# Study of the reconstruction of $\nu_\mu CC$ QE events from the booster neutrino beam with the ICARUS detector

Annual Report - INTENSE Meeting

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Imaging Cosmic And Rare Underground Signals

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# Outline

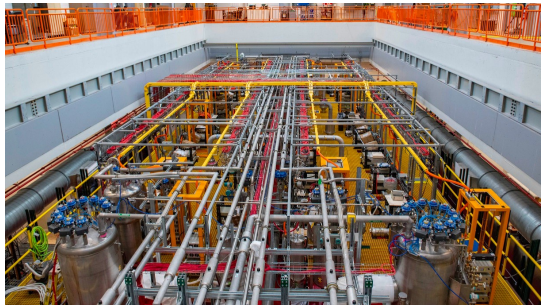
GOAL: perform a precise reconstruction of $\nu_\mu$ $CC$ QE events

STEPS:

1. Is the particle contained? Define containment conditions
2. Is the particle well reconstructed? Check key reconstructed variables and hit completeness → Ongoing studies (LOADING)
3. Is the detector well calibrated? Perform calorimetric reconstruction and particle identification
4. Are we missing something? Validate track and shower discrimination → Ongoing studies (LOADING)

# Short Baseline Neutrino Program at FNAL

- Several anomalies have been observed in neutrino oscillations experiments, some of them can be explained by introducing an additional sterile neutrino state ($\nu_s$)

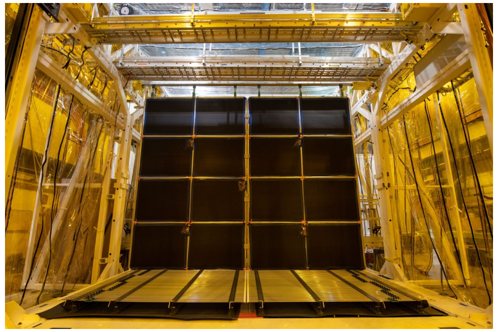


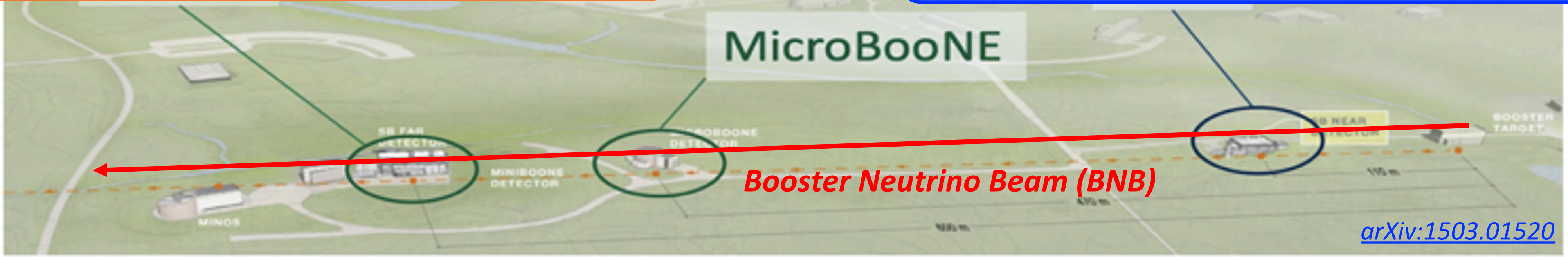
***ICARUS***

*$600\ m$ baseline*
*$476\ t$ active volume*
***Data Taking***

***SBND***

*$110\ m$ baseline*
*$112\ t$ active volume*
***Under Construction***

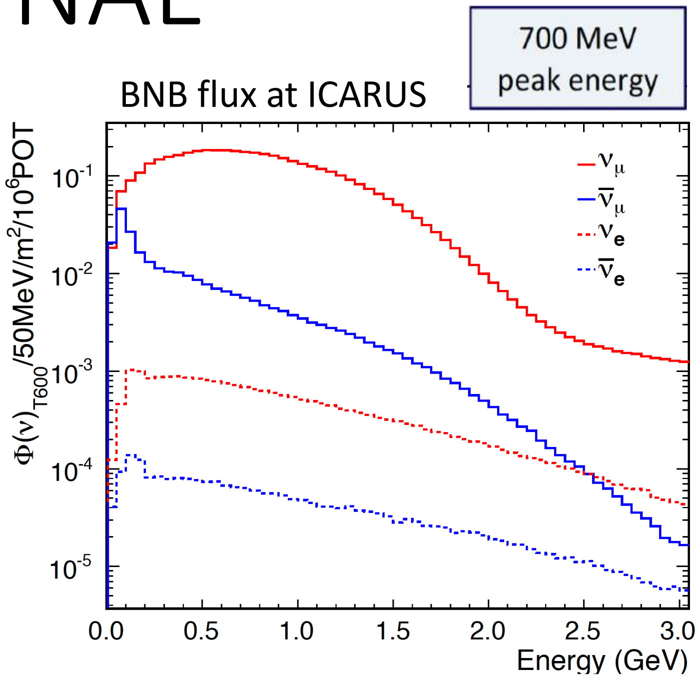




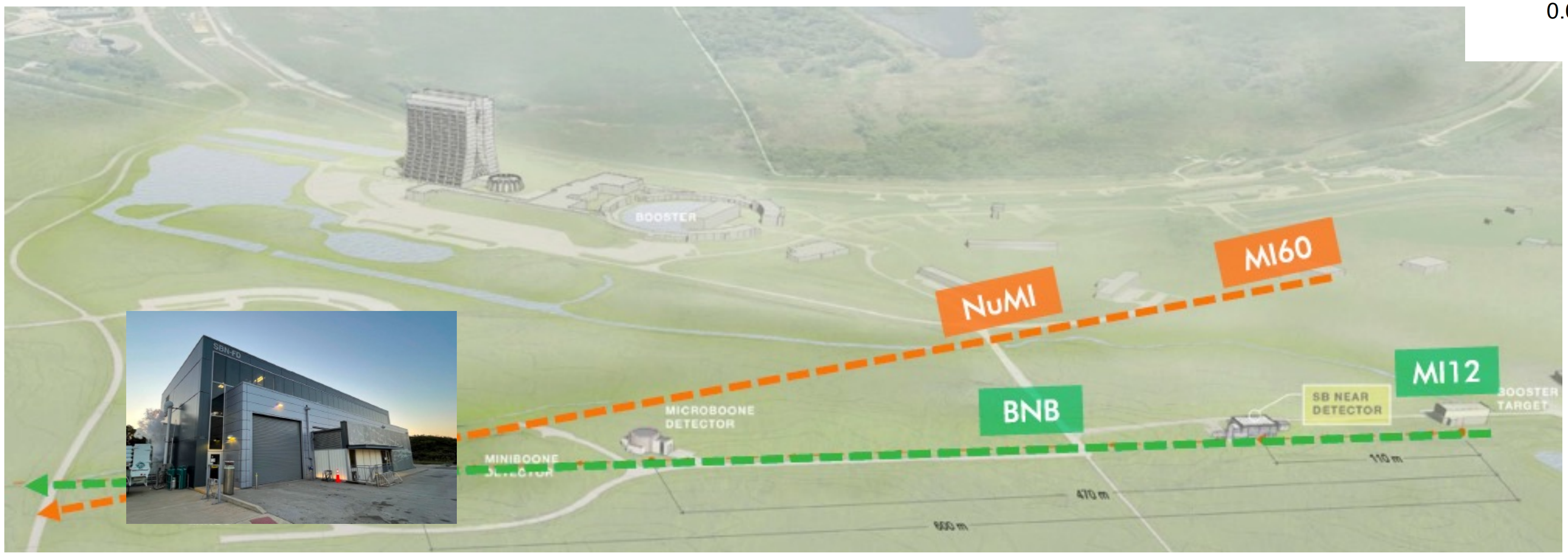

- Short Baseline Neutrino Program (SBN) main goal is to search for sterile neutrino oscillations
- Consists of 3 Liquid Argon time-projection chambers (LArTPCs) sampling the same neutrino beam (BNB) at different distances
- ICARUS is the Far Detector, located at $600\ m$ from the Booster target

# Short Baseline Neutrino Program at FNAL

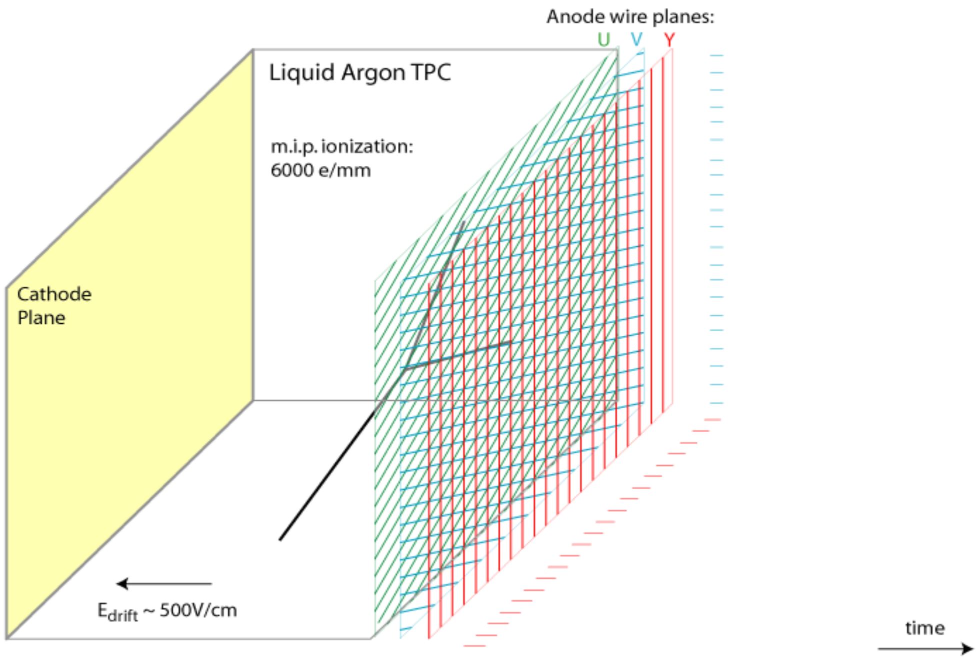
- **BNB** is a well characterized $\nu_\mu$-beam, able to produce $\nu$ and $\bar{\nu}$ beams with low $\nu_e$ contamination ( $0.5\ \%\ \nu_e$ content )
- ICARUS is also exposed off-axis ($6°$) to the **NuMI beam** providing an independent cross check to BNB oscillation results
  - Grant access to the $\nu_e$ rich component of the spectrum (up to $3\ GeV$)




