Panoptic Segmentation for Particle ID in ProtoDUNE

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NuFact
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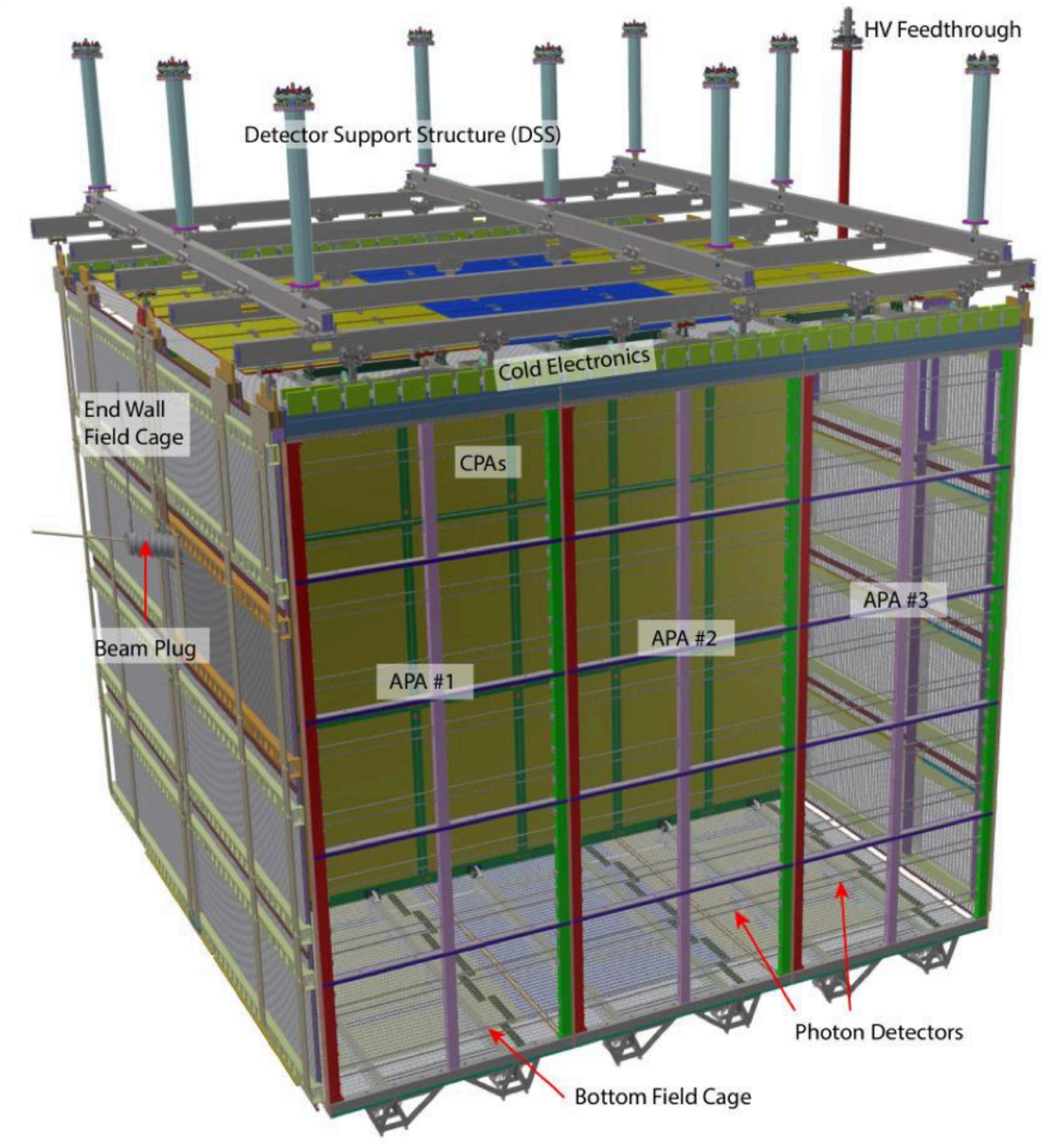
Outline

- The ProtoDUNE-SP detector
- Panoptic segmentation
  - Semantic segmentation
  - Instance segmentation
- Preliminary results of neutral pion mass reconstruction
- Summary

The ProtoDUNE-SP detector

- Is the prototype of the DUNE Single Phase (SP) far detector technology build using full scale components
- Total liquid argon (LAr) mass of 0.77 kt
- Constructed and successfully operated at the neutrino platform at CERN
- Exposed to a dedicated charged particle beam ($\mu^+, \pi^+, K^+, e^+, p$) of momentum between (0.3-7 GeV/c)
  - First beam run was delivered during (Aug - Nov) 2018
- More information [Sowjanya Gollapinni's talk]



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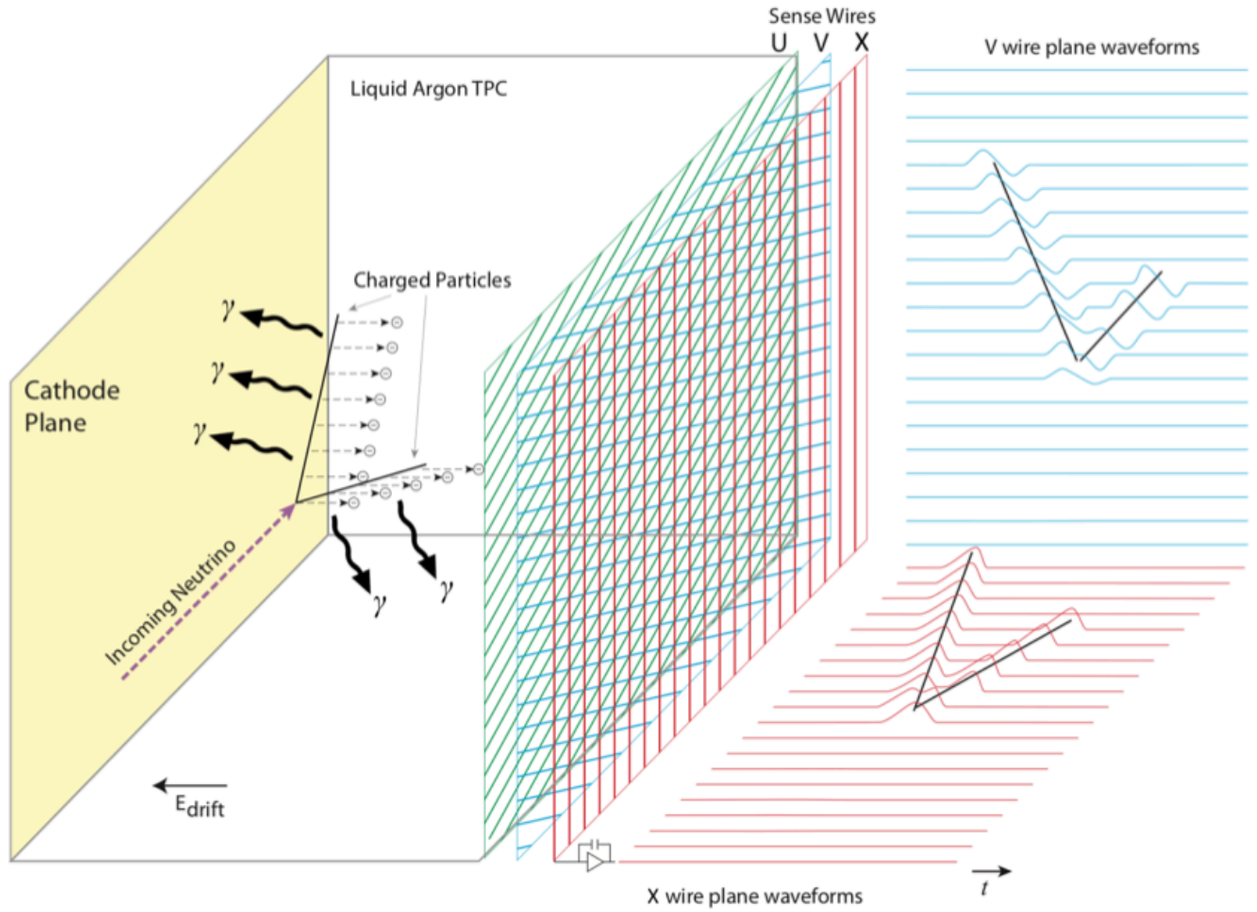
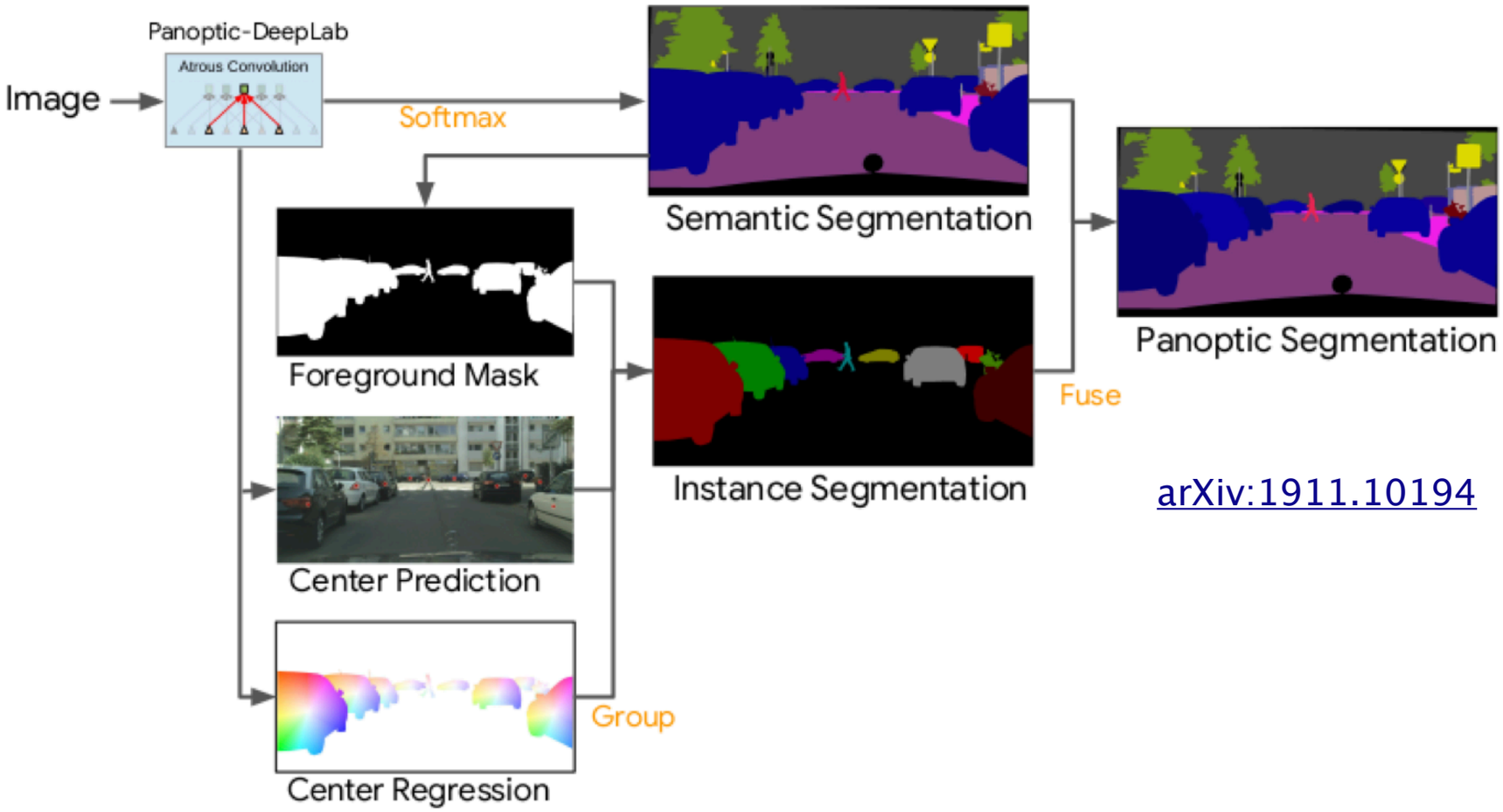
Principle of operation

