Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Combining Conventional and Machine Learning Algorithms for LArTPC Reconstruction

Haiwang Yu (BNL)

2022-07-08

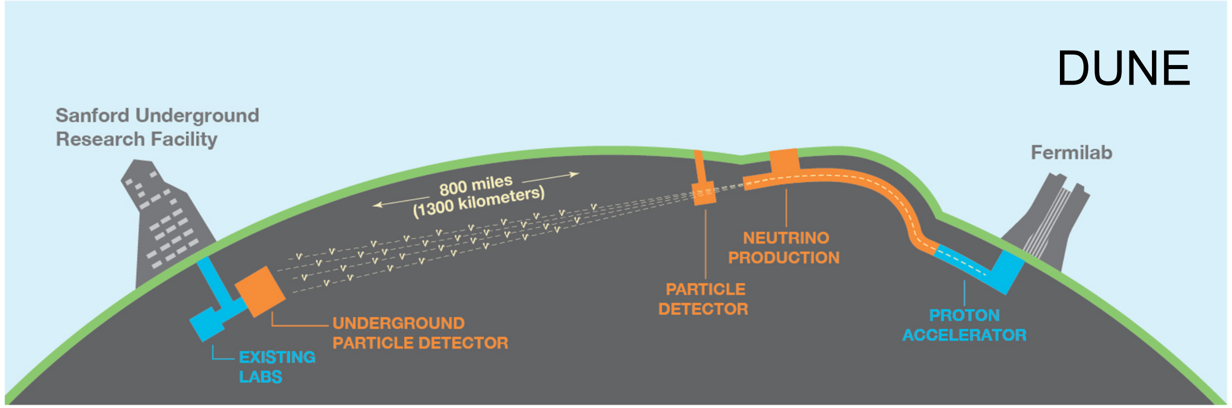
ICHEP 2022, Bologna

Wire-Cell

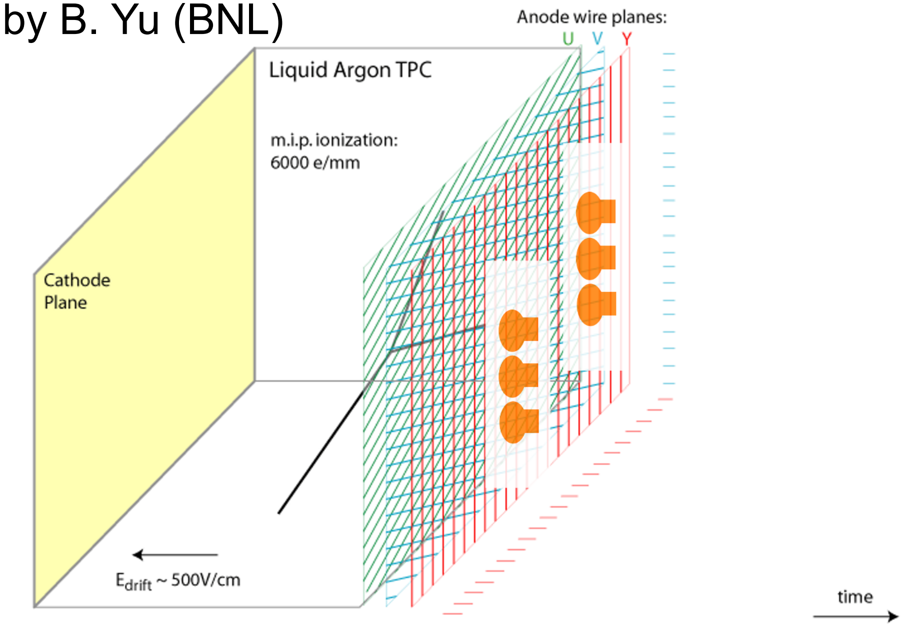
@BrookhavenLab

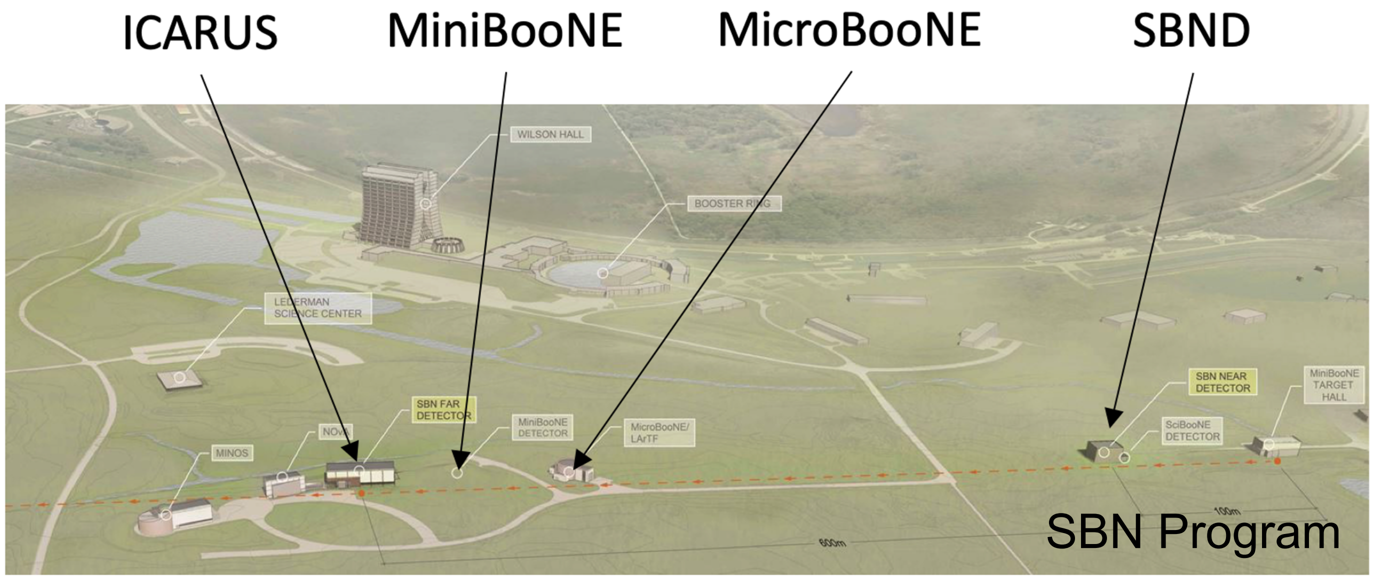
Liquid Argon TPC

- ~mm scale position resolution with multiple 1D wire readouts
- Particle identification (PID) with energy depositions and topologies



LArTPC Signal Formation Illustration
by B. Yu (BNL)

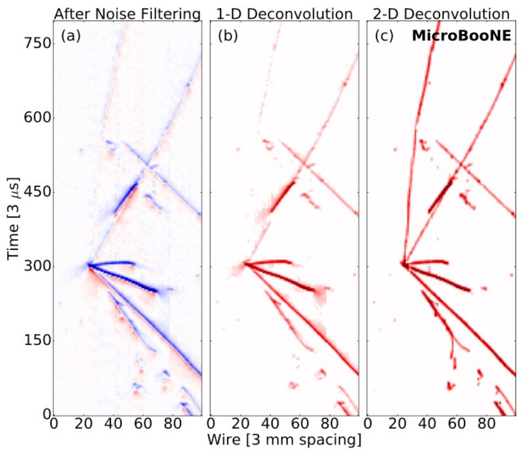




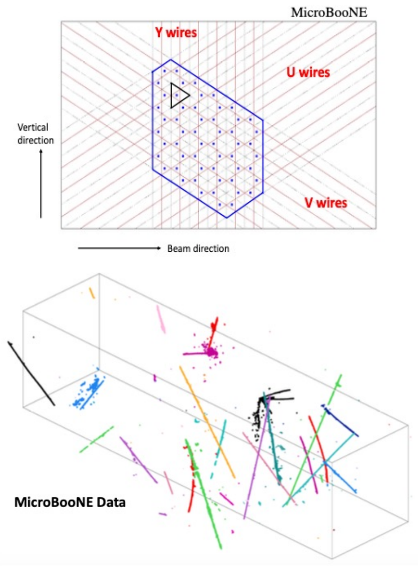
Brookhaven National Laboratory

Wire-Cell Event Reconstruction

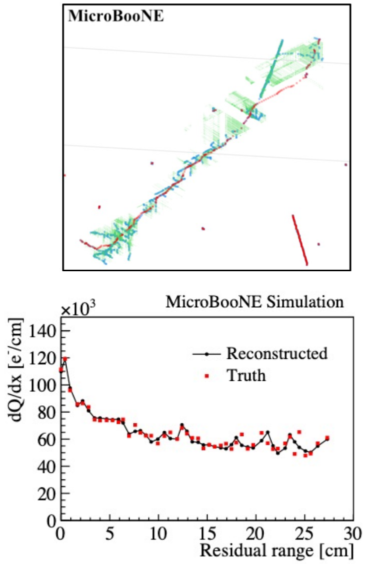
TPC simulation noise filtering signal processing	3D imaging clustering charge-light matching	3D trajectory & dQ/dx fitting cosmic muon tagger	multi-track fitting DL-3D vertexing particle identification