arXiv:1503.01520

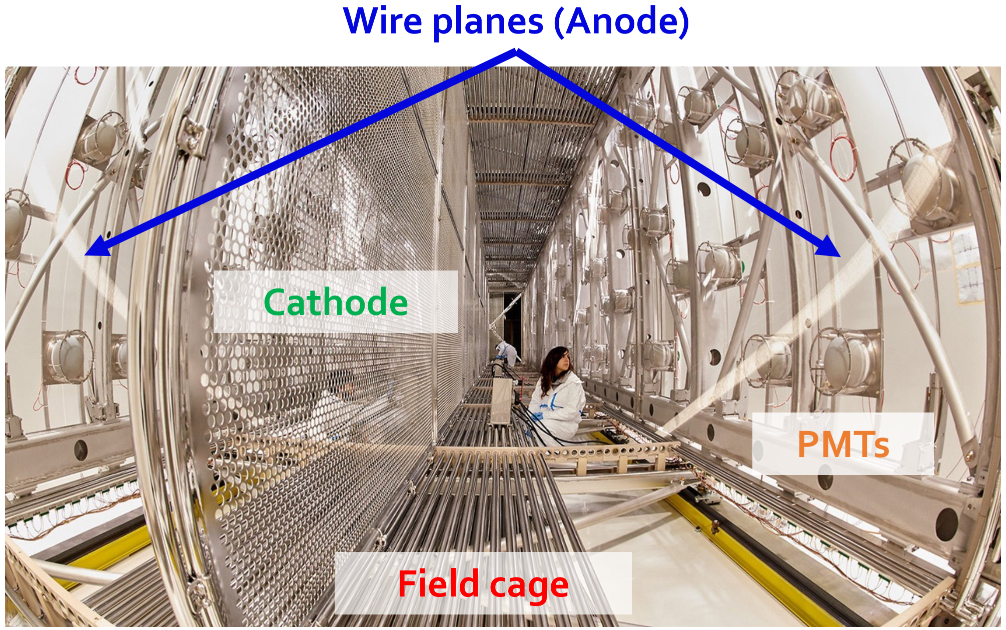


# LAr TPC Working Principle




- When a neutrino interacts with liquid argon it produces charged particles that deposit their energy, creating ionization electrons and scintillation light (VUV photons)
- The scintillation light propagates inside the detector until it is collected by the PMTs behind the wires. We use this light to recognize where and when an interaction has occurred
- The ionization electrons are collected in the wire planes, thanks to the electric field. We combine the collected signals to obtain a complete 3D reconstruction of the event
- To avoid signal attenuation ultra pure liquid argon is mandatory; E.g. ICARUS has a maximum drift distance of $1.5\ m$, the level of electronegative impurities should be lower than $0.1\ ppb\ (3\ ms)$

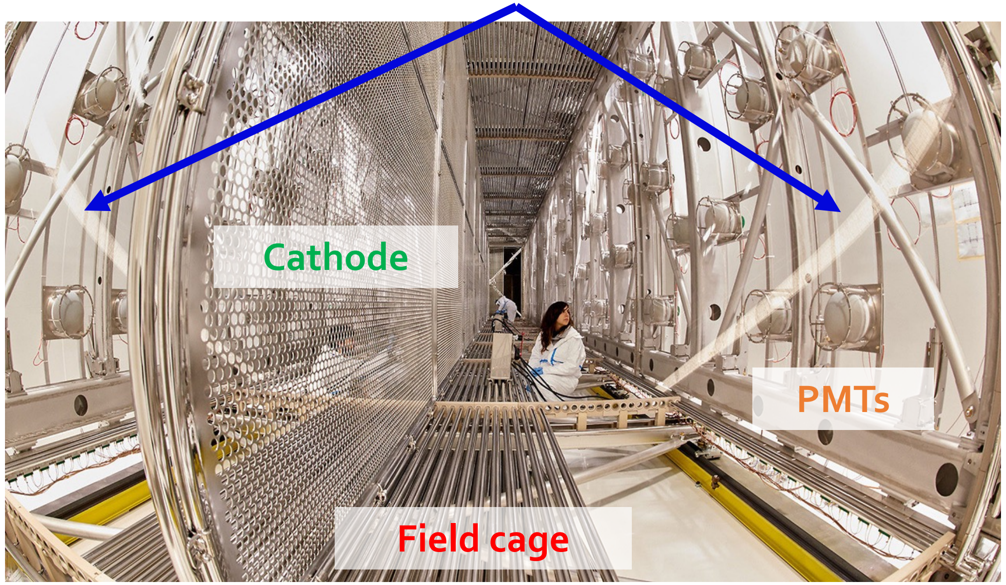
# The ICARUS detector




Inside ICARUS: internal view of one cryostat

- ICARUS-T600 LAr TPC is a high precision self-triggering detector with 3D imaging and calorimetric capabilities, perfect for neutrino physics
- Composed of 2 identical cryostats, each one hosting 2 TPCs with a common central **cathode**
    - $1.5\,m$ drift length and $E_{Drift} = 500\,V/cm$
- Ionization charge continuously read ($400\,ns$ sampling time) by 3 readout **wire planes** per TPC, $\approx 54$k wires, at $0°$, $\pm 60°$ w.r.t horizontal to allow 3D reconstruction and $3\,mm$ pitch

# The ICARUS detector

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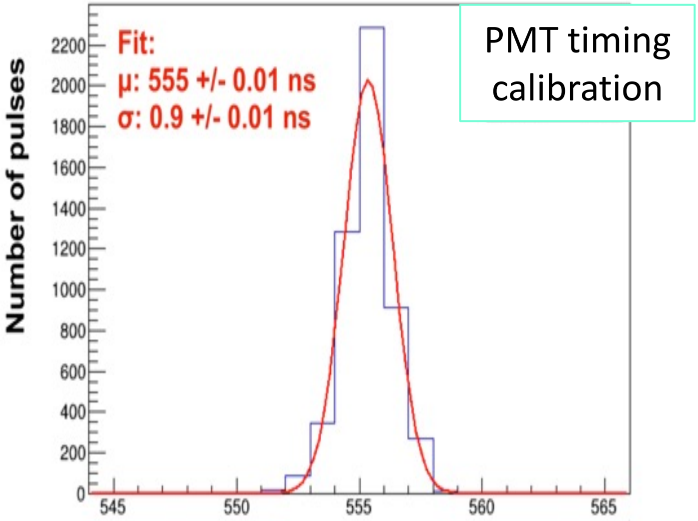
- 360 **PMTs** ($8''$) located behind the wires collect the scintillation light for timing and triggering purposes:
  - Precise identification of interaction time, $\sim ns$ time resolution
  - Localization of events with spatial resolution $< 50\,cm$
- LAr purity level is continuously monitored and allows an efficient signal detection over the full LAr volume



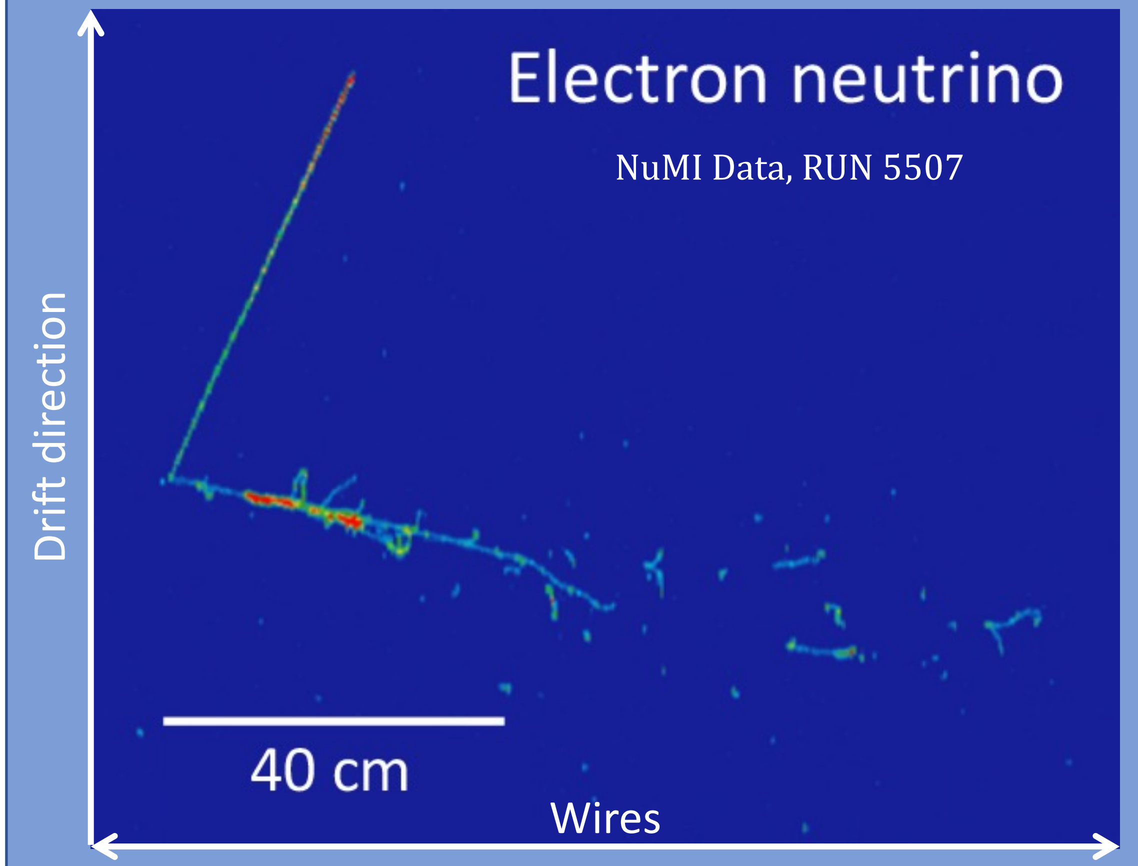

$\Delta t = t_{\mathrm{PMT}} - t_{\mathrm{TRIGGER}}\ (ns)$

# From images to physics

- LArTPC detectors produce high resolution images of particle interactions allowing a precise reconstruction of its trajectories and fine calorimetric measurement