- Ionization electrons drift towards the APAs
  - Induce current in **U & V** planes
    - Collected in the **X** Plane
- Scintillation light is collected by the PDS
- Signal is read out by low noise electronics



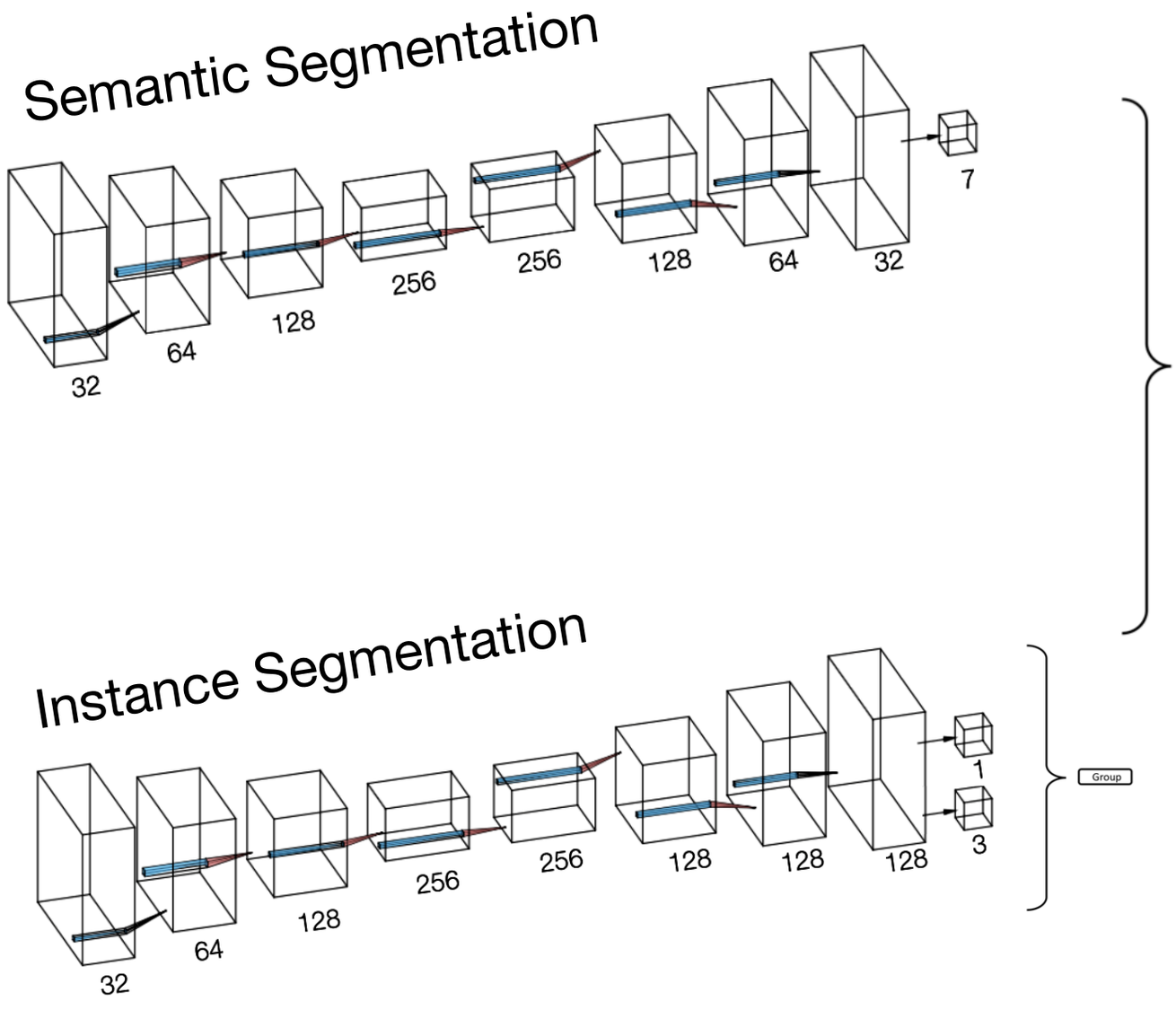
Panoptic segmentation

- In the field of computer vision panoptic segmentation is the task that unifies semantic and instance segmentation
- Semantic segmentation is the process of assigning a class label to each pixel
- Instance segmentation is the task of detecting objects in the image



arXiv:1911.10194

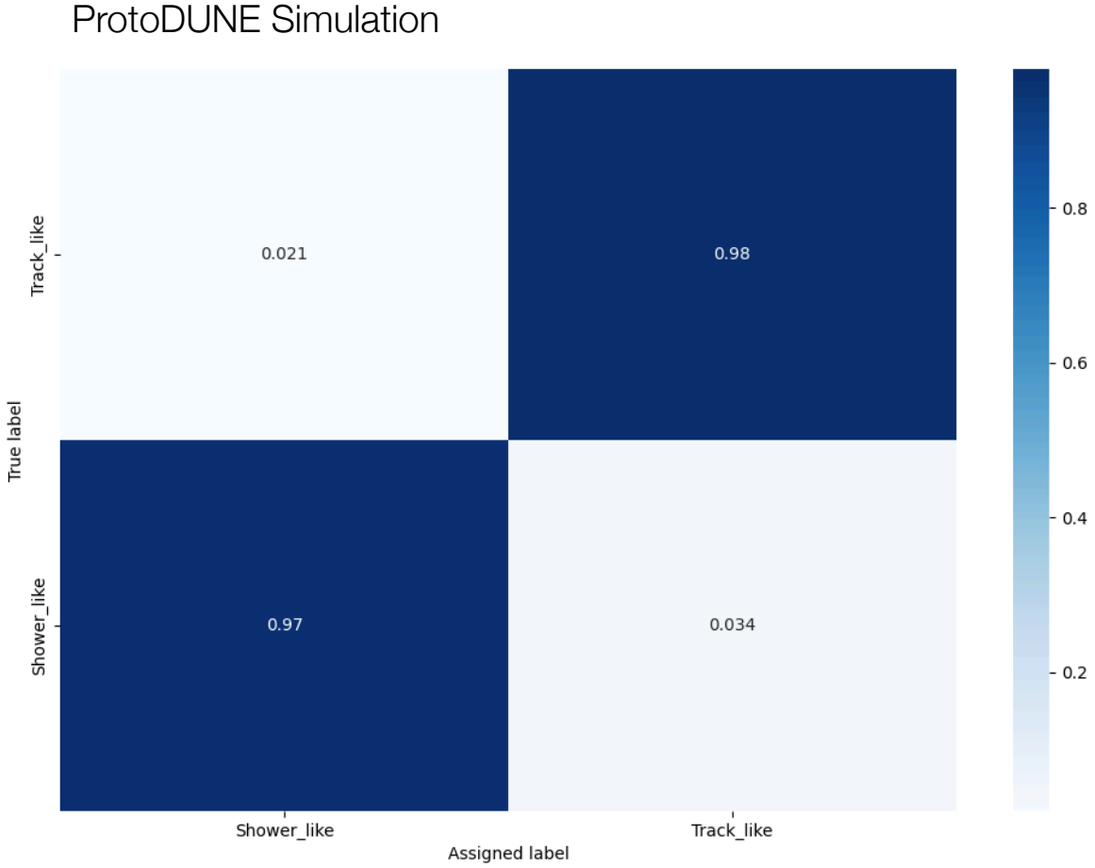
Network architecture

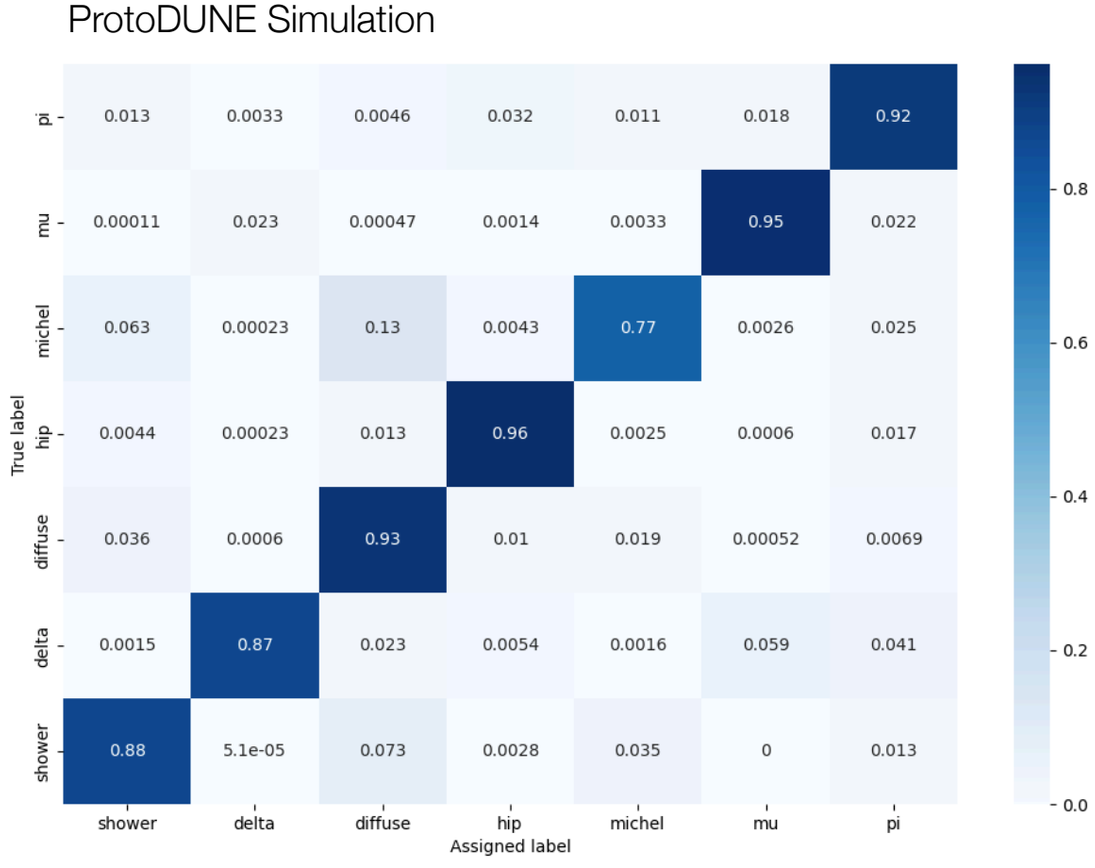


- 2 independent UResNet for semantic and instance segmentation
- The instance segmentation prediction is obtained by finding the object medoids and regressing every voxel to their corresponding medoid
- Semantic segmentation and class agnostic instance segmentation are combined to generate the final panoptic segmentation result

