Identifying Neutrino Final States in MicroBooNE with a New Deep-Learning Based LArTPC Reconstruction Framework

Matthew Rosenberg (Tufts University)

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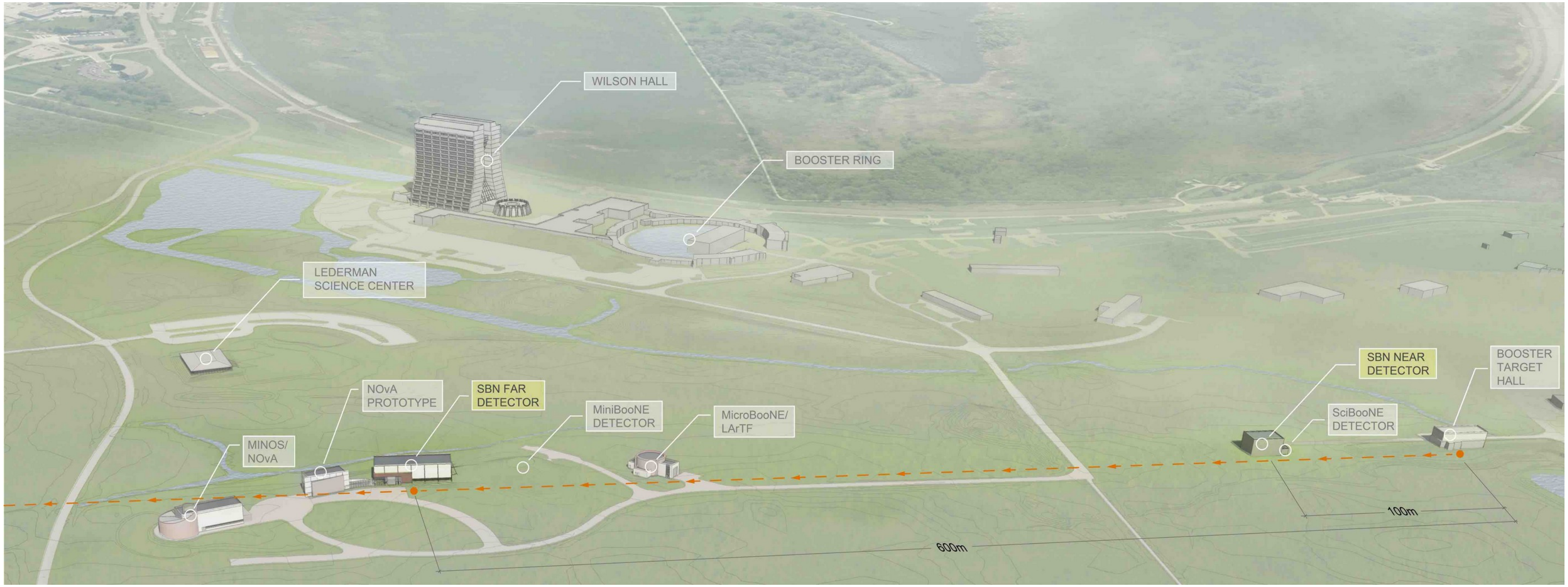
Overview

- A brief overview of the MicroBooNE detector
- A new deep-learning based reconstruction framework in MicroBooNE
- Demonstration of performance and test of data/MC consistency with inclusive CC ν_e and CC ν_μ selections
- Comparison to highest-efficiency published (previous best) MicroBooNE results
- Much more detail on everything here can be found in our MicroBooNE public note release: MICROBOONE-NOTE-1123-PUB

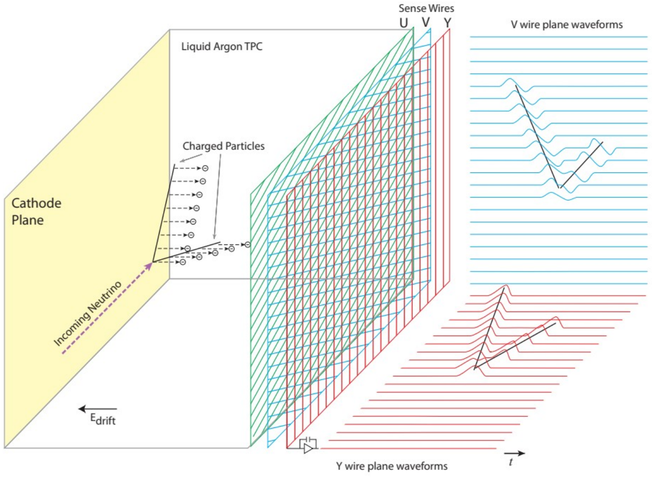
The MicroBooNE Detector

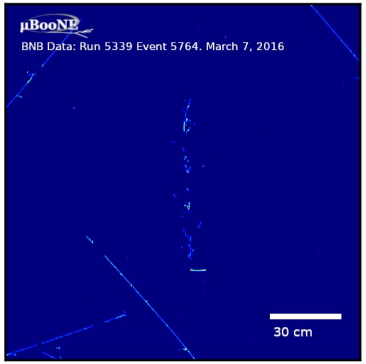
- A LArTPC located in the Booster Neutrino Beam at Fermilab
  - Designed with a primary aim of studying the MiniBooNE low-energy excess (LEE)