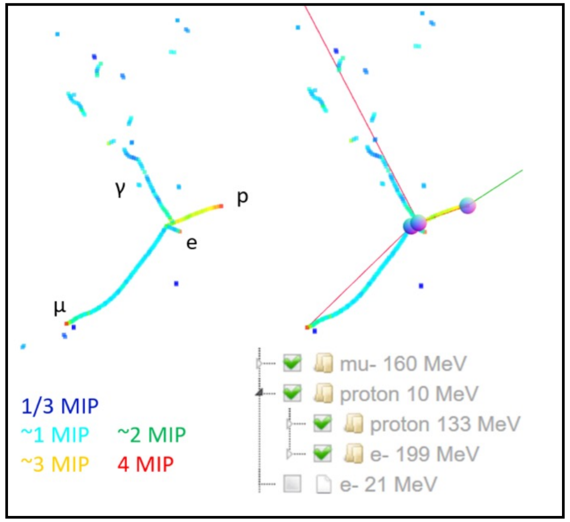
JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)
JINST 16 P01036 (2020)



JINST 13 P05032 (2018)
JINST 16 P06043 (2021)



Phys. Rev. Applied 15, 064071 (2021)



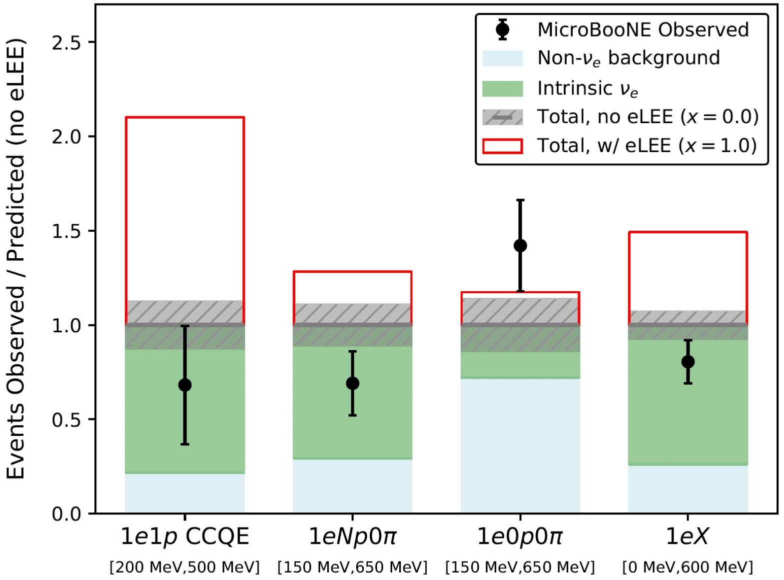
JINST 17 P01037 (2022)

Brookhaven National Laboratory

Search for Low-Energy Excess in ν_eCC

Comprehensive search for (examination of) the MiniBooNE low-energy excess in ν_eCC with multiple final-state topologies with different reconstruction paradigms

Channels	Reconstruction	Purity	Efficiency	Selected Events	References
CCQE 1e1p	Deep Learning	75%	6.6%	25	**PRD 105 112003**
1e0p0π	Pandora	43%	9%	34	**PRD 105 112004**
1eNp0π	Pandora	80%	15%	64	**PRD 105 112004**
Inclusive 1eX	**Wire-Cell**	**82%**	**46%**	**606**	**PRD 105 112005**



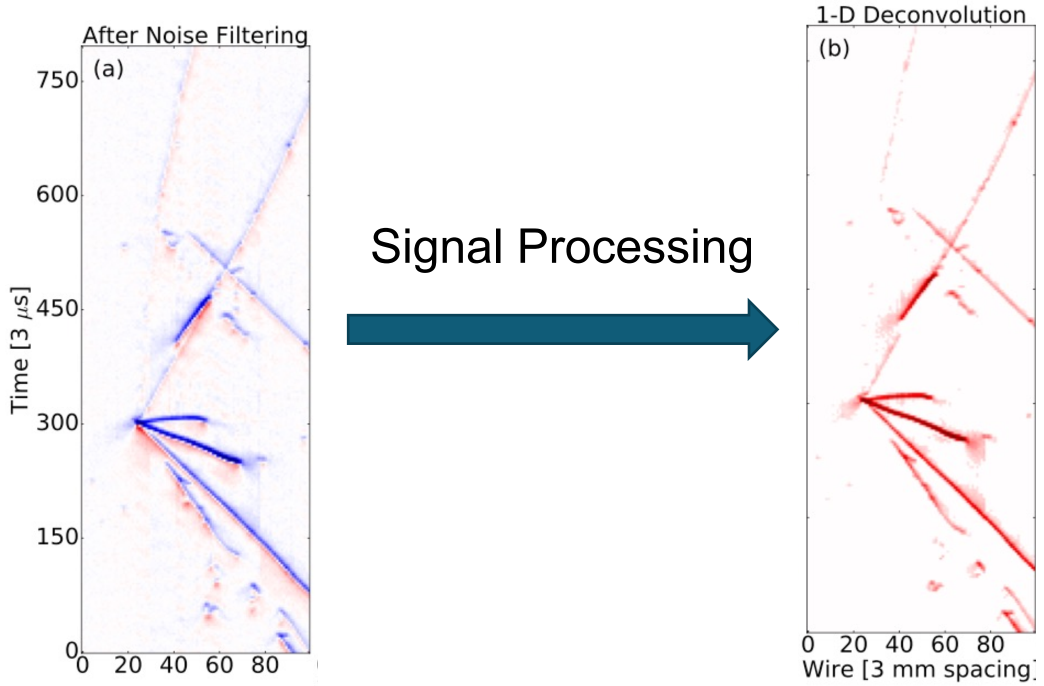
Wire-Cell based inclusive ν_eCC analysis (46% efficiency) currently leads sensitivity in searching for the LEE

Phys. Rev. Lett. 128, 241801

No excess of low-energy ν_e candidates!

TPC Signal Processing → Recover (or Unfold) Ionization Electrons

- Signal processing is based on deconvolution technique
  - $O(N^3)$ matrix inversion is achieved through a $O(N \log N)$ fast Fourier transformation
    - Top 10 algorithms in 20th century
- 1-D deconvolution described in B. Baller "Liquid Argon TPC Signal Formation, Signal Processing, and reconstruction techniques", JINST 12, P07010 (2017)



Time domain

$$M(t_0) = \int_t R(t - t_0) \cdot S(t) \cdot dt$$

↓ Fourier transformation

$$M(\omega) = R(\omega) \cdot S(\omega)$$

Frequency domain

$$S(\omega) = \frac{M(\omega)}{R(\omega)} \cdot F(\omega)$$

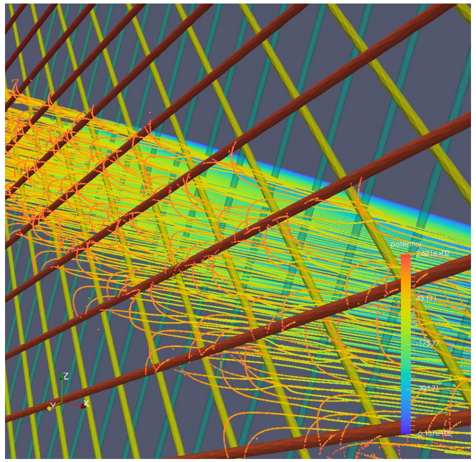
↓ Back to time domain / Inverse-Fourier transformation

$$S(t)$$

Brookhaven National Laboratory

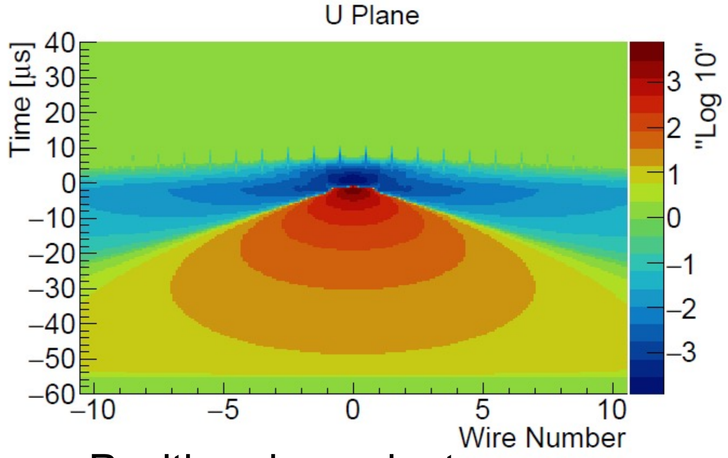
2-D Deconvolution

electron drift paths in 3D



2D measurement formation

$$M(t',x') = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R(t,t',x,x') \cdot S(t,x) dt dx + N(t',x')$$

