Vertex reconstruction for atmospheric neutrinos in LArTPC detectors of DUNE experiment

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1.Introduction

DUNE experiment

- DUNE(Deep underground neutrino experiment)
- Neutrino beam emitted from Fermilab to far detectors (FD) at Sanford
- Use **Liquid Argon TPC (LAr TPC)** for the far detector

Liquid Argon TPC (LArTPC)

A huge chamber (15m*14m*62m) filled with liquid argon (expect 1194 events/year in 10 ktonnes)

The neutrino interacts with the liquid argon in the TPC and produces charged daughter particles, which leave tracks in the detector

Vertex reconstruction

The precise reconstruction of the neutrino interaction vertex is **essential,** because it is the starting point for the event reconstruction (e.g., angle reconstruction, particle type identification, etc)

Atmospheric neutrinos

Interactions of high-energy cosmic rays with the nuclei of atoms in the Earth's atmosphere,generating a cascade of secondary particles, including neutrinos

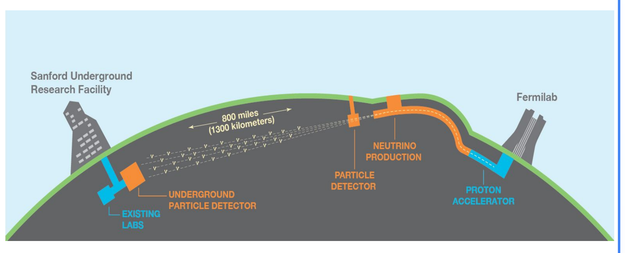


Fig 1. DUNE experiment

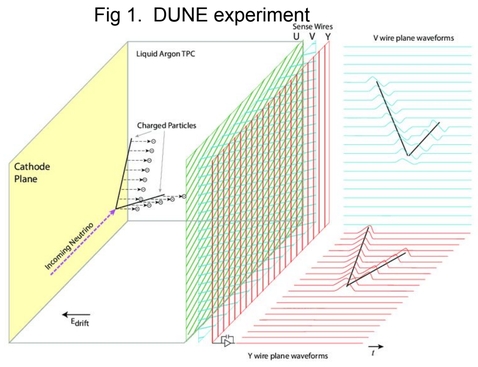


Fig 2. Neutrino detection principle in a LAr TPC

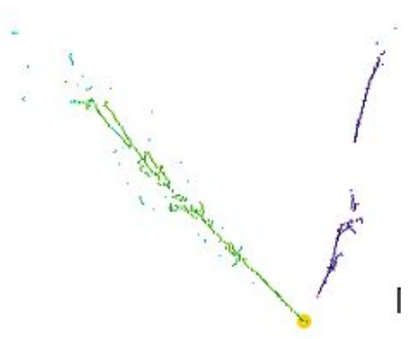


Fig 3. Example of vertex reconstruction. Hits as reconstructed in a LAr TPC

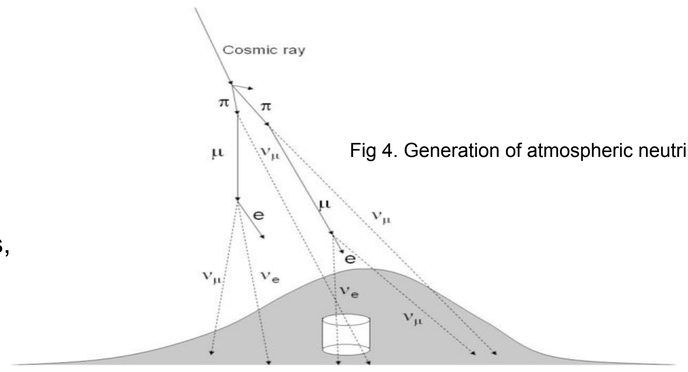


Fig 4. Generation of atmospheric neutrino

2.Pandora Deep learning vertexing & Current performance

