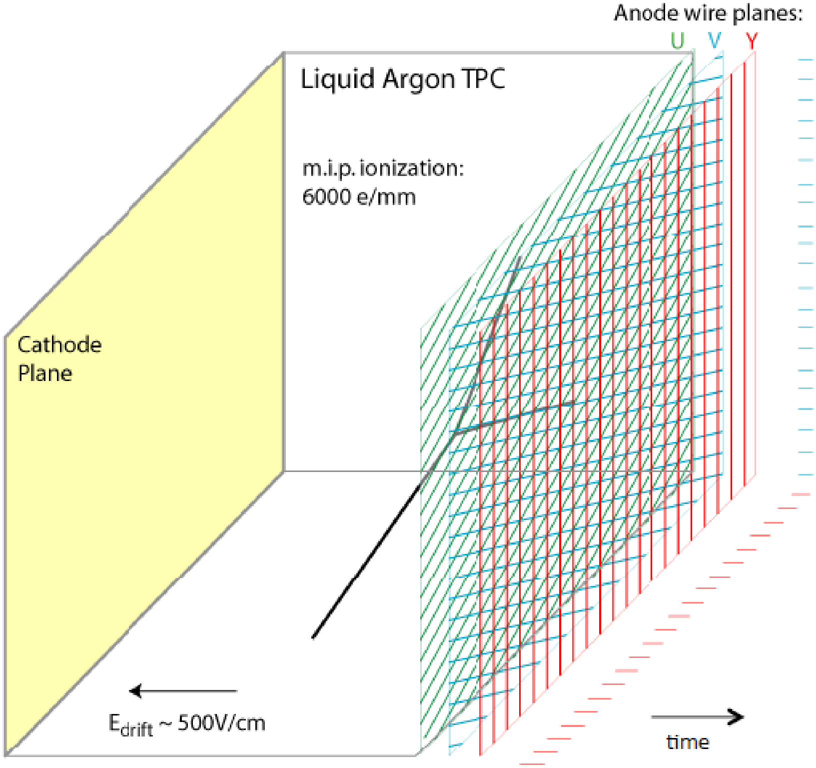
Introduction to Wire-Cell 3D Reconstruction

Chao Zhang

BNL

TPC vs. Tomography



- As electrons drift toward APA, they represent tomographic cross sections at each time slice
- Combining the reconstructed images on the time slices results in the full 3D object

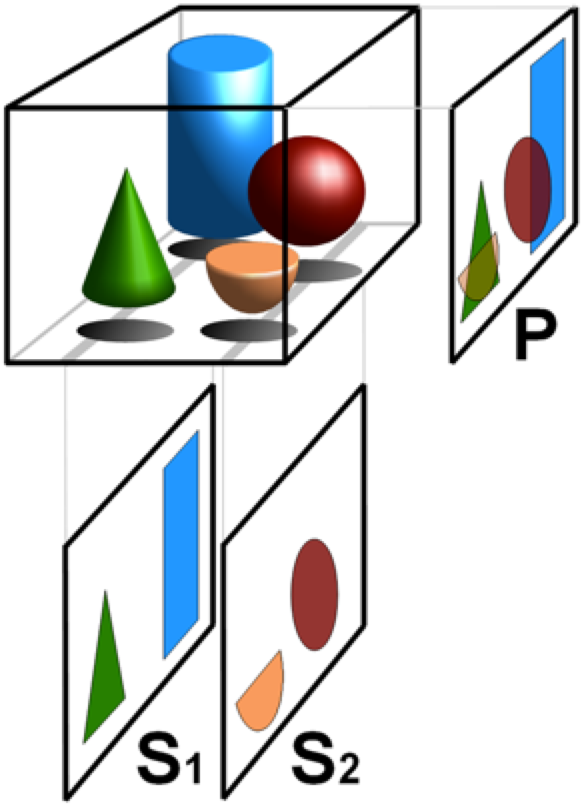


Fig.1: Basic principle of tomography: superposition free tomographic cross sections S1 and S2 compared with the projected image P

