Recent Progress on Wire-Cell 3D Event Reconstruction in MicroBooNE

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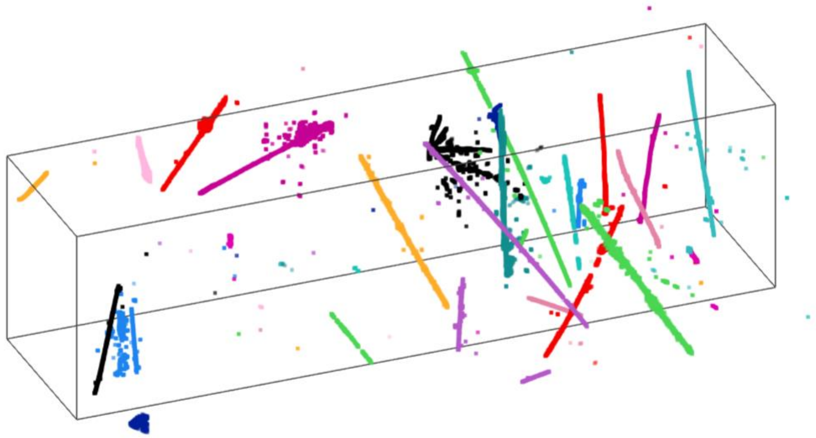
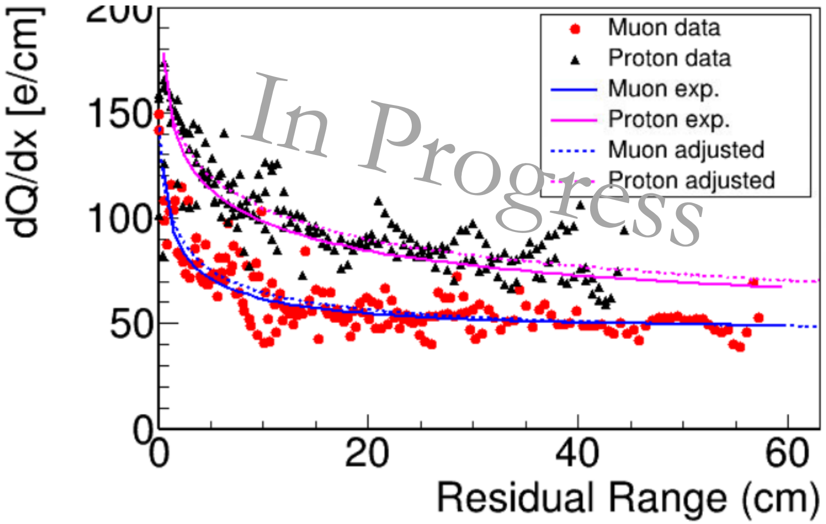
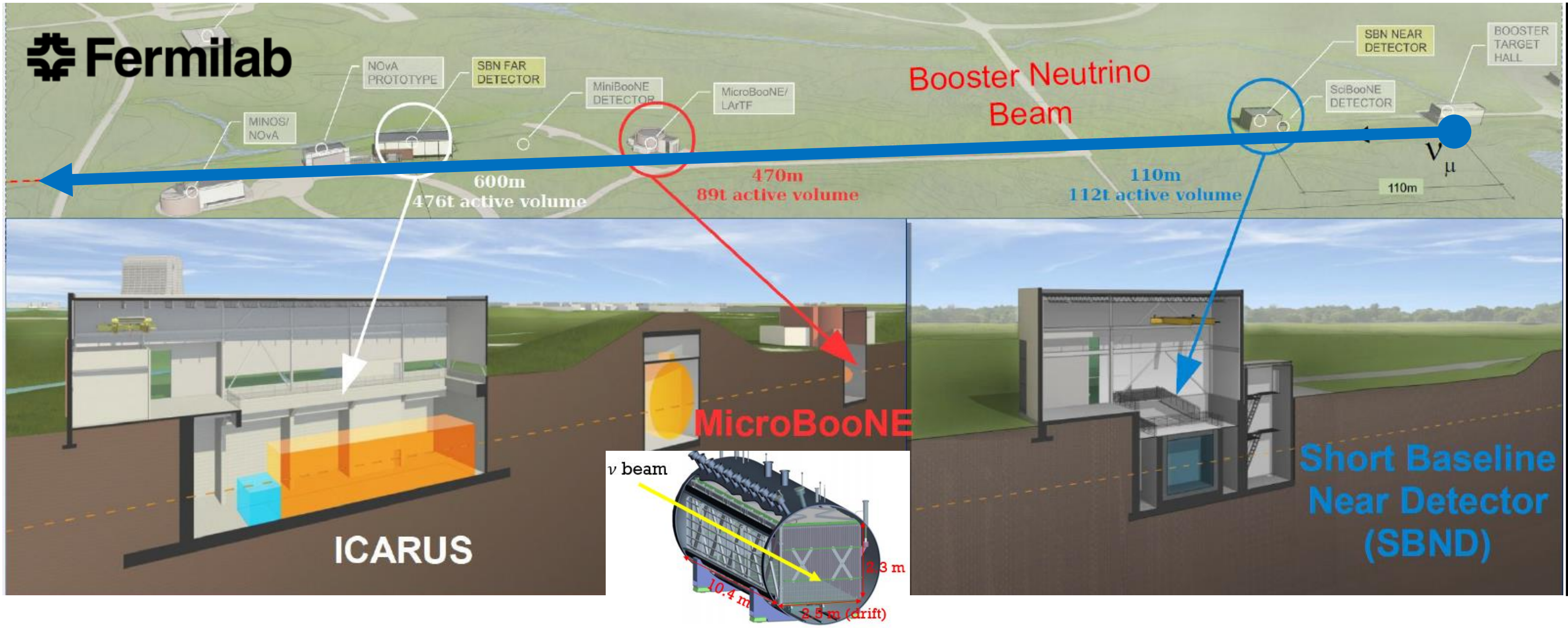
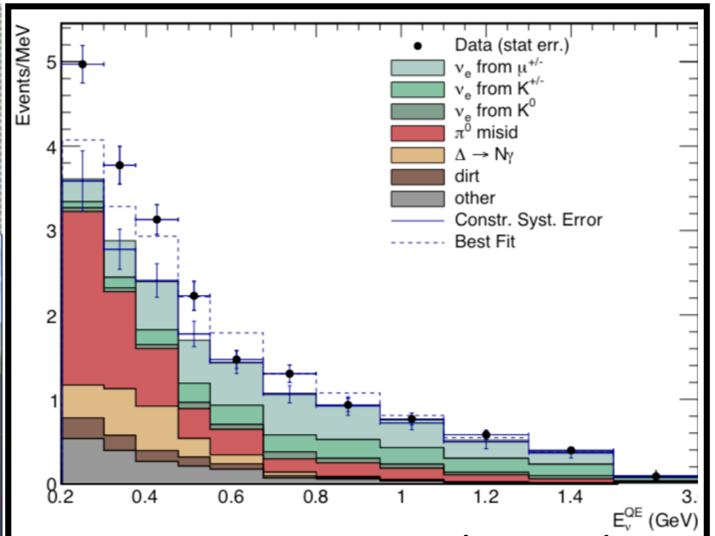




The MicroBooNE Experiment



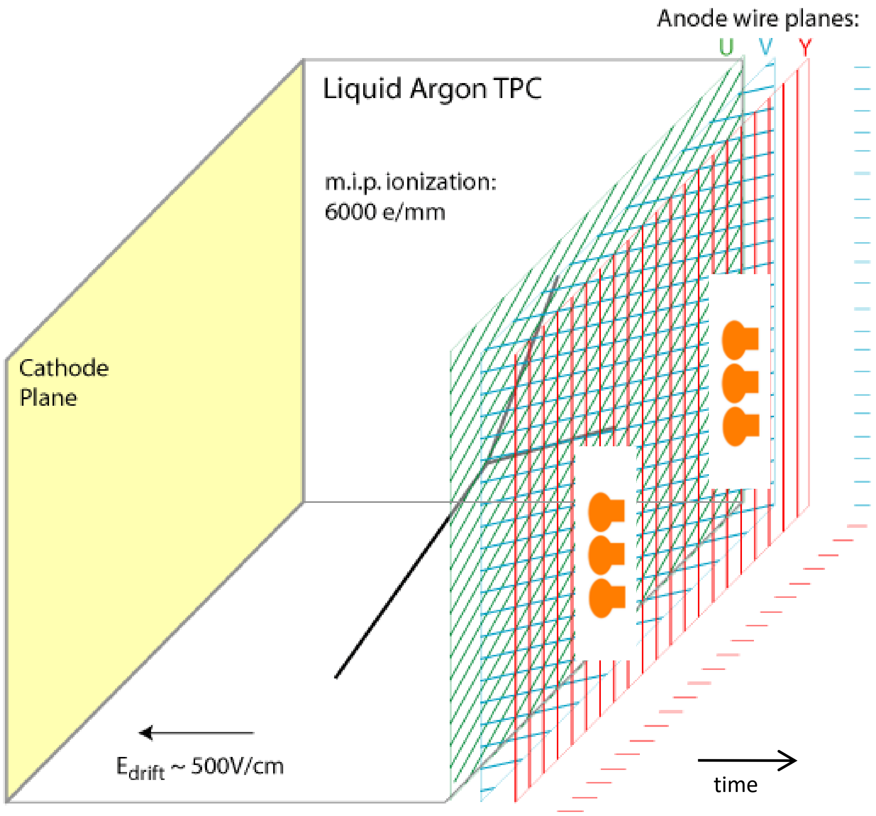


Low-energy excess observed by MiniBooNE

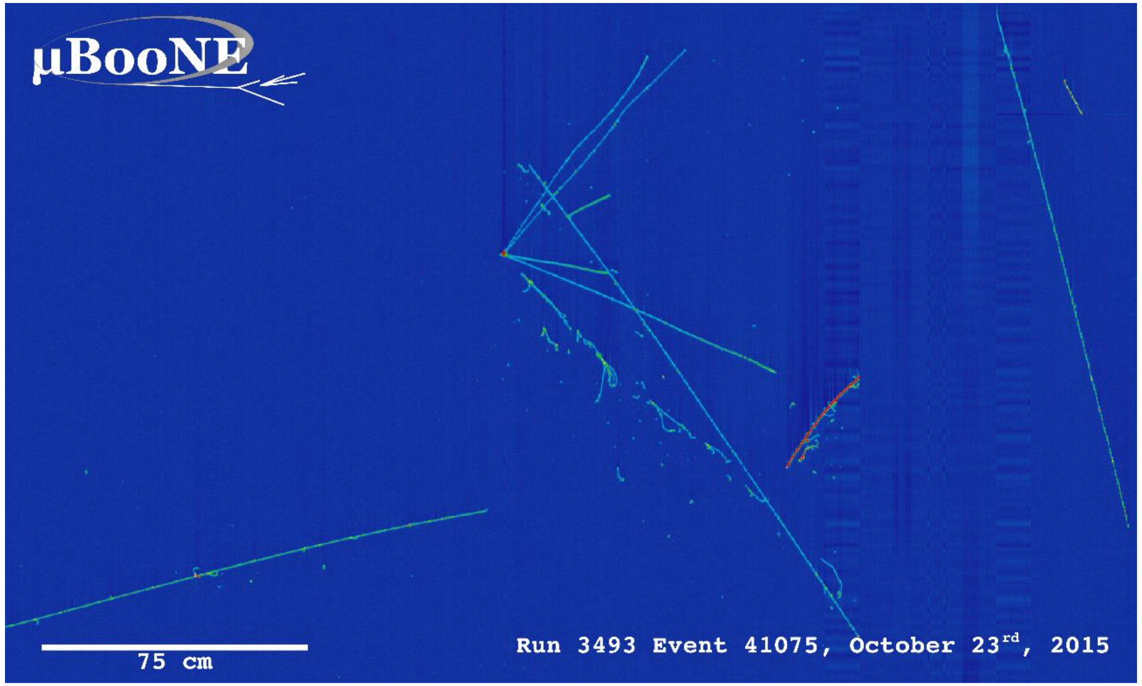
- Goals of the Short Baseline Neutrino Program
  - low-energy excess indicated by MiniBooNE
  - sterile neutrinos
  - ν-Ar interaction cross section

