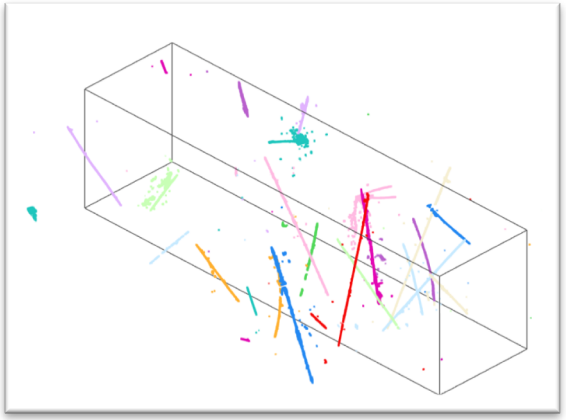
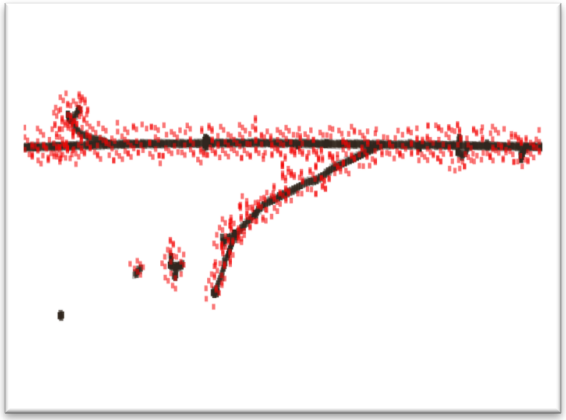
Recent progress on Wire-Cell 3D Imaging & 3D tracking for LArTPCs





Hanyu WEI

Jul 31, 2019

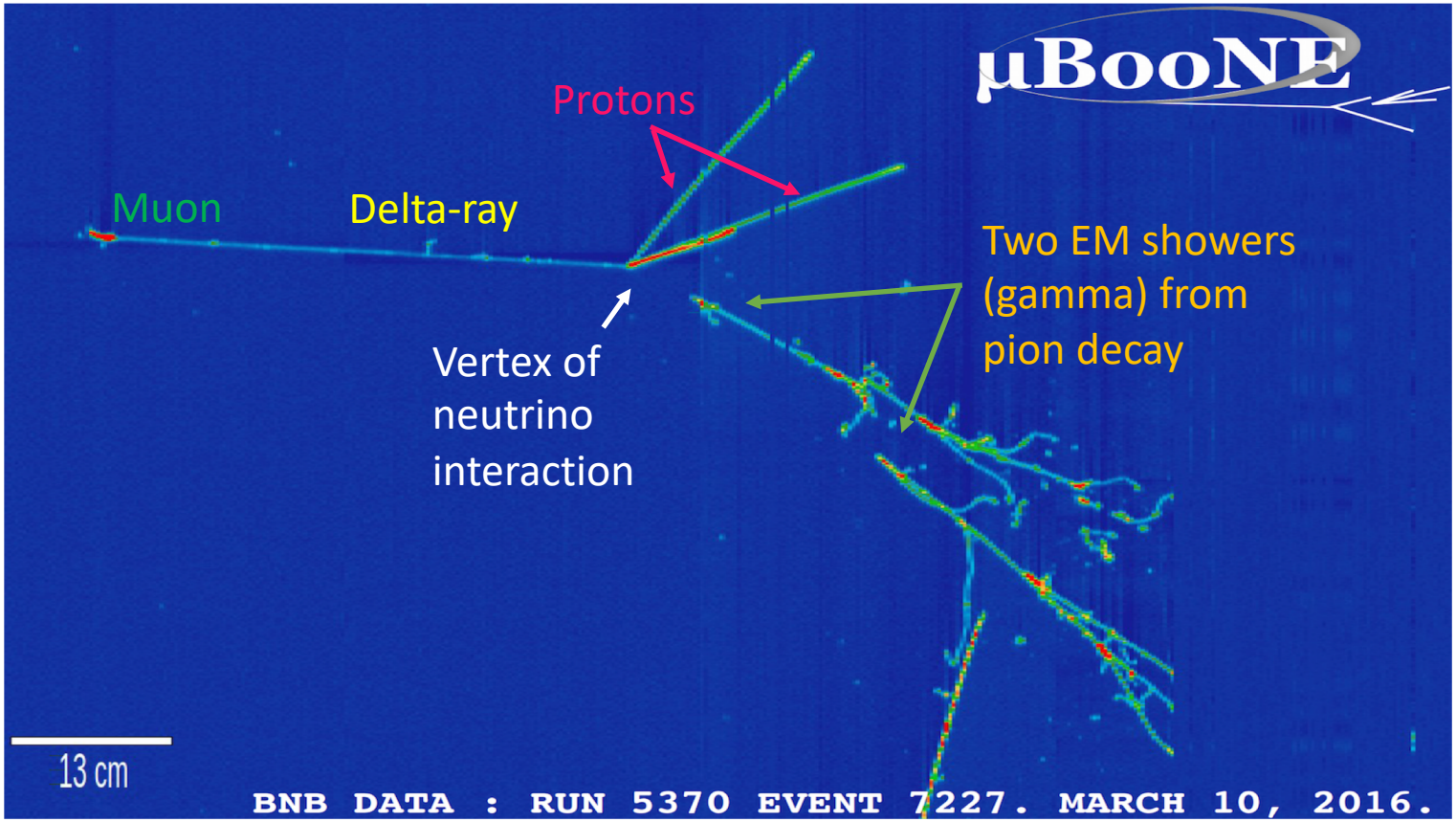
APS DPF2019 @ Northeastern University

Key words

- Accelerator neutrino experiment
- Liquid Argon Time Projection Chamber (LArTPC)
- 3D event reconstruction
  - Open question
  - Various paradigms, e.g. Pandora (Eur. Phys. J. C (2018) 78:82), Deep Learning (2017 JINST 12 P03011; Phys. Rev. D 99, 092001), etc.
  - ***Wire-Cell*** (2018 JINST 13 P05032) is one of the paradigms in development in MicroBooNE, applied for neutrino selection in MicroBooNE

LArTPC

- A state-of-the-art neutrino detector technology with excellent 3D tracking & calorimetry for charged final state particles of neutrino interactions
- Concept raised in 1970s, technology gradually matured since 2000s

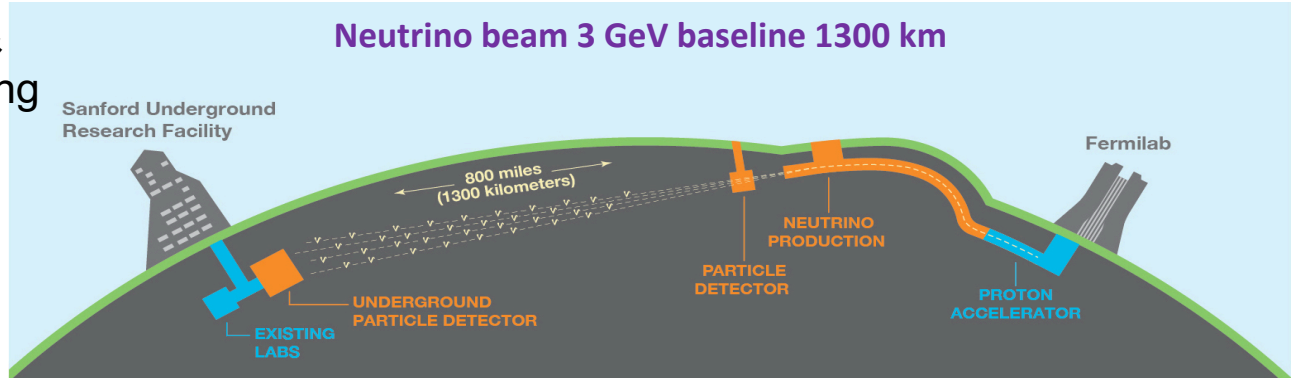


LArTPC Experiments

Deep Underground Neutrino Experiment

- Leptonic CP phase & neutrino mass ordering
- Supernova neutrinos
- Nucleon decay