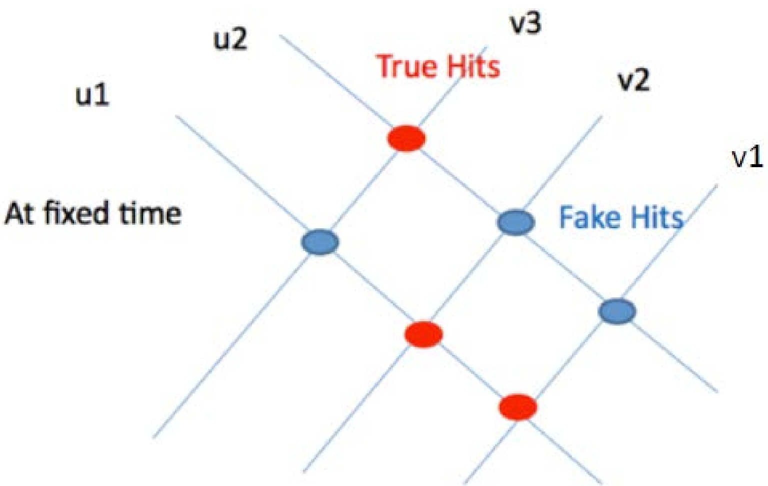
https://en.wikipedia.org/wiki/Tomography

Challenges in Tomographic Reconstruction

- The tomographic view seems to be natural way to do 3D reconstruction
  - Many people thought about it, but gave up eventually
- The challenge comes from the wire readout (compared with the pad pixel readout)
  - Wire readout is necessary to reduce cost
  - However the measured information is reduced from N^2 (pixels) to 3N (wires)
    - Information lost -> exponential degeneracy -> give up

An Illustration

Use two planes as an example



3 true hits

↓

5 measurements (2U + 3V wires)

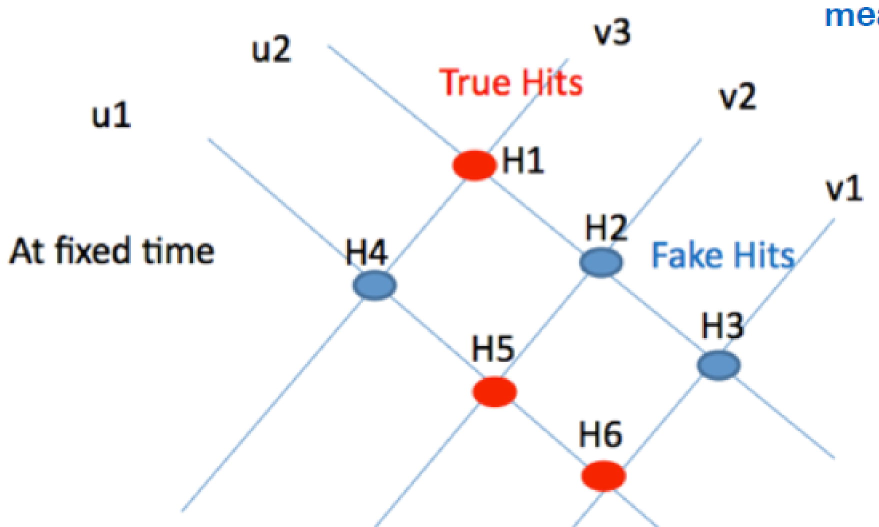
↓

6 possible hits (3 true + 3 fake)
2^6 combinations (some can be removed from the 5-wire constraint)

- Fake hits when there are many hits at fixed time
- Degeneracy increase exponentially with number of hits
  - Need additional information to reduce degeneracy

New Input From Charge Information

- Same charge in a voxel is measured 3 times by wires on the three wire planes
  - Assumption: charge calibrations are good on all three wire planes
- Write down the charge matrix equations
  - If equations can be solved, fake charge will be close to zero



