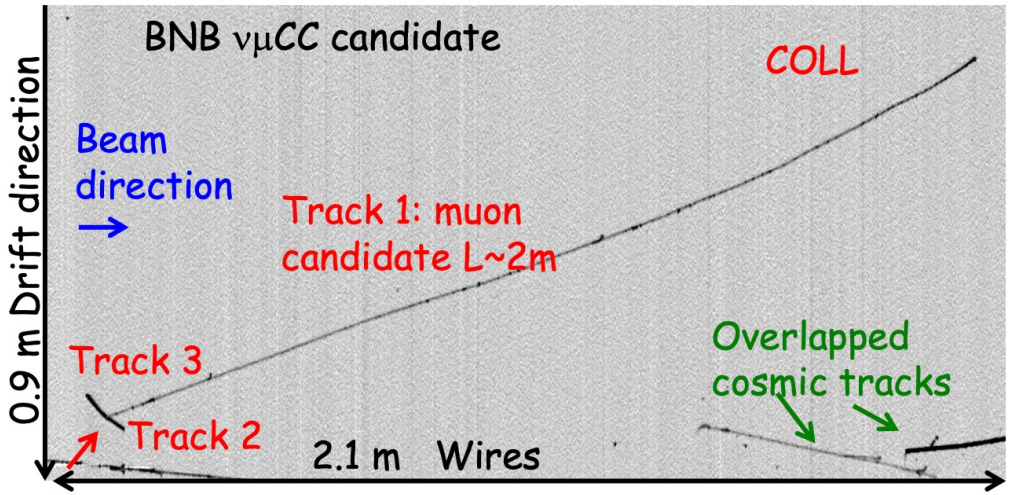
Neutrino event reconstruction tools



Daniele Gibin
Department of Physics and INFN Padova

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Outline

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

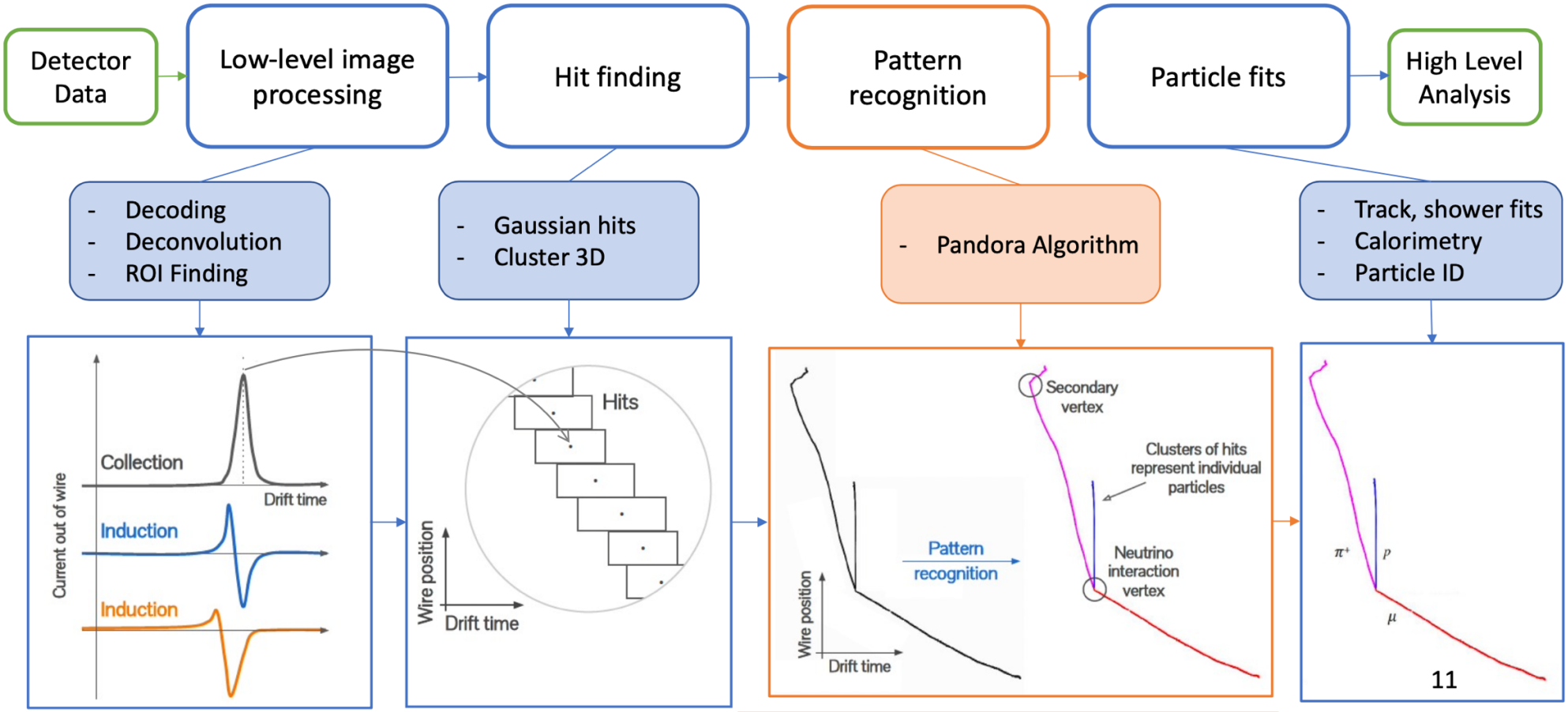
Neutrino event reconstruction

- 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.**

