NuGraph2

A graph network for particle reconstruction

V Hewes (she/they)
NuGraph workshop
13th November 2023

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Neutrino physics

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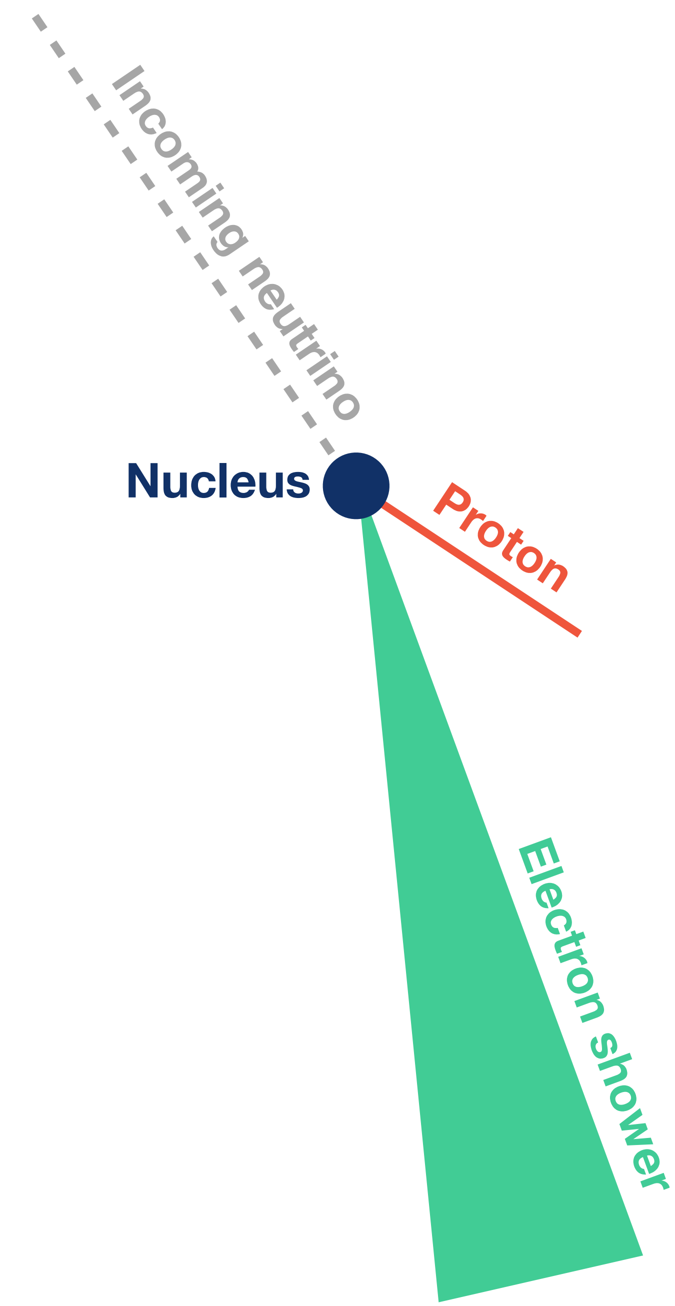

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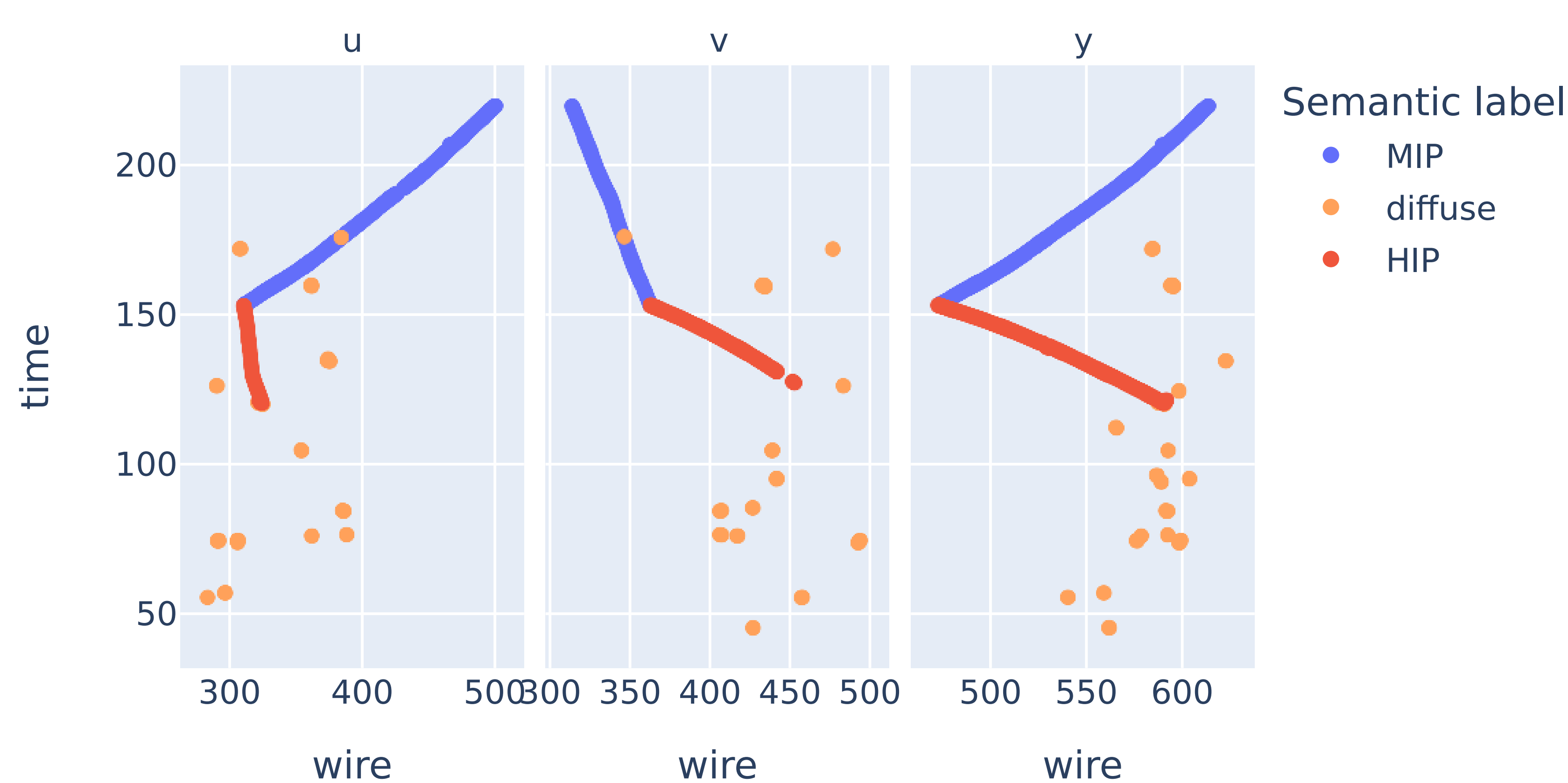

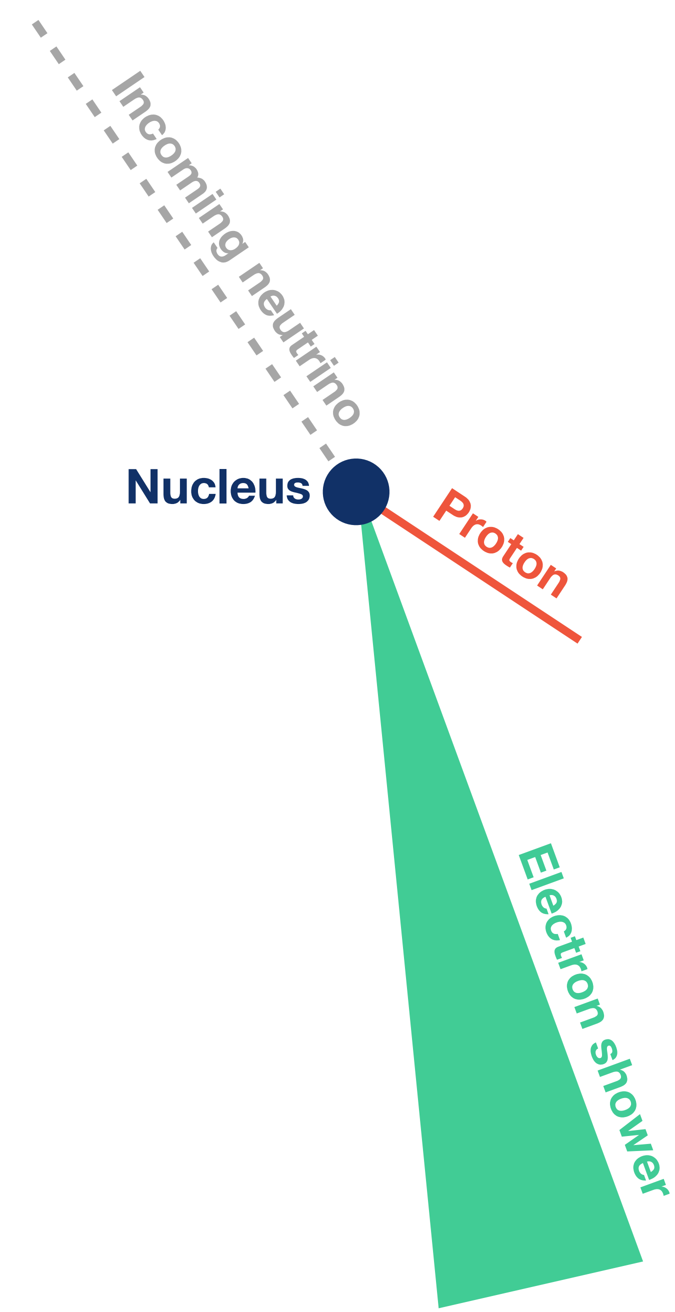

Liquid Argon TPCs

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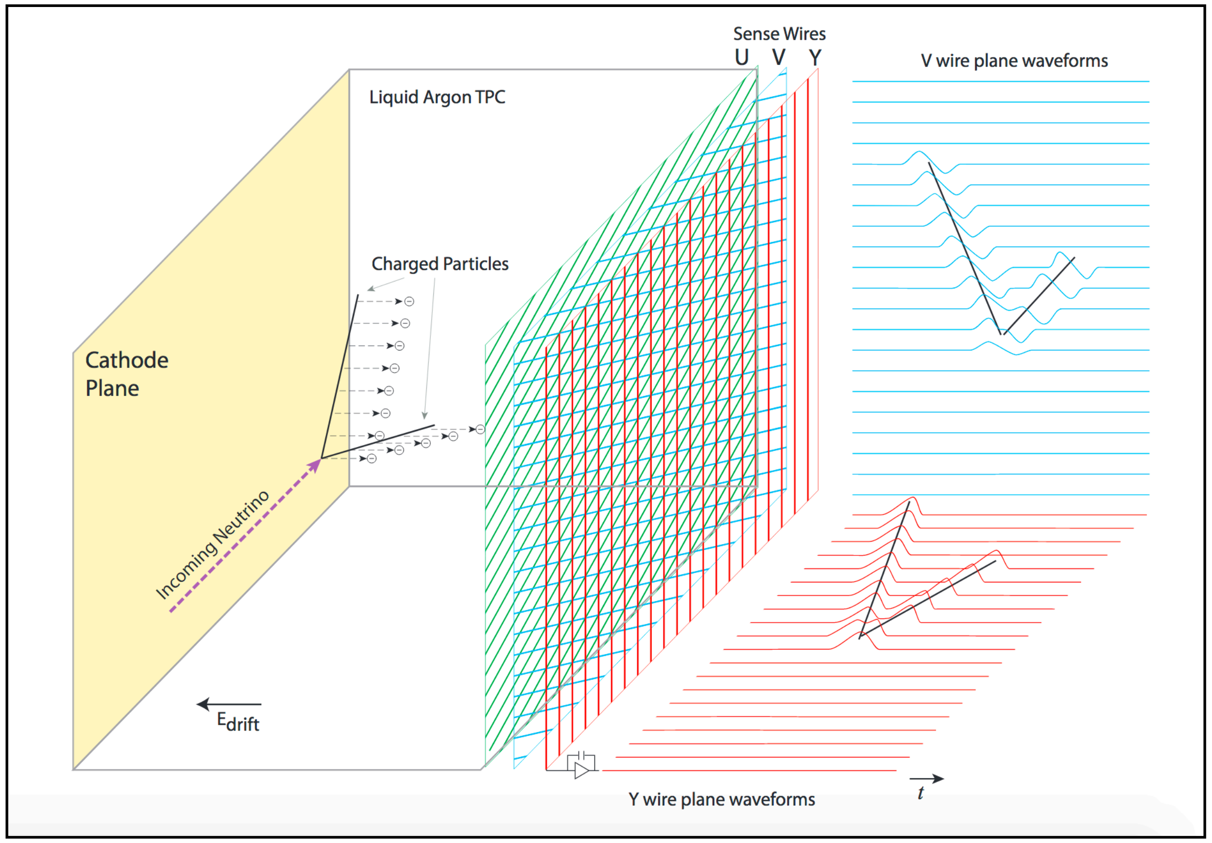
- Charged particles ionize liquid argon as they travel.
- Ionisation electrons drift due to HV electrode field, and are collected by anode wires.
- Wire spacing ~3mm – **high-resolution detector**.



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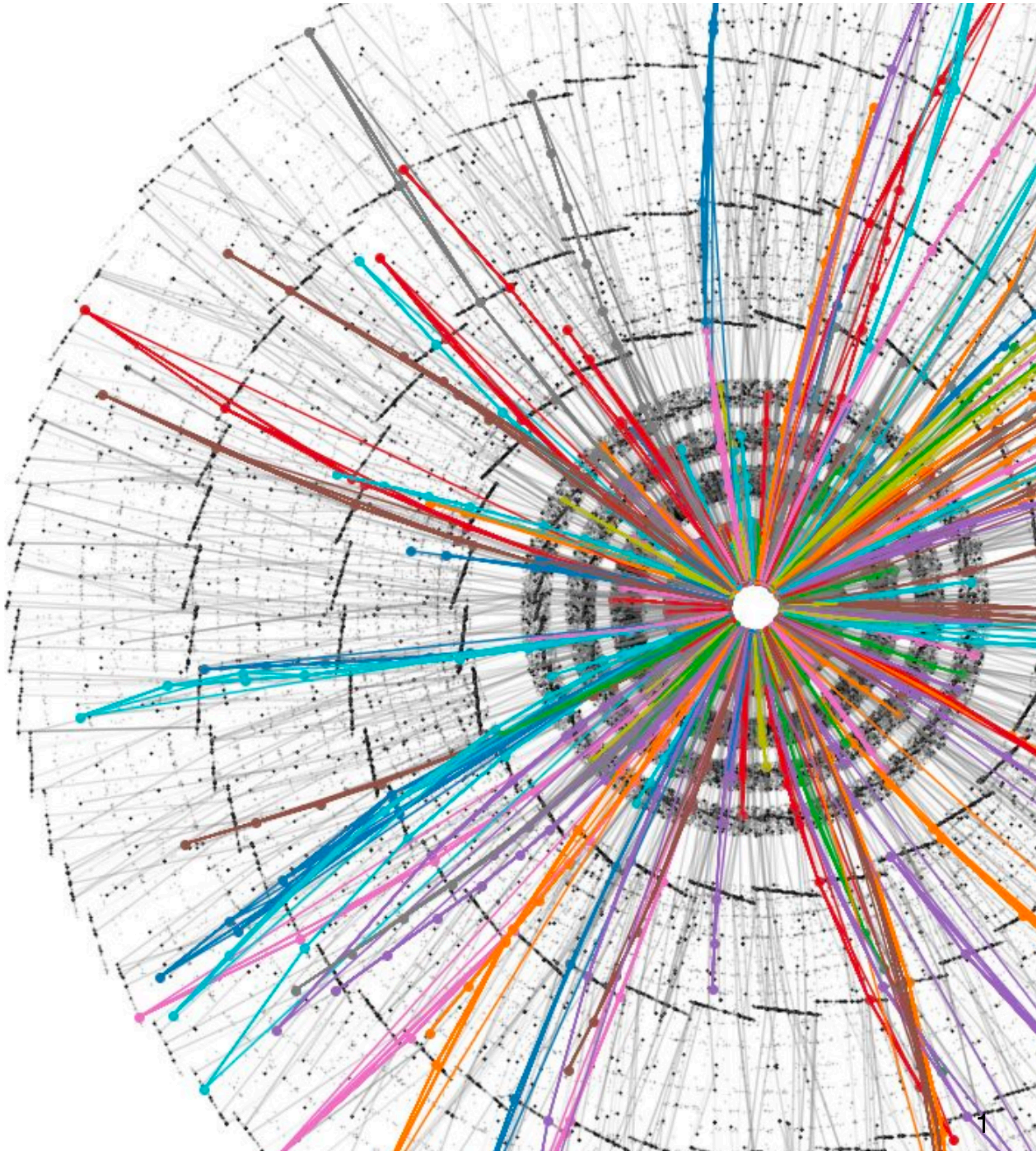
  - **Simulated neutrino interactions** with **cosmic data overlays**.
- This network architecture was originally developed in the context of the **DUNE Far Detector** geometry.
  - Motivation: reconstructing complex and high-multiplicity atmospheric and ν_τ interactions.
- This network architecture is developed to have **broad applicability**, without being tied to any particular detector geometry.
  - NuGraph2 is a **general-purpose particle reconstruction tool**.
  - Developed for use in **neutrino detectors**, but can be deployed for other types of physics interactions!

NuGraph2

Exa.TrkX

- Exa.TrkX is a collaboration developing next-generation Graph Neural Network (GNN) reconstruction for HEP:



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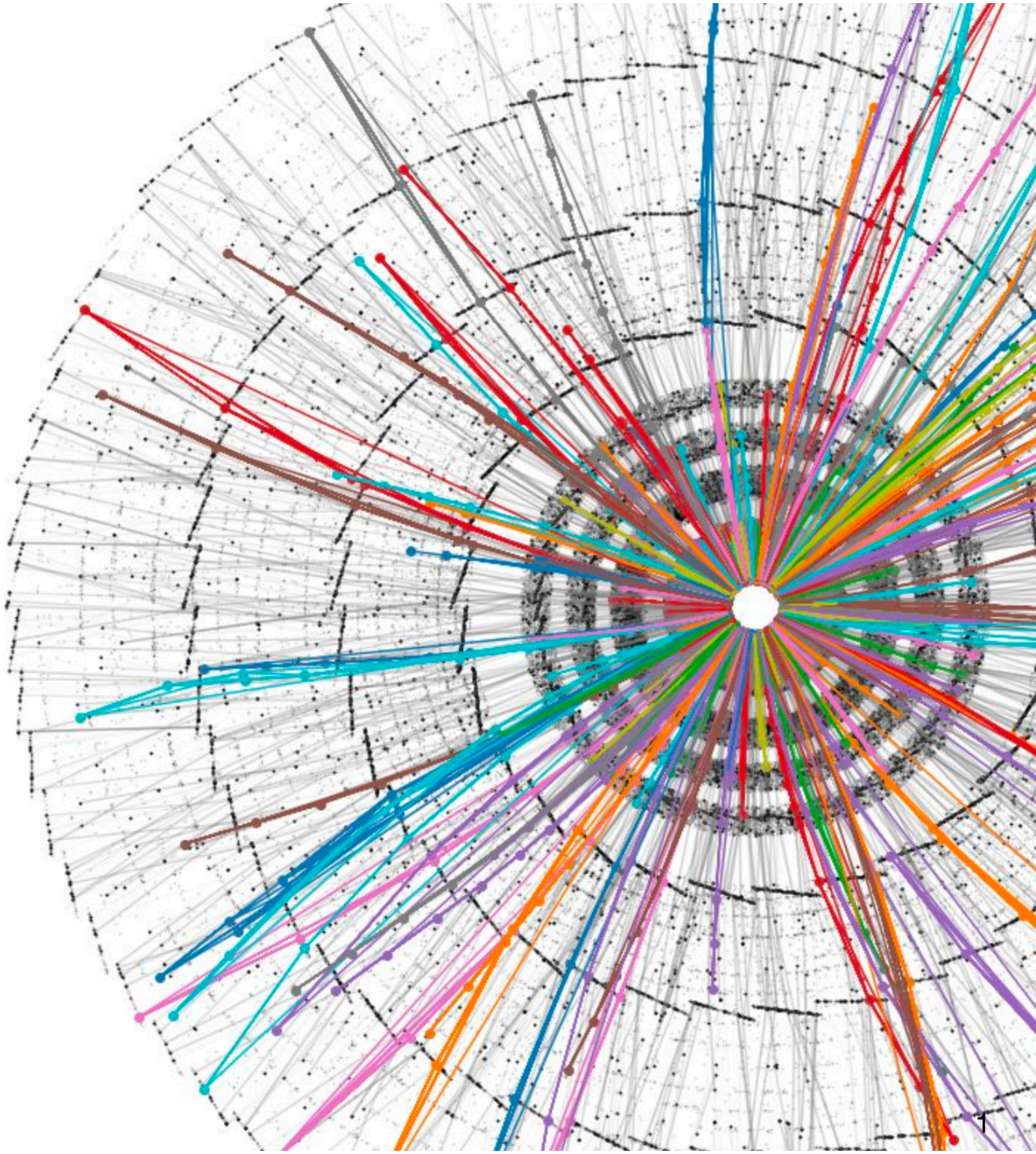

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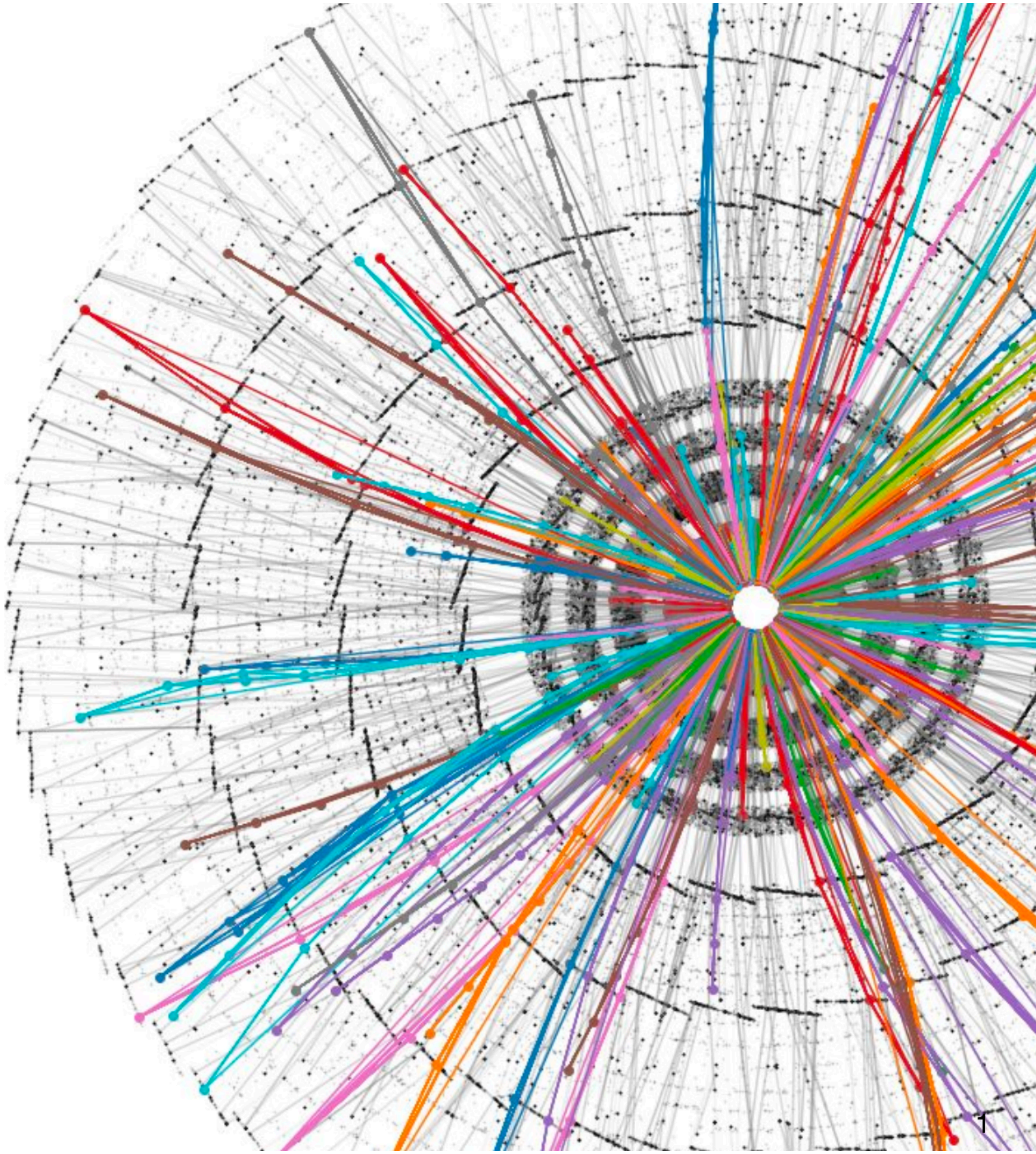
    - Develop GNN-based reconstruction for Liquid Argon TPCs.



