Liquid Argon Detectors

NuSTEC Lecture, part 2

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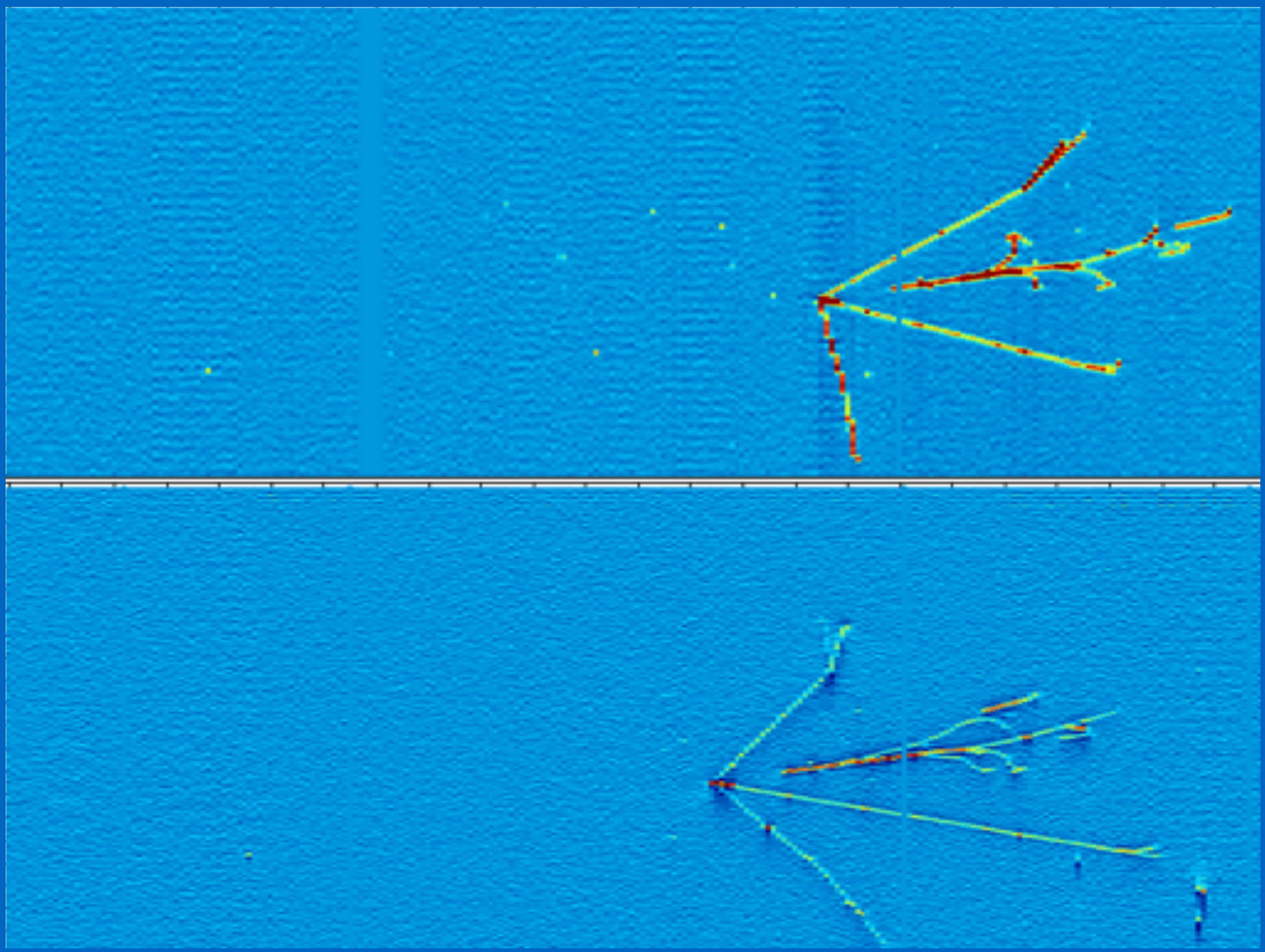
What I'm going to talk about

Last talk:
the technology of liquid argon neutrino detectors



This talk:
the physics capabilities and some of the challenges

Goals For This Lecture

- Show selected examples of physics potential of Liquid Argon Time Projection Chambers (LArTPCs)

- Get everyone thinking about some of the issues associated with analyzing data from a LArTPC.

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- Get everyone thinking about some of the issues associated with analyzing data from a LArTPC.

Please ask questions at anytime!

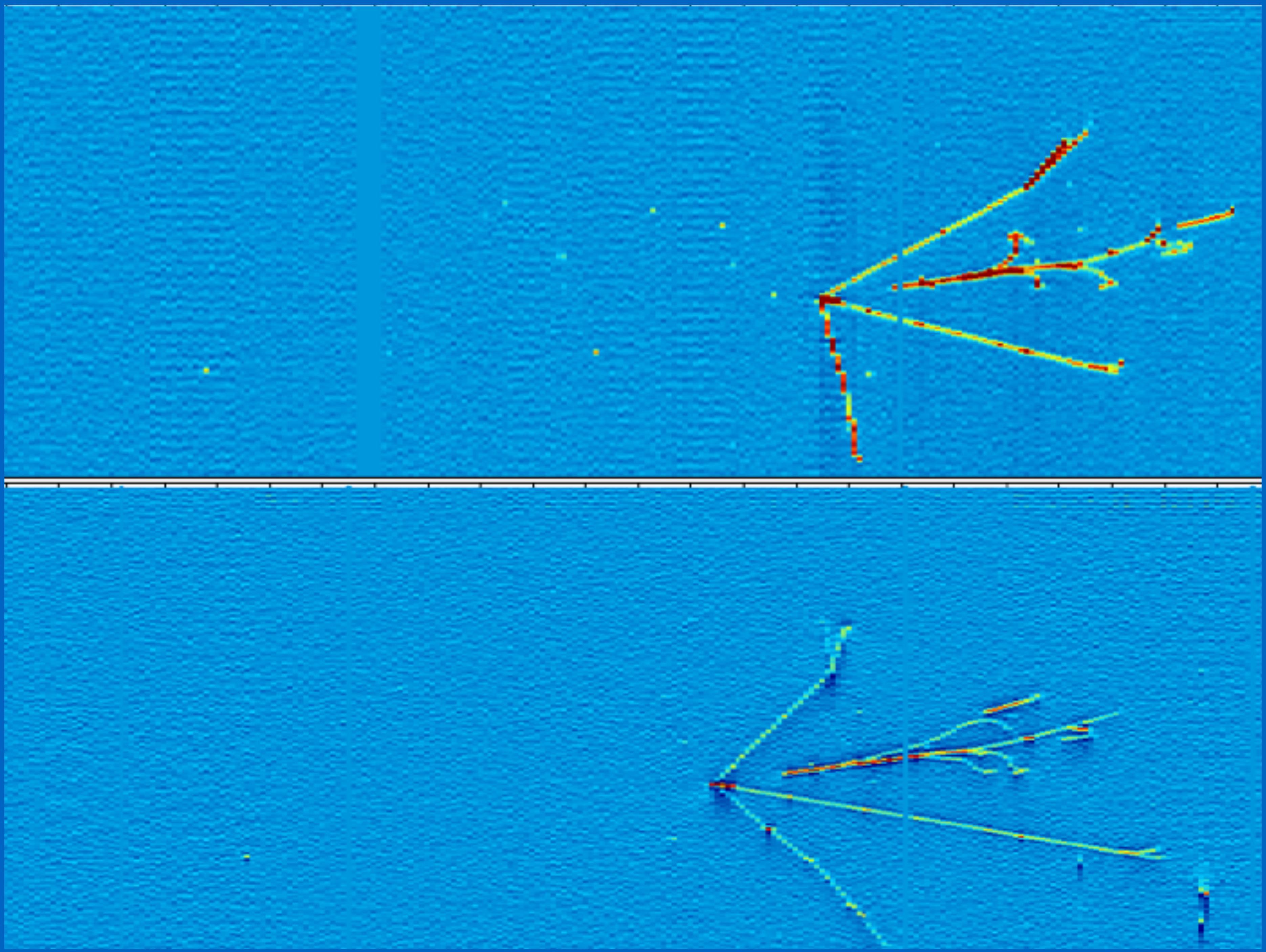
Extracting Physics

- The LArTPC is an imaging device that provides fine-grained detail about interactions. Our analysis of this information should aspire to take maximal advantage of this.

- Argon is a nuclear target, so this presents challenges, and opportunities, when defining physics measurements to be conducted.

- Several people here have asked me to talk about reconstruction issues, so I will spend time on that.

The Challenge



Translate recorded events into detailed information about the interaction. Capture all we can see by eye.

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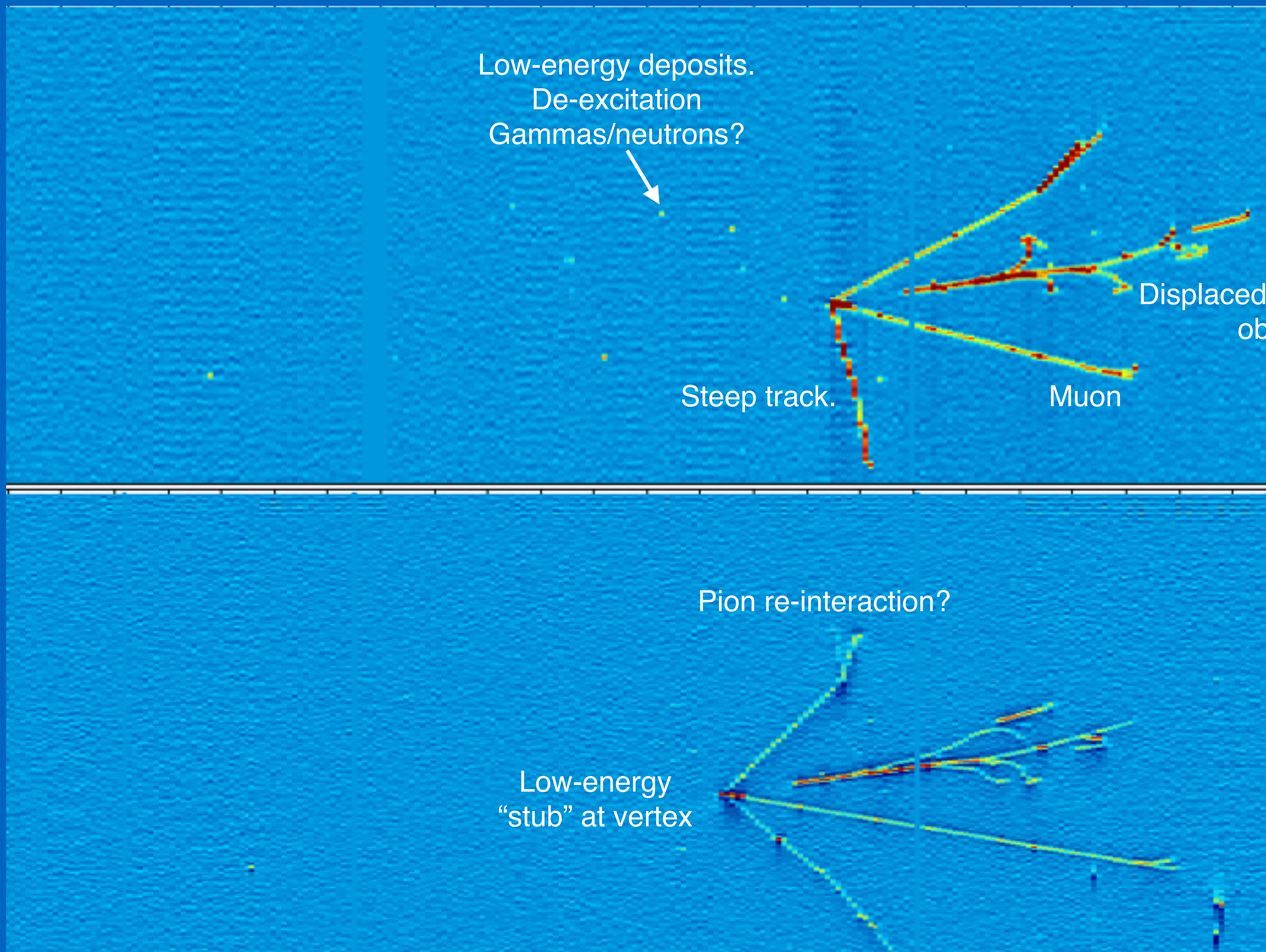

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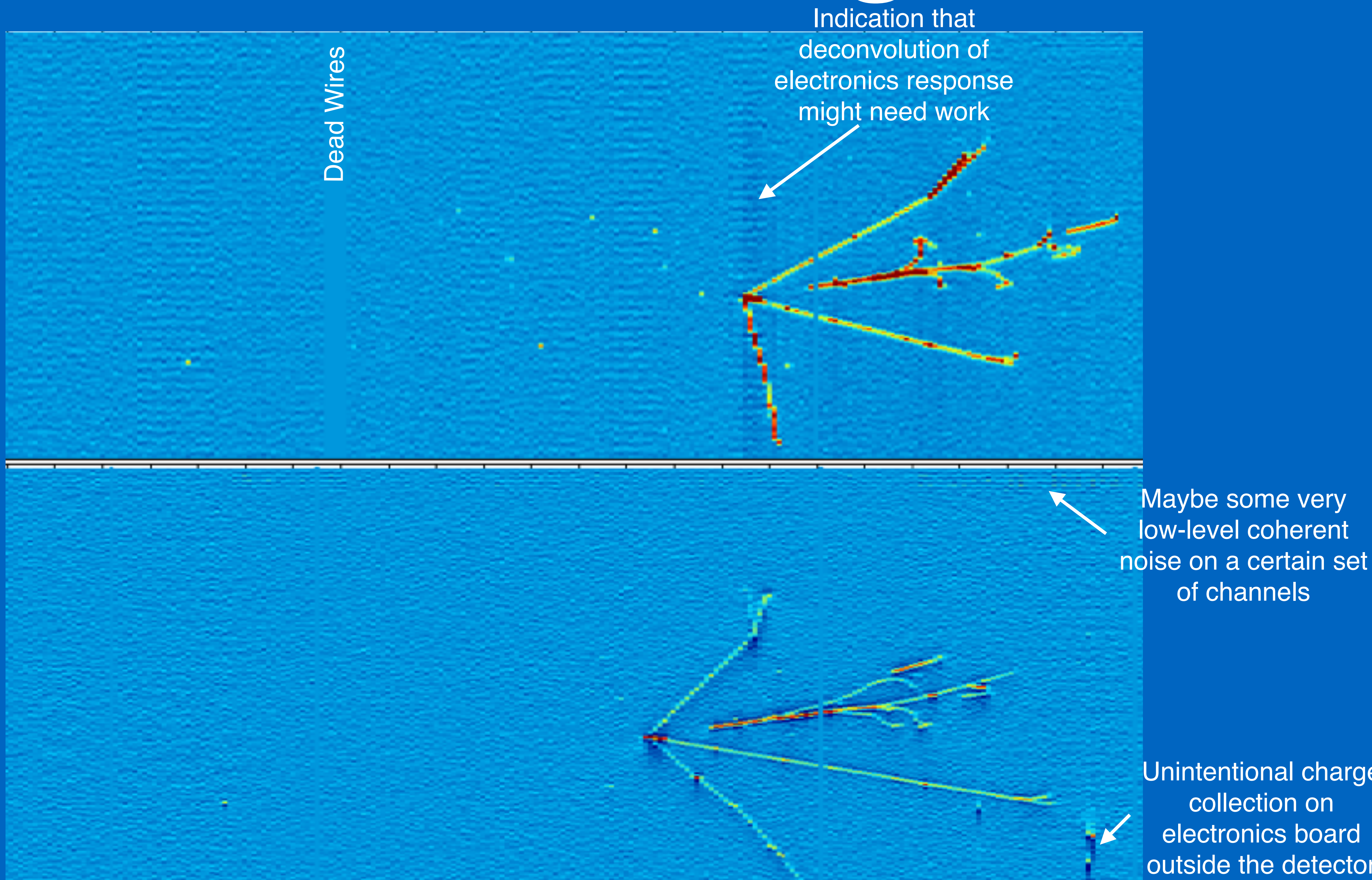

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TPC Signal Development

- Ionization produced by charged-tracks creates a signal on TPC wires.
- The measured signal is the convolution of multiple physical processes.
- Try to model each process, in simulation and data-reconstruction.

Uber-function to represent LArTPC signal development

$$\mathcal{M} = \mathcal{R} \otimes \mathcal{I} \otimes \mathcal{D} \otimes \mathcal{F} \otimes \mathcal{E}$$

$\mathcal{R}$	Recombination
$\mathcal{I}$	Attachment to Impurities
$\mathcal{D}$	Diffusion
$\mathcal{F}$	Drift Field
$\mathcal{E}$	Electronics Shaping

In An Ideal World…

In An Ideal World…

- Apply the inverse of this uber-function to measured signal and recover the distribution of ionization in 3d x-y-z space, then proceed to apply reconstruction.

$\mathcal{S}(\mathrm{wire}, \mathrm{time})$ Signal measured on each wire as a function of time.

$\rho(\mathrm{x}, \mathrm{y}, \mathrm{z}, \mathrm{t})$ Distribution of ionization in TPC as a function of time,space.

$$\mathcal{S} = \mathcal{M} \cdot \rho$$

$$\mathcal{M}^{-1}\mathcal{S} = \rho$$

In An Ideal World…

- Apply the inverse of this uber-function to measured signal and recover the distribution of ionization in 3d x-y-z space, then proceed to apply reconstruction.
- In reality, we have no such transformation function, so we must take a different approach.

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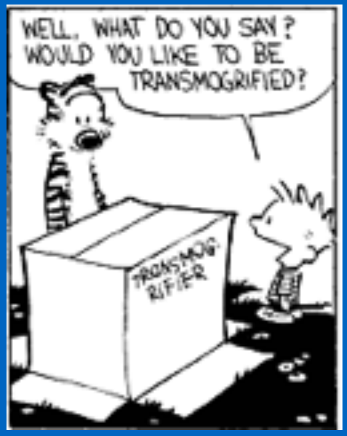
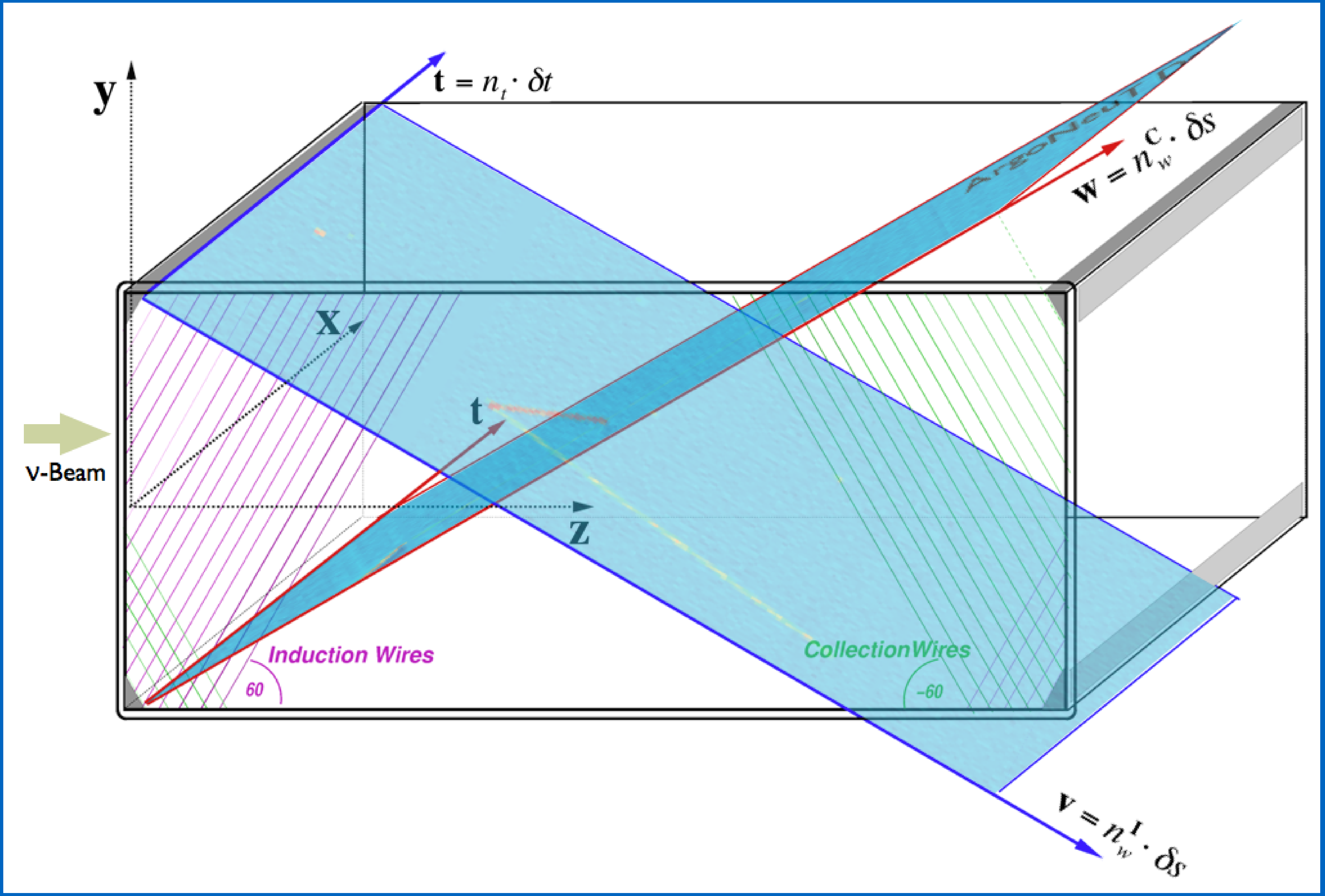


The Reconstruction Challenge

Angled wireplane geometry is very tricky to decipher. Hard enough to think in 3d, let alone in a tilted coordinate system