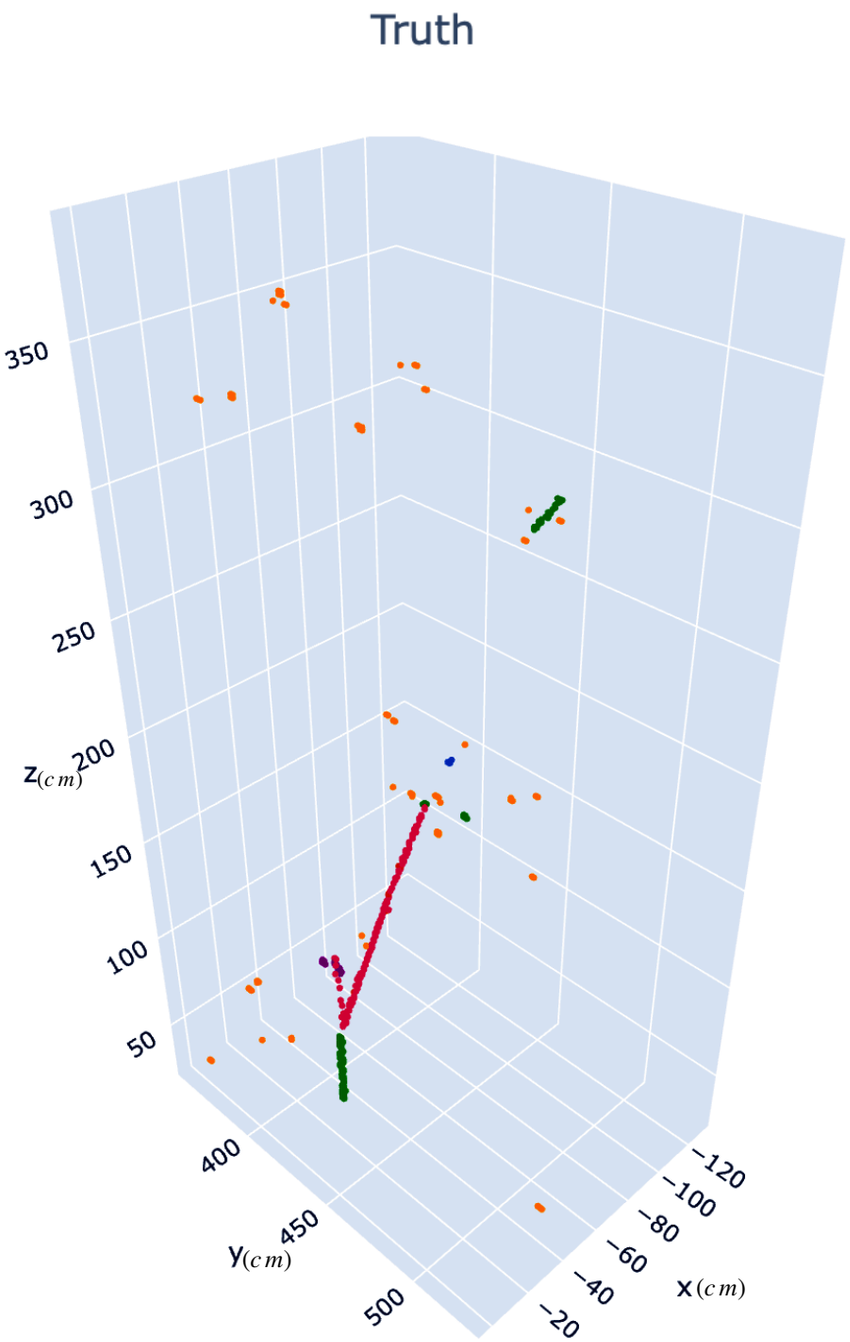
Semantic segmentation

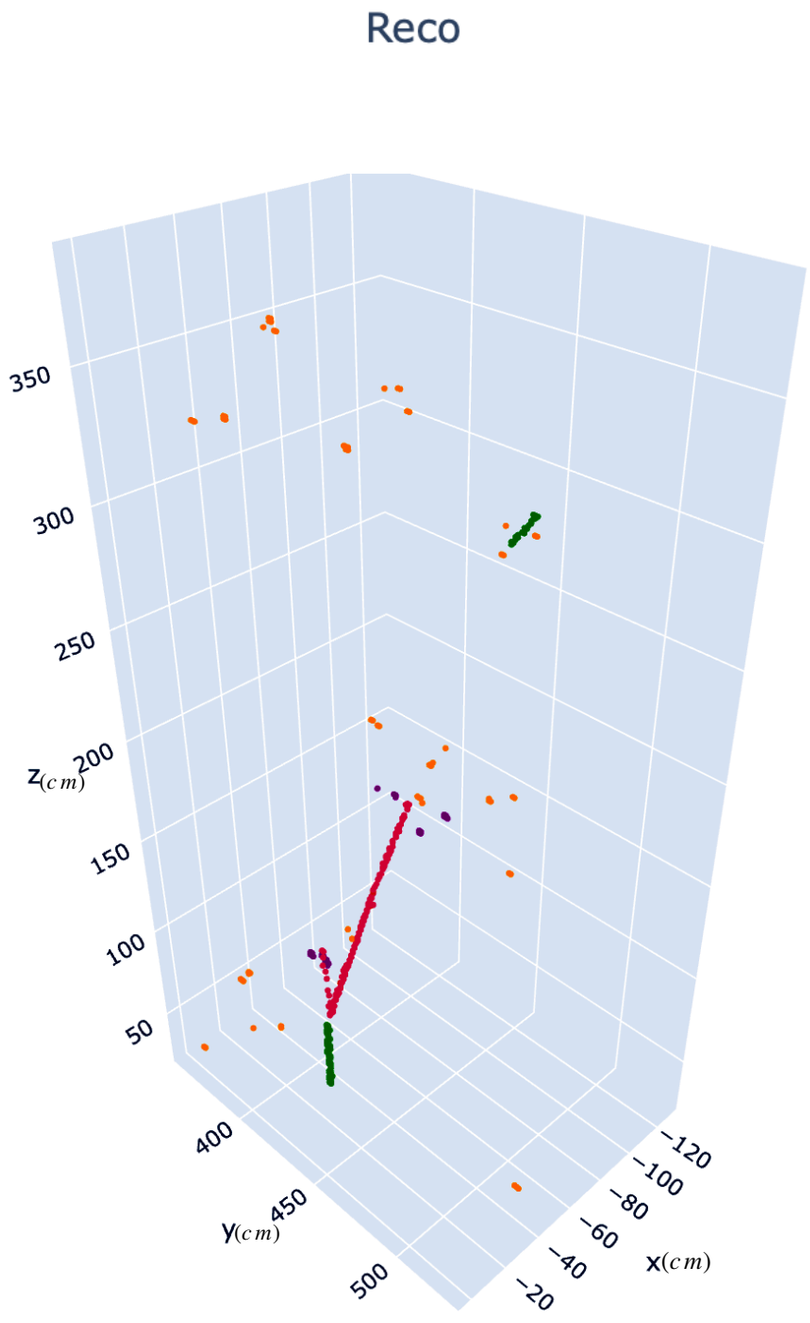
- The network is capable to identify shower like and track like separation with high accuracy
- The confusion matrix shows the overlap between classes





