



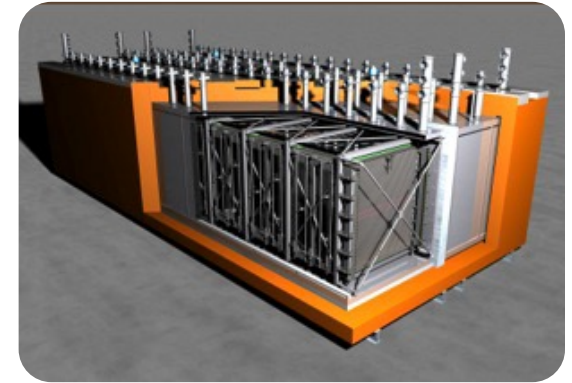
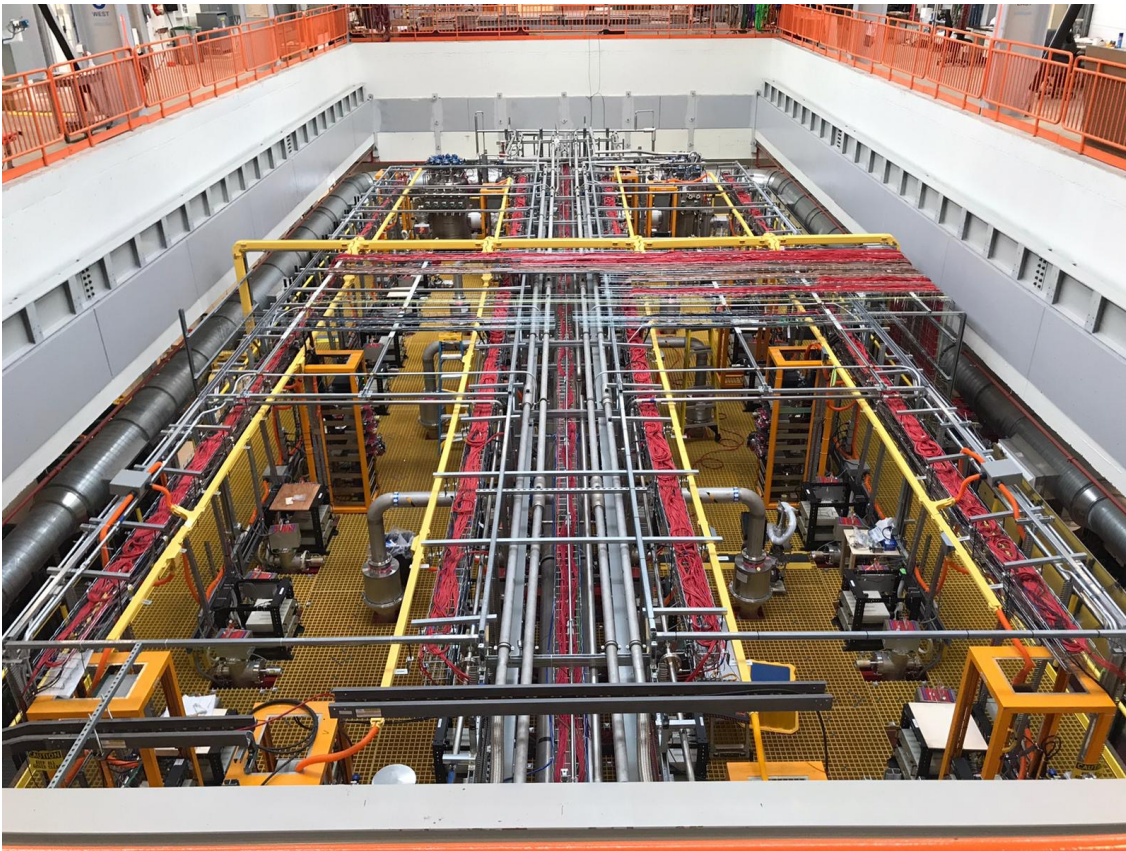
Activation and commissioning of the Icarus detector

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FERMILAB 2021 SUMMER STUDENT MEETING

