

Particle Clustering in LArTPCs with NuGraph

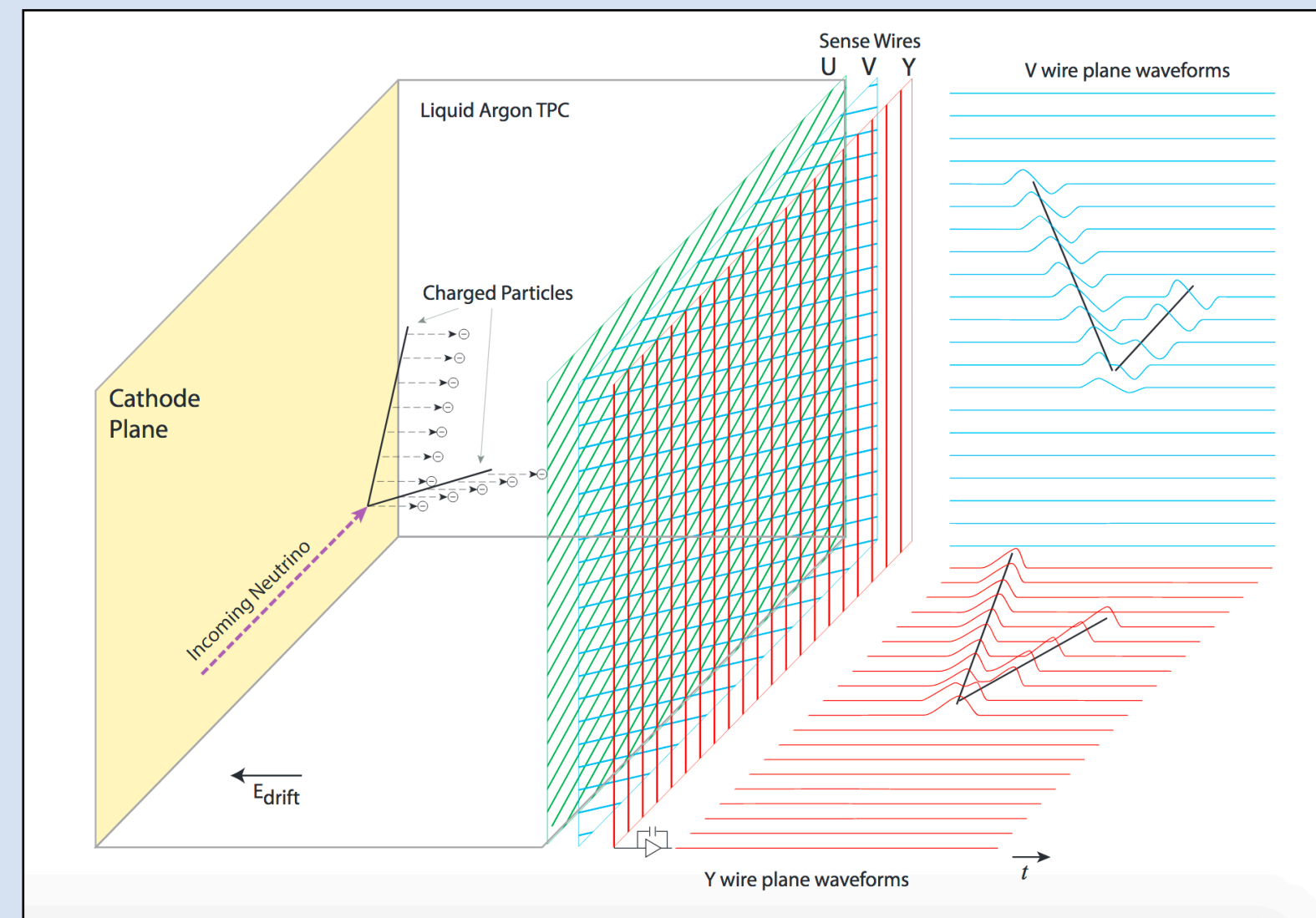
