Detecting Neutrons in LArTPCs with Machine Learning

DUNE Collaboration Meeting (01/25/2023)

Presented by *Nicholas Carrara* on behalf of the ***BLIP ML Group*** at **UC Davis[1], LANL[2], IIT[3], CIEMAT[4], SDSM[5], FNAL[6], NIKHEF[7], FSU[8], UNIBE[9],** :

Nicholas Carrara[1], David Rivera[2], Laura Perez-Molina[4],

Marjolein van Nuland[7], Georgette Kufatty[8], Jan Kunzmann[9], Livio Calivers[9],

Michael Mulhearn[1], Emilija Pantic[1], Robert Svoboda[1], Jingbo Wang[5]

Yashwanth Bezawada[1], Junying Huang[1], Will Forman[3], Walker Johnson[5], Ajib Paudel[6],

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.

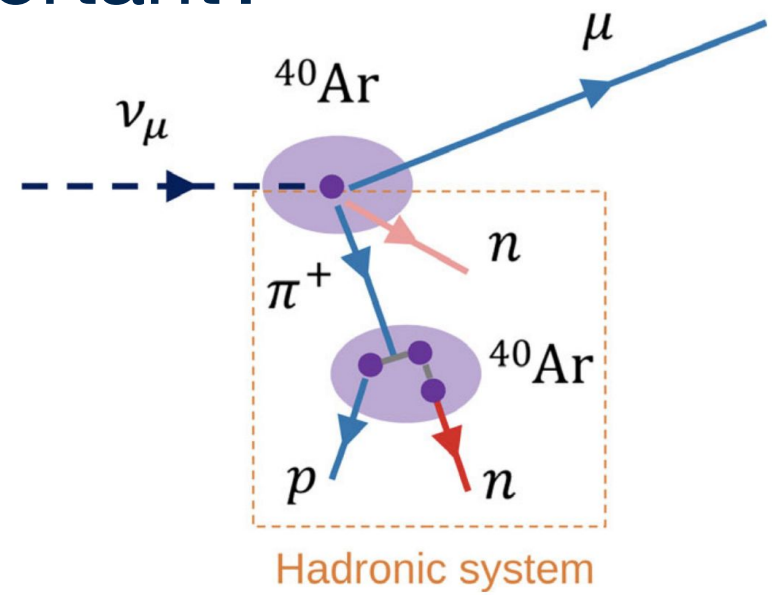

Figure from A. Friedland and W. Li (2019).

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

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

1 A. Friedland and W. Li, *Understanding the energy resolution of liquid argon neutrino detectors*, Physical Review D, **99**, 2019 (https://arxiv.org/abs/1811.06159)
2 ICECUBE Collaboration, *Observation of high-energy neutrinos from the Galactic plane*, Science, **380**, 2023 (https://www.science.org/doi/10.1126/science.adc9818)

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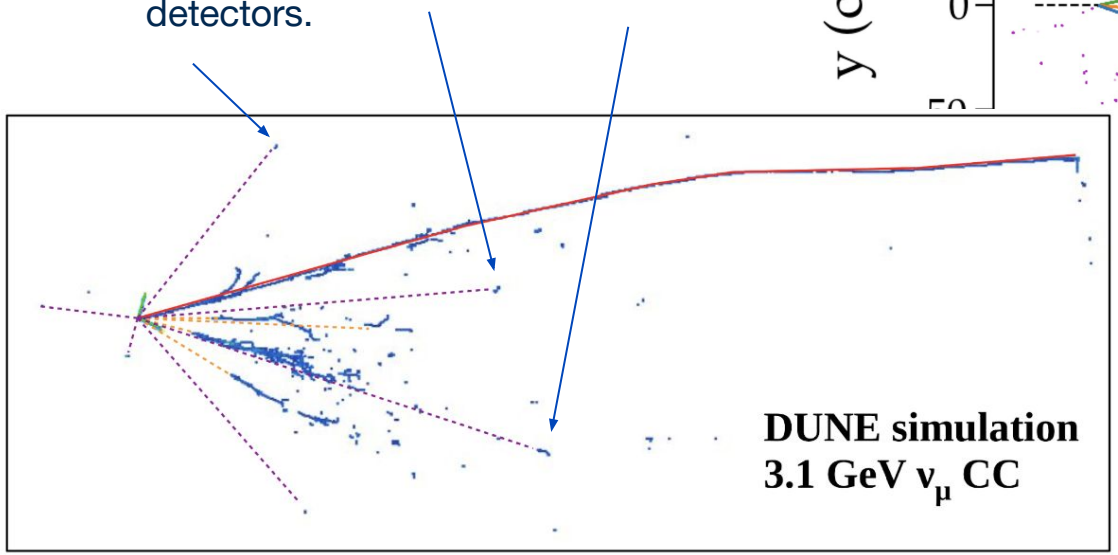
Difficult to detect?

It is necessary to be able to account for the neutron “missing energy” in order to make precision oscillation measurements (production and transport).

- Neutrons show up as small ***blips*** in LAr detectors.



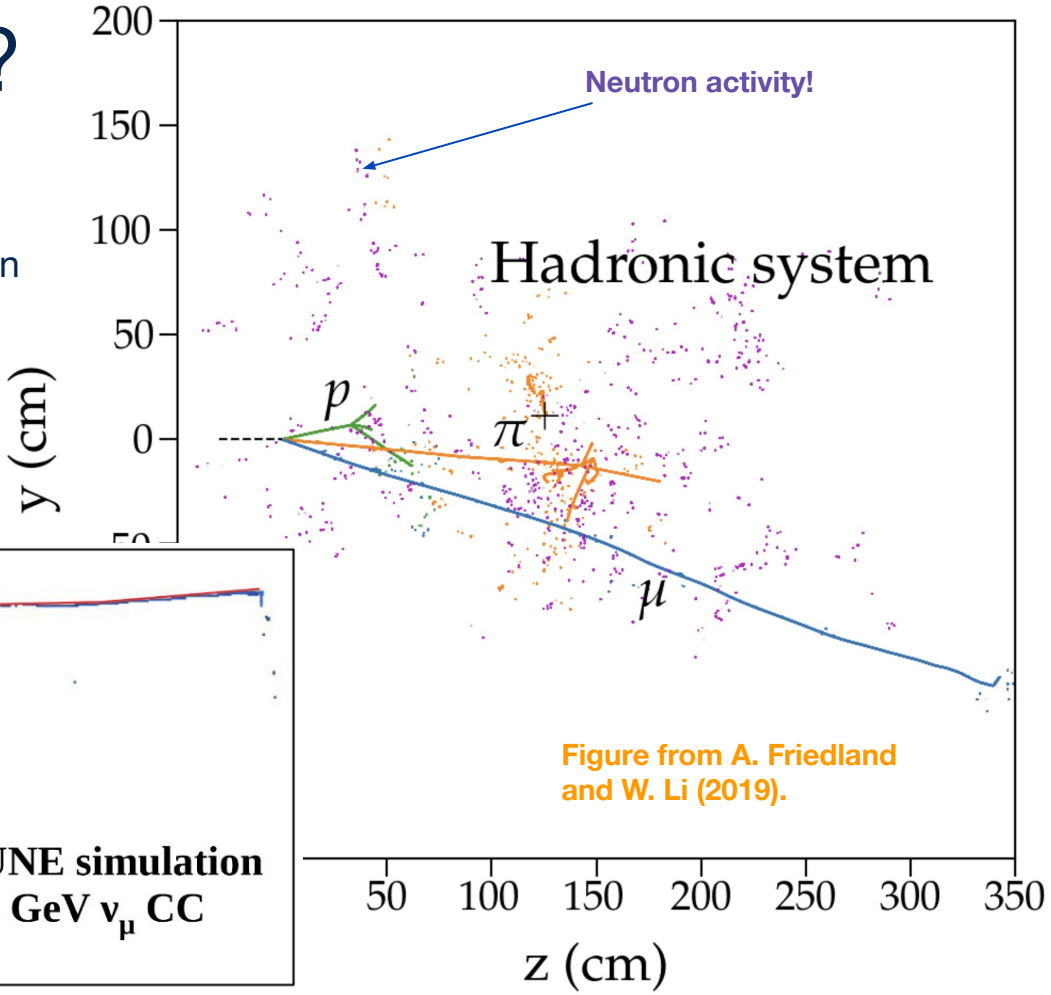


Figure from A. Friedland and W. Li (2019).

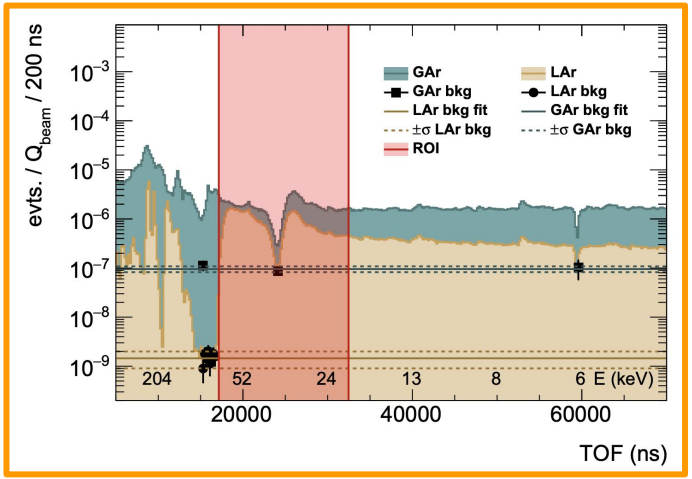
Neutron Calibration (PNS)

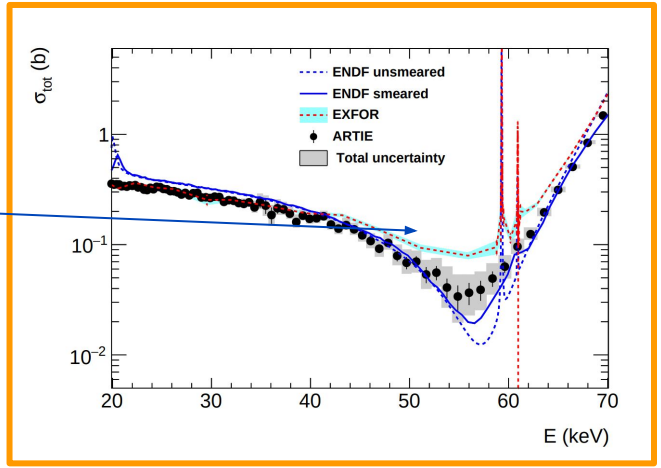
Benefits of low-energy neutrons for calibration:

- ***Standard Candle*** - Neutron captures on Ar-40 emit a 6.1 MeV gamma cascade.

$$\mathrm{n} + {}^{40}\mathrm{Ar} = {}^{41}\mathrm{Ar} + \{\gamma_j\}$$
$$\sum_j E(\gamma_j) \approx 6.1\mathrm{MeV}$$

- ***Scattering Length*** - Some percentage of neutrons above 57 keV will fall into the resonance well.
  - Average *fractional energy loss* is ~4.8%.
  - The *effective scattering length* is ~30 m.
  - The resonance well has been measured by the ARTIE[1] experiment at LANL, with a ***follow-up*** planned for this year (**ARTIE-II**).





3 *Measurement of the total neutron cross section on argon in the 20 to 70 keV energy range,* The ARTIE Collaboration, In review at PRL, 2023, (https://arxiv.org/abs/2212.05448).

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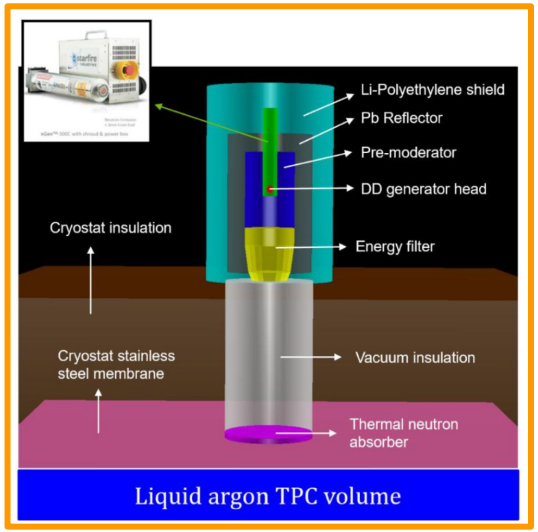
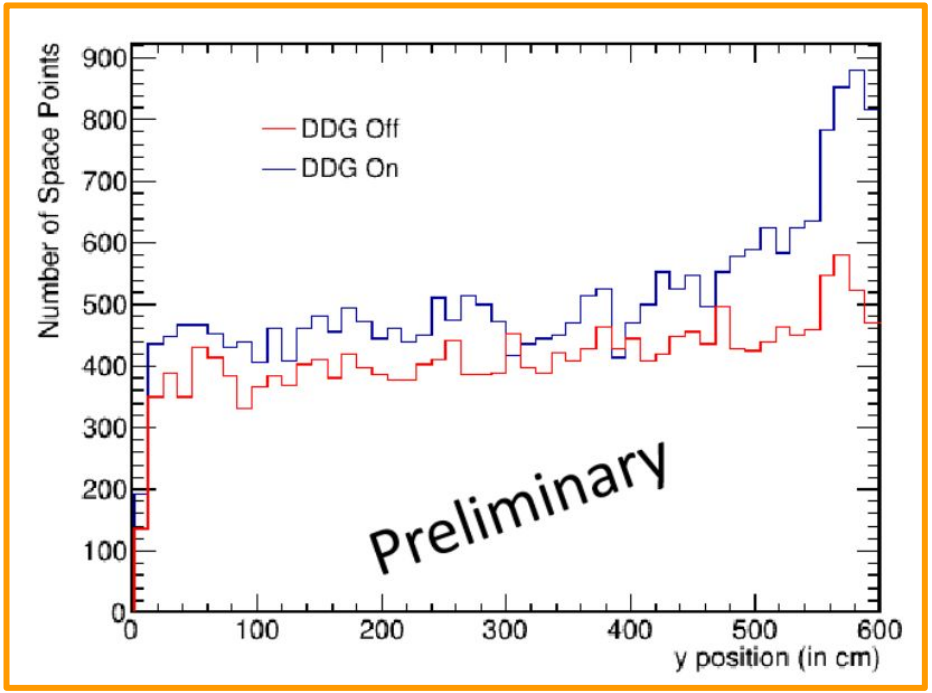
How Can We Isolate Captures?

A **pulsed neutron source**, such as a deuterium-deuterium generator (DDG), can create a *mono-energetic* spray of low-energy neutrons.

- A DDG was used in ProtoDUNE-I, from which the neutrons could be seen in the detector reconstruction.
- So far, we have not had the ability to isolate ***individual neutron captures***.





Work done by Y. Bezawada and J. Huang

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Blip

Two neutron analyses

We introduce ***Blip***[2], a collection of ML algorithms for classifying (e.g. low energy) interactions in LArTPCs.

- Nicholas Carrara (UC Davis)
- David Rivera (LANL) [**BlipNet**]
- Laura Perez-Molina (CIEMAT) [**BlipNet**]
- Marjolein van Nuland (NIKHEF)[**BlipSegmentation**, Arrakis]
- Georgette Kufatty (FSU) [**BlipSegmentation**]
- Jan Kunzmann (UNIBE) [**BlipLight**]
- Livio Calivers (UNIBE) [**BlipLight**]
- Ajib Paudel (FNAL) [**BlipLight**]
- Yash Bezawada (UC Davis) [**BlipNet**/PNS]
- Junying Huang (UC Davis) [**BlipNet**/PNS]
- Will Foreman (IIT)
- Walker Johnson (SDSMT)

pion-neutron final states/blip classification

n-Ar inelastic cross-section measurement at 2x2 (B. Russell)

neutron capture reconstruction for calibration

wire detector reconstruction

4 *BLIP, BLIP ML* Group (UC Davis), 2023, (https://github.com/Neutron-Calibration-in-DUNE/Blip).