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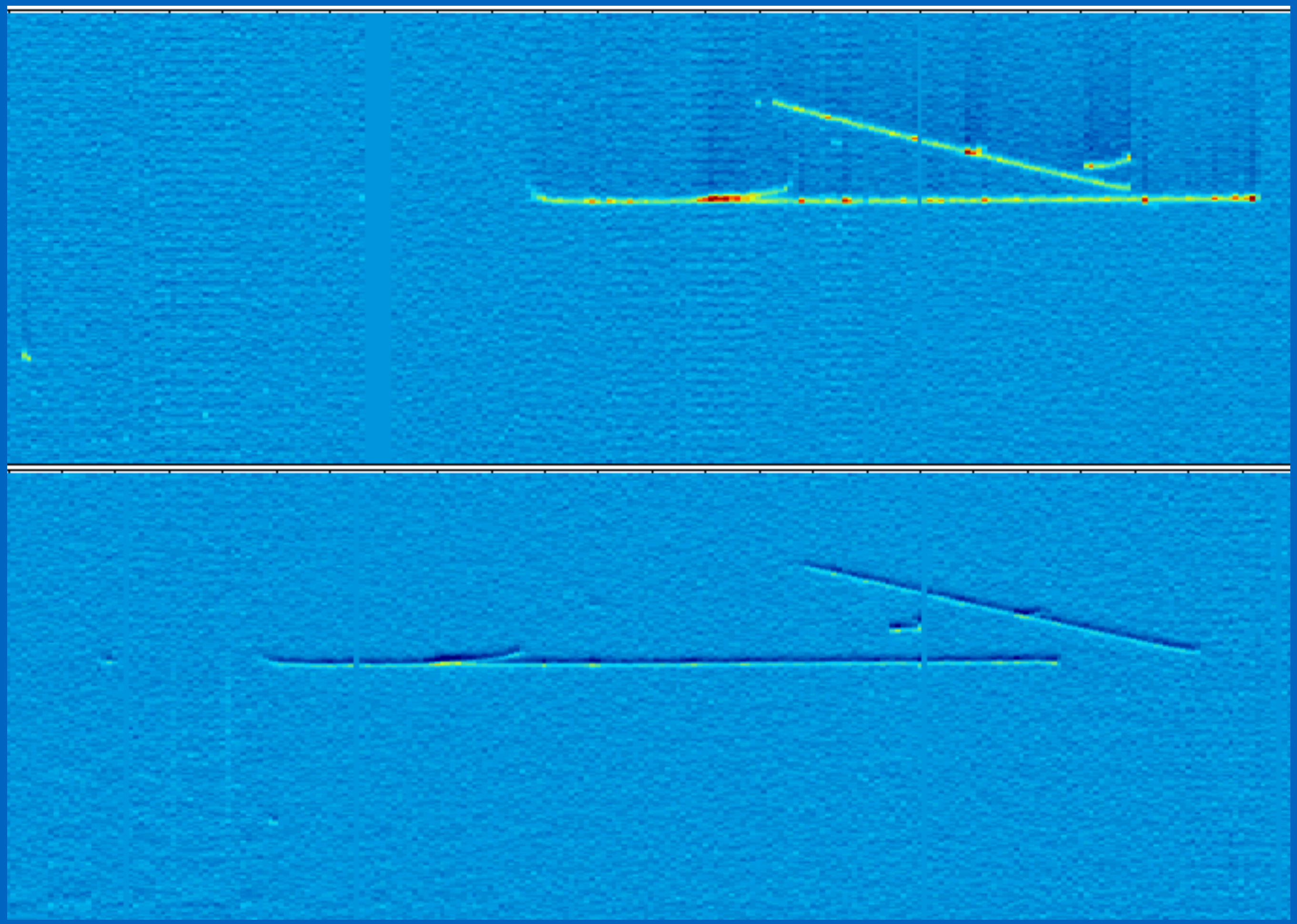
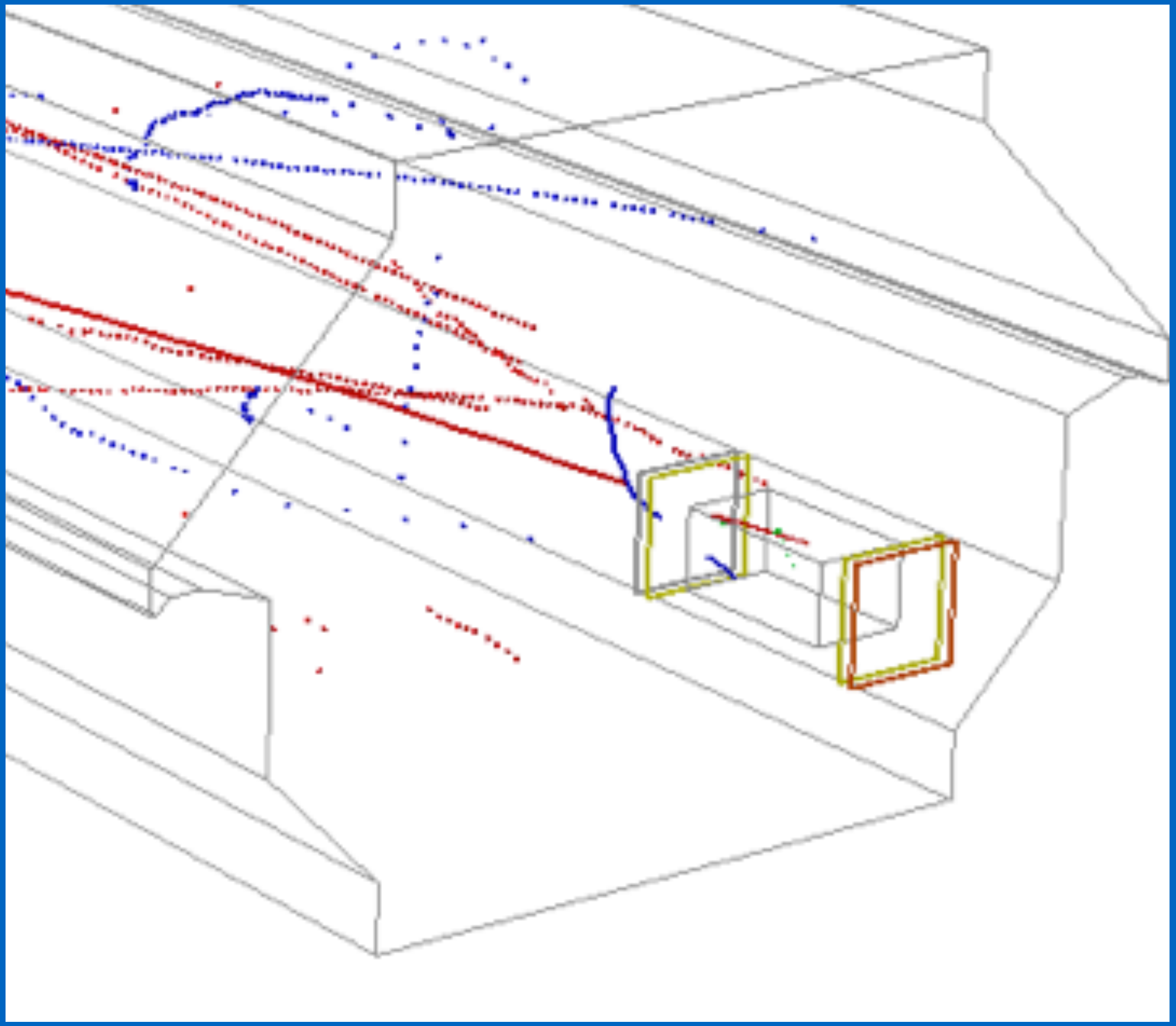


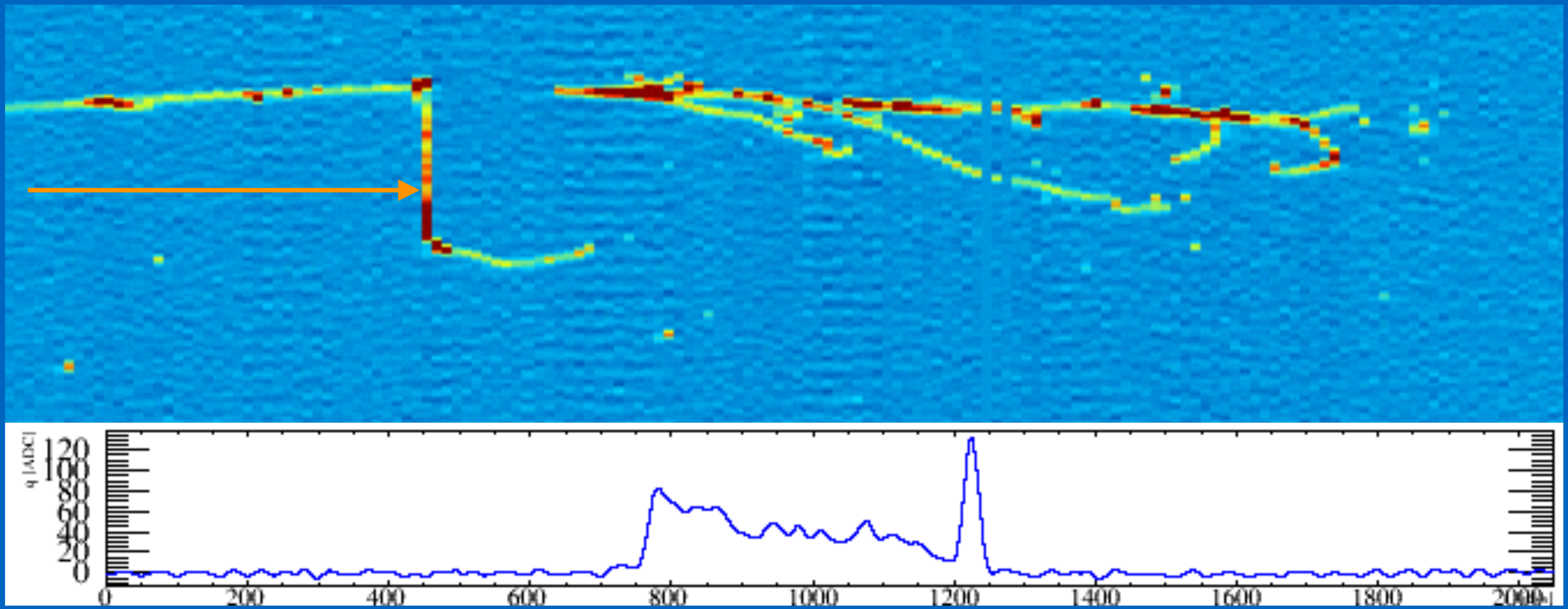


The Reconstruction Challenge

- We rely on common drift-time coordinate that all wireplanes share to “match” objects between planes.
- If a track is parallel to wireplanes (i.e. - all at one drift-time coordinate), there is ambiguity about how it actually travelled in space.
- If a track is steeply inclined to wireplanes (i.e. - all ionization ends up on just a few wires), the pulse shapes become quite challenging to decipher.

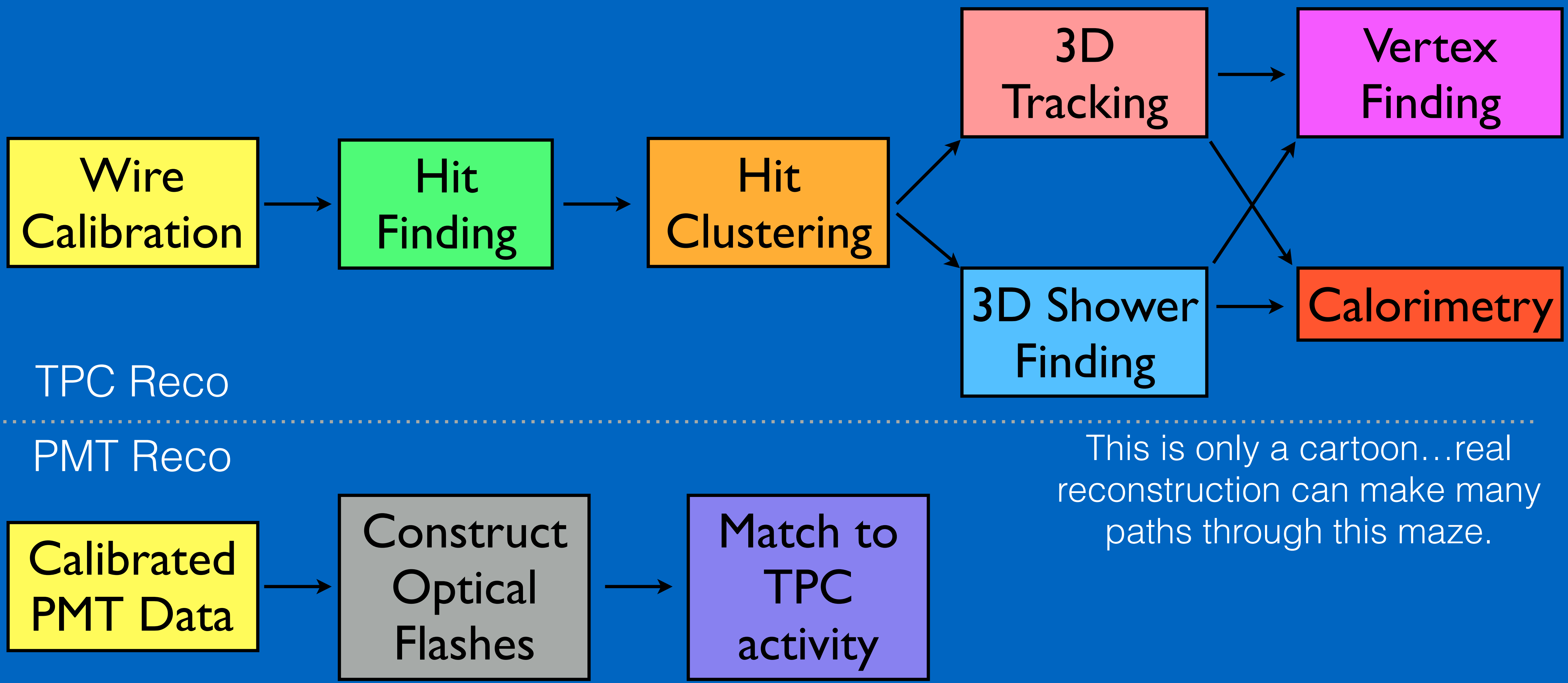
Track traveling towards one wire

Signal on that wire



Reconstruction Approach

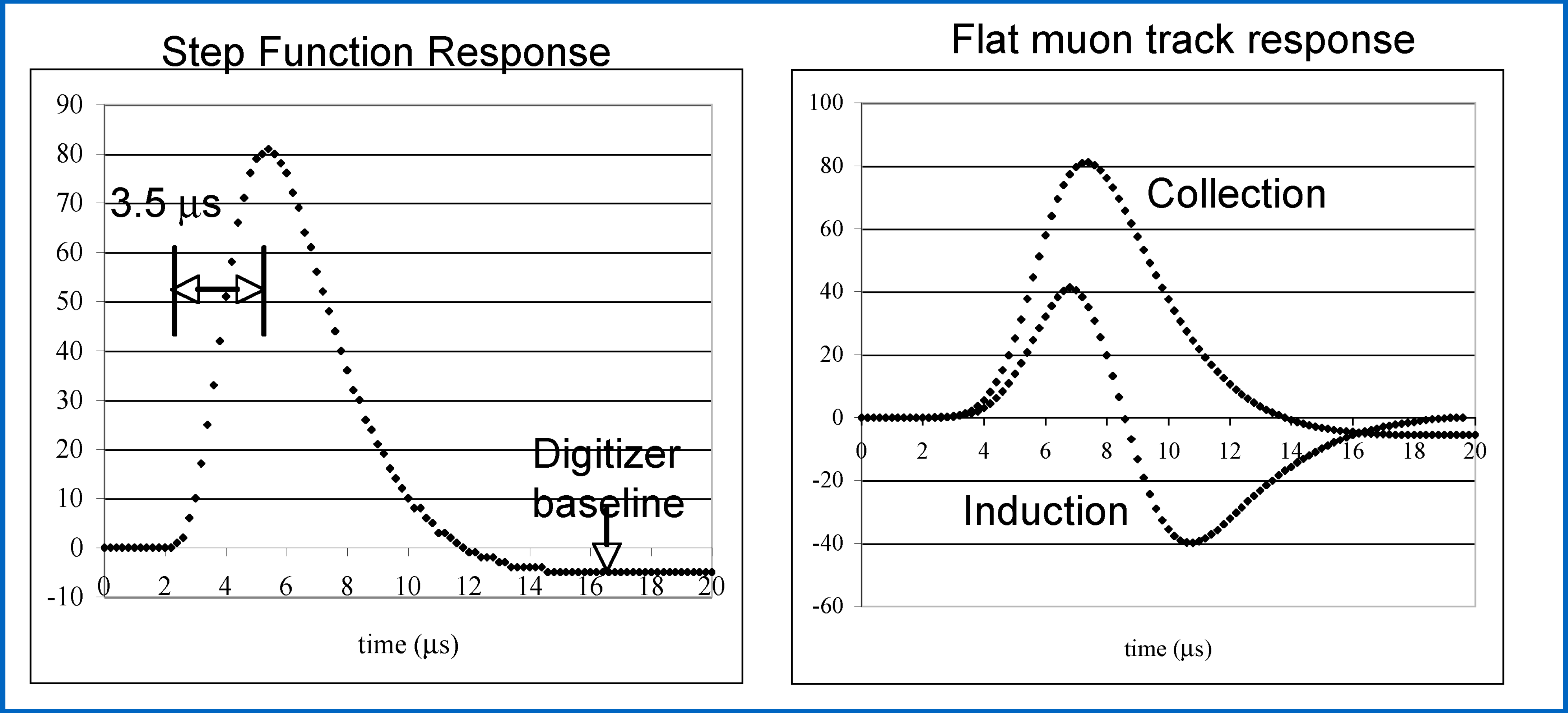
- TPC reconstruction scheme builds up 3D objects from underlying 1-D, 2-D objects.
- Light reconstruction finds signals on multiple PMTs that are consistent in time and space.



This is only a cartoon…real reconstruction can make many paths through this maze.

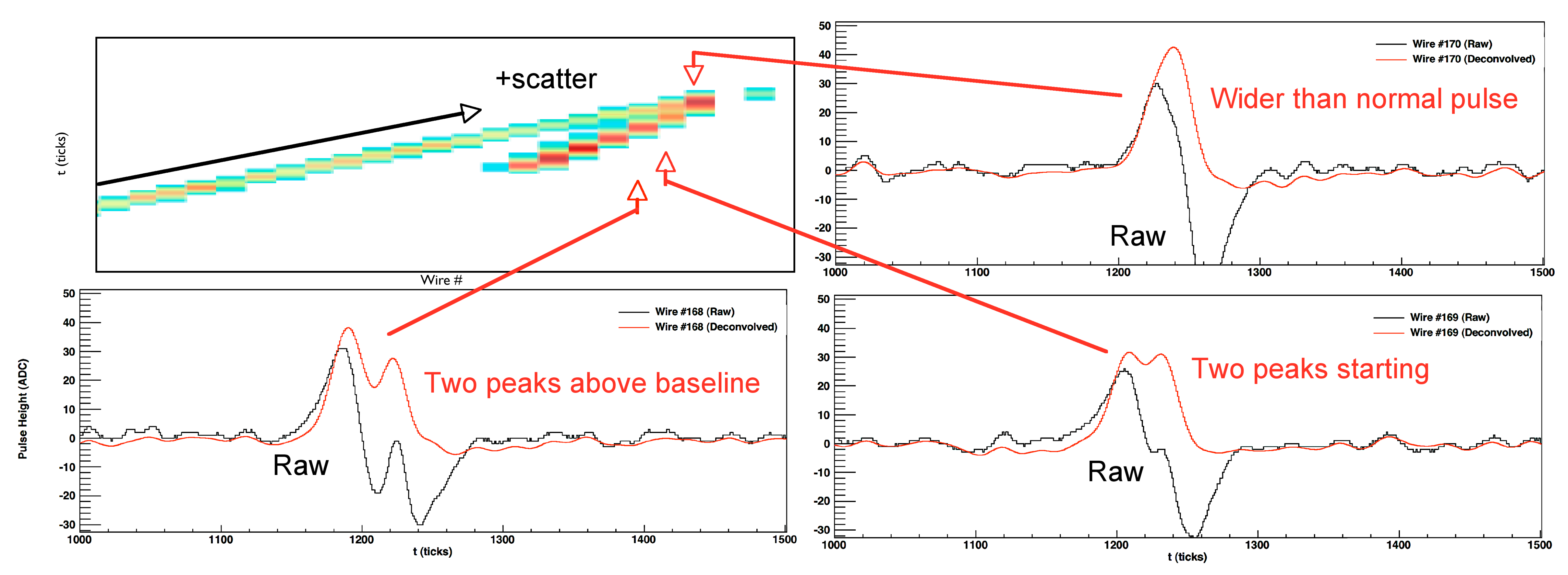
Raw Signal Manipulation

- Before any reconstruction takes place, raw signals from each wire can have electronics response deconvolved via a Fourier transform (FFT).
- Bipolar signal shapes on the induction plane can be converted to unipolar during this FFT, facilitating Hit finding.
- FFT technique also allows filtering to remove high/low freq. noise.



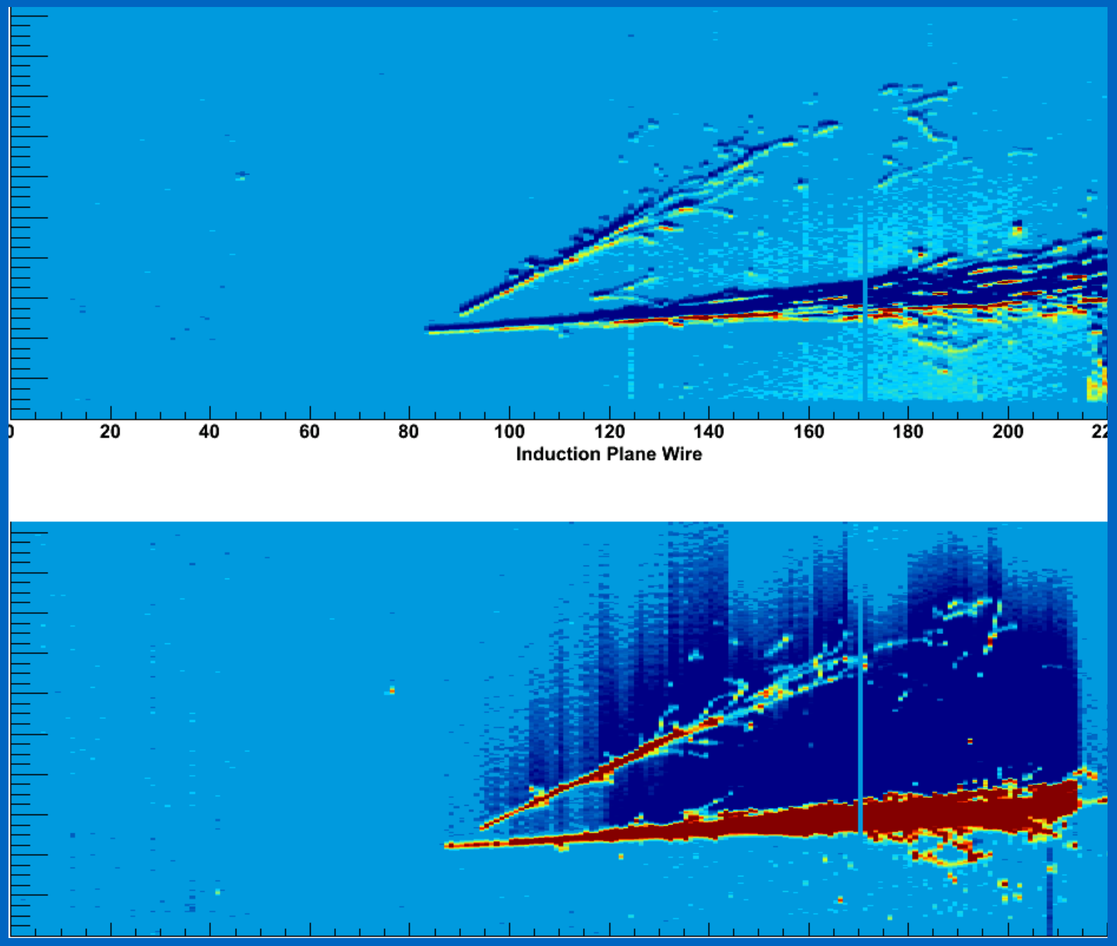
Hit-Finding

- A Hit is defined as a wire signal going above threshold for sufficient time.
- Hits are identified using a Gaussian fitting technique.
- Multi-Gaussian fit can be performed to identify closely spaced Hits.

