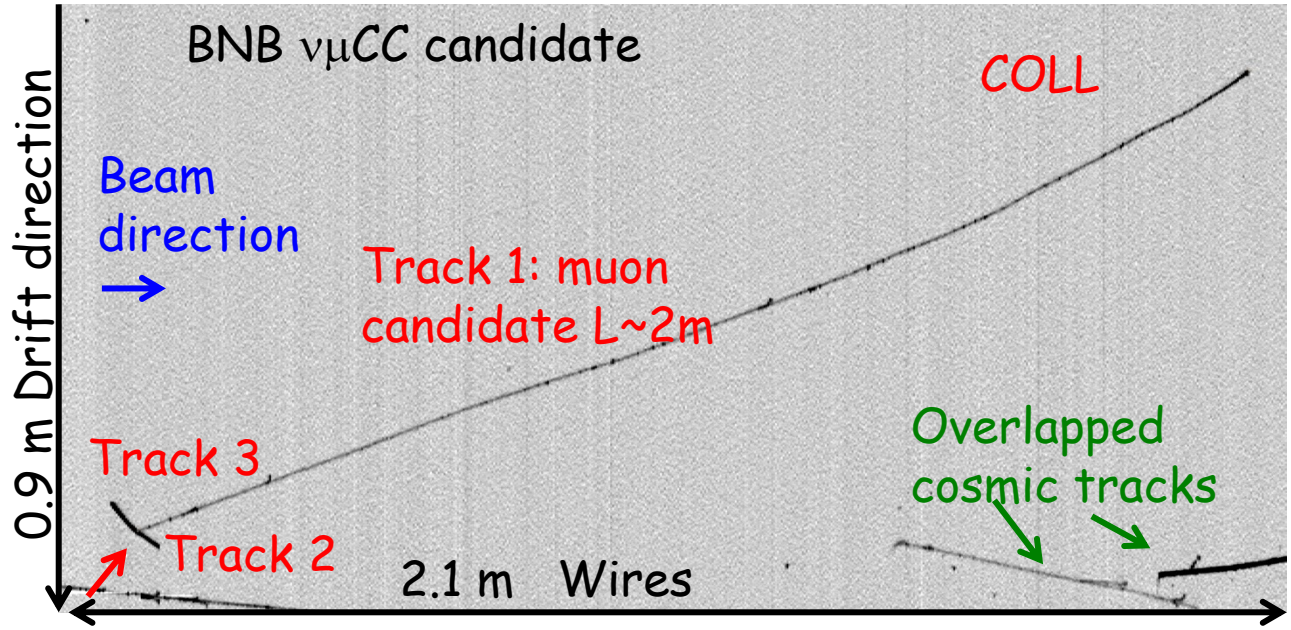
Event reconstruction tools for ICARUS @FNAL



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Outline

- Elements of the reconstruction;
- Data volume and processing strategy;
- Reconstruction and calibration of TPC, PMTs and CRT;
- Conclusions.

Neutrino event reconstruction

- The analysis of the neutrino interactions relies on the information provided by the various detector components:

1. TPC: during the ~1 ms drift time records the signals induced by ionization electrons on the three wire planes at 0^0 and $\pm 60^0$ wrt the horizontal direction:
   - 2D visual image with mm spatial resolution per wire plane → 3D event reconstruction by combining images from the 3 wire planes;
   - Calorimetric reconstruction of the deposited energy;
   - Particle ID by measuring dE/dx Vs residual range for stopping particles;
   - Track shower separation;
   - Unique e-γ discrimination by measuring the initial dE/dx of the shower.
2. PMTs: exploit scintillation light to: 1) provide the event trigger, 2) measure with ns precision the event time, 3) localize the event inside the TPC;
3. CRT rejection of cosmic rays: 1) vetoes in-spill cosmics, 2) distinguishes incoming from outgoing particles; 3) identifies out of spill events

- The implemented ICARUS reconstruction procedure presently applied to the collected data is presented in the following. **Disclaimers: all results shown are preliminary.**

Software processing chain

- Raw data from detector in "artdaq" format:
  - Meant to be a compact data format including lossless compression;
- Stage 0 processing:
  - Convert from "artdaq" to "LArSoft" format for offline processing;
  - Perform Signal Processing for all three systems – goal to output "hits" for reconstruction;
- Stage 1 processing:
  - TPC, PMT and CRT reconstruction;
  - Application of calibrations;
  - etc.
- Analysis Level
  - Common Analysis Framework (CAF) output for final event selection/analysis
  - Calibration tuples for calibration and detector studies
    - Including special subsets that include waveform information

DATA volume and plans for next RUN2

- Data event sizes from the daq system; typically ~160 MB (~148 MB from the four TPCs, after a factor ~3 reduction by lossless compression). Huge data volumes:
  - For first physical run (Run 1) 531 TB total data in just over 1 month (~16% NuMI, ~20% BNB)
  - For next Run 2 (expected trigger rate ~0.5-1 Hz) → will collect O(10TB/day) - O(1PB) in only ~3 months
- Difficult to keep raw data resident on disk → significant bottleneck due to restaging raw data from tape in case of data reprocessing;
- Proposed approach for the next Run 2 (to avoid staging back from tape):
  - From the TPC Signal Processing chain keep only the ROIs and hits
  - Keep full PMT waveform information, plus CRT
- Significant reduction in data size on output from Stage 0 : typically ~20 MB/event (55% from PMT waveforms), with ~60 sec/event (single threaded) processing time

➔ Should be possible to keep resident on disk (e.g. filtered NuMI and BNB data)
➔ to allow Stage 1 reprocessing

1) TPC signals processing and reconstruction chain

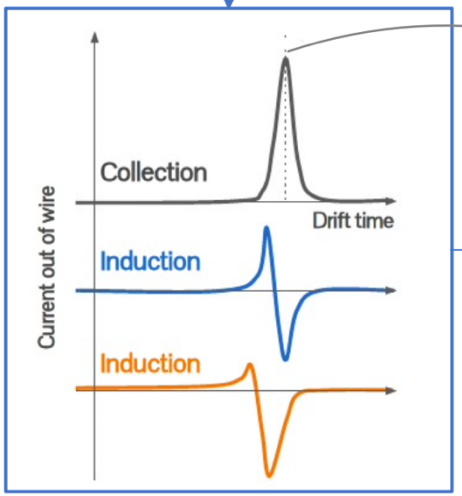
Detector Data → Low-level image processing → Hit finding → Pattern recognition → Particle fits → High Level Analysis

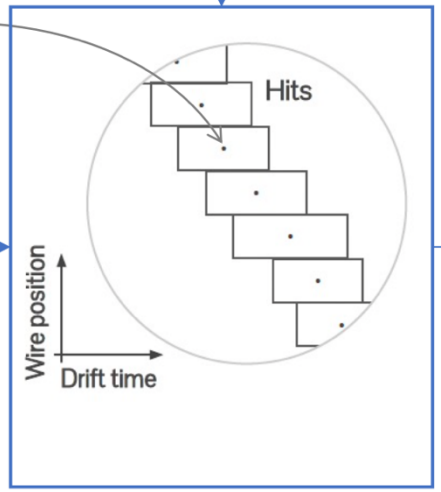
- Decoding
- Deconvolution
- ROI Finding

