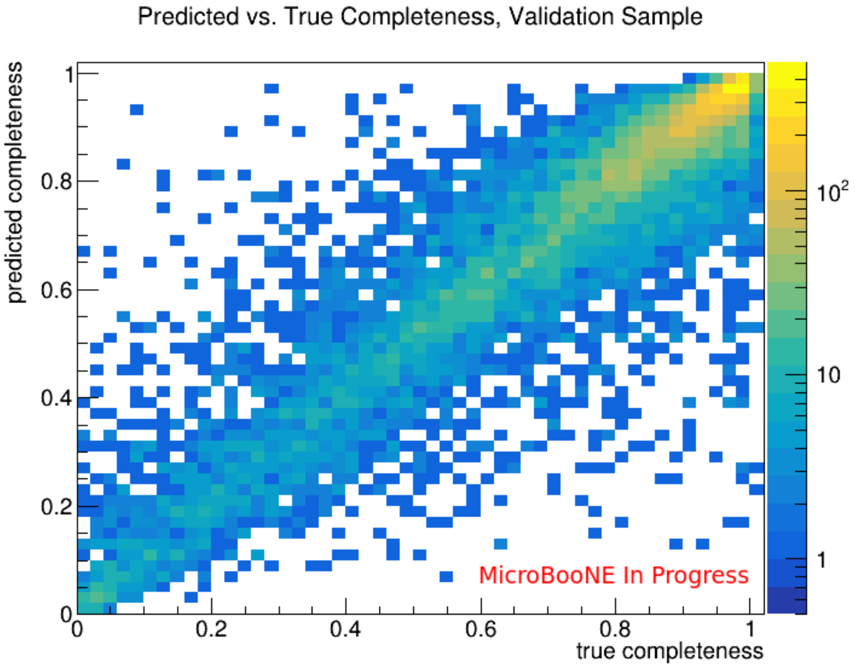
- Results shown with true prong purity > 0.6 cut for accurate labels
- Overall validation accuracy: 91.1%

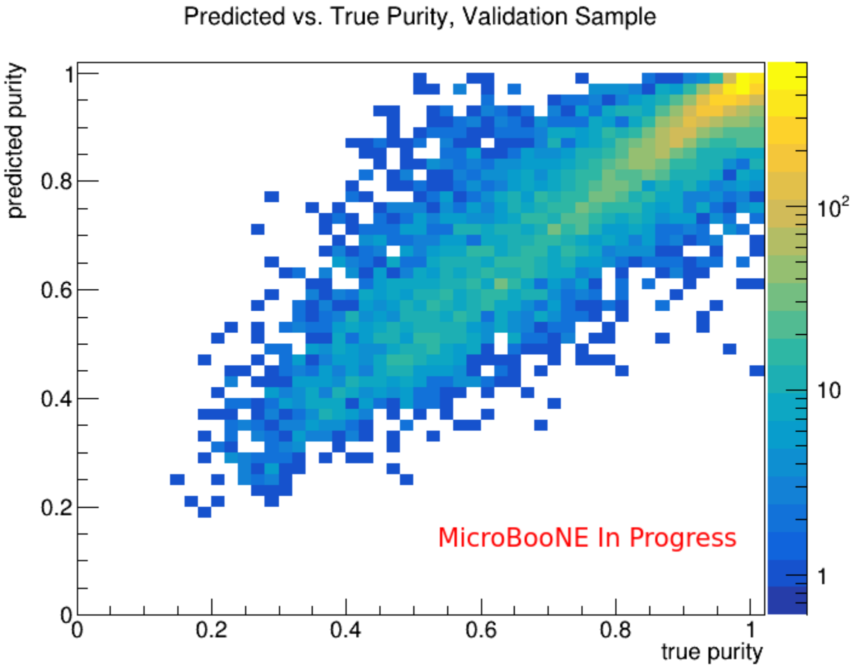



Validation Sample Accuracy Statistics

| | True electrons | True photons | True muons | True pions | True protons |
|---|---|---|---|---|---|
| Fraction classified as electrons | **83.5%** | 4.8% | 0.1% | 0.4% | 0.1% |
| Fraction classified as photons | 13.3% | **94.7%** | 0.1% | 0.2% | 0.2% |
| Fraction classified as muons | 0.4% | 0% | **93.6%** | 12.1% | 0.2% |
| Fraction classified as pions | 2.7% | 0.4% | 6.1% | **85.9%** | 1.4% |
| Fraction classified as protons | 0.2% | 0.2% | 0.2% | 1.5% | **98.2%** |