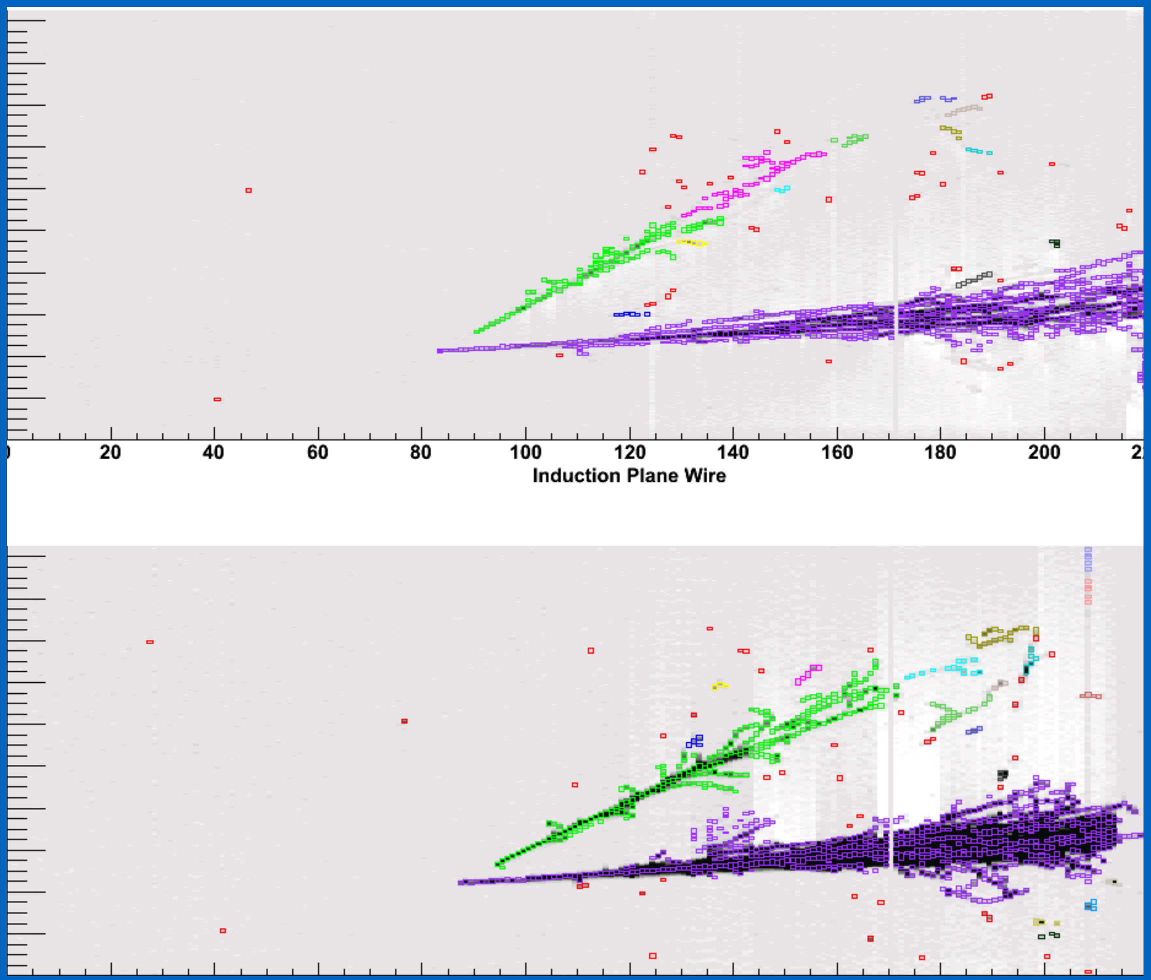


Clustering

- A Cluster is a grouping of associated Hits.
- Several algorithms exist for this.
- Old Example: Density-based clustering (called "DBscan") allows arbitrarily shaped Clusters to be identified.
  - Define some notion of proximity and connectedness (adjustable parameters)
  - Density-connected Hits are placed in a Cluster. "Noise" Hits are ignored.

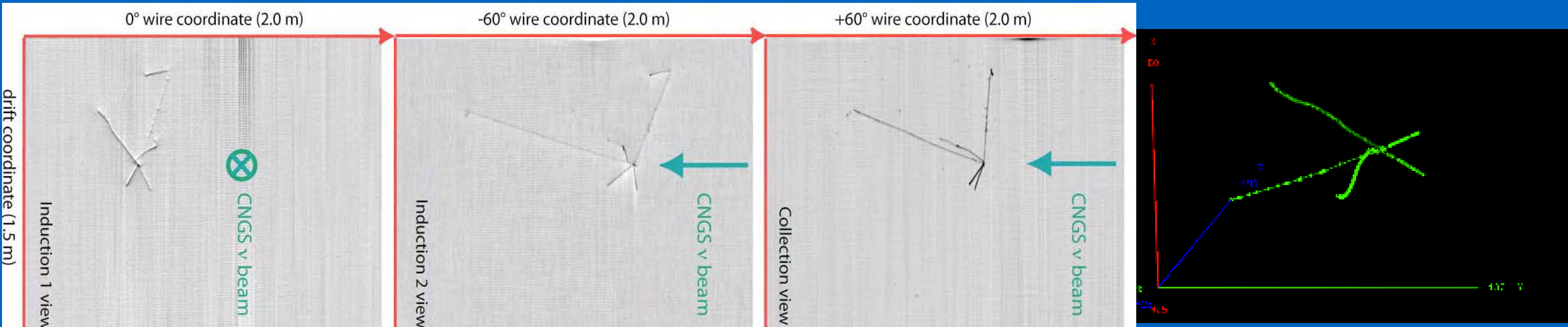


Deconvolution + Hit-Finding + Density-Based Clustering →



Tracking

- 3D reconstruction relies on the common coordinate (i.e. - drift time) shared by all planes.
- Goal is generalized 3D tracking that allows reconstruction of particles following arbitrary directions.
- Input can be Hits or Clusters, depending on algorithm.

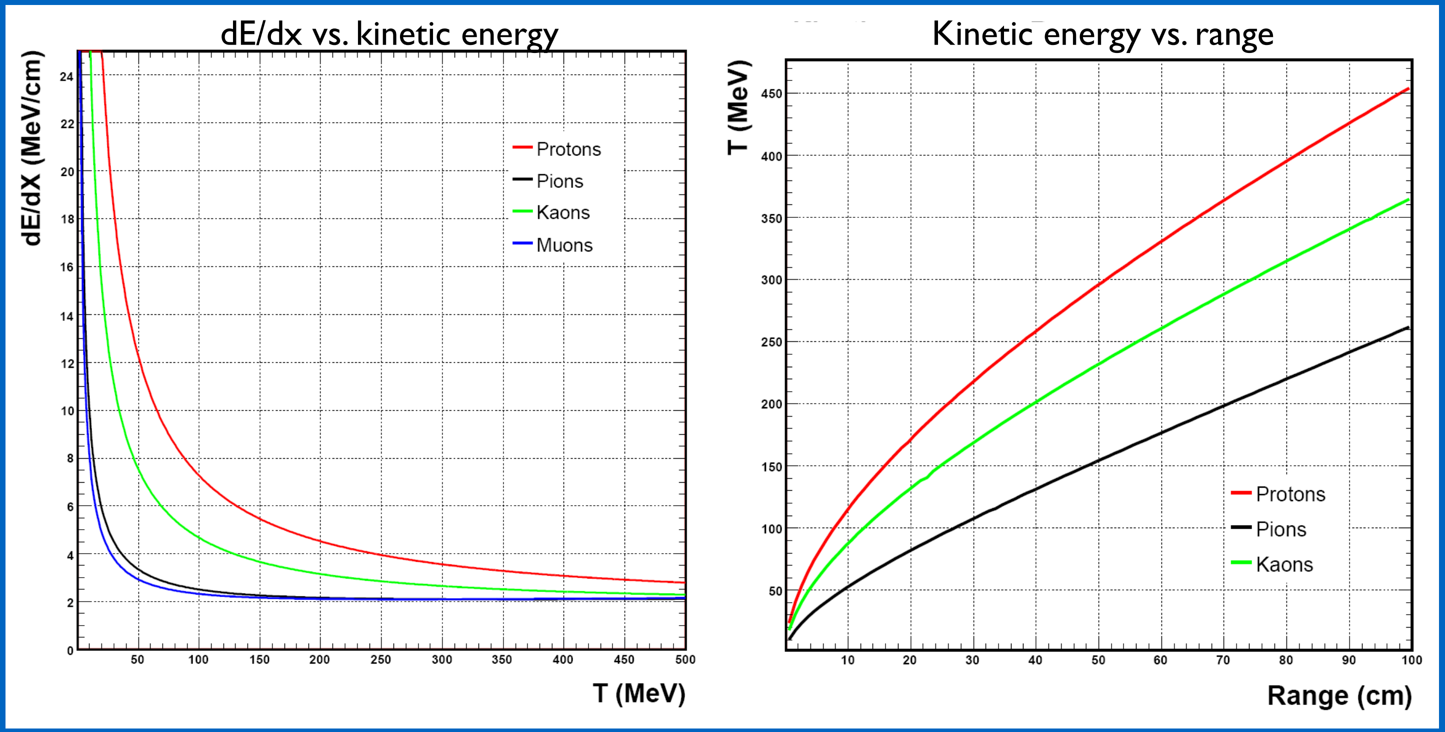


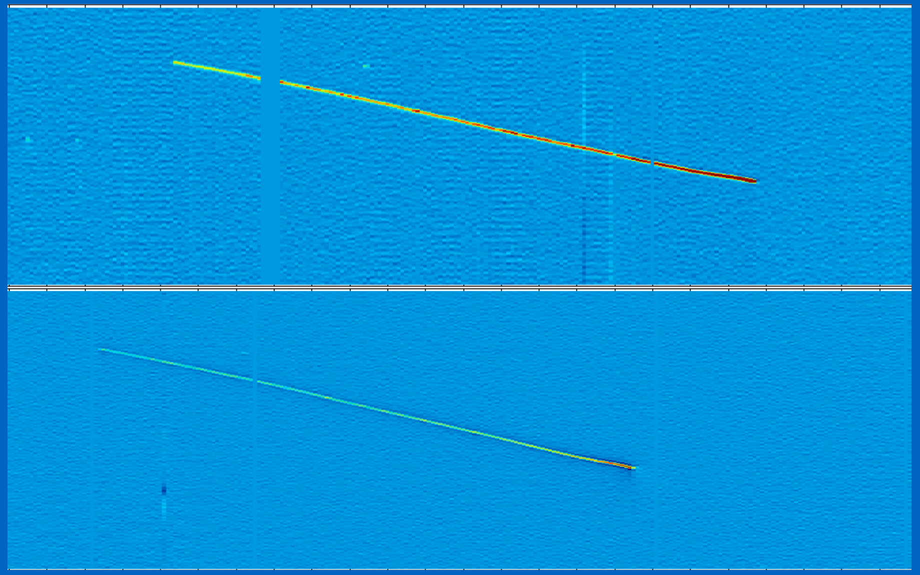
ICARUS Event and Reconstruction

Refs:
1.)ICARUS and Status of Liquid Argon Technology, A. Fava, La Thuile 2011

Particle Identification

- Particles in the detector have distinct energy-deposition profiles as they come to a stop.
- A likelihood comparison is performed between the energy-deposition profile of a reconstructed track and predictions from GEANT.
- Notice that this technique offers little power to distinguish muons from pions.





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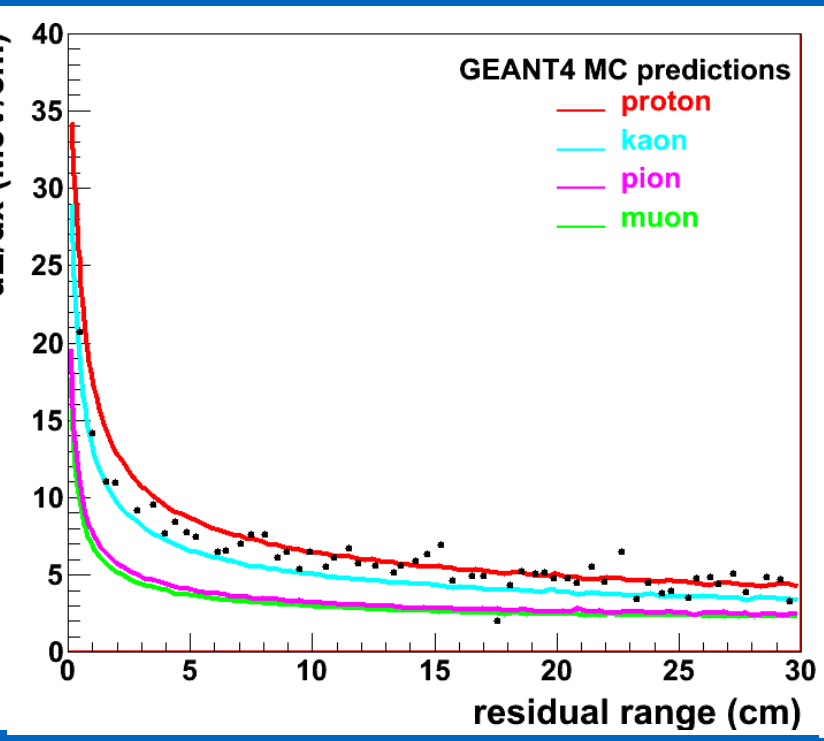

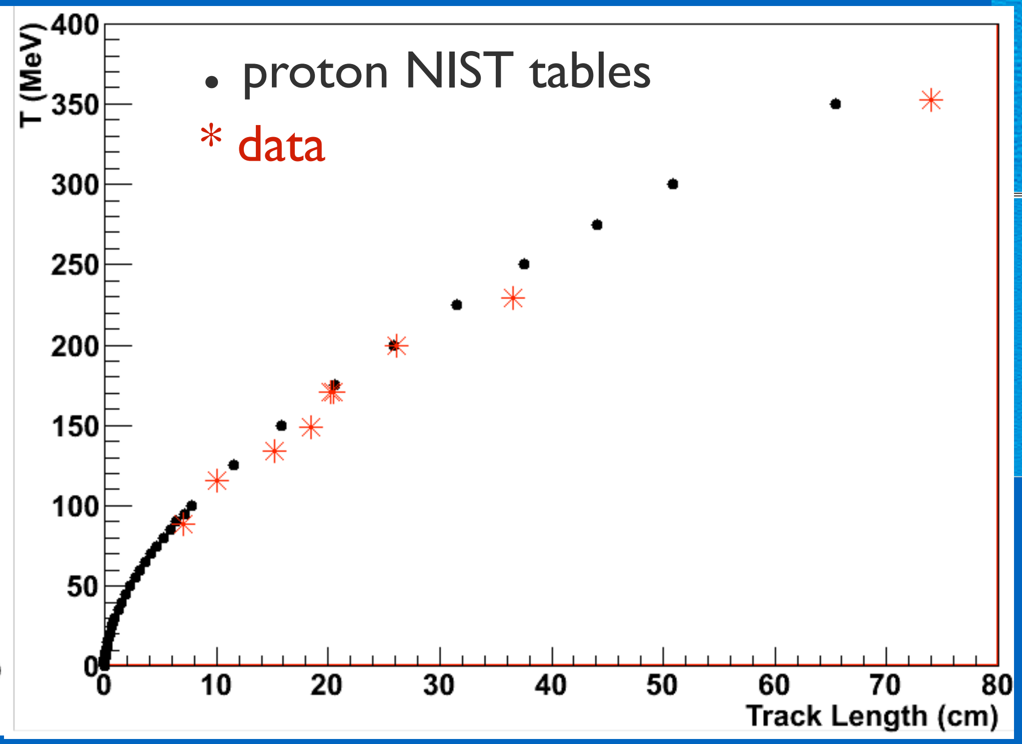

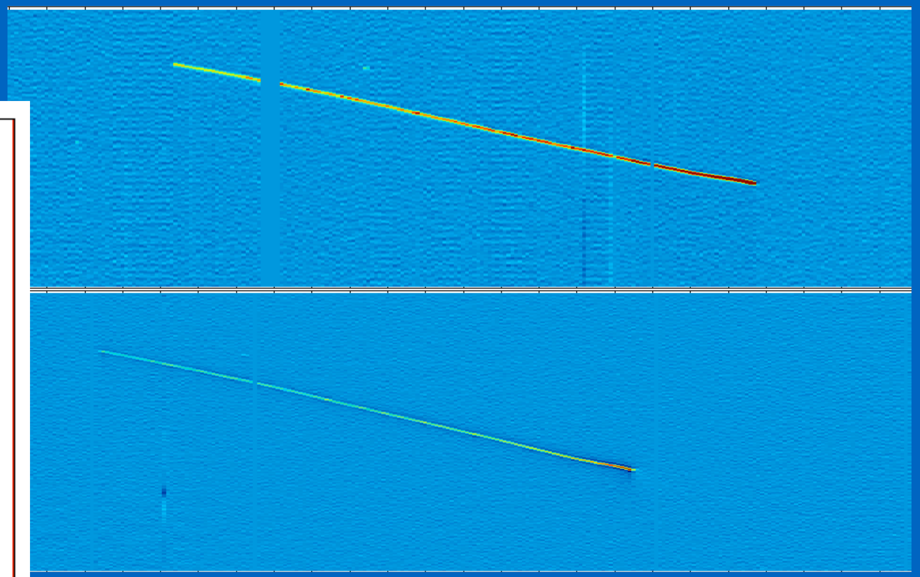

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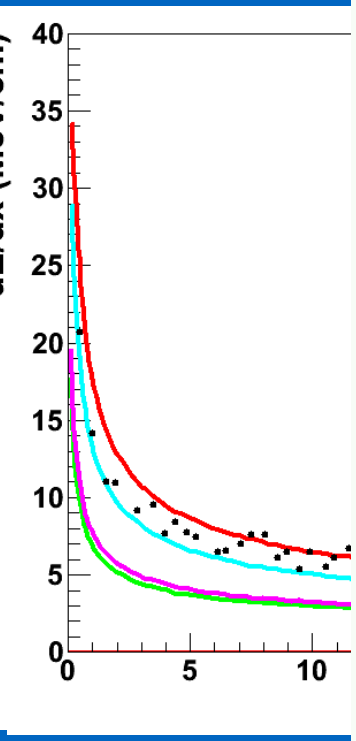
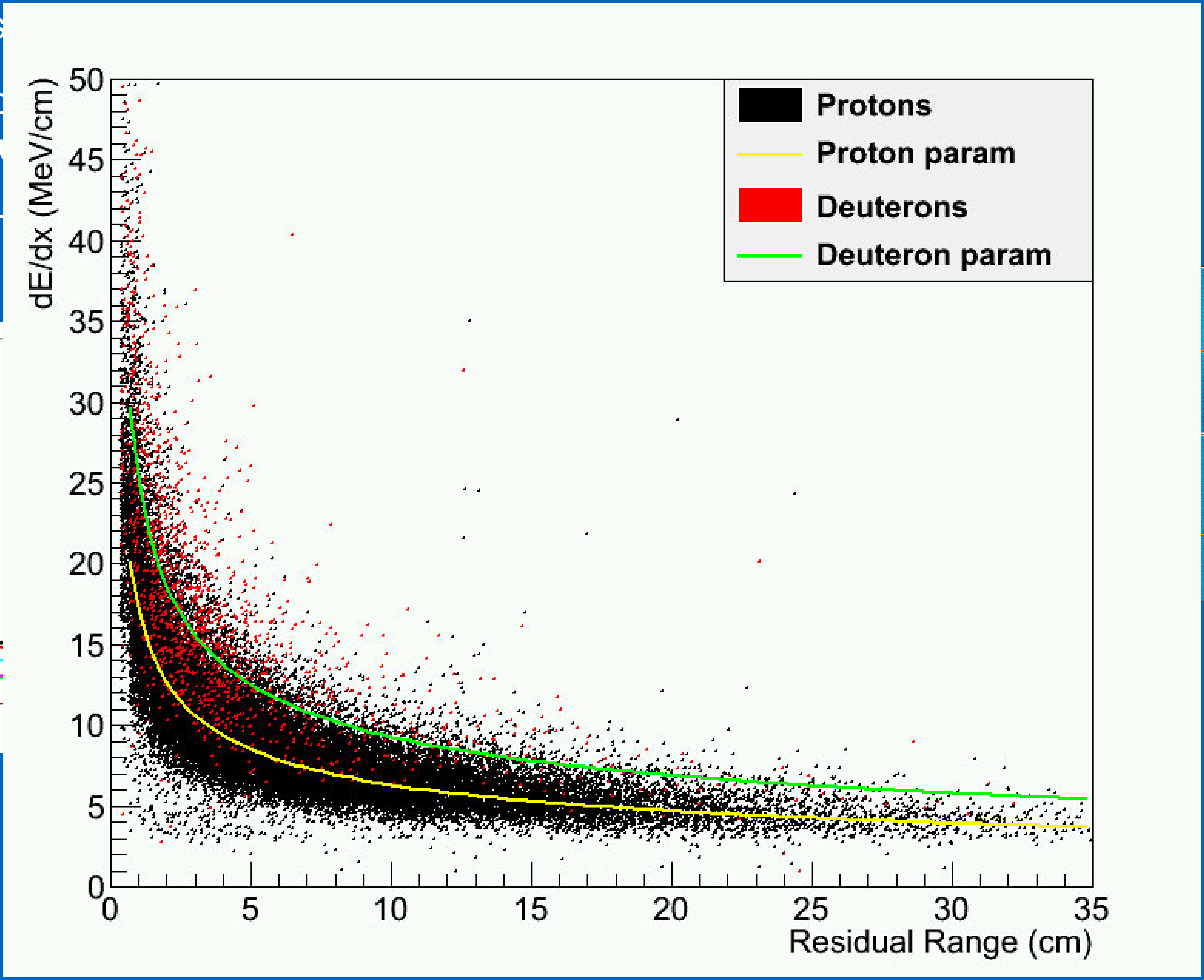
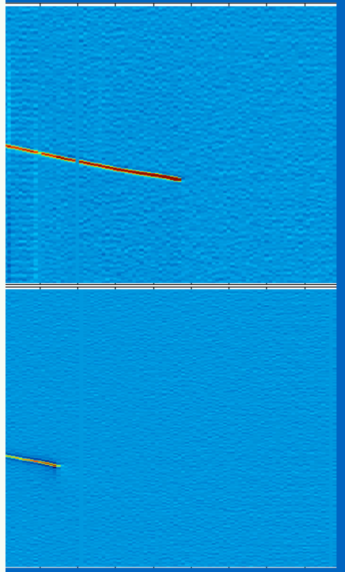
Particle Identification

- Particles … a stop.
- A likeliho… reconstru…
- Notice th…







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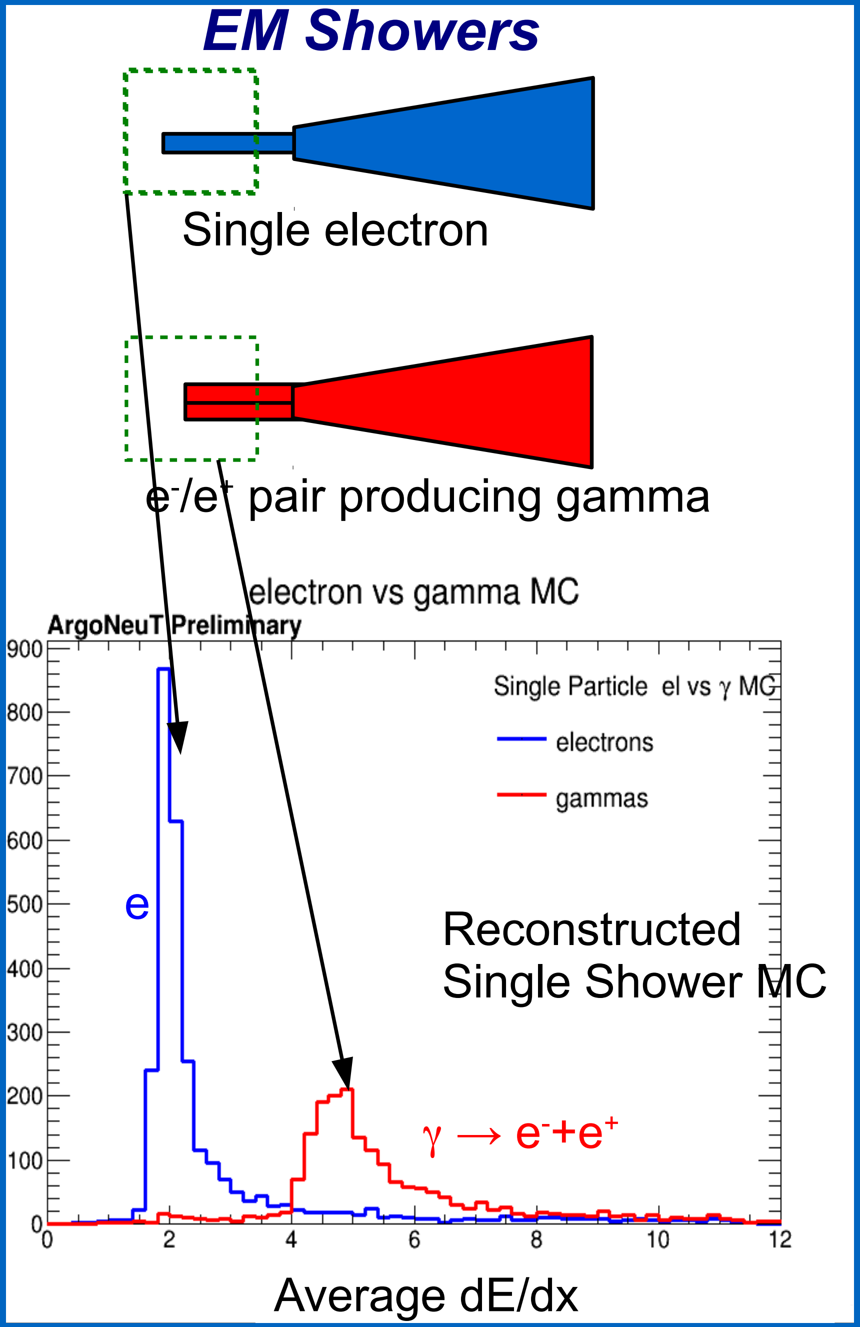
Particle Identification

- Electron/Photon distinction provided by dE/dx difference at beginning of shower, plus topological clues like gaps between primary vertex and shower start.
- Very important capability for electron-neutrino appearance analyses.



