Overview of Reconstruction Software

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Introduction

- LArTPC provides 3D event imaging with excellent spatial resolution.
- Reconstruction of events in LArTPC is challenging.
  - Large amount of information.
  - Tracks and showers overlap near the vertex.
  - Wire readout loses information.
  - Wrapped wires add ambiguities.
- A lot of progress has been made in the development of reconstruction tools over the past years.
- This talk reviews the latest reconstructions tools.

Common Framework

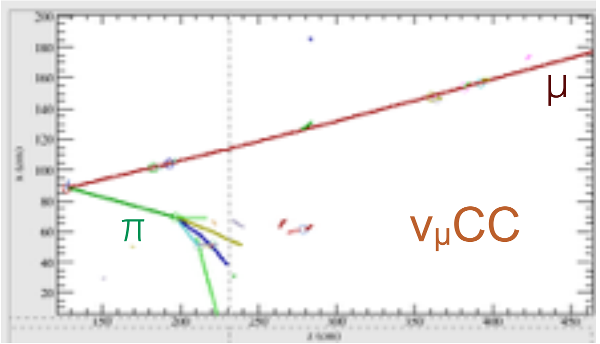
- LArSoft was created by Fermilab scientist Brian Rebel in 2010 to do simulation and reconstruction for LArTPC experiments.

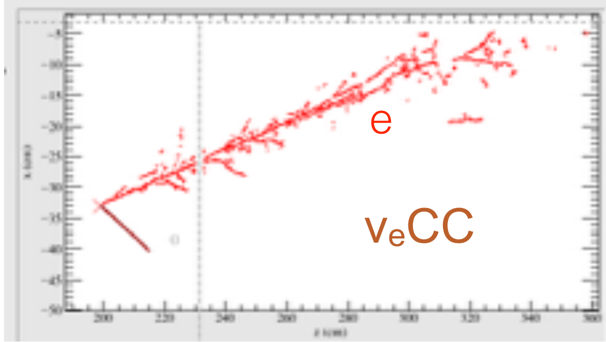
- It has been used by Fermilab LArTPC projects/experiments: ArgoNeuT, LongBo, MicroBooNE, LArIAT, SBND, DUNE, etc.

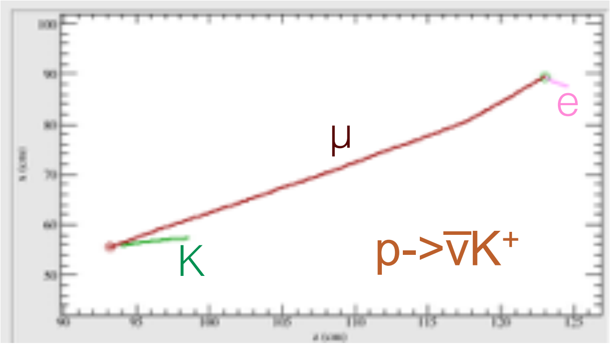
- This talk focuses on reconstruction algorithms in LArSoft or external product that LArSoft can use (e.g. Pandora).

Requirements for Reconstruction

- **Neutrino oscillations (beam and atmospheric)**
  - Neutrino vertex reconstruction
  - Muon reconstruction and μ/π/proton separation.
  - Electron reconstruction and e/γ separation.
- **Proton decays**
  - Track and vertex reconstruction.
  - Calorimetry reconstruction.
  - Photon detector reconstruction.
- **Supernova neutrinos**
  - Low energy electron neutrino reconstruction.
  - Photon detector reconstruction to help determine energy.
- **Cosmogenics**
  - Background to many physics analyses.
  - Sources for detector calibration.







Challenges for DUNE

- DUNE has multiple TPCs
  - Objects reconstructed in multiple TPCs need to be stitched together.
  - A lot of existing algorithms were developed with the concept of single TPC.
  - We have adapted several modules to work for multiple TPCs (e.g. LineCluster, Calorimetry).
  - Newer algorithms are carefully designed to work for multiple TPCs (e.g. Pandora, PMA, BlurredCluster).
- DUNE has wrapped wires
  - We need one additional step to disambiguate induction hits.
- Long drift volume
  - Signal attenuation, diffusion, space charge effects.

Two Reco Approaches

Xin Qian

2D Matching

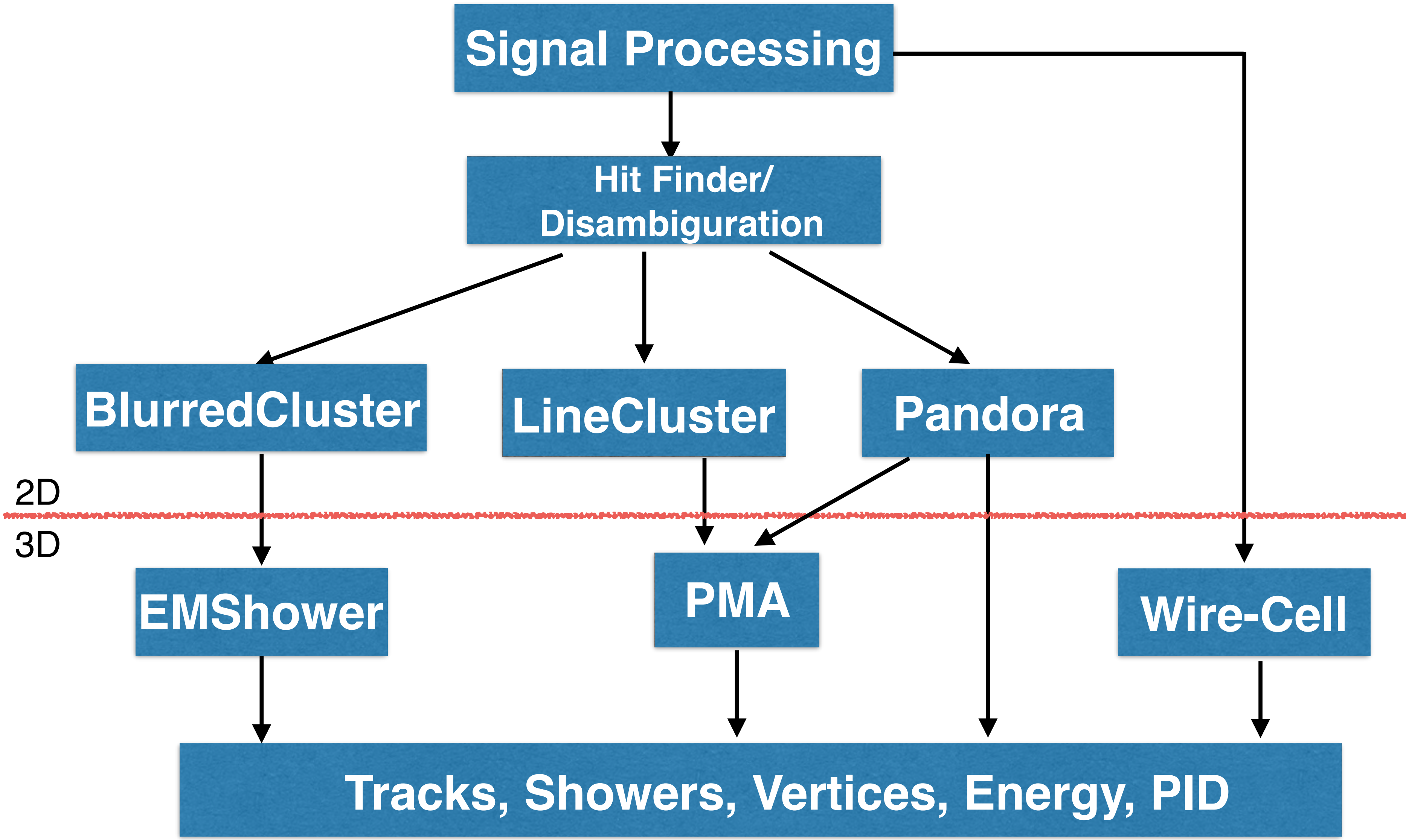
- Start with 2D (time+wire x 3)
- 2D pattern recognition
  - Particle track/cluster information
- Matching 2D patterns into 3D objects
  - **Time** information (start/end of clusters)
  - **Geometry** information
  - Some **charge** information to remove ambiguities in matching

3D Tomography

- Start with 2D (wire+wire+wire at fixed time slice)
- 2D image reconstruction
  - **Explicit Time** + **Geometry** + **Charge** information
  - Some connectivity information can be used
- 3D image reconstruction
  - Straight forward
- 3D pattern recognition
  - Particle track/cluster information (tracks, showers)

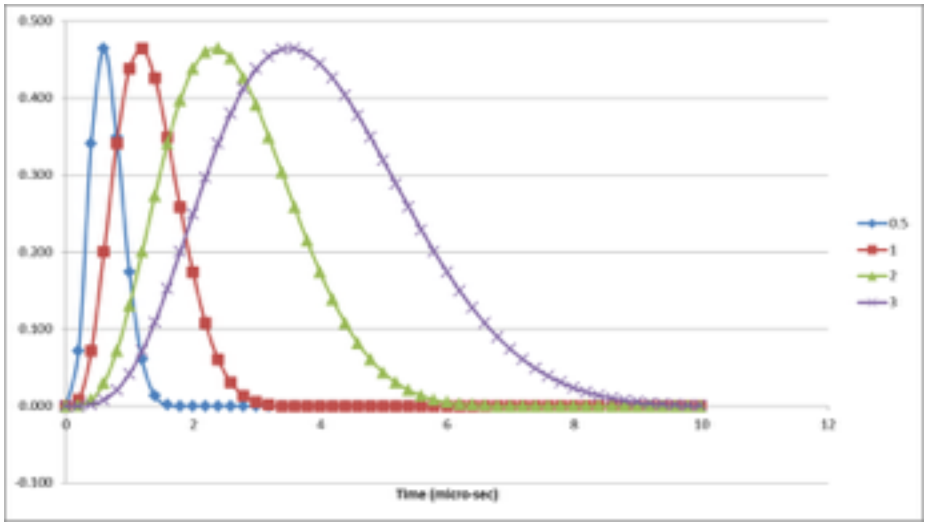
Each approach uses the same set information in different order!

