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

Fermilab 2023 Summer Students School

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Outline

GOAL: perform a precise reconstruction of ν_μ CC QE events

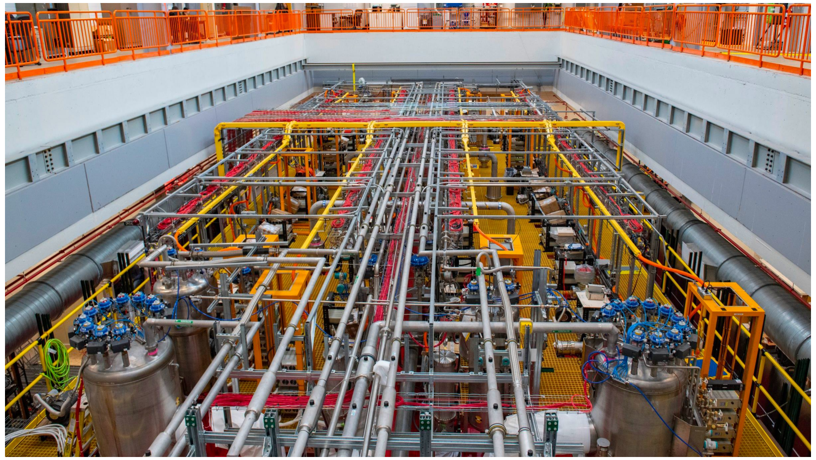
STEPS:

1. Is the particle contained? Define containment conditions
2. Is the particle well reconstructed? Exploit scan information
3. Is the detector well calibrated? Perform calorimetric reconstruction and particle identification
4. Are we missing something? Validate Monte Carlo performance

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

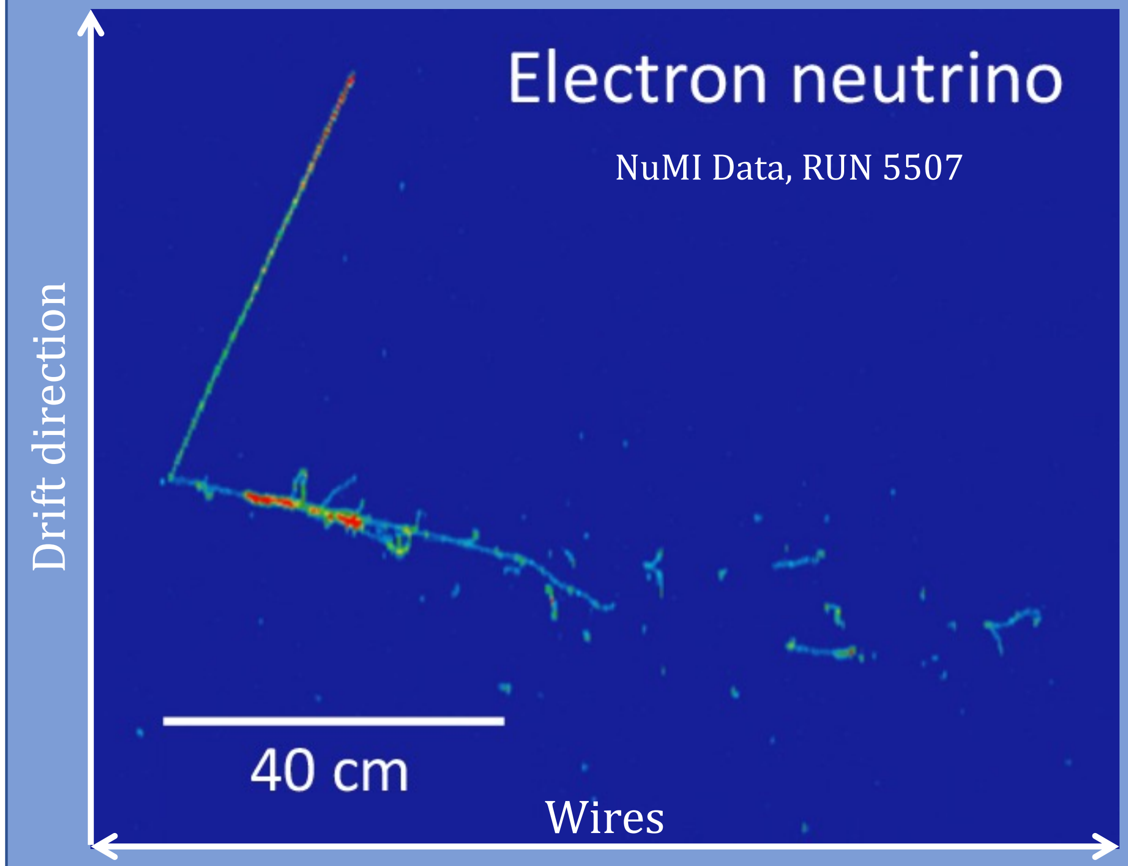
- I joined the ICARUS Neutrino Group based in Padova on January 2021
- The first part of the PhD position, has been intended to the calibration of the ICARUS detector during its commissioning phase at FNAL
- These last period I have focused more in reconstruction analysis

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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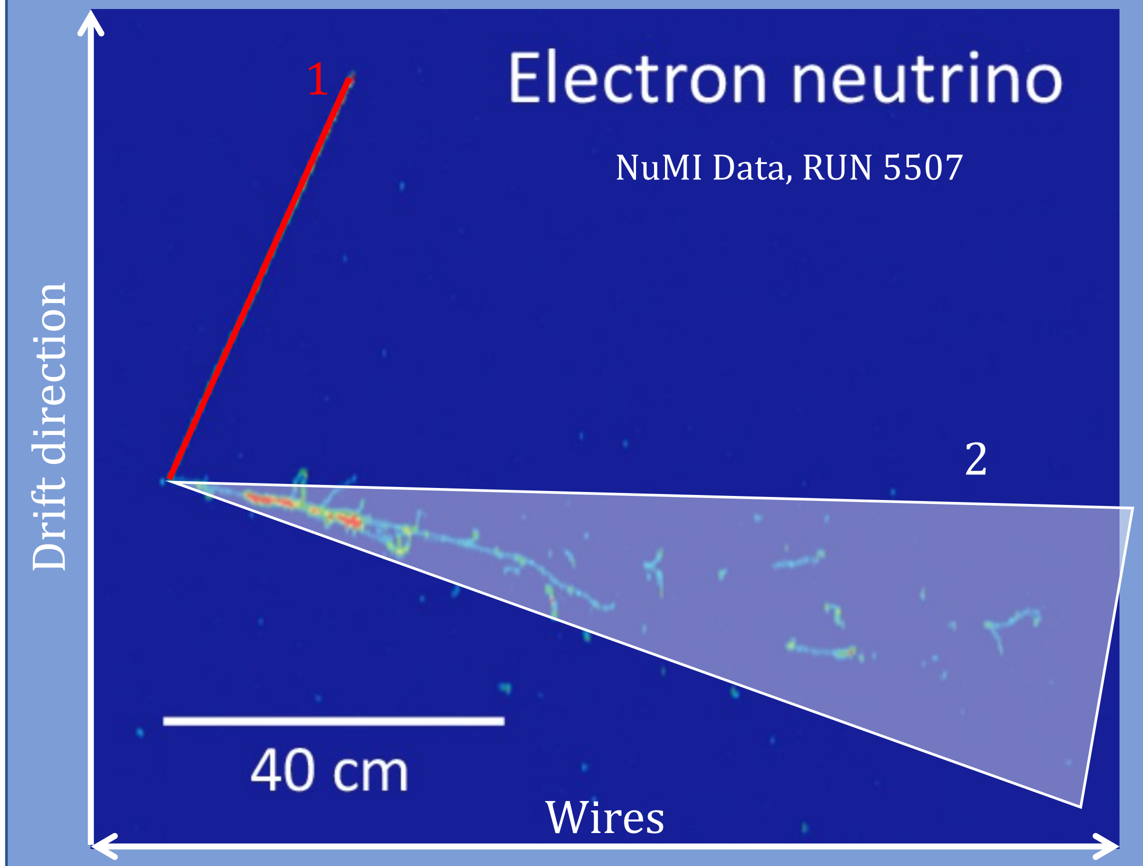

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DUE TO THE LARGE AMOUNT OF DATA TO ANALYSE, AN AUTOMATED SOLUTION IS MANDATORY !!