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1.)A. Szelc, Neutrino 2014

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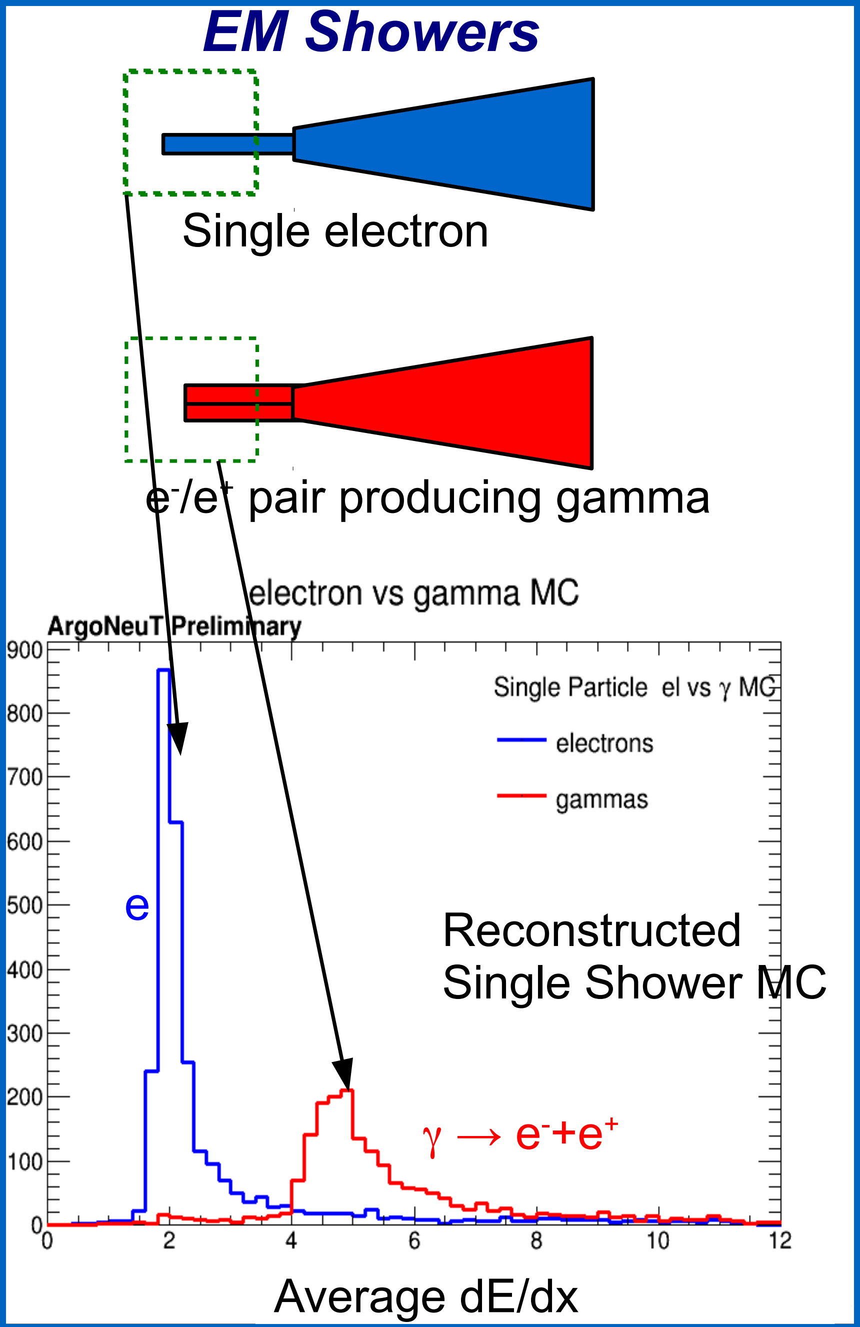

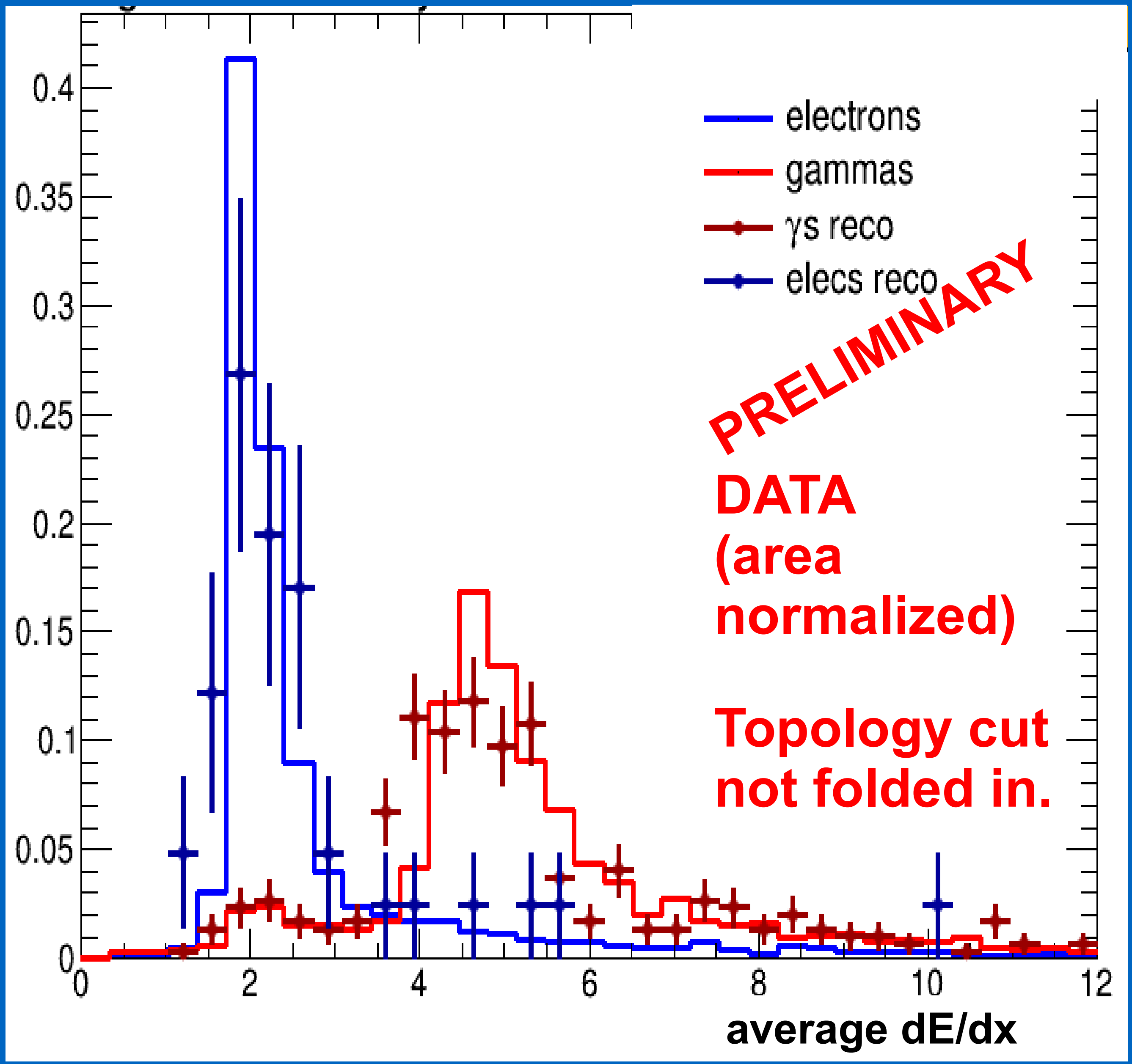

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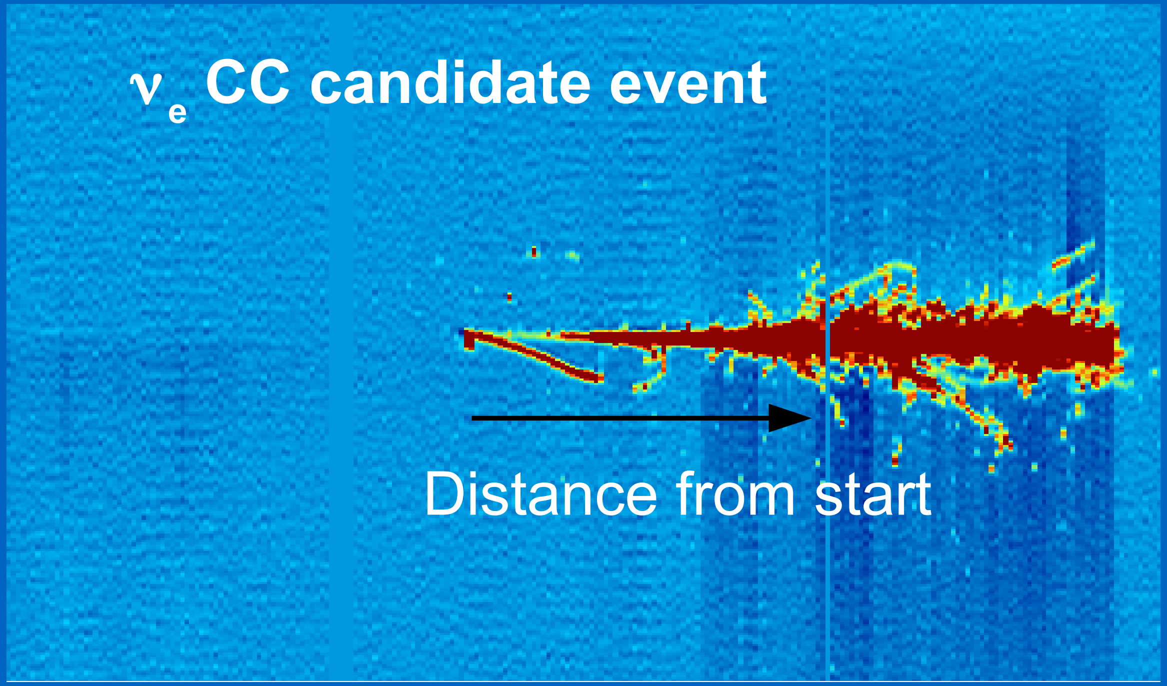
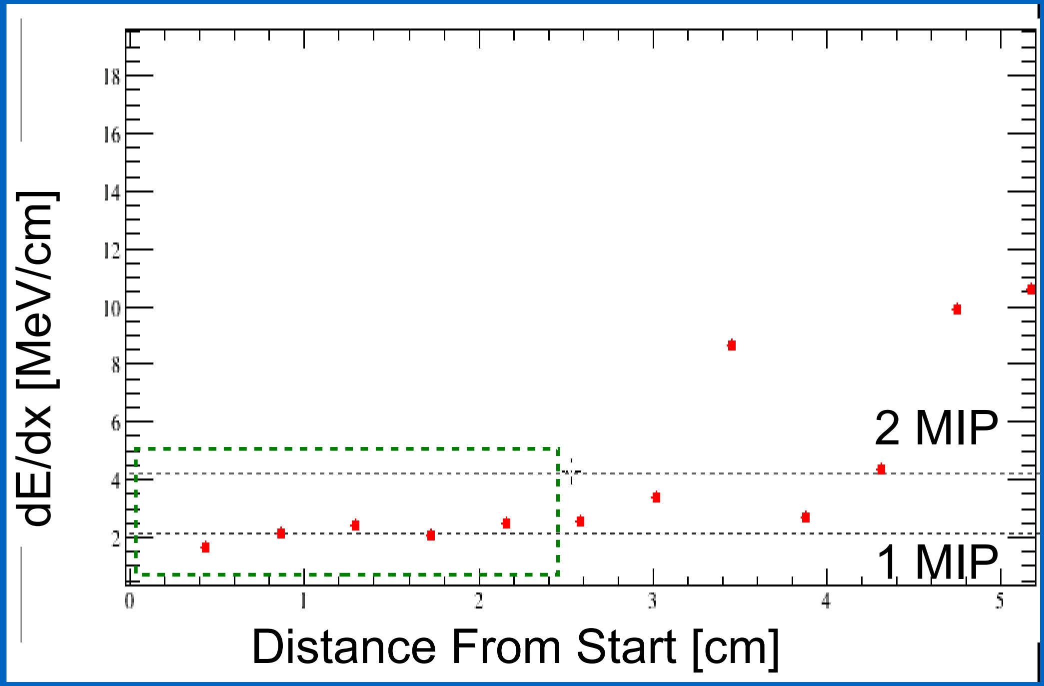
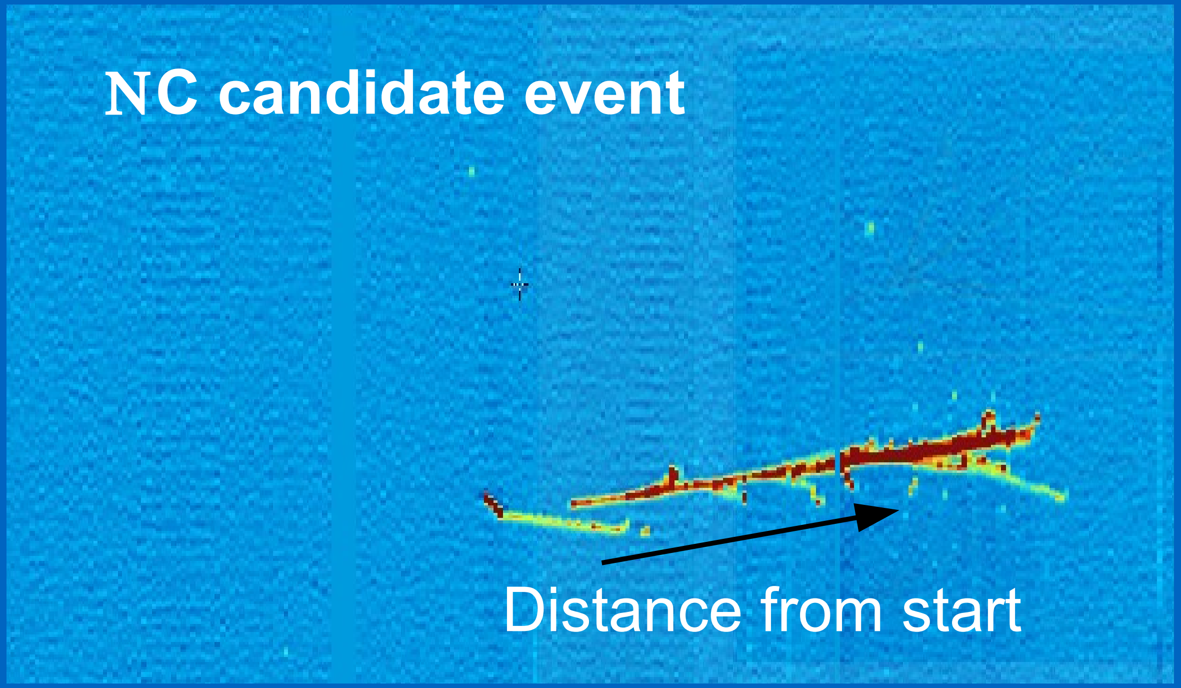
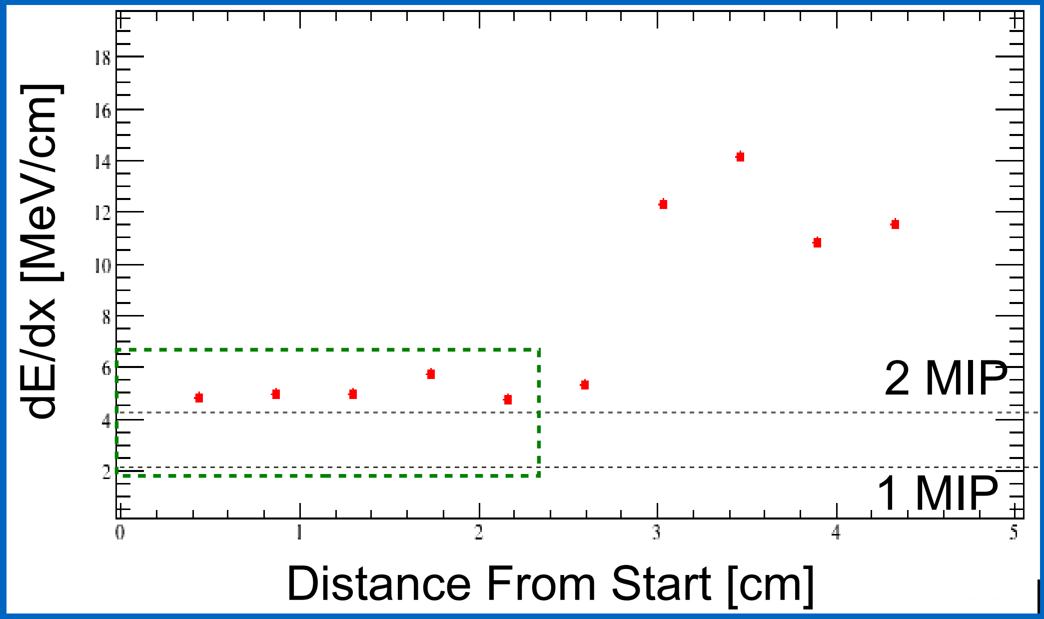
Particle Identification

- Some examples.