Use two-plane as an example

measured charges on wires

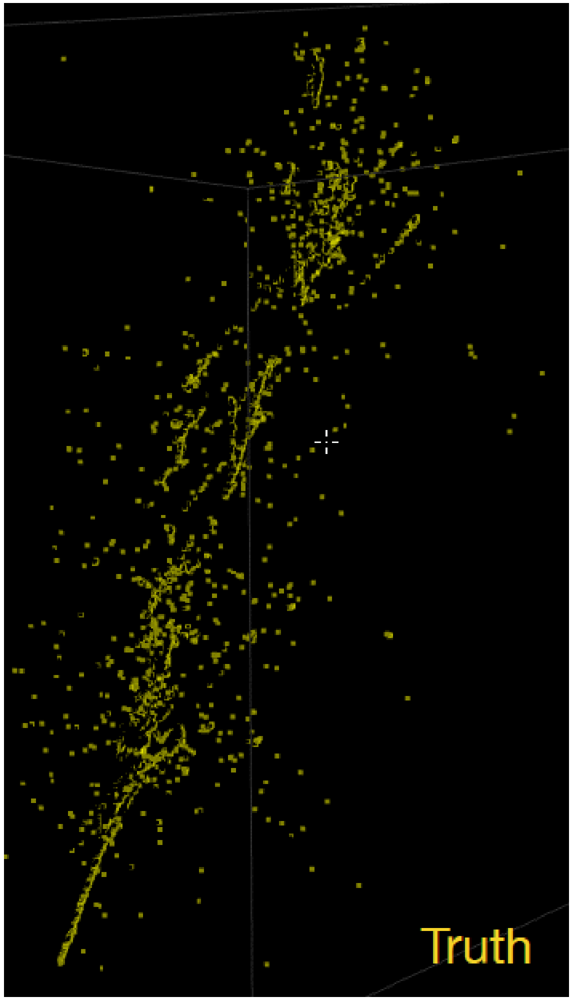
true charges to be solved

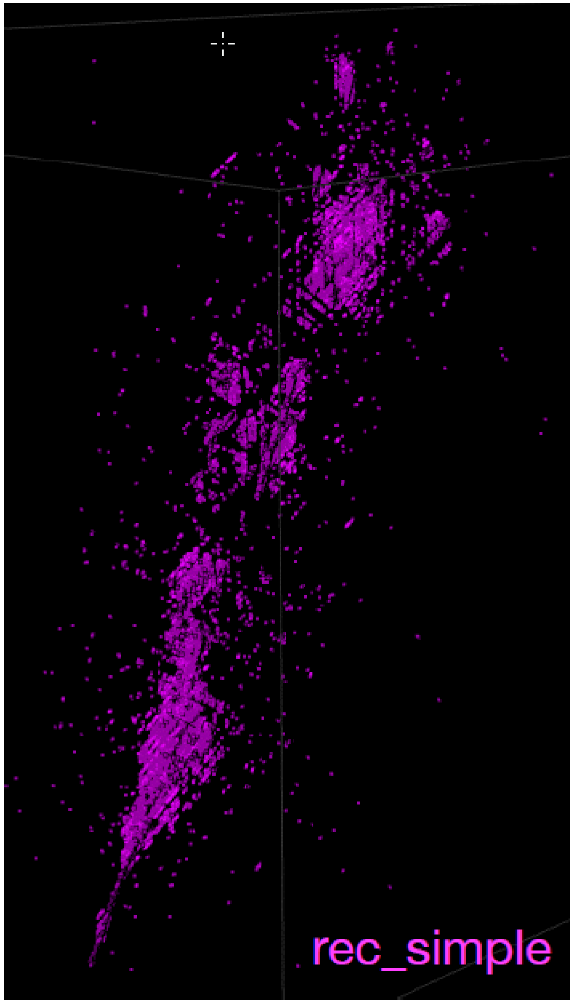
$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & a & a & a \\ a & a & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 & a \\ 0 & a & 0 & 0 & a & 0 \\ a & 0 & 0 & a & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \end{pmatrix}$$

Matrix determined by geometry

(a=1)

Example: a 1.5 GeV electron





Use only geometry information

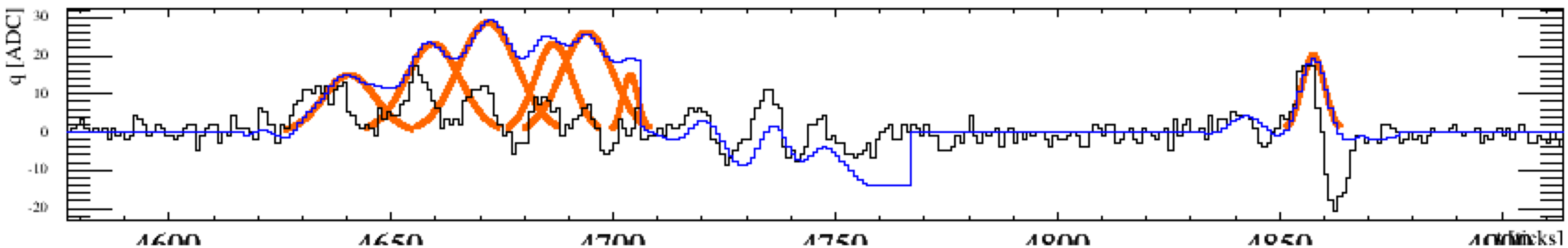
Use geometry and charge information

“Wire-Cell” Reconstruction

1) Form time slices
2) Construct Wire-Cell association
3) Merge adjacent cells into “blobs”
4) Construct $\chi2$ through matrix equations
5) $\chi2$ minimization
6) Obtain best matched 3D space points