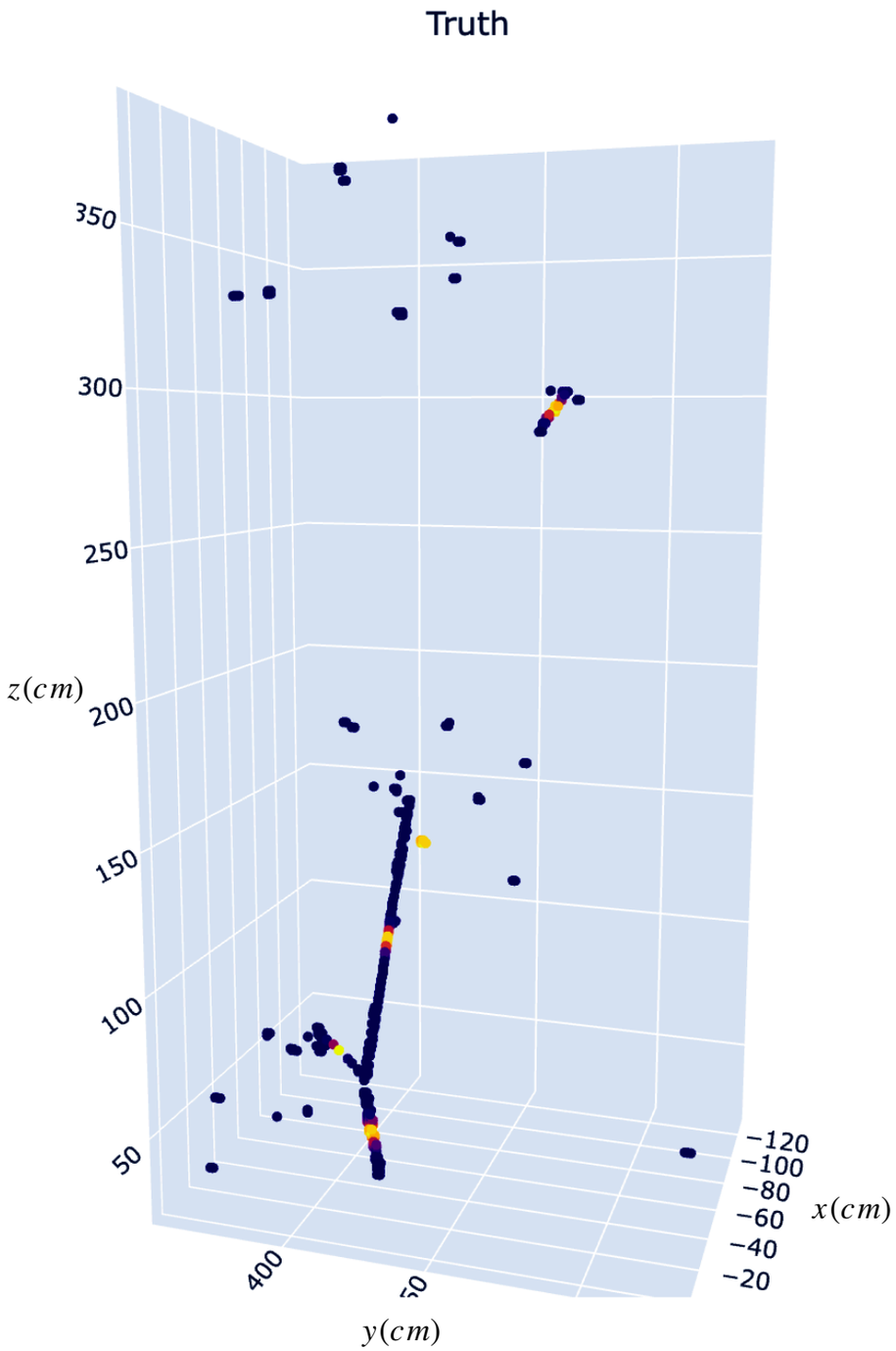
Semantic segmentation





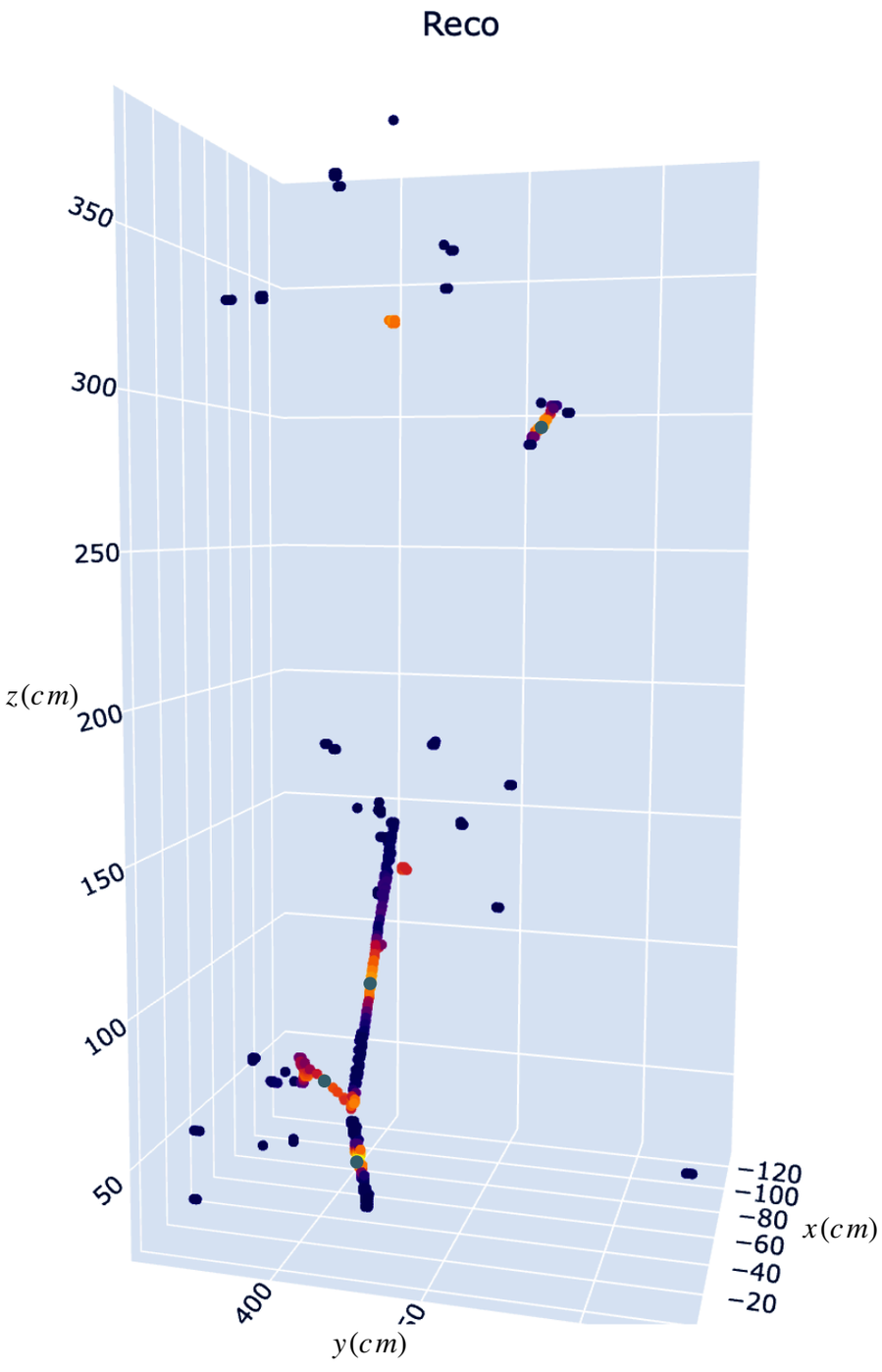
- shower
- delta
- diffuse
- hip
- michel
- pi

Instance segmentation ground truth



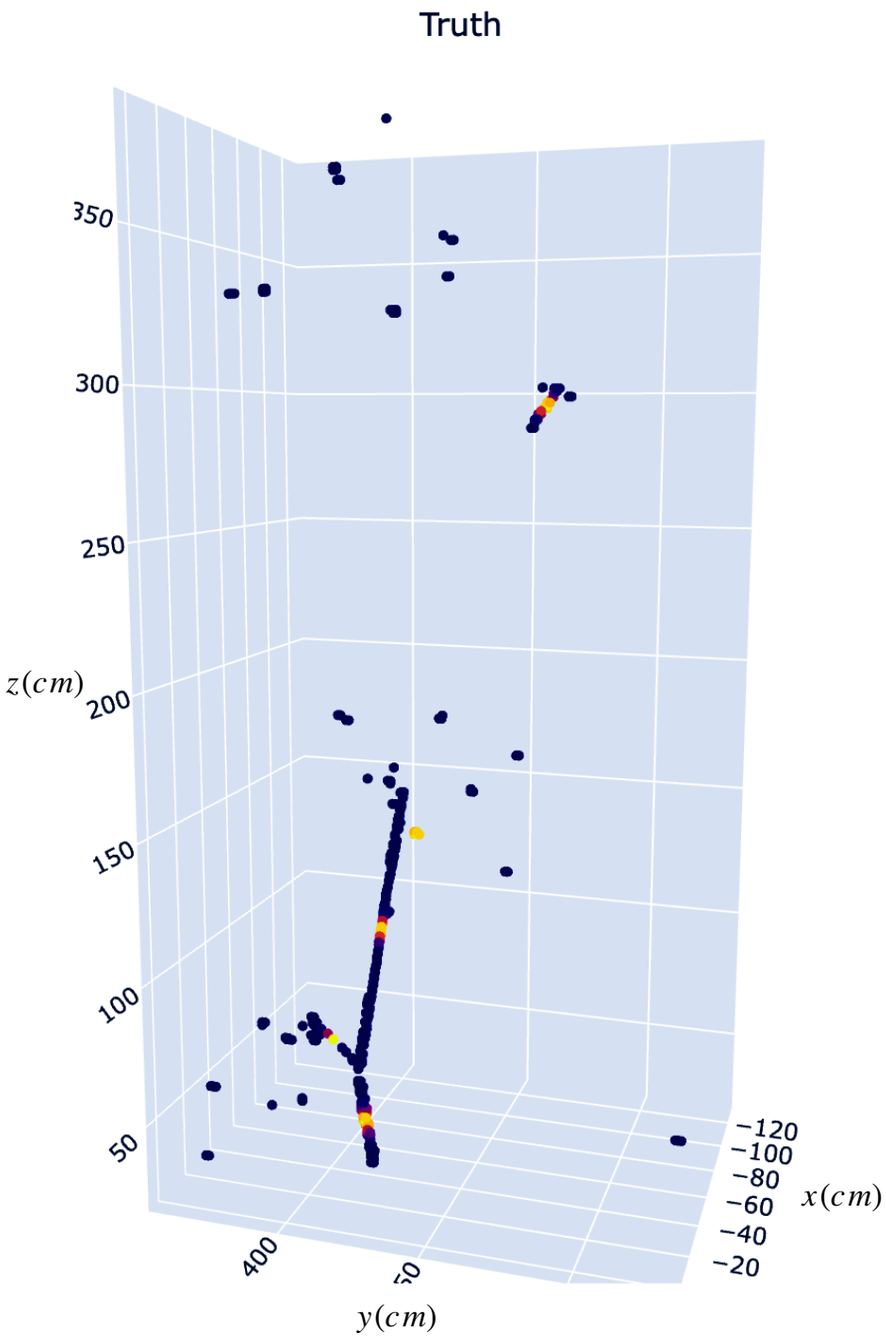
- We represent each object instance by its medoid
- A medoid is a representative object of a cluster for which the average dissimilarity to all other objects is minimal. The concept is similar to centroid but medoids are restricted to be a member of the cluster
- Medoids are encoded in 3D Gaussian pdf with standard deviation of 8 voxels
- Additionally we record the offset of each voxel to its corresponding medoid
  - This is a 3d vector that represents the distance in each dimension