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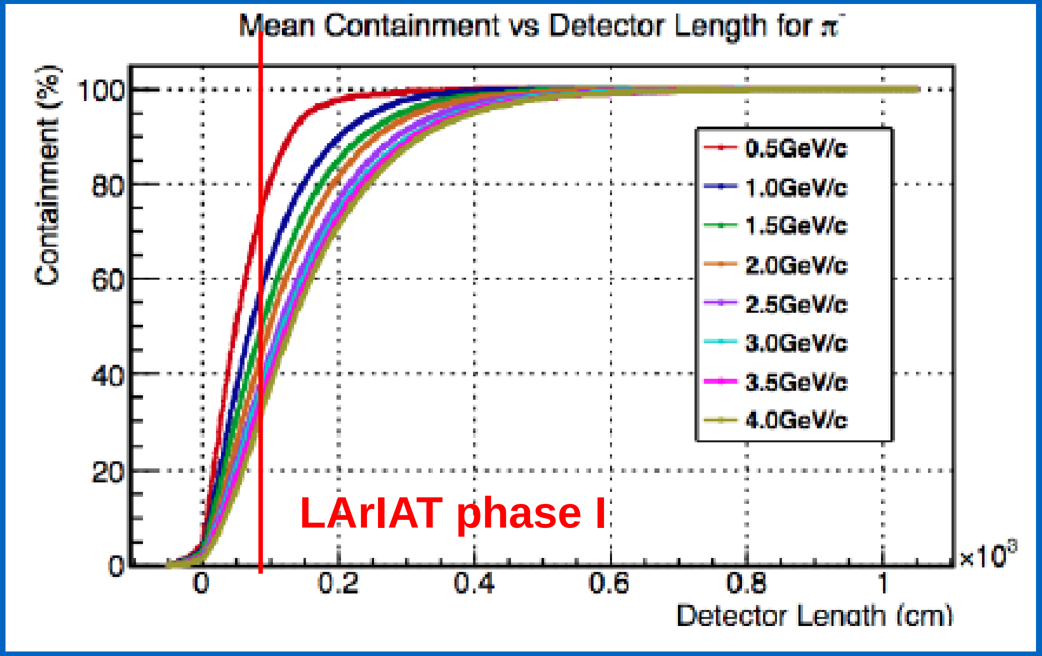
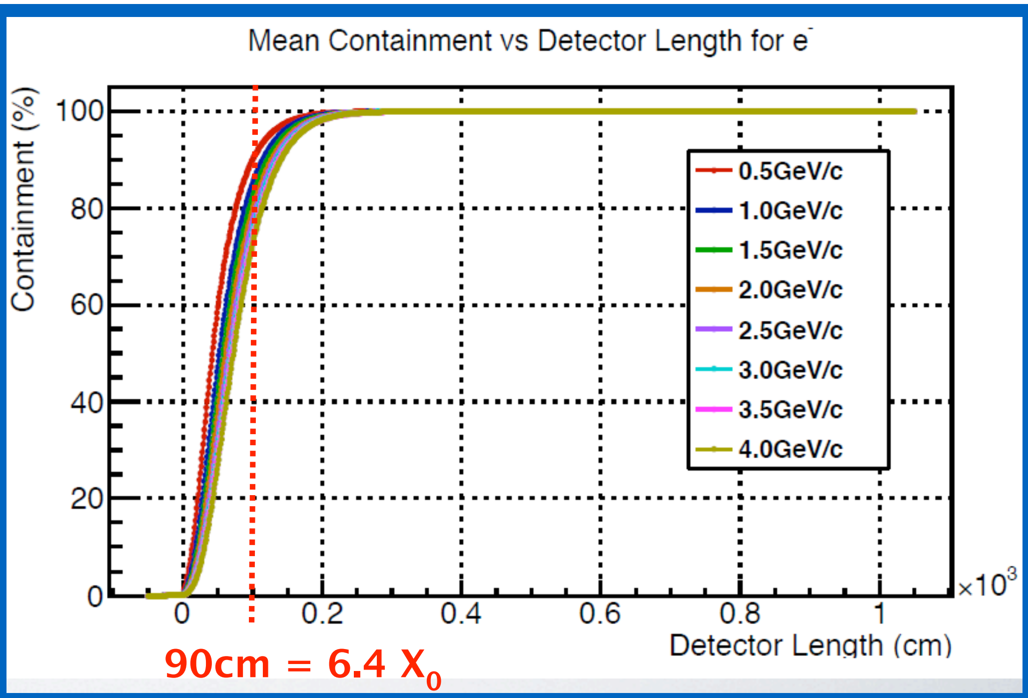
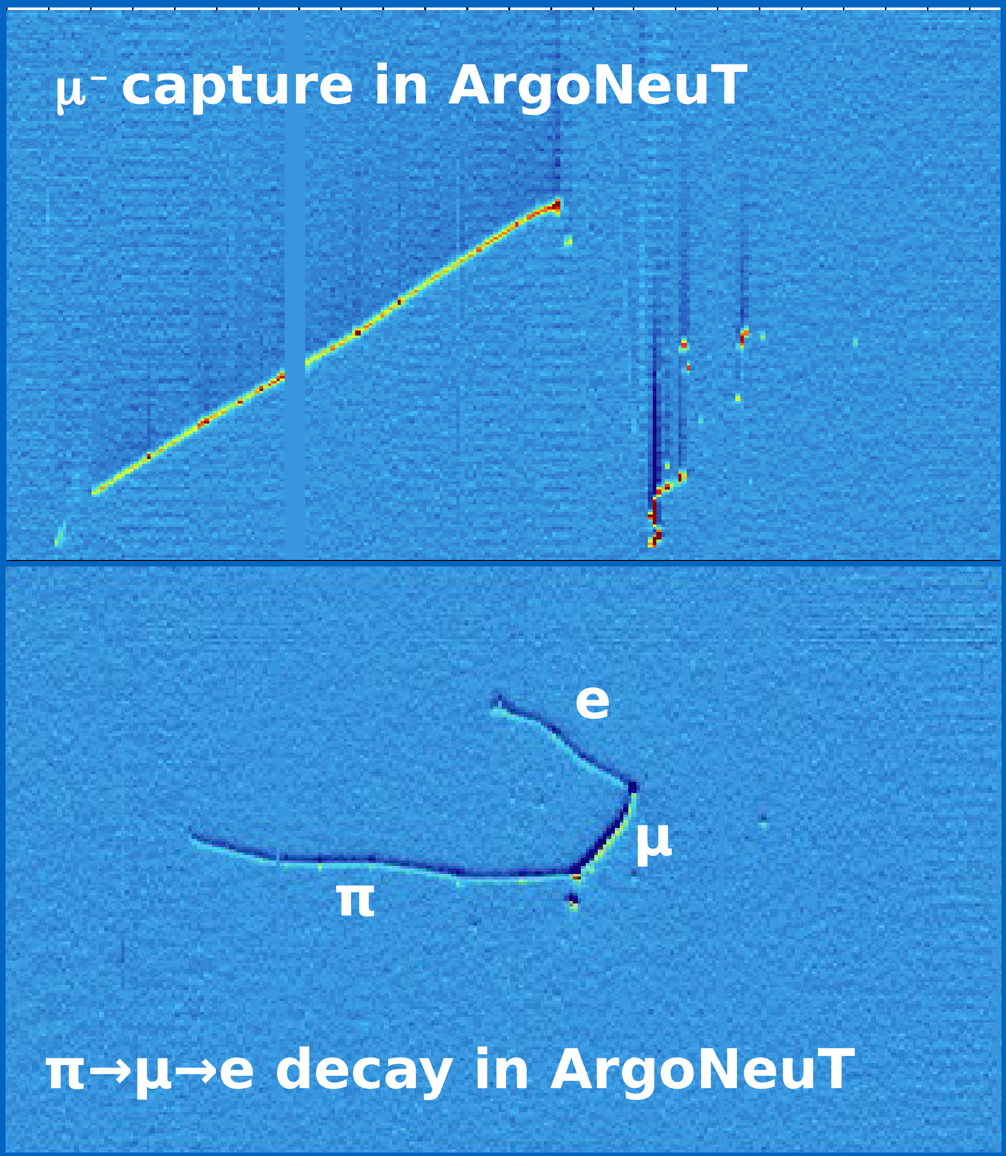
1.)A. Szelc, Neutrino 2014

Calibration

- Test-beam exposure, LArIAT, will give us an invaluable data sample to measure dE/dx profiles for stopping particles of known identity.
- Can also study dependance of recombination on electric-field.
- Beam polarity is tunable, so can study possibility of muon sign-selection in non-magnetized detector (using 100% mu+ decay, and ~75%/25% mu- capture/decay).



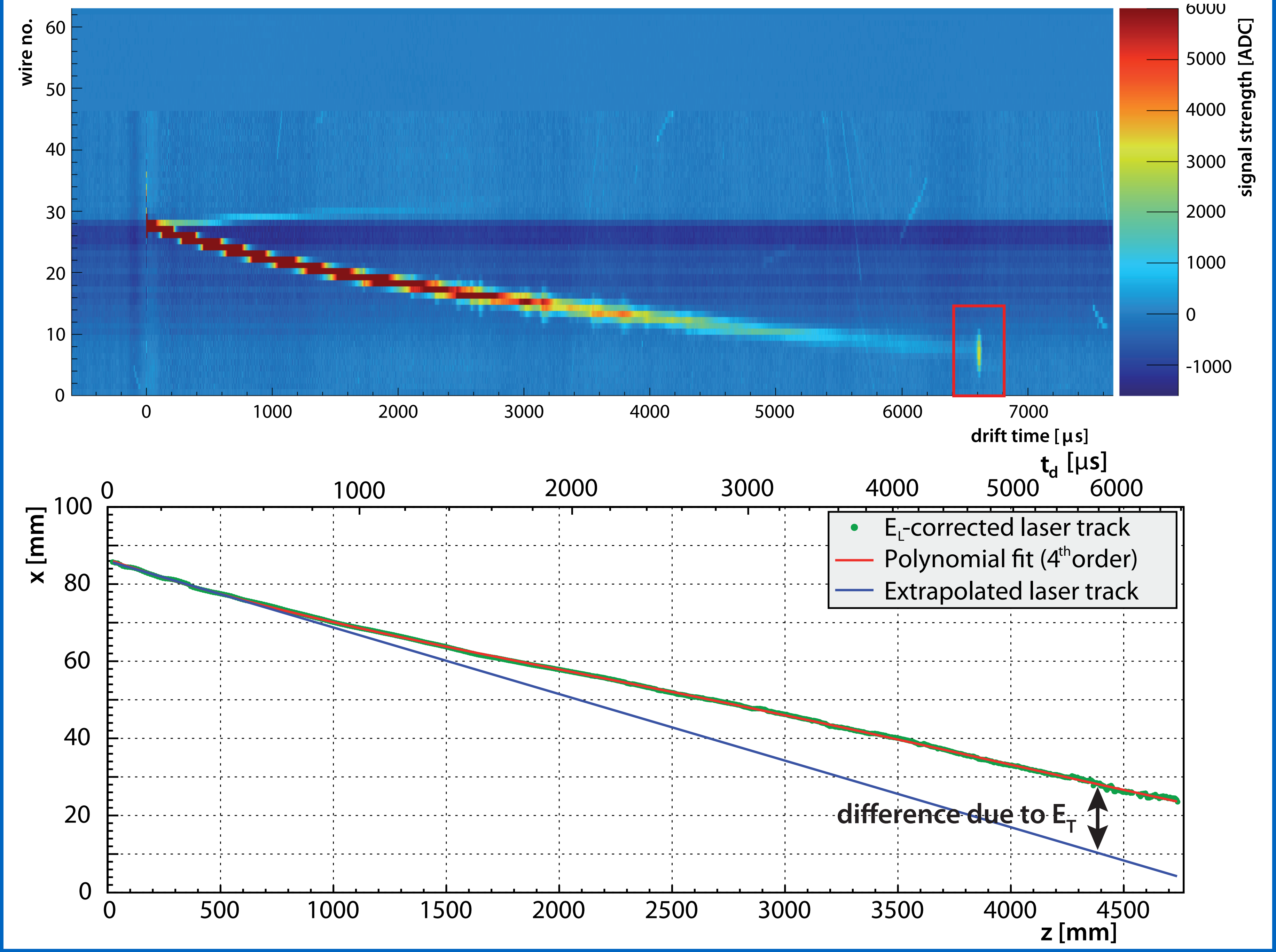




Laser Calibration

- Laser systems allows for in-situ mapping of E-field.
- Can precisely control where laser is pointing, so know exactly what reconstructed track should look like. Removes issues of multiple-scattering and delta-rays that muons have.

Read today's Fermilab Today

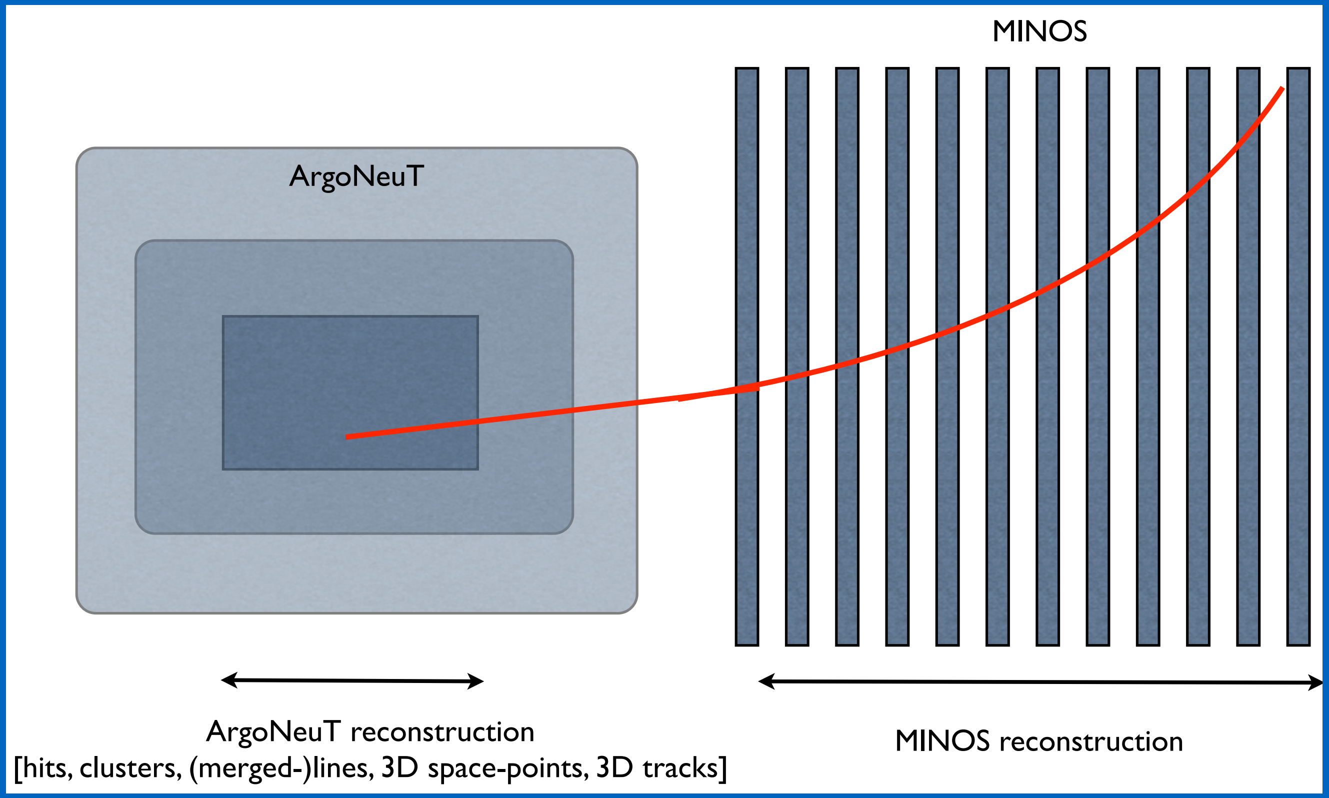


Refs:

1.) *Measurement of the drift field in the ARGONTUBE LAr TPC with 266 nm pulsed laser beams*, A. Ereditato et al, arXiv:1408.6635

Examples

- On the following slides I show examples of using the tools we currently have to do several measurements with ArgoNeuT data.
- As a reminder, ArgoNeuT has no light-collection system or laser calibration, but it does have MINOS as a muon spectrometer, which is a huge advantage.



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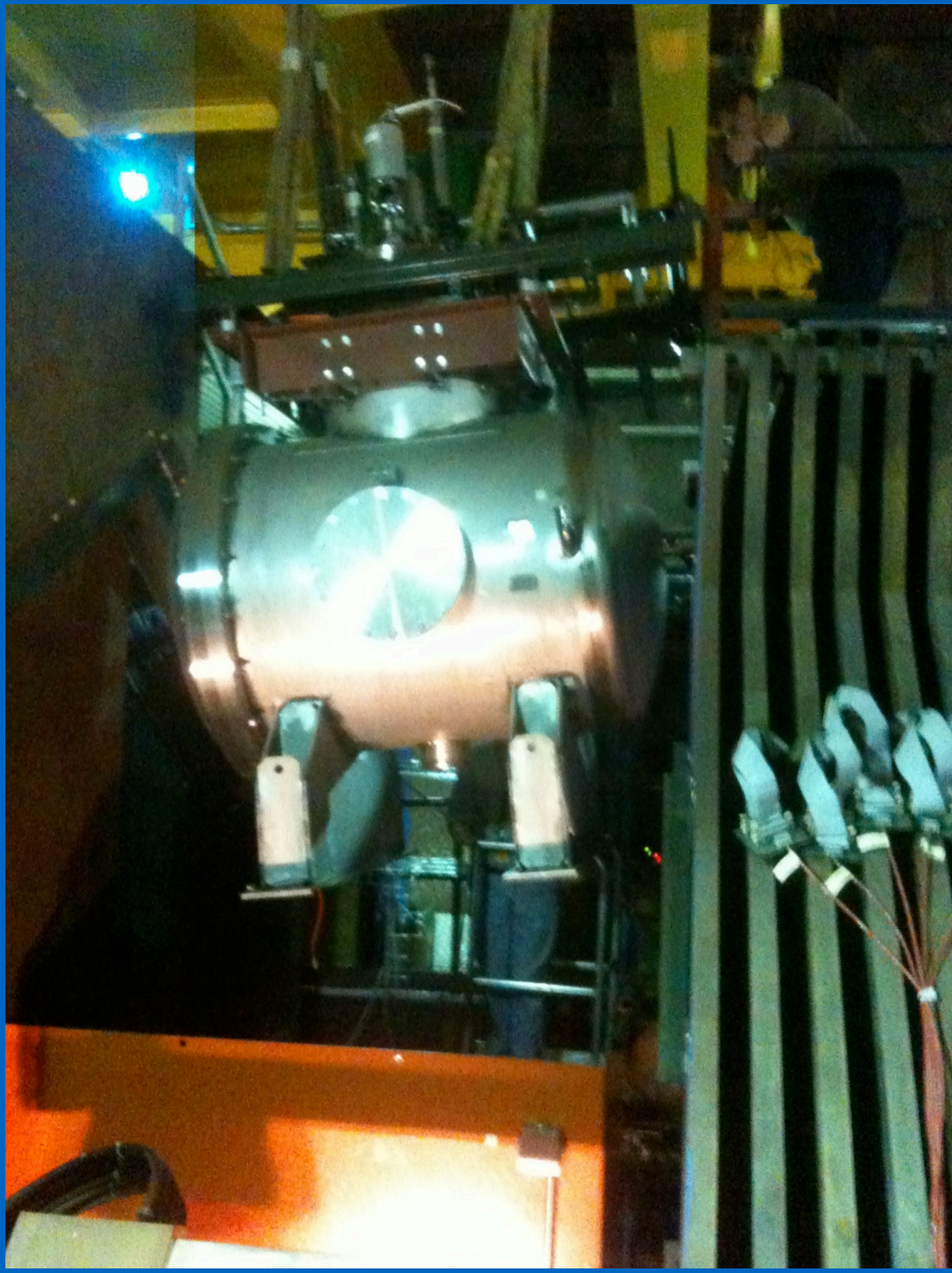
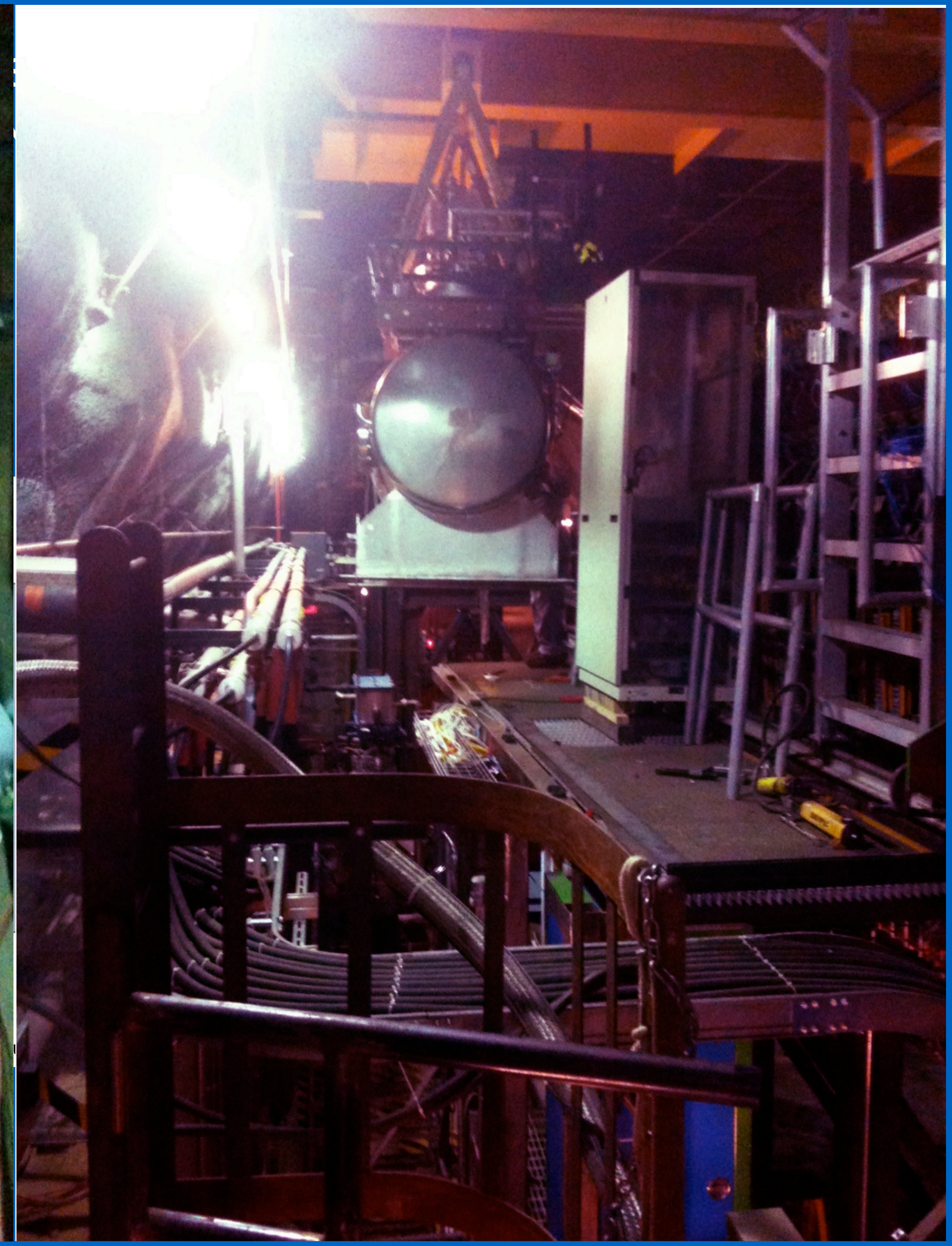
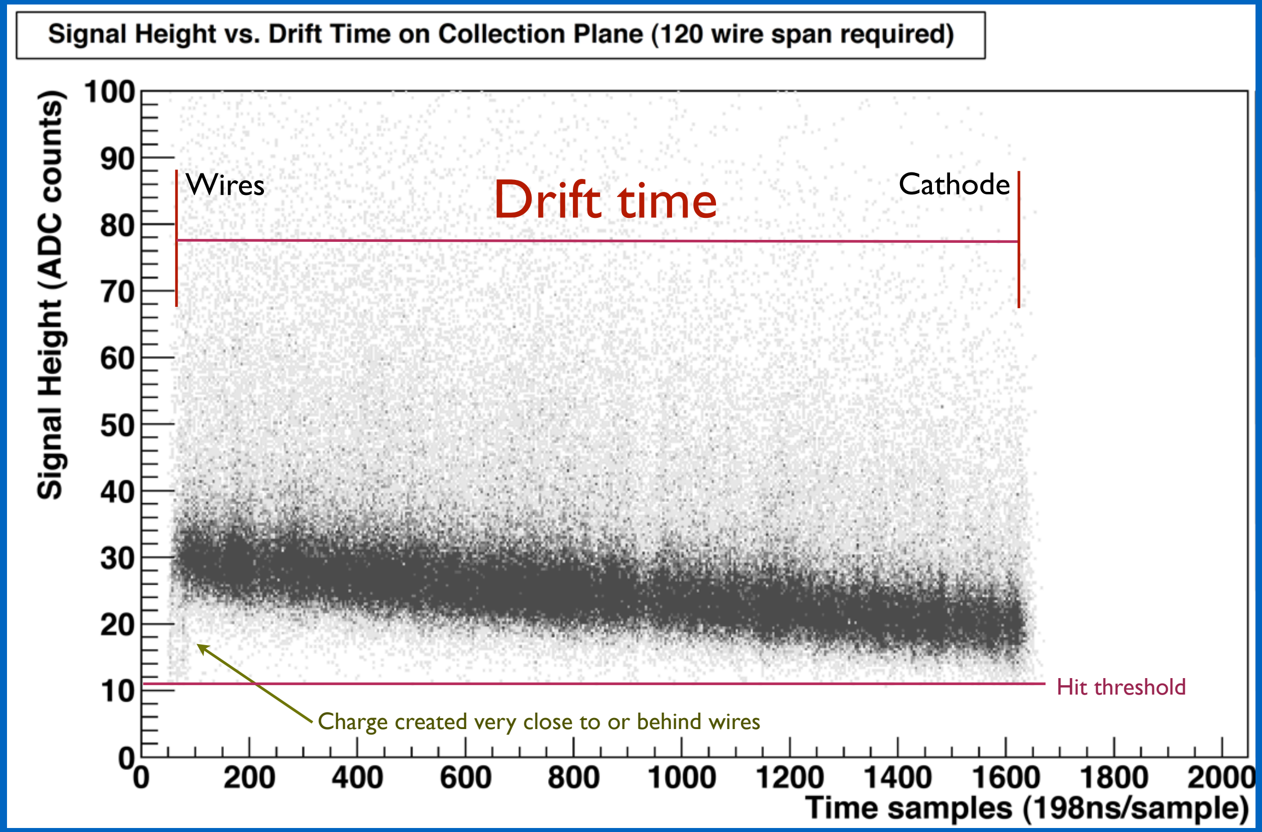
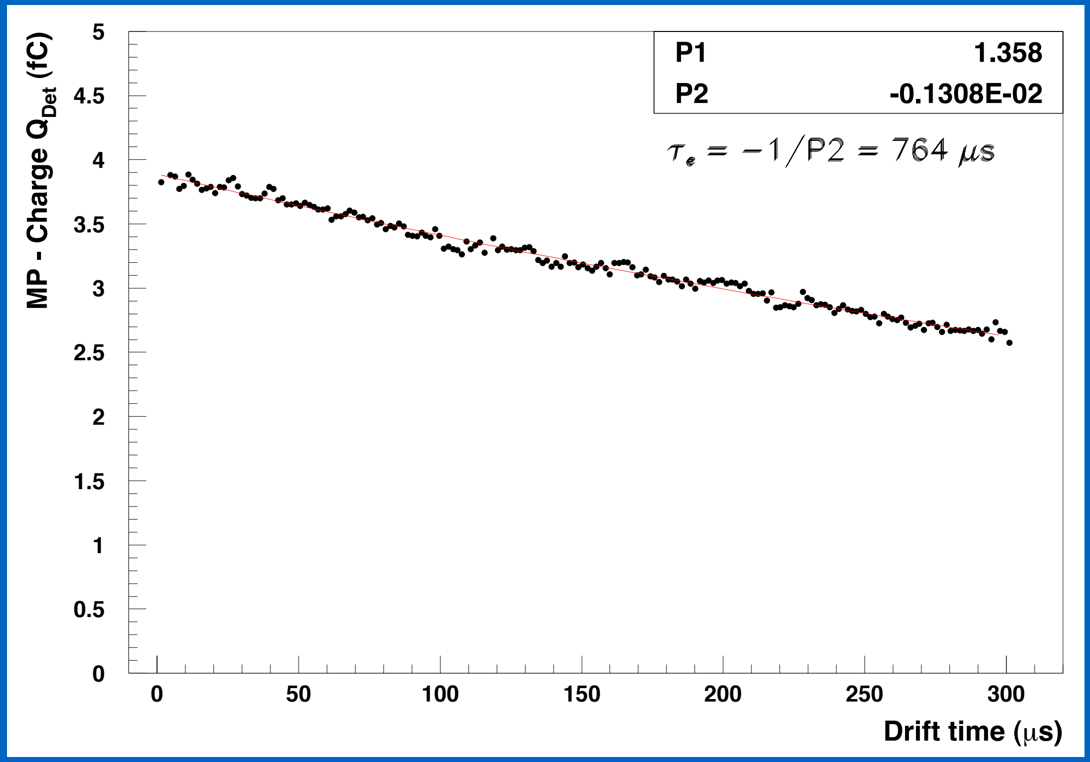