In training hits are assigned a class according to distance from true vertex

Network trained to learn those distances from input images

Network infers hit distances and resultant heat map isolates candidate vertex

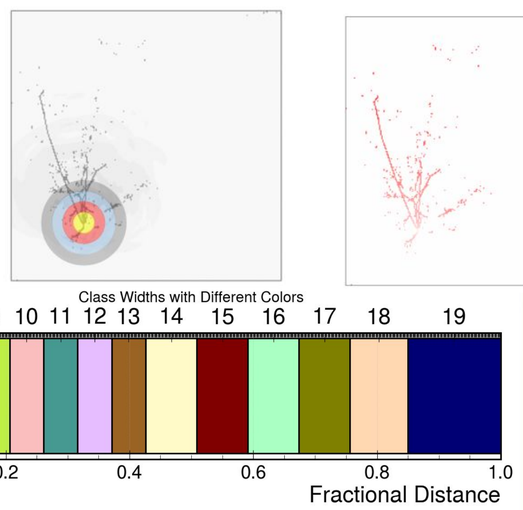


Fig5. Visual illustration of the width (expressed as 'fractional distance') of the 20 class-distances used by the U-Net to classify the distance between each hit in an input image, and the truth vertex. For a 256x256 pixel image (the usual input to the U-Net), a fractional distance of 1 corresponds to 256 pixels, and 0.1 to 26 pixels.

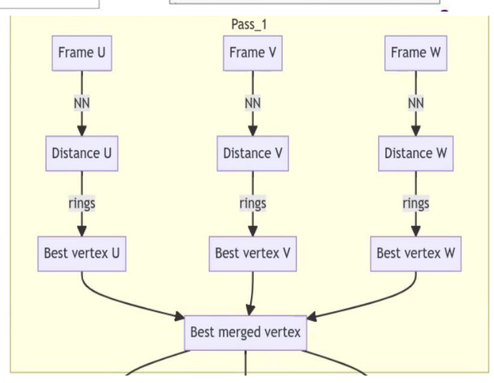


Fig 6. Flowchart of pandora DL vertexing

- Two Passes
  - Pass_2 'zooms-in' into the vertices found by Pass_1
  - but are otherwise identical
- Each pass made of several steps
  - same steps for each frame and Pass_1 & Pass_2
  - final 3D vertex found by merging info from all 3 frames
- For atmospheric analyses:
  - Reconstructed the direction of neutrino is important → vtx reconstruction has to be precise
  - At present:
    - 34% of CC away from 1 cm
    - 57% of NC away from 1 cm

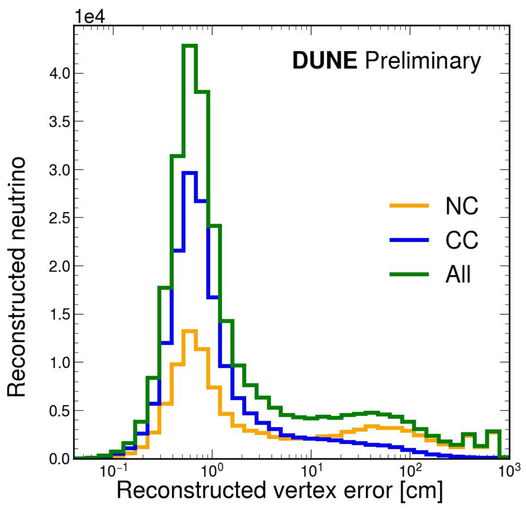


Fig 7. Distribution of the reconstructed vertex position error, for neutral current (NC) and charged current (CC) events, as well as their sum. All neutrino and antineutrino flavors are included in the samples.