- We need to reconstruct these interactions from the raw images to perform high level analysis

- An important piece in the reconstruction process is the **pattern recognition algorithm** which:
  - Identifies the individual particles and their relationship to each other
  - Arranges these particles into hierarchies
  - Determines their 3D trajectories




$$\nu_e + n \longrightarrow p + e$$

Electron neutrino interaction that produced a proton (1) and an electron. The later produced an EM shower with photons and electrons (2)

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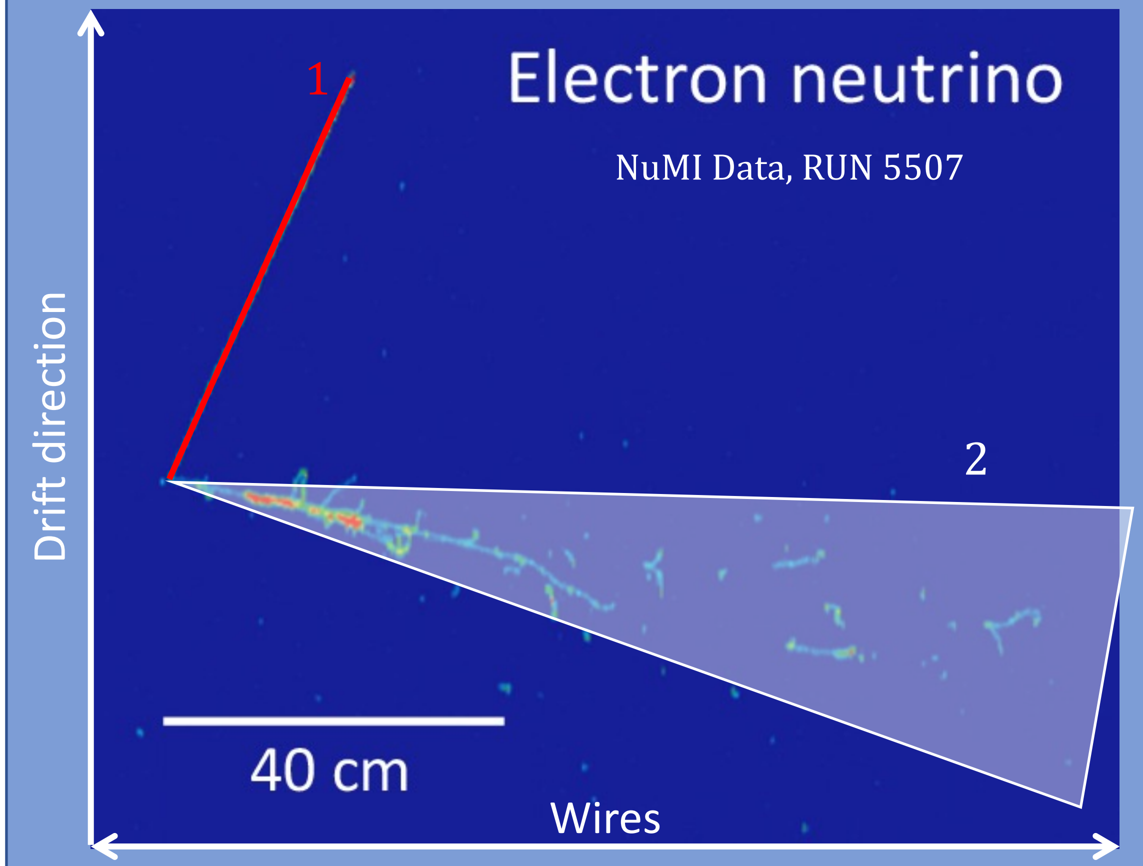


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# From images to physics

- LArTPC detectors produce high resolution images of particle interactions allowing a precise reconstruction of its trajectories and fine calorimetric measurement

**Due to the large amount of data to analyse, an automated solution is mandatory !!**

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# The reconstruction pipeline

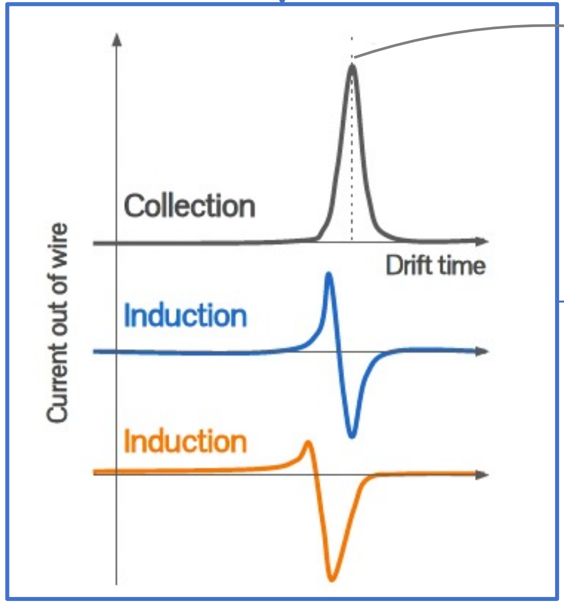
Detector Data → Low-level image processing → Hit finding → Pattern recognition → Particle fits → High Level Analysis

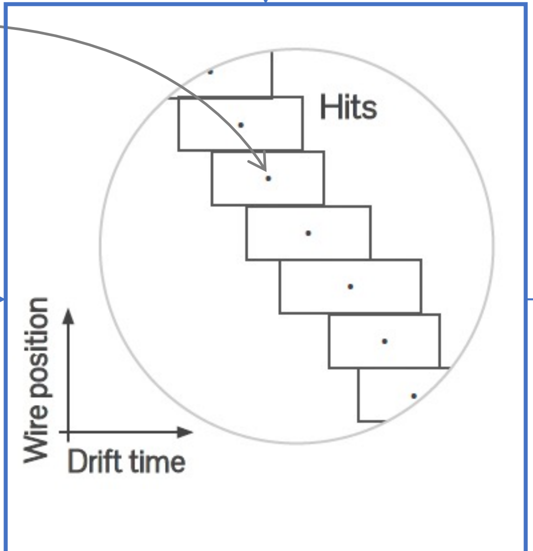
**Low-level image processing**
- Decoding
- Deconvolution
- ROI Finding

**Hit finding**
- Gaussian hits
- Cluster 3D

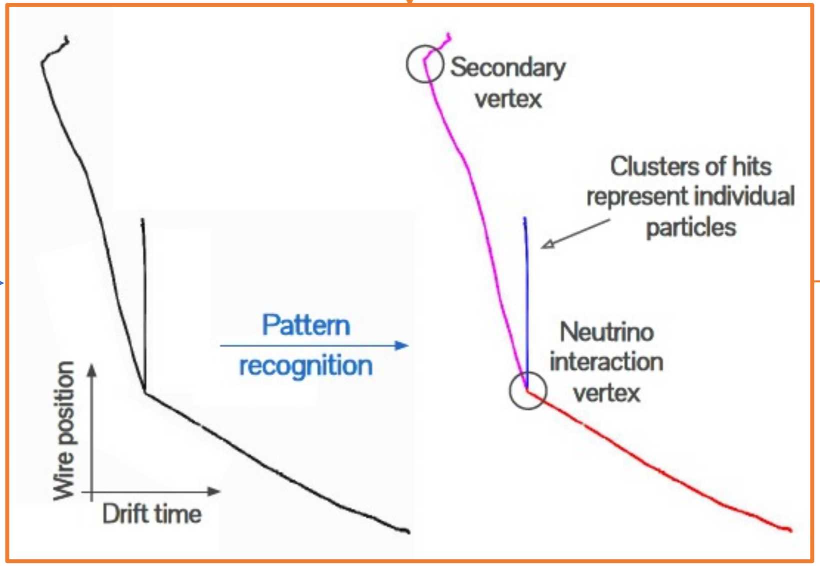
**Pattern recognition**
- Pandora Algorithm

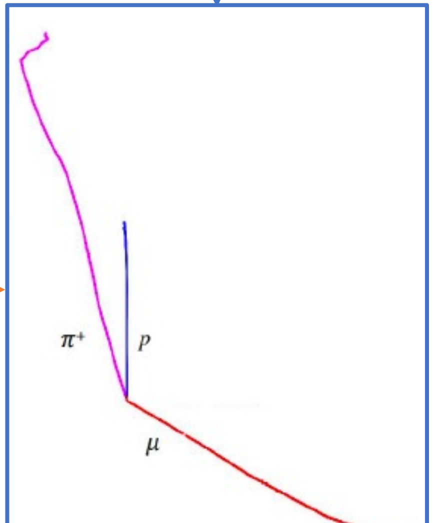
**Particle fits**
- Track, shower fits
- Calorimetry
- Particle ID