Definition of Time Slice

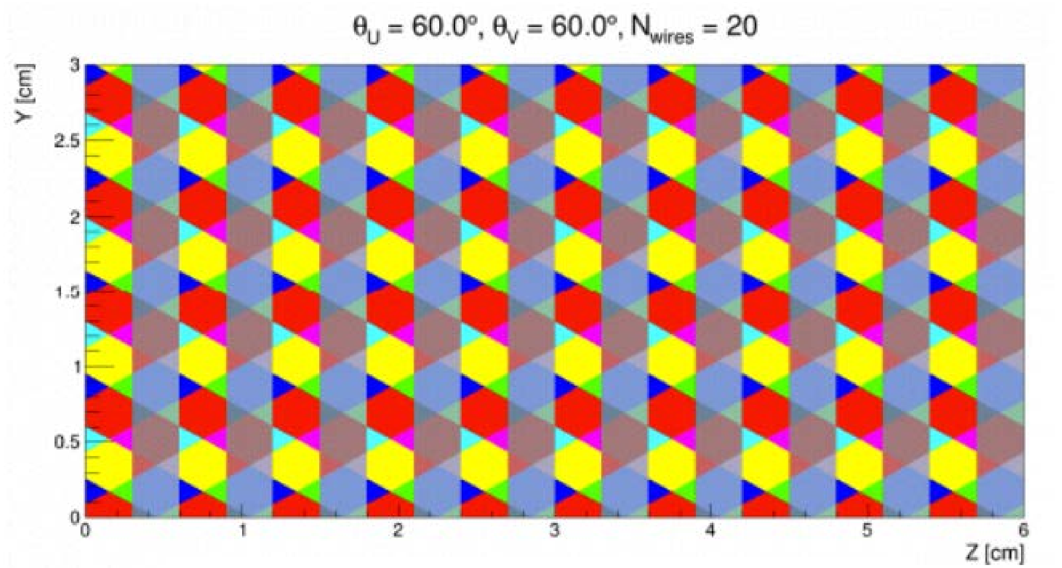
Signal Processing, Jyoti Joshi

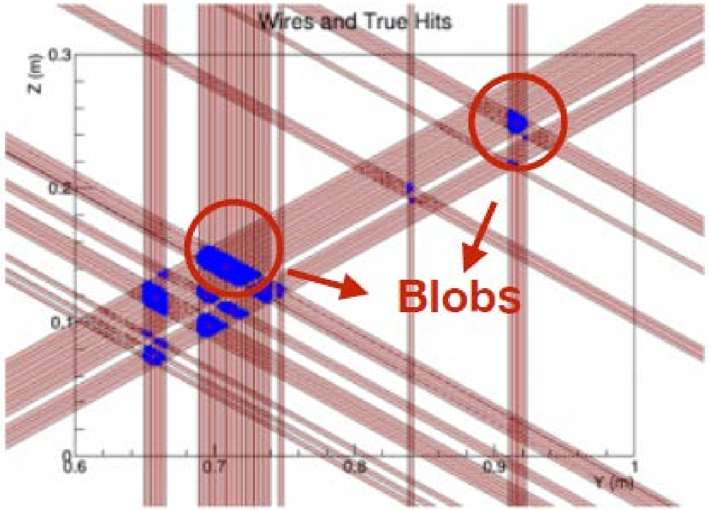


- In Wire-Cell reconstruction, we don't use the traditional concept of "Gaussian Hits".
  - Avoids the complications in fitting the waveform (especially for a long signal)
- Instead, we simply define a time slice as a 2-us bin
  - Binning choice matches the shaping time
- Charge in a time slice on a wire is the sum of its de-convoluted signals

Wires, Cells and Blobs

- Wire: a Wire represents a +- pitch/2 rectangular region centered around the wire
- Cell: a Cell is the overlap region of three Wires. This is the smallest area unit on a plane.
- Blob: group of hit cells that are adjacent
  - Merge cells into blob to reduce degeneracy