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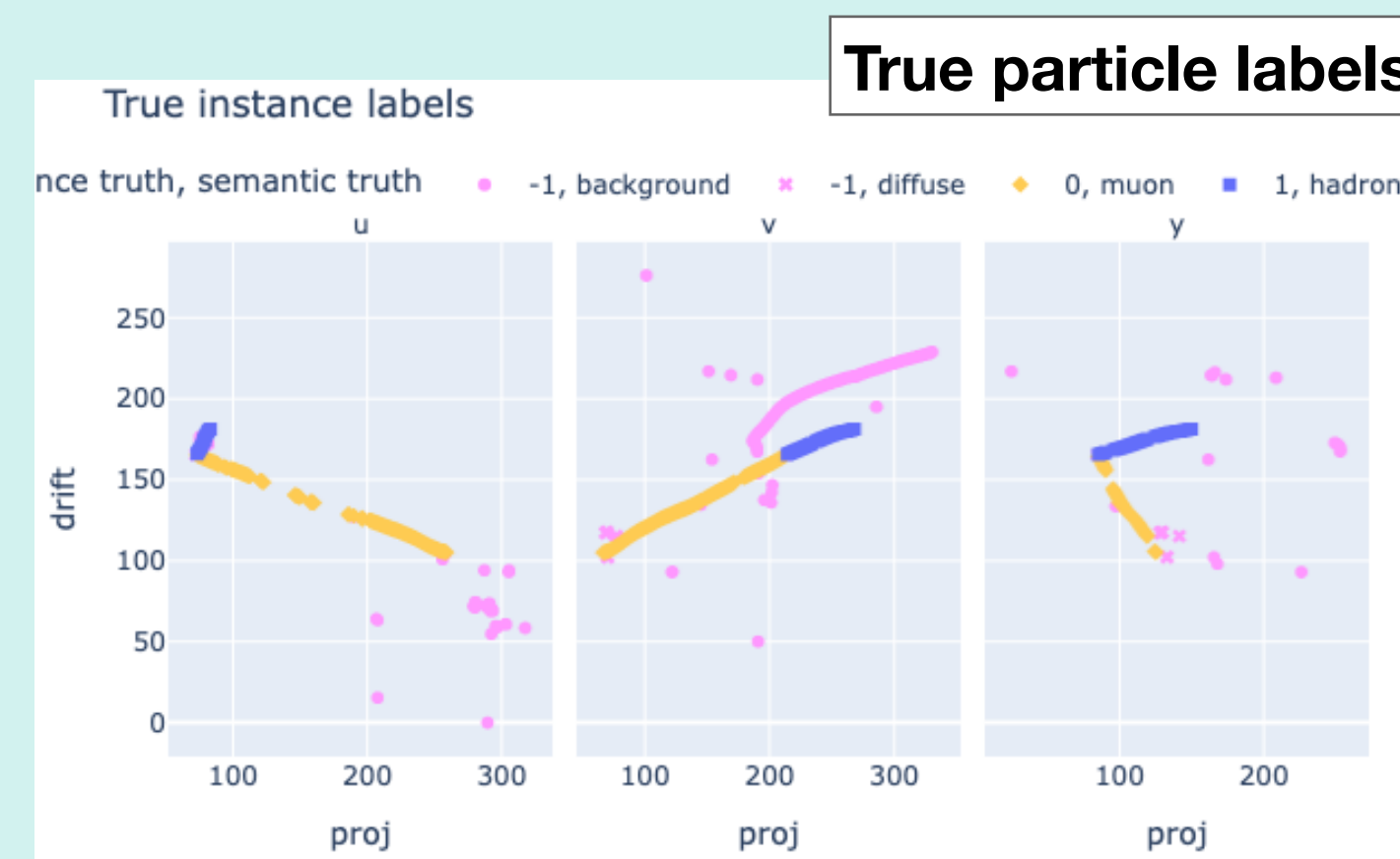
Liquid Argon TPCs

