Activation and commissioning of the Icarus detector

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FERMILAB 2022 SUMMER STUDENT MEETING

Outline

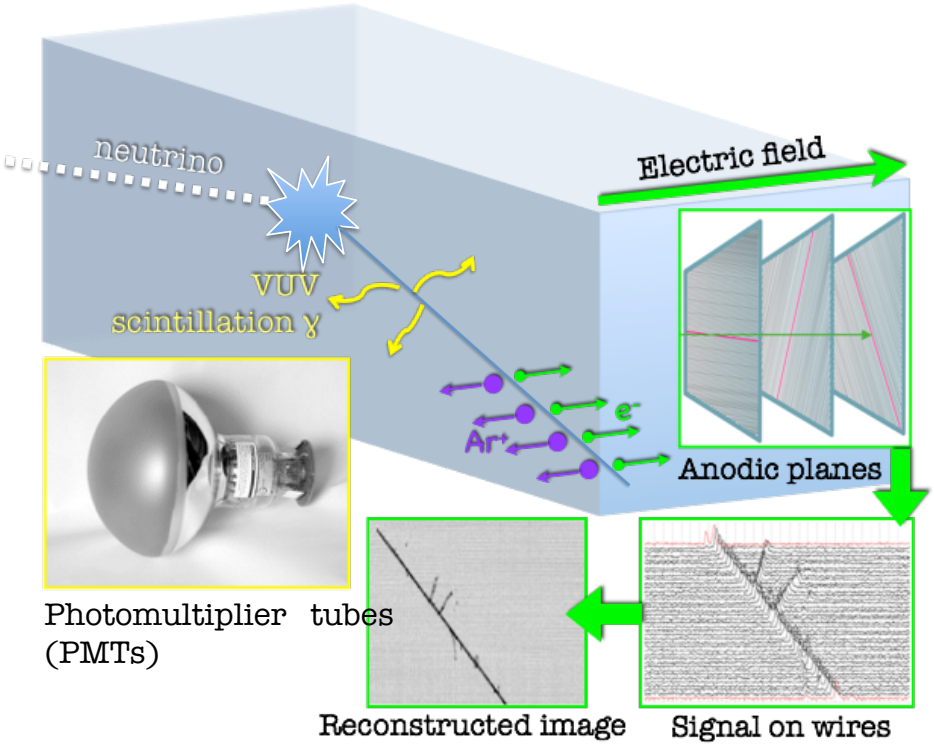
- Introduction
- From overhauling to operation
- Technical status of the detector and its subcomponents
- Data taking
- Initial calibration studies
- Summary

Introduction

Liquid Argon TPC detection technique

Very well suited for the experimental study of Neutrino Physics, pioneered by the Icarus Collaboration.

Massive yet homogeneous target, excellent tracking & calorimetric capabilities.



λ = 128 nm scintillation light:

40000 γ/MeV wo electric field.

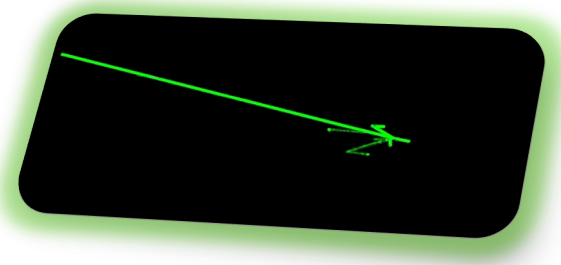
Response time ~ 6 ns ÷ 1.6 μs.

Ionisation electrons:

42000 e^-/MeV.

Drifted (E) toward planes of wires on which they induce a signal.

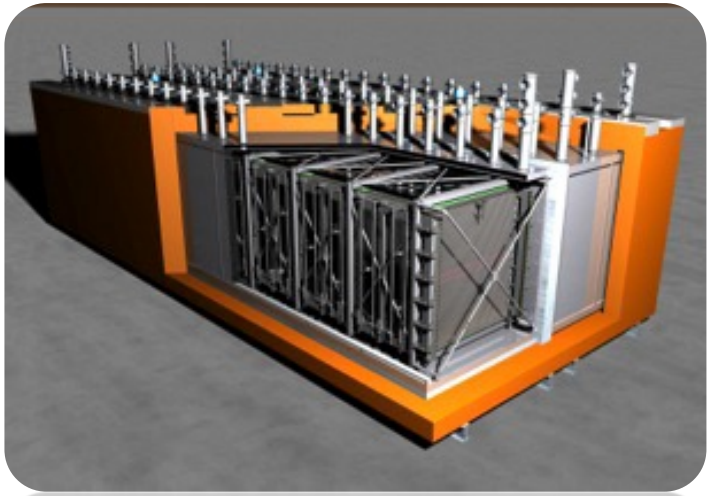
Response time = drift time (~ ms).



3D image reconstruction by combining coordinates on different wire planes at the same drift time.

The ICARUS detector in a nutshell

- International Collaboration with 25 participating institutions from Italy, Mexico, Switzerland, United Kingdom and the United States.
- Far detector in the Short Baseline Neutrino Program (SBN), on-axis on Booster Neutrino Beam at 600 m from target and 6 degrees off-axis on NuMI beam at 800 m
  - Main goal: search for sterile ν oscillations with BNB beam
  - Rich physics program including study of Neutrino-4 anomaly and ν-Ar cross section measurements with NuMI beam



LAr-TPC detector:

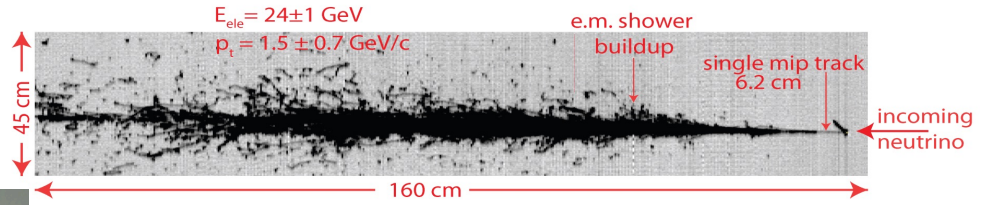
- 760 t of LAr, 476 t active mass, in two identical cryostats sitting side-by-side.
- 4 TPCs with 1.5 m drift and 3 wire planes.
- 360 8” PMTs coated with TPB.
- almost full Cosmic Ray Tagger (CRT) coverage.

From overhauling to operation


IcarusTrip

From LNGS through CERN to FNAL

- Operated underground in Italy in 2010 ÷ 2012 with CNGS ν beam.

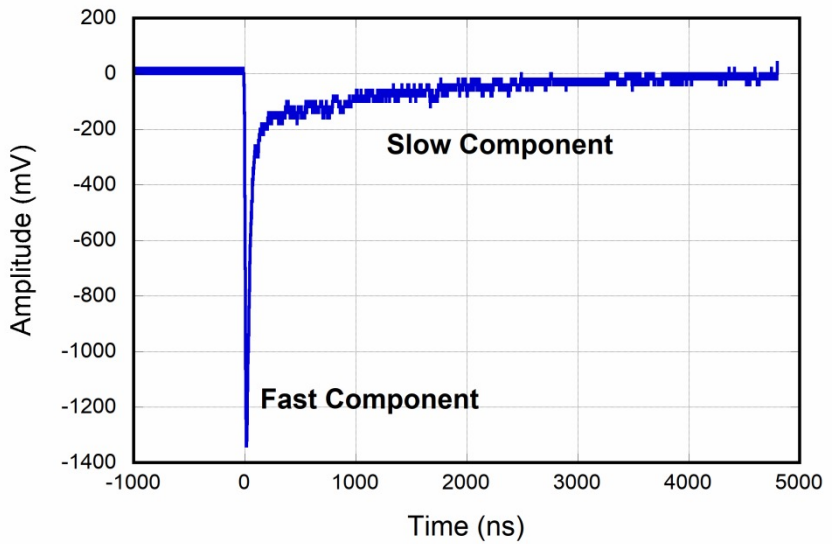


- Overhauling at CERN (2015-2016), including new:
  - cryogenic system;
  - scintillation light system;
  - TPC readout electronics.

- Cryostats containing the detector moved to Fermilab in Summer 2017.
- Final positioning in the warm box inside the building in Summer 2018.
- Installation completed in Jan 2020.

Detector activation

- After LAr filling, all the 360 PMTs were activated:
  - 357 PMTs are working fine;
  - the 3 not working ones, in 3 different chambers, were already marked as “not working” from warm testing.

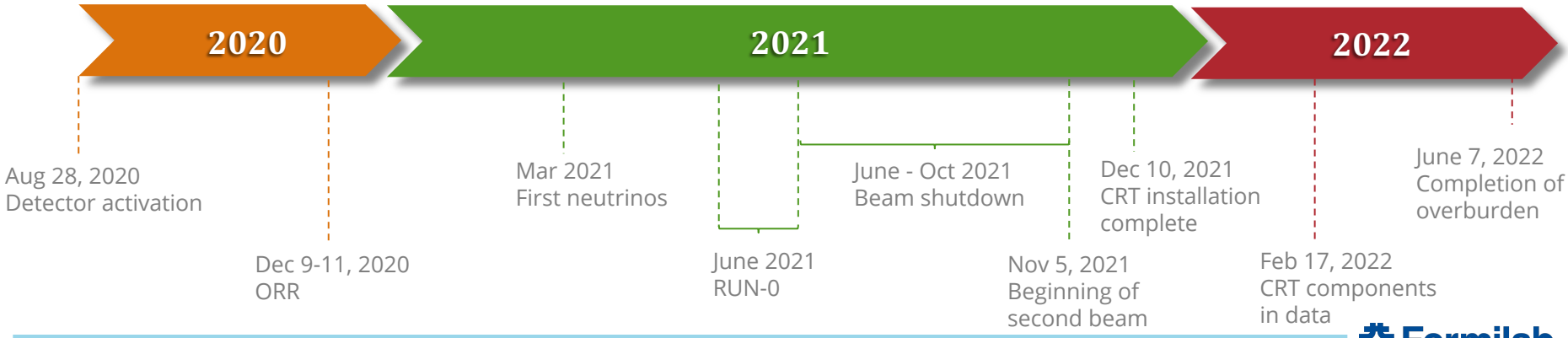


- Two steps activation of the TPC:

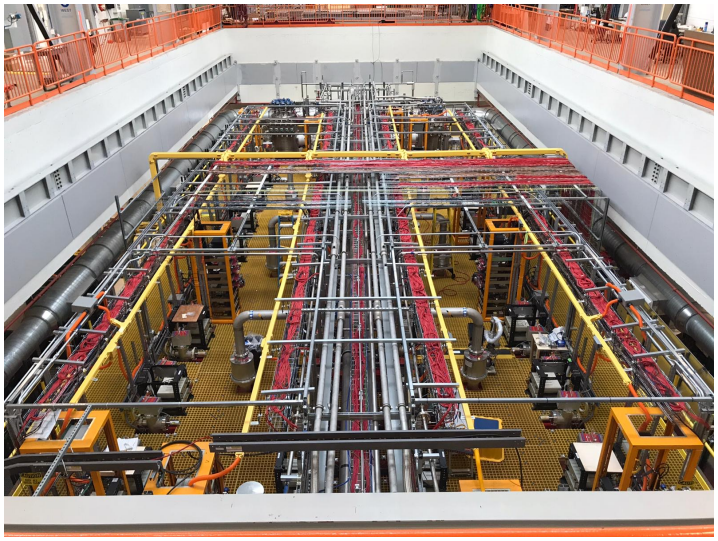
1) Beginning of August _ cathodes HV raised to -40 kV and then to -75 kV with all wires shorted to ground through 50 Ω terminators.
   - Stable HV and first tracks recorded on the first induction planes, operating in semi-collection mode.
2) End of August (Aug 27th) _ all wire planes taken to the nominal voltages and cathodes HV raised to the nominal voltage of -75 kV.
   - HV has remained stable, without any glitches or issues.
   - No significant currents on the wire bias, except for 576 second induction wires of the West module that remain at 0 V (instead of -30 V).

