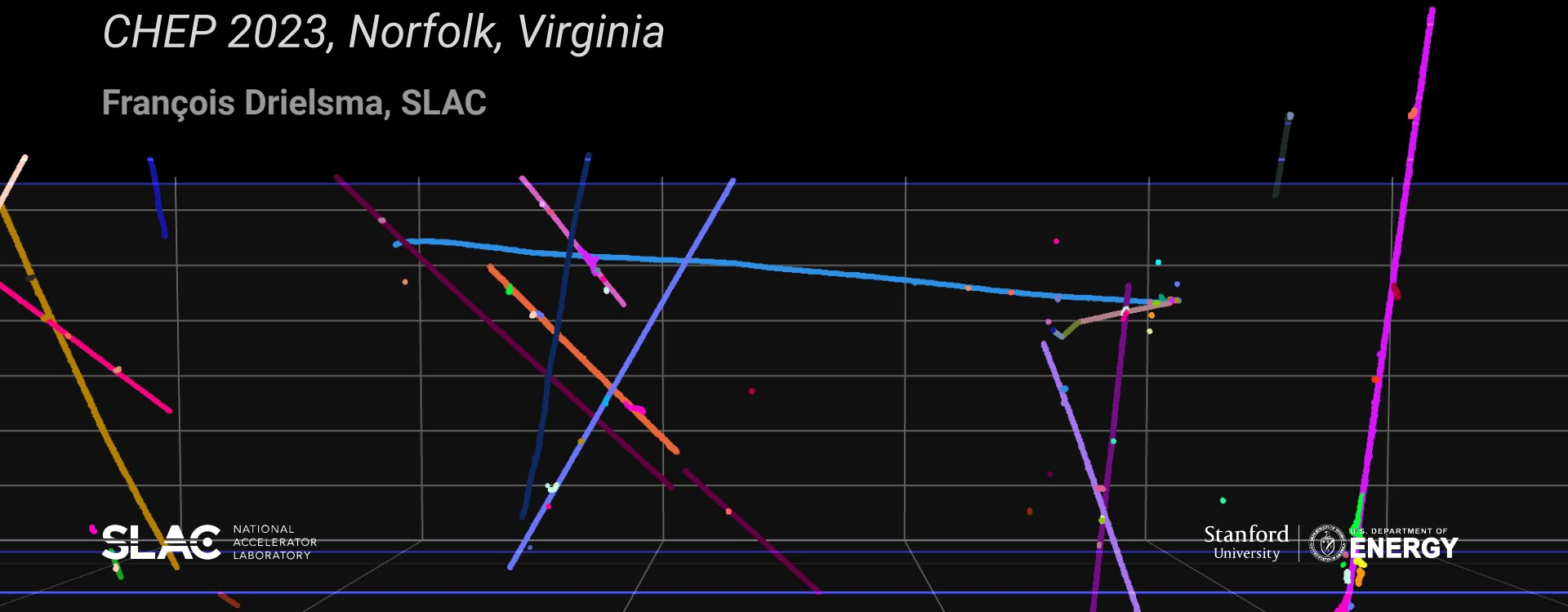
# End-to-end, ML-based Reconstruction Chain for Particle Imaging Detectors

*CHEP 2023, Norfolk, Virginia*

**François Drielsma, SLAC**



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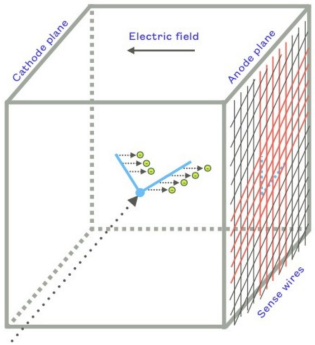
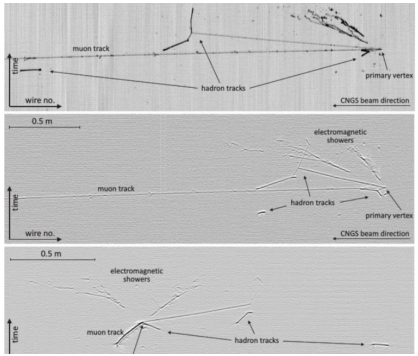
# Liquid Argon Time-Projection Chambers

## The modern Particle Imaging Detector

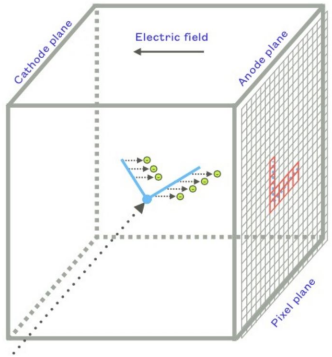
**Wire TPC (2D)**

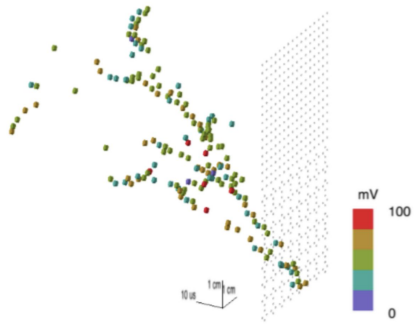



ICARUS, arXiv:1210.5089

**Pixel TPC (3D)**




LArPIX, arXiv:1808.02969

**LArTPC** are at the center stage of **beam $\nu$ physics** in the US

**Short Baseline Neutrino** program

- μBooNE, **ICARUS**, SBND

**DUNE** long-baseline experiment

- **Wire**: DUNE FD
- **Pixel**: DUNE ND-LAr

Advantages:

- **Detailed:** O(1) mm resolution, precise calorimetry
- **Scalable**: Up to tens of kt

