Contrastive Reinforcement Learning for Classifying MeV Scale Physics in LAr TPCs

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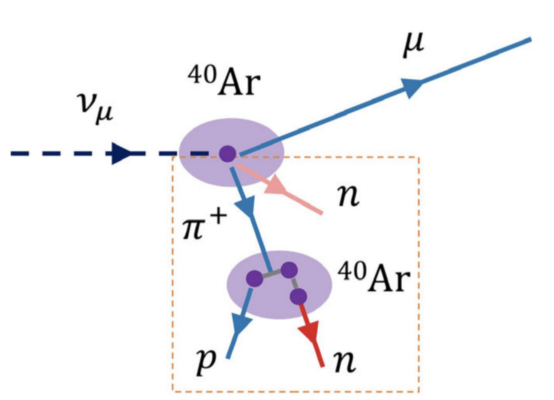
Why Are Neutrons Important?

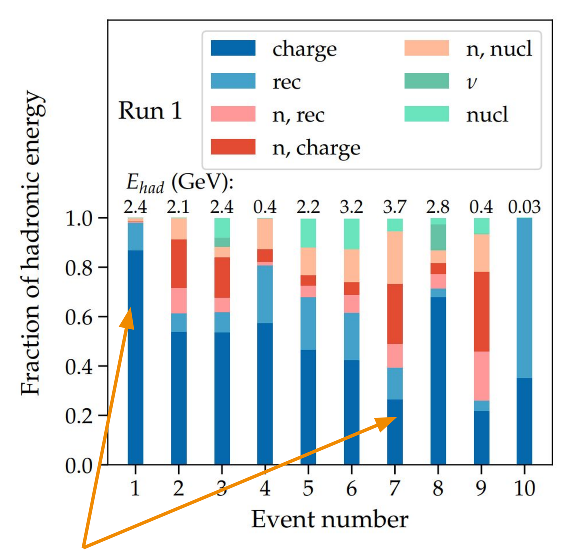
To turn neutrino physics into a precision science, we need to understand complex neutrino-nucleus interactions (specifically on Ar):

- Neutrons carry away a ***large fraction***[1] of energy.
- Neutron final states are ***model dependent***.
- Neutrons are ***difficult to detect*** in LAr.



Neutrons are also important for low-energy physics in LAr:

- e.g., modeling **supernova** and **solar** (and now **galactic**[2]) neutrino physics.

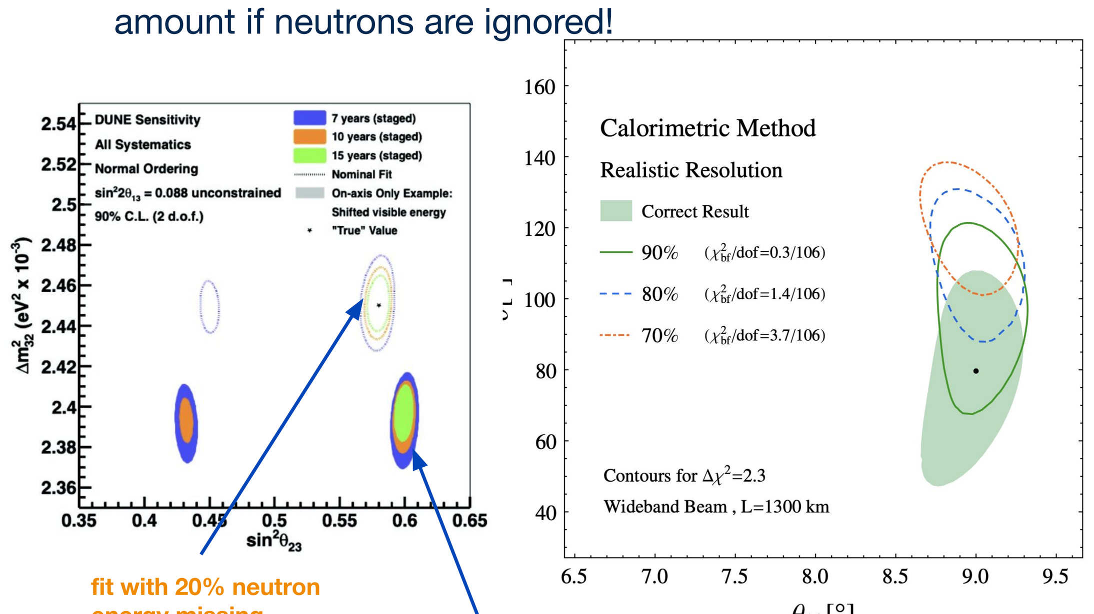


Contributions from neutrons vary widely from event to event!