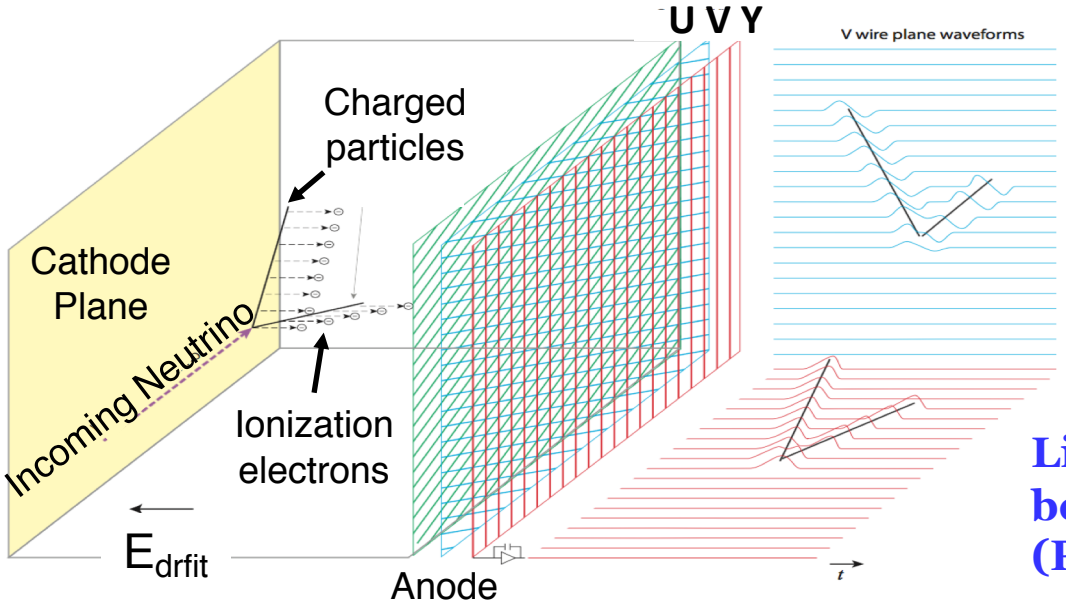
4x 10kt LArTPC modules as far detector

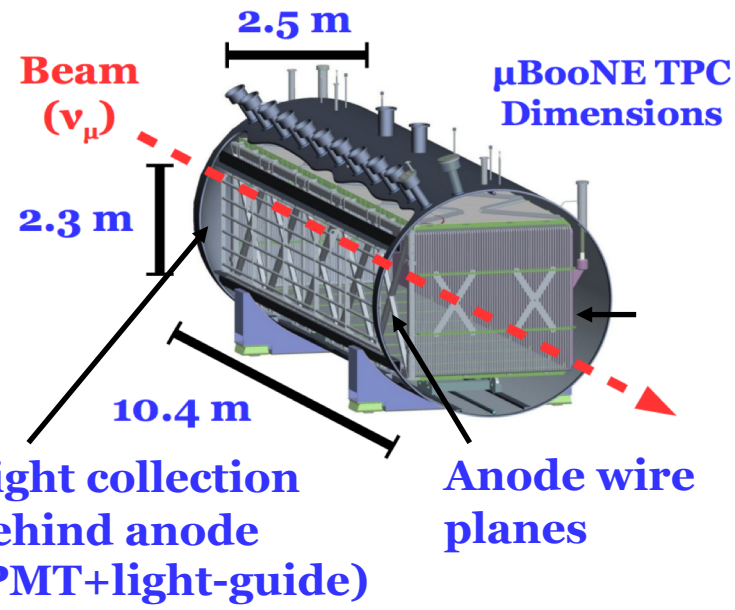


Short-Baseline Neutrino Program

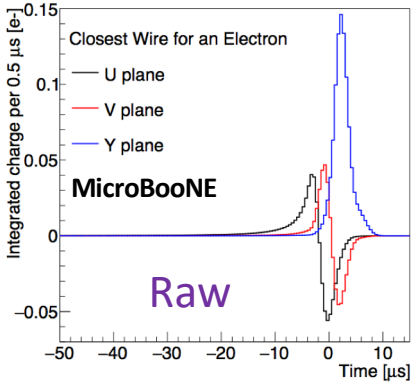
- Phase 1: MicroBooNE since 2015 – a definitive check on MiniBooNE Low Energy Excess, $\nu - Ar$ cross section measurement, LArTPC R&D
- Phase 2: Three detectors coherent check on the existence of sterile neutrinos

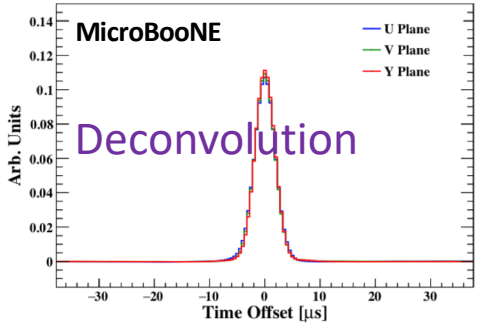
MicroBooNE LArTPC signal





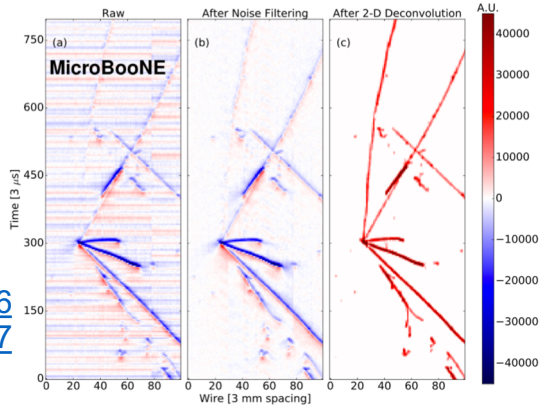
Signal processing
(electronics waveforms → ionization electron spectrum on time vs wire view)





Time [us]
1us ~ 1.1 mm

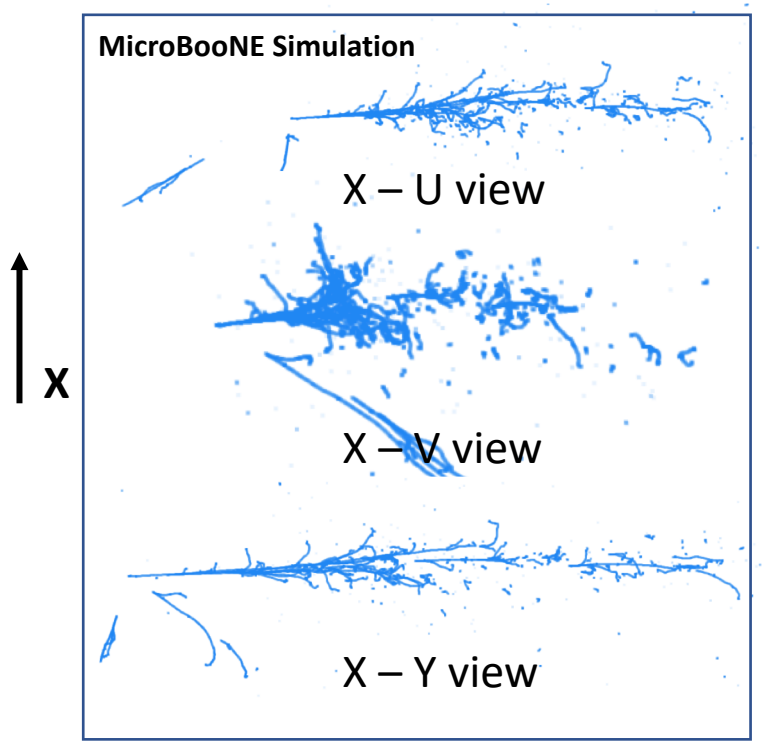
JINST 13 P07006
JINST 13 P07007



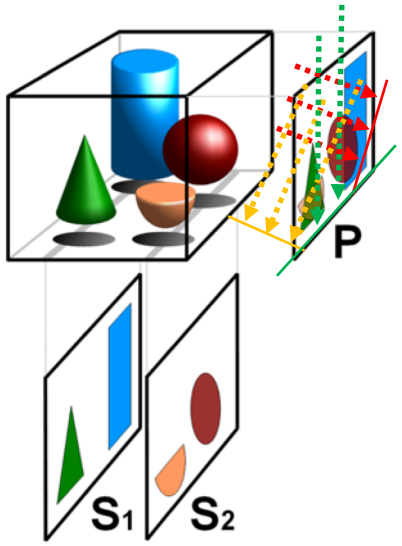
Wire [3 mm spacing]