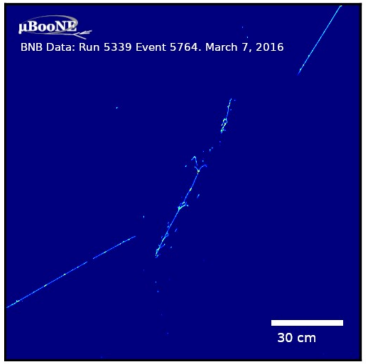


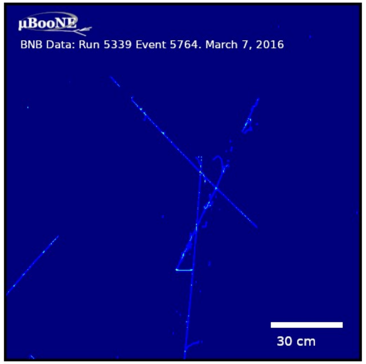
The MicroBooNE Detector

- 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

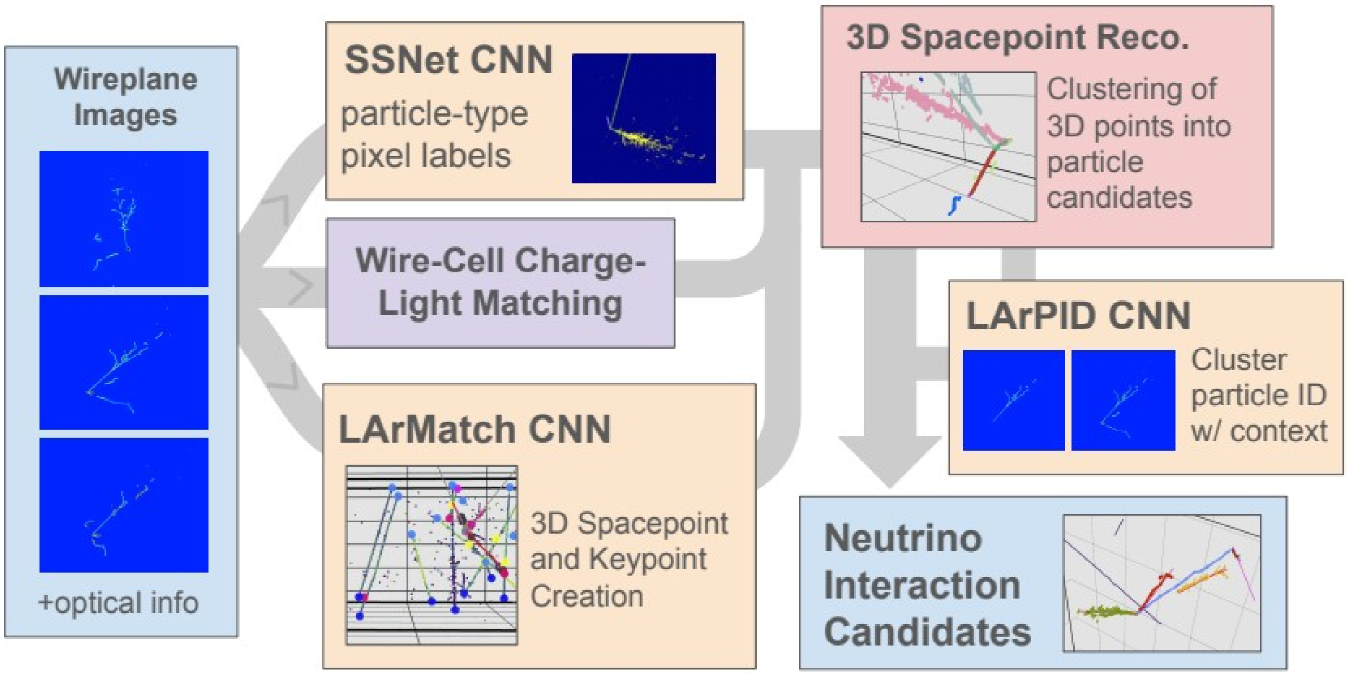








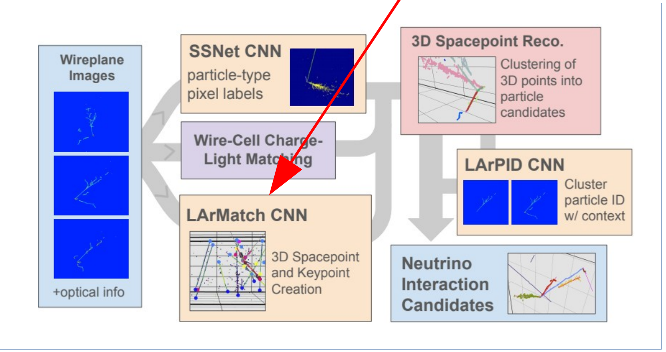
A New CNN-Based Reconstruction Framework



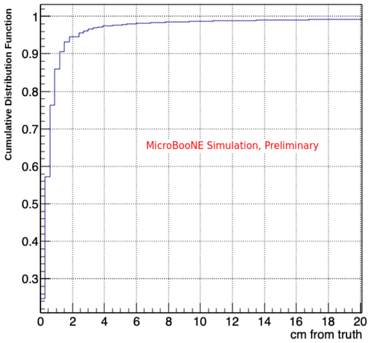
Builds on a previous DL-based framework (designed for the MicroBooNE quasi-elastic CC ν_e LEE search*) to allow for generic neutrino interaction reconstruction

