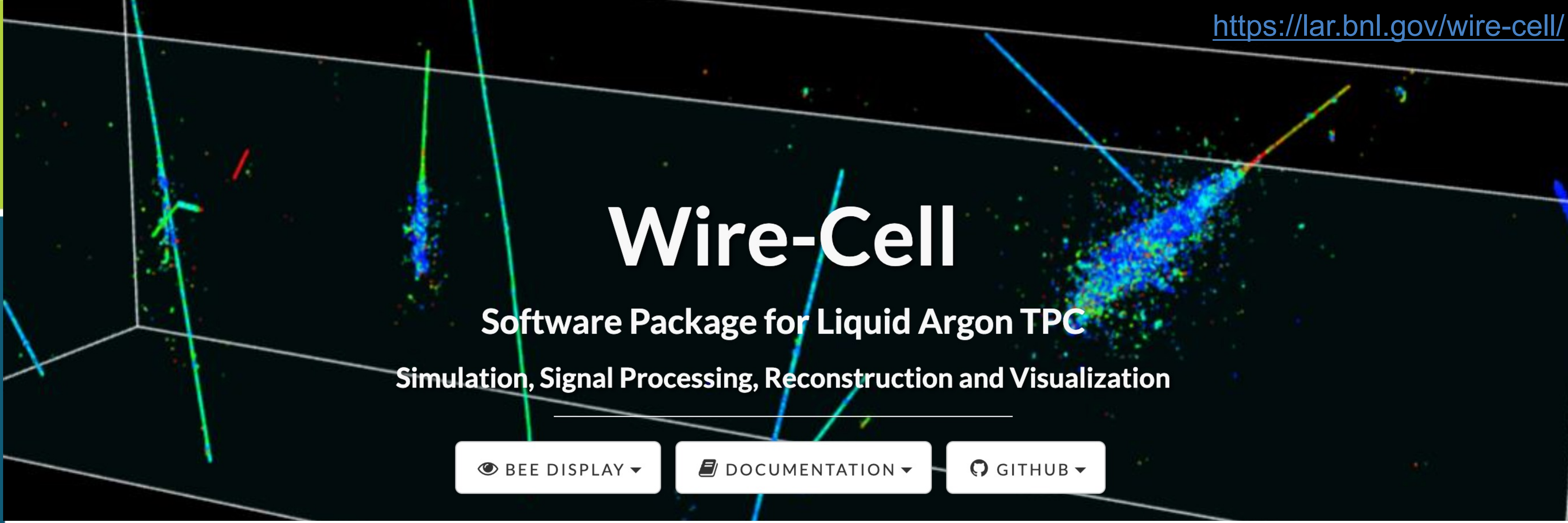
https://lar.bnl.gov/wire-cell/



Chao Zhang
Brookhaven National Lab

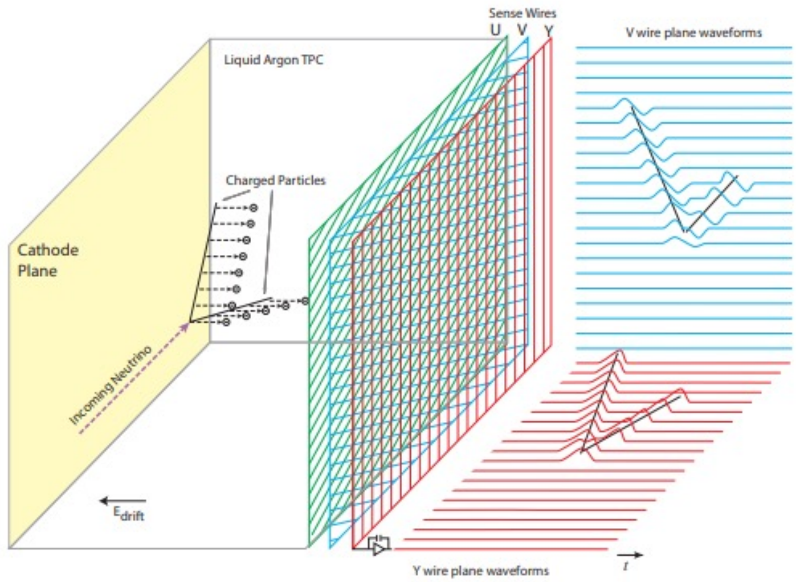
The Second Wire-Cell Reconstruction Summit @BNL, 4/10/2024

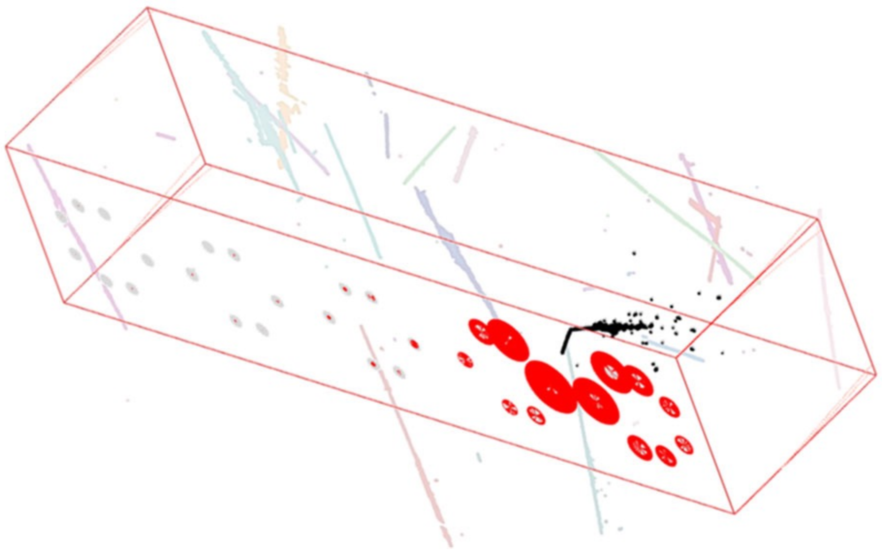
What is Wire-Cell?

- ❑ Wire-Cell is a collection of software tools for LArTPC experiments
  - TPC signal simulation
  - TPC signal processing
    - Noise filtering
    - Signal deconvolution

    } Wenqiang's talk today
  - Event reconstruction
    - 3D imaging
    - Clustering
    - Charge-light matching
    - Reconstruction of track trajectory, dQ/dx, vertex, PID, energy, particle flow, …

    } Haiwang's talk on Friday
  - Visualization
- ❑ Physics analysis with Wire-Cell products



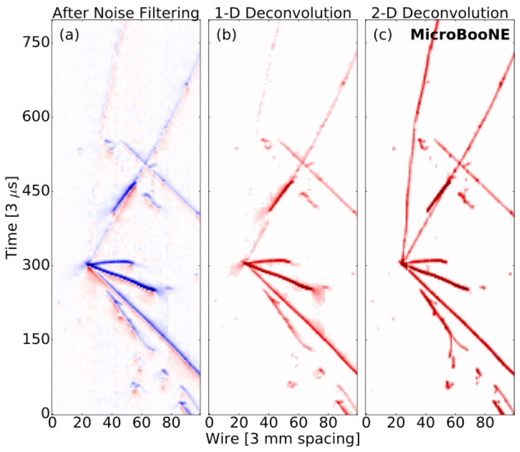


Wire-Cell-Toolkit: a Data Flow Programming Framework Brett's talk

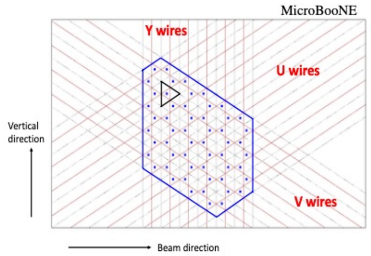
prototyping started in 2015

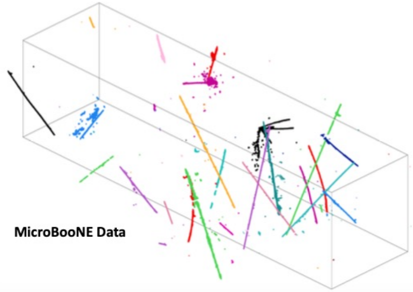
Wire-Cell

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

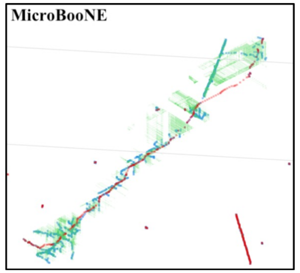


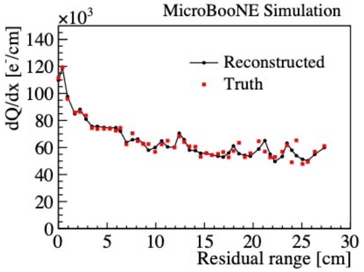
JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)
JINST 16 P01036 (2020)