1) TPC signals processing and reconstruction chain



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

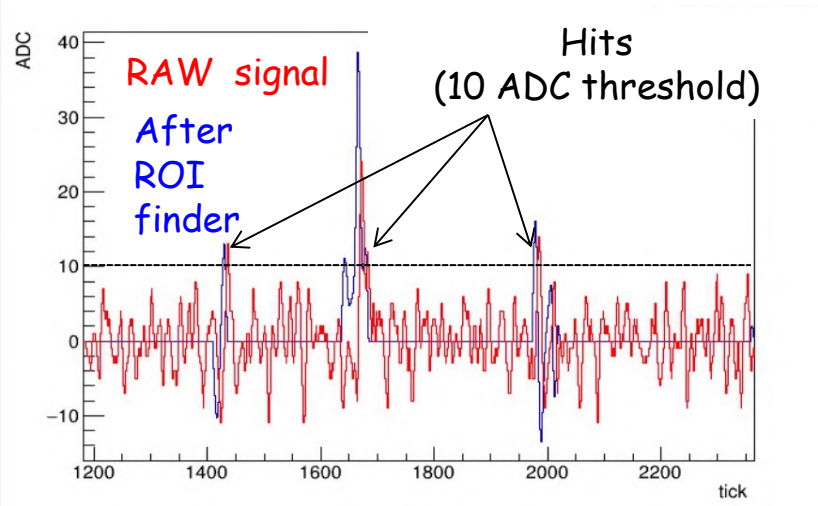
A hit represents the identified signal induced by a track on a wire.

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

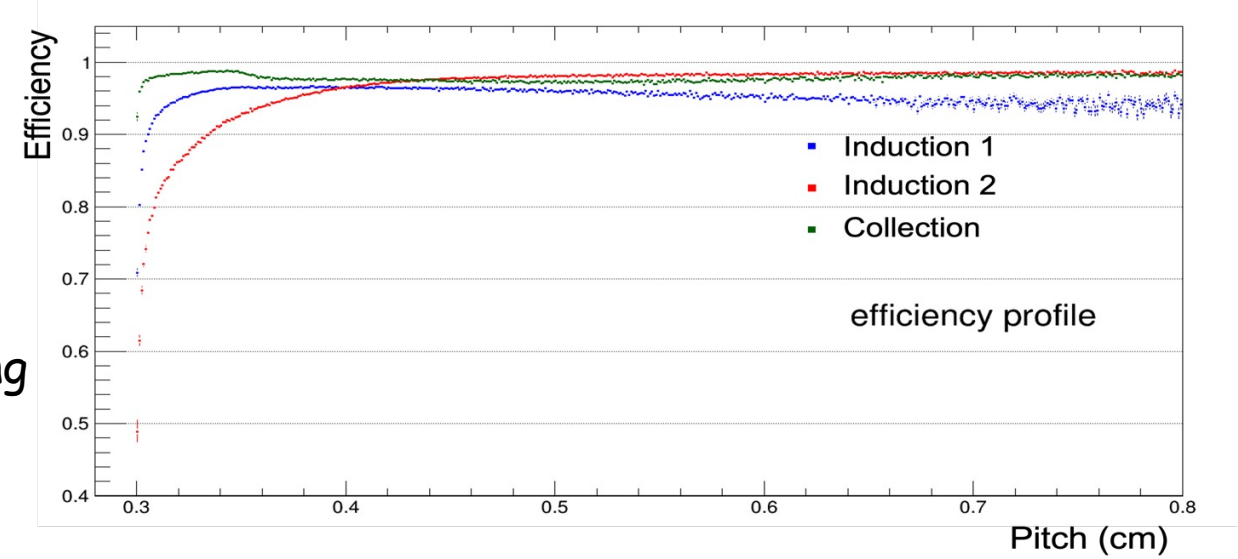
Objects for kinematic reconstruction and event analysis.

