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

INTENSE Meeting

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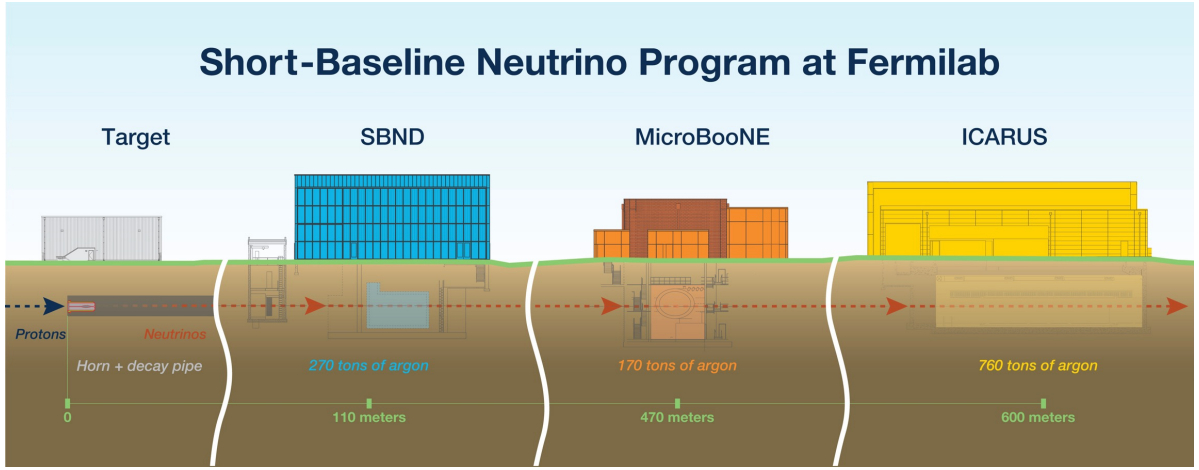
Sterile neutrino search

- Several anomalies have been observed in neutrino oscillation experiments, some of them can be explained by introducing an additional sterile neutrino state (ν_s)
- Short Baseline Neutrino (SBN) program should clarify this question by exploiting the BNB beam and comparing the neutrino interactions observed at different distances along the baseline by ICARUS and SBND



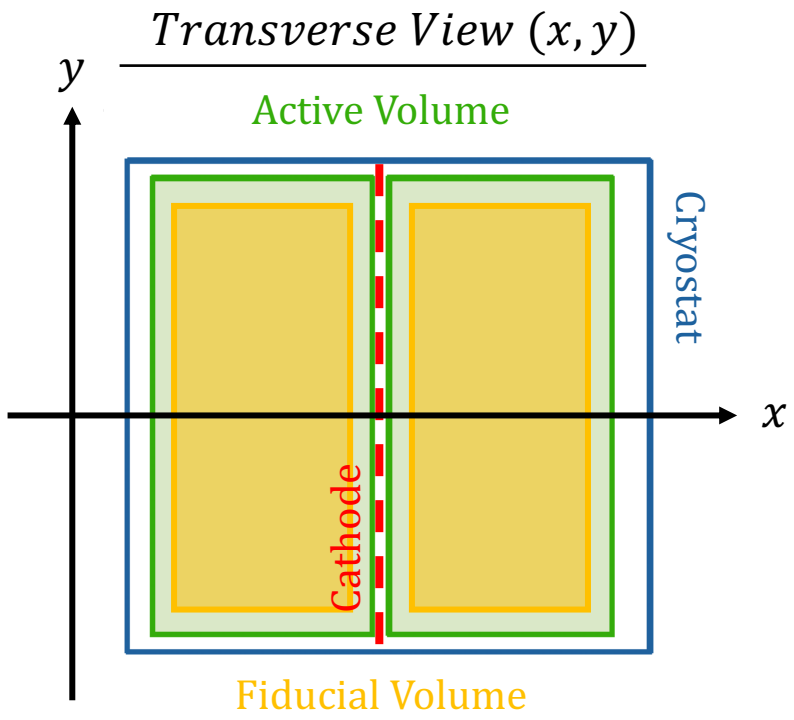
- Both ν_e appearance and ν_μ disappearance channels can be observed, granting access to study the nature of the observed anomalies and shed light on the existence of the sterile neutrino
- NEUTRINO-4 experiment has recently claim the observation of sterile neutrino oscillations, therefore ICARUS has started taking data alone to address this declaration

- A first step towards this goal is to focus on the study of ν_μCC quasi elastic interactions with the BNB

ν event selection

- Quasi elastic ν_μCC neutrino interactions are selected by requiring:

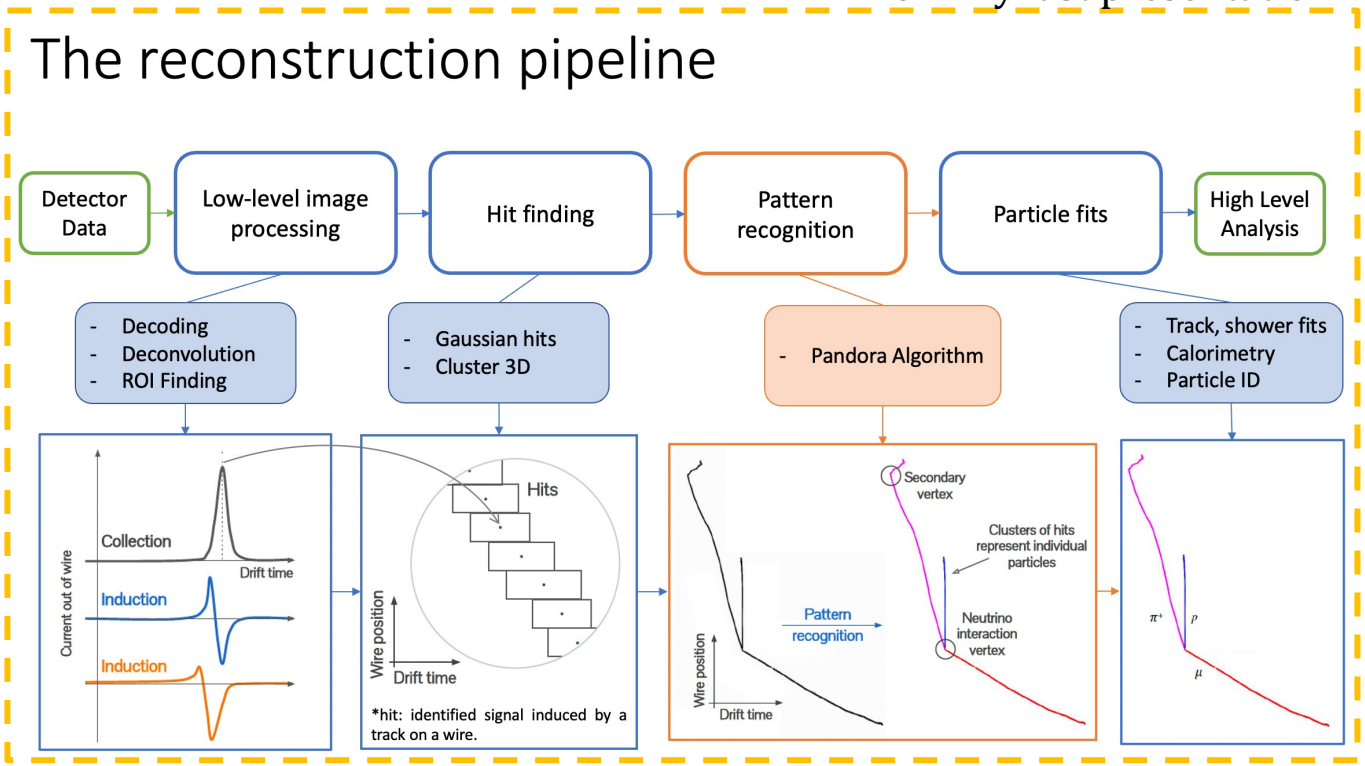
  1. ν vertex should be inside the fiducial volume i.e., 25 cm apart from the lateral TPC walls and 30/50 cm from the upstream/downstream walls
  2. **Fully contained** interactions i.e., no signal in the last 5 cm of the LAr active volume
  3. Stopping muon of $L_\mu > 50$ cm
  4. At least 1 proton $L_p > 1$ cm produced at the primary vertex



- Due to the large amount of statistics, an automated solution is mandatory, Pandora pattern recognition is currently used to
  - Identify neutrino interactions inside the TPCs
  - Provide vertex identification
  - Reconstruction of track and showers

ν event selection

From my last presentation



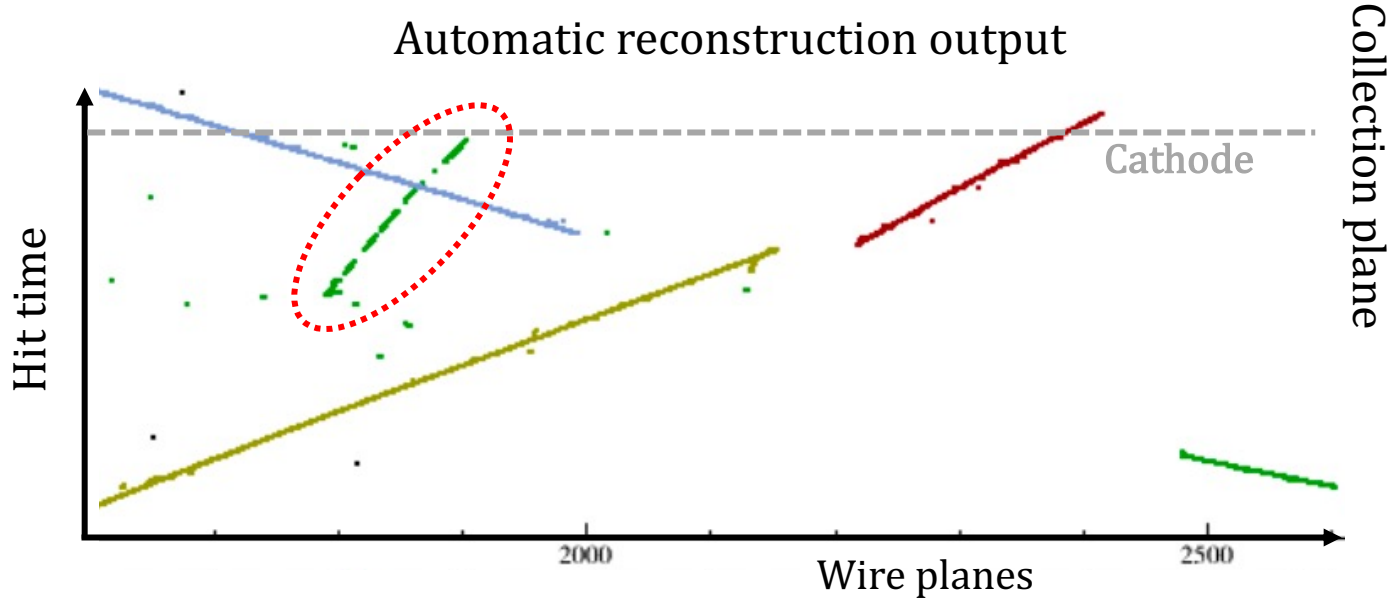
- Efficient and reliable reconstruction of the complete tracks and physical wire signal is required
- Robust Particle Identification tool is also needed to unambiguously recognize stopping muons and protons

- The goal is to fully reconstruct neutrino events with its global kinematics
- The performance of the selection and reconstruction procedures needs to be verified on a large sample of neutrino candidates. Possible thanks to the set of visually scanned events

Improvements since last meeting

1. MYTHICAL POINTS

- In the past, Space Points were required to have matches in all three planes, which introduced inefficiencies if a set of hits was missing in one of them