Latest Reconstruction Chain

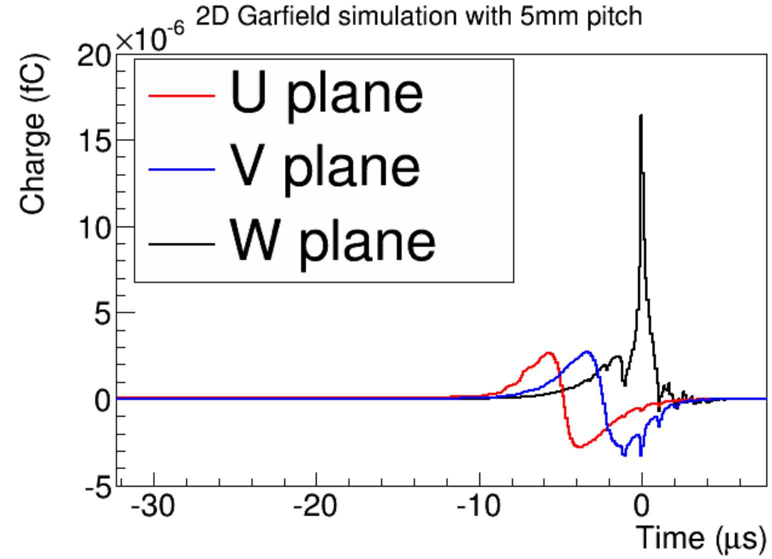


Signal Processing

The foundation of all further reconstruction!

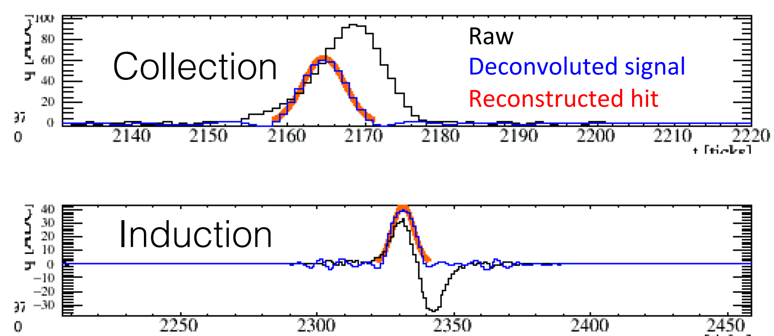


BNL SPICE ASIC simulation



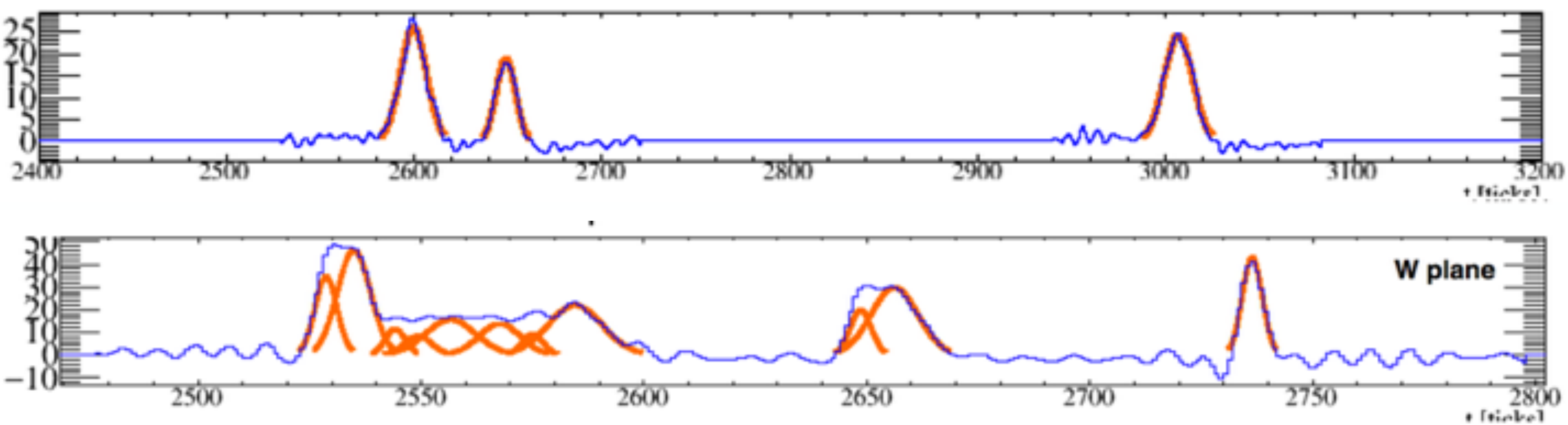
Garfield simulation of field responses

- Filter noise.
- Remove effects of field response and electronics response.
- More details in Xin's talk.



Hit Finder

- Default hit finder in LArSoft is GausHitFinder developed by Jonathan Asaadi.
- Start from deconvoluted signals on wire and define areas above threshold known as “pulses”.
- Once a pulse is found, a “n” Gaussian hypothesis is applied where “n” is defined by the number of peaks initially identified within the pulse.



Long Pulses

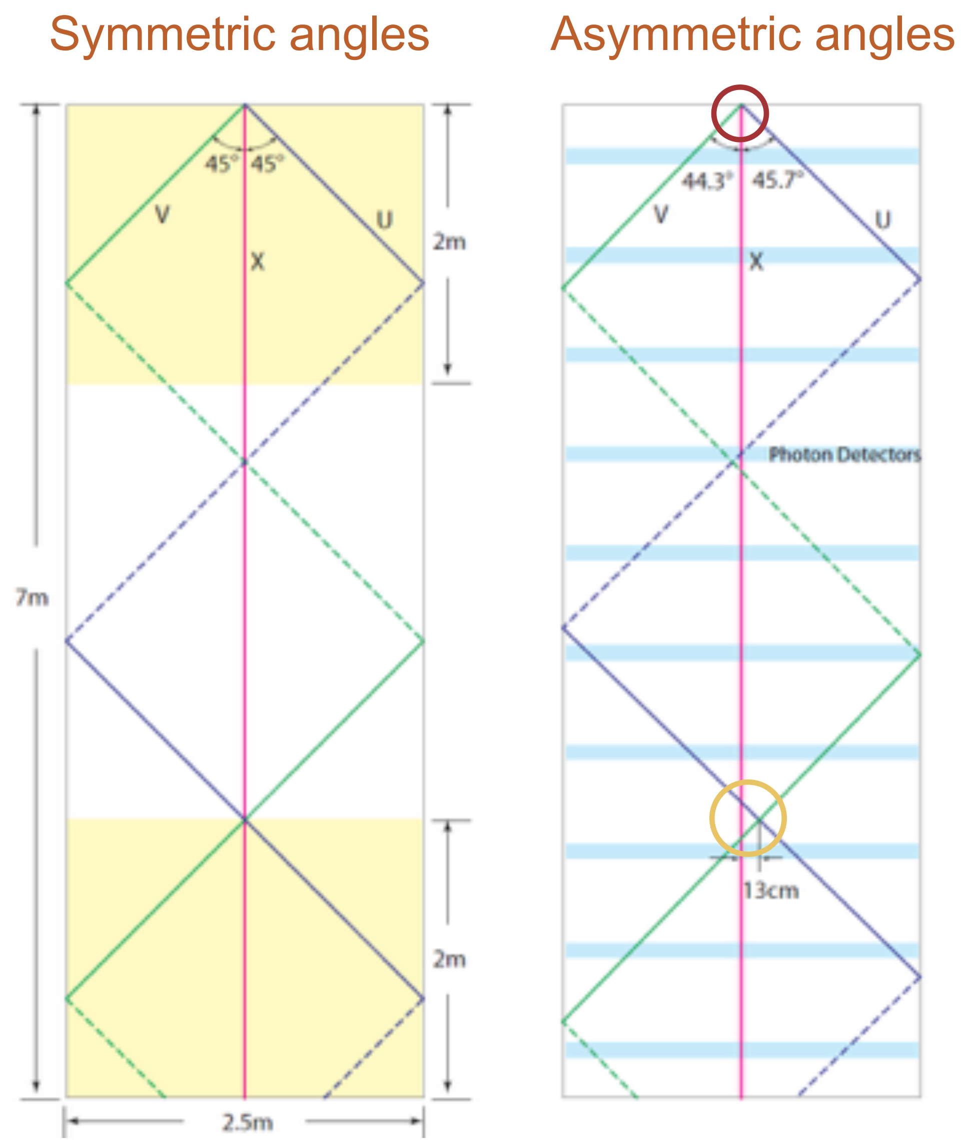
- Sometimes a track can go at an angle and leave a long pulse on a single wire.
- Hit finder with Gaussian fit approach does not work well in this case.
- Downstream reconstruction prefers a series of small hits rather than a single wide hit.
- WellCell does not reconstruct hits by fitting Gaussians. It groups signal on every 4 ticks (2us) on each wire.
  - This concept is being adopted by hit finder to deal with long pulses.

Other hit reconstructions

- CCHitFinder
  - Created by Bruce Baller
  - Part of the ClusterCrawler suite
  - Similar Gaussian fits to get hits
- RawHitFinder
  - Created by Michelle Stancari
  - Works on raw signal rather than deconvoluted signal

Disambiguation

- In 35t, triplets of U, V and Z wires intersect just once because of the slightly different angles: U 45.7°, V 44.3°.
- In FD and protoDUNE, the wire angles were chosen so triplets of U, V, Z wires never intersect more than once: U/V 35.7°.
- We developed a disambiguation algorithm for 35t by selecting triplets of wires that intersect.
- The same algorithm works for FD and protoDUNE.