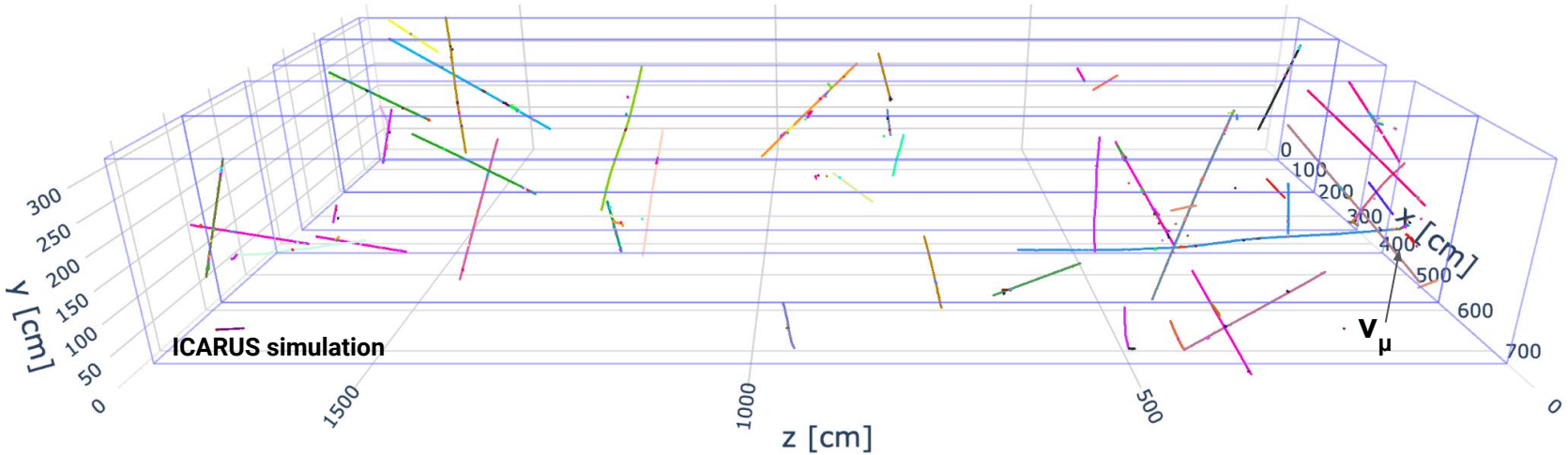
# Liquid Argon Time-Projection Chambers

## Case study: ICARUS Simulation

Realistic **BNB $\nu_\mu$ + Cosmic** ICARUS simulation as a **benchmark**

- **One $\nu_\mu$** + Ar interaction/image
- **~25 cosmic** interactions/image

– TPC boundaries
Color: particle instance ID



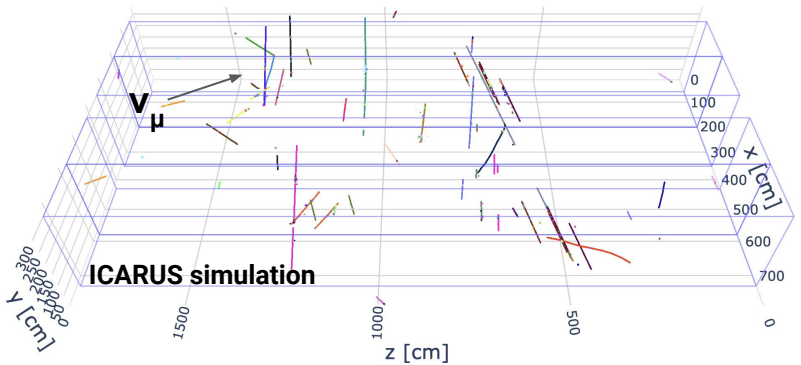
# Reconstruction in LArTPCs

## Challenges with LAr

### Dense medium → Slow

Electron drift velocity O(1) mm/μs

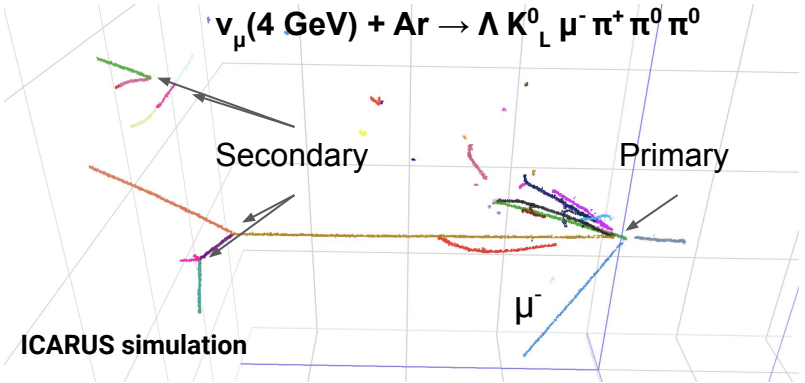
- **Long** (O(1) ms) readout **window**
- Need **light association** for timing




### High Z material → Messy

Argon has a large nucleus (Z=18)

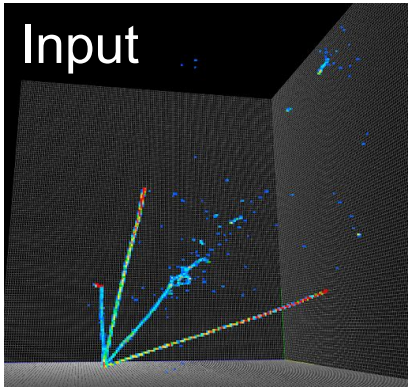
- **Complicated** nuclear physics
- **Secondary** interactions



# Reconstruction in LArTPCs

## Hierarchical feature extraction

What is relevant to pattern recognition in a detailed interaction image?

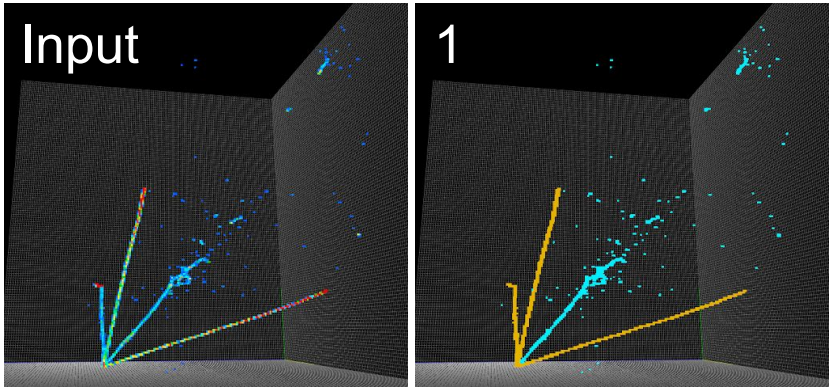


# Reconstruction in LArTPCs

## Hierarchical feature extraction

What is relevant to pattern recognition in a detailed interaction image?

1. Separate topologically distinguishable **types of activity**



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What is relevant to pattern recognition in a detailed interaction image?

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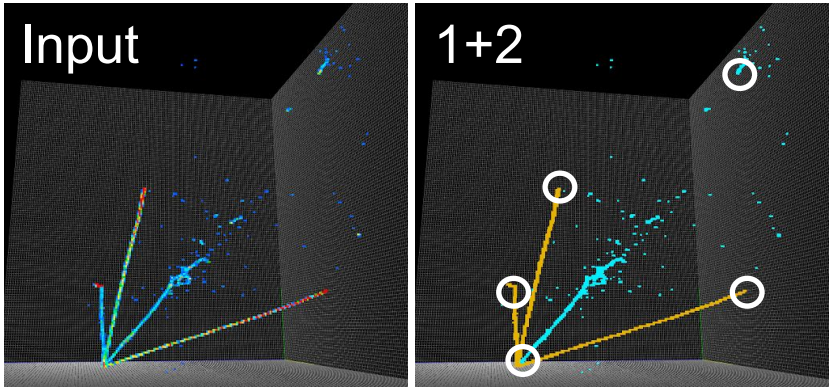
2. Identify **important points** (vertex, start points, end points)



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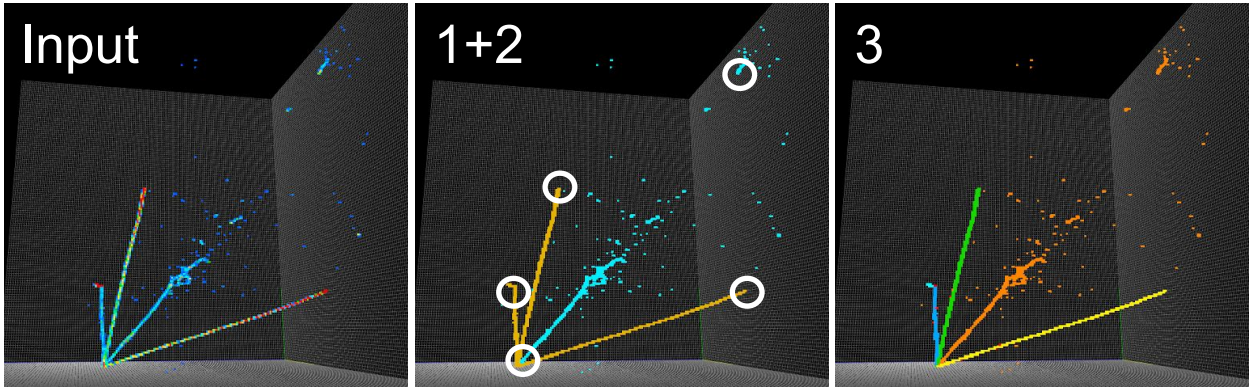