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

The reconstruction pipeline

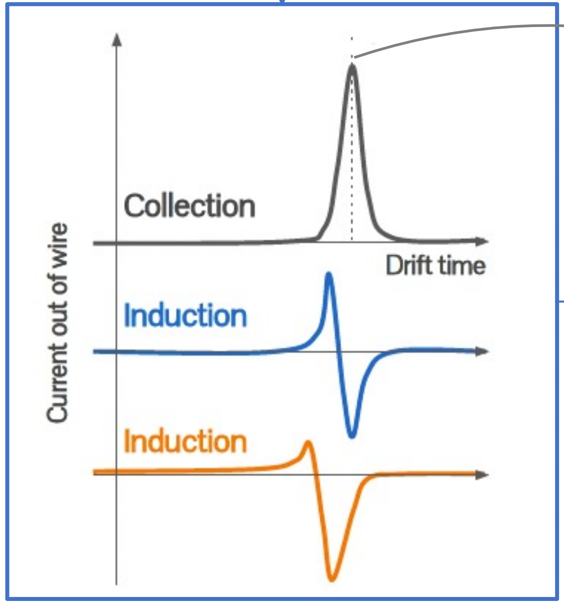
Detector Data → Low-level image processing → Hit finding → Pattern recognition → Particle fits → High Level Analysis

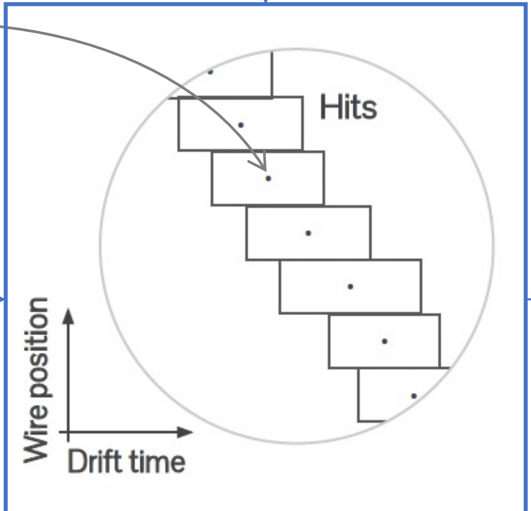
Low-level image processing
- Decoding
- Deconvolution
- ROI Finding

Hit finding
- Gaussian hits
- Cluster 3D

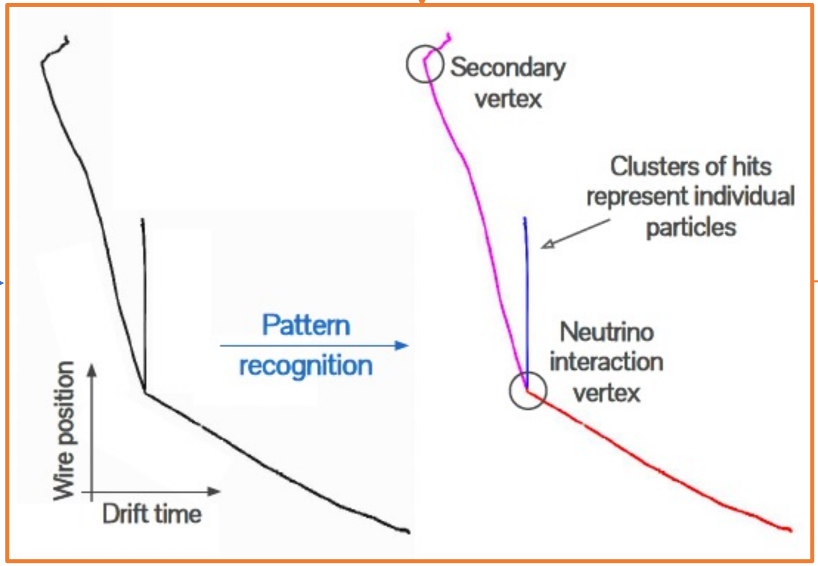
Pattern recognition
- Pandora Algorithm

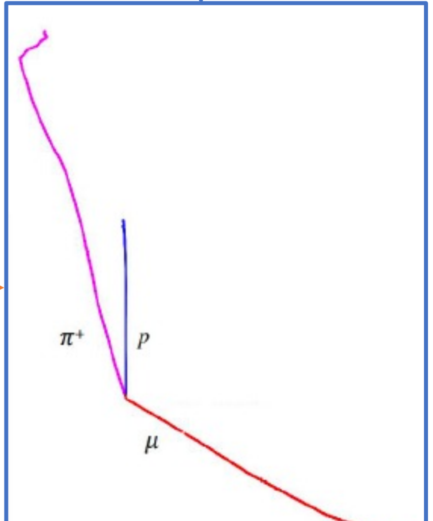
Particle fits
- Track, shower fits
- Calorimetry
- Particle ID





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

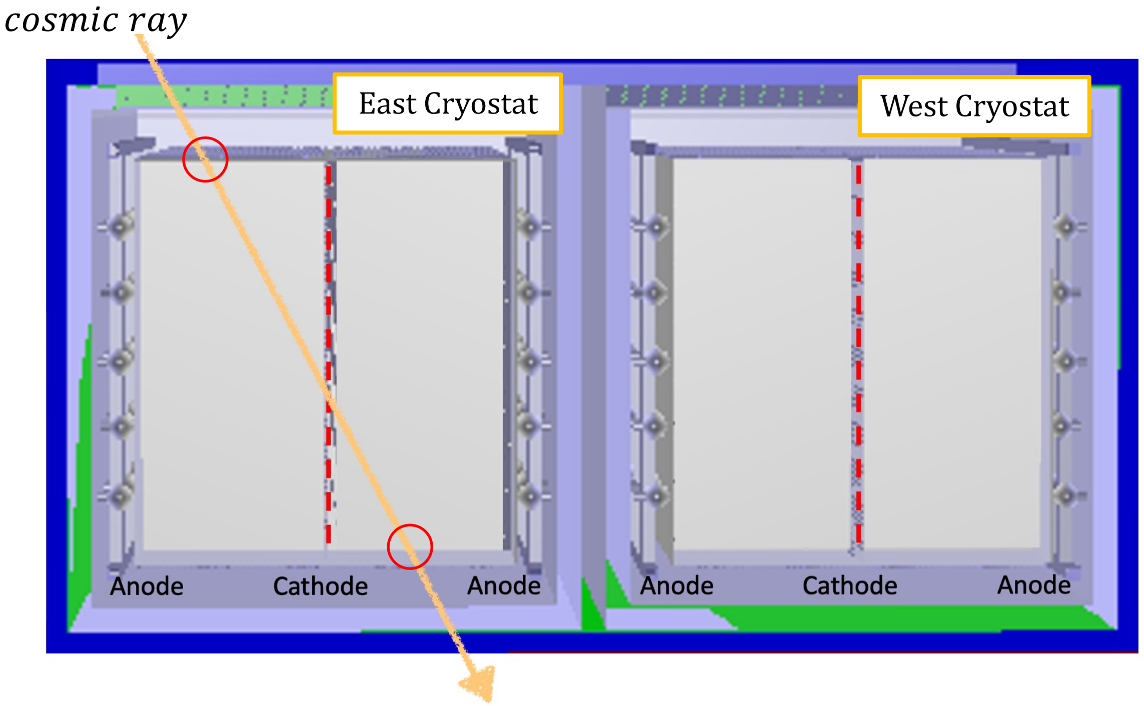




Containment conditions

- 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

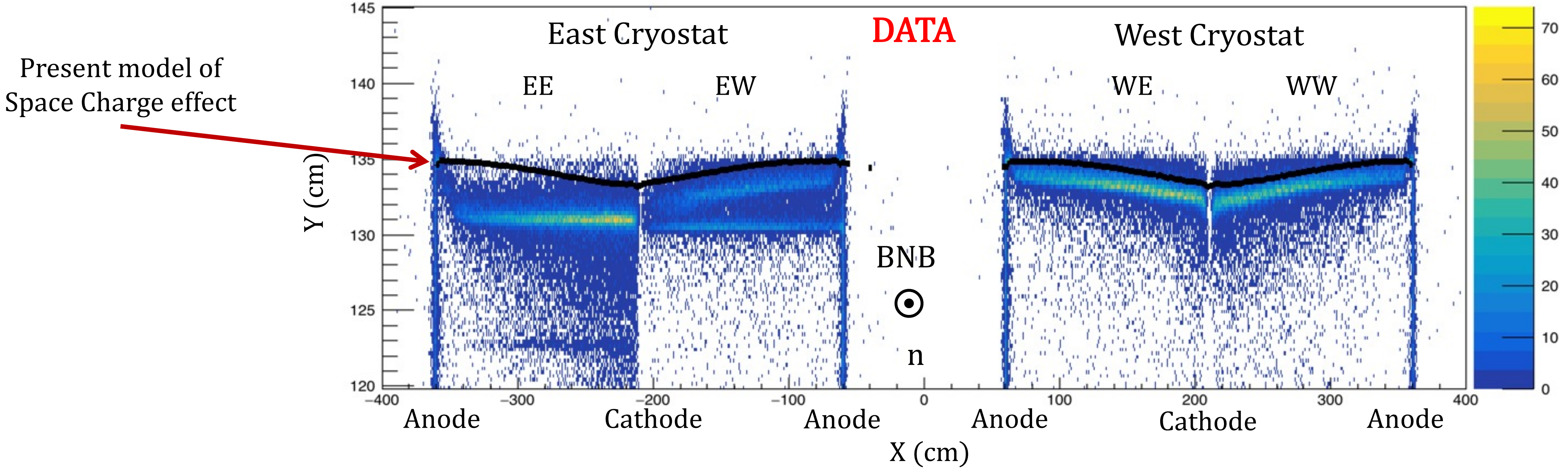
- Necessity to quantify the capability to correctly identify contained events
- We studied a sample of straight cosmic muons crossing the central cathode, for which the absolute position inside the detector is determined with few mm precision