The ICARUS detector

- 760 t of LAr, 476 t active.
- 4 TPCs with 1.5 m drift, 360 8" PMTs.
- Almost full coverage of Cosmic Ray Tagger (CRT)



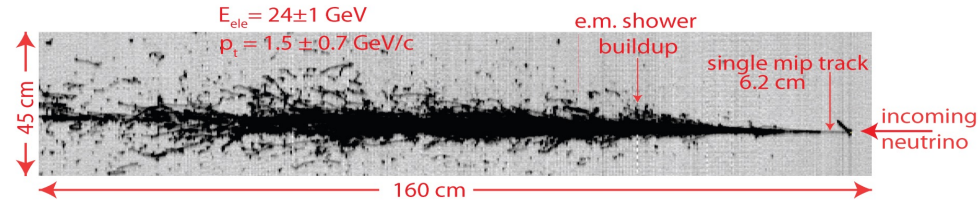
Currently installed at Fermilab 600 m from the target of the Booster Neutrino Beamline (BNB), as Far Detector in the Short Baseline Neutrino (SBN) Program

IcarusTrip



From LNGS through CERN to FNAL

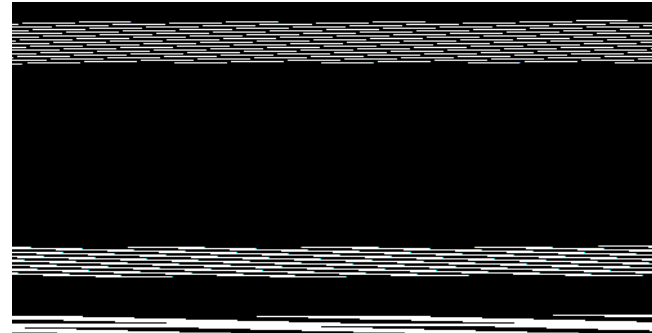
- Operated underground in Italy in 2010 ÷ 2012 with CNGS ν beam.



- 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.



