NuGraph2: A Graph Neural Network for Neutrino Event Reconstruction

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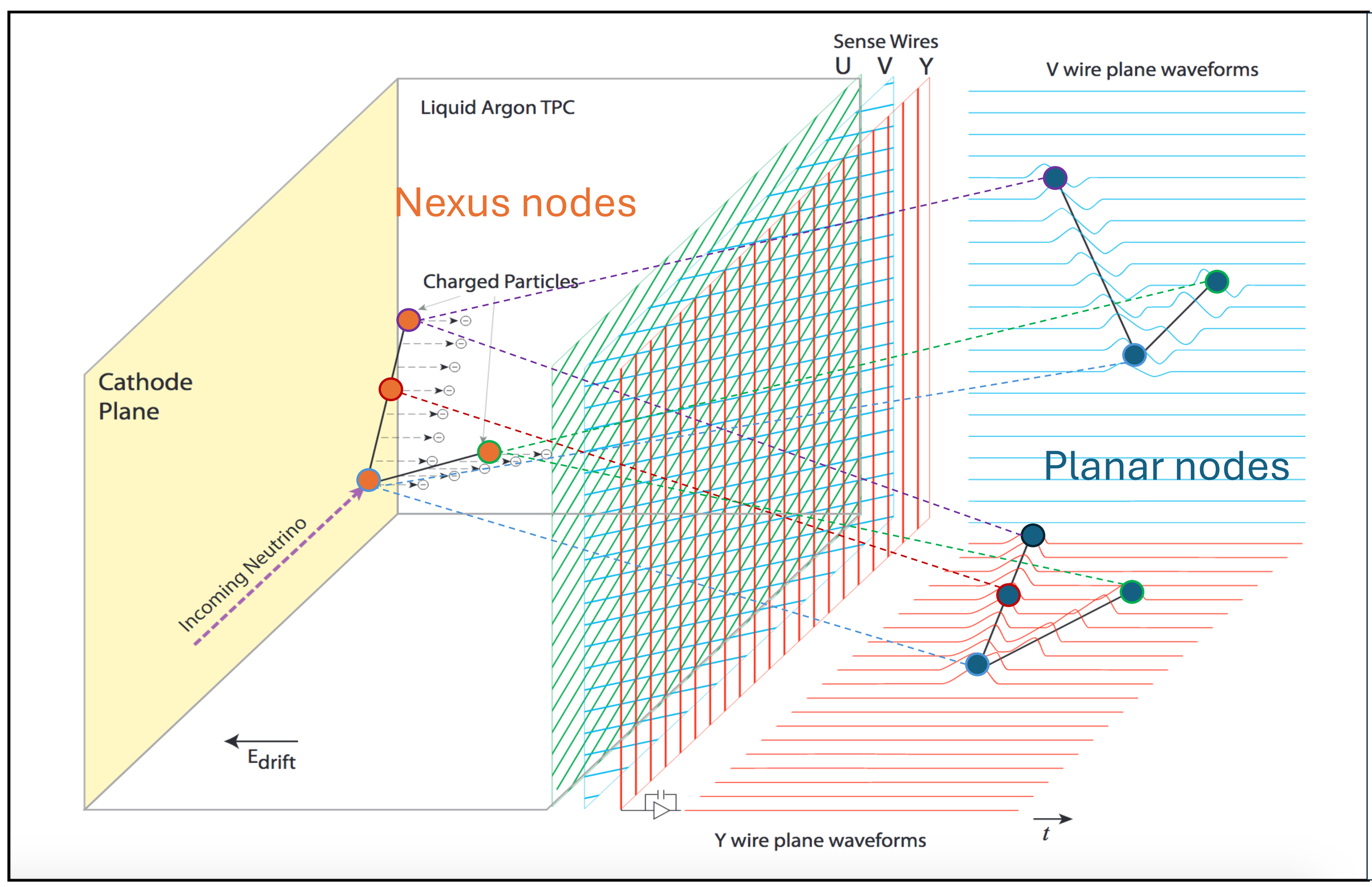
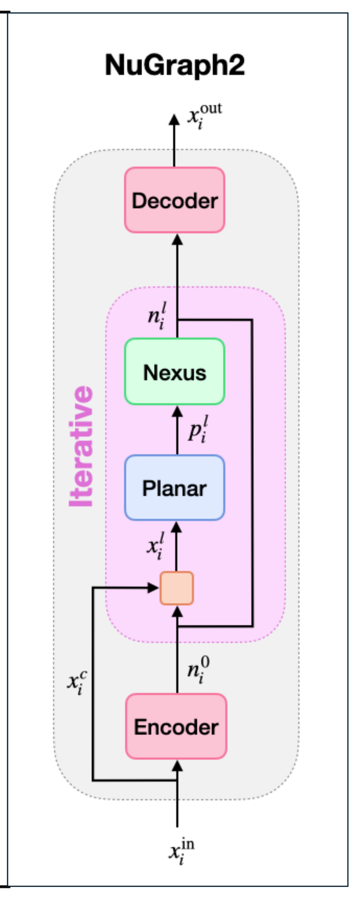
Network definition and performance on simulation