Timeline of ICARUS commissioning and operation

- Detector in nominal operating conditions since August 28th 2020, overall excellent stability.
- 24/7 shifts since February 14th 2020, remote only since March 17th 2020.
  Run Coordinator and Deputy changing every 2 months, one remote expert per each subsystem, one remote shift operation expert and one onsite expert.
- Part-time data taking with neutrino beams since mid-March 2021, aside of commissioning.
- First full time (24/7) neutrino beam run May 31st - June 27th 2021: "RUN-0".
- 7 pm - 7 am weekdays and full weekends minimum time (~ 65%) dedicated to beam data collection since the restart of beams on Nov 5th.
- CRT installation completed on Dec 10th 2021. CRT components in data since Feb 17th 2022.
- 3m thick concrete overburden installation completed on June 7th 2022.
- Second full time (24/7) neutrino beam run since June 9th 2022: "RUN-1".



Evolution of the ICARUS detector



Sept 2020

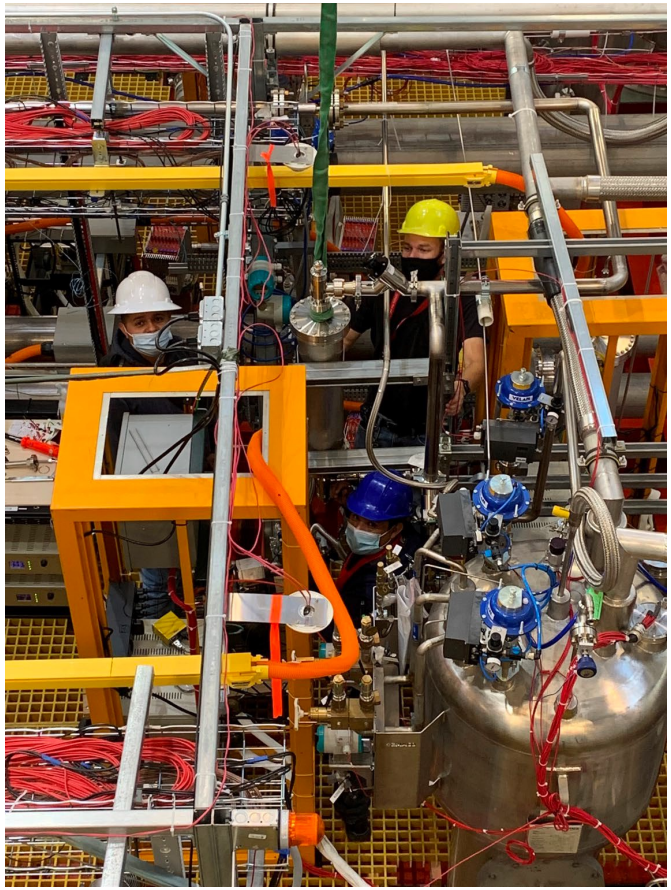
Dec 2021

June 2022

Technical status of the detector and its subcomponents

Cryogenic system

- Cryogenics/purification systems running steadily since detector activation. Some failures occurred with no impact on detector operation, thanks to the high level of redundancy. All functional parameters meet the design values.
- Substantial upgrades during 2021 summer shutdown, including improvement of the gas recirculation system with additional warm filters.
- Free electrons lifetime τ ~ 3/5 ms in West/East cryostats. Although better than initial values ($\tau \leq$ 1 ms in Sept 2020) and within the design, lower than past ICARUS operations at LNGS and unequal between the two cryostats.
- During this summer shutdown regeneration of the liquid recirculation filters of the West module, possibly resulting in an improvement and equalization of the purity.

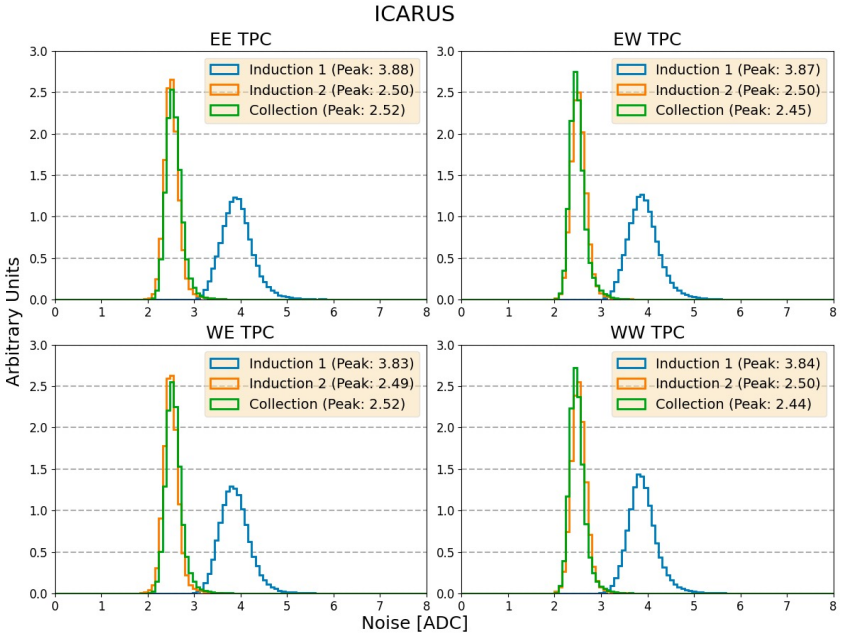


Installation of warm filters during 2021 summer shutdown

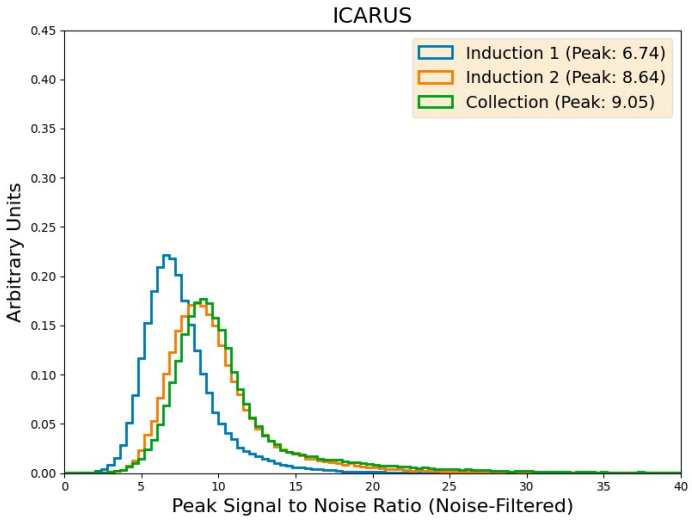
TPC readout electronics

- Anomalous noise level observed in the ICARUS TPC read-out electronics after activation. Studies on a dedicated test bench in Padova and several interventions at FNAL allowed for substantial improvement of the situation.
- Presently uniform noise in all TPCs with the standard baseline setting at ~2020 ADC #: ~ 6 ADC # in Induction 1 and ~ 3.7 # ADC in Induction2/Collection.
- Signal to noise (S/N) for vertical tracks: ~ 7 in Induction 1 and 9 on other planes.

Intrinsic noise for groups of 64 channels (1 board)

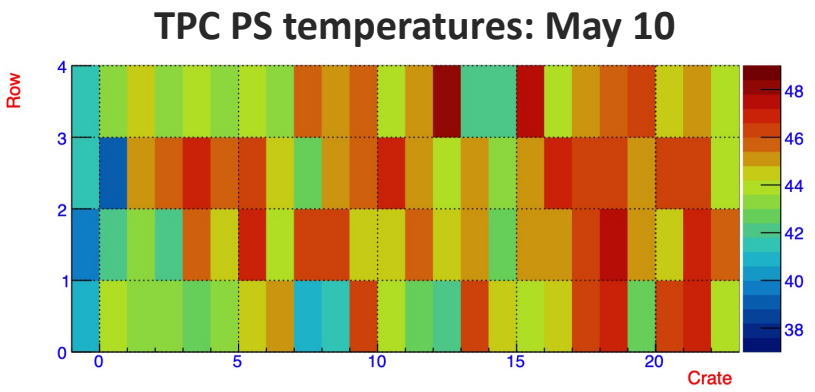


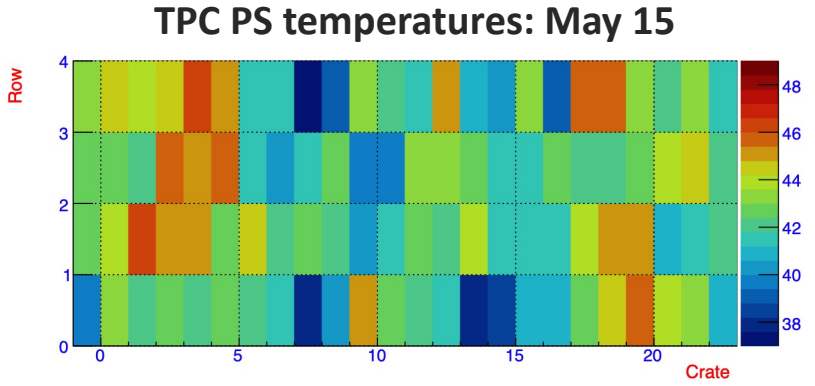
S/N after coherent noise removal



TPC power supply temperatures

- High temperatures on TPC power supplies and front-end boards can impact noise and baseline, and/or force to switch off TPCs to avoid damage.
- After the installation of the top CRT and even more after the first overburden layer, air flow on the ICARUS top strongly decreased – combined with warmer weather – resulting in an increase of several degrees on the TPC-PS (up to 49°C).
- DAQ had to be stopped or ran without a complete TPC readout in several instances.
- Starting on May 12, situation greatly improved thanks to lab support (rebalancing of building HVAC and installation of fans). No temperature over 47°C observed since then.
- A more complete HVAC refurbishing will take place during summer shutdown.