Principle of Single-Phase LArTPC

Made by Bo Yu (BNL)

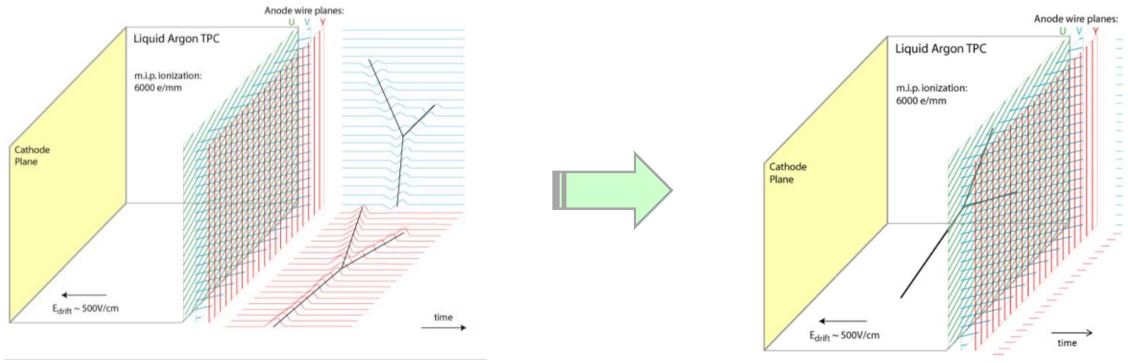


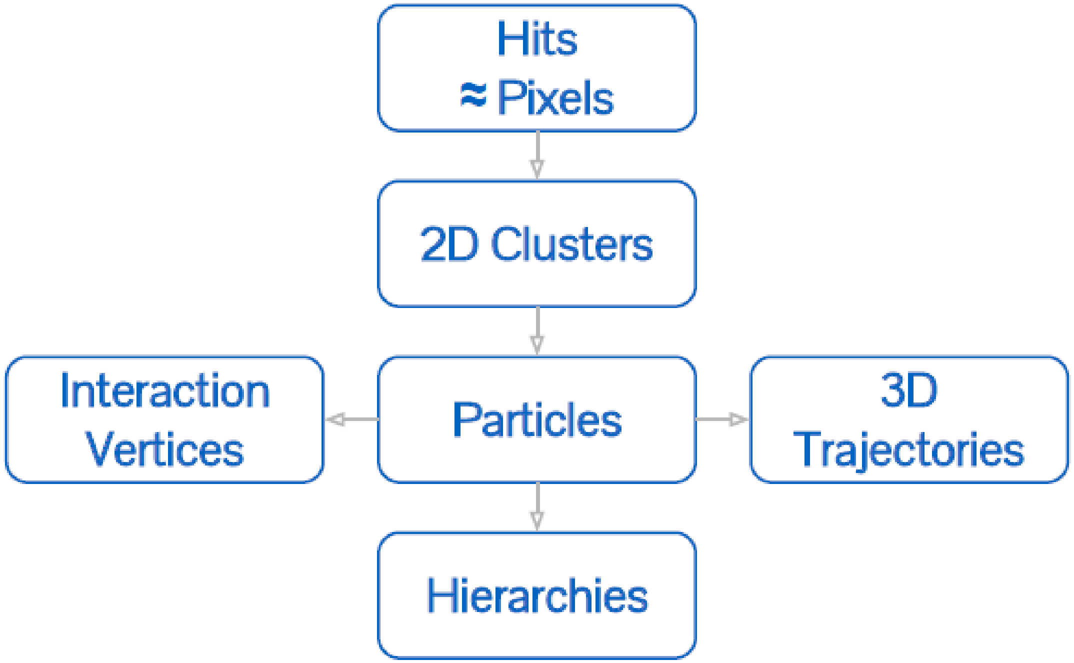
Drift velocity ~ O(1) km/s ⇒ a few ms drift time



- $\sim$ millimeter scale spatial resolution
- Excellent charge resolution
  - e/γ separation: bkg. rejection for ν_e CC

Traditional Reco. Approach: 2D matching ⇒ 3D





By Andrew Smith
@ 2019 APS April

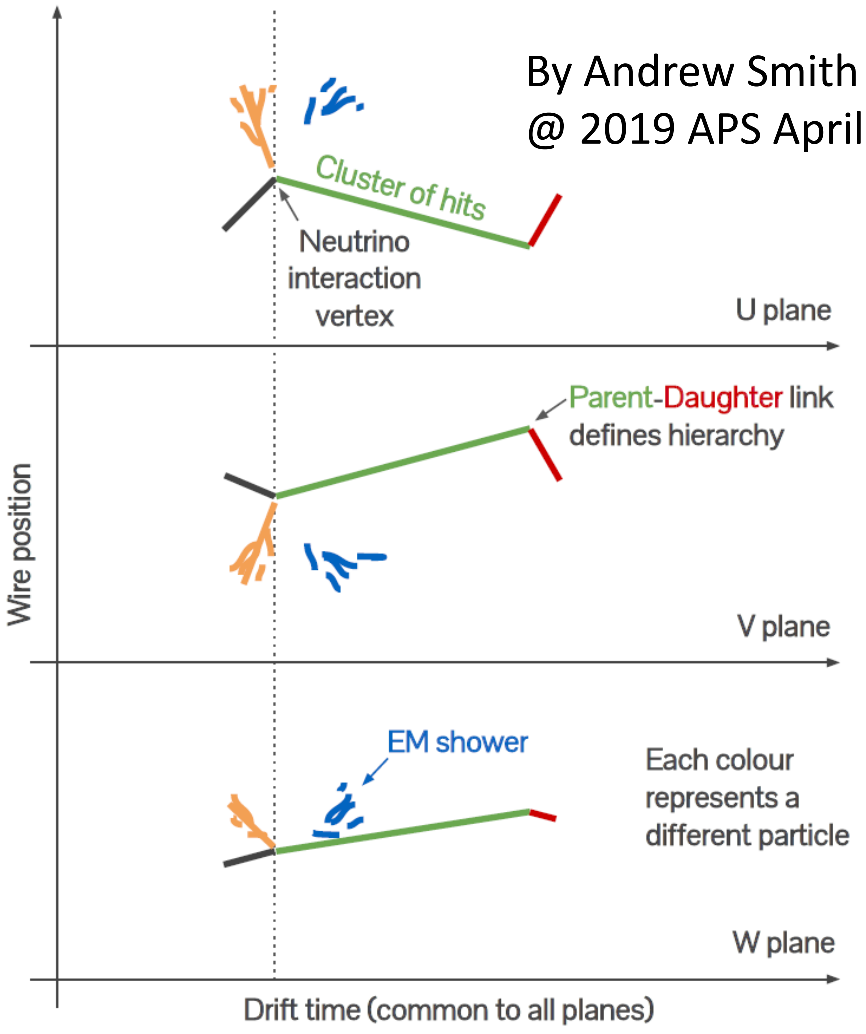


Illustration of LArTPC pattern recognition in the Pandora framework

Wire-Cell Tomographic Event Reconstruction

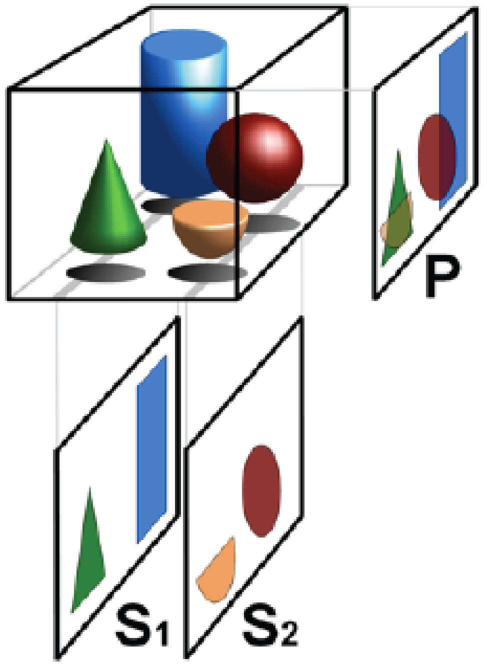
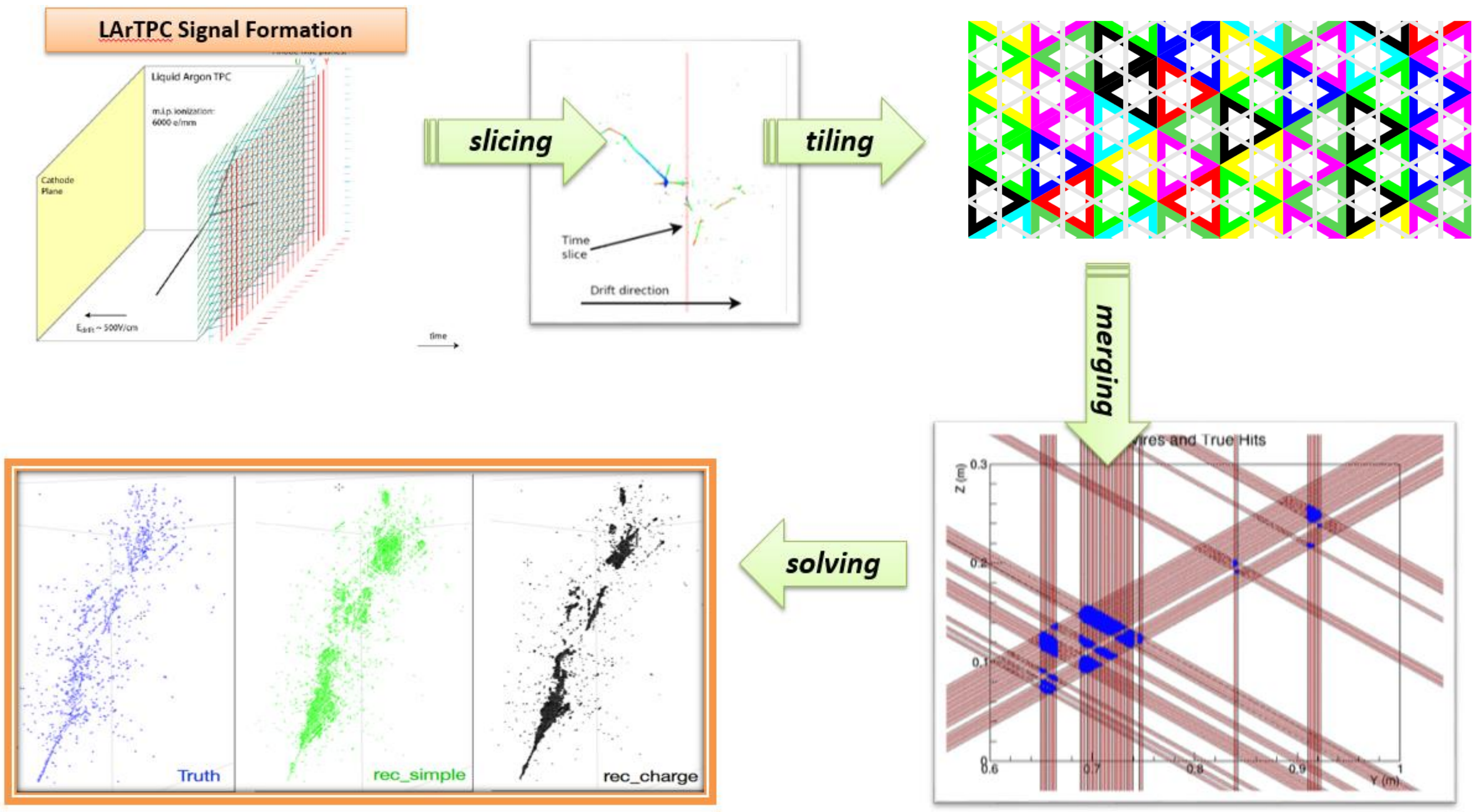


