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

Annual Report - INTENSE Meeting

2nd December 2022

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Imaging Cosmic And Rare Underground Signals

800 Anni 1222·2022 Università degli Studi di Padova

Dipartimento di Fisica e Astronomia Galileo Galilei

European Commission

Intense
H2020 MSCA ITN
G.A. 858199

Outline

GOAL: perform a precise reconstruction of ν_{μ} CC QE events

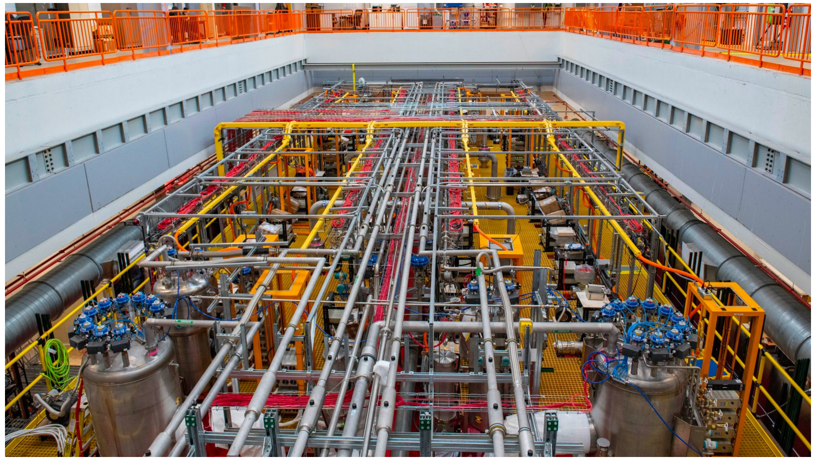
STEPS:

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)

A little bit about myself…

- I was born in Sabadell, Spain
- I studied Physics in Barcelona and then moved to Madrid to do the Master Degree
- I completed my master's thesis at CIEMAT: *"Analysis of light detection with ProtoDUNE dual-phase liquid argon experiment at CERN"*

Where am I currently?



Top view of ICARUS

- I joined the ICARUS Neutrino Group based in Padova on January 2021
- The first part of the PhD position, has been intended to the calibration of the ICARUS detector during its commissioning phase at FNAL
- These last months I have focused more in reconstruction analysis and validation

Courses

- Multimessenger Astroparticle Physics by A. De Angelis “*Neutrinos as Multimessenger particles*” March 2021
- Neutrino Physics by R. Brugnera, M. Lattanzi and S. Dusini “*Where are we with sterile neutrinos?*” June 2021
- Statistical Data Analysis by T. Dorigo, D. Bastieri and L. Stanco *“Statistical status on sterile neutrinos” July 2021*
- Standard Model & Flavour Physics by G. Simi and M. Tosi *“Test of lepton universality in beauty-quark decays” September 2021*
- *EU funding: opportunities for Research and Innovation and proposal writing by M. Schisani June 2022*

Workshops

Finished all my course duties and actively involved in the ICARUS Analysis working groups where I periodically report the status of my progress

- XIX International Workshop on Neutrino Telescopes held online during 18-26th February 2021, organized by INFN Padova
- Calibration Workshop: Ntuples Tutorial held remotely on 27th Sept–1st Oct 2021, organized by SBN Collaboration
- International Workshop on Cosmic-Ray Muography held in Ghent, Belgium during 24-26th November 2021, part of the European Project INTENSE-Rise
- Workshop "Summer Students at Fermilab and other US Laboratories", held in Pisa during 18-21st July 2022, as part of the INTENSE training
- ICARUS Software Workshop held in Frascati and Padova during 7-11st of October 2022

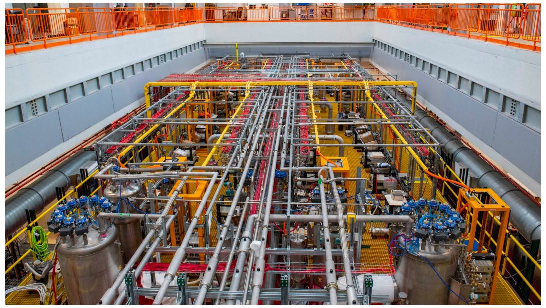
Trainings and Conferences

- *Neutrino Summer Lecture Series* held online during June/July 2021 and organized by Fermilab
- *Fermilab 2021 Summer Student School* at INFN Laboratori Nazionali di Frascati, online attendance during 2-4th August 2021
- *FNAL C++ Software School* held remotely during August/September 2021
- *INFN School Of Underground Physics: Theory & Experiment,* at LNGS, Gran Sasso during 20-24th June 2022
    - Poster: “Calibration analysis at ICARUS experiment”
- *Tri-Institute Summer School on Elementary Particles*, at TRIUMF, Vancouver during 4-15th July 2022

- Research stay at Fermilab, at Batavia, USA from 18-31th July 2022
- *108° Congresso Nazionale* SIF in Milano during 12-16th September
    - Talk: “Short-Baseline neutrino oscillation searches with the ICARUS detector”
- ICARUS Collaboration Meeting at LNF, Frascati during 4-6th of October. Organizer of Flash talks
    - Flash talk: “Cathode planarity and reconstruction analysis”

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 (ν_s)

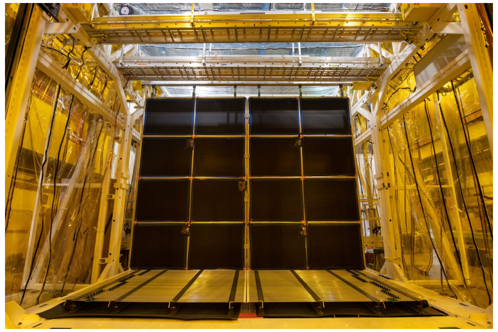


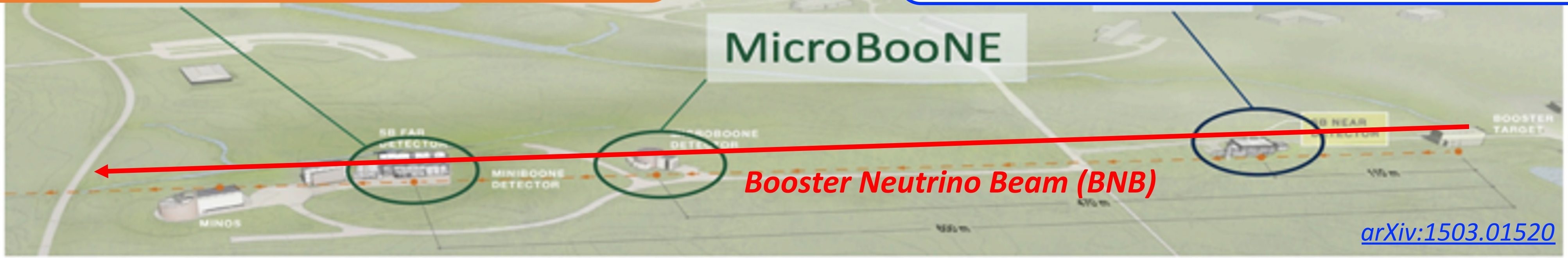
ICARUS

600 m baseline
476 t active volume
Data Taking

SBND

110 m baseline
112 t active volume
Under Construction



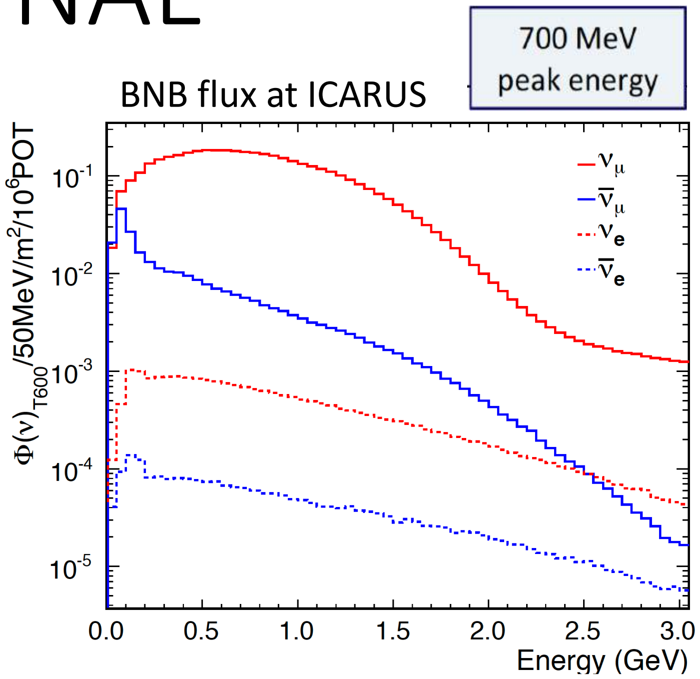


arXiv:1503.01520

- 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 ν_μ-beam, able to produce ν and $\bar{\nu}$ beams with low ν_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 ν_e rich component of the spectrum (up to $3\ GeV$)