*hit: signal in a single wire

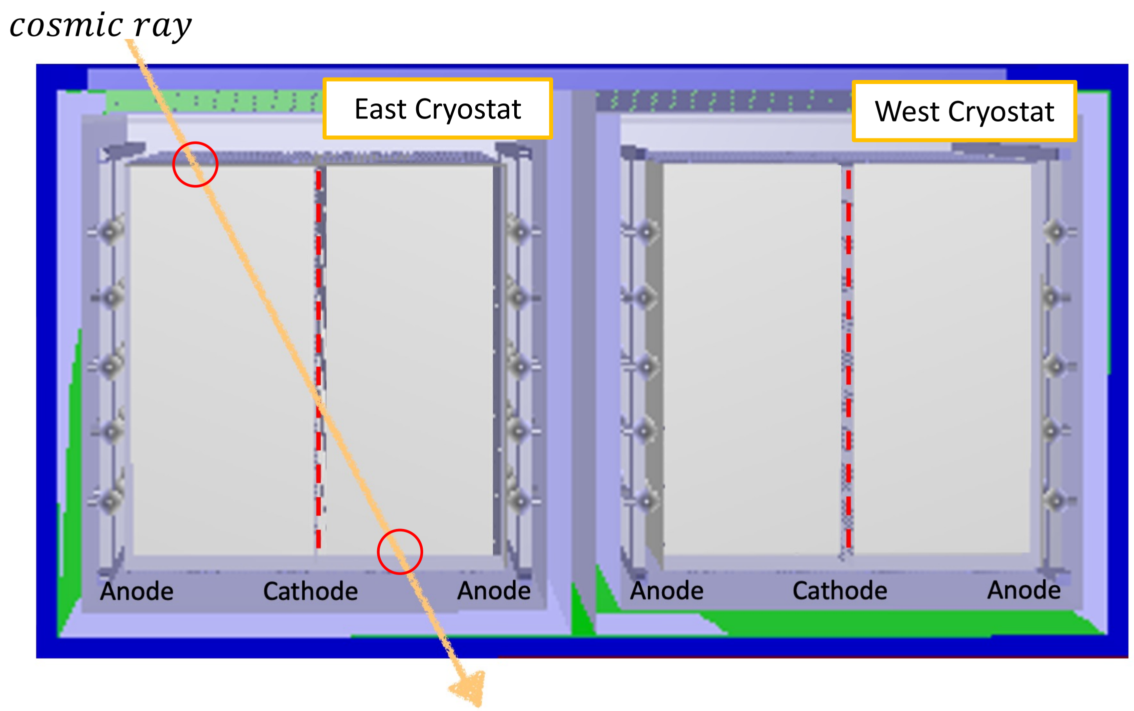


# Containment conditions

- Our main goal is to optimize the detector response in order to perform a high-quality analysis for neutrino events
- At the moment we are interested in $\nu_{\mu} CC$ QE contained events, which guarantees us that all calorimetric variables can be fully reconstructed
- Containment conditions are very effective in rejecting backgrounds events associated to charged cosmics rays

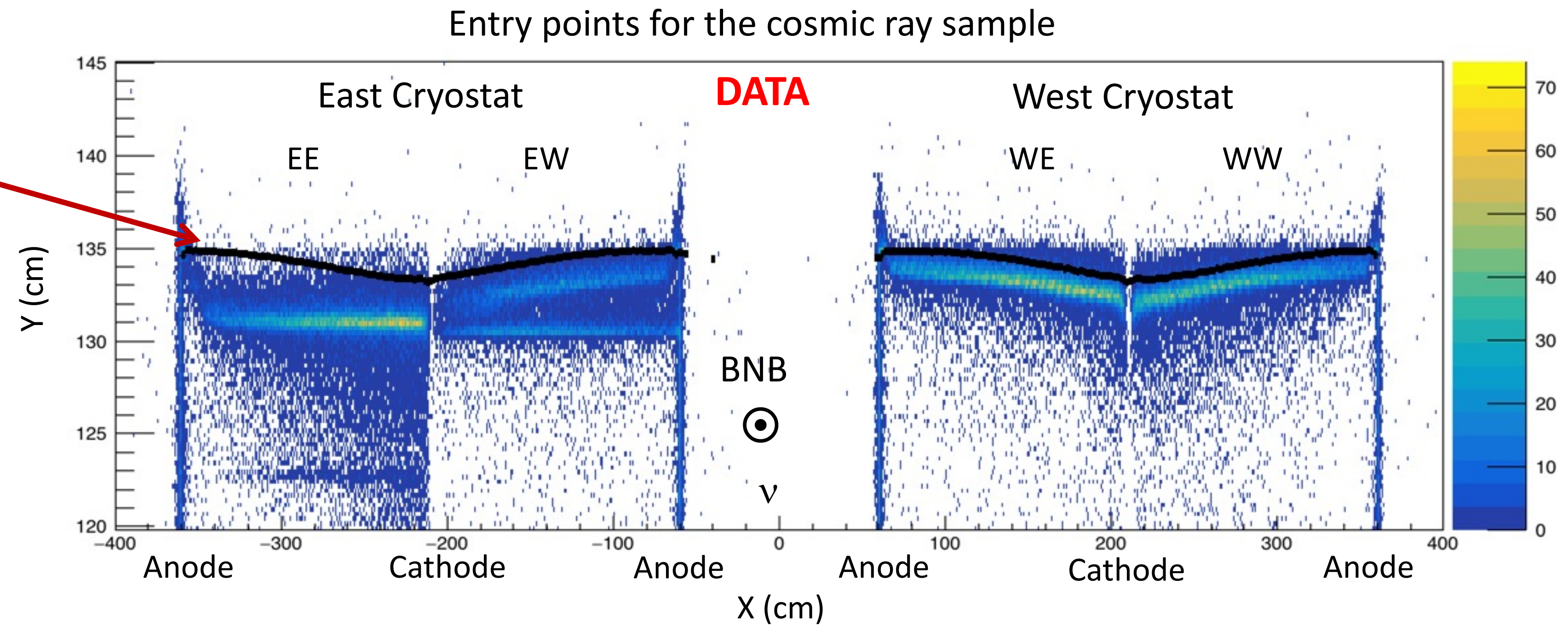
- Necessity to quantify the capability to correctly identify contained events
- We studied a sample of straight cosmic muons crossing the central cathode, for which the absolute position inside the detector is determined with few mm precision



# Containment conditions

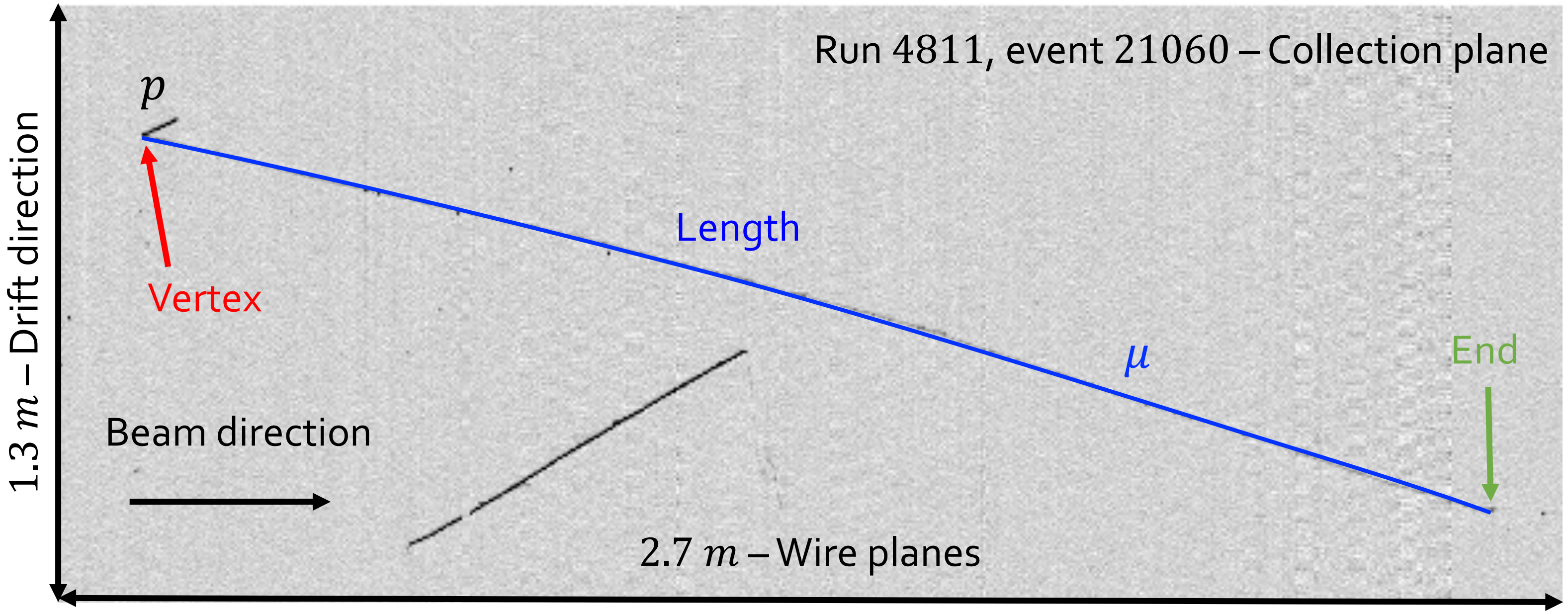
- We realised we were wrongly modelling the borders of the detector due to Space Charge Effects and possible reconstruction failures
- For the following studies, we only considered **fully contained** events, which are events whose tracks fulfil:
  - At least 5 cm away from top and bottom TPC sides $(\hat{y})$
  - 50 cm far from the upstream/downstream TPC wall $(\hat{z})$
  - 5 cm from the anode position $(\hat{x})$