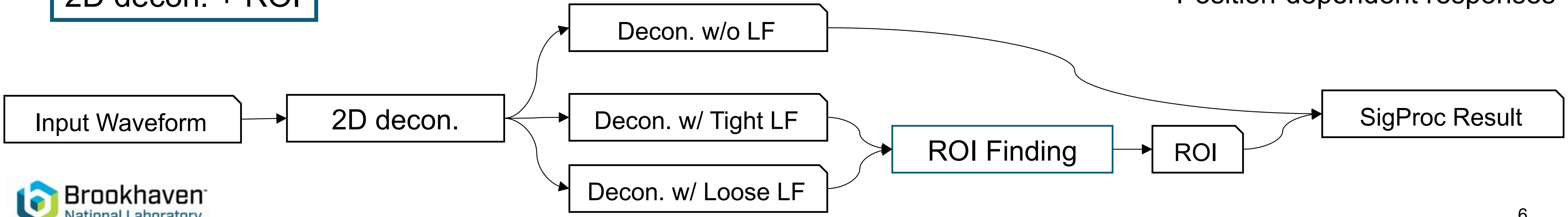


Position-dependent responses

2D deconvolution

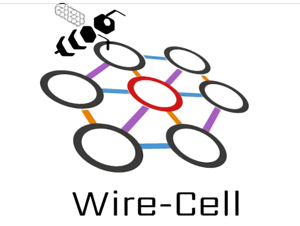
$$S(\omega_t,\omega_x) \sim \frac{F(\omega_t,\omega_x)\cdot M(\omega_t,\omega_x)}{R(\omega_t,\omega_x)} \xrightarrow{IFT} S(t,x)$$

2D decon. + ROI

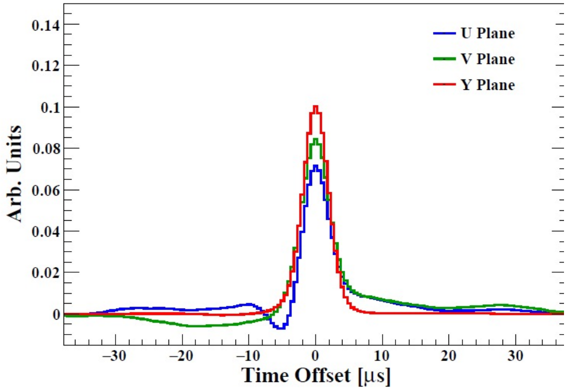


Brookhaven National Laboratory

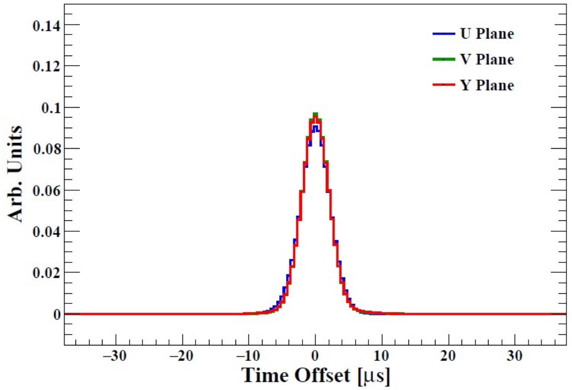
Improved TPC Signal Processing

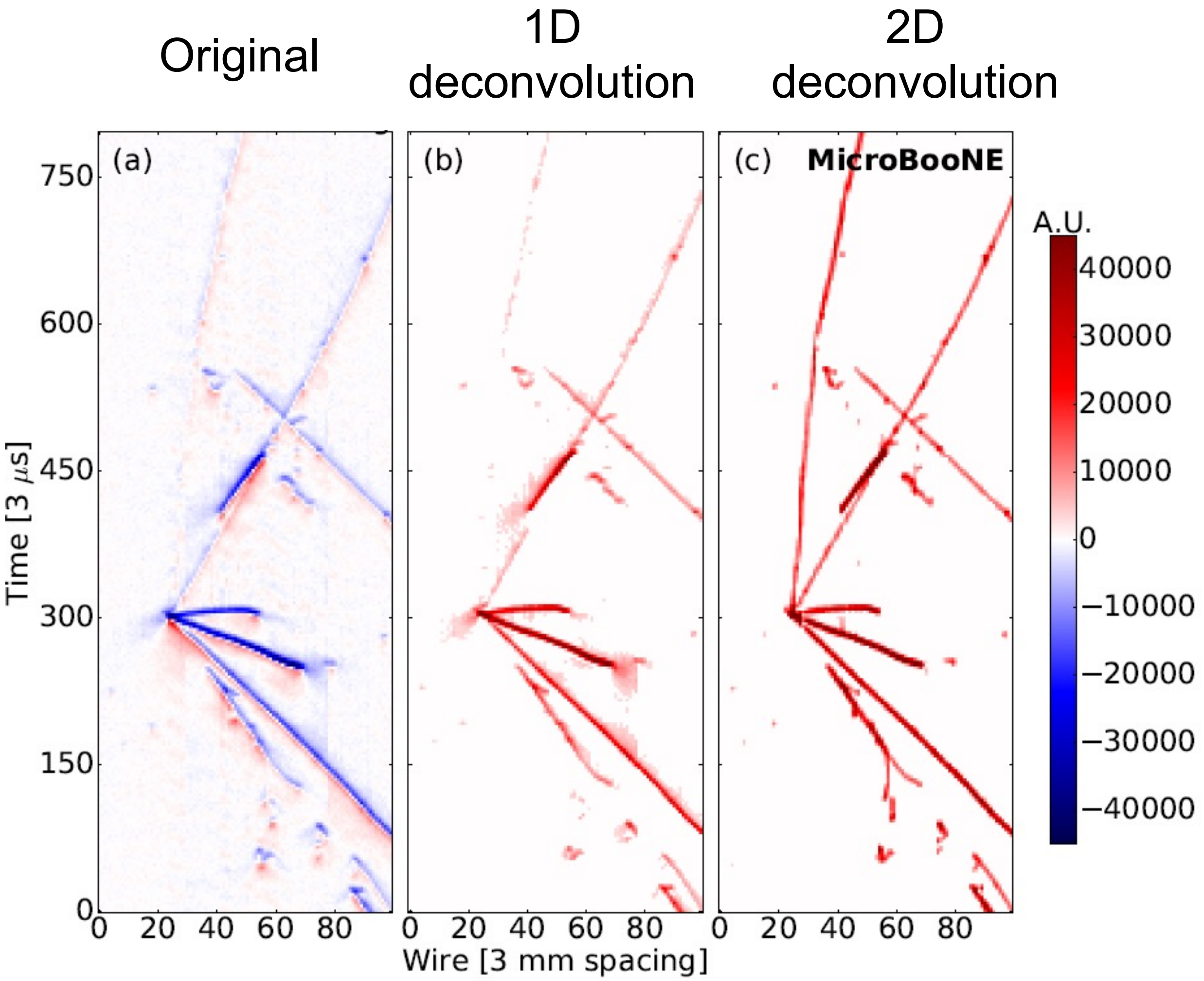


1D deconvolution



2D deconvolution





The 2D deconvolution algorithm in Wire-Cell allows to accurately recover the ionization electrons from recorded original signals