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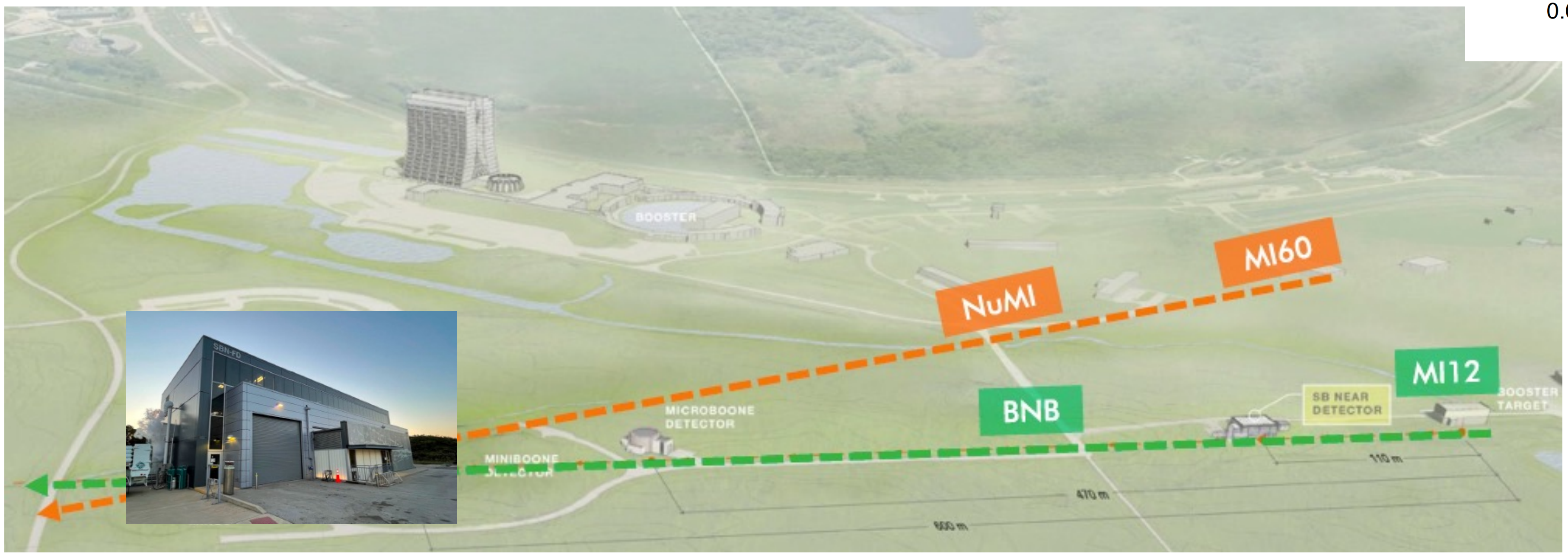
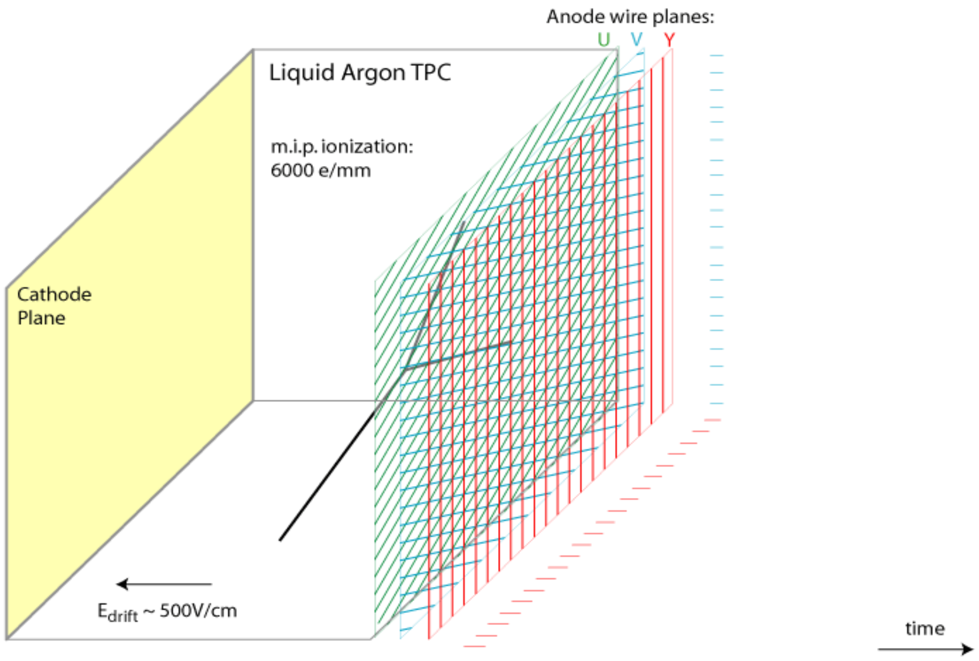
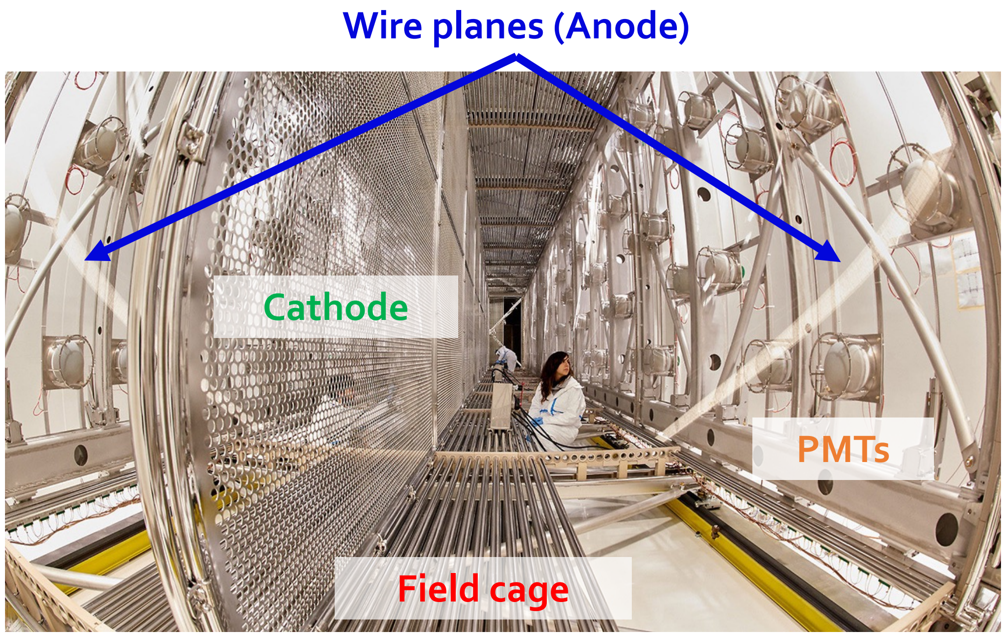


LAr TPC Working Principle



- 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 $0.1\ ppb$ $(3\ ms)$

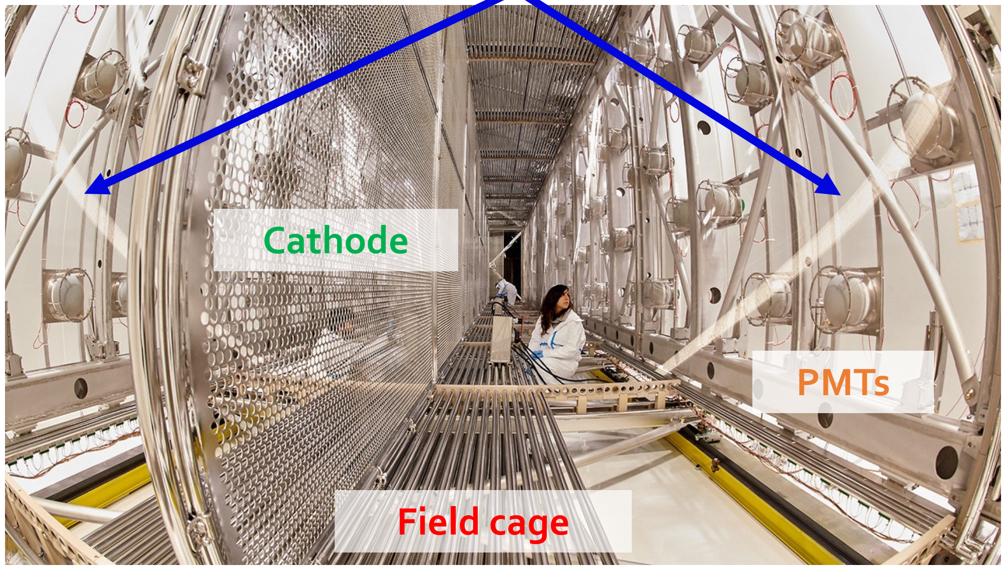
The ICARUS detector



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, ≈ 54k wires, at $0°$, $\pm 60°$ w.r.t horizontal to allow 3D reconstruction and $3\,mm$ pitch

The ICARUS detector



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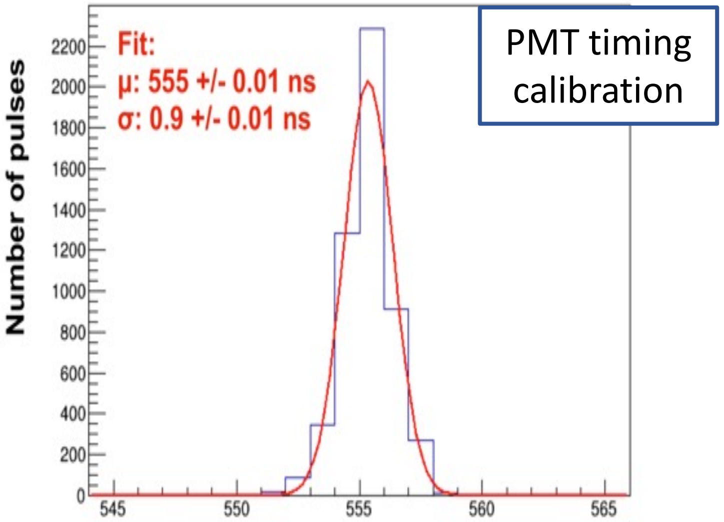
- 360 **PMTs** ($8''$) located behind the wires collect the scintillation light for timing and triggering purposes:
  - Precise identification of interaction time, $\sim ns$ time resolution
  - Localization of events with spatial resolution $< 50\,cm$
- LAr purity level is continuously monitored and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