Containment conditions

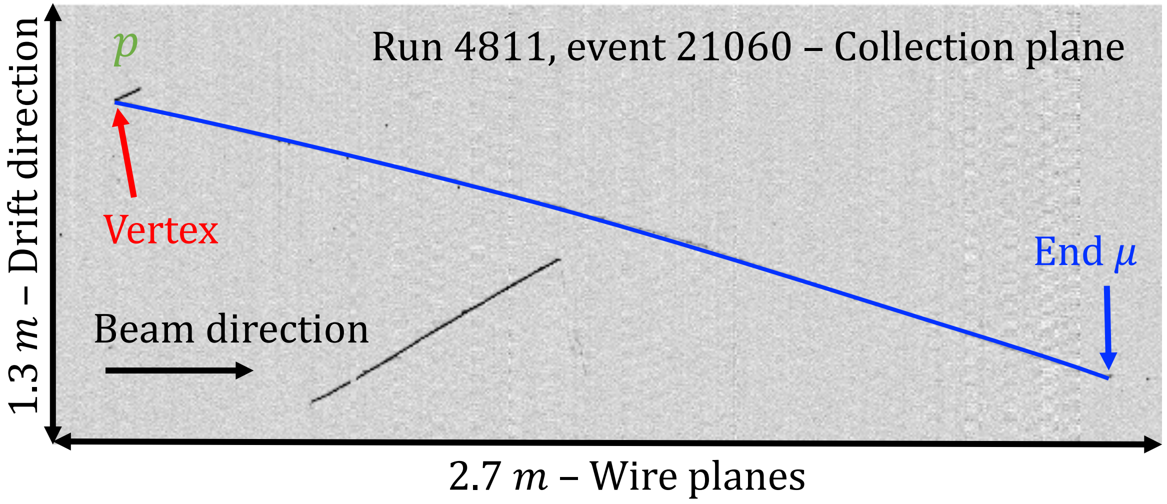
- We realised we were wrongly modelling the borders of the detector due to Space Charge Effects and possible reconstruction failures
- For the following studies, we only considered **fully contained** events, which are events whose tracks fulfil:
  - At least 5 cm away from top and bottom TPC sides ($\hat{y}$)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



Studies on event identification

- Pandora vertex and track reconstructions show some issues that impact a correct automatic reconstruction of neutrino interactions
- To study and mitigate these problems a closer comparison between automatic reconstruction and visually selected events is fundamental
- For each visually scanned event the 3D positions of the vertex, end muon and end proton (when present) are saved

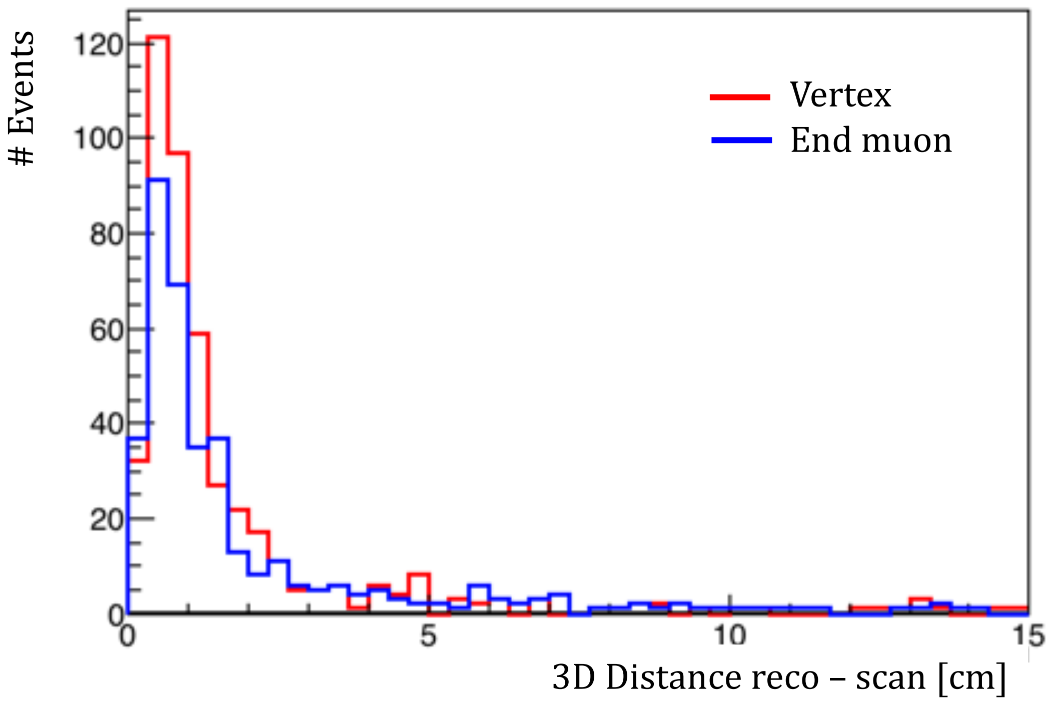


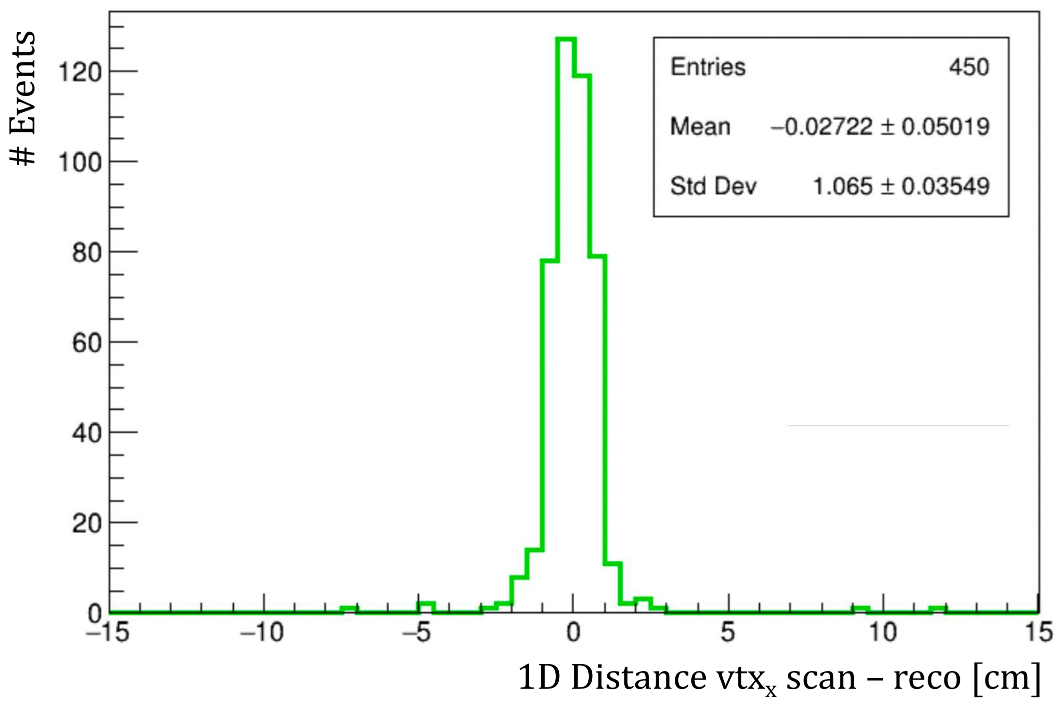
- Cross checking this information with the automatic output allows us to evaluate the vertex identification and track reconstruction capability of Pandora

Studies on event identification

- A sample of 526 ν_μCC BNB events were used to test the TPC reconstruction performance (Run from March 2022 with no overburden)
- In $\sim$ 70% of the cases the reconstructed vertex and end position of the muon are within 15 cm from the scanned information

* Scanning precision O(mm)