Same number of electrons are reconstructed from each projection wire plane

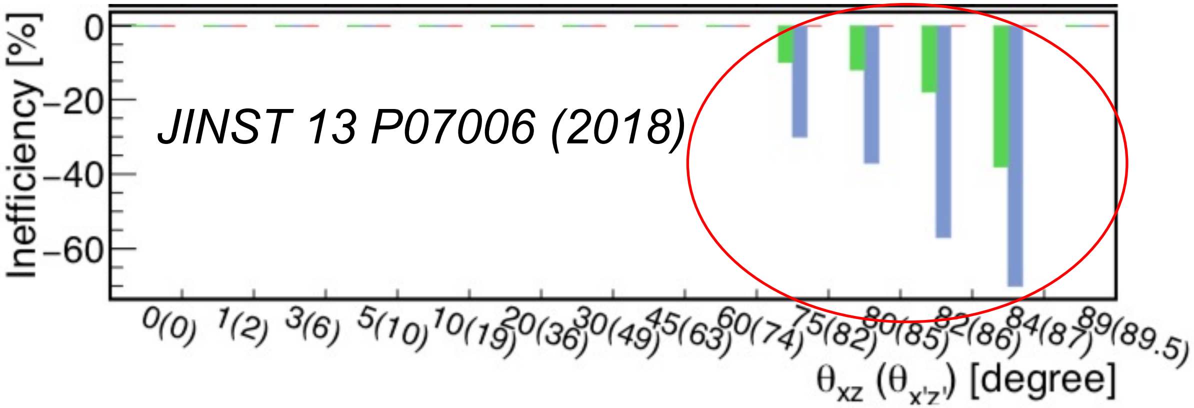
Brookhaven National Laboratory

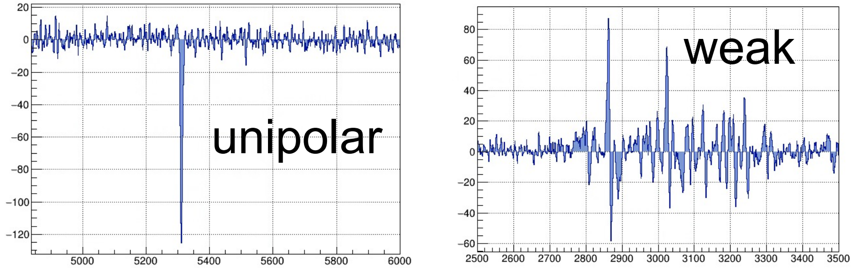
JINST 13 P07006/7

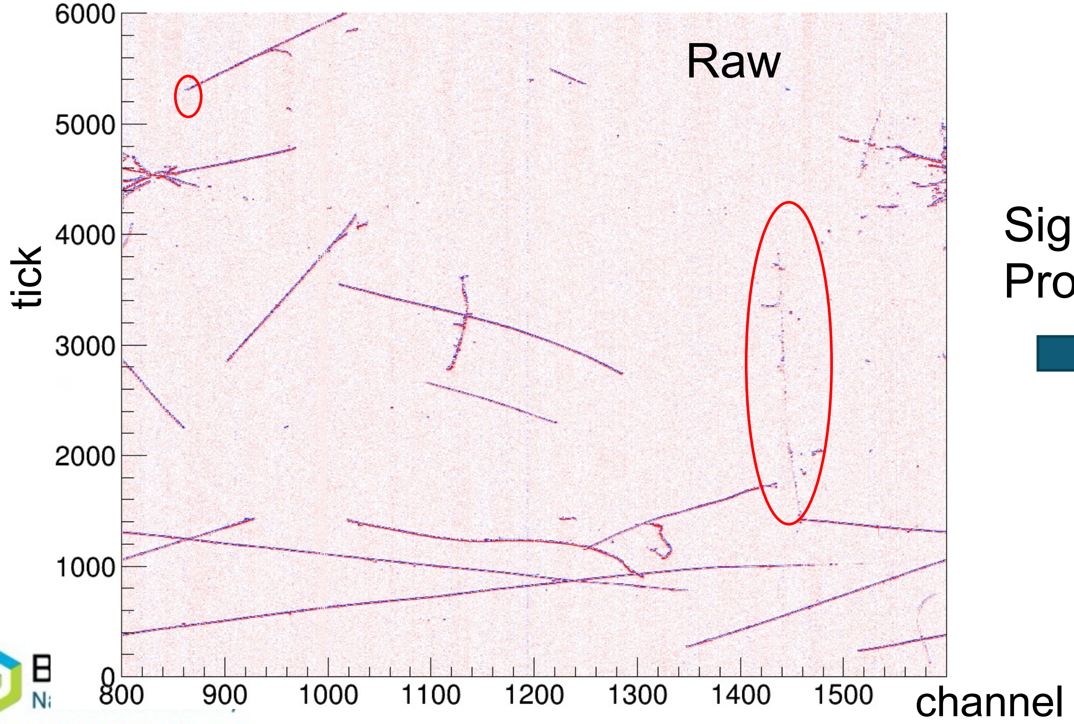
μBooNE

DNN ROI finding to improve LArTPC Signal Processing

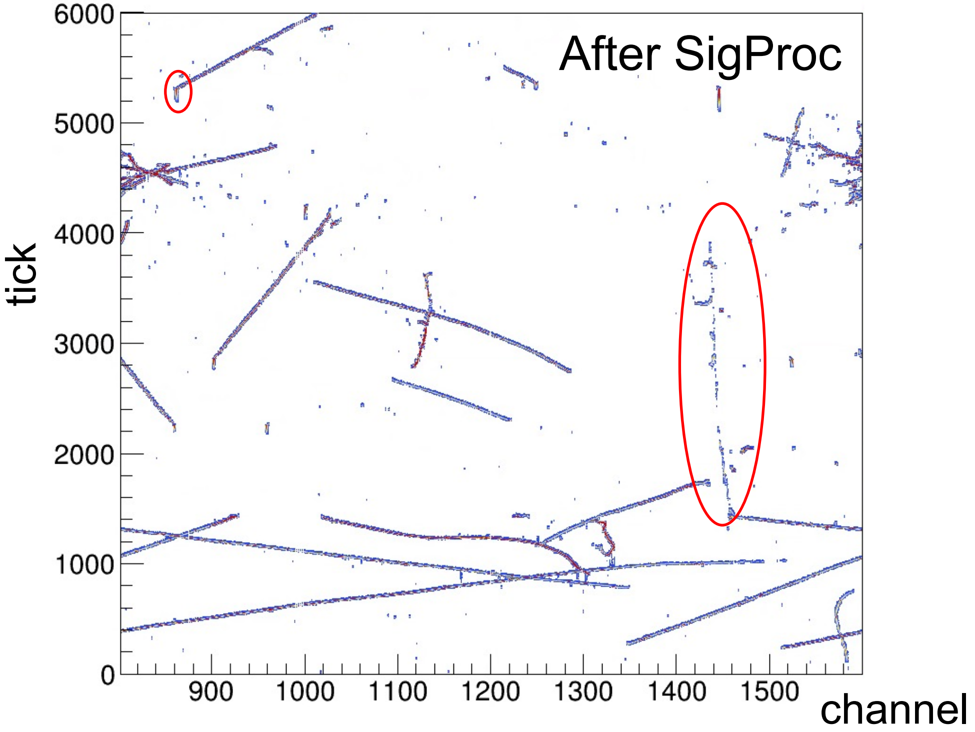
- "Prolonged Track" – weak signal
- "Tear Drop" - distorted waveform