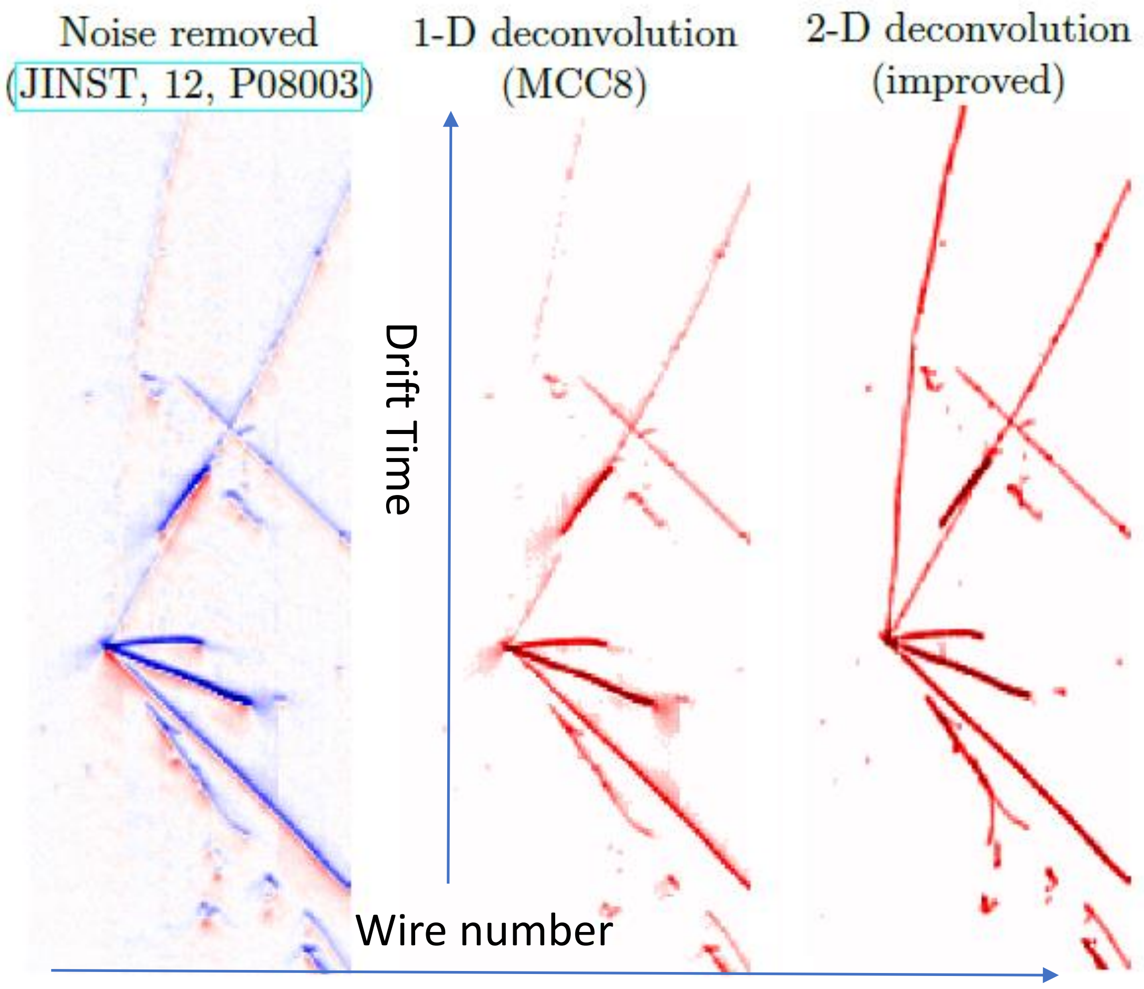
Fig.1:Basic principle of tomography: superposition free tomographic cross sections S1 and S2 compared with the projected image P

https://en.wikipedia.org/wiki/Tomography

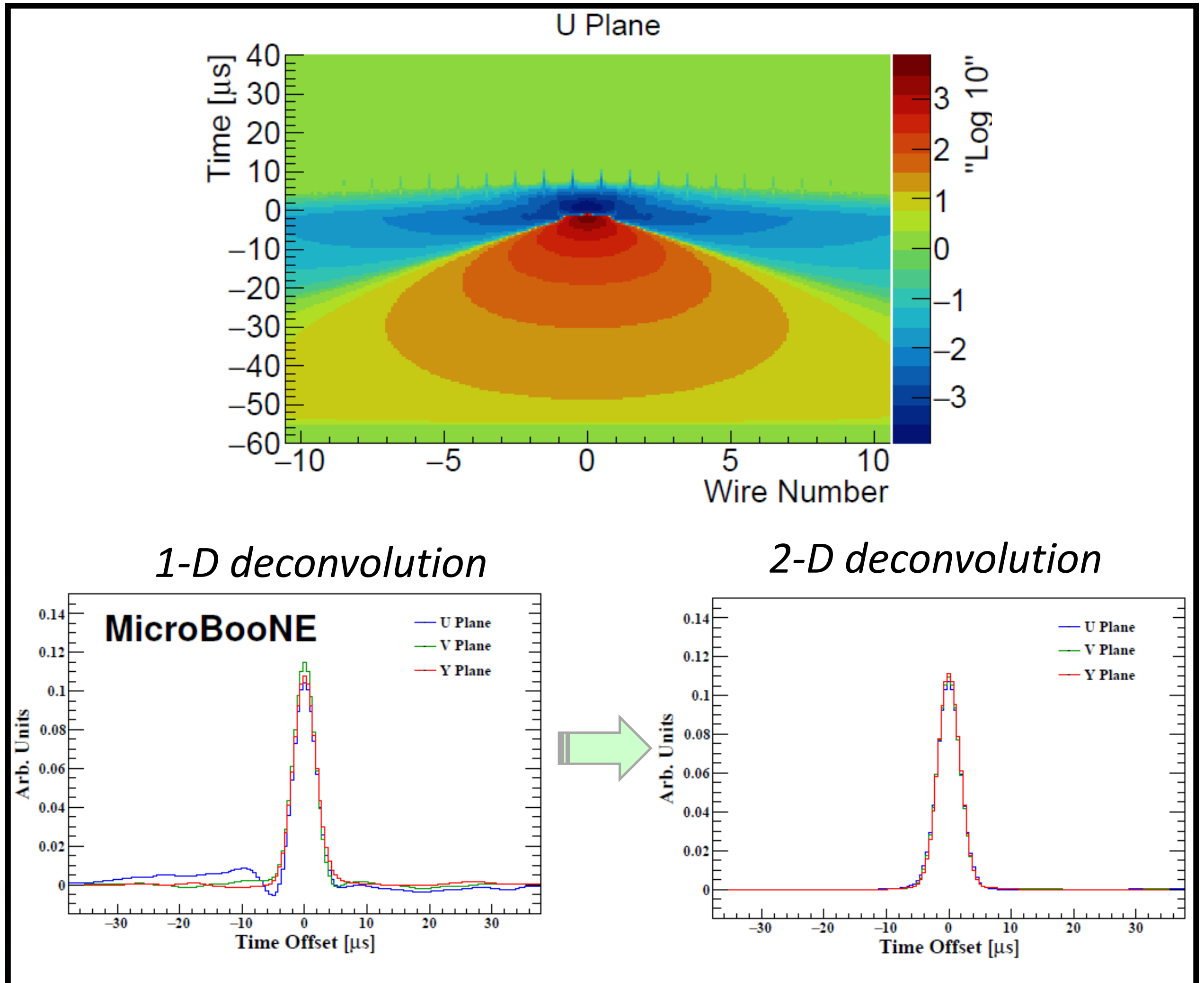


Three-dimensional Imaging for Large LArTPCs
Xin Qian *et al.* **JINST 13, P05032 (2018)**