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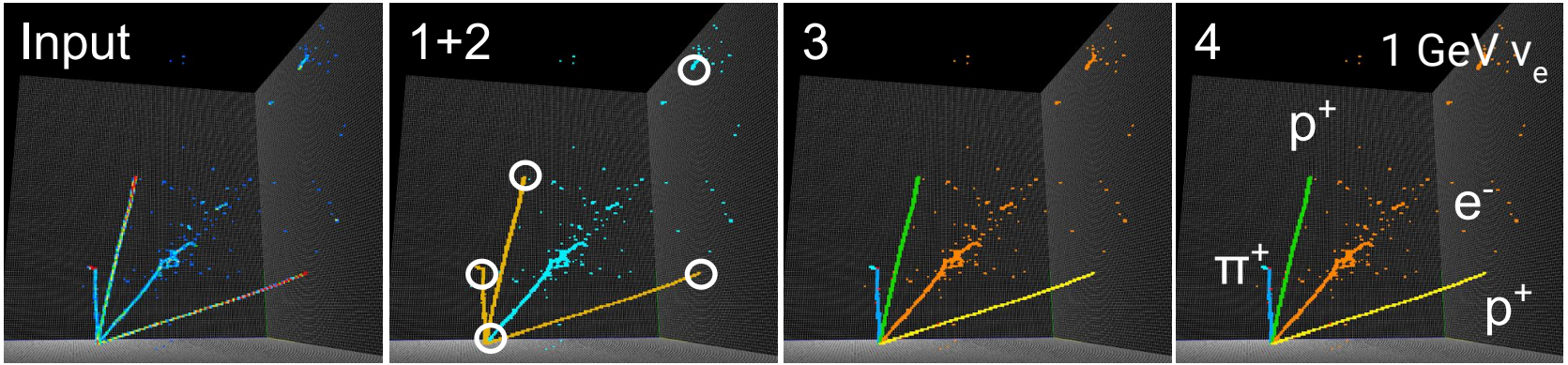
4. Cluster **interactions**, identify **particle properties** in context

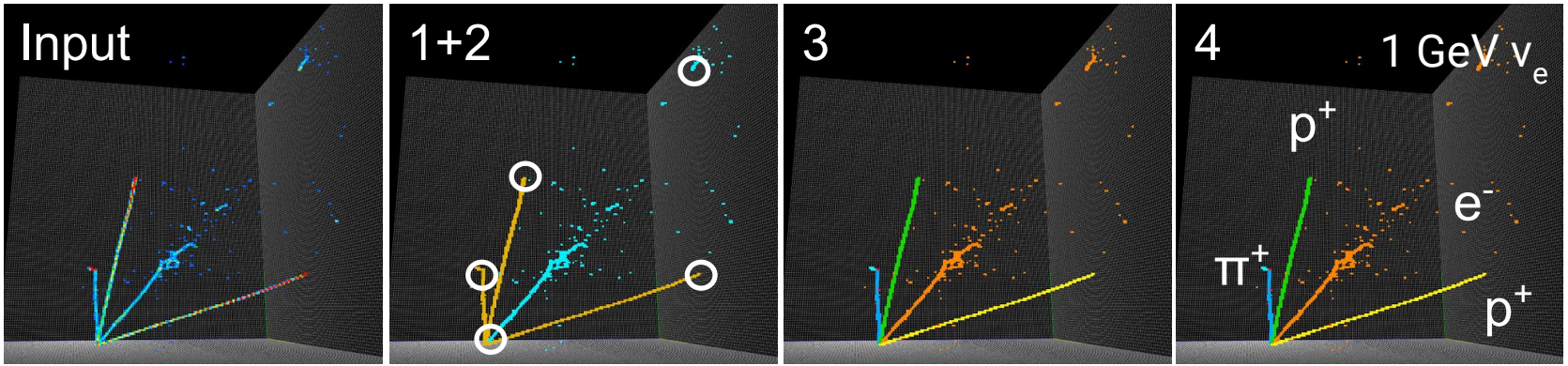


# Reconstruction in LArTPCs

## Hierarchical feature extraction

What is relevant to pattern recognition in a detailed interaction image?

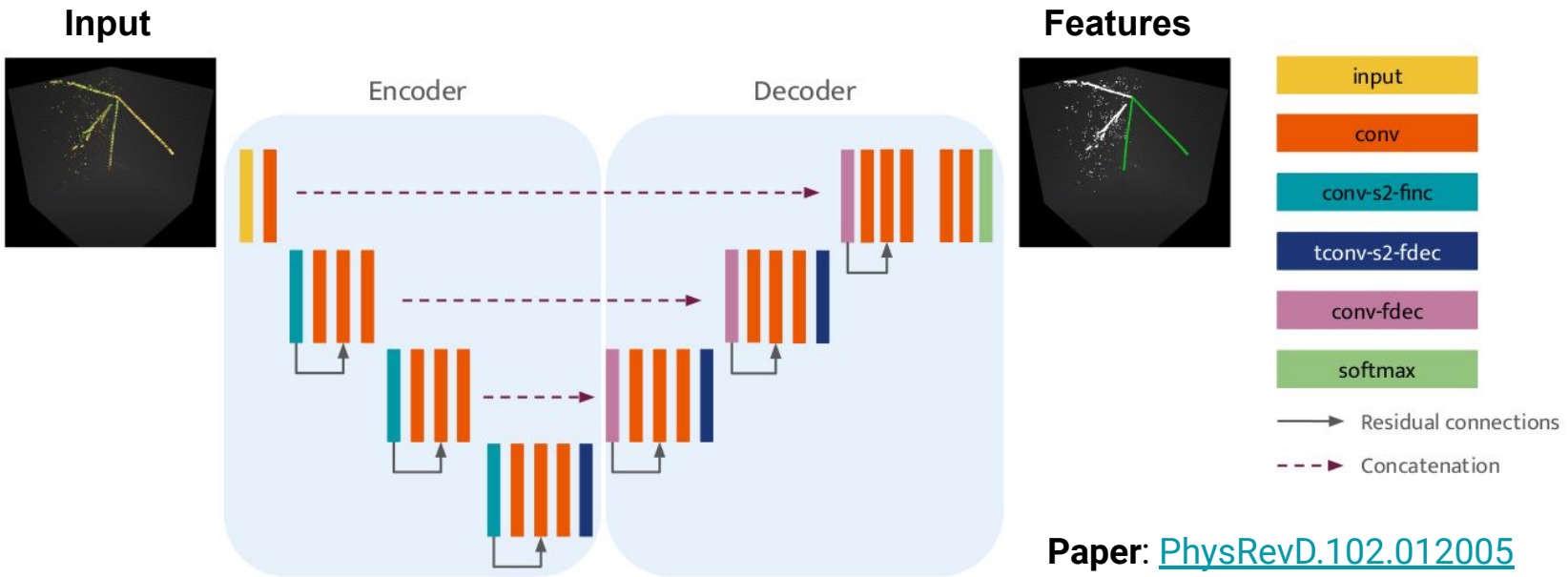
1. Separate topologically distinguishable **types of activity** → **Pixel-level**
2. Identify **important points** (vertex, start points, end points)
3. Cluster individual **particles** (tracks and full showers) → **Cluster-level**
4. Cluster **interactions**, identify **particle properties** in context