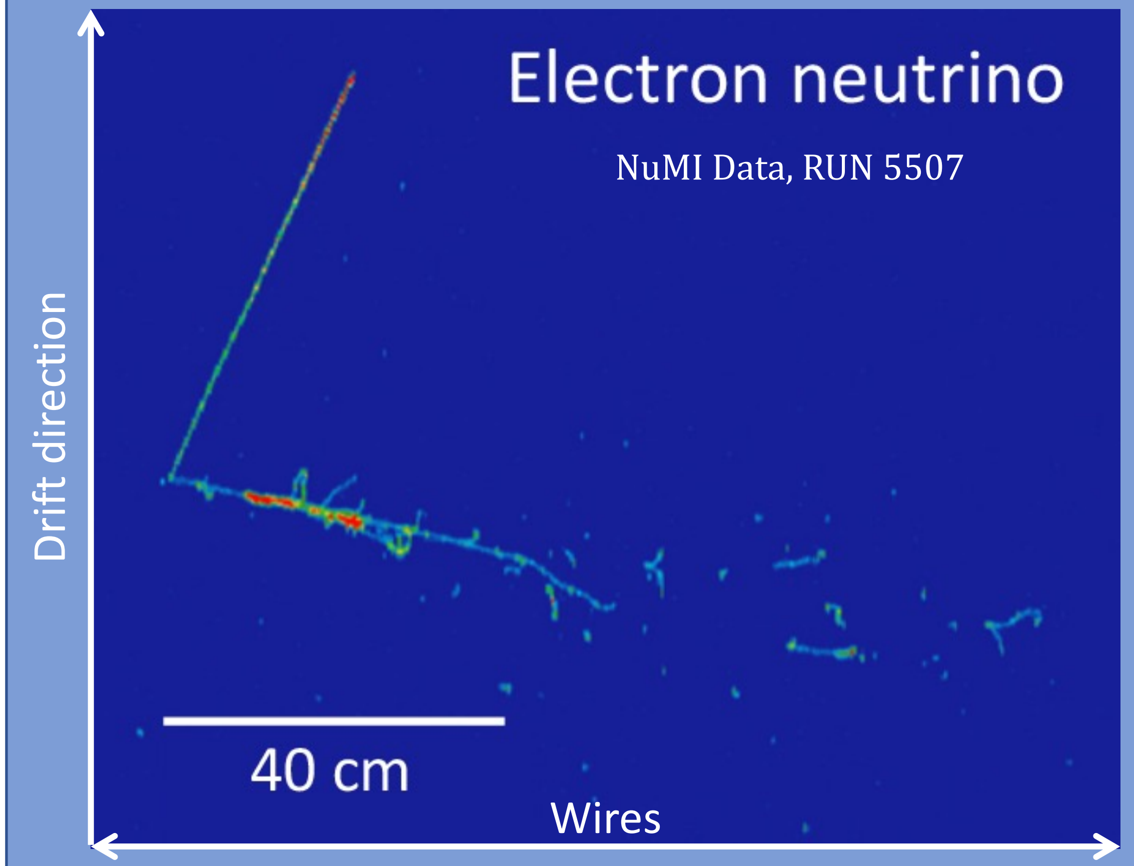
$\Delta t = t_{PMT} - t_{TRIGGER}\ (ns)$

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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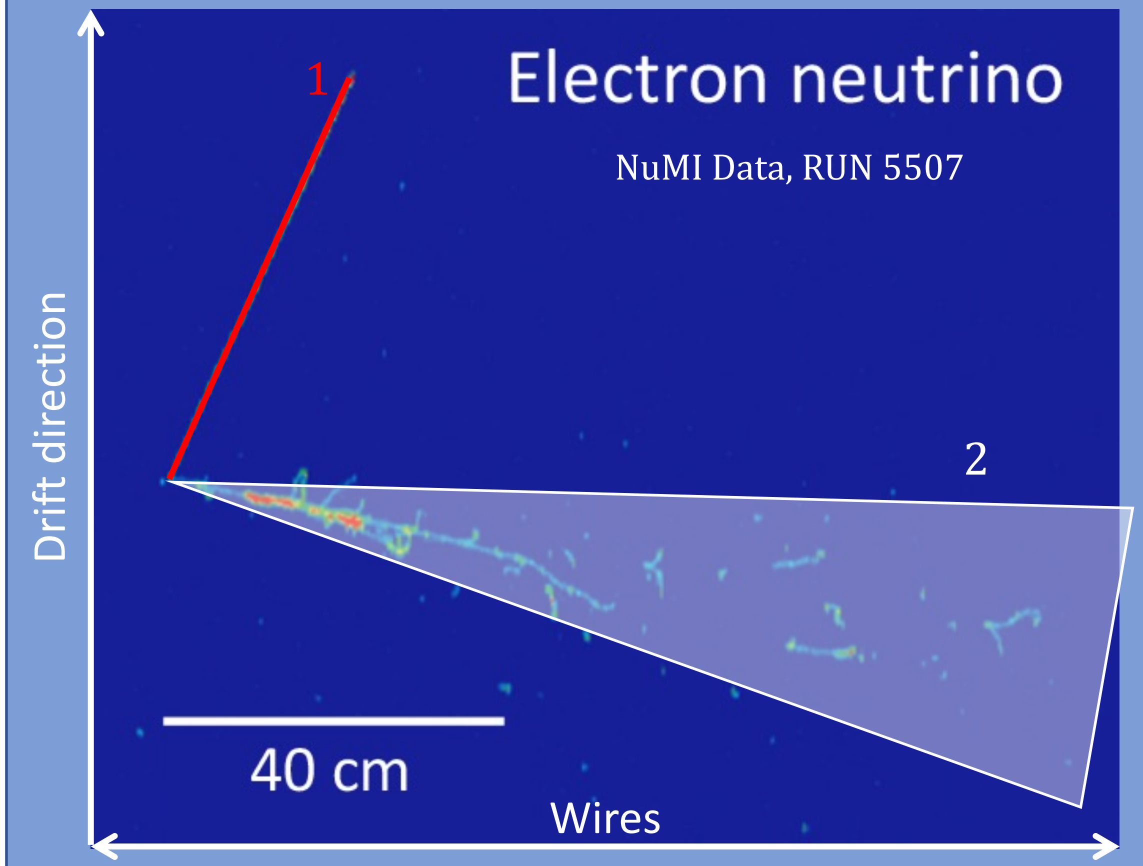

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From images to physics

- 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

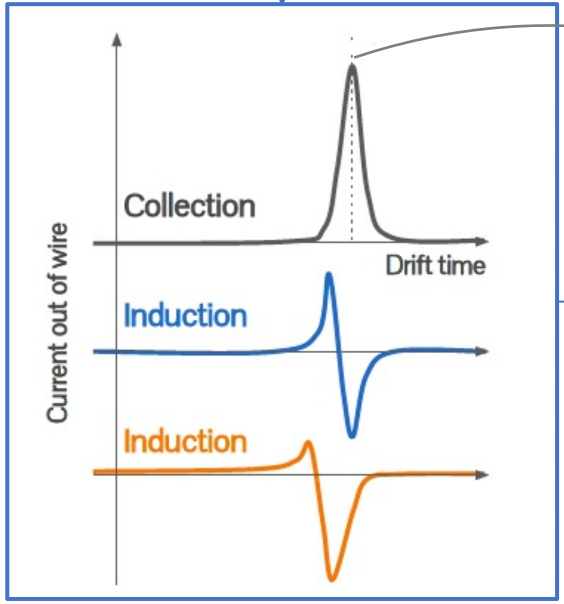
Detector Data → Low-level image processing → Hit finding → Pattern recognition → Particle fits → High Level Analysis

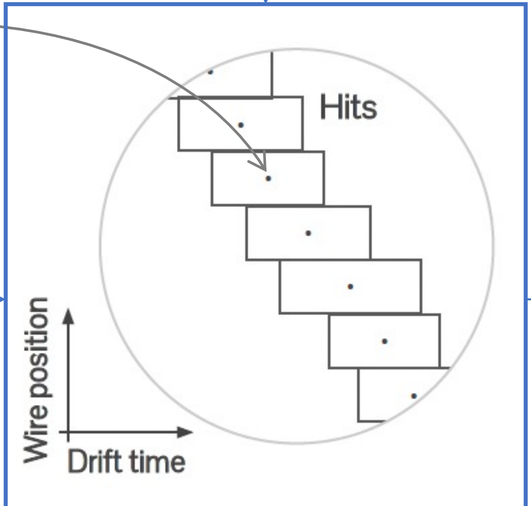
Low-level image processing
- Decoding
- Deconvolution
- ROI Finding

Hit finding
- Gaussian hits
- Cluster 3D

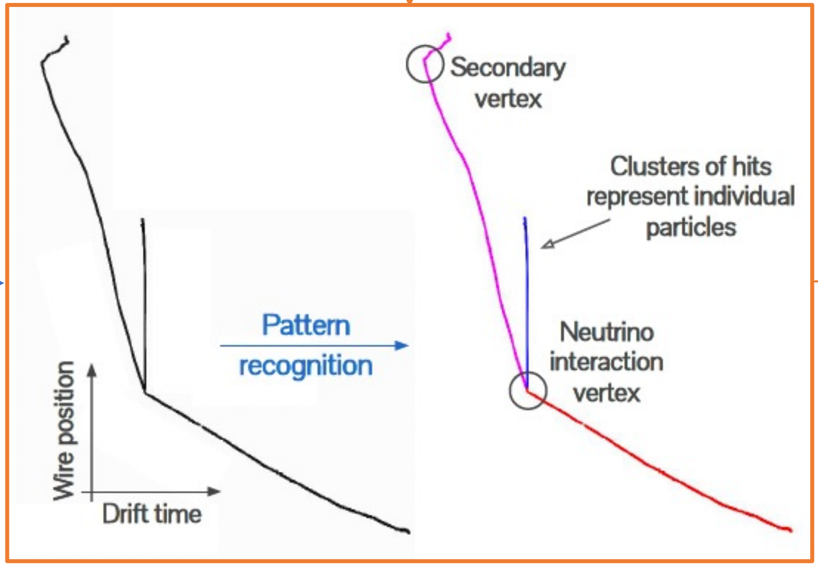
Pattern recognition
- Pandora Algorithm

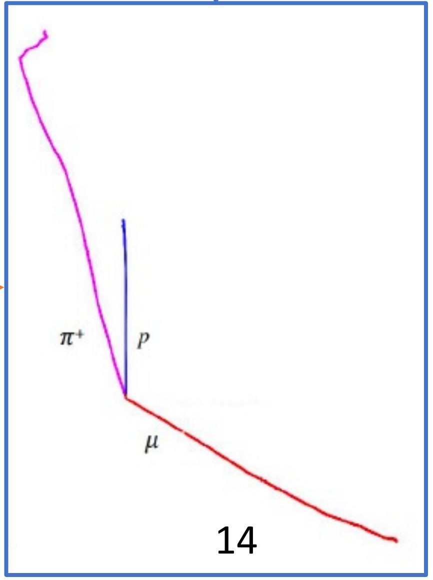
Particle fits
- Track, shower fits
- Calorimetry
- Particle ID





*hit: identified signal induced by a track on a wire.