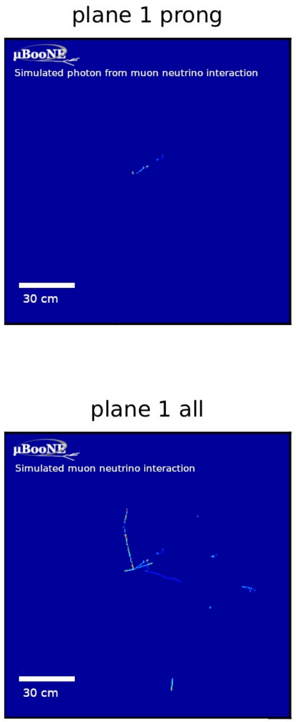
# LArPID: Completeness and Purity Results

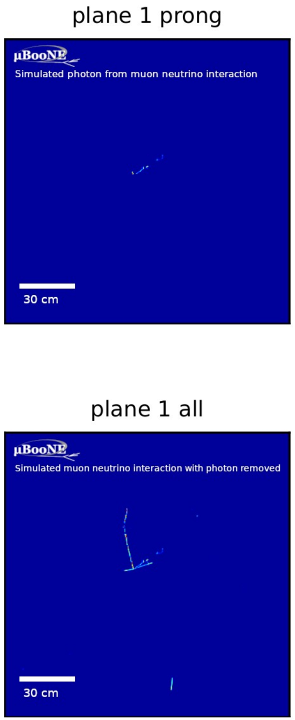


# LArPID: Interpreting the Model

- In progress: image manipulation studies designed to understand what information the model is using to make decisions