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.

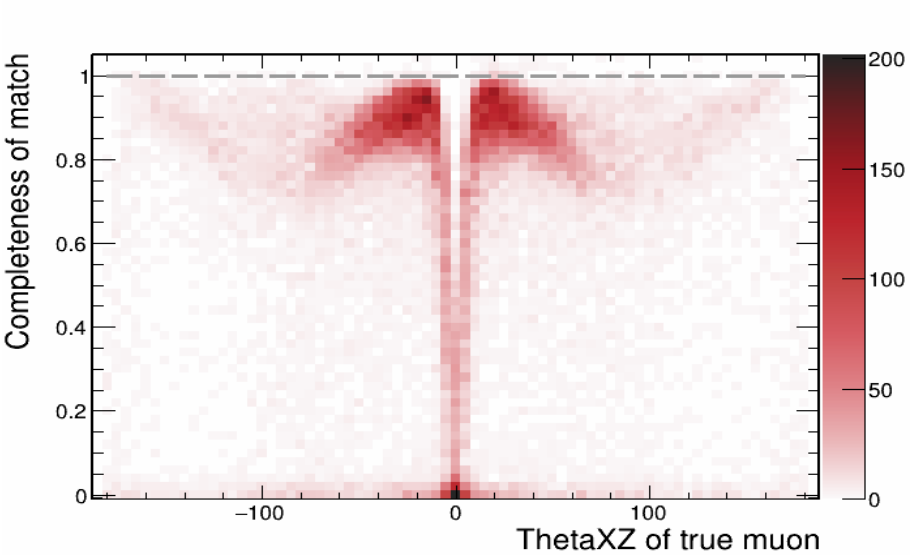
TPC wire signal reconstruction and impact of coherent noise

- 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).

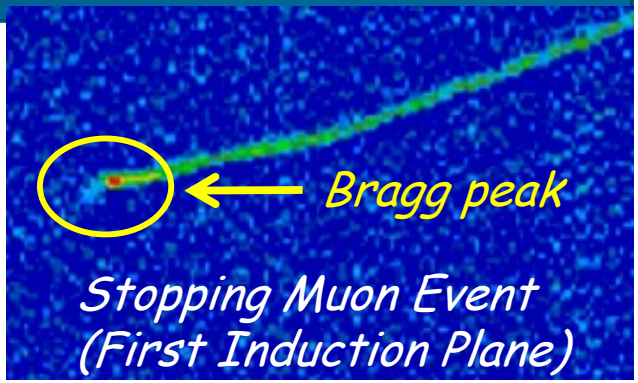


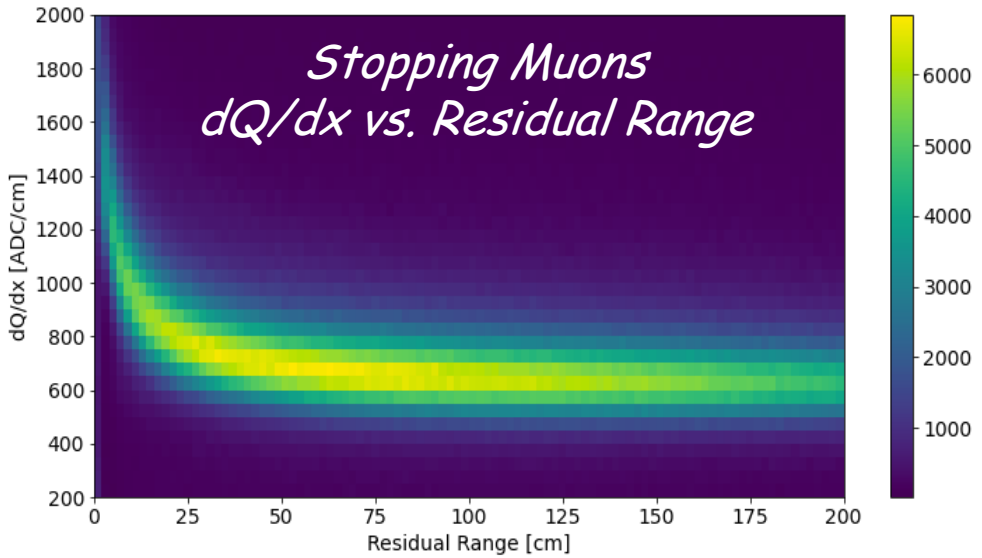
ThetaXZ is the angle *from* Z in XZ (drift-longitudinal axes) plane. 0^0 lies along the beam direction: +/- 90^0 is perpendicular to wire plane.