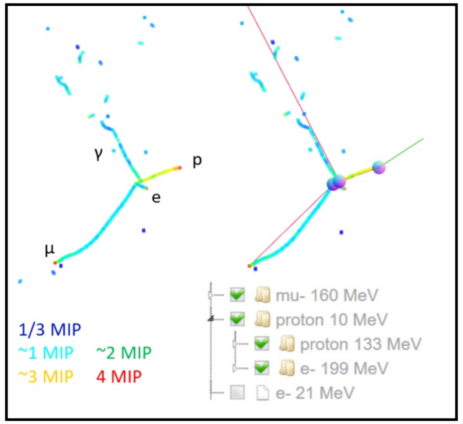


JINST 13 P05032 (2018)
JINST 16 P06043 (2021)

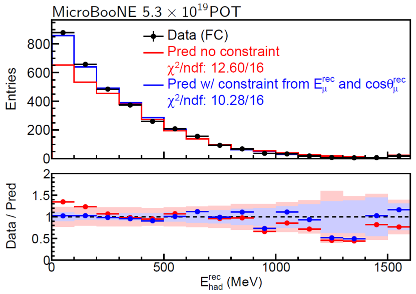




PRApplied 15 064071 (2021)



JINST 17 P01037 (2022)



PRD 105, 112005 (2022)
PRL 128, 151801 (2022)

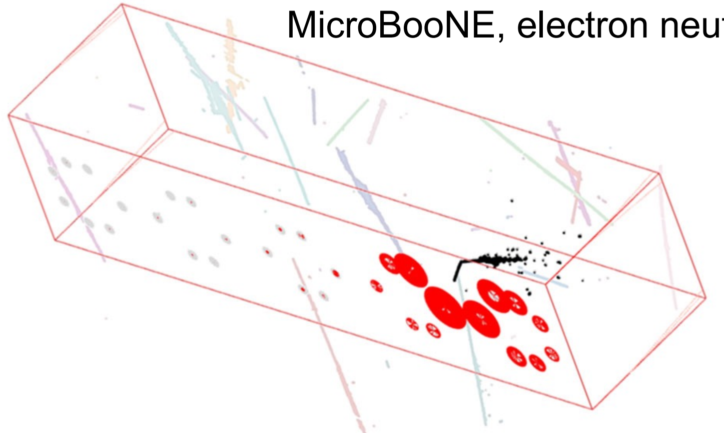
Visualization

- Since a LArTPC is intrinsically an imaging detector, having powerful event-display tools is crucial for both advanced developers and general users
  - We need to think hard about how to best present the data
- In Wire-Cell, we have a multi-purpose web-based 3D event display called "Bee":
  - cross-platform (runs in a web browser)
  - basic server tools to support event catalog, user uploads, etc.
  - interactive 3D display based on WebGL
  - on-demand display of multiple information: multiple reco overlay, truth, charge-light matching, etc.

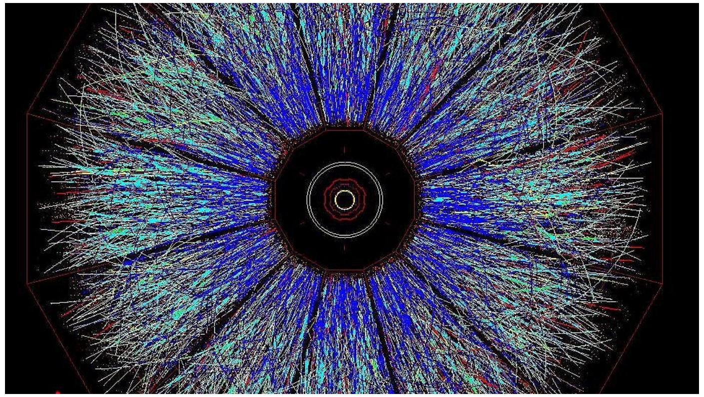
Demo: Example nue events from MicroBooNE

LArTPC vs Collider Gas TPC

MicroBooNE, electron neutrino



STAR – RHIC – BNL, Au + Au

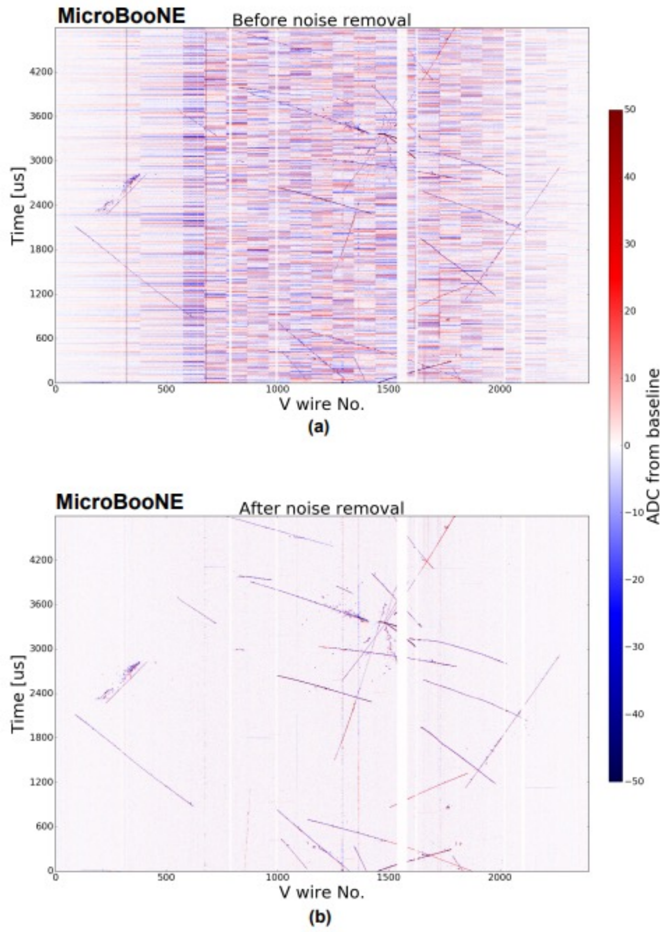


- ❑ Neutrino interaction: anywhere in the detector
- ❑ Secondary interactions are common due to high density
- ❑ Very few auxiliary detectors
  - photon detectors, cosmic ray taggers
- ❑ No magnetic field
- ❑ Both track (μ, p, π) and showers (e/γ) reconstructions are important
- ❑ <u>Main challenge</u>: correctly reconstruct and associate different activities (tracks, showers, light, etc.)