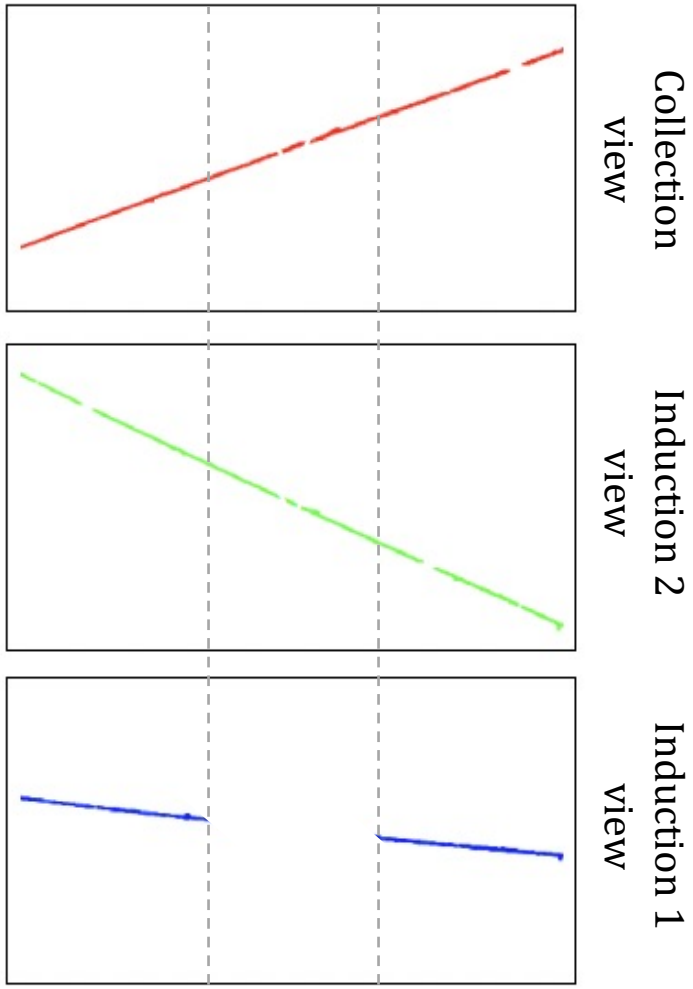


Improvements since last meeting

1. MYTHICAL POINTS

- In the past, Space Points were required to have matches in all three planes, which introduced inefficiencies if a set of hits was missing in one of them

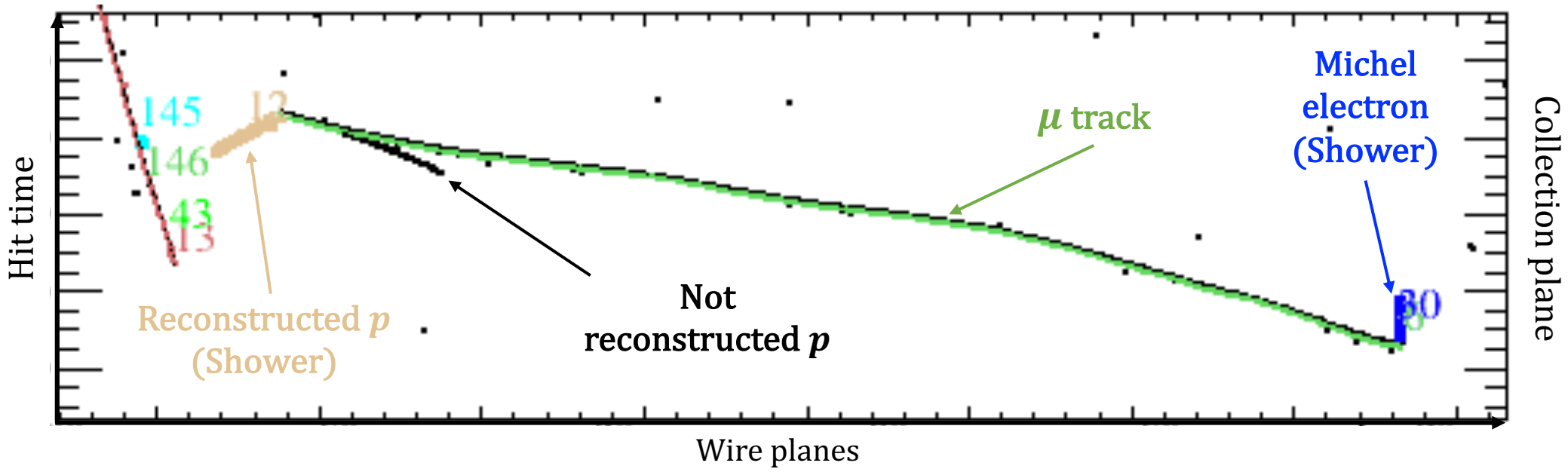
- Modifications to the code were made to allow the creation of space points when hits were only present in two views
- Prevention against the creation of duplicates was also addressed



Improvements since last meeting

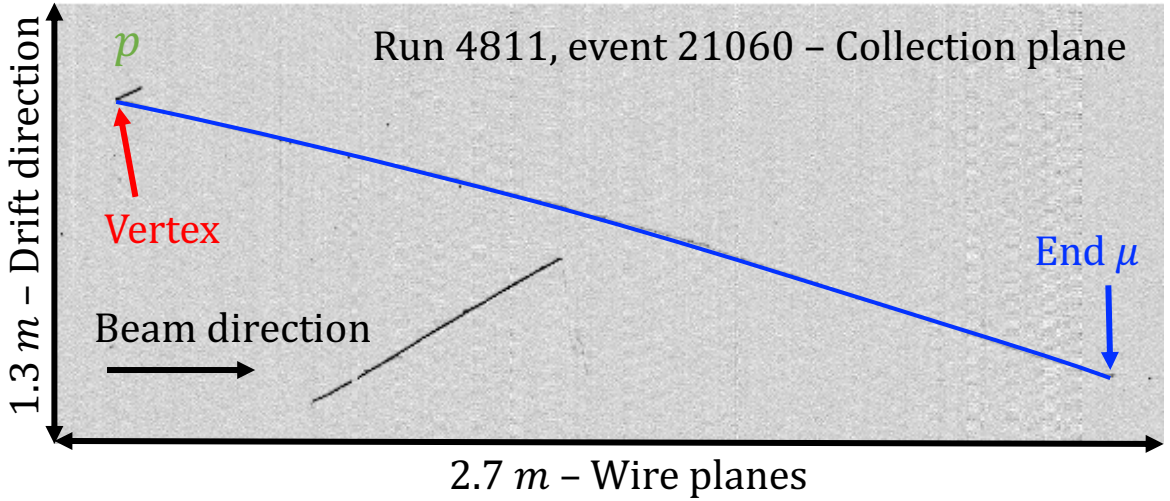
2. TRACK AND SHOWER FIT

- In order to better understand and investigate the discrimination between track and shower the reconstruction chain was modified
- Track and shower fits are now performed to all particles independently from Pandora's output