- **Liquid Argon Time Projection Chambers** (LArTPCs) utilized across MicroBooNE, ICARUS, SBND, and DUNE.
- Ionization electrons produced by charged particles drift under E field, measured by wires/pixel readout.
- LArTPCs provide **excellent spatial resolution**, but automated reconstruction is challenging.



Particle Clustering

- Utilize **object condensation** (*Eur. Phys. J. C* **80**, 886 (2020), arXiv:2002.03605) to project hits into learned clustering space.
- Predict condensation embedding β_i and coordinates x_i .
- **Materialize clustering space** using DBSCAN clustering algorithm.
- Form **particle nodes** from materialized clusters.
- Instance decoder projects 2D hit nodes on all planes into a consistent clustering space to **cluster hits across views**.
- NuGraph3 clustering with object condensation achieves **Adjusted Rand Score of 0.76** for the MicroBooNE open data release.

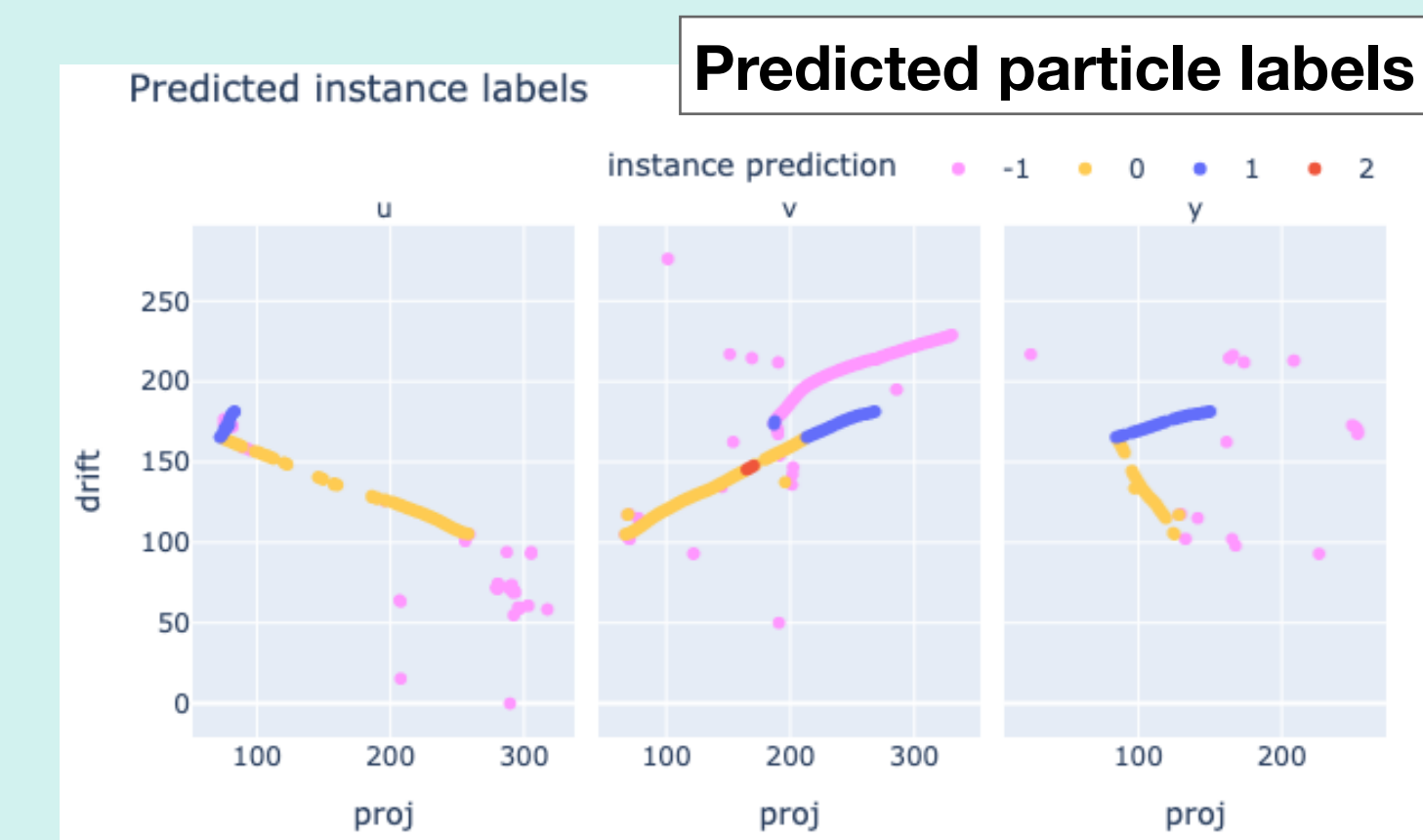
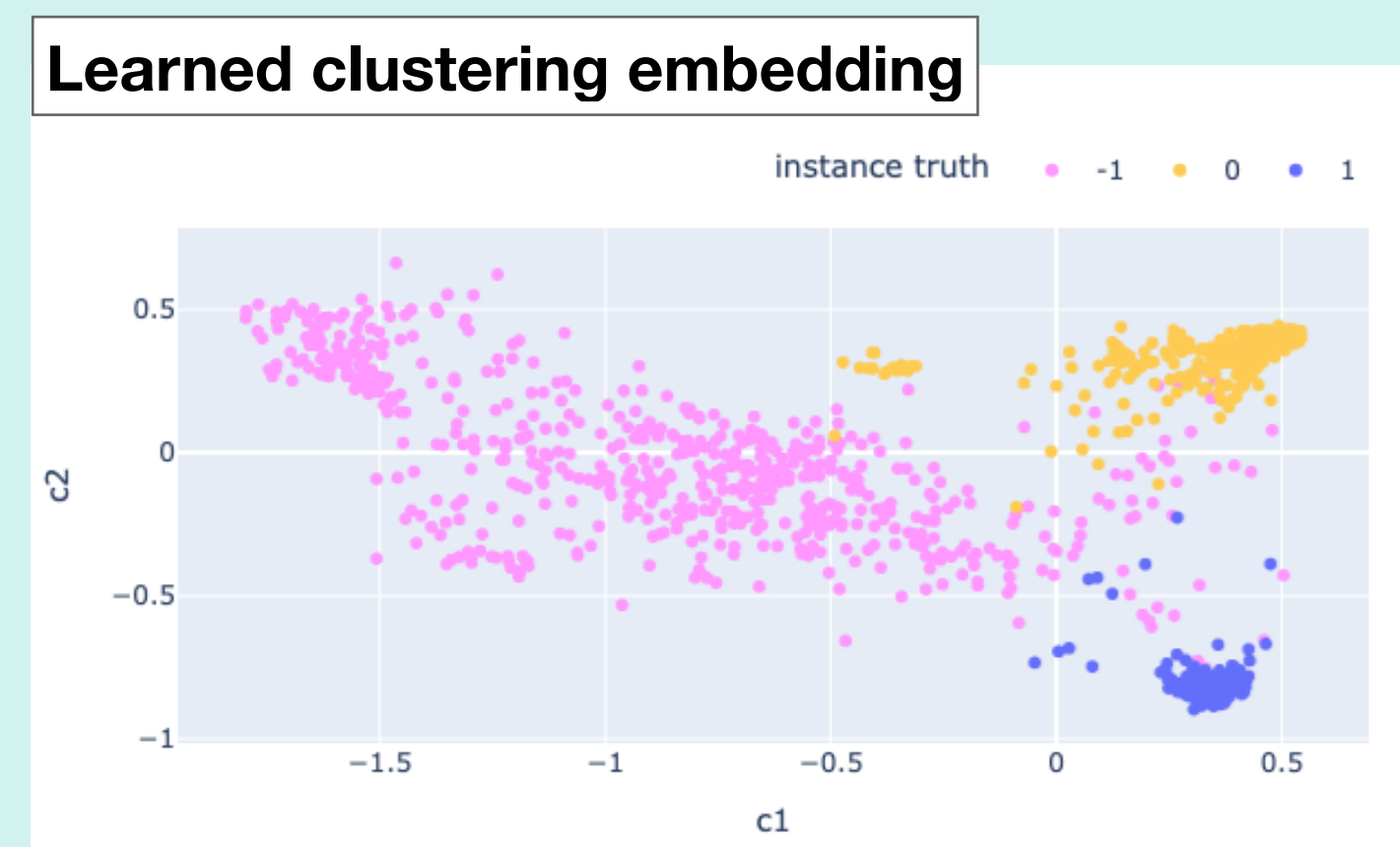