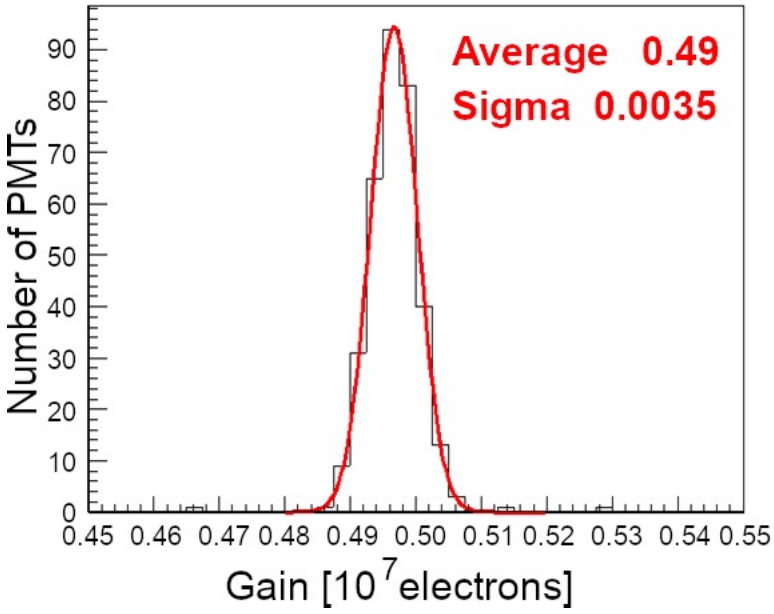




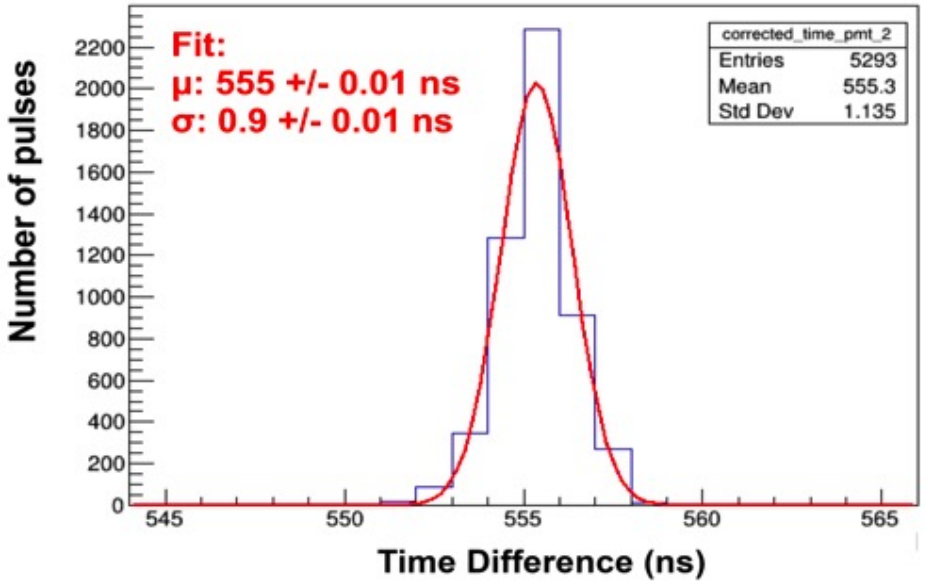
Scintillation light detection system

- The PMT light detection system is working smoothly since its activation.
- The PMT gains are equalized to G = 0.5x10^7 with a spread <1%. Set point takes into account unexpected decrease of the gain with time measured after filling with LAr, possibly caused by fatigue of the dynodes due to the high current value induced by the ~250 kHz photon rates produced by cosmic rays at shallow depth and ^{39}Ar.
- PMT transit time and signal timing can be measured with ~ 1 ns precision.

Distribution of the gain of the 360 PMTs



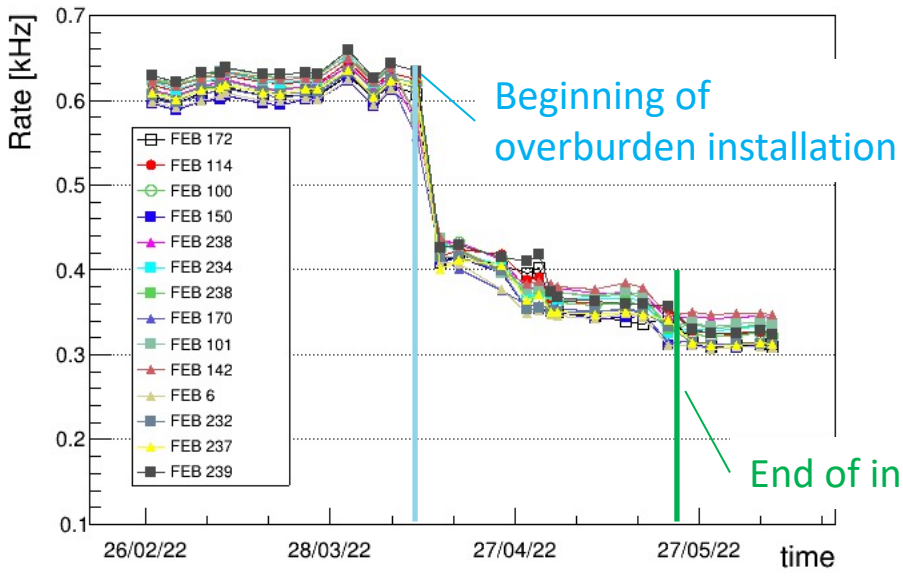
Distribution of time difference between PMT signals and trigger time



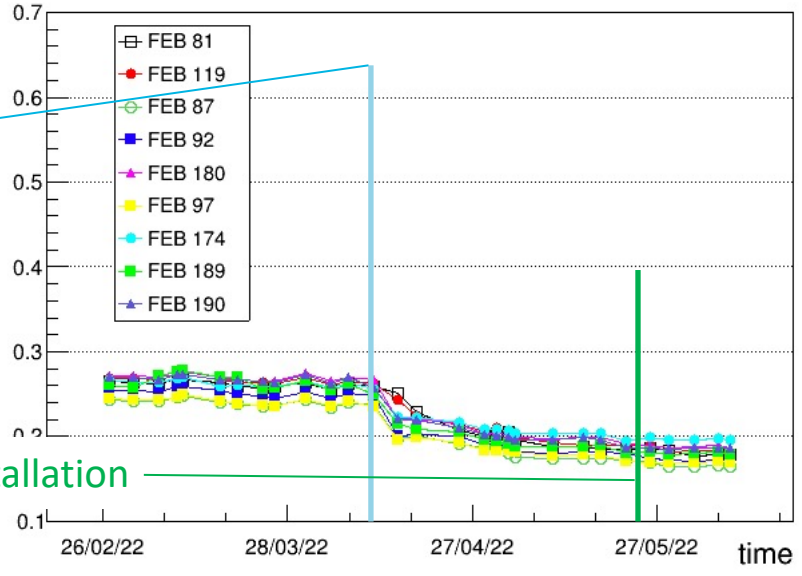
Cosmic Ray Tagger (CRT)

- Side and top CRT have been taking cosmic and neutrino data steadily with TPC and PMT systems, for over one year for side CRT and four months for top CRT. Bottom CRT DAQ still not operative.
- Rates without overburden for top CRT: 260/610 Hz for side/top. For side CRT, rates ~ few kHz, except for higher 20 kHz rate for North module, due to interference with cryogenic pumps.
- Rates for top CRT decreased to 180/330 Hz for side/top with 3 m overburden .

Rates for horizontal modules of top CRT



Rates for vertical modules of top CRT

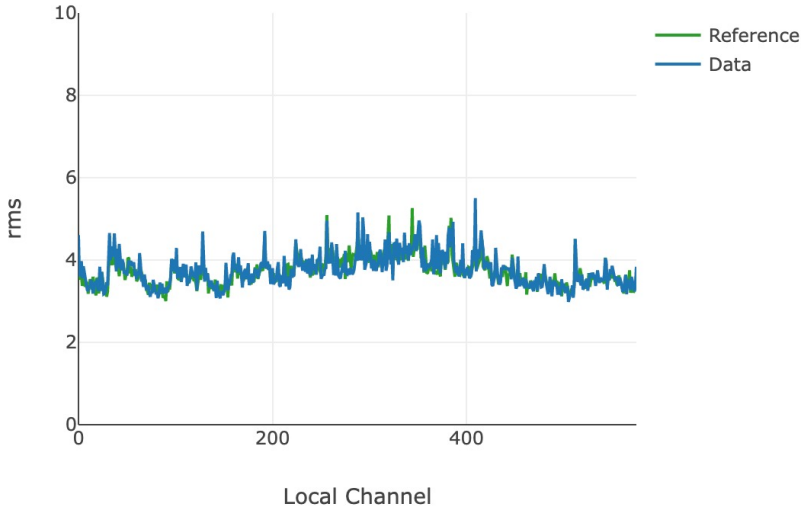


Data acquisition

- ICARUS DAQ runs using artdaq software framework developed by Fermilab Scientific Computing Division (SCD):
  - BoardReader applications collect data from PMT, TPC, CRT, trigger front-end;
  - EventBuilder applications request, receive, and combine data fragments together corresponding to the same event number or common time window;
  - Dispatcher applications receive data stream for data quality monitoring.
- During periods of steady data taking, DAQ uptime >90%, with excellent stability on long runs (several days) at BNB rates > 4 Hz.
- High efficiency of event building, issues of empty or missing data fragments largely mitigated during commissioning and now less than 0.1%.
- Online data writing with filtering of files in different streams based on trigger type and data compression. Total online (RAID-backed) storage volume is 180 TB, with ~11 TB in consistent use: enough space for ~two weeks of storage.
- File transfer performed steadily during commissioning, with no signs of loss or corruption of data. Transfer from FNAL offline storage to CNAF regularly performed, more than 700 TB already replicated.

Data Quality Monitoring

- Real-time monitoring of data quality (DQM) from all subdetectors is crucial for physics.
- DQM receives data from DAQ, produces metrics from TPC/PMT/CRT and plots them on a front-end website:
  - Channel status
  - Noise RMS
  - Waveforms
  - Higher level (e.g. LAr purity, …)
- This information is summarized as a "detector status" with corresponding alarms.
- Recently fully integrated and made available to shifter for continuous monitoring.