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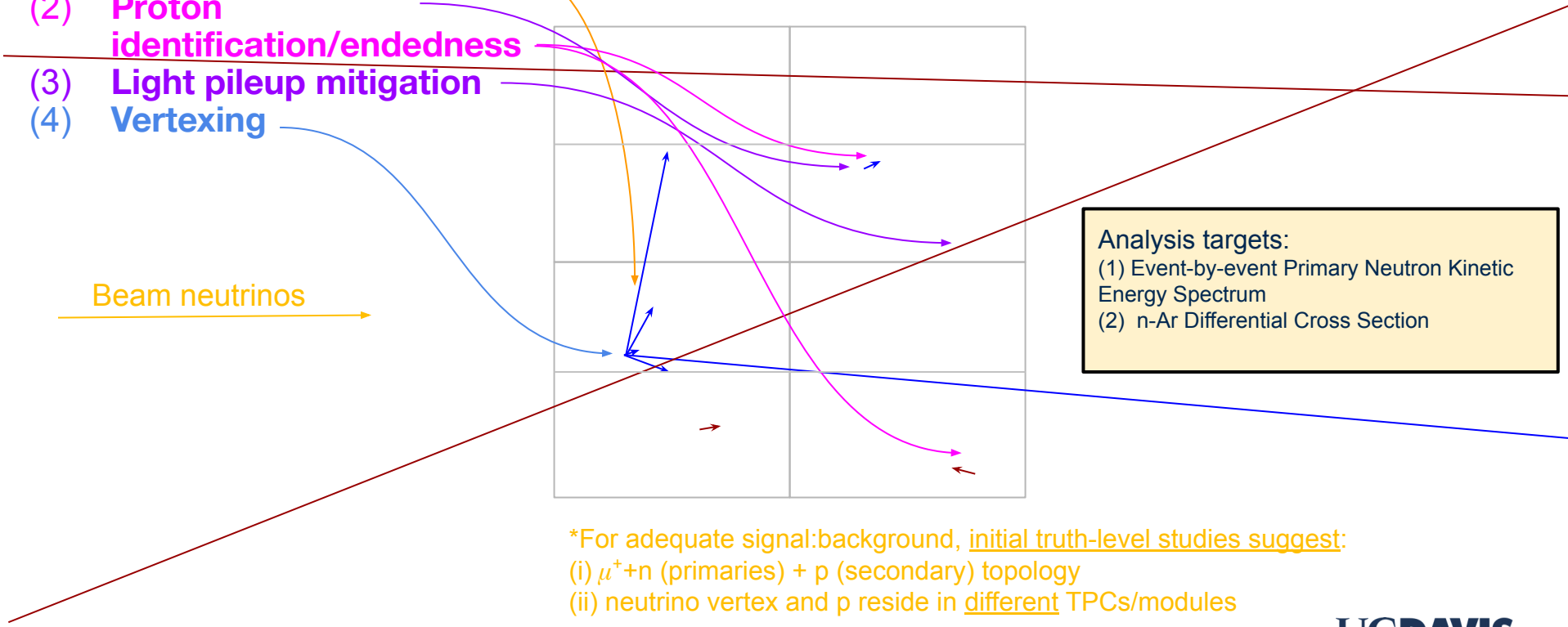
n-Ar inelastic cross-section measurement at 2x2

Key analysis elements:

(1) **Neutrino identification**
(2) **Proton identification/endedness**
(3) **Light pileup mitigation**
(4) **Vertexing**



Analysis targets:
(1) Event-by-event Primary Neutron Kinetic Energy Spectrum
(2) n-Ar Differential Cross Section

*For adequate signal:background, initial truth-level studies suggest:
(i) μ^++n (primaries) + p (secondary) topology
(ii) neutrino vertex and p reside in different TPCs/modules

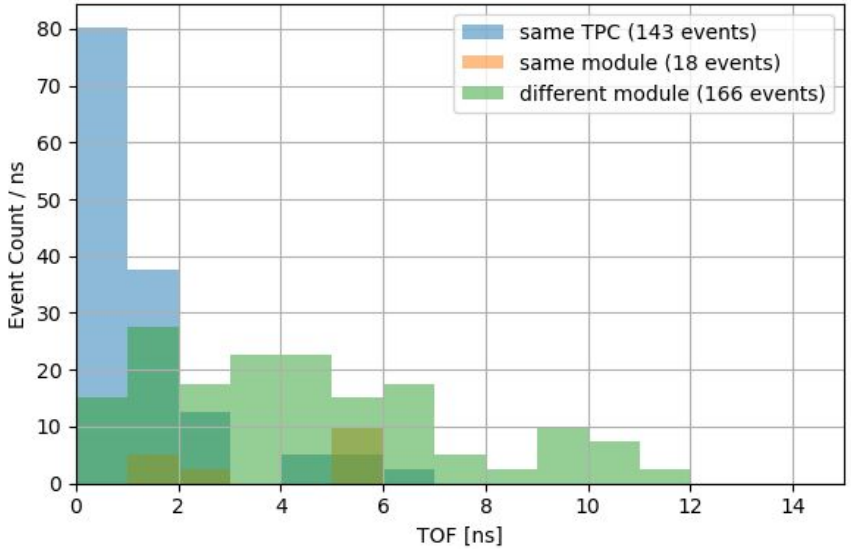
From 2x2 workshop (A. White)

Importance of Light Readout System:

1. **Light Pileup Mitigation**: need **time of flight** of neutron from proton track
   a. Need to have signal shape well-characterized
2. **T0** of interactions (neutrino & proton)
   a. Tof ~ **5 ns**
   b. Timing resolution ~ **2ns**
3. L (lever arm)
   a. Vertex resolution: to be investigated

$$T_n = (\gamma - 1) m_n$$

$$\text{where } \gamma = \frac{1}{\sqrt{1 - \left(\frac{l_{lever}}{c t_{tof}}\right)^2}}$$



From 2x2 workshop (A. White)

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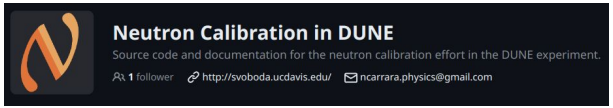
Reconstruction

Goal: Identify ***distended proton tracks*** originating from a ***neutrino interaction***.

The reconstruction consists of three stages,

1. Infer ***high-level variables*** from low-level detector reconstruction.
2. Select ***neutrino events*** with ***distended proton tracks***.
3. Infer ***inelastic n-Ar interactions*** from selection.



Key analysis elements:

(1) Neutrino identification
(2) Proton identification/endedness
(3) Light pileup mitigation
(4) Vertexing

From 2x2 workshop (A. White)

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ArrakisND [N. Carrara, M. van Nuland]

ArrakisND works with h5flow to produce ***high-level variables*** for each reconstructed charge/light hit.

Each category represents a different ***scale*** and is constructed to be ***exhaustive*** and ***mutually exclusive***; (i.e. each hit MUST be described by ONE and ONLY ONE label in each category).

The categories are chosen to capture ***ALL*** relevant physical information.

From 2x2 workshop (A. White)

High-level features	Description
topology	topological descriptor of physics (e.g. blip, track, shower)
particle	the pdg code of the particle which caused the energy deposition
physics_micro	low-level descriptor of physics processes (e.g. mip_ionization, gamma_conversion, etc.)
physics_meso	mid-level descriptor of physics processes (e.g. hip, delta_electron, capture_gamma, etc.)
physics_macro	high-level descriptor of physics processes (e.g. cc_qe, neutron_capture, radiological, etc.)
unique_topology	unique identifier of individual topology instances
unique_particle	unique identifier of individual particle instances (i.e. track id)
unique_physics_*	unique identifier of individual physics instances

https://github.com/Neutron-Calibration-in-DUNE/ArrakisND/blob/main/arrakis_nd/dataset/common.py

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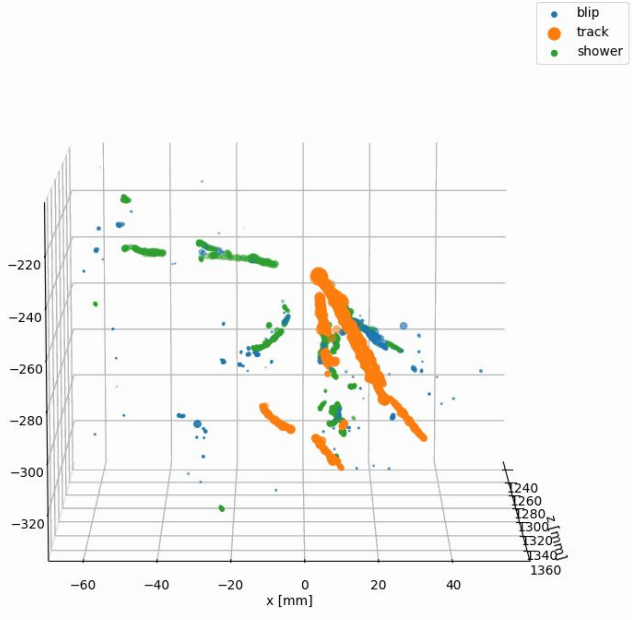
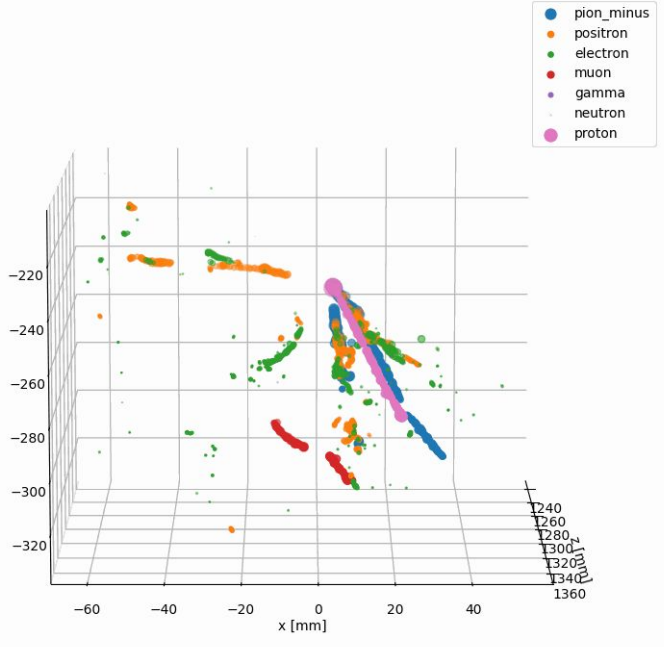
ArrakisND [N. Carrara, M. van Nuland]

Topology



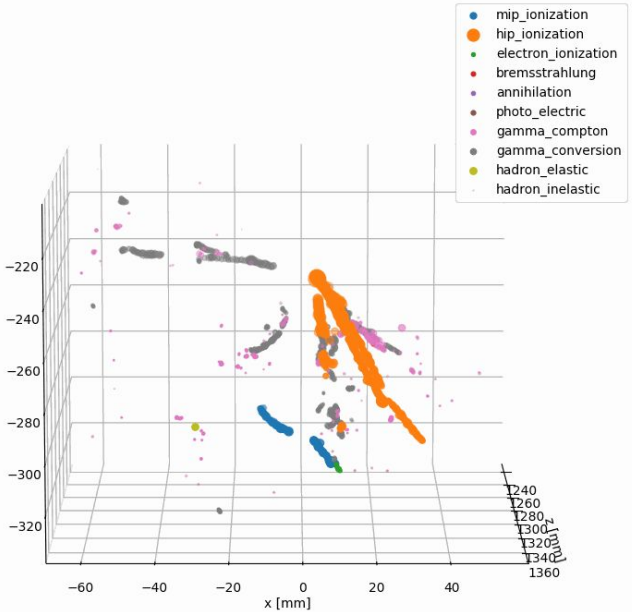
Particle



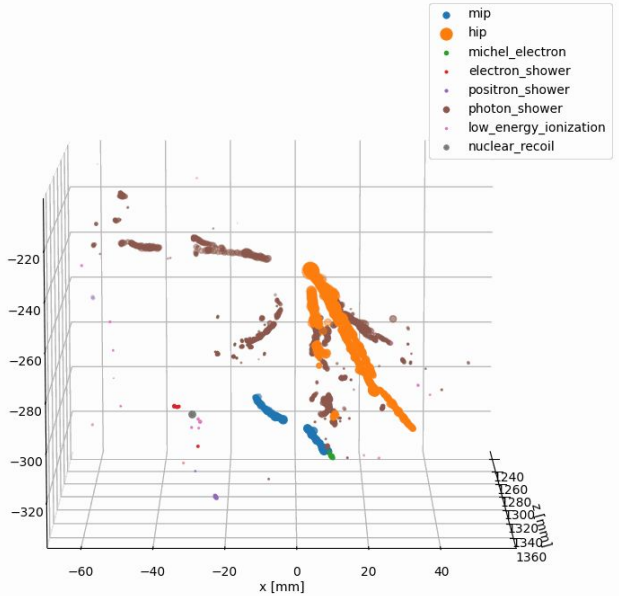
From 2x2 workshop (A. White)

ArrakisND [N. Carrara, M. van Nuland]

Physics Micro



Physics Meso



From 2x2 workshop (A. White)

ArrakisND [N. Carrara, M. van Nuland]

Work in progress:

- ❏ Add in ***track_topology*** variables (vertices, track begin/end, etc.).
- ❏ Add **CAF** variables for each event (tracks, showers, etc.)
- ❏ Add in ***light reco truth*** and ***low level variables*** for reconstruction.
- ❏ Finish ***physics_macro*** logic.

Arrakis is being optimized to run with the flow.

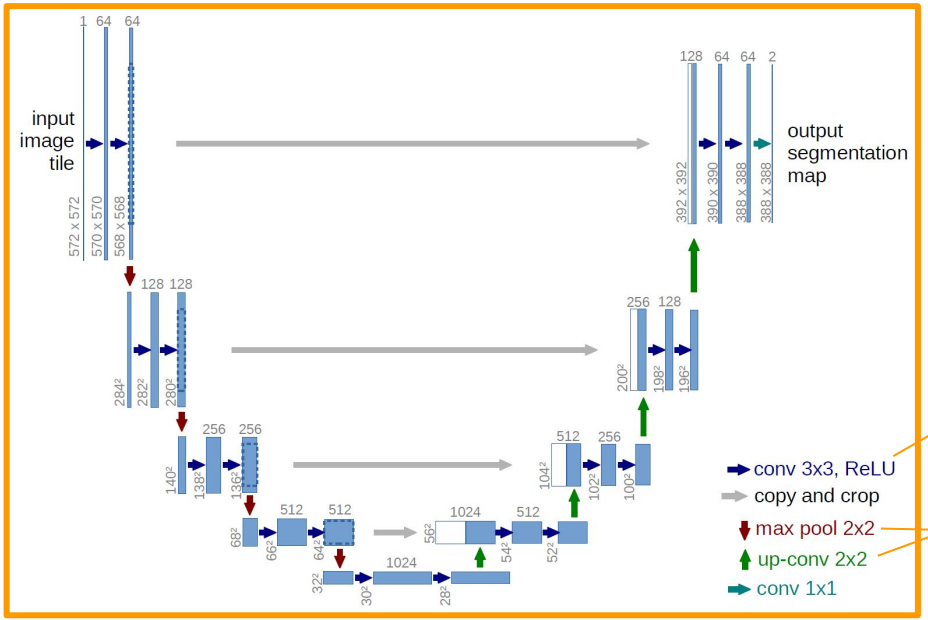
```
module:
  module_name:  'prep_data'
  module_type:  ['dataset']
  module_mode:  ['dataset_prep']
  gpu:          True
  gpu_device:   0
  verbose:      True

dataset:
  skip_processing:  false
  transform:        null
  pre_transform:    null
  pre_filter:       null
  dataset_type:   "tpc"
  dataset_folder: "/local_data/"
  dataset_files:  [
    "MiniRun4_1E19_RHC.flow.00000.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00001.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00002.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00003.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00004.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00005.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00006.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00007.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00008.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00009.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00010.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00011.FLOW.arrakis_nd.npz"
    "MiniRun4_1E19_RHC.flow.00012.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00013.FLOW.arrakis_nd.npz",
    "MiniRun4_1E19_RHC.flow.00014.FLOW.arrakis_nd.npz"
  ]
  variables:
    positions:      ['x', 'y', 'z']
    features:       []
    classes:        ['particle', 'topology', 'physics_micro', 'physics_meso']
    labels:         []
    clusters:       []
    hits:           []
    position_normalization:   []
    features_normalization:   []
    classes_mask: []
    labels_mask:  [[]]
    voxelization: [1, 1, 1]

  weights:
    class_weights:  []
    sample_weights: False      You, 3 weeks ago • some changes
```

From 2x2 workshop (A. White)

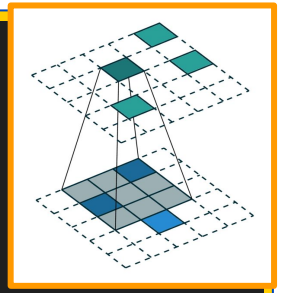
BlipSegmentation [G. Kuffaty]

Blip is run using a config file structure by specifying ***modules*** (such as the “ml” module).