3. Investigation of failure modes

Failure modes: **event topologies**

'**Normal failure**': vtx reco-ed >3cm away from truth, but in the right direction 48%

'**Track flipped**': PV reco-ed at end of track instead of start 13%

'**SV as PV**': a secondary vtx is wrongly identified as PV 34%

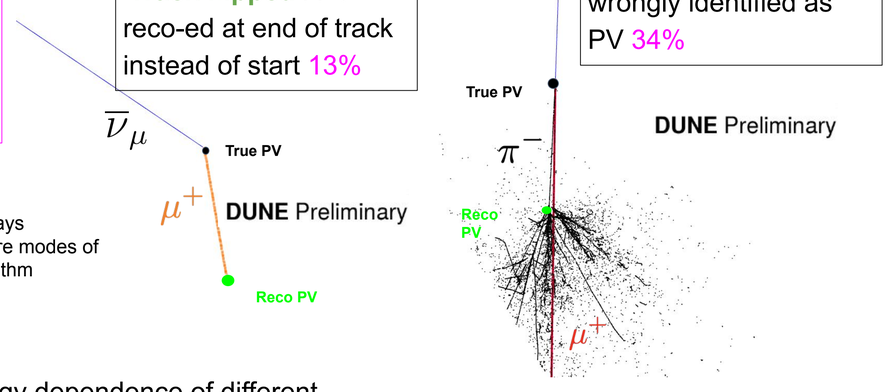


Fig 8. Examples of event displays corresponding to different failure modes of the vertex reconstruction algorithm

We observe an energy dependence of different failure modes, which might be correlated to predominance of different types of neutrino interactions in different energy ranges.

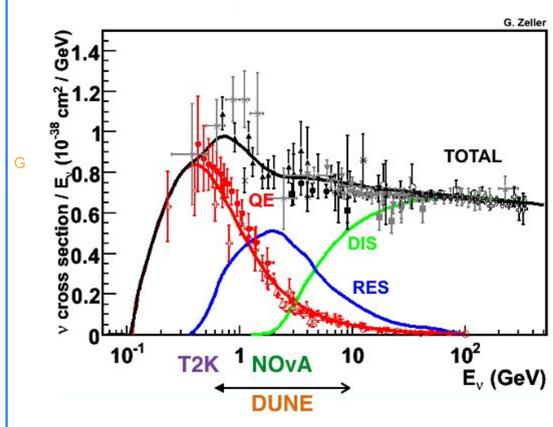


Fig 9. Energy dependence of different types of neutrino interactions.

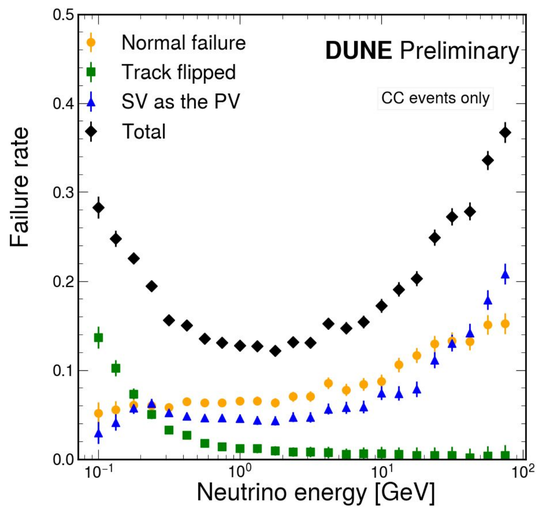


Fig 10. Energy dependence of vtx reconstruction failure modes.

Main point of failure of the algorithm

$$\text{Average class difference} = \frac{1}{n_{views}} \sum_{j=1}^{n_{views}} \left(\frac{1}{H_j} \sum_{i=1}^{H_j} |class_{i,j}^{truth} - class_{i,j}^{prod}| \right)$$

- n_{views} =3, the total number of views (U, V, W)
- H is the total number of hits in each of the 3 views

More than 1 class difference:

- Bad reco: 45%
- Good reco: 9%

The main point of failure happens at the very beginning of the vertex algorithm, at the the NN stage: the class assigned to hits is wrong.