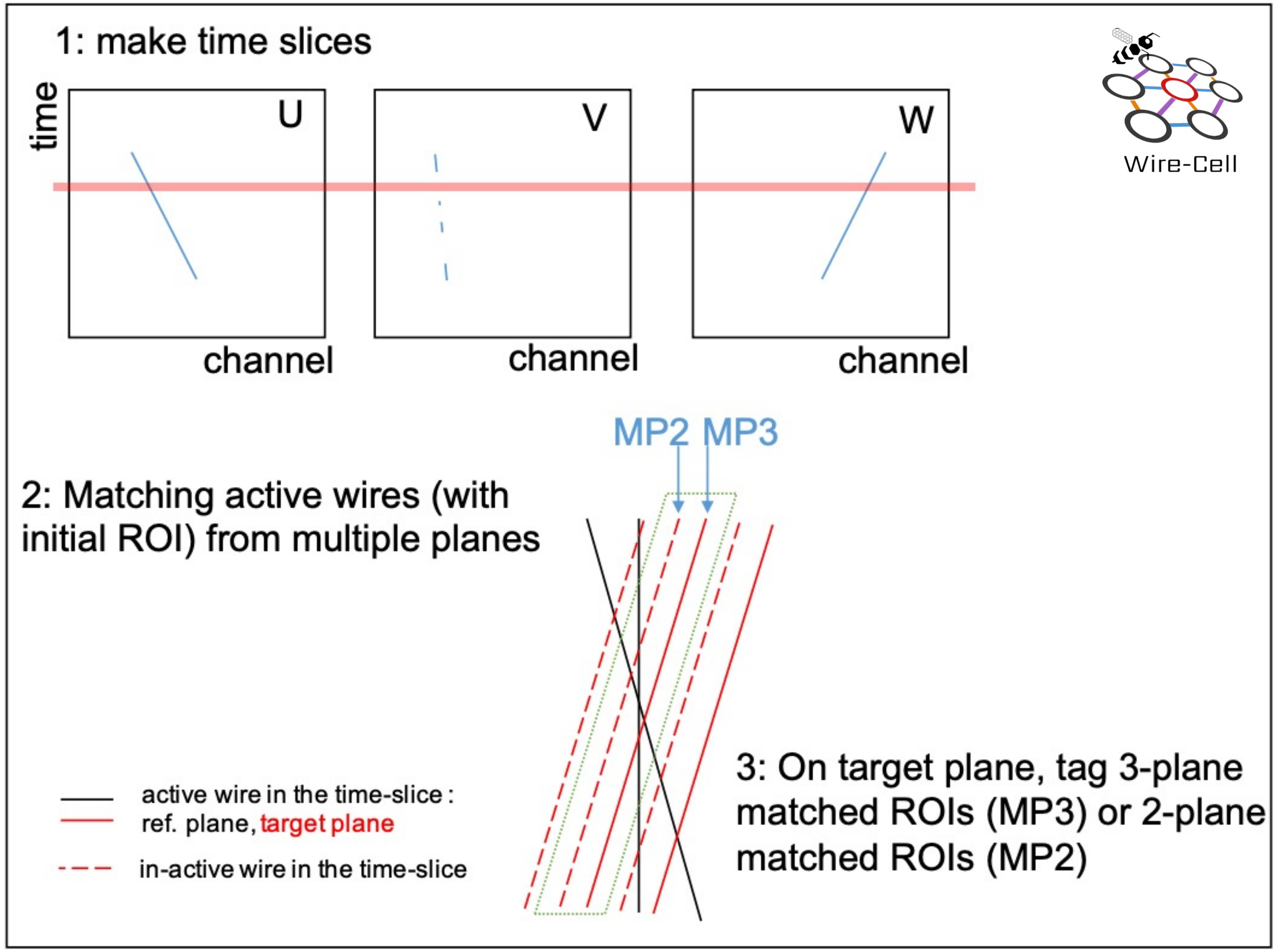
Signal Processing



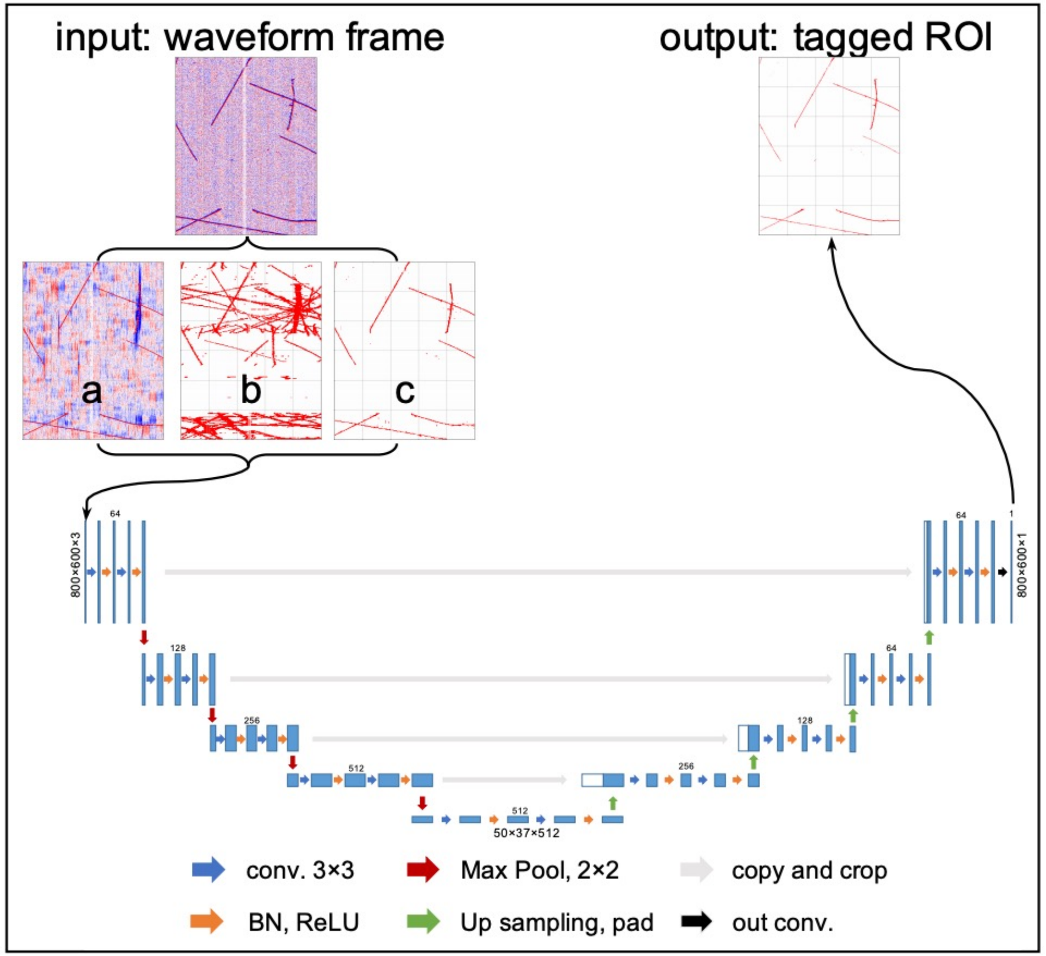
DNN ROI finding with multi-plane information

JINST 16 P01036 (2021)