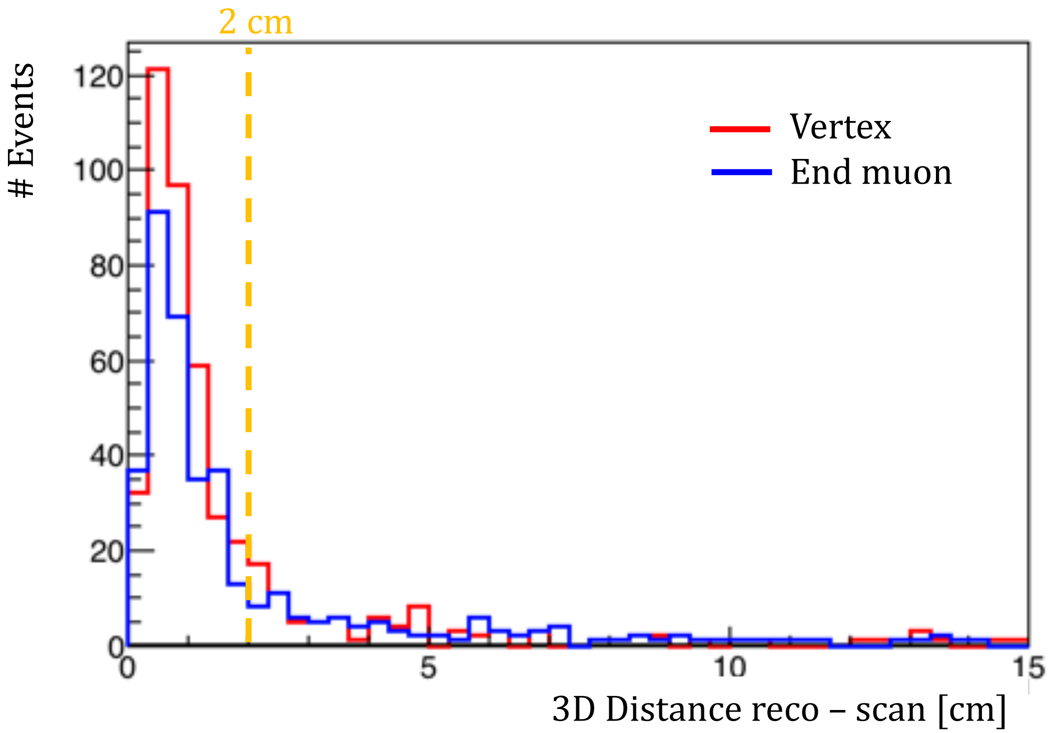


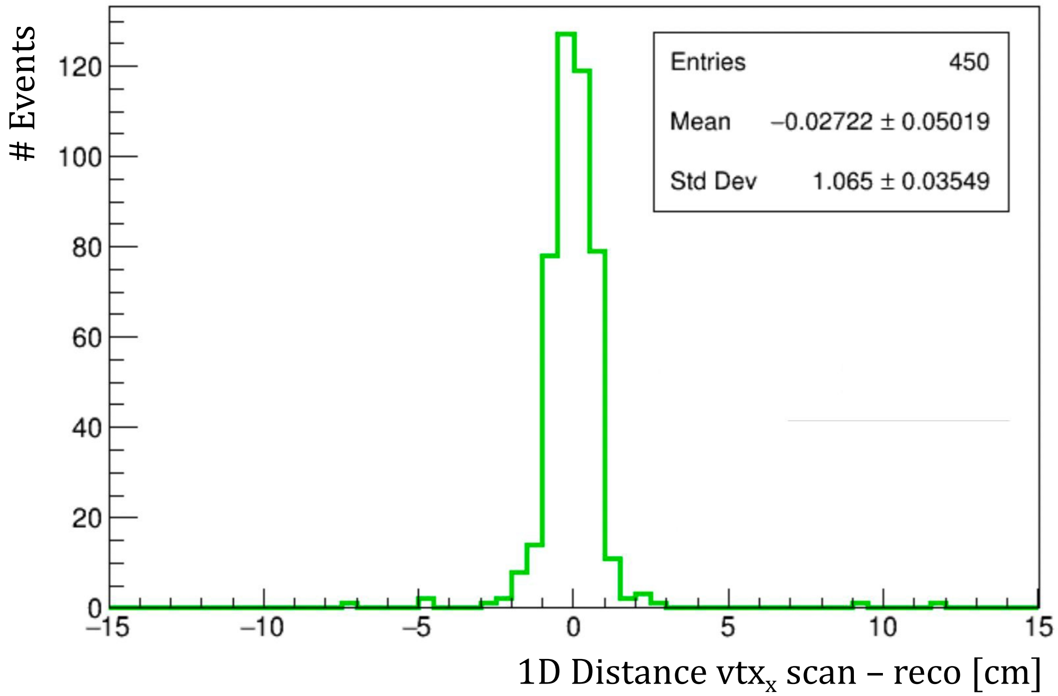


Studies on event identification

- A sample of 526 ν_μCC BNB events were used to test the TPC reconstruction performance (Run from March 2022 with no overburden)
- In ~ 70% of the cases the reconstructed vertex and end position of the muon are within 15 cm from the scanned information
- If we ask a tighter cut, ~ 45% of the events agree within 2 cm with the scanned information

* Scanning precision $O(mm)$





Studies on event identification

- The events where the vertex and/or the end of the muon are not well recognized are studied in more detail to improve our TPC reconstruction

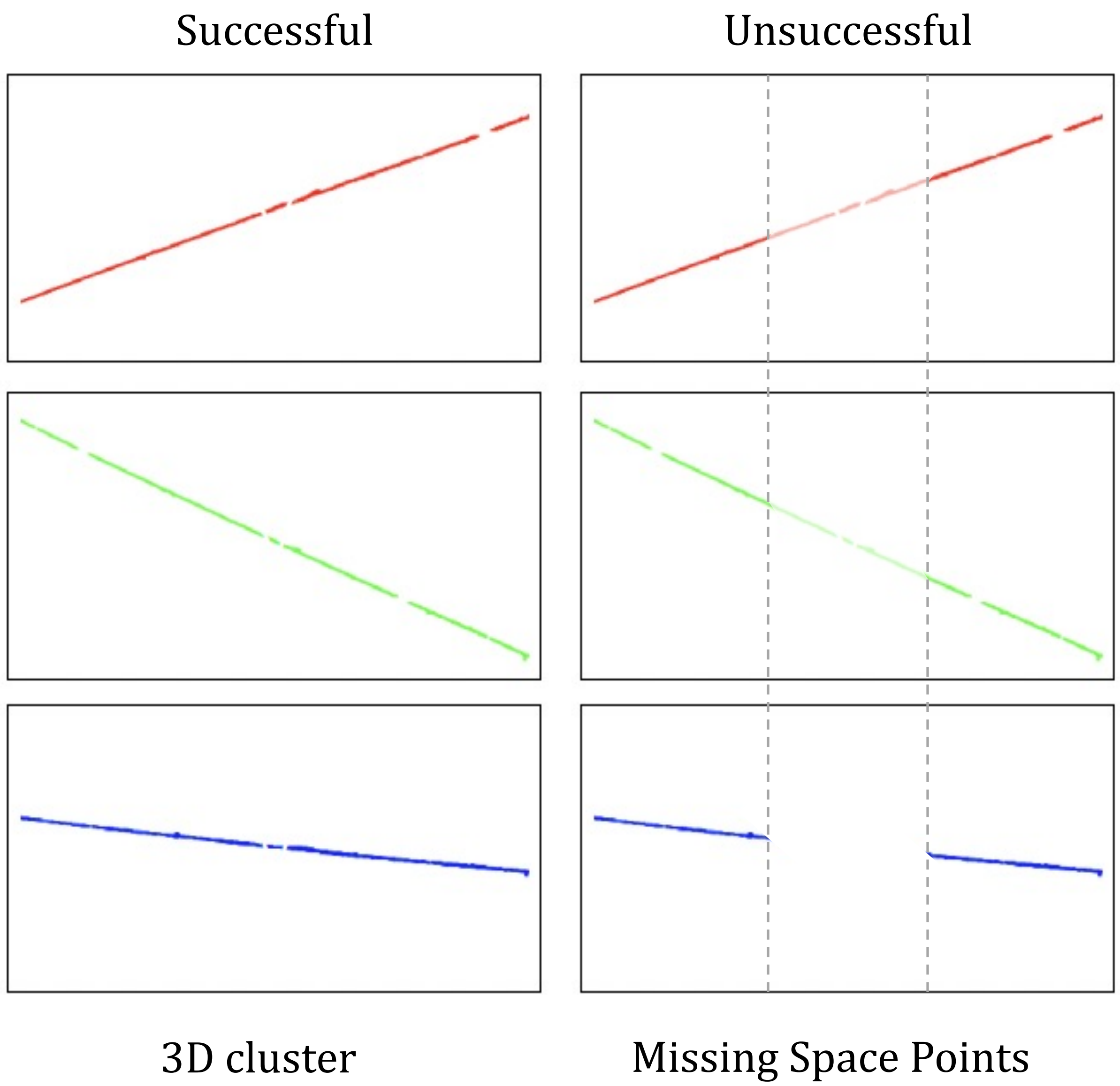
Total events	526		
Not available	8		
Matches	76.45%	Perfect match	73.75%
		Split μ track	2.70%
Pathological	23.55%	Scan - reco distance > 15 cm	6.95%
		Well reconstructed vertex but bad end μ track	7.14%
		Reversed track	3.86%
		No match found for μ track	5.60%

* % are computed wrt the available 518 events and the classification is made with a 15 cm cut

How are Space Points made?

Merge of 2D hit cluster?