* P. Abratenko et al. (MicroBooNE), Phys. Rev. D **105**, 112003 (2022)

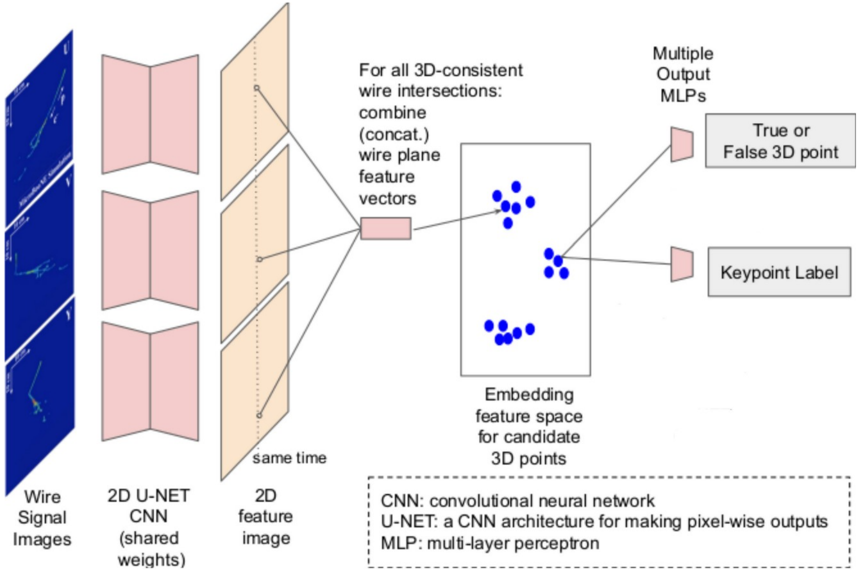
Spacepoint Creation with LArMatch



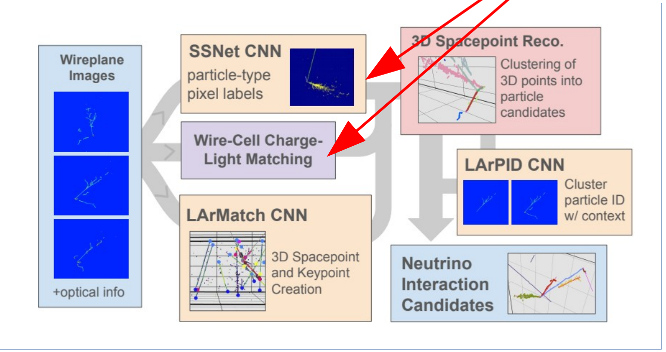
- LarMatch: a U-NET CNN developed by Taritree Wongjirad
- Finds true 3D energy deposition points and keypoints (neutrino vertices, track start/end points, shower start points, etc.) from wire-plane images



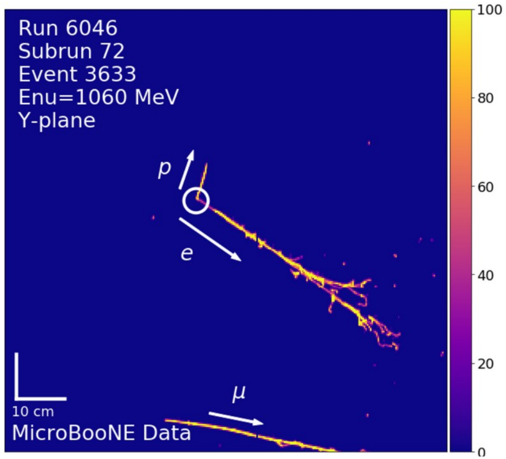
Fraction of spacepoints vs. distance from the ground truth trajectory of simulated tracks

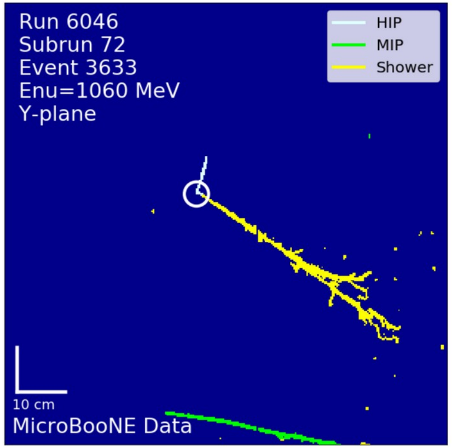


Spacepoint Tagging

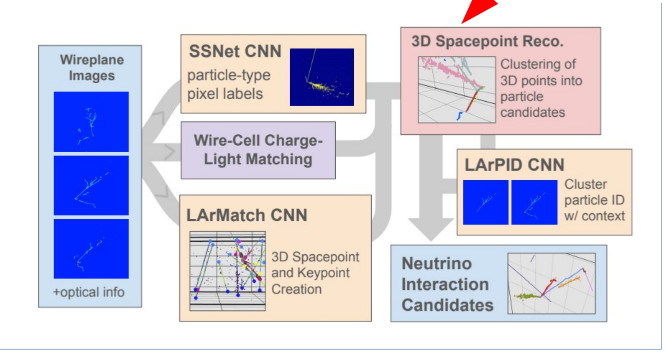


- Tag 3D spacepoints as:
  - Cosmic or neutrino, using the charge-light matching algorithms of the MicroBooNE Wire-Cell reconstruction
    - P. Abratenko et al. (MicroBooNE), Phys. Rev. D **105**, 112005 (2022)
  - Track or shower, using the labels for constituent pixels from the SSNet CNN (developed for the MicroBooNE quasi-elastic CC ν_e LEE search)
    - P. Abratenko et al. (MicroBooNE), Phys. Rev. D **105**, 112003 (2022)