Figure from A. Friedland and W. Li (2019).

How Does Missing Energy Affect DUNE?

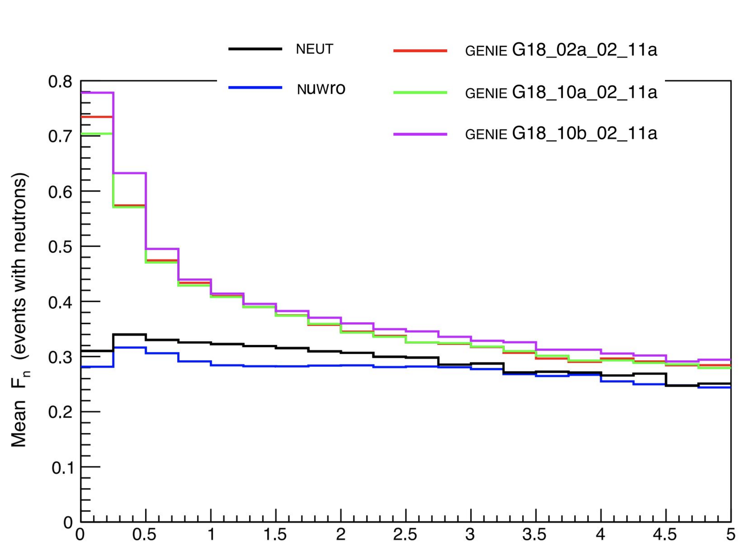
- Measurements of the CP phase[3] are shifted by a large amount if neutrons are ignored!



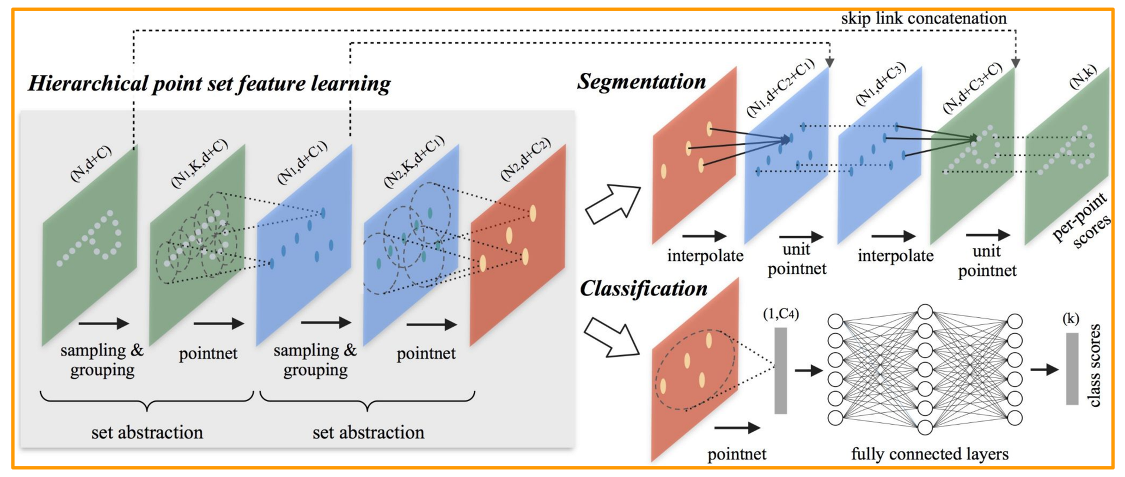
fit with 20% neutron energy missing

actual

- The fraction of total energy given to hadrons (when at least one hadron is a neutron) is shown as a function of incident neutrino energy in a CC-interaction.
- GENIE varies in the lower energy regime by a factor of 2!

