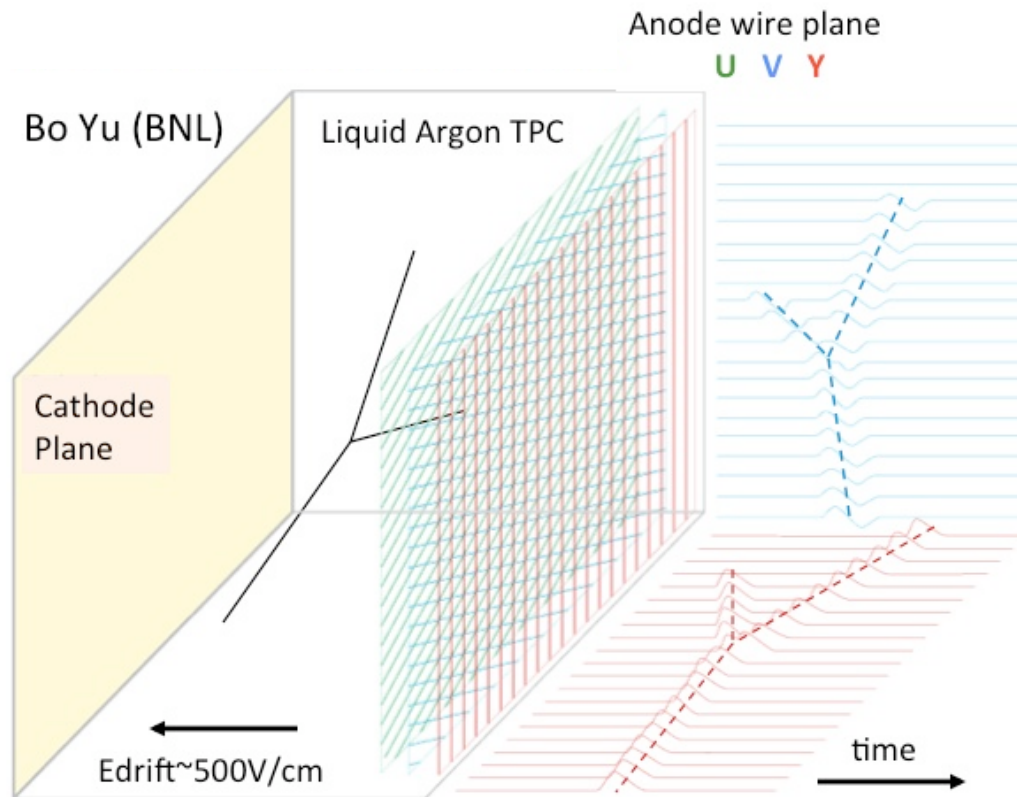


Automated Reconstruction, Signal Processing and Particle Identification in DUNE

Tingjun Yang for the DUNE Collaboration
FNAL

August 5, 2016

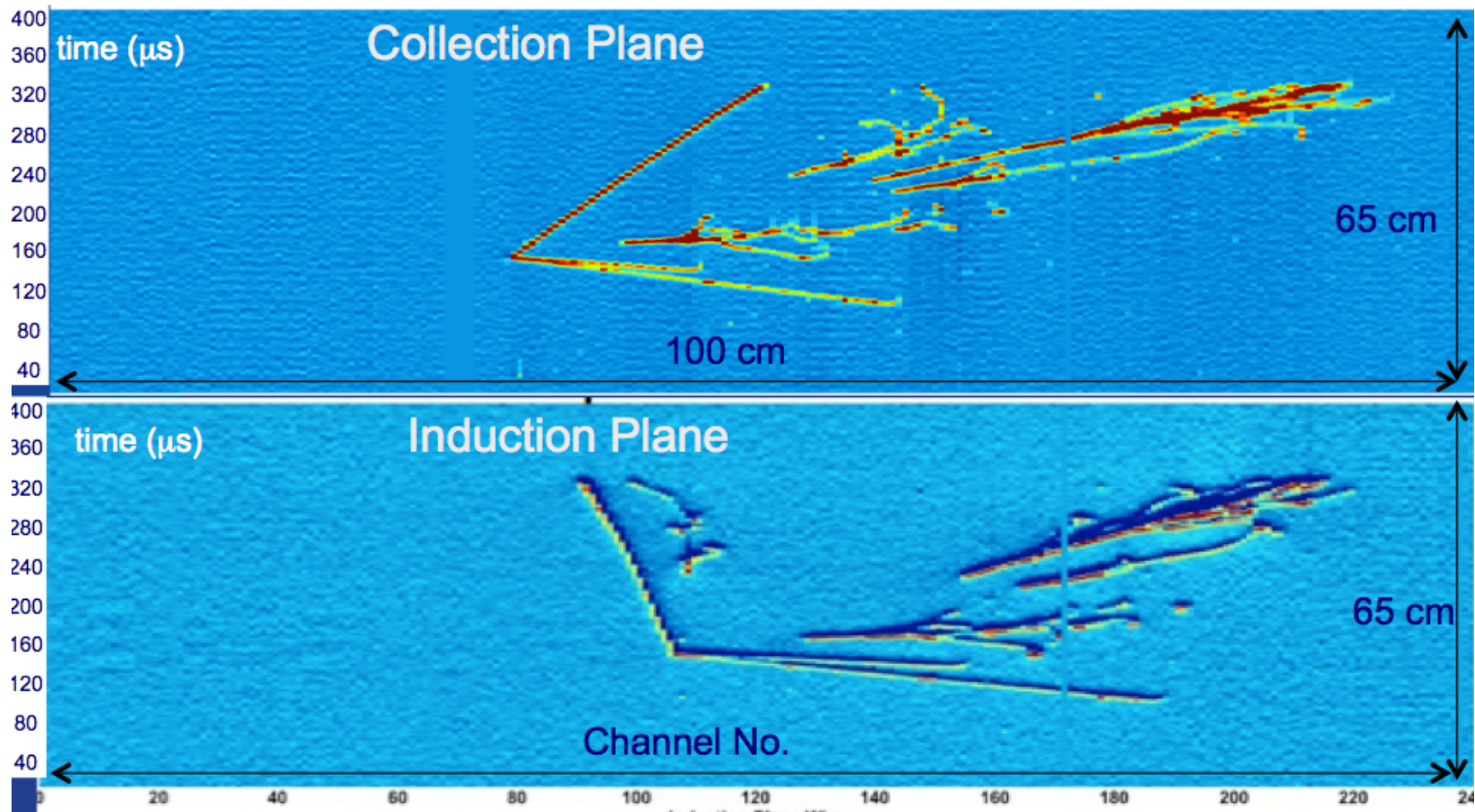
Liquid Argon Time Projection Chamber



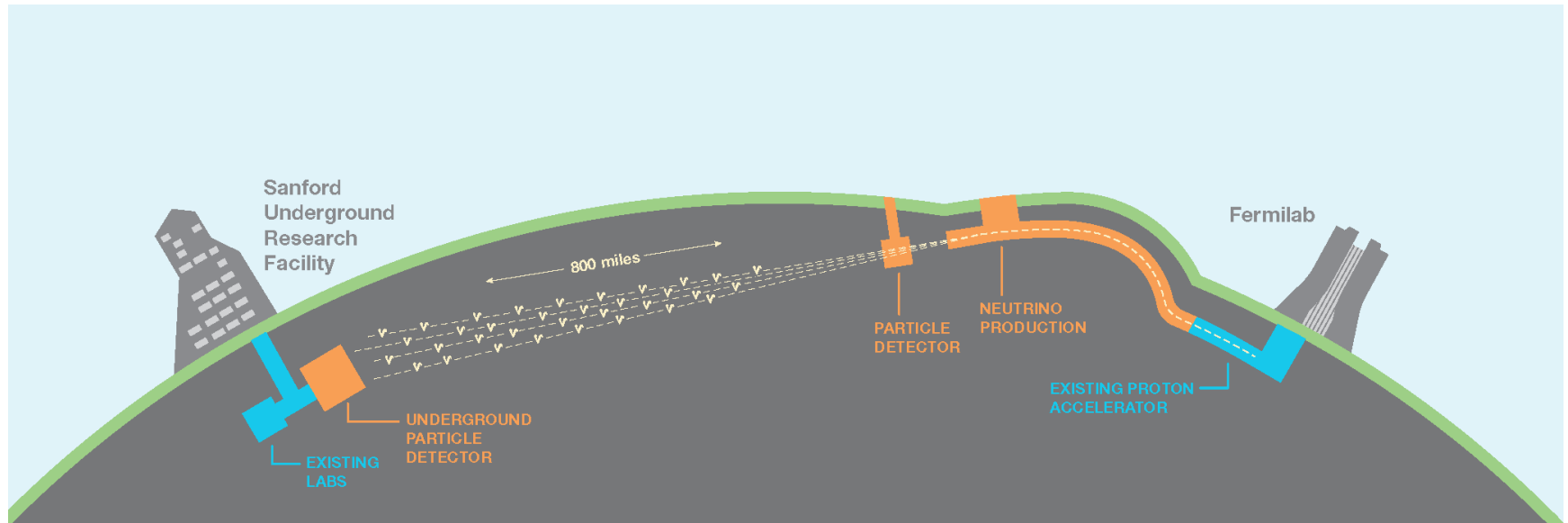
- HV on cathode to provide electric field to drift ionization electrons.
- Three wire planes to record electron signals. Wire spacing 3-5 mm.
- Photon detectors to record scintillation light.

High Resolution Image

A real neutrino event in ArgoNeuT TPC: 3 track, 4 photons.



Deep Underground Neutrino Experiment (DUNE)



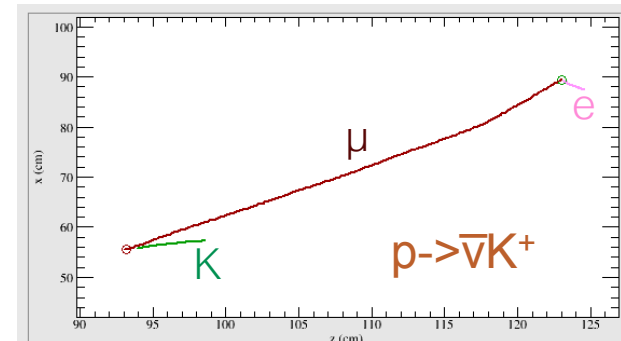
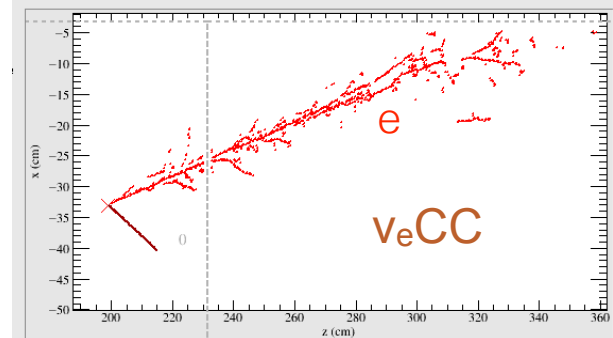
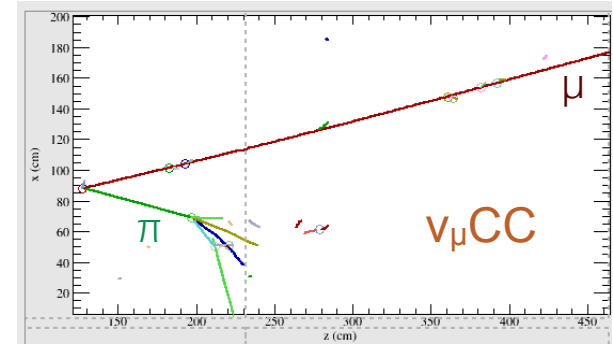
- The DUNE experiment is designed to achieve discoveries that could transform our understanding of the origins and evolution of the universe by studying neutrino oscillations and other phenomena.
- Two detectors 1300 km away, far detector (FD) uses LArTPC.

Event Reconstruction in DUNE

- 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 neutrino 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 in DUNE.
- Most algorithms are available in the common software framework LArSoft. <http://larsoft.org/>

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.



Two Reconstruction Approaches

Raw Signal Processing

2D Matching

(LineCluster, Pandora, PMA)

3D Tomography

(WireCell)