- 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



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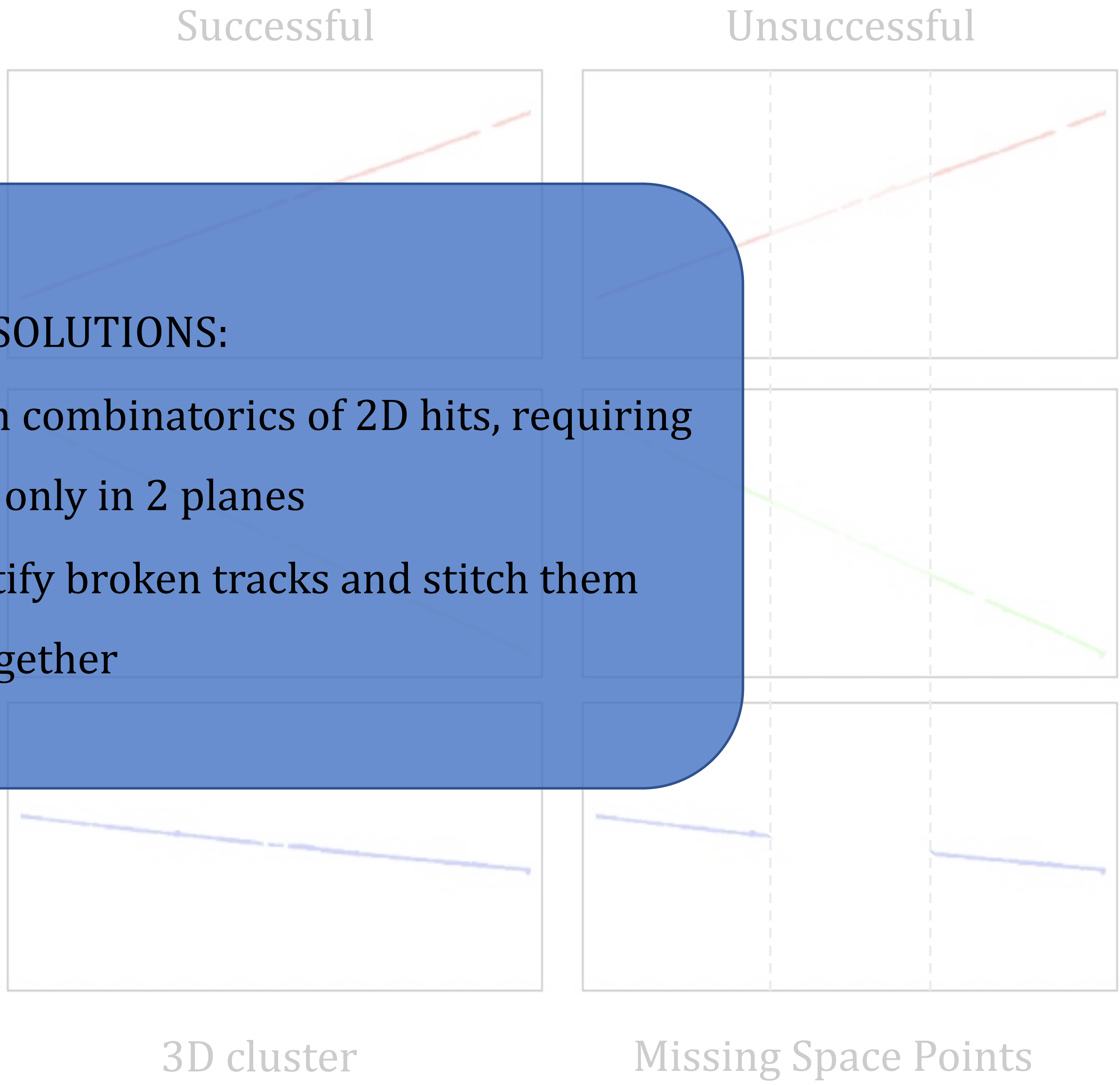
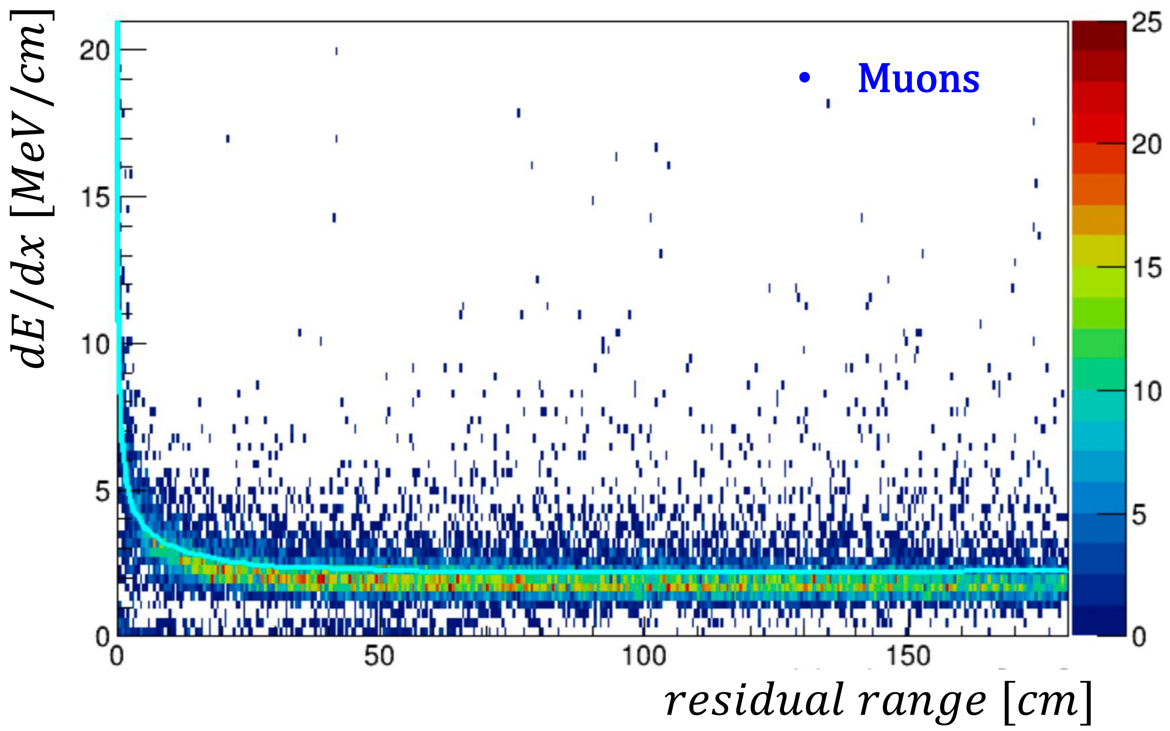
POSSIBLE SOLUTIONS:

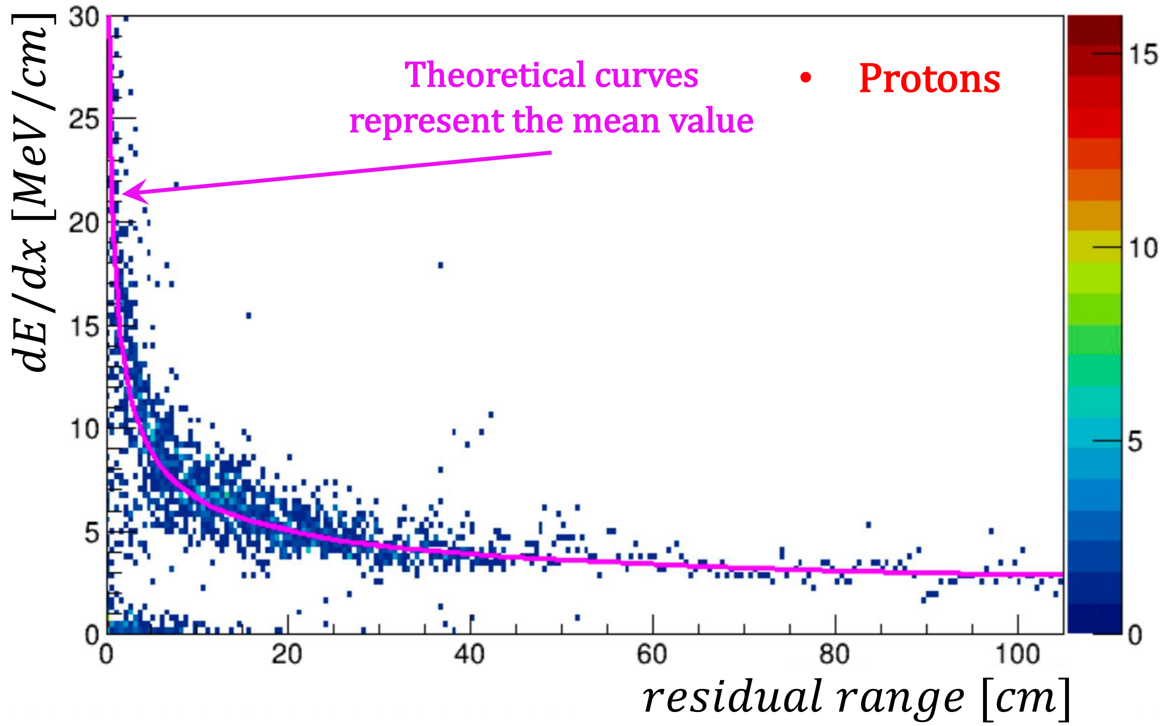
- find all candidate 3D points from combinatorics of 2D hits, requiring coincidence only in 2 planes
- Develop an algorithm to identify broken tracks and stitch them together



Particle identification

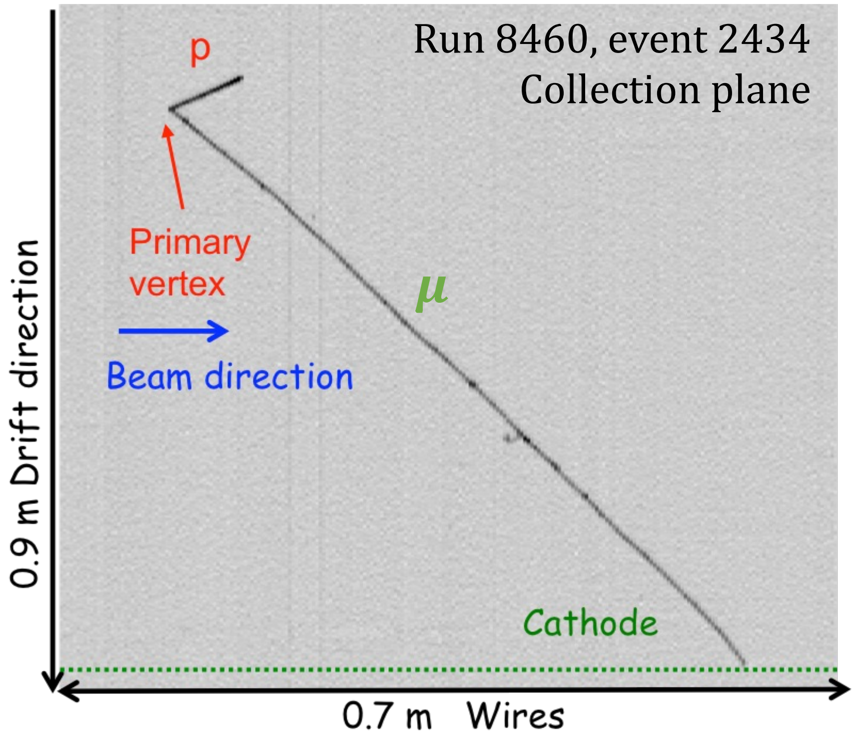
- The identification of the ν interactions requires a Particle Identification (PID) tool to effectively recognise the particles at the primary vertex
- The current algorithm relies on the comparison between the measured dE/dx vs residual range along the track with the theoretical profiles from different particles (μ, p, K, π)
- The χ^2 fit is performed considering **only** the last 25 cm of the track and using information from collection plane