- 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.

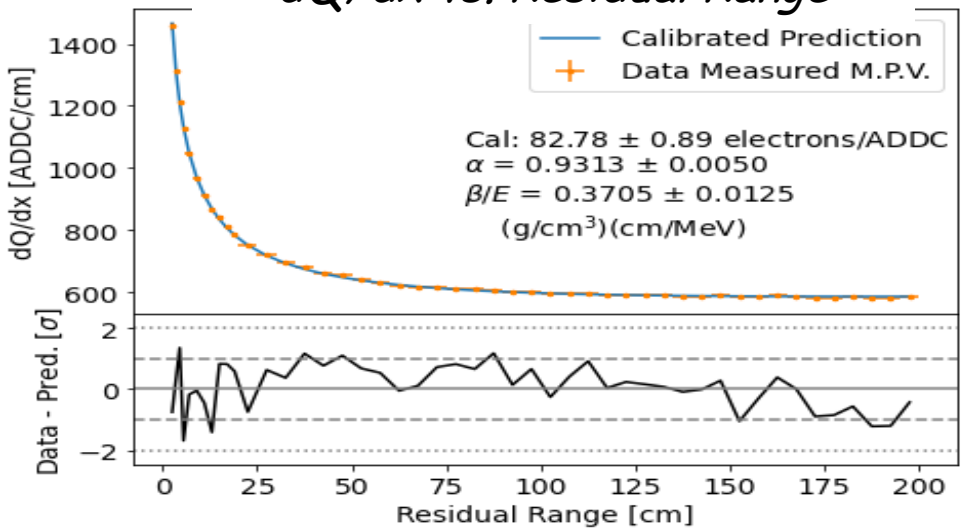
TPC wire signal calibration

- 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.
- It allows to
  - correct for the electron lifetime
  - equalize the electronic response over the full detector
  - calibrate the absolute energy scale
  - improve modeling of e- recombination, diffusion, space charge, wire field response





dQ/dx vs. Residual Range

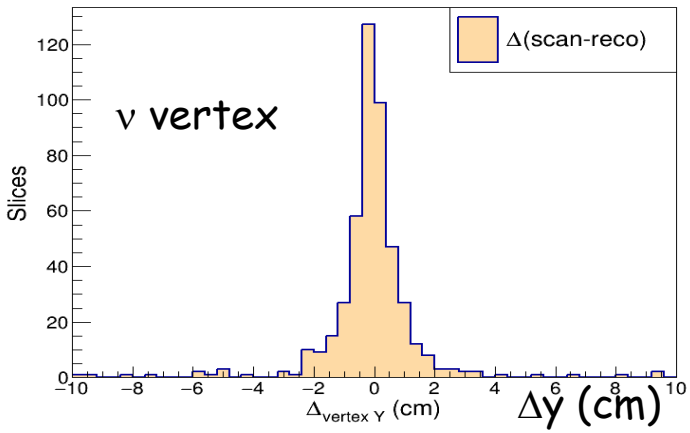


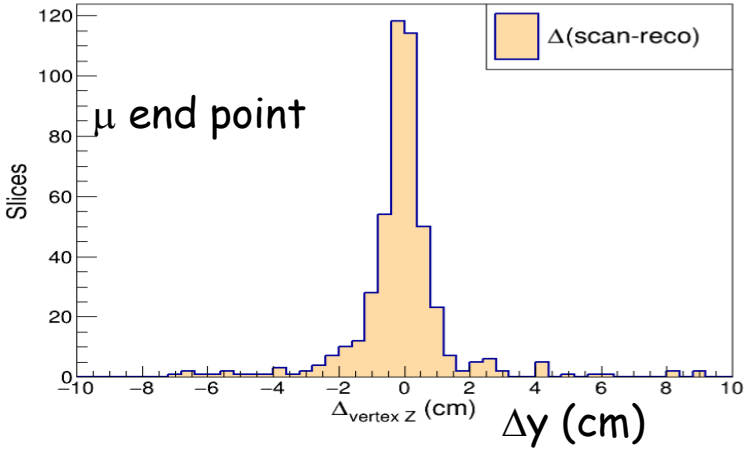
- This study is meant to tune and quantify the performance of the PID algorithm based on the measurement of dQ/dx Vs residual range for stopping particles.