Track and Shower Reconstruction

- First discuss the 2D matching approach.
- Reconstruct clusters in each view by grouping hits belonging to the same particle.
- Match clusters between different views based on time information and reconstruction 3D tracks and showers.
- Two types of clusters
  - Line-like clusters: for track reconstruction.
  - Shower-like clusters: for shower reconstruction.
- Several cluster reconstruction algorithms:
  - **LineCluster**: optimized for tracks.
  - **BlurredCluster**: optimized for showers.
  - **Pandora**: reconstruct both line-like and shower-like clusters.
- Track Reconstruction algorithms:
  - **PMA** and **Pandora**
- Shower Reconstruction
  - **EMShower**

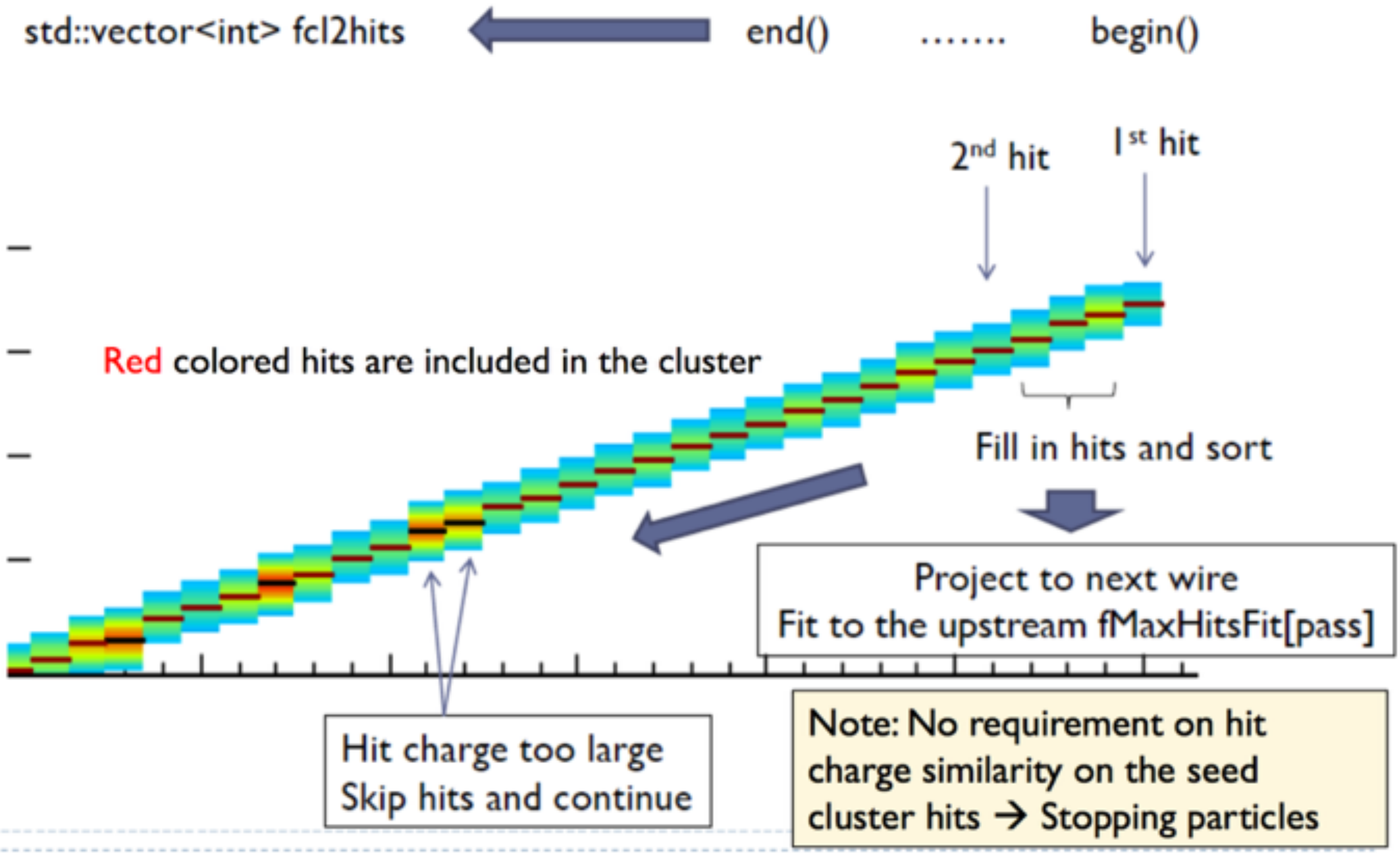
LineCluster

- Developed by Bruce Baller. Algorithm name is ClusterCrawler.
- Proximate hits in a cluster or track should have similar characteristics, e.g.
    - Hit charge = integral of the hit signal (not the pulse height)
    - Hit width (in time) - currently unused
- Use cluster tracking information from low hit density regions (DS of primary vertex) to extrapolate into high density regions (at the primary vertex) or through high hit density regions (δ-rays and showers)

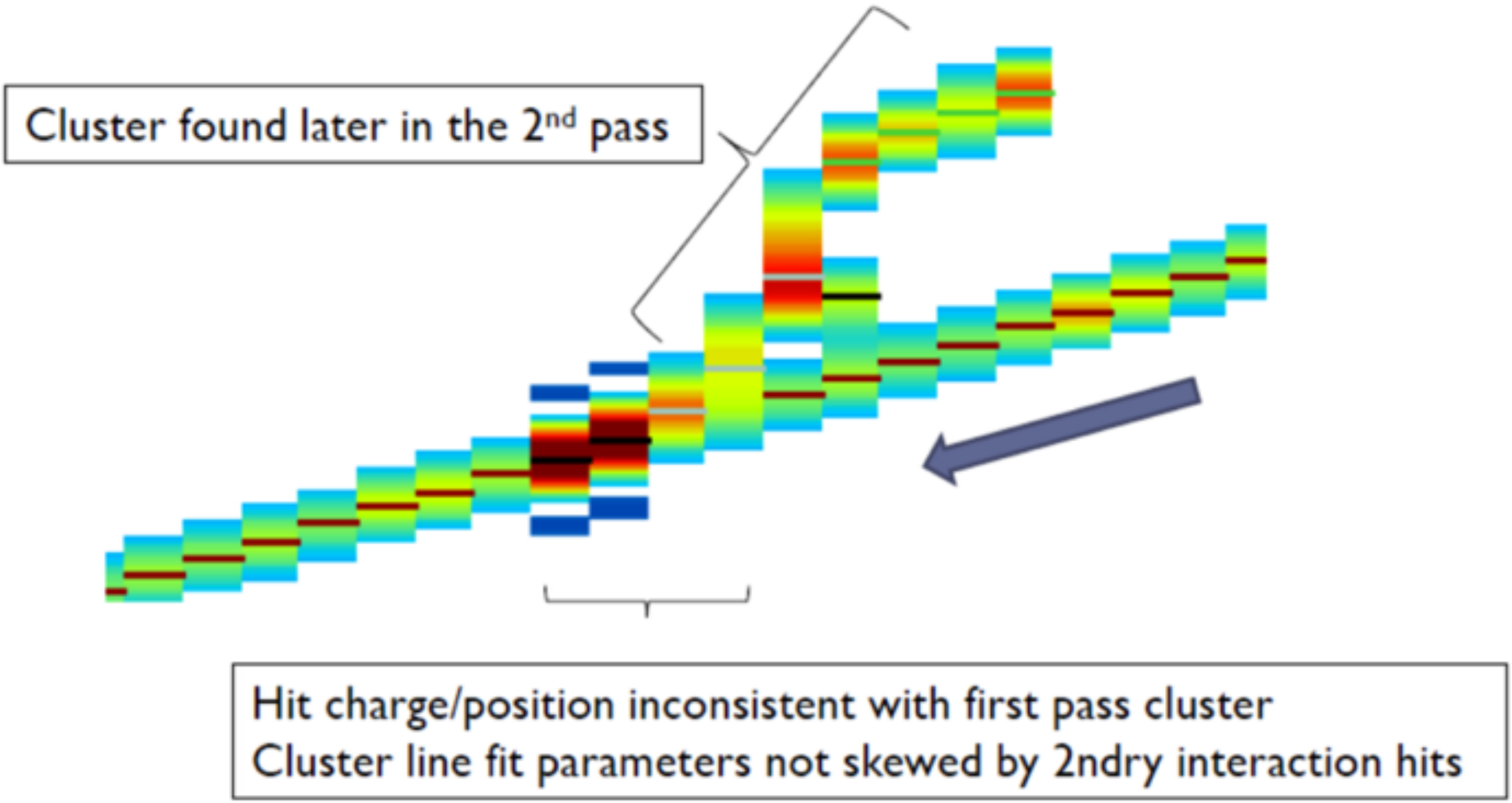
Algorithm Details

- Make multiple passes through the hits in each plane
- First pass – find clusters from high momentum tracks
  - Form a seed cluster using “unused” hits on 3 adjacent wires starting at the DS end
  - Fit to a line, project to the next US wire and look for a nearby “unused” hit that meets the position and charge criteria
  - If one is found, add it to the leading edge of the cluster, mark the hit “used”, re-fit the cluster and continue crawling US
- Subsequent passes – reconstruct lower momentum tracks
  - Only consider unused hits
  - The same only with looser cuts on length, fit χ^2, etc

Seed Cluster

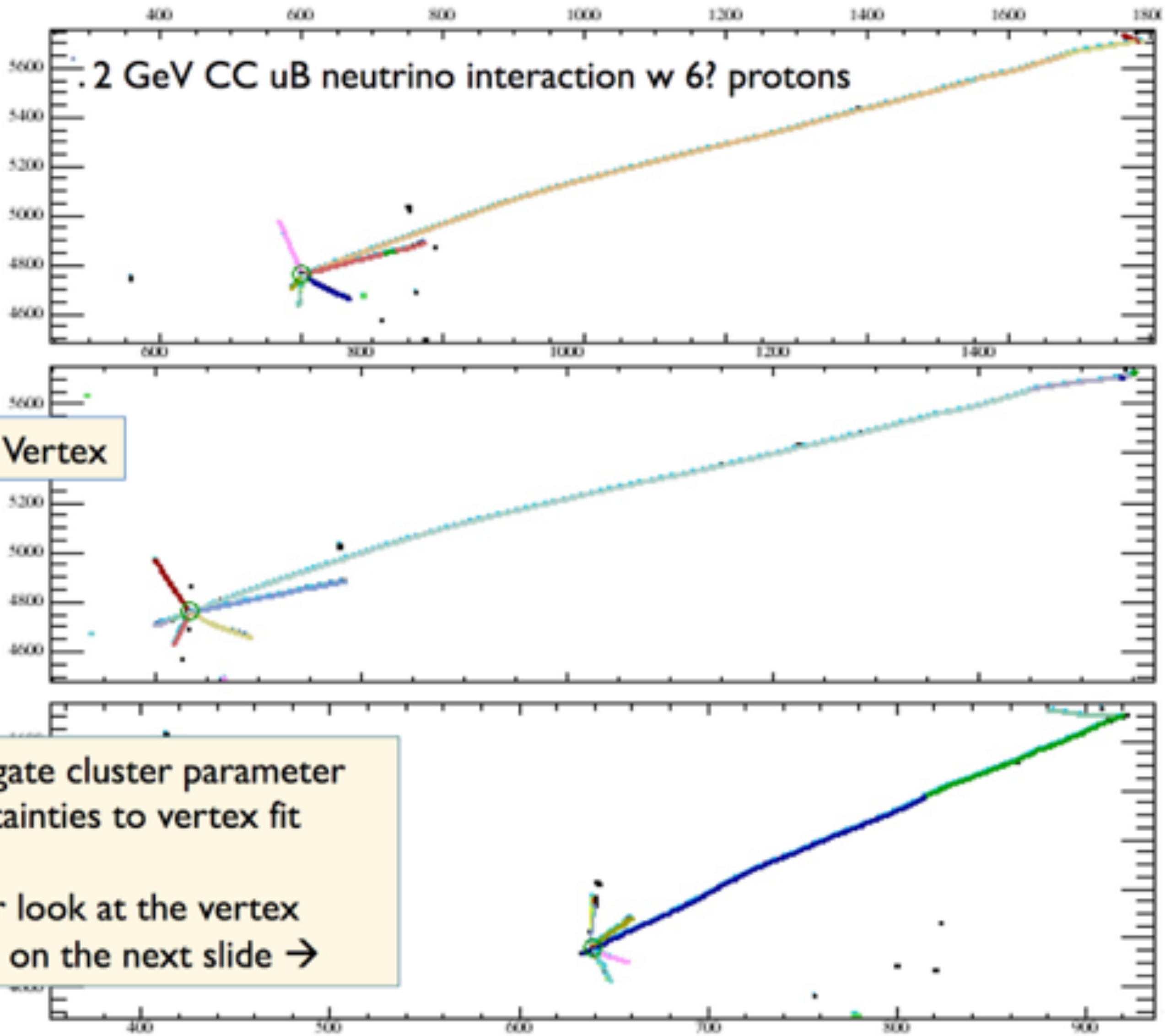


Crawling Upstream (US)