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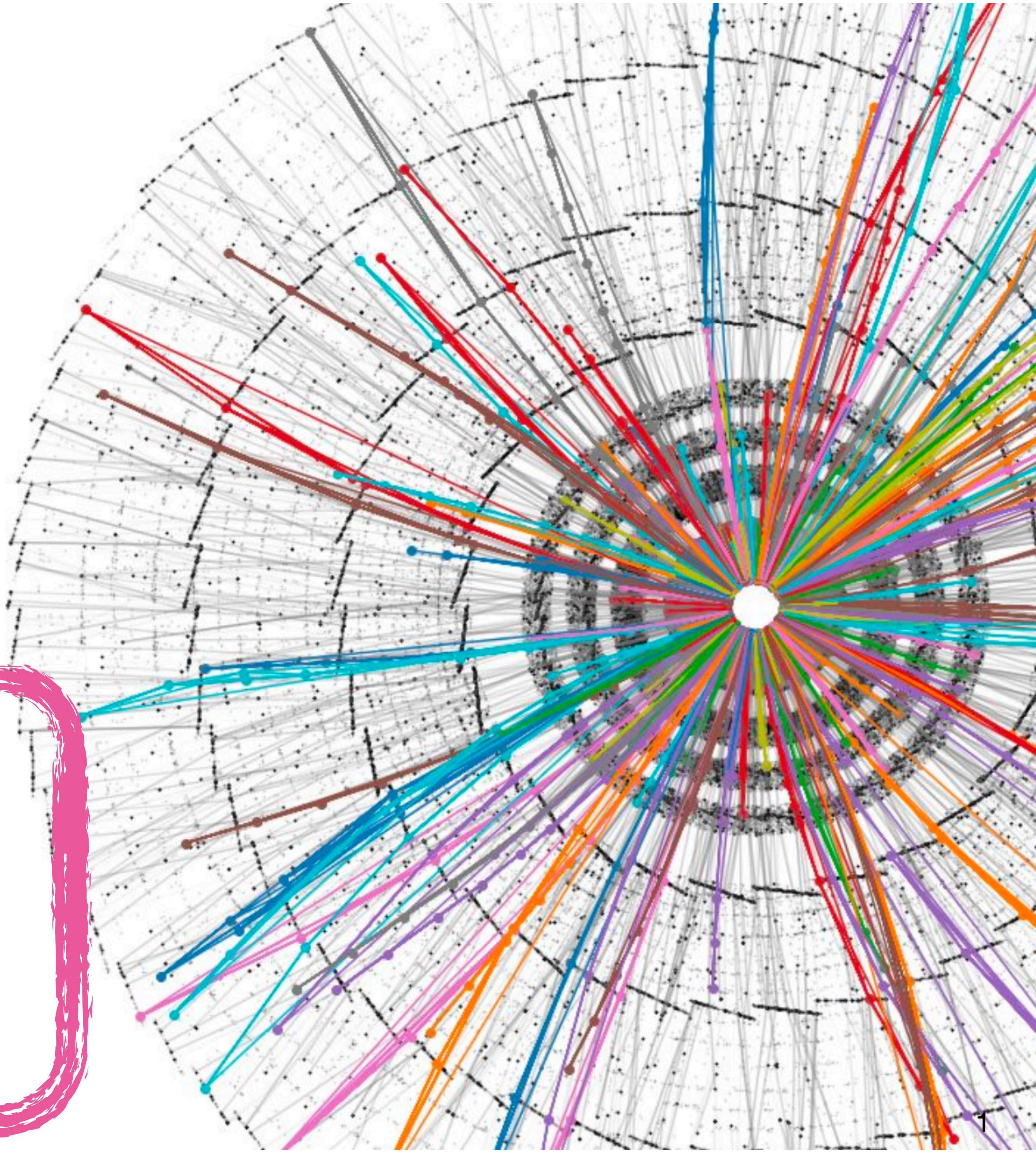
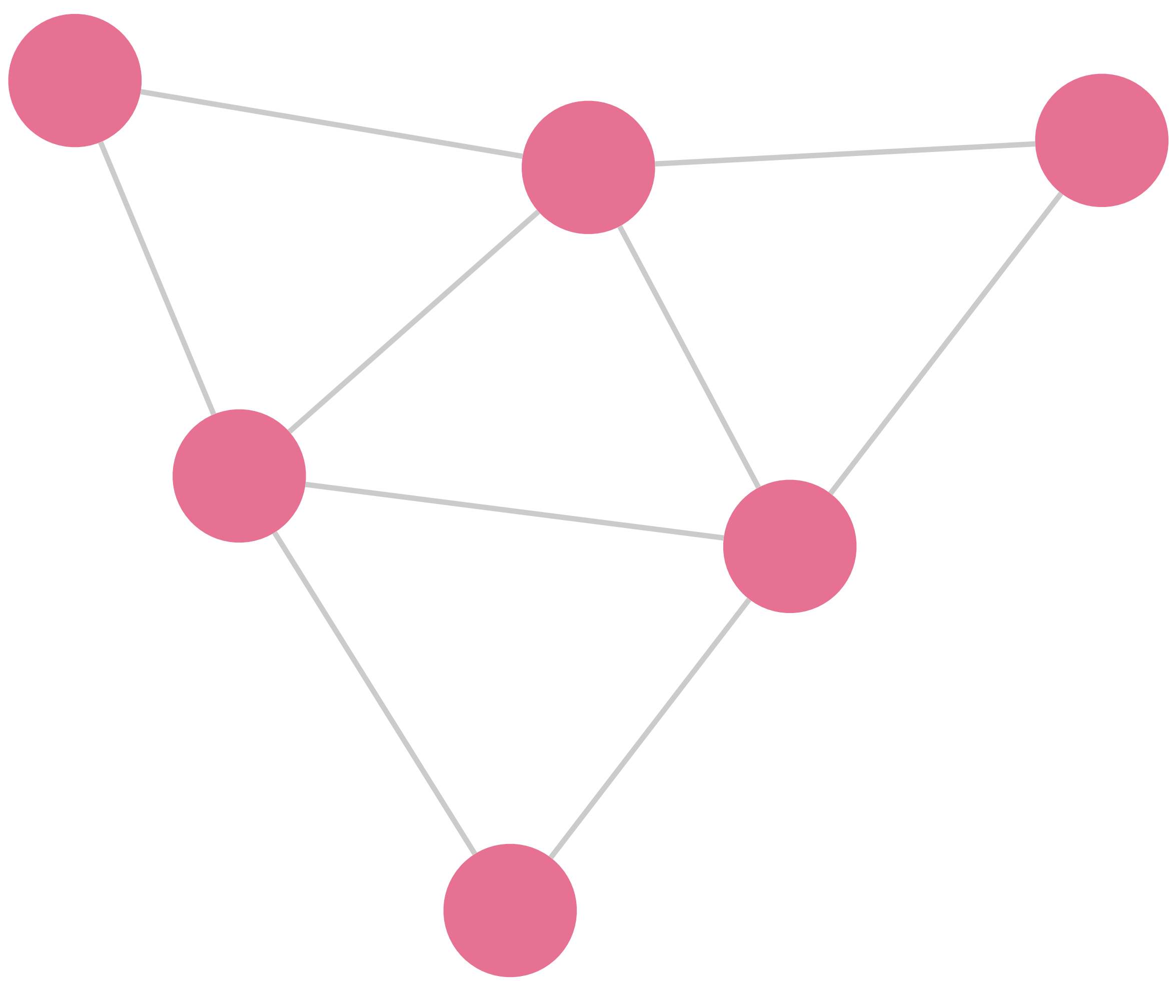
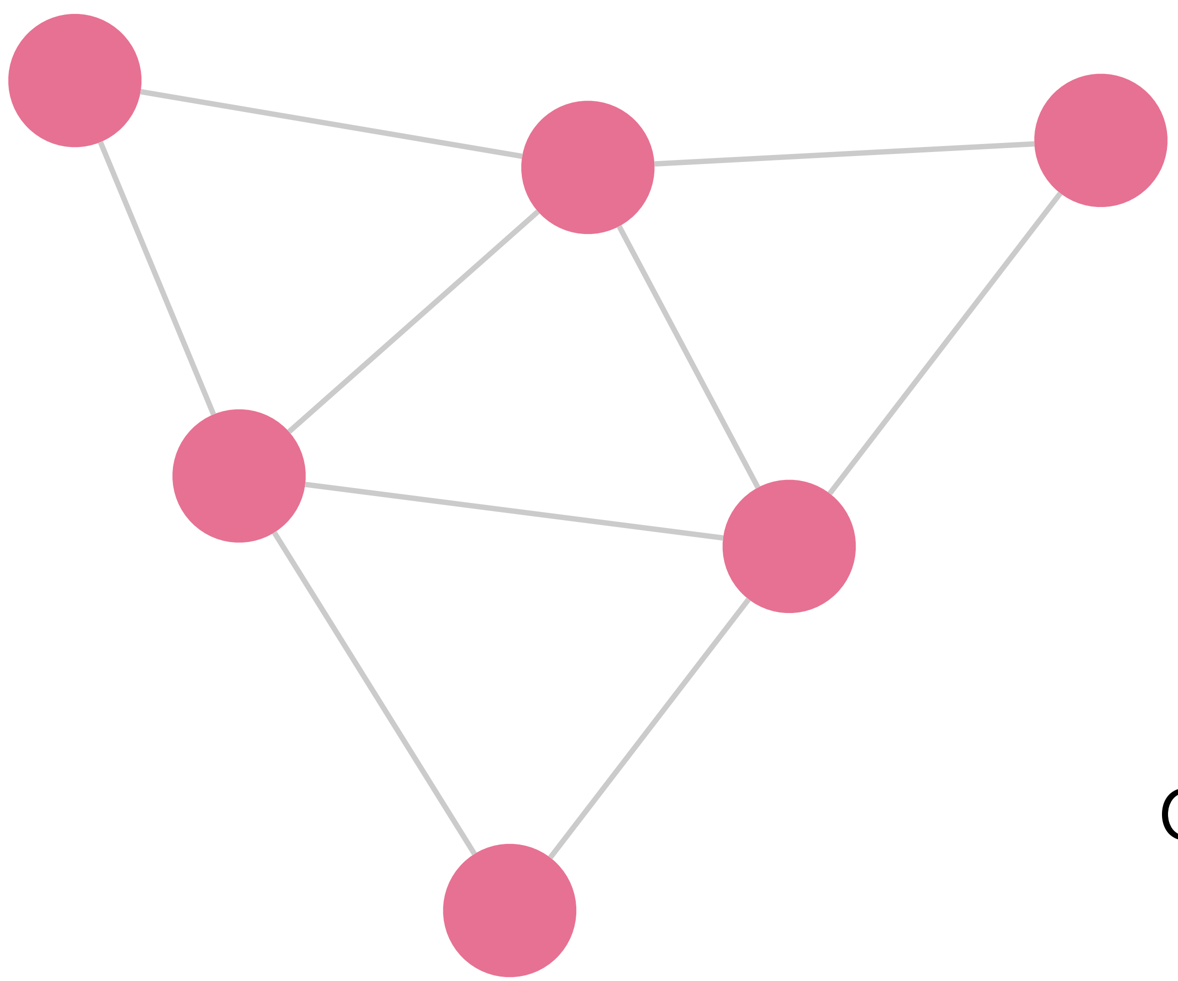


Graph Neural Networks

Construct **graph** where each **node** is a **detector hit**

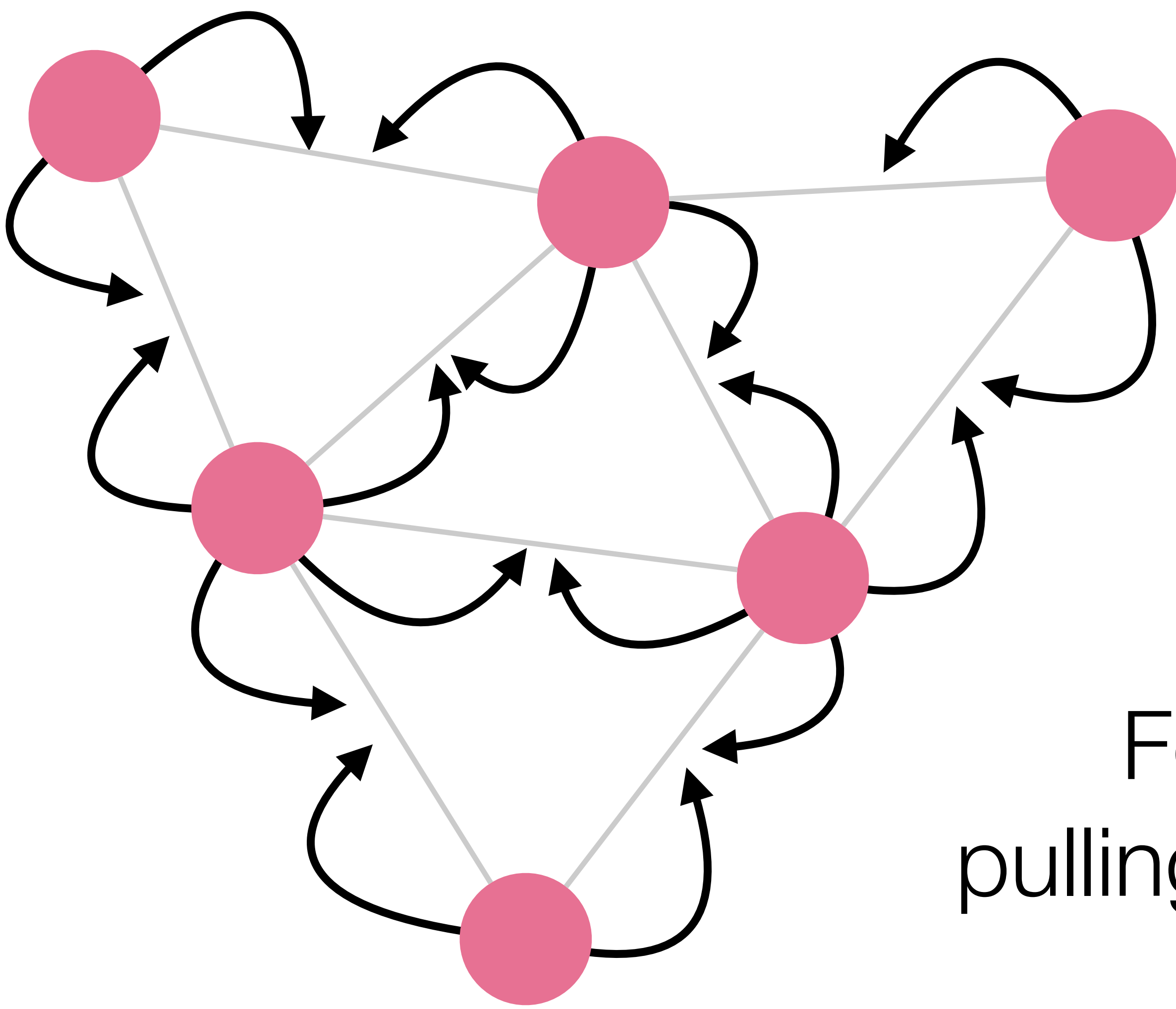


Graph Neural Networks



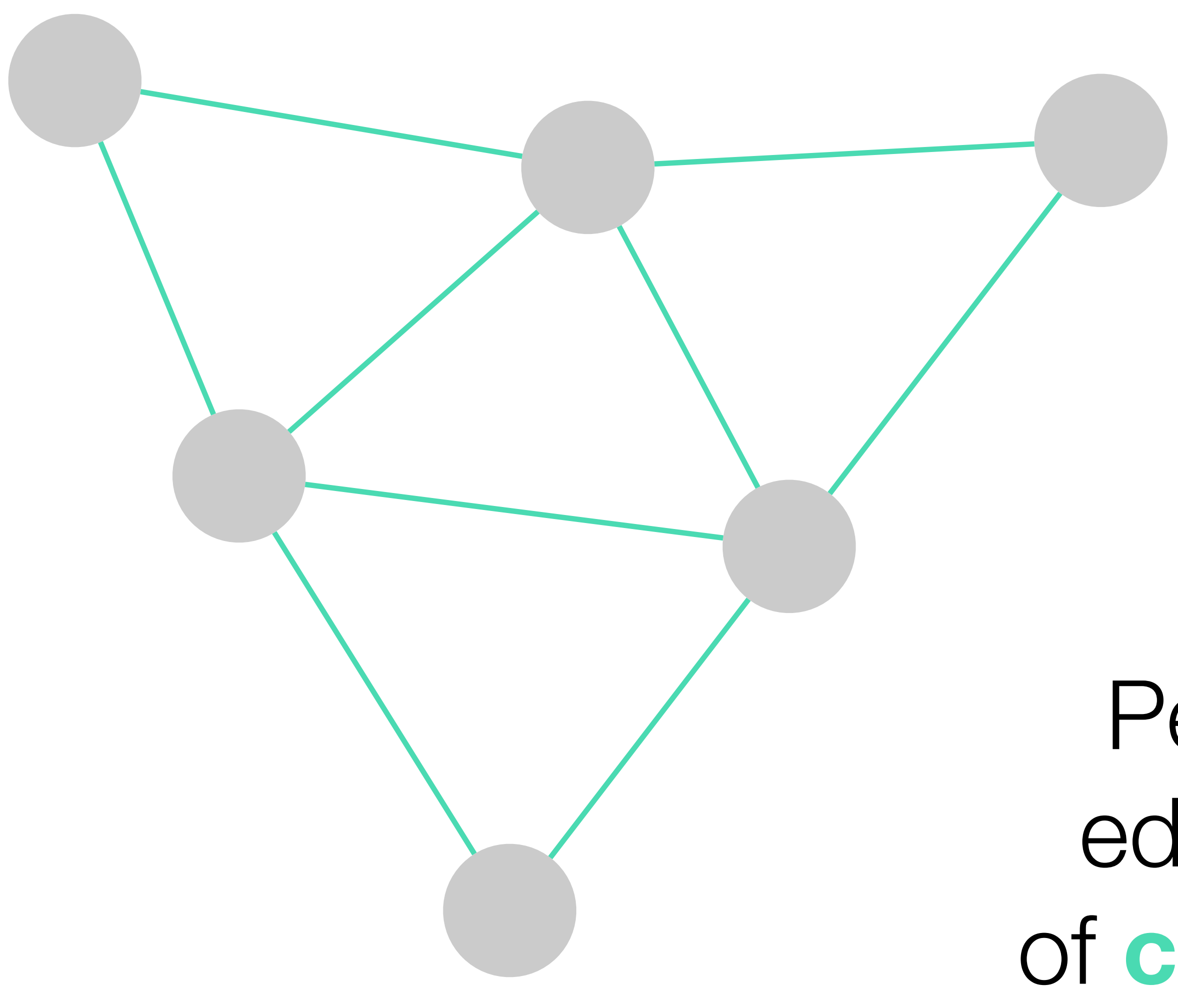
Node features:
wire index, time tick,
charge integral & RMS

Graph Neural Networks



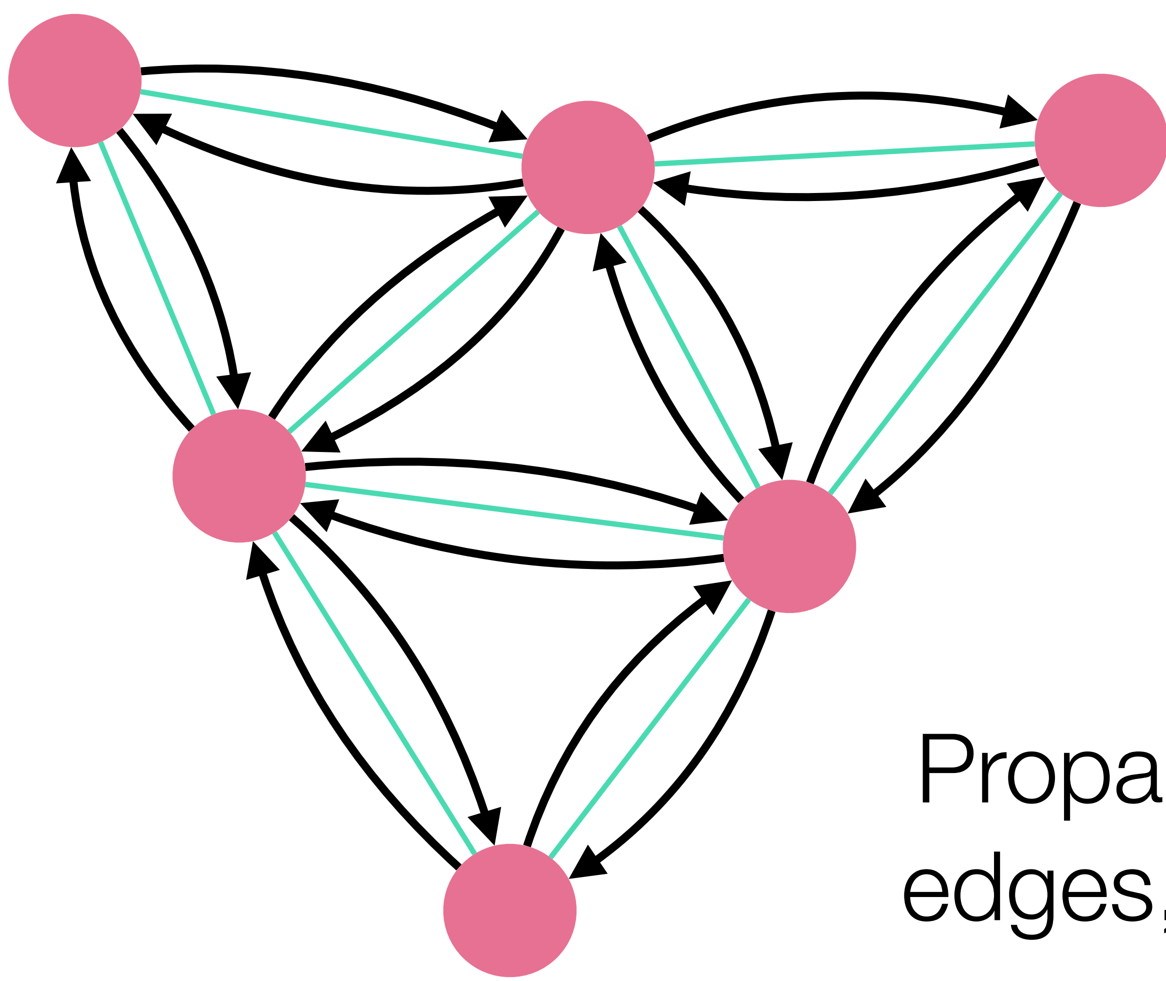
Form **edge features** by pulling in features from incoming and outgoing nodes

Graph Neural Networks



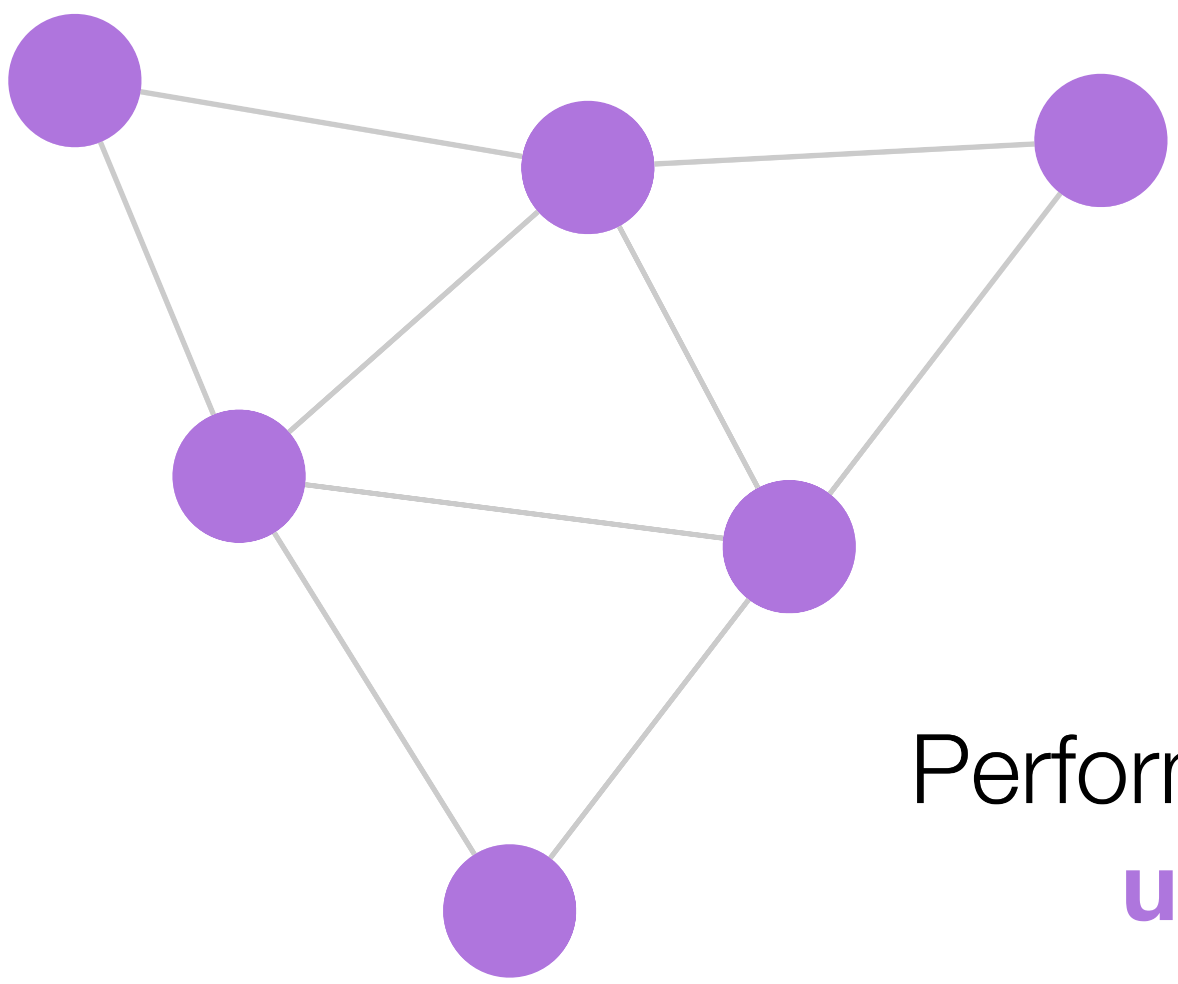
Perform convolutions on edge scores to form a set of **class-wise probabilities**