The long path from activation to operation

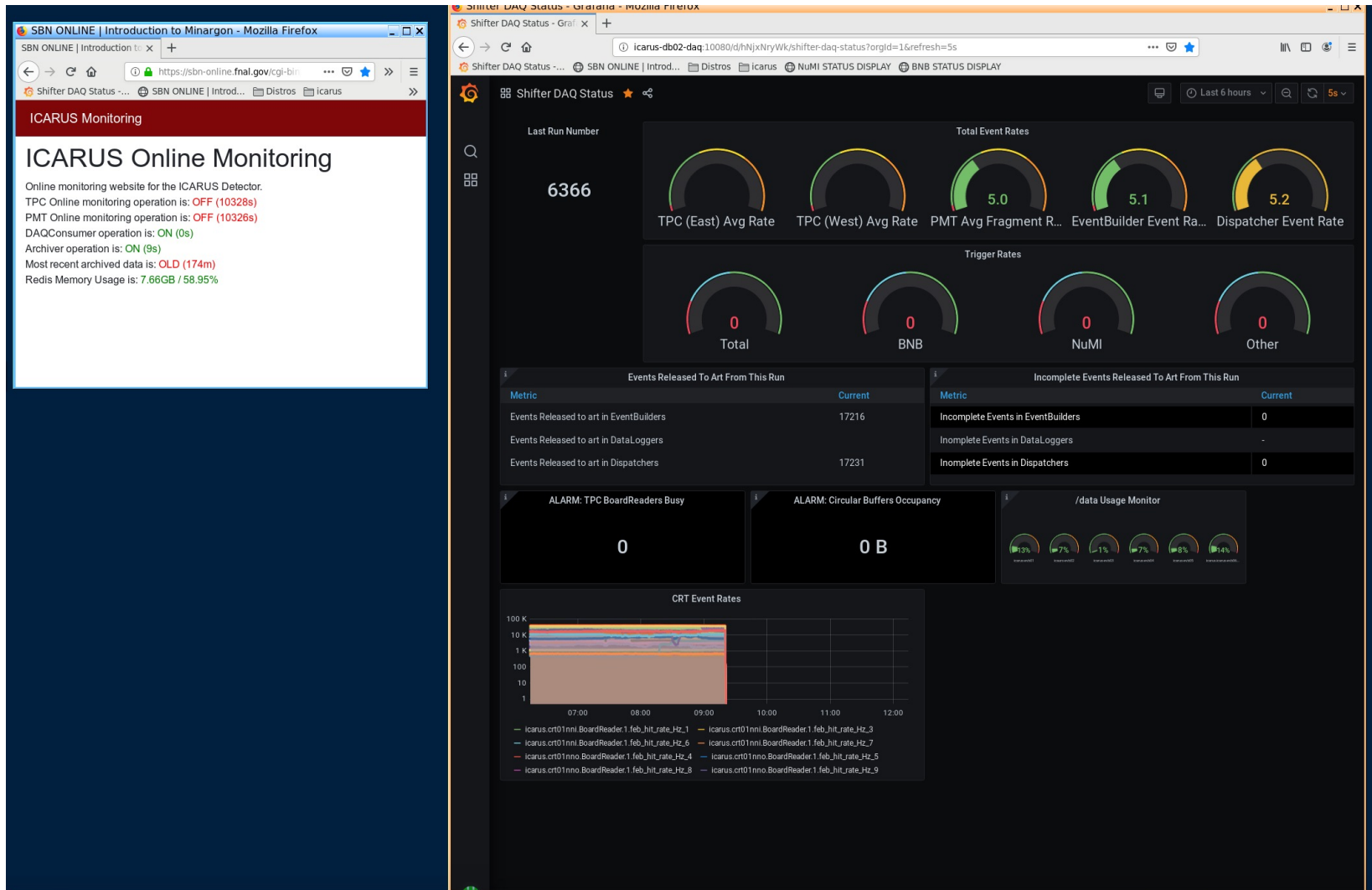
- After completion of installation, cryogenic commissioning started on Feb 13th, 2020 by breaking the vacuum in the two main cold vessels followed by cool-down (2 weeks). Filling with LAr from Feb 24th to Apr 19th. Cryogenic stabilization completed by the end of May 2020.
- Procedures paused for ~ 2 months to allow for reorganization of activities taking accounting for restrictions to travel and access onsite due to Covid-19 pandemic.
- Detector activation initiated at the beginning of August 2020 and completed on Aug 27th. First data taking with cosmic rays!
- Commissioning of all detector components (TPC, PMT, DAQ, slow controls, trigger) led to detection of first neutrino interaction candidates from BNB in early March 2021 and from NuMI beam in April.
- May 30th – June 27th 2021: full-time beam run to verify readiness for operations.
- Commissioning activities presently continuing to improve detector performance in preparation for restart of the FNAL accelerator complex in mid September.
- 24/7 shifts since February 14th, remote-only since March 17th.