Present model of
Space Charge effect



# Validation of automatic reconstruction

- The goal is to validate the selection of $\nu$ events collected from the BNB and NuMI beams at ICARUS
- Thanks to a set of visually scanned runs, we can compare some manually and automatically reconstructed variables to identify pathologies in the reconstruction chain and try to mitigate them
- A sample of fully contained $\nu_\mu CC$ events was used to do the validation based on :
  - 3D position of the vertex (V)
  - 3D position of the end (E) of the muon track
  - Length (L) of the muon track



# Validation of automatic reconstruction

Validation based on:

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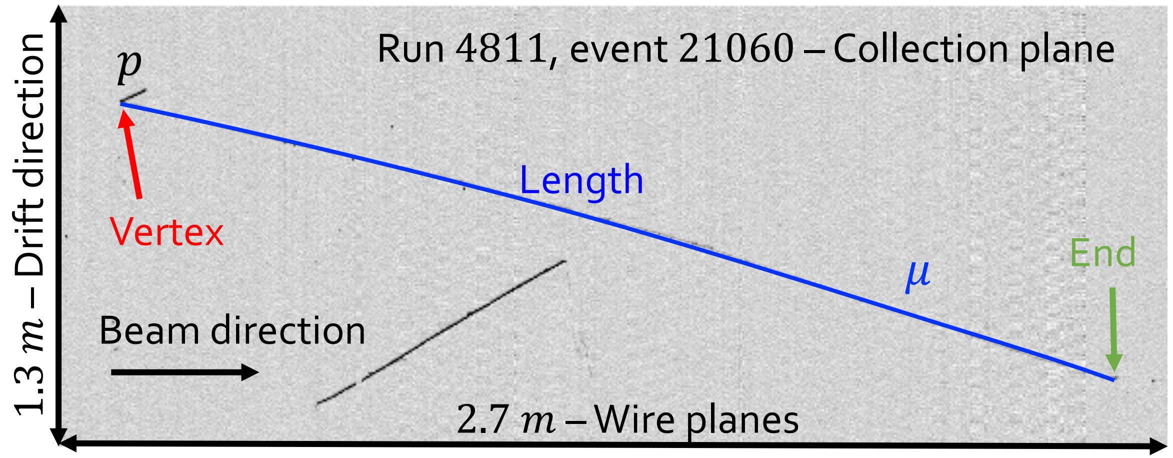



Events recognised by the automatic reconstruction were divided in 3 categories depending on the agreement with scanning information

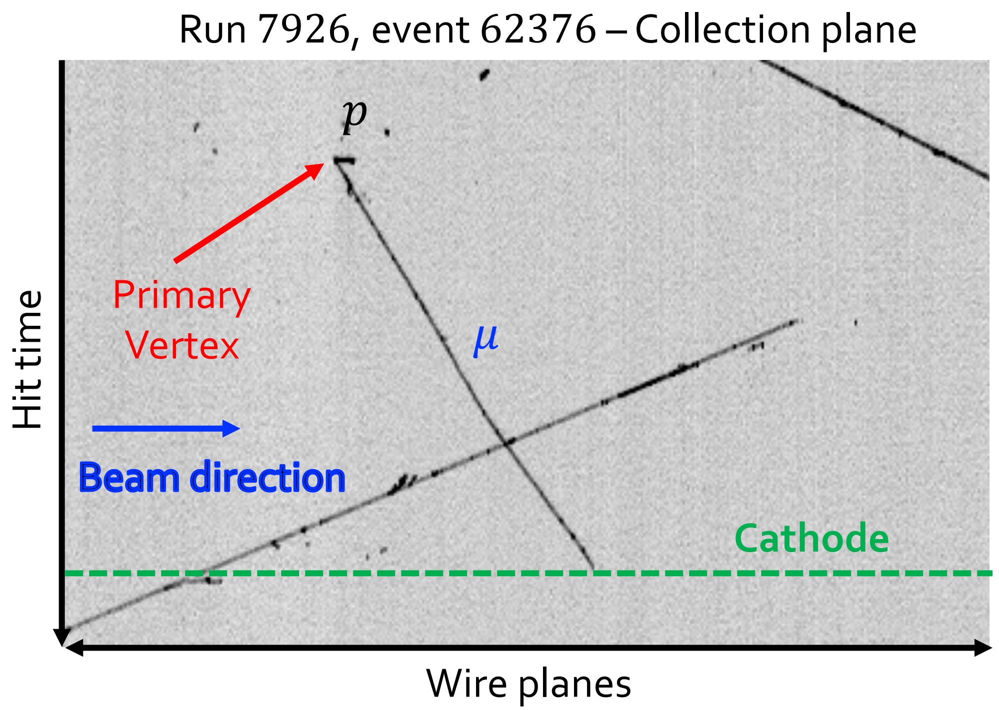
1. Perfect matches: Vertex, End and Length of the track are well reconstructed — 61 %

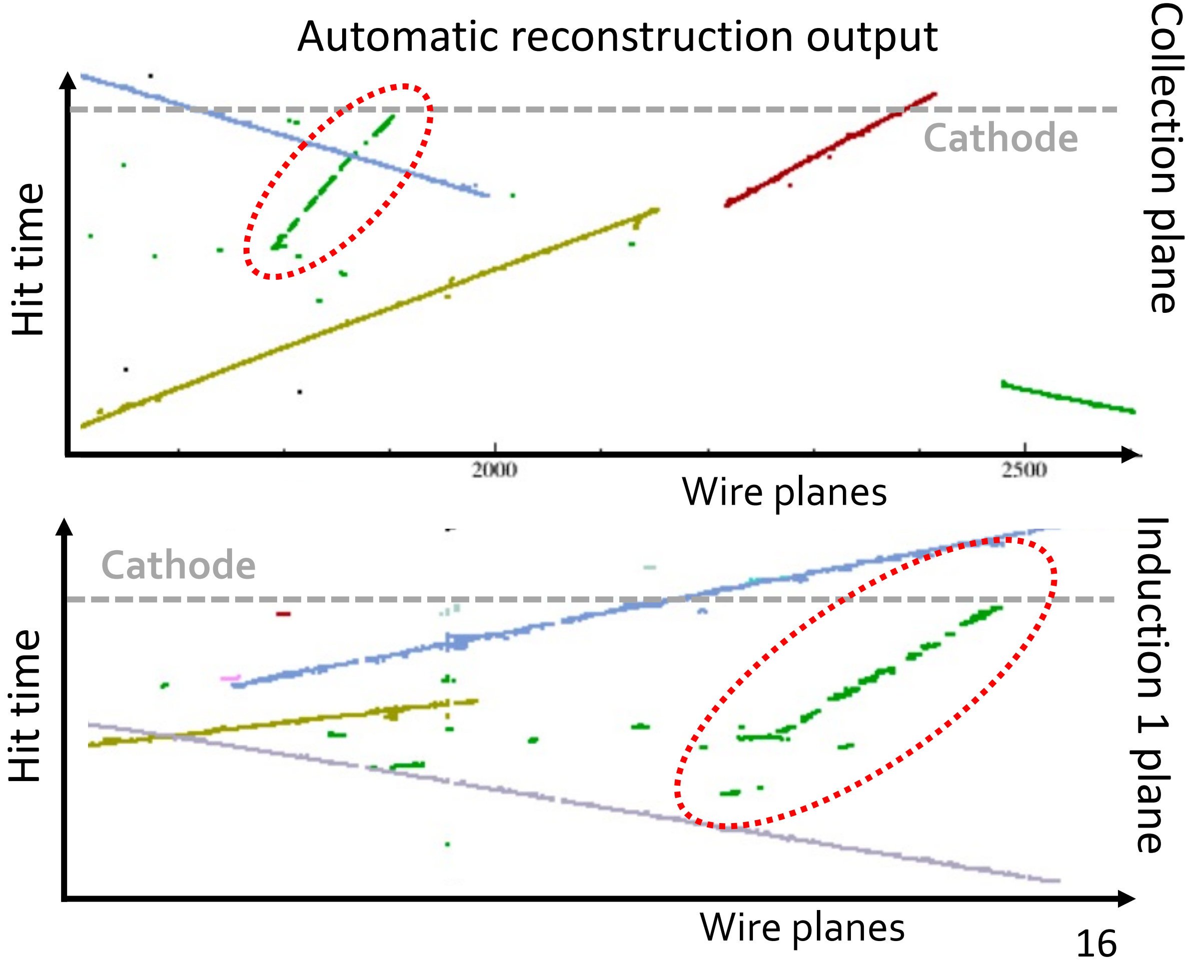
   $\Delta V_{scan-reco} < 15$ cm, $\Delta E_{scan-reco} < 15$ cm, $\Delta L_{scan-reco} < 30$ cm

2. Almost good matches: Vertex is well reconstructed but there is some problem with the $\mu$ track — 25 %
3. Bad matches: Event not found in the reconstruction, classified as clear cosmic or vertex and end of the track are swapped — 14 %