The simplest model is a UNet structure which can be parameterized at run time.




```
module:
  module_name:  'optimize_blip_segmentation'
  module_type:  ['ml']
  module_mode:  ['training']
  gpu:          true
  gpu_device:   0
  verbose:      true
  debug:        true

dataset:
  dataset_params:   ""
  dataset_type:     "tpc"
  skip_processing:  true

loader:
  loader_type:          "minkowski"
  quantization_mode:    "random_subsample"
  minkowski_algorithm:  "speed_optimized"
  batch_size:       16
  test_split:       0.1
  test_seed:        42
  validation_split: 0.3
  validation_seed:  42
  num_workers:      4

training:
  iterations:   1       You, 3 weeks ago • some changes
  epochs:       100
  checkpoint:   25
  progress_bar: "all"     # train, validation, test, all
  rewrite_bar:      false # wether to leave bars after each epoch
  save_predictions: false # wether to save network outputs in original file
  no_timing:    true      # wether to keep timing/memory info in callback
  skip_metrics: true      # wether to skip metrics except for testing sets
  seed:         0

model:
  model_type:       "single"
  BlipSegmentation:
    in_channels:      1
    out_channels:     [5]
    classifications:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    filtrations:      [64, 128, 256, 512]
    residual:         true
    sparse_conv_params:
      kernel_size:     3
      stride:     1
      dilation:   1
      activation: "prelu"
      dimension:  3
      batch_norm: True
      num_of_convs: 2
      dropout:    0.1
    conv_transpose_params:
      kernel_size: 2
      stride:     2
      dilation:   1
      dimension:  3
    max_pooling_params:
      kernel_size: 2
      stride:     2
      dilation:   1
      dimension:  3
```



Hyper-parameter Tuning [N. Carrara, G. Kuffaty]

Blip is configured through a container on NERSC.

A Blip program can generate a collection of config files with varying parameters for hyperparameter tuning.

Several models can be deployed for training simultaneously on Perlmutter. The results are then analyzed after training.

infophysics/blip ☆

By infophysics • Updated 2 days ago

Docker image for the blip package.

Image

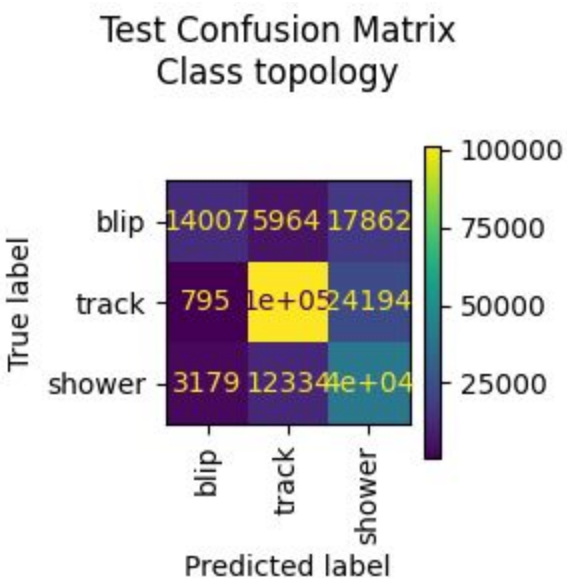
```
setfacl -m u:nobody:x /global/cfs/cdirs/dune/users/${USER}
shifter --image=docker:infophysics/blip:latest \
        --volume="${LOCAL_SCRATCH}:/local_scratch;${LOCAL_BLIP}:/local_blip;${LOCAL_DATA}:/local_data" \
        ./blip_segmentation_optimize.sh $hyper_parameter_config      You, 3 weeks ago • some changes
```

```
#!/bin/bash
cd /local_scratch

prep_data_config="/local_blip/BlipModels/blip_segmentation/2x2/configs/prep_data.yaml"
optimization_config="/local_blip/BlipModels/blip_segmentation/2x2/configs/optimize_blip_segmentation.yaml"

# download data to /local_data/ and process it
blip "$prep_data_config"

# generate hyper-parameter configs
create_hyper_parameter_configs "$optimization_config" -hyper_parameter_location=${LOCAL_BLIP}      You, 3 w
```

From 2x2 workshop (A. White)

BlipSegmentation [N. Carrara, G. Kuffaty]

Very early!



Losses and metrics can also be configured at run time.

```
criterion:
  CrossEntropyLoss:
    alpha:    1.0
    target_type:  "classes"
    targets:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    outputs:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    augmentations:  0

metrics:
  ConfusionMatrixMetric:
    target_type:  "classes"
    when_to_compute:  "test"
    targets:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    outputs:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    augmentations:  0
  AdjustedRandIndexMetric:
    target_type:  "classes"
    when_to_compute:  "test"
    targets:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    outputs:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    augmentations:  0
  AUROCMetric:
    target_type:  "classes"
    when_to_compute:  "test"
    targets:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    outputs:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    augmentations:  0
  DiceScoreMetric:
    target_type:  "classes"
    when_to_compute:  "test"
    targets:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    outputs:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    augmentations:  0
  JaccardIndexMetric:
    target_type:  "classes"
    when_to_compute:  "test"
    targets:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    outputs:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    augmentations:  0
  AveragePrecisionMetric:
    target_type:  "classes"
    when_to_compute:  "test"
    targets:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    outputs:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    augmentations:  0
  PrecisionMetric:
    target_type:  "classes"
    when_to_compute:  "test"
    targets:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    outputs:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    augmentations:  0
  RecallMetric:
    target_type:  "classes"
    when_to_compute:  "test"
    targets:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    outputs:  ['particle', 'topology', 'physics_micro', 'physics_meso']
    augmentations:  0
```

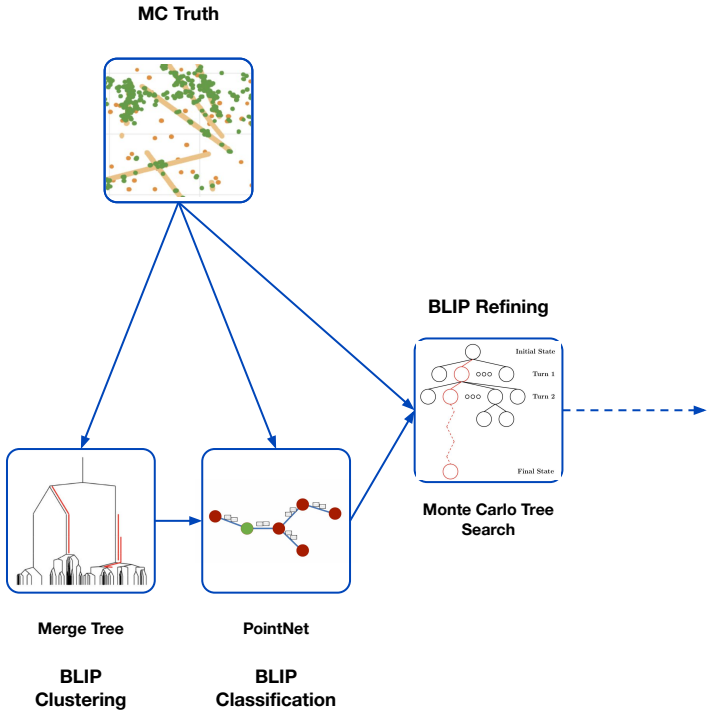
From 2x2 workshop (A. White)

BlipNet

N. Carrara, D. Rivera, L. Perez-Molina

Let's compare our results with MC Truth at each stage of the reconstruction. The full chain begins with,

1. **Merge Tree** - First we construct a topological description of the event called a *decorated merge tree*.
2. **BLIP Classification** - BlipGraph is used to classify blips as different types (Ar39, Kr85, Rn222, Capture Gammas, etc.)
3. **BLIP Refining** - A Monte Carlo Tree Search algorithm is used to refine blips and construct higher-level structures.



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BlipNet

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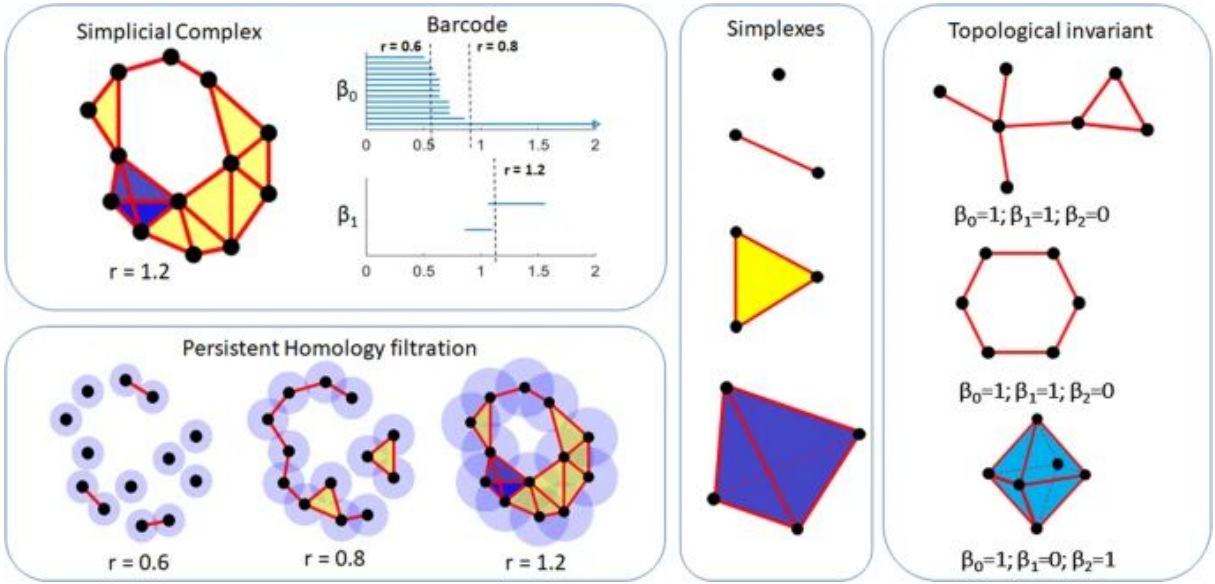
1. **Merge Tree** - First we construct a topological description of the event called a *decorated merge tree*.

Persistent Homology - A set of theorems and techniques in ***topological data analysis*** for studying topological features of point sets.



5 G. Carlsson, Topology and Data, (https://www.ams.org/journals/bull/2009-46-02/S0273-0979-09-01249-X/S0273-0979-09-01249-X.pdf).

6 H. Edelsbrunner and J. Harer, Persistent Homology - A Survey, (https://www.maths.ed.ac.uk/~v1ranick/papers/edelhare.pdf).

7 H. Edelsbrunner et al., Topological Data Analysis in Information Space, (https://arxiv.org/abs/1903.08510).

BlipNet

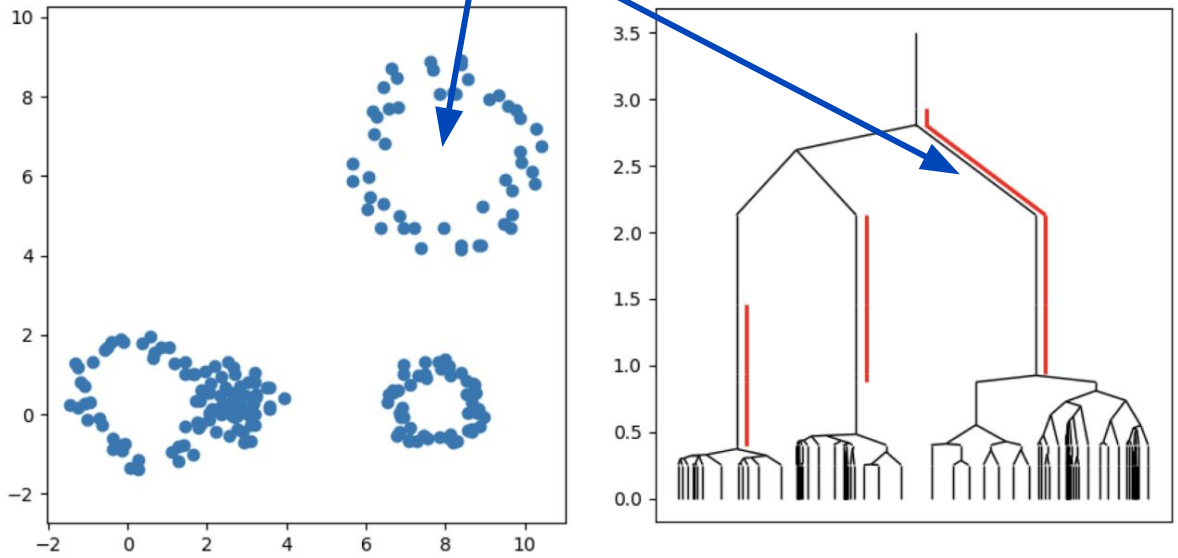
N. Carrara, D. Rivera, L. Perez-Molina

Let's compare our results with MC Truth at each stage of the reconstruction. The full chain begins with,

1. **Merge Tree** - First we construct a topological description of the event called a *decorated merge tree*.

Decorated Merge Tree - Topological description of a point set where a *merge tree* is decorated with degree (n > 0) features.

Degree 1 features



8 J. Curry et al., Decorated Merge Trees for Persistent Homology, (https://arxiv.org/abs/2103.15804).

BlipNet

N. Carrara, D. Rivera, L. Perez-Molina

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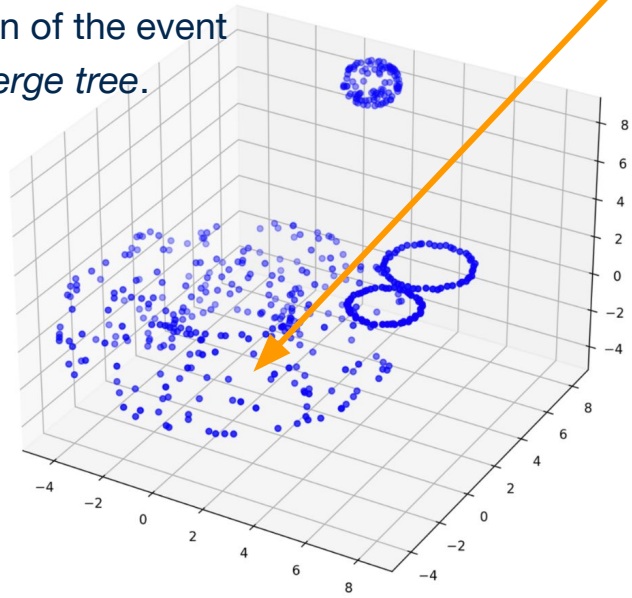
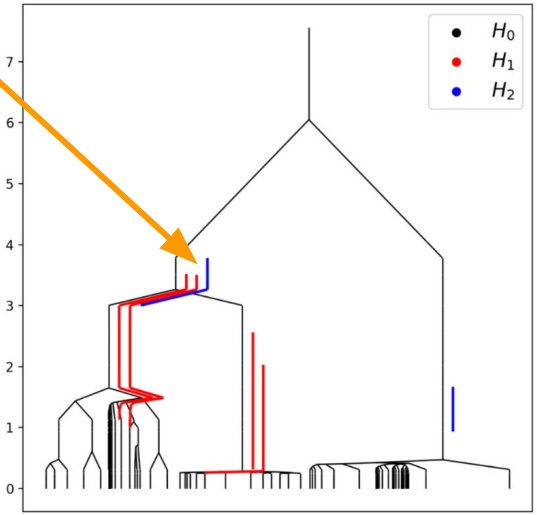
Decorated Merge Tree - Topological description of a point set where a *merge tree* is decorated with degree (n > 0) features.