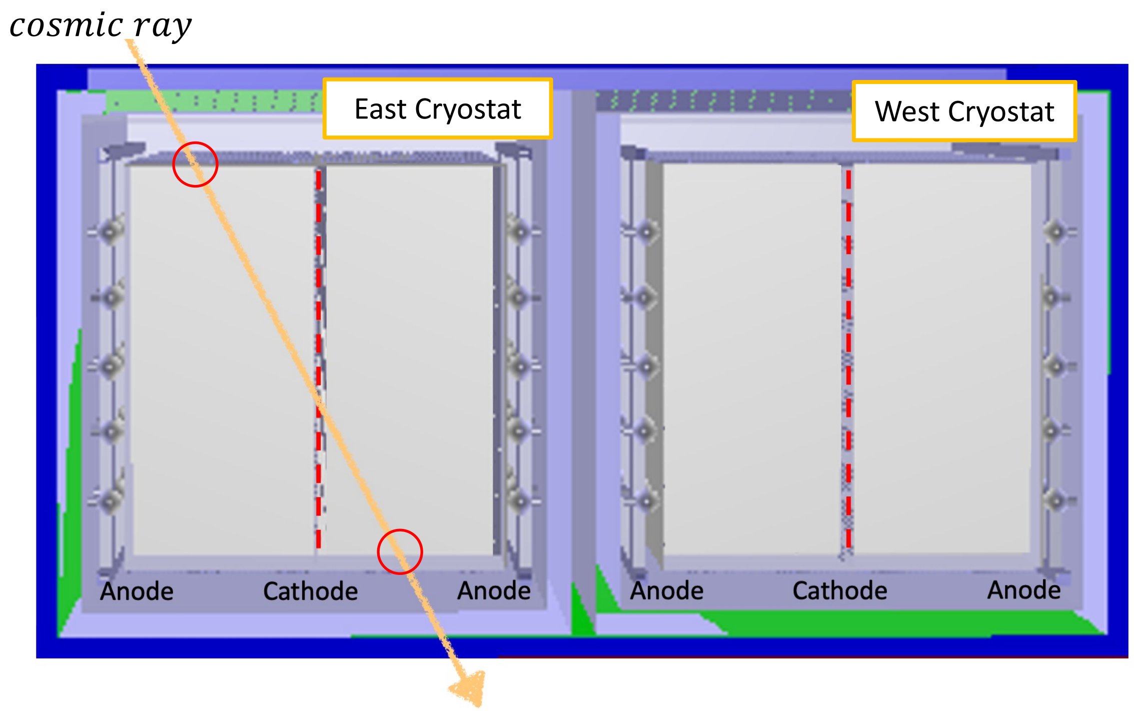




Containment conditions

- 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

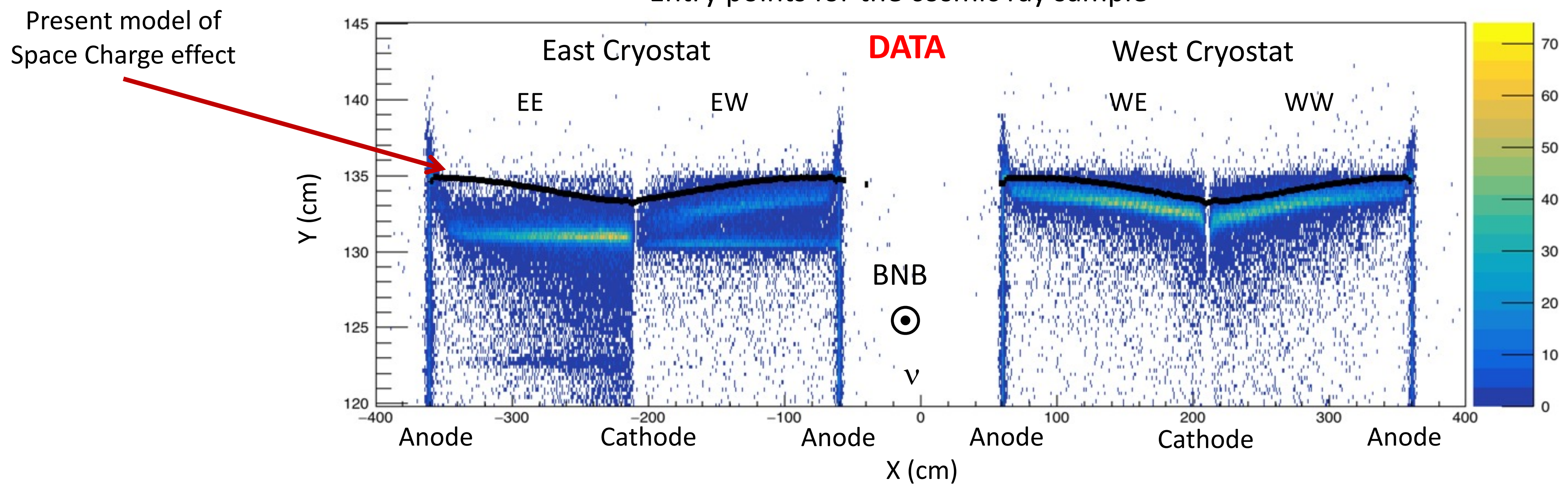
- Necessity to quantify the capability to correctly identify contained events
- We studied a sample of straight cosmic muons crossing the central cathode, for which the absolute position inside the detector is determined with few mm precision



Containment conditions

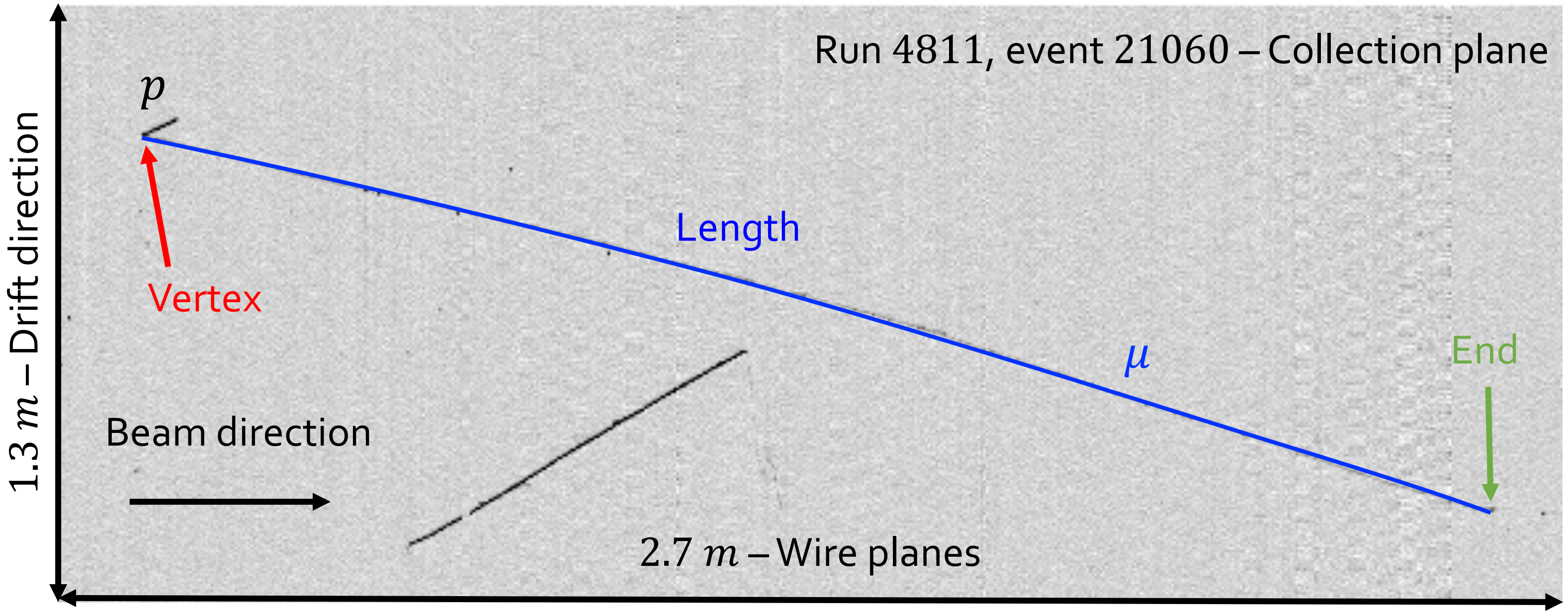
- We realised we were wrongly modelling the borders of the detector due to Space Charge Effects and possible reconstruction failures
- For the following studies, we only considered **fully contained** events, which are events whose tracks fulfil:
  - At least 5 cm away from top and bottom TPC sides ($\hat{y}$)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