One example

[Techincal Note]



○ = 3D Vertex

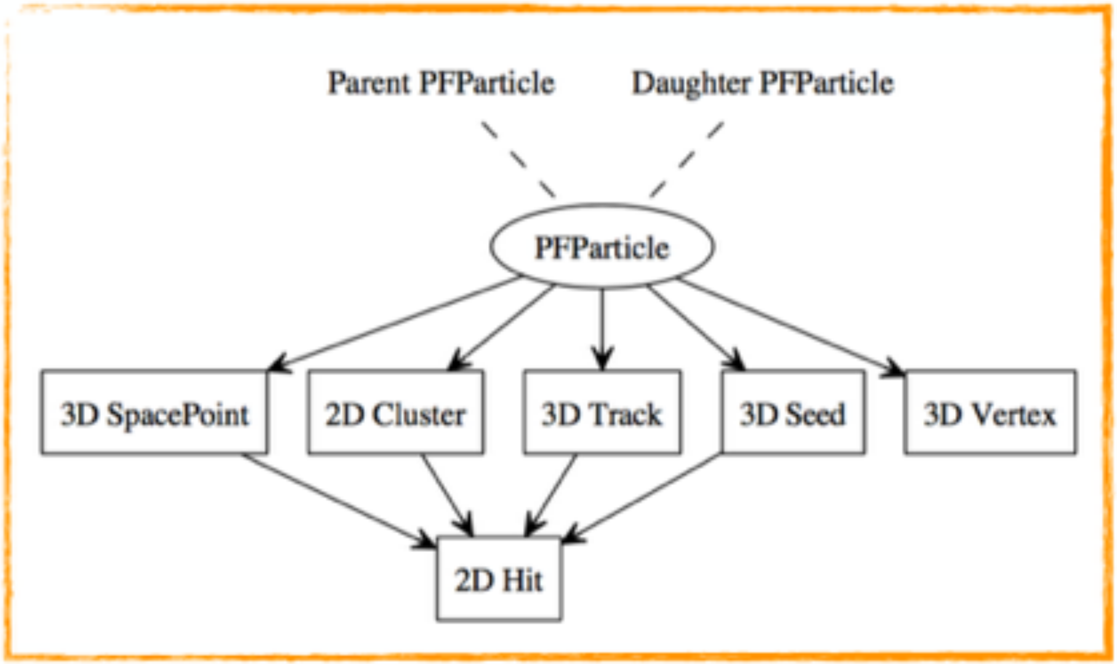
Propagate cluster parameter uncertainties to vertex fit

Closer look at the vertex region on the next slide →

Pandora

https://github.com/PandoraPFA

- Pandora is a well-established tool for fine-grain pattern recognition in high energy physics (future linear collider, LHC, LArTPCs)
- Supports multi-algorithm approach to automated and optimized pattern recognition.
- Takes hits as input. Outputs PFParticles with hierarchies
  - Reconstruct both track-like and shower-like PFParticles for further track/shower reconstruction.

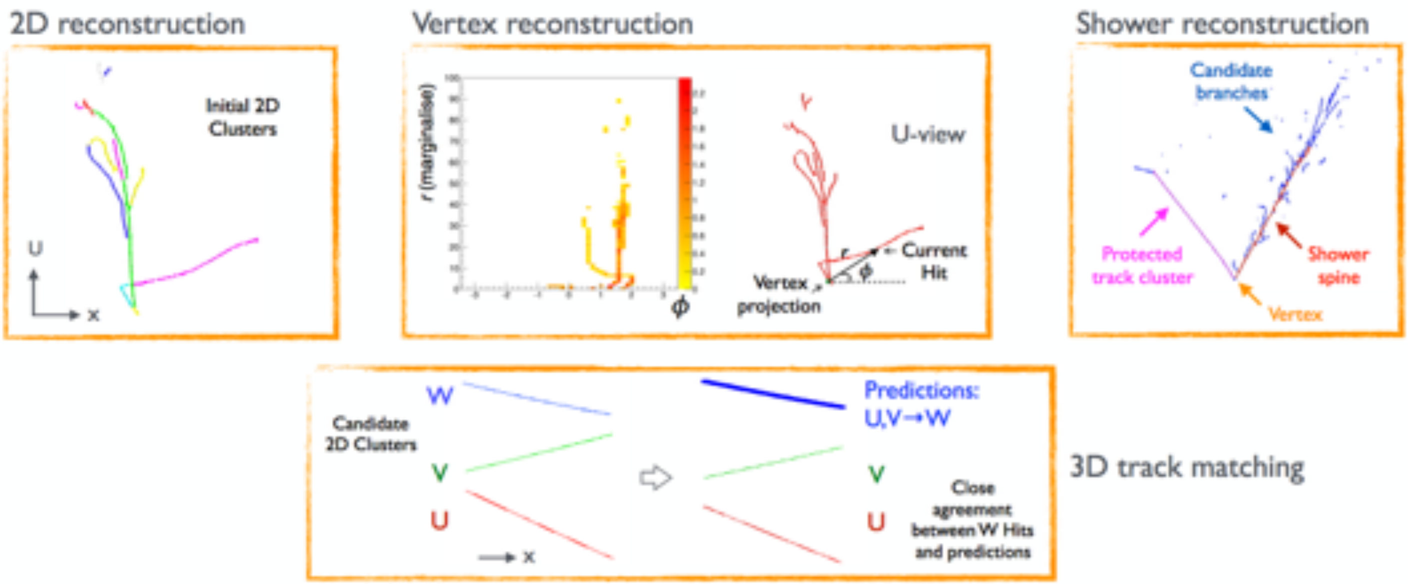


Two Chains of Algorithms

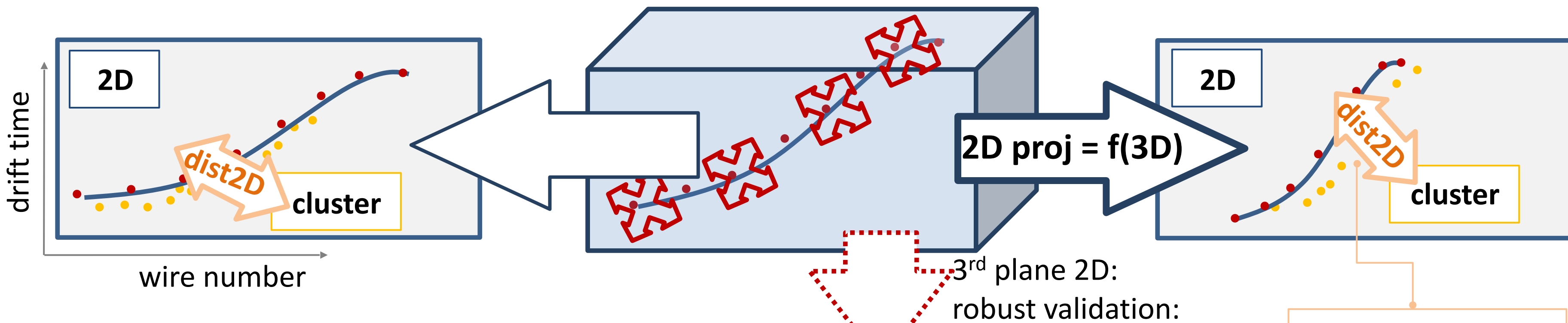
- PandoraCosmic (35t):

More details in Joris de Vries' talk.

    - more strongly track-oriented; showers assumed to be delta rays, added as daughters of the muons; muon vertices at track high-y coordinate.
- PandoraNu (FD):
    - more careful to find interaction vertex and to protect particles emerging from vertex. Careful treatment to address track/shower tension.



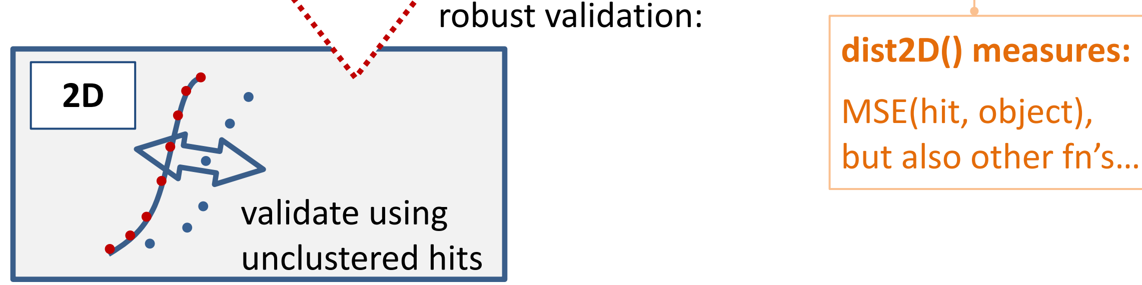
Projection Matching Algorithm (PMA)



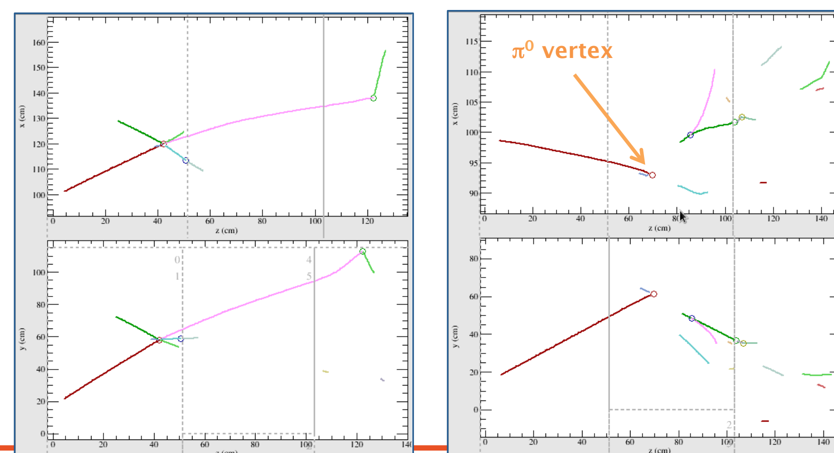
Cluster association is verified using projection to the 3rd view:

Dorota Stefan, Robert Sulej

paper: "*Precise 3D track reconstruction ...*", ICARUS Collab., AHEP 1601 p.260820 (2013)



- Instead of building 3D object by matching 2D hits between different views, build 3D object by minimizing distance the object's 2D projection to 2D hits.