χ2 Construction and Minimization

$$\chi^2 = (\mathrm{B}\cdot \mathrm{W} - G\cdot C)^T V_{BW}^{-1} (\mathrm{B}\cdot \mathrm{W} - G\cdot C)$$

$$\frac{\partial \chi^2}{\partial C} = 0 \rightarrow G^T V_{BW}^{-1} (\mathrm{BW} - GC) + (\mathrm{BW} - GC)^T V_{BW}^{-1} G = 0$$

$$G^T V_{BW}^{-1} BW + W^T B^T V_{BW}^{-1} G = G^T V_{BW}^{-1} GC + C^T G^T V_{BW}^{-1} G$$

$$C = (\mathrm{G}^T\, V_{BW}^{-1}\, \mathrm{G})^{-1} G^T V_{BW}^{-1} BW$$

- C: charge in each (merged) cell (to be solved)
- G: Geometry matrix connecting cells and wires
- W: charge in each single wire
- B: Geometry matrix connecting merged wires and single wires
- V_{BW}: Covariance matrix describing uncertainty in wire charge

When equations can not be solved

- When the matrix $G^T V_{BW}^{-1} G$ can not be inverted, it must contain more than one zero eigenvalues
  - Often an indication of more unknowns than constraints
  - Need to find the "best" solution
- One hypothesis is to eliminate certain number of "Blobs" (i.e. unknowns) so that the updated matrix can be solved
  - Assume number of real cells are smaller than the constraints
  - Assume smaller $\chi 2$ representing situation closer to the truth
  - Try all combinations and find the minimum $\chi 2$
    - Degeneracy scales exponentially with number of possible cells
    - The key is to develop algorithms to improve the speed and accuracy: Iterative, MCMC, Time …

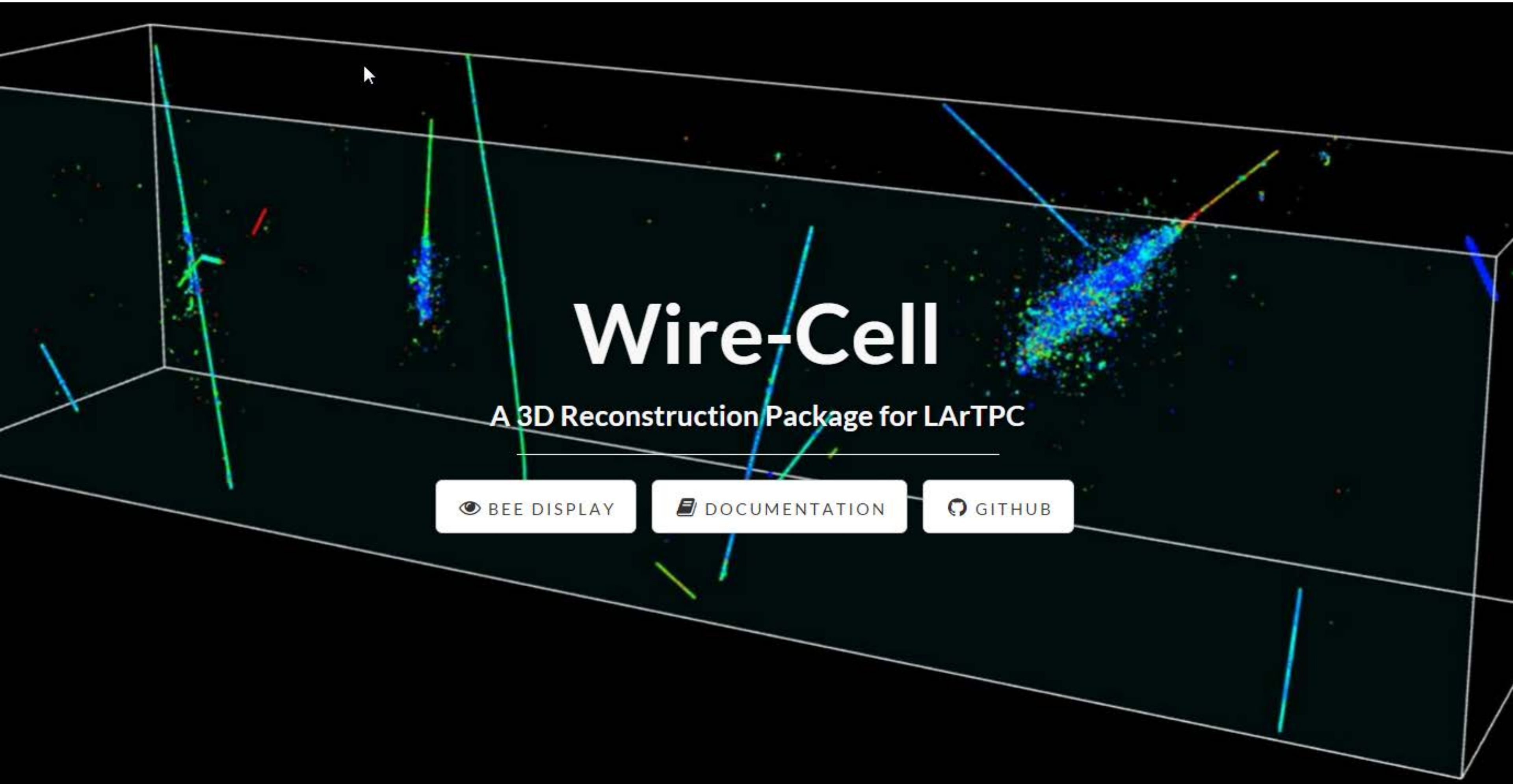
Comparison With Tradition Reconstruction