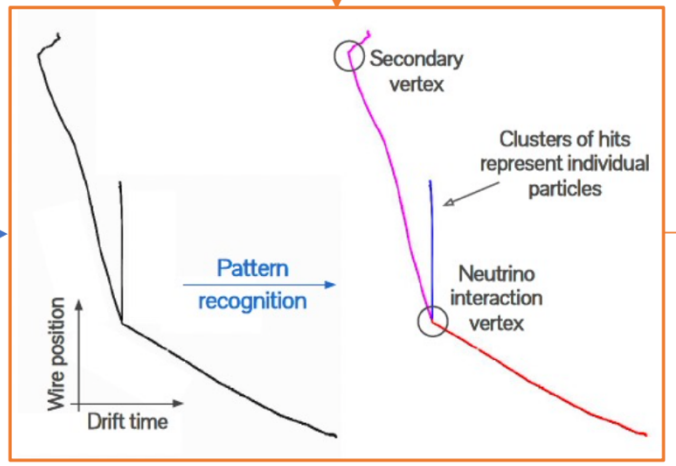
- Gaussian hits
- Cluster 3D

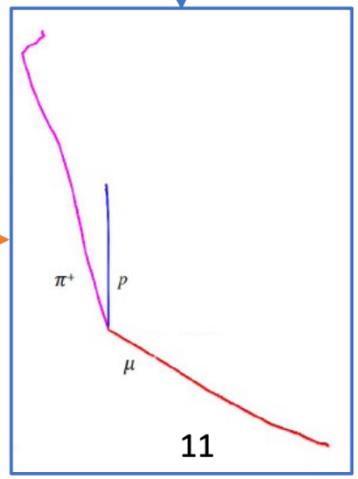
- Pandora Algorithm

- Track, shower fits
- Calorimetry
- Particle ID









Includes electronic noise filtering; unipolar signals for all wire plane after this stage

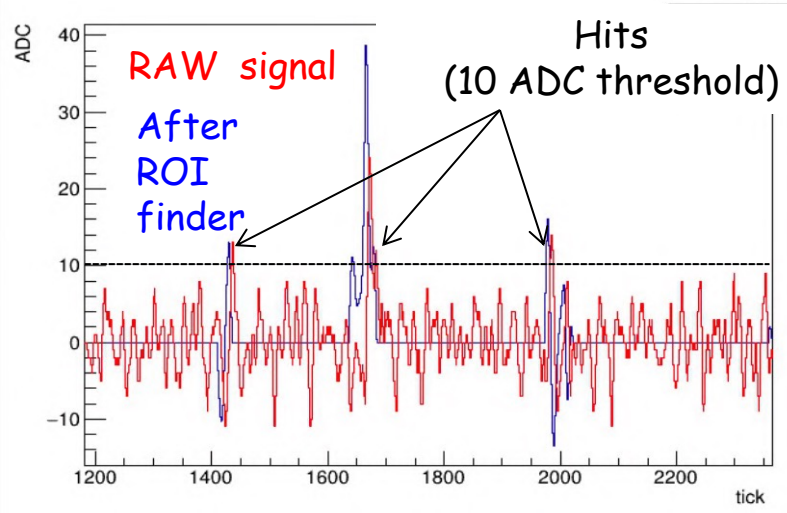
A hit represents the identified signal induced by a track on a wire.

Identifies primary & secondary vertexes; tracks/showers 3D reconstruction (organized in hyerachical order). Passing cosmic rays identification.

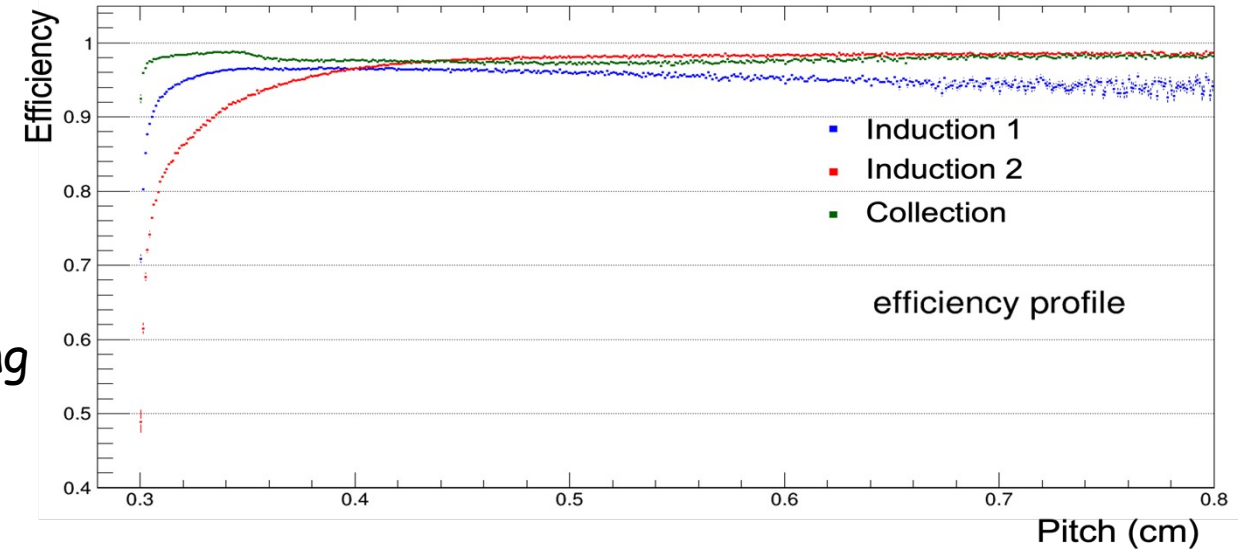
Objects for kinematic reconstruction and event analysis.

TPC wire signals reconstruction

- The first steps involve hit reconstruction threshold optimized for high signal reconstruction efficiency while maintaining low the fake hit rate.



- The efficiency for the identification of signals on wires has been measured with straight cosmic muons crossing the cathode as a function of the track segment length contributing to the signal on a wire ("pitch");



- Presently a relevant effort is ongoing to improve the modeling of the wire signals and increase the hit efficiency in particular for small pitches and for Induction 2 wires.

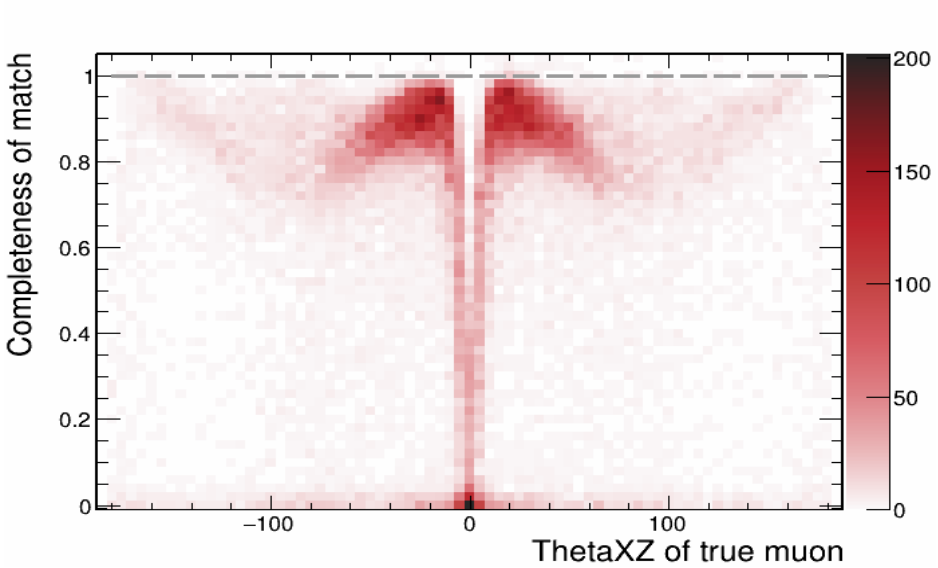
TPC wire signal reconstruction and impact of coherent noise

- The removal of the coherent noise component can decimate the signal too, reducing the hit and track efficiency for tracks ~ perpendicular to the drift direction.