2D Pattern Recognition

3D Image Reconstruction

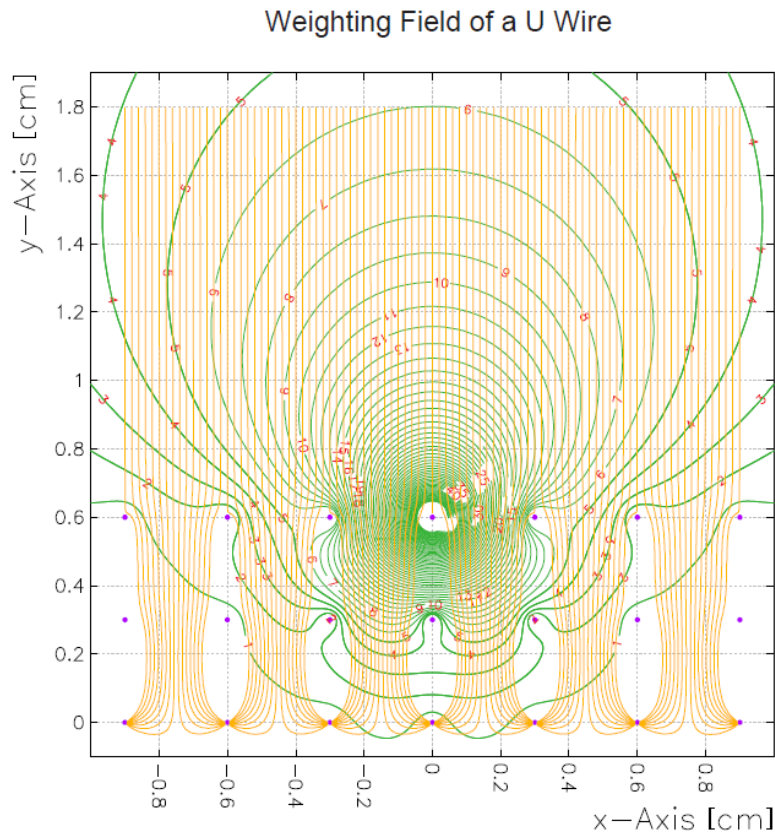
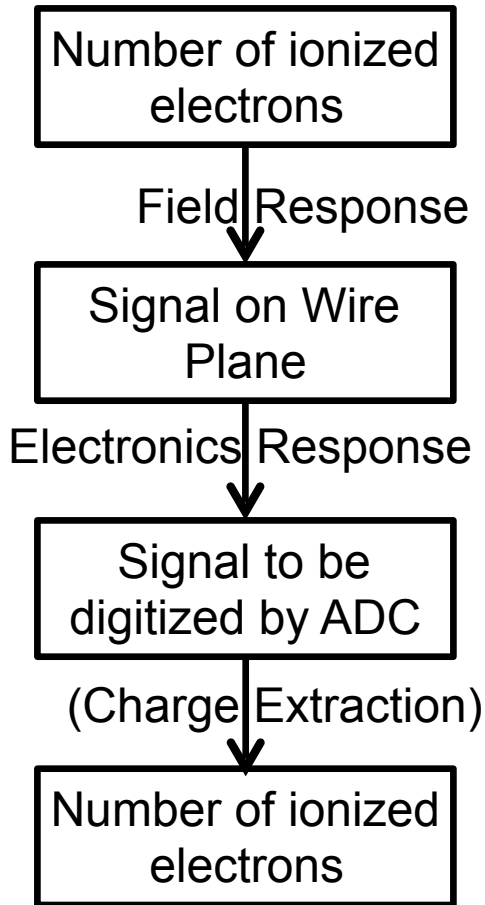
2D Matching and 3D reconstruction

3D Pattern Recognition

Tracks, Showers, Vertices, Energy, PID

Each approach uses the same information in different order!

TPC Signal Formation



Garfield simulation of weighting field

Shockley–Ramo theorem

$$i = -q \cdot \vec{E}_w \cdot \vec{v}_q$$

v_q : velocity

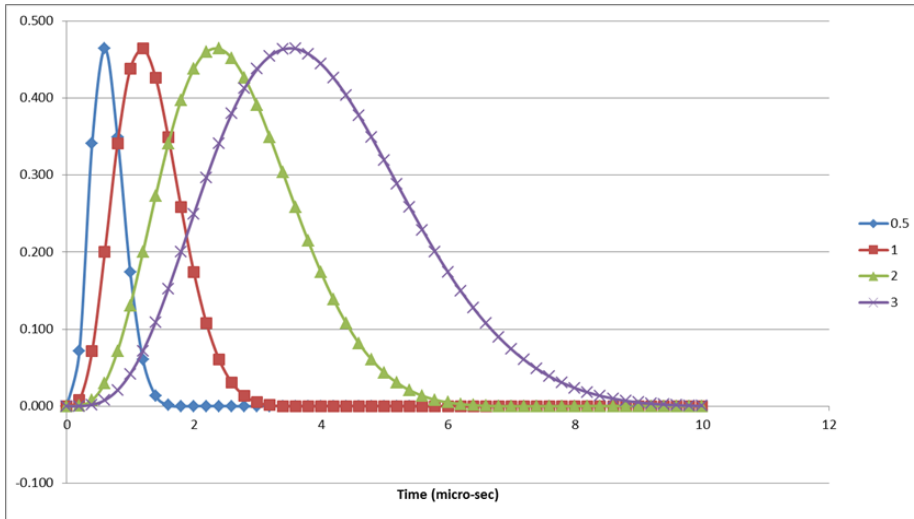
E_w : weighting field

q : charge

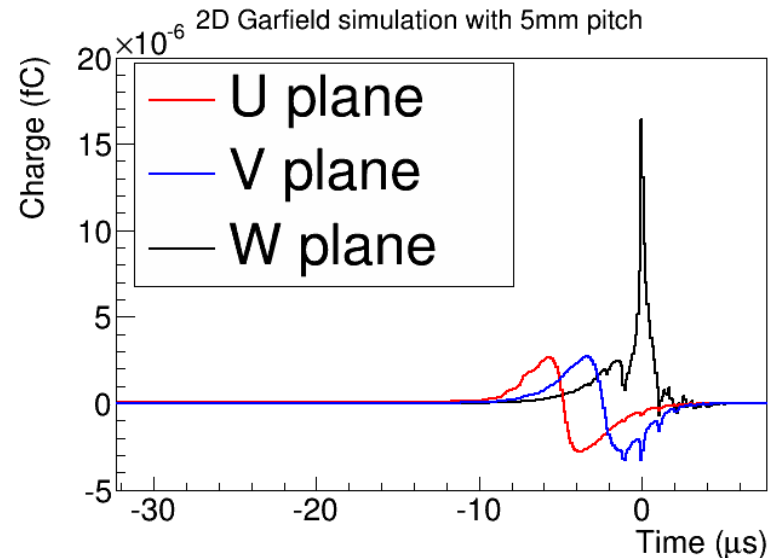
- Need to remove effects of field response and electronics response from raw signal.
- More details: <http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1017-PUB.pdf>

Signal Processing

The foundation of all further reconstruction.