Graph Neural Networks



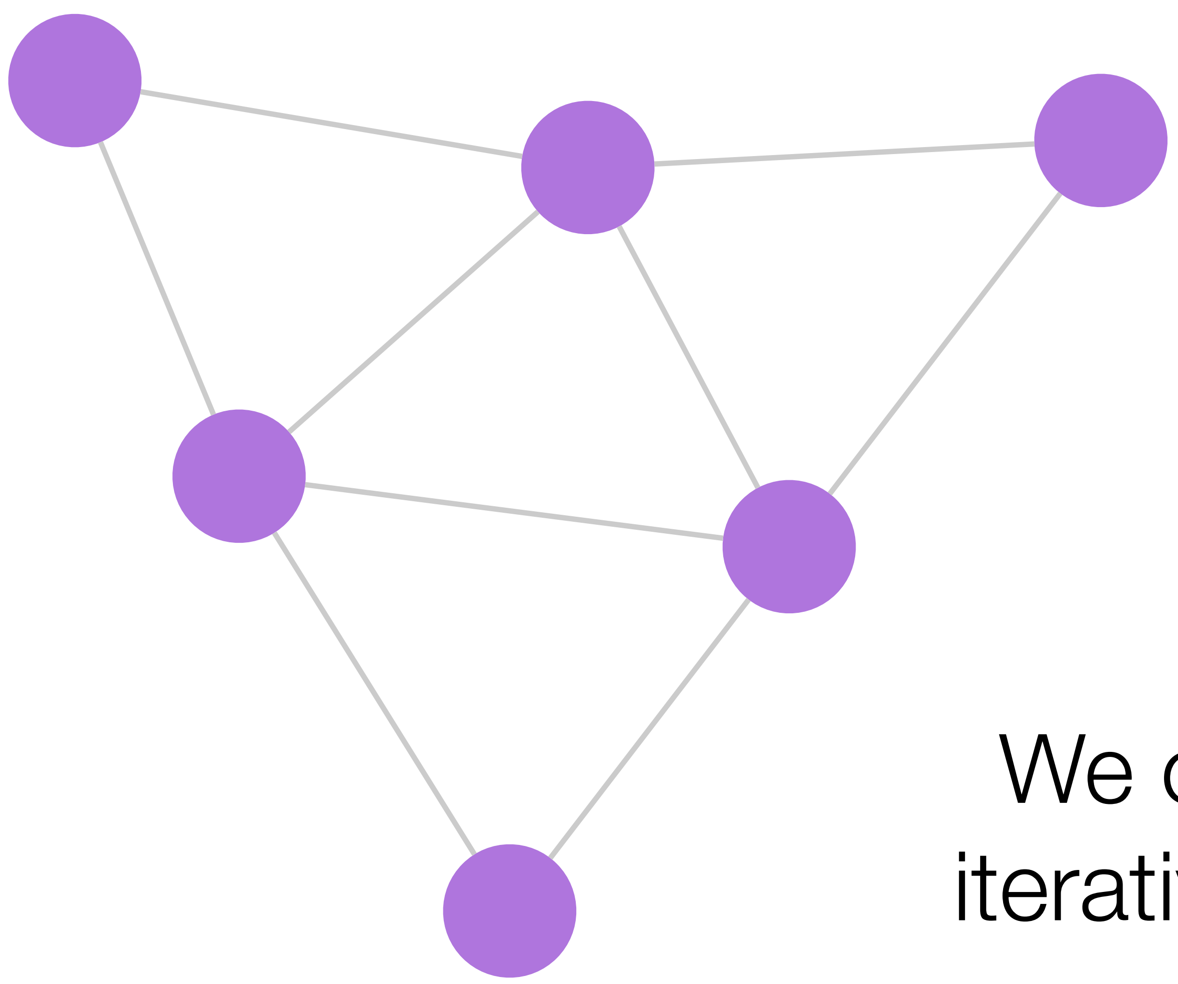
Propagate **node features** across edges, weighting by **edge scores**

Graph Neural Networks



Perform convolutions on nodes to **update node features**

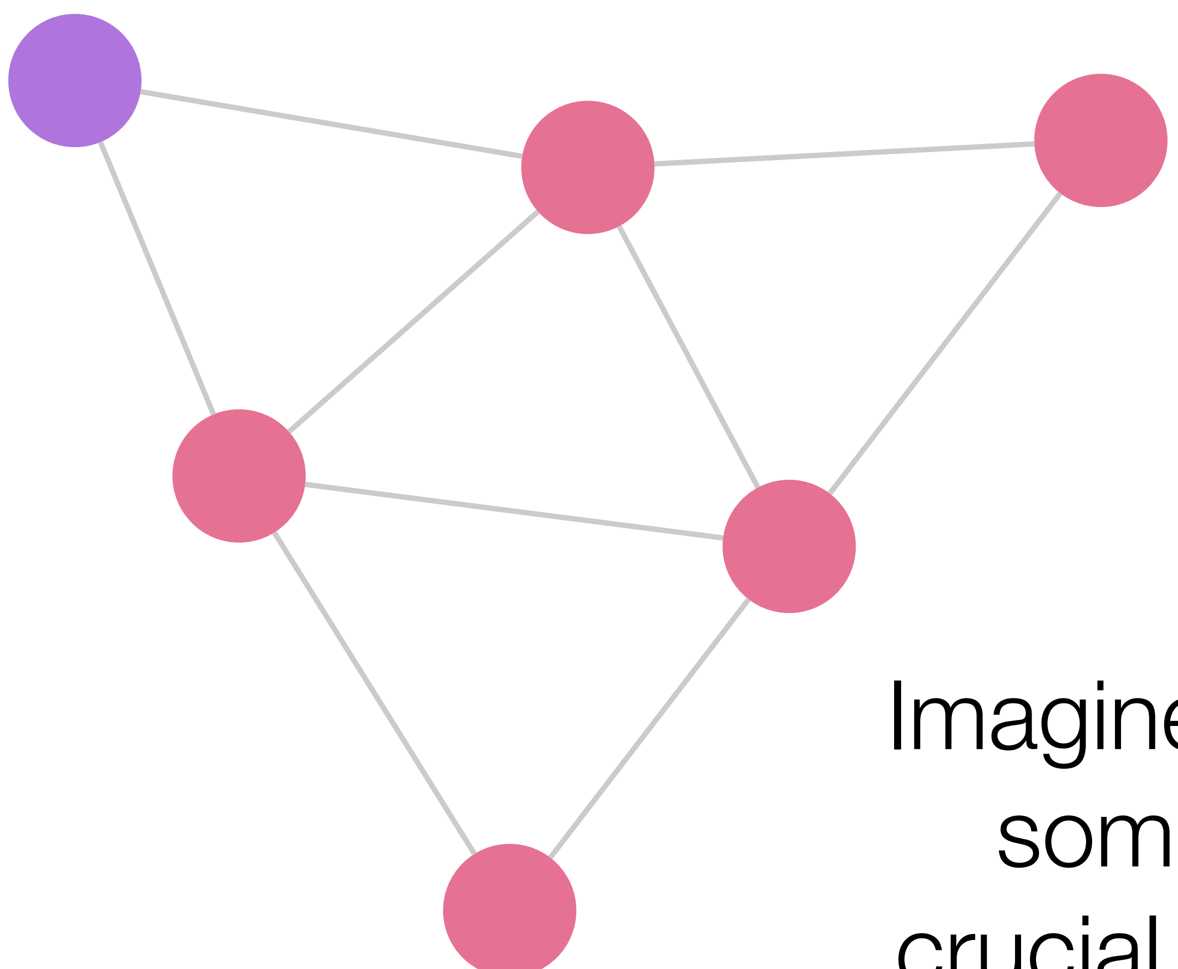
Graph Neural Networks



We can repeat this procedure iteratively to **"pass messages"**

Graph Neural Networks

0 iterations



Imagine that one graph node holds some **key information** that's crucial for understanding the event

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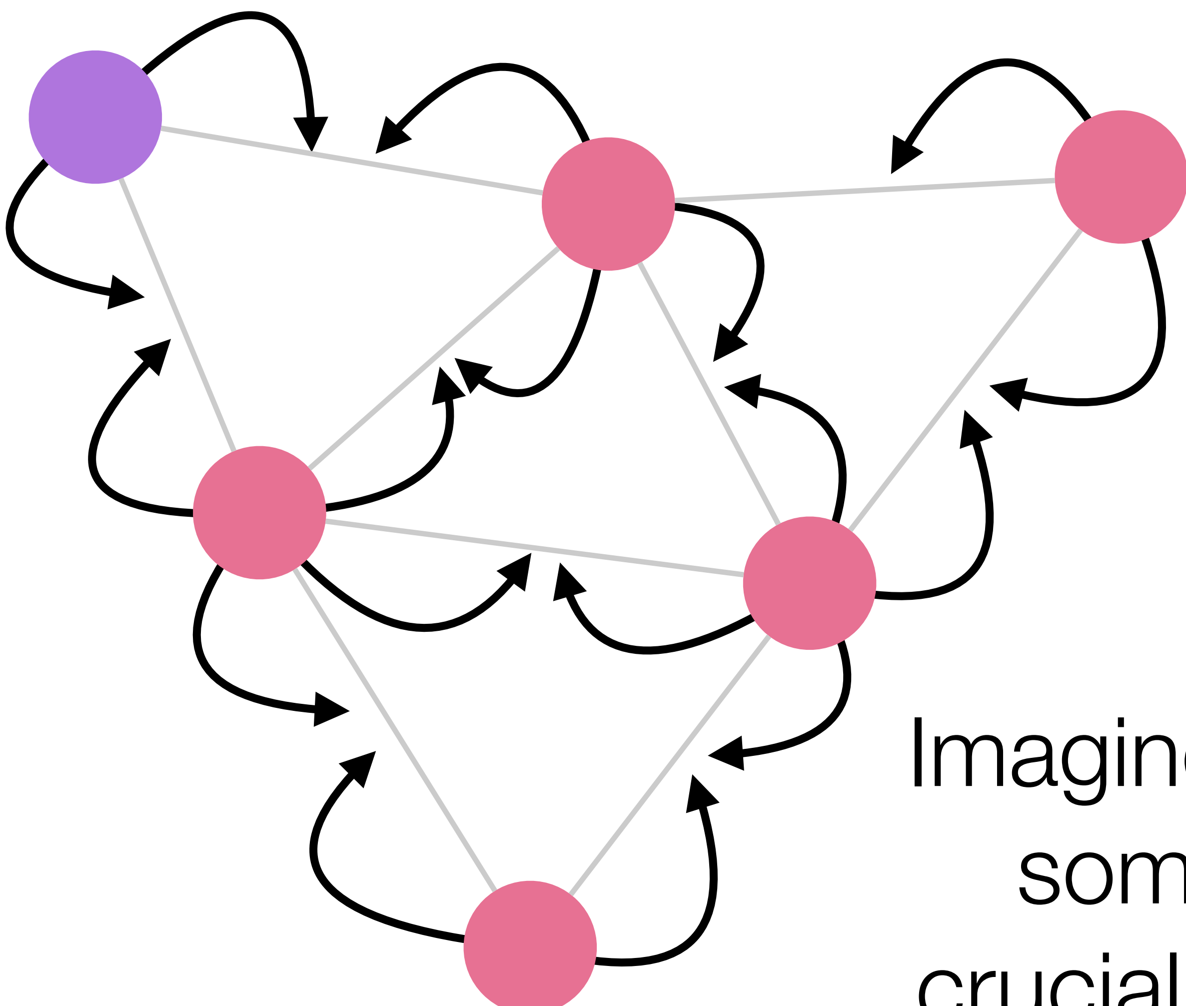

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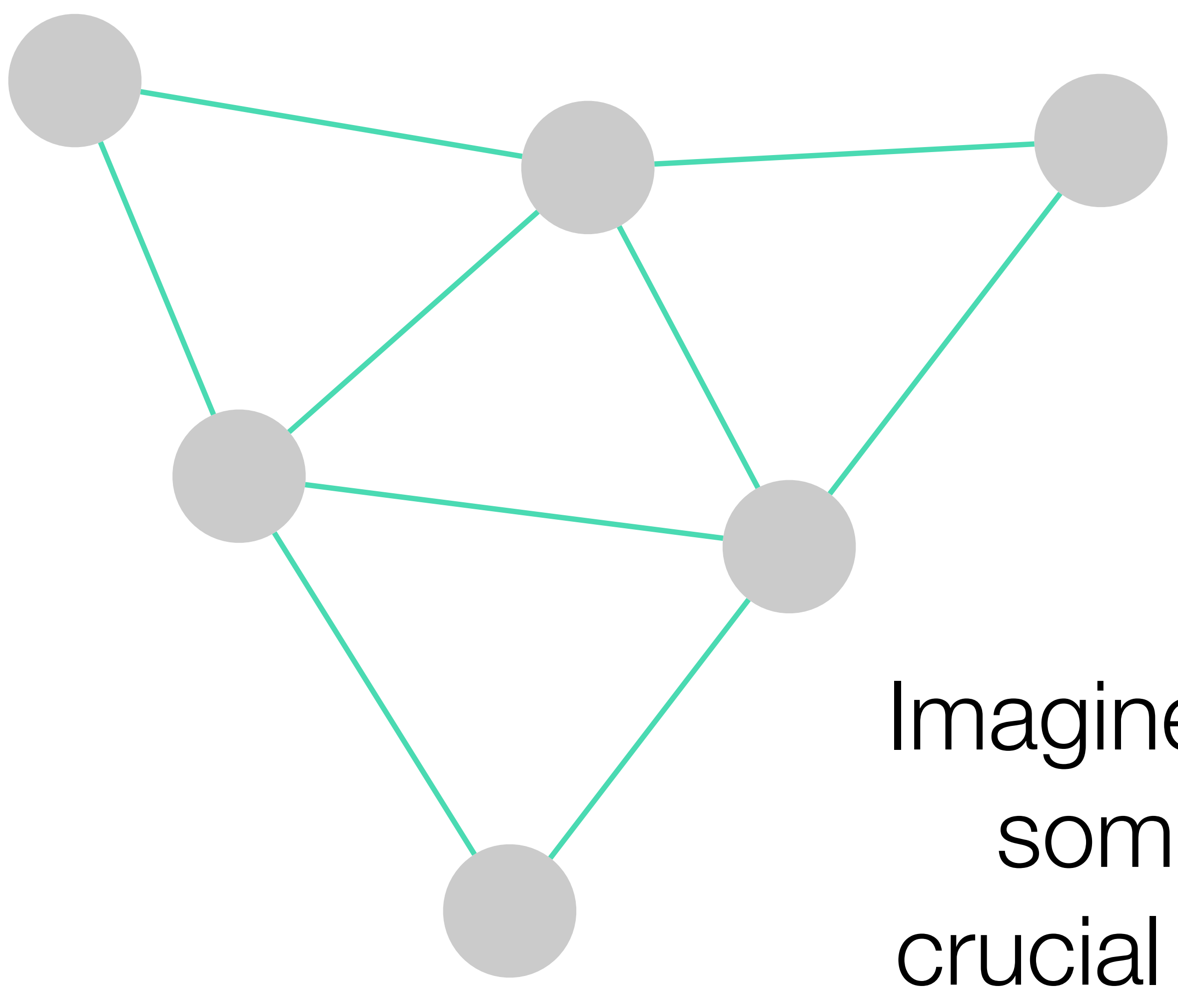

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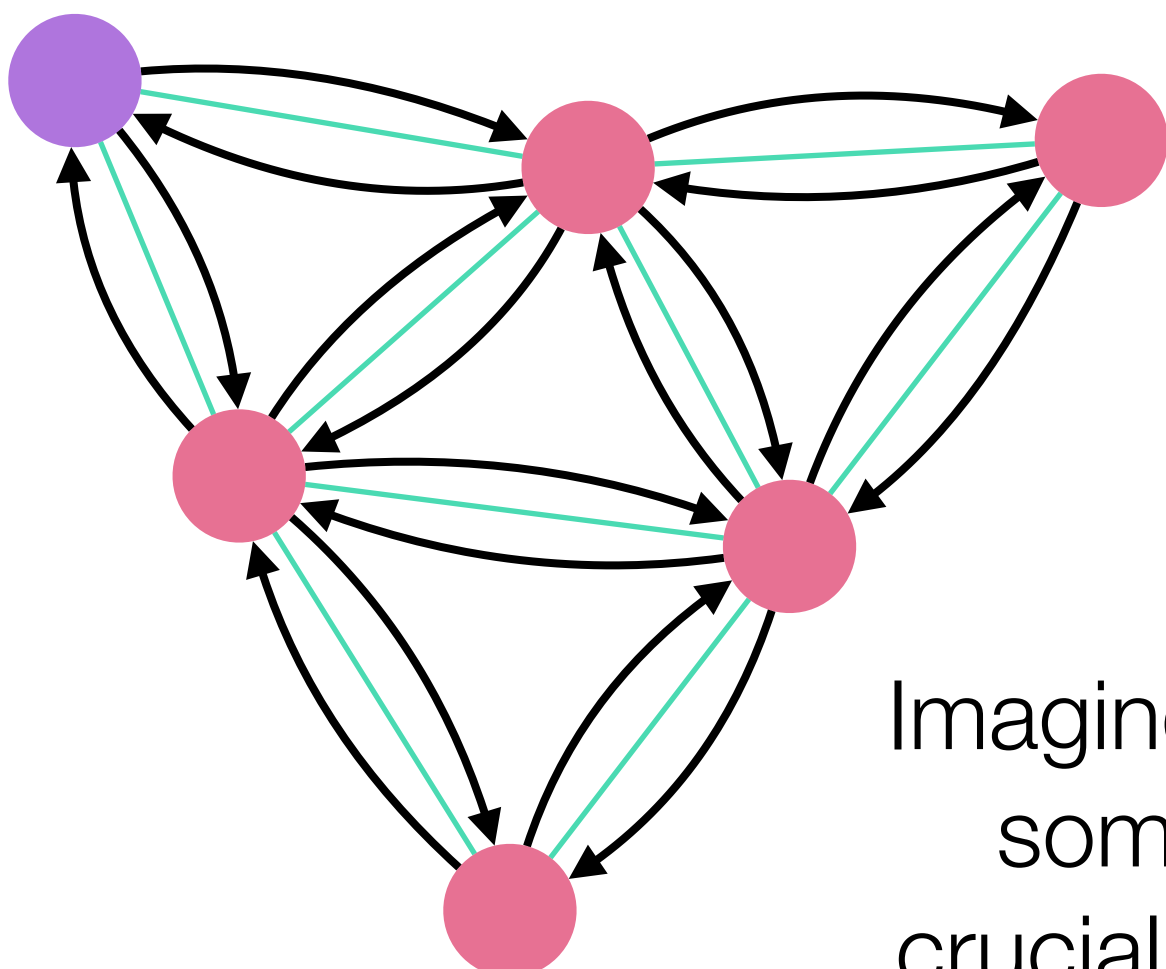

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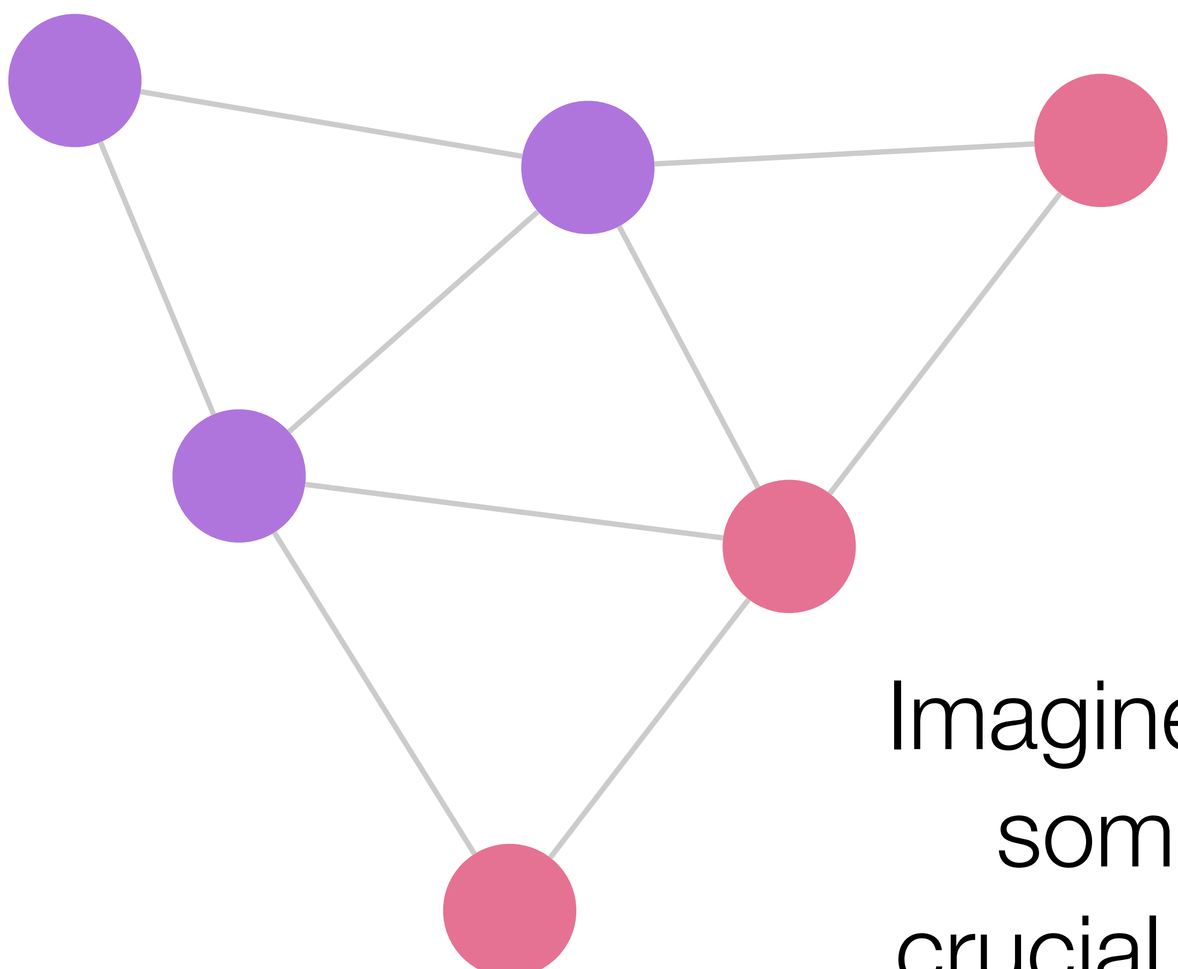

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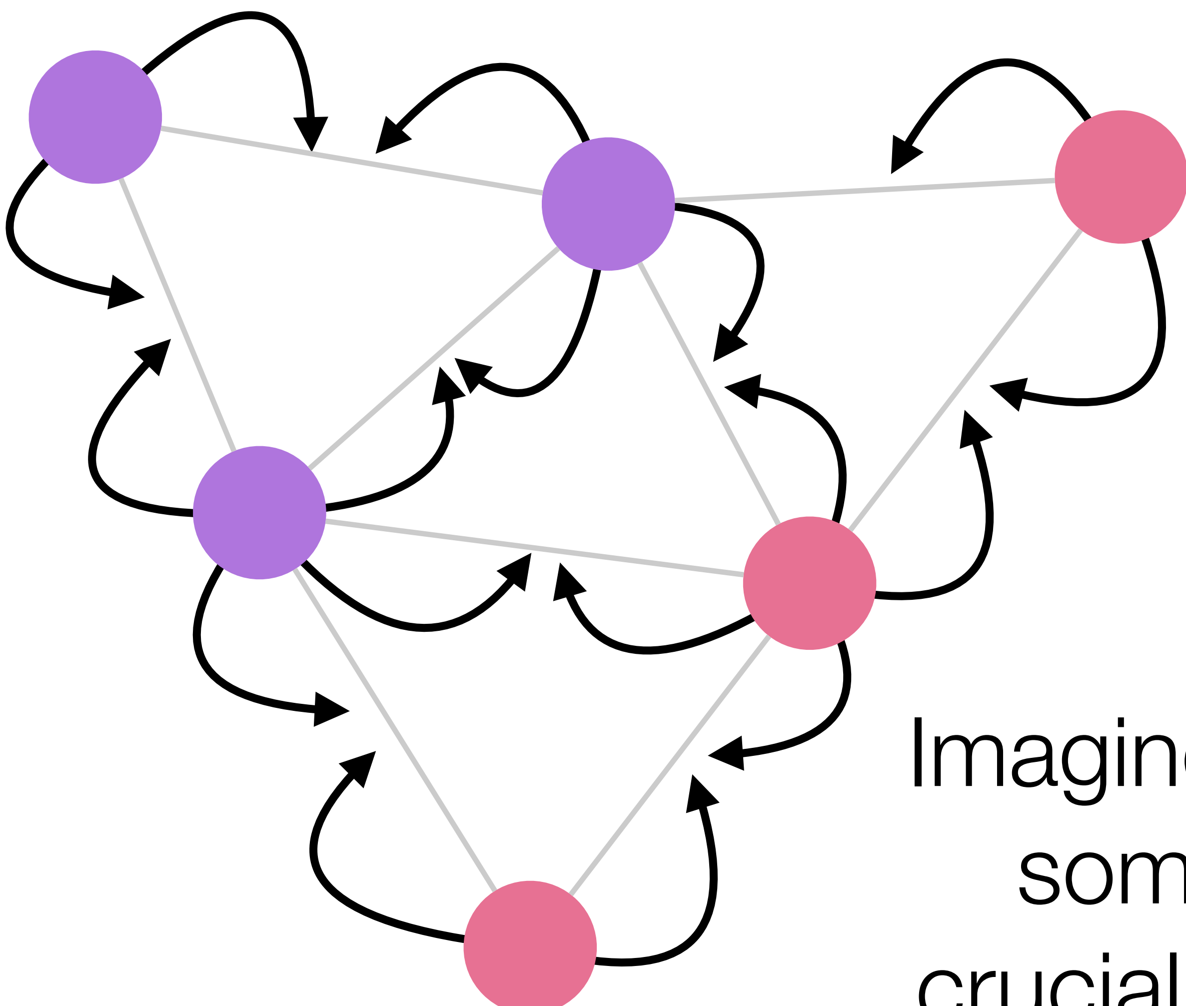

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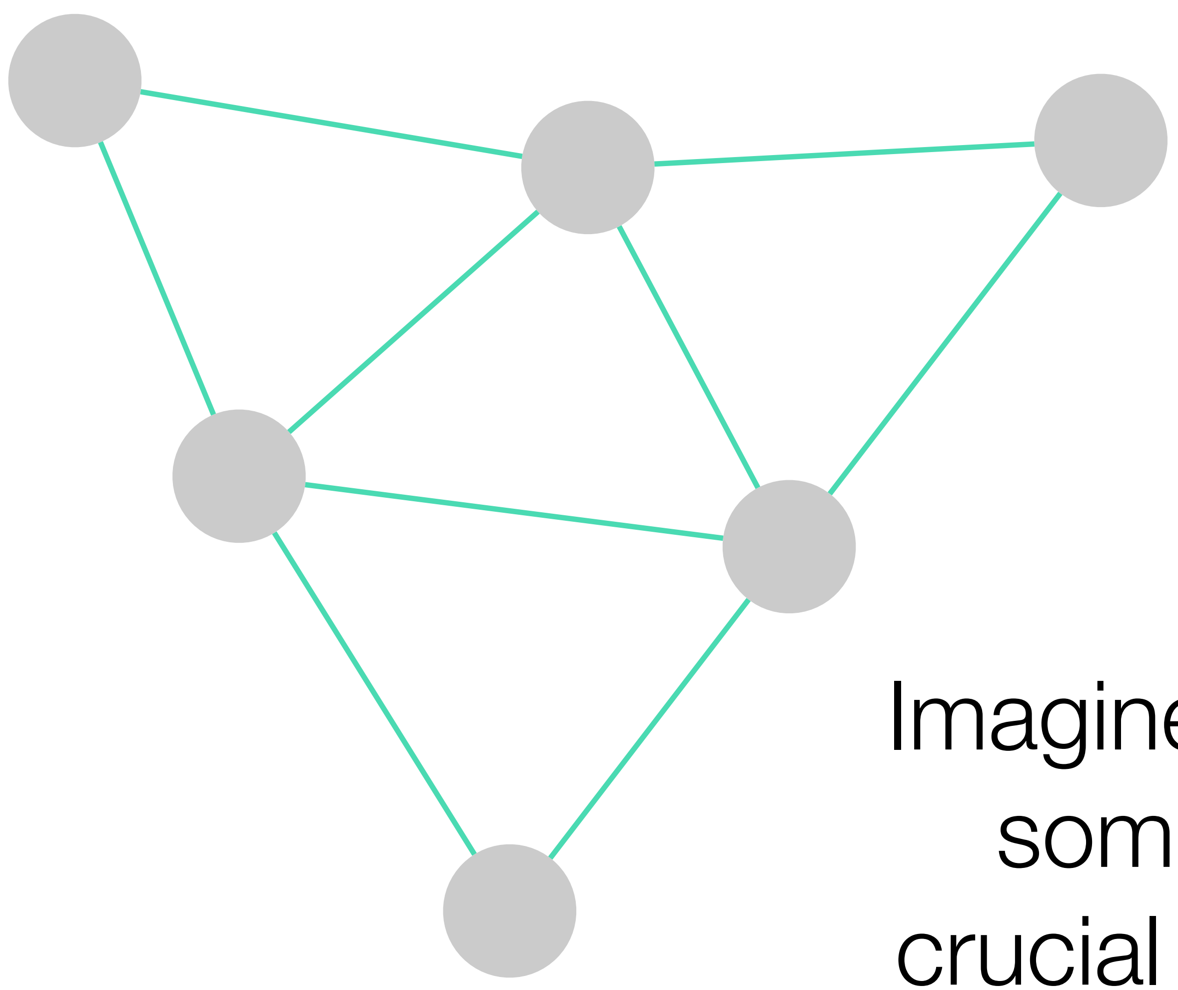