- *The effect is visible also in MC events,*

  - f.i. the **muon Completeness*** shows a dip for ThetaXZ =0^0 angle

*completeness: the fraction of energy deposited by μ that is present in the reconstructed track (f.i. comp=80% if μ deposited 1 GeV and the track has 0.8 GeV matched to it).



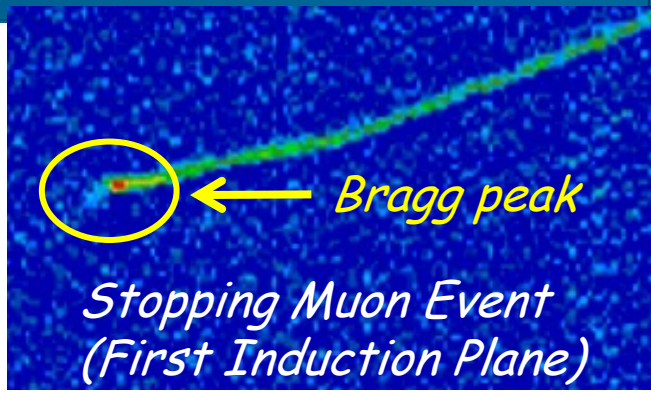
ThetaXZ is the angle *from* Z in XZ (drift-longitudinal axes) plane. 0^0 lies along the beam direction: +/- 90^0 is perpendicular to wire plane.

- Relevant area:

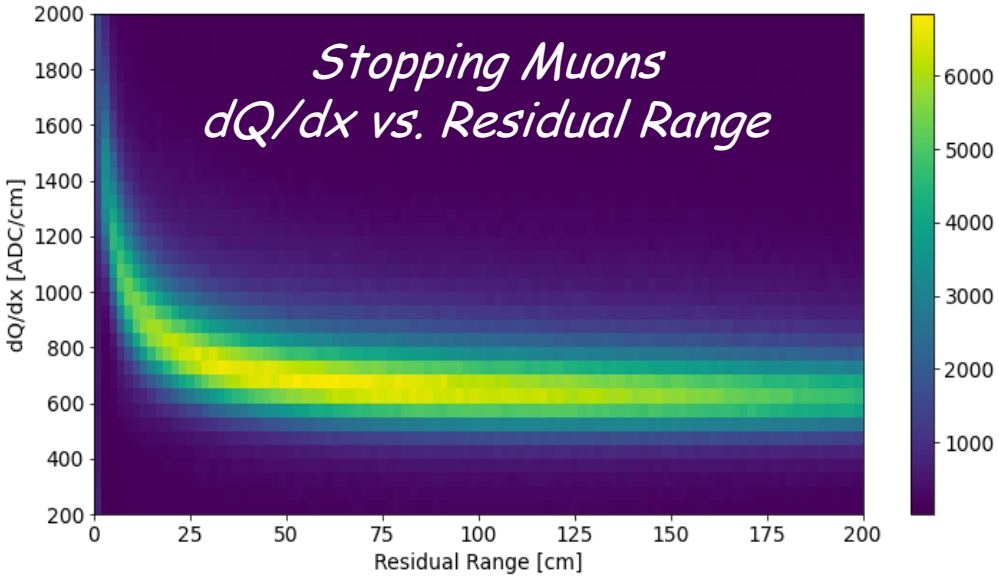
  - Continuing hardware interventions to reduce the electronic noise;
  - Several mitigation strategies under study in the reconstruction for the optimization of the hit selection.

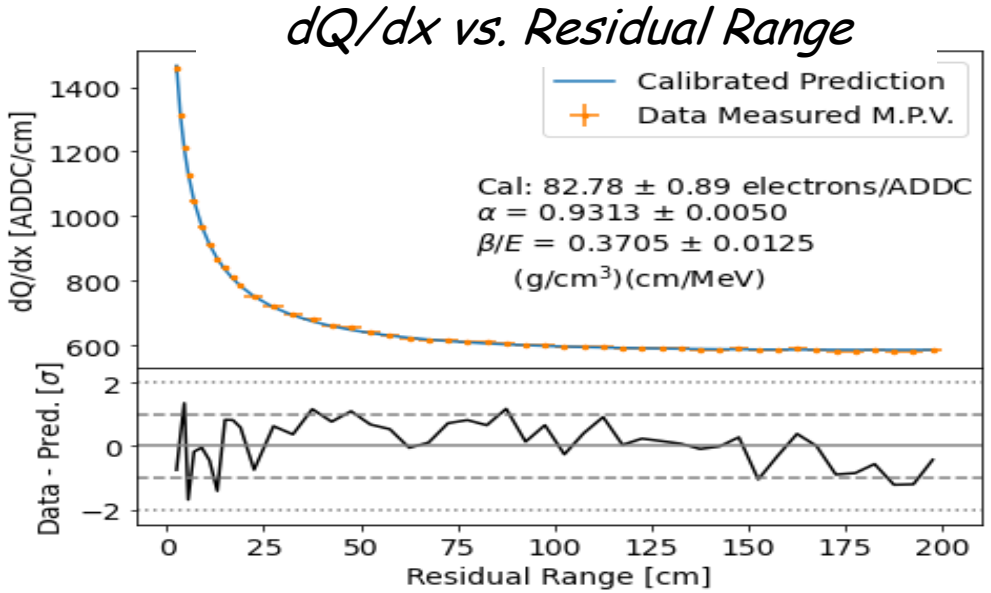
TPC wire signal calibration

- A full calibration chain has been developed. It is based on the study of the ionization vs residual range for cosmic μs crossing the cathode stopping/decaying in the active LAr.