$$L = L_\beta + L_V$$

$$L_\beta = \frac{1}{K} \sum_k (1 - \beta_{ak}) + s_B \frac{1}{N_B} \sum_i n_i \beta_i$$

$$L_V = \frac{1}{N} \sum_{j=1}^N q_j \sum_{k=1}^K (M_{jk} \check{V}_k(x_j) + (1 - M_{jk}) \hat{V}_k(x_j))$$

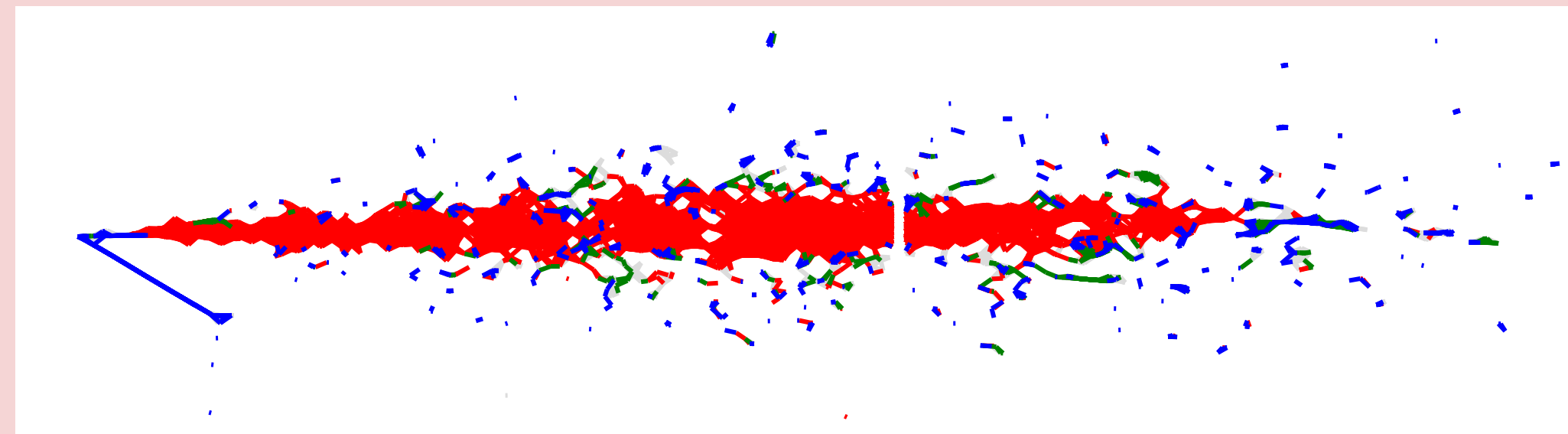
M_{jk} = object membership matrix