Improved Signal Processing for Tomography

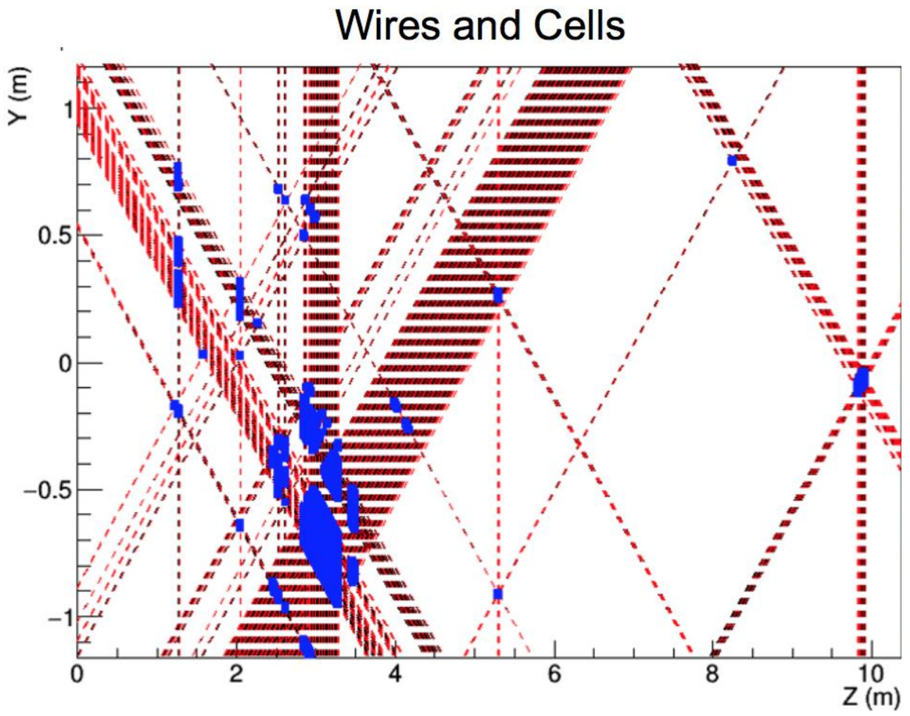


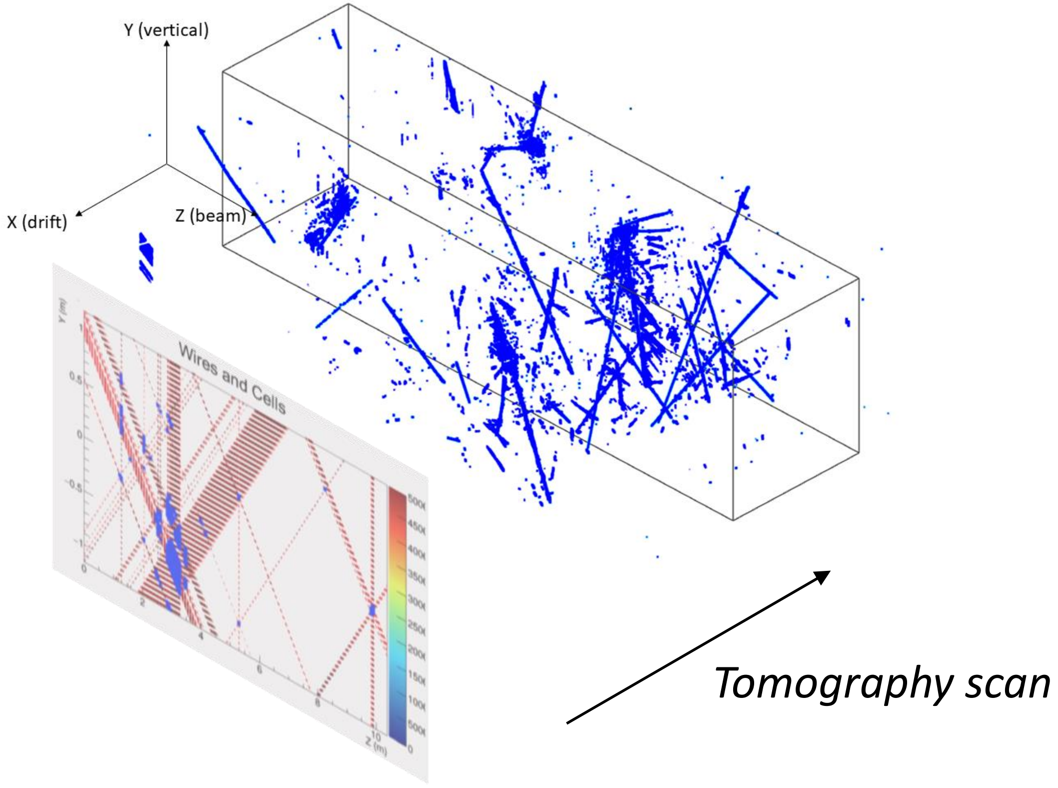
JINST 13 P07006/7 (2018)



Key for tomographic imaging

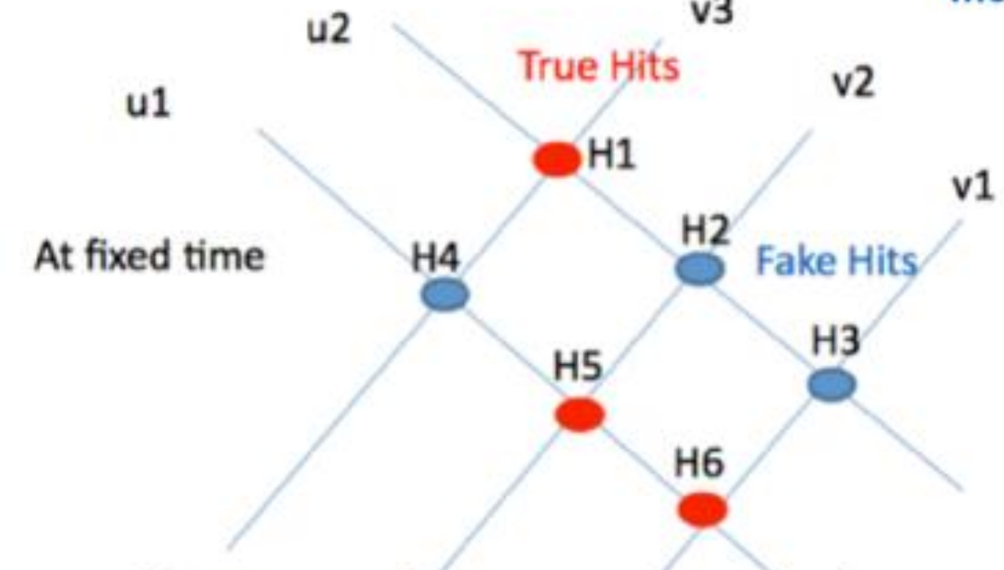
Tomographic Reconstruction: Slicing and Tiling





- 2-plane tiling: at least two planes to be "fired" in a time slice

Eliminate Fake Hits: Charge Solving



Use two-plane as an example

measured charges on wires

true charges to be solved

$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & a & a & a \\ a & a & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 & a \\ 0 & a & 0 & 0 & a & 0 \\ a & 0 & 0 & a & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \end{pmatrix}$$

Matrix determined by geometry

(a=1)

$$y = Ax$$

- **Fake hits** cannot be avoided when tiling the hit cells
- Instead, eliminated by solving a linear system with the wire geometry
  - However, this particular example, 6 unknowns with 5 equations. What to do??

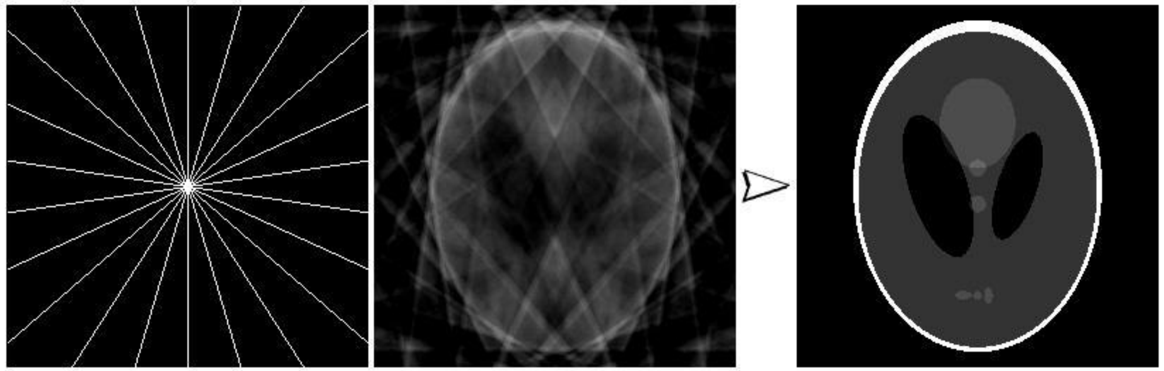
Compressed Sensing

- Compressed sensing is a mathematical technique to recover **sparse signal** from under-determined (linear) system
  - However, very expensive in computing for a brute force solution
- A breakthrough comes from the proof that L0 problem can be well approximated by the L1 regularization

$$\text{minimize} \qquad \chi^2 = (y - A \cdot x)^2 + \lambda \cdot \sum_i |x_i|$$