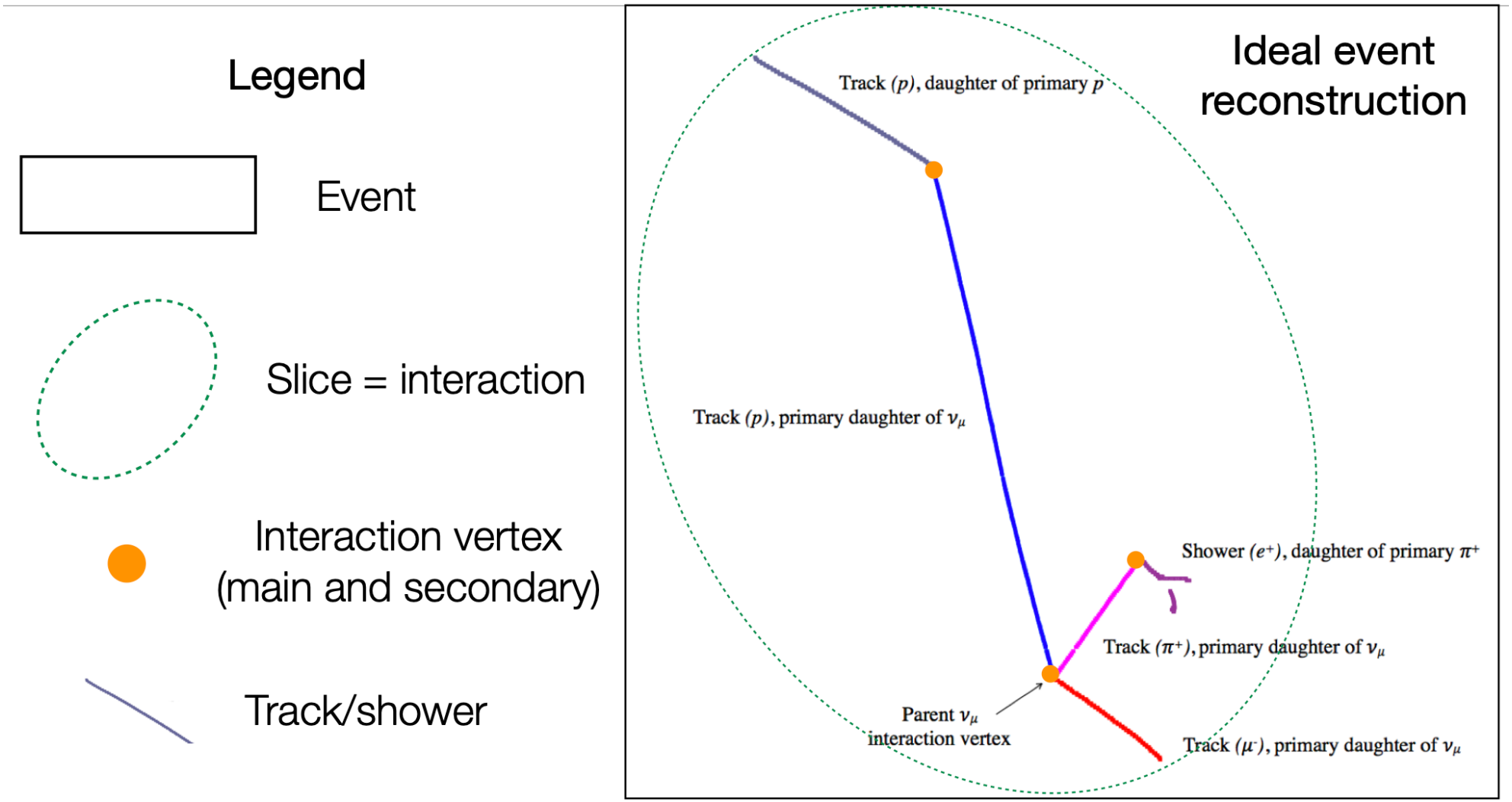
- Goals: a) correct for the electron lifetime; b) equalize the electronic response over the full detector; c) calibrate the absolute energy scale; d) improve the modeling of e- recombination, e- diffusion, space charge effects, and detector properties like drift velocity and the detailed wire response.





- This study is meant to tune and quantify the performance of the PID algorithm based on the measurement of dQ/dx Vs residual range for stopping particles.

The ICARUS event reconstruction chain: some details on Pandora

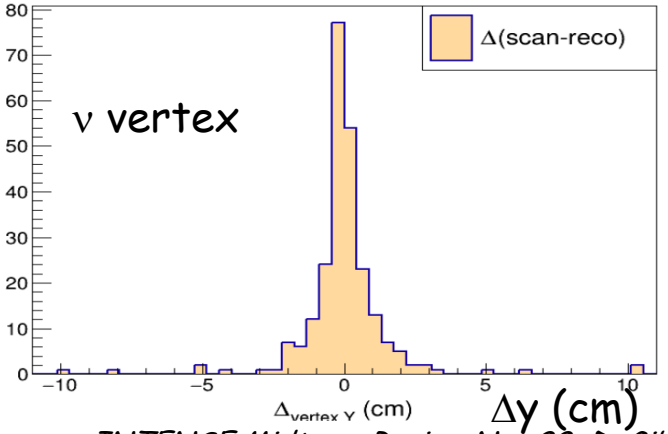


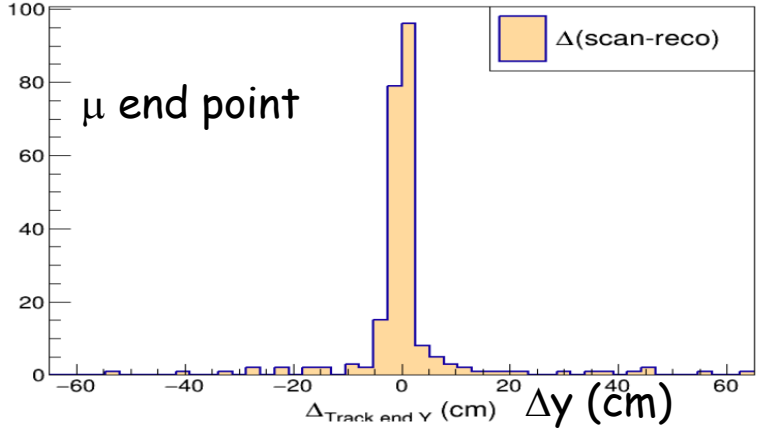
- A parallel approach based on machine learning treatment of the TPC information is also being developed.

Validation of pattern reconstruction with visually identified ν events

- A sample of ~300 νμCC interactions collected in ICARUS with BNB has been visually identified and manually measured by physicists.
- The results from the automatic pattern recognition procedure have been compared with the manual reconstruction of scanned event
- First results for the identification of ν vertex and full reconstruction of μ track:
  - 63% good matches (automatic reconstruction well matched to scanned events for both the 3D ν vertex and μ track length);
  - 25% almost good matches (automatic reconstruction well matched to scanned events for the 3D ν vertex but with poor μ track length match);
  - 12% are not recognized by the pattern recognition procedure.