Degree 2 features





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N. Carrara, D. Rivera, L. Perez-Molina

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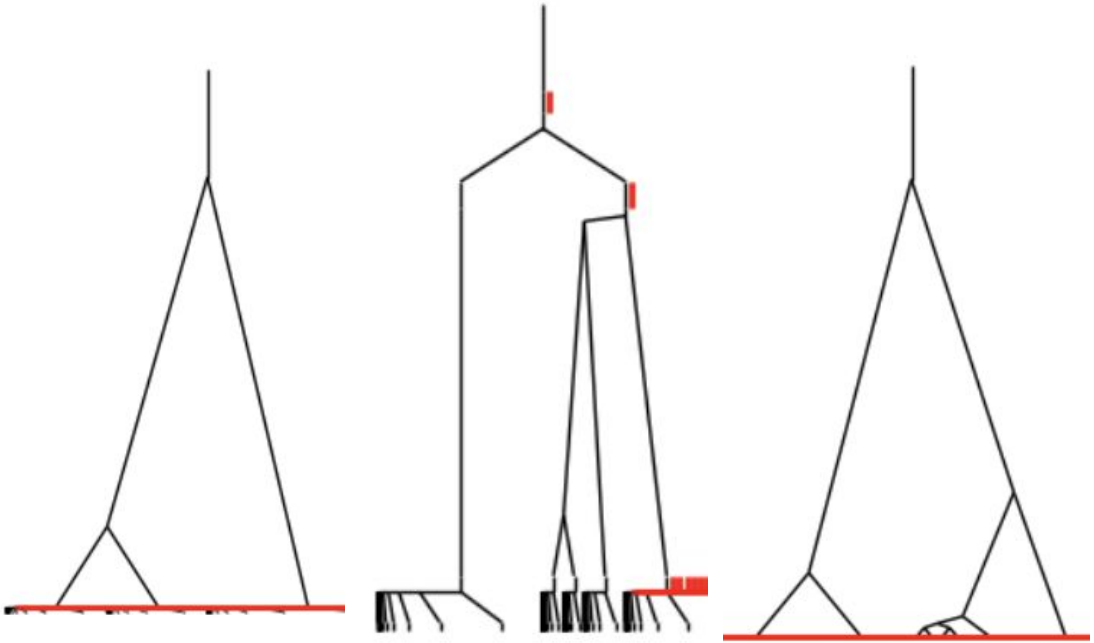
Merge Tree code developed by Laura Perez-Molina.

Decorated Merge Tree - Topological description of a point set where a *merge tree* is decorated with degree ($n > 0$) features.

Merge Trees from capture gammas



BlipNet

N. Carrara, D. Rivera, L. Perez-Molina

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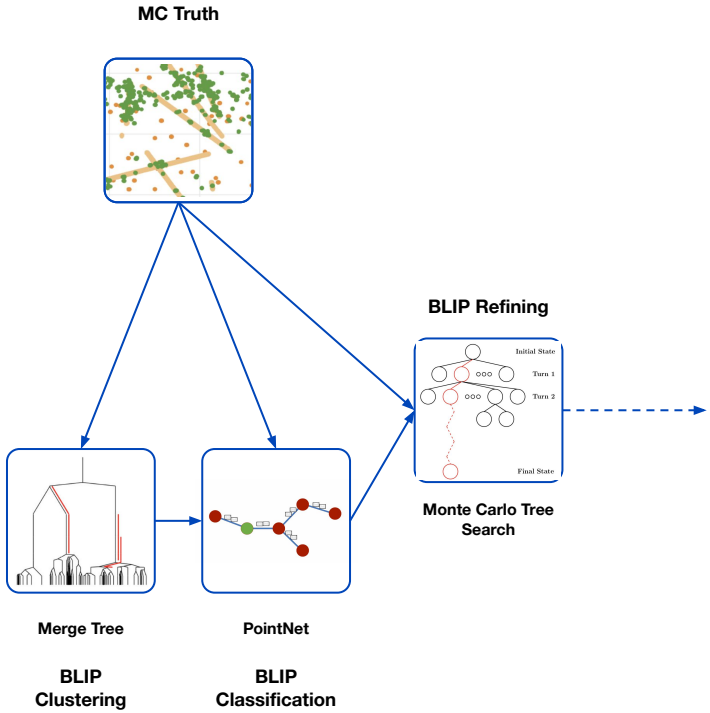
3. **BLIP Refining** - A Monte Carlo Tree Search algorithm is used to refine blips and construct higher-level structures.



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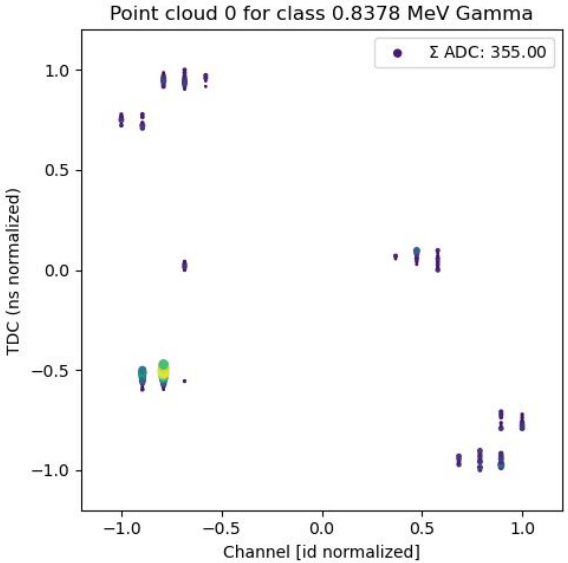
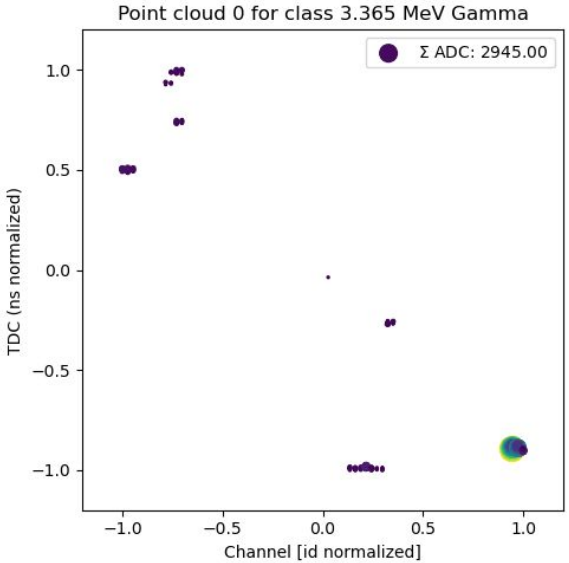
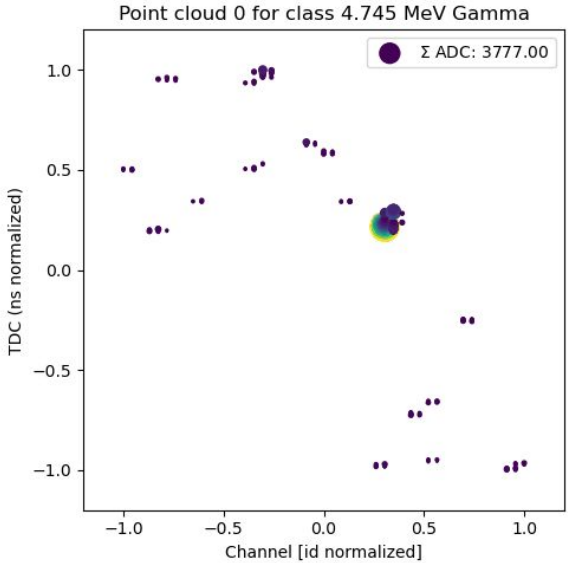
Blip Examples

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.



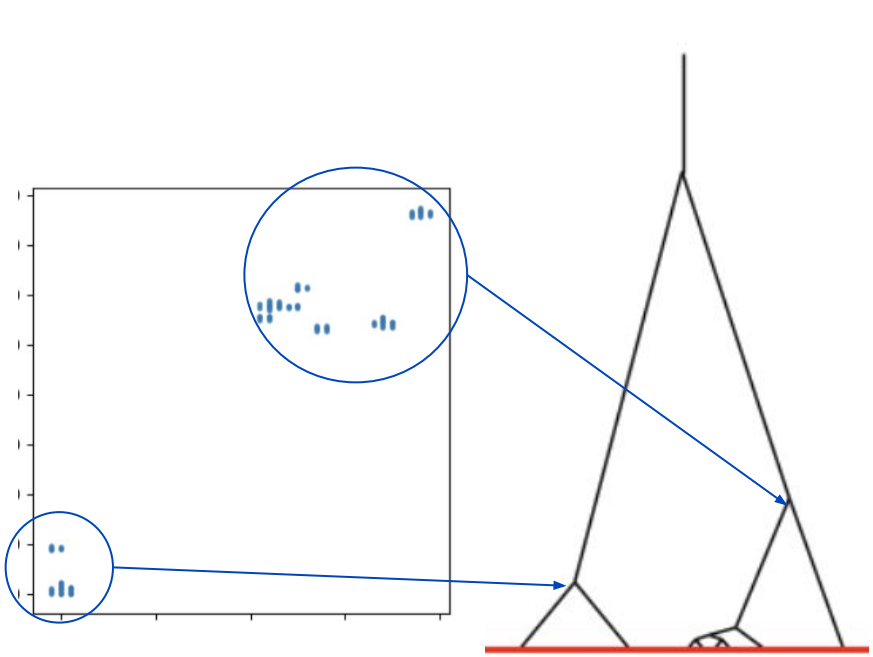


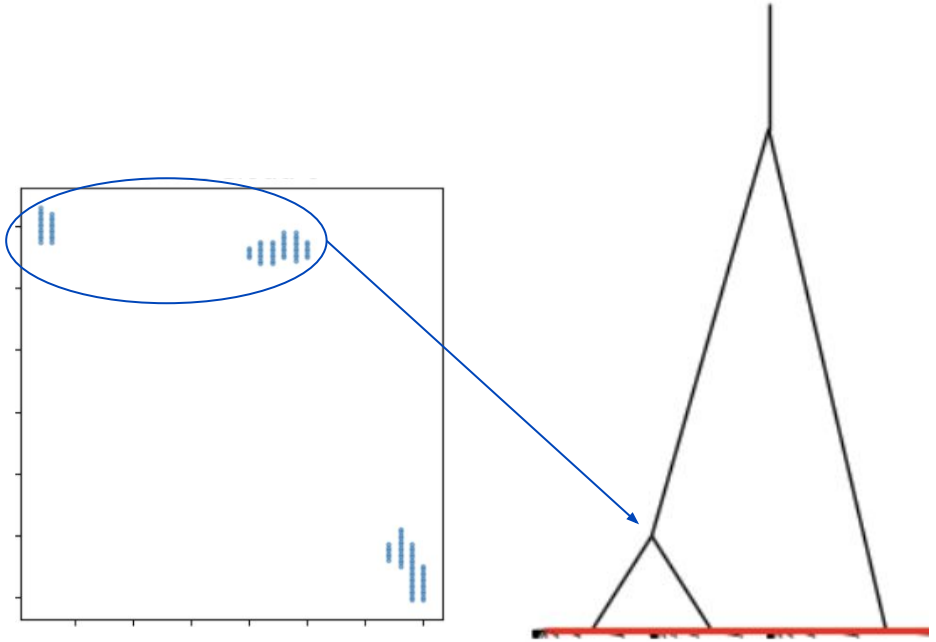


Blip Examples

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

- Merge Trees for 2.5661 MeV Gammas.



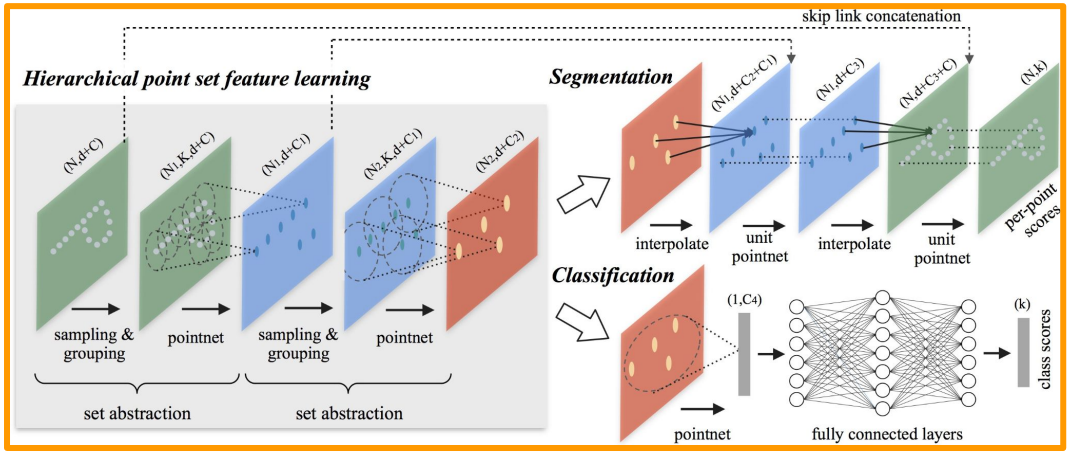


BLIP Classification

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]).



Models are built using the ***PyTorch Geometric*** API (https://pytorch-geometric.readthedocs.io/en/latest/)

4 *PointNet: Deep Learning on Point Sets for 3D Classification and Segmentation,* C. Qi et. al., CVPR 2017, (https://arxiv.org/abs/1612.00593).
5 *PointNet++: Deep Hierarchical Feature Learning on Point Sets in a Metric Space*, C. Qi et. al., (https://arxiv.org/abs/1706.02413)
6 *Dynamic Graph CNN for Learning on Point Clouds,* Y. Wang et. al., 2018, (https://arxiv.org/abs/1801.07829)

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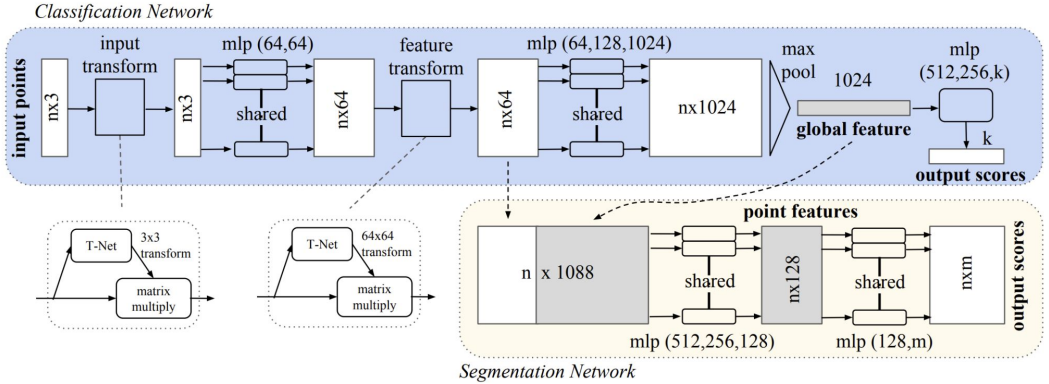
PointNet/DynamicEdgeConv

Figure from C. Qi et al. (2017).

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.



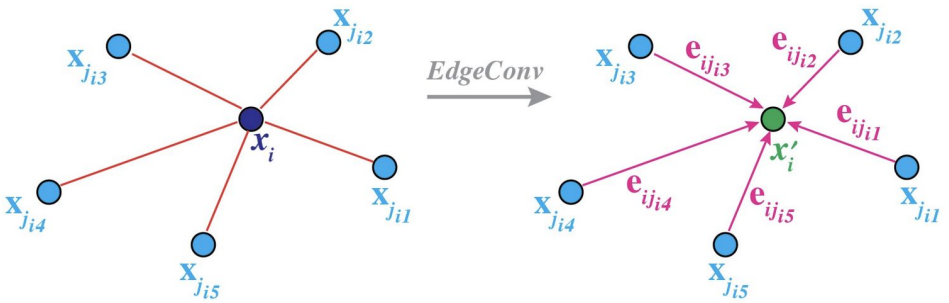


Figure from Y. Wang et al. (2019).

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Contrastive Learning

We can utilize symmetries in our dataset to conduct a semi-supervised learning in which point clouds are grouped together by symmetries in their representation.