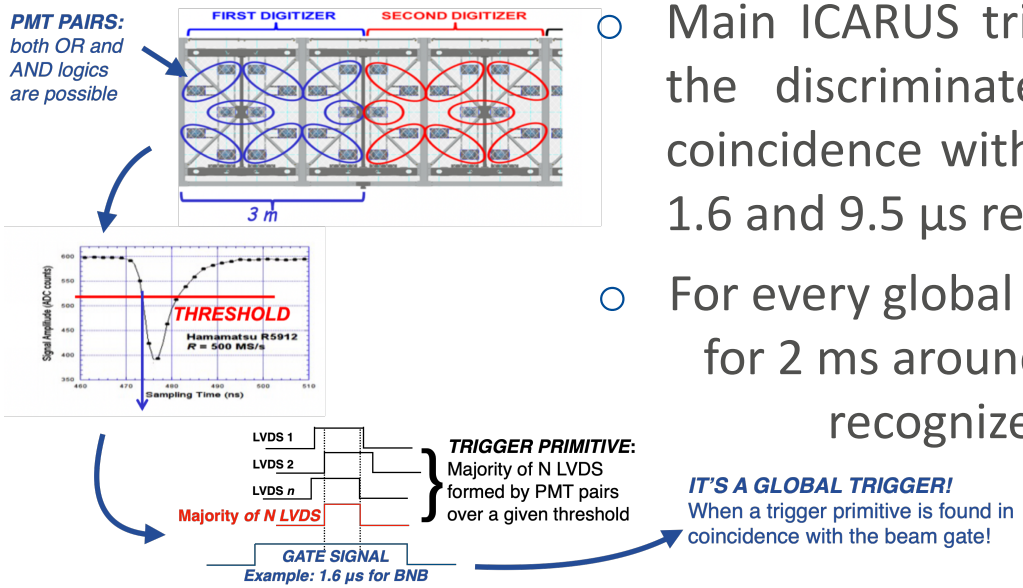


Example of DQM for TPC: rms of noise

Detector Status

TPC Status:	OK
PMT Status:	OK
Side CRT Status:	OK
Top CRT Status:	OK

Trigger and clock distribution system



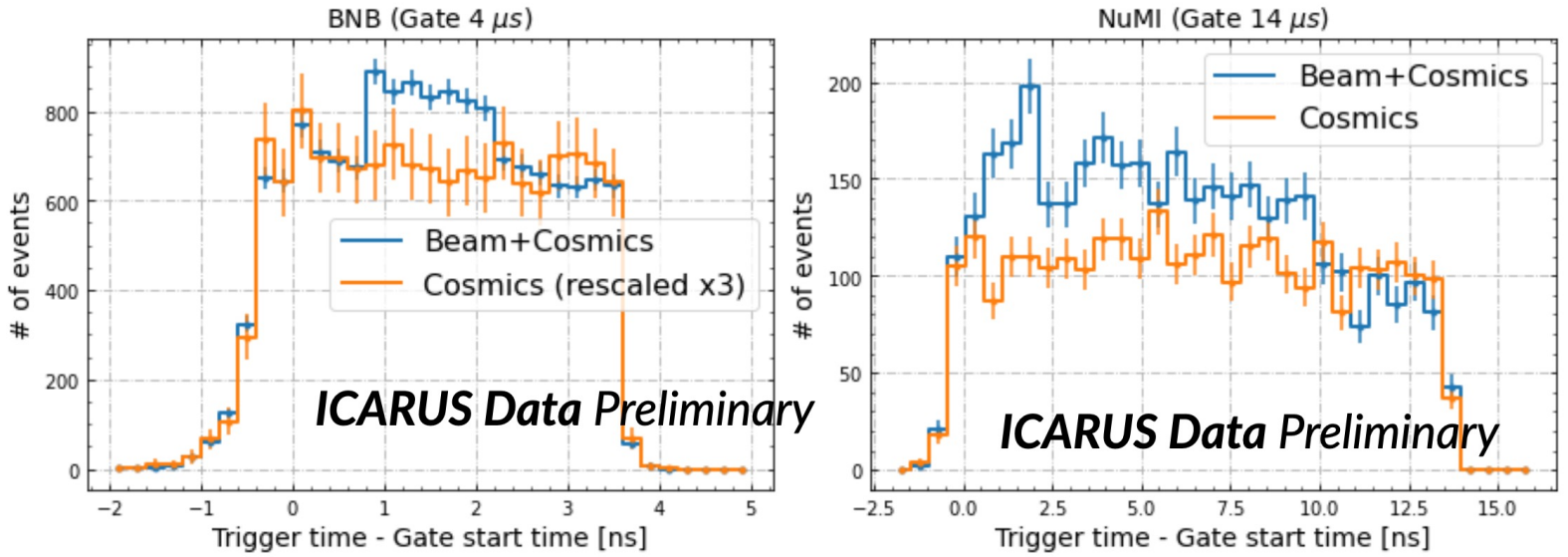
- Main ICARUS trigger signal generated by majority of the discriminated pairs of PMT signals (LVDS) in coincidence with the BNB and NuMI beam spill gates, 1.6 and 9.5 µs respectively.
- For every global trigger, light and CRT activity occurring for 2 ms around the trigger time are also recorded, to recognize and tag cosmics crossing the detector during the 1 ms e^- drift time.

- Additional trigger signals generated in correspondence with a subset of the beam spills without any request on the scintillation light (Min-Bias), and outside of the beam spills to detect cosmic ray interactions (Off-Beam).
- The generation of the beam gates is based on "Early Warning" signals distributed hundreds of µs before the extraction through a White Rabbit network.
- An absolute GPS timing in form of pulse per second (PPS) is used as a reference for generating phase locked digitization clocks and for time-stamping the beam gates and trigger signals.

Trigger performance

- Rates for the main trigger at the current setting of parameters (400 ADC = 13 photoelectrons PMT digitization threshold, majority of 5 PMT LVDS signals) are 164 mHz for BNB and 187 mHz for NuMI without overburden. Corresponding offbeam rates are 123 and 119 mHz respectively, compatible with ~ 14 kHz cosmic rate.
- Additional 0.2 Hz of minimum-bias triggers, for a total rate < 1 Hz.
- Verification of correct timing of beam signals by looking for excess of PMT light flashes over the cosmic background rate in minimum-bias runs.

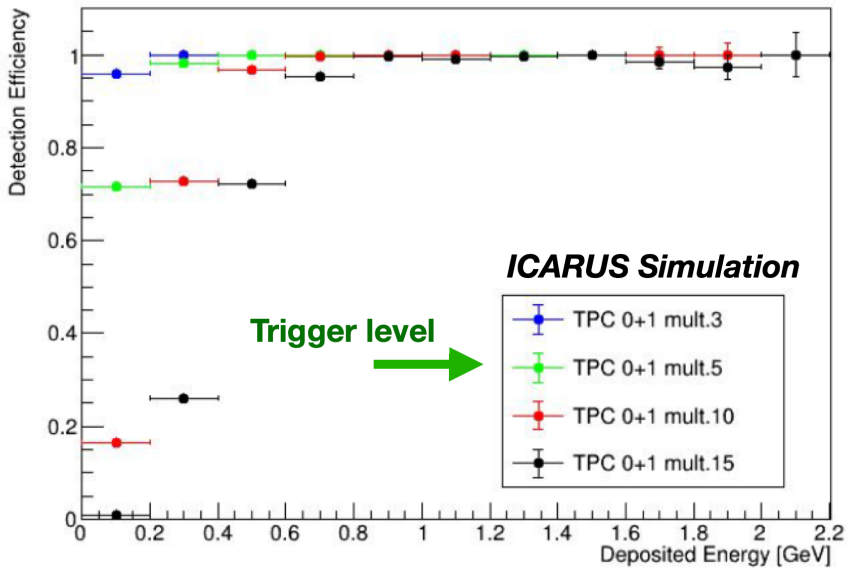
Excess of PMT flashes in the BNB (left) and NuMI (right) gates



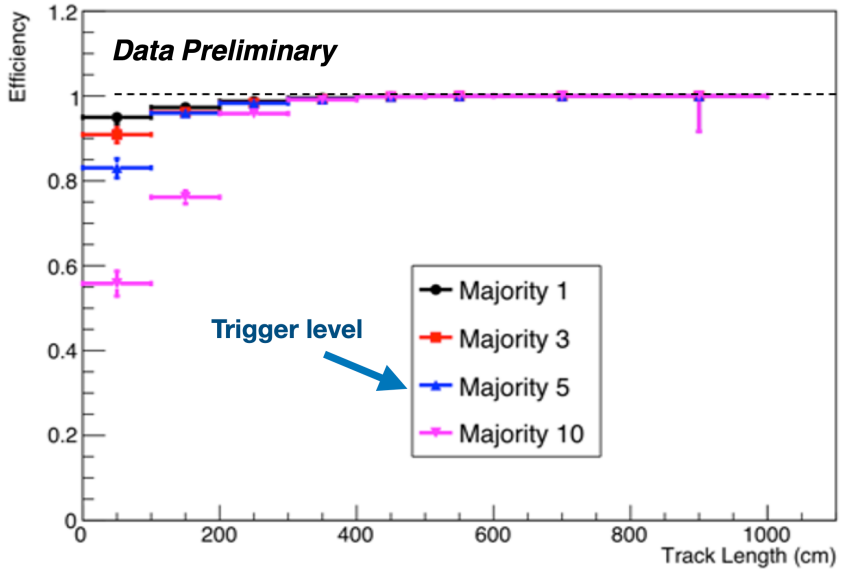
Trigger efficiency studies

- At the current trigger settings, MonteCarlo simulation predicts > 97% efficiency in detecting ν_μCC with deposited energy > 300 MeV.
- Evaluation of trigger efficiency on data started on samples collected with the Minimum Bias trigger. Cosmic ray μ crossing the TPC cathode are selected because characterized by a well-known time. The response of the Majority trigger logic is emulated in software, by analyzing the PMT light activity associated to the selected tracks. Similar ~97% efficiency reached at 300 MeV.