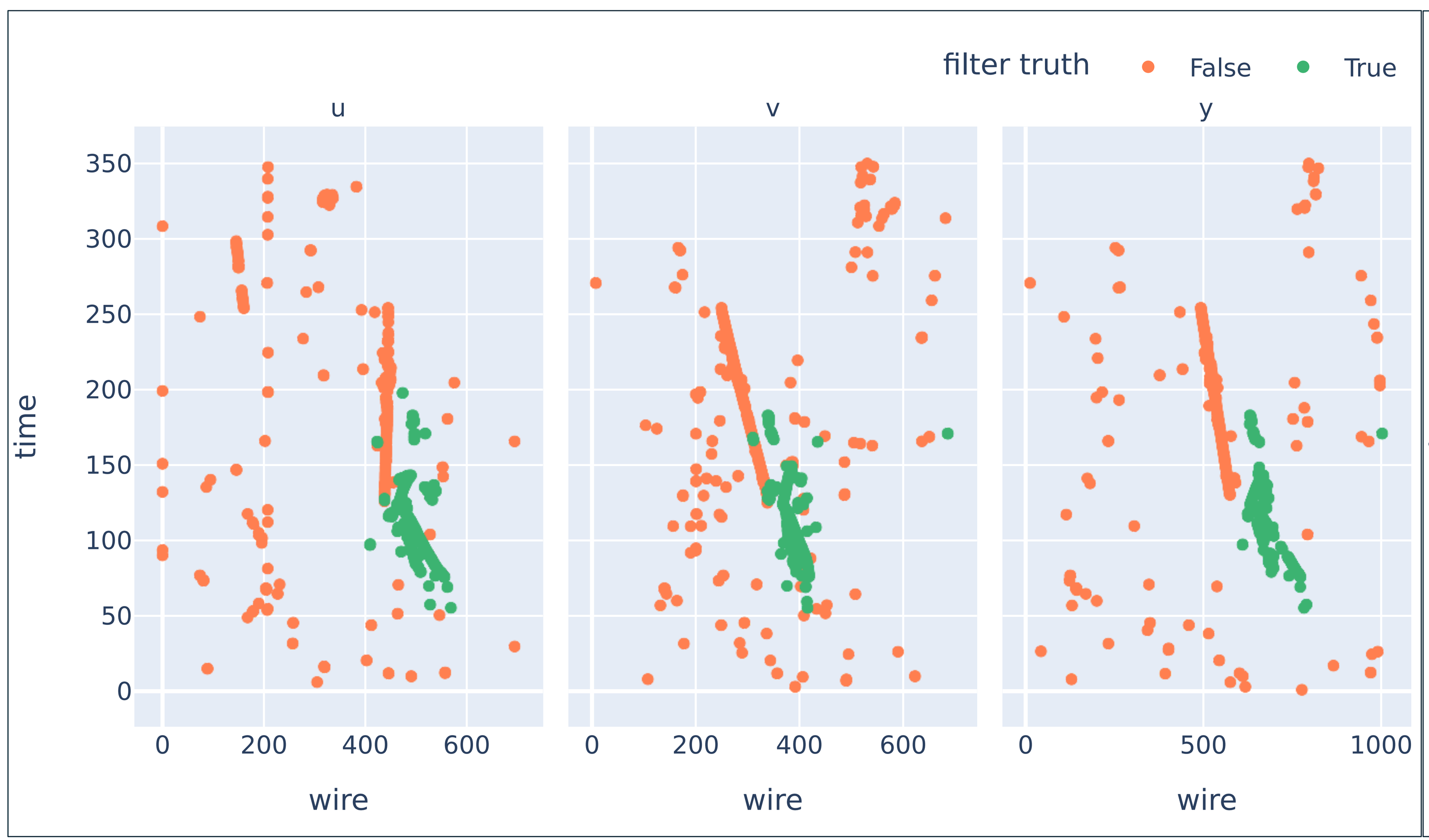
Paper submitted to Phys. Rev. D [arXiv:2403.11872]