Studies on event identification

- Pandora vertex and track reconstruction still shows 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

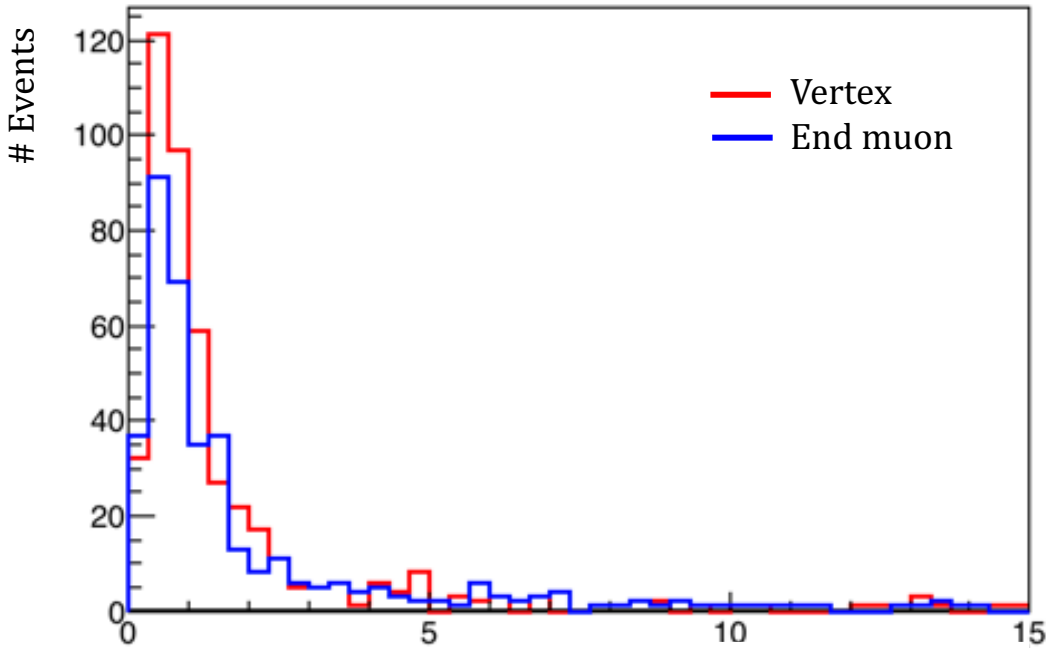


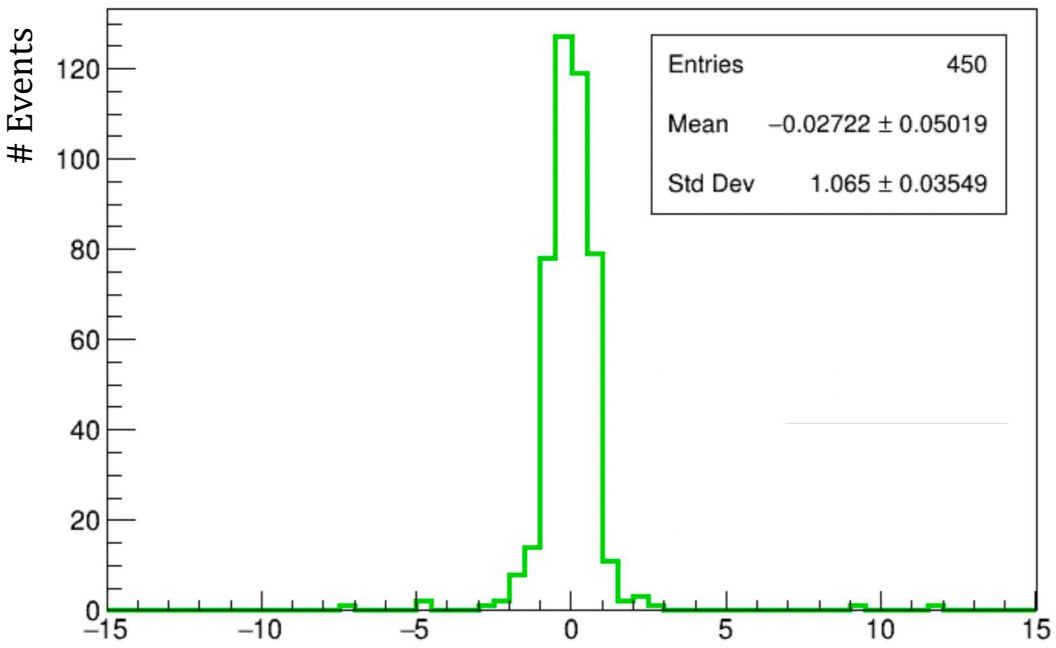
- Cross checking this information with the automatic output allows us to evaluate the vertex identification and track reconstruction capability of Pandora

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 ~ 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

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- 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