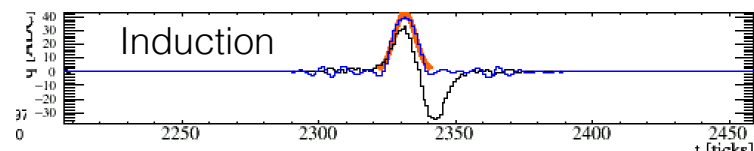
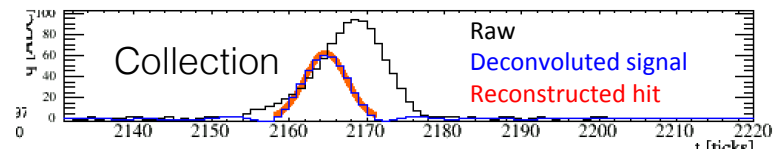


BNL SPICE ASIC simulation



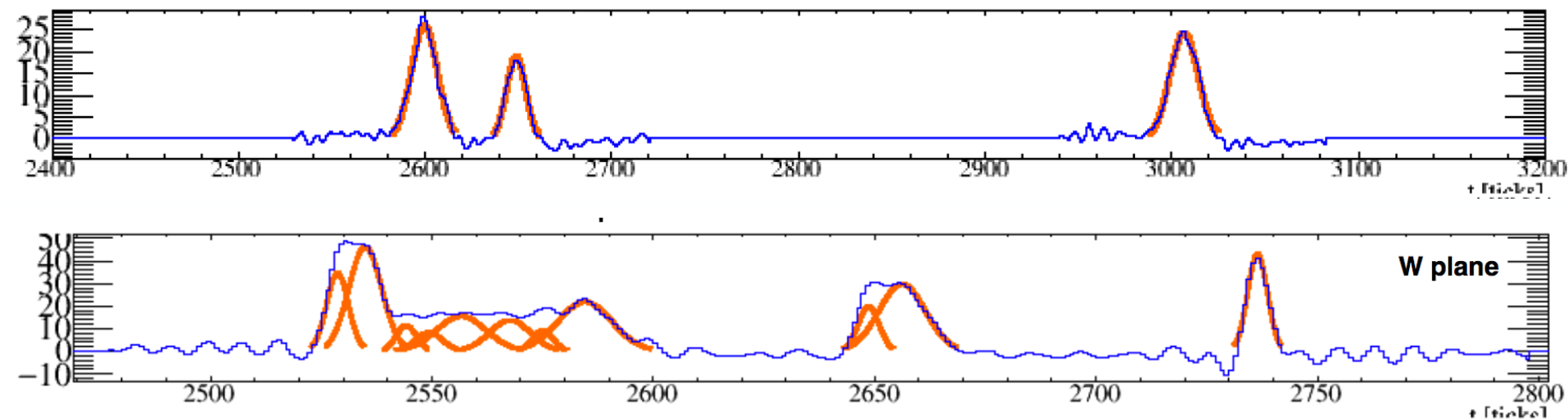
Garfield simulation of field responses

- Filter noise and remove effects of field response and electronics response through deconvolution.
- It is important to take into account induced signals from faraway electrons to recover ionization charge.



Hit Finder

- Default hit finder in LArSoft is GausHitFinder.
- 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.

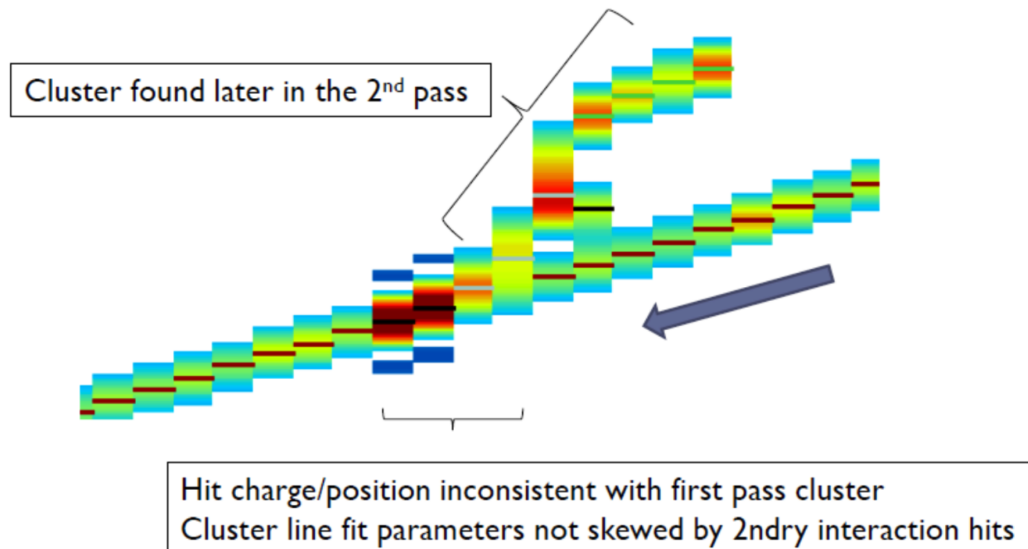


Track and Shower Reconstruction

- 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.
- Several cluster reconstruction algorithms:
 - **LineCluster**: optimized for tracks.
 - **BlurredCluster**: optimized for showers.
 - **Pandora**: reconstruct both track-like and shower-like clusters.
- Track Reconstruction algorithms:
 - **PMA** and **Pandora**
- Shower Reconstruction
 - **EMShower**