Trigger efficiency on ν_μCC from MonteCarlo

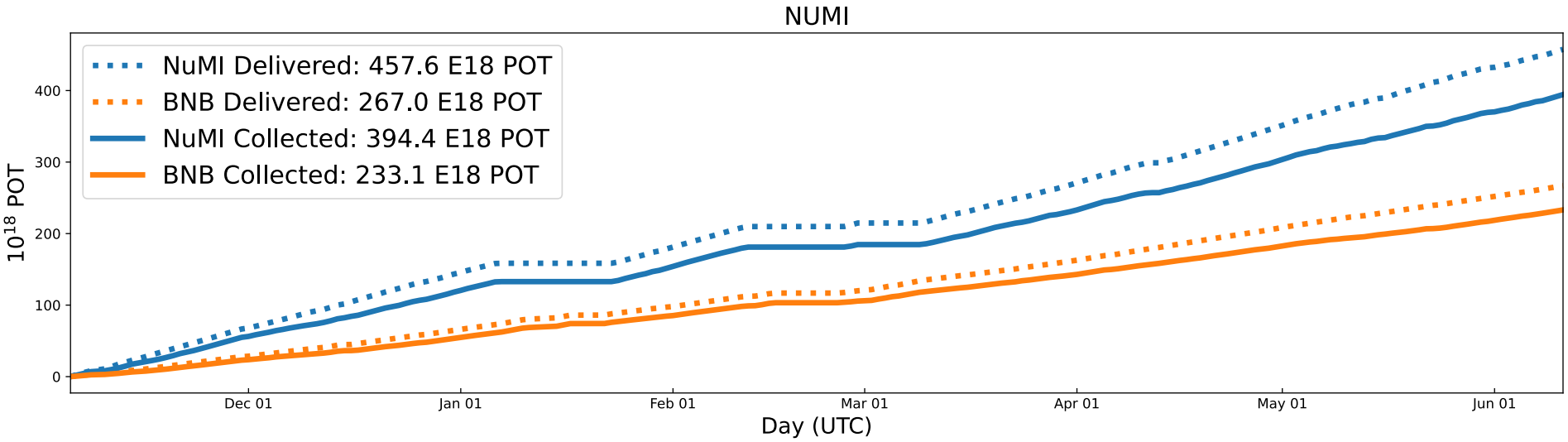


Trigger efficiency measured on crossing cosmic μ



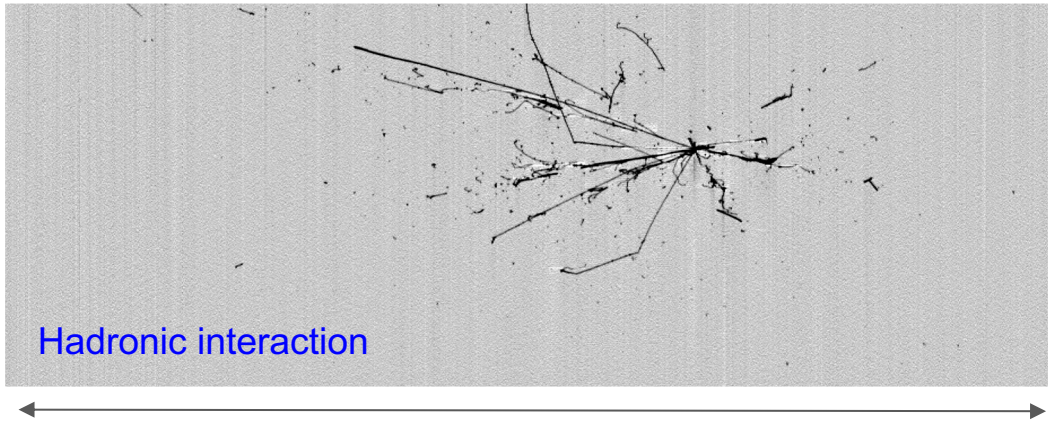
Data taking

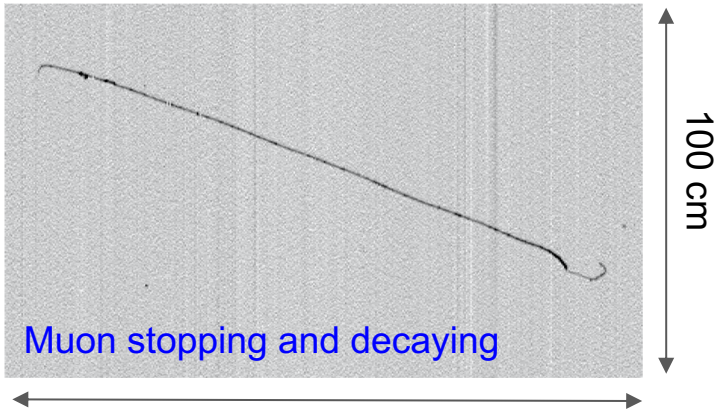
Data taking with BNB and NuMI beams

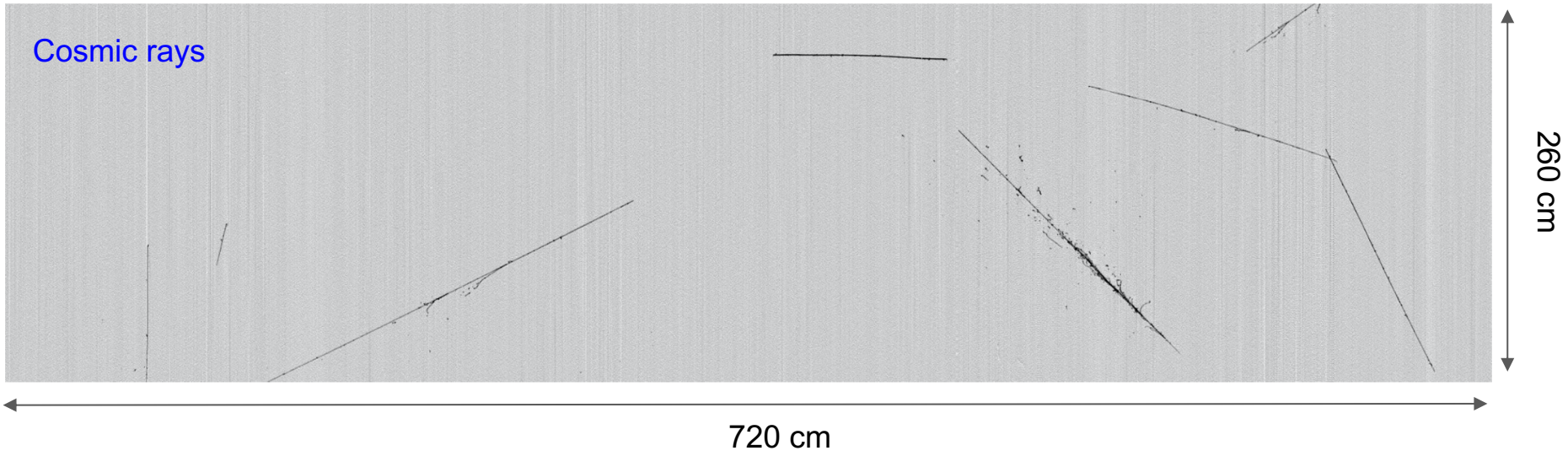


- Average repetition rate 4Hz. Short successful test at 5 Hz on June 3rd 2022.
- Overall efficiency of beam data collection >86%, despite part-time operation!
- Main trigger: majority of the discriminated pairs of PMT signals (LVDS) in coincidence with the spill gates of BNB (1.6 μs) and NuMI (9.5 μs). Additional triggers: without any request on the scintillation light for a subset of the beam spills (Min-Bias), and outside of the beam spills (Off-Beam).
- Data collected so far instrumental for calibrating the detector and tuning simulation and reconstructions tools.