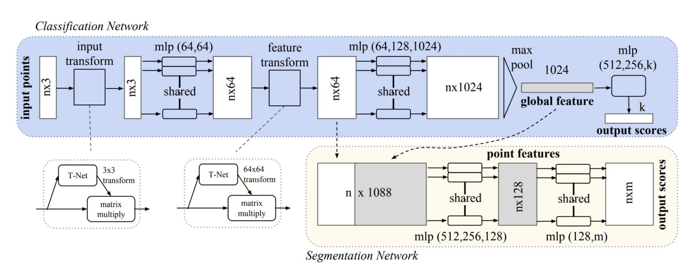


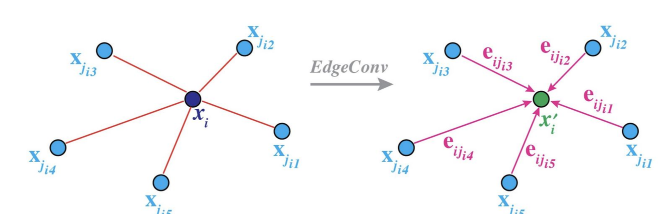
Blip Classification



BLIP Classification will consist of at least the following two models:

- **PointNet++** - The first network will take in an entire detector readout for an event and learn to semantically label blips (e.g. PointNet++[5]).





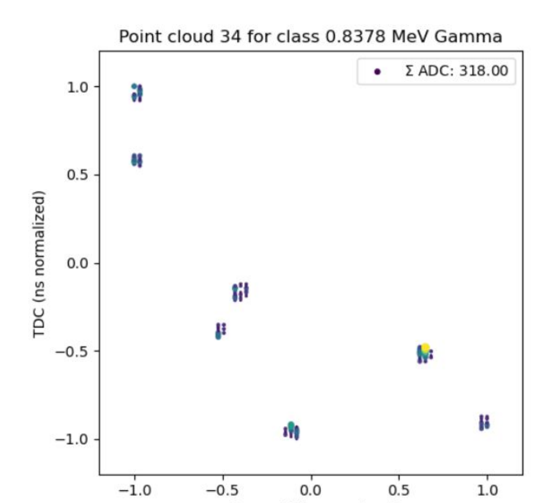
- **BlipGraph** - The second network will learn to classify clusters at different scales (e.g. PointNet[4], DynamicEdgeConv[6]).

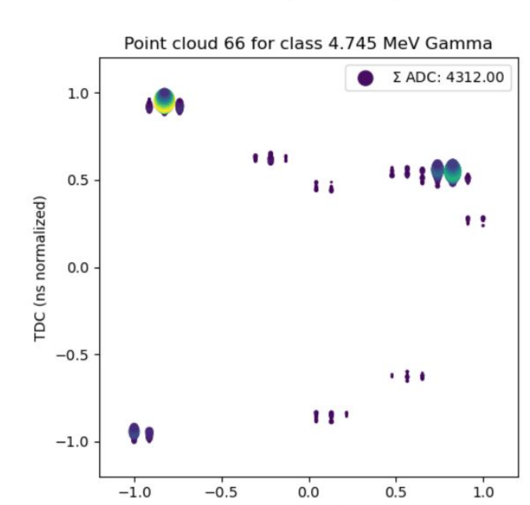
Point cloud neural networks take advantage of three main properties of the datasets:

1. **Unordered** - Point clouds, unlike pixel arrays, are unordered and can have a variable number of points!
2. **Distance Metric** - Our point clouds have a geometry and local interaction information.
3. **Symmetries** - Due to physics/geometry, the point clouds are invariant under certain transformations.

Below are examples of different neutron capture gammas simulated in LArSoft.

- Each cluster is normalized so that it is centered at zero and extends from [-1,1] in each variable.
- ADC is normalized over all events.