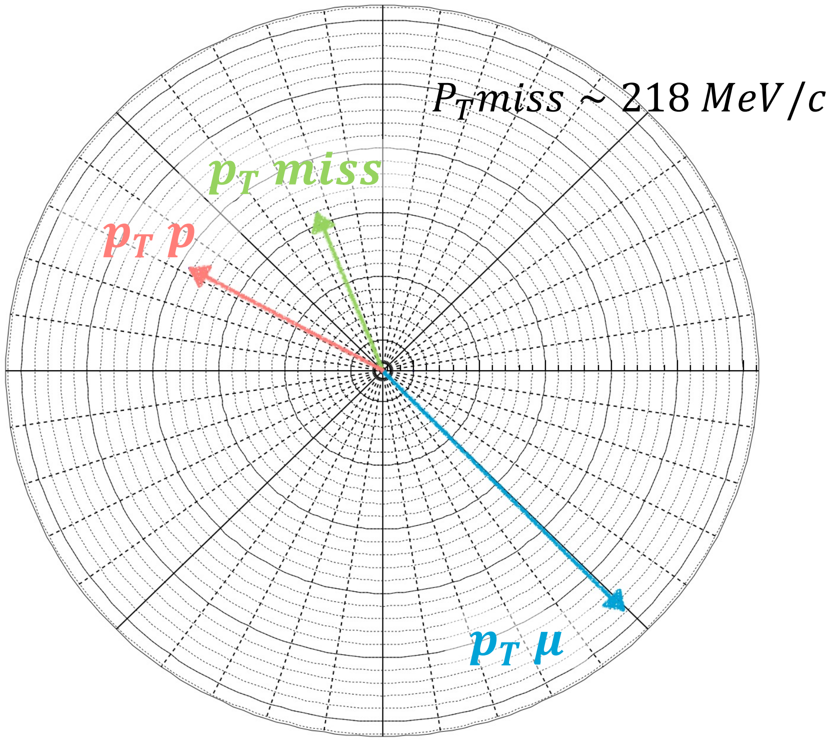


Particle ID and calorimetric reconstruction

- 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



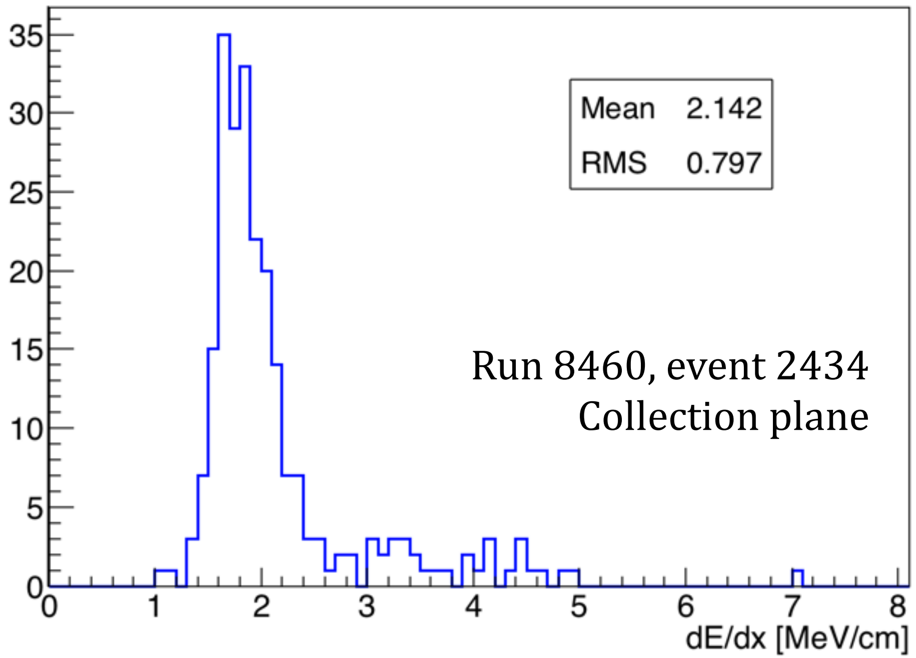
Transverse momenta $[MeV/c]$



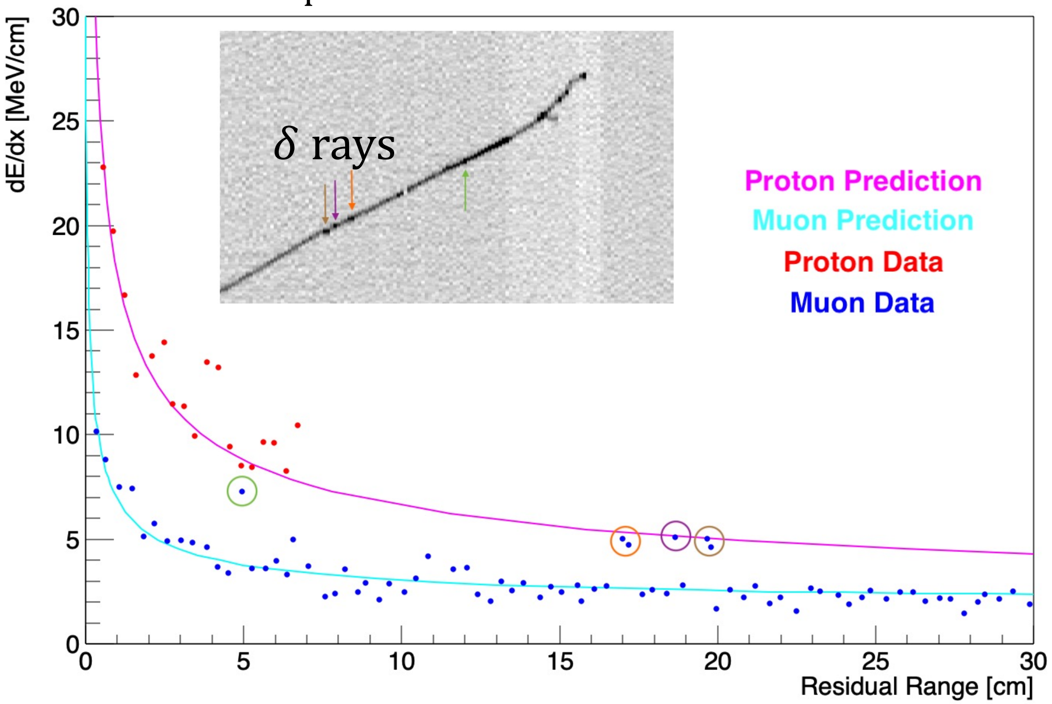
Particle ID and calorimetric reconstruction

- 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

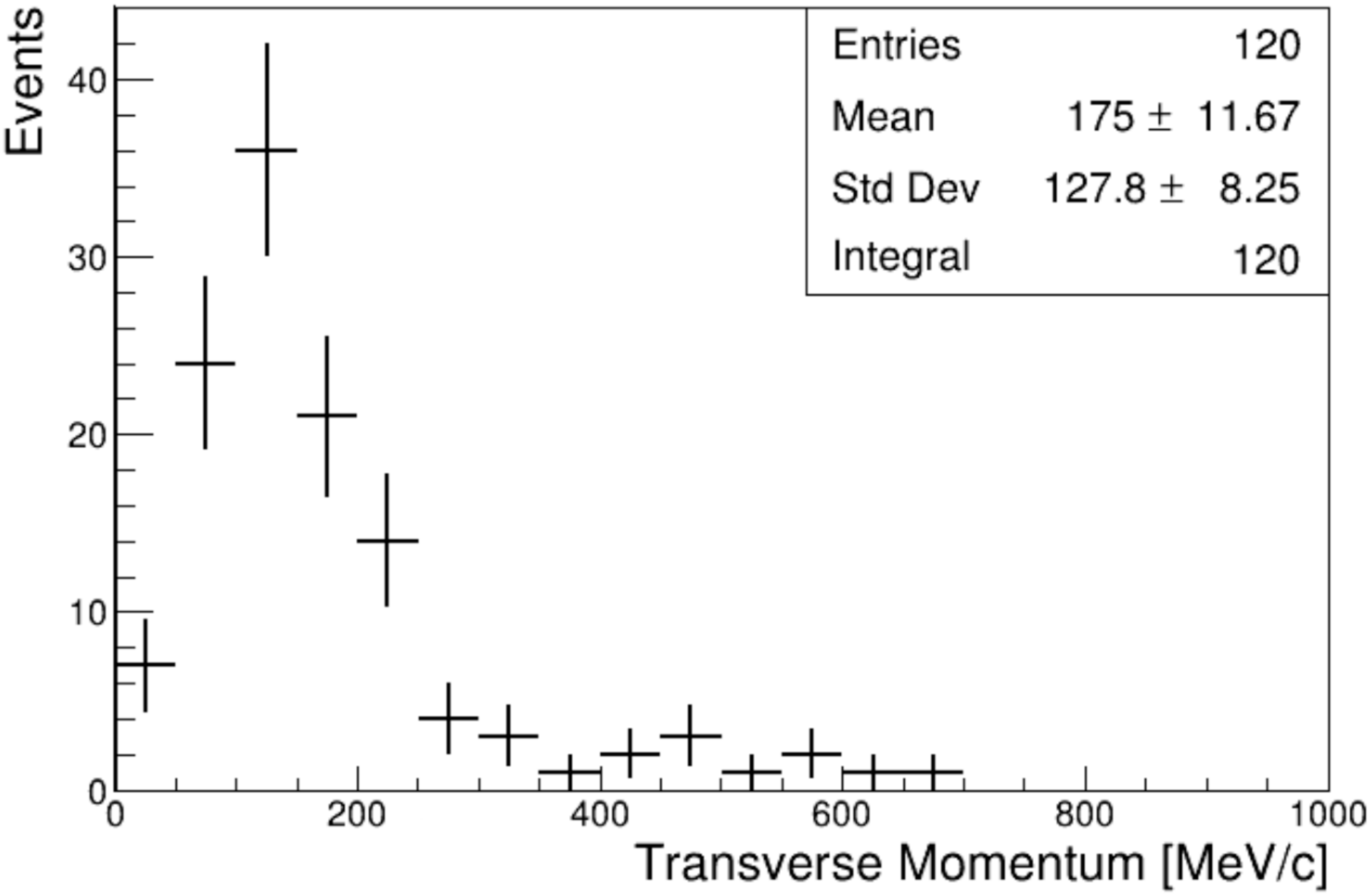
dE/dx distribution excluding last 50 cm of the track