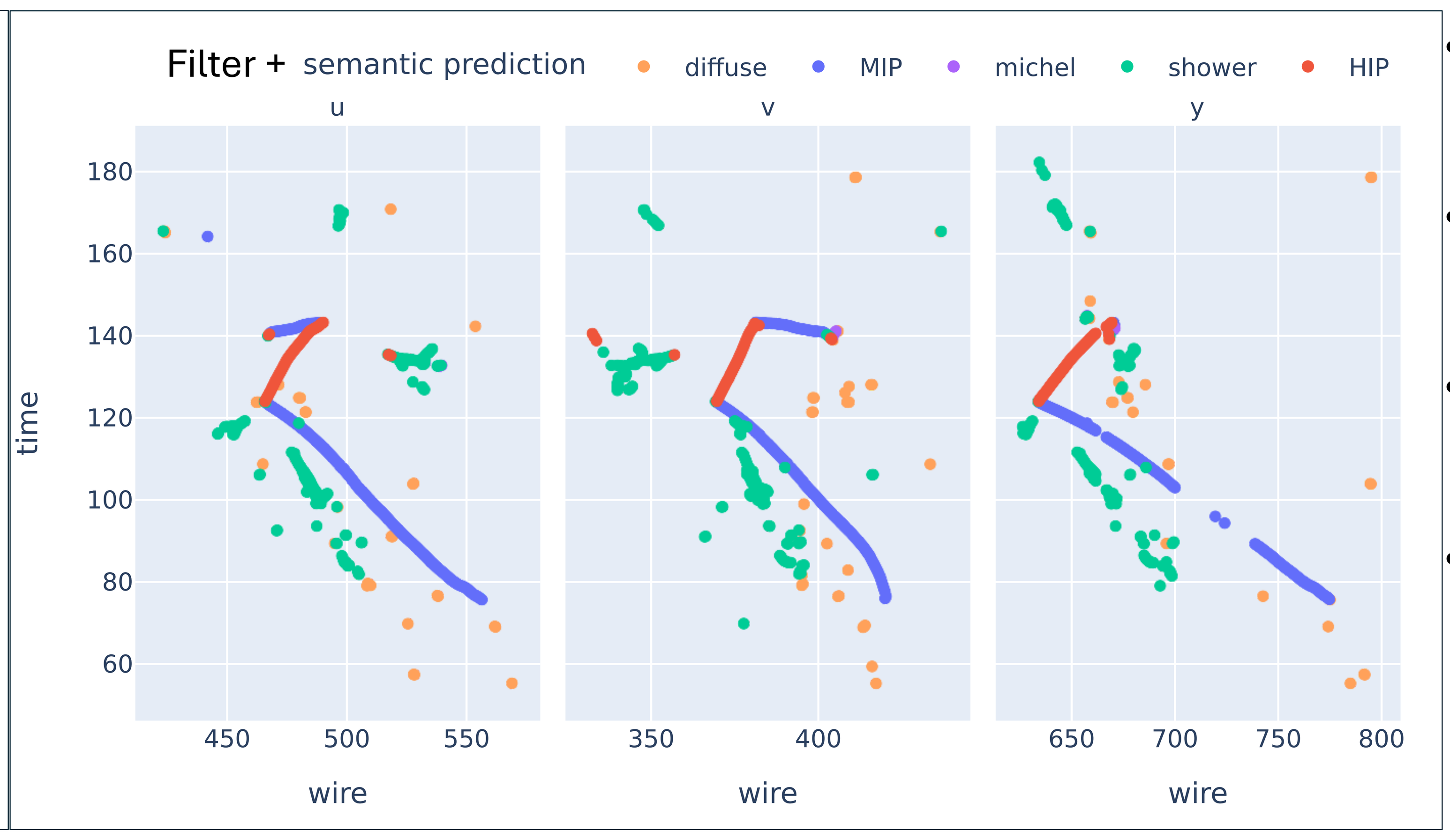




- NuGraph2 is a **Graph Neural Network** for event reconstruction in LArTPC experiments.
- A graph is built connecting **2D hits (nodes)** within planes using Delaunay triangulation. Hits across planes are connected to **3D "nexus" nodes** based on the Space Point Solver algorithm.
- **Input features** to the network encoder are: hit wire, peak time, RMS, integral.
- Information flows in 5 **message passing** iterations across the planar and nexus edges.
- After the last step two **decoders** extract the physics output: filter (neutrino vs background hit) and semantic (label hits by particle type).

True label \ Assigned label	MIP	HIP	shower	michel	diffuse
diffuse	0.03	0.031	0.058	0.021	0.86
michel	0.06	0.012	0.11	0.72	0.1
shower	0.02	0.0094	0.91	0.029	0.036
HIP	0.042	0.93	0.013	0.0033	0.013
MIP	0.97	0.012	0.0086	0.0065	0.005