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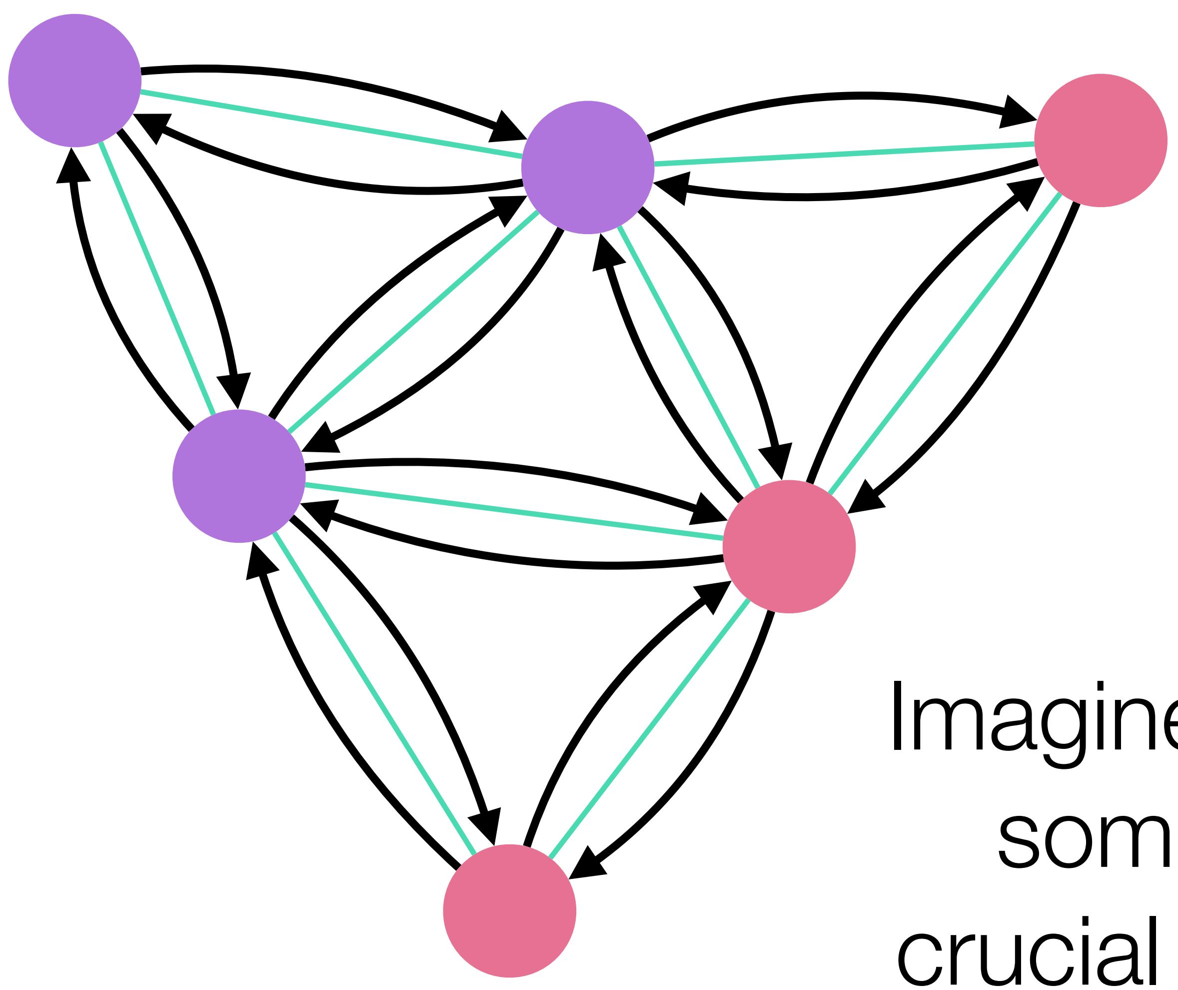

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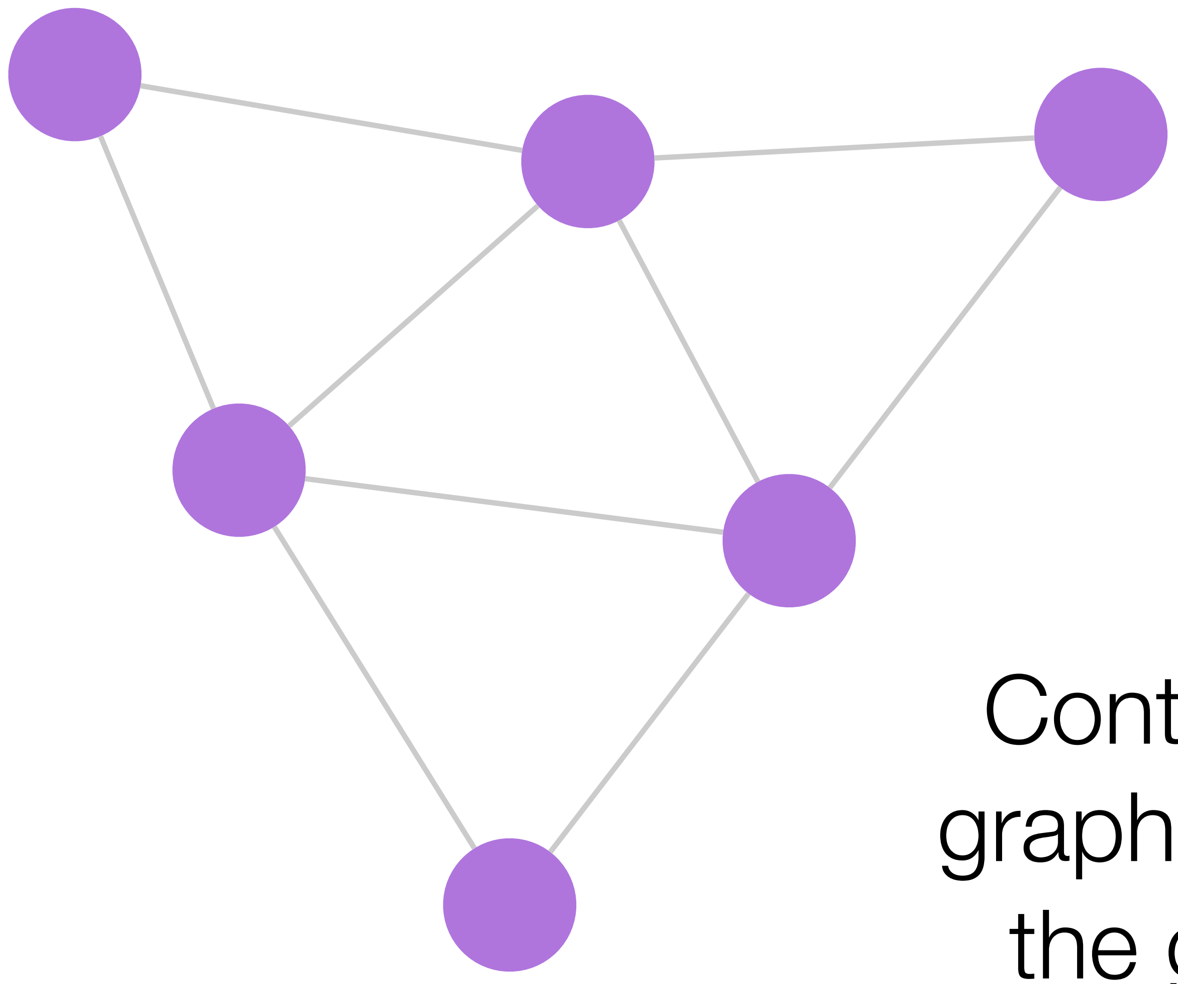
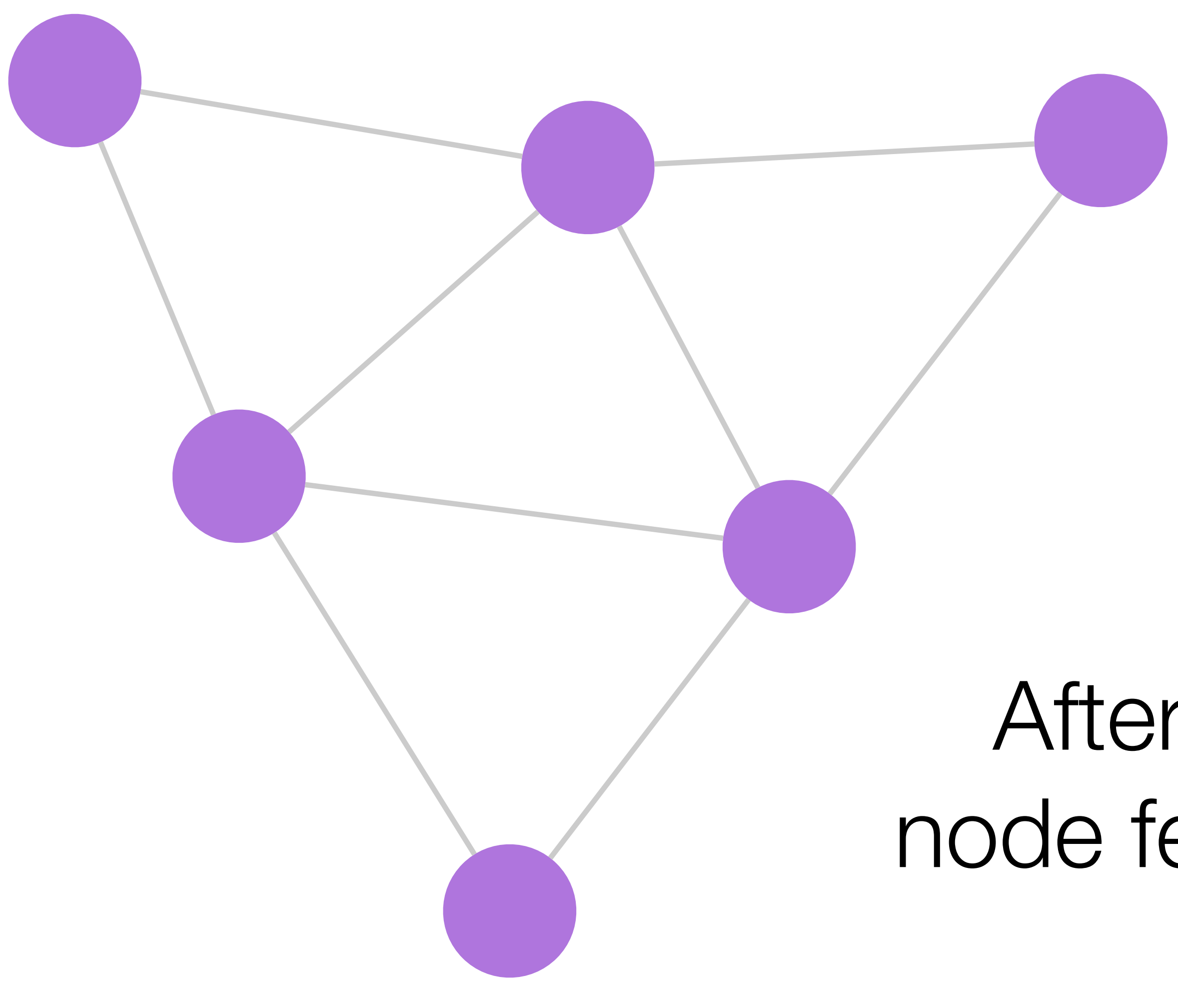
Graph Neural Networks

2 iterations



Context information from each graph node is dispersed through the graph with each iteration.

Graph Neural Networks



After multiple iterations, graph node features can be convolved to **label graph nodes**

NuGraph2

NuGraph1

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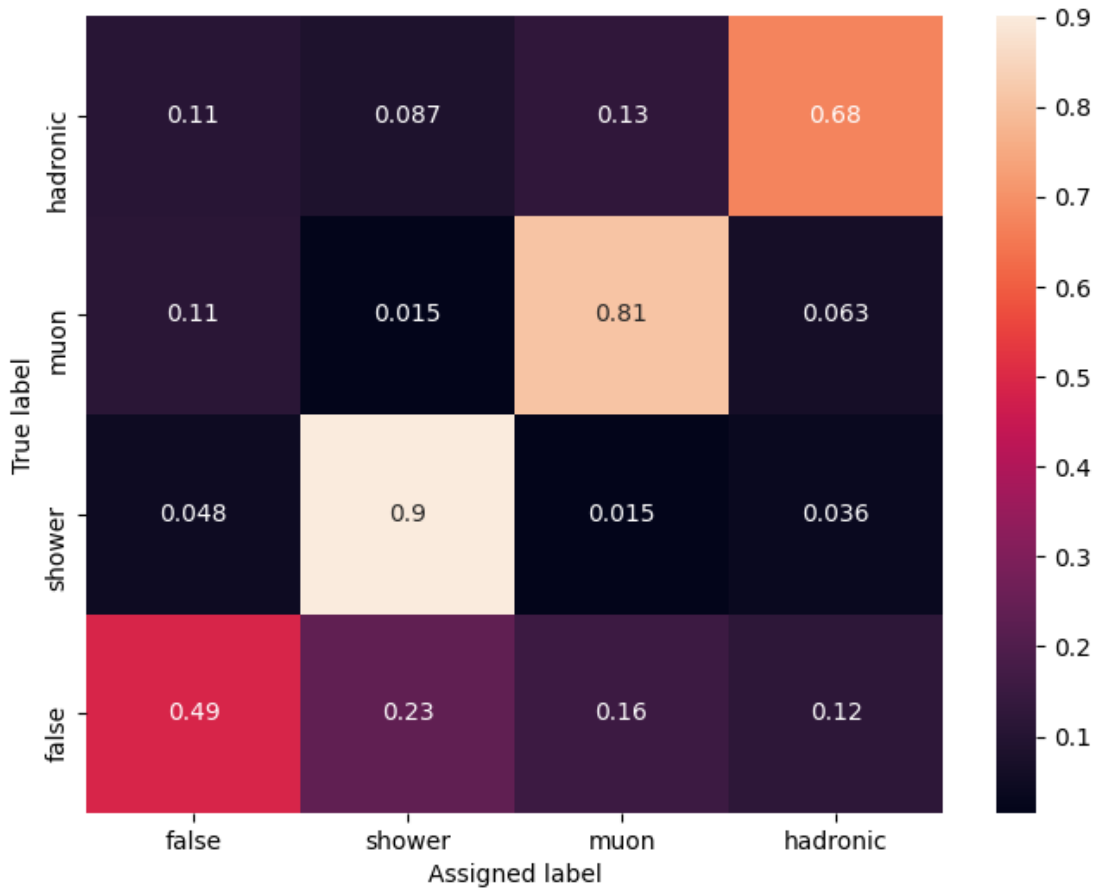

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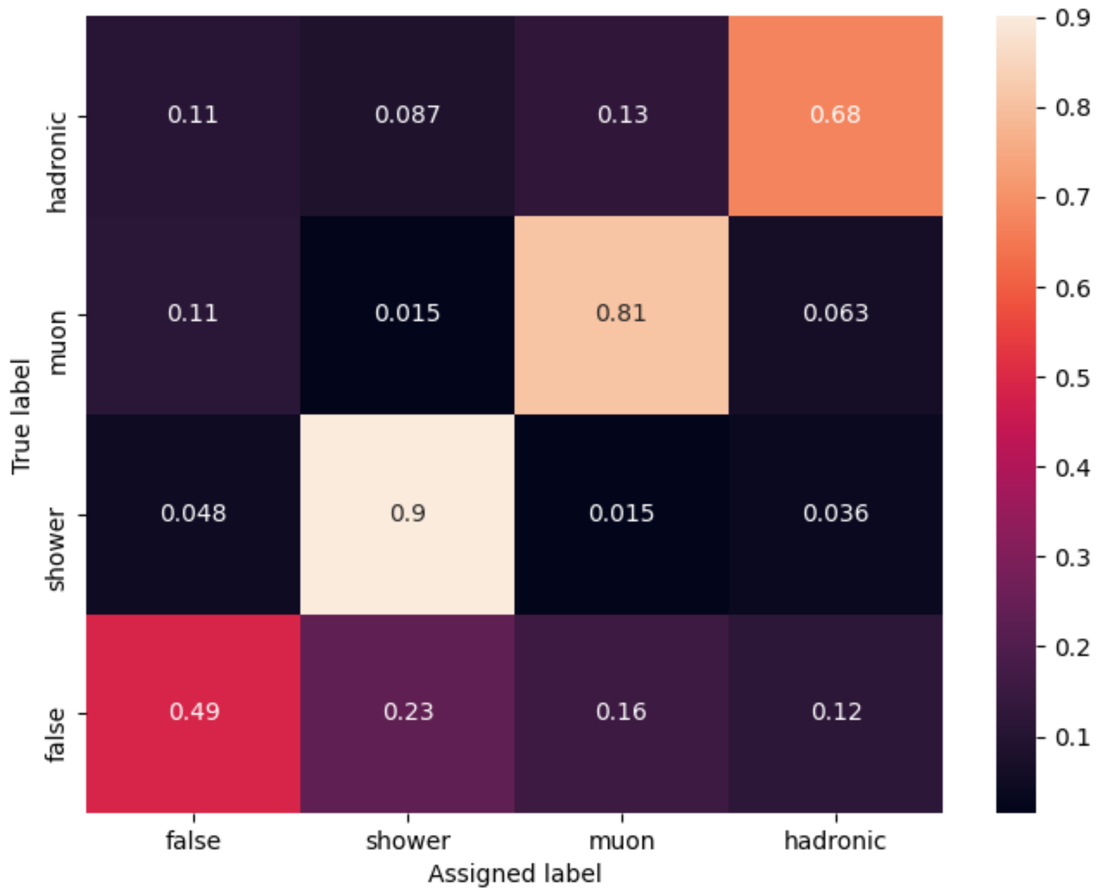

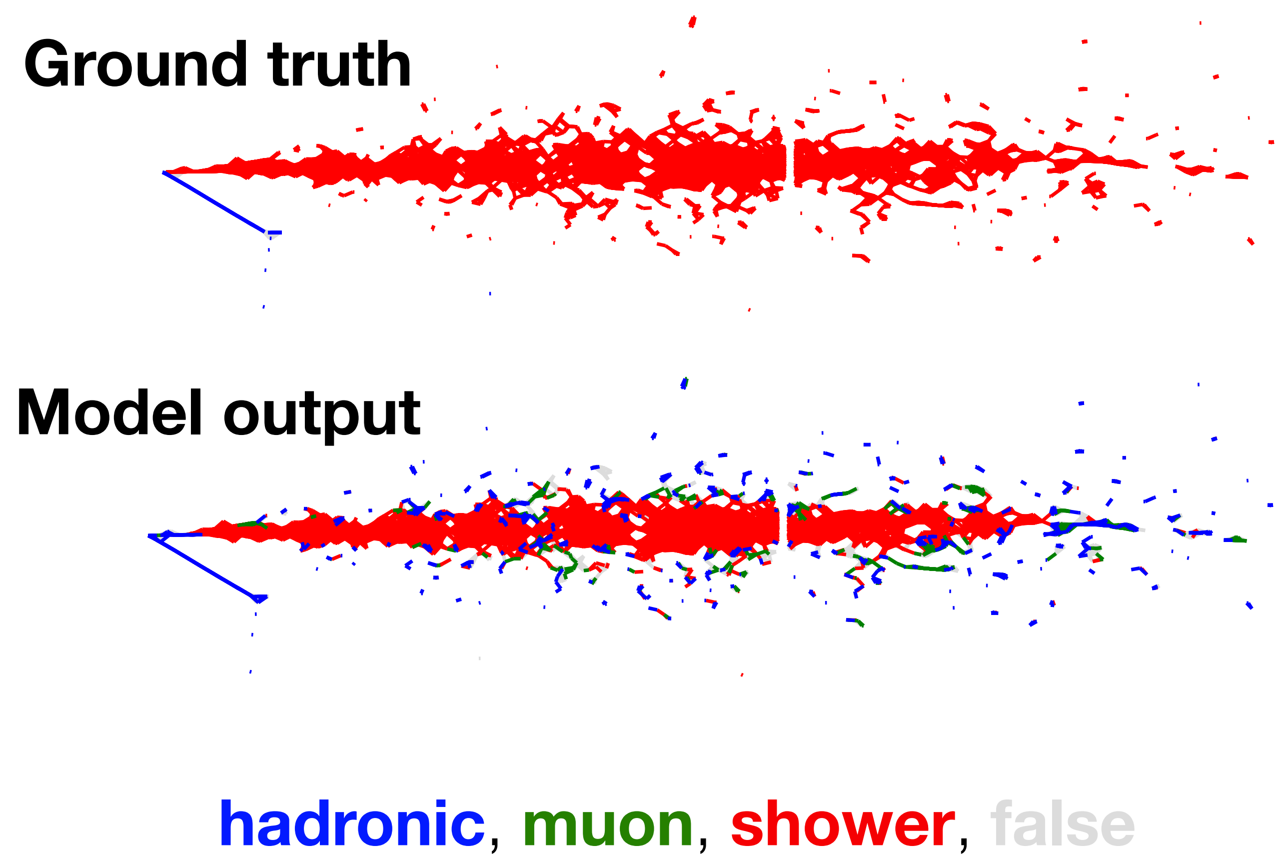

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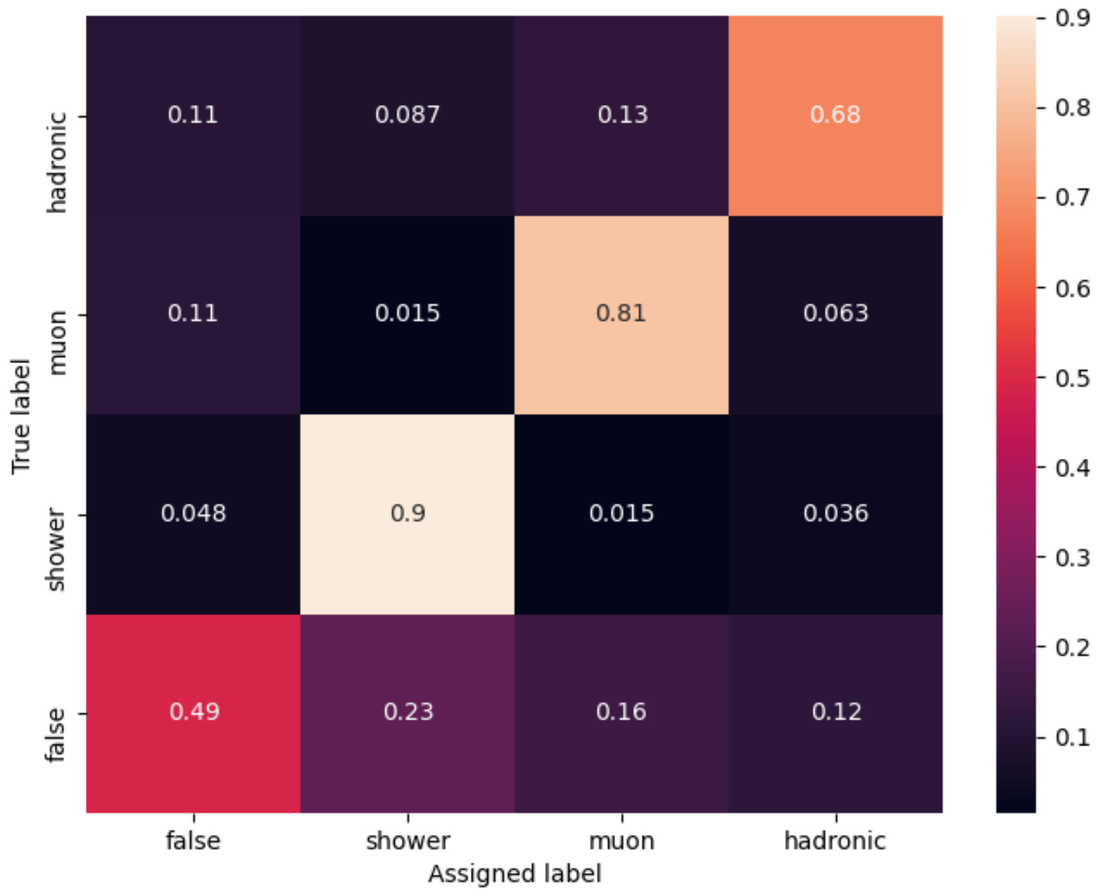