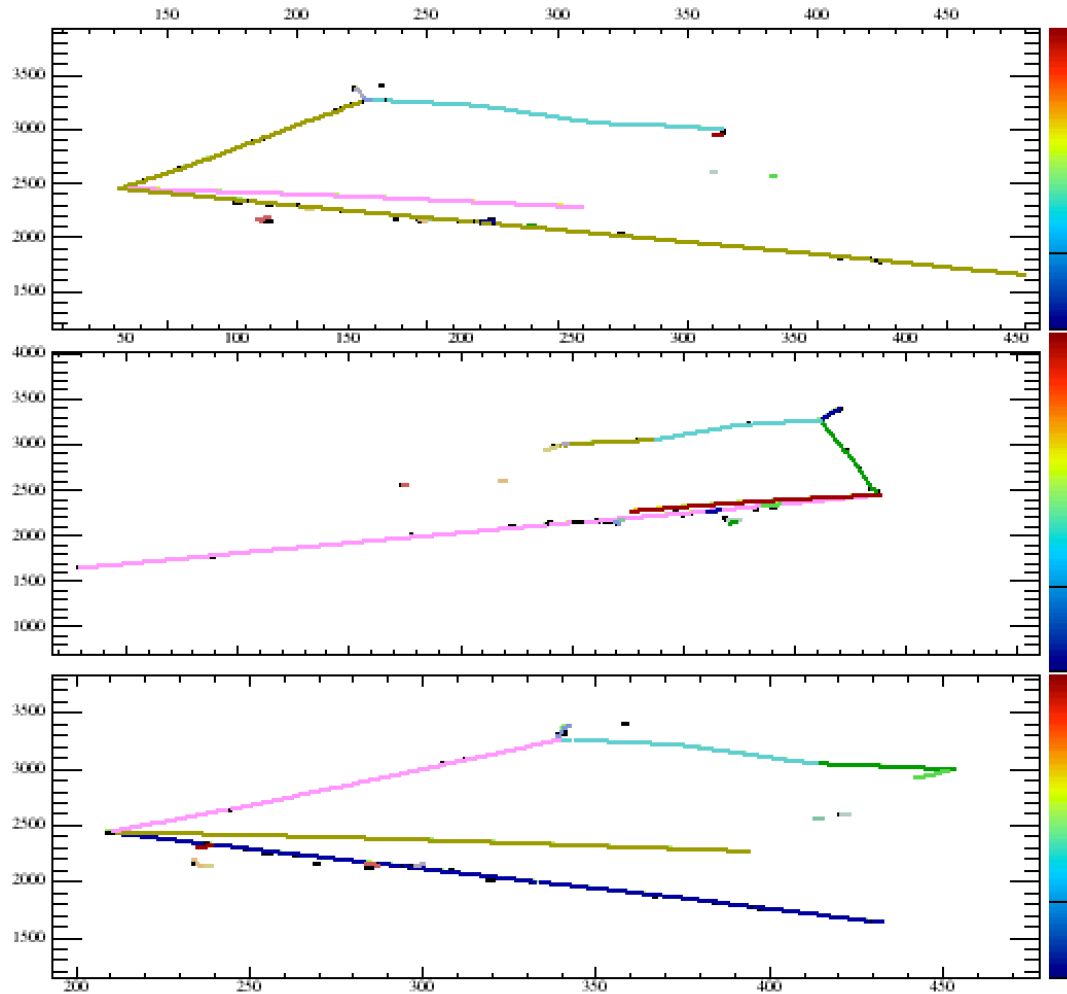
LineCluster

- Proximate hits in a cluster or track should have similar characteristics, e.g.
 - Hit charge = integral of the hit signal (not the pulse height)
- Use cluster tracking information from low hit density regions (down stream of primary vertex) to extrapolate into high density regions (at the primary vertex) or through high hit density regions (δ -rays and showers)



One example

2.4 GeV muon neutrino in DUNE TPC

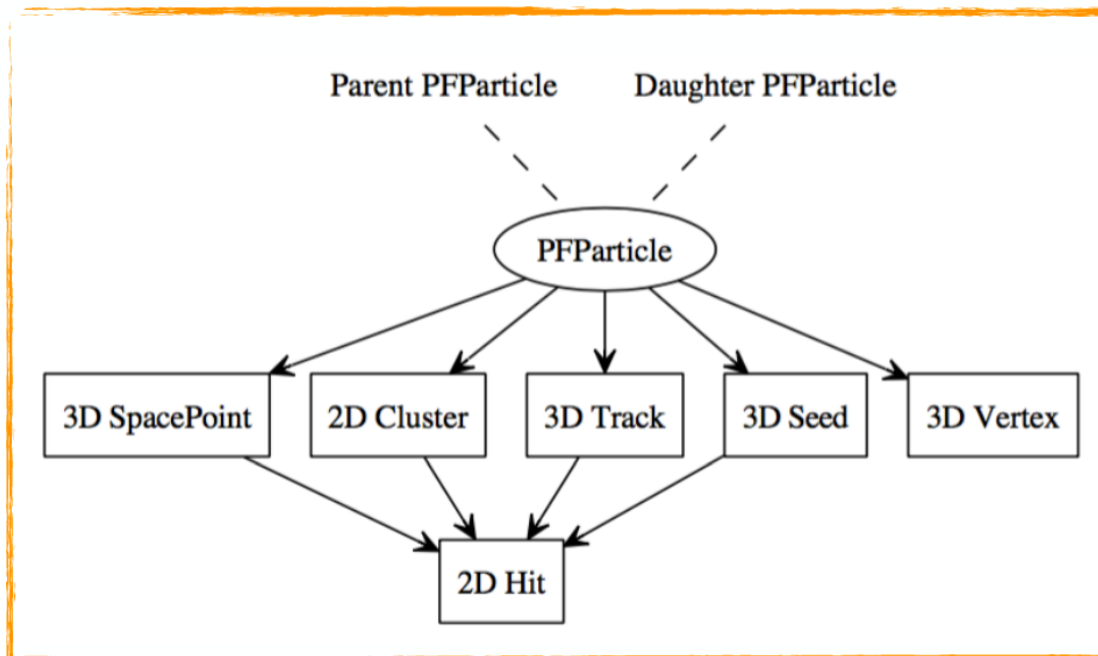


Different colors represents different clusters.

Pandora

<https://github.com/PandoraPFA>

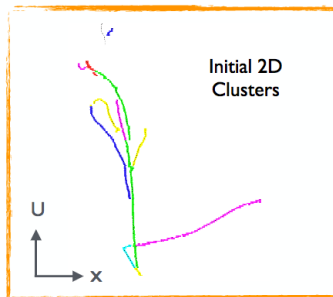
- Pandora is a well-established tool for fine-grain pattern recognition in high energy physics (future linear collider, LHC, LArTPCs)
- Supports multi-algorithm approach to automated and optimized pattern recognition.
- Takes hits as input. Outputs PFParticles with hierarchies
 - Reconstruct both track-like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



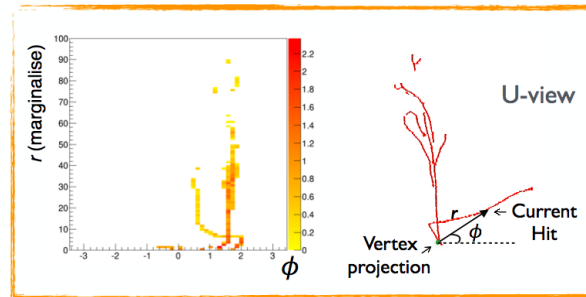
Two Chains of Algorithms

- PandoraCosmic (35t):
 - more 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.

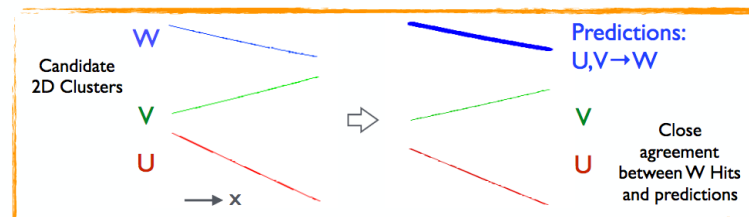
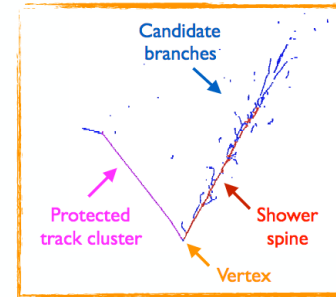
2D reconstruction