# Pixel-Level Feature Extraction

## Backbone

UResNet (UNet + ResNet + Sparse Conv.) as the **backbone feature extractor**



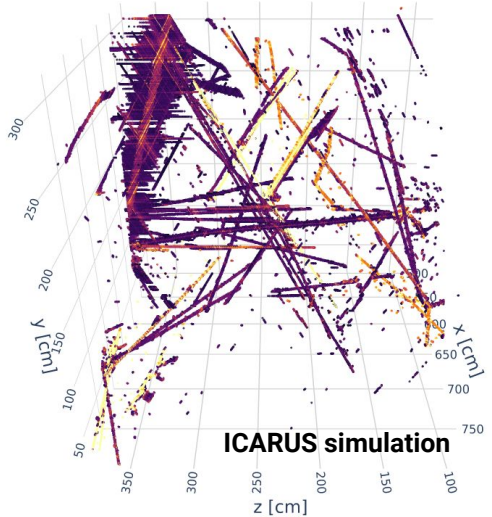

**Paper**: PhysRevD.102.012005

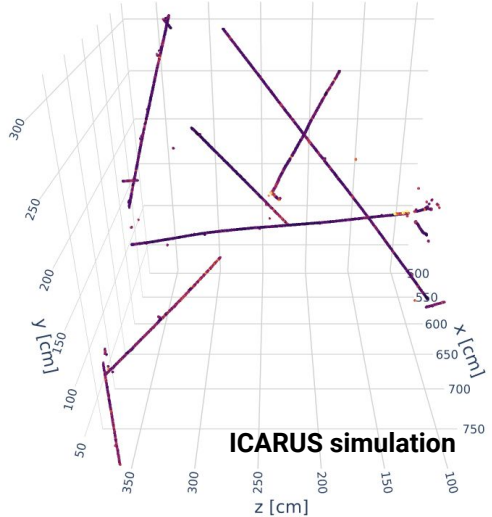
# Tomographic Reconstruction

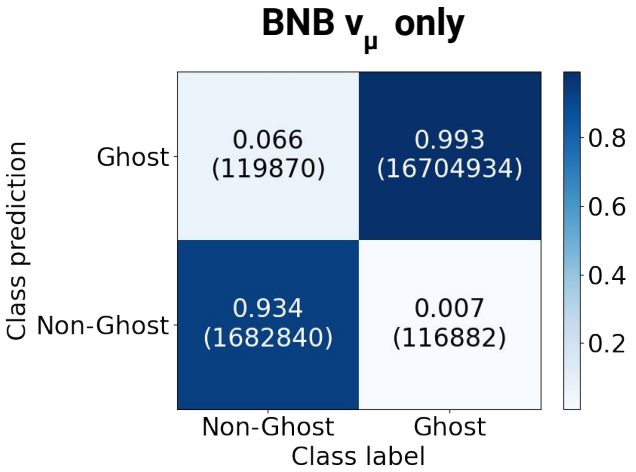
## Ghost buster

In a **wire TPC**, we do not get 3D images, but rather 3 x 2D projections

- Find **valid combinations of 2D hits**: legitimate + artifacts (**ghosts**)
- Classify artificial space points as such: **ghost removal**



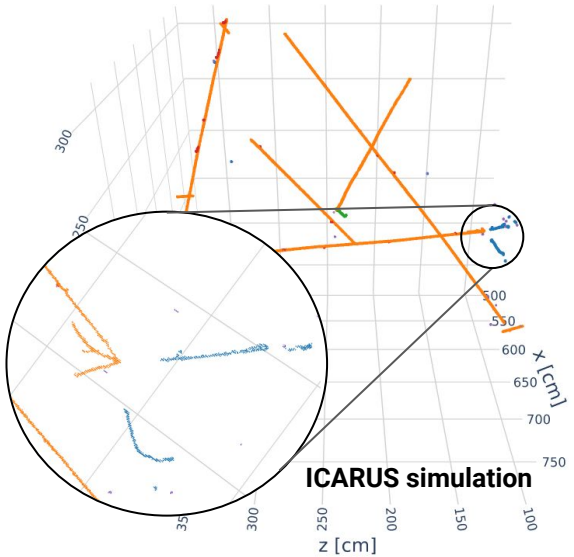



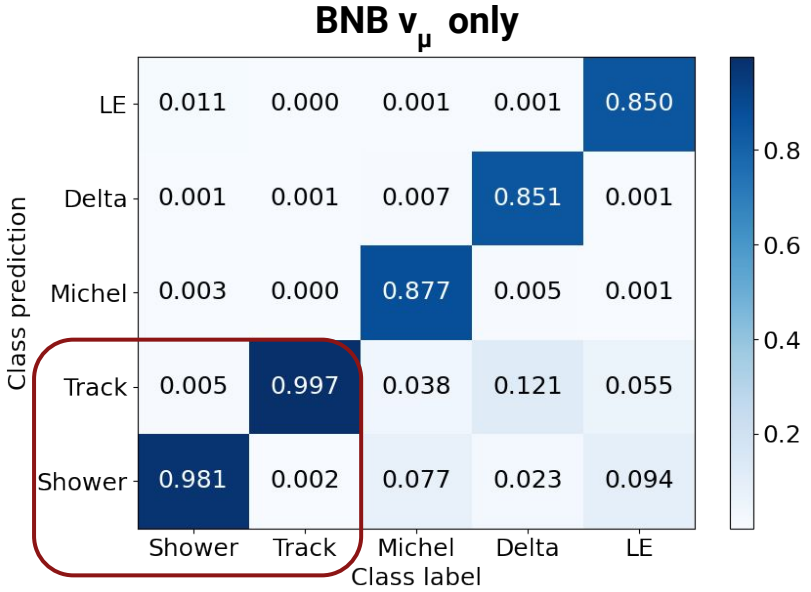
# Semantic Segmentation

## Particle voxel class classification

Separate **topologically different** types of activity

- **Tracks**, **Showers**, **delta rays**, **Michel electrons**, **low energy blips**



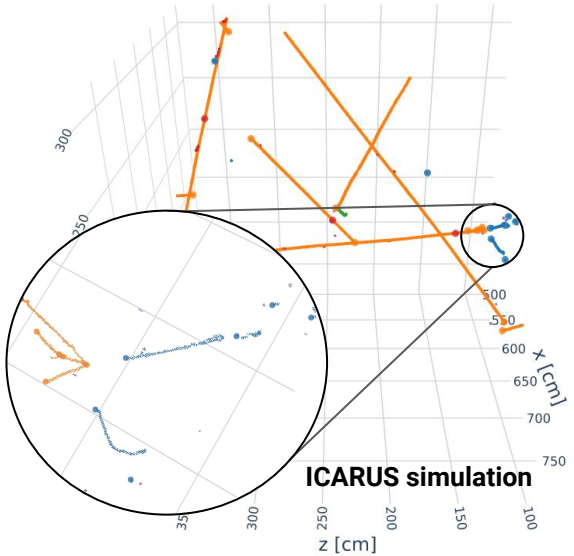

Paper: PhysRevD.102.012005

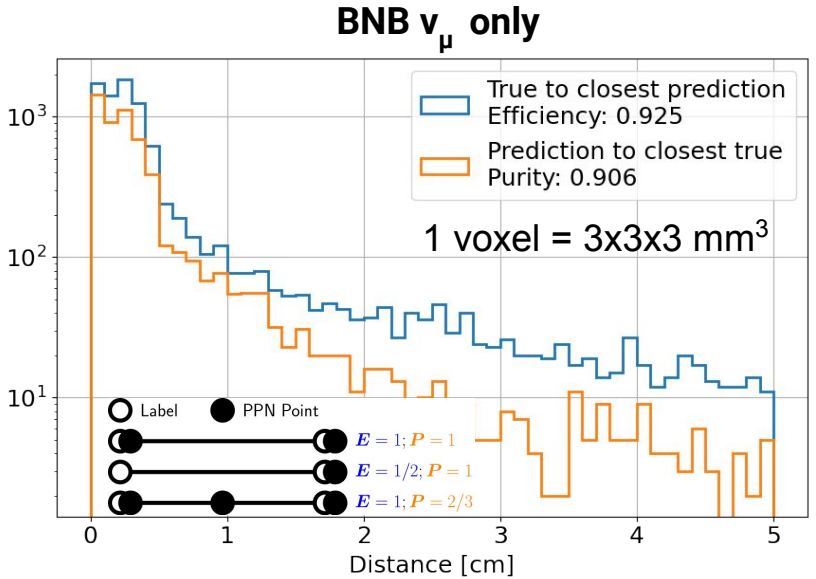
# Point Proposal Network (PPN)