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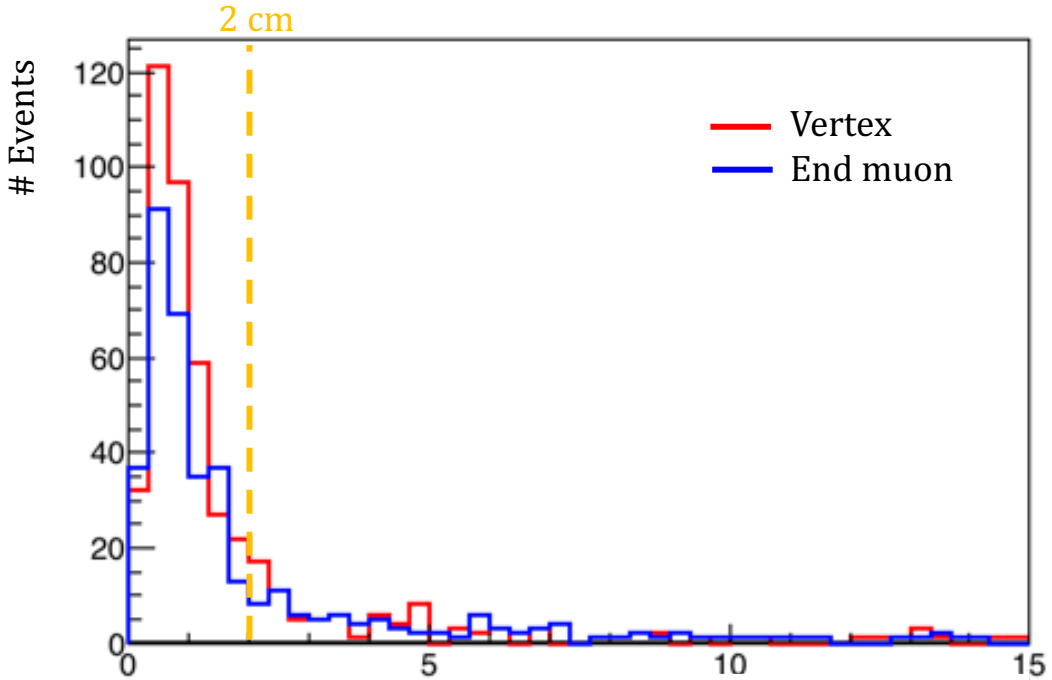
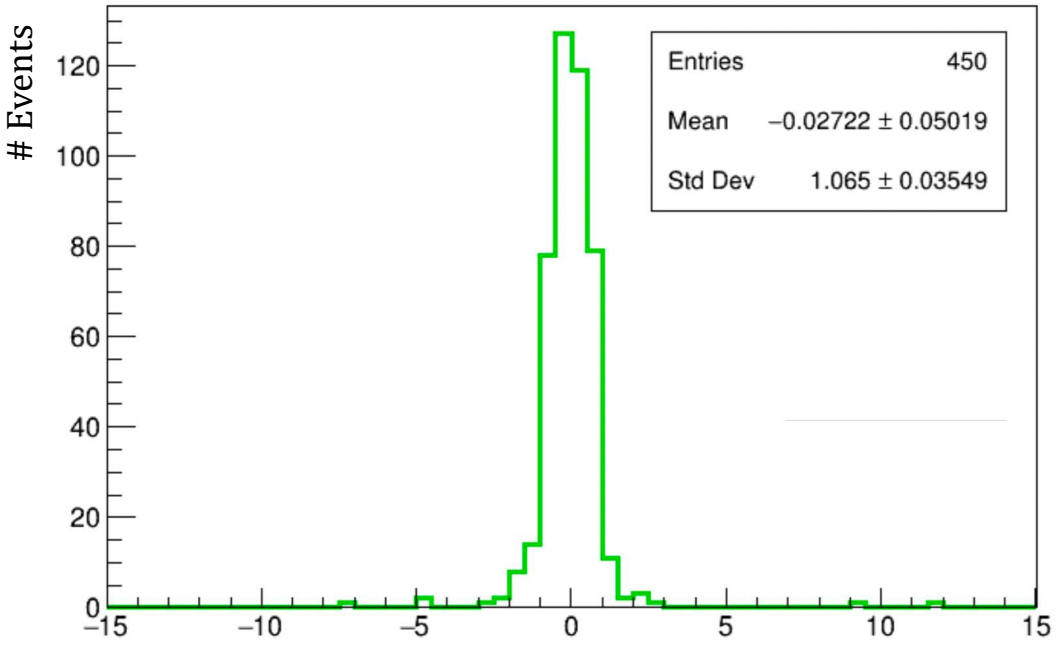




Studies on event identification

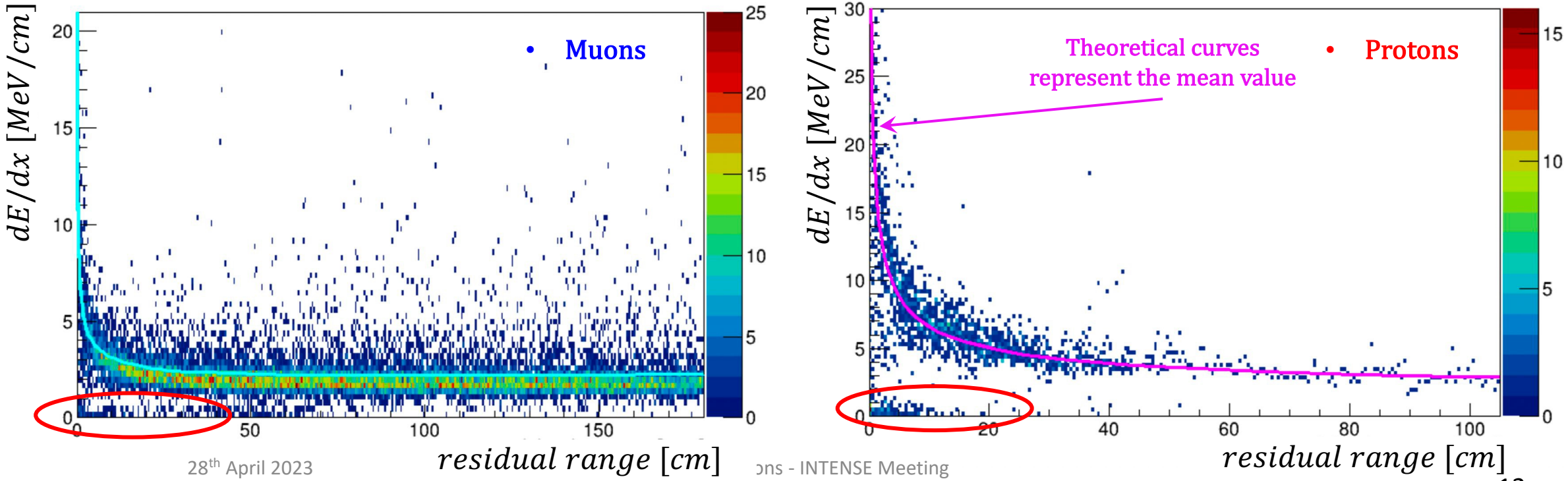
- The events where the vertex and/or the end of the muon are not well recognized are studied in more detail to improve our TPC reconstruction