# Validation of automatic reconstruction

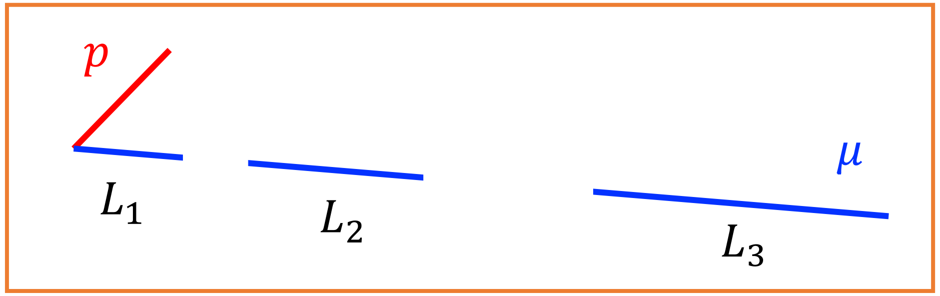
- We chose an almost good match: vertex and end muon well reconstructed but $\Delta L_{scan-reco} = 108$ cm
- $\nu_\mu$ interaction with a small proton and a muon, which is crossing the cathode stopping inside the detector



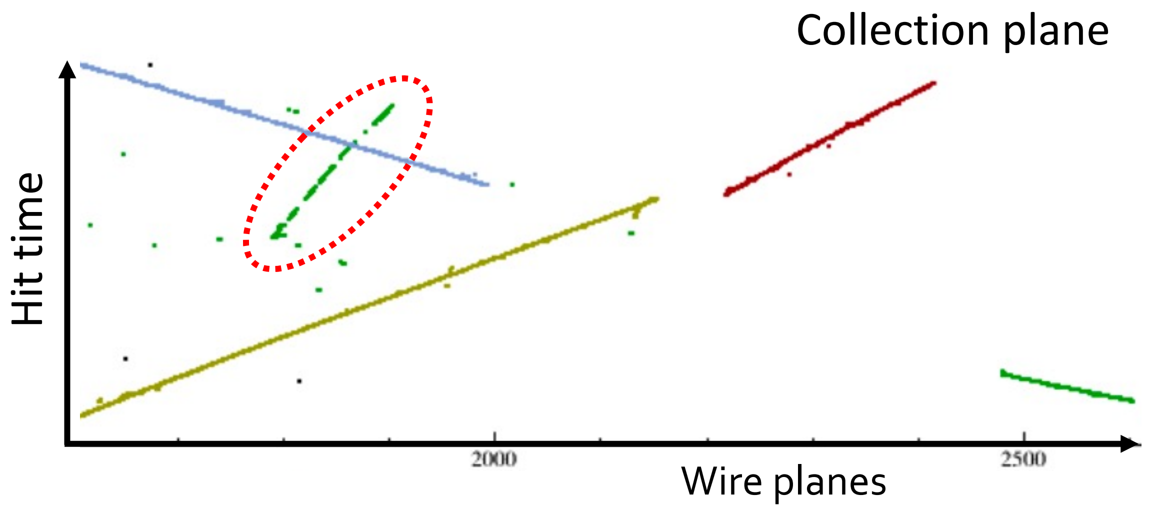



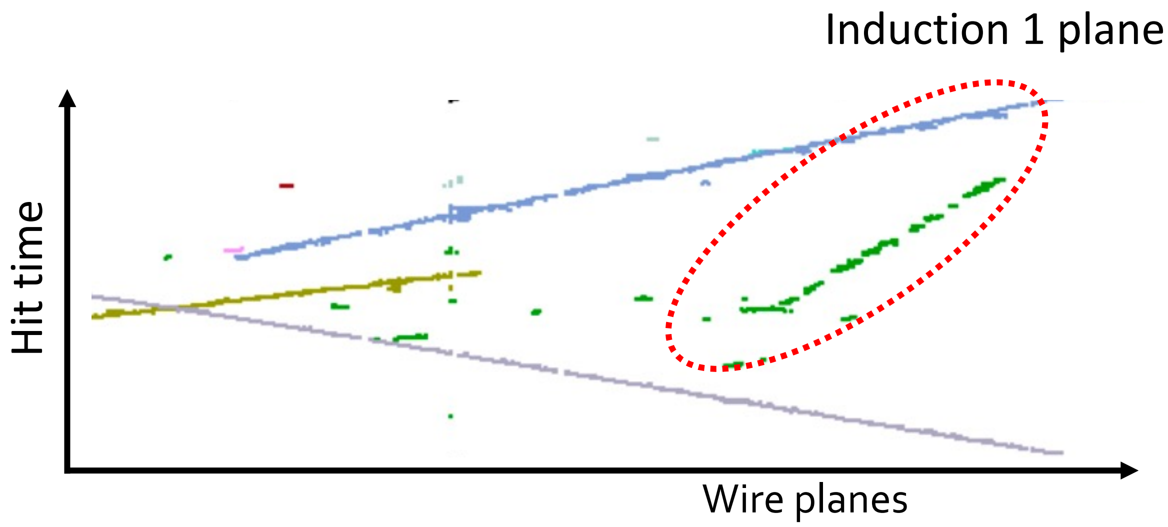
# Validation of automatic reconstruction

- The muon track shows bad reconstruction due to missing hits in Induction 1
- The result of this poor hit finding is the split of the track into 3 pieces
- Pandora's reconstructed length corresponds to the length of the longest piece $L_{reco} = L_3$




- In this case space point inefficiency can be driven by small pulses height which are indistinguishable from background noise

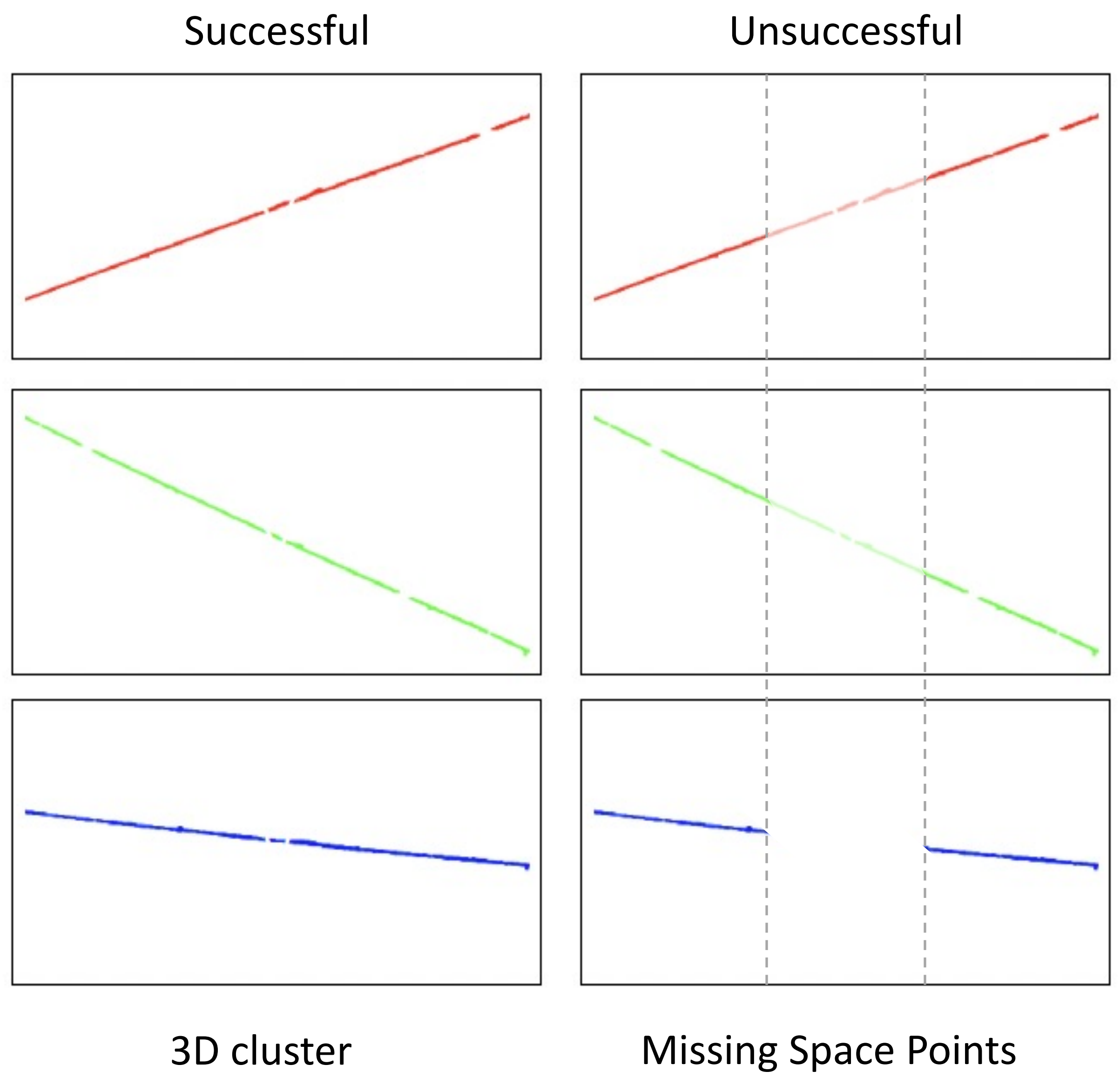


# How are Space Points made?

- A Hit is a 2D object in the wire-time space. It gives the drift time as the peak position of a gaussian shaped pulse and an associated wire
- Space Points are 3D objects build from combinations of 2D hits on different planes where
  - The hit times are consistent: gaussian pulses overlapped
  - The wires must intersect (YZ projection)
- In order to reduce the level of noise hits, Space Points are required to have matches across the three planes. That will introduce inefficiencies if a set of hits is missing on one plane
- Reconstruction of 3D points is affected by the inefficiency of each of the three wire planes

Merge of 2D hit cluster?