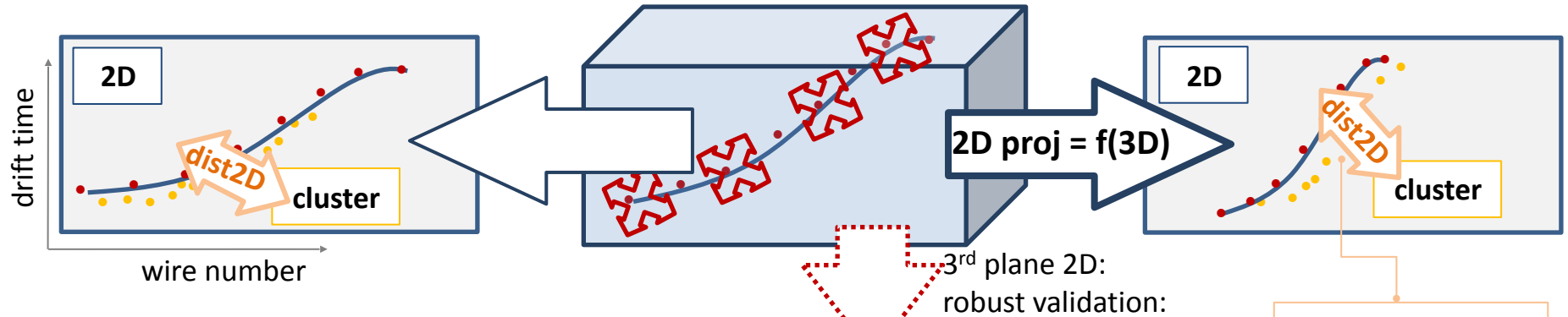
Vertex reconstruction



Shower reconstruction



Projection Matching Algorithm (PMA)

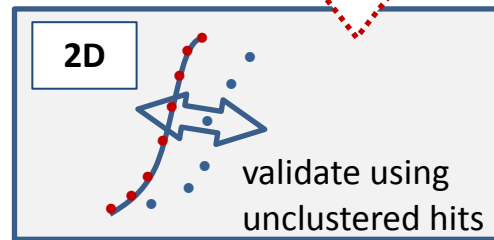


Cluster association is verified using projection to the 3rd view:

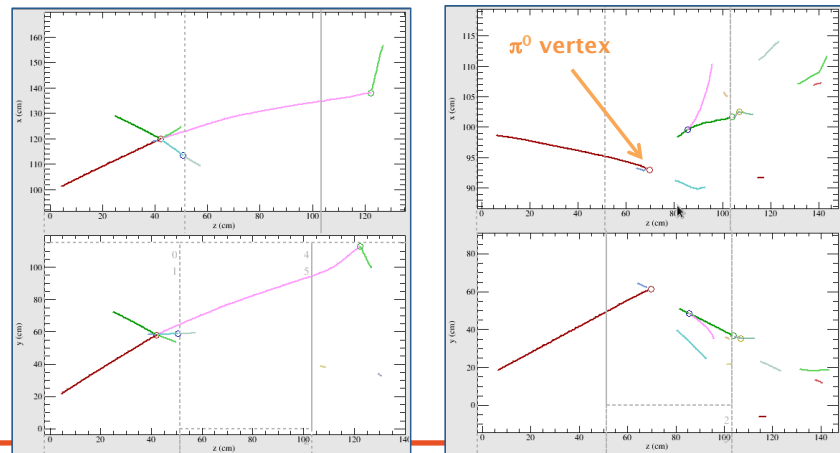
Dorota Stefan, Robert Sulej

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

dist2D() measures:
MSE(hit, object),
but also other fn's...

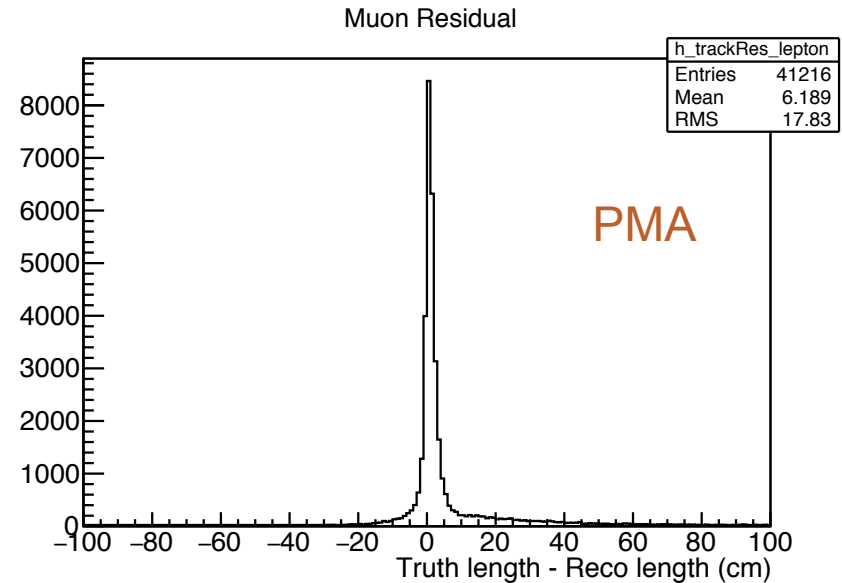
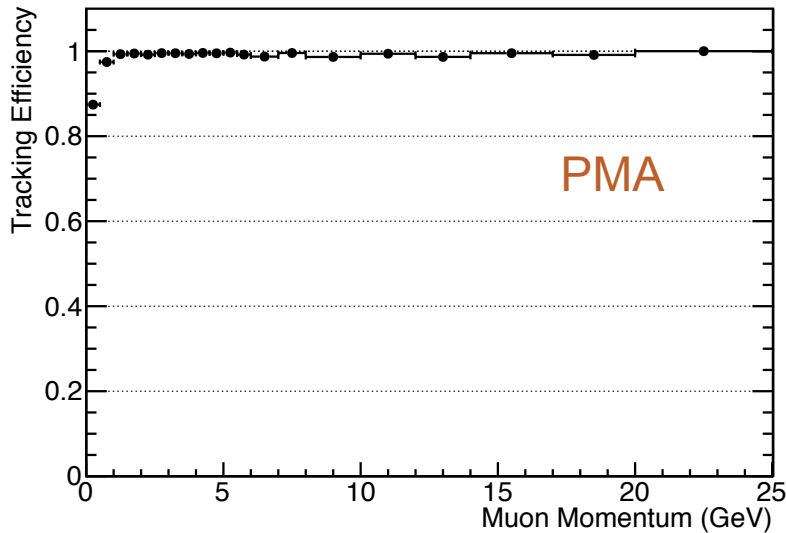


- Instead of building 3D object by matching 2D hits between different views, build 3D object by minimizing distance the object's 2D projection to 2D hits.
- Fit vertex and reoptimize tracks.