TPC reconstruction

- Quality of the automatic (Pandora-based) pattern recognition of both vertices and tracks in the TPC is being validated by comparison with visual scanning
- A first sample of ~600 $\nu\mu$CC interactions from BNB has been analyzed:
  - ~61% of them are "good matches" (automatic reconstruction well matched to scanned events for both the 3D neutrino vertex position and 3D muon track length)
  - ~25% "almost good matches" (the vertex is well reconstructed but the muon track is not – often "broken" in two or more pieces)
  - ~14% are not recognized by the pattern recognition procedure

Difference between automatic and manual measurement of vertical coordinate y



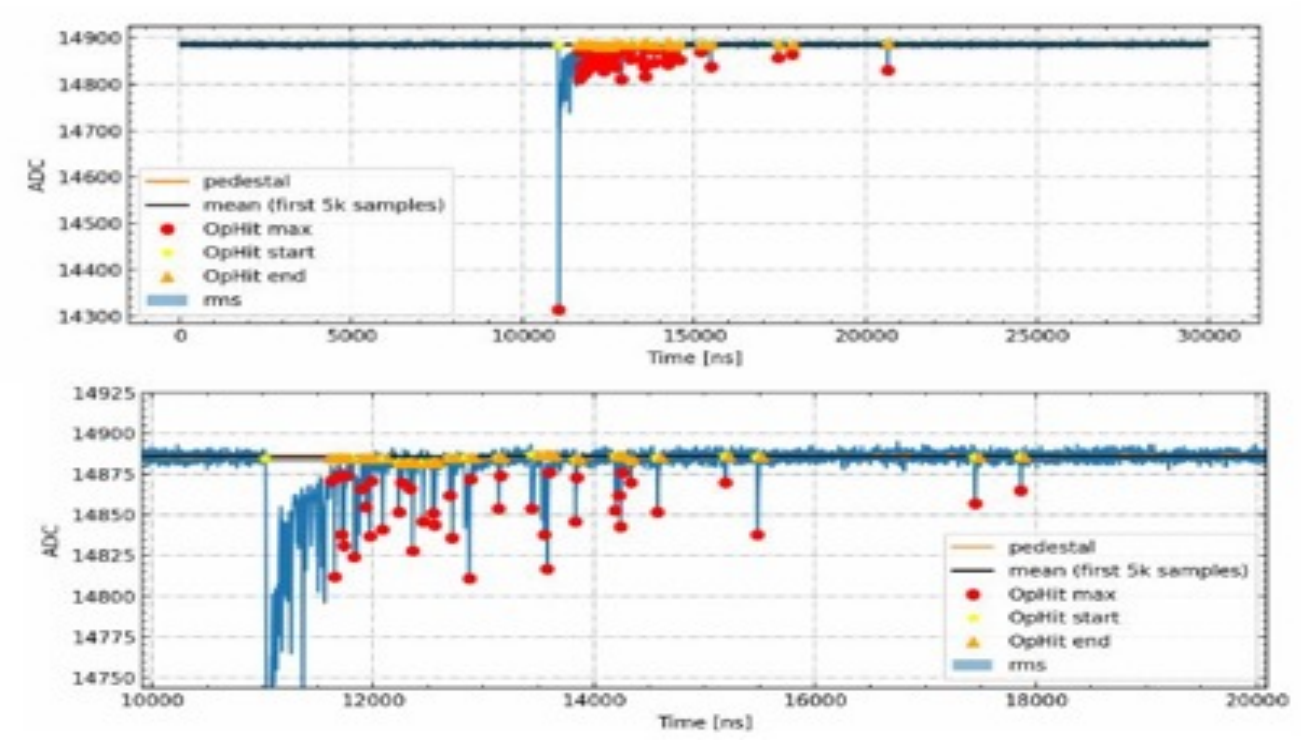


Outliers and reconstruction failures are being studied in detail

Alternative algorithms for matching between wire planes and track "stitching" are being developed