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

$$\ell_{i,j} = -\log \frac{\exp(\text{sim}(\boldsymbol{z}_i, \boldsymbol{z}_j)/\tau)}{\sum_{k=1}^{2N} \mathbb{1}_{[k \neq i]} \exp(\text{sim}(\boldsymbol{z}_i, \boldsymbol{z}_k)/\tau)}, \qquad (1)$$

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

? K. Sohn, *Improved Deep Metric Learning With Multi-class N-pair Loss Objective*, NIPS (2016), (https://proceedings.neurips.cc/paper_files/paper/2016/file/6b180037abbebea991d8b1232f8a8ca9-Paper.pdf)

Contrastive learning scheme (https://ai.googleblog.com/2020/04/advancing-self-supervised-and-semi.html)

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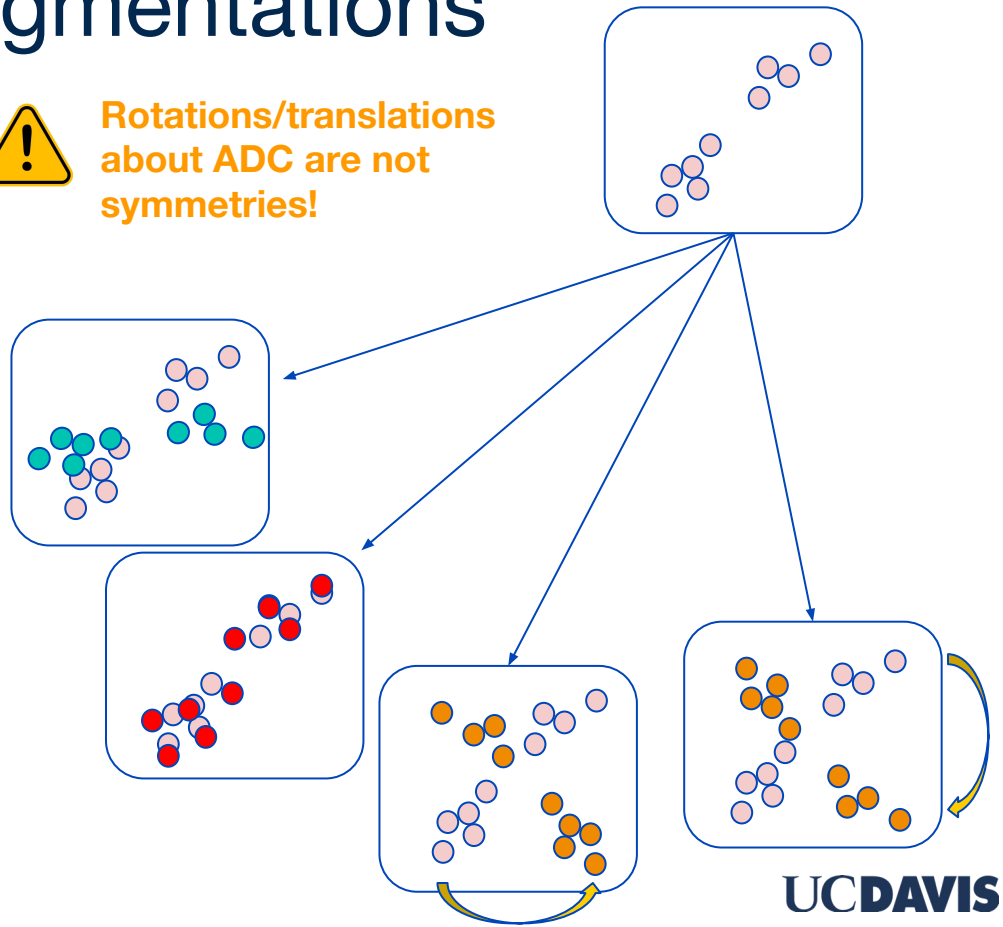
Symmetries -> Augmentations

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!



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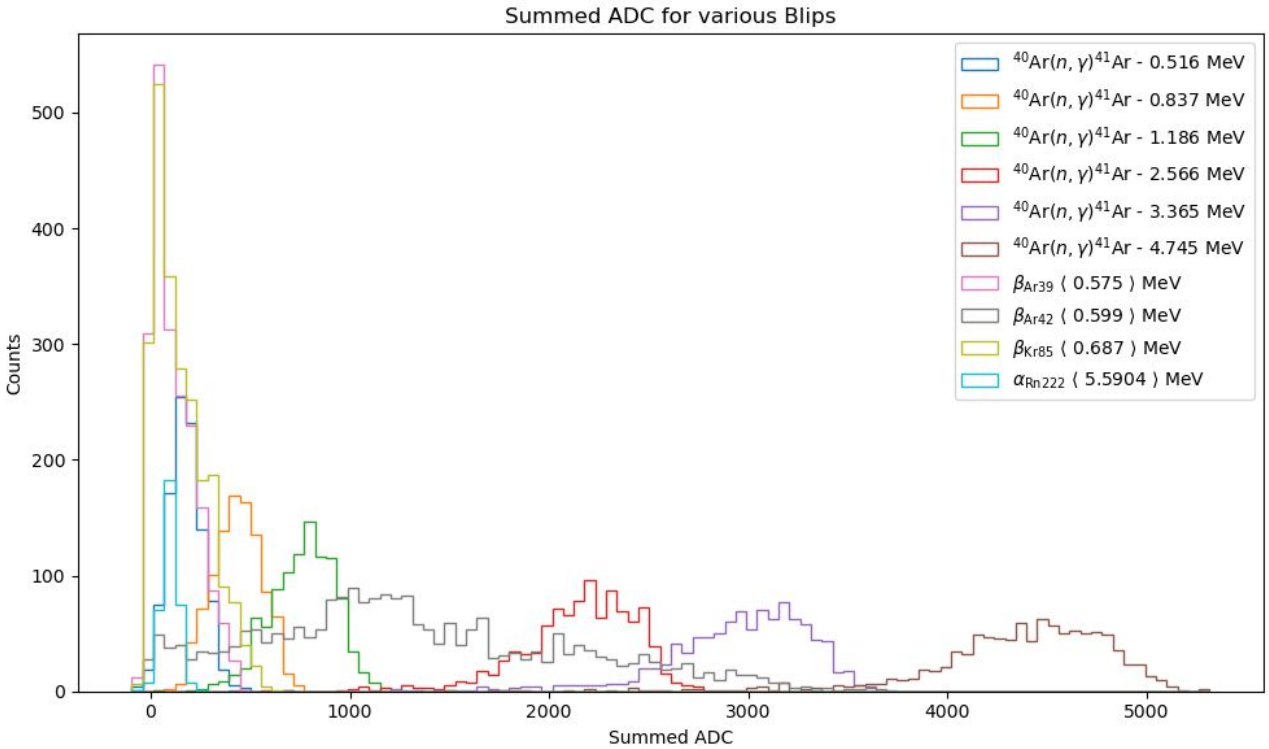
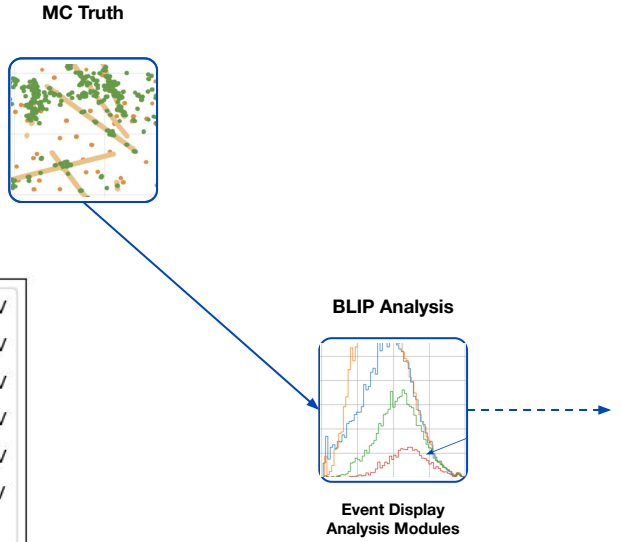
Far Detector (channel, tdc, adc)





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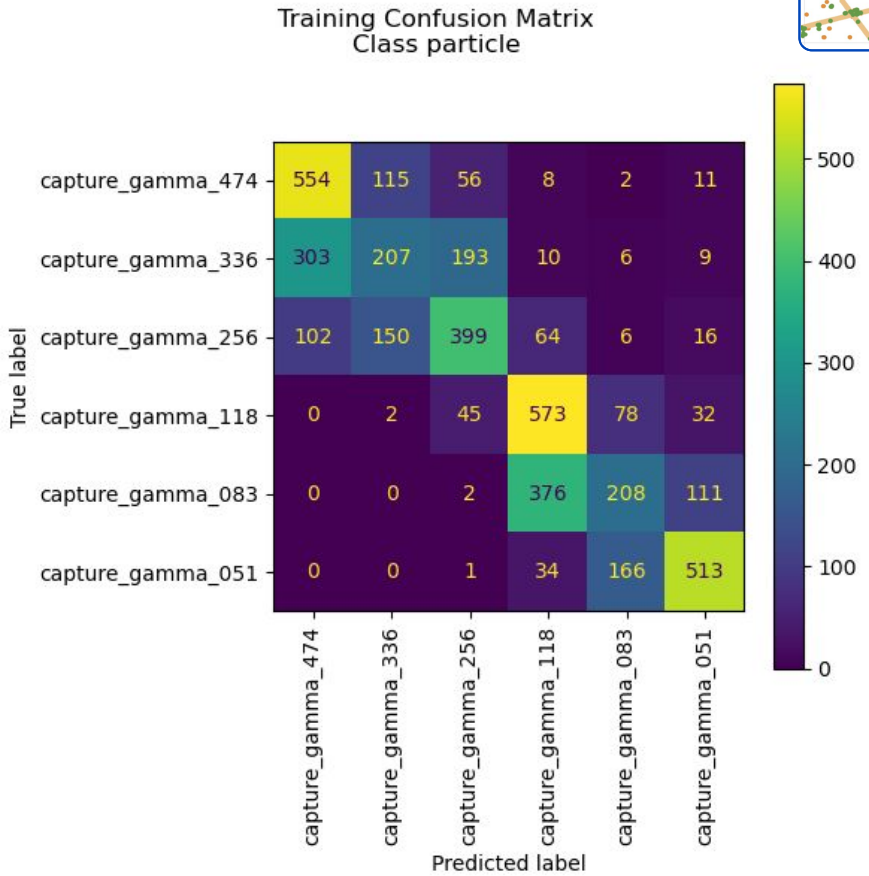
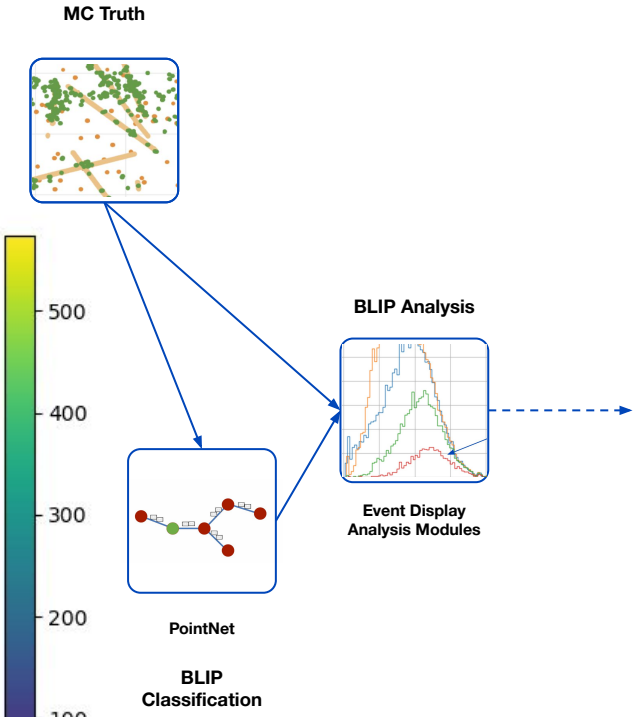
MCTruth + BlipGraph

The model needs some tuning, but the current version seems to be learning something about the shapes of the point clouds.





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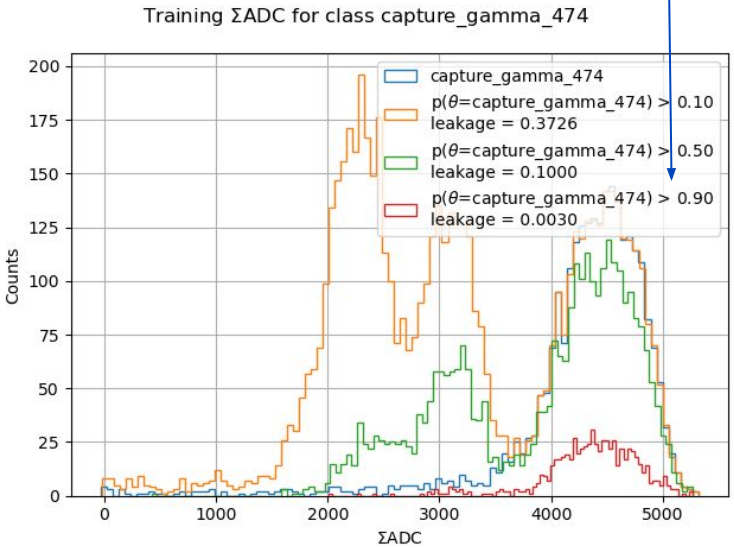
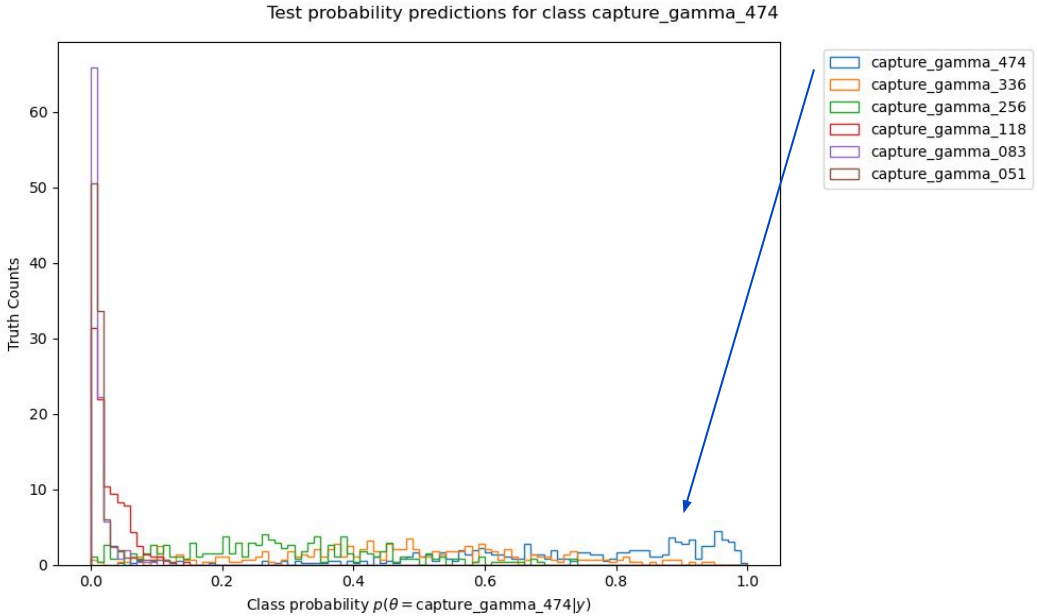
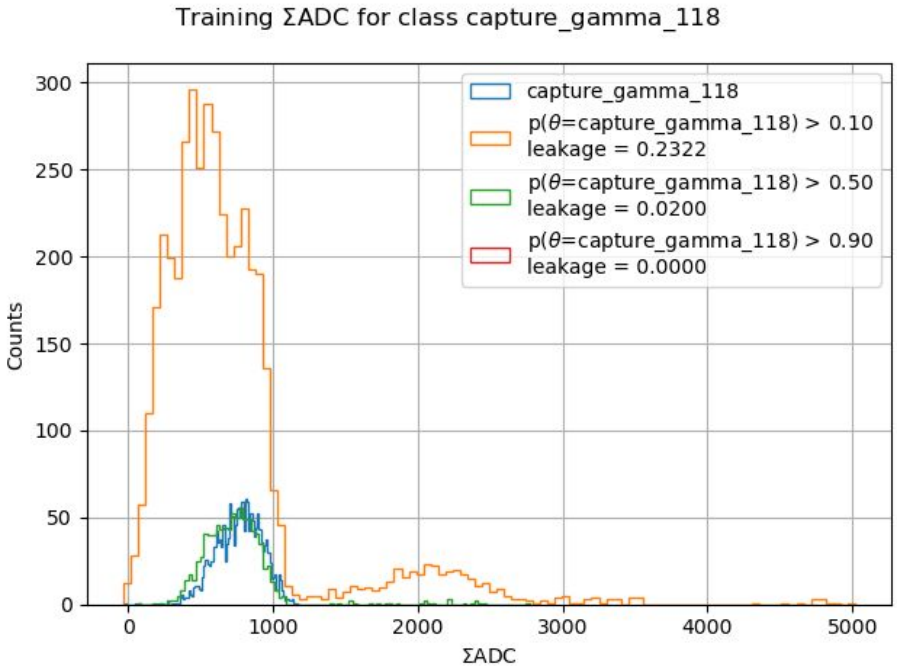
MCTruth + BlipGraph

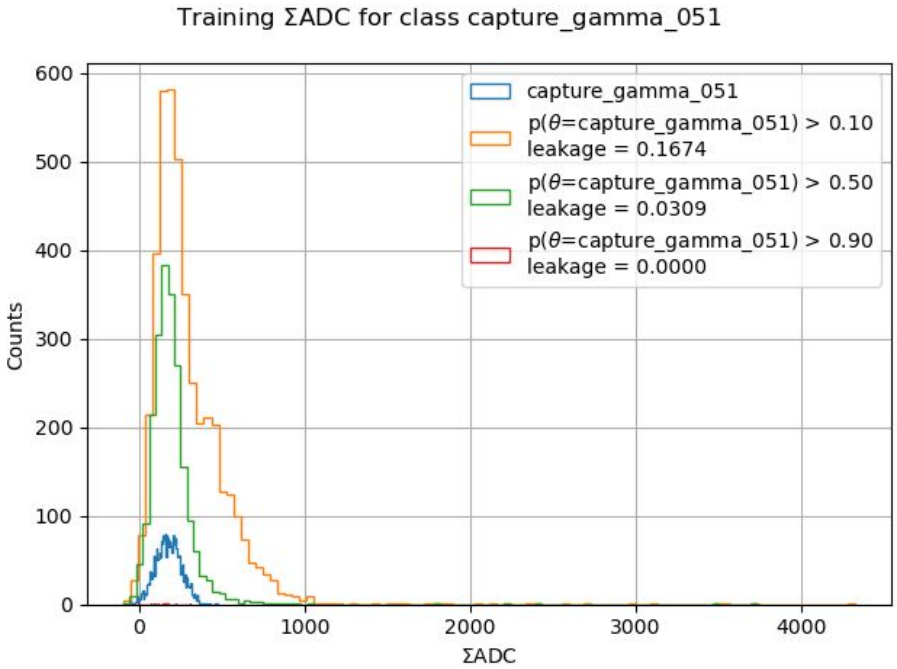
This early model rejects 99.7 % of all other blip types when imposing a 90% cut on the probability to being a 4.745 MeV gamma.