Entry points for the cosmic ray sample



Validation of automatic reconstruction

- The goal is to validate the selection of ν 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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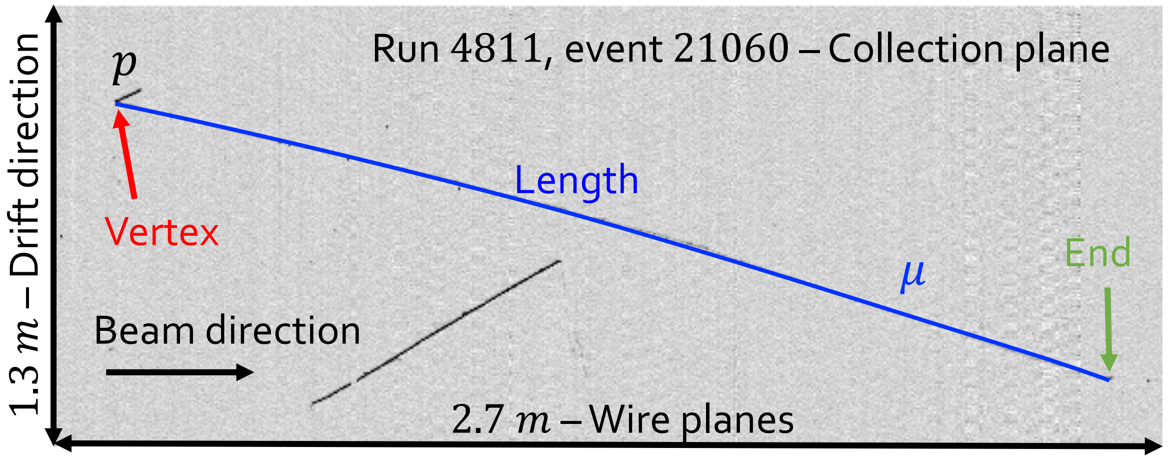


Events recognised by the automatic reconstruction were divided in 3 categories depending on the agreement with scanning information

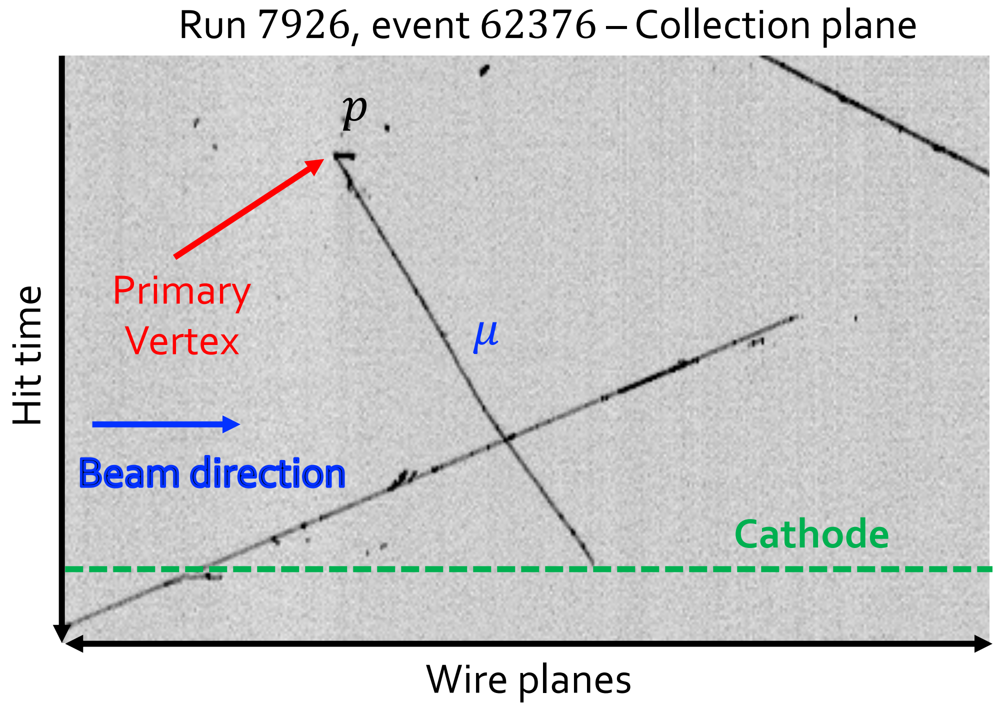
1. Perfect matches: Vertex, End and Length of the track are well reconstructed

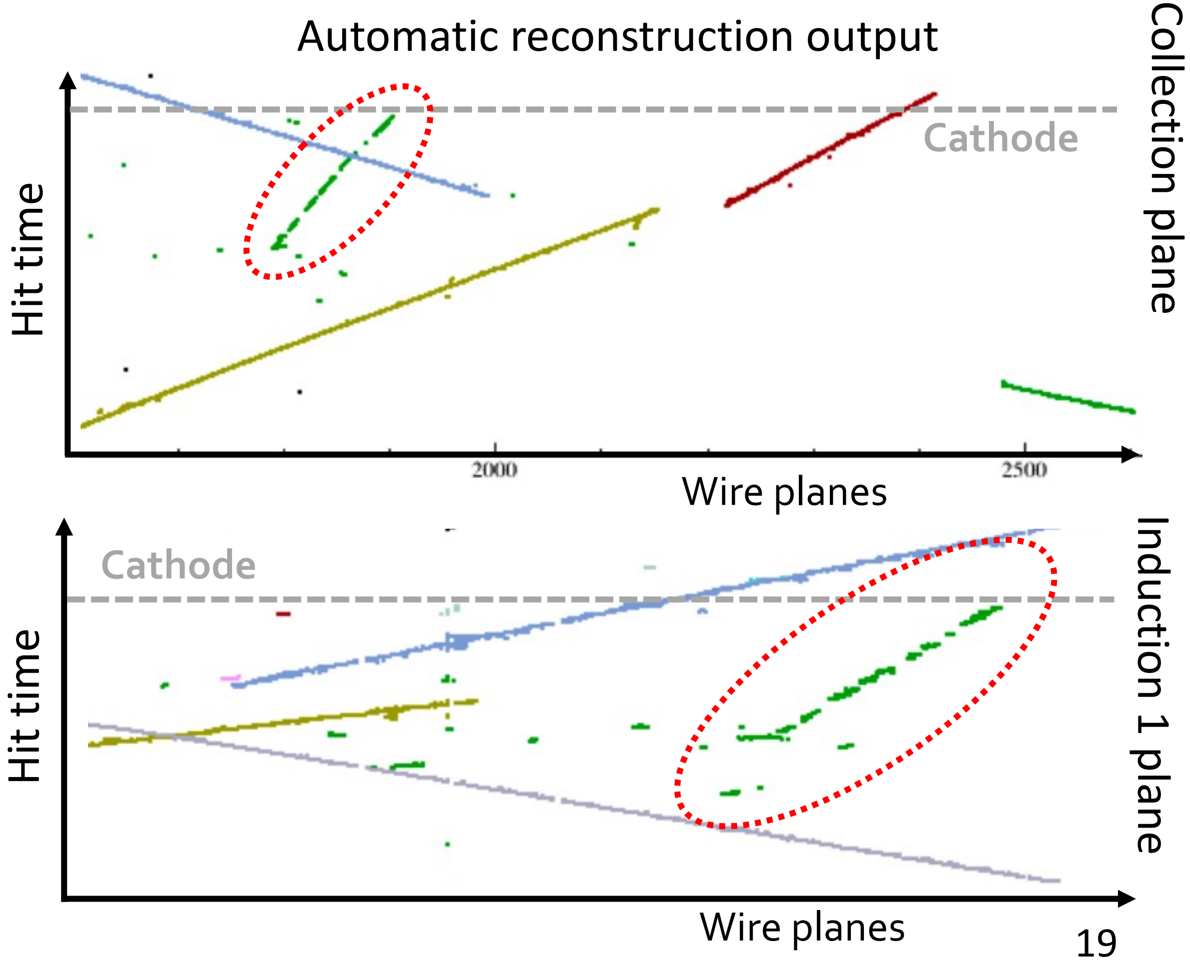
   $\Delta V_{scan-reco} < 15$ cm, $\Delta E_{scan-reco} < 15$ cm, $\Delta L_{scan-reco} < 30$ cm — 61 %

2. Almost good matches: Vertex is well reconstructed but there is some problem with the μ 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

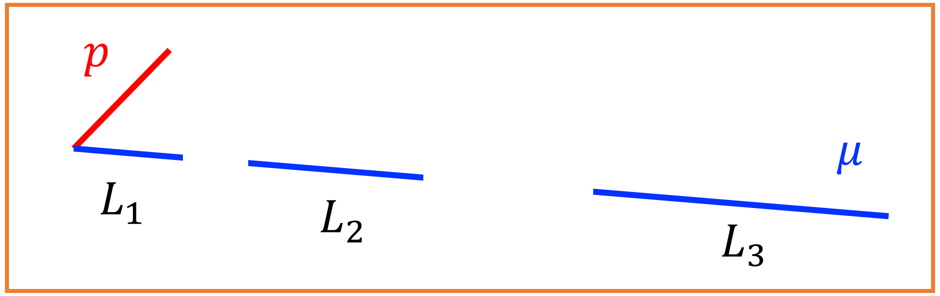
- We chose an almost good match: vertex and end muon well reconstructed but $\Delta L_{scan\,-reco} = 108$ cm
- ν_μ interaction with a small proton and a muon, which is crossing the cathode stopping inside the detector