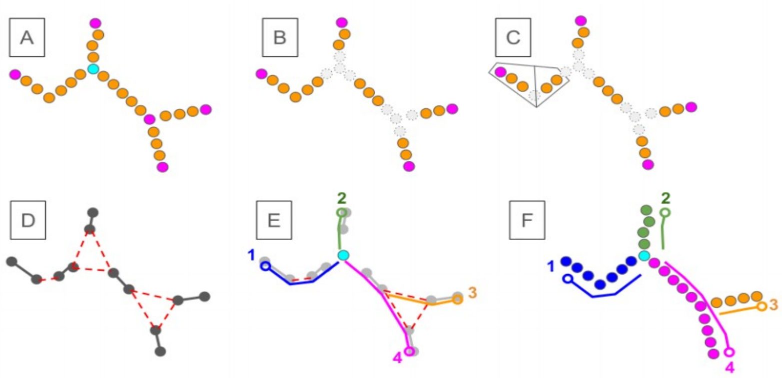


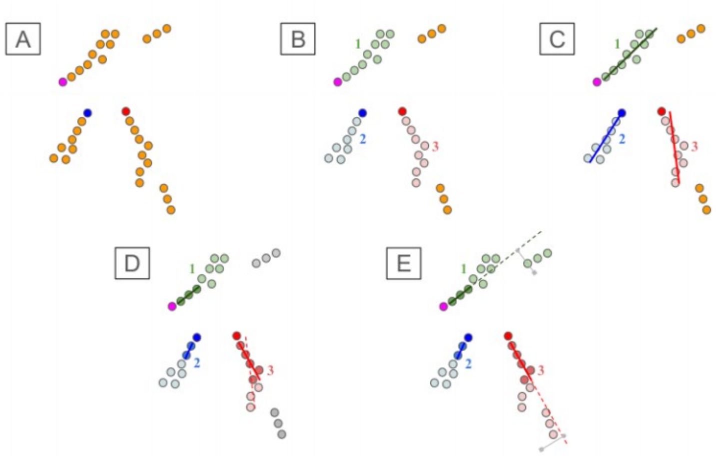


Spacepoint Clustering

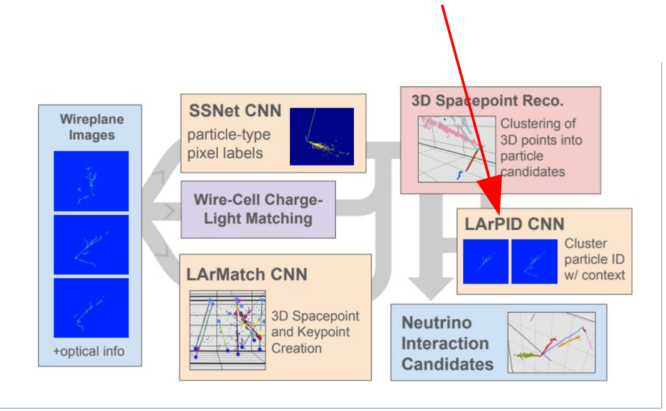


- Cluster spacepoints into particle candidates:
  - Partition points using track vs. shower tags and cosmic vs. in-time neutrino tags
  - Within each partition reconstruct clusters using DBScan and other non-ML algorithms for refinement