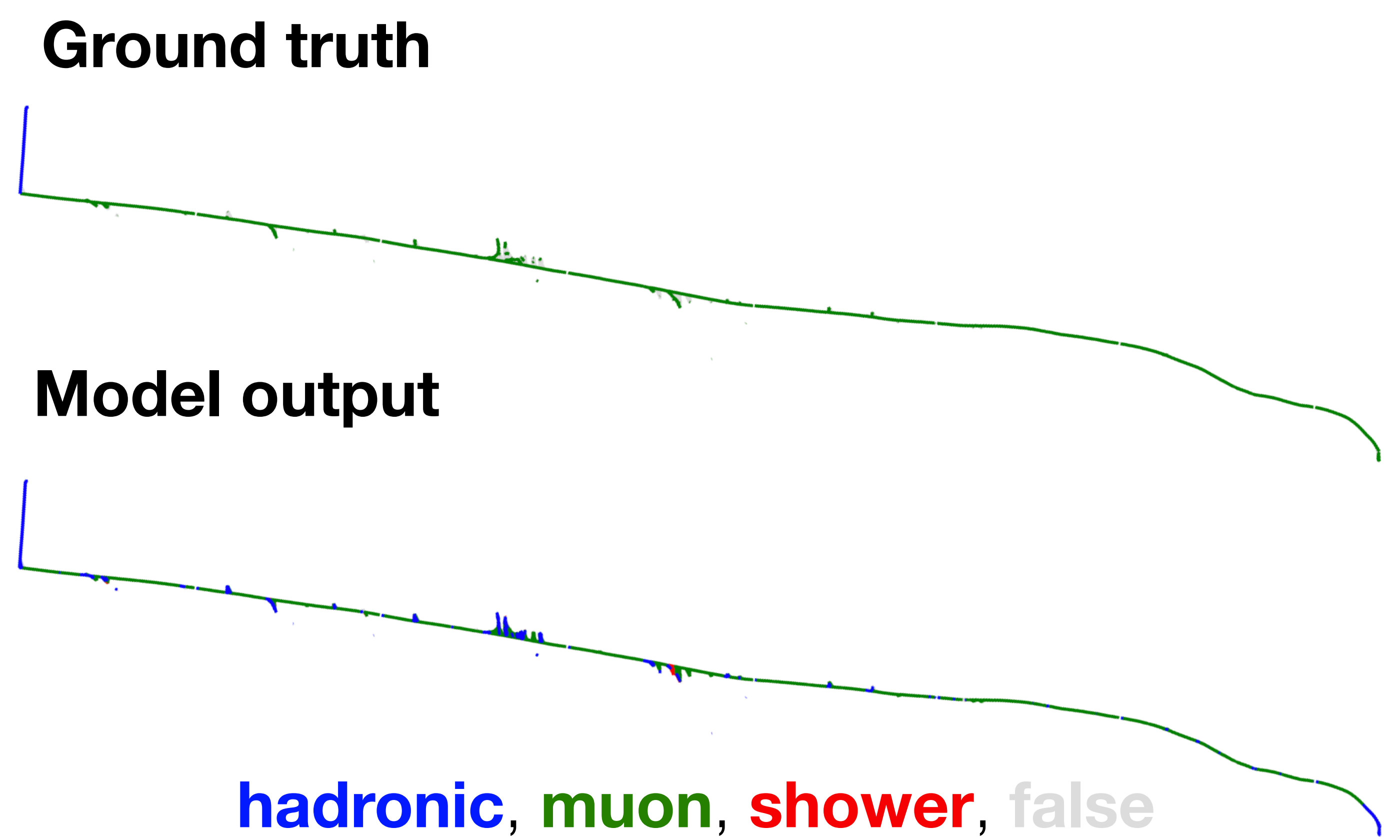

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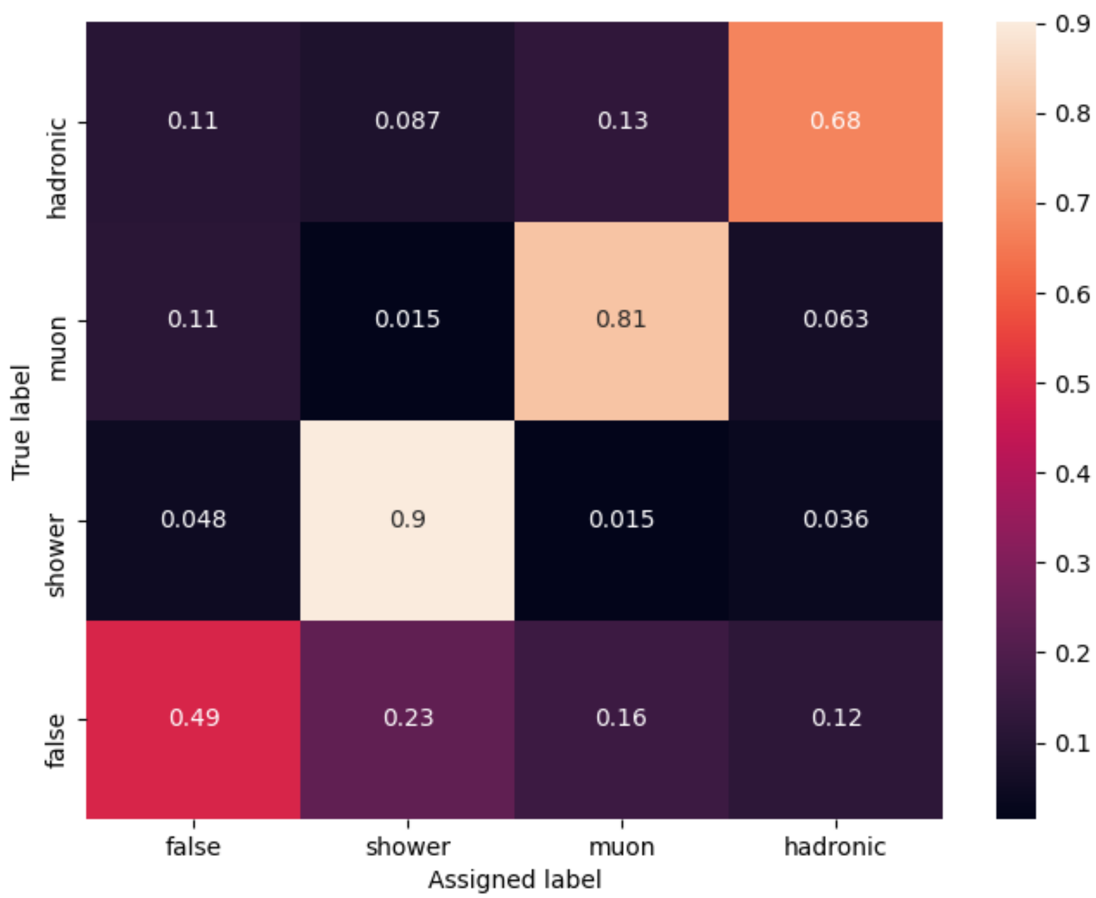

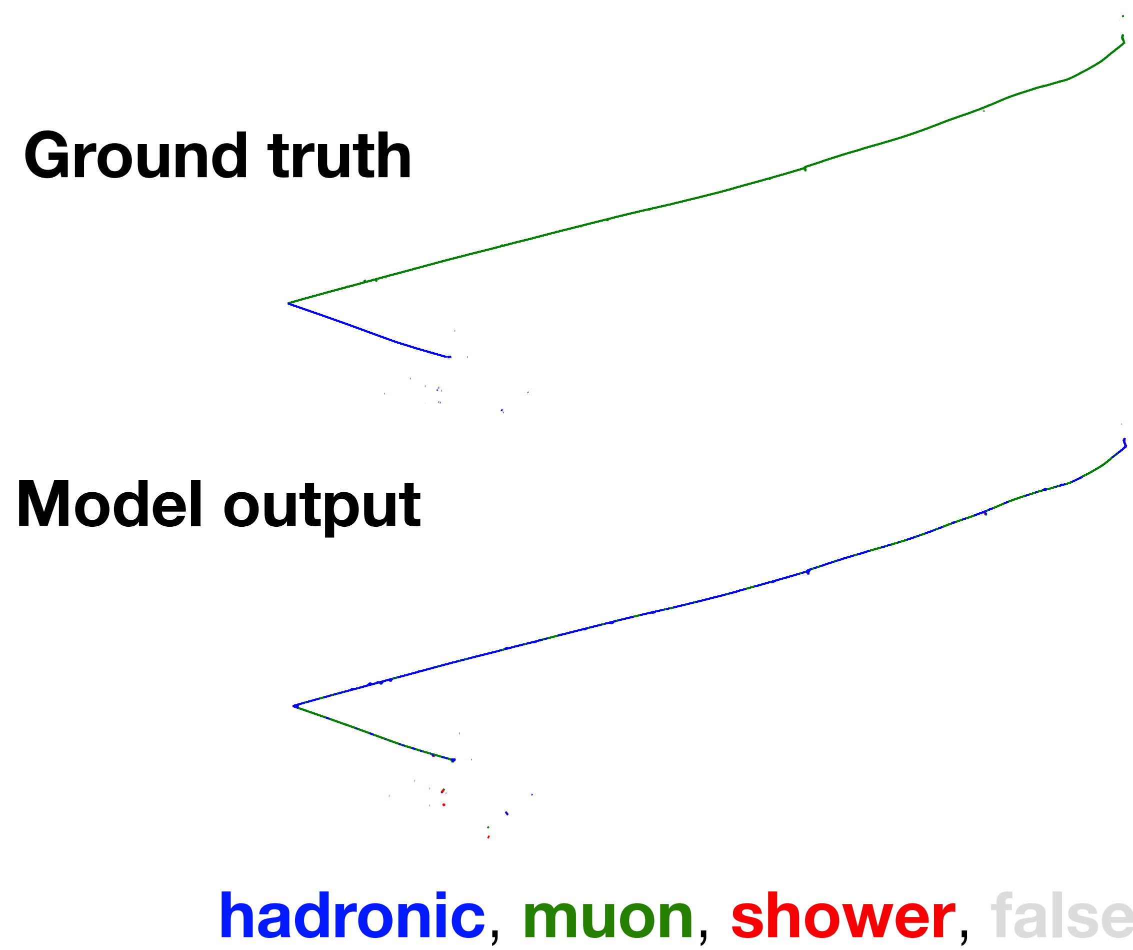

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- Move from **edge classification** to **node (ie. hit) classification**.
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  - Dense LArTPC environment provides no such constraints, and number of edges explodes.
- Introduce **more sophisticated semantic labelling** which considers a wider variety of particle types, ie. EM showers, Michel electrons, diffuse EM activity.
- Build a model which **classifies all views simultaneously**, instead of classifying each detector views as an independent event.
  - Furthermore, allow **information exchange between 2D views** to break degeneracies.

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- Use five semantic categories:
  - **MIP: Minimum ionising particles (muons, pions etc)**
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- Also perform **hit filtering** to remove hits that are not part of the primary physics interaction.

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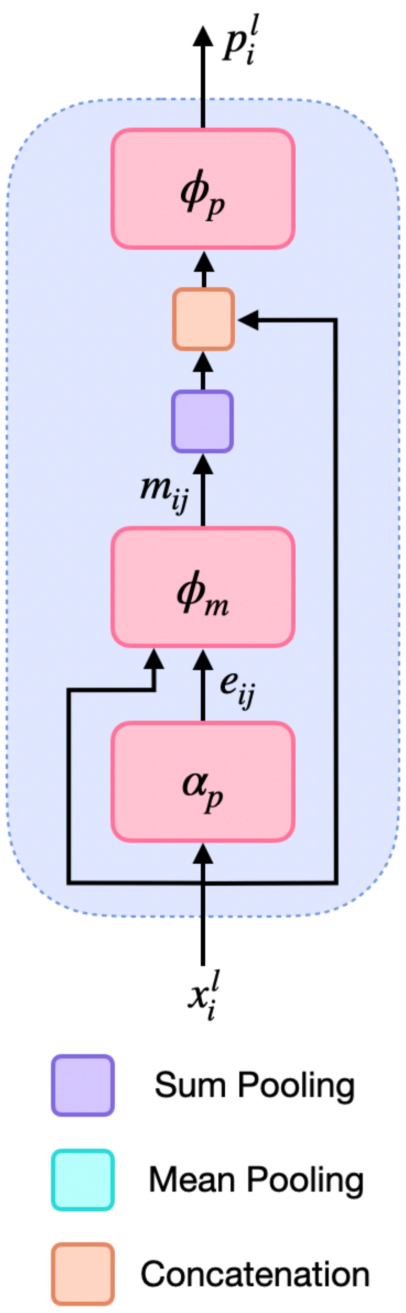
Planar block



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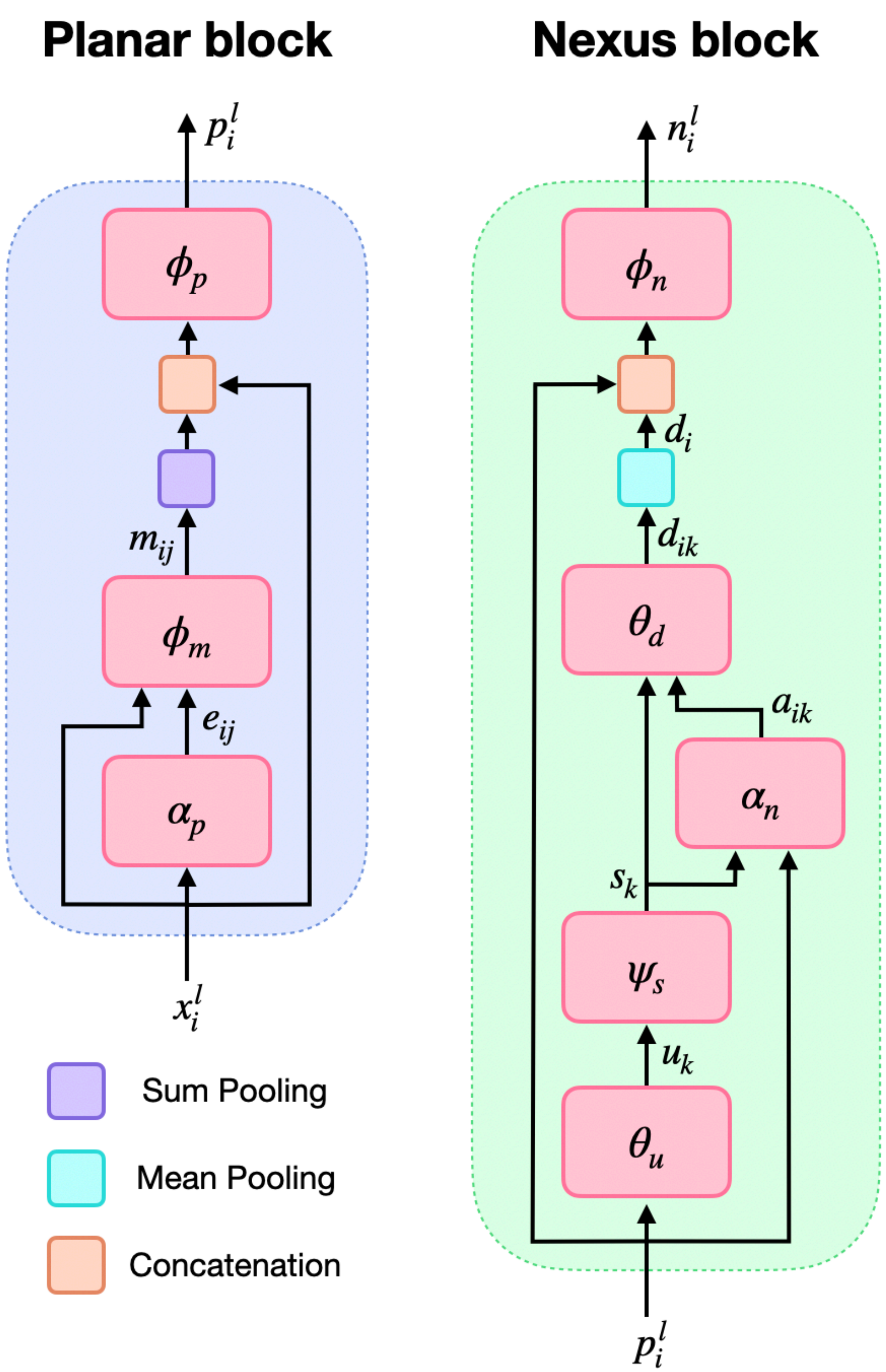
    - Pass messages up to 3D nexus nodes to share context information.



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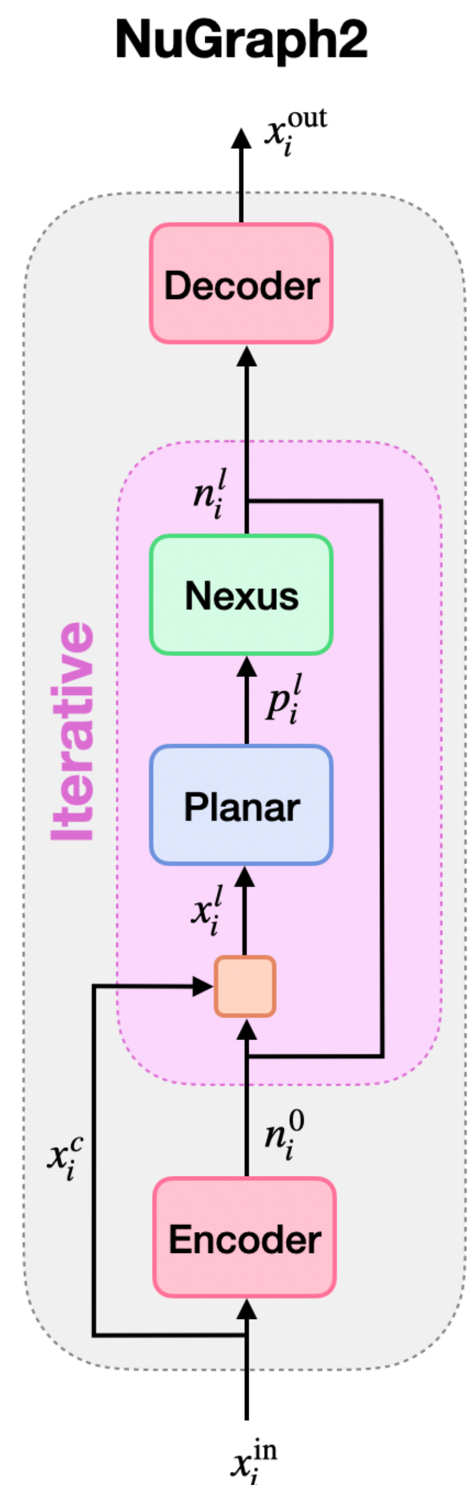
- This **iterative two-step message-passing engine** forms the backbone of the NuGraph2 architecture.



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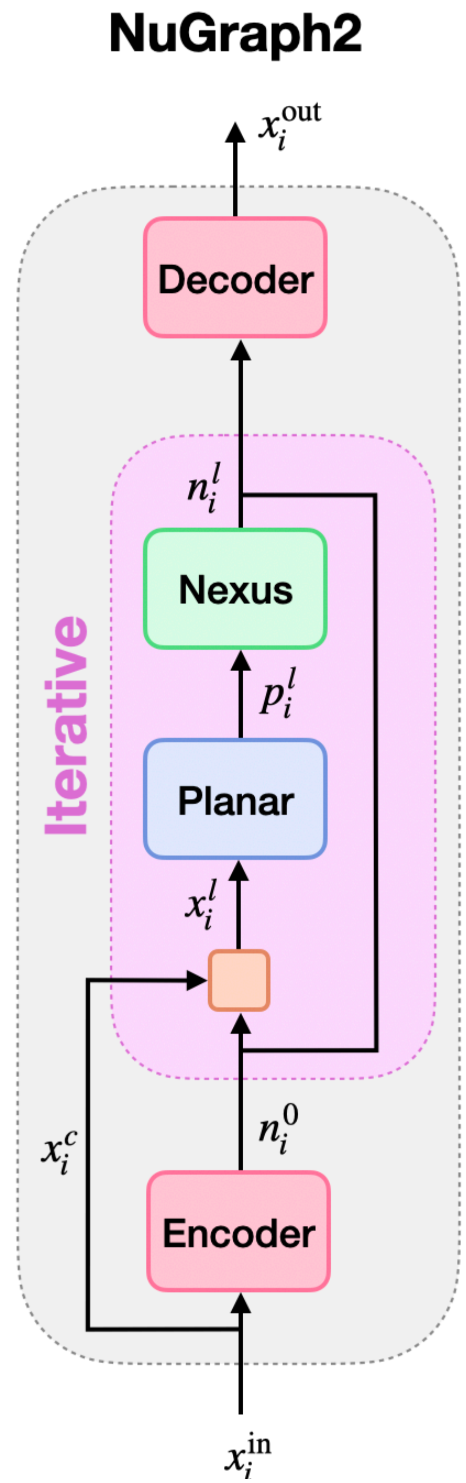

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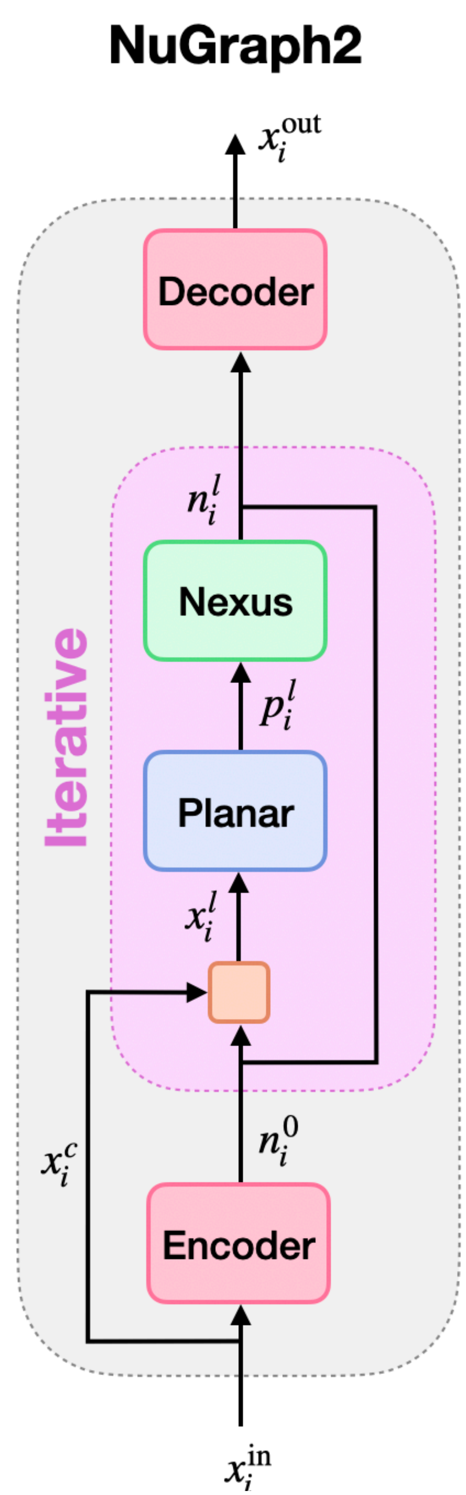

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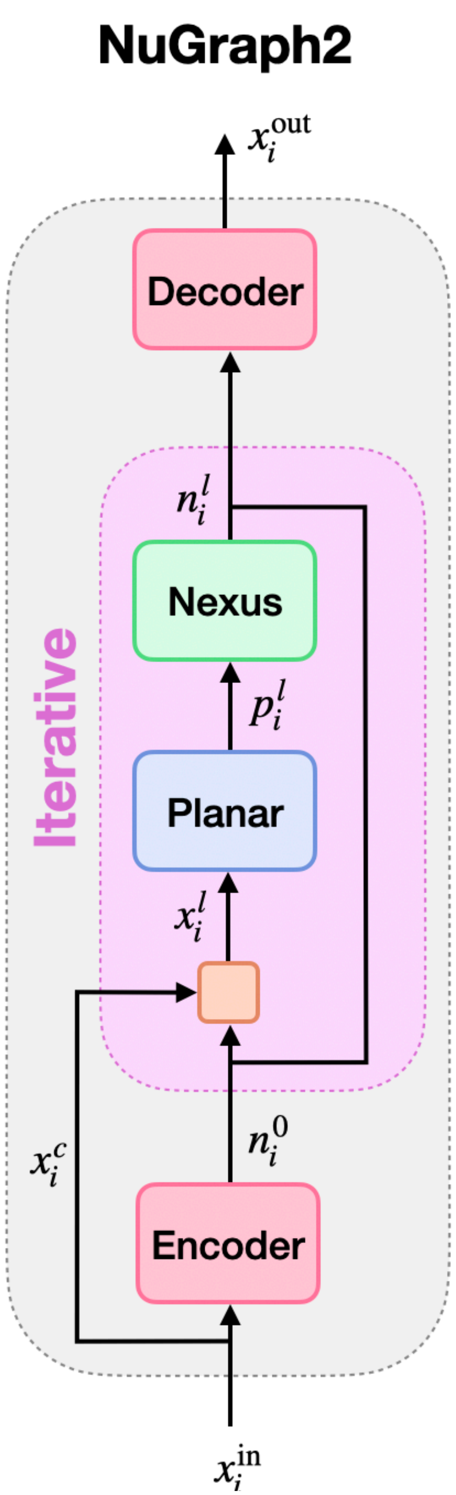
  - In this talk, we present two tasks: **semantic hit segmentation** and **background filtering**.