Difference Δy of vertical coordinate y between automatic and manual

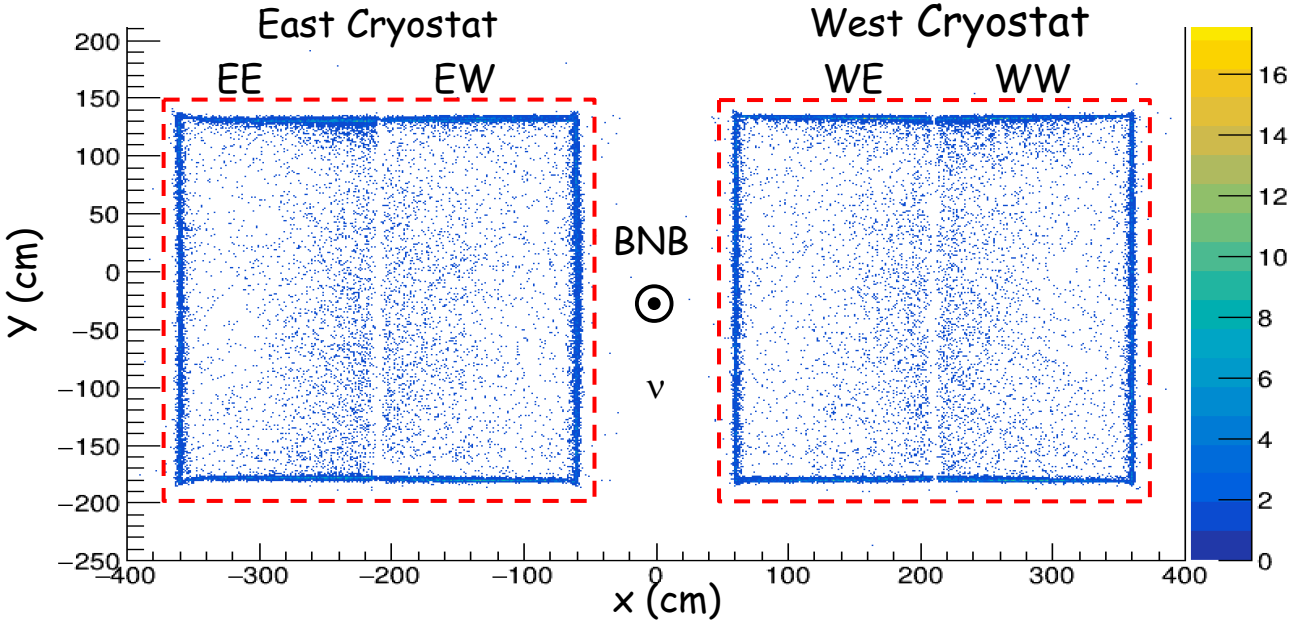




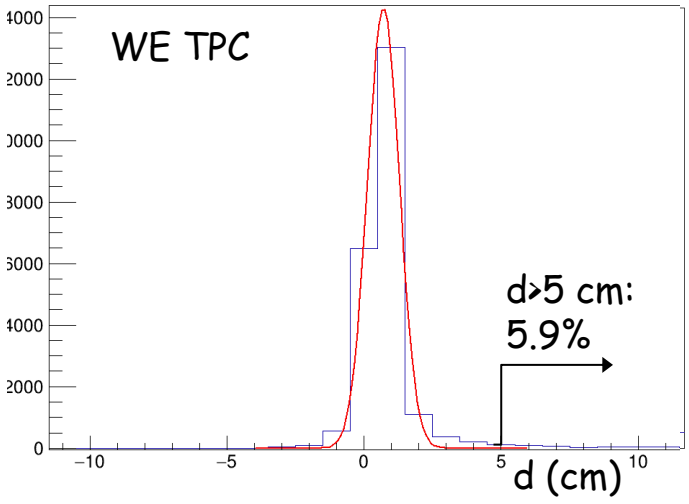
Tails of residuals and failures of reconstruction under investigation.

Assessing/defining the containment condition

- The reconstruction of Run0 data allowed to select a large sample of fully reconstructed cosmic muons crossing the cathode.
- Studying the first and last 3D point of the μ track allows to investigate TPC reconstruction features and define a possible condition for (non)-contained tracks (relevant for the selection of fully contained neutrino interactions).



Entry and exit points of cosmic muons entering in the detector

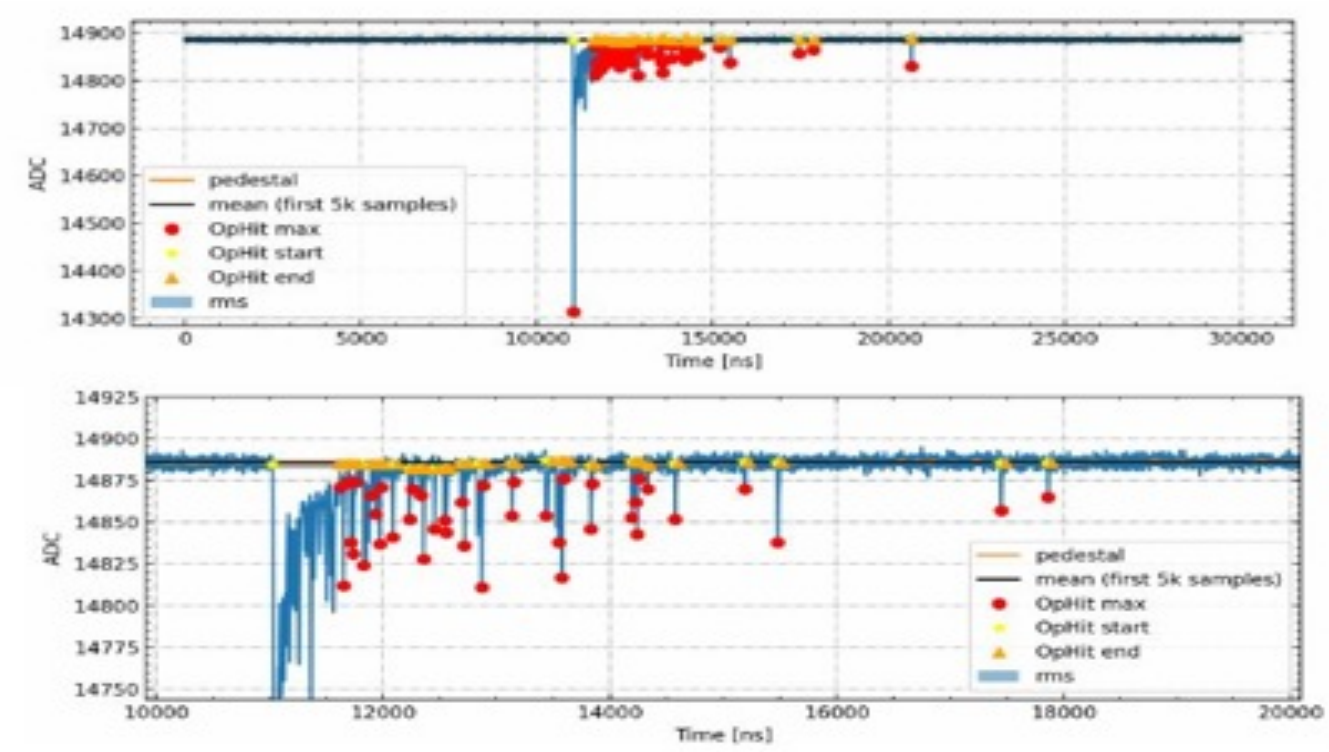


Distance of the μ entry point from the detector walls

- This study look promising to further reject cosmic tracks crossing the border of the TPC.