## Points of interest

**Narrow down** a region proposal all the way to a **point**

- Predict **masks** at different scales with UResNet, predict **position** in voxel



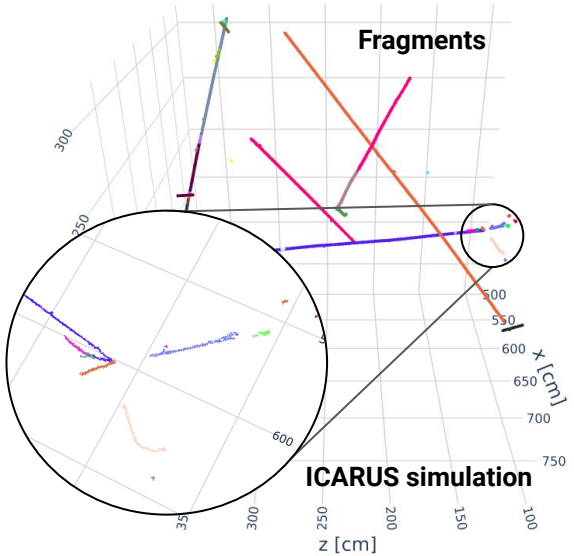

Paper: PhysRevD.104.032004

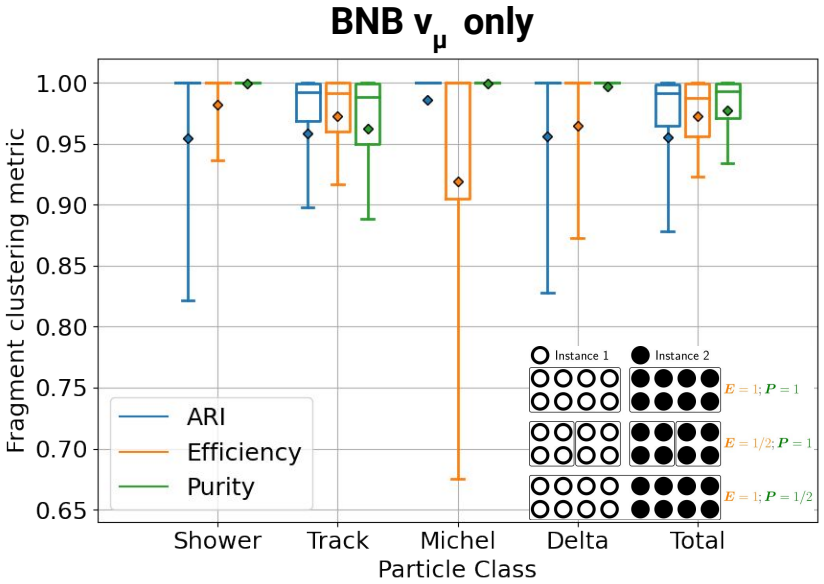
# Dense Fragment Formation

## Spatial embedding transformation

**Transform** coordinates to an space in which tracks are spatially separated

- Cluster track/shower **fragments** at this stage



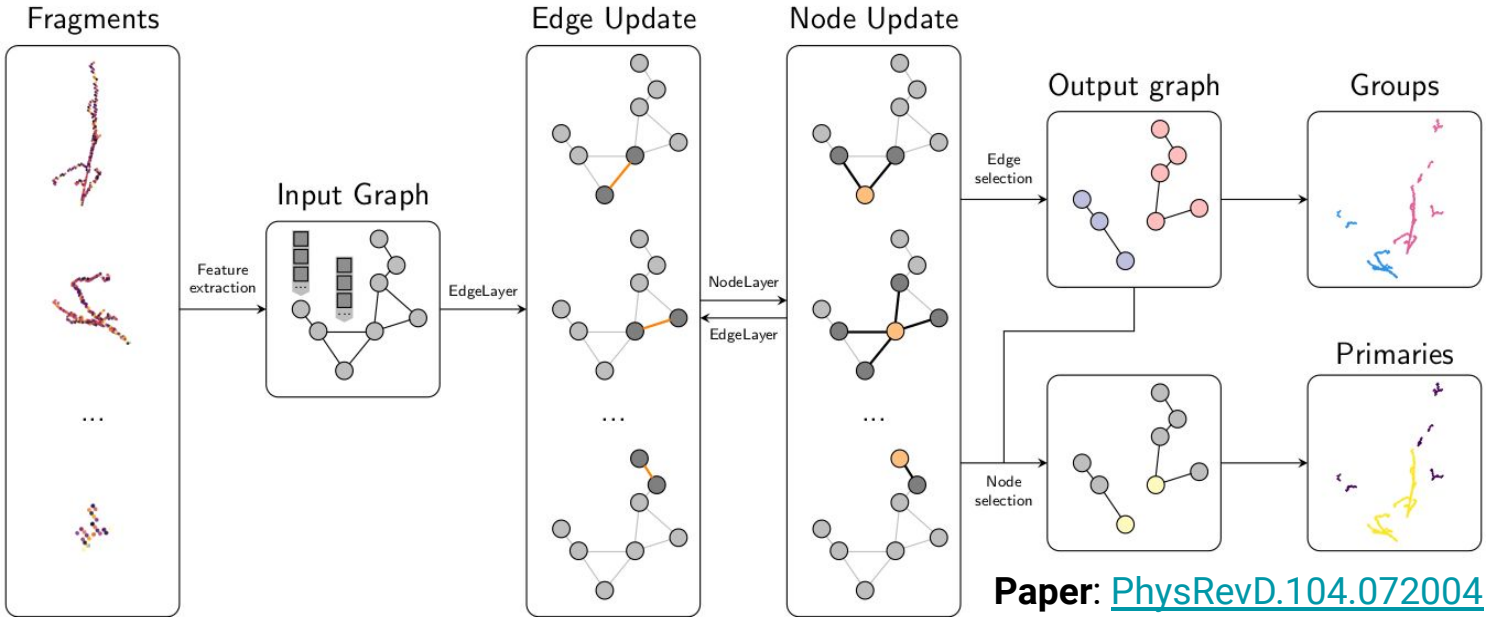




Paper: arXiv:2007.03083

# Particle-Level Aggregation

## Graph Particle Aggregator (GrapPA)

**Graph Neural Network:** fragments/particles (**nodes**), correlations (**edges**)



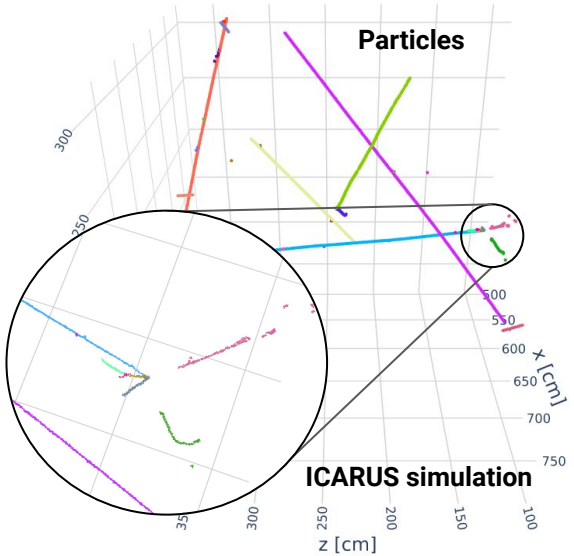