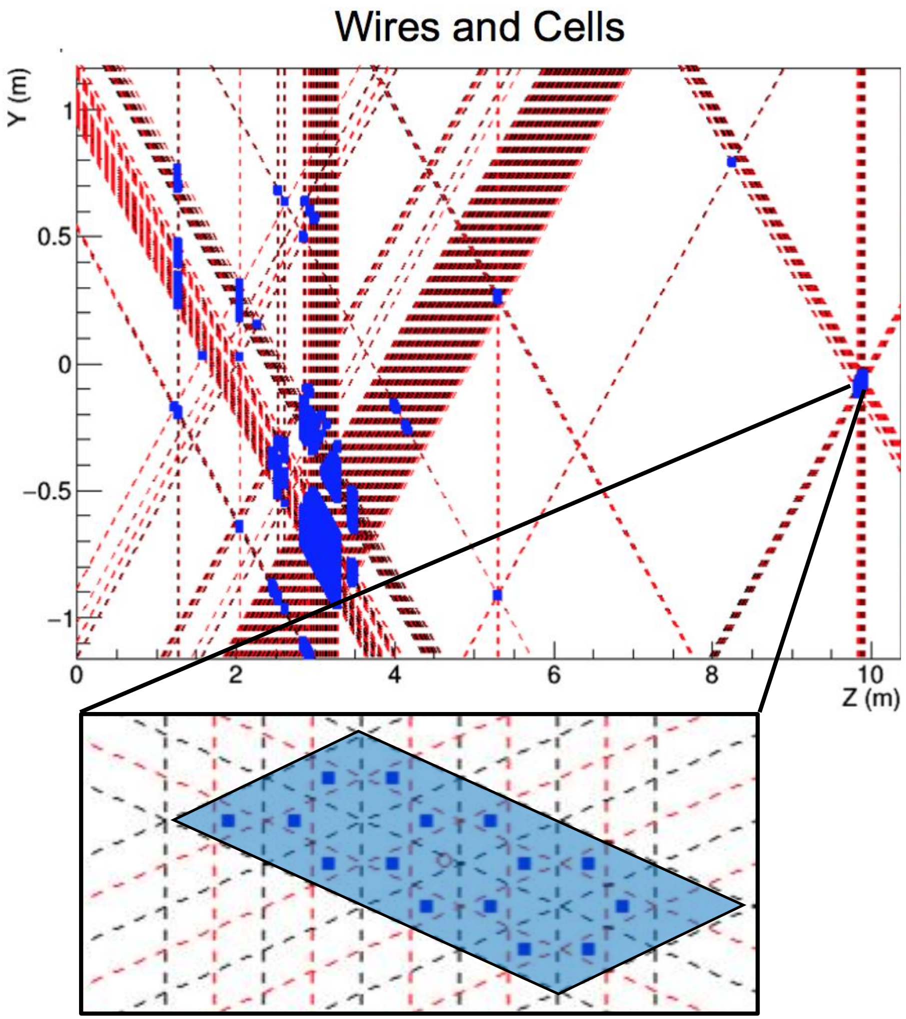
- *Sparse projections: 11 radial lines*

Hours of computing time with L0
⇒ minutes of computing time with L1

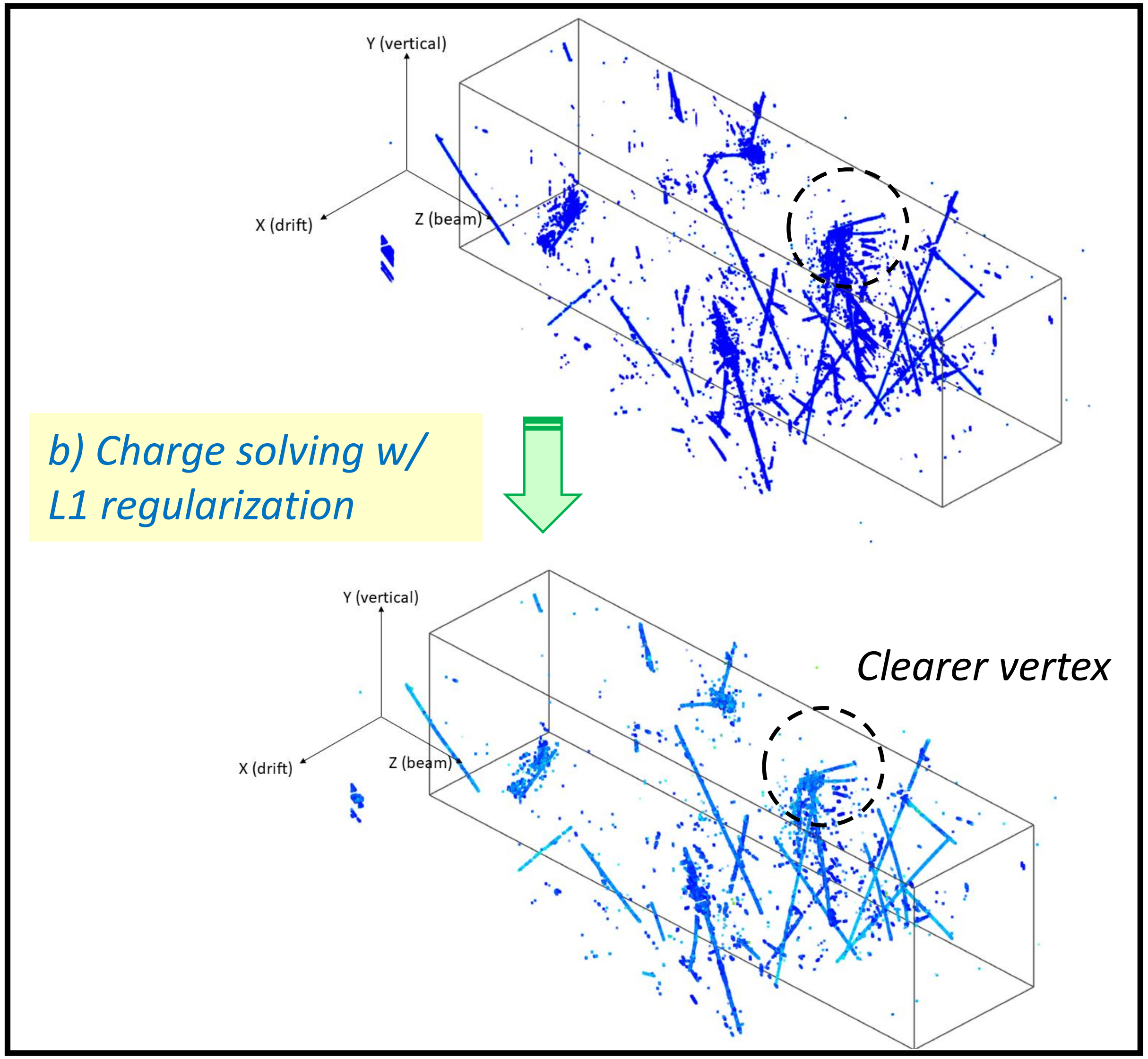


available portion of the spectrum (11 radial lines) | Back-projection estimate | Estimate after convergence (exact reconstruction)

Tomographic Reconstruction: Charge Solving



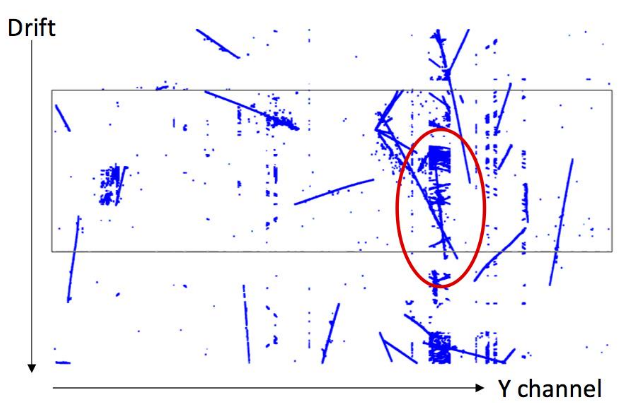
*a) Merge the hit cells as **blob***
⇒ further reduce unknowns



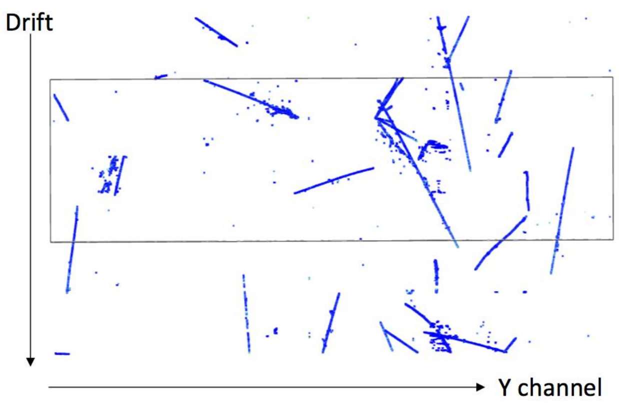
Deghosting

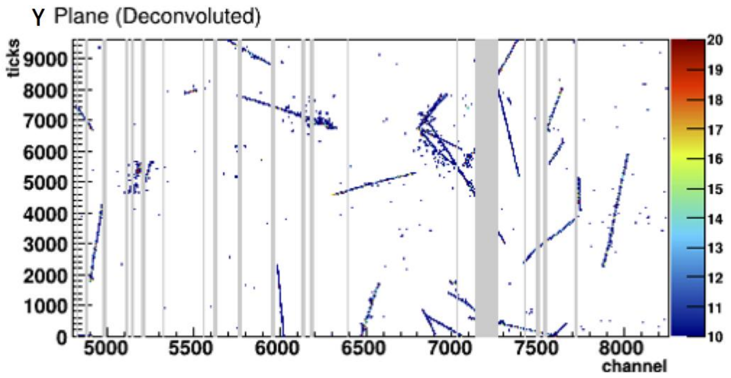
- 10% nonfunctional channels add ambiguity
- Detach blobs mainly present in the nonfunctional region