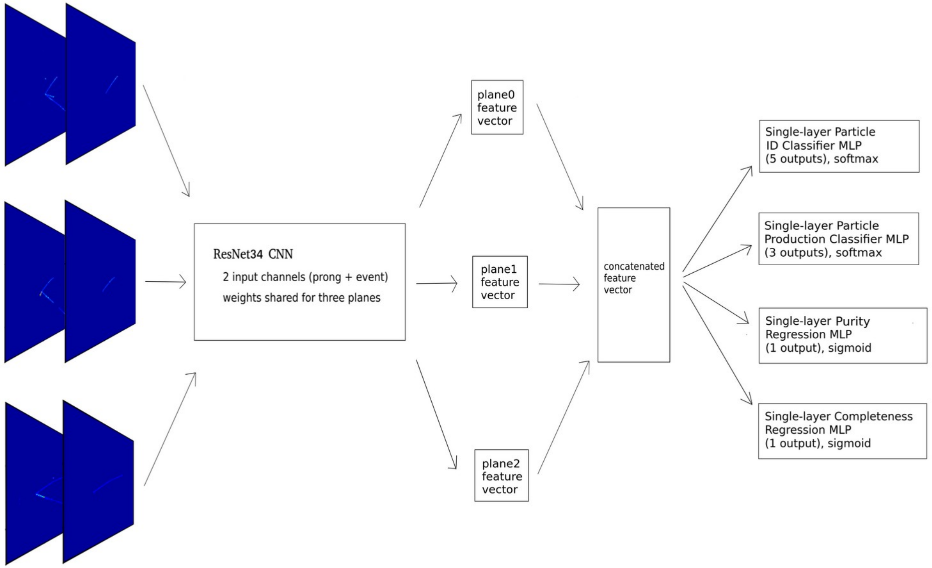
Particle Identification with LArPID



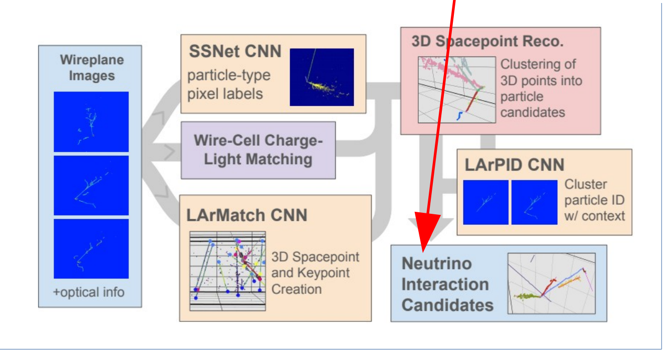
- LArPID: a particle identification CNN
- Takes cropped 2D images of pixels associated with 3D particle clusters and full event context images as input
- Assigns particle labels, classifies as neutrino-interaction primary vs. secondary particle, and outputs reconstruction quality metrics (purity and completeness)

LArPID Particle Classification Performance

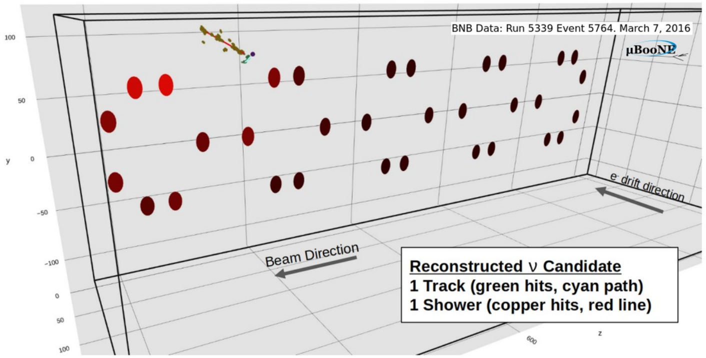
	True $e^{\pm}$	True γ	True $\mu^{\pm}$	True $\pi^{\pm}$	True p
Fraction classified as $e^{\pm}$	**84.5%**	5.2%	0.1%	0.5%	0%
Fraction classified as γ	12.7%	**94.3%**	0.2%	0.2%	0.1%
Fraction classified as $\mu^{\pm}$	0.4%	0.1%	**93.9%**	11.5%	0.3%
Fraction classified as $\pi^{\pm}$	2.3%	0.3%	5.6%	**86.5%**	1.6%
Fraction classified as p	0.1%	0.1%	0.2%	1.4%	**97.9%**

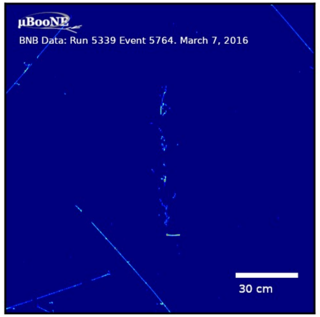


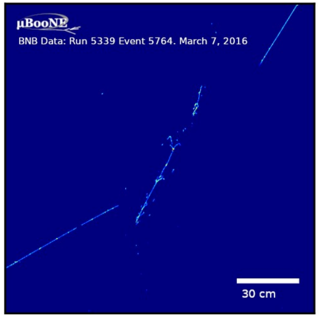
Neutrino Candidate Formation

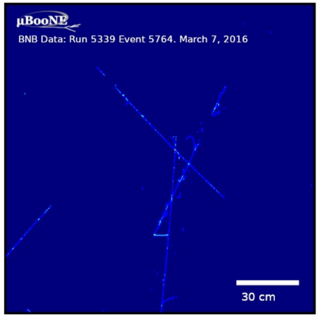


- Attach reconstructed particle clusters to Neutrino vertex keypoints found by LArMatch to form neutrino interaction candidates









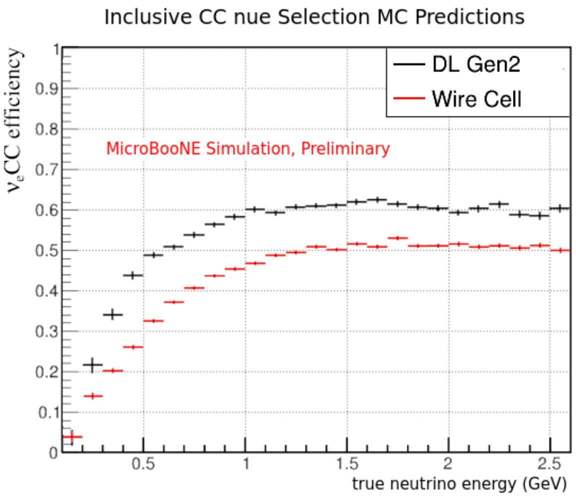
Inclusive CC Neutrino Selections with DL-Based Reconstruction