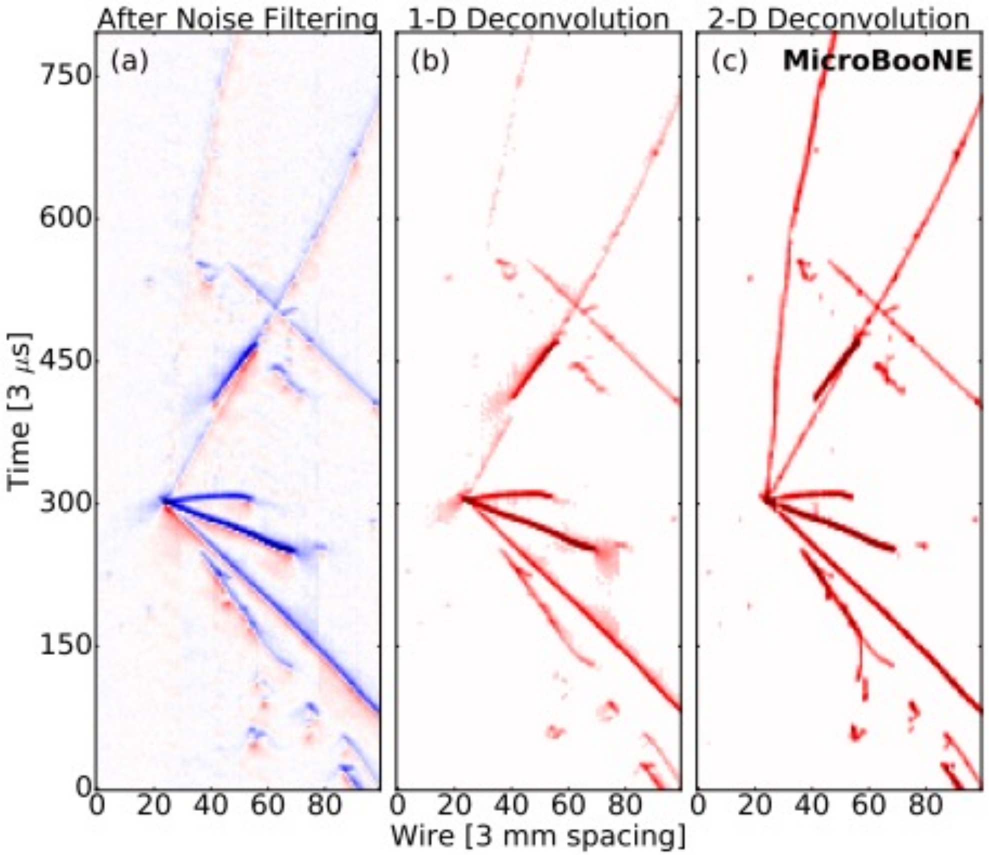
- ❑ Interaction: mostly at the colliding vertex
- ❑ Few secondary interactions in the gas
- ❑ Many auxiliary detectors
  - vertex detector, muon detector, TOF, EM/hadron calorimeter, etc.
- ❑ Magnetic field to help determine particle momentum and predict particle trajectory
- ❑ Shower reconstruction typically only through separate calorimeter
- ❑ <u>Main challenge</u>: high multiplicity of tracks.

Noise filtering and Signal Processing

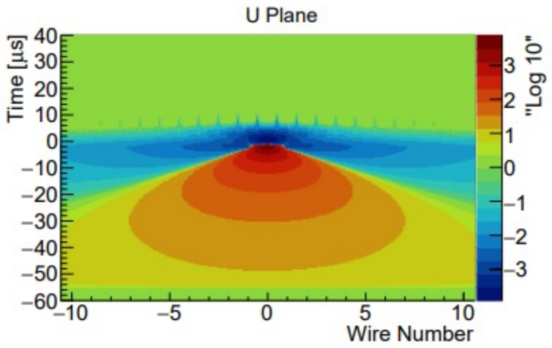
Example event from MicroBooNE before and after noise filtering
JINST 12, P08003 (2017)



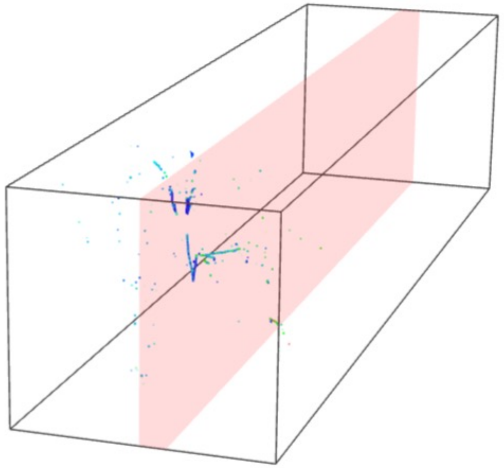
Example event from MicroBooNE before and after signal processing
JINST 13, P07006 (2018)



2D field response taking into account long range induction effect up to ±10 wires

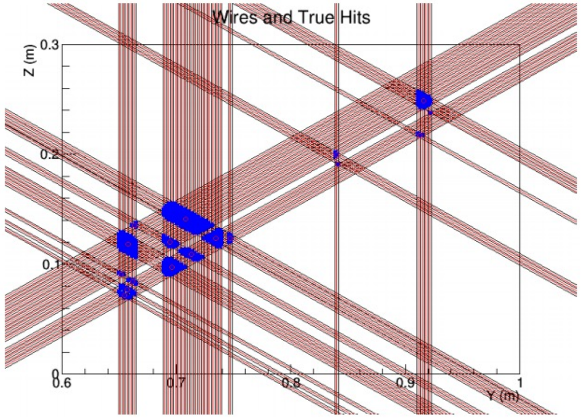


Tomographic 3D Imaging



Time slicing →

+ geometry information



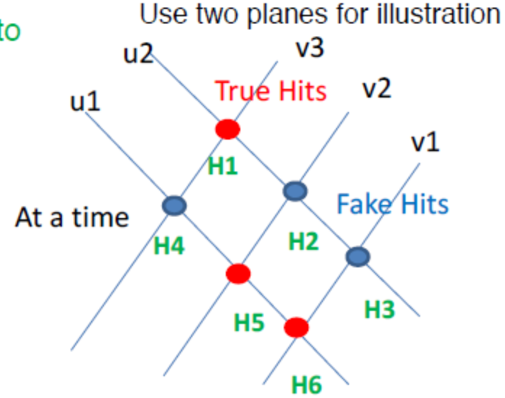
Measured charges on wires

True charge hits to be solved

$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H1 \\ H2 \\ H3 \\ H4 \\ H5 \\ H6 \end{pmatrix}$$