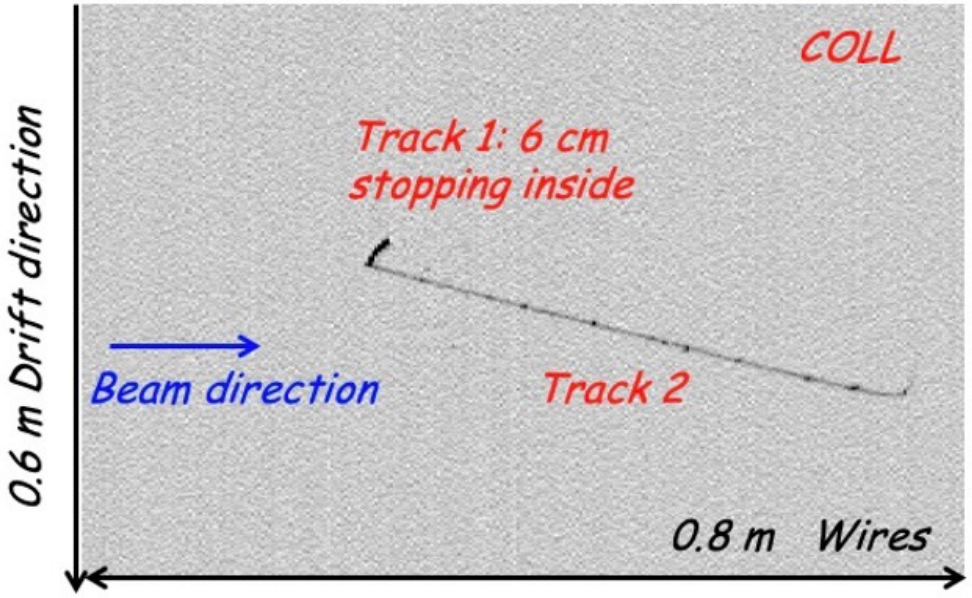
Sample event displays

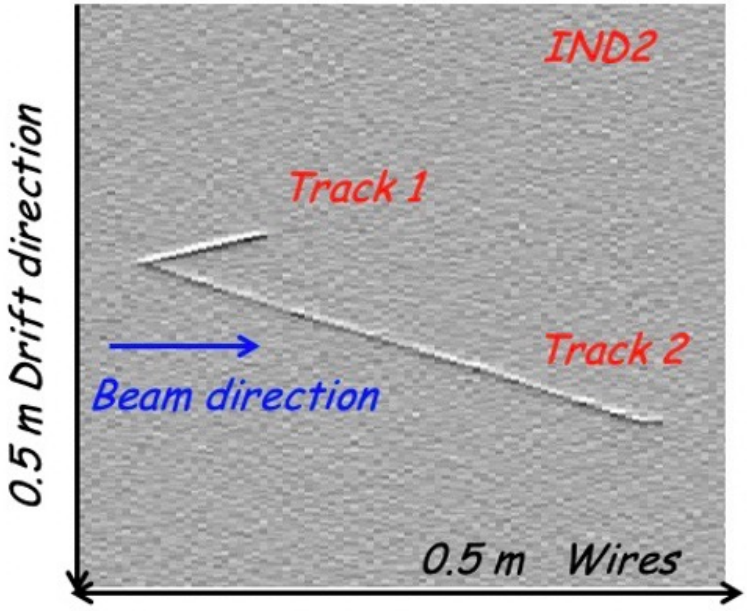






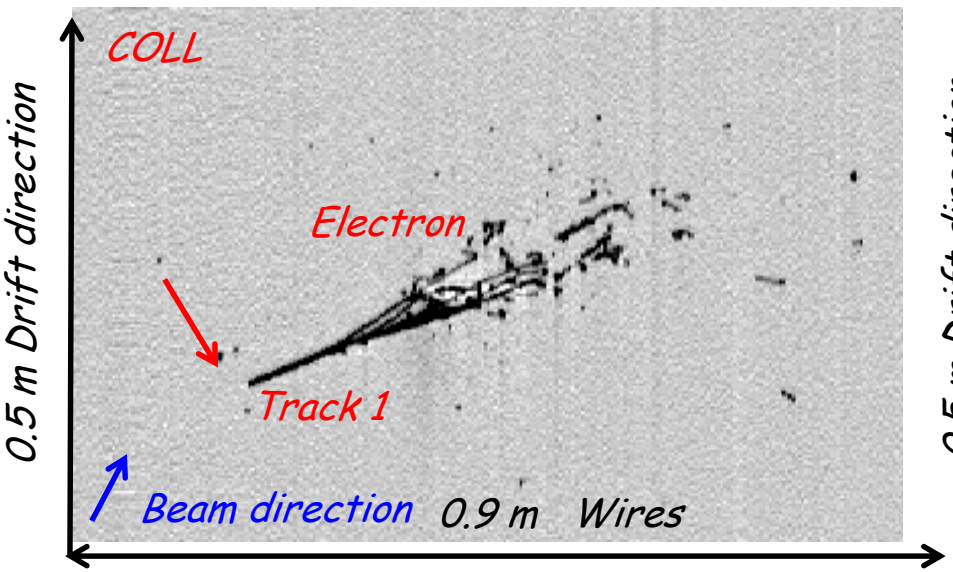
Example of BNB ν_μCC candidate

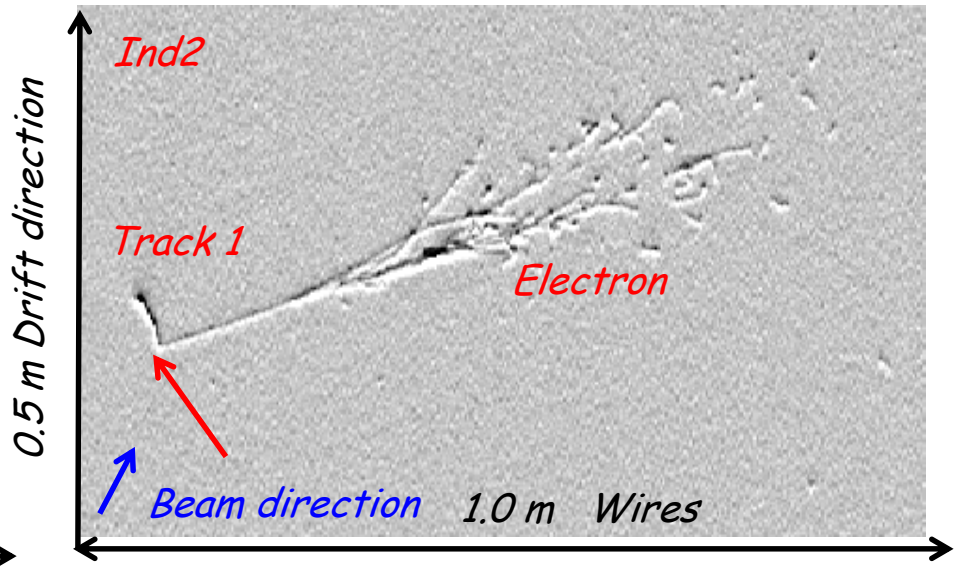




- QE ν_μCC candidate (run #4626, ev #227) in COLL and IND2 views.
- Vertex at 29 cm from the bottom wall. Two tracks produced, E_{DEP} ~ 170 MeV
  - Track 1 is the proton candidate with E_K ~ 70 MeV, stopping after L = 6 cm
  - Track 2 is likely the μ exiting on bottom wall after L = 51 cm.

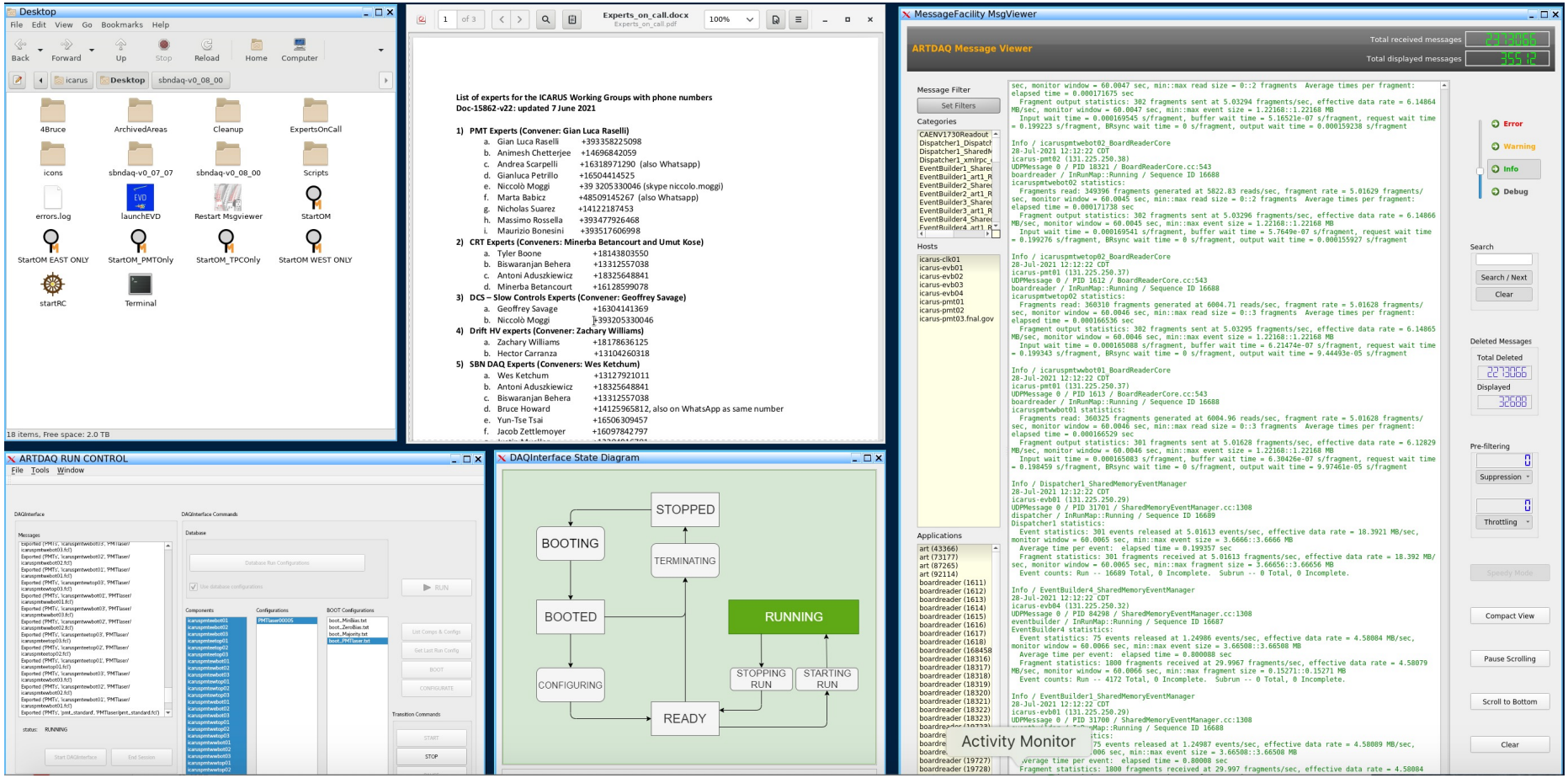
Example of NuMI ν_eCC candidate





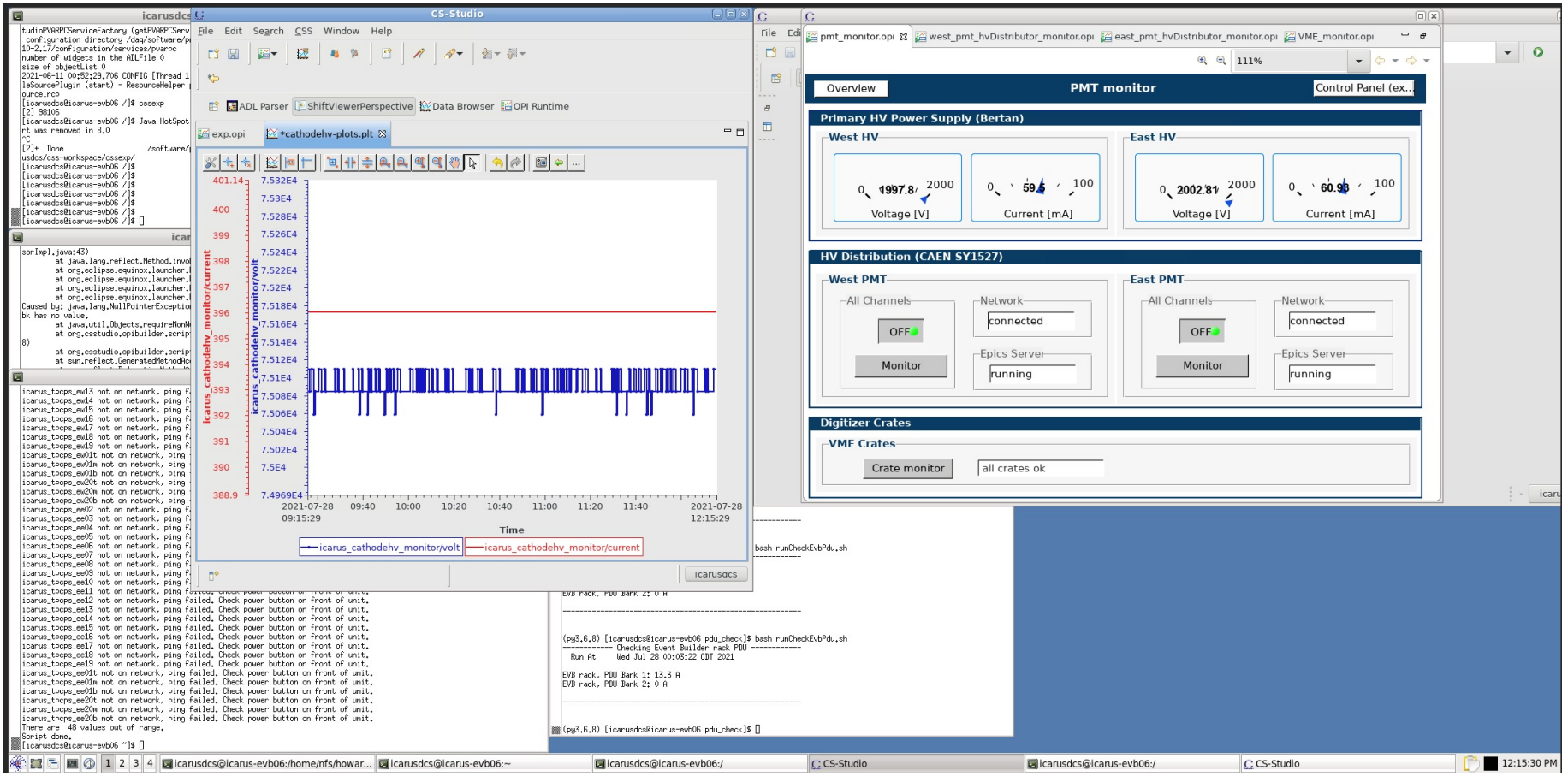
- QE electron neutrino candidate with two particles at the primary vertex (indicated by red arrows):
  - Track 1 is the upward going proton candidate stopping inside L= 13 cm
  - The electron shower is downward going: the beginning of the shower is clearly visible in particular in Induction 2 view (in Collection the e^- and track 1 are overlapped).