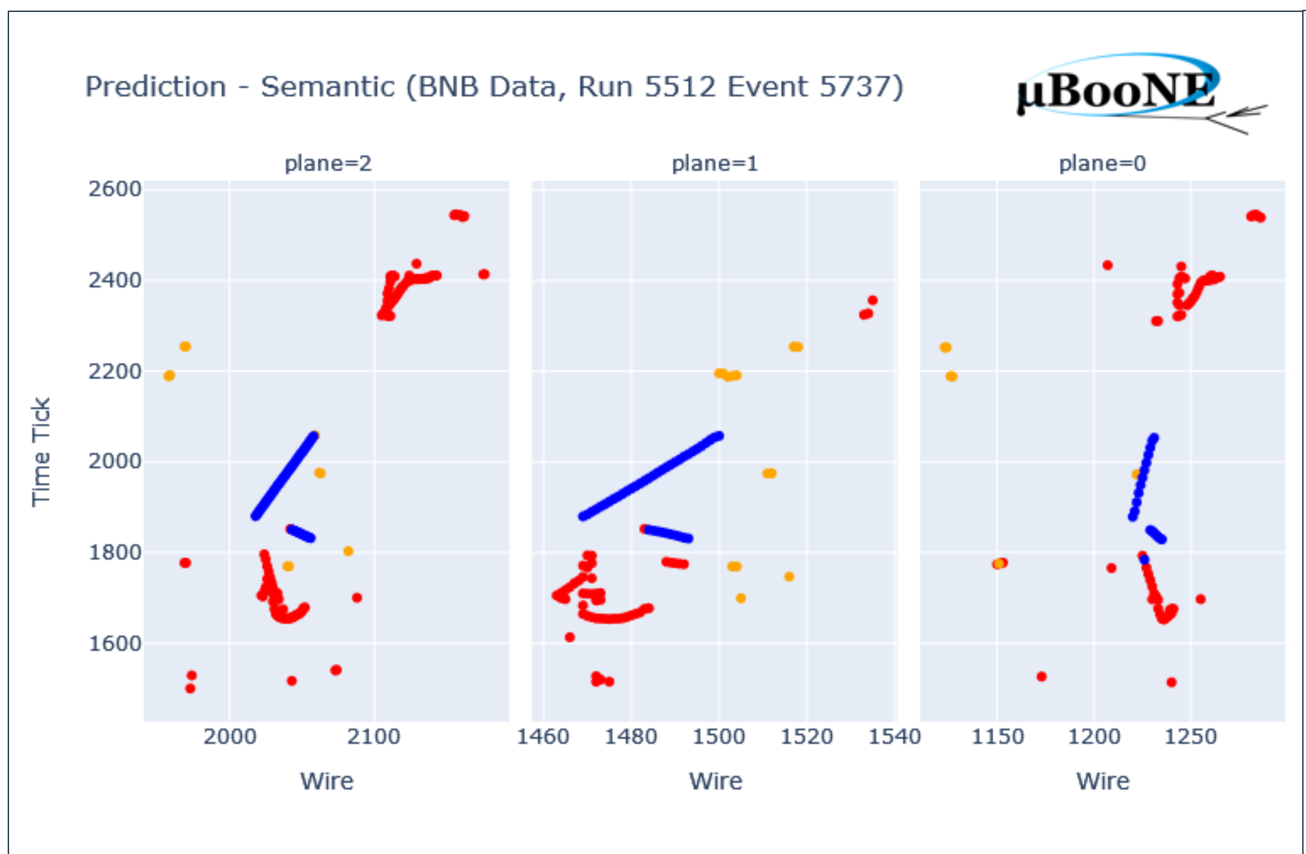


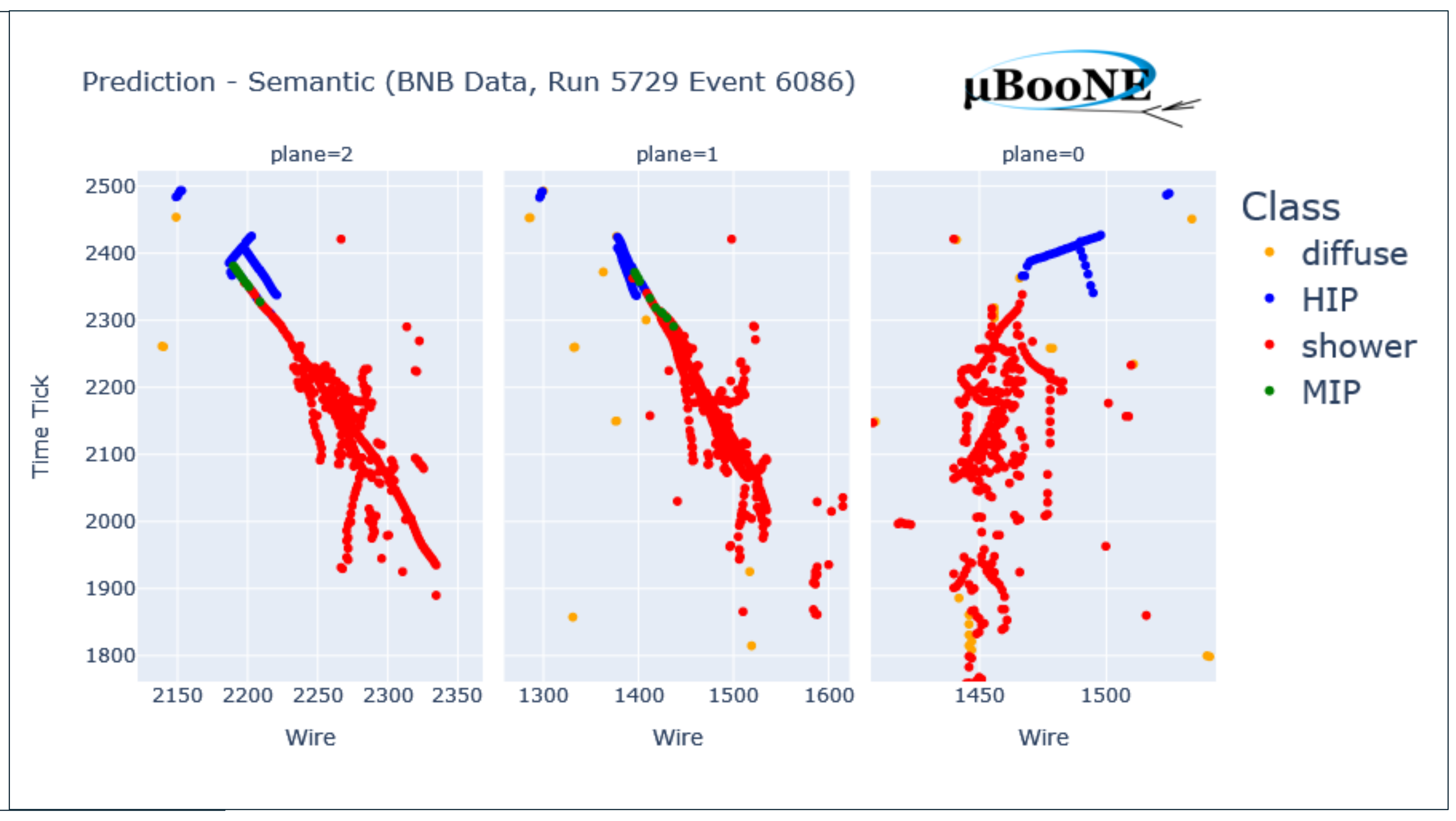
- NuGraph2 is trained on the **MicroBooNE open data** sets [arXiv:2309.15362].
- It achieves an **accuracy of 98% for filter and 95% for semantic** decoder.
- The nexus edges ensure a **consistent 3D interpretation** of the event at ≥95% level.
- Event displays show that NuGraph2 can identify cosmics close to the ν interaction and resolve non-trivial topologies.

See **poster #150** in this session NuGraph3 developments towards a full GNN-based event reconstruction in LArTPC detectors.

Integration in LArSoft and First Tests on MicroBooNE data

- Inference time on CPU is < 1 s/event, including graph construction. When running on GPU in batches, inference time is reduced down to 0.005 s/event.
- NuGraph2 is **integrated in LArSoft** (larrecodnn/NuGraph package), starting form v09_83_01 release. Requires libtorch v2_1_1, torch_scatter v2_1_2, delaunator v0_4_0.
- Integration enables NuGraph2 to run in reconstruction workflows of the LArTPC experiments and facilitates testing NuGraph2 on real data.