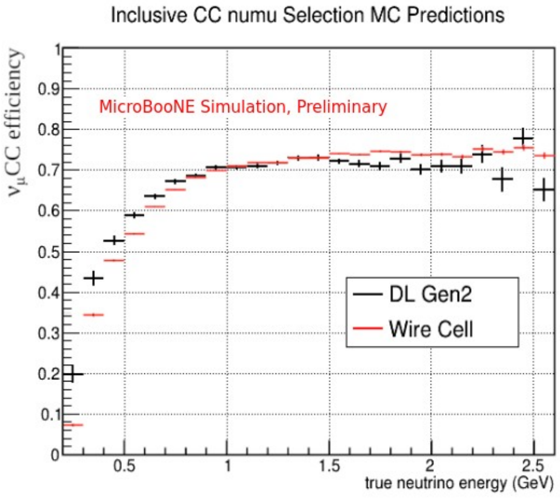
- Select CC ν_e and CC ν_μ interactions by cutting on LArPID outputs of clusters attached to neutrino interaction candidates
  - Inclusive CC ν_e selection:
    - No LArPID-classified muon or any tracks with a high muon score
    - At least one LArPID-classified electron shower
    - Largest LArPID-classified electron shower is also classified as a primary particle and has low photon and pion scores
  - Inclusive CC ν_μ selection:
    - At least one LArPID-classified muon track
- Compare to MicroBooNE's highest-efficiency published (previous best) inclusive selection results, which utilize the Wire-Cell reconstruction
  - P. Abratenko et al. (MicroBooNE), Phys. Rev. D **105**, 112005 (2022)

Predicted Selection Results

- Inclusive CC selections have high purity and efficiency, compare favorably to MicroBooNE's previous-best results

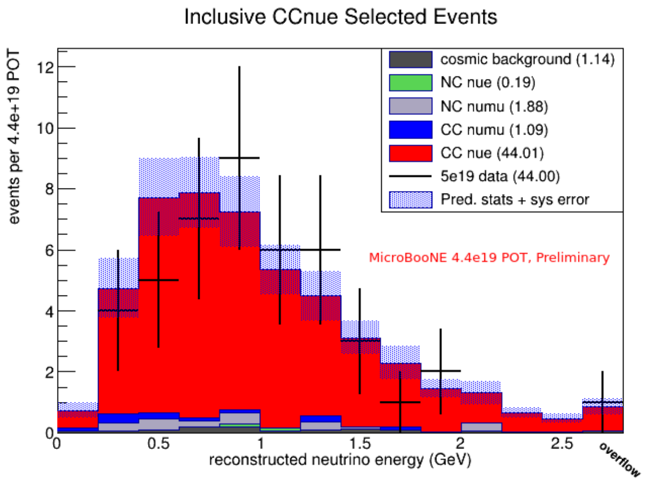
	DL Reco	Wire Cell
CC ν_e Efficiency	57%	46%
CC ν_e Purity	91%	82%
CC ν_μ Efficiency	68%	68%
CC ν_μ Purity	96%	92%

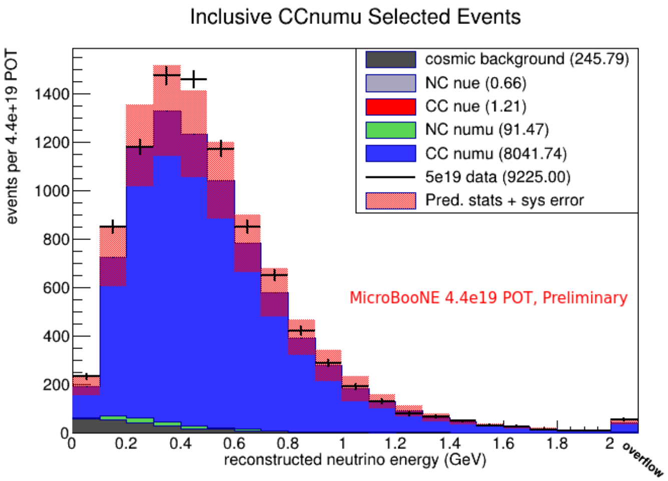




Selection Results with MicroBooNE Open Data

- Good data/MC consistency in high-level kinematic distributions (see backup slides for lepton momentum and cos(θ) distributions)





	CC ν_e Selection, E_ν Binning	CC ν_e Selection, p_{e^-} Binning	CC ν_e Selection, $\cos(\theta)$ Binning	CC ν_μ Selection, E_ν Binning	CC ν_μ Selection, p_μ Binning	CC ν_μ Selection, $\cos(\theta)$ Binning
χ^2/DOF	3.80/9	3.06/8	5.18/6	25.08/21	11.91/21	9.73/16
p value	0.924	0.931	0.521	0.244	0.942	0.880

Comparison to Wire-Cell: CC ν_e Open Data Results

- Comparing selected events in open data, all manually hand scanned
- Number of probable signal events found by DL reco but not Wire Cell: 11
- Number of probable signal events found by Wire-Cell but not DL reco: 6