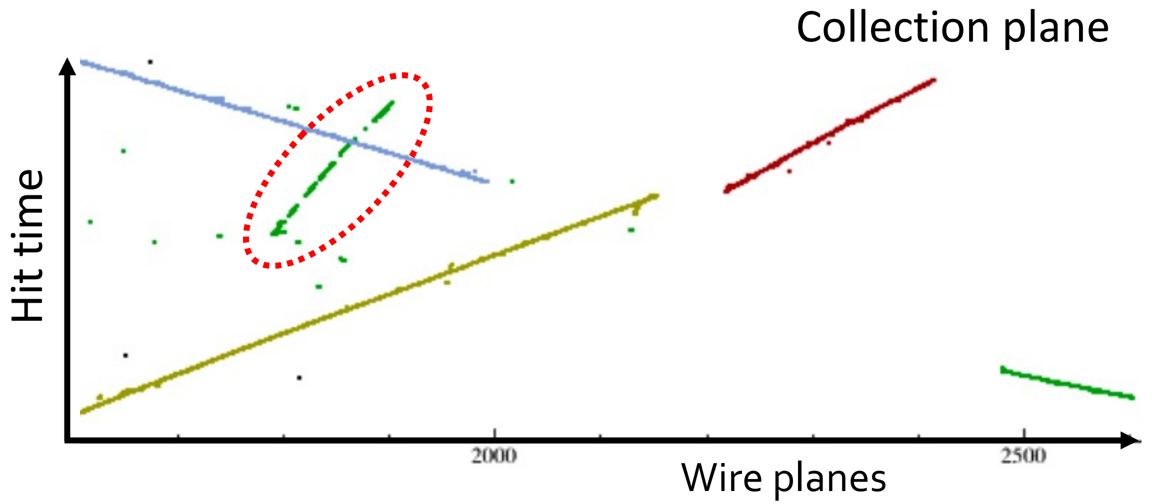


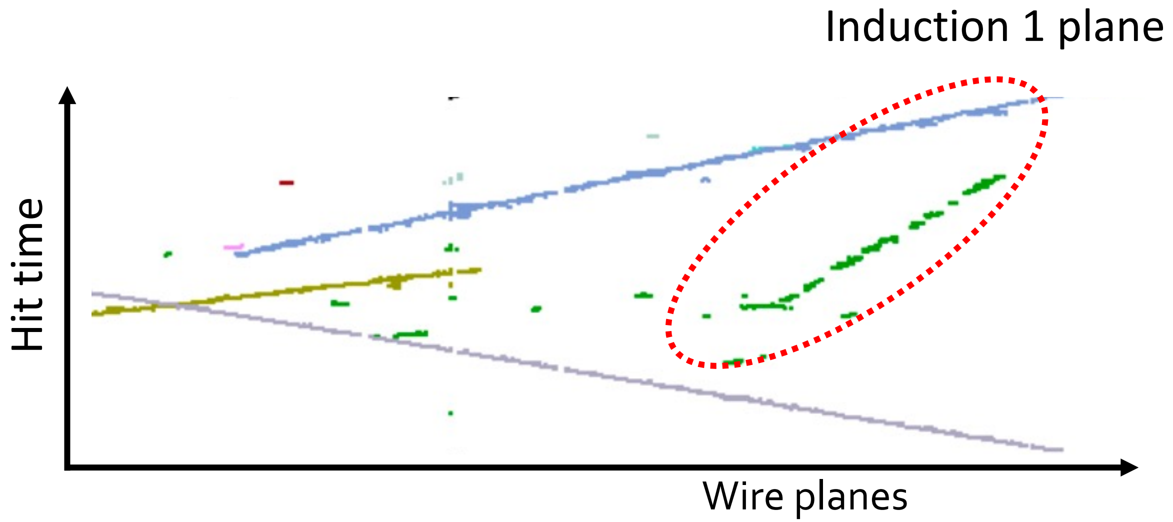


Validation of automatic reconstruction

- 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 $L_{reco} = L_3$





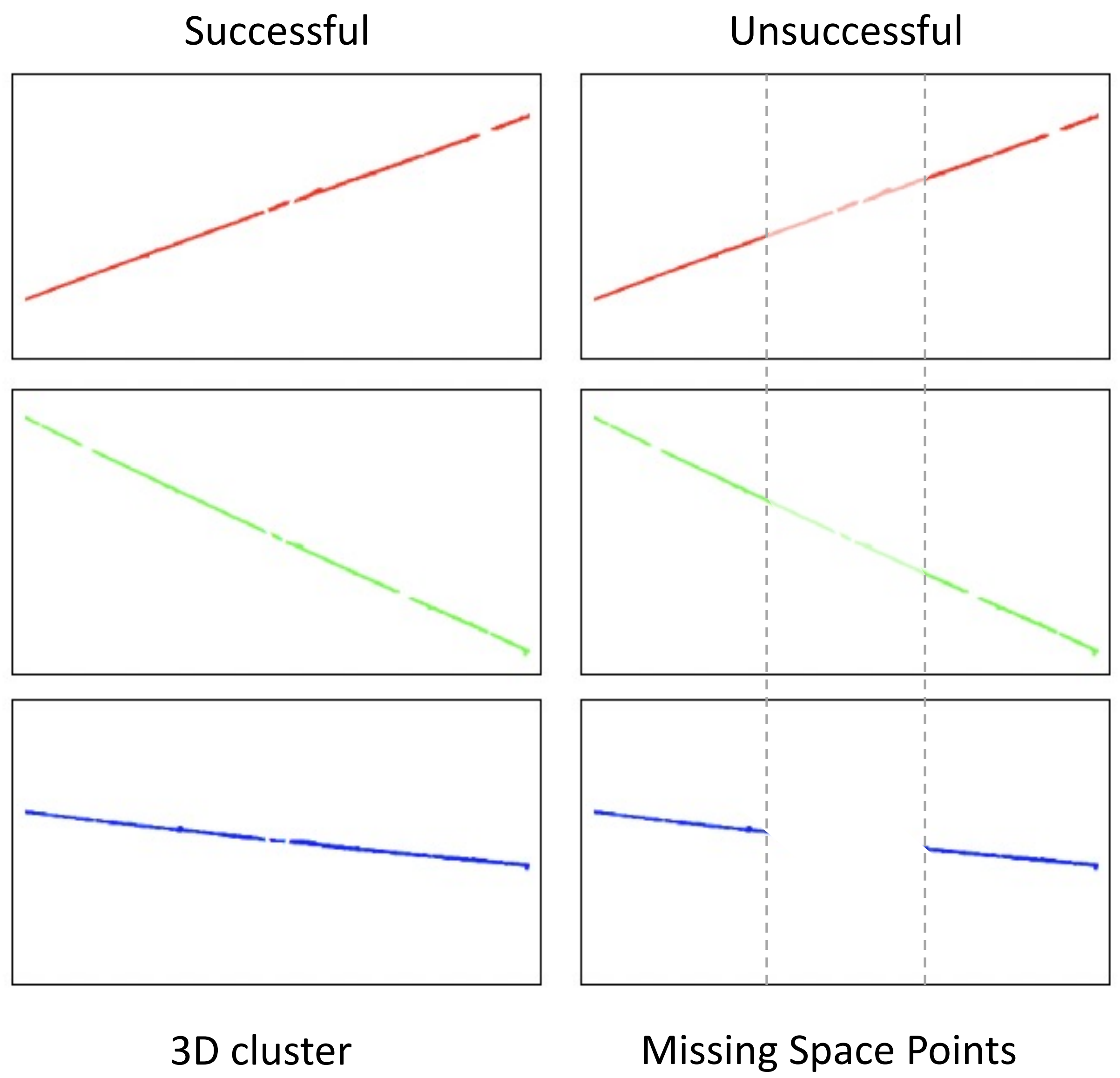


- In this case space point inefficiency can be driven by small pulses height which are indistinguishable from background noise

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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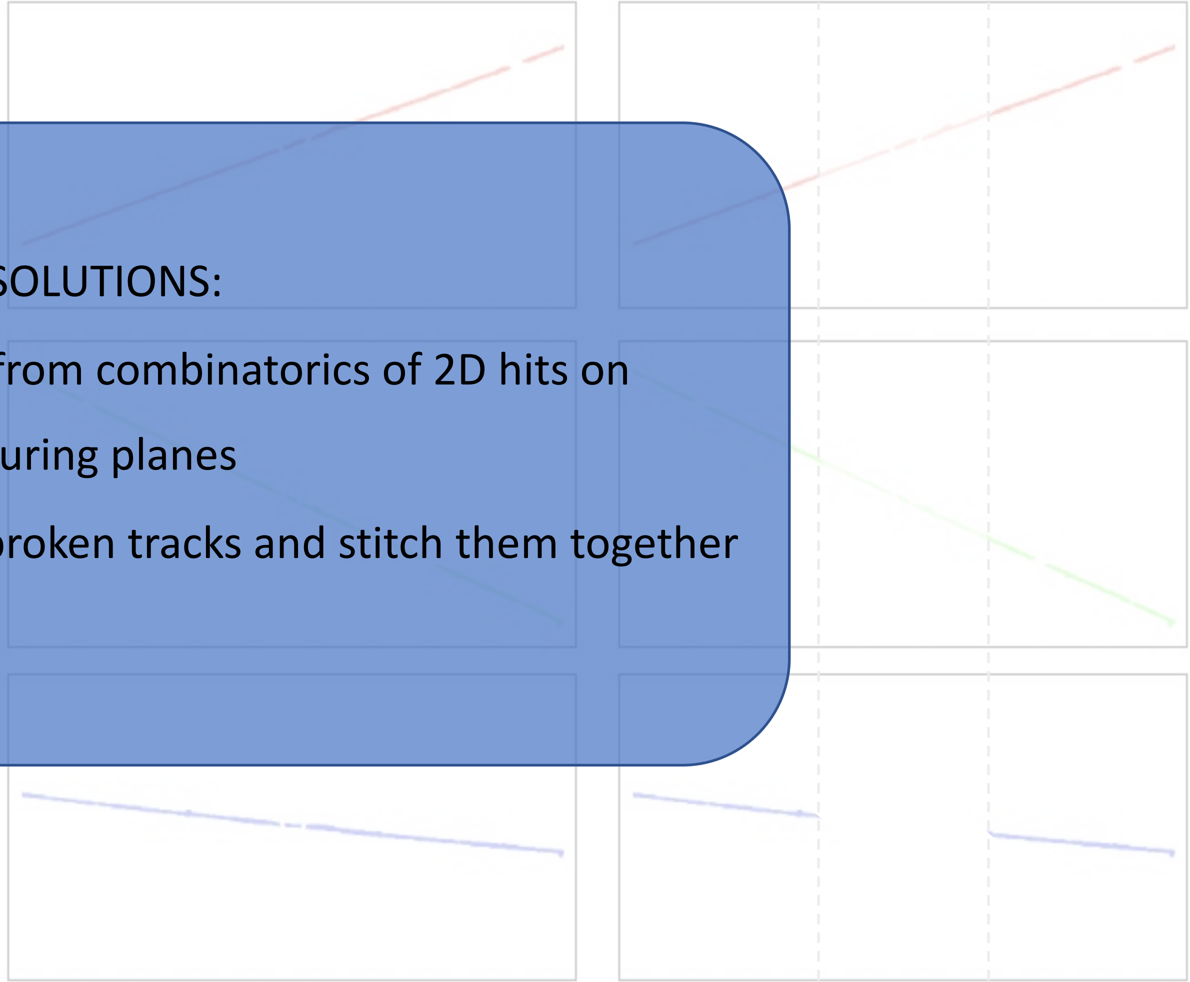
Merge of 2D hit cluster?