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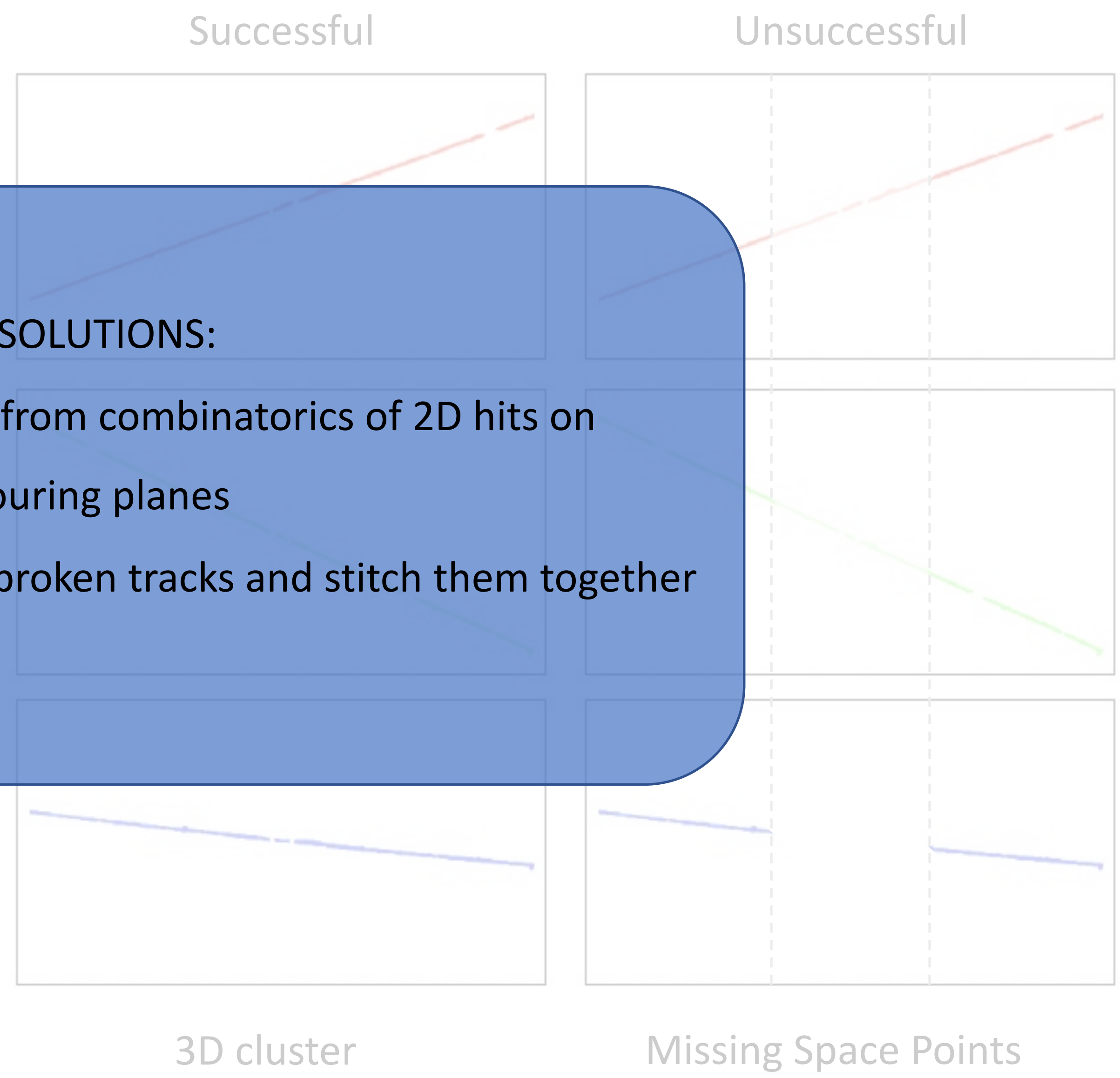
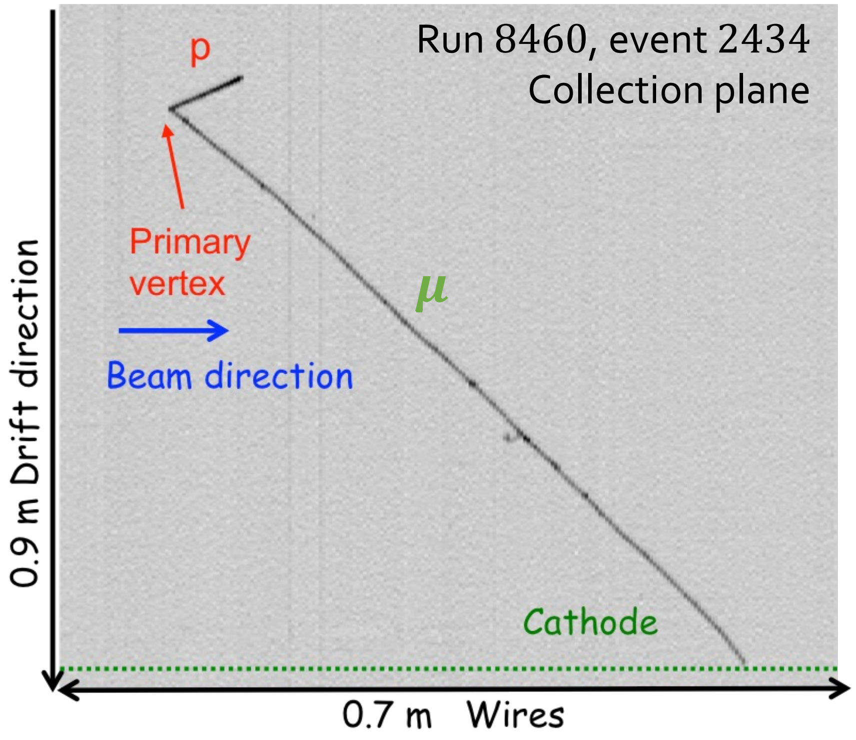



POSSIBLE SOLUTIONS:

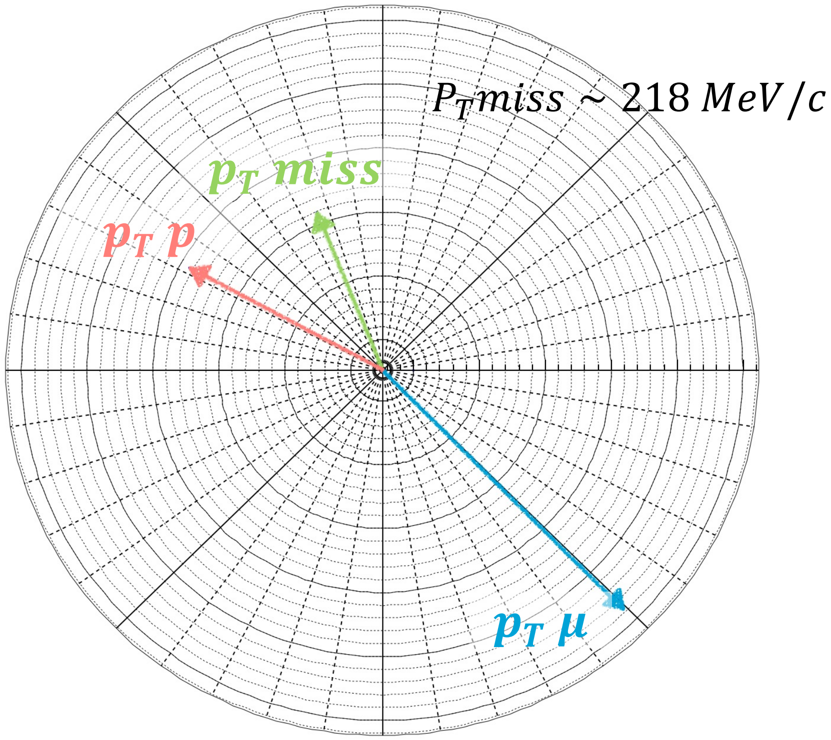
- find all candidate 3D points from combinatorics of 2D hits on neighbouring planes
- Develop an algorithm to identify broken tracks and stitch them together

# Particle ID and calorimetric reconstruction

- Full analysis of a $\nu_\mu CC$ QE candidate
- The CC muon is $2.3\ m$ long, crossing the cathode and stopping inside the active volume
- The highly ionizing track is recognized as a $\sim 7.7\ cm$ long stopping proton
- Total deposited energy $\sim 620\ MeV$
- Total momentum $\overrightarrow{p_{tot}} = \overrightarrow{p_p} + \overrightarrow{p_\mu}$ at $16°$ from the beam axis