Matrix determined by geometry

+ charge information



underdetermined linear system: + sparsity constraint

$$\text{minimize } \|x\|_1 \text{ , subject to: } y = Ax$$

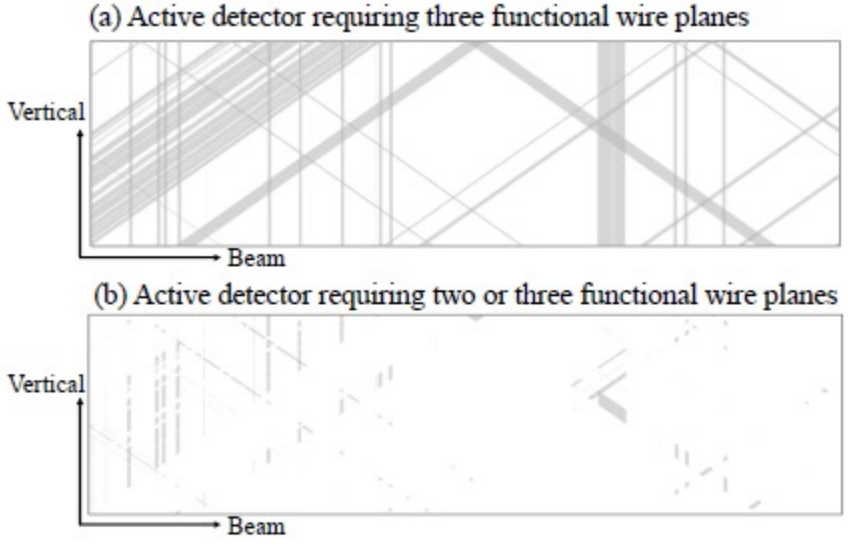
Or, equivalently, minimize

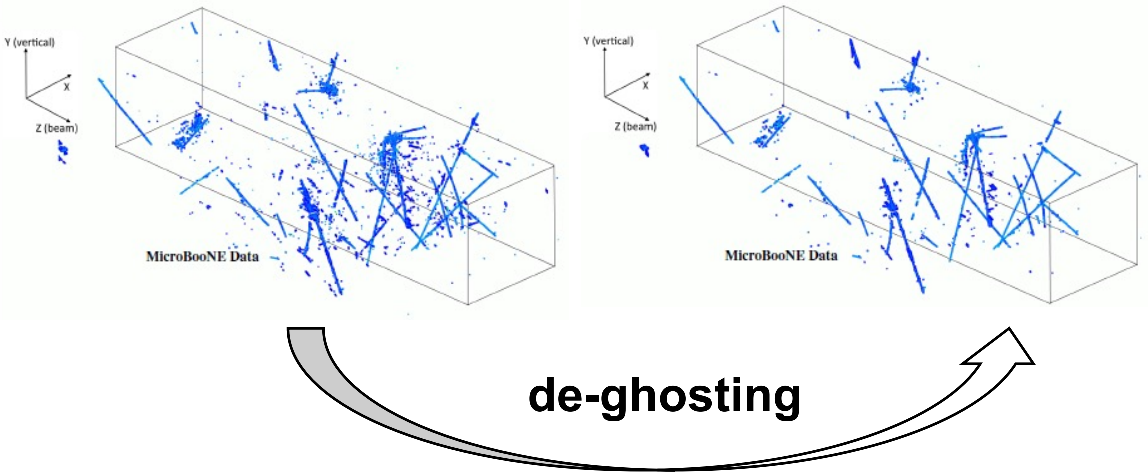
$$\chi^2 = (y - Ax)^T \cdot V^{-1} \cdot (y - Ax) + \lambda \big|\big|x\big|\big|_1$$

Dealing with imperfect detector

Realistic issues:

- ❑ MicroBooNE has ~10% dead channels
  - Require all 3 planes: 30% dead region
  - Require 2 planes: → 3% dead region
- ❑ Two-plane tiling creates more ambiguities (ghost hits) depending on the topology of the event; need dedicated de-ghosting algorithm
  - Check position overlap with dead channels
  - Check redundancy in projective views
  - Iterative charge-solving + de-ghosting

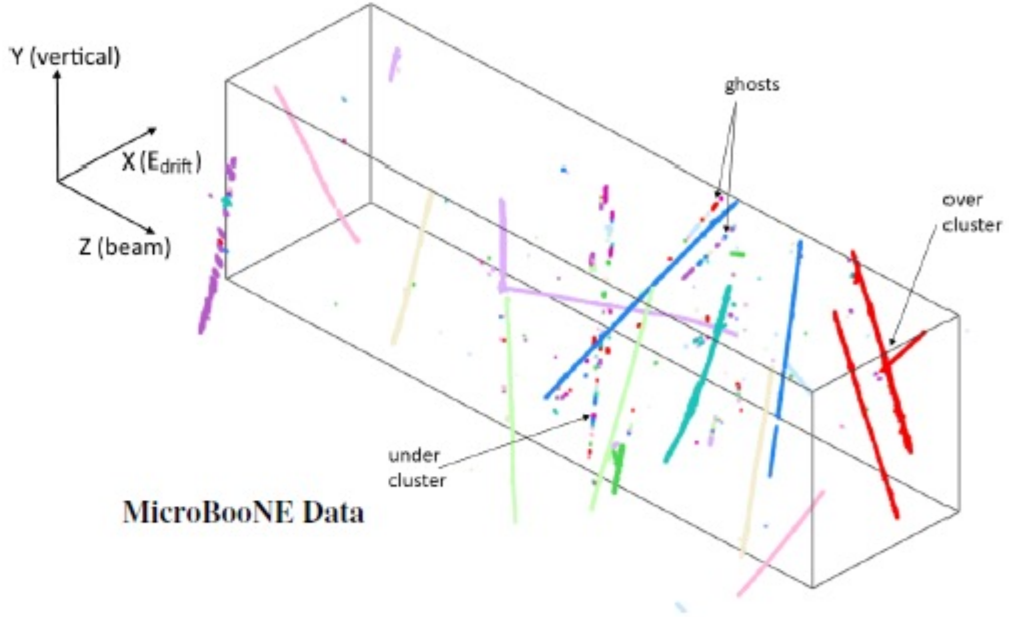


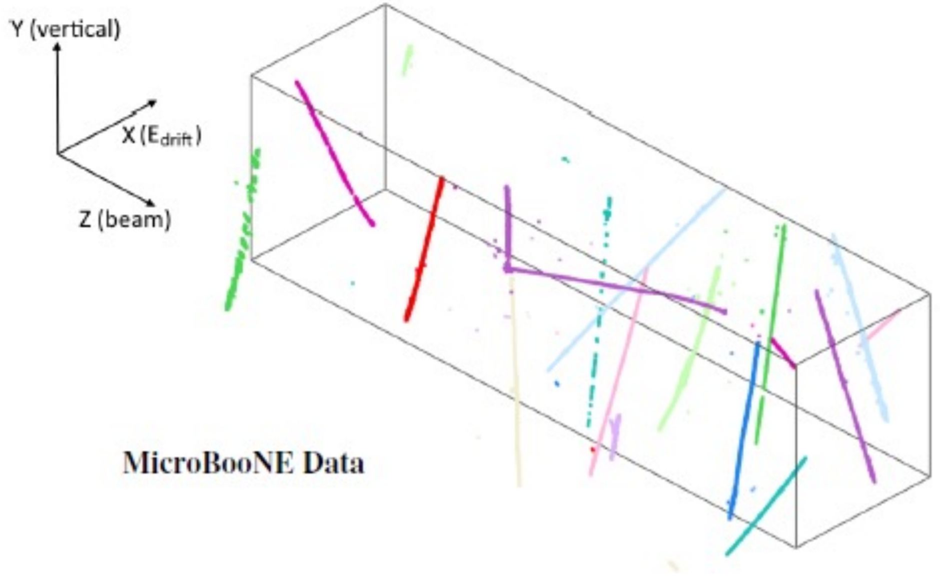


Clustering

- ❑ Cluster 3D points into individual objects based on proximity
  - k-d tree, an efficient space-partitioning data structure for organizing spatial points
- ❑ Realistic issues:
  - gaps caused mainly by dead channels → under-cluster
  - accidentally overlapping tracks → over-cluster
  - Residual ghosts