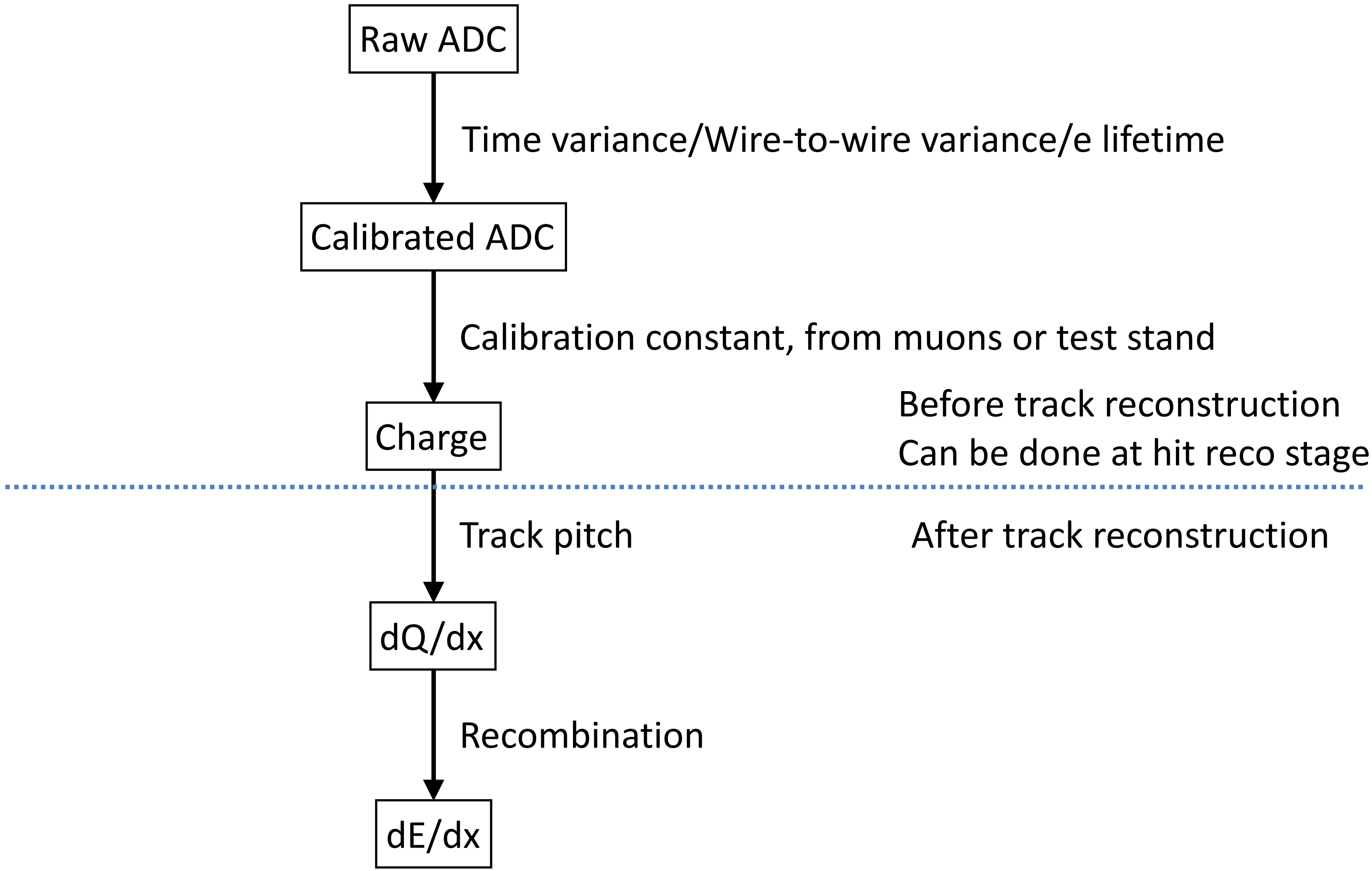
Reconstructed event examples: π^- @ 2GeV/c, 35t geometry, vertices indicated with circles, red track: incident particle.

Highlights of PMA

More details in Dorota's talk.

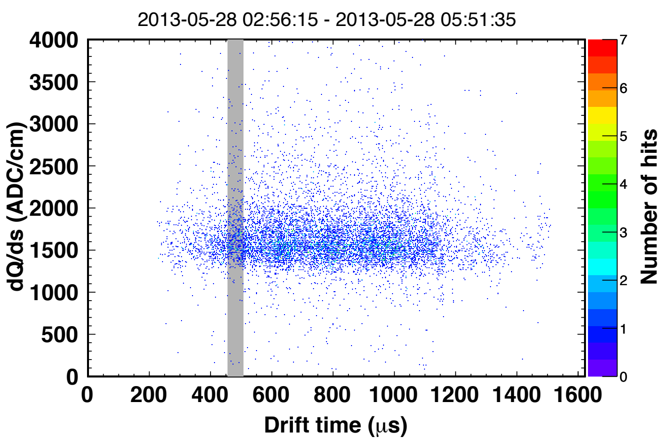
- Hit – hit association is not needed, each 2D hit has its own 3D position on the trajectory.
- Can use hit input from only two views - ArgoNeuT, LArIAT, dual-phase TPCs
- Improve reconstruction of wire-plane-parallel orientation by using clean endpoints (i.e. entry/exit points).
- Reconstruct vertices and optimize tracks using vertices.
- Correct t0 if track goes through APA.
- Has been optimized for multiple inputs: LineCluster and Pandora.

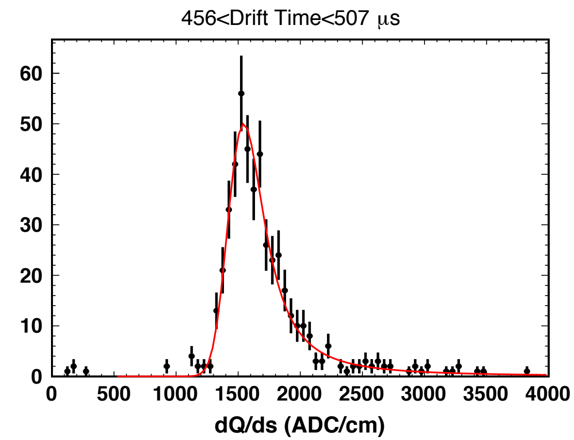
Track Calorimetry Reconstruction

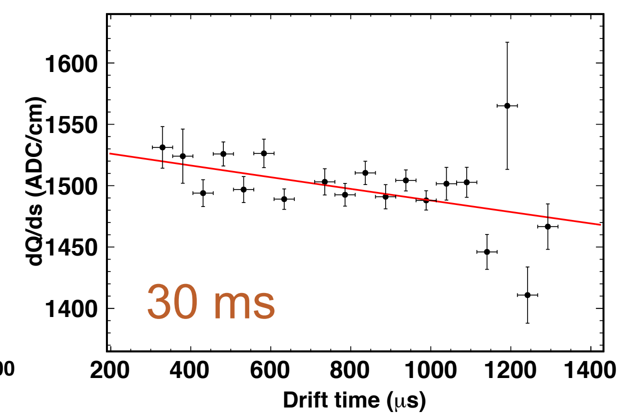


Reconstruction in Calibration

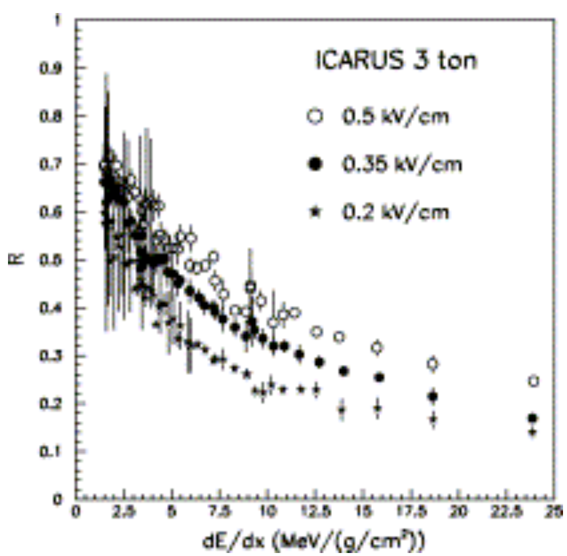
Purity measurement using cosmic muons, an example in LongBo: arXiv:1504.00398