MCTruth + BlipGraph





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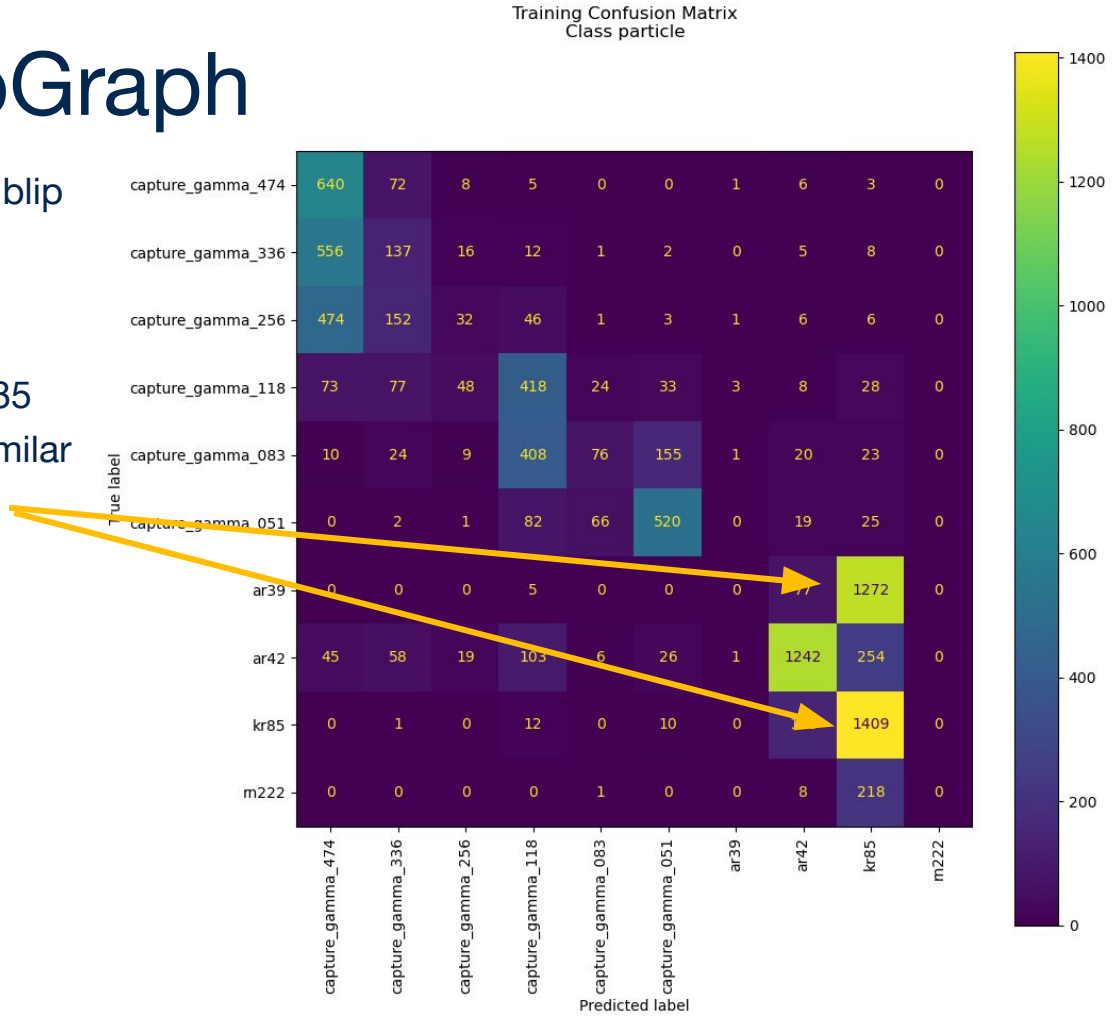
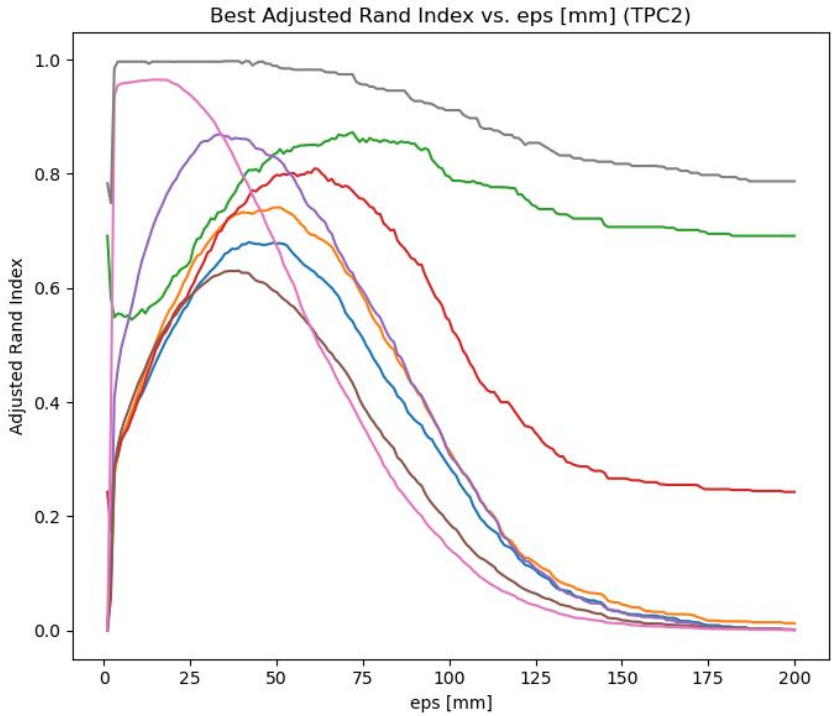
MCTruth + BlipGraph

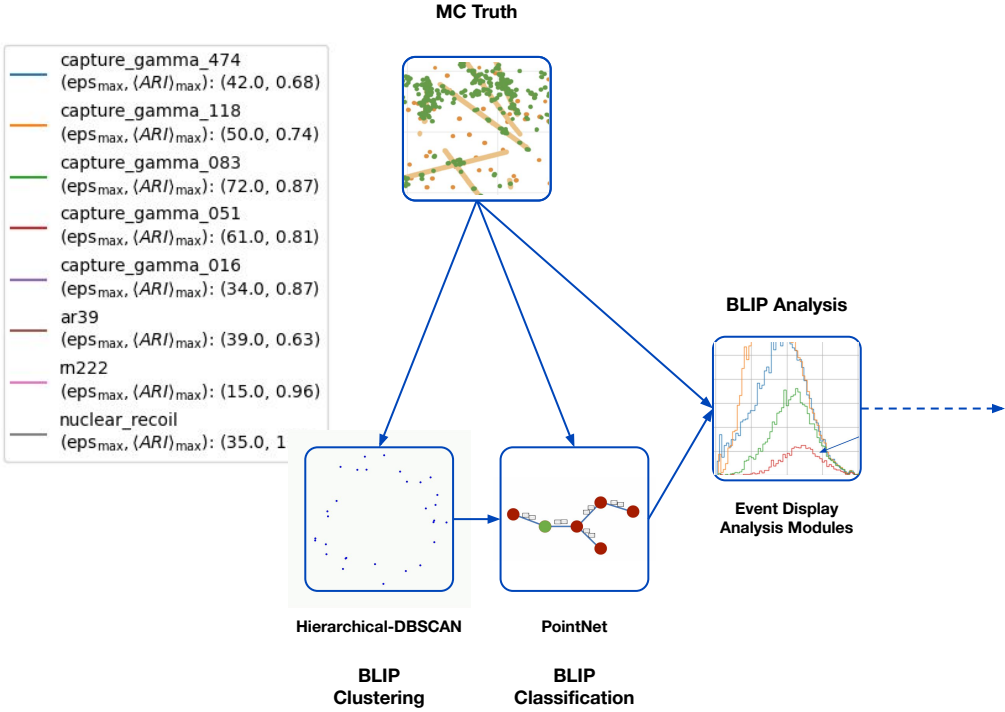
Some preliminary results on all current blip types.

Perhaps unsurprising that Ar39 and Kr85 are difficult to distinguish given their similar physics.



MCTruth + Clustering + BlipGraph





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BlipNet

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3. **BLIP Refining** - A Monte Carlo Tree Search algorithm is used to refine blips and construct higher-level structures.

N. Carrara, D. Rivera, L. Perez-Molina

Stay tuned for progress on BlipNet! See this recent publication (https://arxiv.org/abs/2309.08516) for some details on Monte Carlo Tree Search:

USING MONTE CARLO TREE SEARCH TO CALCULATE MUTUAL INFORMATION IN HIGH DIMENSIONS

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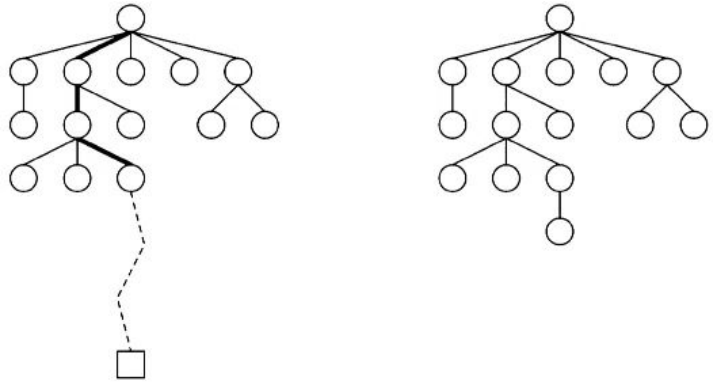

Work in Progress

Arrakis:

- ✓ module for gathering simulation/data products.
  - ✓ Wire plane/Raw digit data.
  - ❑ Reconstructed 3D space point data.
- ✓ module for labeling logic.
- ❑ integrate into ‘lar’ repositories.
- ❑ methods for ‘registering’ custom labeling logic.

Wilson Cluster/NERSC:

- ❑ Implement BLIP as a module that users can easily access without having to install (e.g. ‘module load blip’).
- ❑ Jupyter-lab/event-display over ssh integration.

BLIP:

- ✓ Construct infrastructure for generating training data/implementing models and training.
- ✓ Construct Semantic Segmentation model.
  - ❑ Optimize semantic segmentation.
- ✓ Construct Simple PointNet model.
  - ❑ Optimize BLIP Classification models (PointNet++ and HDBSCAN-PointNet).
- ❑ Continue adding new models/modules to extend the scope of the neural network applications.
- ✓ Implement a system to allow users to integrate their own model/analysis code.

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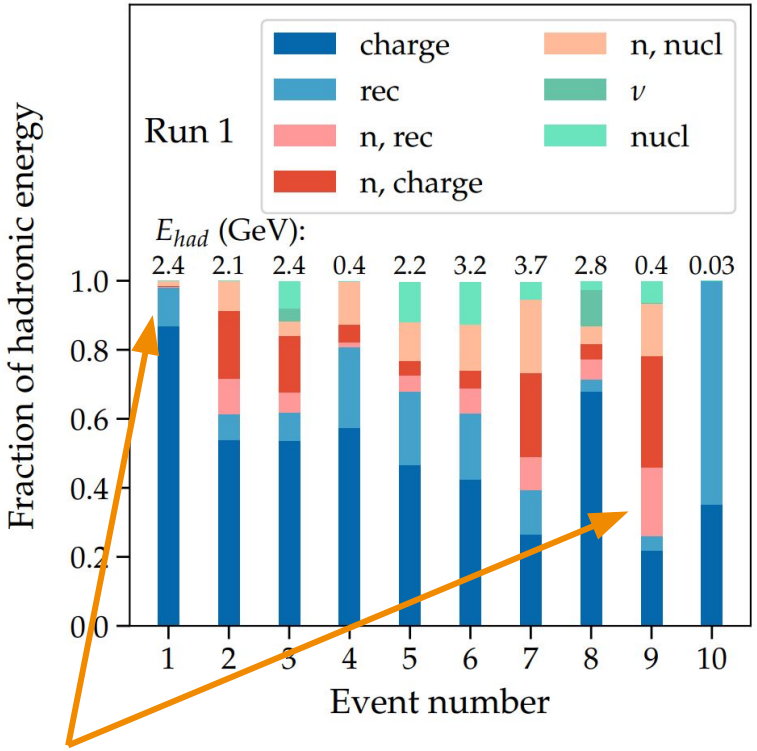
Backup

Energy resolution?

It is necessary to be able to account for the neutron "***missing energy***" in order to make precision oscillation measurements (production and transport).

A. Friedland and W. Li (2019) characterized the sources of missing energy in LArTPCs as,

1. Electronic shower sprays (**charge**)
2. Recombination effects (**rec**)
3. Nuclear breakup (**nucl**)
4. Outgoing neutrinos (***ν***)
5. Subthreshold particles
6. **Primary and secondary neutrons**



Contributions from neutrons vary widely from event to event!

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

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Energy resolution?

This pie chart from the same paper (2019) shows the average amount of missing energy over many events (~10K).

- Neutrons contribute nearly **~30%** of the missing energy on average!

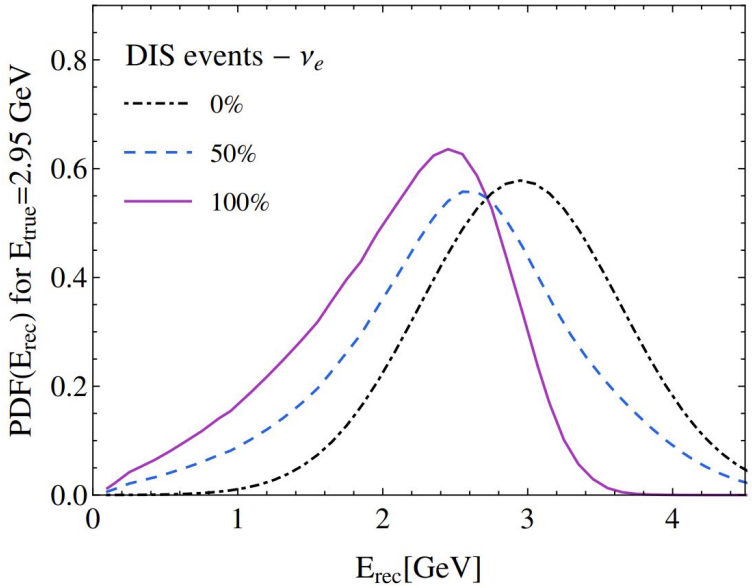

Figure from A. Ankowski et al. (2015).