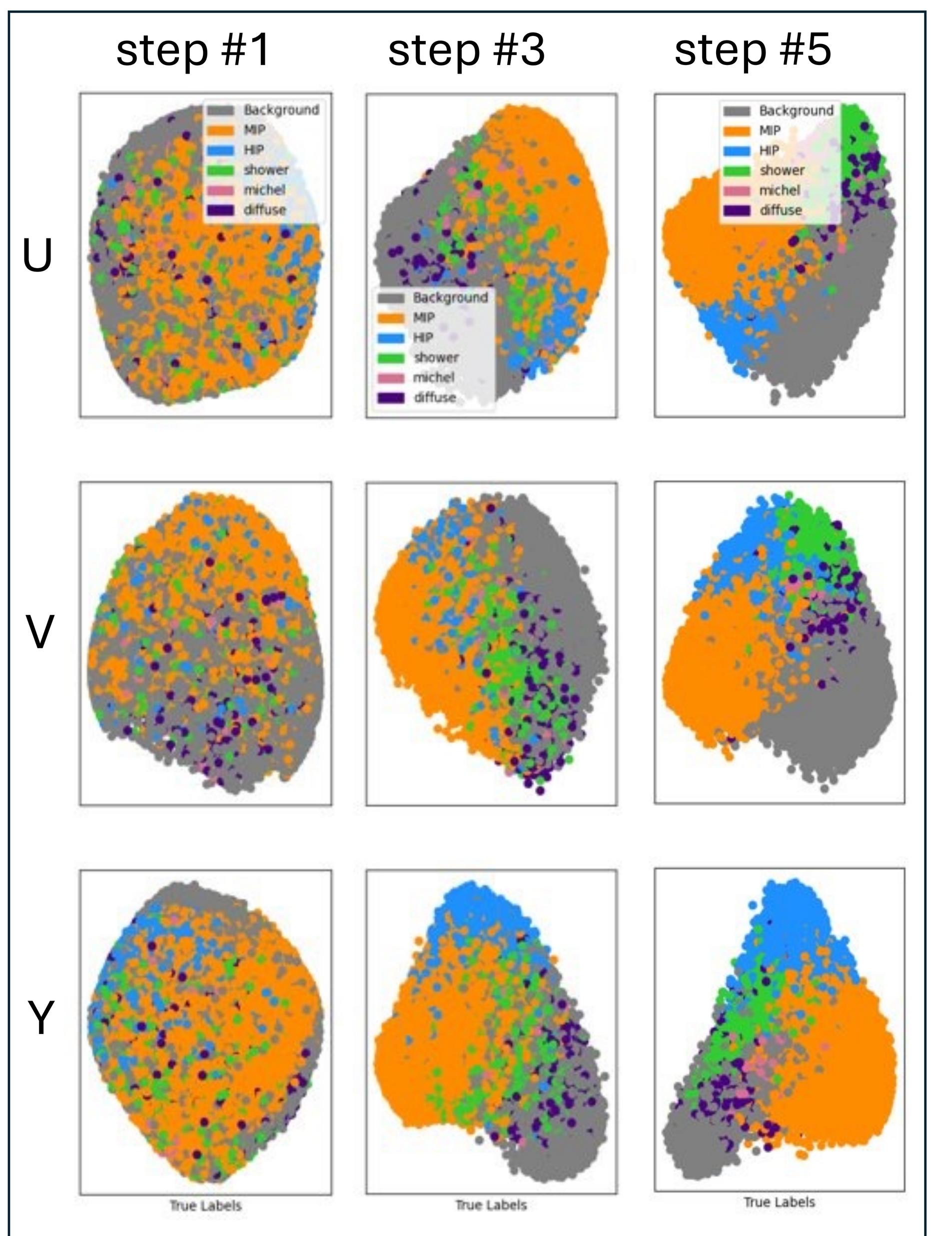




- First tests on MicroBooNE data events passing a loose ν_e CC preselection show **encouraging performance** for the **semantic decoder**: NuGraph2 correctly tags shower hits both from primary electrons (left plot) and photons (right) from π^0 background.
- The filter decoder seems to overly reject shower hits from the neutrino interaction, so **domain shifts** between the training data set and the application data are being investigated.

See **posters #130 and #389** in this session for applications of NuGraph to τ neutrino event reconstruction in DUNE.