Successful | Unsuccessful



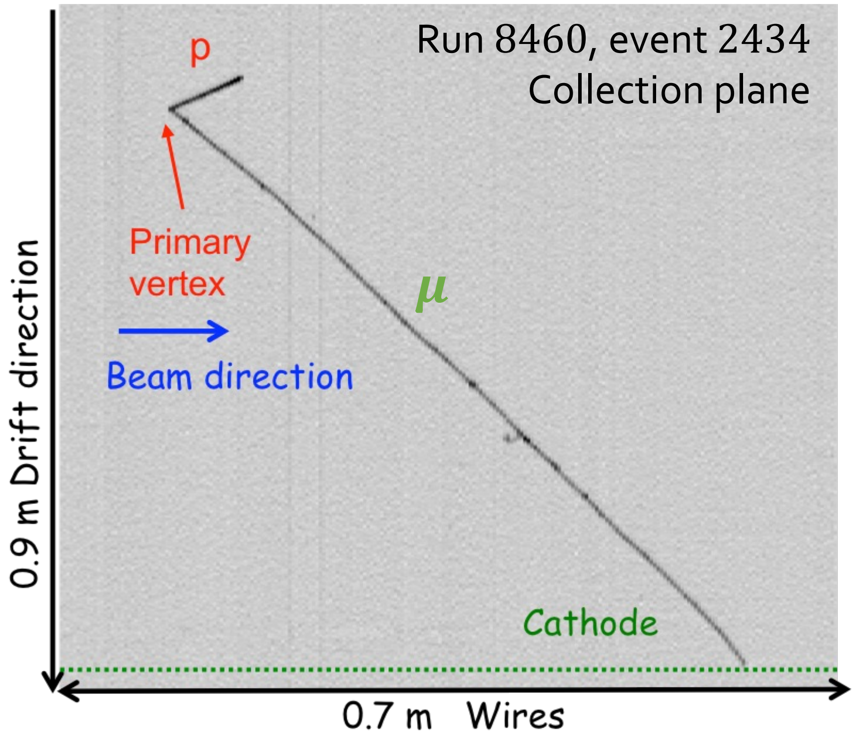
3D cluster | Missing Space Points

POSSIBLE SOLUTIONS:

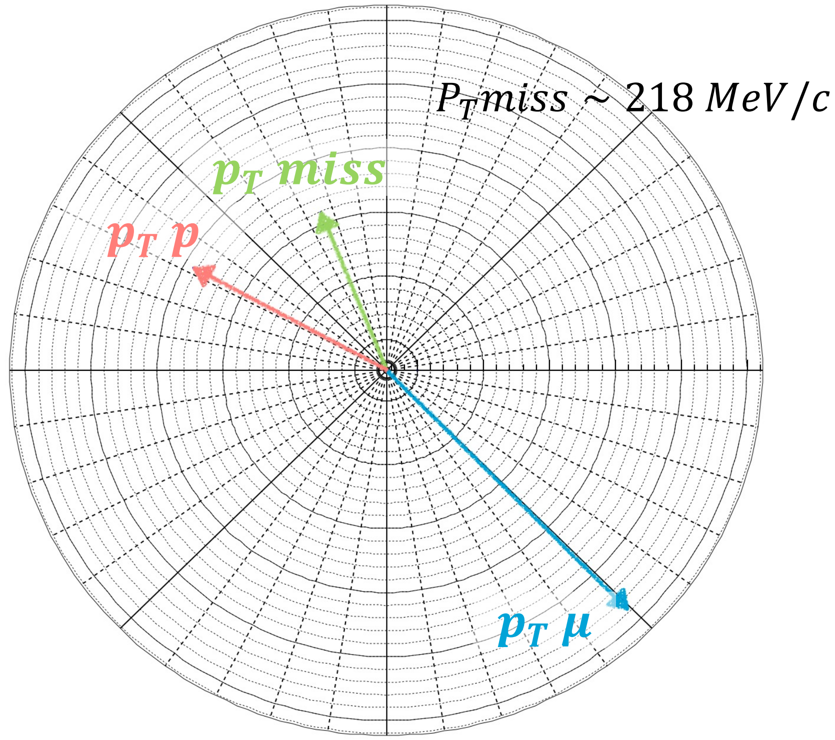
- find all candidate 3D points from combinatorics of 2D hits on neighbouring planes
- Develop an algorithm to identify broken tracks and stitch them together

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



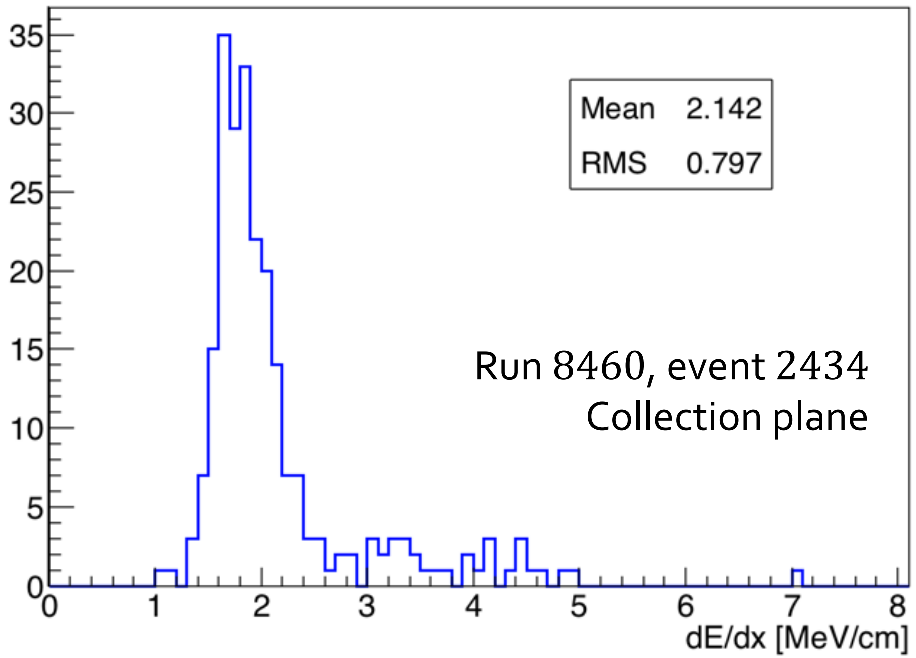
Transverse momenta $[MeV/c]$



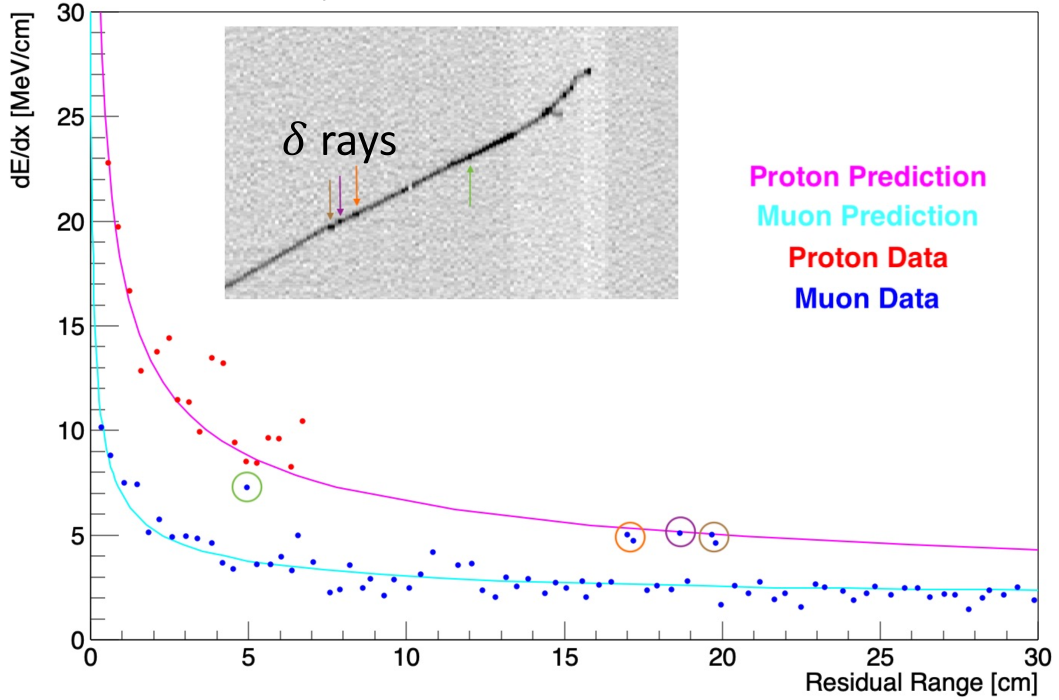
Particle ID and calorimetric reconstruction