- Start with “time” Information
- Do clustering and tracking in the three 2D time-wire planes
- Match the three 2D views to obtain the 3D space points
- Use 3D space points and the charge on wires to do physics

- Start with “charge” Information
- Obtain 3D space points (with charge) by solving equations in the 2D tomographic plane
- Do clustering and tracking in 3D directly
  - Use time/tracking information to iteratively improve equation solving
- Do physics

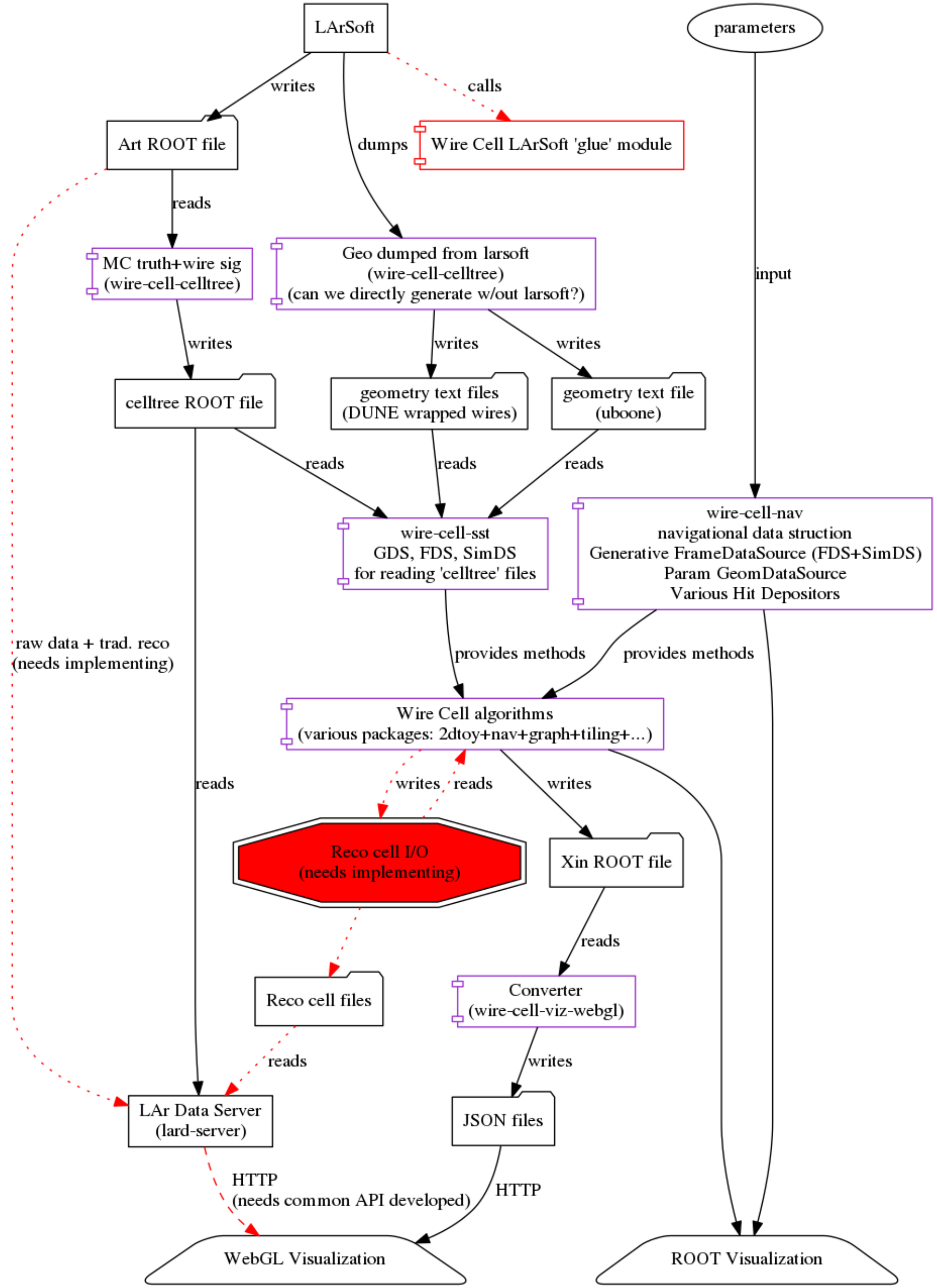
The Wire-Cell Homepage

http://www.phy.bnl.gov/wire-cell/



Software

- This is an external software package outside of LArSoft
  - https://github.com/BNLIF/wire-cell/
- Maintained by Brett Viren
- Interface with LArSoft in development