	DL Reco Data Hand Scan Estimate	DL Reco MC Prediction	Wire-Cell Data Hand Scan Estimate	Wire-Cell MC Prediction
Total Events	44	48.3	40	41.2
Signal Count	42-43	44.0	37-38	33.8
Background Count	1-2	4.3	2-3	7.3
Purity	95% - 98%	91%	93% - 95%	82%

Conclusions

- This work represents the first demonstration of a deep-learning based generic neutrino interaction reconstruction framework on real LArTPC data
- Predicted CC ν_e and CC ν_μ selection results compare favorably to MicroBooNE's previous-best results
  - Reduced backgrounds and predicted 24% increase in number of selected CCnue events
  - Predictions consistent with hand scans of CC ν_e events selected from MicroBooNE open data set
- Predicted distributions of high-level kinematic kinematic variables for selected CC events are consistent with data, and systematic uncertainties are similar to non-DL-based reco frameworks
  - Evidence of the robustness of the framework and a lack of significant data/MC domain shifts introduced by deploying CNNs trained on MC
- Results show potential for DL tools to improve the sensitivity of future analyses in MicroBooNE and other LArTPC experiments
  - Full framework or individual tools (especially LArPID) could be adapted in other reconstruction frameworks or LArTPC experiments

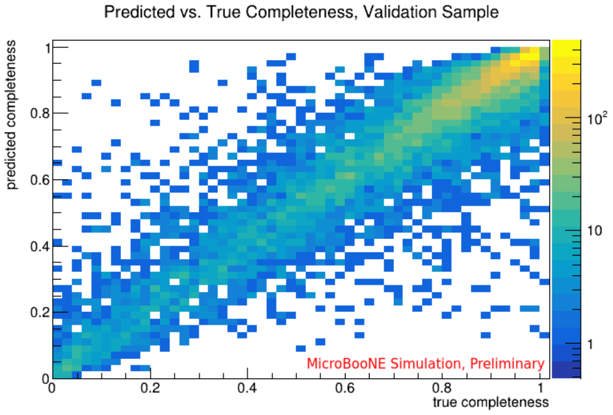
Backup Slides

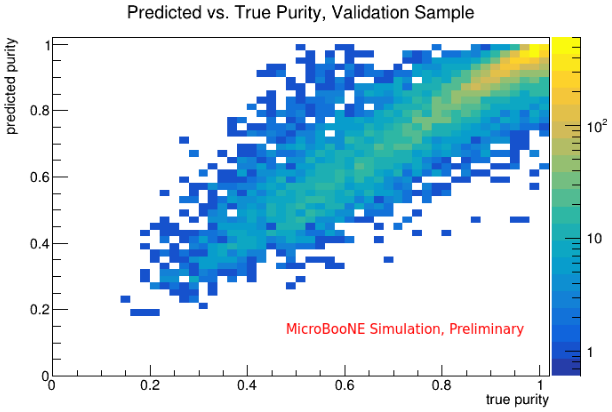
Additional LArPID Evaluation Metrics

- Particle production process classification accuracy
  - Classes: primary neutrino-final-state particle, secondary with a charged parent, and secondary with a neutral parent

	True primary	True neutral parent	True charged parent
Fraction classified as primary	**87.8%**	3.4%	6.5%
Fraction classified as neutral parent	2.9%	**93.6%**	6.9%
Fraction classified as charged parent	9.3%	3.0%	**86.7%**

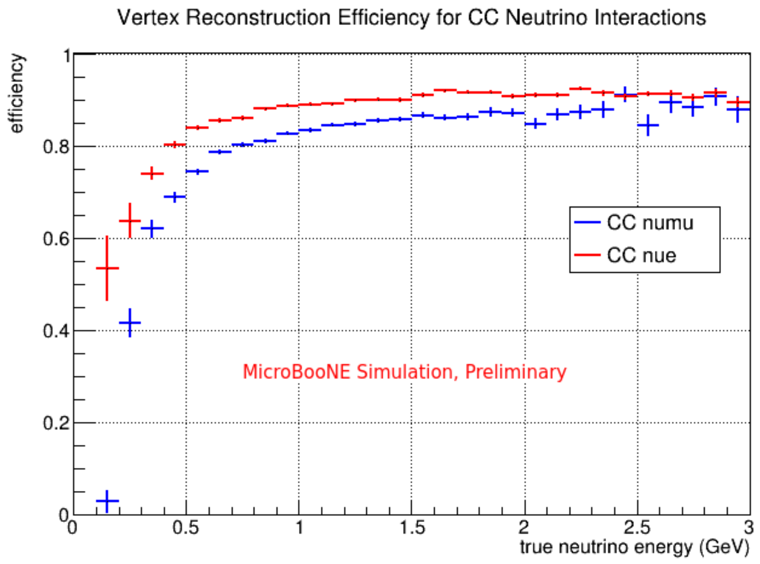
- Reconstruction quality metrics
  - Purity: fraction of the reconstructed cluster that was created by the true (simulated) particle
  - Completeness: fraction of the true (simulated) particle that was reconstructed in the cluster