**Paper**: [PhysRevD.104.072004]

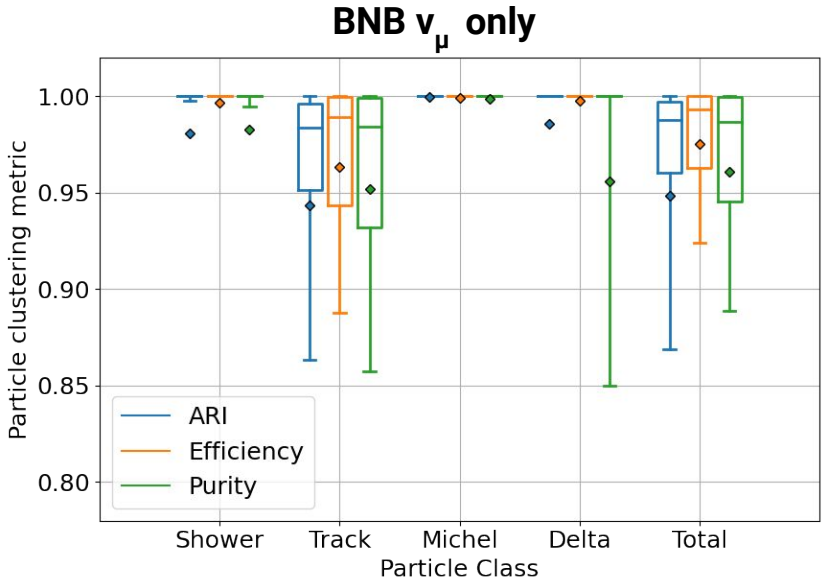
# Aggregation

## Graph edge classification

Two aggregation steps: **fragments → particles → interactions**

- **Select edges** in the graph that minimize loss, find **connected components**

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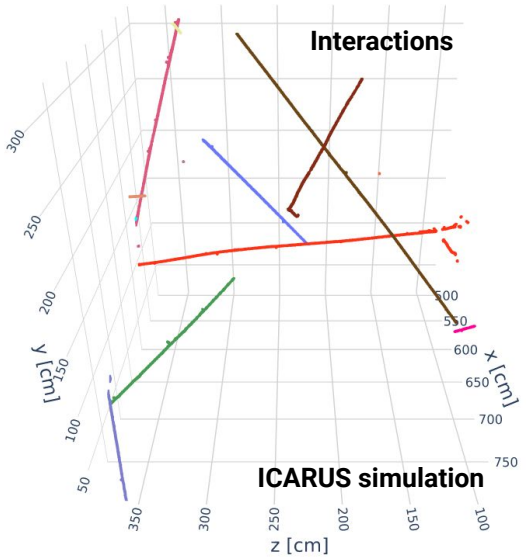


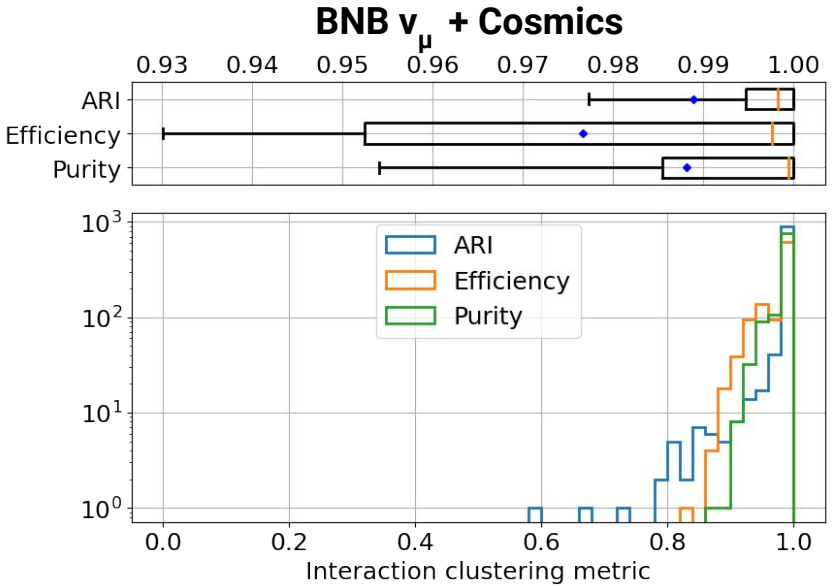


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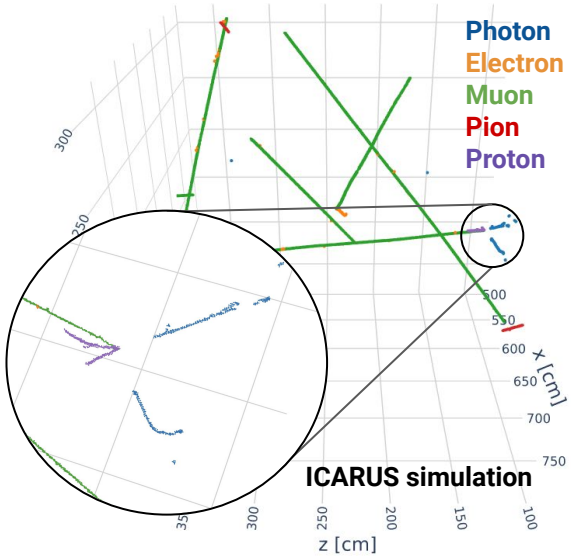
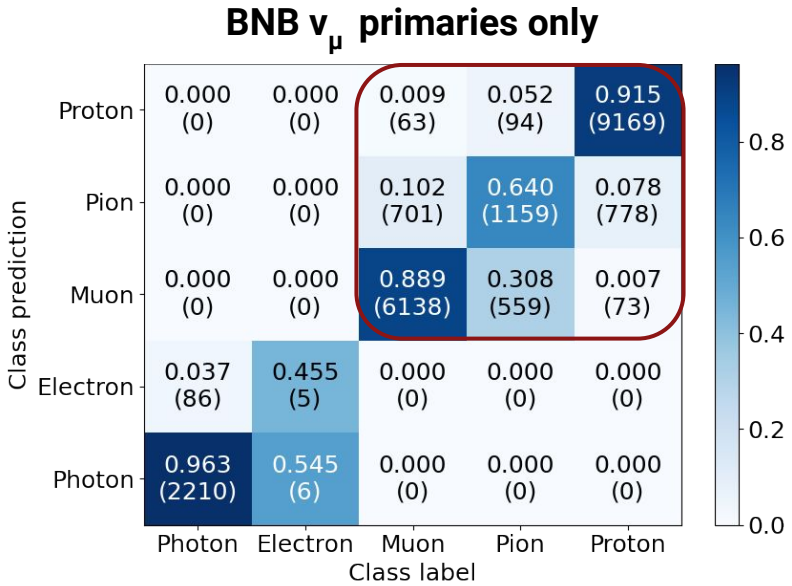
# Particle Identification

## Graph node classification

Particle species much easier to **infer in context**

- Michel decays, secondary hadrons, shower conversion gaps, etc.