Wire-Cell 3D (Tomographic) Imaging

- One traditional path (hand-engineered approach) to reconstruct 3D image of charges based on THREE measurements on 2D views



X: drift E field direction
Y: vertical direction
U: 60° relative to **Y**
V: -60° relative to **Y**



JINST 13, P05032 (2018)

LArTPC vs Tomography

- Time = Cross section
- Wire = 1D projection view
- Charge = Radiograph (integral along 1D projection)

3D image of **ionization electrons** = 1D time + 2D anode plane position

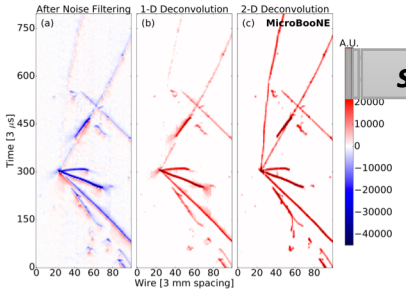
✓ Topology (pattern recognition) agnostic

Wire-Cell Tomographic Imaging

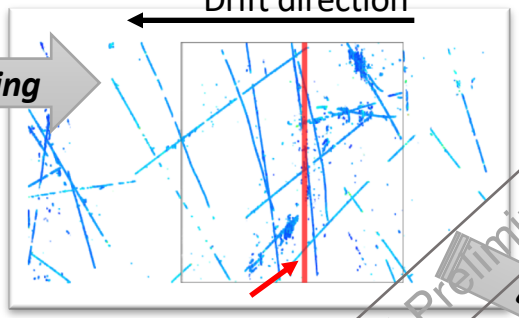
Challenges of 2D anode plane image

- Complex topologies in high density medium liquid argon, e.g. EM showers
- Wire readout ambiguity – unknown position of charge along wire, i.e. "3 wire planes" $(3\times n) \neq$ 2D position readout (n^2)

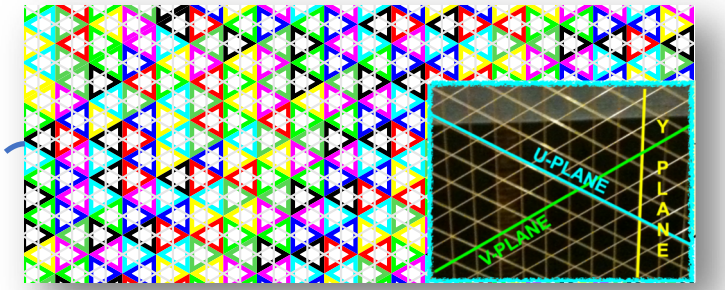
LArTPC Signal Processing



slicing

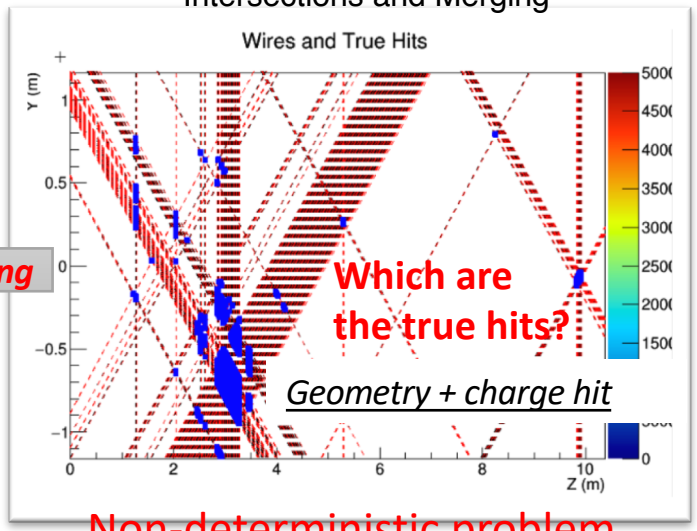


Cells from Wires



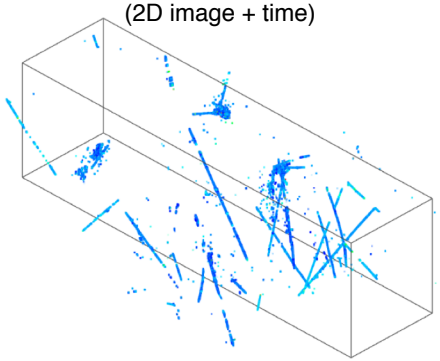
tiling

Intersections and Merging



solving

3D image
(2D image + time)



2D image

Not real time slice (much wider)

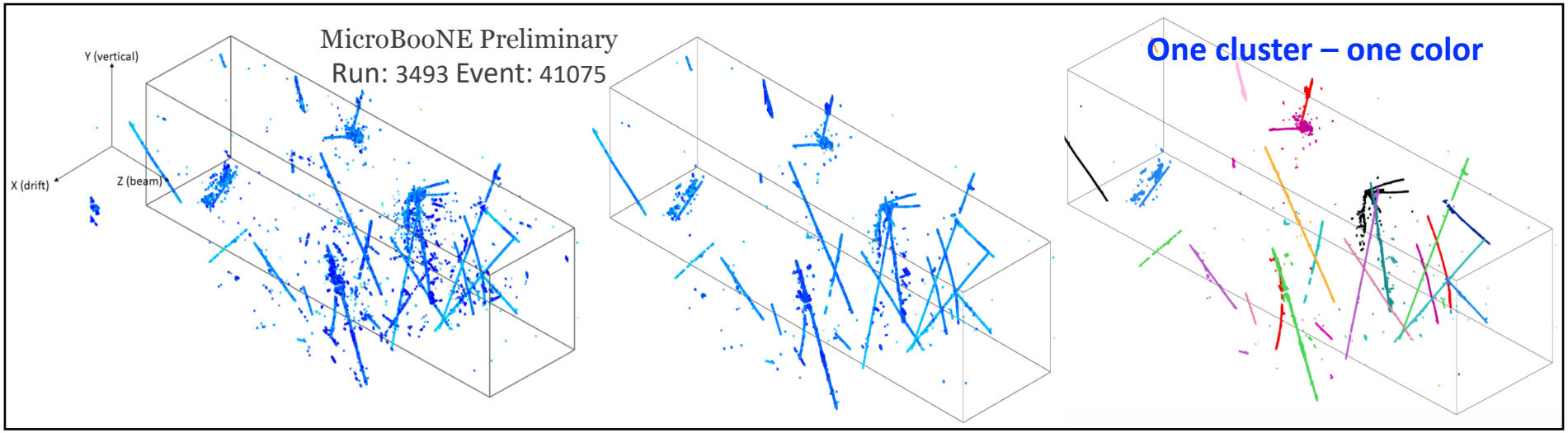
MicroBooNE Preliminary

Compressed sensing technique to remove fake hits
(L1-regularization in a chi2 fitting)

Non-deterministic problem

Realistic Issues

- TWO available wire plane views or Gaps due to non-functional channels/wires (dead or noisy), signal processing inefficiency, and noise removal, etc.
- De-ghosting, bridging of gaps, clustering (group initial clusters) → Good images