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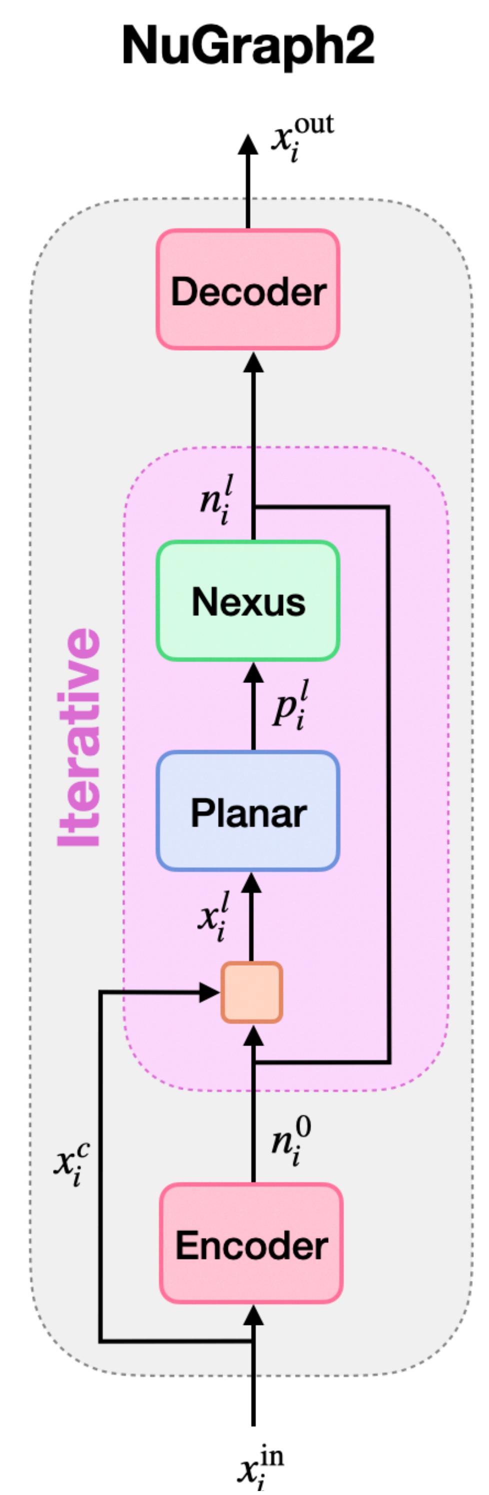
  - In this talk, we present two tasks: **semantic hit segmentation** and **background filtering**.
  - This engine can be leveraged for much more than just these two tasks. See the **NuGraph3** talk later for more details ;)

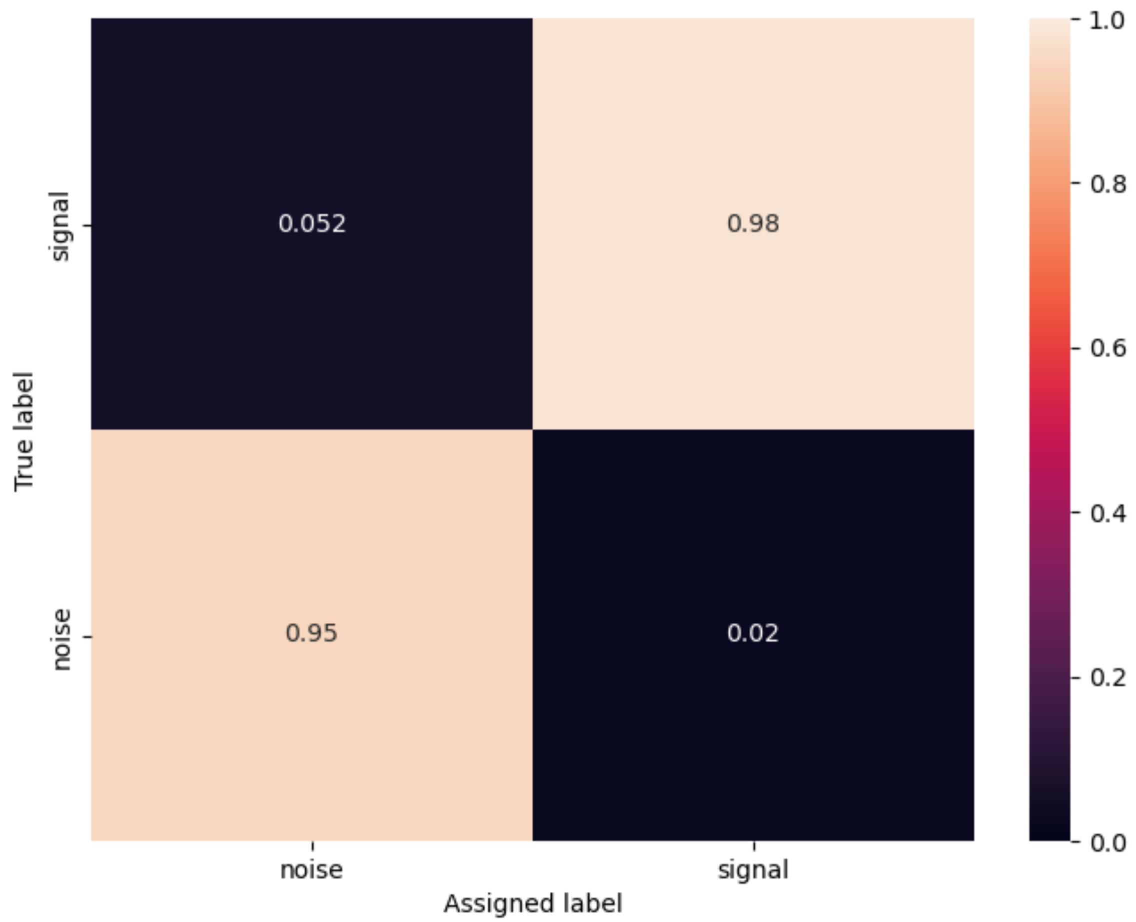


NuGraph2

Background filtering

- Performance metrics: **recall 0.978**, **precision 0.977**.

Recall matrix



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- Inference time: **0.12 s/evt on CPU**, **0.005s/evt batched on GPU**

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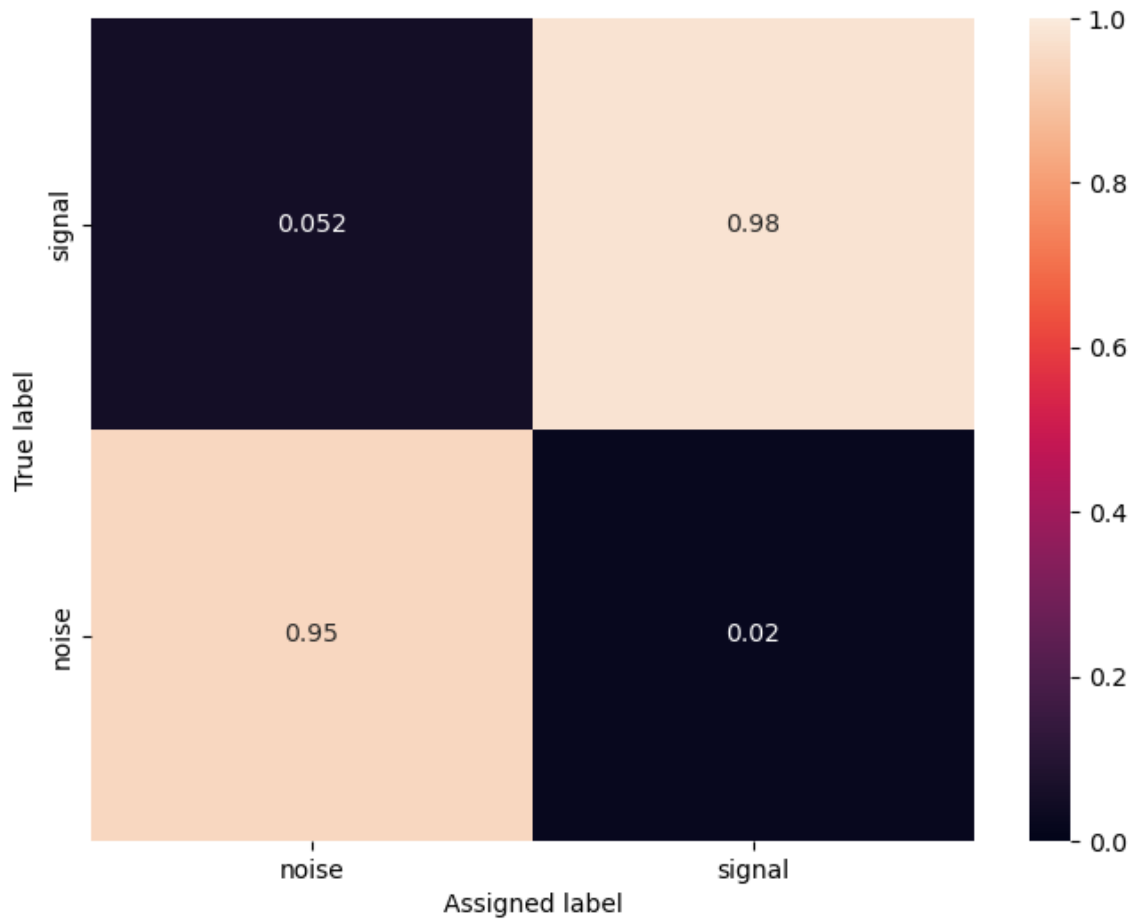
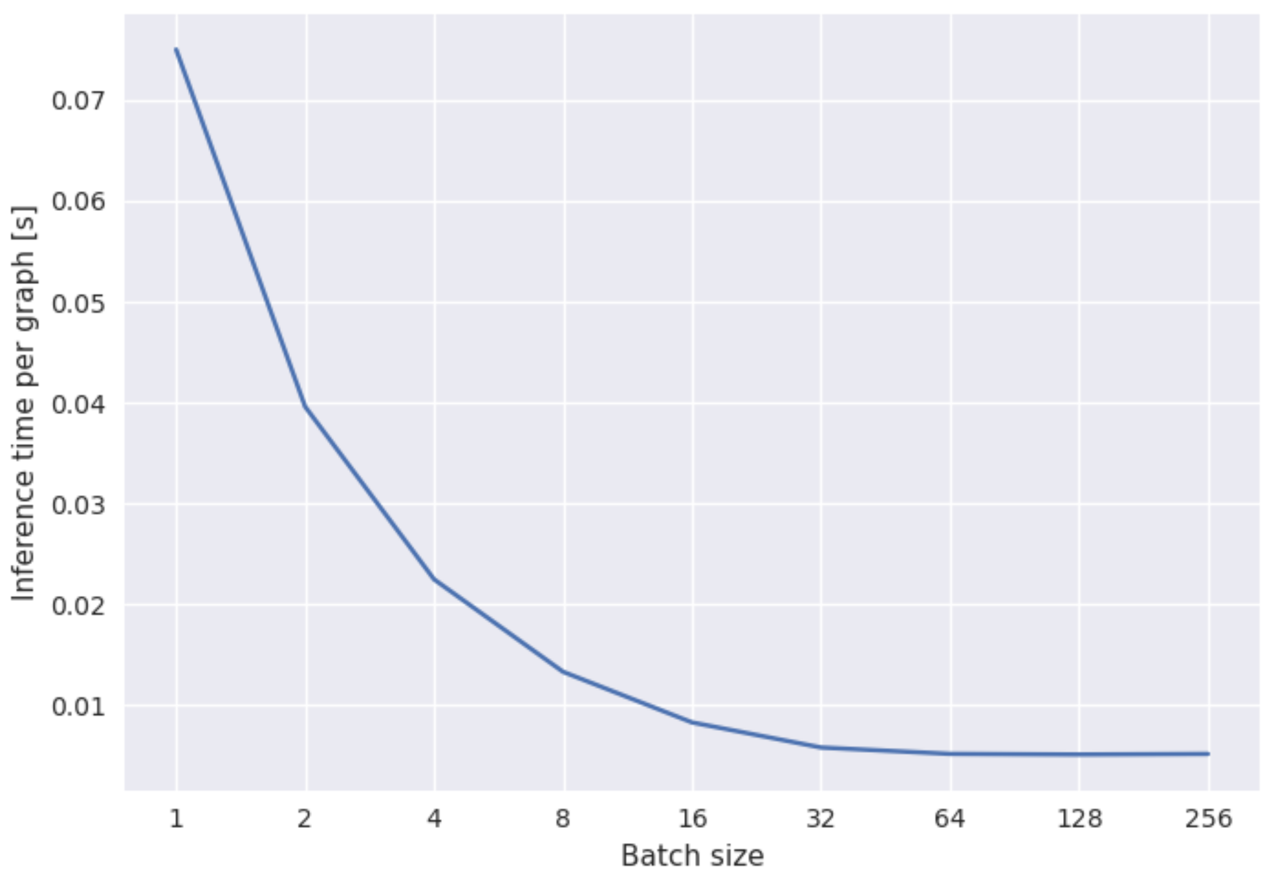


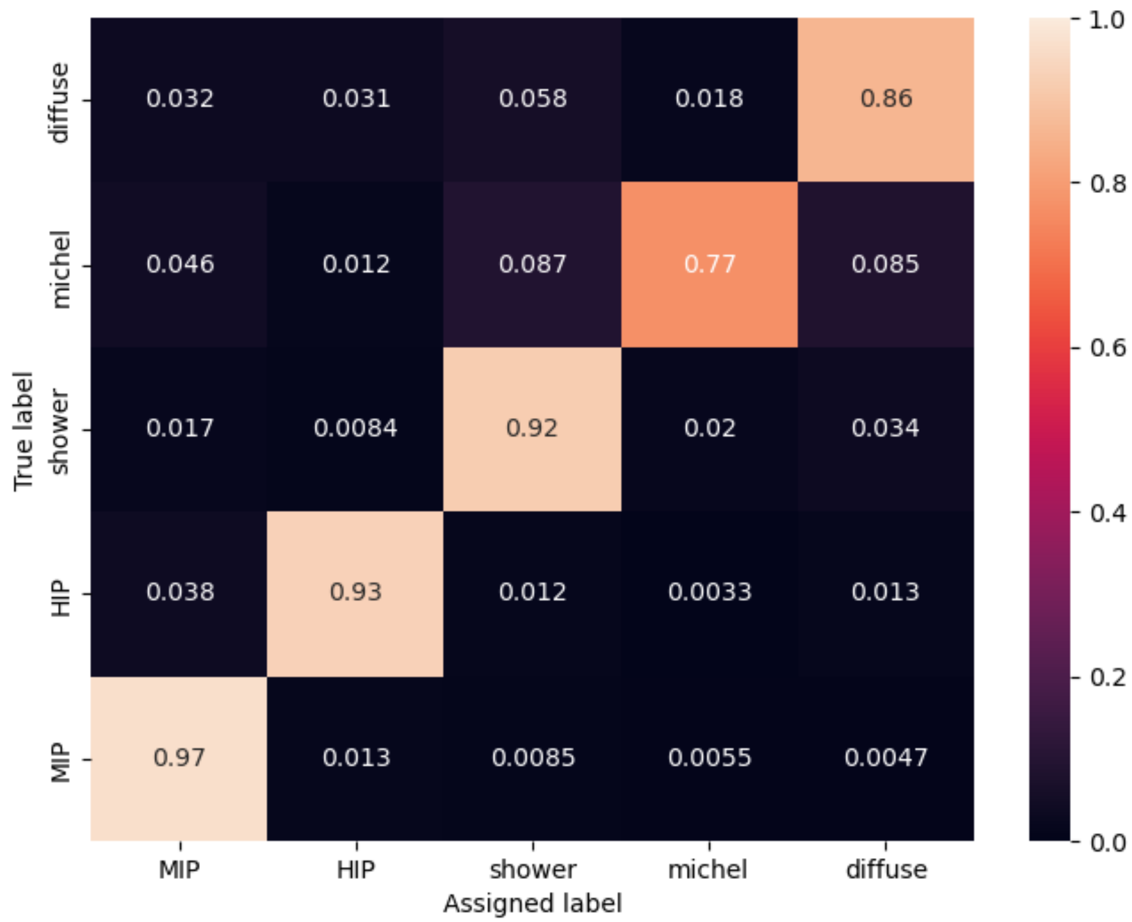
GPU inference time vs batch size



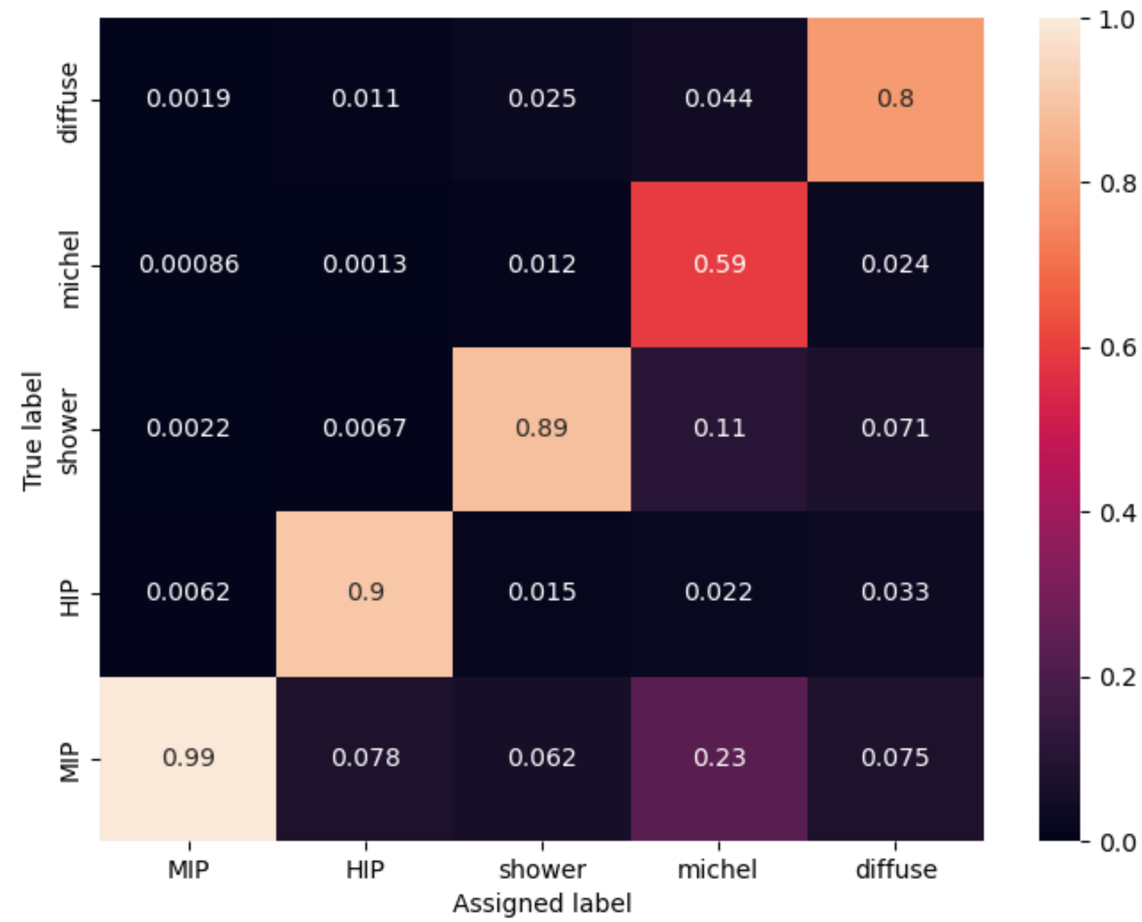
Hit classification

- Performance metrics: **recall 0.948**, **precision 0.948**.
- Recently improved performance by enhancing ν_μ component of dataset, and using **recall loss** to counteract class imbalance.

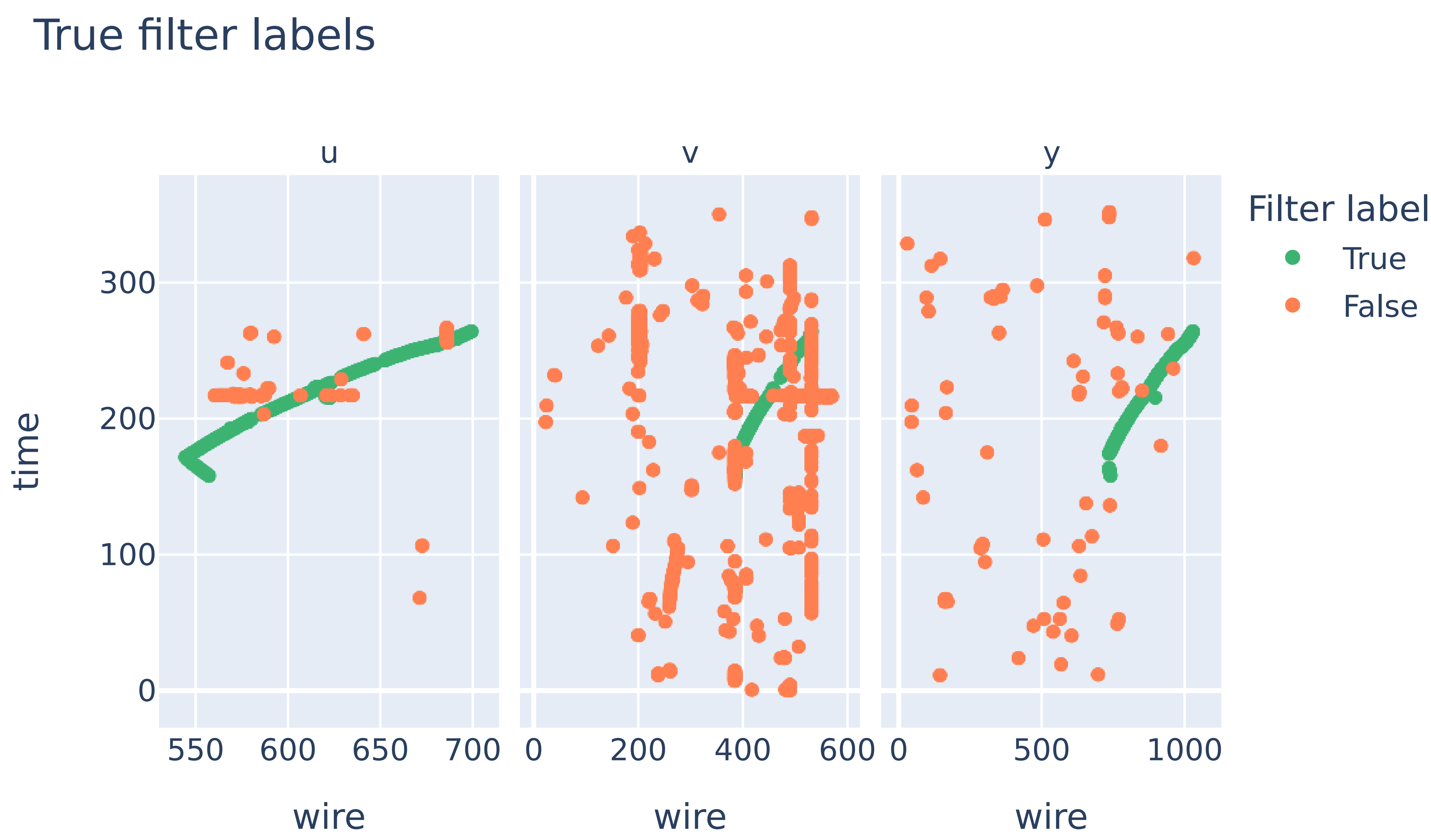
Recall matrix



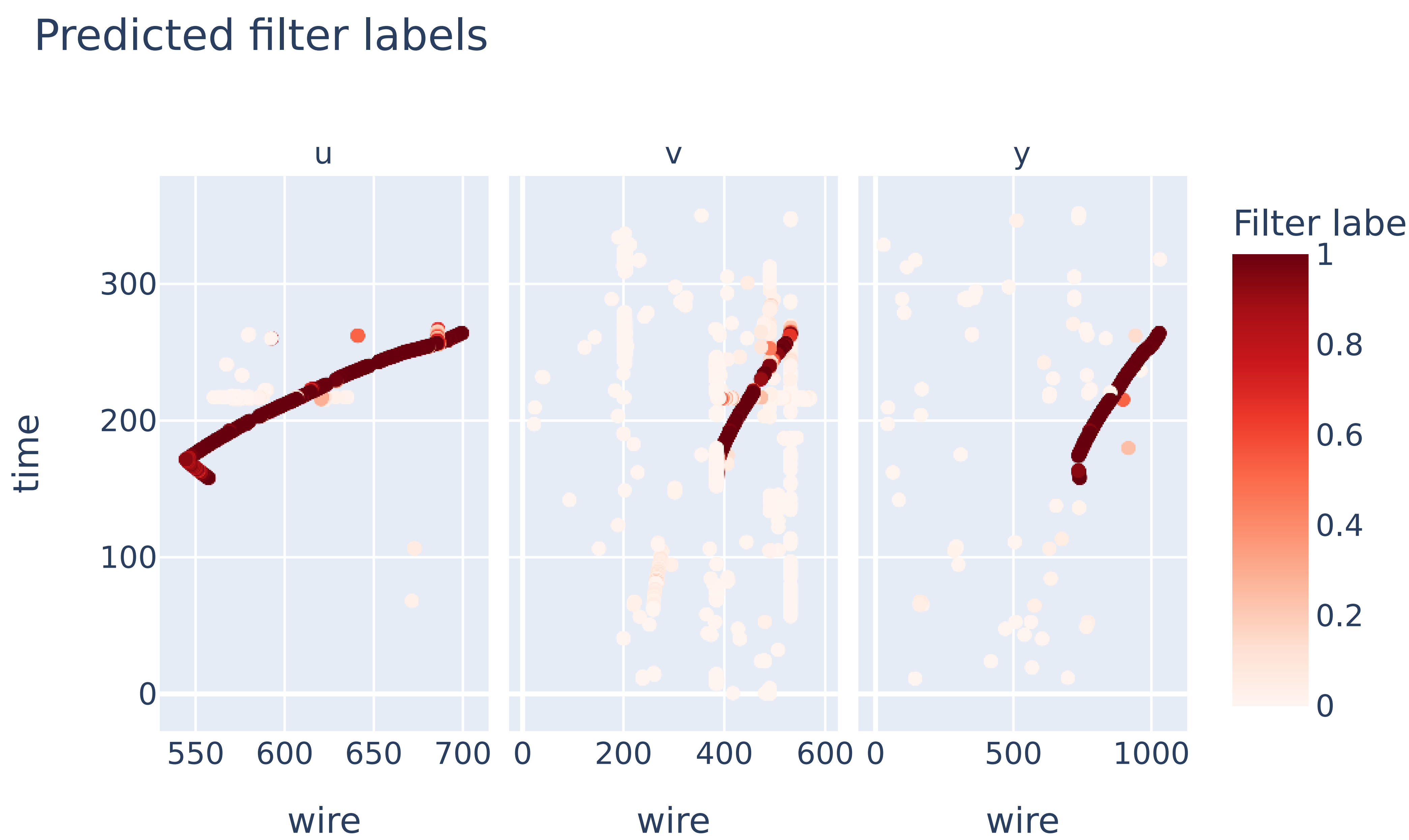
Precision matrix



Example event #1



Example event #1



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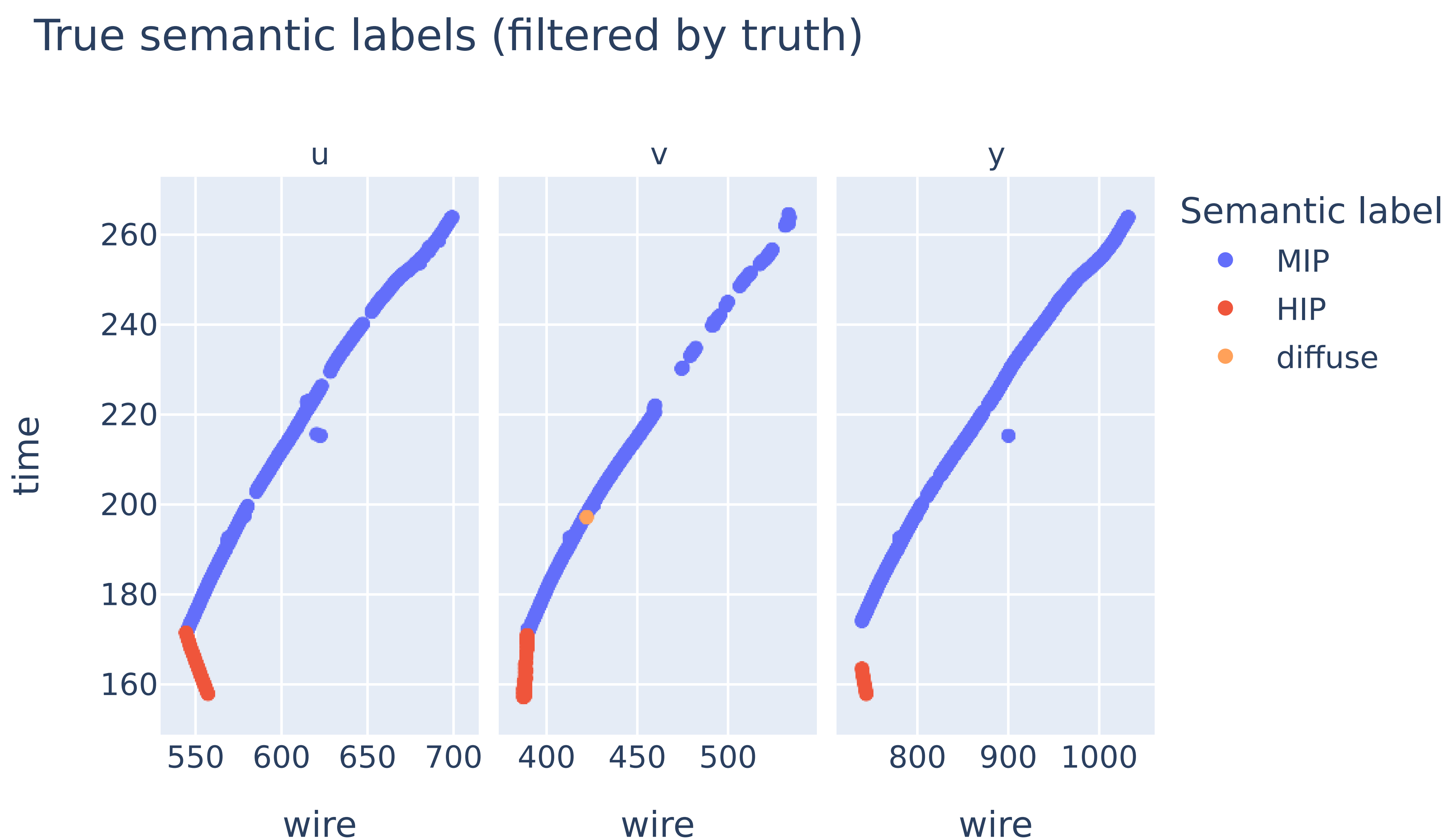