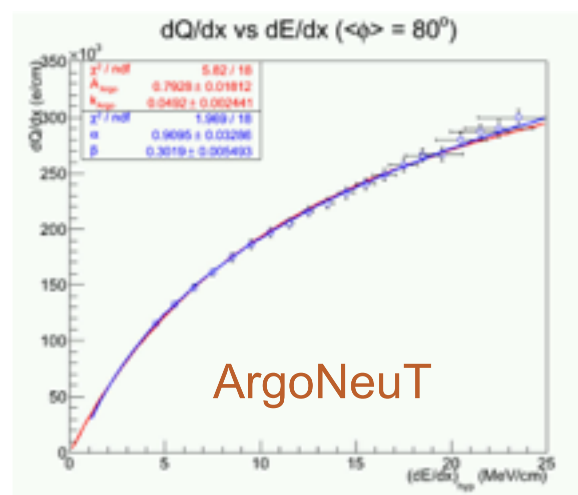






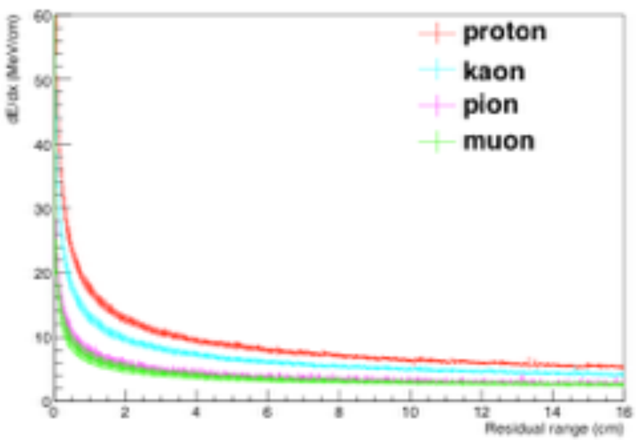
Recombination measurement using stopping muons or protons

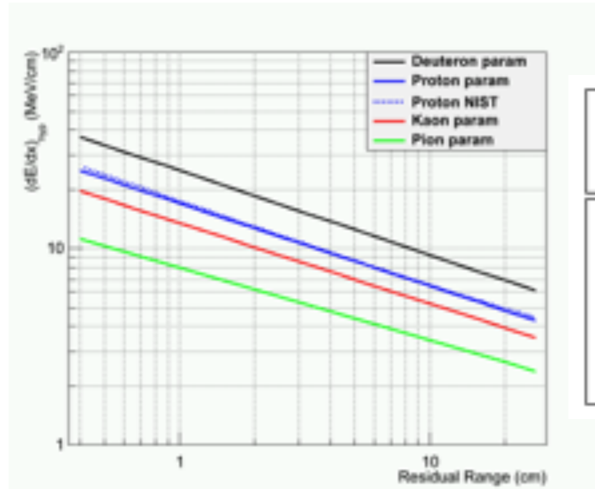




NIM A 523 (2004), 275 JINST 8 P08005 (2013)

Particle Identification



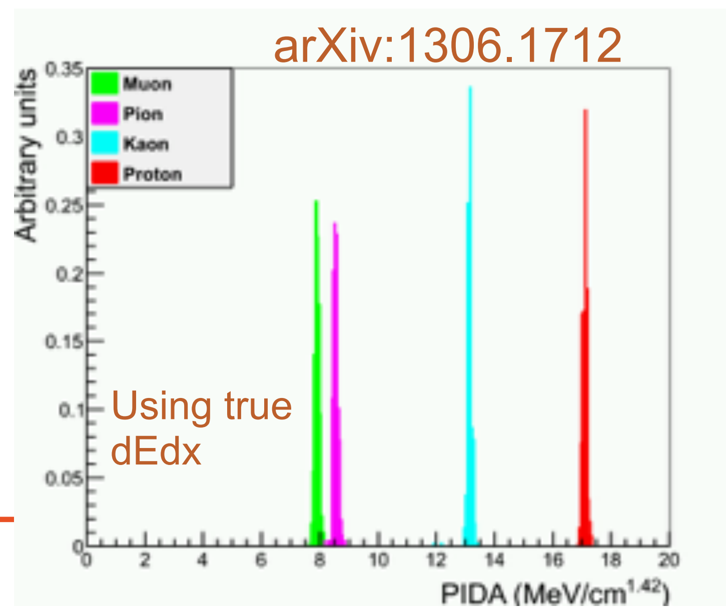


$dE/dx = A\,R^b$

Particle	A MeV/cm^{1-b}	b
pion	8	-0.37
kaon	14	-0.41
proton	17	-0.42
deuteron	25	-0.43

Note the weak dependence on b

- Calorimetry information provide powerful particle ID.
- <Ai> for each track
- $Ai = (dE/dx)_{calo}\, R^{0.42}$



Shower Reconstruction

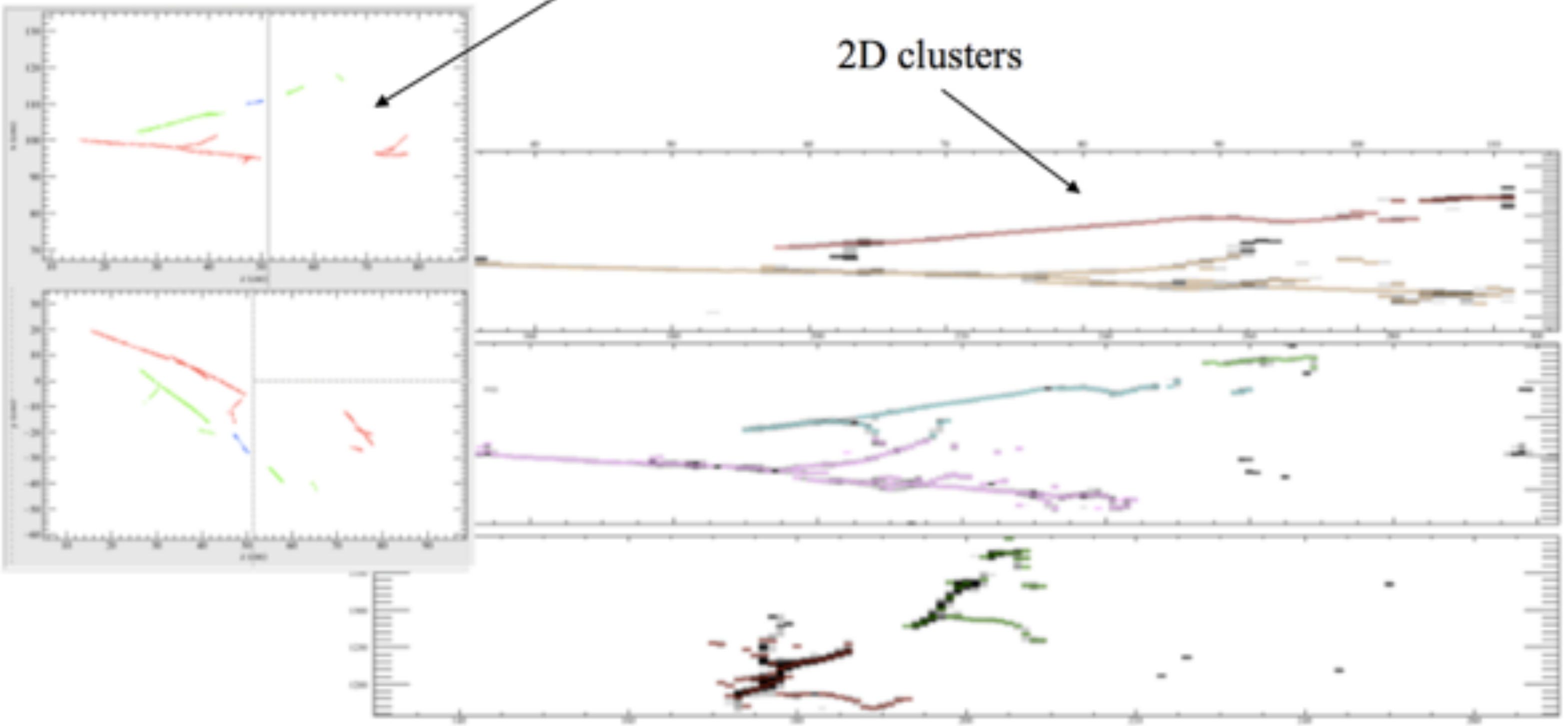
- There are a nice group of people working on the shower reconstruction in MicroBooNE and a lot of progress has been made. Hopefully the tools they are developing can be shared with DUNE and other experiments soon.
- Mike Wallbank is also actively working on the shower reconstruction for DUNE 35t and FD.
- Mike starts by reconstructing 2D clusters - BlurredCluster
  - Convolve the hit map with a Gaussian kernel to ‘blur’ the image: form more complete clusters.
- The next step is to form 3D shower objects using the BlurredCluster outputs - EMShower
  - Use track information to associate clusters between views.
  - Determine shower properties: start point, shower direction, dE/dx, energy.
  - Fit hits at the beginning of shower using PMA.