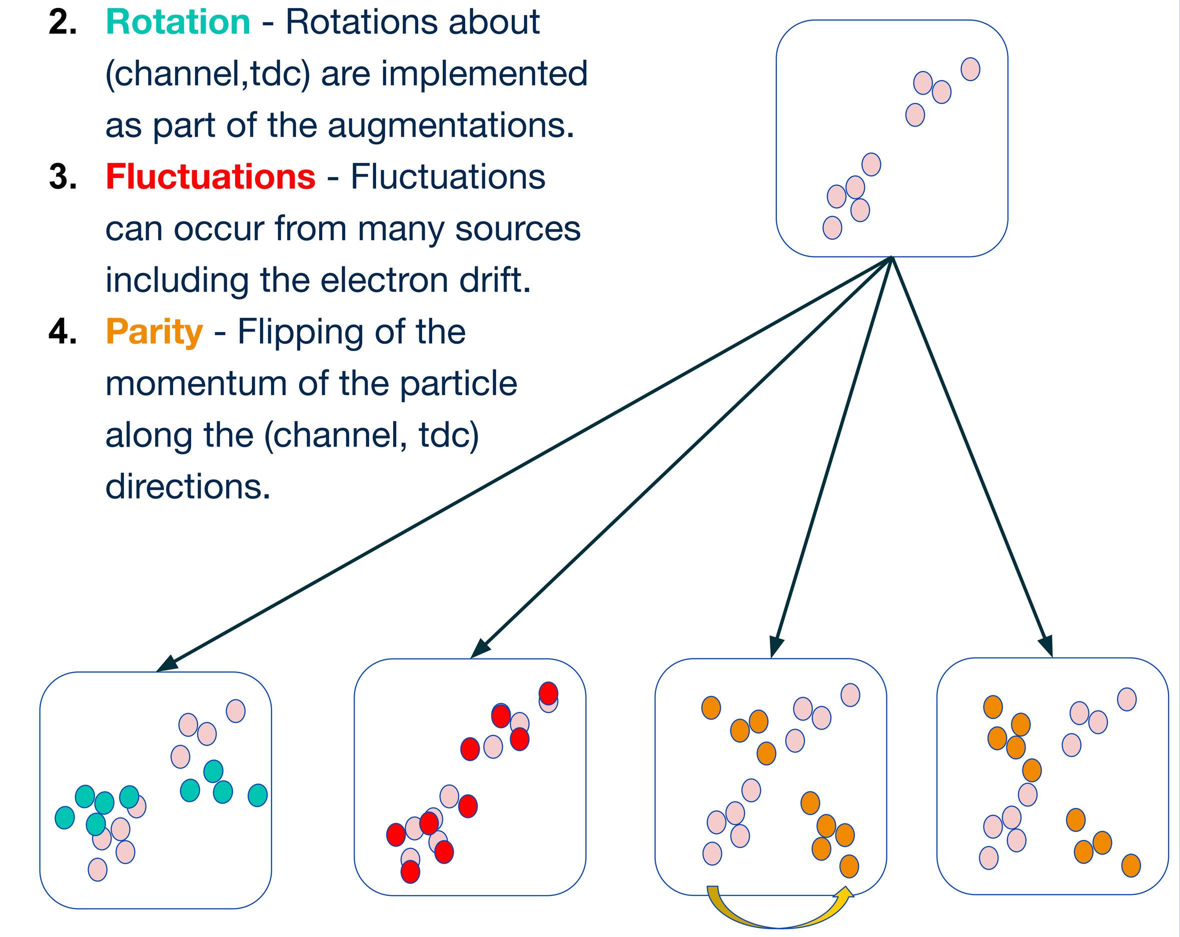
Contrastive Learning

Symmetries -> Augmentations

There are several symmetries in our dataset due to physics:

1. **Translation** - Translations in (channel,tdc) are handled by normalizing each point cloud to the origin.
2. **Rotation** - Rotations about (channel,tdc) are implemented as part of the augmentations.
3. **Fluctuations** - Fluctuations can occur from many sources including the electron drift.
4. **Parity** - Flipping of the momentum of the particle along the (channel, tdc) directions.