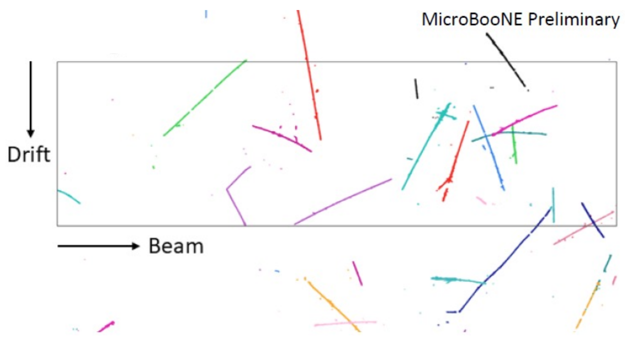
same color: same cluster

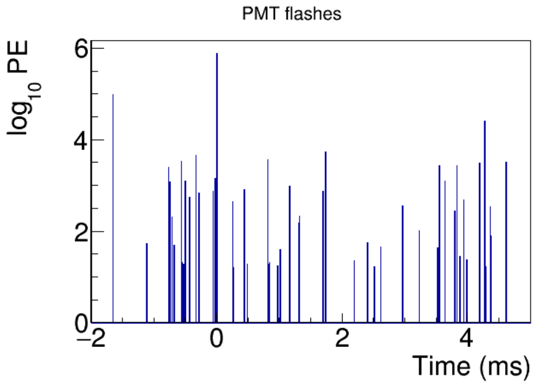


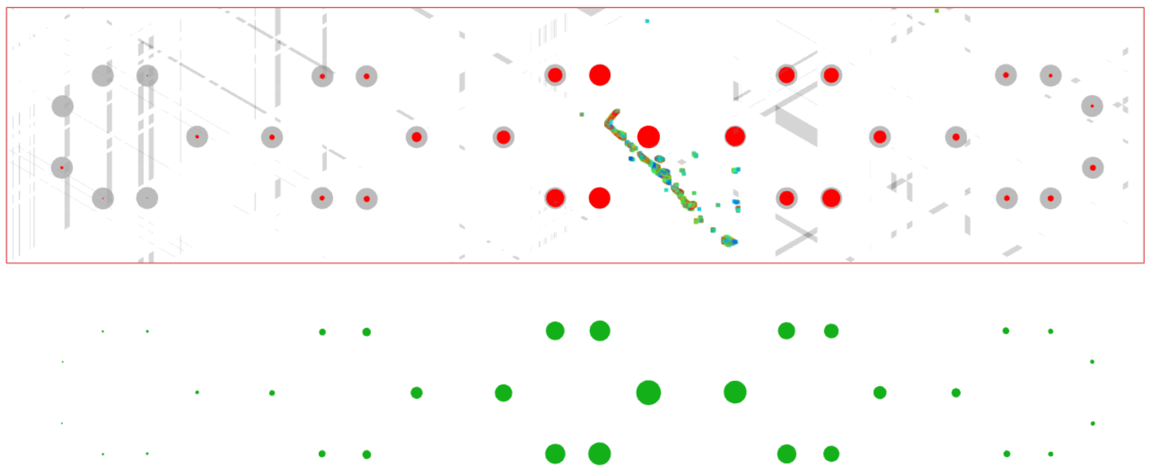


Charge-light matching

- Matching between 20-30 TPC clusters and 40-50 PMT flashes
  - correcting x-position of each cluster
  - Important for neutrino selection and cosmic-ray rejection
- Method: form a cluster-flash pair, compare predicted light pattern based on charge cluster vs measured light pattern
- All possible hypotheses
  - 1 cluster → 1 or 0 flash (inefficiency in the light system)
  - 1 flash → 0, 1, or many TPC clusters (inactive volume, under-clustering)
  - Solved efficiently with Compressed Sensing (L1-regularization)

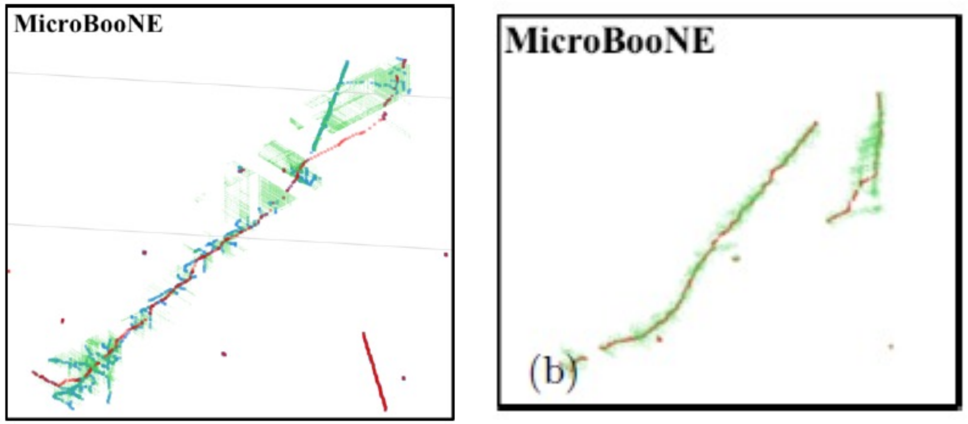






Track Trajectory Fitting

- ❑ Goal: determine an ordered fine-grained trajectory from the un-ordered 3D points in the cluster
- ❑ Approach:
  1. Find initial 3D trajectory seed with a coarse spacing (1.2 cm)
     - Steiner tree (Graph theory): find shortest path through point of interests
  2. Associate the 3D seed with the 2D measurement
  3. Form a test statistic T to fit the trajectory
     - Minimization: biconjugate gradient stabilized method (BiCGSTAB)
  4. Iterate again with a finer spacing (0.6 cm)



Green: original 3D points from imaging/clustering
Red: trajectory seed found with Steiner Tree

$$T = \sum_{k=u,v,w} (M_k - R_k \cdot S)^2$$

projection matrix: R_k
2D measured points: M_k
3D trajectory to be fitted: S

dQ/dx Fitting

- ❑ Approach: form a test statistic T' to fit a charge Q_j for each trajectory point (x_j, y_j, z_j)

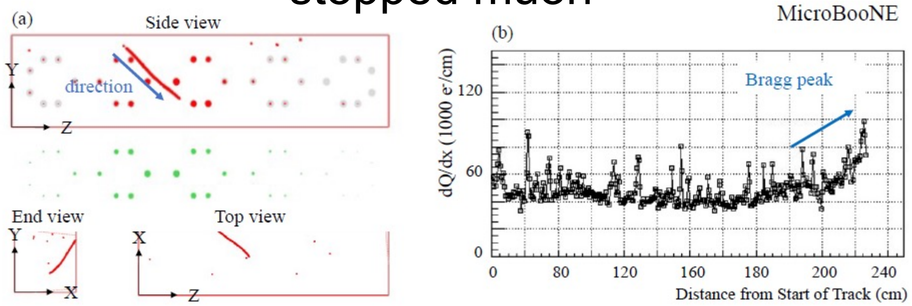
$$T'\left(S\{Q_j\}; S\{x_j, y_j, z_j\}\right) = \sum_{k=u,v,w} T'_k + T'_{\text{reg}},$$

$$T'_u = \sum_i \frac{1}{\delta q_i^2} \cdot \left(q_i - \sum_j R^u_{ij} Q_j\right)^2$$

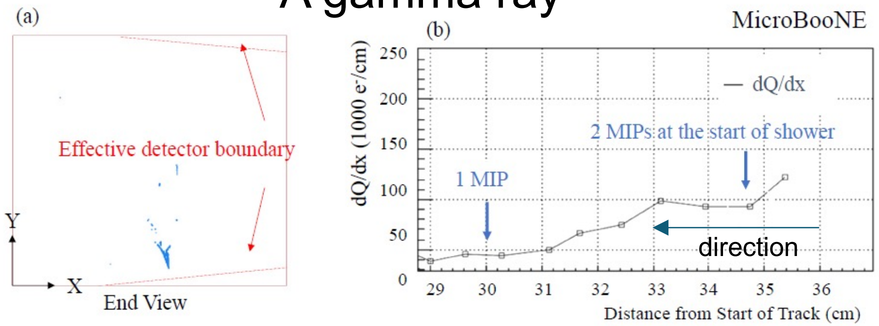
Regularization term
(smoothness of the charge curve)

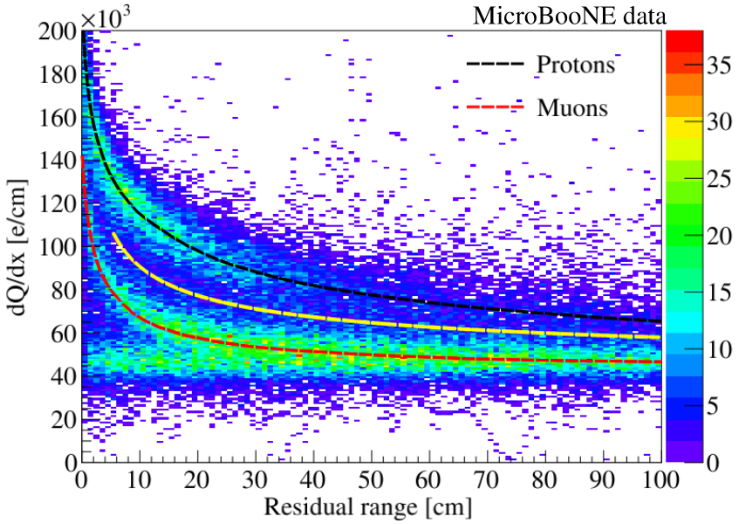
Response matrix
(diffusion, noise, signal processing, etc.)