Electron Lifetime from Muons

- An example of the full reconstruction chain being used in an automated analysis is the measurement of argon purity using through-going muons.
- Due to non-infinite electron lifetime, tracks crossing further from the wireplanes will appear to have diminished signals.
- A fit is done to charge deposition vs. drift distance to extract the electron lifetime.





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1.)*The ArgoNeuT Detectorin the NuMI Low-Energy Beam Line at Fermilab*, C. Anderson et al, JINST 7 P10019 (2012)

Electron Lifetime from Muons

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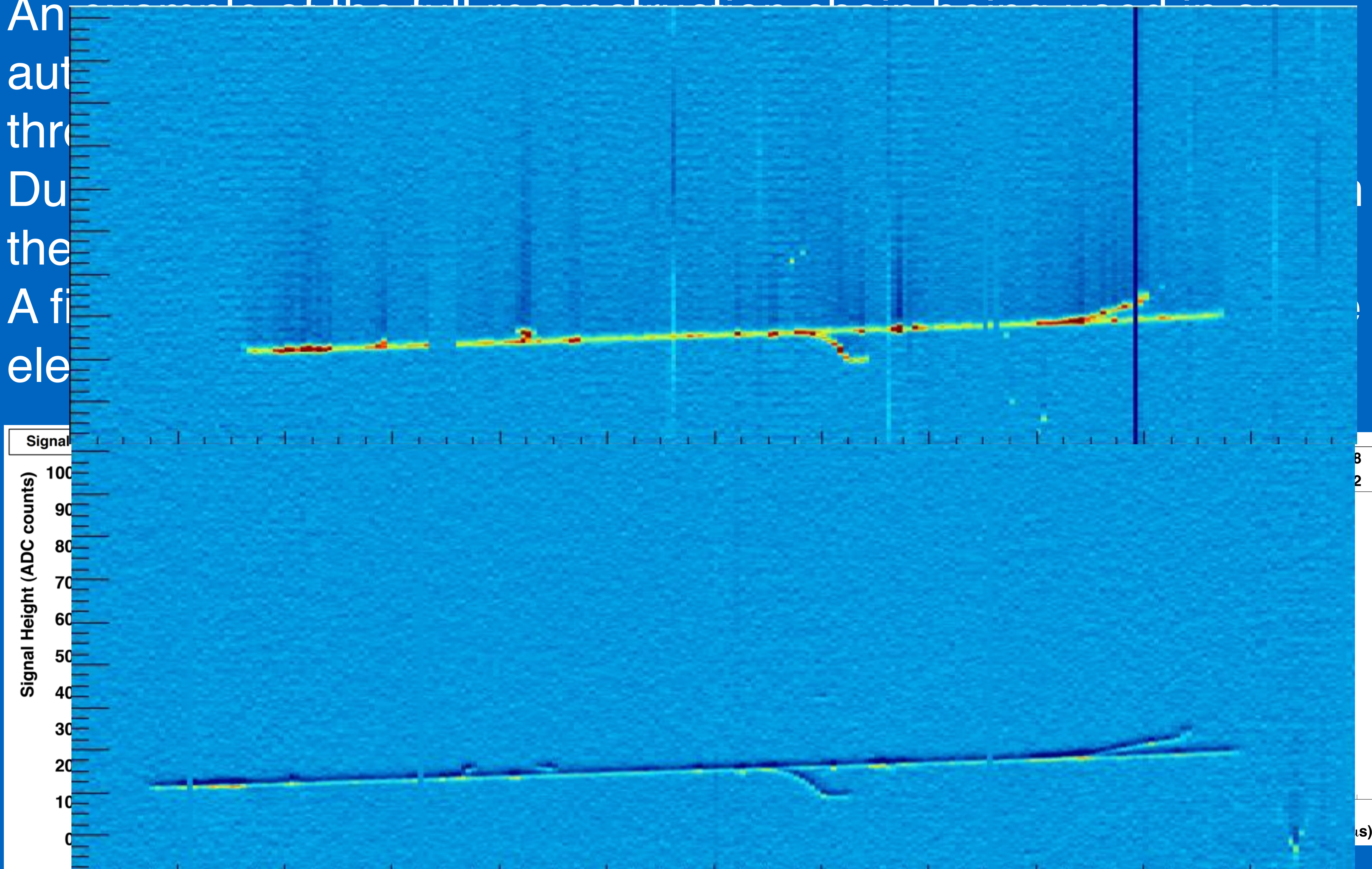

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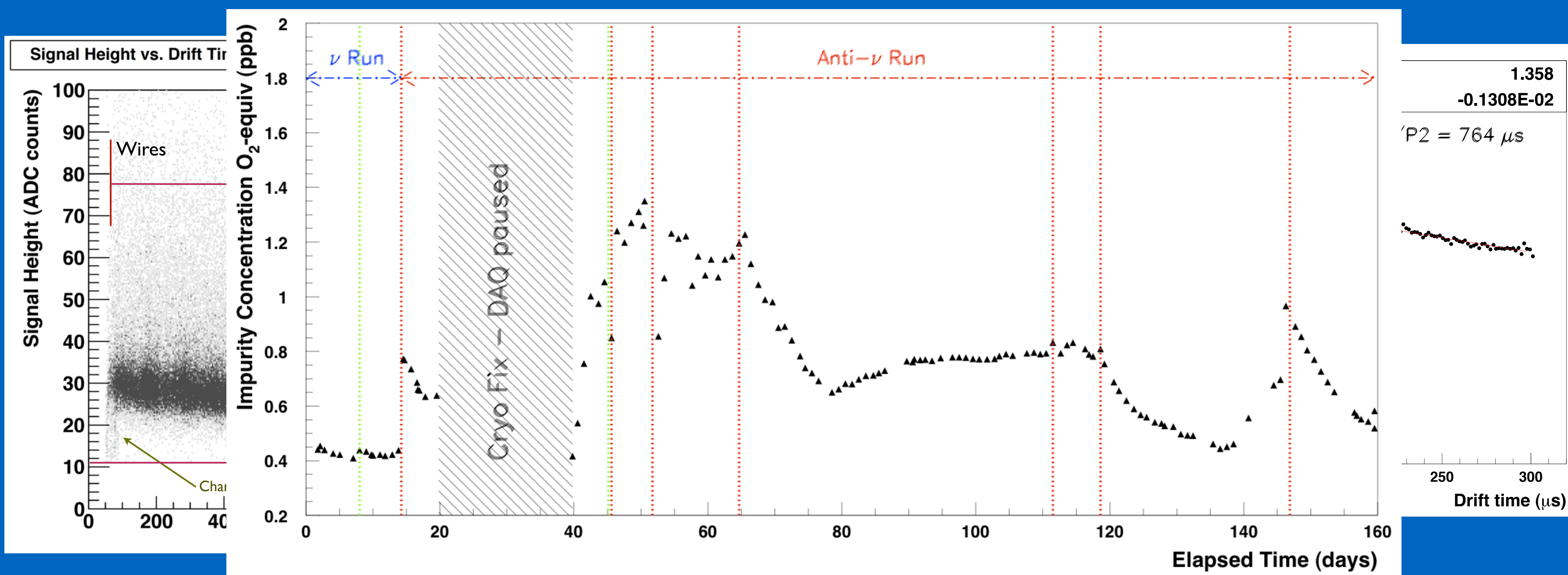

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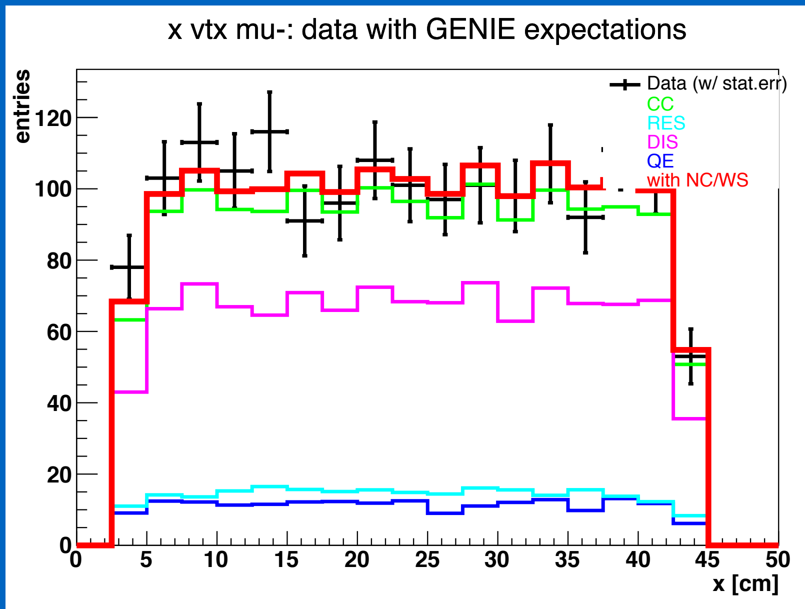
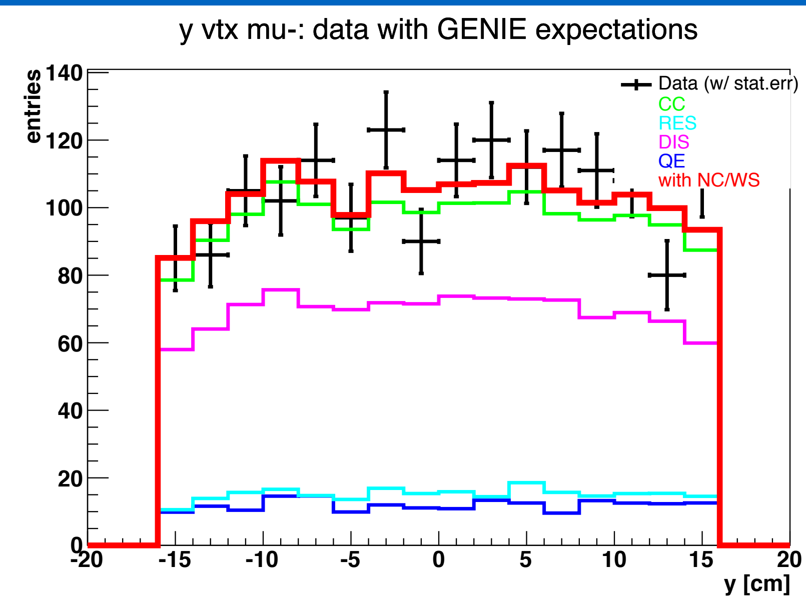
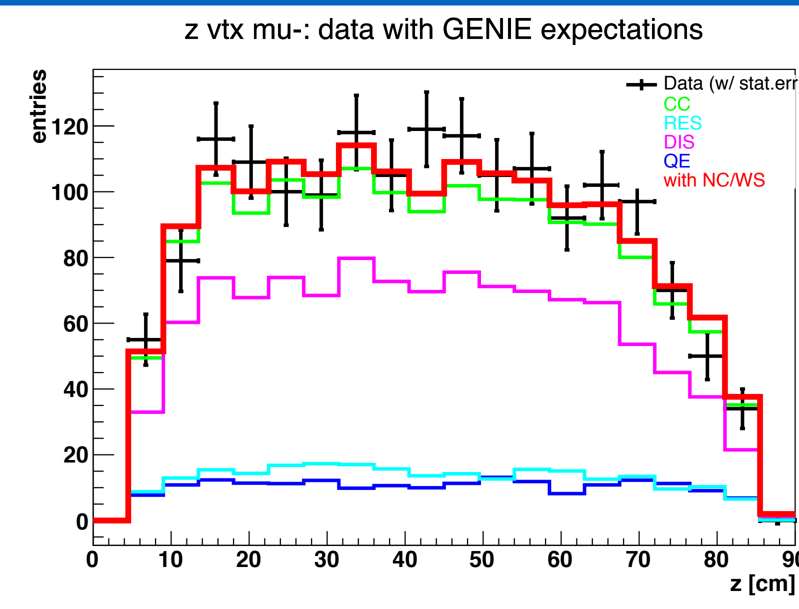
1.) *The ArgoNeuT Detectorin the NuMI Low-Energy Beam Line at Fermilab*, C. Anderson et al, JINST 7 P10019 (2012)

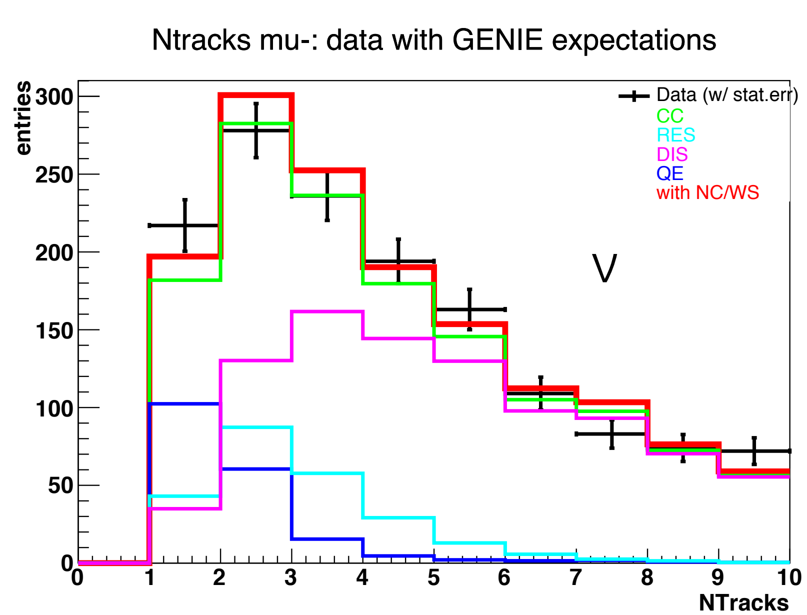
CC-Inclusive

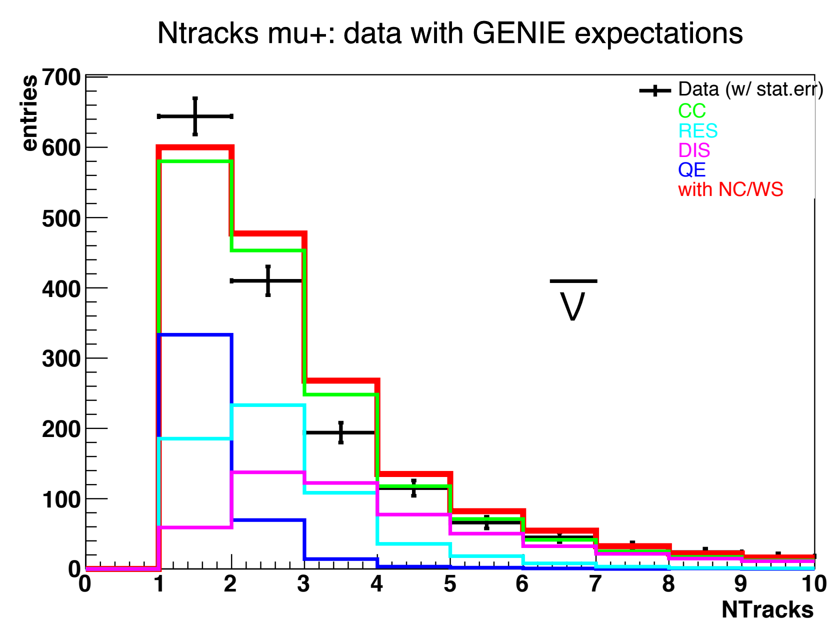
- Identify charged-current muon events in both neutrino and antineutrino mode.
- Selection simply requires a well reconstructed muon track originating in the TPC, matched to MINOS. No other restriction on activity in the event (i.e. - could be QE, Res, DIS, etc…).
- Fully automated analysis.







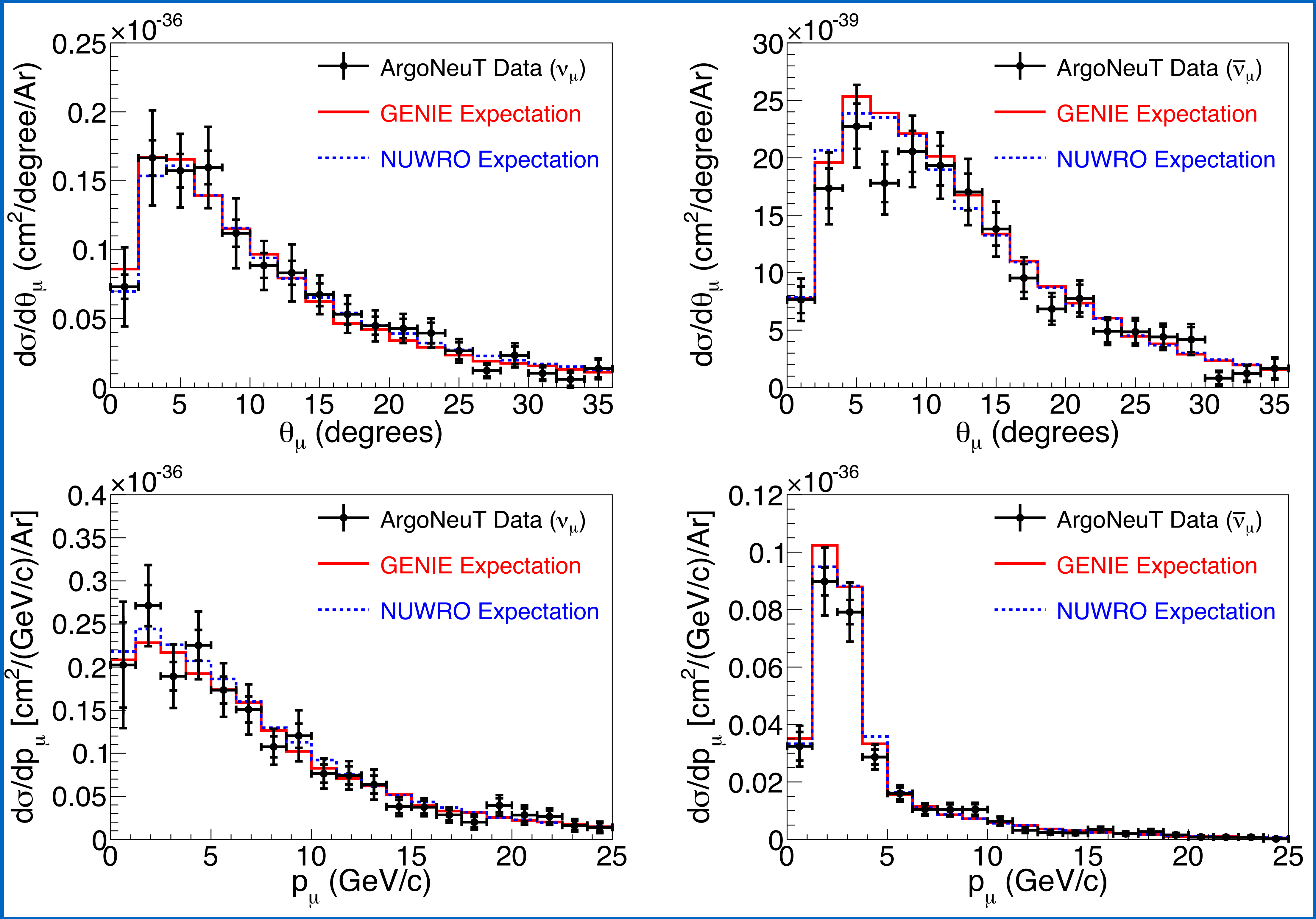




Refs:
1.)*Measurements of Inclusive Muon Neutrino and Antineutrino Charged Current Differential Cross Sections on Argon in the NuMI Antineutrino Beam*, R. Acciarri et al, PRD 89, 112003 (2014)

CC-Inclusive

- Differential cross-sections in terms of muon angle and momentum.