Multi-plane information in Signal Processing

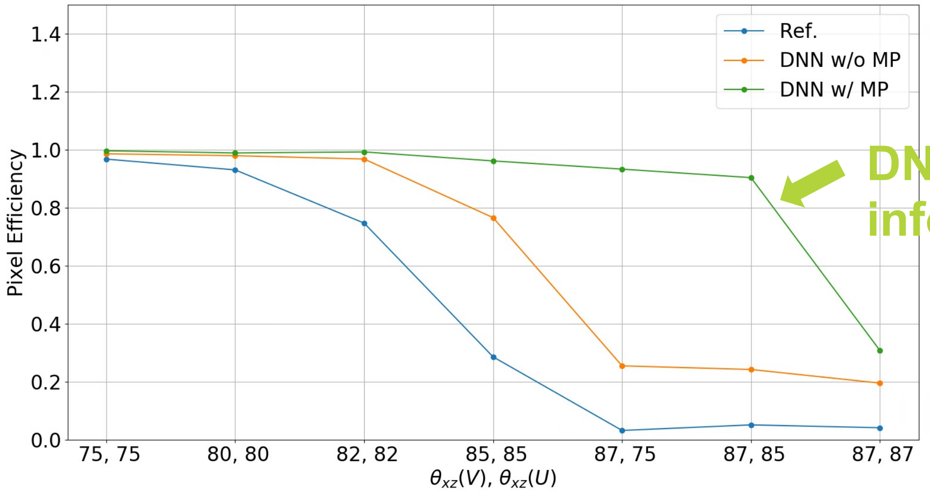


DNN ROI finding with multiple input channel

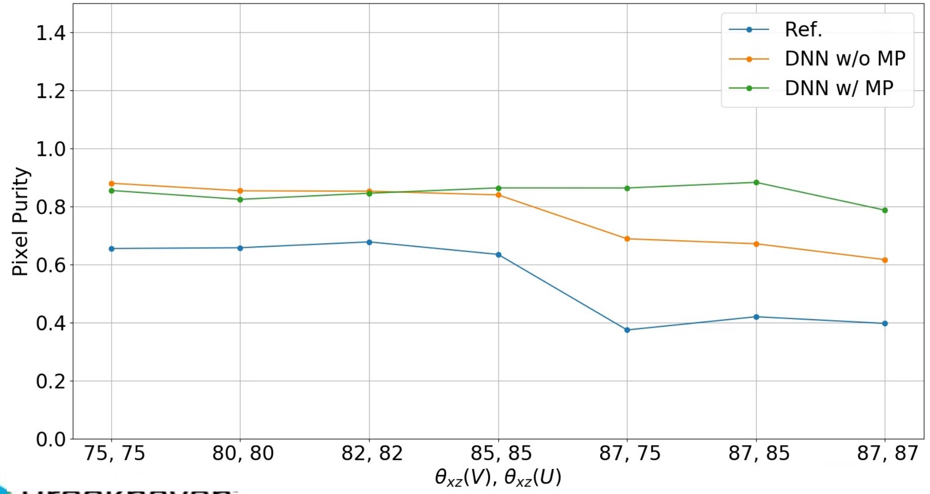


DNN ROI finding with multi-plane information

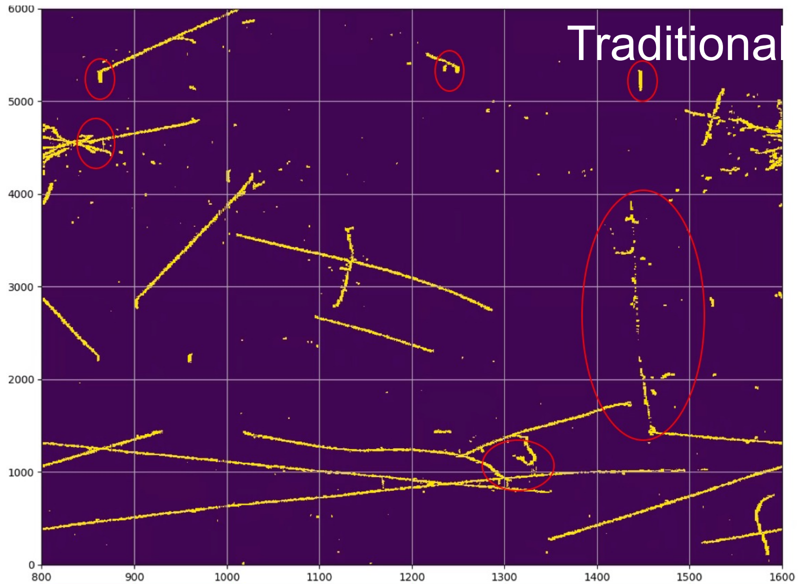
ProtoDUNE simulation
ROI finding on V plane (2nd induction)

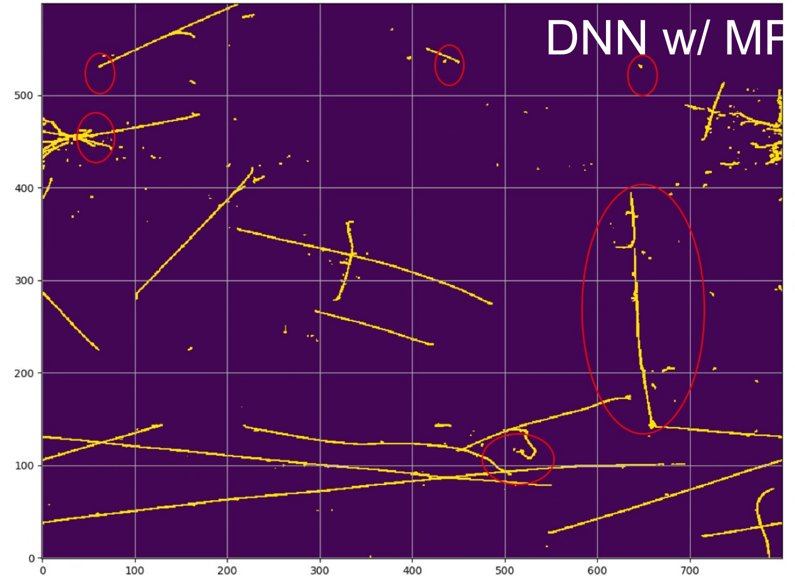


DNN With 3-plane information



tested on ProtoDUNE-SP data

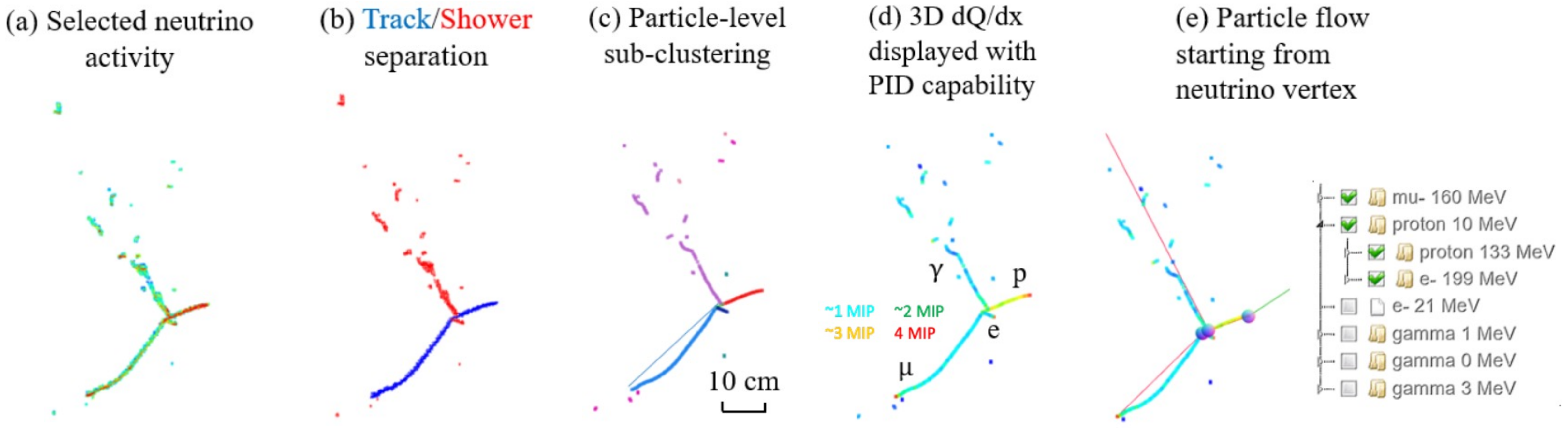


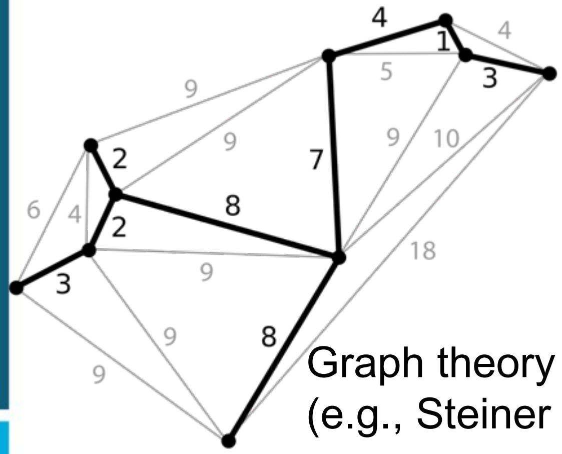


Brookhaven National Laboratory

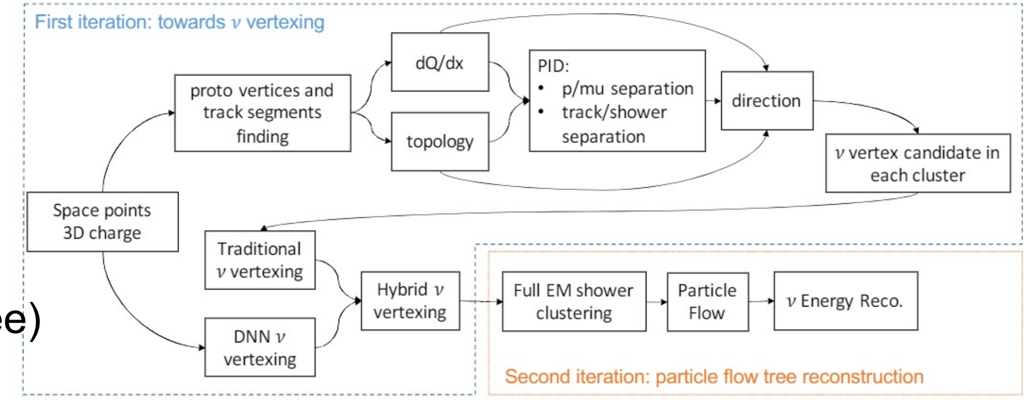
[JINST 16 P01036 (2021)](https://doi.org/10.1088/1748-0221/16/01/P01036)