3D showers

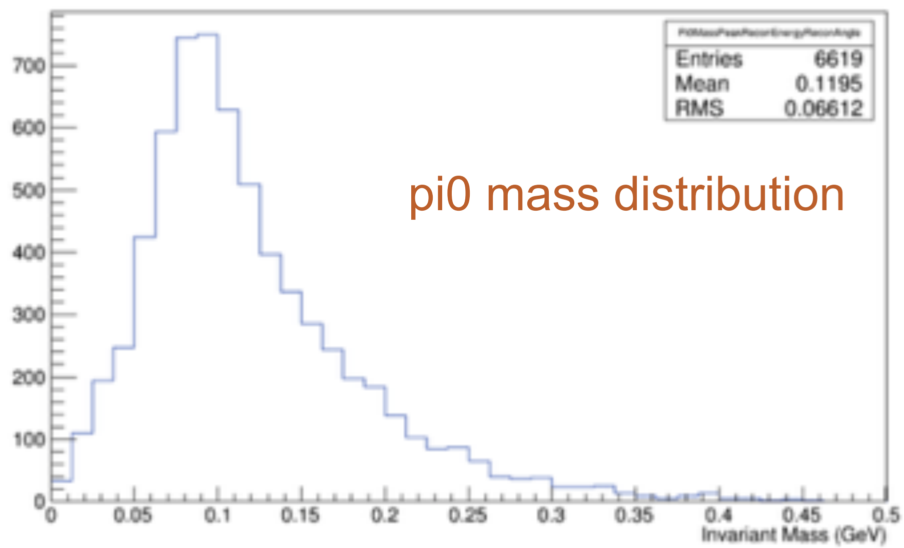
2D clusters

x-z plane

y-z plane

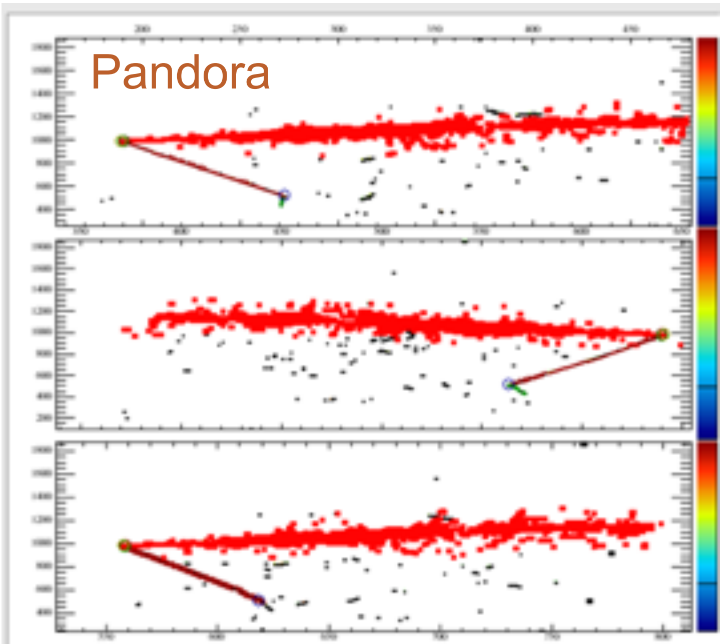


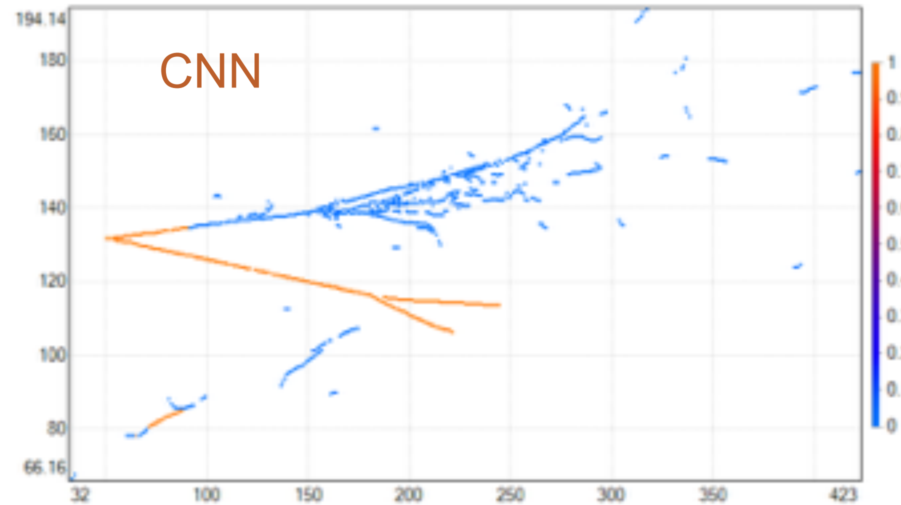
DUNE 35t π^0 particle gun event



pi0 mass distribution

Track/Shower Separation

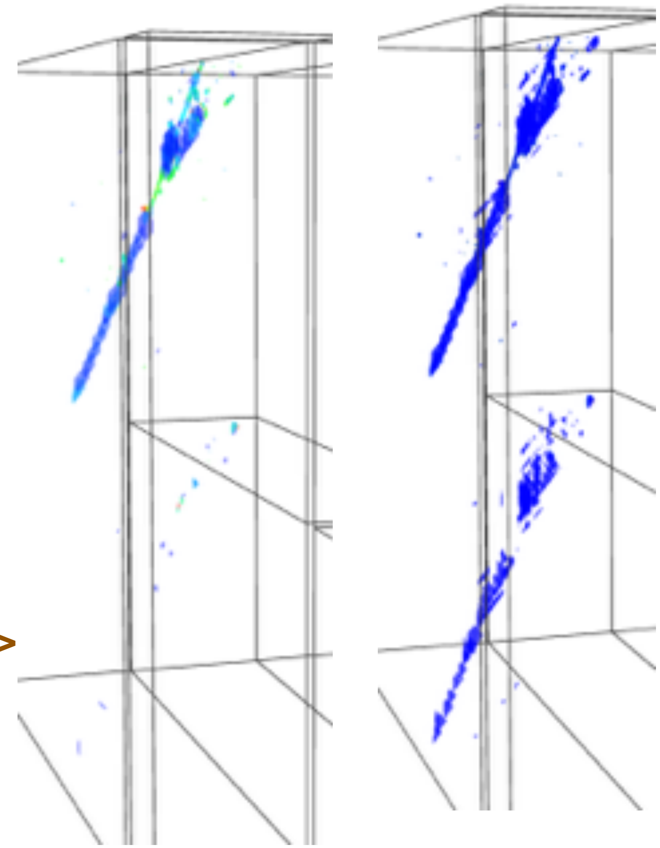




- One important task is to separate shower hits from track hits.
- Pandora outputs track-like and shower-like PFParticles.
- Another promising approach is to use CNN to separate track/shower hits. More details in Robert Sulej's talk.

Wire-Cell 3D Reconstruction

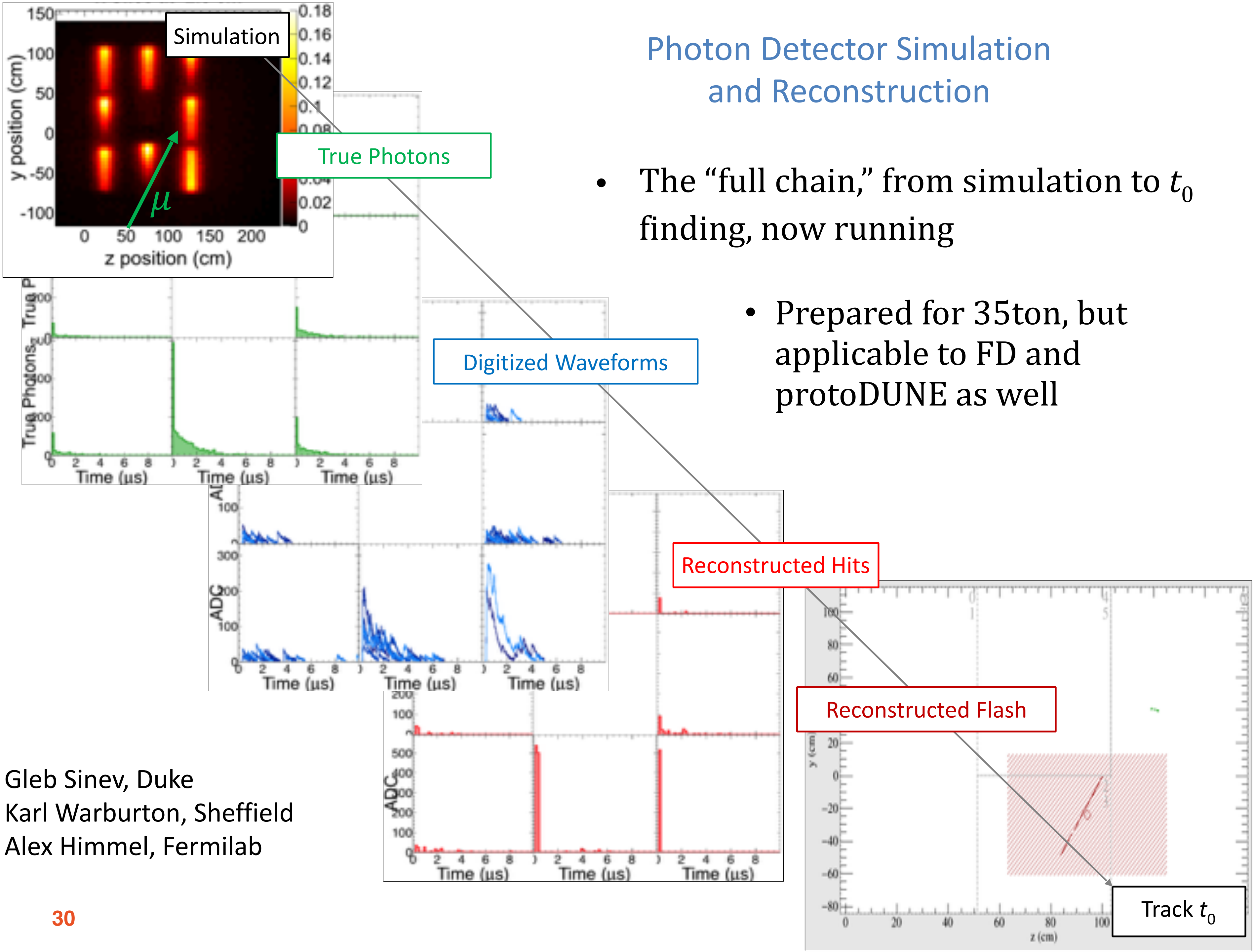
- Wire-Cell is based on the principle that the same amount of ionization electrons are observed by all the wire-planes.
- Wire-Cell Imaging:
  - 2D images at fixed time slice are reconstructed with charge information
- Wire-Cell Pattern Recognition:
  - 2D images are then stitched together -> 3D objects
- Wire-Cell works for wrapped wire geometry.
- More details in Xin's talk.



With Charge Without Charge

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

Photon Detector Simulation and Reconstruction



- The “full chain,” from simulation to t_0 finding, now running
  - Prepared for 35ton, but applicable to FD and protoDUNE as well

Gleb Sinev, Duke
Karl Warburton, Sheffield
Alex Himmel, Fermilab

Reconstruction in dual-phase TPC

- See Dorota's talk at the collection meeting:
  - https://indico.fnal.gov/getFile.py/access?contribId=57&sessionId=19&resId=0&materialId=slides&confId=10612