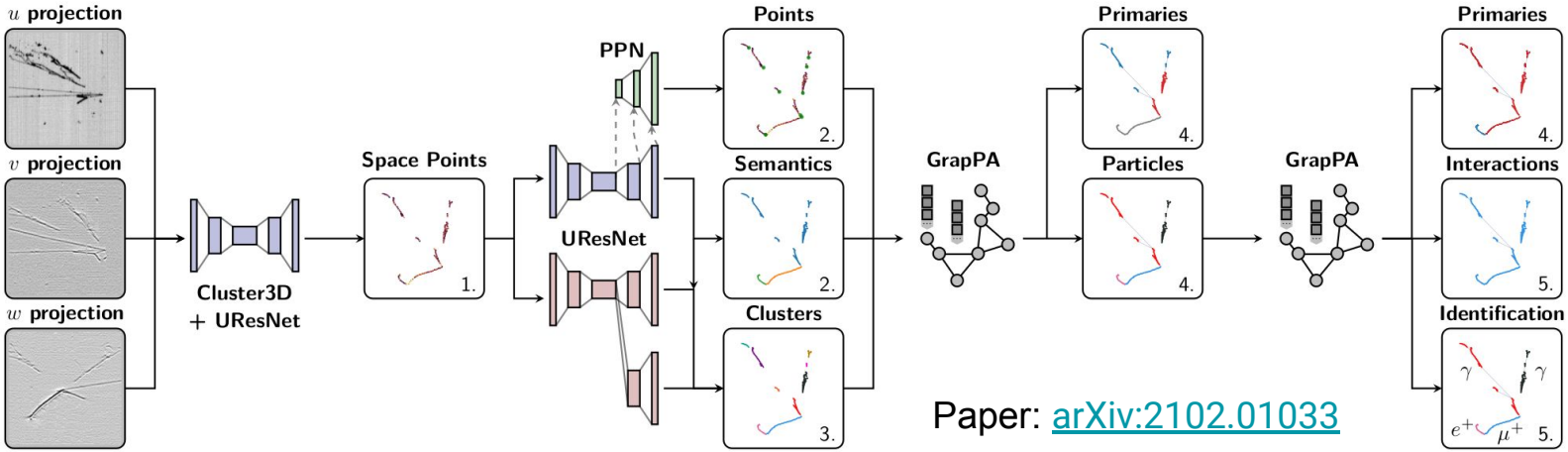



# Conclusions

## Takeaways

**End-to-end ML-based reconstruction chain mature and functional**

- **UResNet** for pixel feature extraction, **GrapPA** for superstructure formation
- Used on **ICARUS** sim./data and **DUNE-ND** (high neutrino pileup) sim. **today**
- Check out this ICARUS **interactive reconstructed event** !



# Backup Slides

# Liquid Argon Time-Projection Chambers

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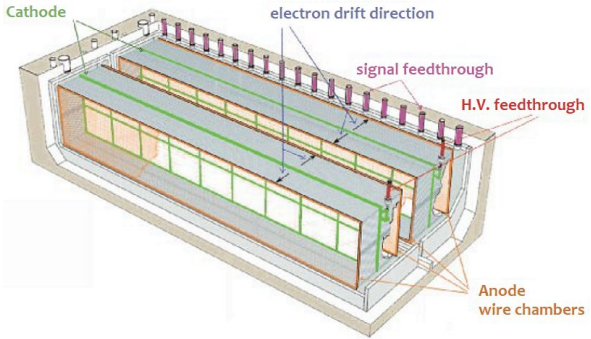
## Case study: Detector

The **largest LArTPC** in operation is **ICARUS**

- **Surface**-level detector
- **500 t** fiducial mass (2 cryos, 4 TPCs)
- **Physics**: sterile neutrinos (MiniBooNE / Neutrino-4), cross sections, BSM




Event rates

- BNB beam: ~ 0.03 Hz neutrinos
- NuMI off-axis: ~ 0.015 Hz neutrinos
- In-time cosmic activity: ~ 0.25 Hz

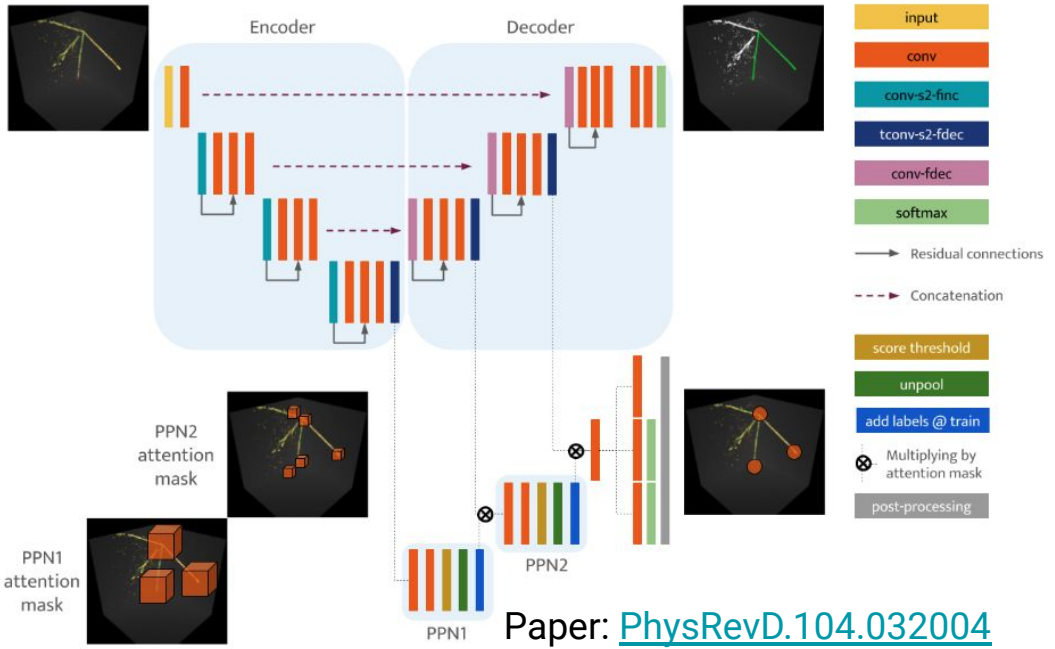

**Low-rate** neutrino experiment with a **significant cosmic background**

# Point Proposal Network

## Architecture

The Point Proposal Network (PPN) uses decoder features:

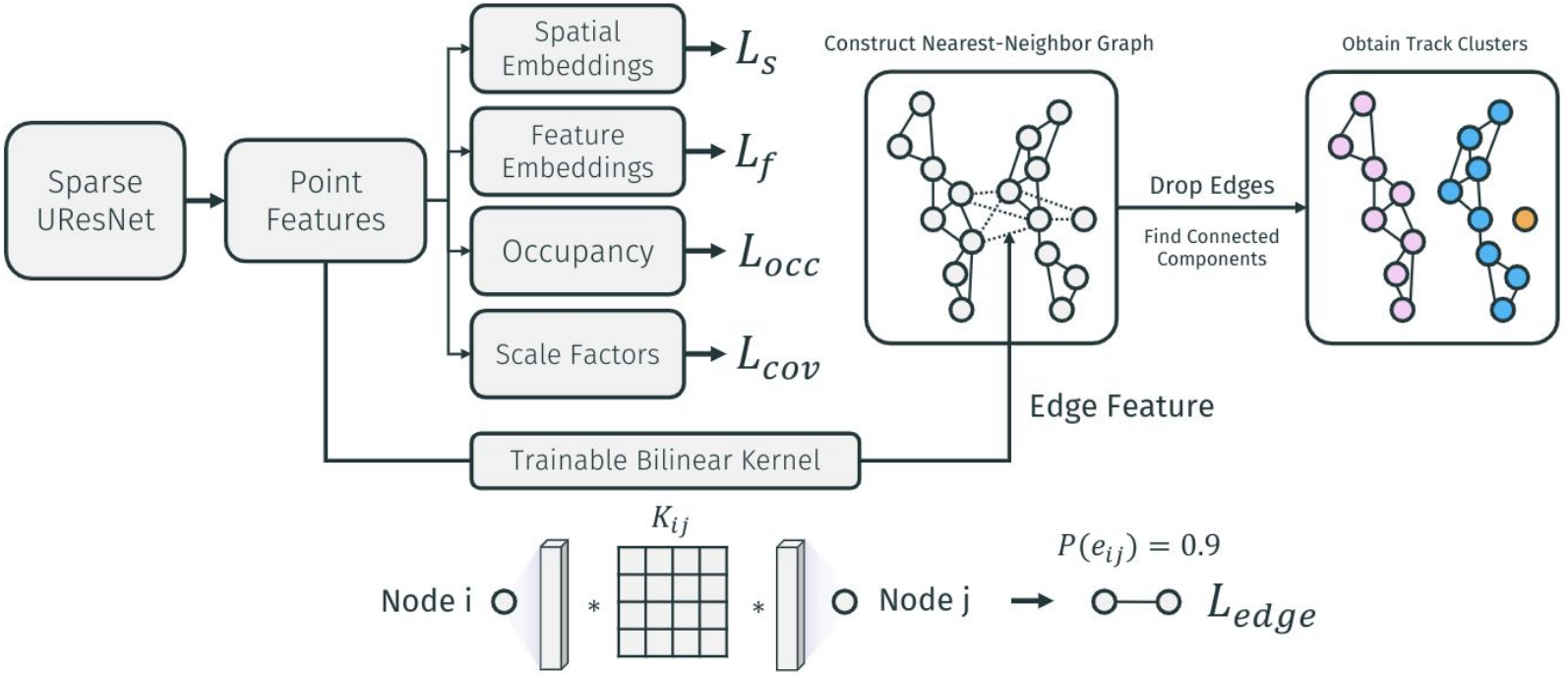
- Three CCN layers to progressively narrow ROI
- Last layer reconstructs:
  - Relative position to voxel center of active voxel
  - Point type
- Post-processing aggregates nearby points




Paper: [PhysRevD.104.032004]

# Graph-SPICE

## Architecture



# GrapPA Aggregation Method

## Edge selection procedure

What the network gives you:

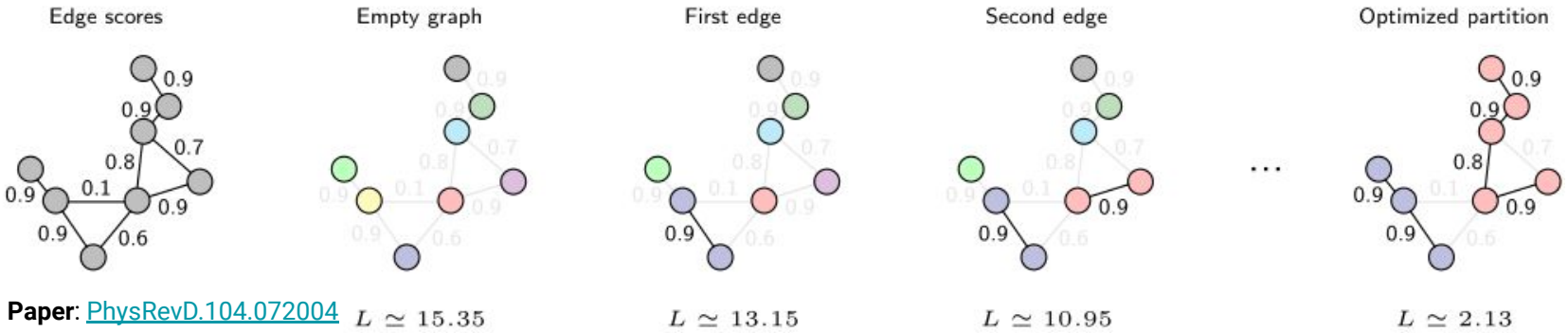
- Likelihood that an edge connects two objects in the same group

Target:

- Find the optimal partition

Method:

- Iteratively add the most likely edge to optimize CE loss

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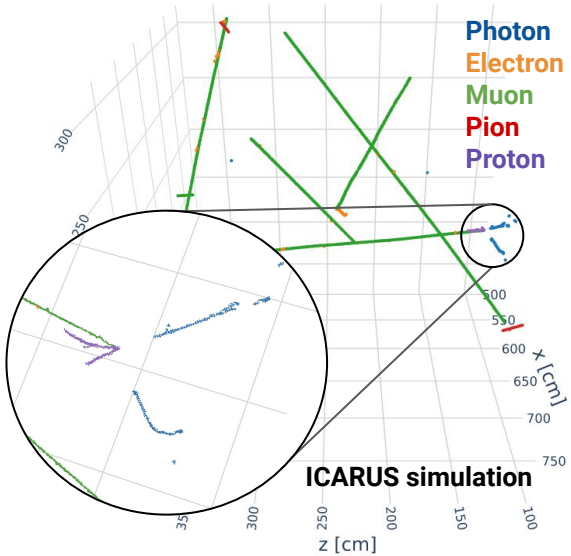


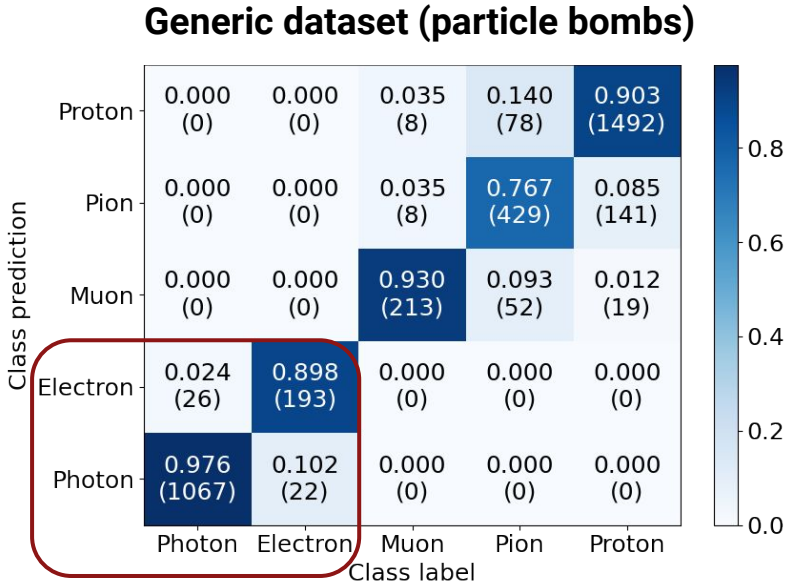

# Primary Identification

## Graph node classification

Important to know **which particle originate from the vertex**

- Central to any **exclusive analysis** (study specific channels)