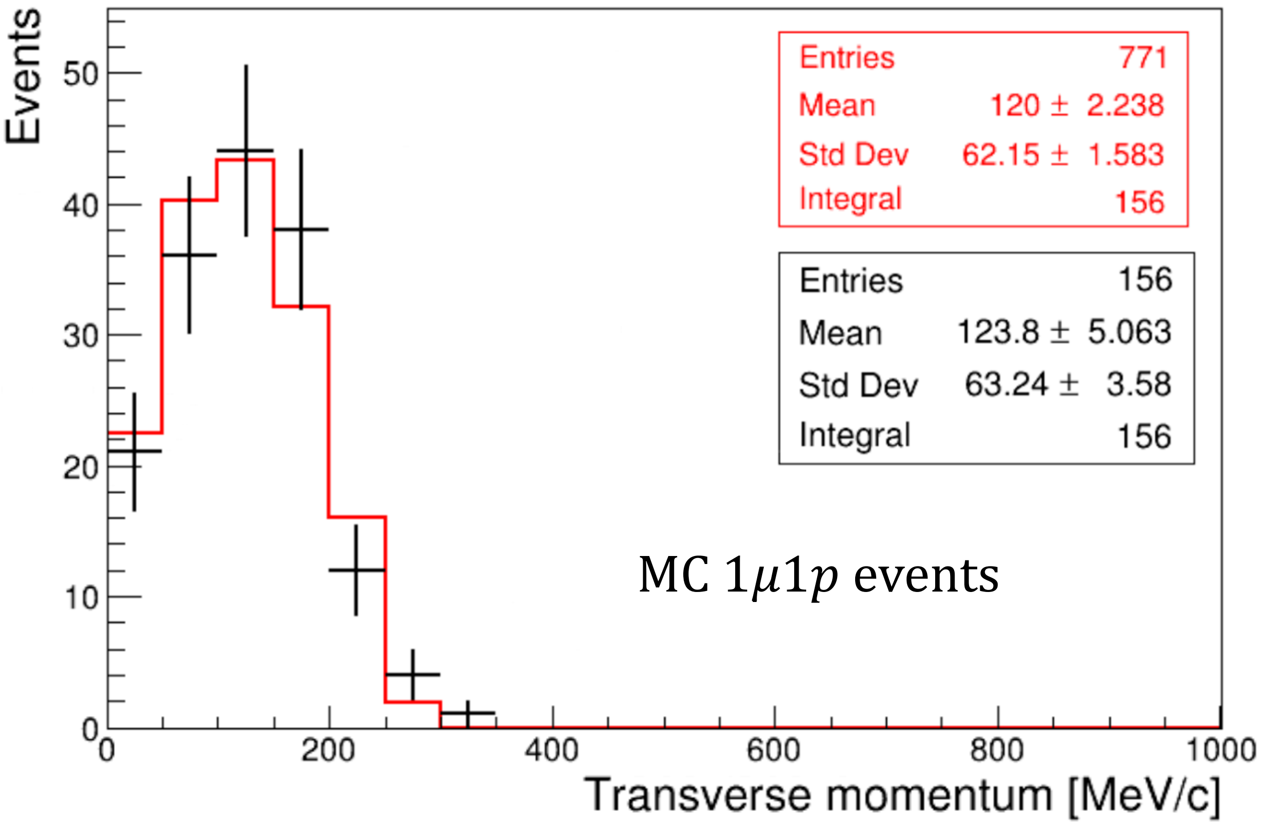
Data comparison to Bethe Bloch theoretical curves