Network Explainability and Injection of Physics Domain Knowledge

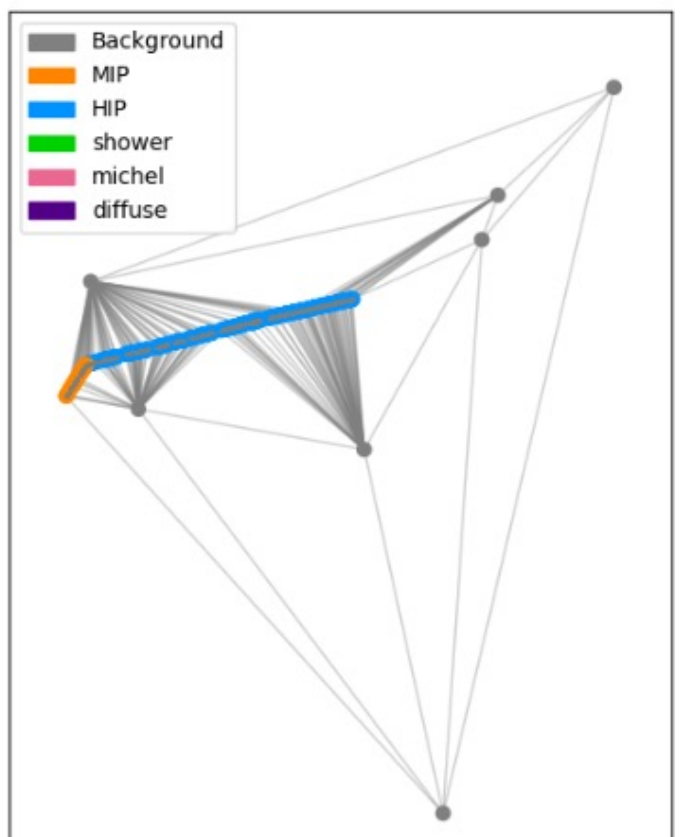


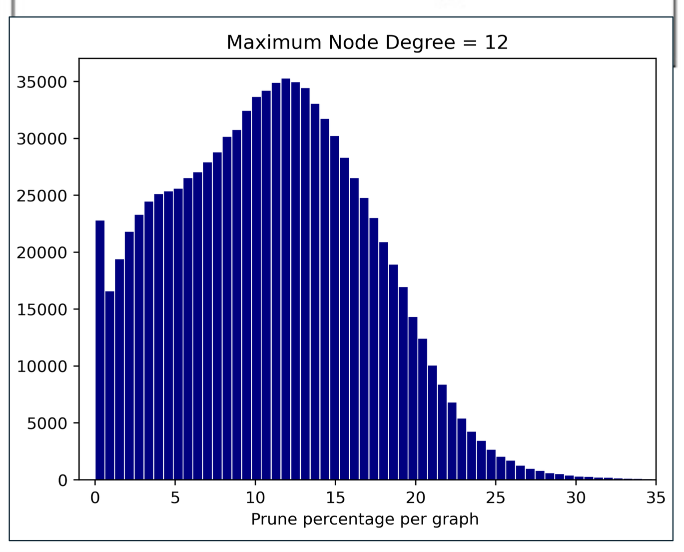
Explainability: *Goal is to "open the black box" to build confidence and drive developments.*

1. Visualization of latent space (left figure)
   - Cluster latent space features and project in 2D for visualization
   - Separation between different categories achieved by the last (5th) network iteration
2. Understanding the role of "hub" nodes (right figures)
   - Detached nodes with large edge multiplicity connect nodes within and across objects
   - Pruning test: 12 is the lowest upper bound in multiplicity without affecting performance, when pruning edges uniformly in terms of length
   - Demonstrates that there is a large degree of redundancy and that both short and long edges matter. Can also lead to network speedups.

Domain Knowledge: *Goal is to drive the learning and mitigate training dataset limitations.*

1. Force learning correlations between semantic classes
   - Add a decoder to regress the fraction of hits in each semantic category
   - Evaluation of impact on the network performance is in progress.
2. Add non-local and topological node features
   - Add the following quantities to the input node features: Δtime and Δwire between the two closest nodes, distance to closest node, edge multiplicity
   - Improves the network accuracy by ~5% (relative) for the Michel category





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