A shifter's life I

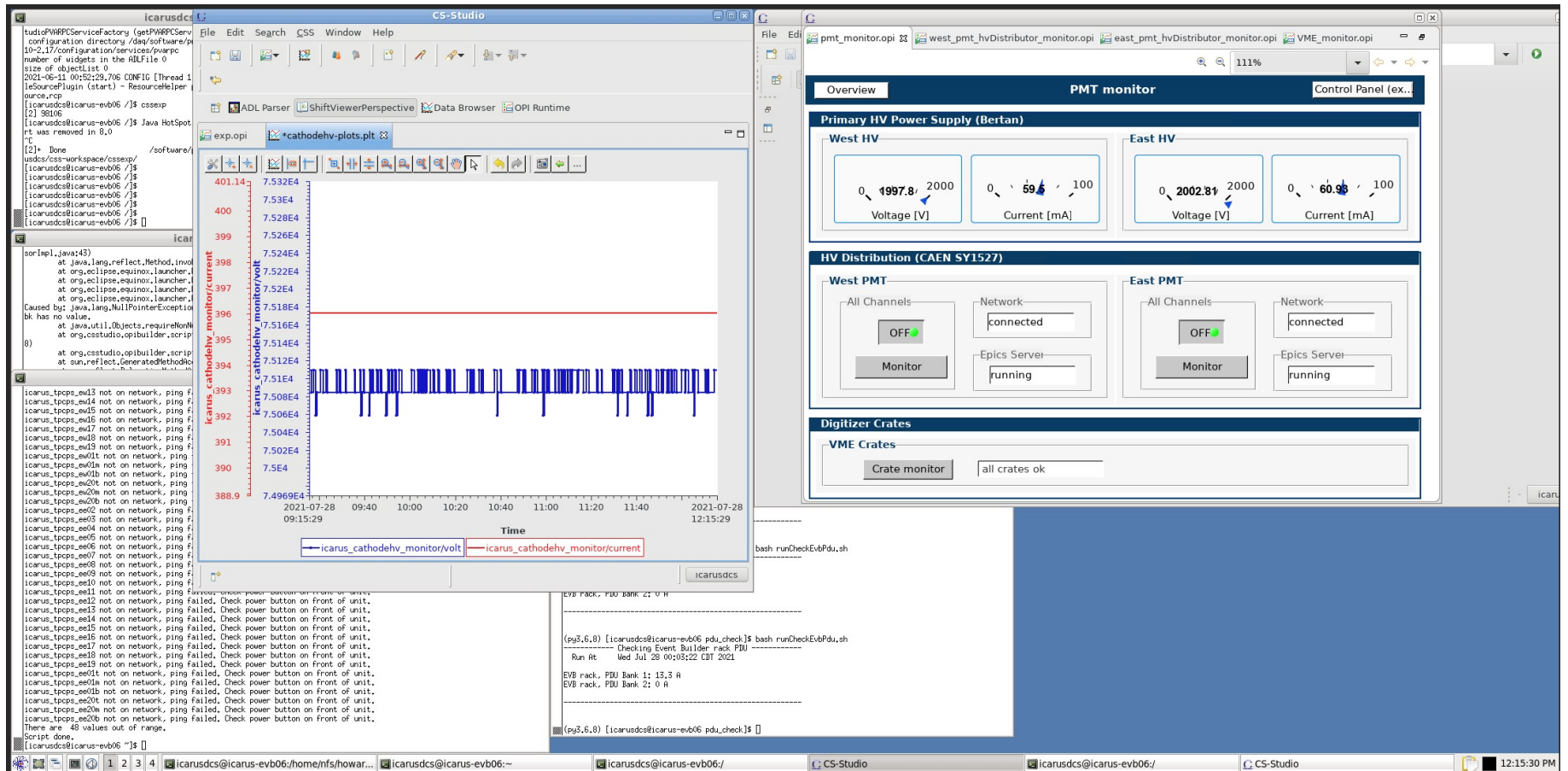
The collage displays a typical Linux desktop environment used for monitoring and controlling the ICARUS experiment. The windows shown are:

- File Manager:** Shows the desktop with various folders and files, including 'sbndaq-v0_07' and 'sbndaq-v0_08'.
- Experts_on_call.docx:** A document listing contact information for the ICARUS Working Groups, categorized by PMT Experts, CRT Experts, DCS - Slow Controls Experts, Drift HV experts, and SBN DAQ Experts.
- Message Facility MsgViewer:** A window showing detailed statistics for the ARTDAQ Message Viewer, including message counts, rates, and buffer wait times.
- ARTDAQ RUN CONTROL:** A window for managing the DAQInterface, showing a list of components and their configurations.
- DAQInterface State Diagram:** A state machine diagram showing the sequence of states: BOOTING, BOOTED, CONFIGURING, READY, STOPPED, and RUNNING.