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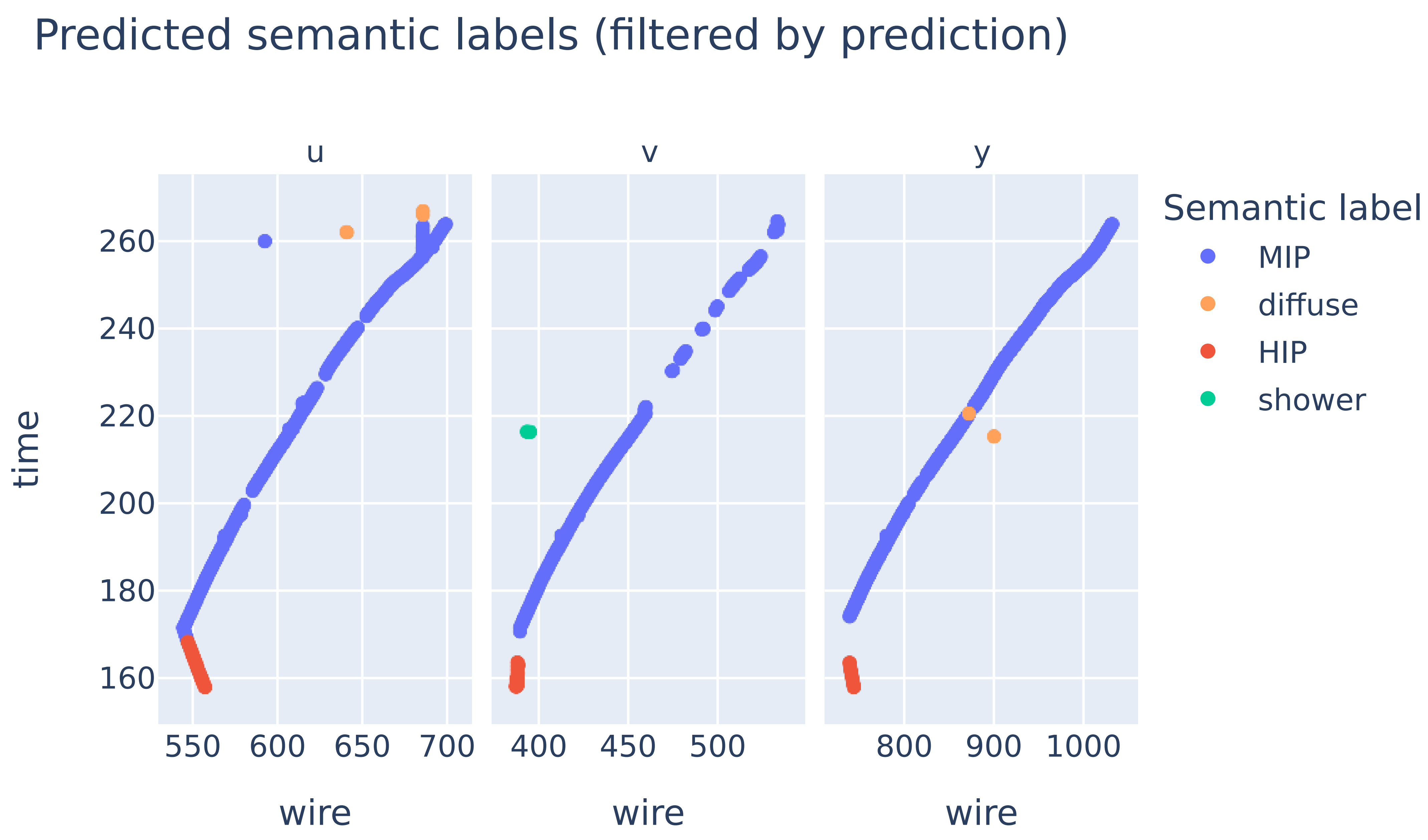
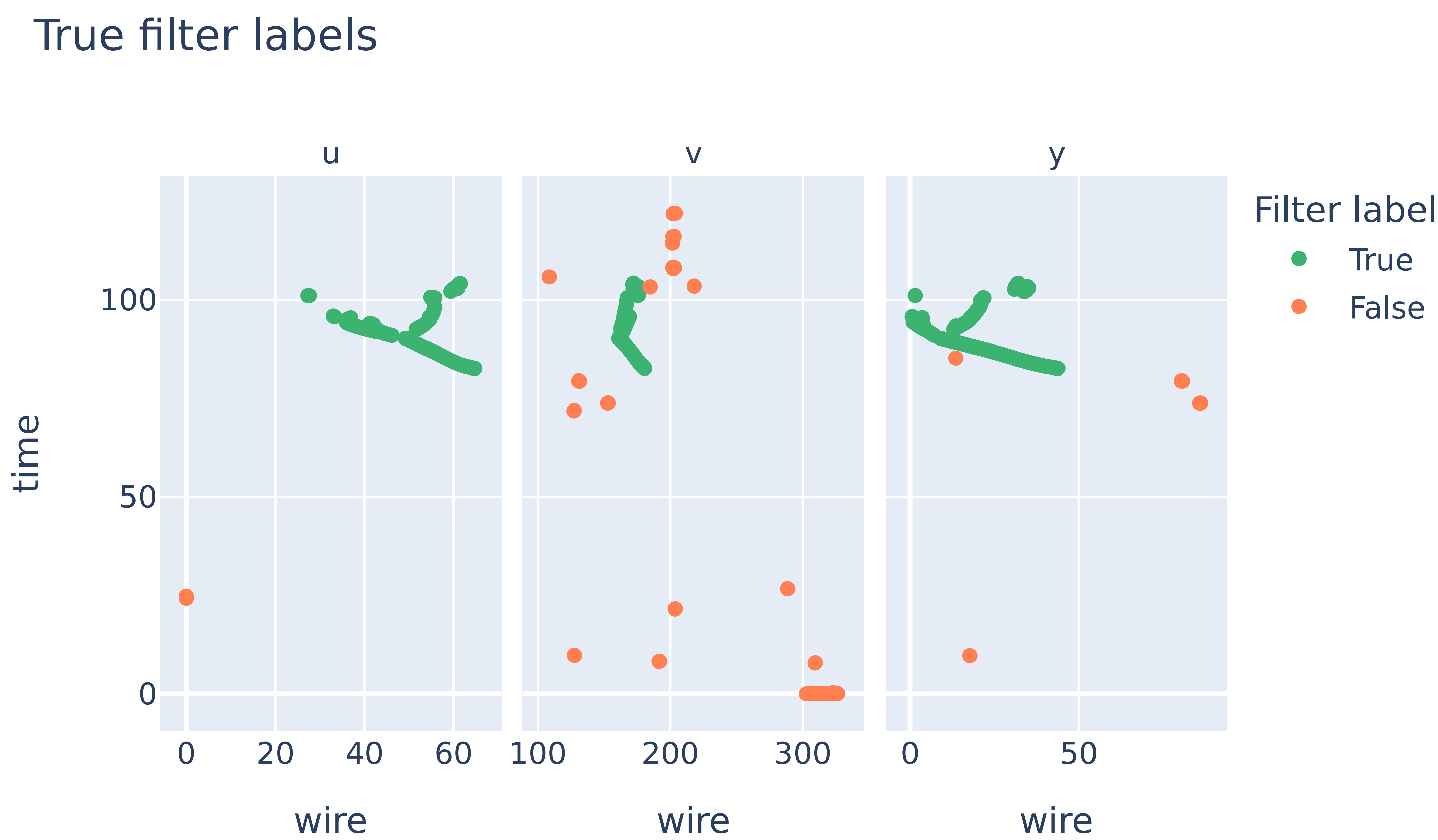
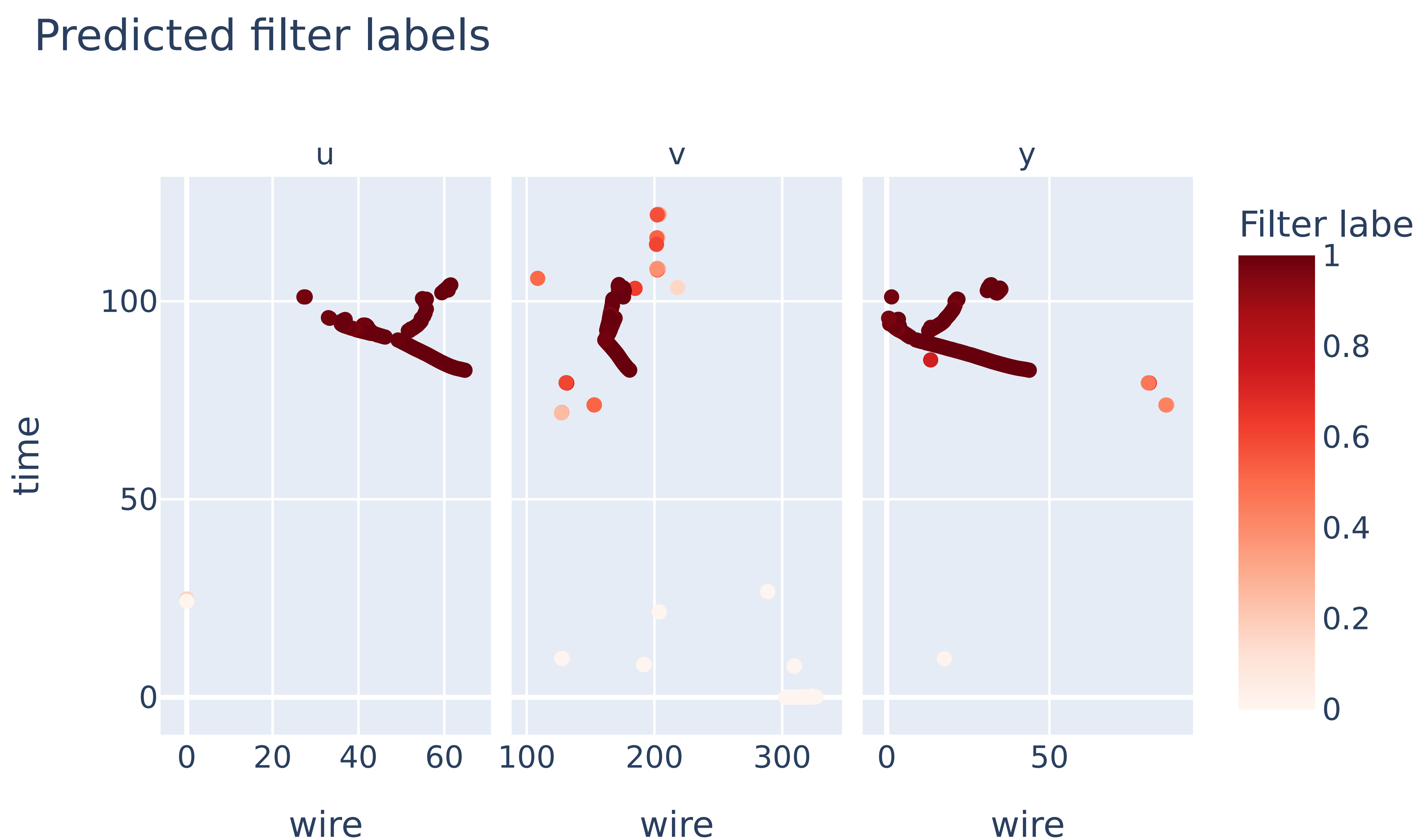


Example event #2



Example event #2



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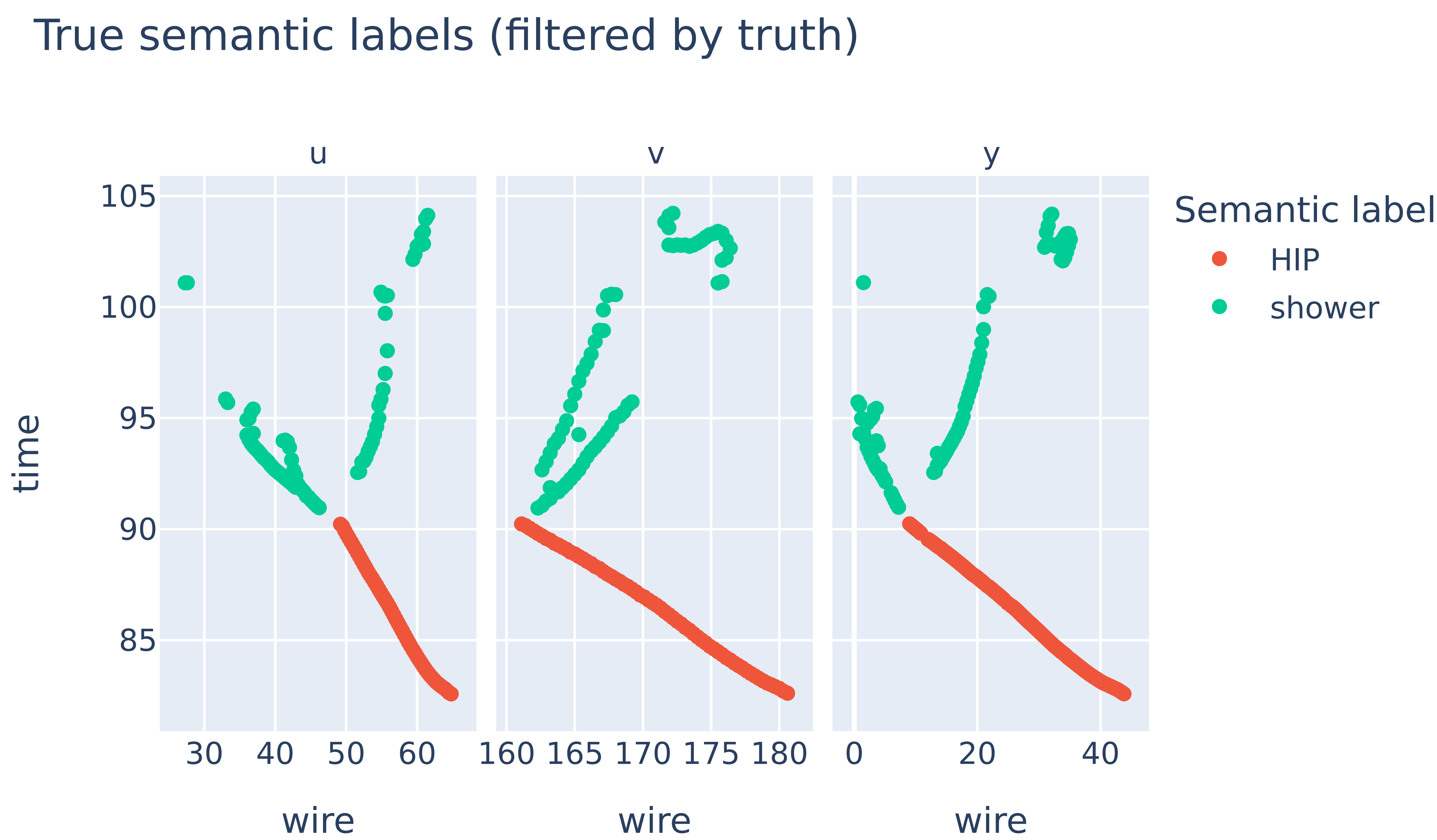

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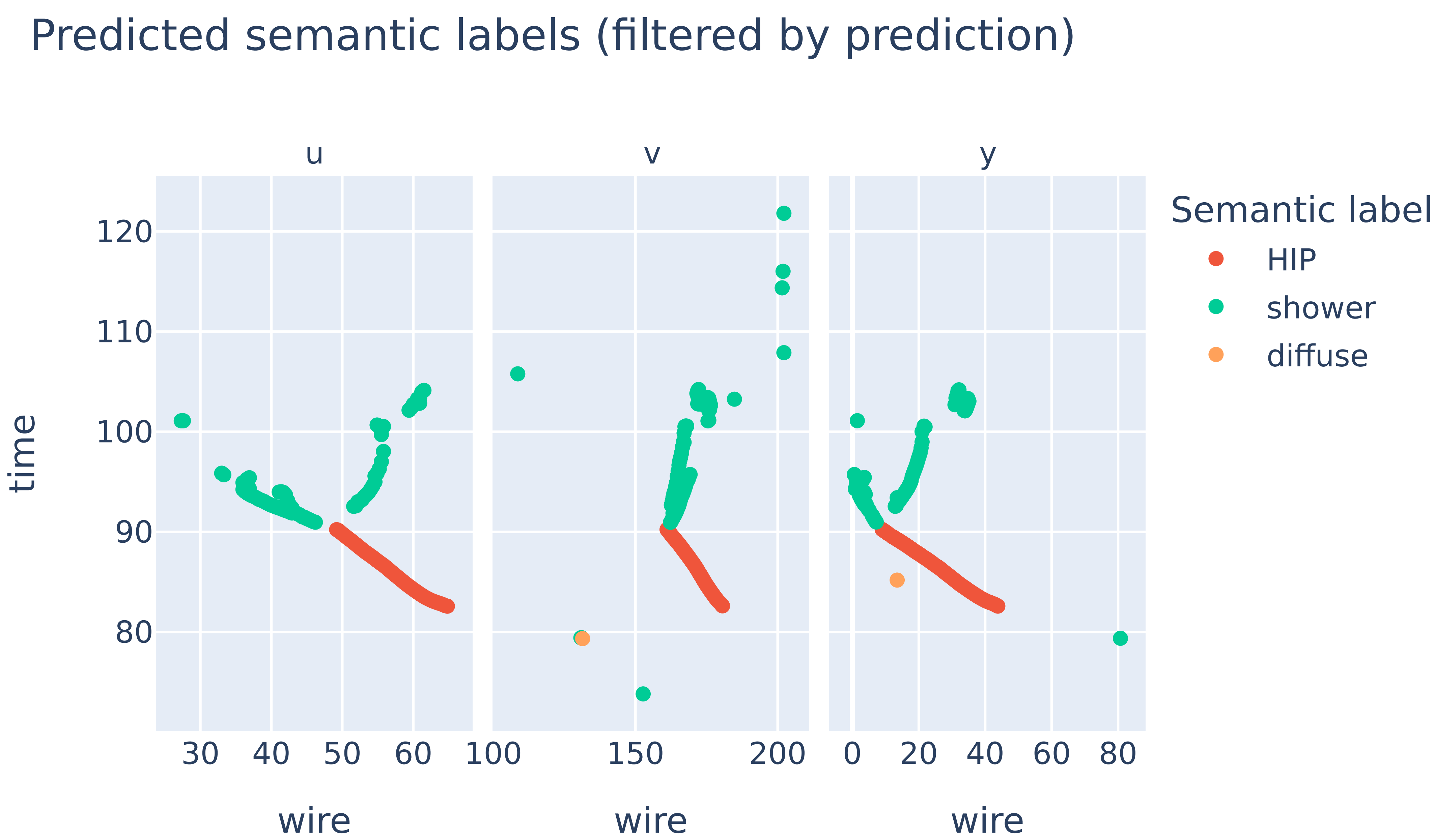
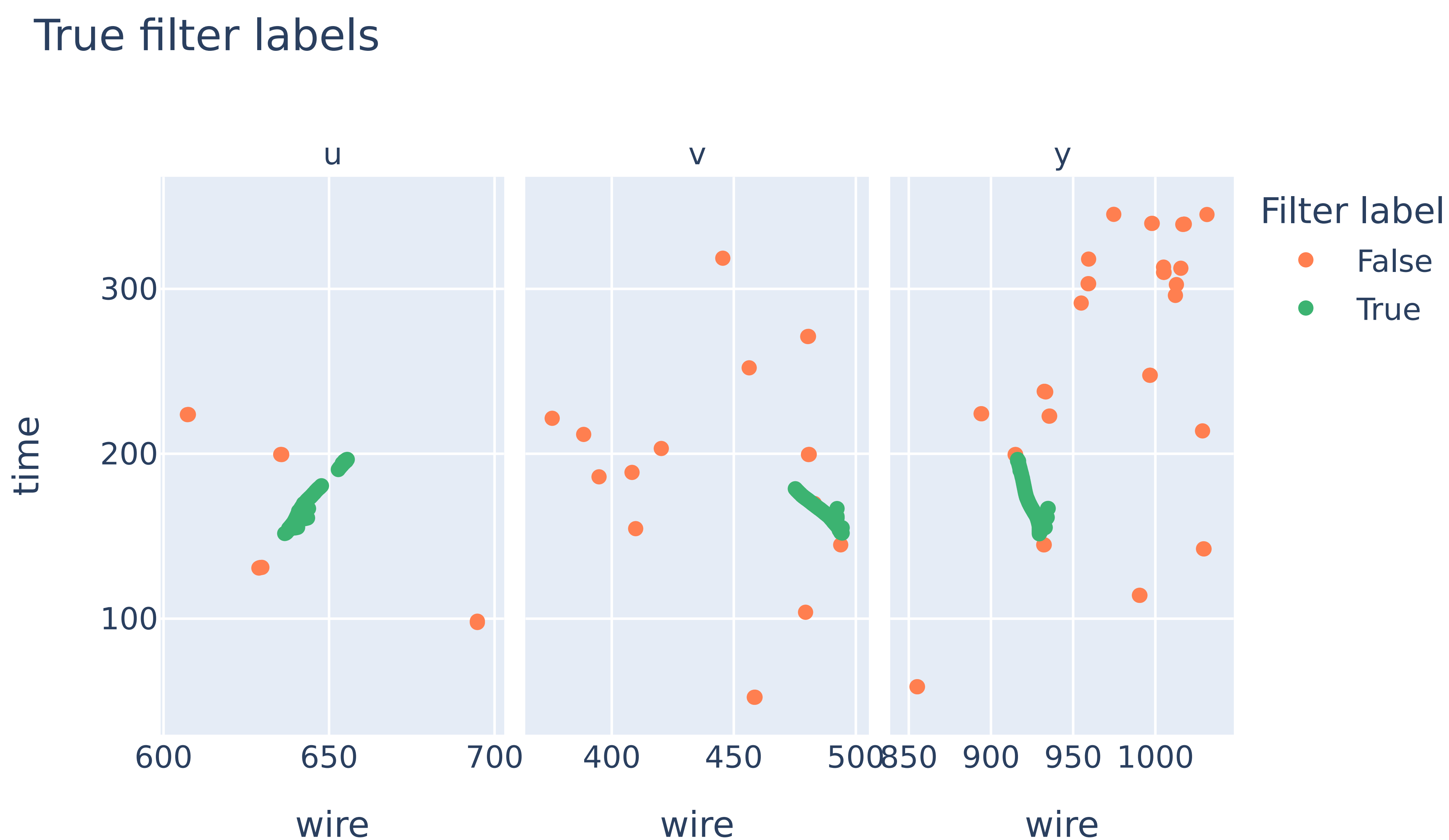