stopped muon

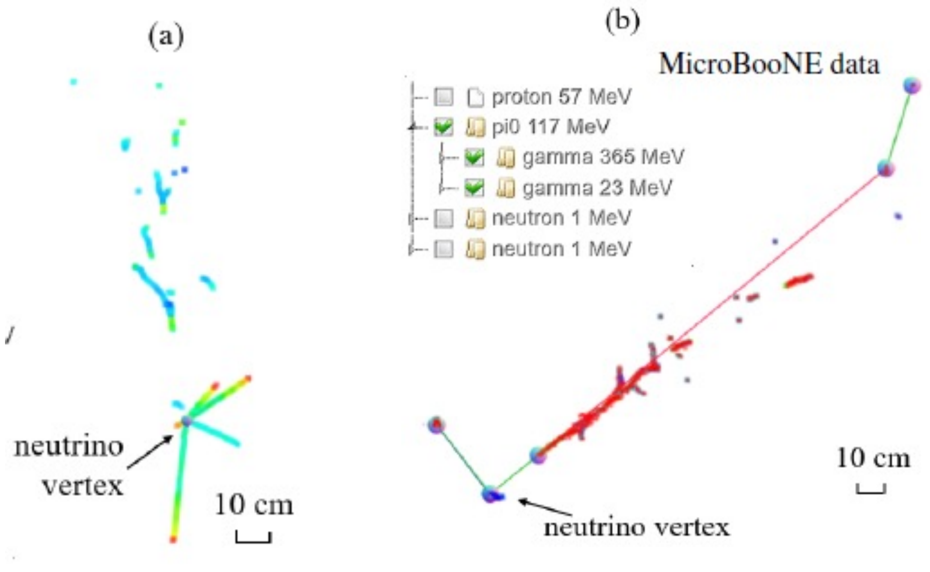


A gamma ray



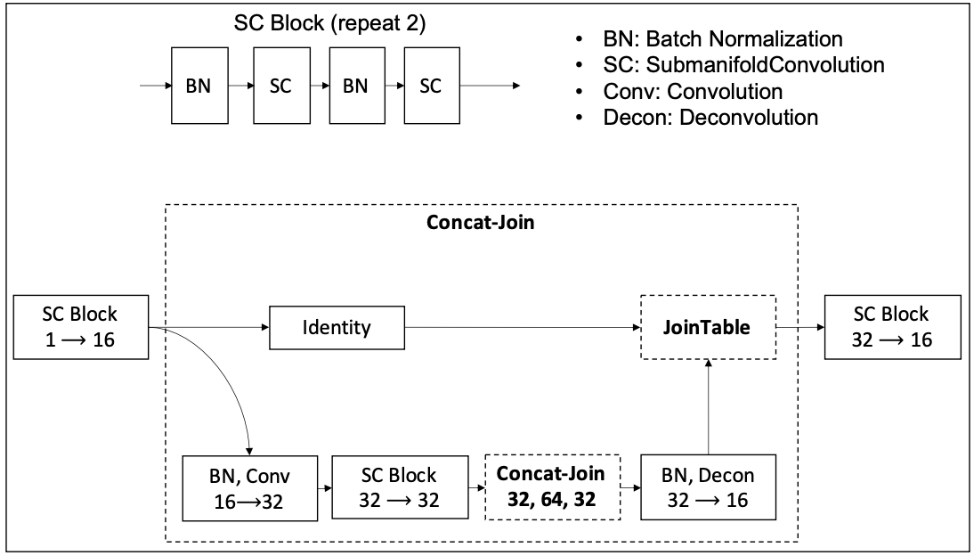


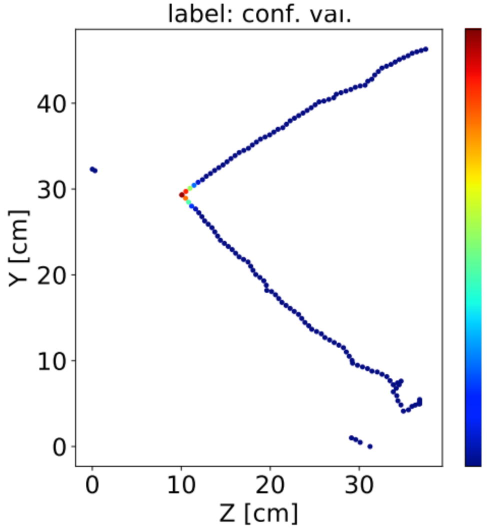
Neutrino Vertex Fitting

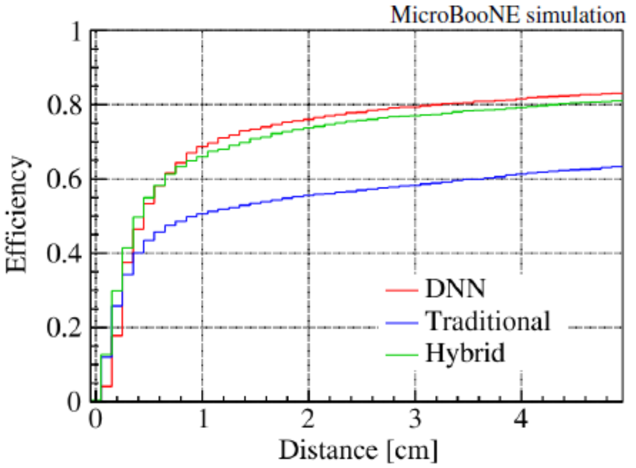


- ❑ Traditional fitter
  - Direction from dQ/dx
  - Position, multiplicity, connection rules, etc.
- ❑ Deep Neutral Network fitter
  - Sparse Regression U-Net
  - Predict: distance map of each voxel (a 3D pixel) to the neutrino vertex

Truth label: $Conf_{\text{truth}} = \exp\left(-\frac{\|\vec{x} - \vec{v}_{\text{truth}}\|^2}{2\sigma^2}\right)$,





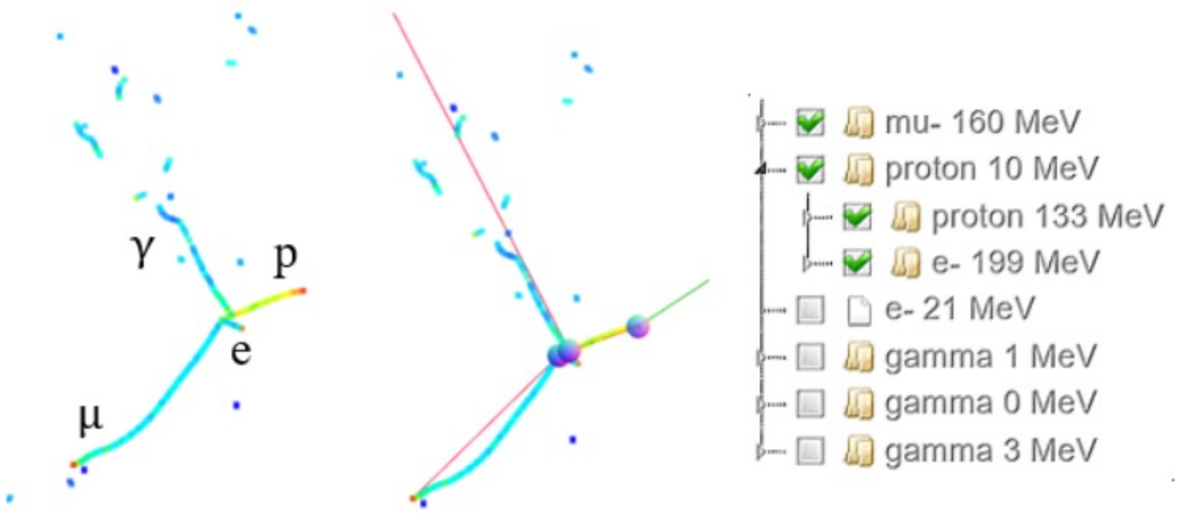


PID, Energy, and Particle Flow

- Particle ID
  - track PID based on dQ/dx
  - e/gamma separation based on gap and dQ/dx
  - π^0 reconstruction (a pair of γ's)
- Energy reconstruction
  - Track: range, dQ/dx
  - Shower: dQ/dx
  - Neutrino
- Starting from neutrino vertex, build the entire particle flow hierarchy