A shifter's life II

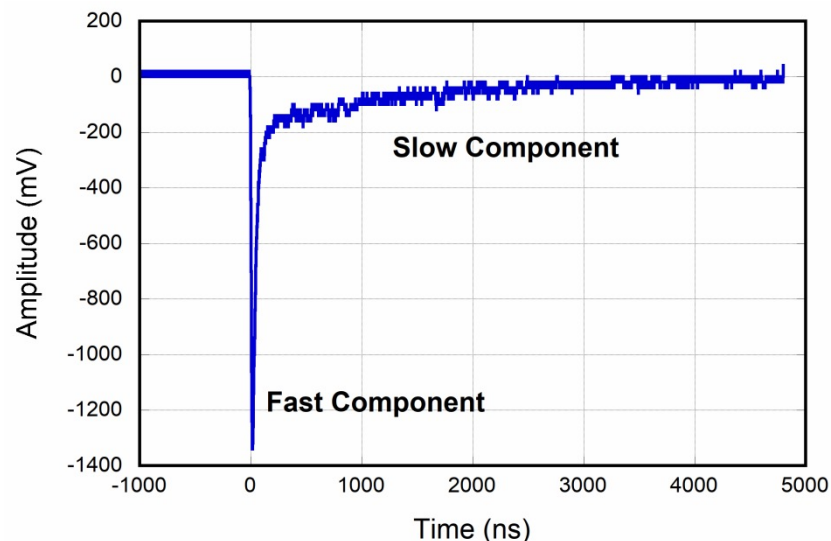


A shifter's life III



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.

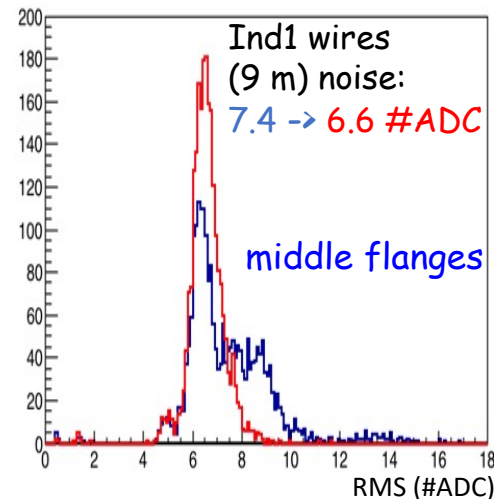
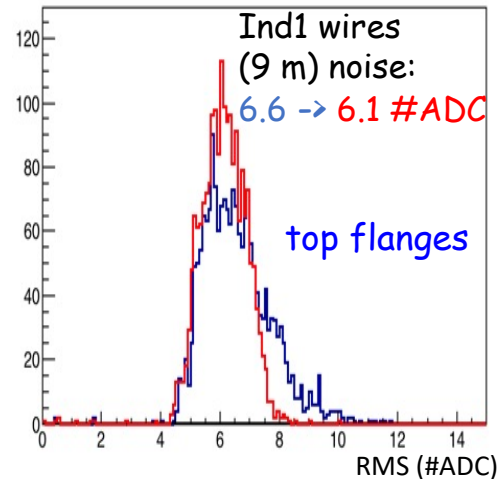
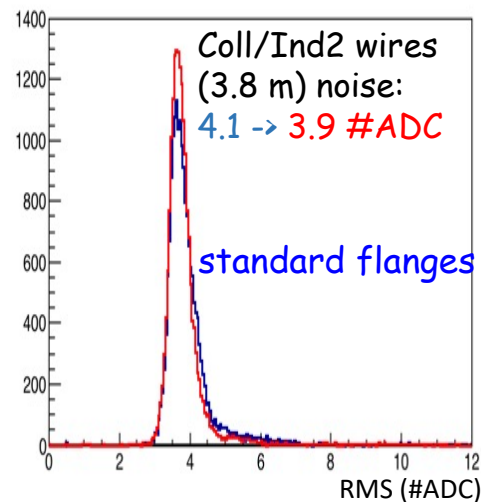


- Two steps activation of the TPC:

- 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).

TPC electronic noise mitigation

- Increase of TPC electronic noise by $\sim 30\%$ after LAr filling, well above expectations from dielectric effect. However not preventing neutrino events collection.
- Intervention in Dec '20 allowed to mitigate in the West cryostat a 120 kHz noise detected in several boards, disentangling contributions of front-end electronics from external ancillary devices and restoring some ground connections.