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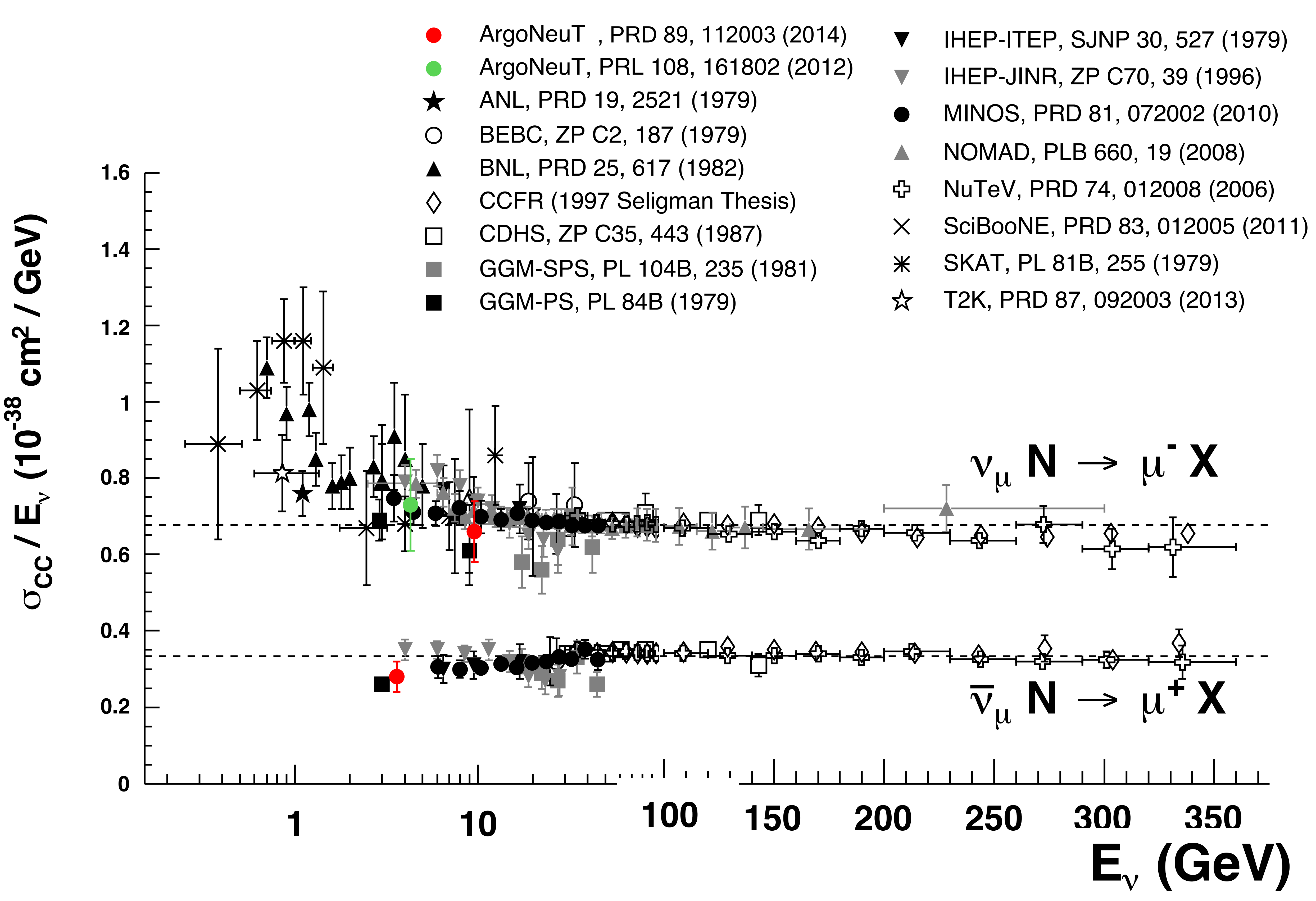
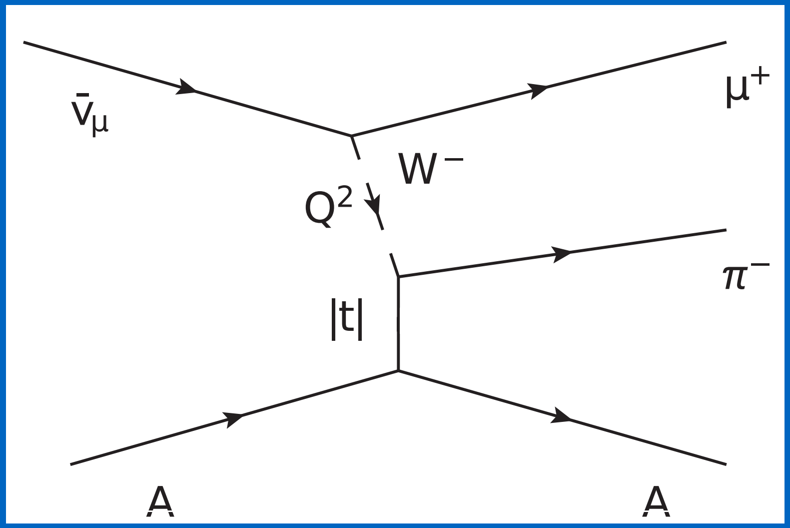
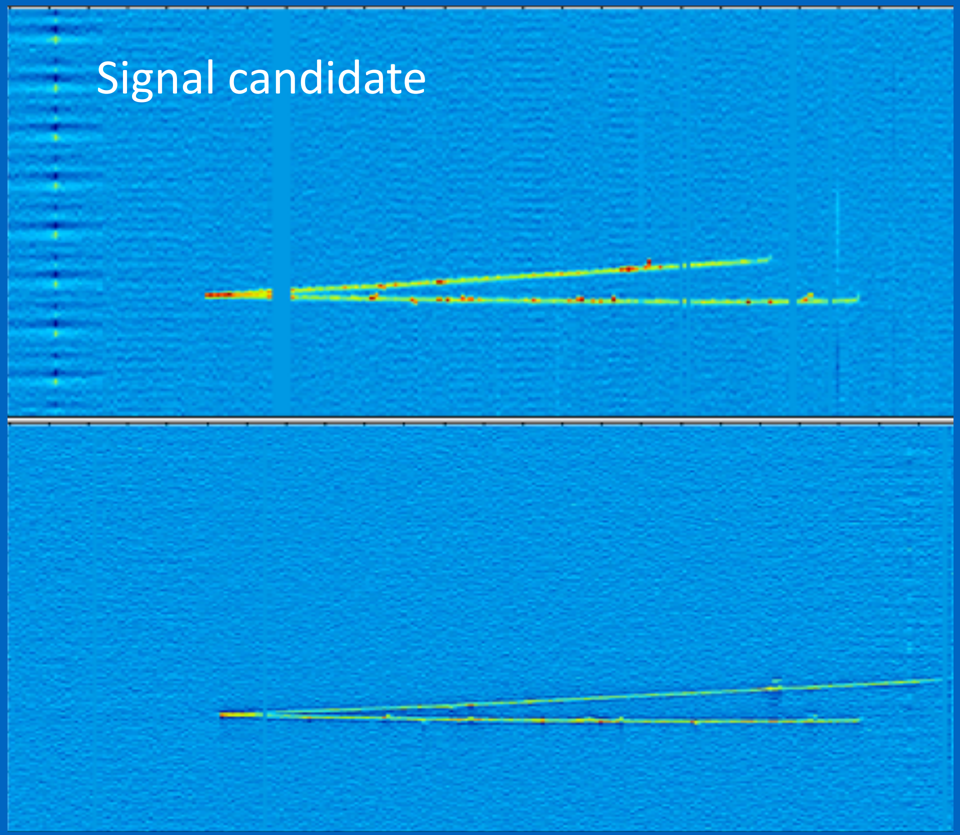


CC-Coherent

- Two-track event selection.
  - muon matched to MINOS
  - pion candidate track likely not contained, so:
    - must have <dE/dx> consistent with MIP
    - if contained, use calorimetry-based PID
  - no activity around vertex
- Fully automated analysis.

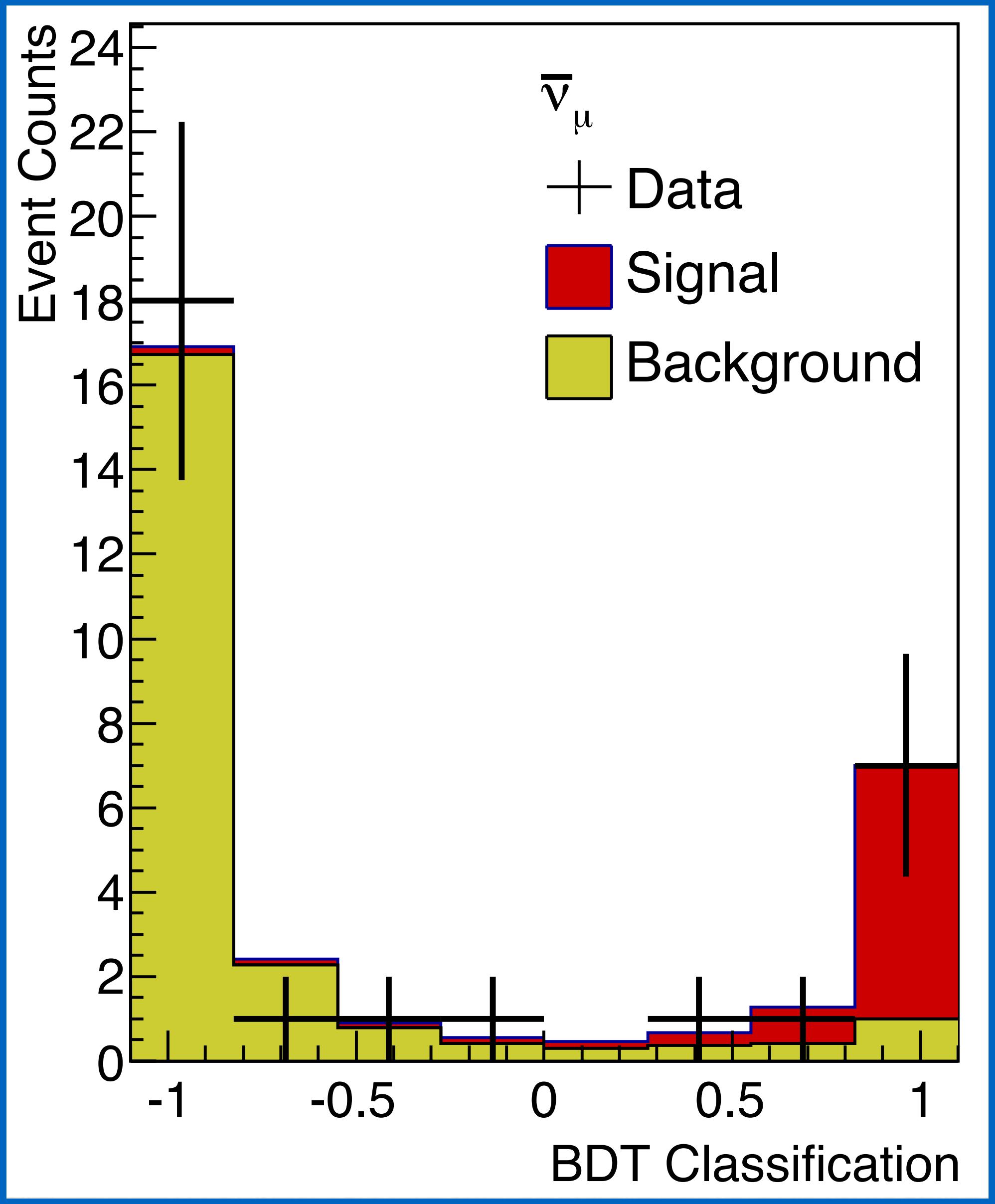


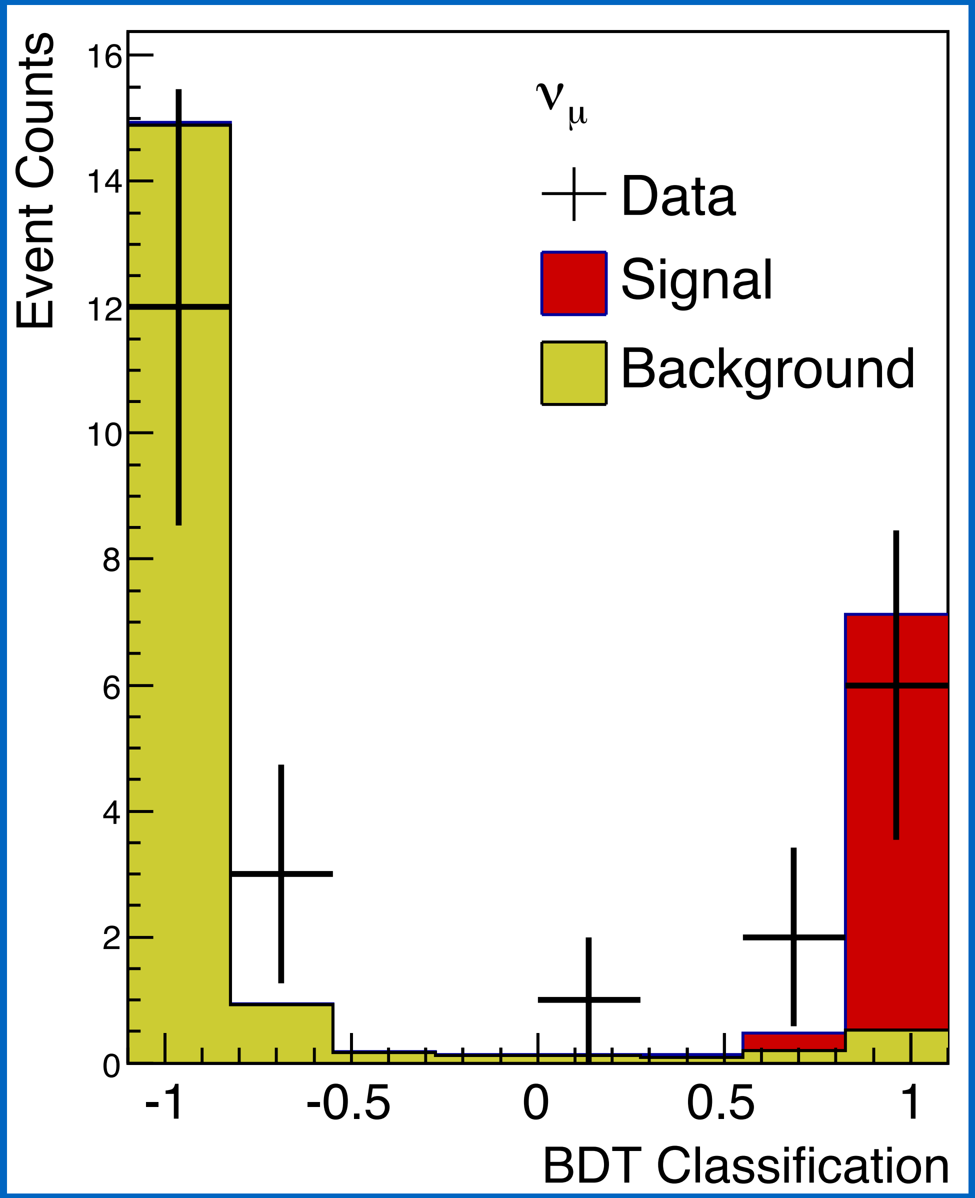
$$\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$$
$$\bar{\nu}_\mu + A \rightarrow \mu^+ + \pi^- + A$$



CC-Coherent

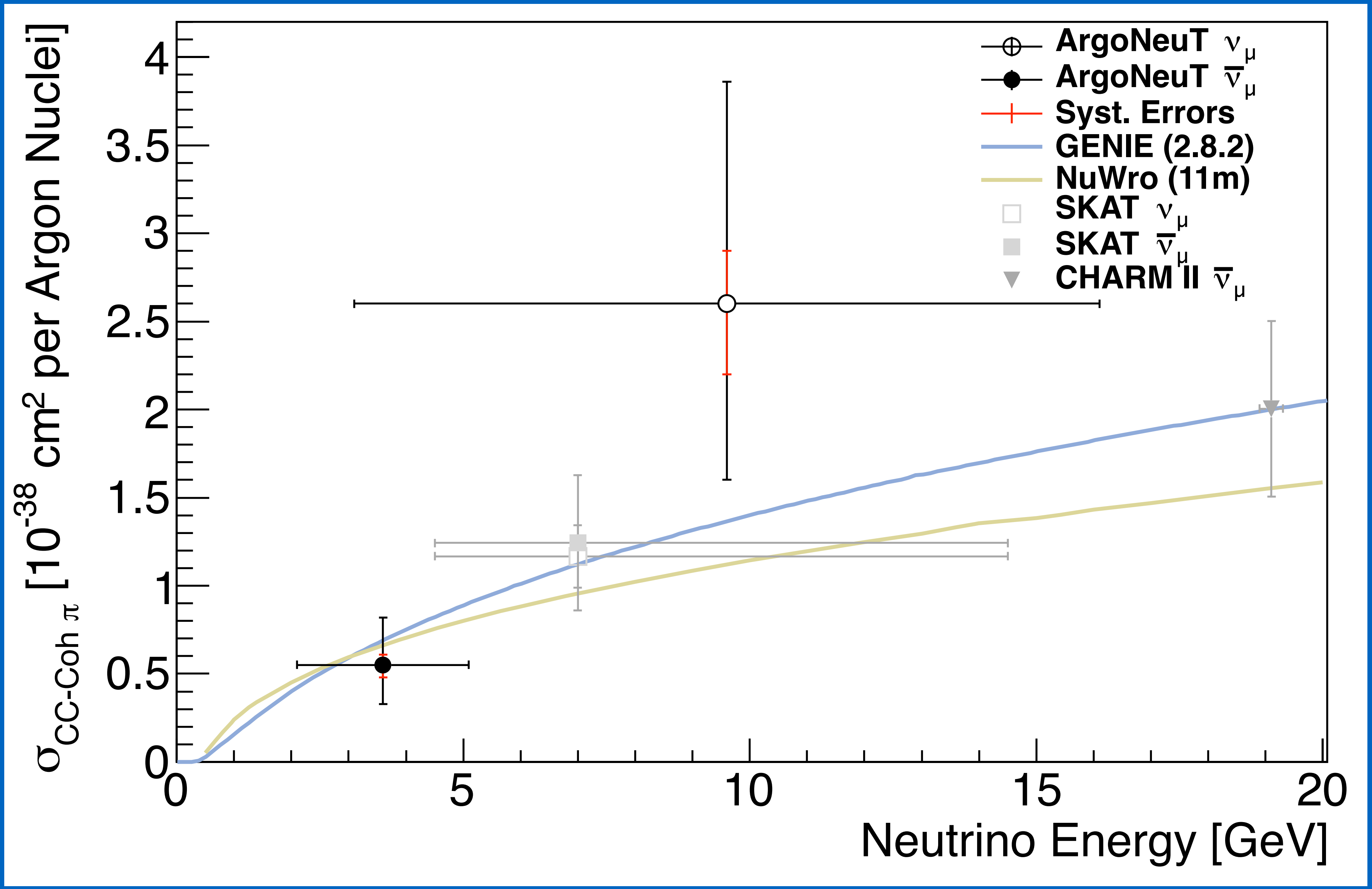
- Low statistics in ArgoNeuT, and small detector size removes ability to contain pion and cut on |t|
- MicroBooNE will solve both of those issues, in addition to being in a lower-energy beam where this process has been the source of experimental intrigue.





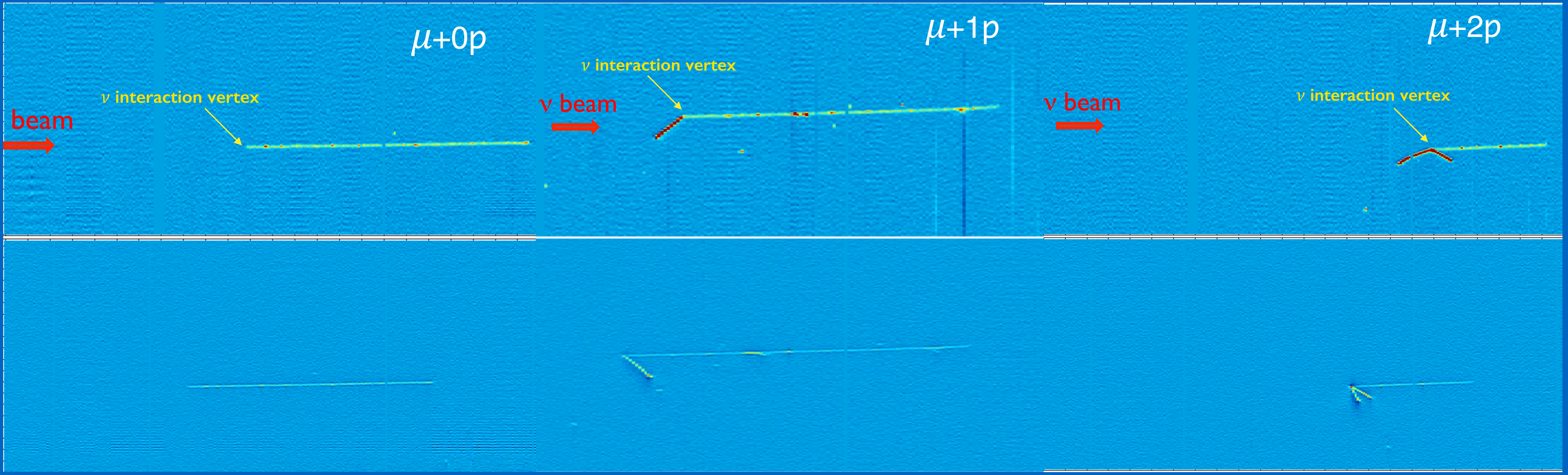
CC-Coherent

- Cross-sections measured for ArgoNeuT's neutrino/antineutrino sample.
- Use of BDT and similar machine-learning algorithms offer powerful discrimination tools.