(d) 3D dQ/dx displayed with PID capability

(e) Particle flow starting from neutrino vertex



Wire-Cell enabled multiple physics analyses in MicroBooNE

- Neutrino Selection
  - Generic neutrino selection: Cosmic-ray removal
  - Inclusive numuCC selection
  - Inclusive nueCC selection
  - Exclusive final states
- Oscillation analyses: Low Energy Excess, single photon, 3+1 fit with BNB + NuMI
- Cross section measurements

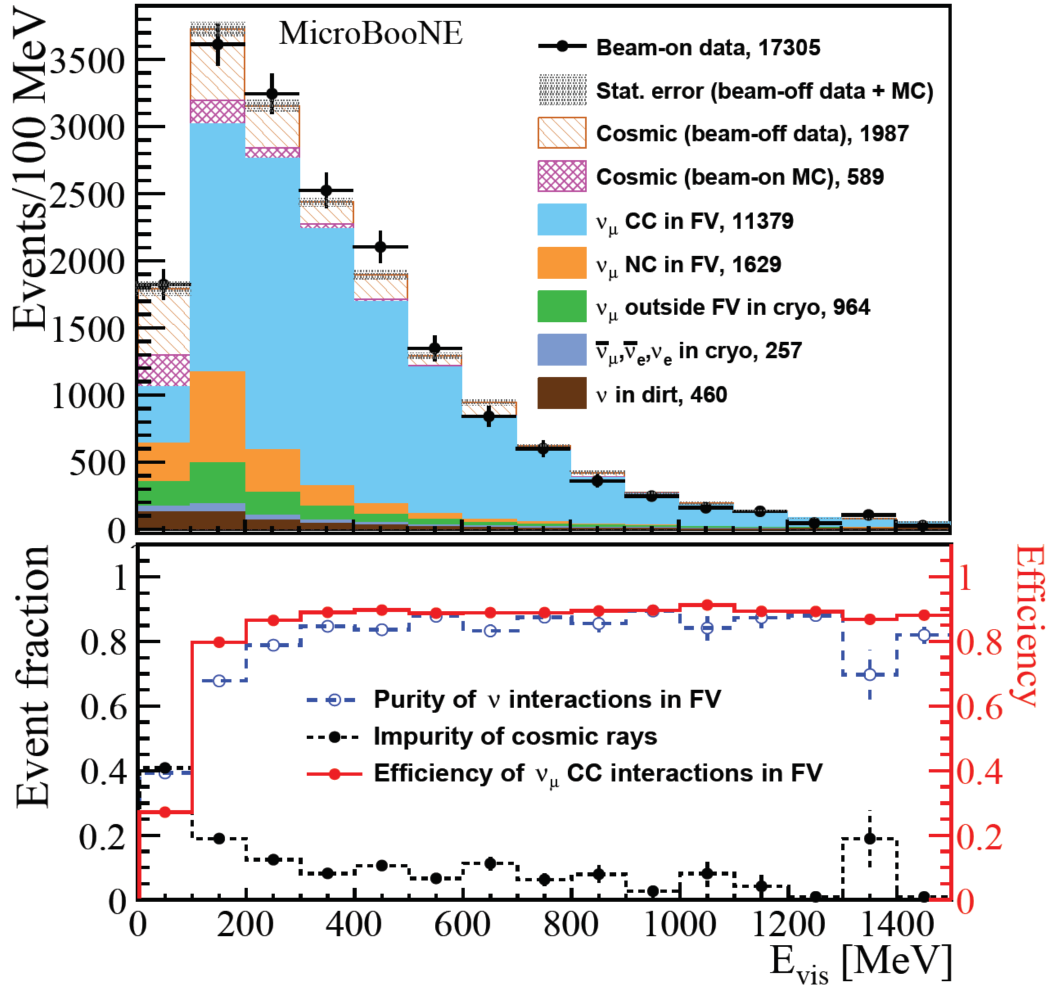
Generic Neutrino Selection

After charge-light match
+ through-going muon removal
+ stopped muon removal

- ❑ 99.98% in-beam-coincident cosmic-ray backgrounds are rejected
- ❑ ν_μ charged-current (CC) efficiency: 80%
- ❑ ν_eCC efficiency: 90%

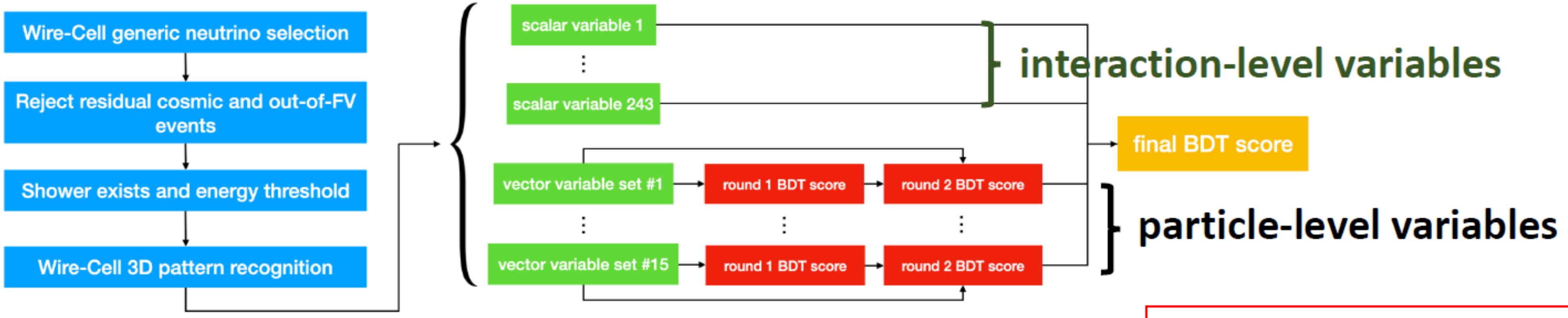
❑ However, ν_e is only ~0.5% of all neutrino interactions