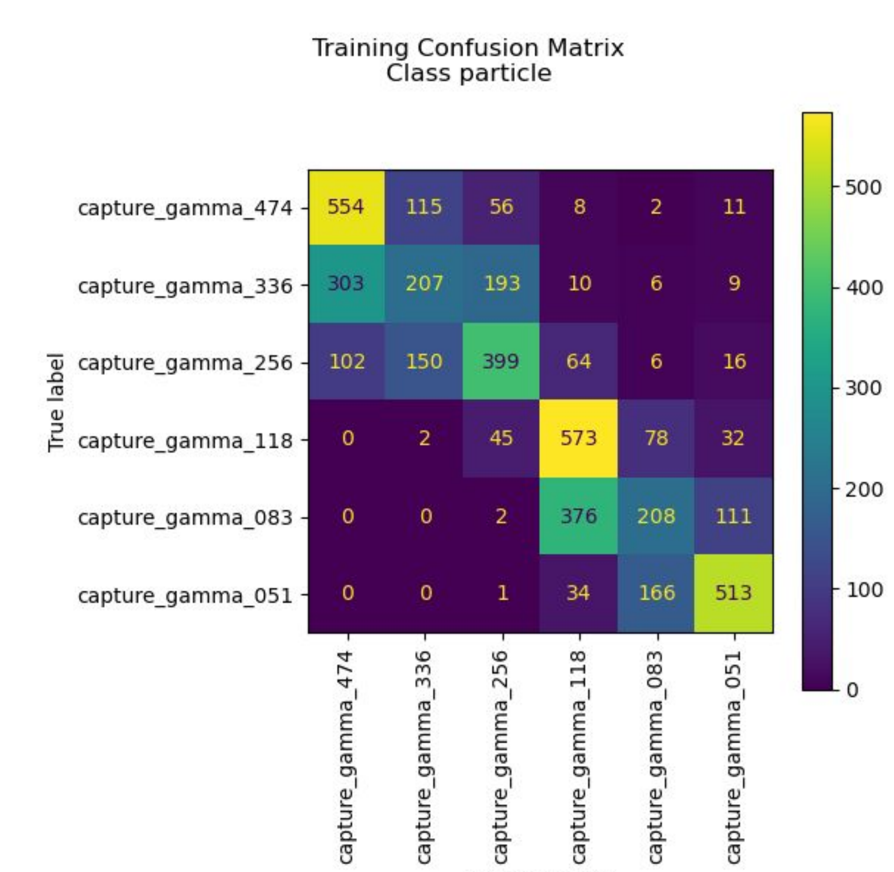
Rotations/translations about ADC are not symmetries!



Using the *Normalized Temperature-scaled Cross Entropy Loss* (***NTXent***)

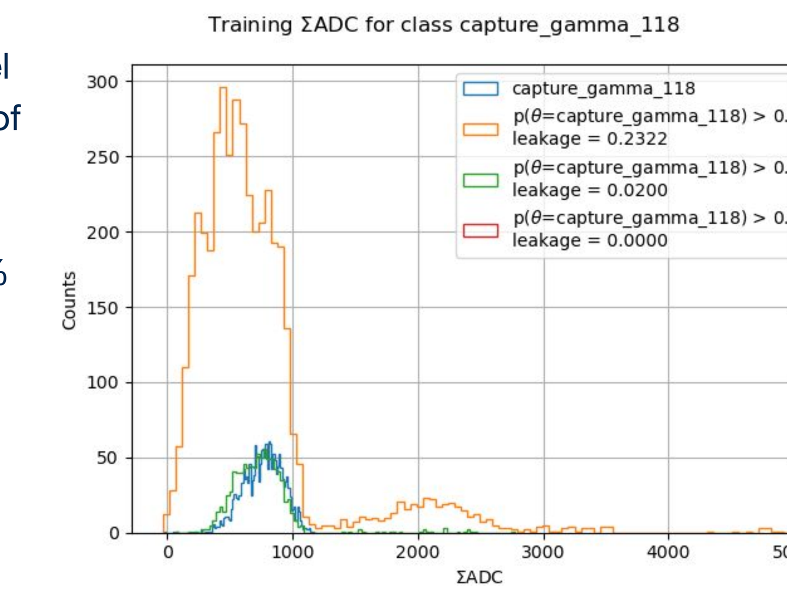
$$\ell_{i,j} = -\log \frac{\exp(\mathrm{sim}(z_i, z_j)/\tau)}{\sum_{k=1}^{2N} \mathbb{1}_{[k\neq i]} \exp(\mathrm{sim}(z_i, z_k)/\tau)}, \quad (1)$$