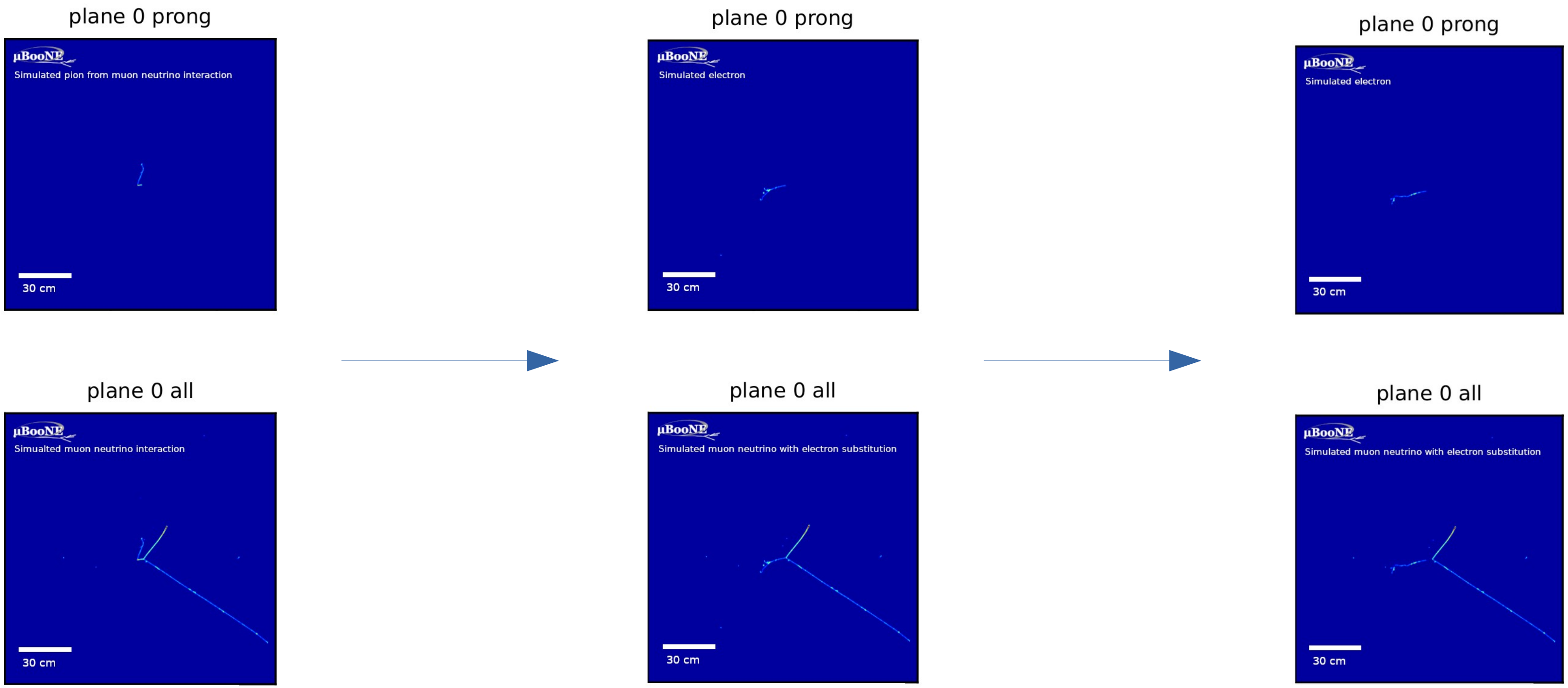




electron score = -3.63, photon score = -0.03

electron score = -1.53, photon score = -0.25

# LArPID: Interpreting the Model

- In progress: image manipulation studies designed to understand what information the model is using to make decisions




electron score = 0, photon score = -7.02, pion score = -6.02

electron score = -0.01, photon score = -5.03, pion score = -8.63

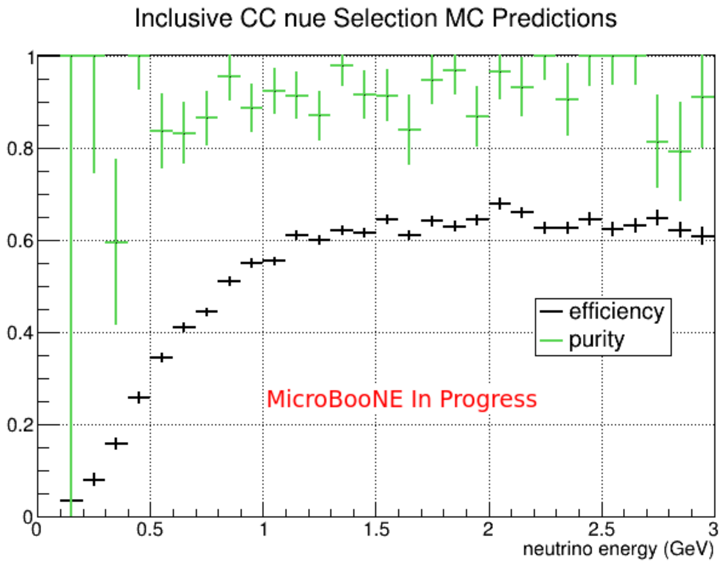
electron score = -7.87, photon score = 0, pion score = -12.84

# An Inclusive CC $\nu_e$ Selection with New DL-Based Reconstruction

- Will show that new DL-based reconstruction utilizing LArMatch and LArPID networks are competitive in selecting CC $\nu_e$ events in MicroBooNE
  - Great potential to improve the sensitivity of future MicroBooNE analyses
- Selection simply utilizes:
  - Basic reconstruction quality cuts
    - Neutrino vertex found by LArMatch, doesn't overlap with tagged cosmic activity
  - Cuts on LArPID particle scores
    - No muon tracks
    - One forward-going electron shower identified with high confidence (high electron score, low photon and pion scores)

# Preliminary Inclusive CC $\nu_e$ MC Selection Results

- Backgrounds included: cosmic, CC numu, NC numu, and NC nue
- Selection purity above 80%, efficiency rises above 60% around 1 GeV
- **Caveat**: MC samples used to calculate purity and efficiency numbers were also used in prong CNN training (additional MC simulation not available in time)
  - Large training sample, not much over-fitting
- Selection is preliminary, performace will increase as selection criteria are refined