- need another factor of ~1000 improvement in purity to be sensitive to LEE



Phys. Rev. Applied 15, 064071

Improved Selection through BDT

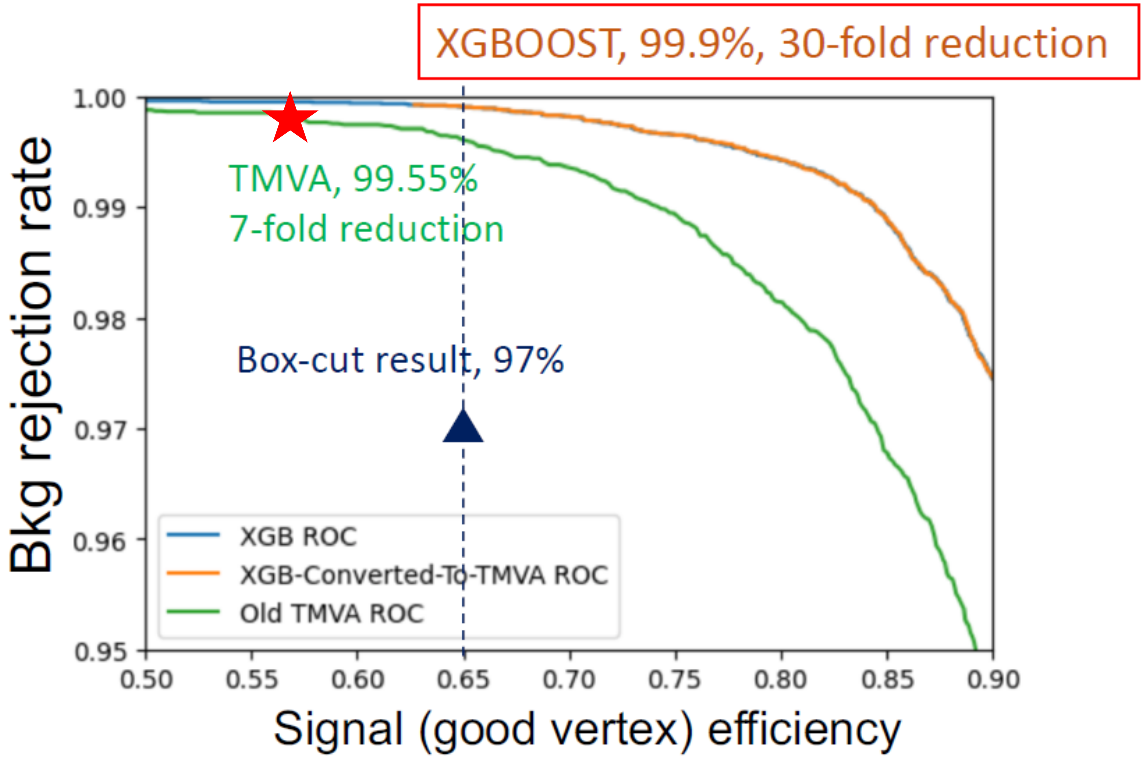


Human feature engineering

+

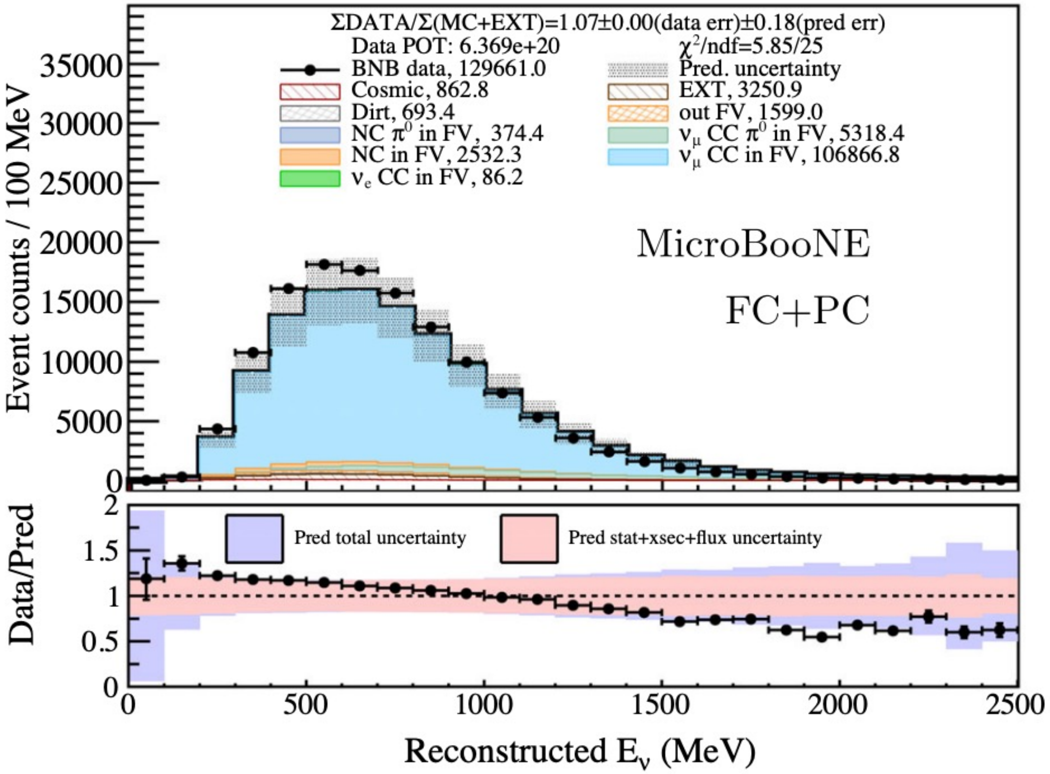
Machine learning algorithm:

XGBOOST: extreme Gradient Boosting



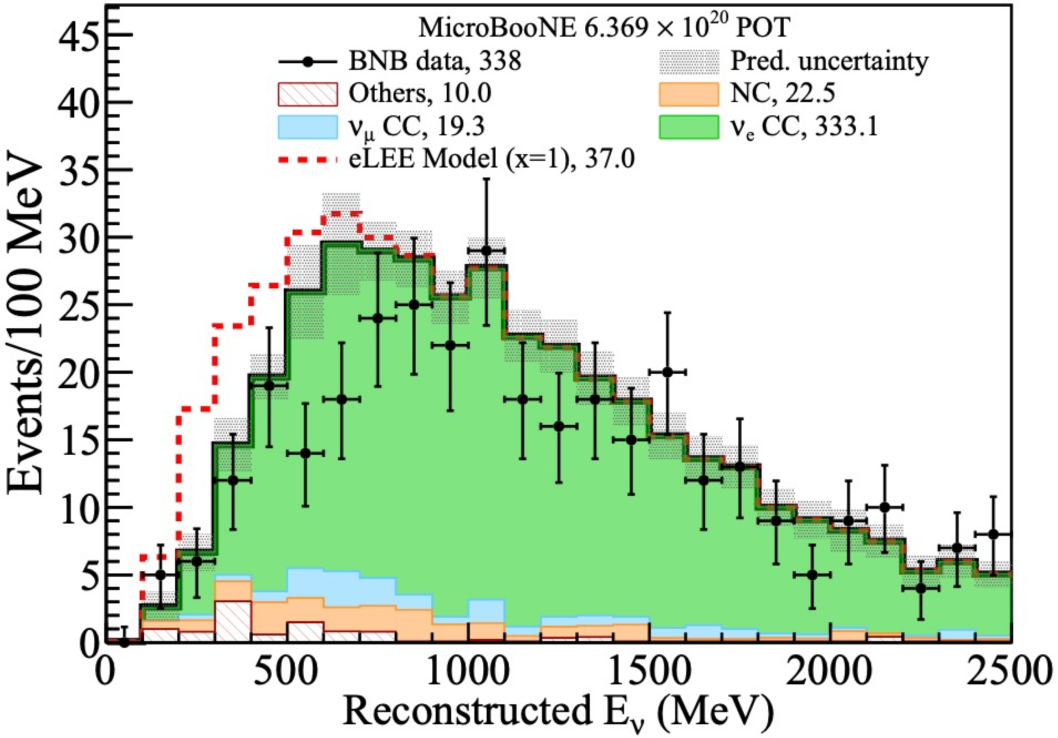
Performance of CC Selection

PRD 105, 112005 (2022)



Efficiency: 68%
w.r.t to all ν_μCC w. vertex in fiducial volume
Purity: 92% (**>5** improvement in S/B)

PRL 128, 241801 (2022)



Efficiency: 46%
w.r.t to all ν_eCC w. vertex in fiducial volume
Purity: 82% (**>800** improvement in S/B)

Wire-Cell: Moving Forward

- Porting from prototype code to Wire-Cell Toolkit
  - Signal simulation, signal process, and 3D imaging have been ported to WCT and are available for SBN, protoDUNE, and DUNE-FDs.
  - Other tools only exist in MicroBooNE. Significant collaborative efforts are needed to make them available for other experiments: we need your support!
- Improve IO and Integration with LArSoft / other tools
- Improve event reconstruction performance
  - Mathematical / Physics–based algorithms
  - AI/ML algorithms
- Grow user base
  - documentations, tutorials, workshops, …

Let’s have a productive workshop!