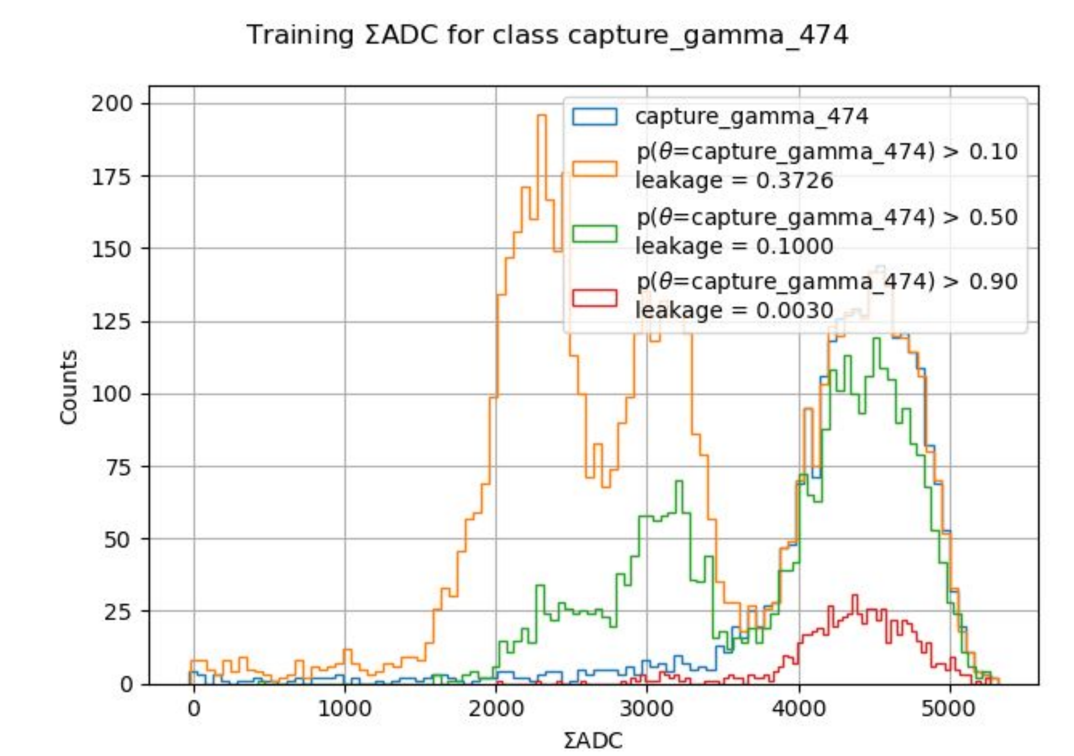
we push "like" clusters closer together in the embedding space and push all others away.



BlipGraph Results

This early model rejects 99.7 % of all other blip types when imposing a 90% cut on the probability to being a 4.745 MeV gamma.





Software

All of the related software can be found on github, which includes the following repositories:

- **Arrakis/ArrakisND** - a set of packages for constructing training datasets from LArSoft and larnd-sim simulation.
- **Blip** - machine learning and clustering tools including the SparseUNet and BlipGraph..

Acknowledgements

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[1] O. Ronneberger et. al., *U-Net: Convolutional Networks for Biomedical Image Segmentation*, arXiv:1505.04597, 2015.
[2] C. Choy et. al., *4D Spatio-Temporal ConvNets: Minkowski Convolutional Neural Networks*, arXiv:1904.08755, 2019.
[3] M. Ester et. al., *A density-based algorithm for discovering clusters in large spatial databases with noise*, 1996.
[4] Eric Church, *LArSoft: A software package for liquid argon time projection drift chambers*, arXiv:1311.6774, 2013.
[5] DUNE Collaboration, *Status of single phase and dual phase DUNE prototype detectors at CERN*, XXXIX International Conference on High Energy Physics, 2018.

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