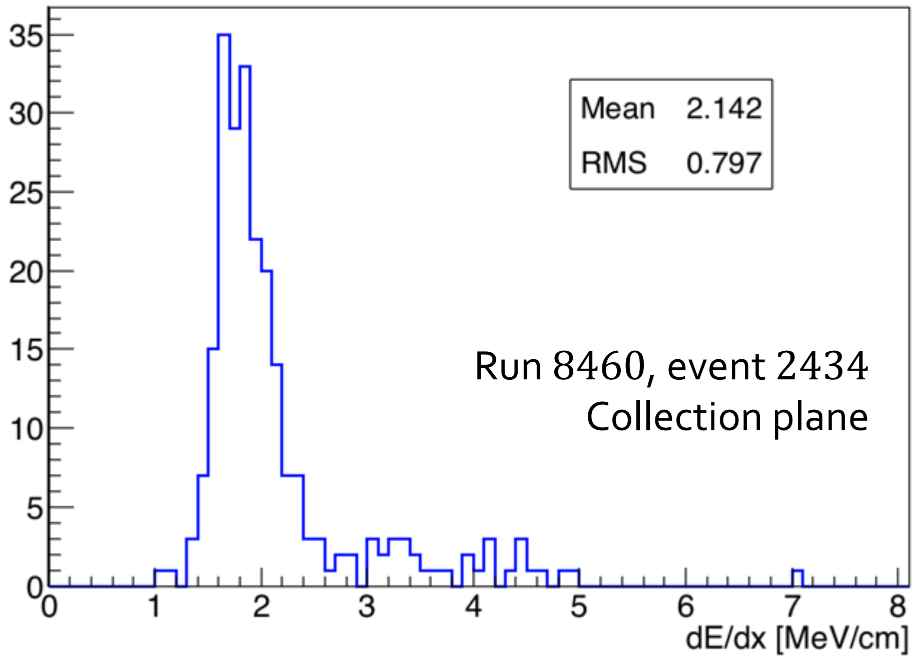

Transverse momenta $[MeV/c]$



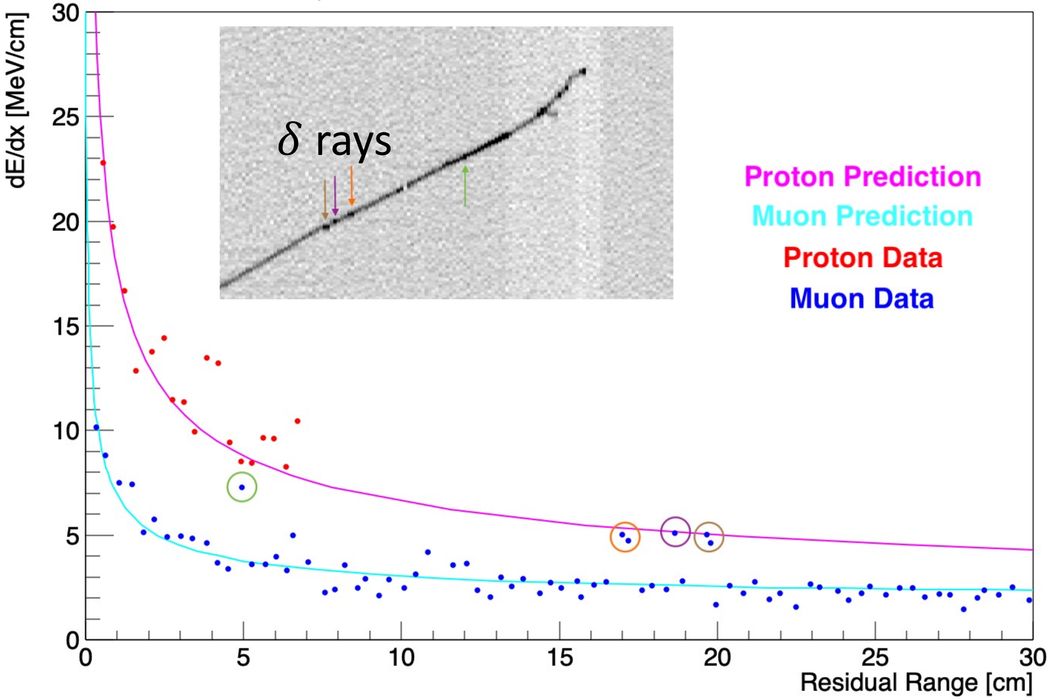
# Particle ID and calorimetric reconstruction

- Full wire signal calibration in still ongoing, but with a preliminary wire signal conversion to measure the deposited energy it is possible to reconstruct $dE/dx$ associated to individual hits
- $dE/dx$ distributed as expected for a MIP particle like the muon
- For particle identification we can exploit $dE/dx$ as a function of residual range
- The present calibration allows to correctly reconstruct Bragg peaks for both the stopping muon and proton

$dE/dx$ distribution excluding last 50 cm of the track

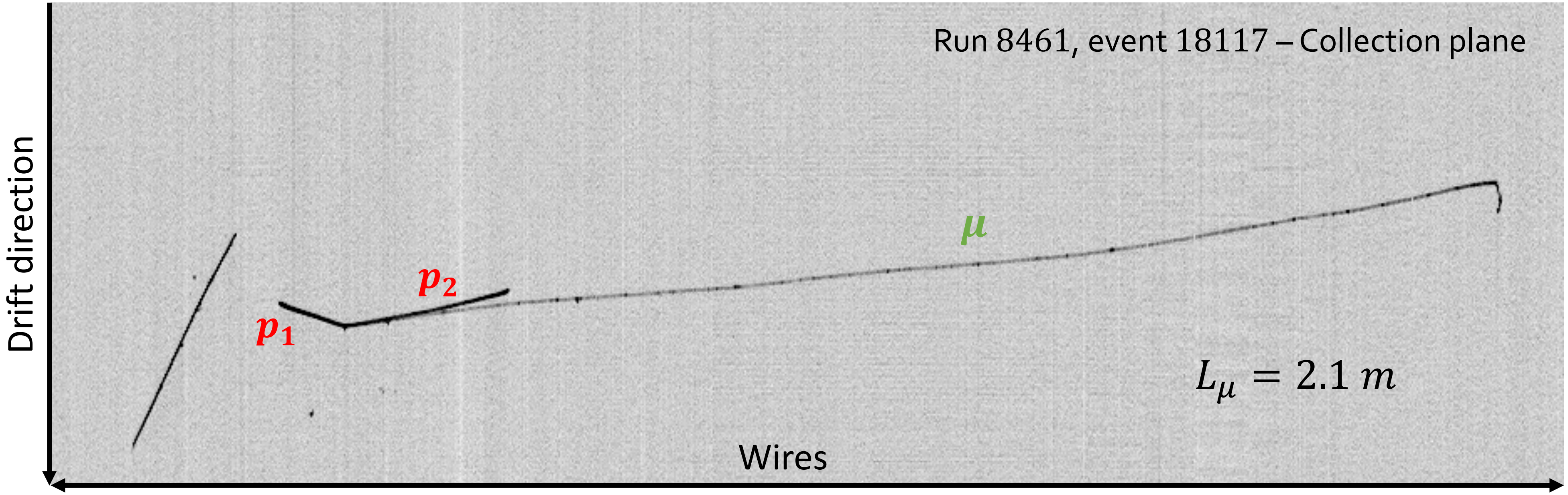



Data comparison to Bethe Bloch theoretical curves



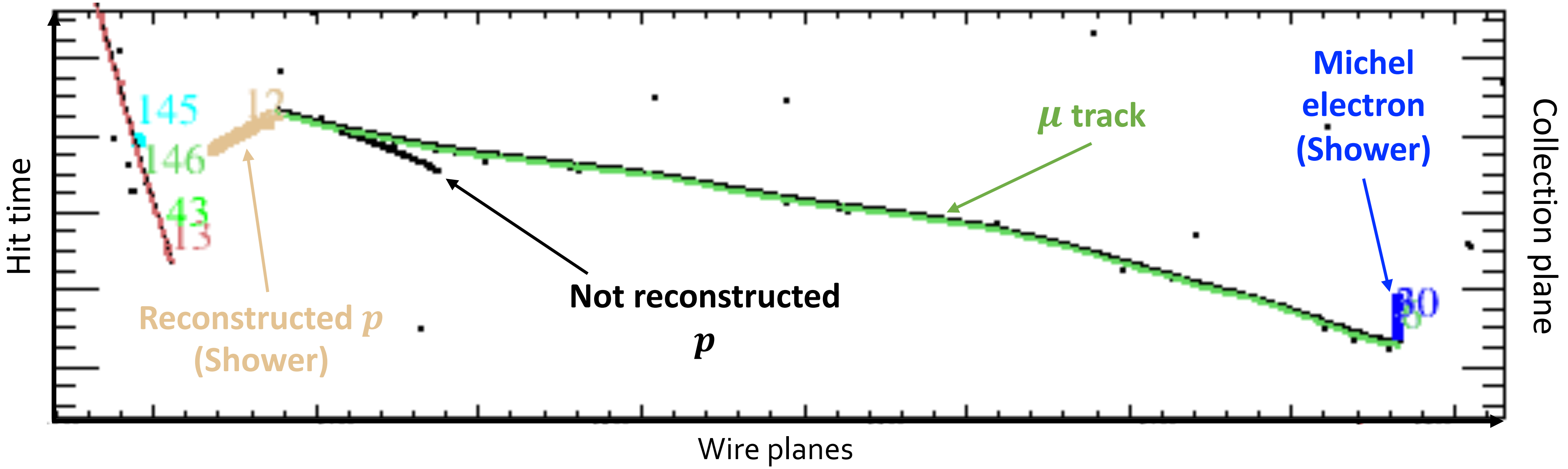
# Classification within the automatic reconstruction

- $\nu_\mu$ candidate with a 2 m long muon and two proton candidates
- With the current software release used to perform all the reconstruction chain, the algorithm was able to identify the muon and only one of the two protons



# Classification within the automatic reconstruction

- The reconstructed proton is reconstructed as a shower instead of a track
- Some changes have been made to the code to perform both, track and shower fit regardless of Pandora's outcome
- Really useful to improve the reconstruction of particles mis-identified as showers



# Conclusions and perspectives

- Some progress have been done on the validation of automatic reconstruction
- Preliminary results were obtained proving ICARUS' capability to perform calorimetric studies and particle identification, essential for oscillation studies
- Specific events were selected for an exhaustive study identifying pathologies and failures of the automatic event reconstruction and their possible causes
- At the moment, some MC studies are ongoing towards understanding and fixing these problems
- Next steps
    - Exploit hits with matches across only 2 planes and evaluate the improvement, if any
    - Study towards the track/shower discrimination
    - Develop a stitching algorithm to improve track reconstruction


77 cm
32 cm
77 cm

# THANK YOU !

IMAGING
COSMIC
AND
RARE
UNDERGROUND
SIGNALS