Before deghosting

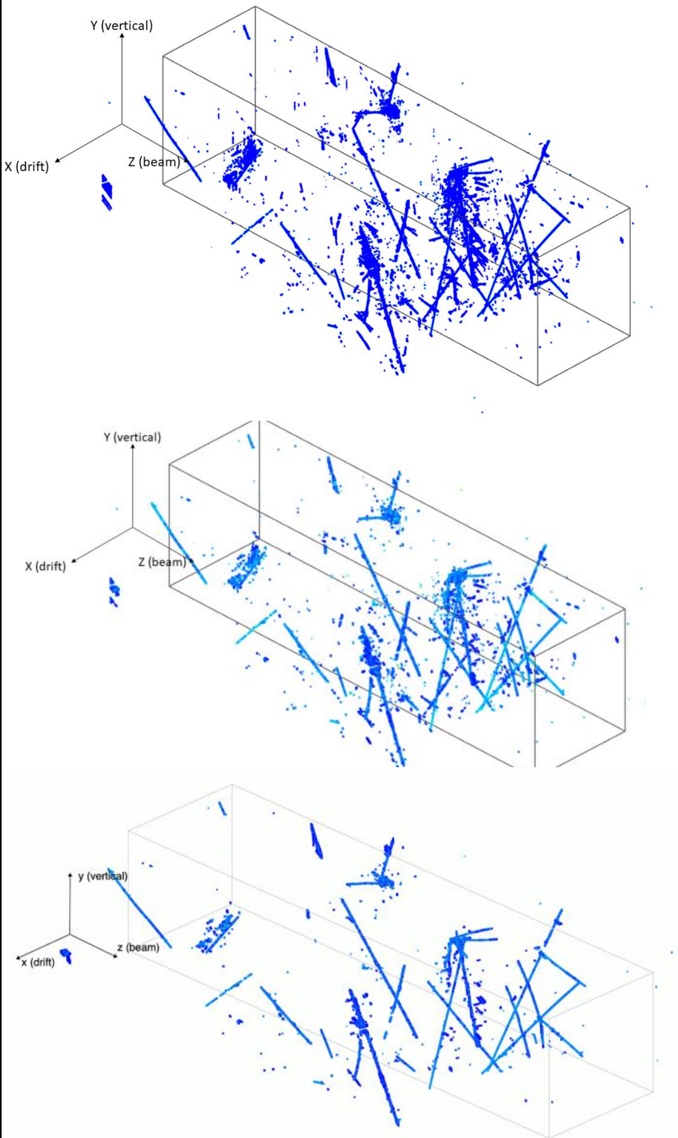


After deghosting





Non-func. region

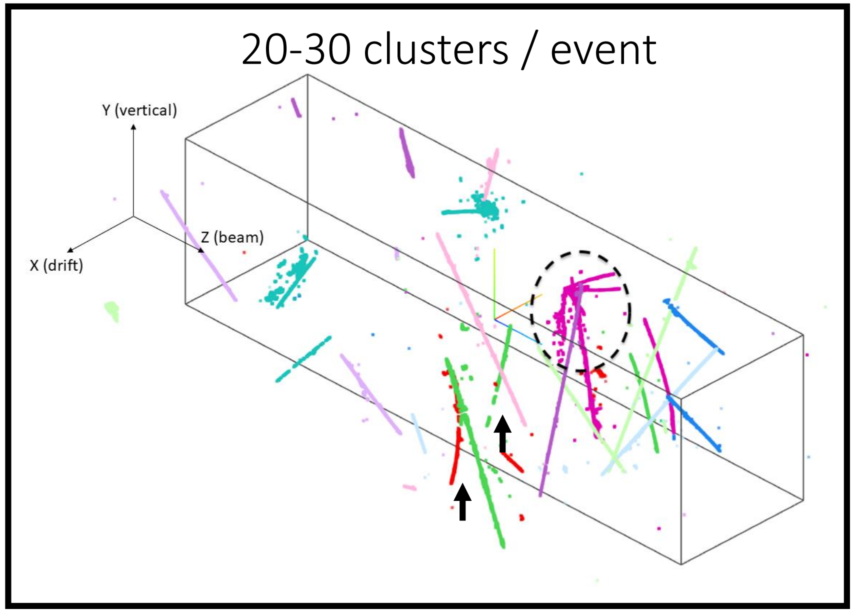


Tiling

Solving

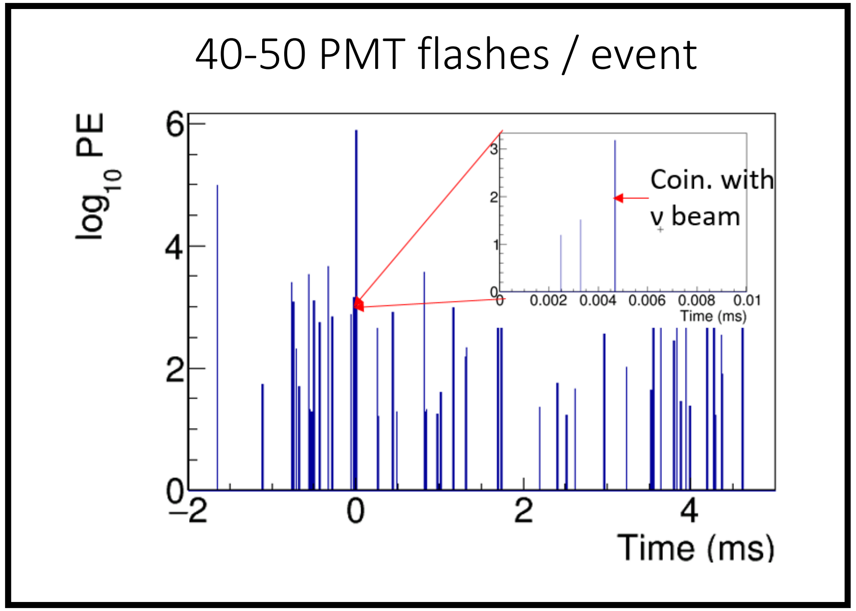
Deghosting

Clustering and "in-beam" flash matching



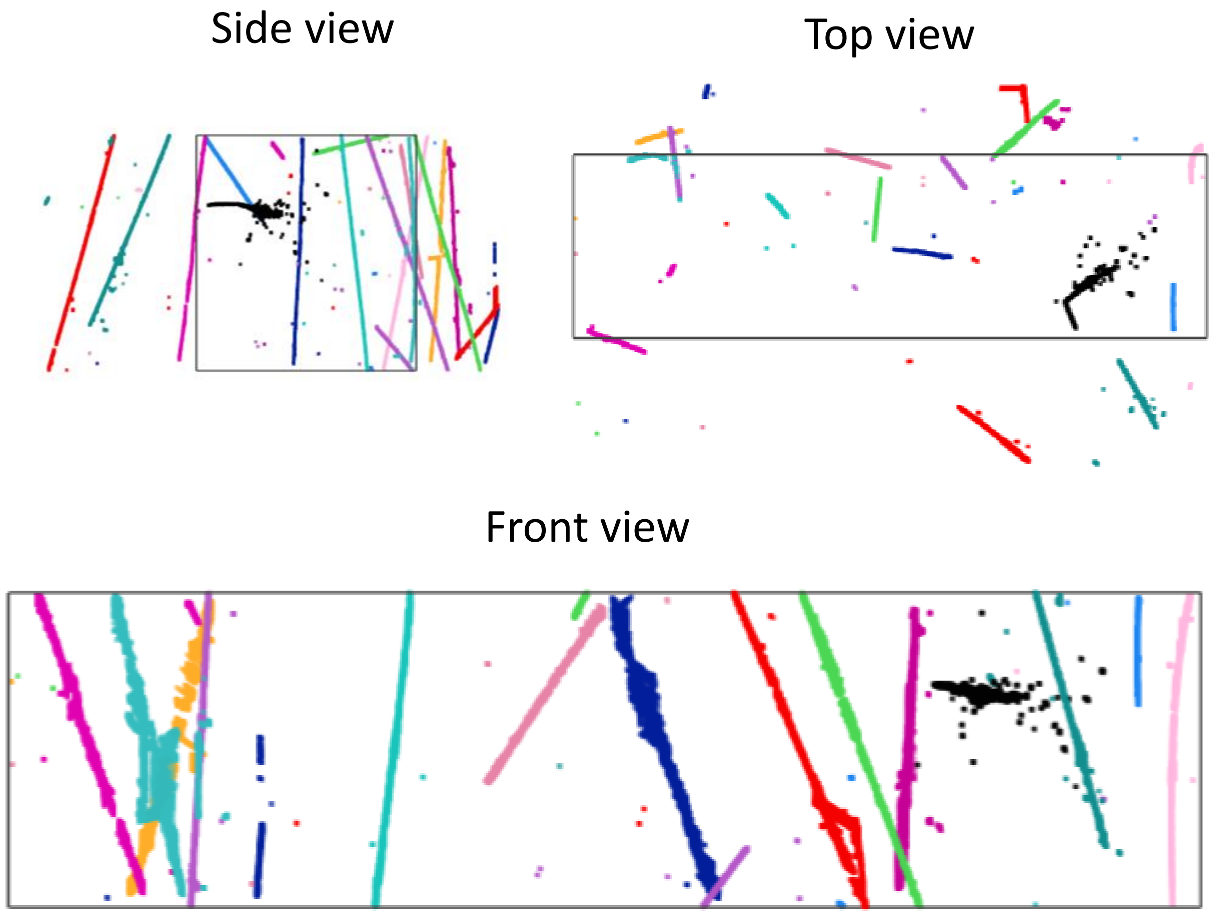
Can we find the ν cluster in coin. with beam flash?

⟺

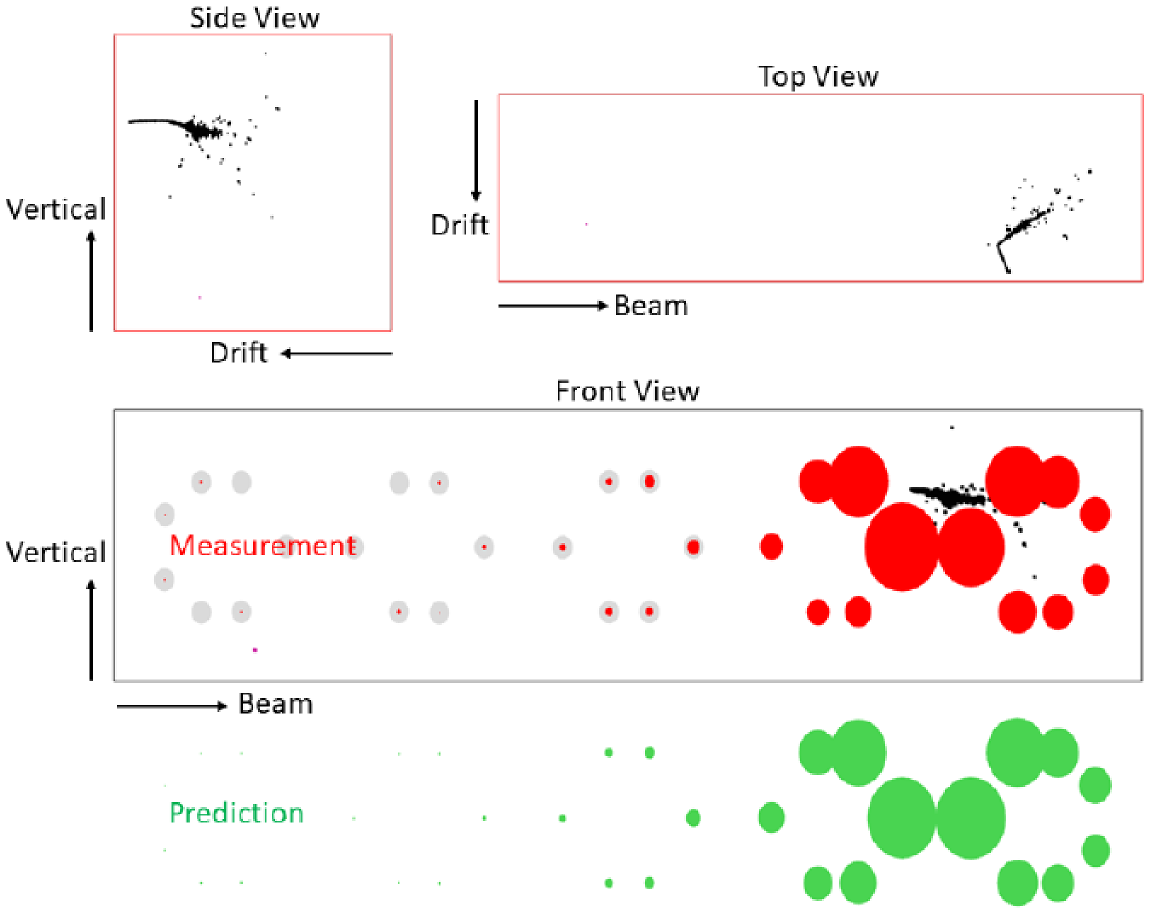


- Further clustering based on blob **distance** and **directionality**
  - gap bridging
  - primary track separation: PCA, Kalman-filter, etc.
- PMT flash: key for calibrating T0
  - One cluster matches at most 1 flash
  - One flash can match any # of cluster (0,1,2, …)
- Under-determined system
  - **compressed sensing** again!

Before and After Flash Matching



[CC ν_e candidate]



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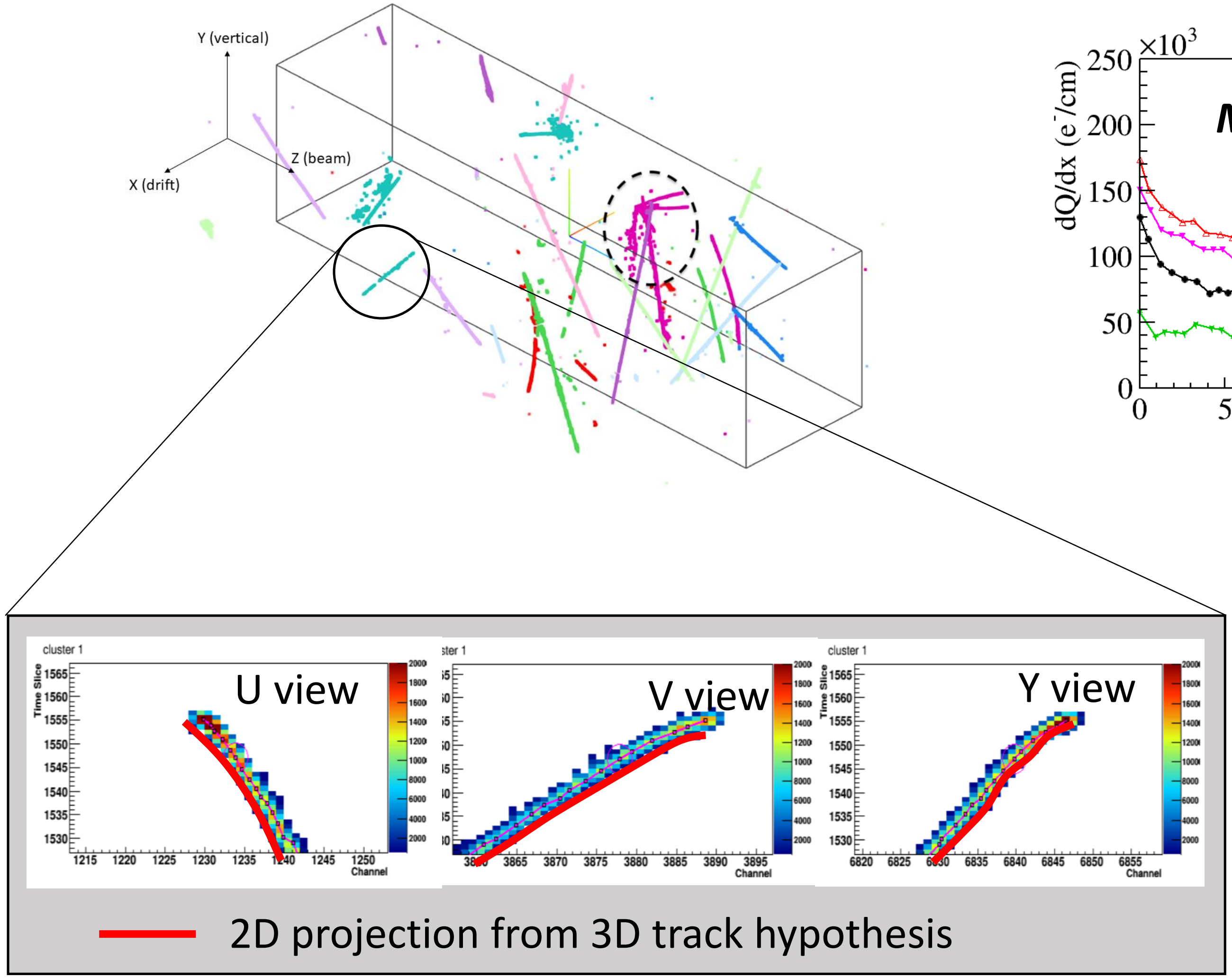
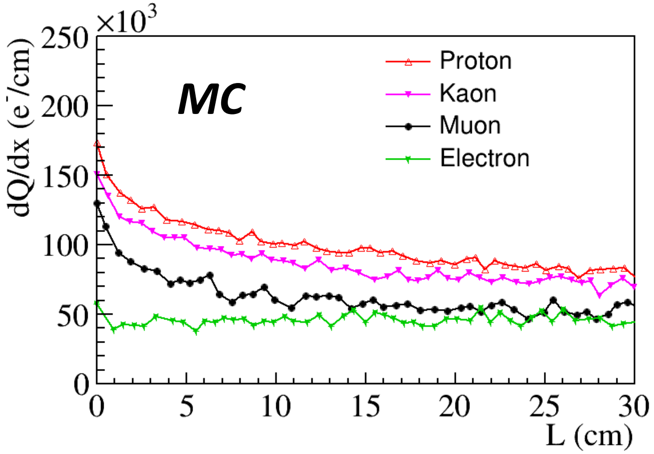
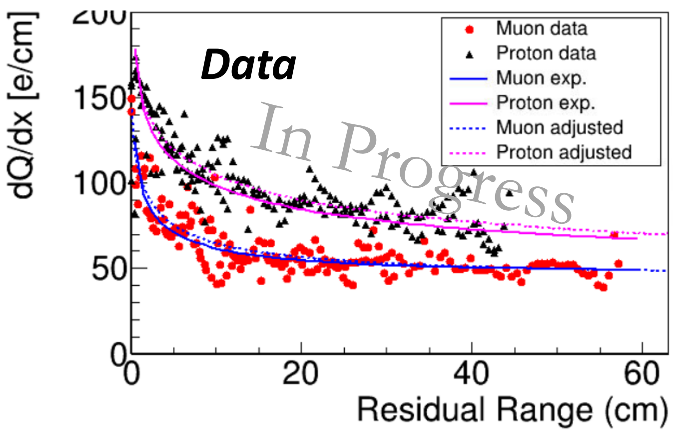
Over 98% matching accuracy evaluated with cosmic muons