Before deghosting

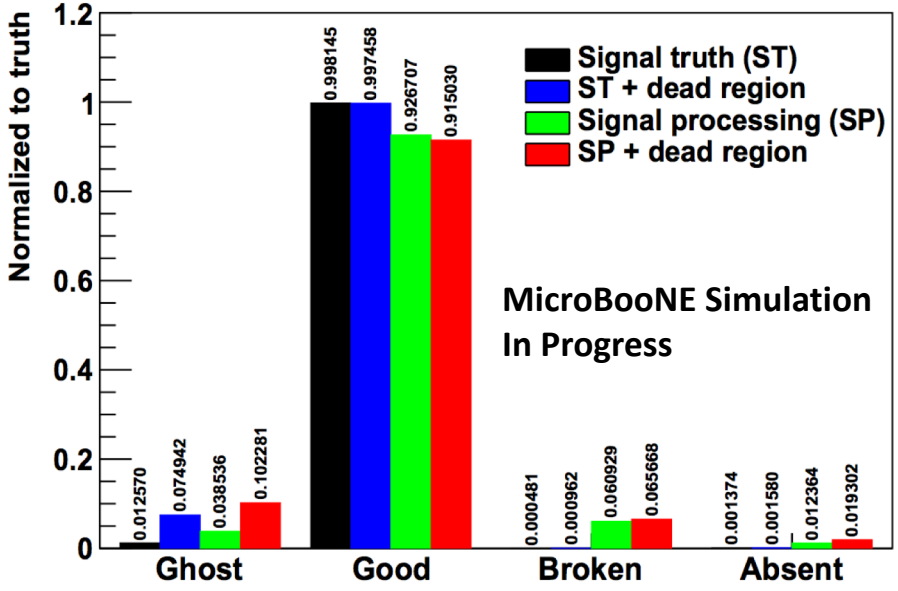
After deghosting

Final clustering

Performance of Wire-Cell 3D imaging

Reconstructed position vs True position for each 3D space point (voxel)

Ideal (line) MIP tracks
Similar "charge density" (# of charge hits in a time slice) in the real data

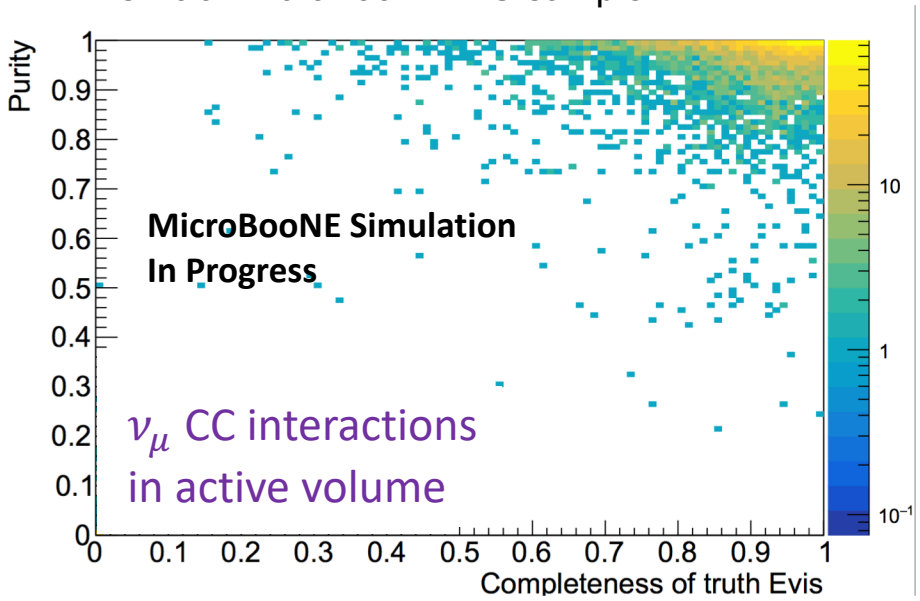


A few cm long

>95% overlap in reco vs truth

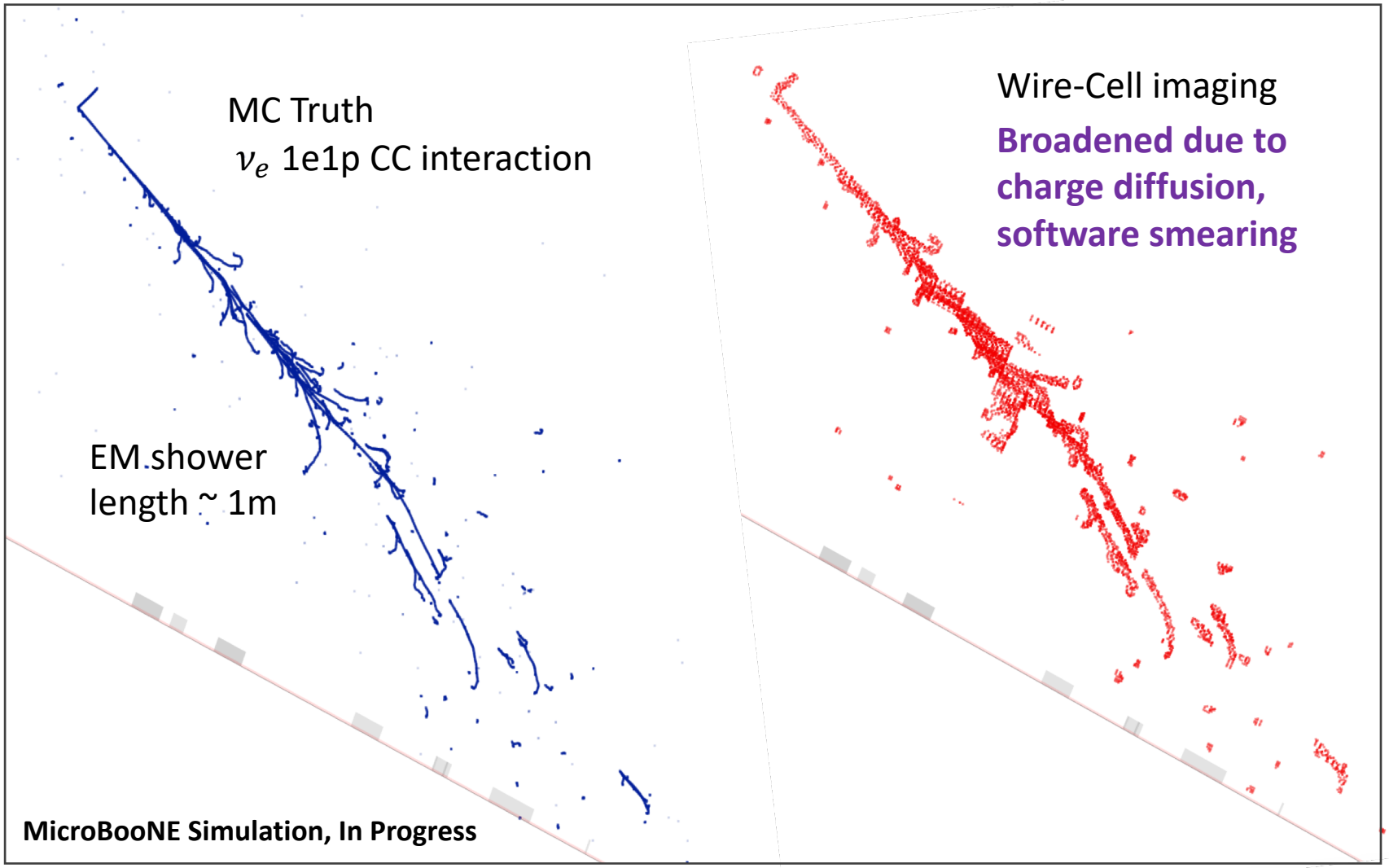
Prolonged tracks

The most realistic (Geant4-based) simulation for neutrino interactions
Official MicroBooNE MC sample