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reco: [ rns, caldata, fasthit, gaushit, cchit, linecluster, pmtrack ]
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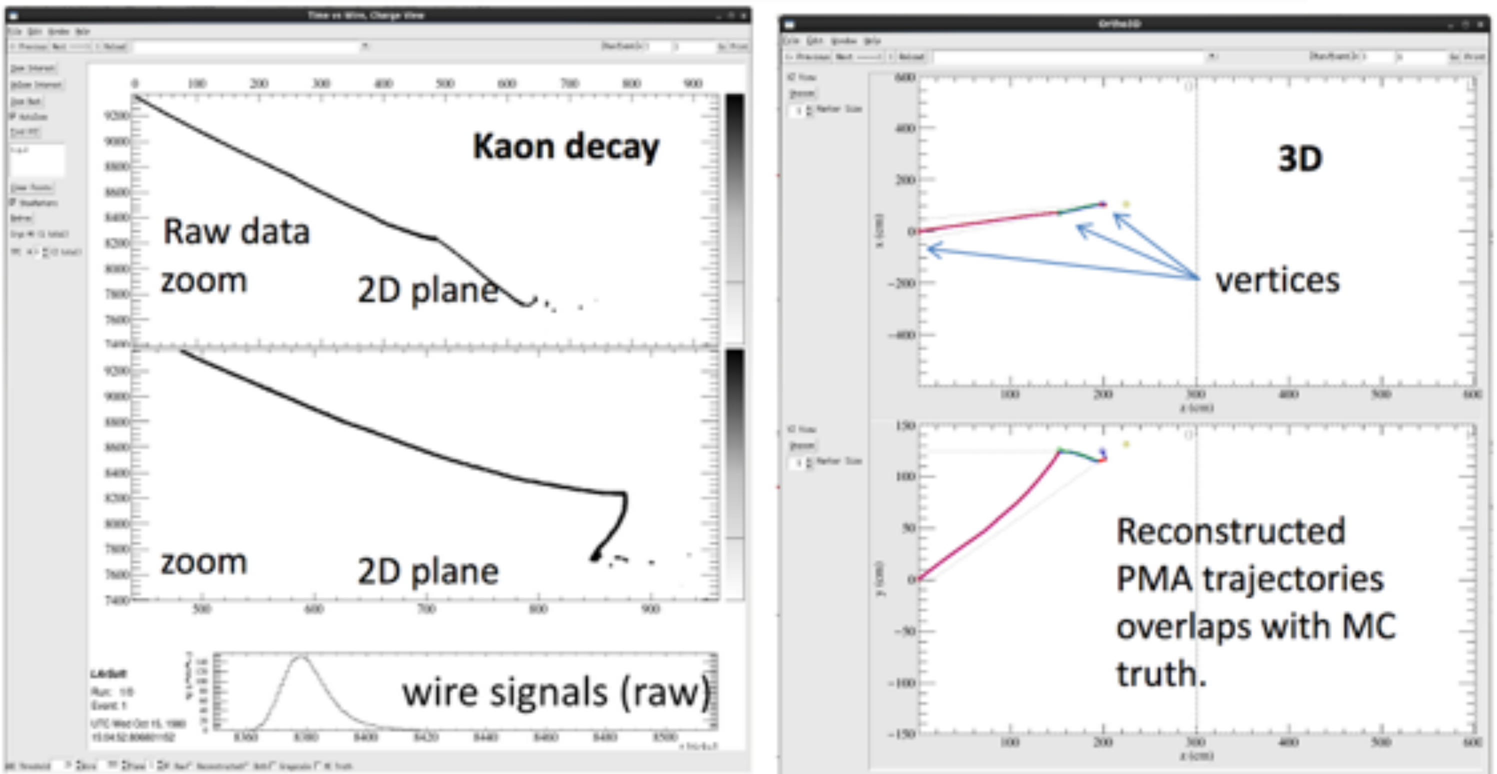
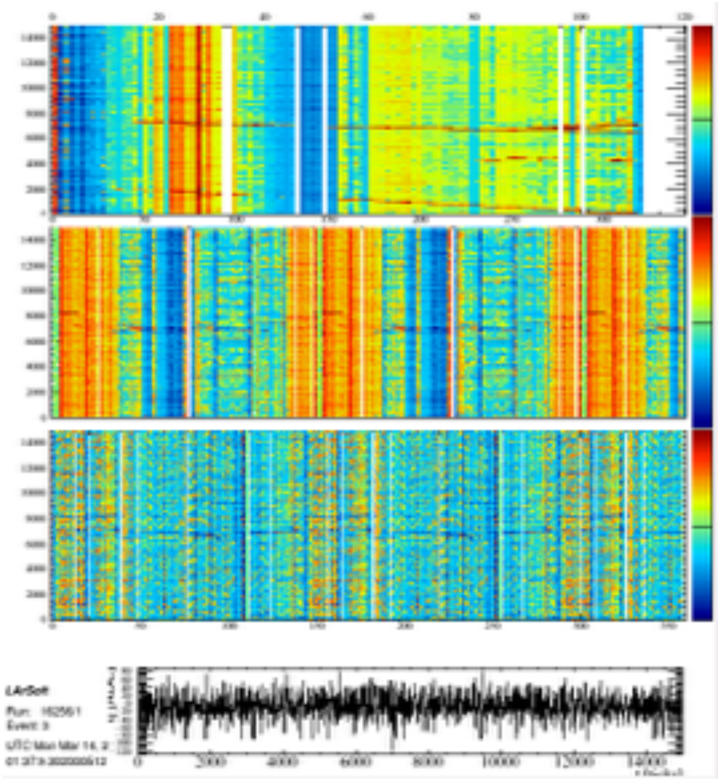


Test on Data

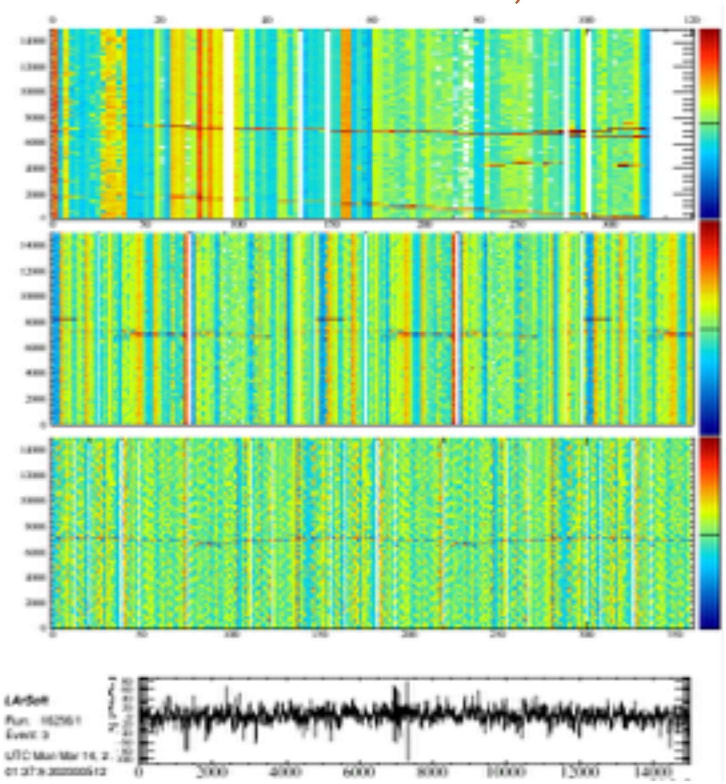
- LArIAT
  - Excellent signal to noise ratio, pattern recognition works beautifully.
  - GausHitFinder+LineCluster+PMA+Calorimetry is the primary reconstruction chain, used for the inclusive pion cross section measurement and other analyses, see Jen's talk yesterday.
  - Pandora is being adapted.
- MicroBooNE
  - Good signal to noise ratio after noise filter. Lots of pattern recognition algorithms tested and work well.
  - Inclusive CC cross section measurement:
    - Selection I: PandoraNu for track and vertex reconstruction.
    - Selection II: Pandora+PMA for track reconstruction, LineCluster+PMA for vertex reconstruction, Calorimetry.
  - Pi0 reconstruction
    - Several algorithms, one is Pandora based.
- 35t
  - Challenging due to high noise level.

Noise filter on 35t data

Run 16256, Event 3



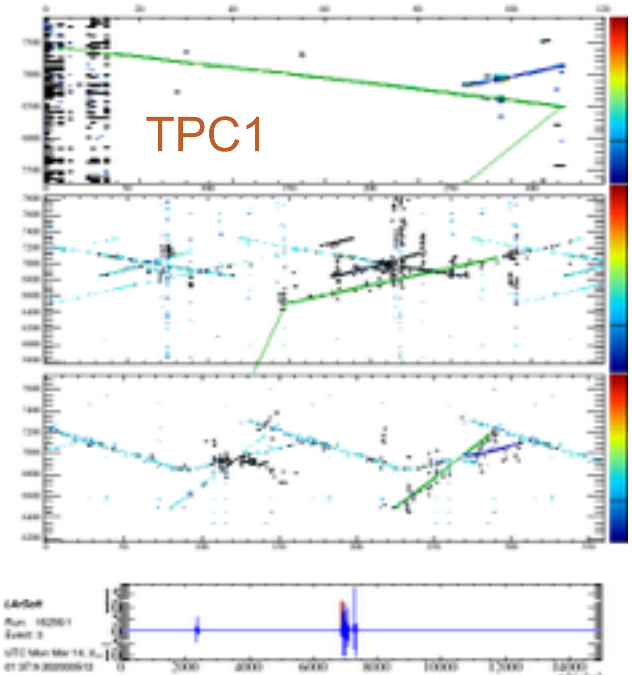
Raw Data

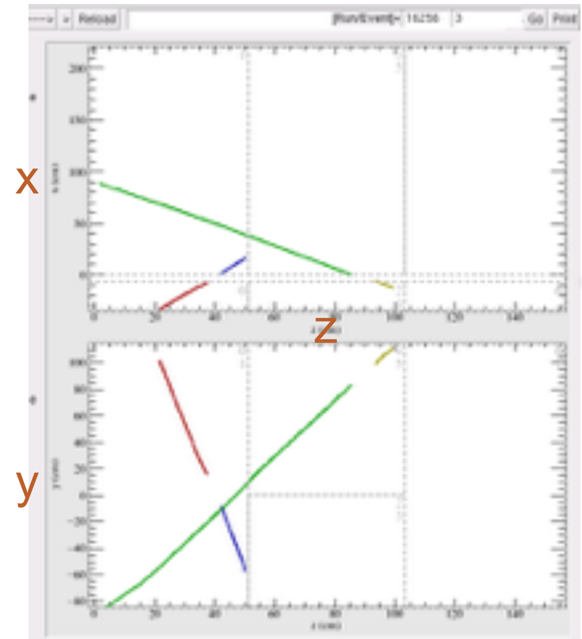


After noise filter

- Many people contributed to noise filter
  - Stuck code mitigation, coherent noise removal, Wiener filter optimization, low-frequency noise removal

Reconstructed 3D tracks in 35t





Disambiguation+GausHitFinder+LineCluster+PMA

- Disambiguation works on data!
- Bruce Baller tuned LineCluster for MicroBooNE data. The same tuning works well on 35t data.
- PMA is able to reconstruction tracks across TPC boundaries and correct for t0 for tracks across APA, more details here (slide 3).
- Even though we can reconstruct some tracks, we cannot do reliable calorimetry because of high noise level.

Conclusions

- A lot of progress on LArTPC reconstruction over the past few years.
- Many algorithms are being developed and tested on real data.
- The common software framework LArSoft boosts development work.