Trajectory Fitting and Particle Identification







- Fine trajectory and dE/dx fitting
  - tomographic clusters as skeleton
- Trajectory and charge info matched to three views

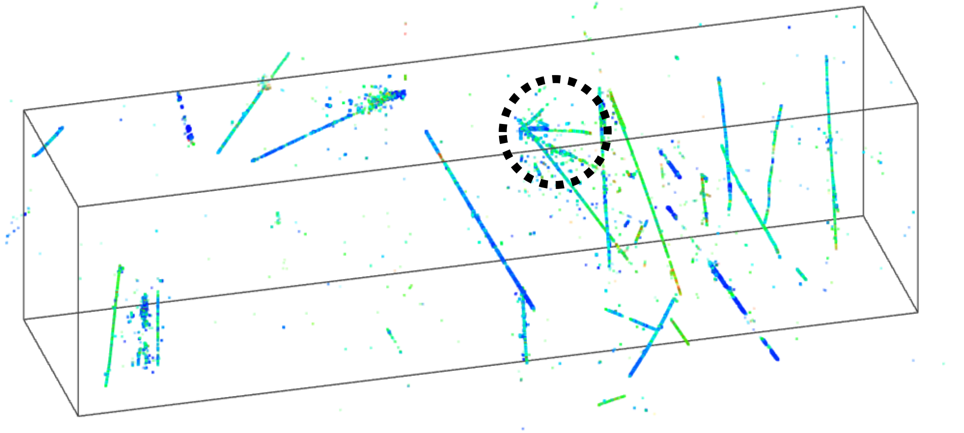
Summary

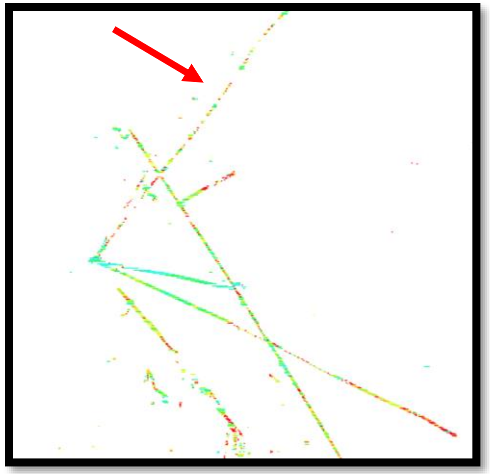
- MicroBooNE is a LArTPC capable of imaging neutrino interactions with very fine resolution
  - broad scope of physics topics – look out for the other MicroBooNE talks!
- Wire-Cell tomographic reconstruction is a new paradigm for LArTPC
  - topology-agnostic 3D space points by utilizing geometry, time, charge and sparseness to reduce ambiguity from individual 2D views
- Trajectory and calorimetry reconstruction is in good progress
  - particle identification
  - particle flow
  - ...

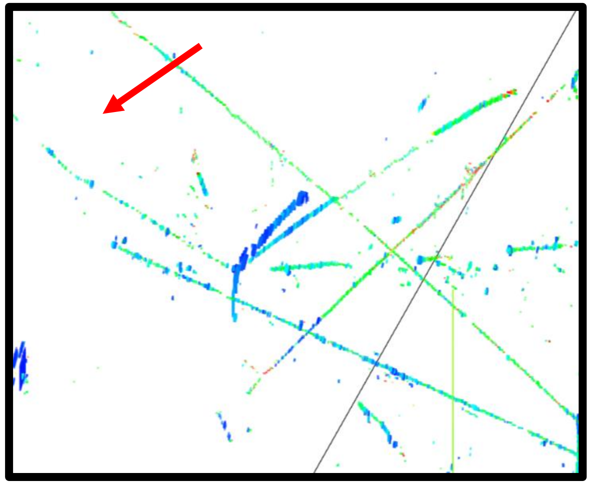
Backup Slides

several hours of CPU running

[Bee link]







- (upper) 1D deconvolution + L0 compressed sensing

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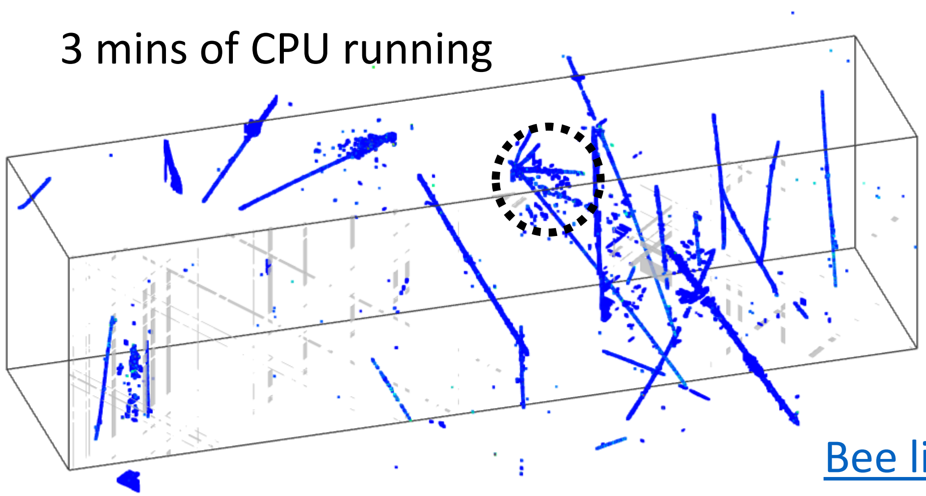
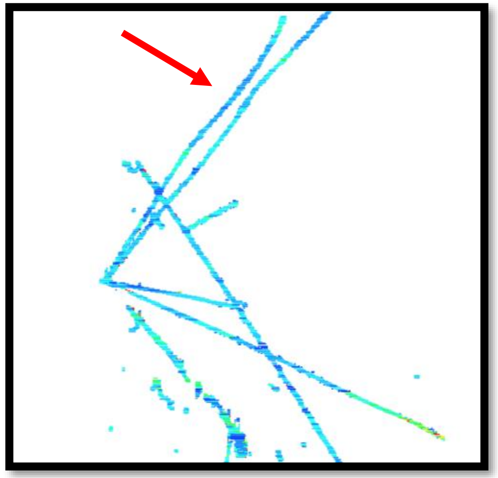
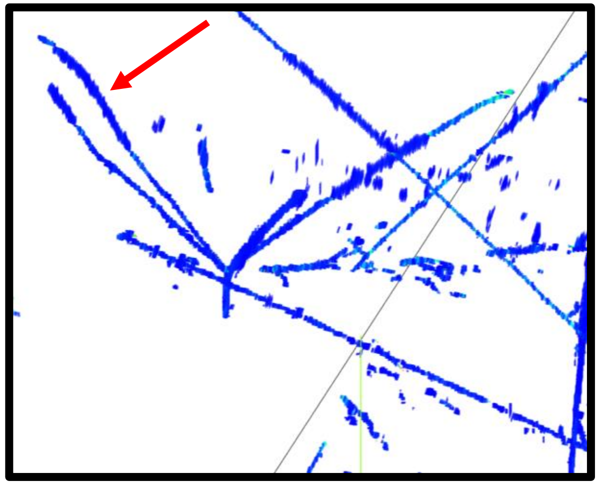
3 mins of CPU running



[Bee link]





- (lower) 2D deconvolution + L1 regularization

[JINST 13, P05032 (2018)]

Compressed Sensing

- Compressed sensing is a mathematical technique to **recover sparse signal from under-determined (linear) system**

Sovle $\quad y = A \cdot x \quad n_x > n_y$

L0: $\quad \text{minimize } \|x\|_0, \quad \text{subject to} \quad y = A \cdot x$

Here $||x||_0$ is the L0-norm of x, which counts the number of non-zero entries in x

Find the sparsest solution approaching the true signal

- Example: Tomography with few projections:

- Sparse projections: 11 radial lines

available portion of the spectrum (11 radial lines)

Back-projection estimate

Estimate after convergence (exact reconstruction)

Candes, Romberg, and Tao, "Stable Signal Recovery from Incomplete and Inaccurate Measurements"

https://arxiv.org/abs/math/0503066

Emmanuel Candes. (Photo courtesy of Emmanuel Candes.)

Justin Romberg. (Photo courtesy of Justin Romberg.)

Terence Tao. (Photo courtesy of Reed Hutchinson/UCLA.)

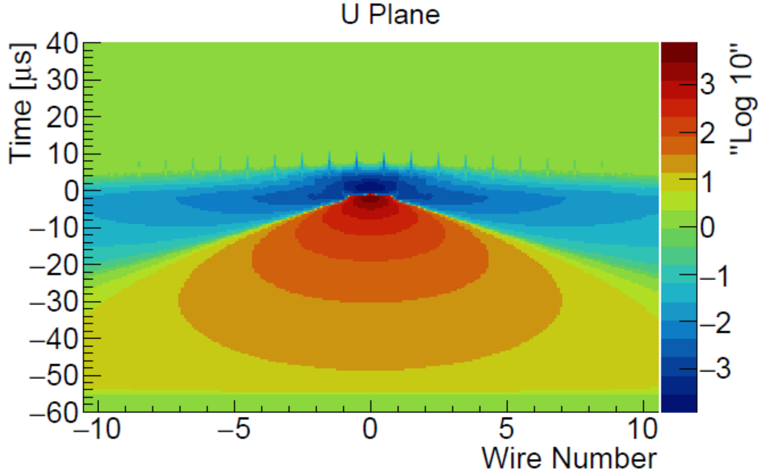
Allow one to reconstruct the image with far less projections

Direct application to LArTPC problem

2D Deconvolution

$$M_i(t_0) = \int_t \left(R_0(t_0 - t) \cdot S_i(t) + R_1(t_0 - t) \cdot S_{i+1}(t) + \ldots \right) \cdot dt$$