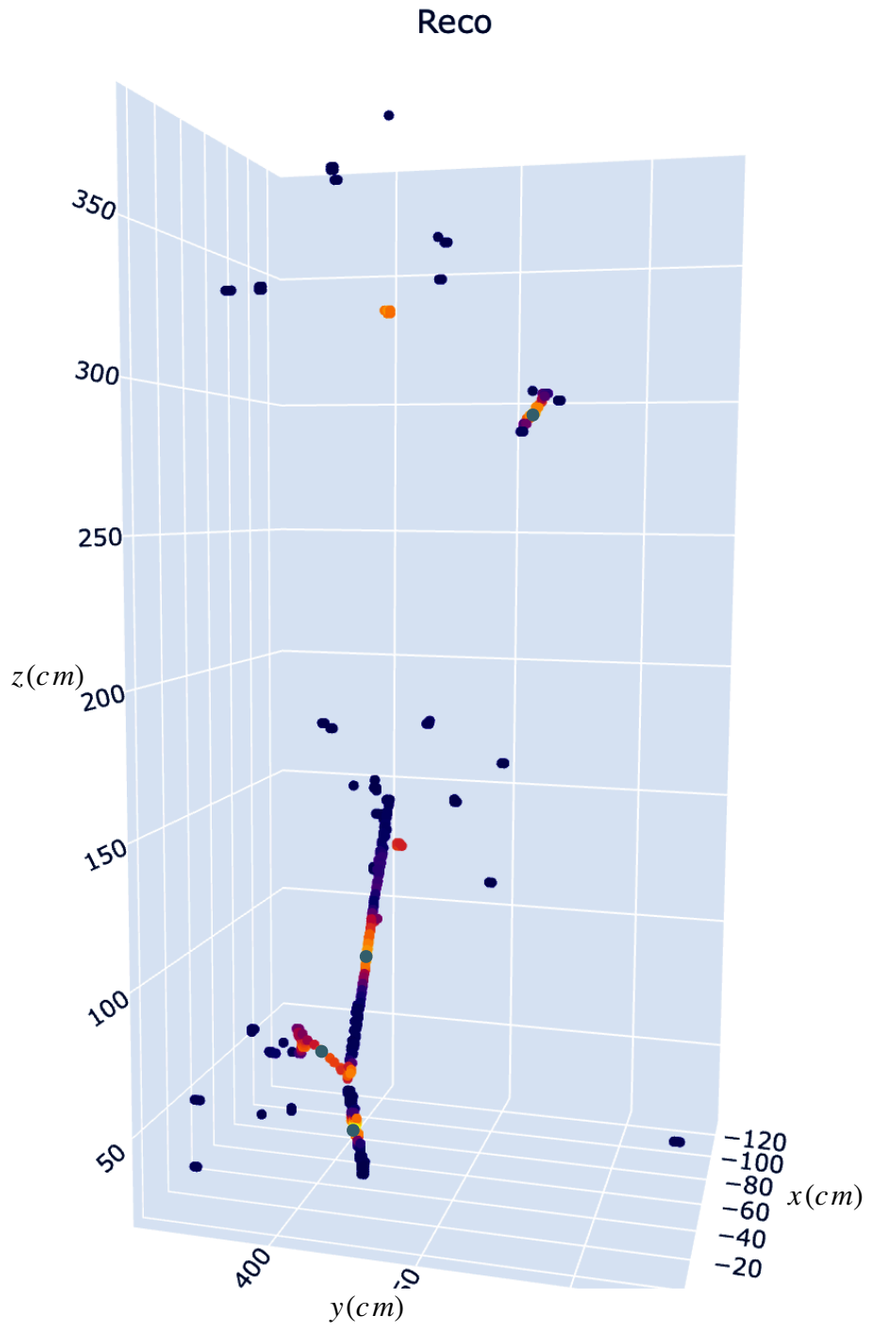
Instance segmentation inference



- We apply max pooling on reconstructed heatmaps and keep the location whose values don't change before and after max pooling
- Hard thresholding to filter location with low confidence

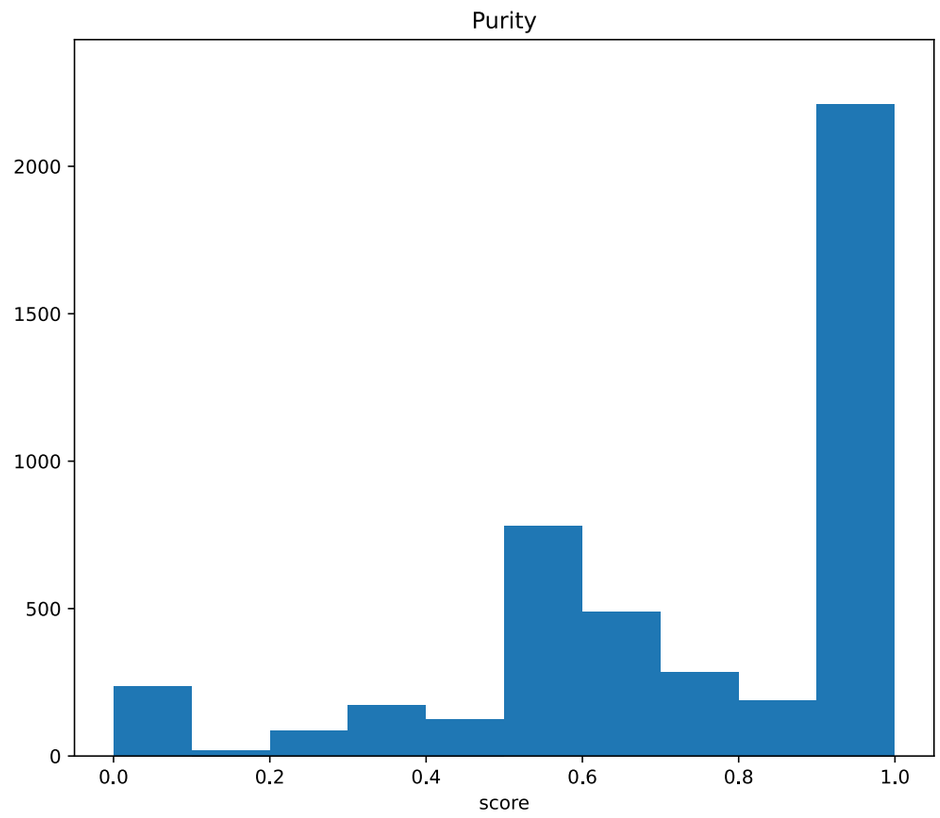
Instance segmentation

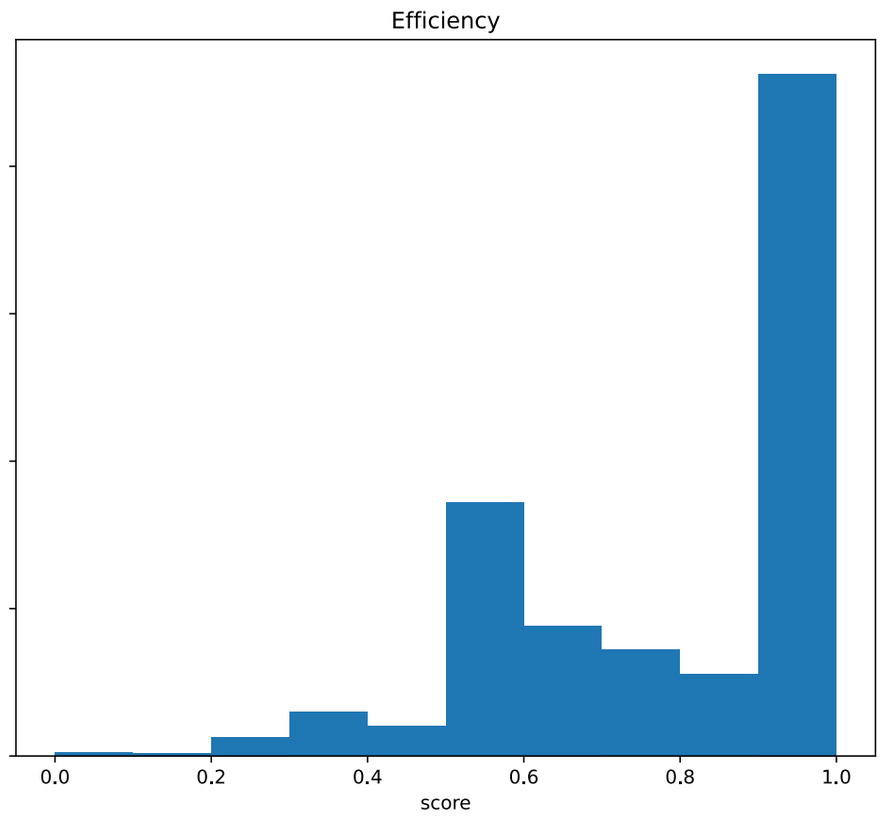




- Color scale represents the probability of a voxel to be a medoid

Instance segmentation metrics



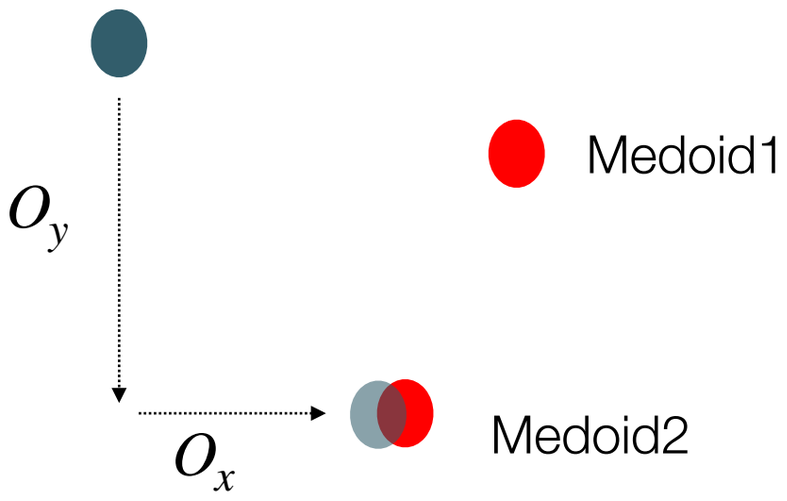


- **Purity: Is the fraction of reconstructed medoids that are no more than 7 cm from the true medoid. ~ 81.3%**

- **Efficiency: Is the fraction of true particles with at least one reconstructed particle ~84.2%**

Instance segmentation

- We use a simple grouping operation to obtain instance masks.
- Consider a voxel i at location $P_i(x, y, z)$, and and offset vector $O_i(x, y, z)$ predicted by the network to its corresponding medoid. The instance id for voxel i is thus the closest medoid after moving the voxel location $P_i(x, y, z)$ by the offset $O_i(x, y, z)$