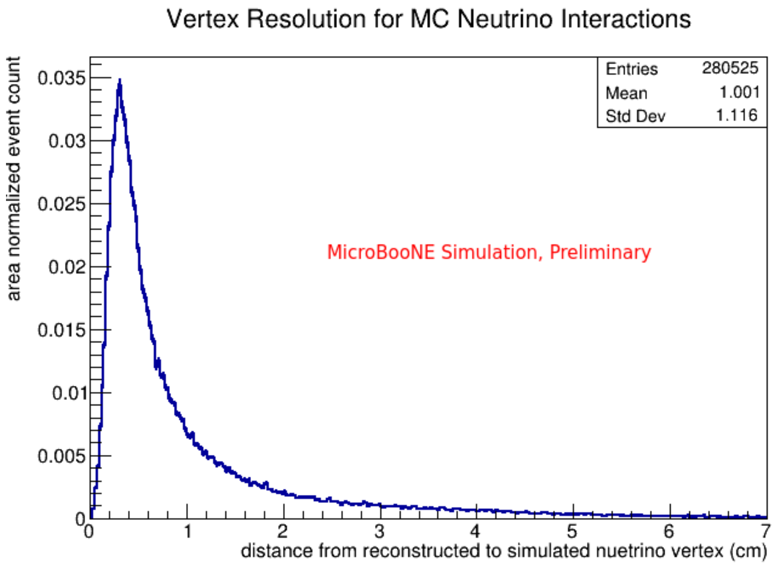




Reconstruction Performance: Neutrino Vertex Efficiency and Resolution

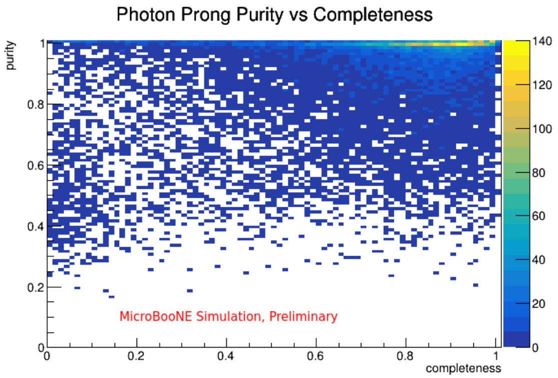
- Neutrino vertices found through LArMatch keypoint network
- In MC, 68% of neutrino vertices are within 9.2mm (~3 wires) of true interaction position

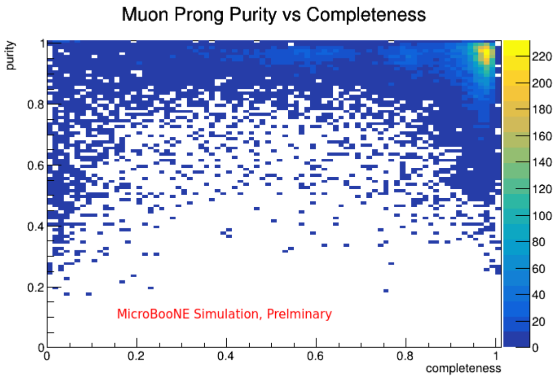


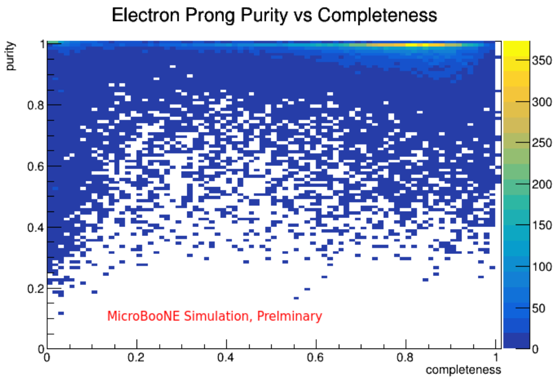


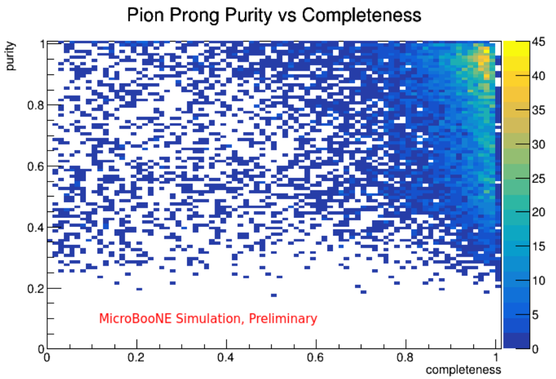
Reconstruction Performance: Particle Clustering Quality

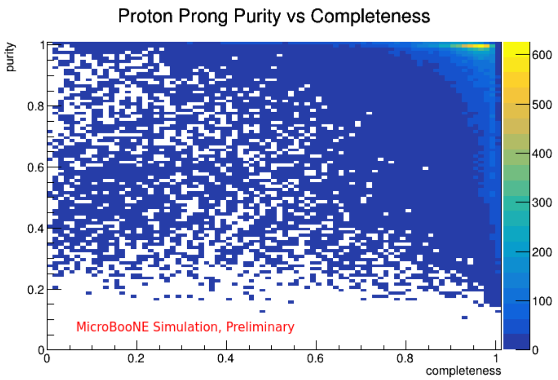
- Check purity and completeness of clusters reconstructed from simulated particles in MC neutrino interactions
  - Purity: fraction of the reconstructed cluster that was created by the true (simulated) particle
  - Completeness: fraction of the true (simulated) particle that was reconstructed in the cluster











Additional Primary Lepton Distributions for Inclusive Selections