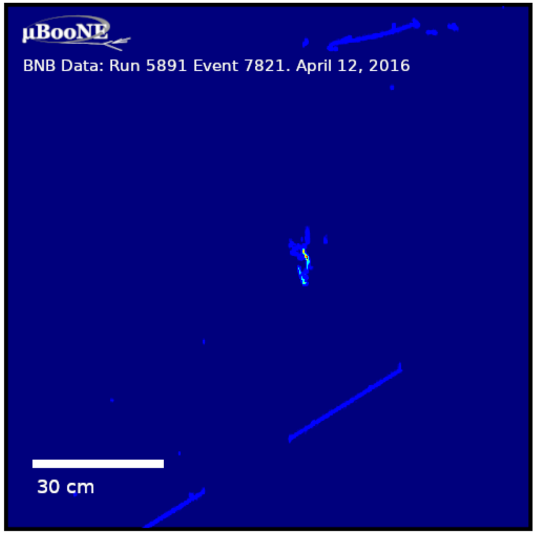


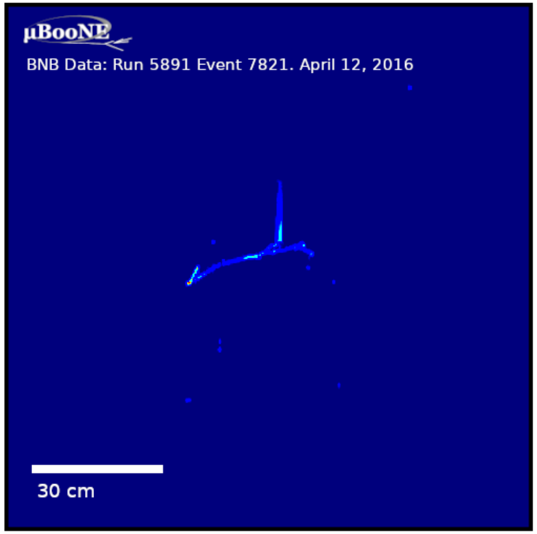
# Testing the CC $\nu_e$ Selection on Data

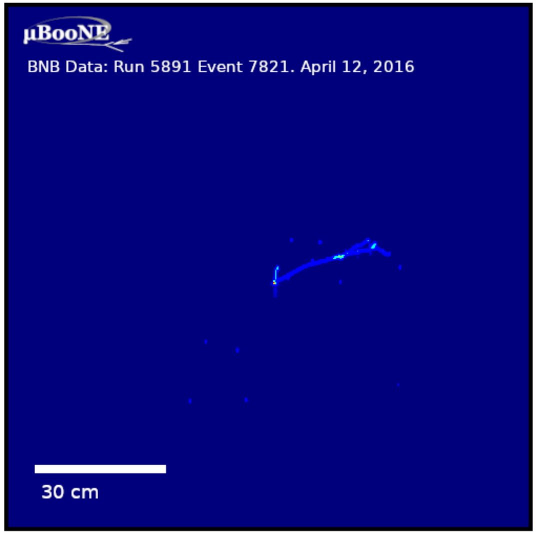
- We ran our new selection on a small MicroBooNE open data set
- New probable CC $\nu_e$ events were found!
  - Event displays for four low-energy probable CC $\nu_e$ events not identified in other reconstruction frameworks are shown on the following slides