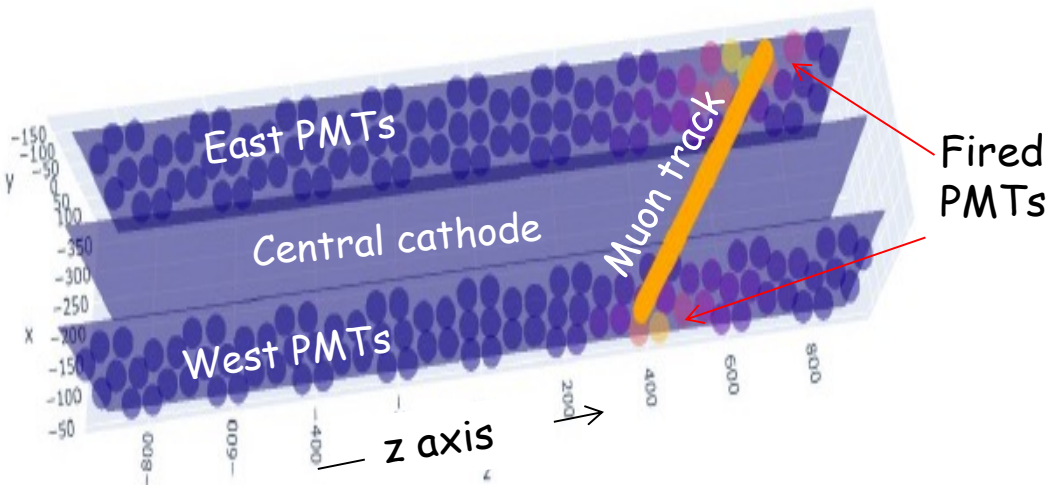
2) PMT reconstruction

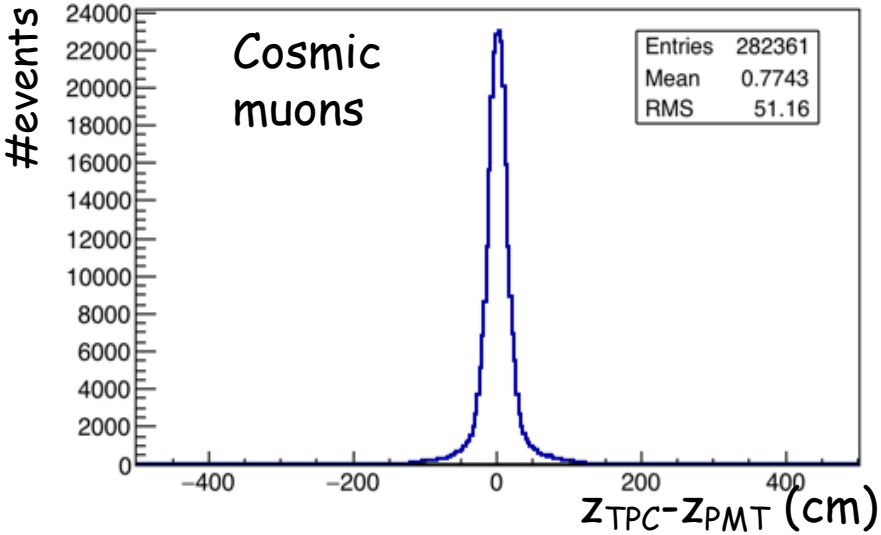
- The digitized PMT signals, sampled at 500 MHz, allow to reconstruct the scintillation light produced in the LAr in a ± 1ms around the beam spill gate;
- The reconstruction code identifies the signals ("*Optical Hits*") of fired PMTs using a threshold-based algorithm (threshold ~0.5 photo-electron);
- *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



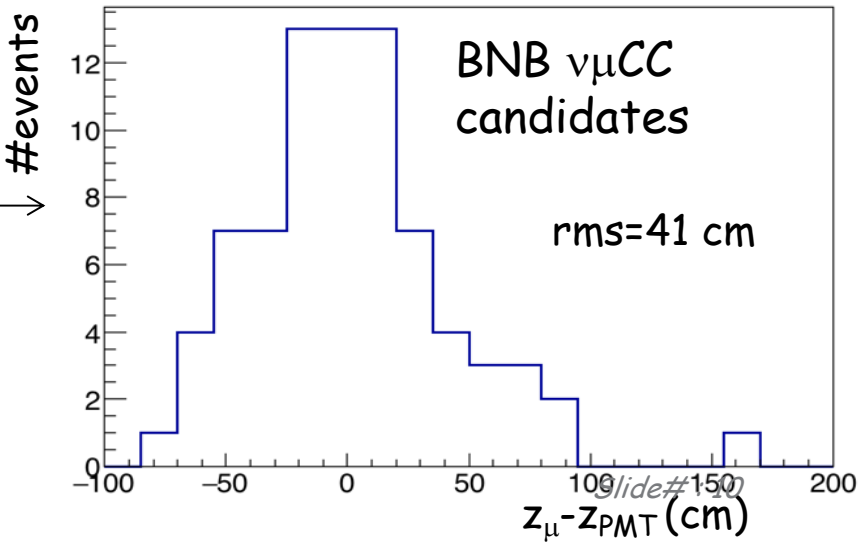
Exploiting the light to localize the event along the longitudinal axis