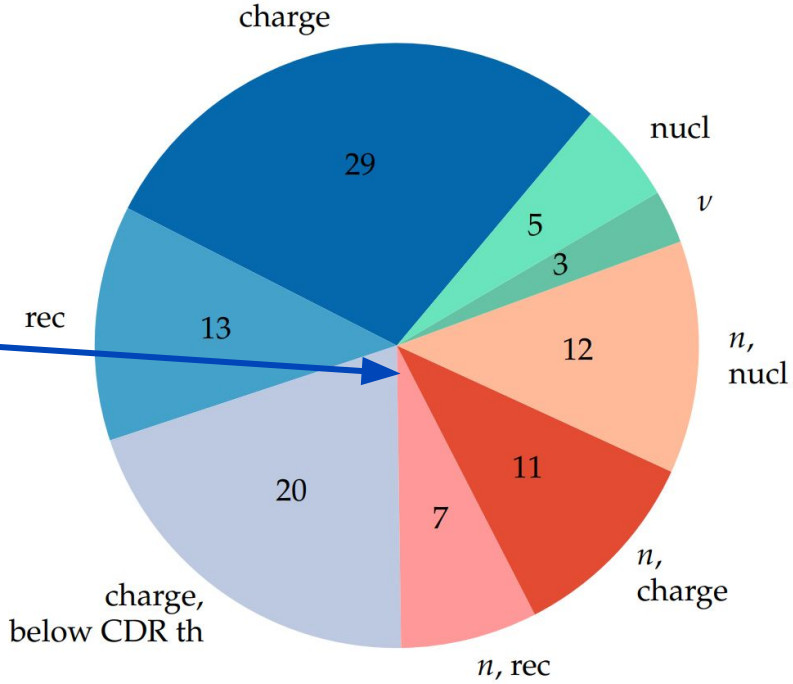

Figure from A. Friedland and W. Li (2019).

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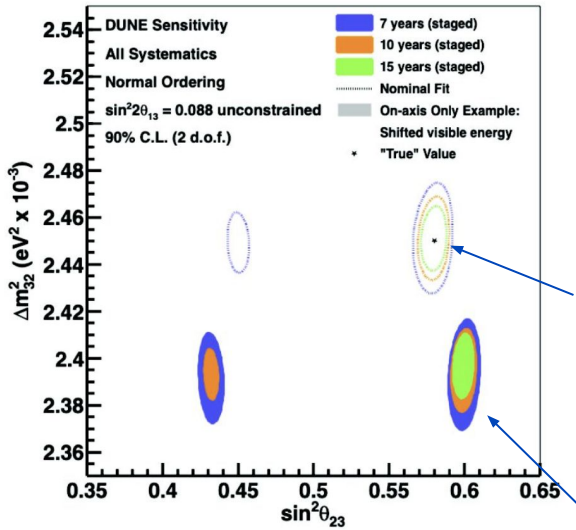
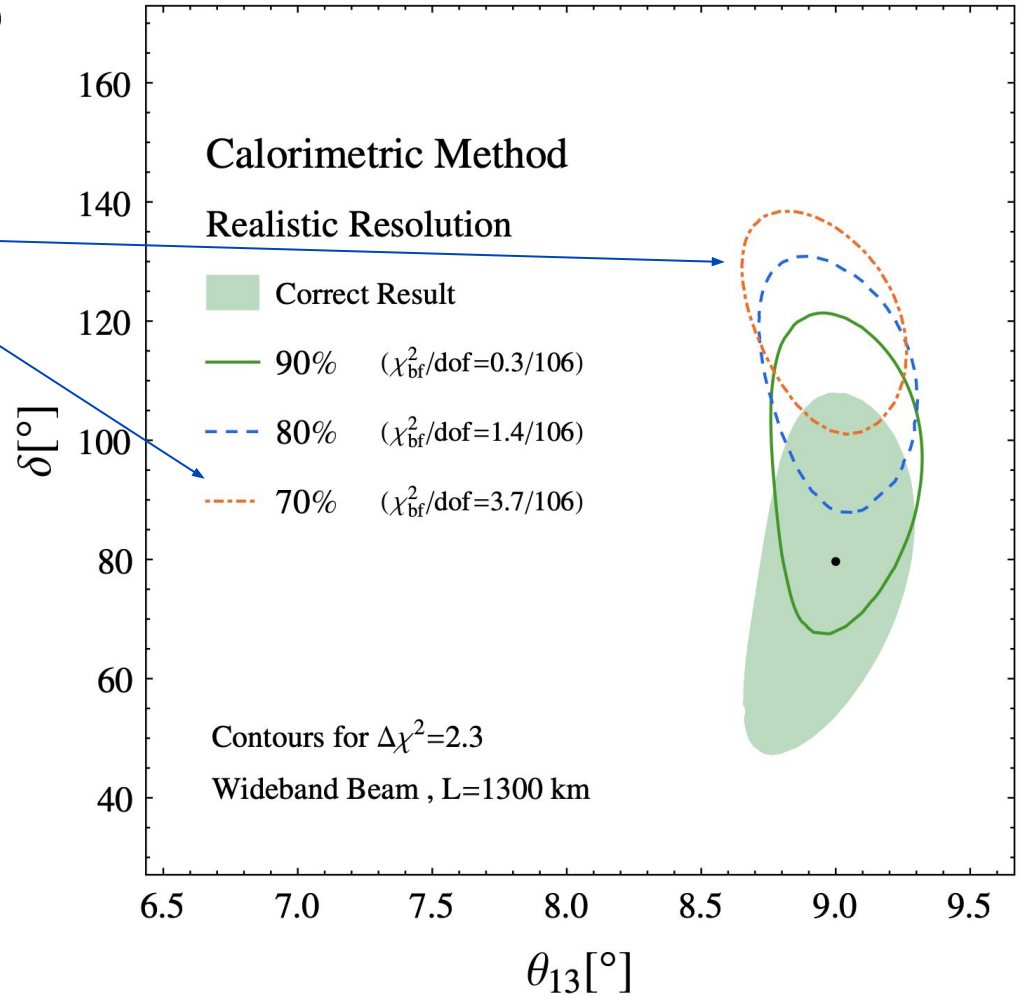
Energy resolution?

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



fit with 20% neutron energy missing

actual

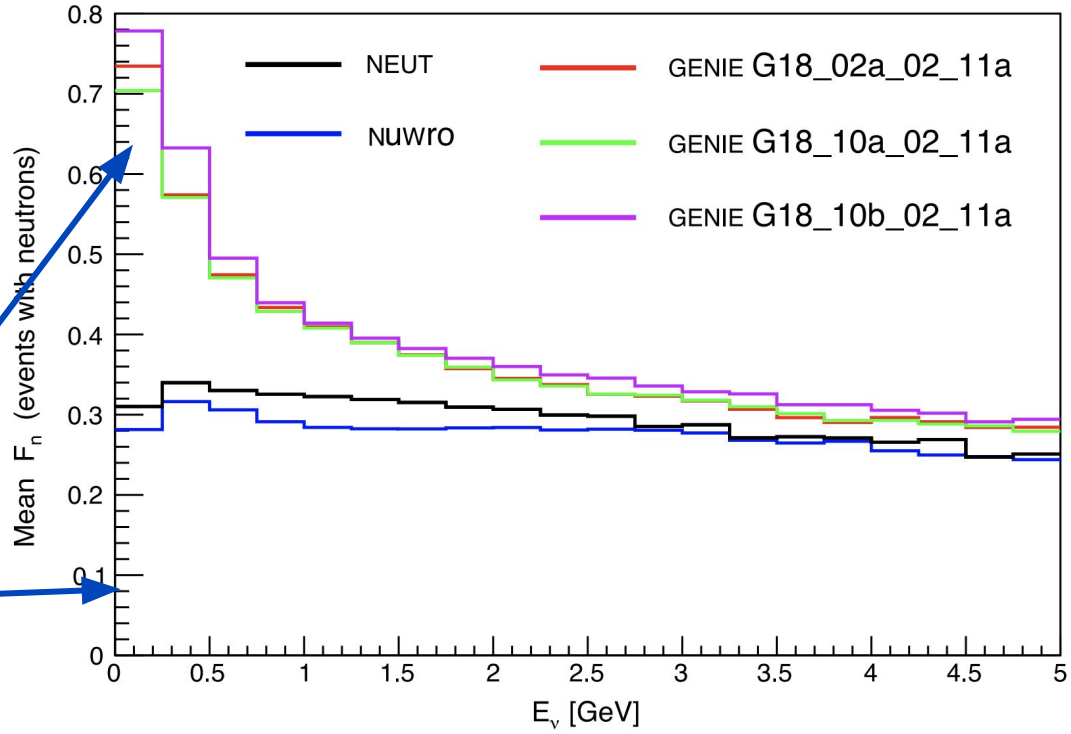


3 A. M. Ankowski et al., *Missing energy and the measurement of the cp-violating phase in neutrino oscillations*, Phys. Rev. D, **92** 2015 (https://arxiv.org/abs/1507.08561)

Model dependent final-states?

M. Buizza Avanzini et al. examined the differences in neutron final-states from the generators **NEUT**, **NuWro**, and **GENIE**.

- 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!



4 M. Buizza Avanzini, *Comparisons and challenges of modern neutrino-scattering experiments*, Phys. Rev D, **105** 2022 (https://journals.aps.org/prd/pdf/10.1103/PhysRevD.105.092004)

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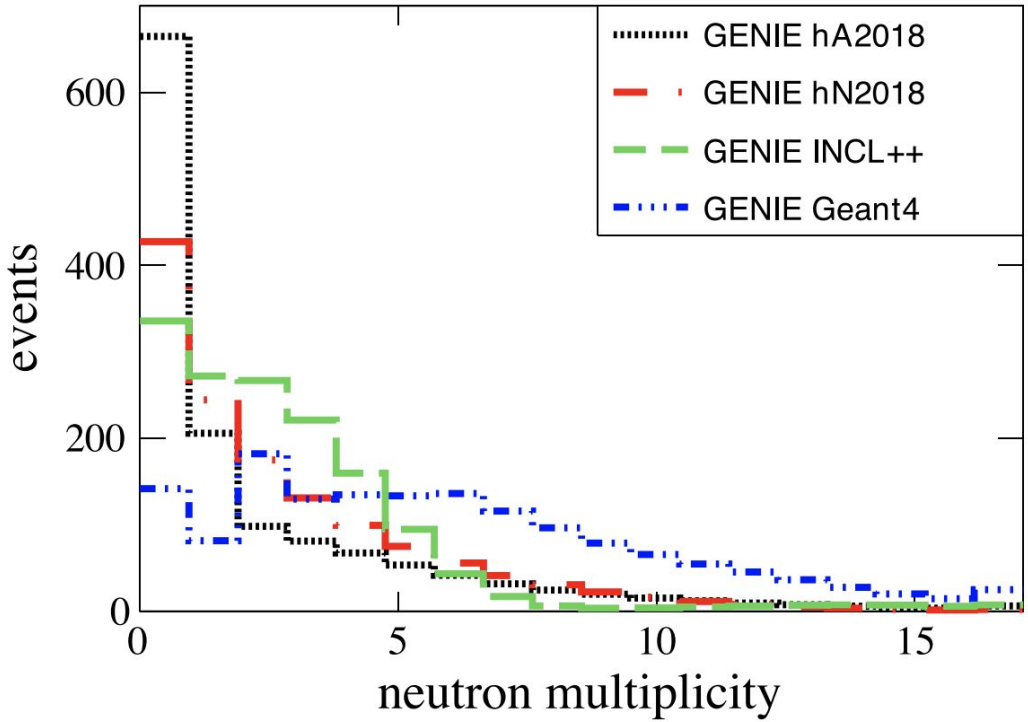
Model dependent final-states?

The various models within GENIE[5] also show a discrepancy in the predictions of neutron multiplicity.

- Neutron distributions from a simulated 2GeV muon neutrino interaction on Ar40.

Our group is working on a potential experiment to be deployed in ANNIE to measure neutron multiplicity on Ar!



5 The GENIE Collaboration, *Recent highlights from GENIE v3*, Eur. Phys. J. Spec. Top. (2021) (https://link.springer.com/article/10.1140/epjs/s11734-021-00295-7)

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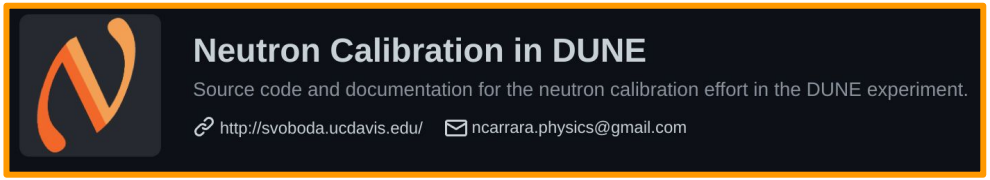
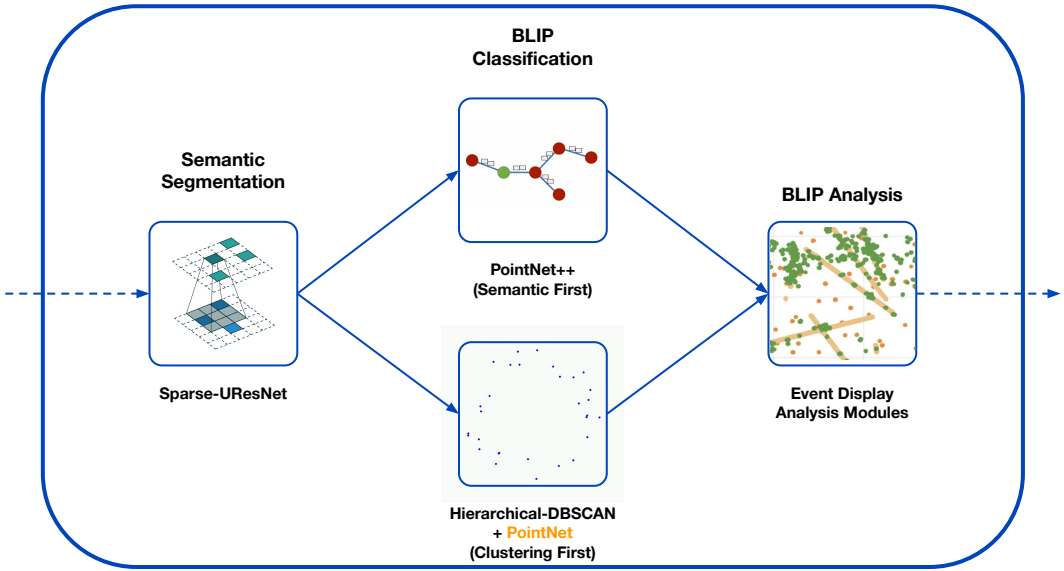
BLIP

We introduce ***BLIP***[2], a collection of ML algorithms for classifying low energy interactions in LArTPCs.

- **Semantic Segmentation**:
  - Pixel/point-cloud level classification for detector readout and/or reconstructed space points.
  - Identification of tracks/showers in order to **isolate** Blips.
- **Heirarchical Clustering**:
  - DBSCAN and Heirarchical-DBSCAN for clustering BLIPs.
- **Point-cloud Classification**:
  - BlipNet models for classifying BLIP point clouds.
- **Topological Data Analysis (TDA)**:
  - State-of-the-art algorithms for characterizing the topology of point sets (e.g. persistent homology).





2 *BLIP, BLIP ML* Group (UC Davis), 2023, (https://github.com/Neutron-Calibration-in-DUNE/Blip).

BLIP

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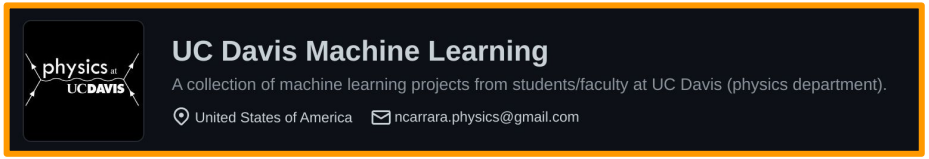
Arrakis LArSoft Module



The ***Arrakis***[3] LArSoft module is responsible for collecting MC truth/detector output information and generating point clouds for training.