 $q_j = \arctanh(\beta_j) + \beta_{min}$
 $\check{V}_k(x_j), \hat{V}_k(x_j)$ = attractive, repulsive potentials
 s_B = background suppression strength
 N_B = number of background hits
 K = number of objects



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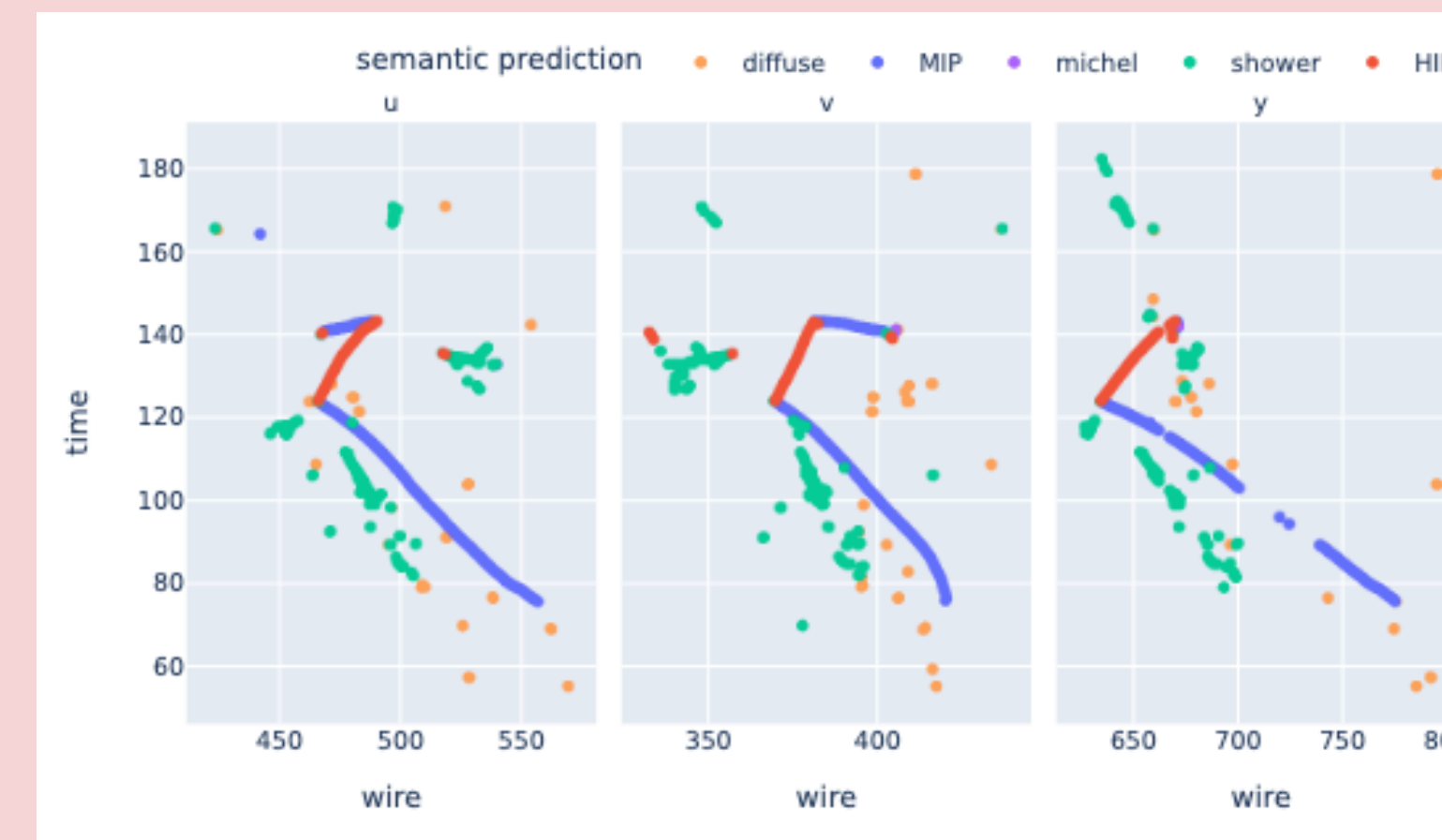
Exa.TrkX and NuGraph