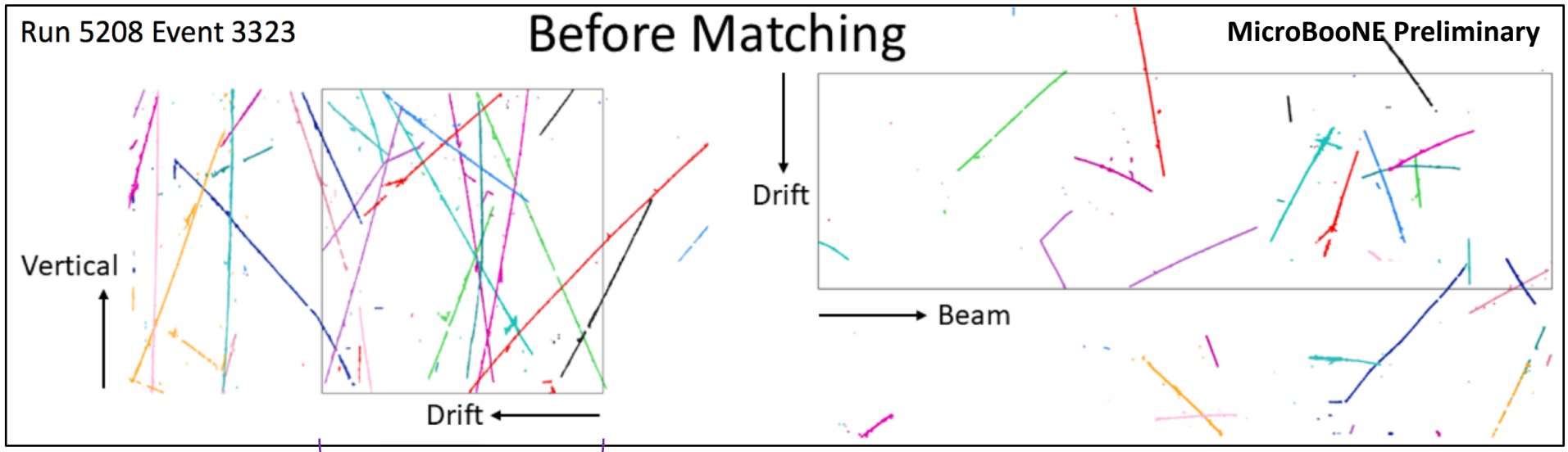


Completeness: **overlap** over **true**
Purity: **overlap** over **reco** [ghost, over-clustering, etc.]

An example EM shower event



TPC-PMT matching



In-beam drift window (2.3 ms)

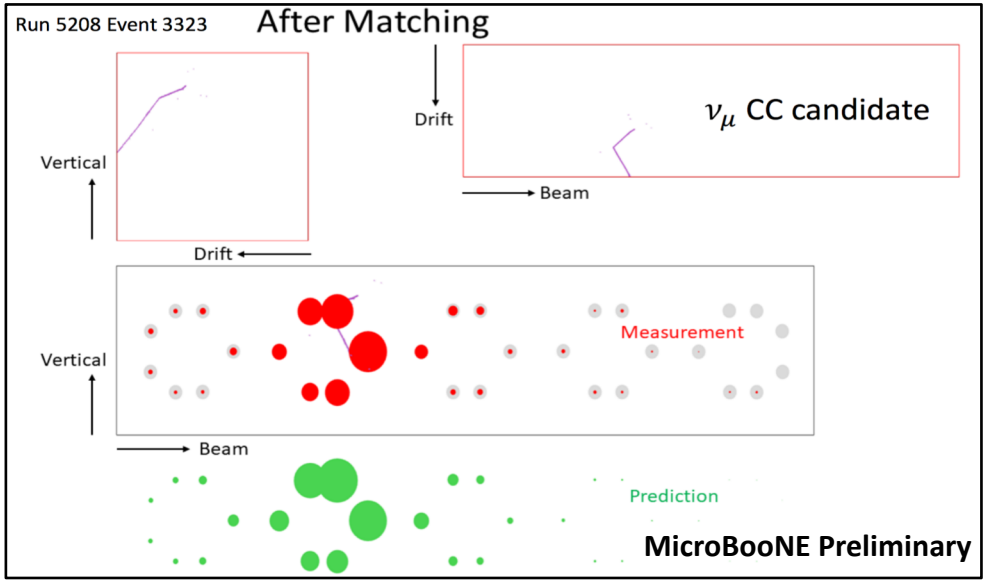
Entire readout window (4.8 ms)

Beam spill (neutrino) window ~2us

Readout time (pseudo drift distance)
= **t0** + **drift distance**

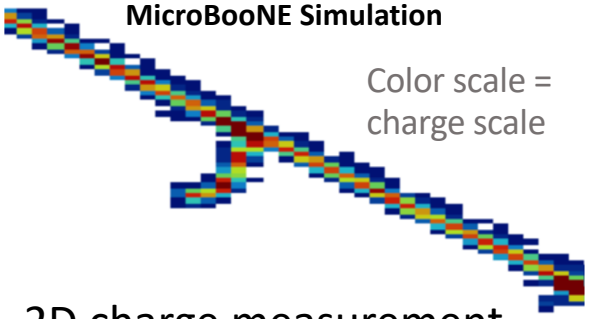
t0 = PMT flash time (scintillation light)

Compressed sensing technique to do many-to-many matching
PMT meas. vs PMT pred. (TPC charge)



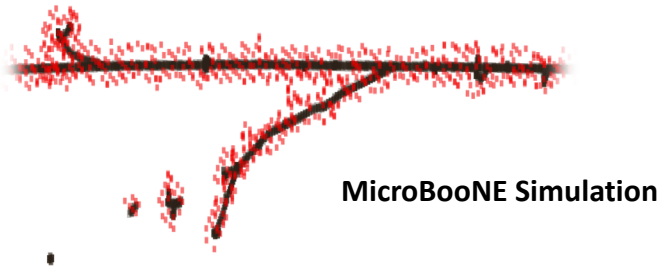
Wire-Cell 3D tracking

- Trajectory fitting based on the reconstructed 3D space points of a TPC activity (cluster) post tomographic imaging
- Good trajectory fitting → precise dQ/dx (dE/dx) fitting to select (remove) signals (backgrounds)



2D charge measurement

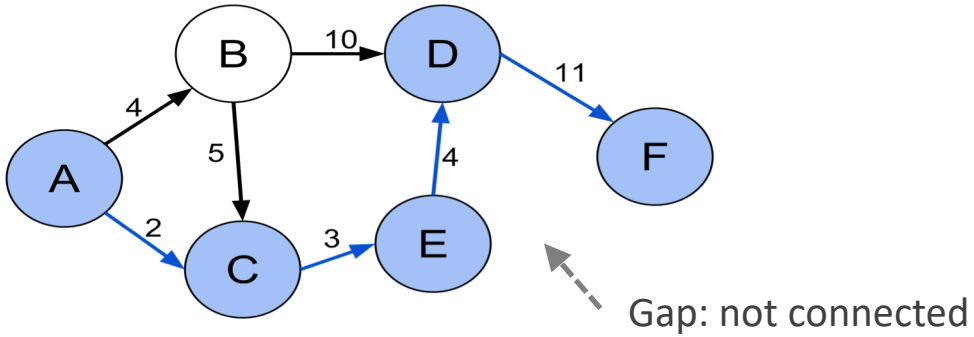
Red dots: 3D space points (voxel size ~2 mm)
Black line: trajectory (truth)



- *Initial guess of the trajectory (seeds)*
- Define segments (regions of interest)
- Charge-weighted center (chi2 fitting)
  - 3D point association with 2D position (time vs wire)
  - Based on the most accurate & complete 2D charge measurement on each wire plane view

- **The seeds (initial guess) of the trajectory fitting is crucial to limit the degree of freedom and to define the region of interest for each charge-weighted center, especially for complicated topologies**
- **Construct seeds in a "graph" of the point cloud**

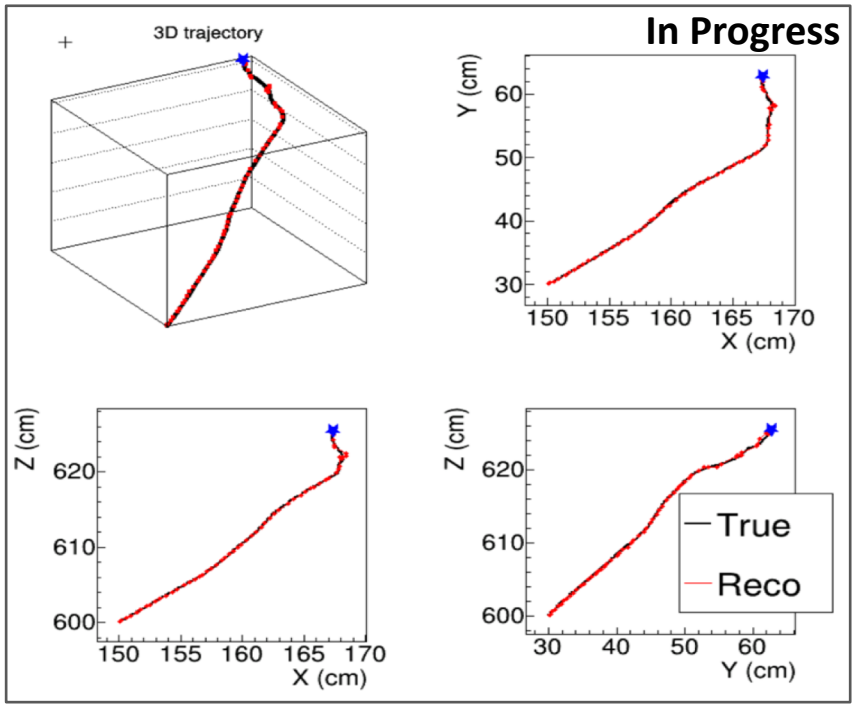
Graph (point cloud)
Circle: node (point)
Arrow: edge [two connected points]
Number: edge weight [distance]