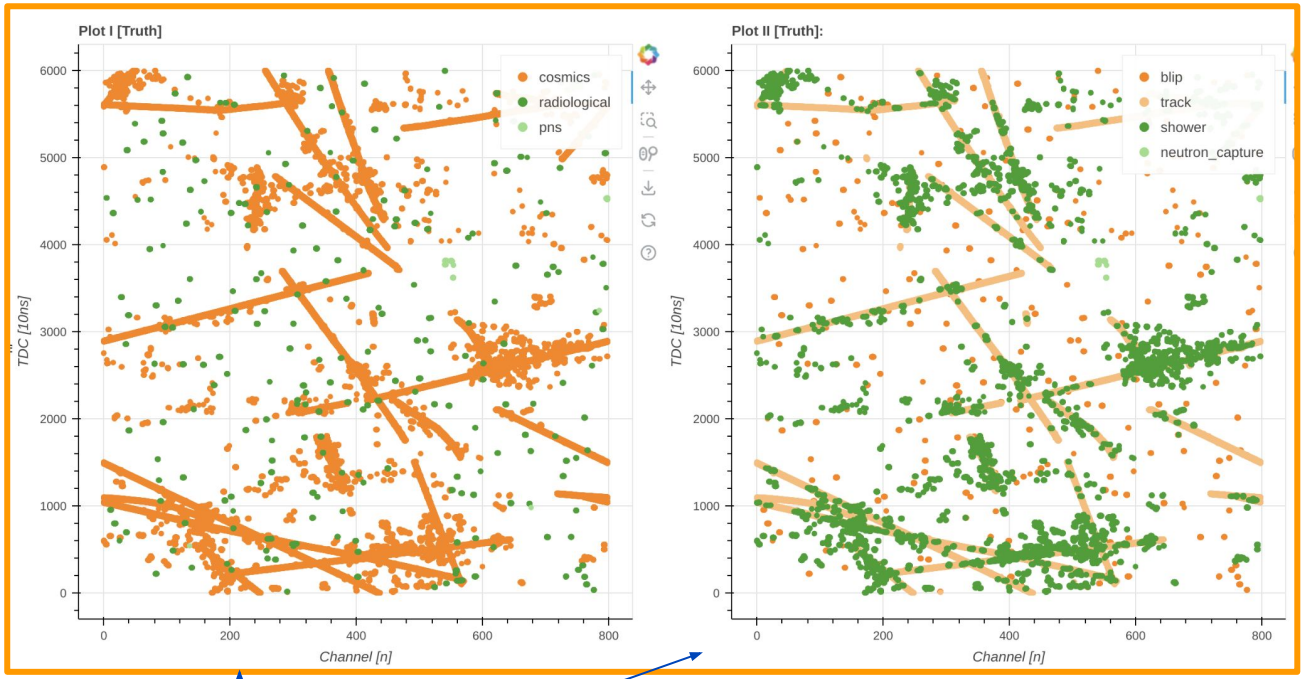
Current Labeling Schemes:

[Segmenation]

- **Source -** specifies the generator.
- **Shape -** generic topological descriptor (track, shower, blip, …)
- **Particle -** particle type responsible for the energy deposition (mu+-, neutron, proton, michel, delta, …)

[Clustering]

- **UniqueShape -** individual instance of a particular shape.
- **UniqueParticle -** individual instance of a particular particle.



‘source’ and ‘shape’ labels for a simulated ProtoDUNE event

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3 *Arrakis (LArSoft module),* DUNE PNS Group (UC Davis), 2023, (https://github.com/UC-Davis-Machine-Learning/Arrakis).

Arrakis LArSoft Module

To use Arrakis,

[Current setup]

- Can use the LArSoftArrakis repository to set up a local LArSoft install on an FNAL server.
- Download Arrakis into larana and compile.
- Add “arrakis” as an analyzer module and specify parameters.

```
#include "Arrakis.fcl"

physics:
{
    analyzers: {ana: @local::Arrakis}
    analysis:  [ana]
    trigger_paths:  [simulate]
    end_paths:      [analysis]

}
```

[Future setup]

- Eventually, Arrakis will be integrated into LArSoft and will be available as an analyzer module.
- Allow the user to register custom *logic* for generating training datasets.

```
module_type:    "Arrakis"

# which products for the wrangler to handle
ProcessType:                "data"  # simulation, data
ProcessMCTruth:             true
ProcessMCParticles:         true
ProcessSimEnergyDeposits:   true
ProcessSimChannels:         true
ProcessRawDigits:           true

# module labels
LArGeantProducerLabel:      "largeant"
SimEnergyDepositProducerLabel:   "IonAndScint"
SimEnergyDepositInstanceLabel:   "priorSCE"
SimChannelProducerLabel:    "tpcrawdecoder"
SimChannelInstanceLabel:    "simpleSC"
RawDigitProducerLabel:      "tpcrawdecoder"
RawDigitInstanceLabel:      "daq"

GeneratorLabels:
{
    Ar39Label:          "Ar39"
    Ar42Label:          "Ar42"
    Kr85Label:          "Kr85"
    Rn222Label:         "Rn222"
    BeamLabel:          "Beam"
    CosmicsLabel:       "Cosmics"
    HEPevtLabel:        "HEPevt"
    PNSLabel:           "PNS"
}

# which products to save
SaveMeta:       true
SaveGeometry:   true
SaveSimulationWrangler:         false   # save SimulationWrangler maps
SaveWirePlanePointCloud:        true    # save wire plane point cloud data
SaveEnergyDepositPointCloud:    true    # save energy deposit point cloud data

# whether to collect detector simulation by edep or
# by particle track id.
FilterDetectorSimulation:   "TrackID"   # ["TrackID", "EdepID"]

# labeling scheme for neutron captures,
# simple labels all gammas as "other", while medium labels
# 4.75 and 1.81 MeV gammas separately from others, and full
# labels all energies as different types.
NeutronCaptureGammaDetail:  "Simple"    # ["Simple", "Medium", "Full"]

ADCThreshold:                   20      # ADC threshold for saving points
InducedChannelInfluence:        10      # number of wires which are influenced by signals
InducedTDCInfluence:            200     # number of tdc ticks which are influenced by signals
```

FHiCL parameters

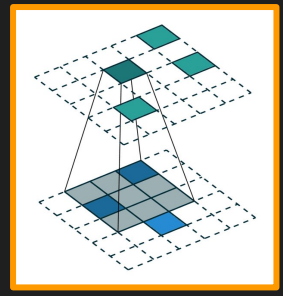
Config file training/evaluation

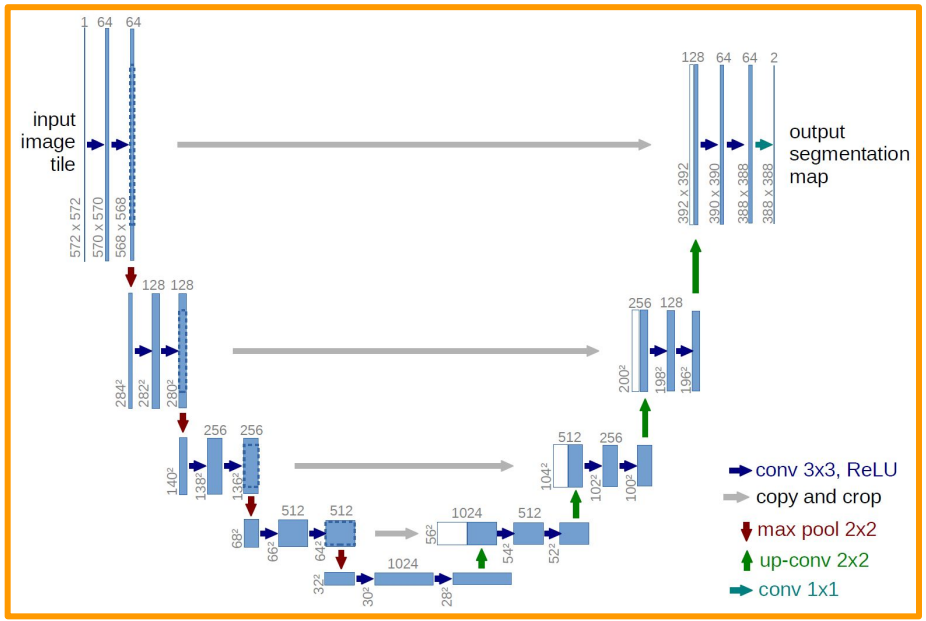
BLIP models can be constructed at run time with tunable parameters.

- The long term goal is to make a completely modular setup so that different models can be chained together.
- Model parameters/weights are saved in a config dictionary for reproducability.

```
model:
  # uncomment the line below and specify the model to load from a checkpoint.
  # load_model:   ".checkpoints/checkpoint_200.ckpt"

  # multiple options for model_type:
  # [ "single", "composite", ... ]
  model_type: "single"
  PointNet:
    input_dimension:      3
    classifications:      ["particle"]
    augmentations:
      jitter: 0.03
      flip:
        positions:     [0, 1]
        probabilities: [0.5, 0.5]
      shear:  0.2
      rotate:
        degrees:  [15]
        axis:     [2]
    number_of_augmentations:  5
    embedding_type:       "dynamic_edge_conv"
    number_of_embeddings: 4
    number_of_neighbors:  [5, 10, 15, 20]
    aggregation:          ["max", "add", "mean", "max"]
    embedding_mlp_layers: [
      [64, 128, 64],
      [64, 128, 64],
      [64, 128, 64],
      [64, 128, 64]
    ]
    embedding_activations: ['leru', 'leru', 'leru', 'leru']
    linear_output:        512
    mlp_output_layers:    [512, 256, 128, 64, 32]
    out_channels:         [10]
```





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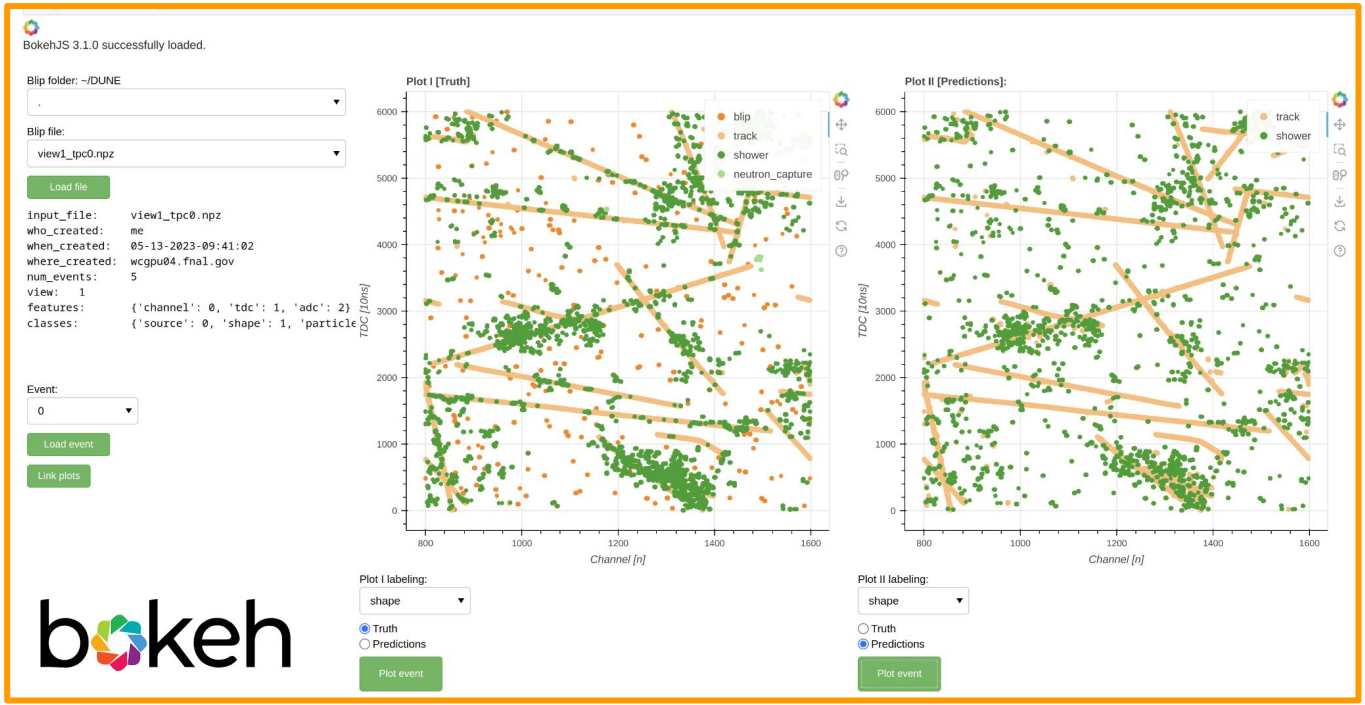
Event display

We are also working on an event display for BLIP which has the following features:

- Uses *bokeh* to create an interactive GUI.
- GUI can be run in a Jupyter notebook, or as a stand-alone html page.
- Obtain **point by point information** to quickly diagnose/access Arrakis and BLIP performance.
- Interface for analysis on network output.
- The BLIP-display could be made accessible through a **Wilson Cluster** jupyter interface.



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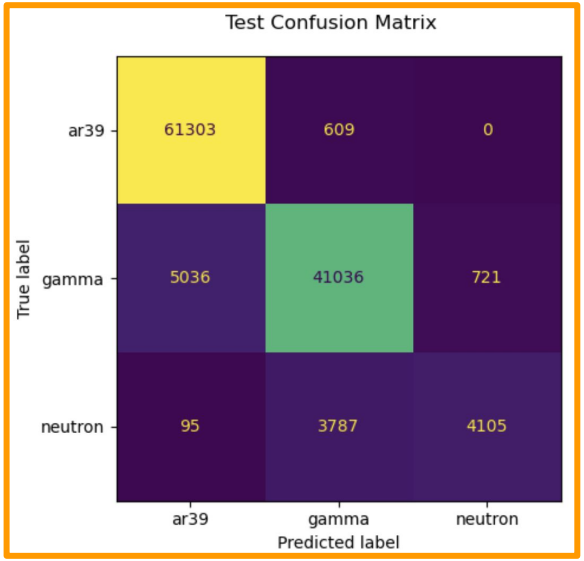
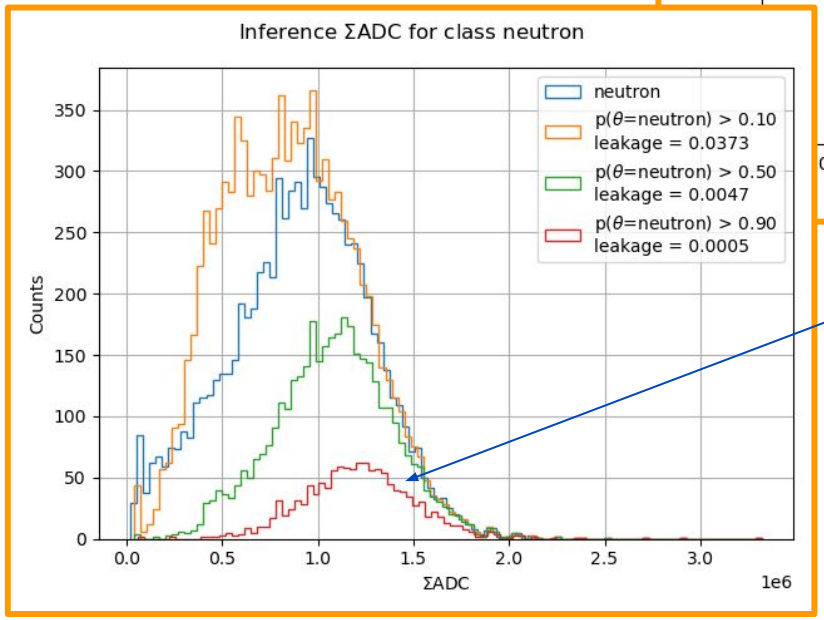
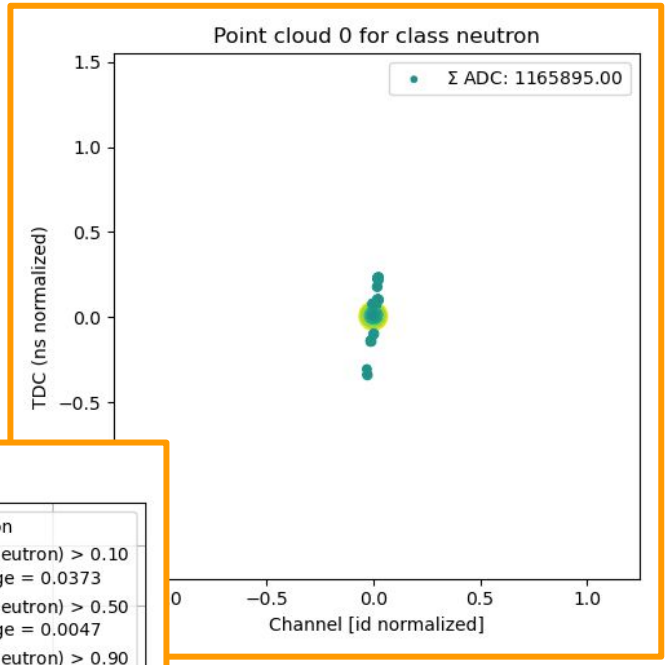
Preliminary PointNet Results

We trained a BLIP model on 116K point clouds with a 70/30 train/test split and the following classes:

- Argon-39: 61,912 events (~53%)
- Capture Gammas: 46,793 events (~40%)
- Neutron Captures: 7,987 events (~7%)







Can calibrate against this distribution!

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