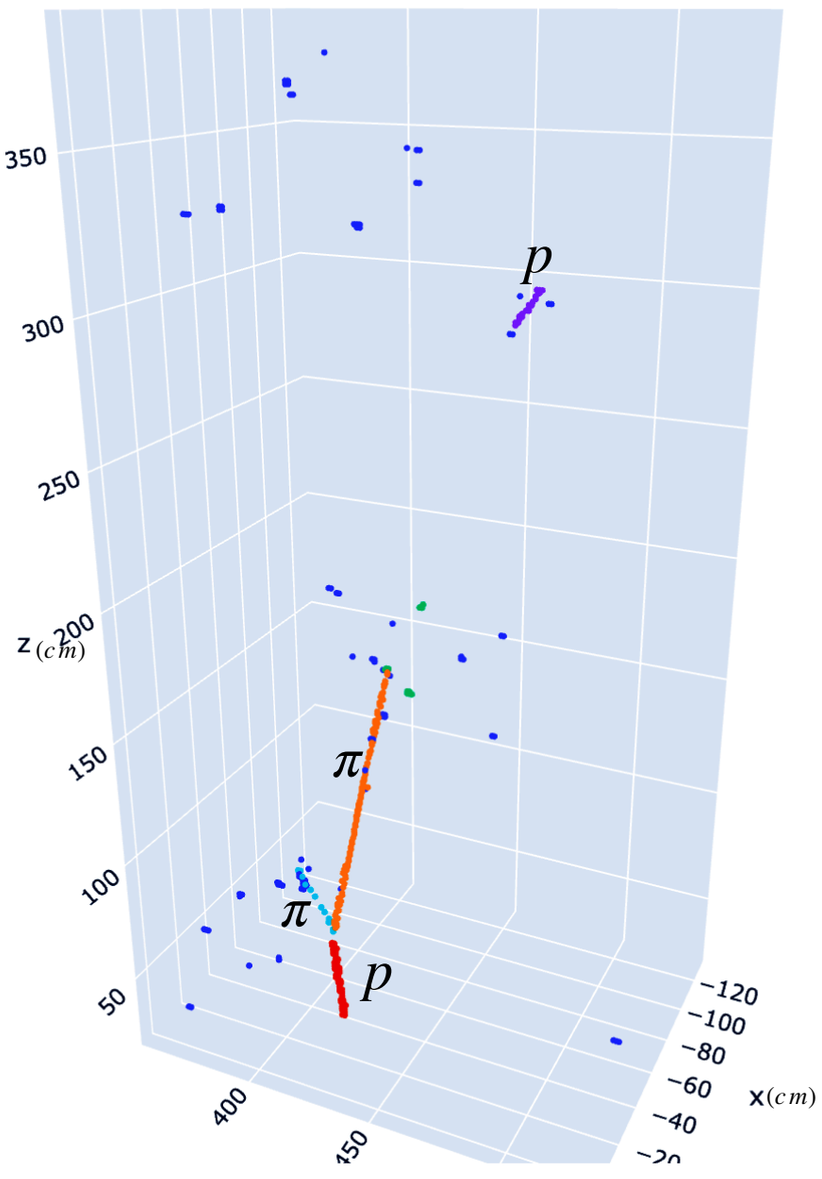


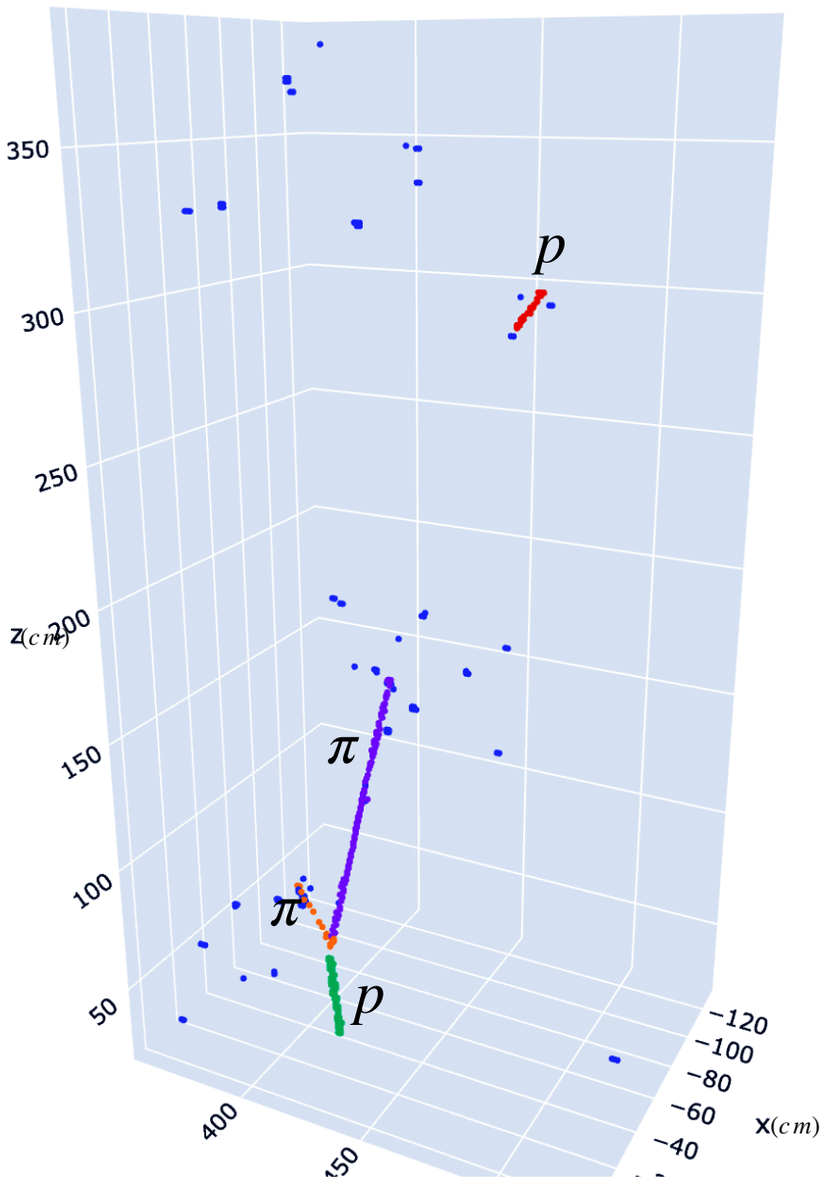
- $O_i(x, y, z)$ represents the offset in x, y and z coordinates of voxel i
- $P_i(x, y, z)$ represents the the location of voxel i
- C_k is the set of all reconstructed medoids

$$Id\_Voxel_i = \underset{k}{argmin} \, || \, C_k - (P_i(x, y, z) + O_i(x, y, z)) \, ||^2$$

Panoptic segmentation

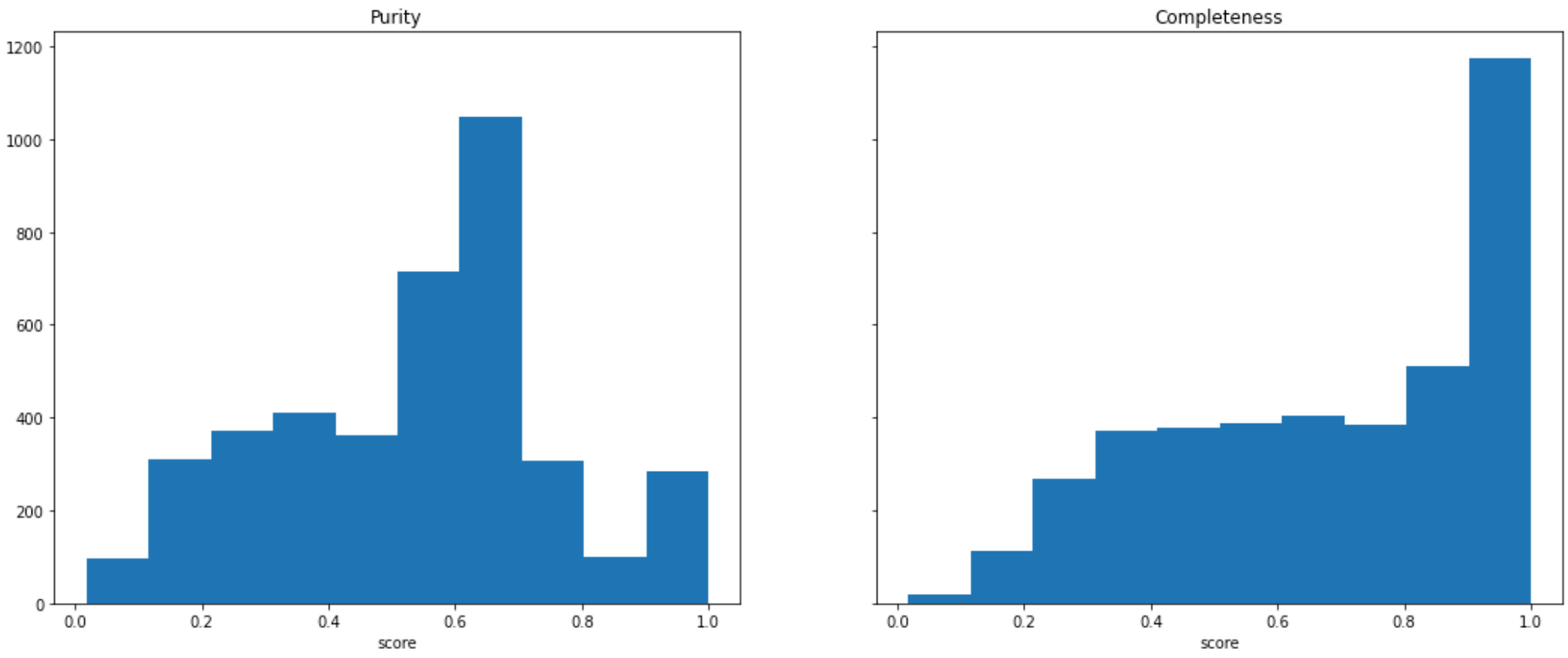
- The panoptic label is obtain by merging semantic segmentation and class agnostic instance segmentation results
  - The class of each instance is determined by an efficient majority voting algorithm





Panoptic segmentation metrics

- **Metrics:**

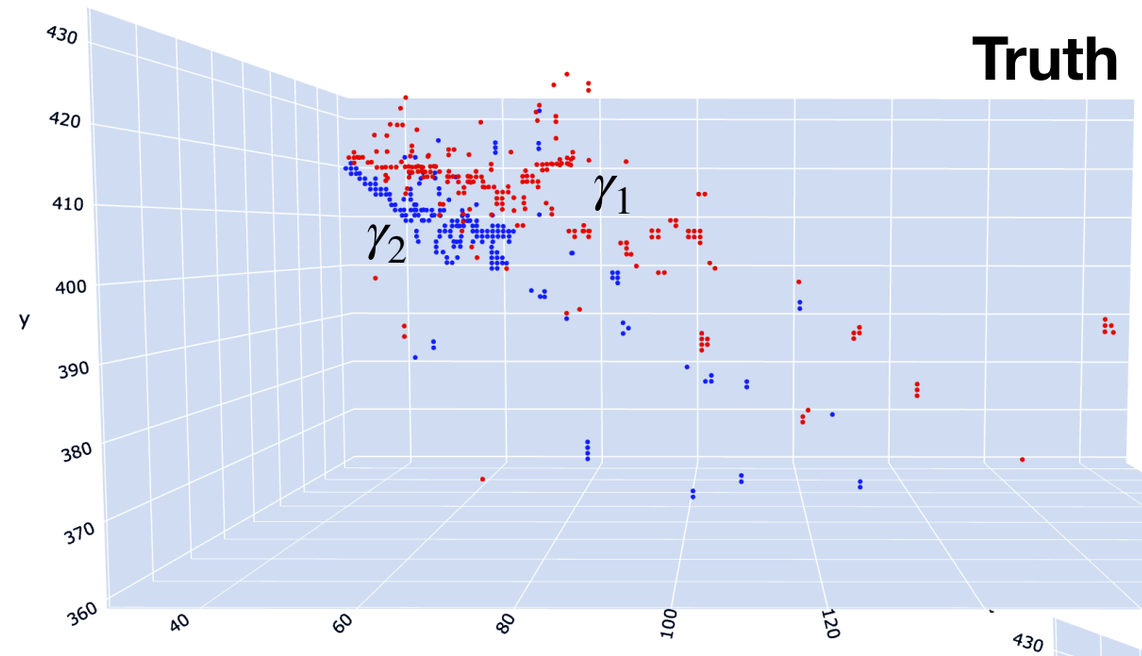


- **Purity: Is the fraction of voxels in the reconstructed particles shared with the true particle. ~ 60.1%**