A shifter's life I



A shifter's life II

A shifter's life III

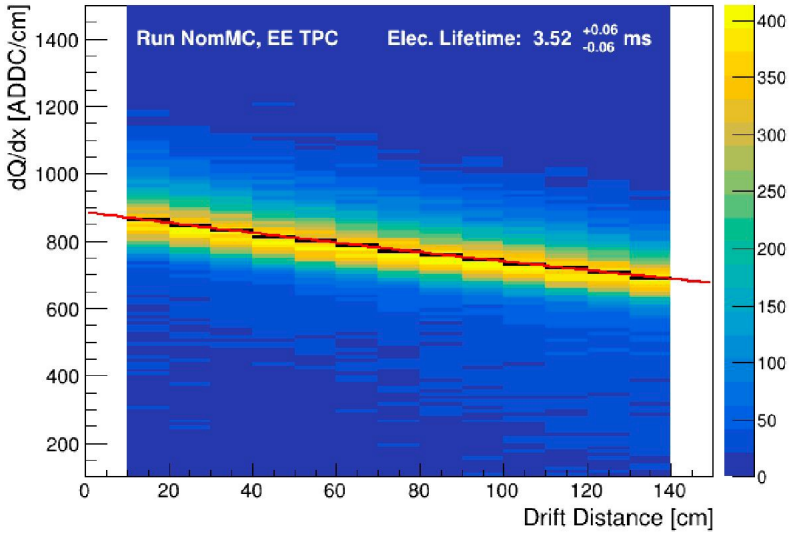


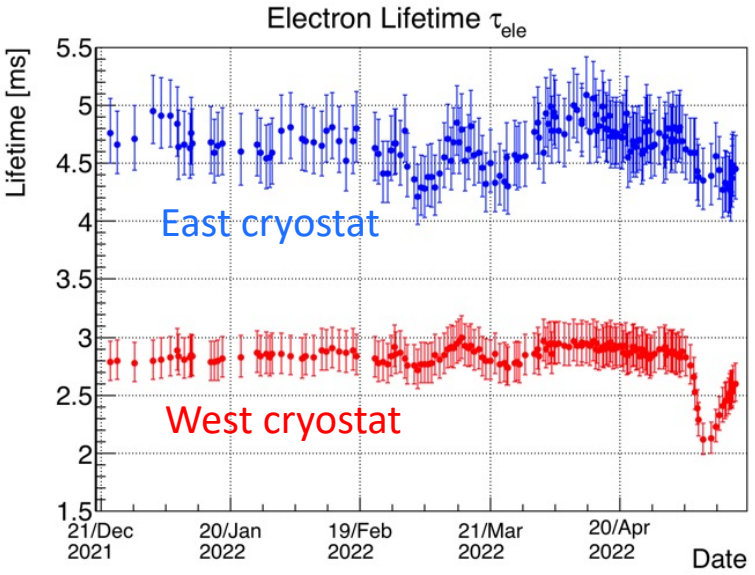
Initial calibration studies

Electron lifetime (purity) measurement

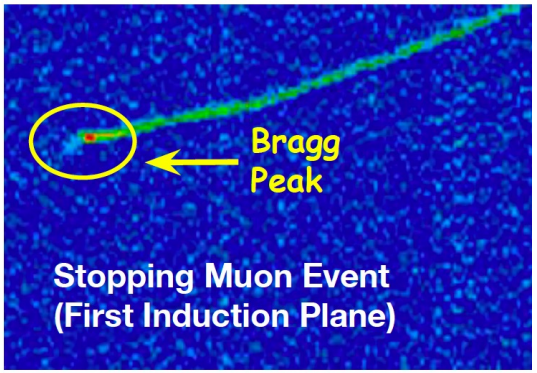
- Free electron lifetime τ_{ele} measured by the attenuation along the drift path of the electron ionization signals generated by cosmic ray tracks crossing both the cathode and anode.
- Two complementary procedures developed and tested on MonteCarlo.
  - Method presently applied based on simplified physical signals and track reconstruction in 2D and measurement of the attenuation on each track. 7% total statistical + systematic uncertainty.

Attenuation of ionization along μ track

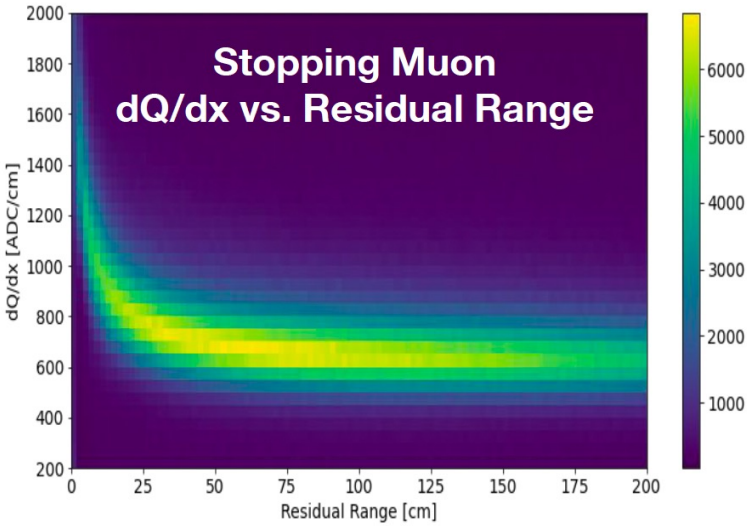


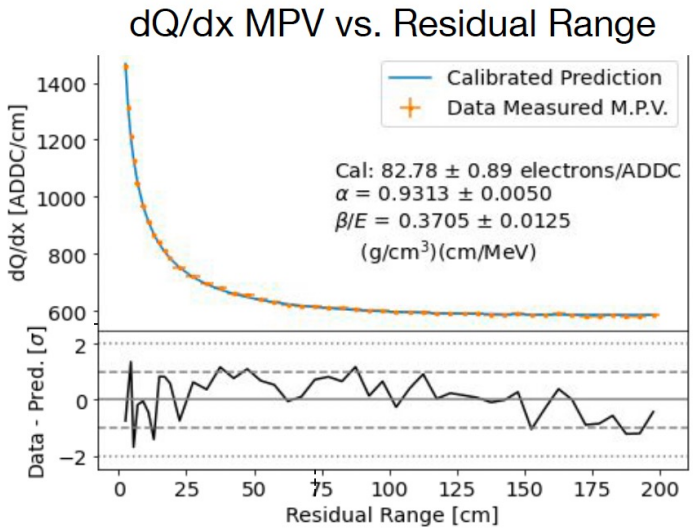


TPC wire signal gain calibration



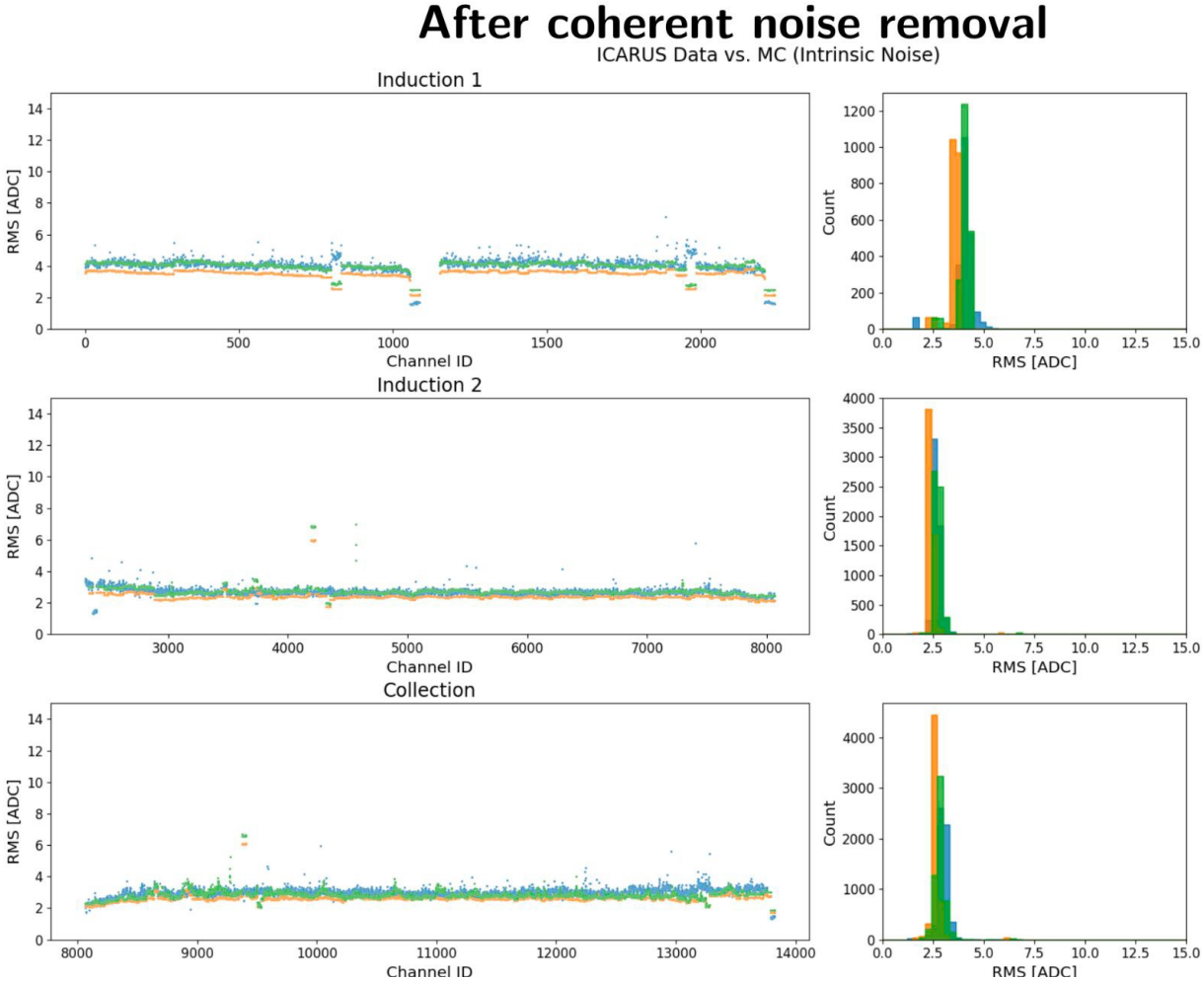
- Calibration chain based on the study of ionization vs residual range for cosmic μ crossing the cathode, stopping/decaying in the active LAr and identified by the reconstruction program.
- Goals: calibrate the absolute energy scale, equalize the individual wire electronic response, improve the modeling of recombination, diffusion and space charge effects, and measure detector properties like drift velocity and 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.