- 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

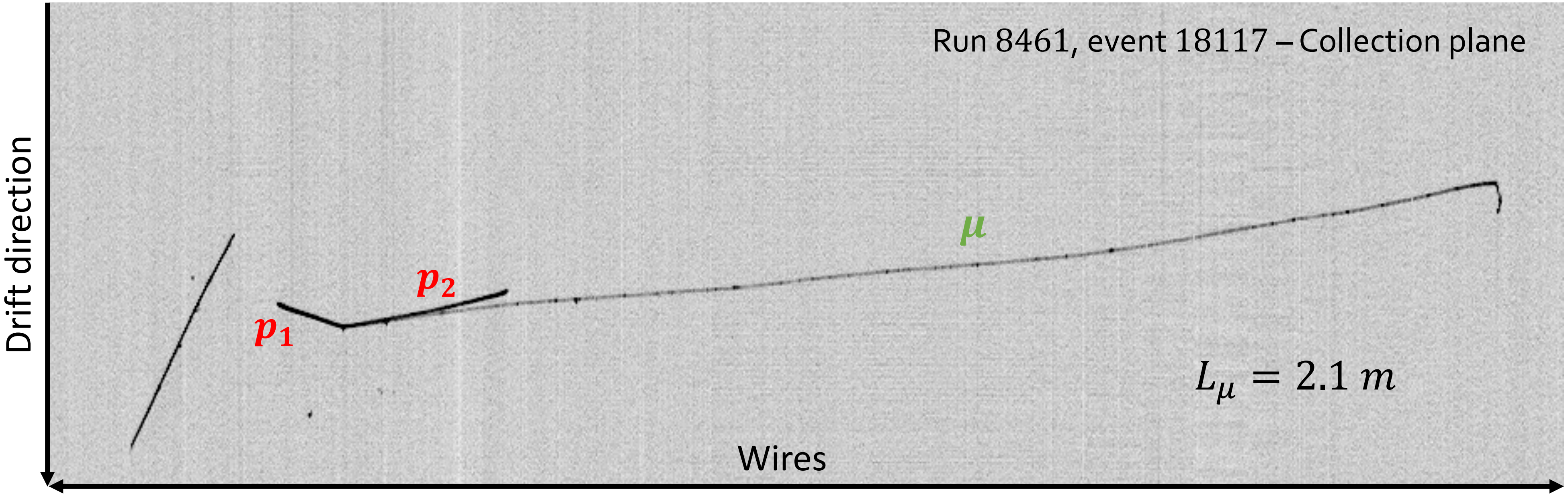


Data comparison to Bethe Bloch theoretical curves



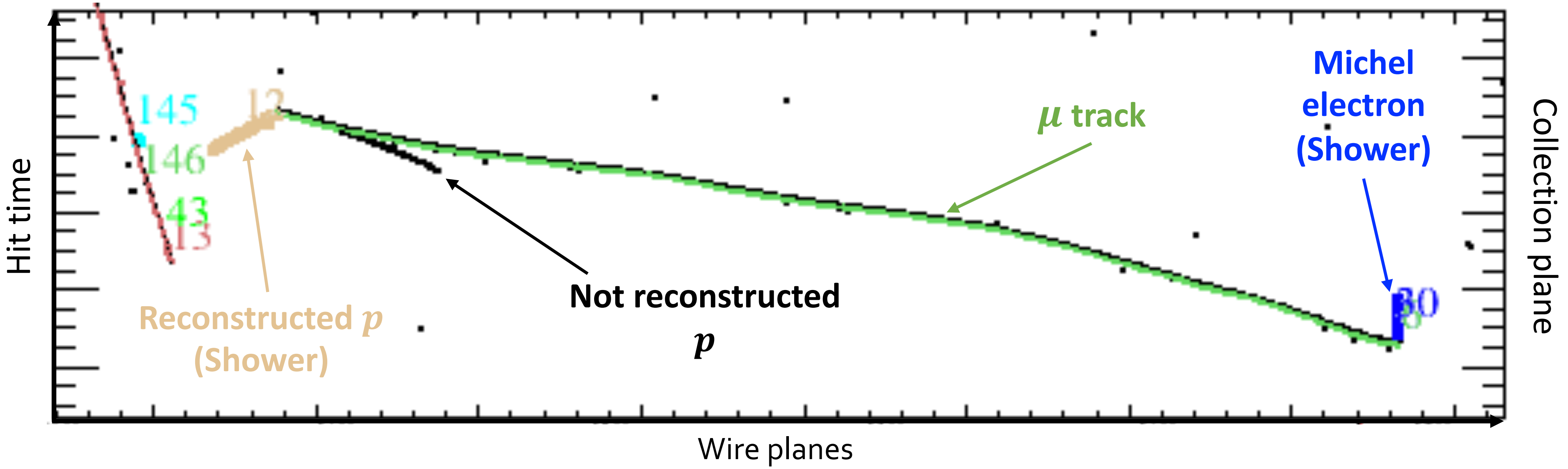
Classification within the automatic reconstruction

- ν_μ 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



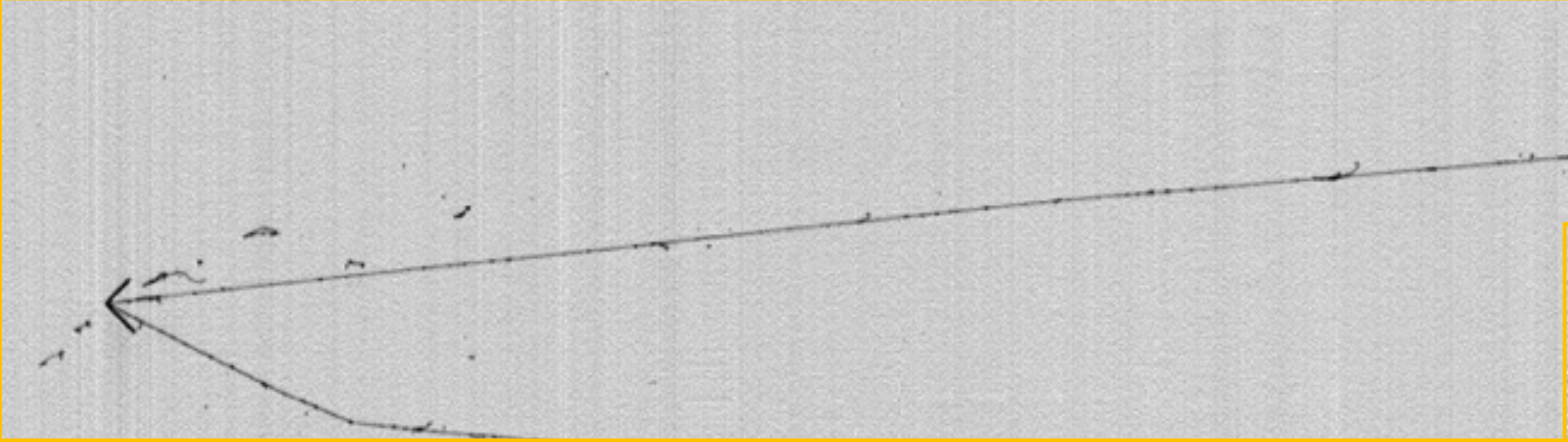
Classification within the automatic reconstruction

- 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

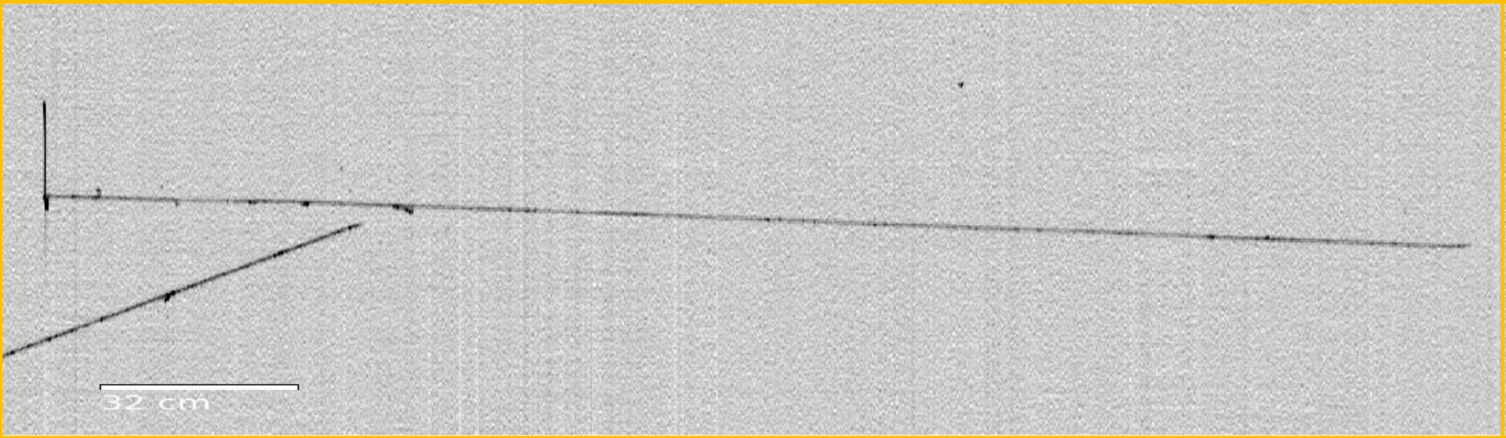


Conclusions and perspectives

- 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



THANK YOU !



IMAGING COSMIC AND RARE UNDERGROUND SIGNALS