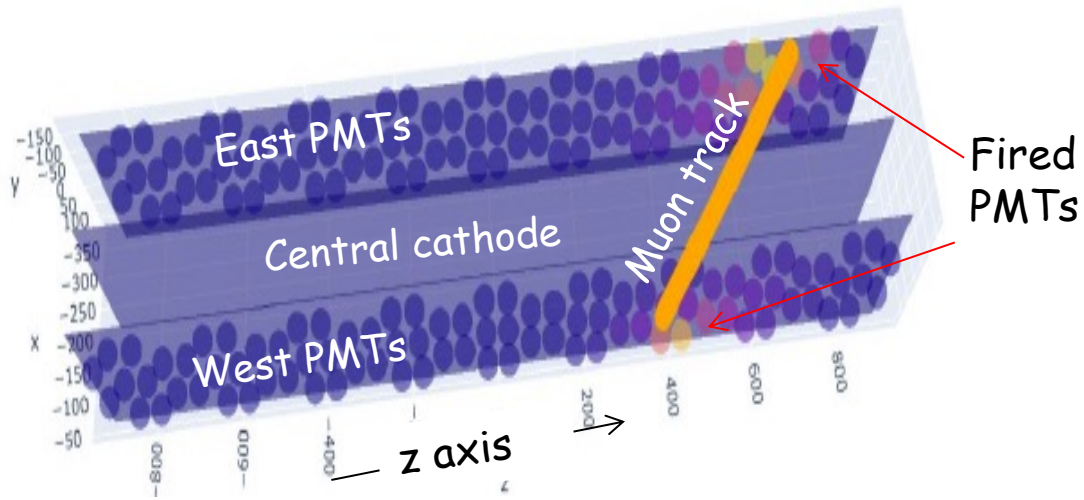
2) PMT reconstruction

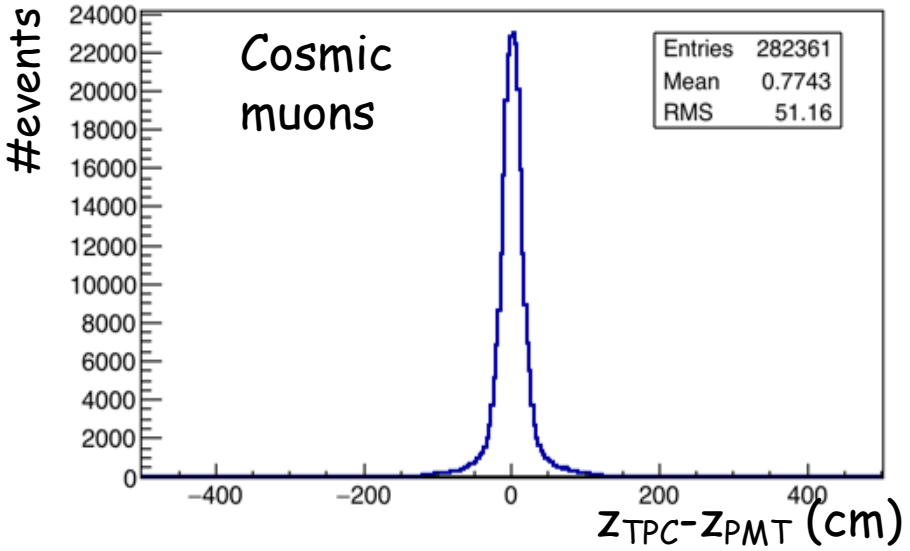
- The digitized PMT signals, sampled at 500 MHz, allow to reconstruct the scintillation light produced in the LAr in a ± 1ms around the beam spill gate;
- The reconstruction code identifies the signals ("*Optical Hits*") of fired PMTs using a threshold-based algorithm (threshold ~0.5 photo-electron);
- *Optical hits* in temporal coincidence are clustered into *Optical Flashes* and integrated for 1 μs after their leading edge. After n Optical flash produced by another interaction can be identified if it occurs after 1 ms from the previous one



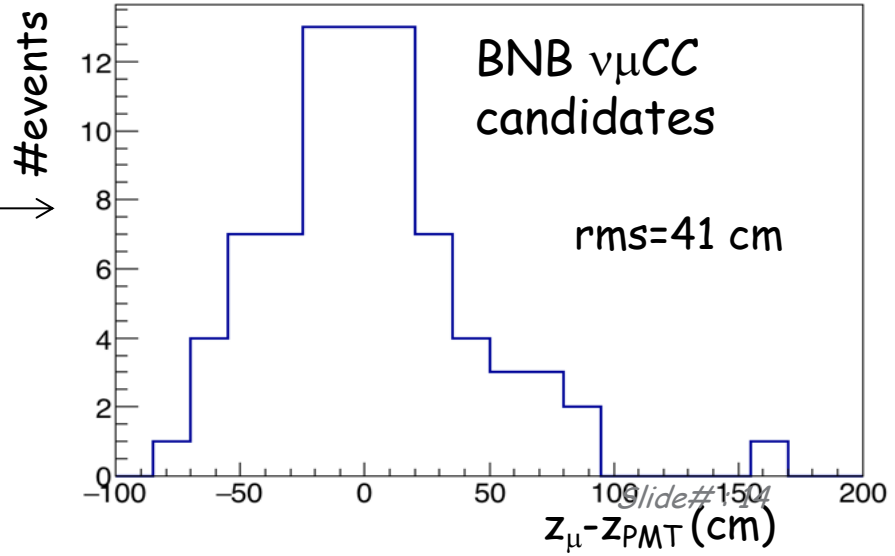
Exploiting the light to localize the event along the longitudinal axis

- A validation of the simple algorithm comparing the track and the light barycenter (z_{TPC}, z_{PMT}) has been performed with cosmic muons