- **NuGraph** was developed within Exa.TrkX project to develop GNN-based reconstruction in the HL-LHC and LArTPCs.
- **NuGraph1** architecture adapted HEP.TrkX prototype for LArTPCs (arXiv:2103.06233).



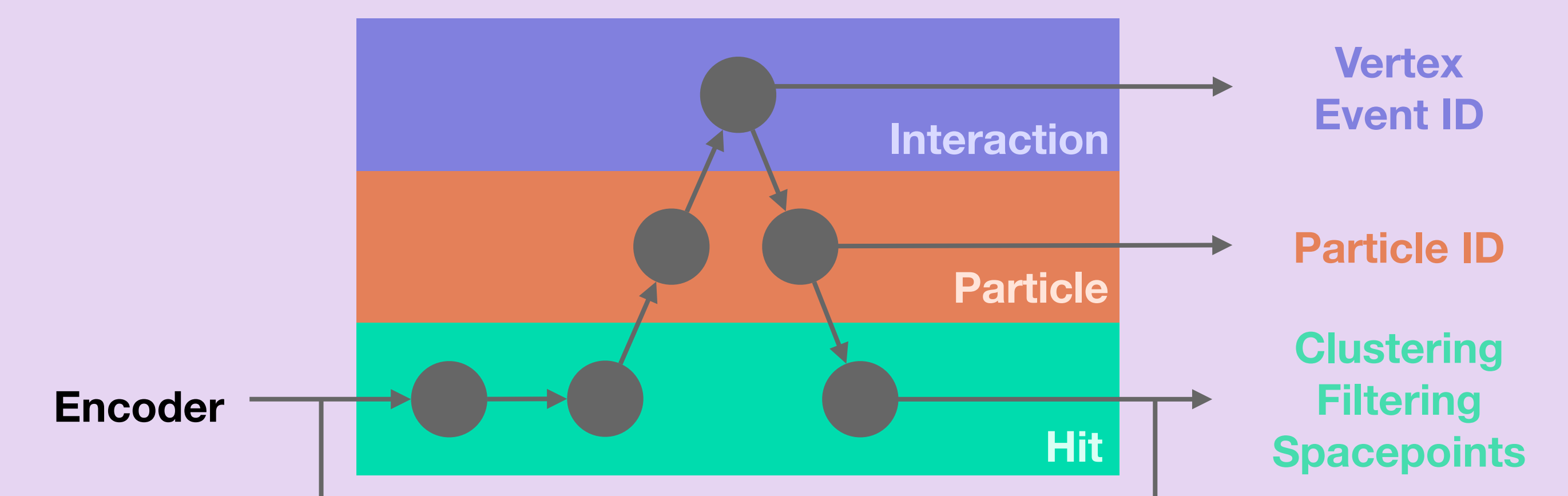
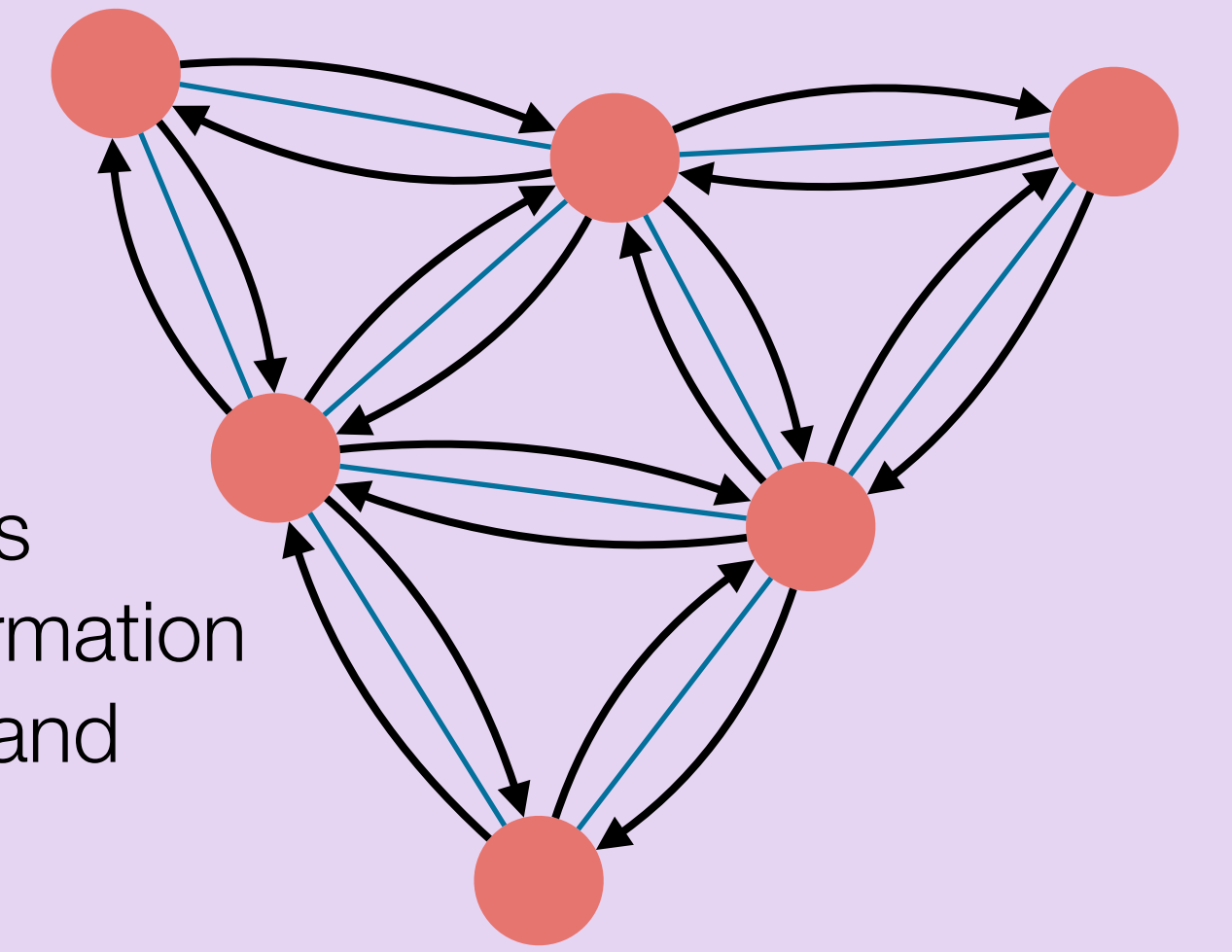
- Promising performance, but found link prediction to be inappropriate for neutrino interactions in LArTPCs.
- **NuGraph2** architecture performs node classification on detector hits (*Phys. Rev. D* **110** (2024) 3, 032008, arXiv:2403.11872):

- **98% efficient** at removing **cosmic background hits**.
- **95% efficient** at **classifying hits according to particle type**.