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

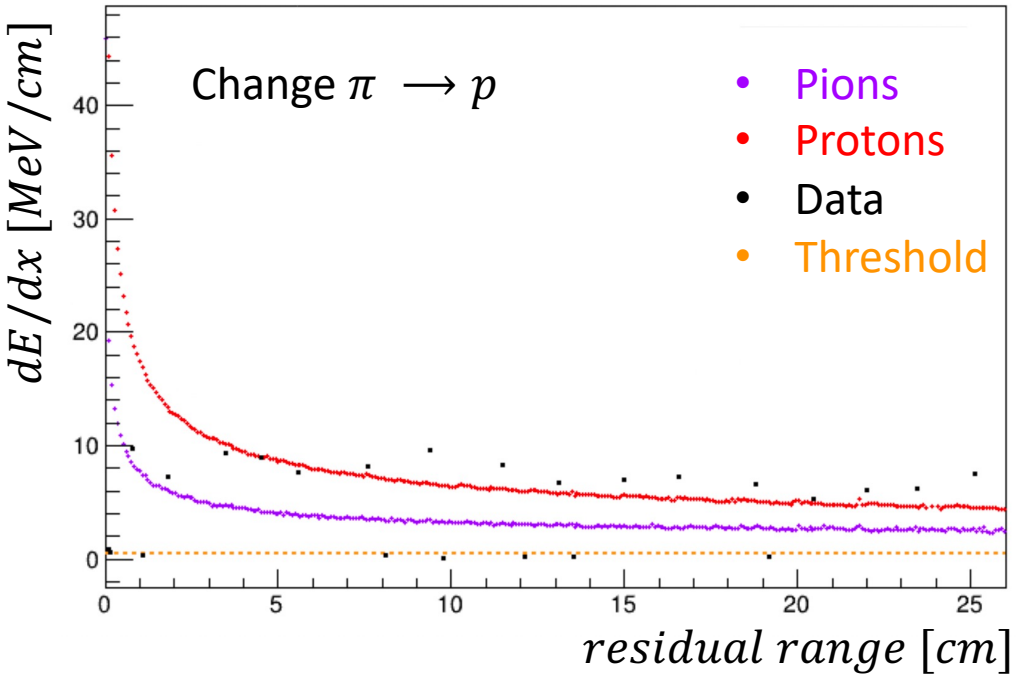
Particle identification

- 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 identification

- Highly inclined tracks generate long hits, which are sometimes wrongly addressed by splitting them into several low energy hits
- To avoid problems with the χ^2 algorithm, I decided to perform the fit removing all hits below $0.5\ MeV/cm$
- The particle id tool defines a parameter $\chi^2_k(j)$: χ^2 value for particle j under the hypothesis of being a k particle



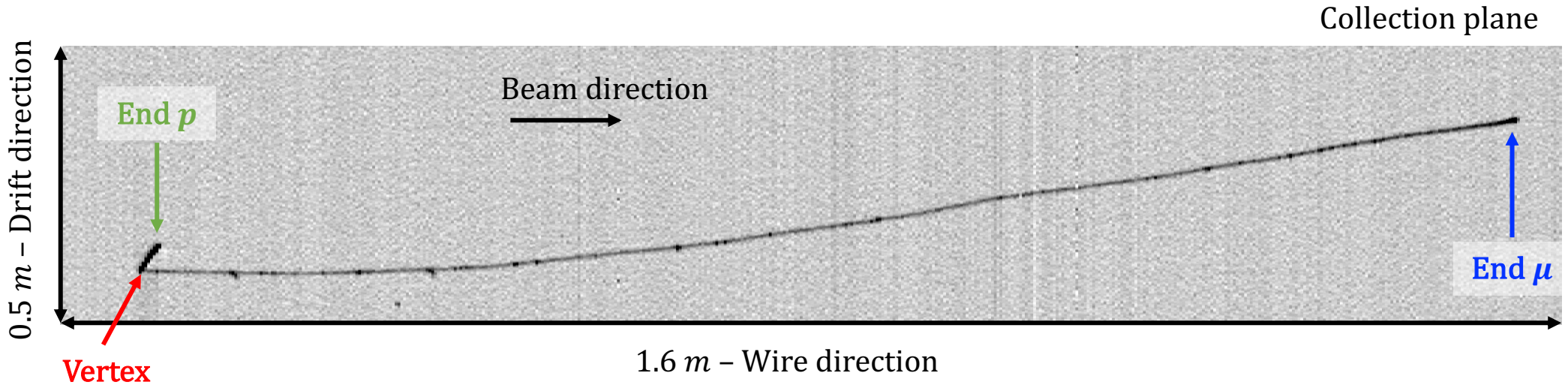
- Muons are selected if they fulfil both conditions $\chi^2_\mu(\mu) < 30\ \ \&\ \ \chi^2_p(\mu) > 60$
- While protons are classified according to the best particle hypothesis i.e., the minimum χ^2 value

* These cuts are arbitrary and there is still space for improvement

- Some events did not have enough hits in collection plane to perform the calculation, hence a refinement is under consideration to use the best plane instead (plane with most hits) in these cases