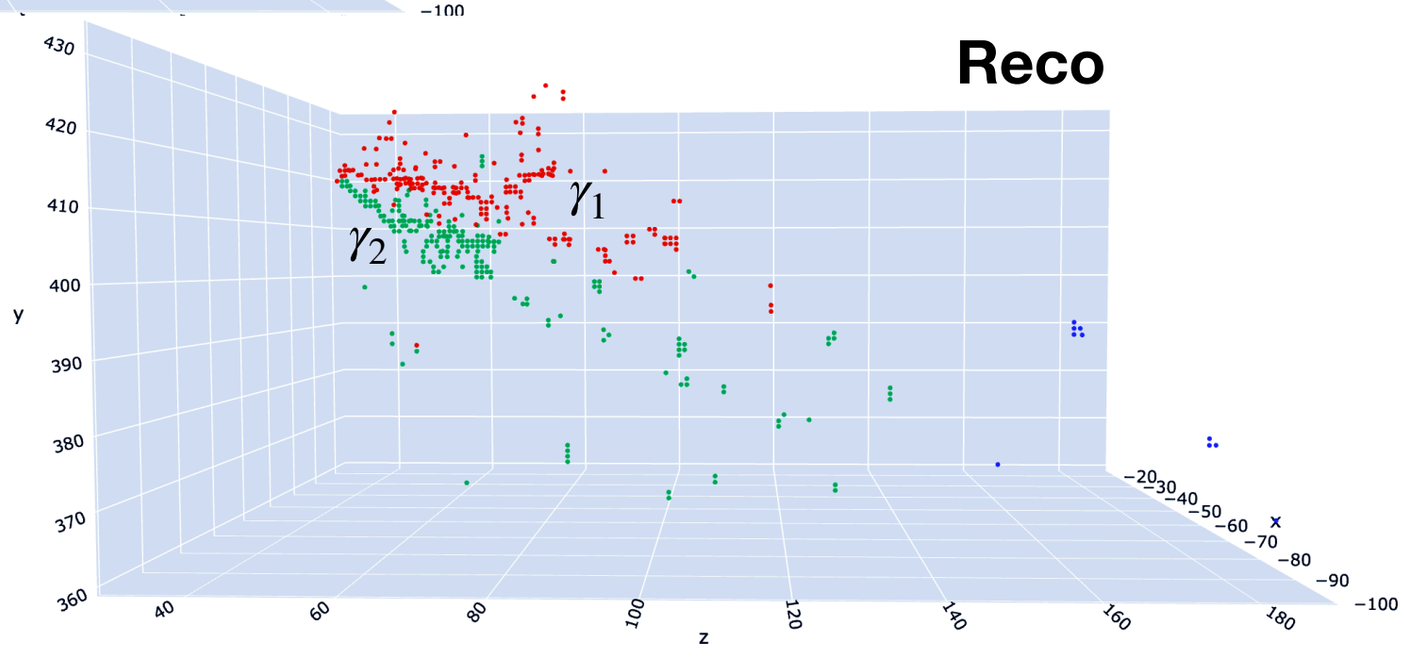
- **Completeness: Is the fraction of true voxels that are shared with the reconstructed particle. ~ 70.2%**

Neutral pion invariant mass reconstruction

- Using panoptic segmentation we could attempt to reconstruct the neutral pion invariant mass

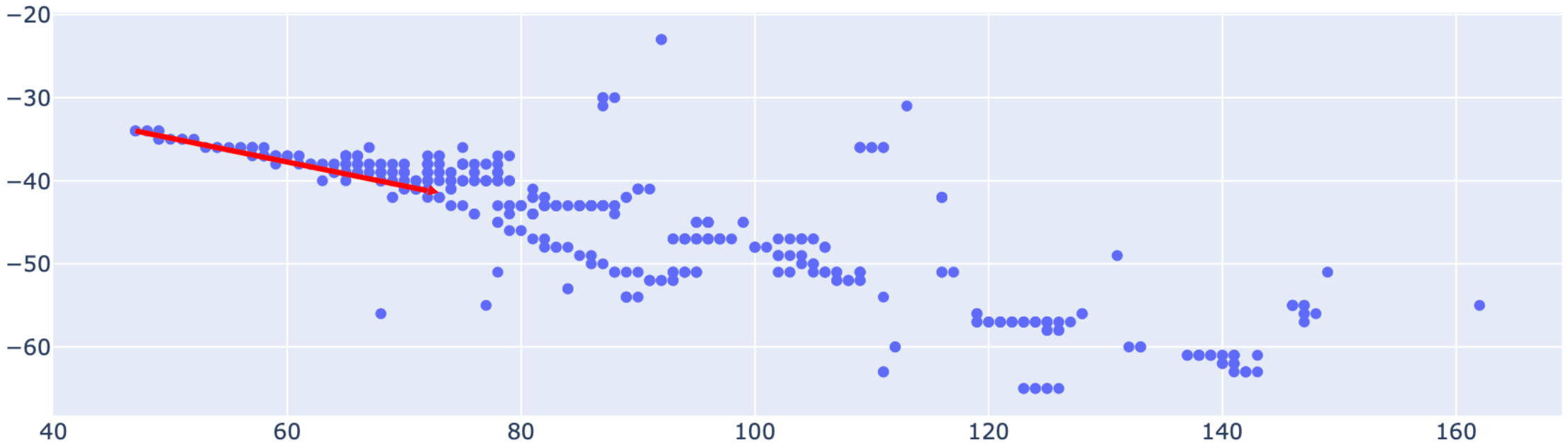


- Two showers from neutral pion decay



Neutral pion invariant mass reconstruction

- We can attempt to reconstruct the neutral pion invariant mass using panoptic segmentation network
- Principal Component Analysis is used to find direction of showers
  - Find direction that maximize the variance of the projected data
  - Compute covariance matrix
  - Compute eigenvectors, eigenvalues
- Energy is estimated using a CNN



Neutral pion invariant mass reconstruction

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- PCA is used to find direction of shower
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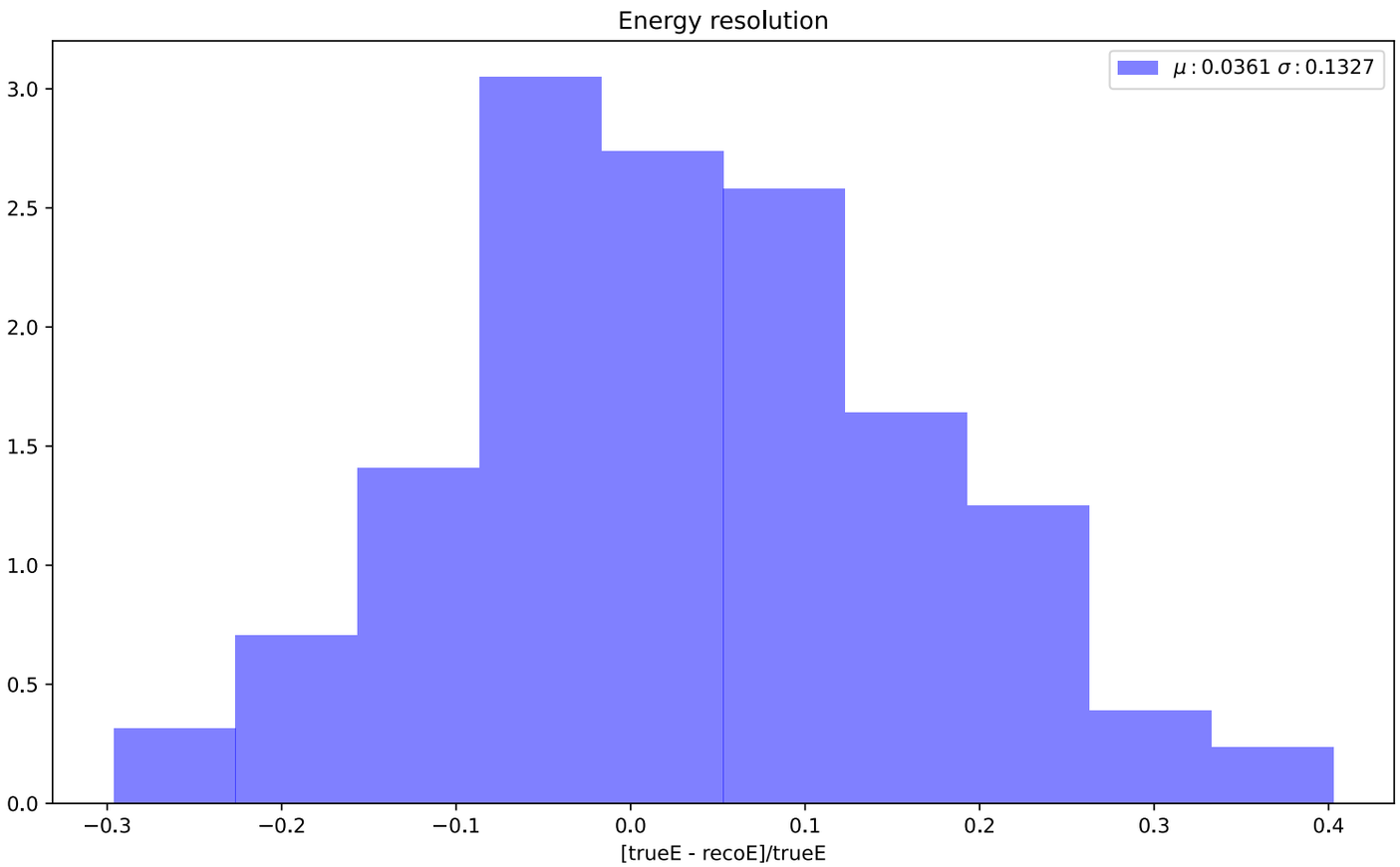