# New Low-Energy Event Found by CC $\nu_e$ Selection

Reconstructed neutrino energy: 197.3 MeV

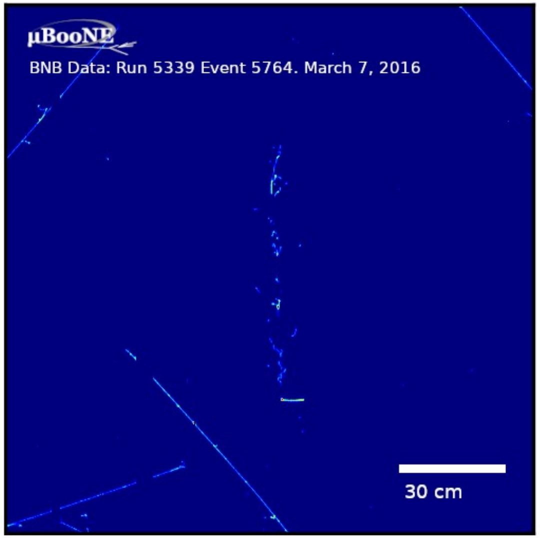


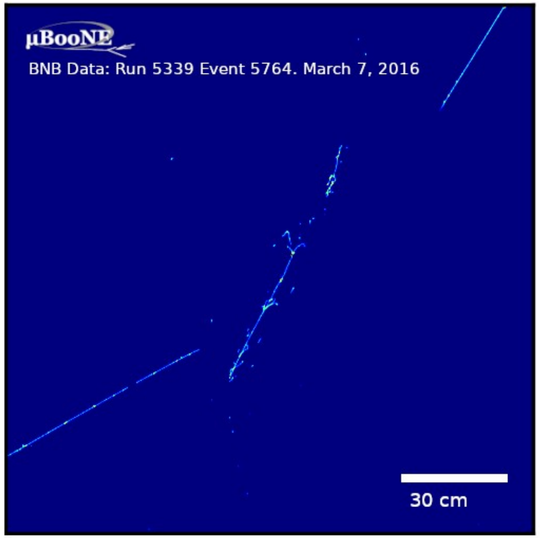



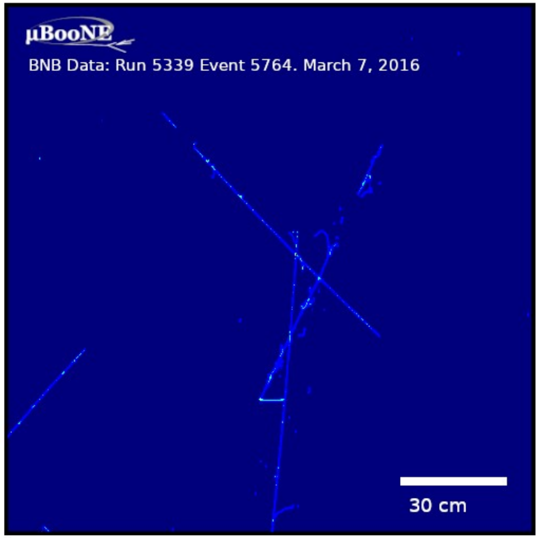



# New Low-Energy Event Found by CC $\nu_e$ Selection

Reconstructed neutrino energy: 305.6 MeV

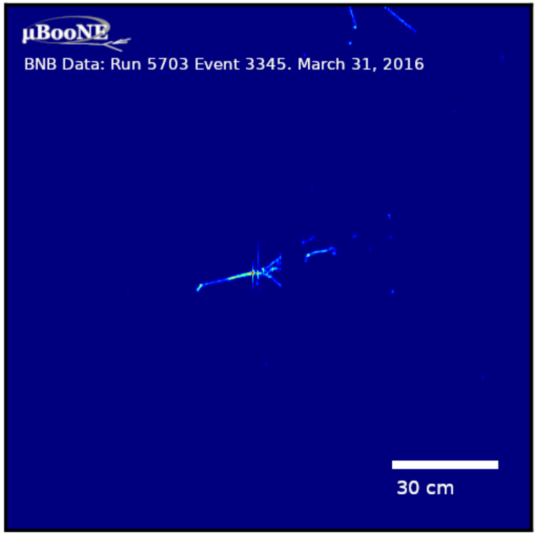


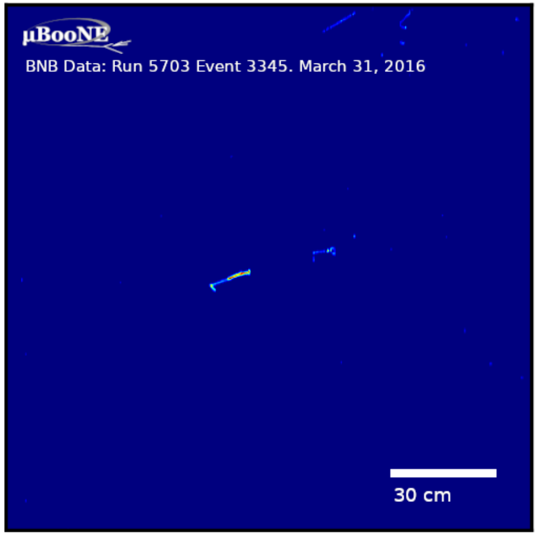



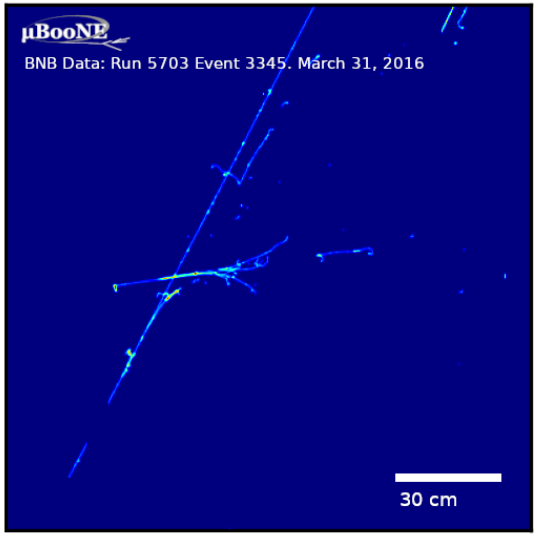



# New Low-Energy Event Found by CC $\nu_e$ Selection

Reconstructed neutrino energy: 318.6 MeV

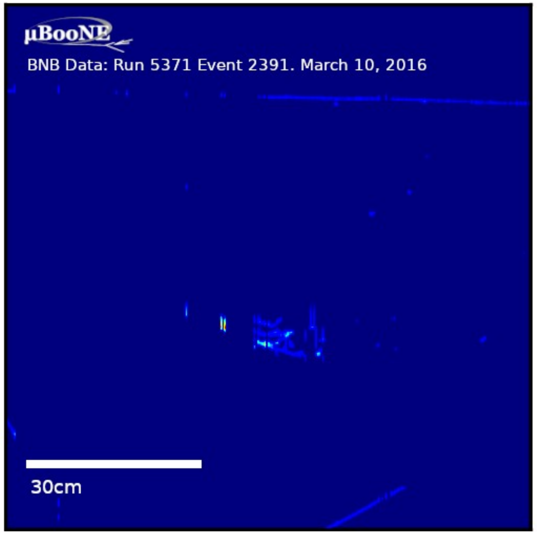


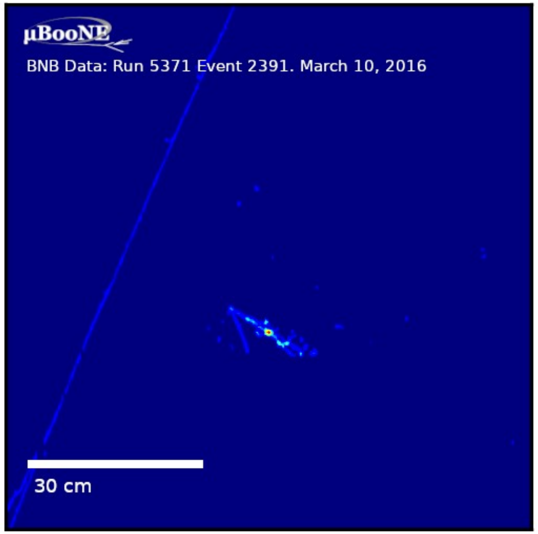



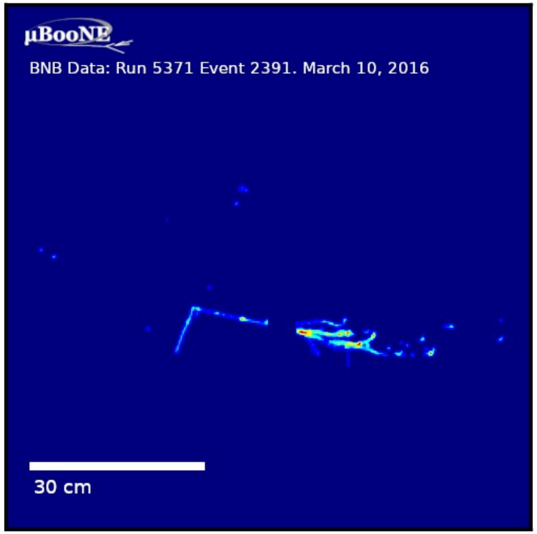



# New Low-Energy Event Found by CC $\nu_e$ Selection

Reconstructed neutrino energy: 411.8 MeV



# Conclusions

- New DL-based MicroBooNE reconstruction framework with LArMatch and LArPID in place
  - Good neutrino vertex resolution, track/shower clustering, and particle identification
  - Allows for competitive CC $\nu_e$ selection that can find new events in open data
    - Further improvements expected!
  - Great potential to improve the sensitivity of future MicroBooNE analyses
- Applicability in other reconstruction frameworks and LArTPC experiments
  - Work ongoing to implement LArMatch in SBN
  - Should be easy to retrain LArPID network for other reconstruction frameworks used by MicroBooNE, SBN (ICARUS and SBND), and DUNE
    - Currently collaborating with Wanwei Wu and Donna Naples at the University of Pittsburgh to implement LArPID in the Pandora reconstruction framework (used in all of these LArTPC experiments)