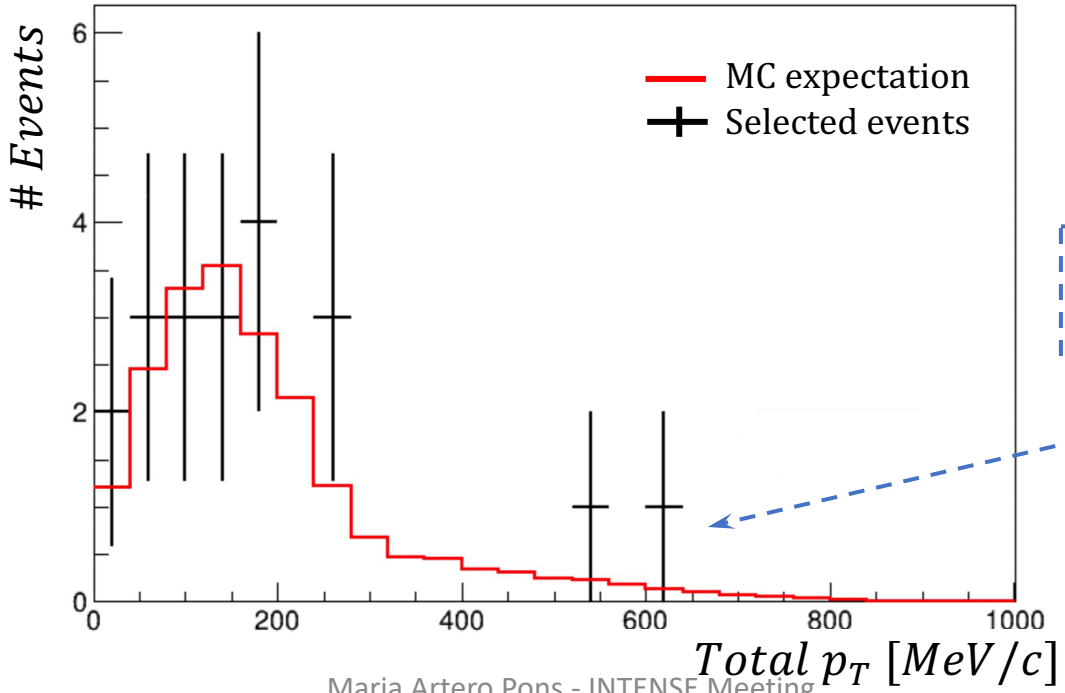
Particle identification

- The visually selected $\nu_\mu CC$ events can be used to test the performance of the PID algorithm
- Among the 526 interactions, **91** of them are **QE fully contained ν_μCC** events with a single proton at the primary vertex
- In 33 out of 91 events, the reconstructed vertex and the end points of the muon and the proton agree within 2 cm from the scanned information



Particle identification

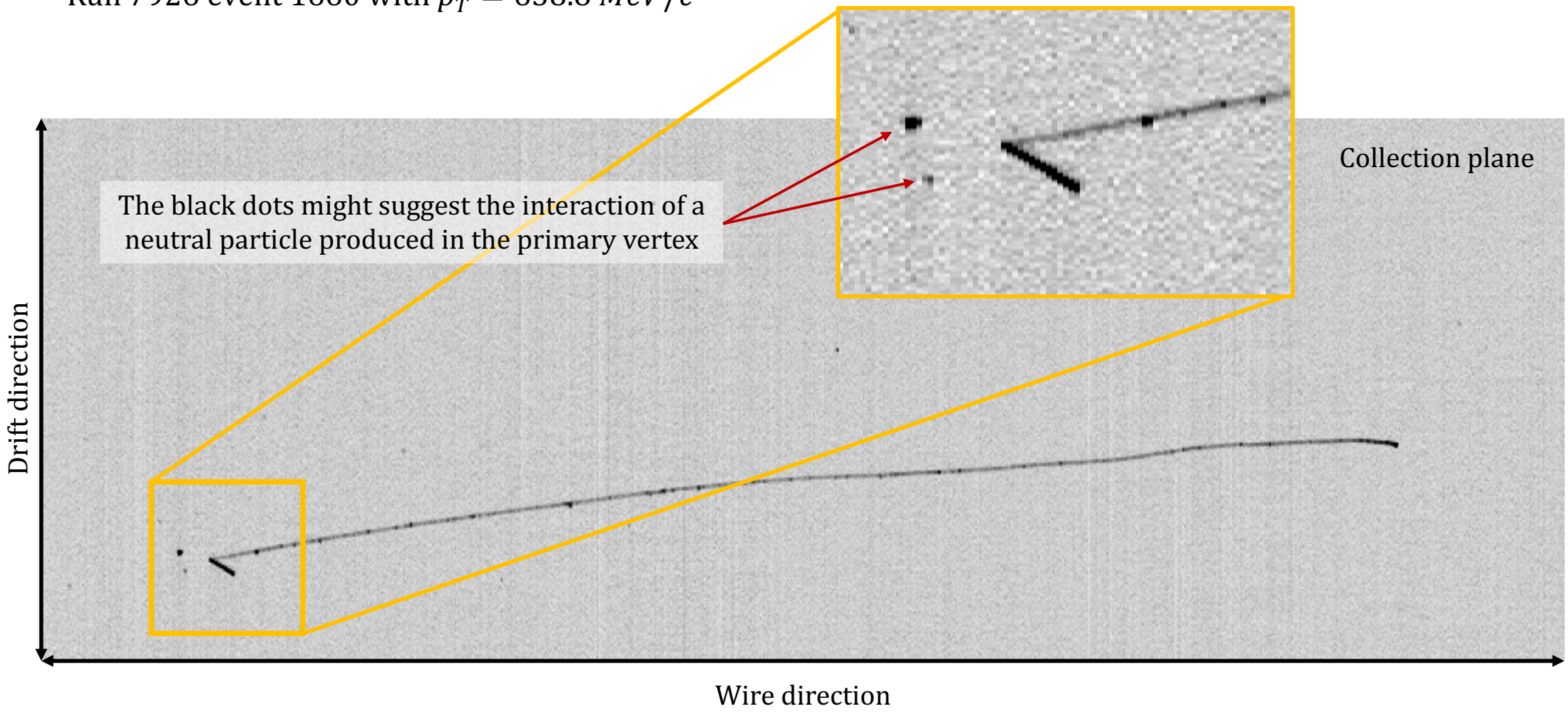
- Further requiring that the PID correctly identifies both particles according to the previous conditions, only 20 events are selected from the 91 initial $1\mu 1p$ candidates
- For this latter subsample, the μ and the p momenta are measured from their range, checking the event kinematic reconstruction through the total transverse momentum
- For genuine $\nu_\mu CCQE$ events the transverse momentum should be dominated by the Fermi momentum in Ar nucleus



Higher p_T events, even if they are within the expectations, are worth a closer look!