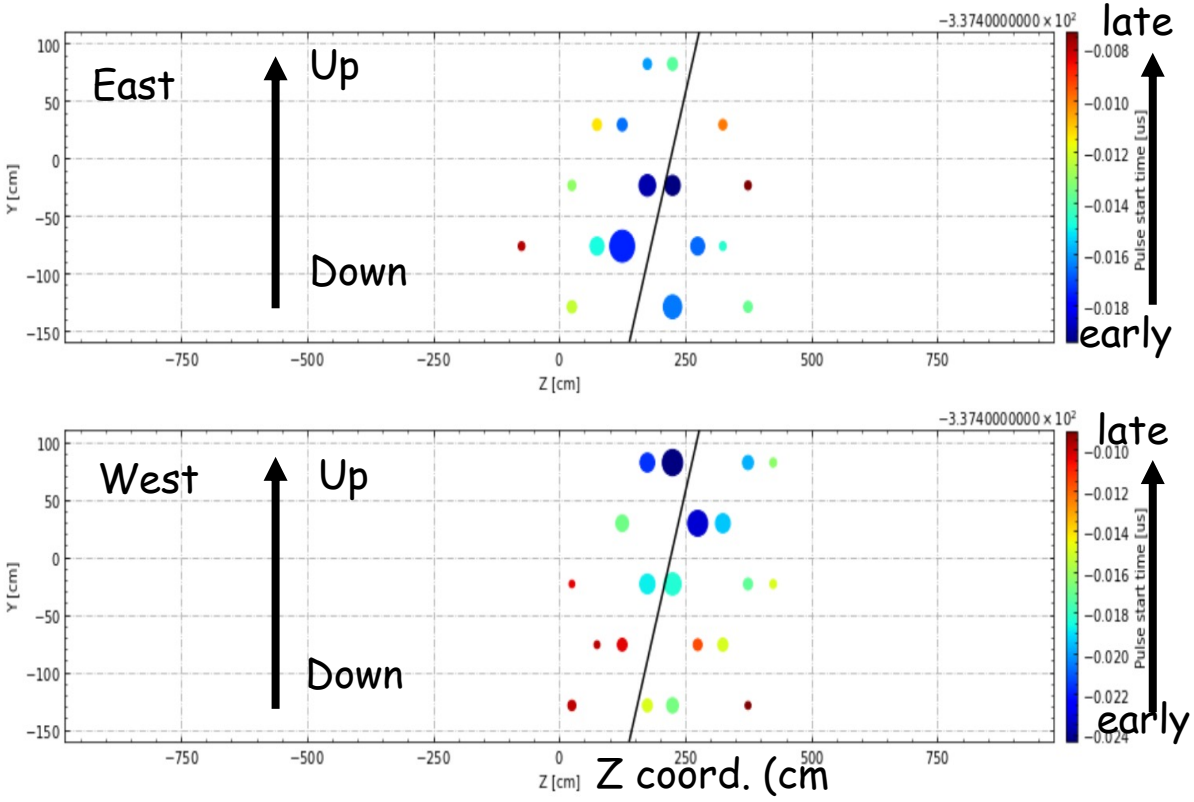


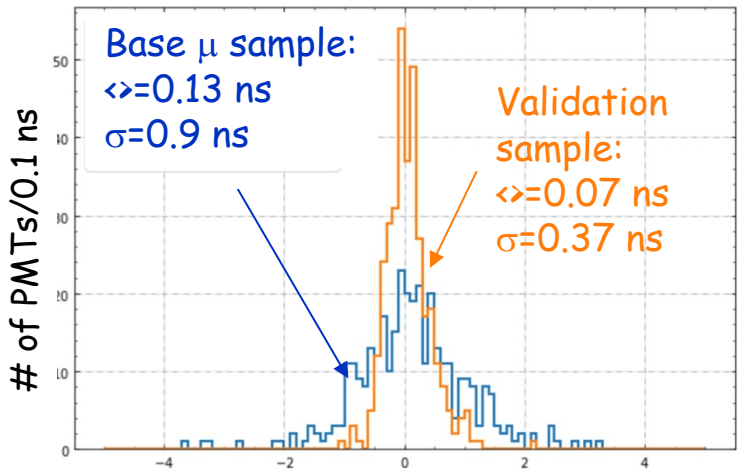
- A similar study has been performed on a set of BNB νμCC candidates with Lμ>50 cm identified by scanning: the average z coordinate of the muon z_μ agrees with the light barycenter within ~1 m.
- A larger statistics study is mandatory to improve the method and tune the selection of neutrino events.



Exploiting the light in the analysis: timing calibration

- Individual PMT transit time is obtained by flashing PMTs with a laser and measuring the difference between the time of the PMT with a reference laser start time;
- The PMT time reconstruction is checked with vertical cosmic μs:
  - A linear fit of PMTs time Vs their vertical coordinate is performed, computing the time residual of each PMT wrt the fit;





Average residuals from μ procedure (ns):

- The PMT time calibration is finely corrected with the average PMT residual times (σ~1 ns);
- Iterating the procedure on a different μ sample the residual distribution becomes sharper (σ~0.4 ns)

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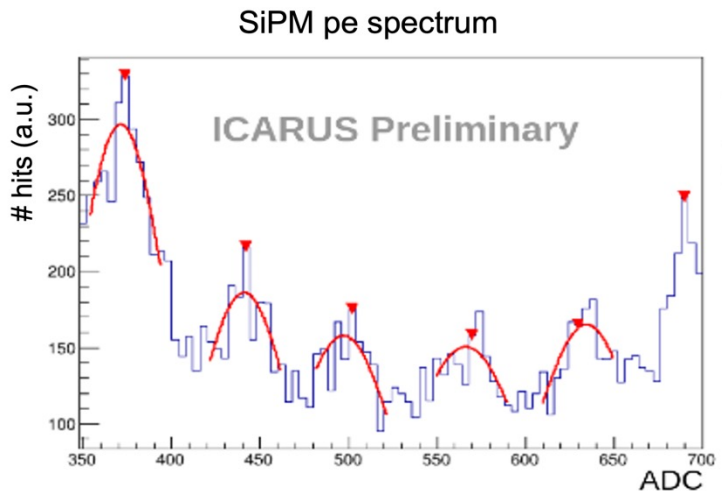
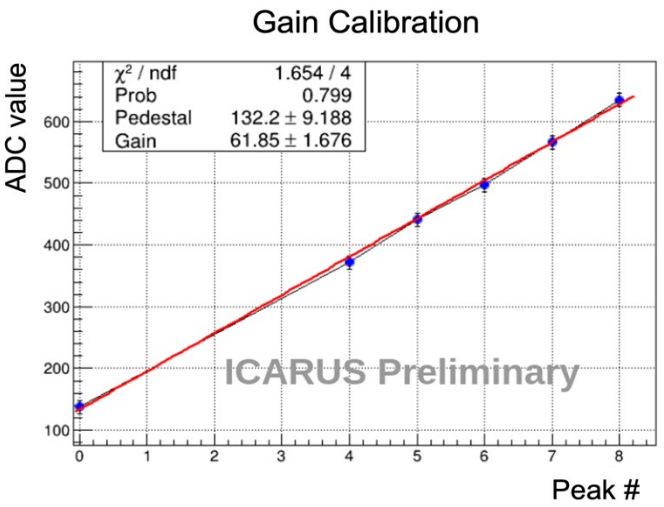
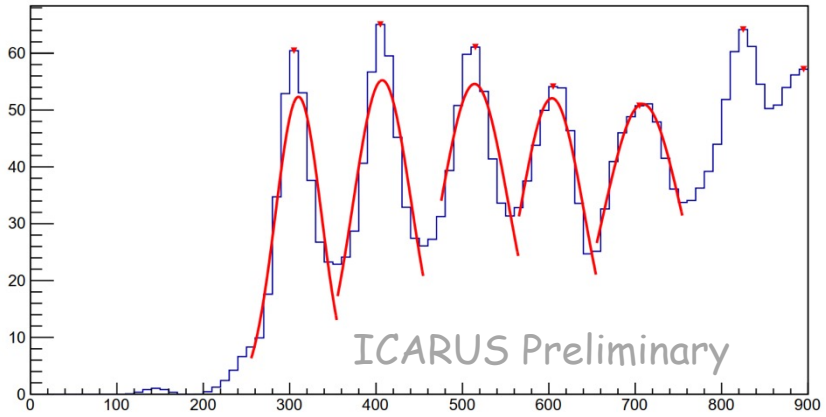
3) CRT reconstruction

- Calibration of the CRT slab to define the threshold to discriminate signals from noise.