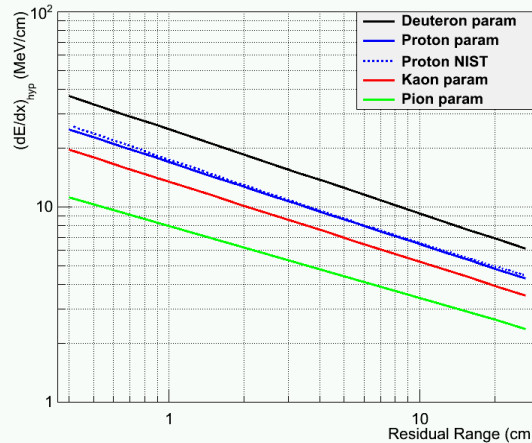
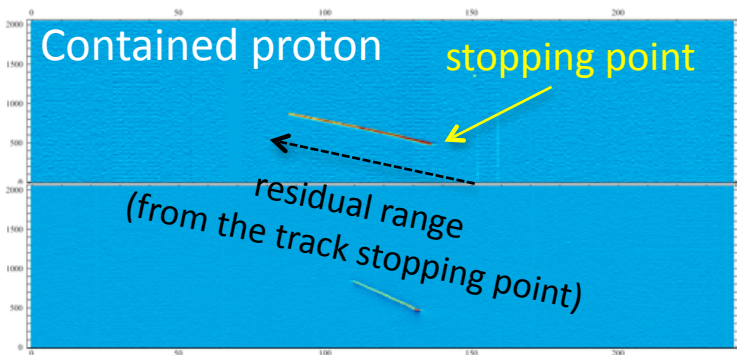
Reconstructed event examples: π^- @ 2GeV/c, 35t geometry, vertices indicated with circles, red track: incident particle.

Tracking Efficiency



- The efficiency to reconstruct muons in the neutrino beam is very high.
- The reconstructed track length matches true length very well.

Particle Identification



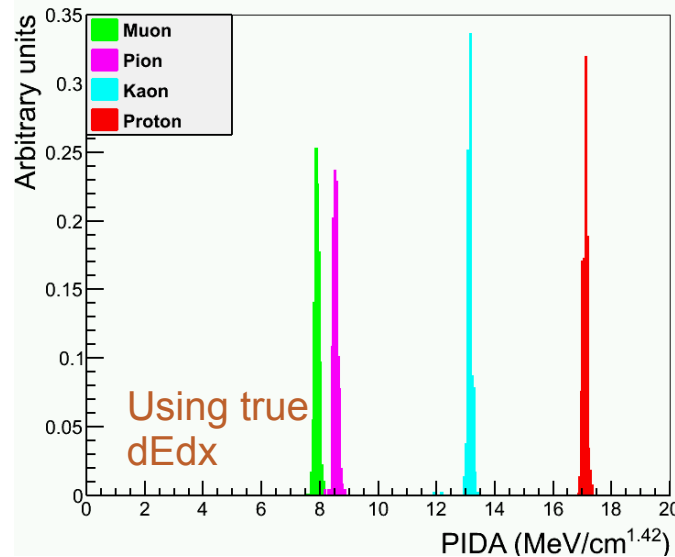
$$dE/dx = A R^b$$

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



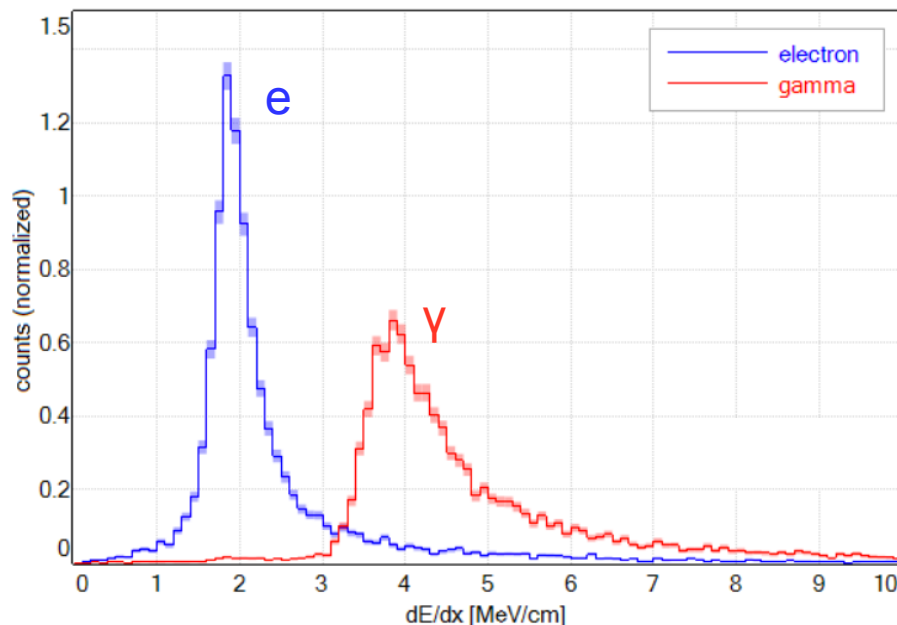
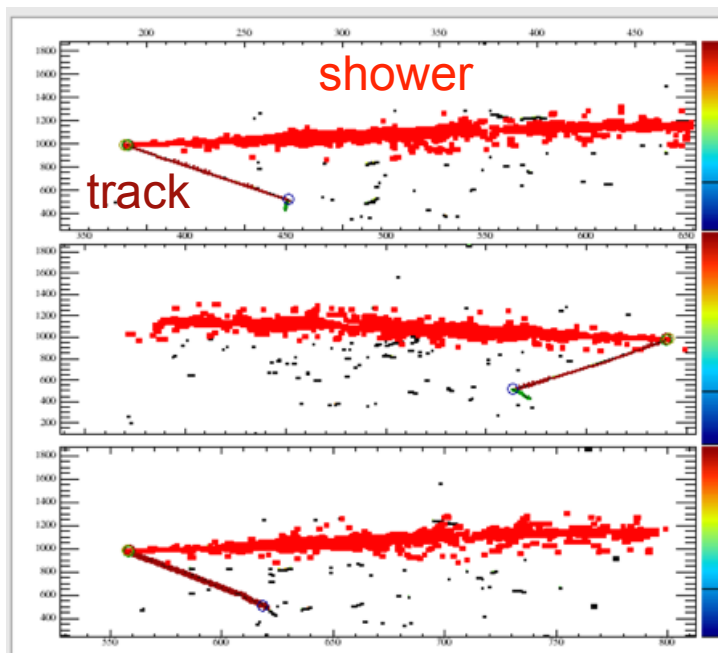
Note the weak dependence on b