Example event #3



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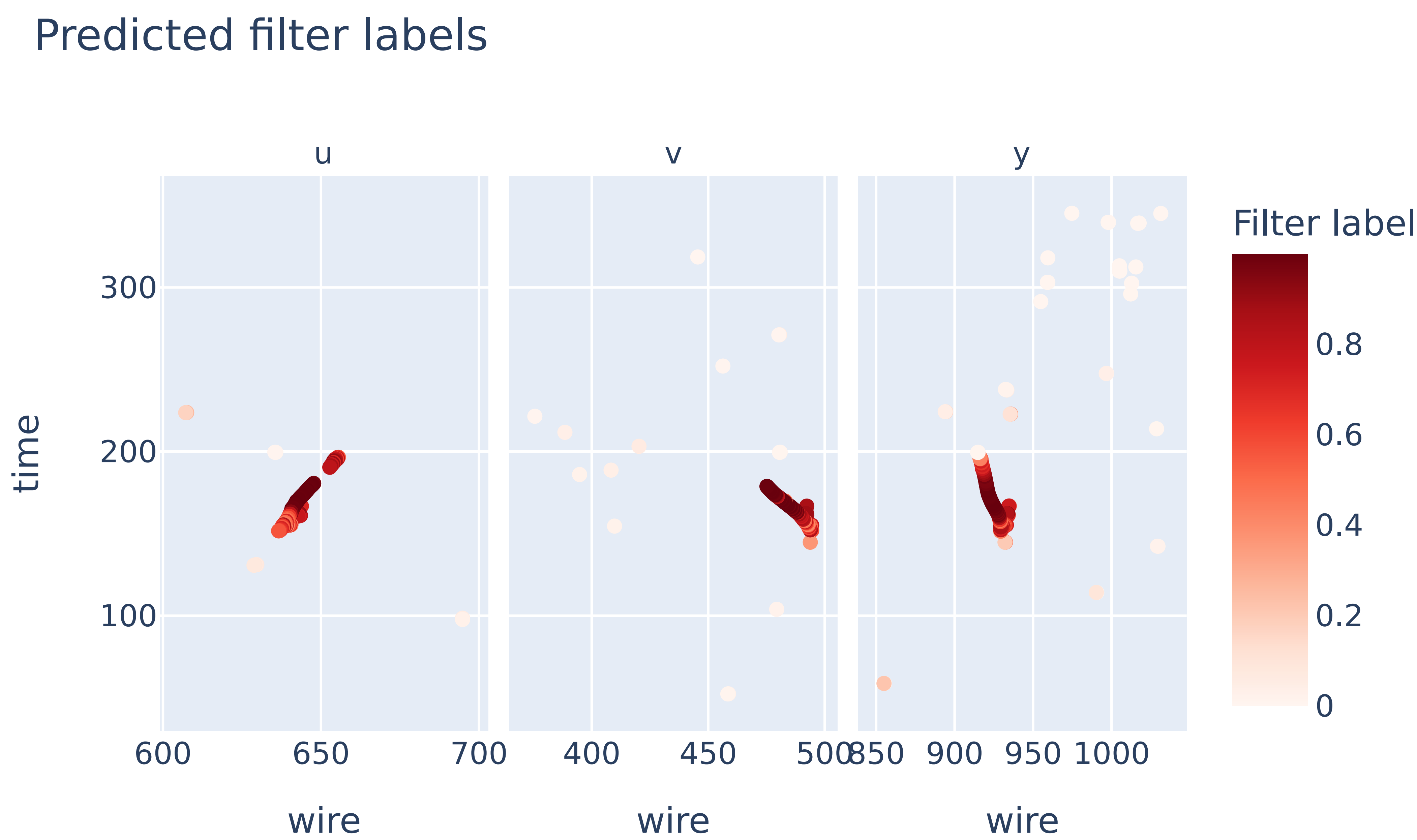
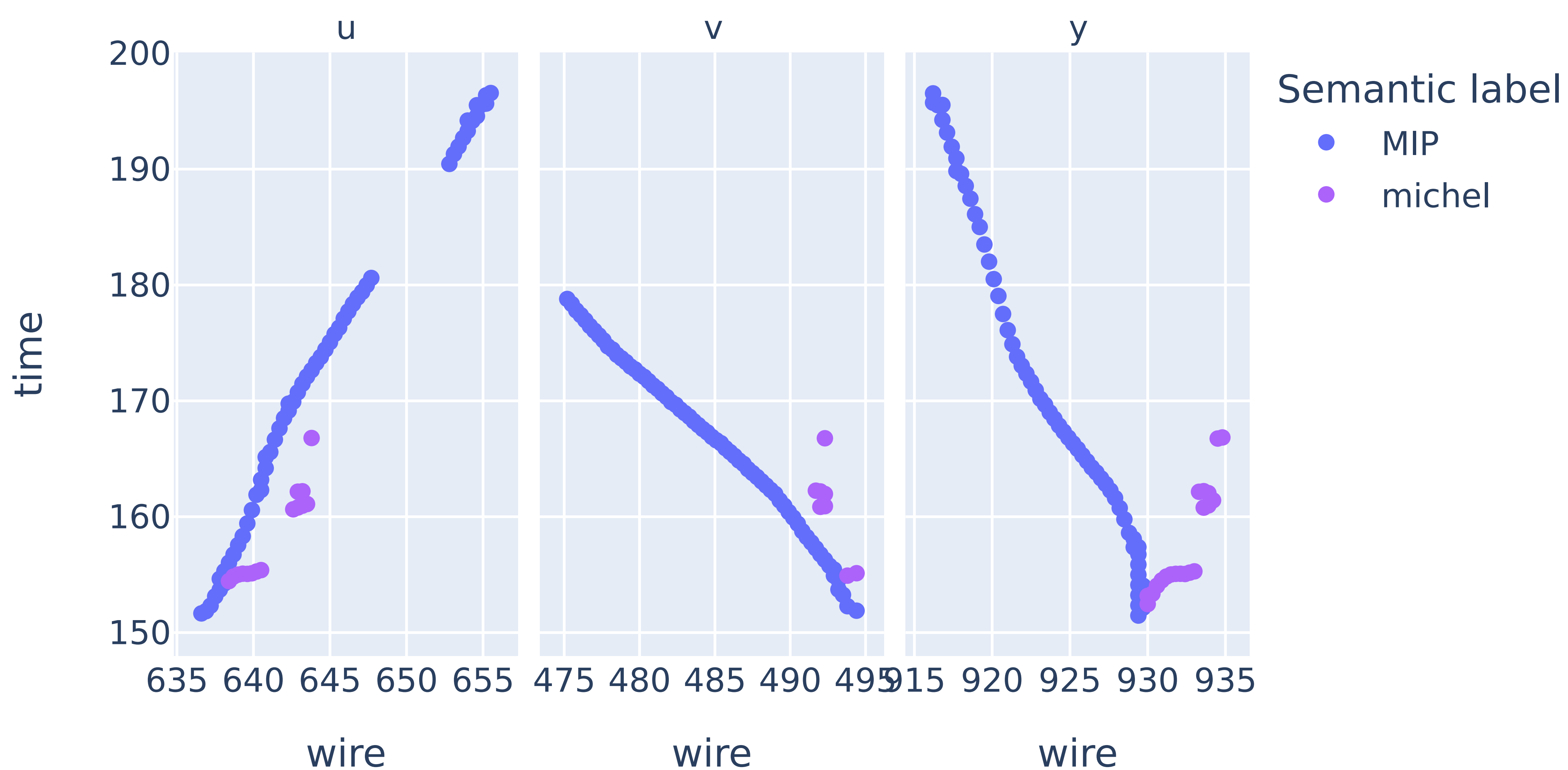
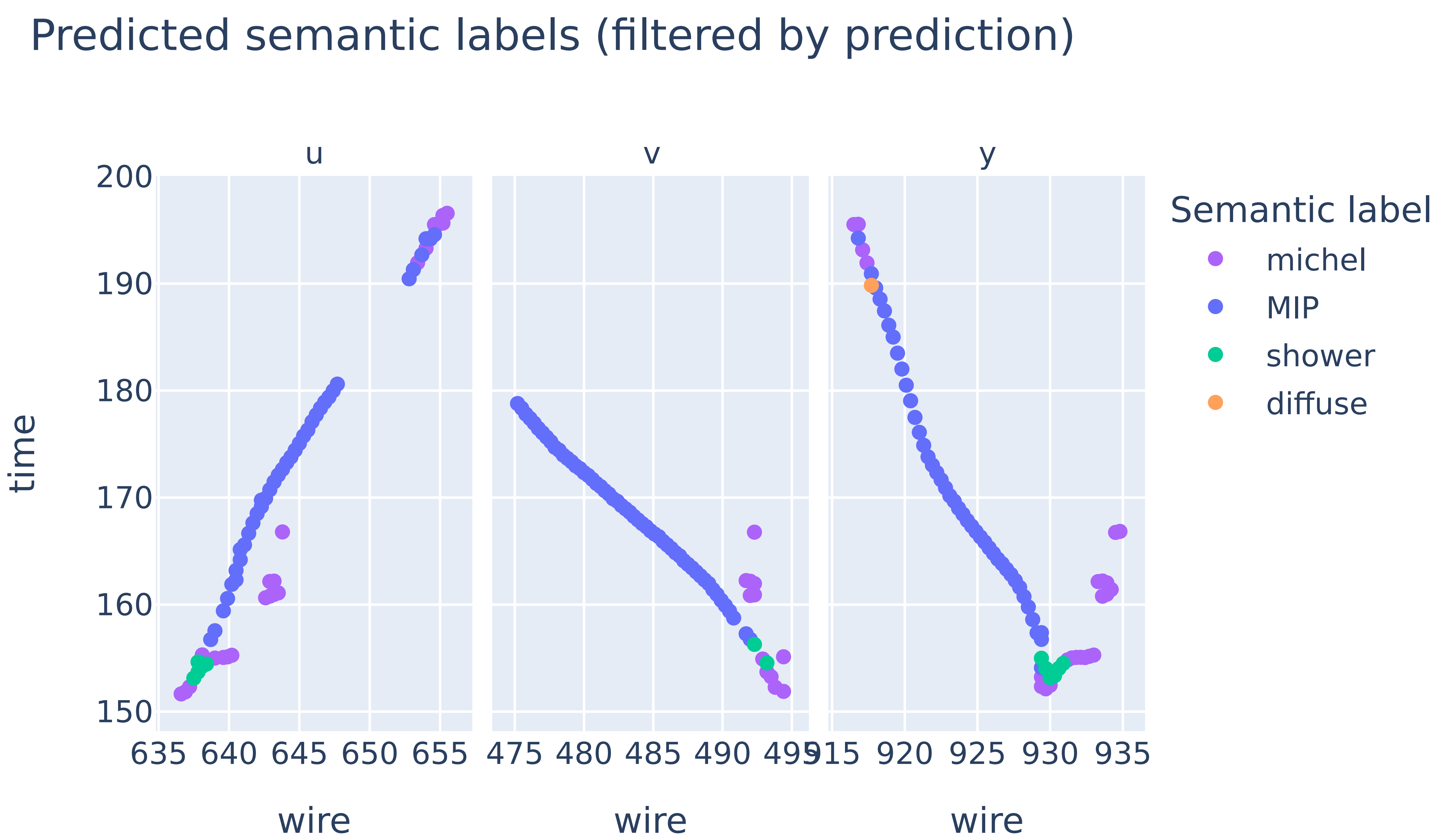


Example event #3

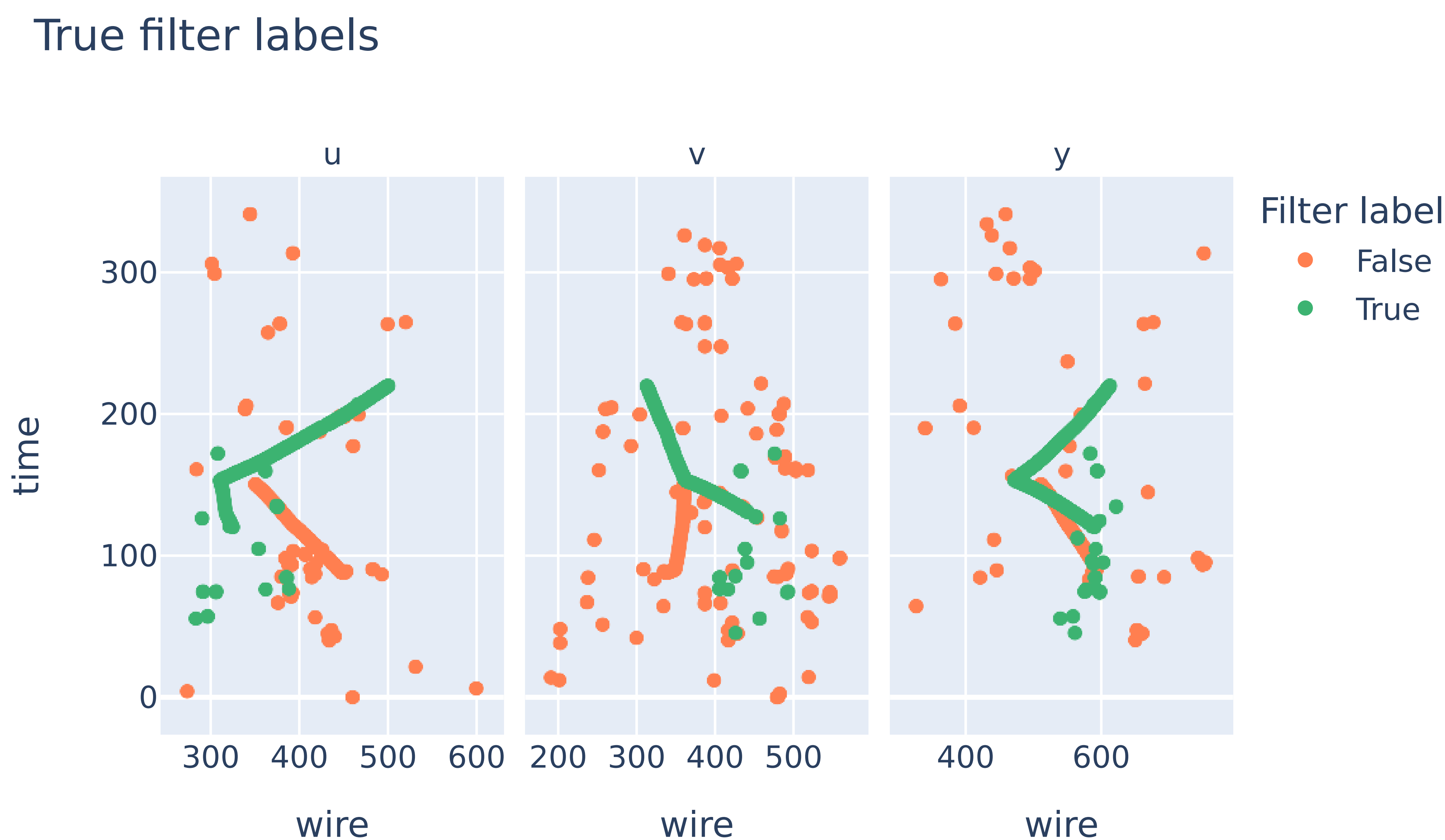
True semantic labels (filtered by truth)



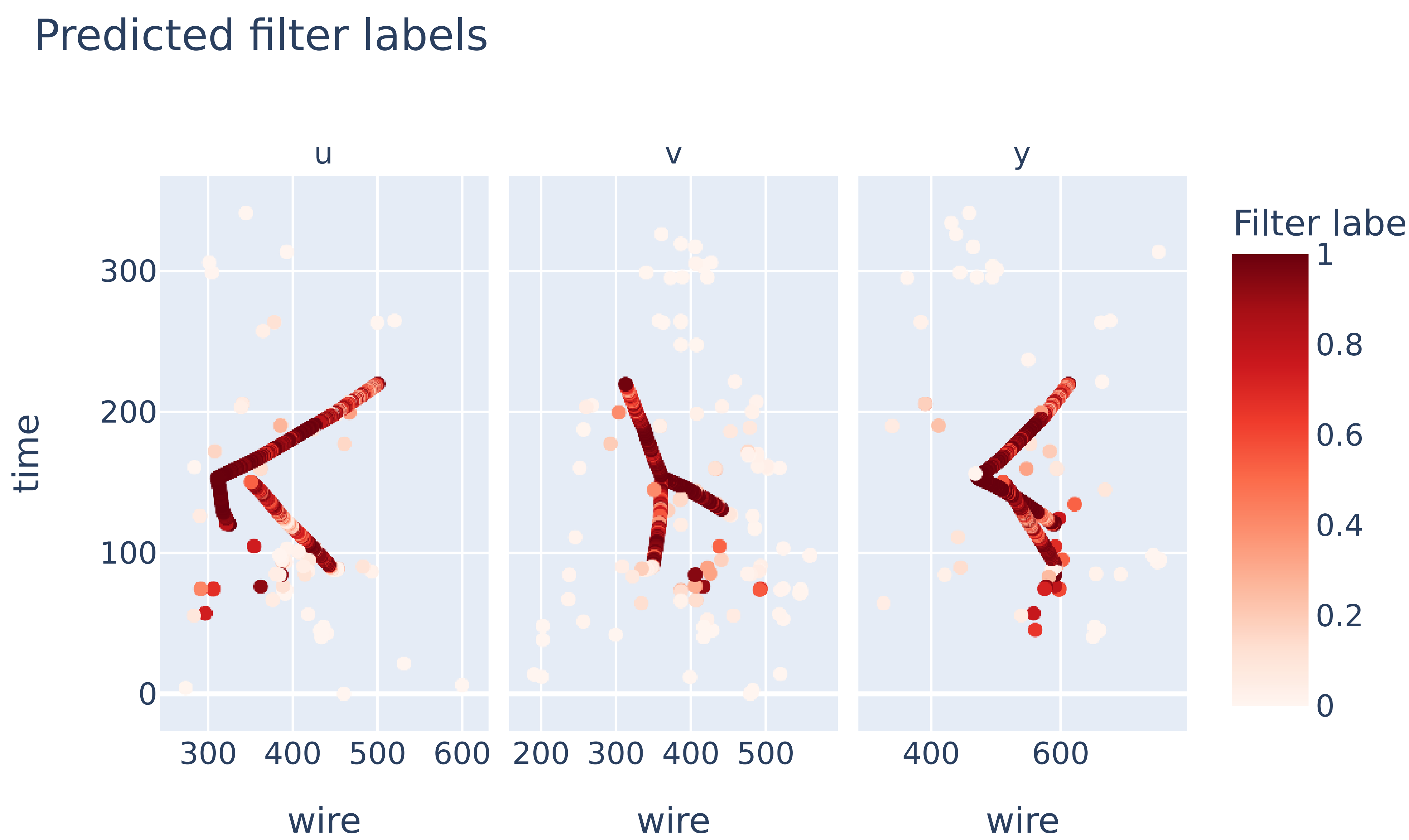
Example event #3



Example event #4



Example event #4



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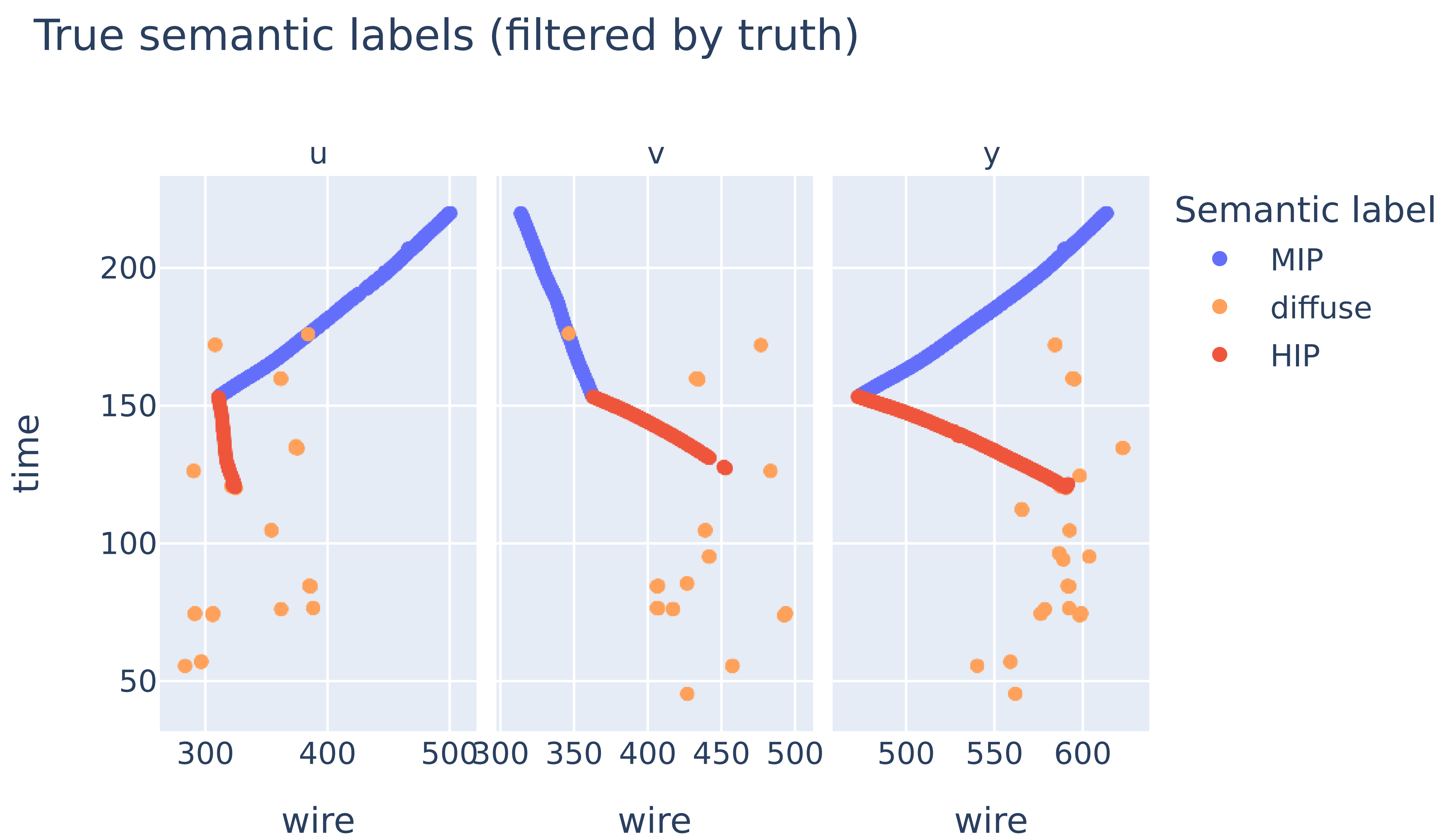
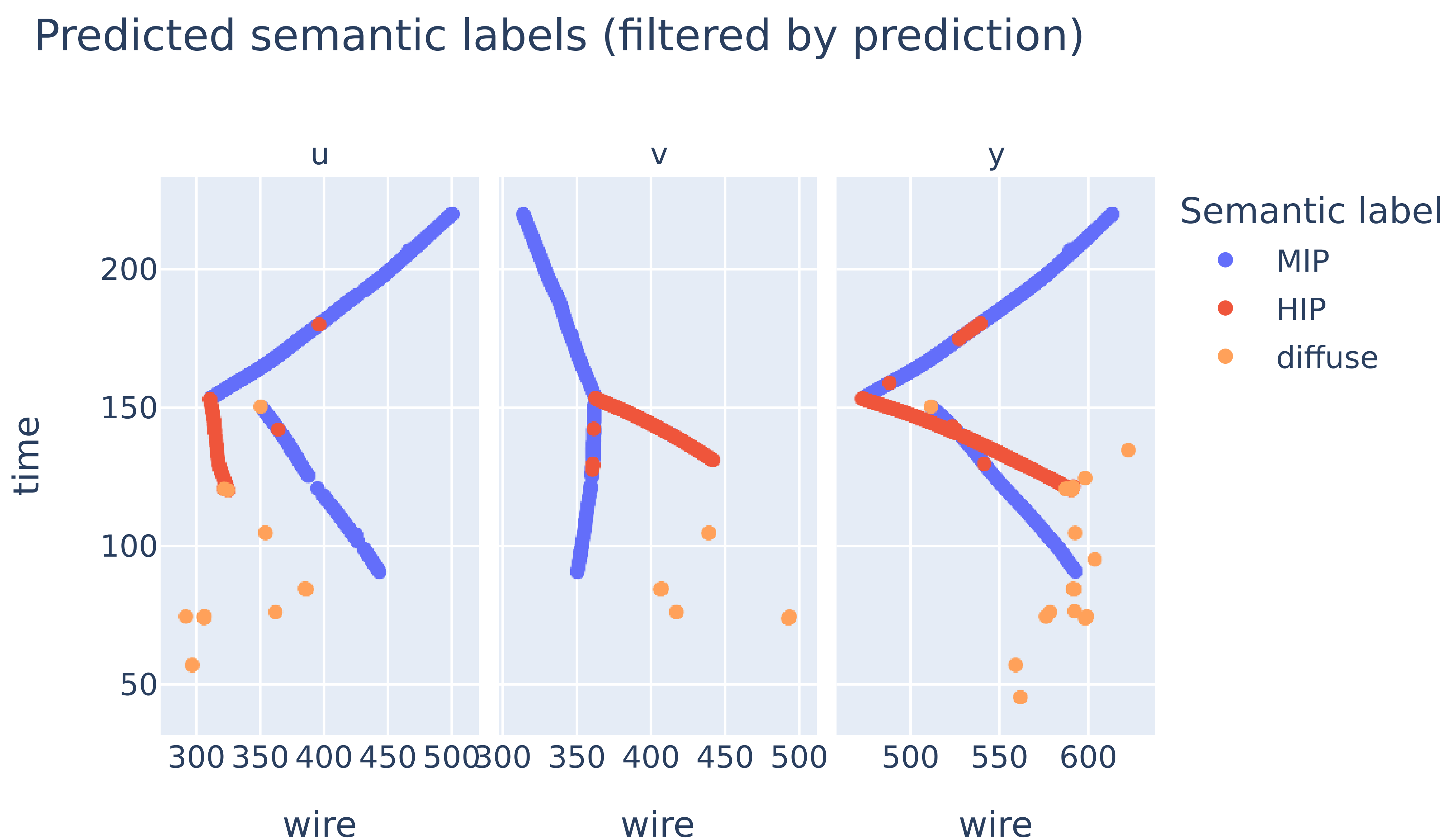
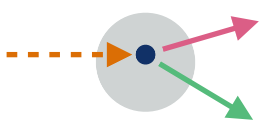
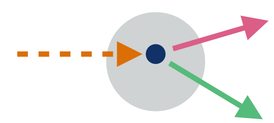
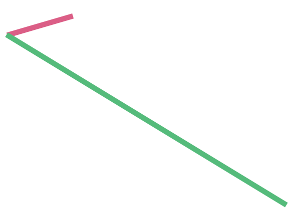
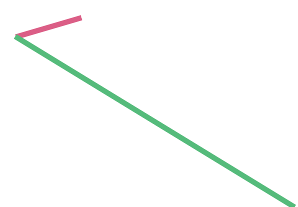
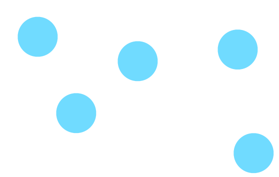
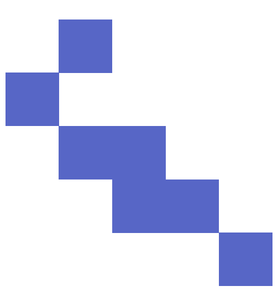
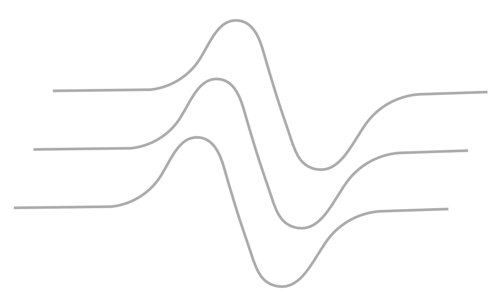


Example event #4



Common abstraction for neutrino experiments

- Although the details of many neutrino physics experiments vary, the majority of them share a common paradigm at a high level.

NOvA		MicroBooNE		Shared structure
	Neutrino generator (GENIE)		Neutrino generator (GENIE)	**Event information**
	Particle simulation (Geant4)		Particle simulation (Geant4)	**True particles**
	True light depositions		True ionization electrons	**True energy deposits**
	Photoelectrons on APDs		Pulses on TPC wires	**Detector hits**

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- A **conda environment** to easily install these packages and all their dependencies is available here.

Summary

- **NuGraph2** is a multi-purpose GNN architecture for reconstructing neutrino interactions in MicroBooNE, DUNE and elsewhere.
  - **Efficiently reject background detector hits**.
  - **Classify detector hits according to particle type**.
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  - Future: **vertexing**, **clustering**, **hierarchical graphs**!
- **NuML** toolkit for standardising the process of producing ML inputs from HEP data for general use.
  - Utilised for MicroBooNE's public data release.
  - Open-source, easy-to-install code packages.