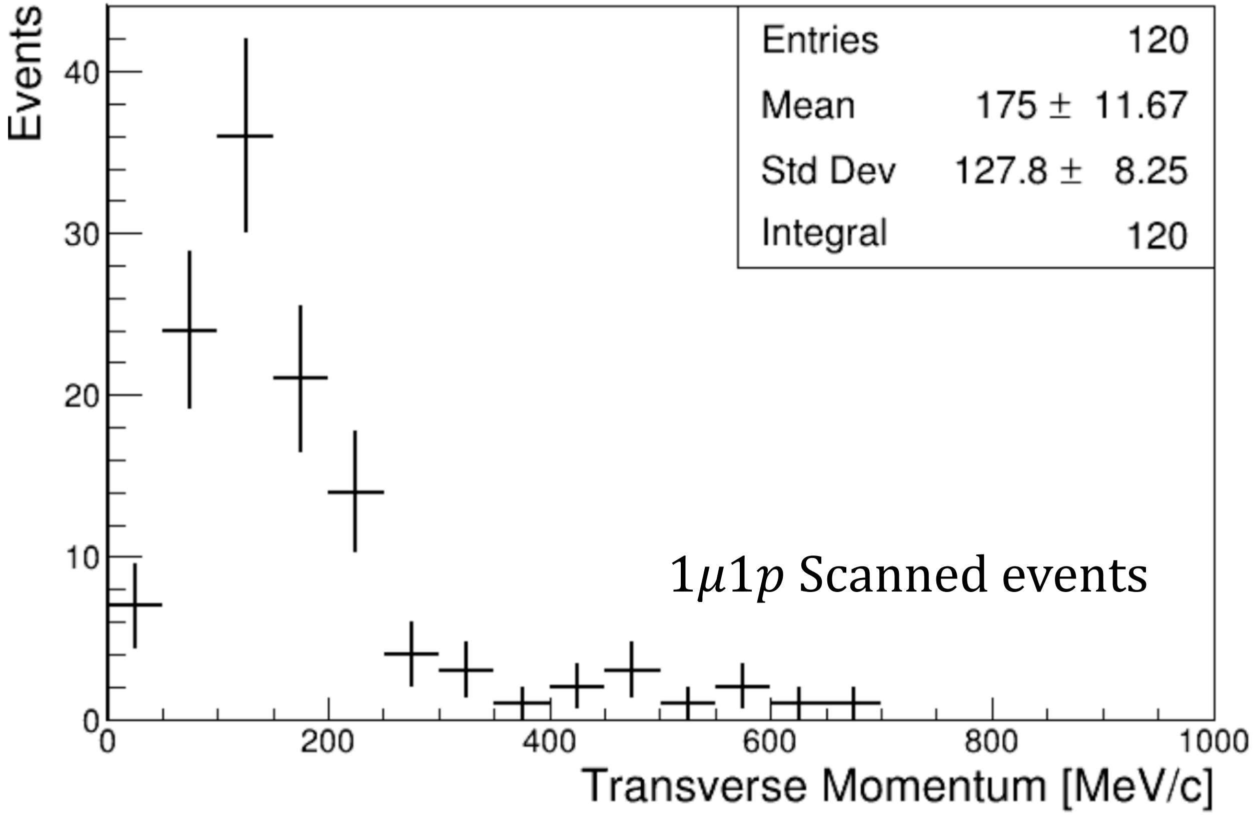


- Neutrino transverse momentum for well reconstructed events



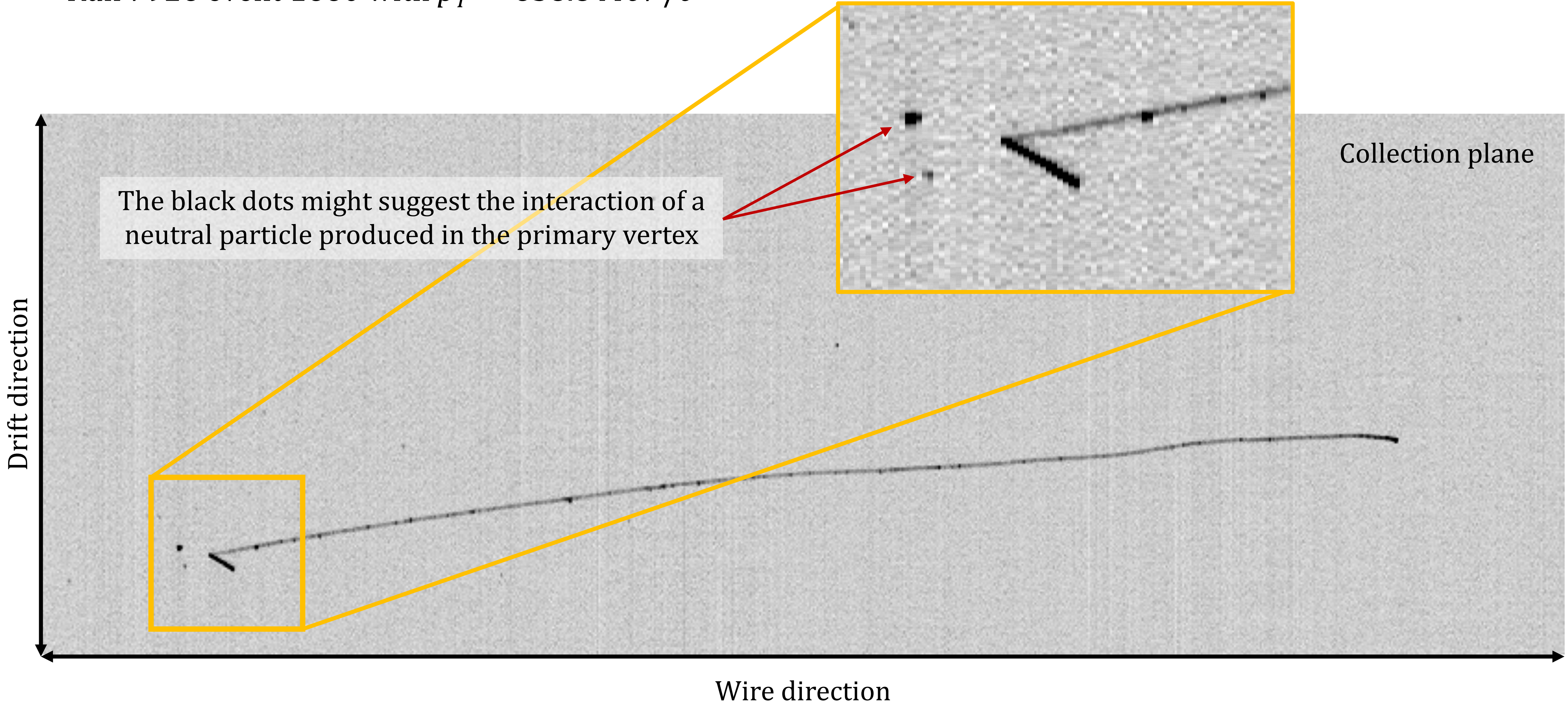
- Neutrino transverse momentum for selected events
- Left plot: reconstructed MC events are in black, red line indicates the truth values scaled to the its well reconstructed number of events (MC)
- Right plot: Well reconstructed **data** events



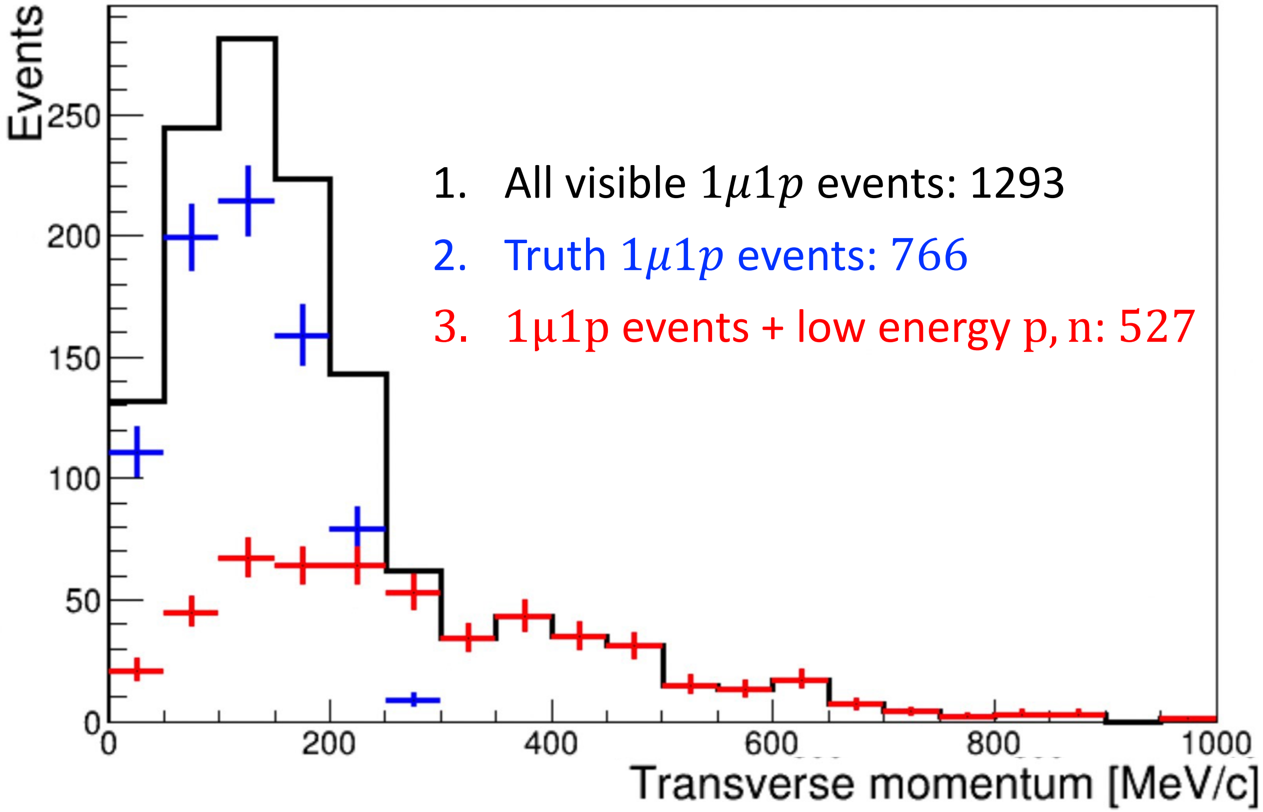


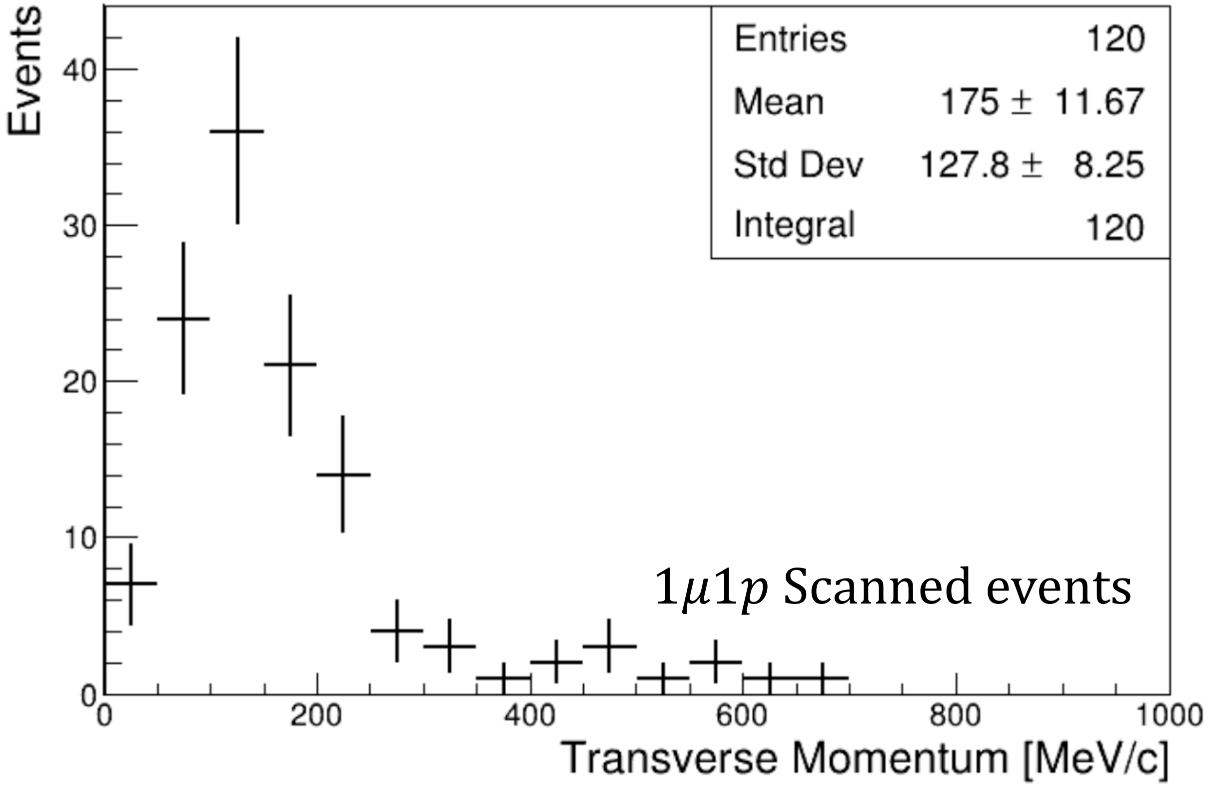
High transverse momentum event

- Run 7926 event 1660 with $p_T = 638.8\ MeV/c$



- The visible $1\mu 1p$ sample contains both truth $1\mu 1p$ events (only 2 primary tracks) plus the remaining events which include also some low energy protons, neutrons and photons
- We can distinguish both sets to see its contribution to the reconstructed transverse momentum





Conclusions and perspectives

- Some progress has been made in validating the 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
- Some MC studies were performed in order to validate our results
- We are currently working to develop an efficient automatic selection of $1\mu 1p$ candidate events

THANK YOU !

Imaging Cosmic And Rare Underground Signals