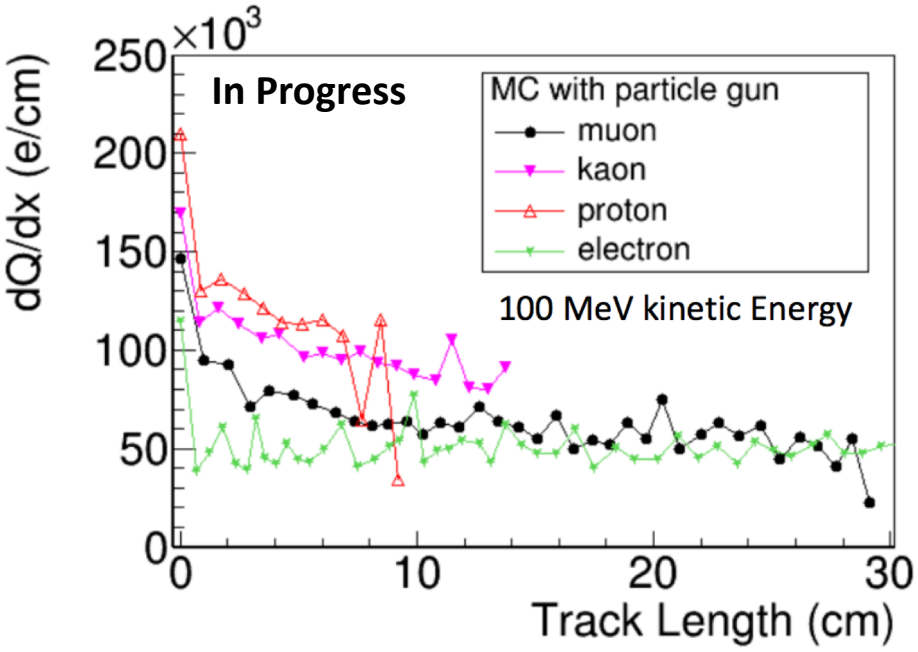
Seed V1.0

- Shortest path, e.g. Dijkstra's algorithm, between extreme points

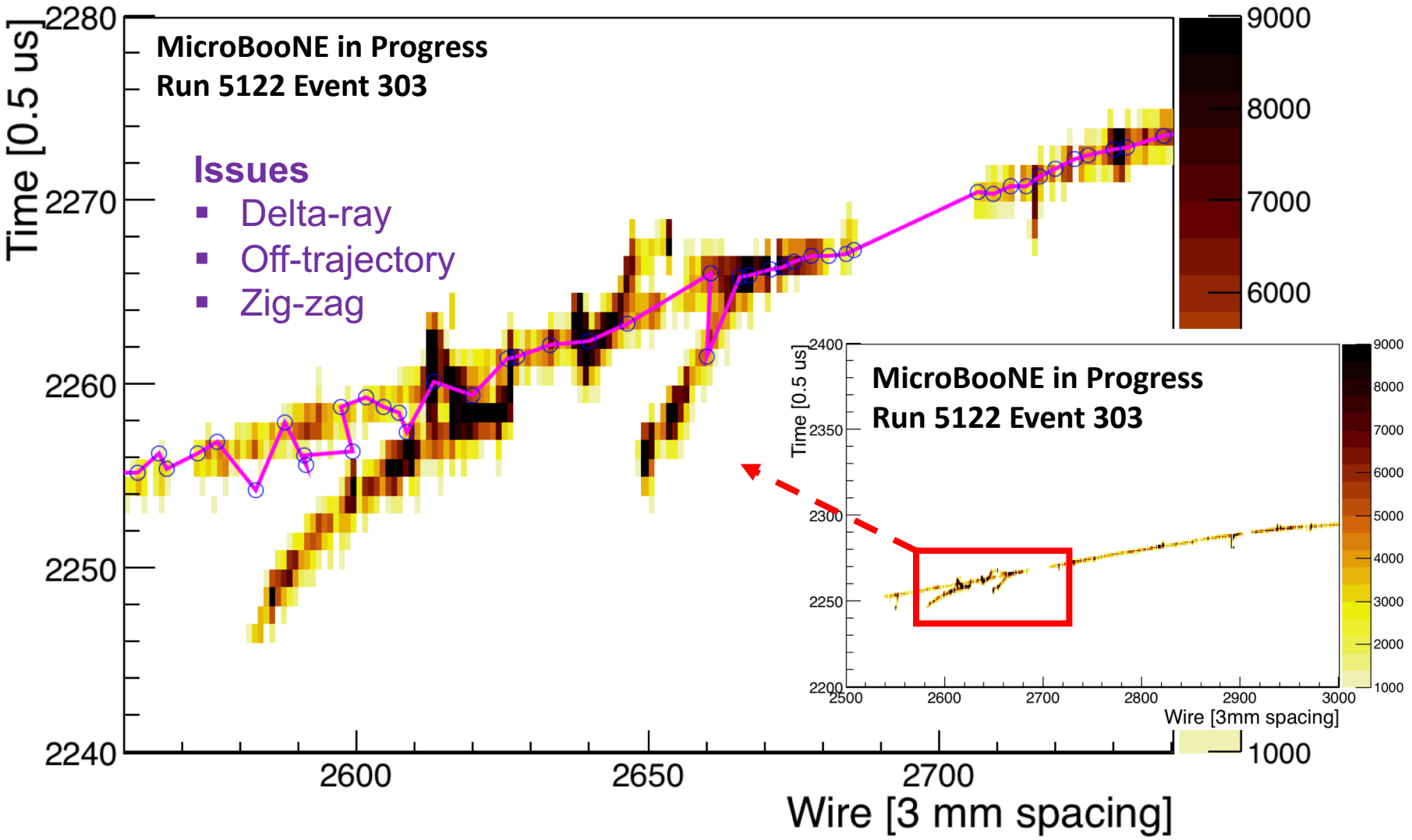
Performance on a toy MC (only dE/dx & MCS)



100 MeV kinetic energy Electron



Issues in real data



Seed V2.0

How can we limit the seeds to the peaking charge?

The Steiner Tree

the (non-negative) shortest path and the minimum spanning tree, and containing specified points (terminals).

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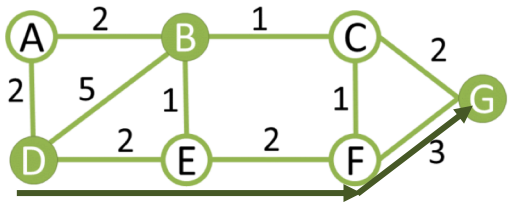
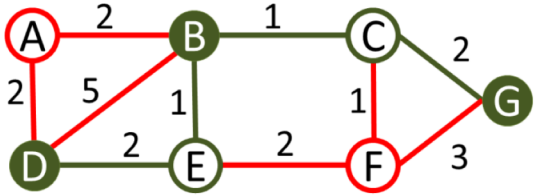


Shortest path from D to G:
D-E-F-G

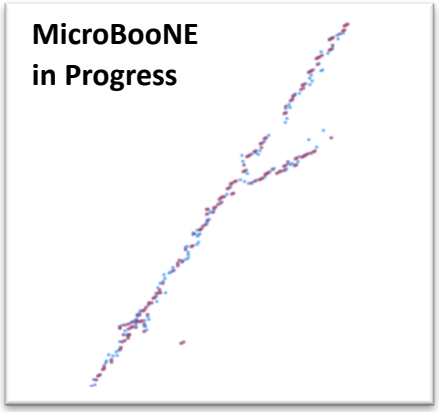


Steiner Tree: Red: edge removal
D-E-**B**-C-**G**

Contain nodes **D**, **B**, **G**
(called terminals)

NP-complete problem

Example of the Steiner Tree constituent points
Red: terminals (peaking charge)
Blue: non-terminals



Trajectory fitting based on the Steiner Tree stays tuned!