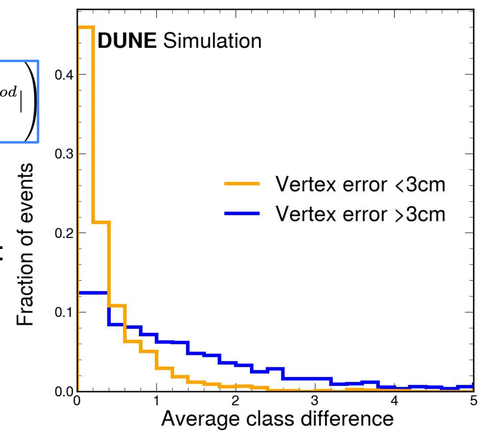
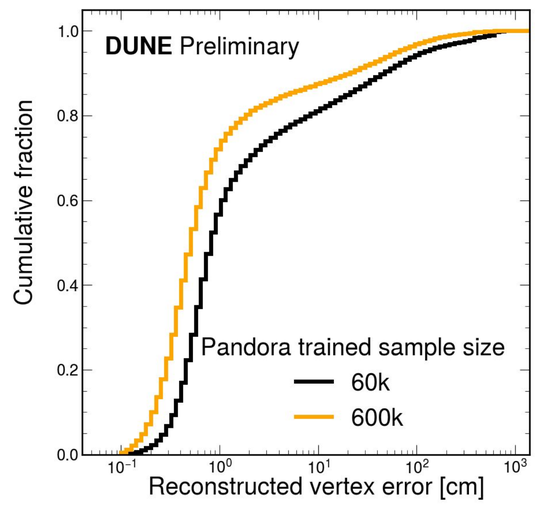


Fig. 11 Distribution of the predicted class output from the network

4. Finding solutions to improve performance

Train the network with more events



Reco-Truth vtx distance	<1cm	<3cm	<10cm	<100cm
Events used for CNN training: 60k / 600k				
All	56% / 72%	73% / 83%	81% / 87%	94% / 97%
CC	65% / 81%	84% / 93%	91% / 96%	99% / 100%
NC	43% / 63%	58% / 73%	66% / 78%	87% / 94%

Other attempts made

1.Choosing the second highest-score vertex
2.Train the network in specific energy ranges

Fig12 . Cumulative histogram of the error in vertex reconstruction, when training the U-Net with two different event sample sizes.

Use another Neural Network---Graph neural network

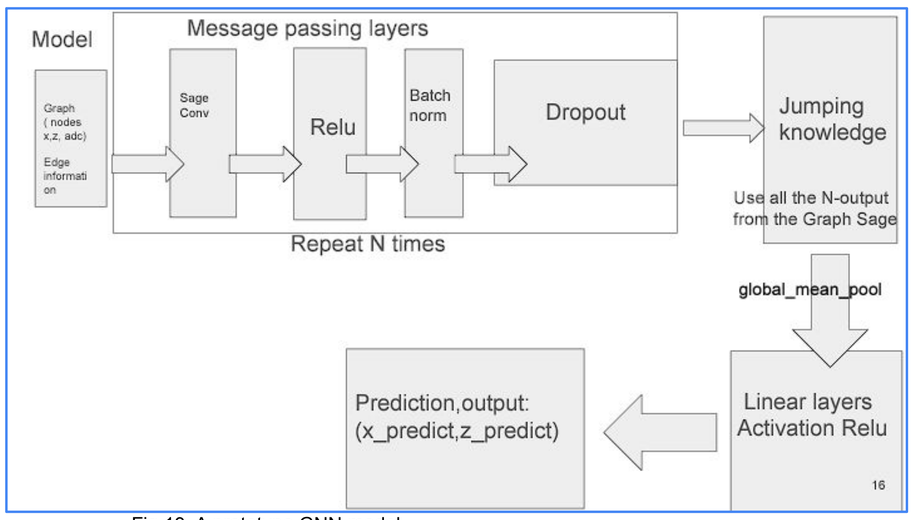


Fig 13. A prototype GNN model.

Instead of using U-Net, we are investigating the possibility of using Graph Neural Networks (GNNs), as they might better understand the underlying topology of neutrino interaction.