3D Pattern Recognition

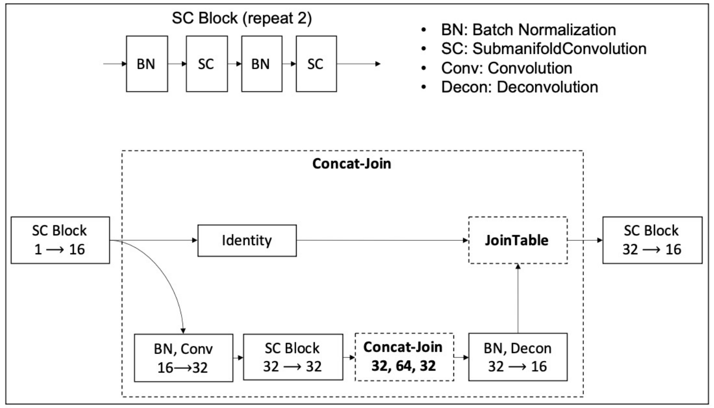




Graph theory
(e.g., Steiner tree)



Sparse Regression U-Net



Brookhaven National Laboratory

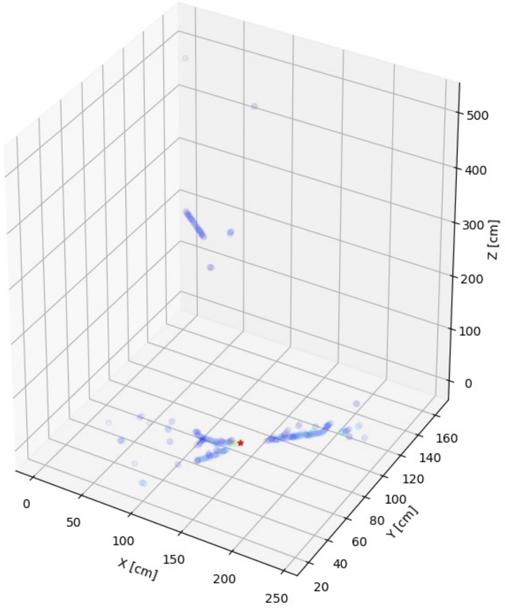
JINST 17 P01037 (2022)

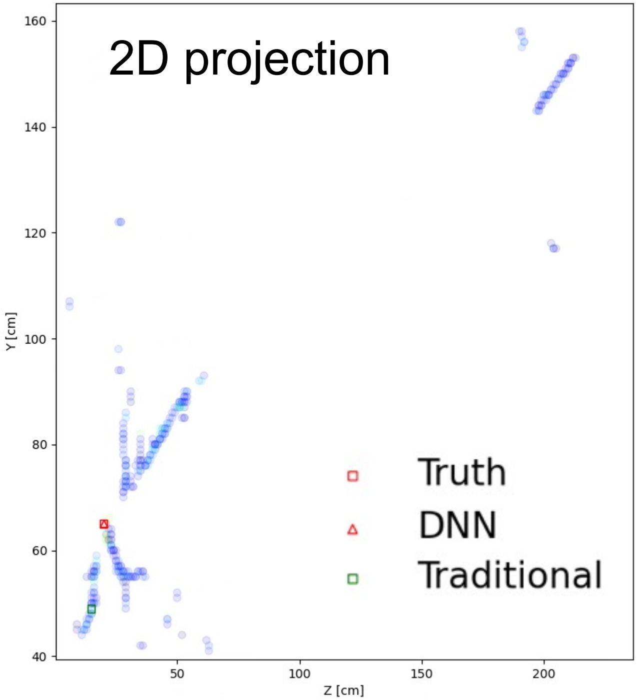
Deep Learning based Neutrino Interaction Vertex Finding

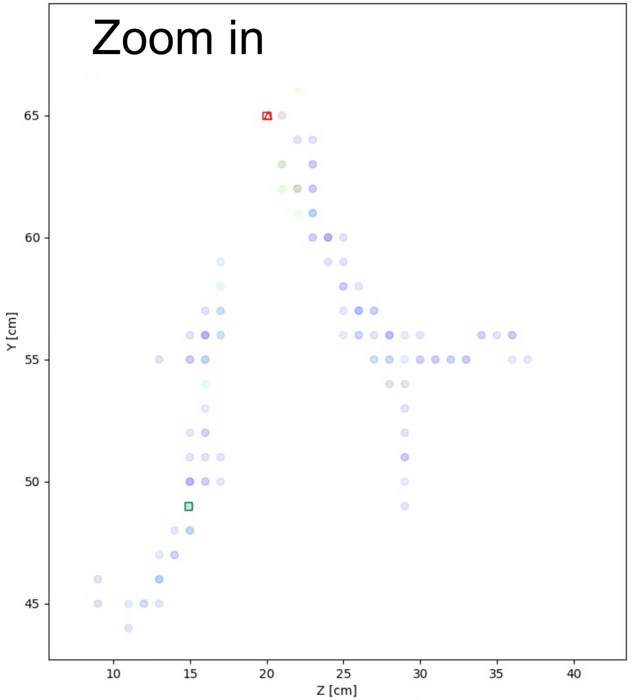
Regressional segmentation with a sparse U-Net

- U-Net: efficiently use geometry info which is critical
  - compared to graph networks
- Regressional loss on distance based “confidence map” to use a region of points instead of only one
  - otherwise, data is highly imbalanced (Z. Cao etc, arXiv:1812.08008)
- Sparse: boosted computing efficiency with our sparse 3D data
  - Submanifold Sparse Convolutional Networks (B. Graham etc, arXiv:1706.01307)

3D points from Wire-Cell







Regressional segmentation

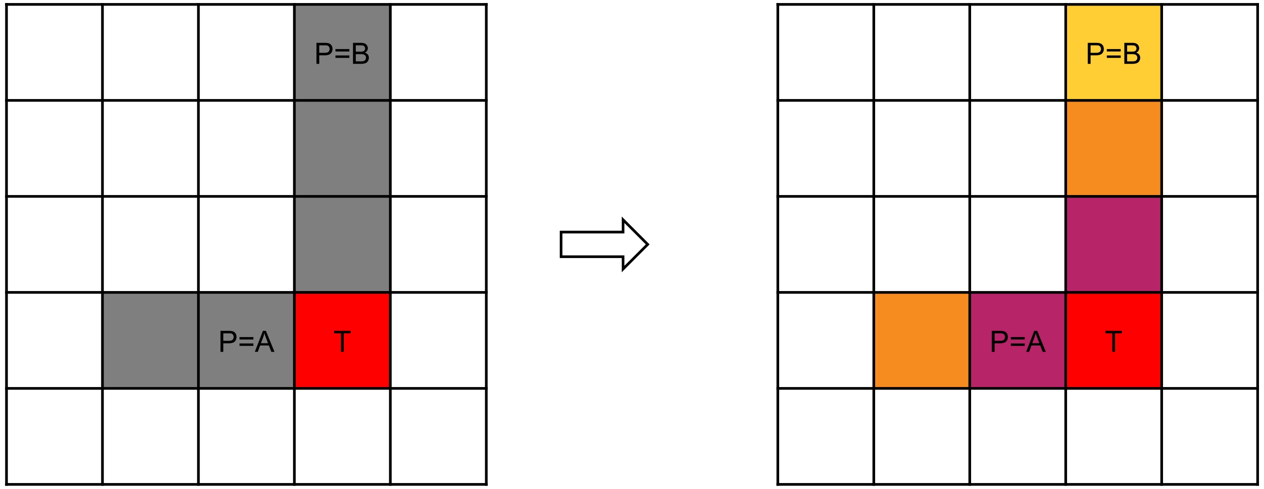
Initially we used Cross Entropy loss

- effectively only use the vertex information for one space point
- doesn’t care about the distance between the prediction and the target.
  - while our main metric is this distance.