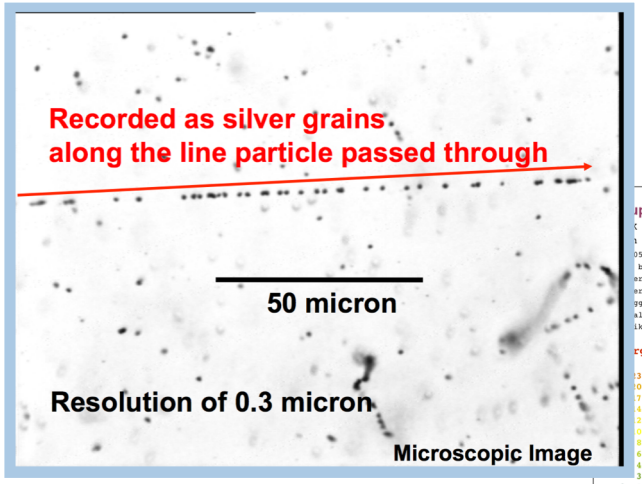
Summary

- The Wire-Cell tomographic imaging is a new paradigm of LArTPC 3D event reconstruction.
  - Topology agnostic & 3D imaging, only involving charge, time, geometry, connectivity
  - It has a good performance for the complicated neutrino interactions in liquid argon.
  - It was developed using MicroBooNE data and evaluated using MicroBooNE simulation, is being applied in MicroBooNE neutrino analysis. It can be naturally extended to other LArTPC detector context.
  - The output can feed to various downstream pattern recognition tools (traditional or machine learning).
- The development of Wire-Cell 3D tracking is in good shape.
  - Part of 3D pattern recognition
  - It takes advantage of the ideas and algorithms in graph theory to operate 3D point cloud.
  - One attempt to do traditional tracking & dQ/dx fitting in 3D view.

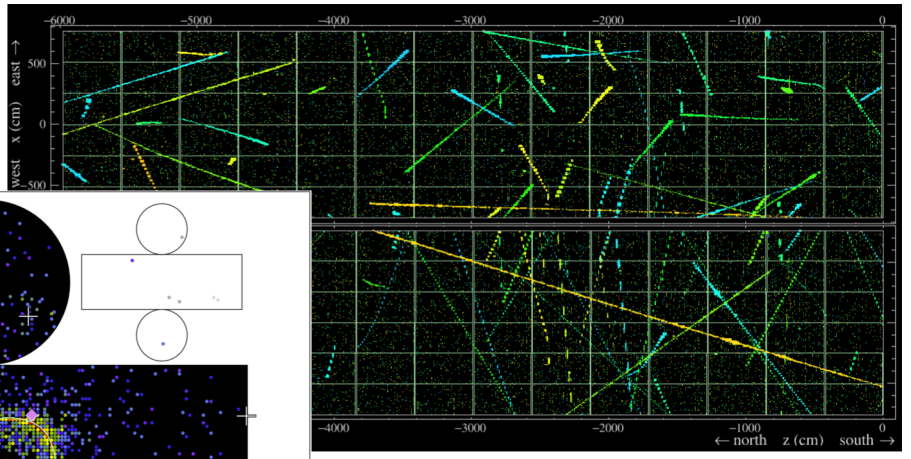
Backup

Accelerator Neutrino Experiment Detectors

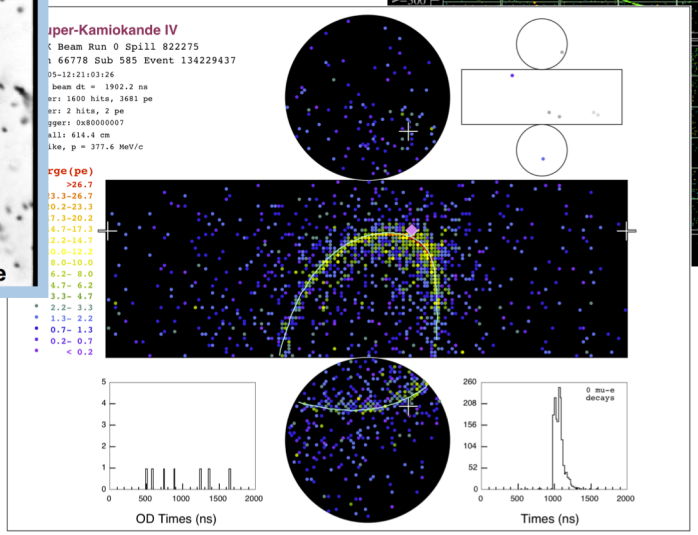
- A wide range of accelerator neutrino (fixed baseline + well understood neutrino energy spectrum) experiments and detectors to detect the neutrino signals, aiming for a good understanding of the neutrino mixing (oscillation), cross sections, and other exotic topics.
- Detector technology: target mass, calorimetry, topology



OPERA (Nuclear emulsion)



NOvA
(segmented scintillator)



T2K (Cherenkov)