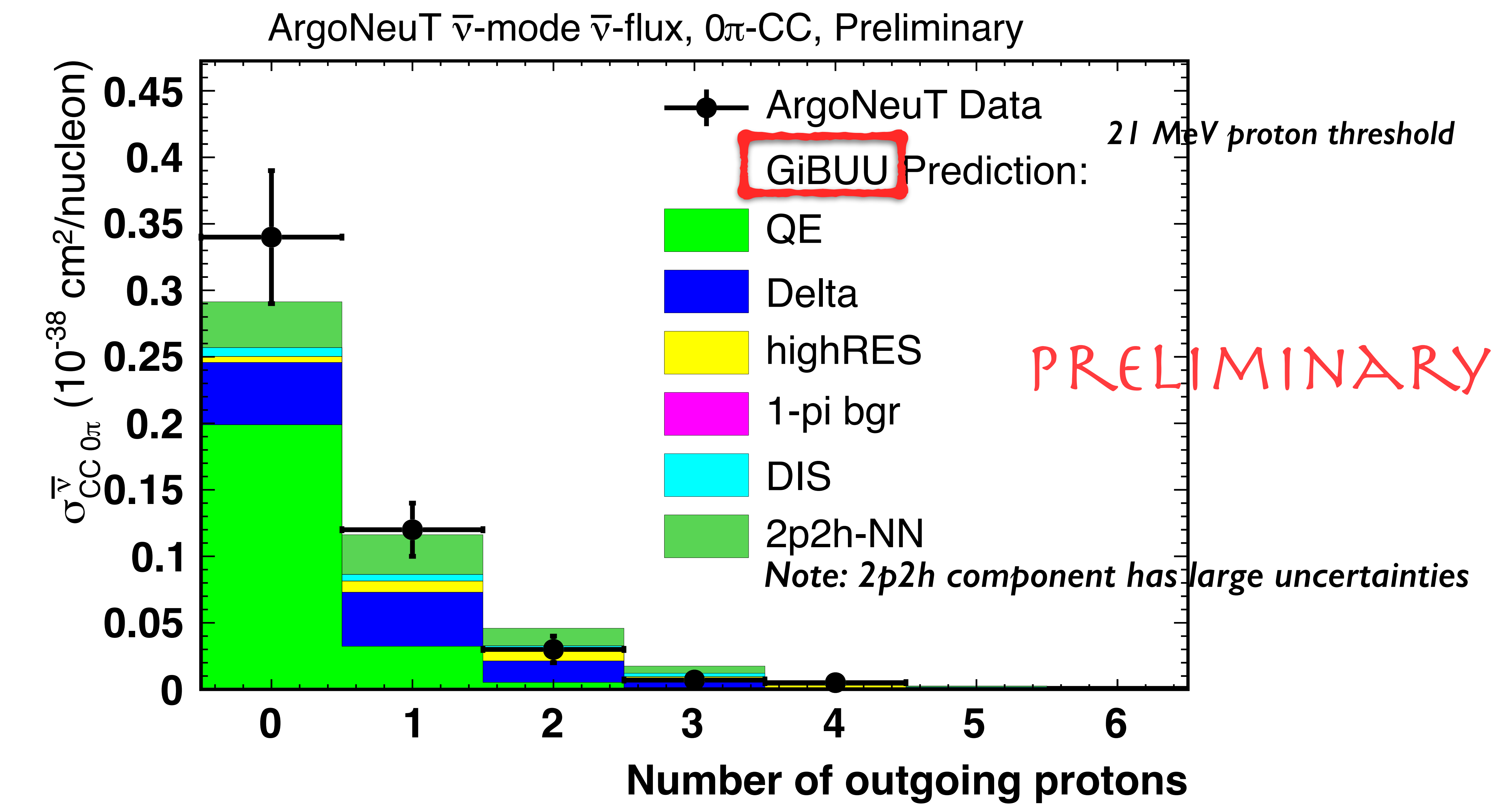
CC 0-pion

- Study charged-current events with no final-state pions, and any number of protons.
- Muons are matched to MINOS, and protons are contained and identified based on calorimetry.
- Proton kinetic energy threshold is 21 MeV.
- Hand-scanning is used in reconstruction of very low-energy protons.



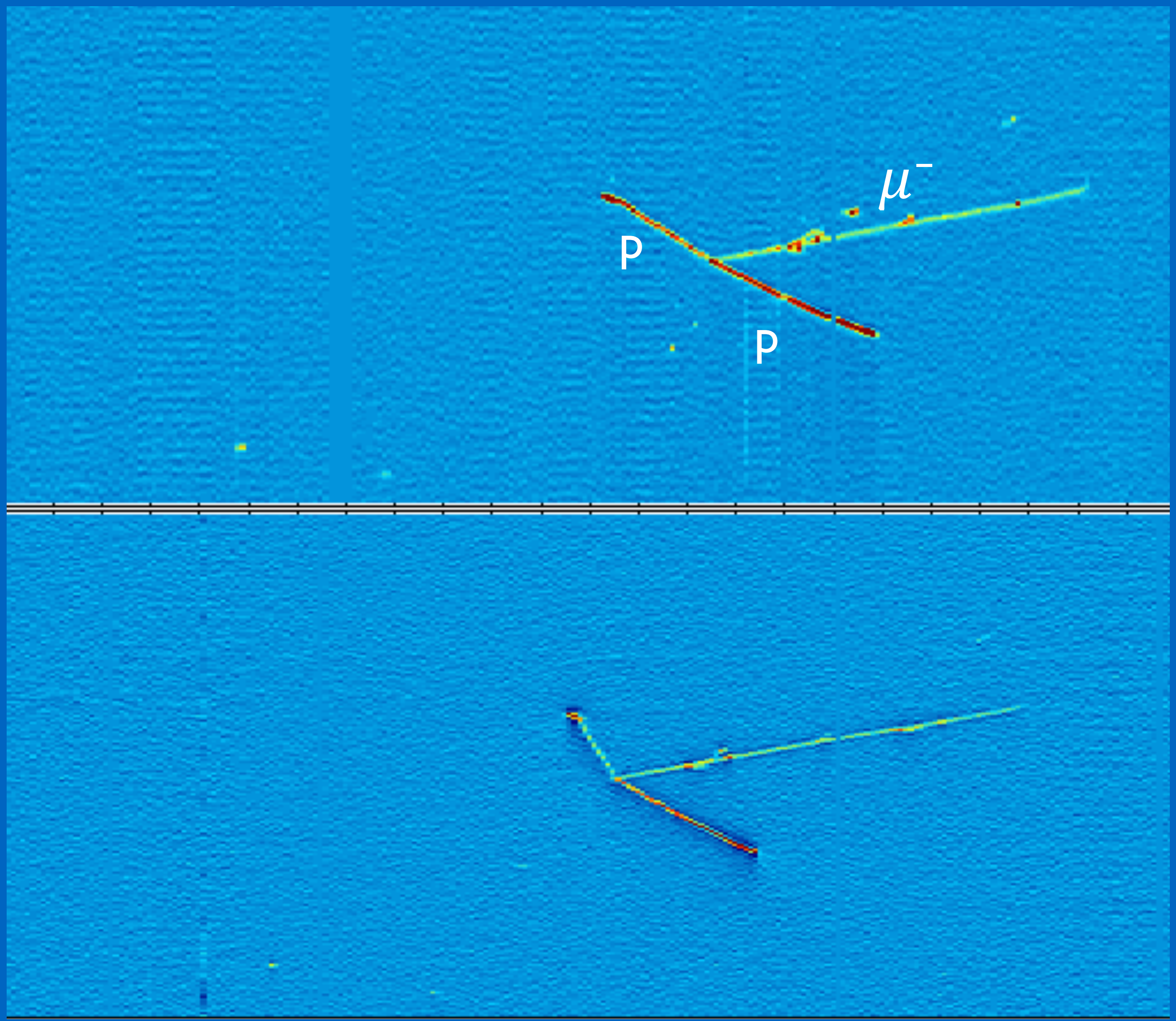
CC 0-pion

- Distribution of N-protons in these events compared to model.



Surprises?

- Looking in two-proton subsample, find events with protons in back-to-back configuration that is a signature of correlated nucleons.
- Statistics are low, but results are suggestive that SRC are active. MicroBooNE can look for this, and will have an even lower proton threshold.



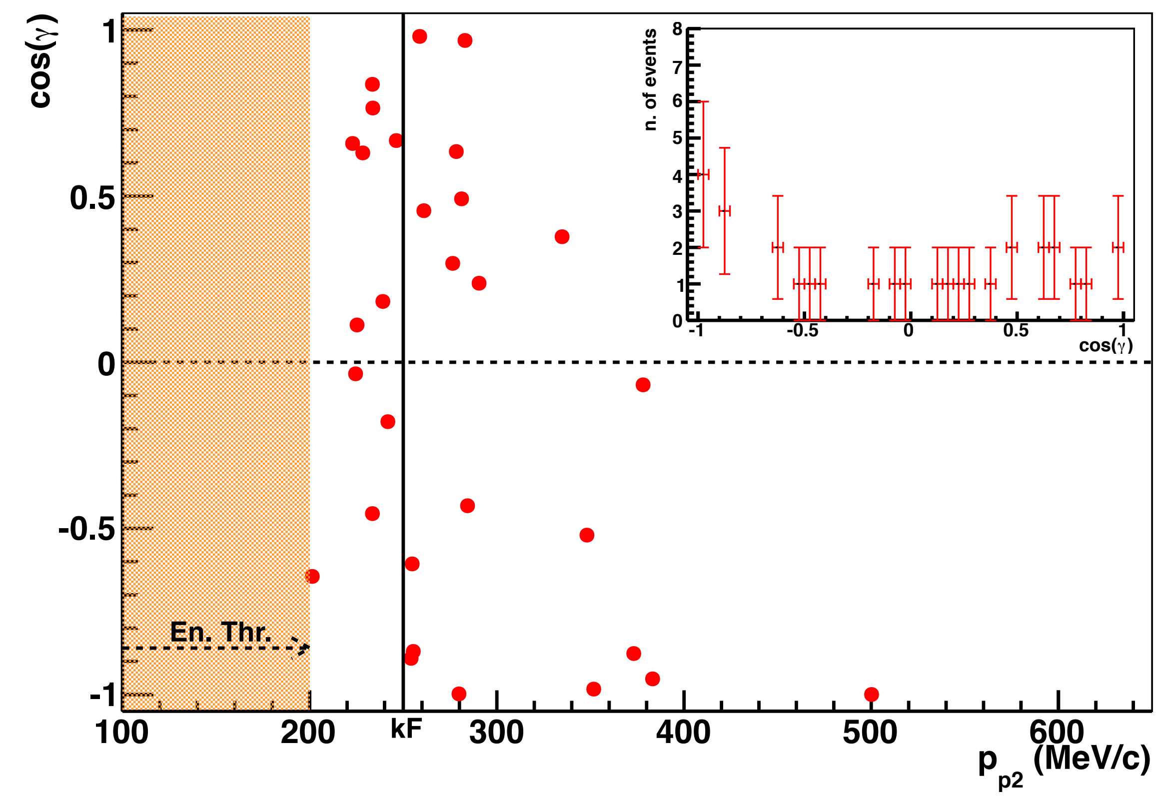
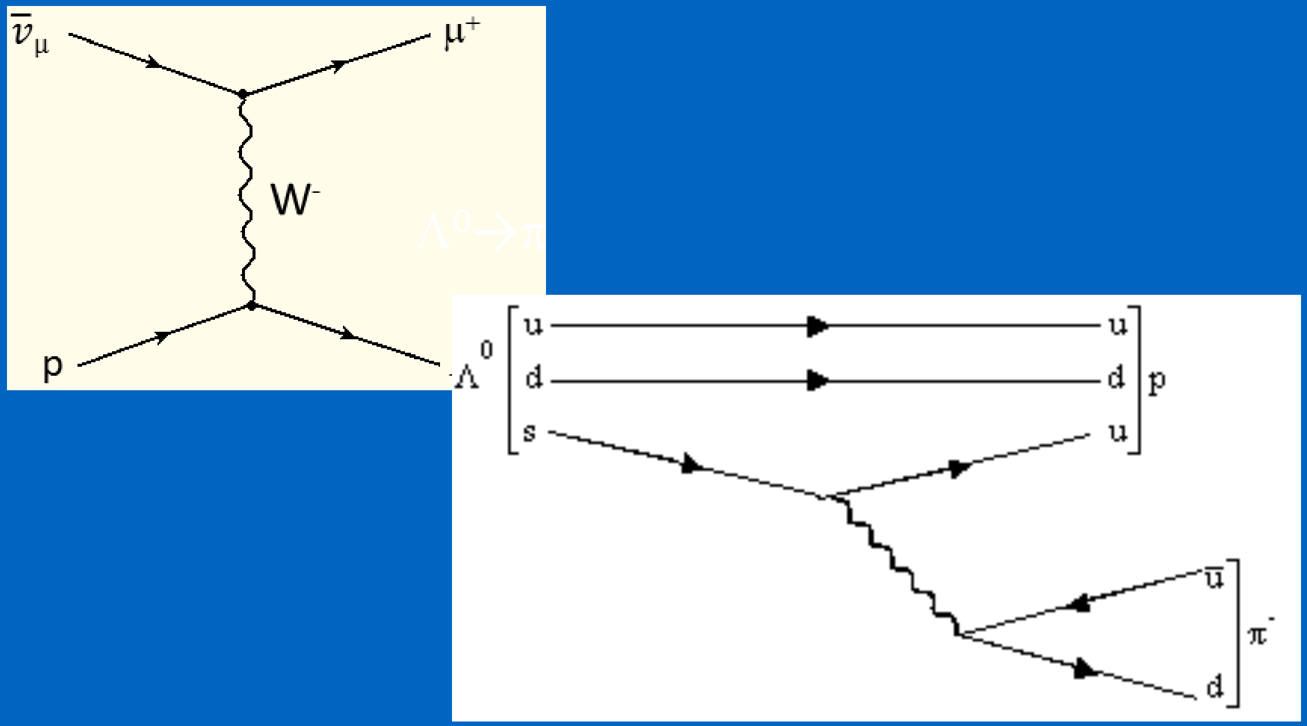


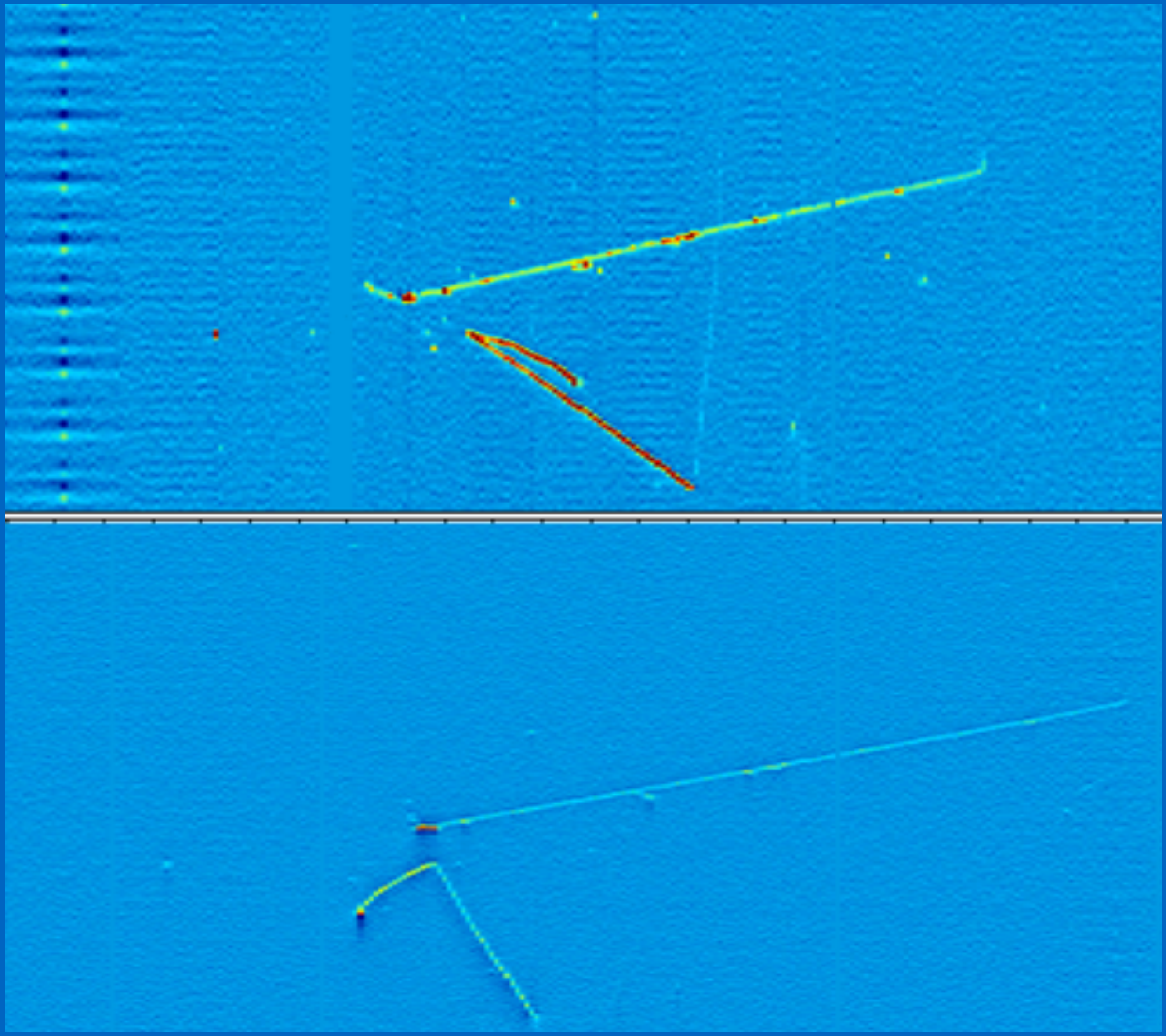
FIG. 2. Cosine of the angle γ between the two protons (Lab frame) vs. the momentum of the least energetic proton in the pair for the 30 events in the $(\mu^- + 2p)$ sample. In the inset is the distribution of $\cos(\gamma)$.

Refs:
1.)*The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT Detector in the NuMI low energy beam line*, R. Acciarri et al, PRD 90 012008 (2014)

Hyperon Production

- Spatial resolution allows displaced vertices to easily be identified.
- Look for displaced vertex consistent with neutral Lambda decay.
- ArgoNeuT has a small sample of candidates that are being analyzed.





Apologies for skipping…

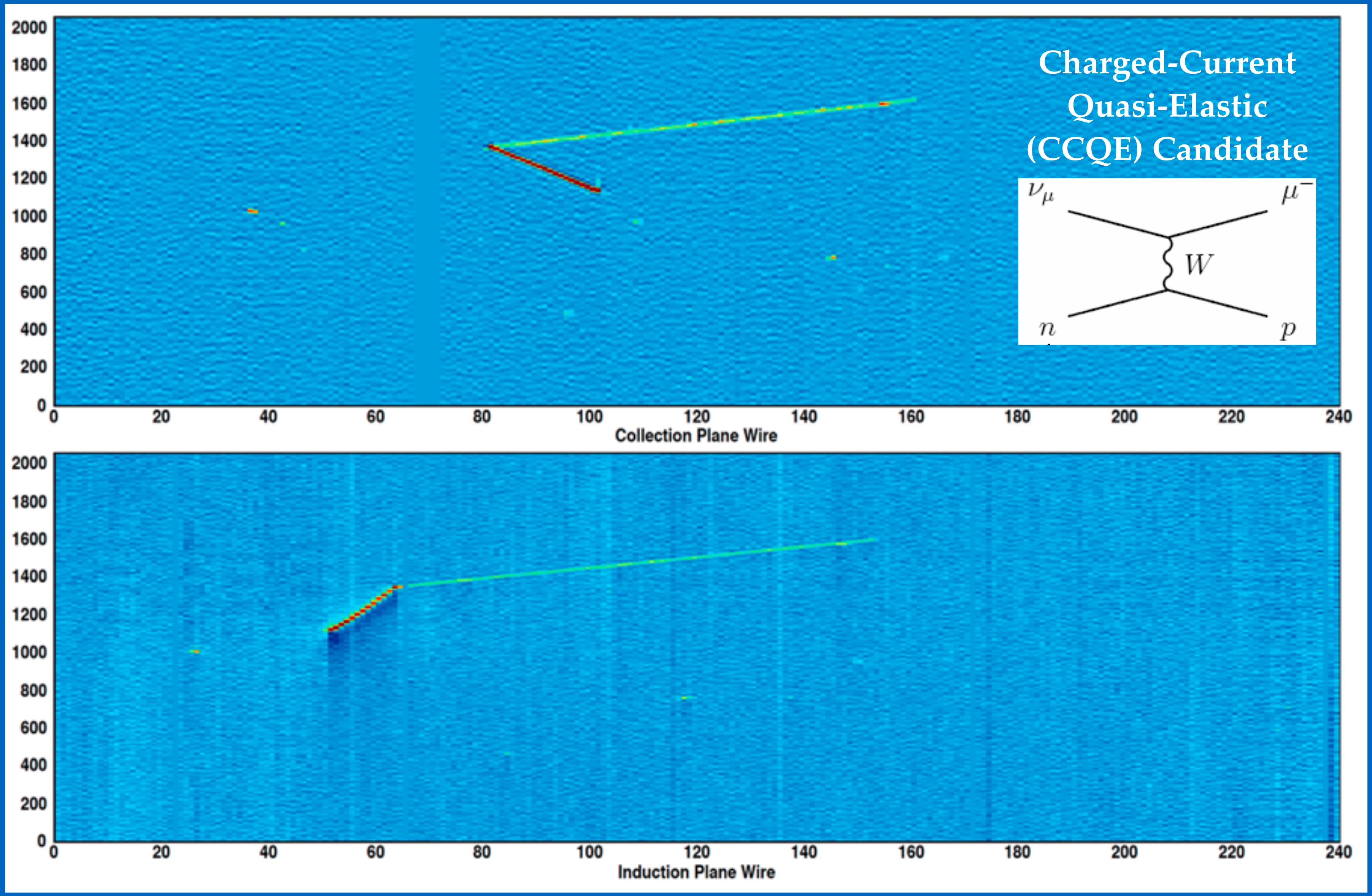
- Light-collection system reconstruction and matching to TPC information.
- Neutral-current analysis and pi0 mass reconstruciton.
- Lots of other great topics pursued by MicroBooNE/ LArIAT/LAr1-ND/LBNF/ICARUS/etc…

Conclusions

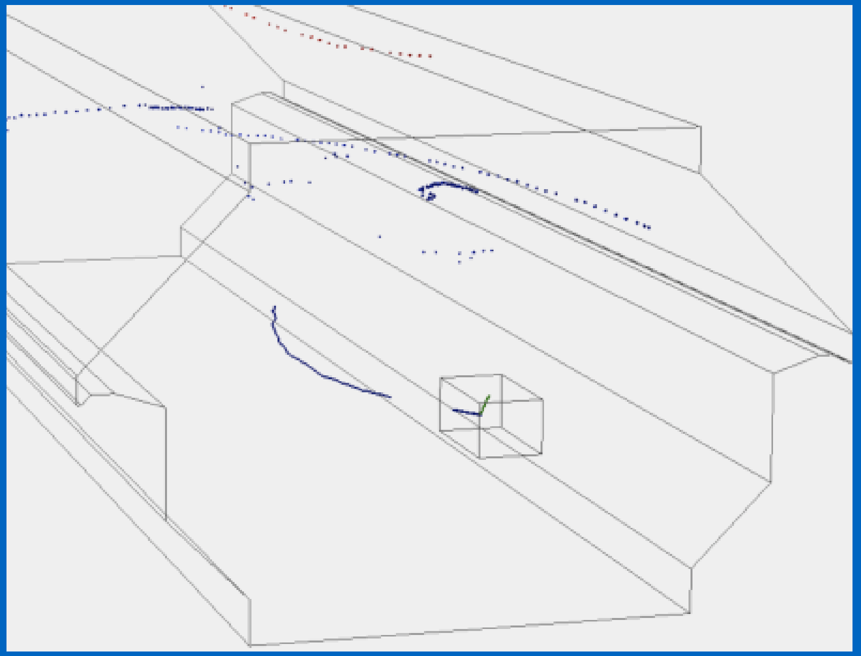
- LArTPCs offer detailed view into neutrino interactions.
- Reconstructing interactions presents interesting challenges. Very active software development effort ongoing to catch up to the pace of hardware development.
- Numerous physics results have already emerged (e.g. - ArgoNeuT, ICARUS), and with MicroBooNE/LArIAT poised to take data you should expect many more.

THANK YOU FOR YOUR ATTENTION!

Tracking



Charged-Current
Quasi-Elastic
(CCQE) Candidate
ν_μ
μ^-
W
n
p
Collection Plane Wire
Induction Plane Wire



Particle Identification

- Neutral pions can be identified through both calorimetry and topology.
- Two showers, with photon-like dE/dx, pointing to a common vertex.