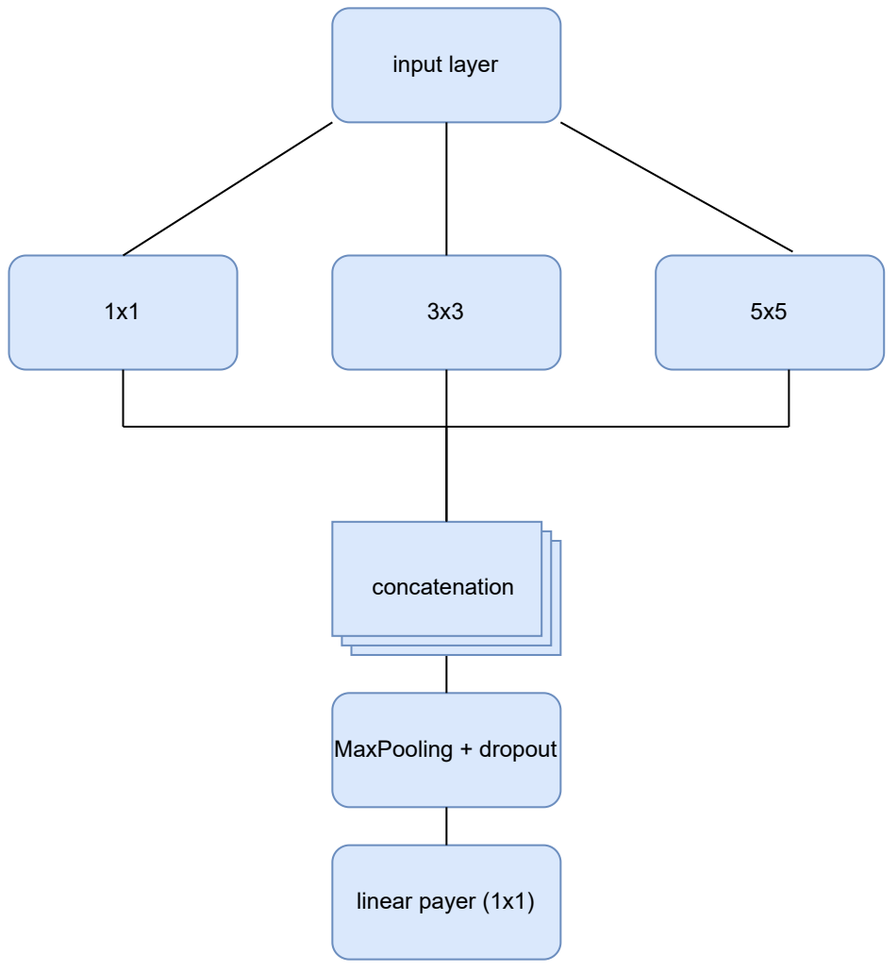

- Inspired on Inception block and Wenjie Wu's energy reconstruction neural network

Neutral pion invariant mass reconstruction

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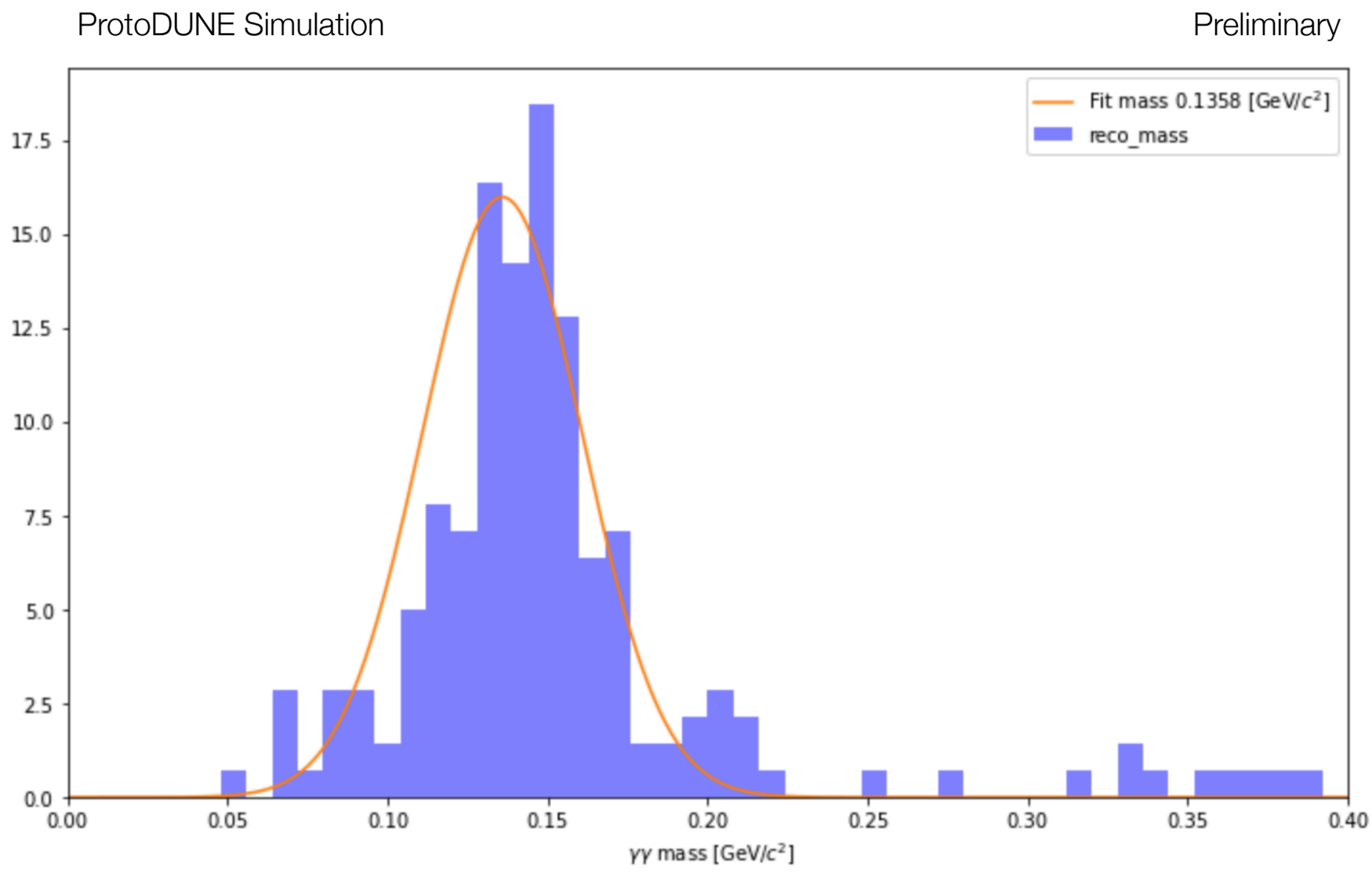


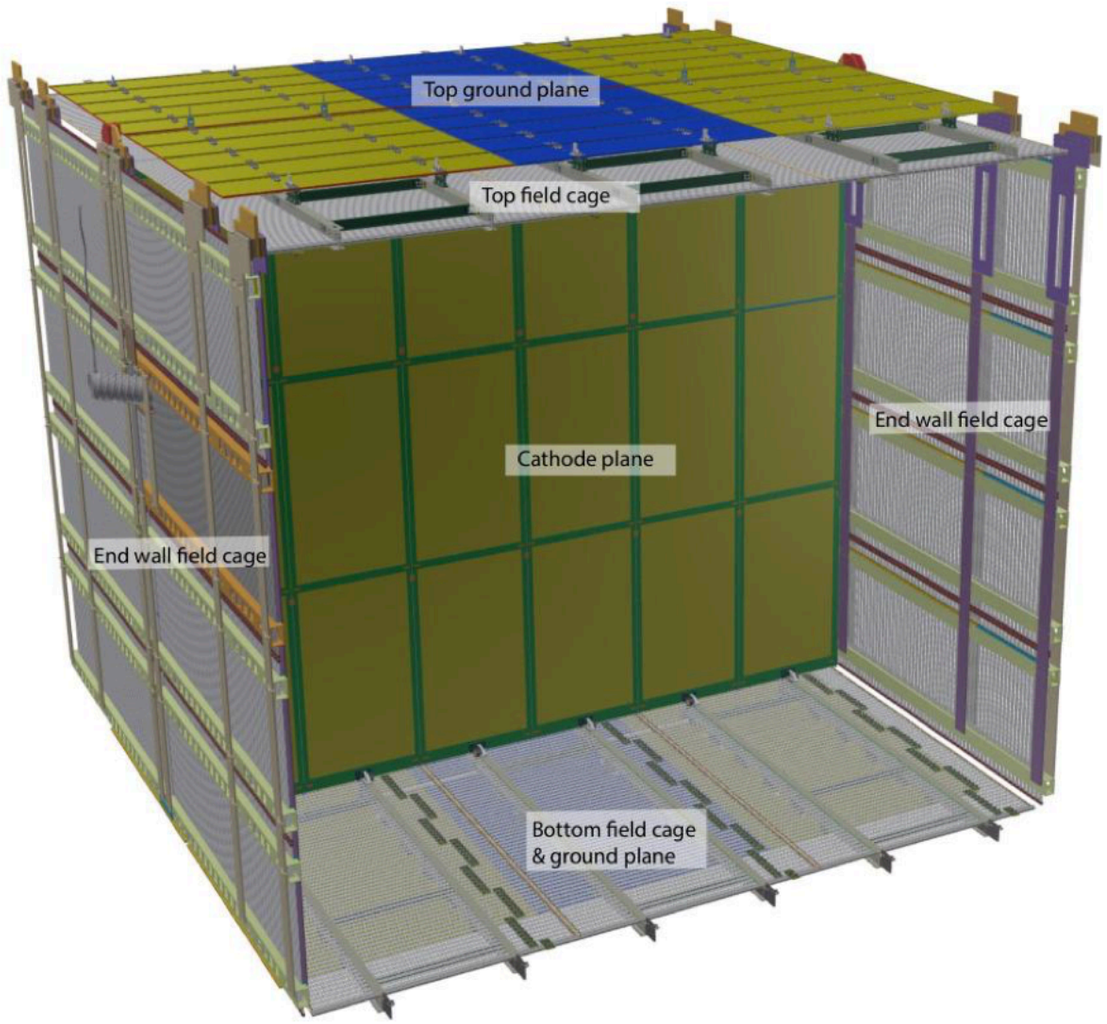
Summary and comments

- The semantic segmentation network is capable to predict 7 particle classes with high accuracy
- The instance segmentation network is able to reconstruct the medoid's location and offset vector accurately
- The panoptic segmentation model is showing promising results, but there is still room for improvement
- A very preliminary result of neutral pion mass reconstruction using panoptic segmentation network looks promising
- Comments and suggestions are more than welcome
- Thank you

Backup slides

The ProtoDUNE-SP detector

- Cathode Plane Assemblies (CPA)
  - Held at 180 kV
  - Provides an E field 500 V/cm in each of the 3.6 m drift regions
- 6 Anode Plane Assemblies (APA)
  - 6.1 m long x 2.3 m wide
  - 3 planes of sense wires/APA oriented at different angles
  - **15360** sense wires (99.74% active channels)
- Photon Detection System (PDS)
  - Light collecting bars read out by SiPMS installed in the APA frame (10 detectors/ APA)



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