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



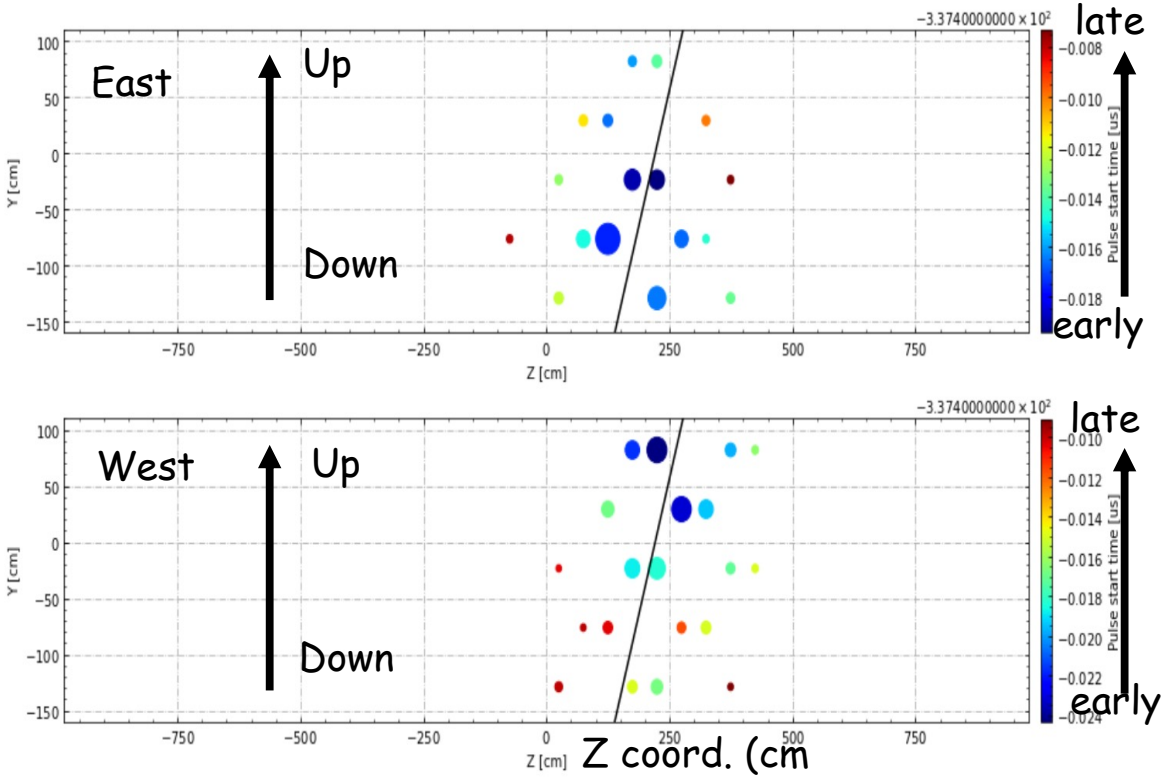


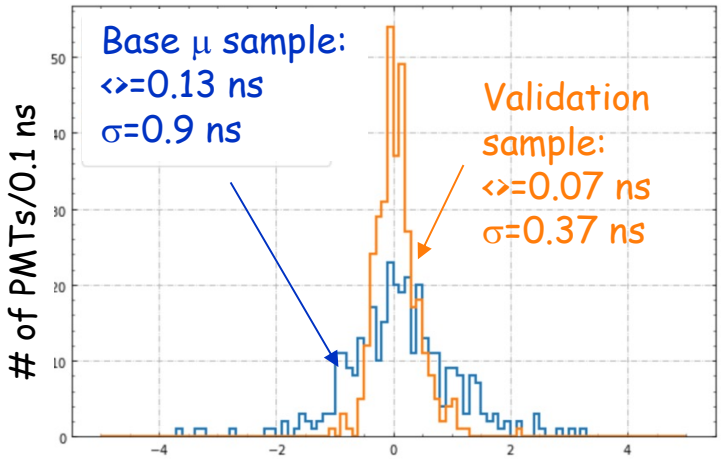
- A similar study has been performed on a set of BNB νμCC candidates with Lμ>50 cm identified by scanning: the average z coordinate of the muon z_μ agrees with the light barycenter within ~1 m.
- A larger statistics study is mandatory to improve the method and tune the selection of neutrino events.