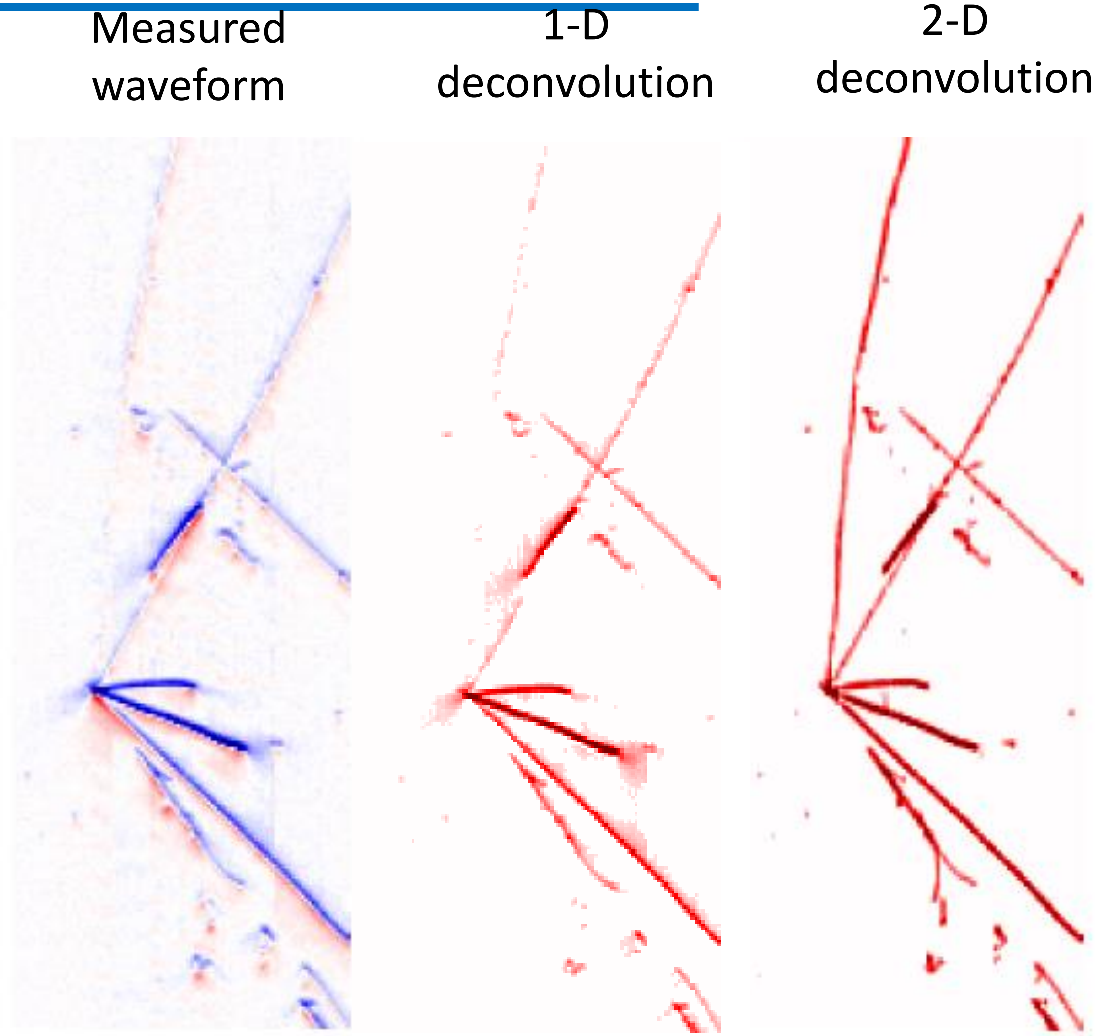
$$M_i(\omega) = R_0(\omega) \cdot S_i(\omega) + R_1(\omega) \cdot S_{i+1}(\omega) + \ldots$$



R_1 represents the induced signal from (i+1)th wire signal to ith wire

$$\begin{pmatrix} M_1(\omega) \\ M_2(\omega) \\ \ldots \\ M_{n-1}(\omega) \\ M_n(\omega) \end{pmatrix} = \begin{pmatrix} R_0(\omega) & R_1(\omega) & \ldots & R_{n-2}(\omega) & R_{n-1}(\omega) \\ R_1(\omega) & R_0(\omega) & \ldots & R_{n-3}(\omega) & R_{n-2}(\omega) \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ R_{n-2}(\omega) & R_{n-3}(\omega) & \ldots & R_0(\omega) & R_1(\omega) \\ R_{n-1}(\omega) & R_{n-2}(\omega) & \ldots & R_1(\omega) & R_0(\omega) \end{pmatrix} \cdot \begin{pmatrix} S_1(\omega) \\ S_2(\omega) \\ \ldots \\ S_{n-1}(\omega) \\ S_n(\omega) \end{pmatrix}$$

The inversion of matrix R can again be done with deconvolution → 2-D Fast Fourier Transformation



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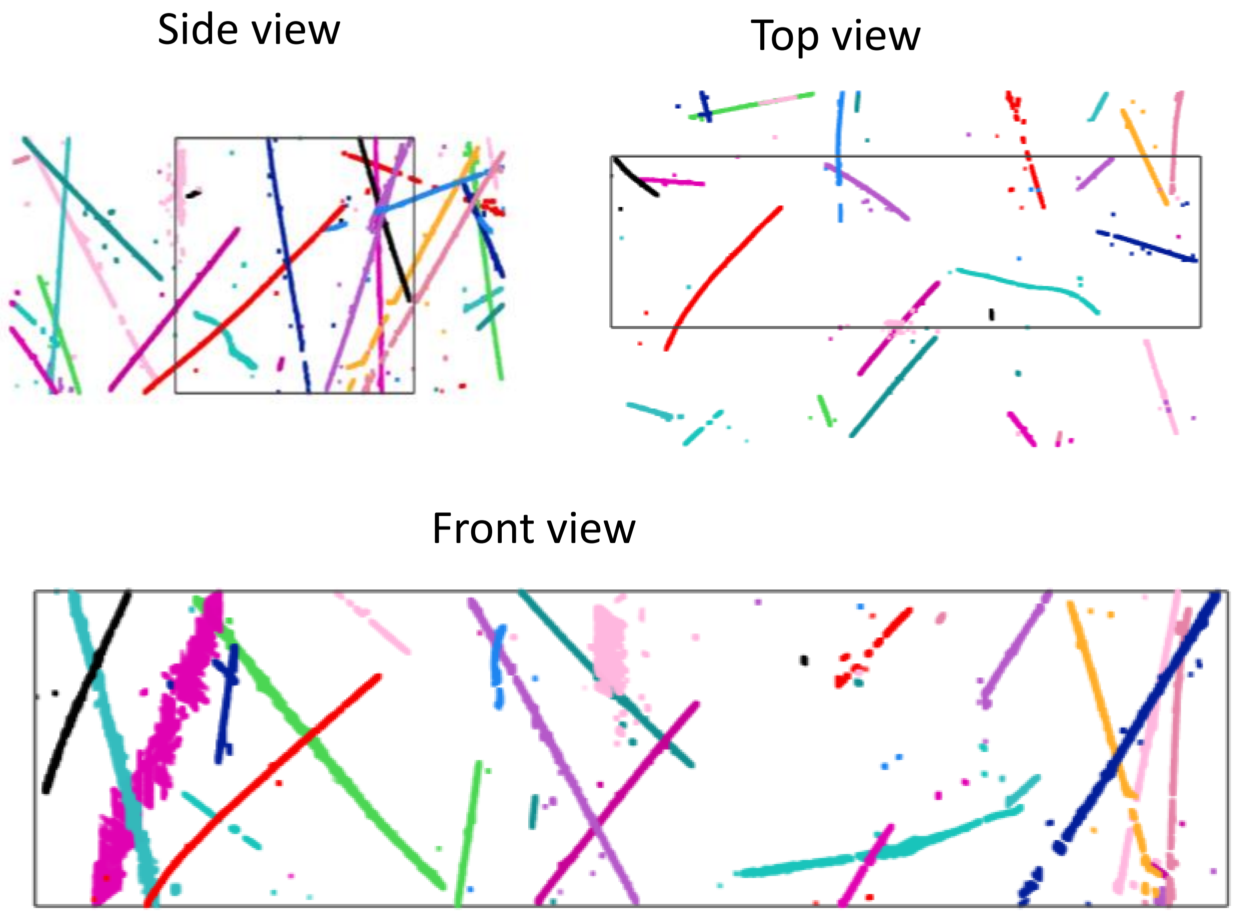
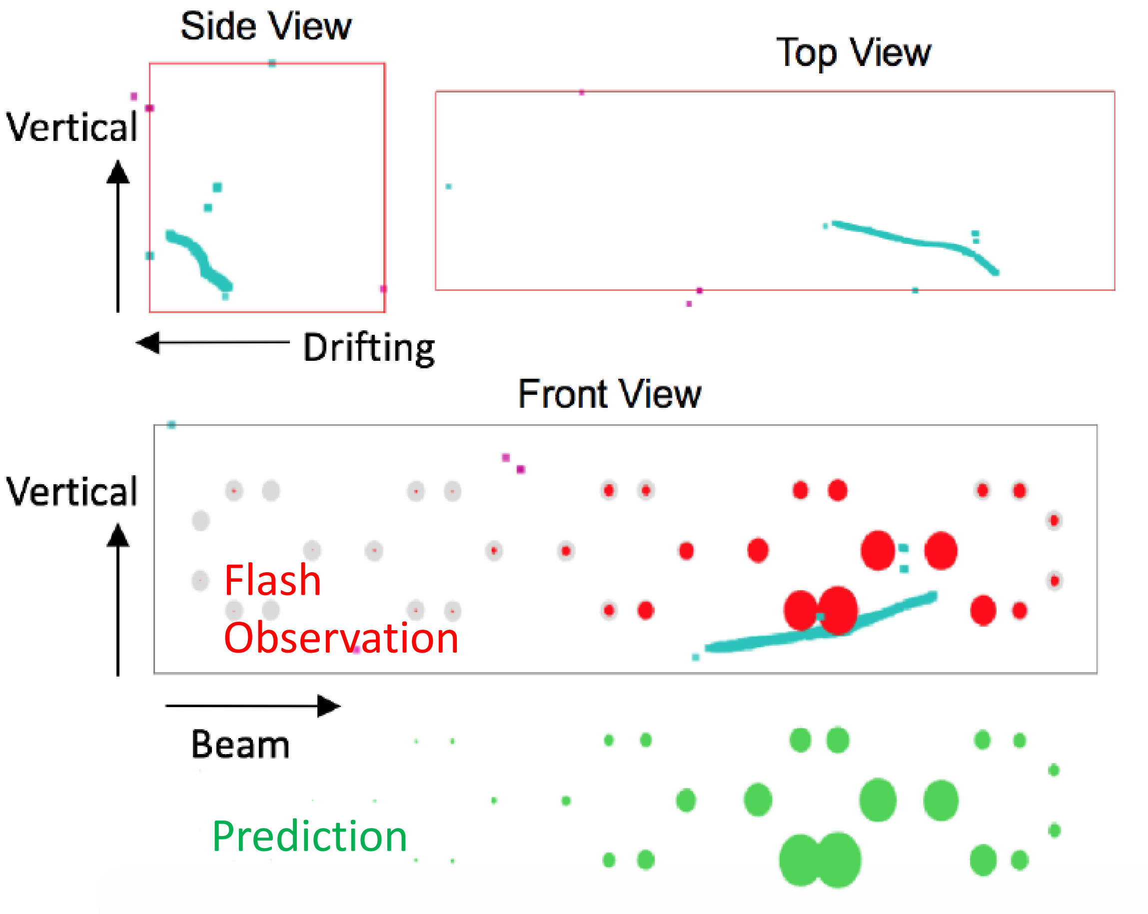
Before and After L1 Matching





Charged-Current ν_{μ} candidate

More details in MICROBOONE-NOTE-1040-PUB