Wire-cell Data Flow, Components and Status

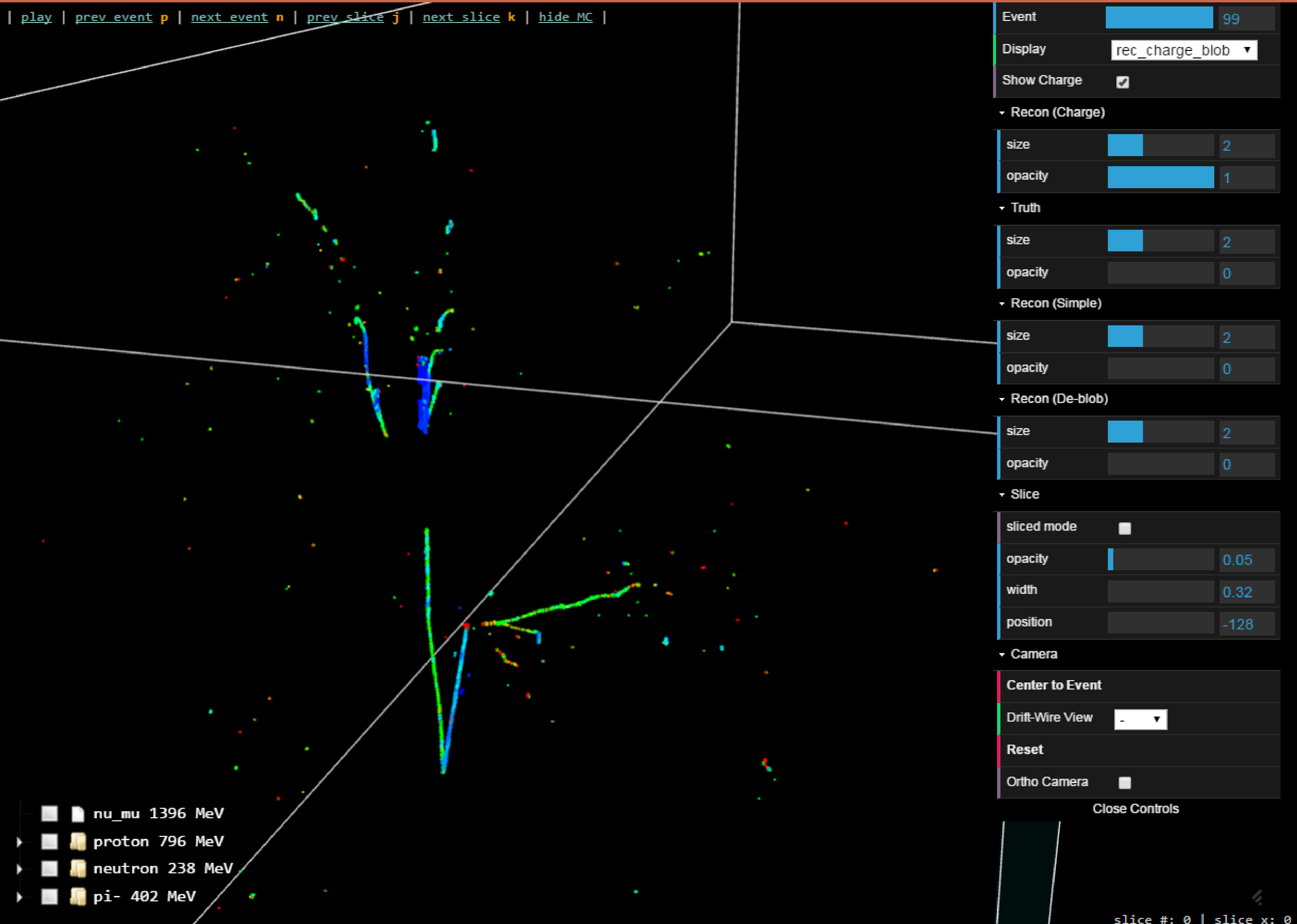
The “Bee” Event Display

- We’ve made a web-based event display to help
  - Developers: compare the performance of different reconstruction algorithms
  - Users: eye san various events to gain intuitions of different interactions in LAr
- List of simulated event sets:
  - http://www.phy.bnl.gov/wire-cell/examples/list/
  - Currently, all are using the microboone single TPC geometry.
  - There are some 3 GeV events (numu-cc, numu-nc, nue-cc) that we made to get familiar with DUNE-type events

The “Bee” Event Display

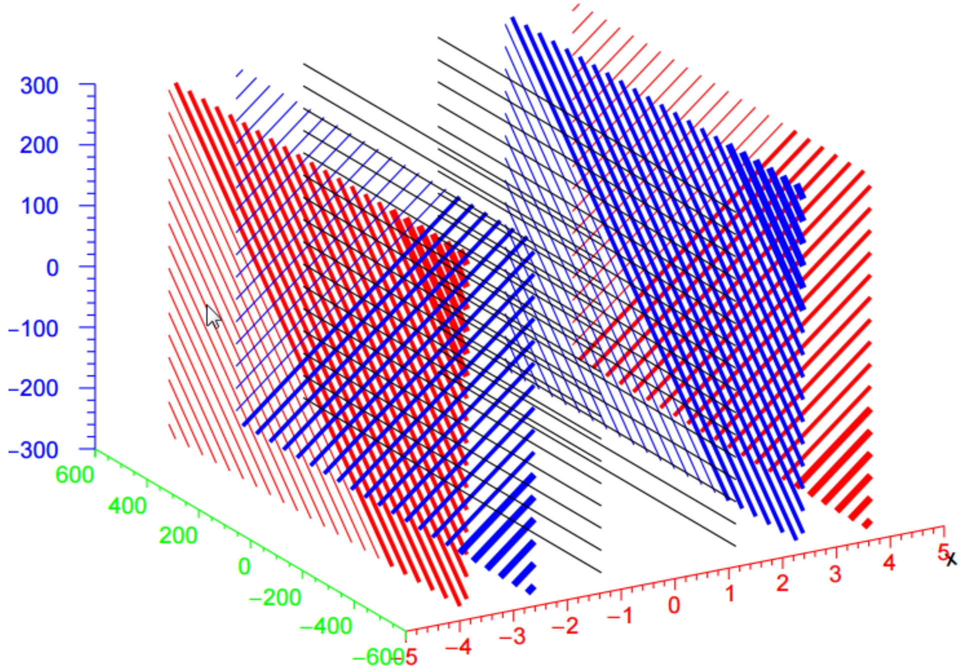
- Developed with WebGL via the three.js library http://threejs.org
  - Runs everywhere with a modern browser (Chrome, Firefox, Safari, IE11+, etc. http://caniuse.com/#feat=webgl)
  - A good discrete GPU helps

	Mouse / Keyboard	Touch
Rotate	**Drag with left button**	**One finger touch**
Zoom	**Mouse wheels**	**Pinch & zoom / two finger scroll**
Pan	**Drag with right button / arrow keys**	**Three finger swipe**


| play | prev event p | next event n | prev slice j | next slice k | hide MC |
Event 99
Display rec_charge_blob
Show Charge
Recon (Charge)
size 2
opacity 1
Truth
size 2
opacity 0
Recon (Simple)
size 2
opacity 0
Recon (De-blob)
size 2
opacity 0
Slice
sliced mode
opacity 0.05
width 0.32
position -128
Camera
Center to Event
Drift-Wire View -
Reset
Ortho Camera
Close Controls
nu_mu 1396 MeV
proton 796 MeV
neutron 238 MeV
pi- 402 MeV
slice #: 0 | slice x: 0

To-do List

- Add capability of wrapped wire, multiple TPCs, and parametrized TPC
- Study disambiguity
- Study TPC optimization
- Implementing interface with LArSoft
- Improve the clustering and tracking
- Improve the equation-solving algorithms
- …



Lots of work to do and need many helps!