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;





- 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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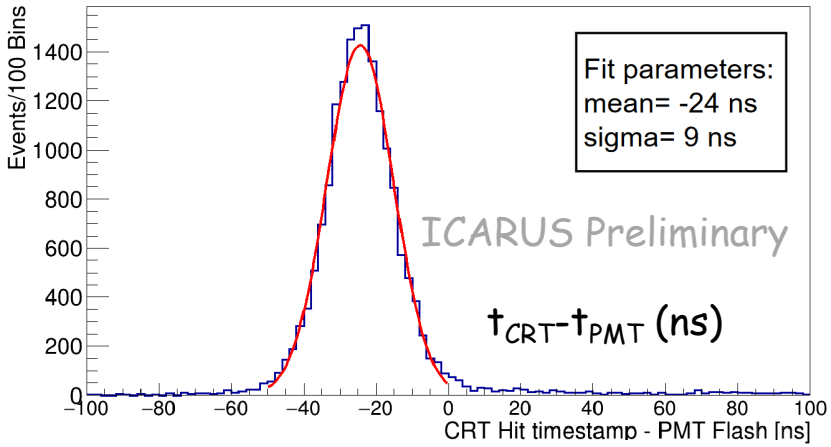
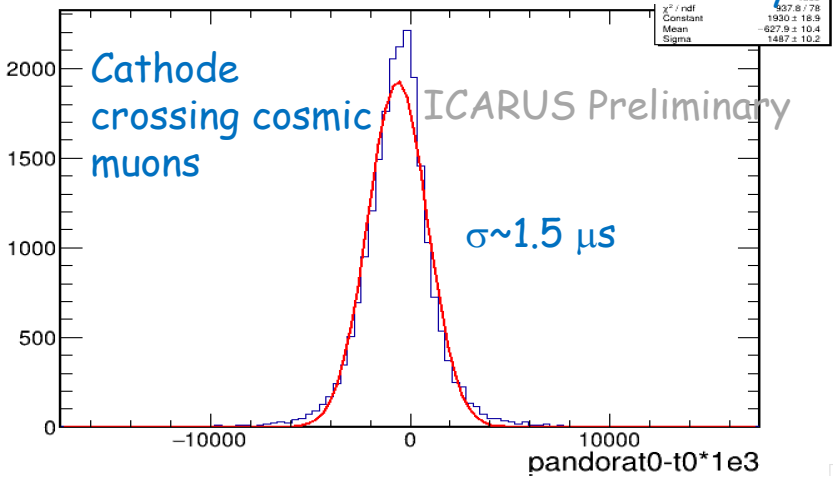
CRT matching with TPC and PMTs

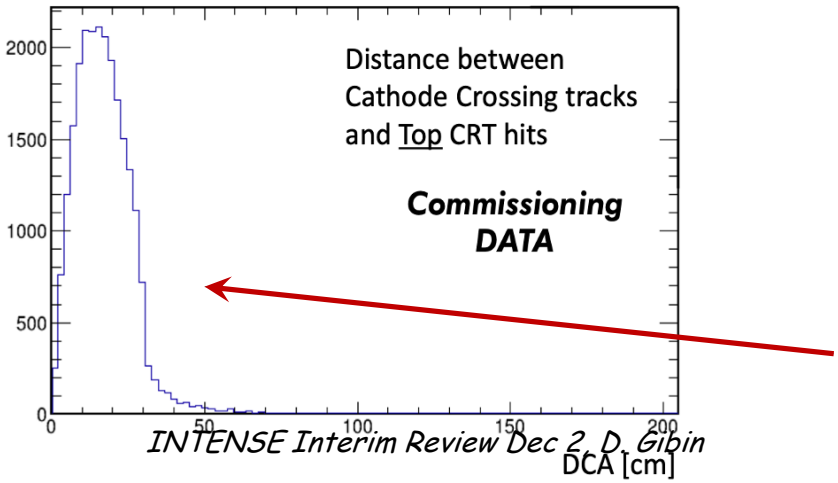
- CRT time offset have been corrected for. It is now possible to match CRT signals in time with both PMT and TPC;
- The time difference between the top CRT and internal PMTs shows a clear peak for incoming cosmics: the width ~9ns includes intrinsic resolution, geometrical variance and light propagation effects in LAr;
- Matching with the TPC was checked with cathode-crossing cosmic muons.
  σ~1.5 μs is dominated by the TPC resolution.

Top CRT-PMT time difference



CRT-TPC time difference for West cryo





Matching in space (distance of closest approach, SBND algorithm) with cathode-crossing cosmic muons

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.