Charge solving

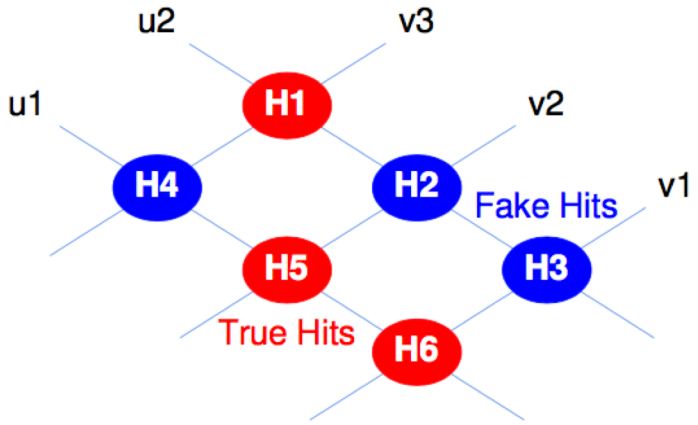
Measured charges on wires

True charge hits to be solved

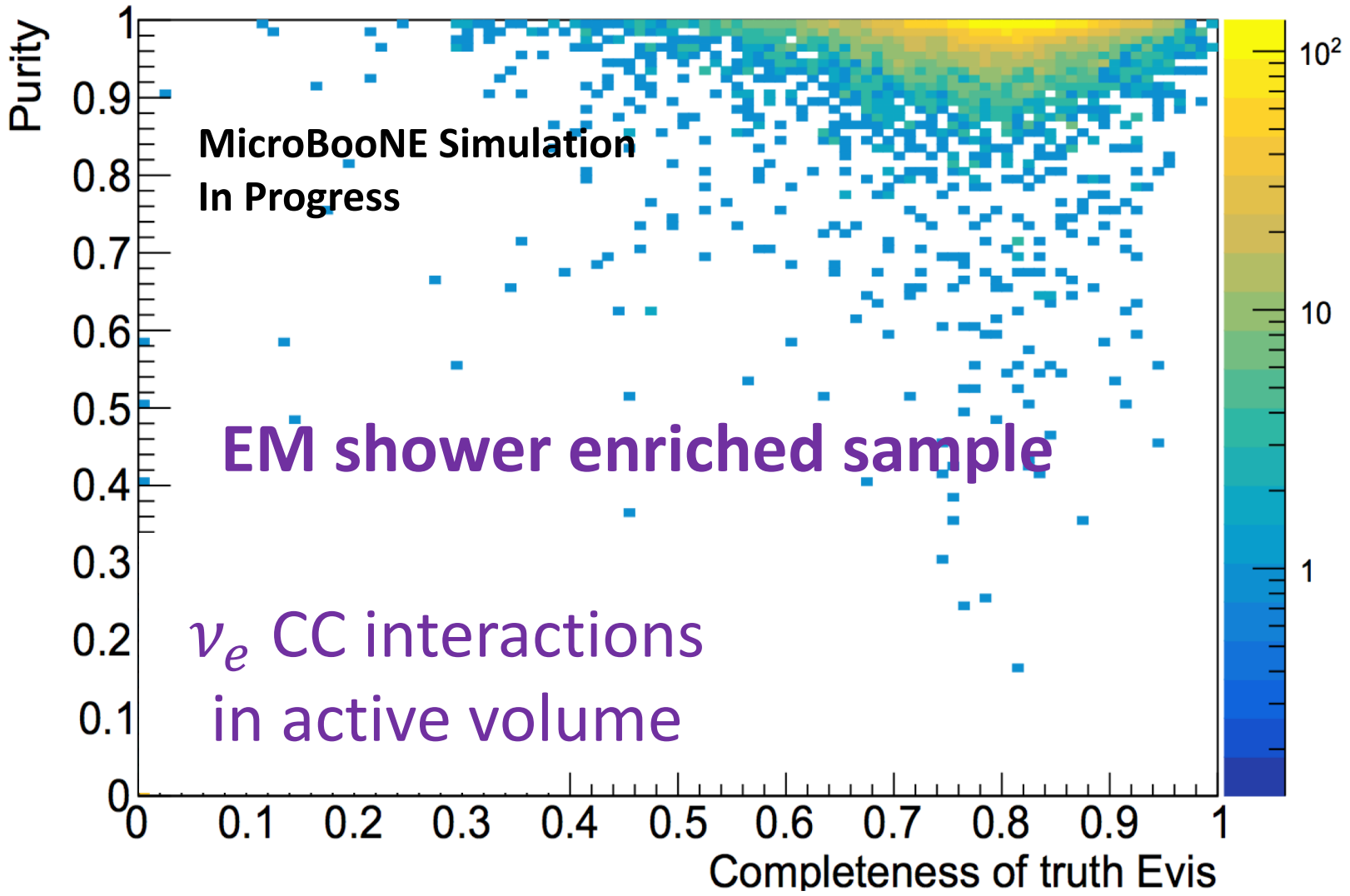
$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H1 \\ H2 \\ H3 \\ H4 \\ H5 \\ H6 \end{pmatrix}$$

Matrix determined by geometry

Use two planes for illustration

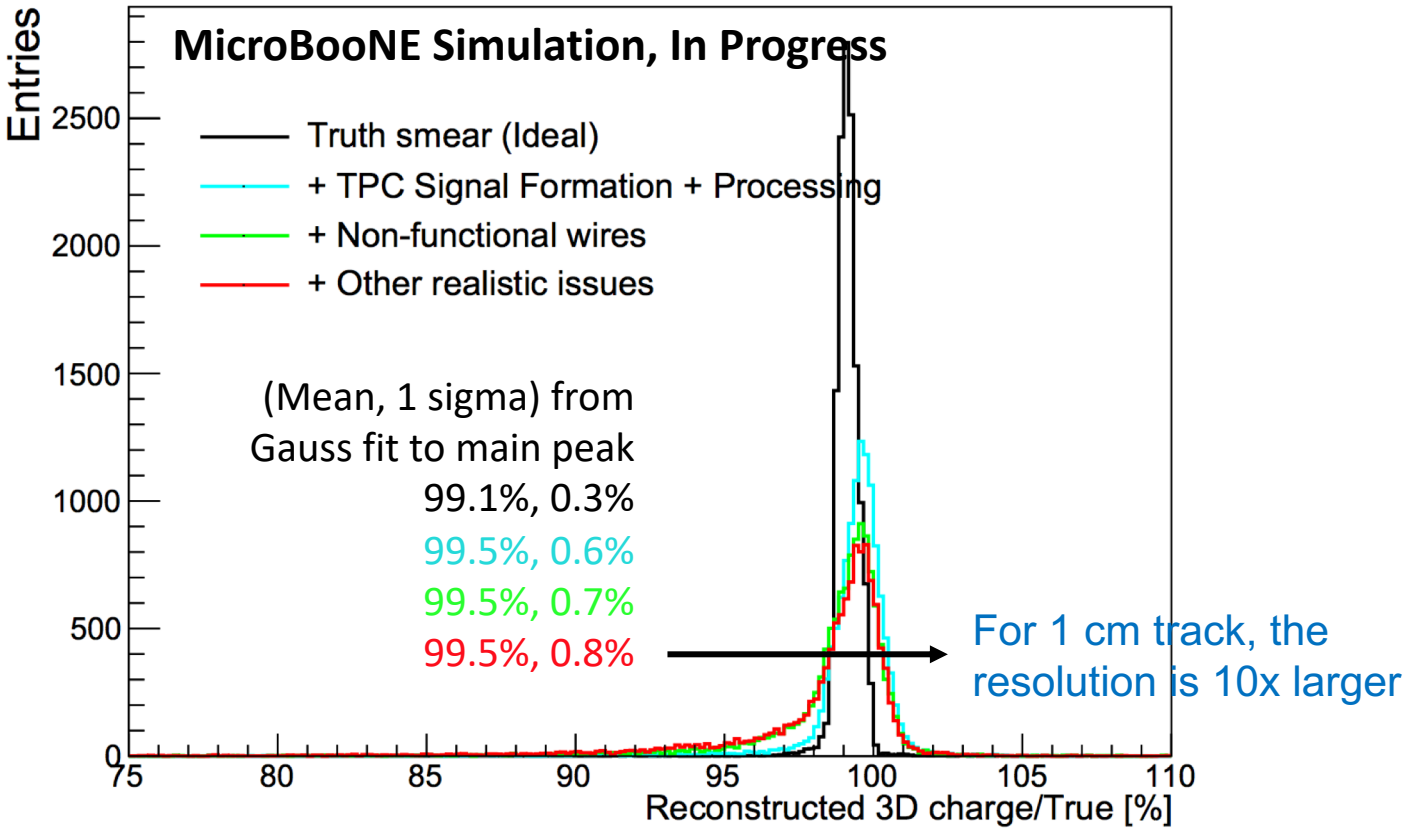


- More unknowns than knowns -- Non-deterministic linear equation
- NP-hard problem
- L0-regularization approach (hours for a MicroBooNE event):
  - Remove unknown(s) till a solution can be found
  - Unrealistic, in real case pick up the "best" solution out of e.g. $C_{35}^{10} = 1.8\times10^{8}$
- L1-regularization approach (compressed sensing technique, 1 min for a MicroBooNE event):
  - Well approximate (most cases exactly same) L0-regularization approach
  - Minimize $\chi^2 = (y - Ax)^2 + \lambda\|x\|_1$, L1-norm is the sum of the absolute value of each element of vector $\boldsymbol{x}$
  - Convex, local minimum = global minimum [fast algorithms]


Purity
Completeness of truth Evis
MicroBooNE Simulation
In Progress
EM shower enriched sample
ν_e CC interactions
in active volume
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^2
10
1

Performance of Wire-Cell 3D imaging

- 3D charge: the result charge associated with each 3D space point after tomographic imaging
  - Indicate the “correctness” – solution to the first principle equation
  - Used to predict scintillation light signals in PMTs for TPC-PMT matching



Trajectory fitting chi2

$$\chi^2(x_j, y_j, z_j, Q_j) = \chi^2_U + \chi^2_V + \chi^2_W$$

Trajectory fit:

$$\chi^2_{U/V/W} = \sum_j \sum_i \frac{q_i^2}{\delta q_i^2} \cdot dis(U/V/W)^2_{ij}$$

← *Charge weighted unbinned likelihood*

i : pixel in 2D projection j : 3D trajectory point

$$dis(U)^2_{ij} = \Delta U^2 \cdot \left(U_i - U_j(x_j, y_j, z_j)\right)^2 + \Delta x^2 \cdot \left(t_i - t_j(x_j, y_j, z_j)\right)^2$$

ΔU: bin size in U view, Δx : b in siz in drift time t