⟶ encode the distance information for a region of points

- predicting the full “confidence map” instead of only one point
- current mapping: $\mathrm{Conf}_{\mathrm{truth}} = \exp\left(-\frac{\|\vec{x} - \vec{v}_{\mathrm{truth}}\|^2}{2\sigma^2}\right)$

OpenPose:
https://arxiv.org/pdf/1812.08008.pdf



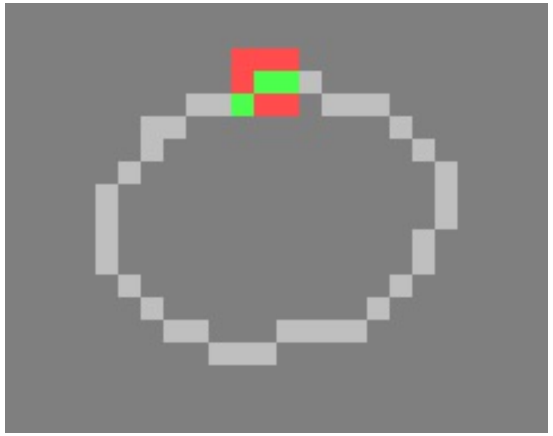
Brookhaven National Laboratory

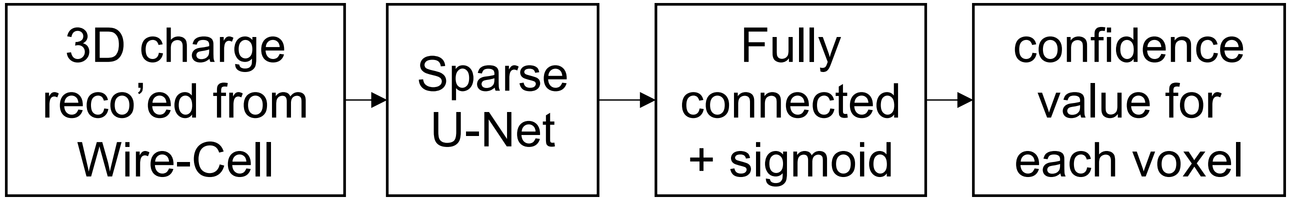
Network structure and data format

Used *SparseConvNet* to realized 3D sparse conv. DNN
https://github.com/facebookresearch/SparseConvNet

This work: https://github.com/HaiwangYu/uboone-dl-vtx

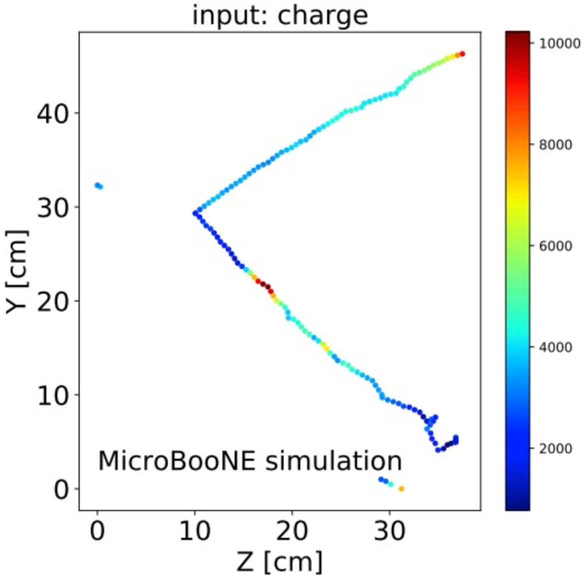
SparseConvNet



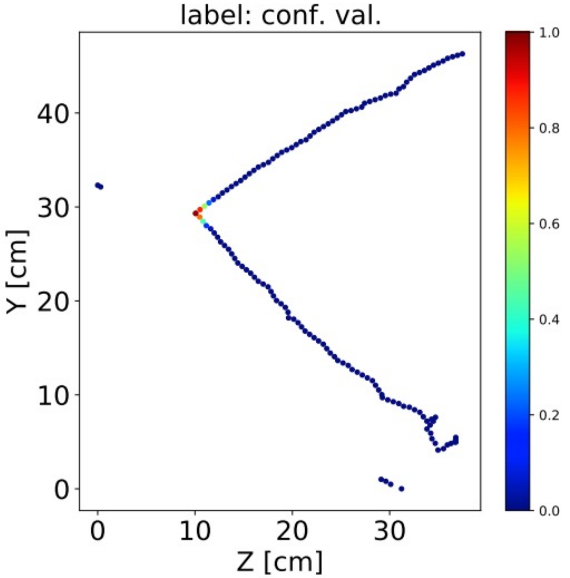


coordinates			features		label
x	y	z	q	…	conf.
int	int	int	float	…	float
int	int	int	float	…	float
int	int	int	float	…	float
…	…	…	…	…	…

input: color is charge



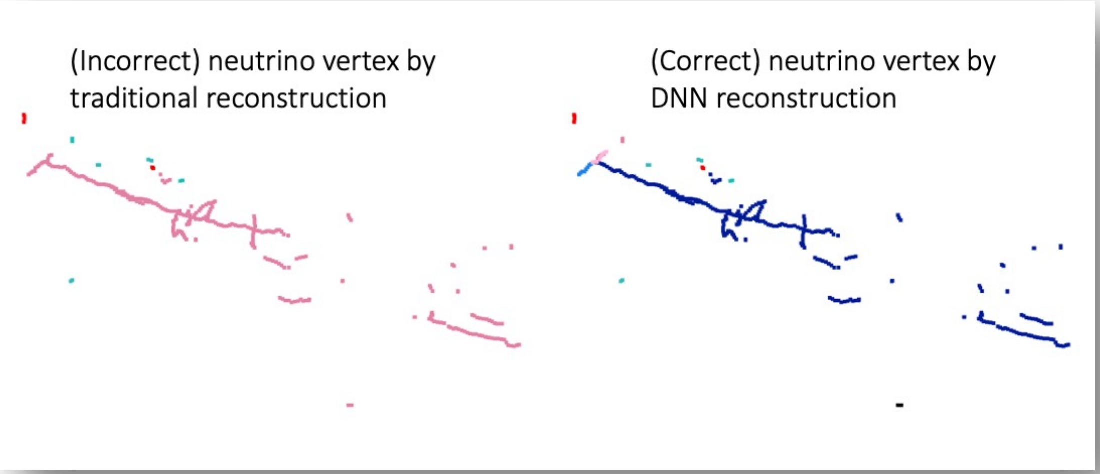
label: color is truth confidence map



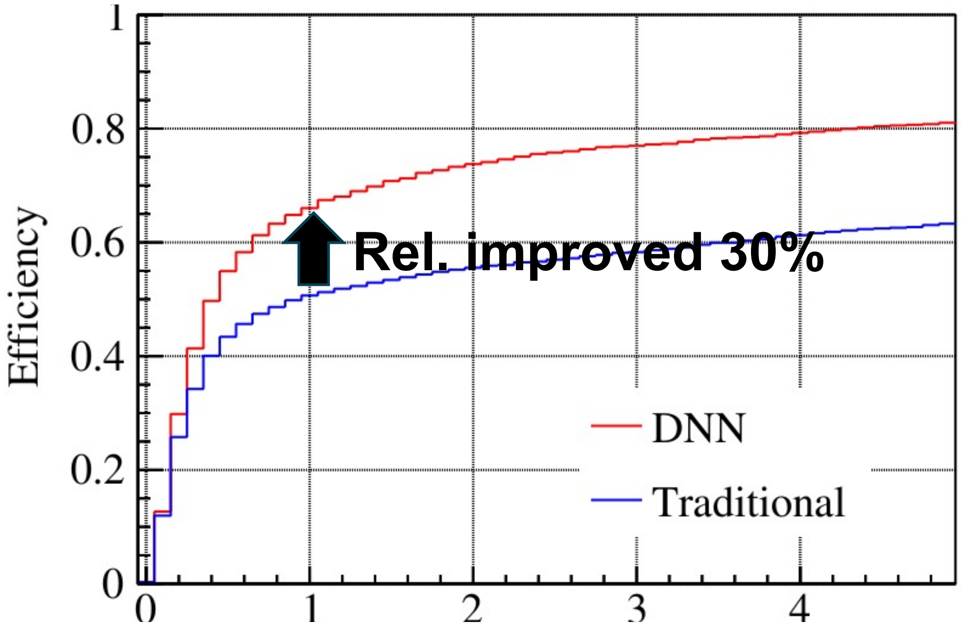
Deep Learning based Neutrino Interaction Vertex Finding

JINST 17 P01037 (2022)

Illustration of impact of vertex ID on the full event reconstruction



ν_eCC vertex identification efficiency



Distance between reco. and true vertex (cm)

Brookhaven National Laboratory

Summary

- The Wire-Cell team has developed a fully automated reconstruction chain for LArTPC reconstruction for neutrino experiments
- Its good performance was demonstrated in MicroBooNE analyses
- We learned that some tasks in the chain fit better for conventional alg. while some others fit better for ML alg.
- I believe combining both would give us the best performance with limited data and computing resources