- Calorimetry information provide powerful particle ID.
- $\langle A_i \rangle$ for each track
- $A_i = (dE/dx)_{calo} R^{0.42}$



arXiv:1306.1712

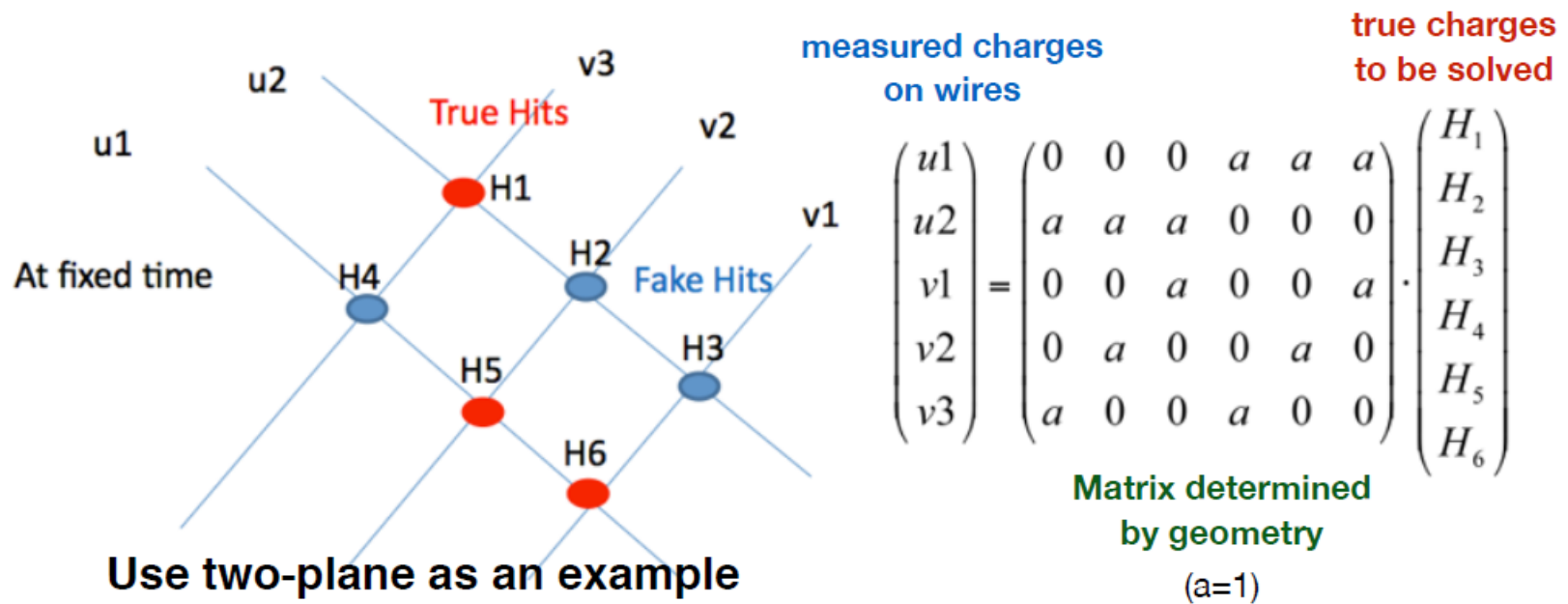
Shower Reconstruction



- Blurred cluster: uses a Gaussian blurring on an image of the hit map to form more complete clusters. <http://larsoft.org/single-record/?pdb=110>
- Match clusters in different views to construct 3D shower object. <http://larsoft.org/single-record/?pdb=113>
- Average dE/dx of the first 1 cm of shower provides information for e/gamma separation.

Wire-Cell Reconstruction

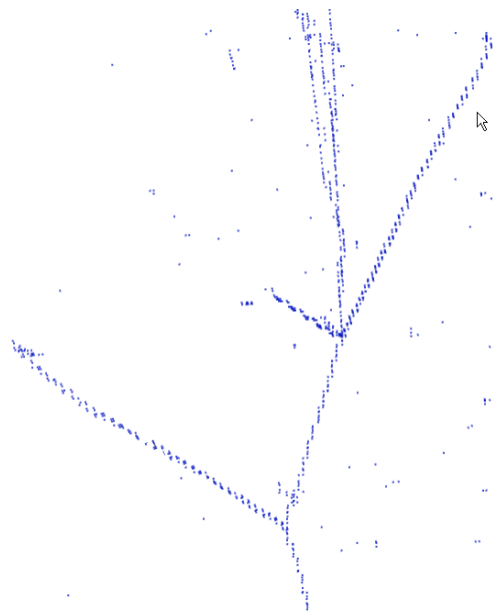
- 3D Tomographic reconstruction
- Reduce degeneracy by using the charge information: same charge in a voxel is measured 3 times by wires on the three wire planes



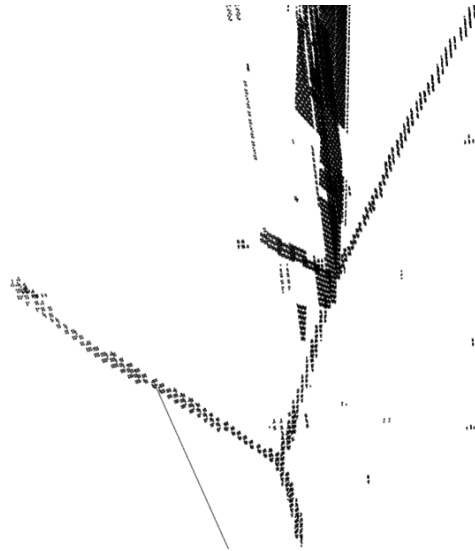
Reconstruction Procedures

- ❑ Obtain 3D space points (with charge) with close to 100% efficiency by solving charge-equations in the 2D tomographic plane
- ❑ Do clustering and tracking in 3D directly

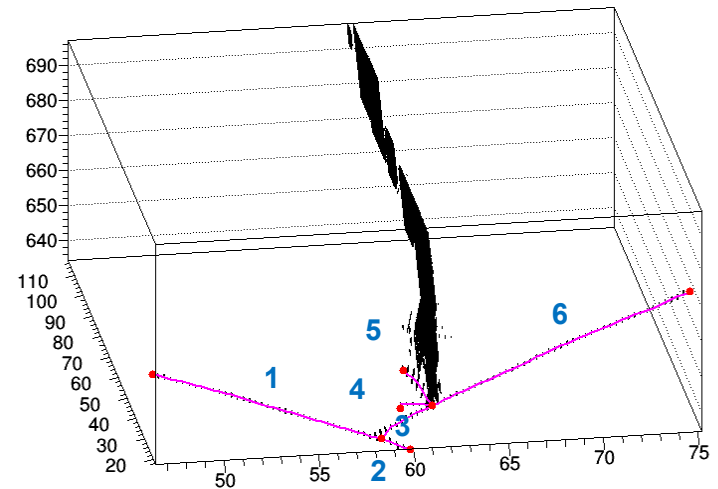
Truth



**Wire-Cell
reconstructed
space points**



3D track finding



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

Conclusions

- After many years of dedicated efforts, the event reconstruction in liquid argon TPC has reached an advanced level.
- There is a fully automatic reconstruction chain in DUNE to do signal processing, pattern recognition, track and shower reconstruction and particle identification.
- The common framework LArSoft has boosted the reconstruction development.