- Side CRT

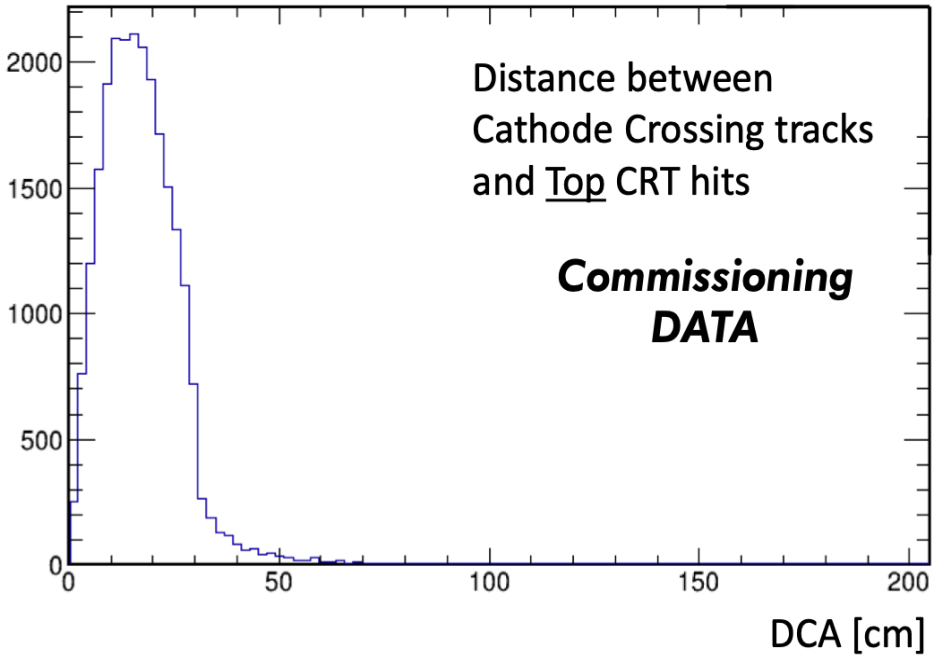


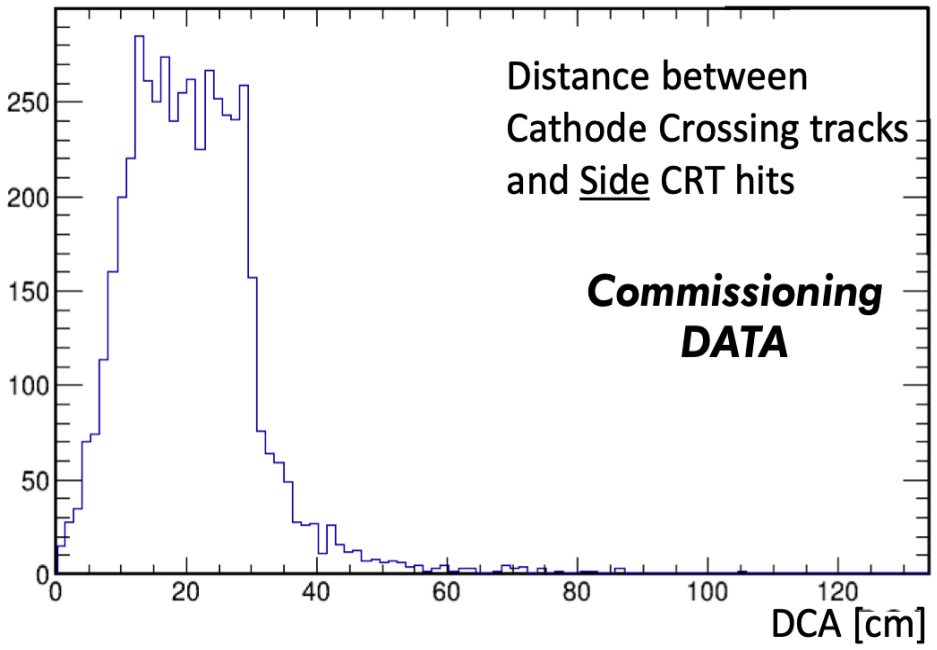
- TOP CRT

- The reconstruction builds "CRT hits" with the time and the geometrical information about the fired CRT slab(s).

TPC track-CRT hit association algorithm

- Algorithm developed for SBND then tuned and applied also to ICARUS collected data: association between CRT hits and cosmic muons crossing the cathode reconstructed in the TPC and extrapolated to the CRT.



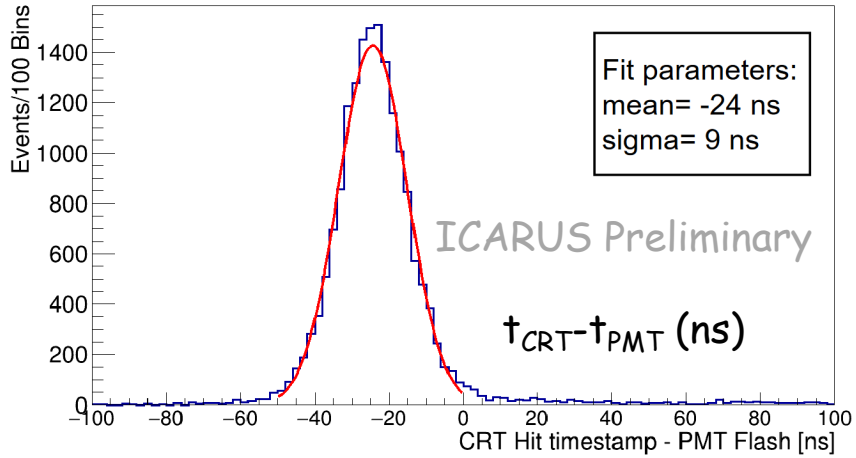


Association between the CRT and PMTs and TPC

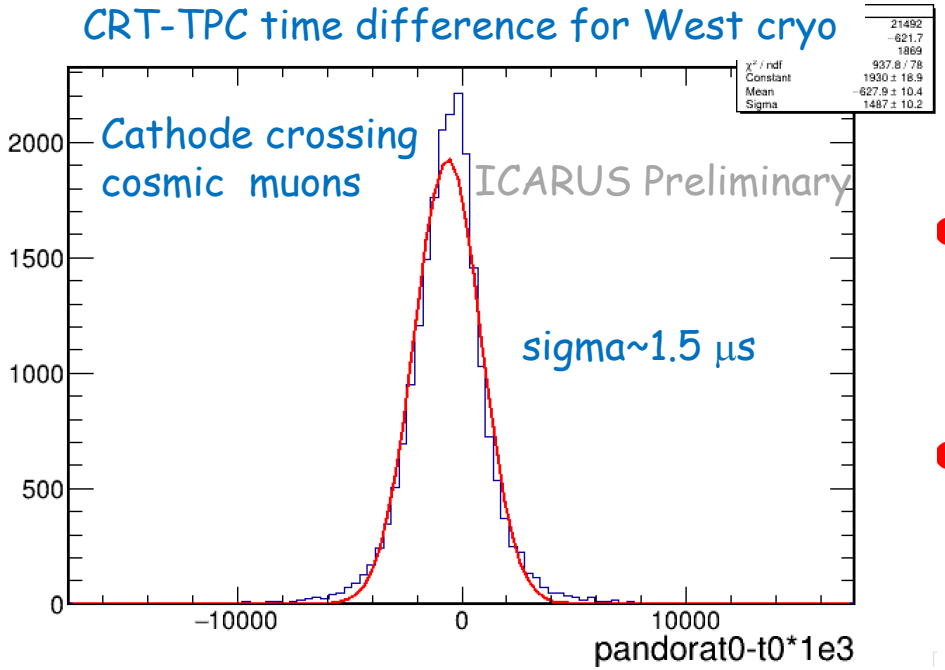
- Time offsets due to cables, signal propagation etc. have been corrected for.it is possible to measure the CRT signal in the same time reference of the inner PMTs and of the TPC.

- The time difference between the TOP CRT and inner PMTs shows a clear peak for incoming cosmic rays: the width σ=9.2 ns includes the intrinsic resolution and the geometrical variation of the travelled distance.

CRT-PMT time difference



CRT-TPC time difference for West cryo



- For cosmic muons crossing the cathode the TPC permits to reconstruct the time with 1.5÷2 μs resolution.

- The time correlation between the tracks in the TPC and the signals on the CRT is dominated by the TPC resolution.

Conclusions

- A first complete chain of event reconstruction has been deployed for the data collected by the ICARUS detector during the first physics run in the summer 2022;
- A complete processing flow from raw data to low and high-level reconstruction has been established, verifying the computing and storage resources required for the steady run and for the analysis of the experiment;
- The reconstruction includes all the element of the detector: TPC, PMTs and CRT;
- A first calibration of the detector has been prepared to allow the physical exploitation of the collected data;
- The performance of the reconstruction has been tested and validated with collected cosmic and neutrino data;
- Intense activities to improve the performance of the reconstruction algorithm are ongoing. A scheme to allow the inclusion of achieved improvements at a later stage of the event reconstruction has been worked out.