Improved data-driven TPC noise modeling

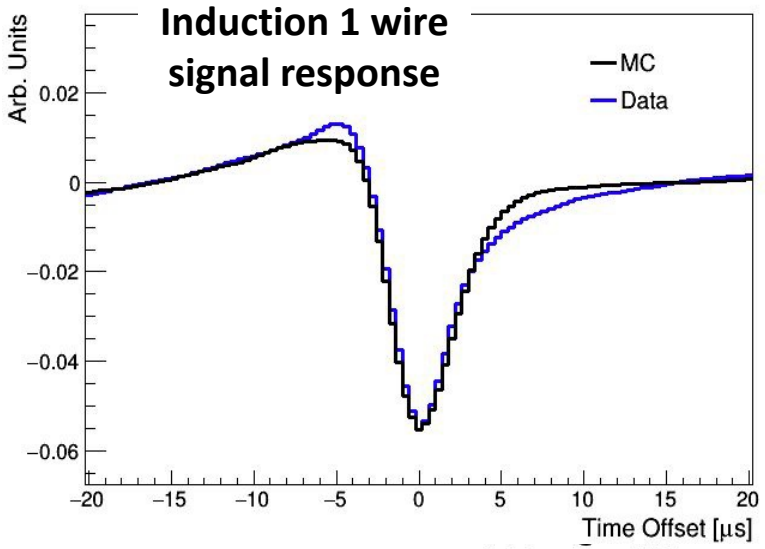
- Update to TPC noise model in simulation to better match data, applying scale factors scale factors plane by plane. Much better agreement.

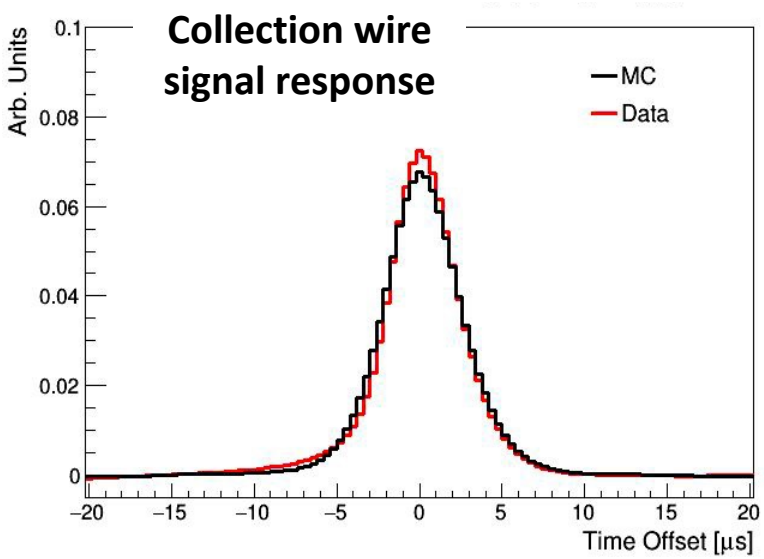


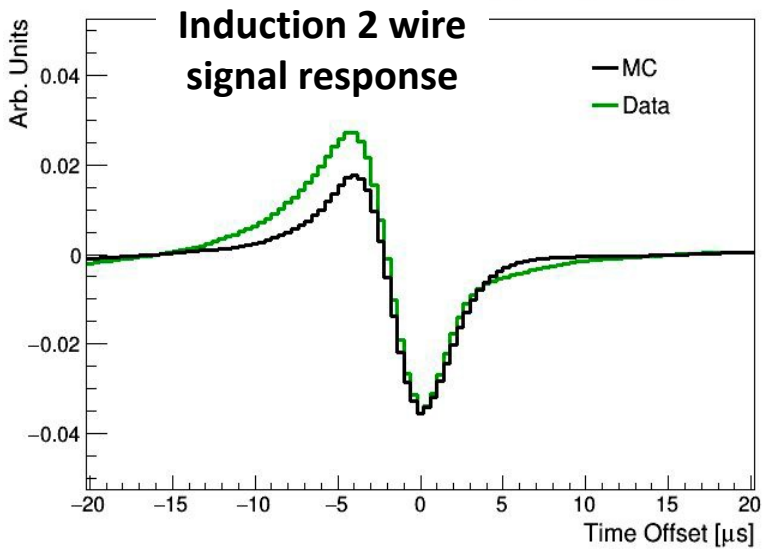
Plane	Scale Factor
Ind1	1.151
Ind2	1.152
Coll	1.096

First look at TPC wire signal response

- Average waveform at anode across many anode-cathode-crossing tracks: signal adds, noise cancels out
- Drift coordinates: [2 cm, 5 cm] away from anode (minimizes diffusion)
- Some data/MC discrepancy for induction plane response – will improve once we move to Wire-Cell (2D) signal simulation

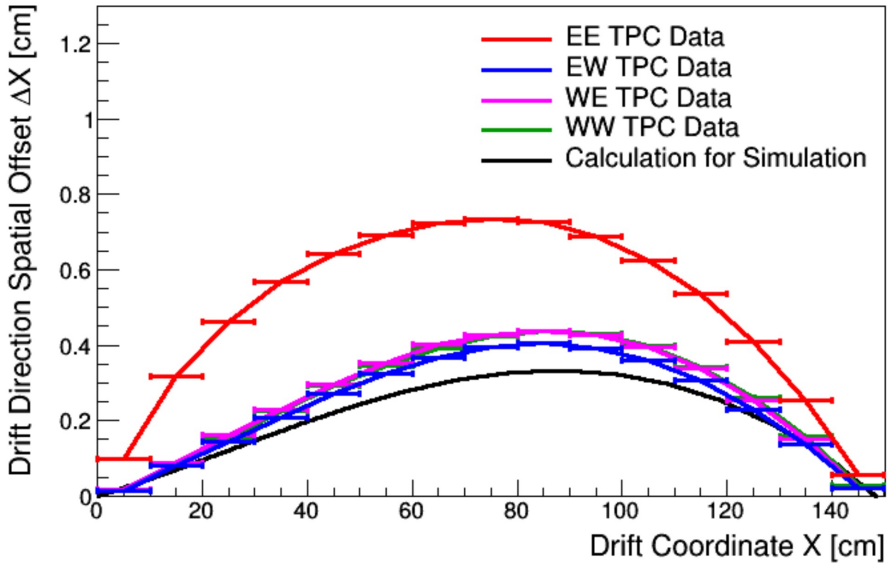




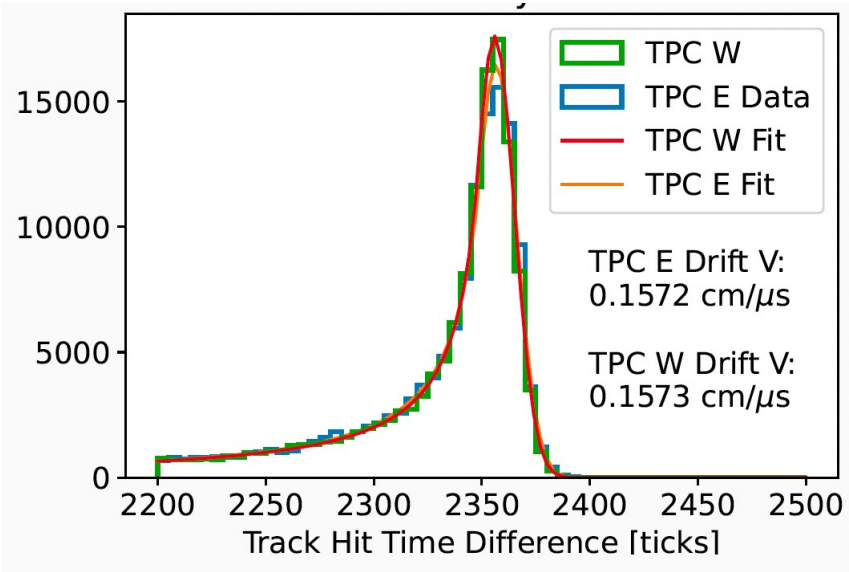


First look at TPC performance

Spatial distortions in drift direction due to space charge



Drift velocity in West cryostat



- Space charge effects (SCE) measured using anode-cathode-crossing cosmic muon tracks, looking at spatial distortions in drift direction. Good agreement with simulation, apart from one TPC where E field distortions associated with a possible field cage short are being investigated.
- Same track sample used to measure drift velocity by maximum drift time of charge associated with tracks - results in line with previous ICARUS measurements.

Summary

- The ICARUS detector has continued to operate with excellent stability since its activation in August 2020, taking data with BNB and NuMI beams part-time as installation/commissioning progressed.
- From the technical point of view, all sub-components are now in steady operational state and have for the most part met, if not exceeded, the expected performance.
- Installation and commissioning can be considered completed. Improvements will continue opportunistically, compatible with maximizing beam data collection.
- Two full time beam runs were performed for ~ 1 month in 2021 and 2022. Currently the ICARUS detector is collecting cosmic ray data during the summer shutdown of the Fermilab accelerator complex.
- The data collected so far with both cosmic rays and neutrinos from BNB and NuMI have been instrumental for calibrating the detector and tuning simulation and reconstructions tools.
- The ICARUS detector is well on its way for intriguing physics searches in the SBN Program and beyond!