High transverse momentum events

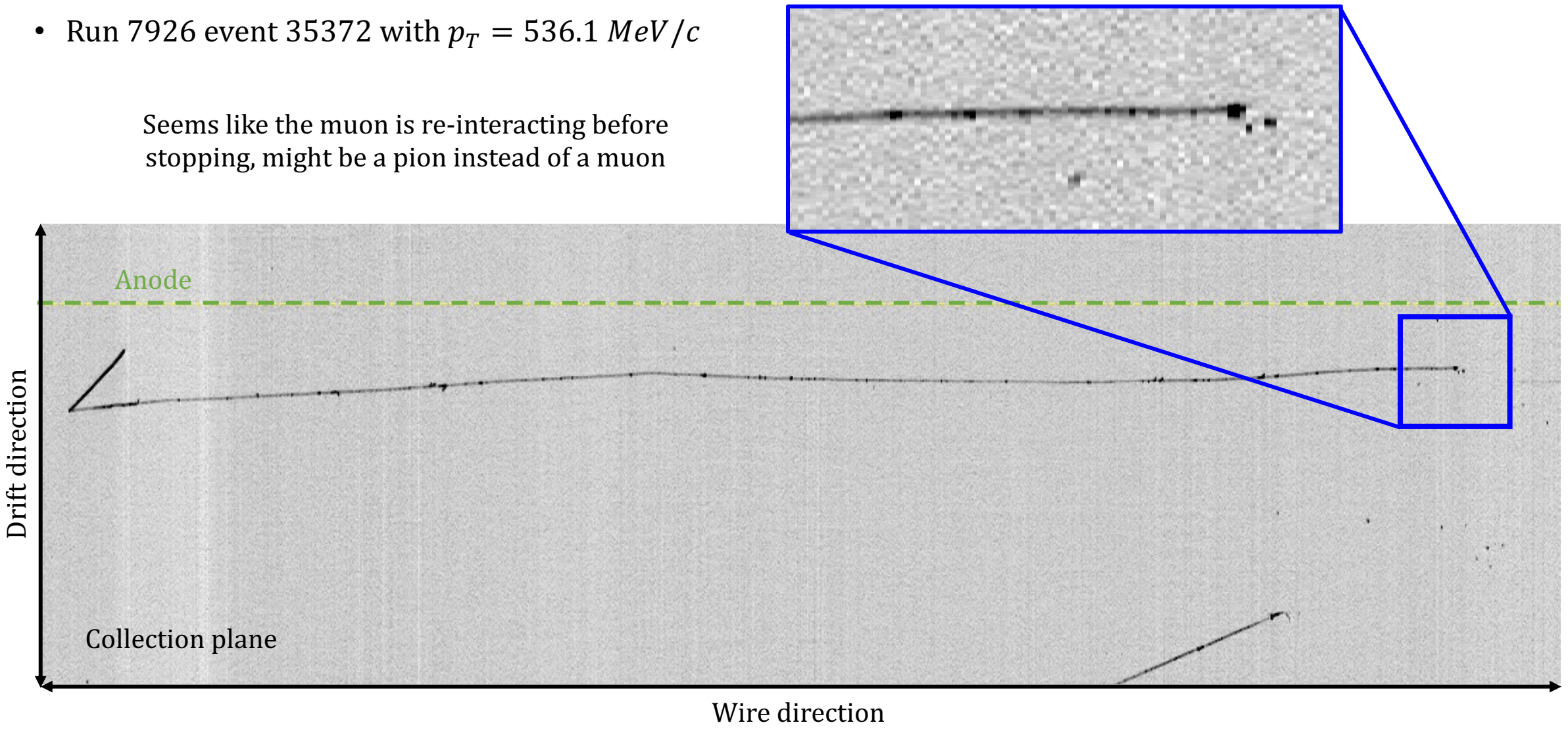
- Run 7926 event 1660 with $p_T = 638.8\ MeV/c$



High transverse momentum events

- Run 7926 event 35372 with $p_T = 536.1\ MeV/c$

Seems like the muon is re-interacting before stopping, might be a pion instead of a muon



Conclusions

- Several changes have been introduced trying to improve the event reconstruction performance
- The results obtained from the reconstruction of visually selected $\nu_\mu CC$ events look promising (vertex and μ track)
- A test for the $\nu_\mu CC$ QE events with a single proton has been performed and the outcome of the study can be used to enhance the selection and reconstruction efficiency
- For these subsample we showed that, after ensuring the quality of the reconstruction with tighter cuts, the kinematic in the transverse plane seems to confirm the event interpretation
- Couple events were spot as possible more complex topologies
- The studies will benefit from larger statistics. Recently increase of ν events from a more recent run: 29th January 2023 with overburden. Additional 300 ν, of which 115 are $1\mu 1p$ candidates

Future plans

- Include the new statistics to the analysis
- Need to optimize and establish a solid strategy to be applied to the automatic reconstruction to select a pure and well measured ν sample
- Cross check the obtained results with the new Monte Carlo production
- Try to improve the PID algorithm, a possible option is to use the integrated energy
- Mitigate the existing pathologies, addressing long hits treatment, pitch definition, broken tracks, etc

THANK YOU !

IMAGING COSMIC AND RARE UNDERGROUND SIGNALS