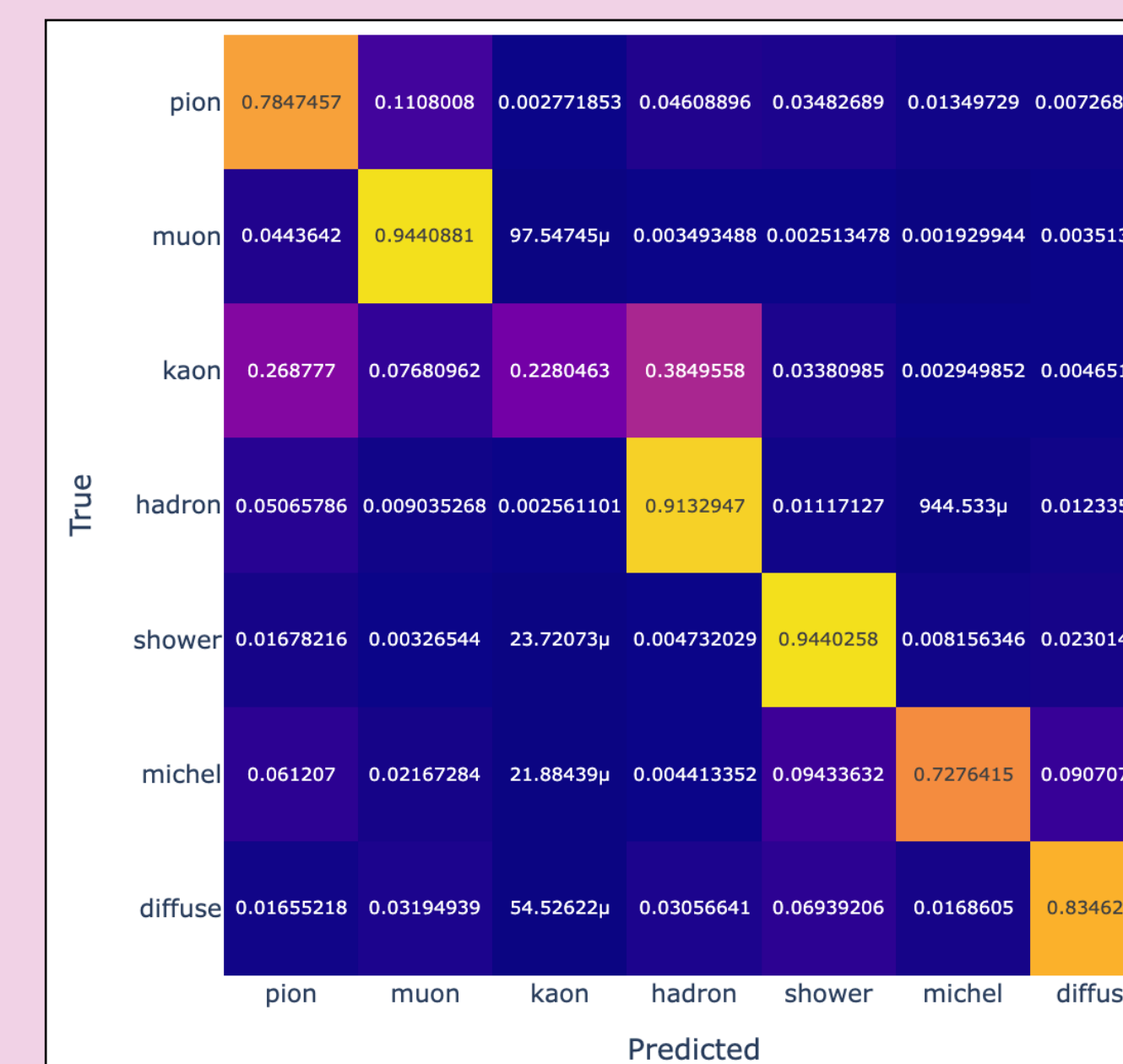
NuGraph3 Hierarchical GNN

- **NuGraph3** architecture adopts a hierarchical graph network approach.
- Represent physics interaction as **heterogeneous graph** with nodes representing different levels of information such as **detector hits, particles** and **interactions**.
- Utilize **sawtooth mechanism**, which steps up and down hierarchy with each message-passing iteration.
- All hierarchical levels converge towards a consistent final state.
- Train decoders to **predict multiple outputs simultaneously**, leveraging correlations between tasks to improve performance.



Results

- NuGraph is utilized across multiple LArTPC experiments, and results shown are from **MicroBooNE open data release**.
- **98% efficient** at removing background hits.
- Expanded semantic labelling:
 - Add μ/π separation, k/p separation.
 - **90% efficiency** at **classifying hits according to particle type**.
 - Predict **event-level quantities**:
 - Classify entire event with semantic label.
 - eg. ν flavour, proton decay.



- Reconstruct **3D vertex position**.
 - Achieve **~5cm spatial resolution in MicroBooNE**.
- **Spacepoint reconstruction**:
 - Predict 3D spatial position for each 2D detector hit.