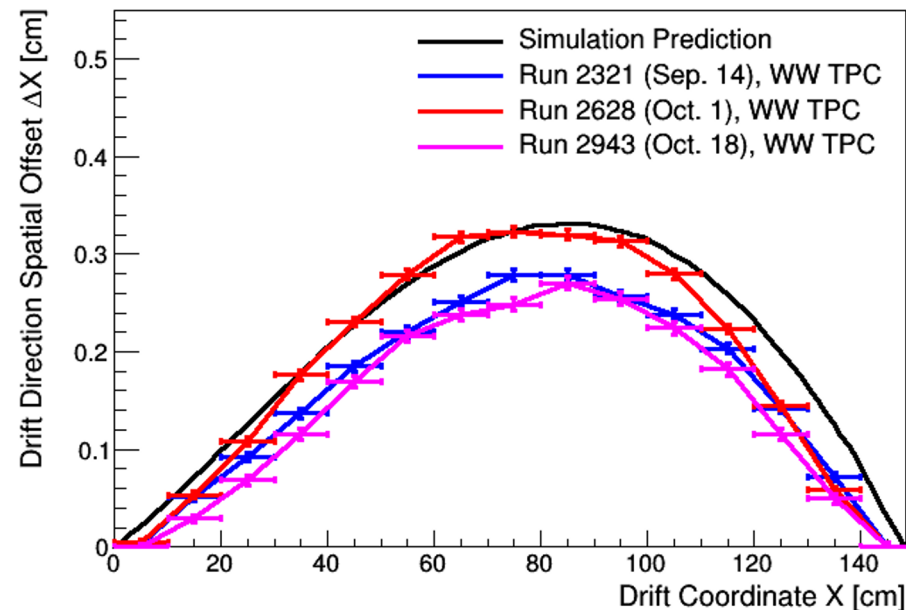


Before intervention
After intervention

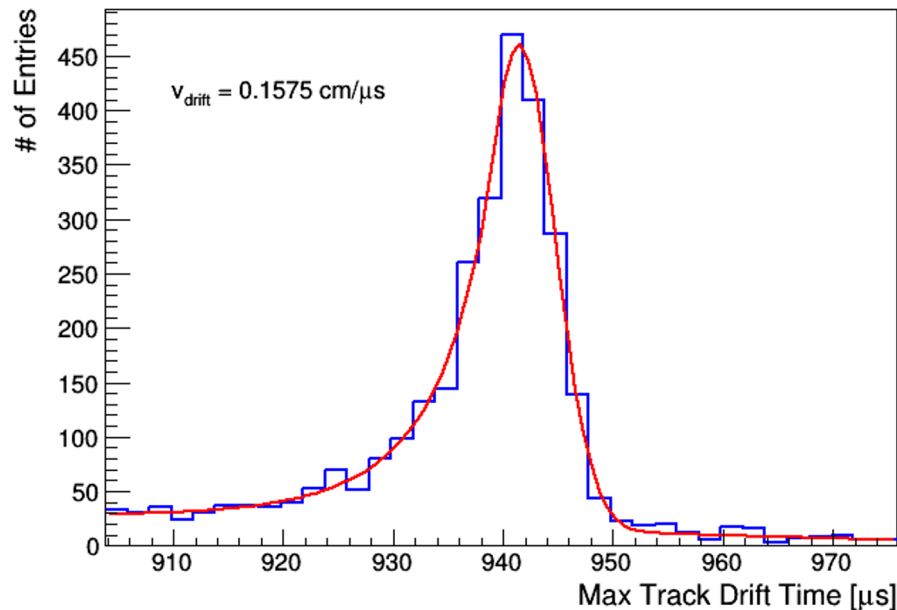
- Several potential external noise sources (TT-Link trigger/clock, cathode HV, wire bias and test-pulse distribution systems) excluded through investigations in situ. Deep investigation of coherent noise on all signal flanges needed but extremely difficult within the pandemic; test-bench in Padova studying the issue.

Early assessment of TPC performance

ICARUS SCE Comparison: ΔX vs. X



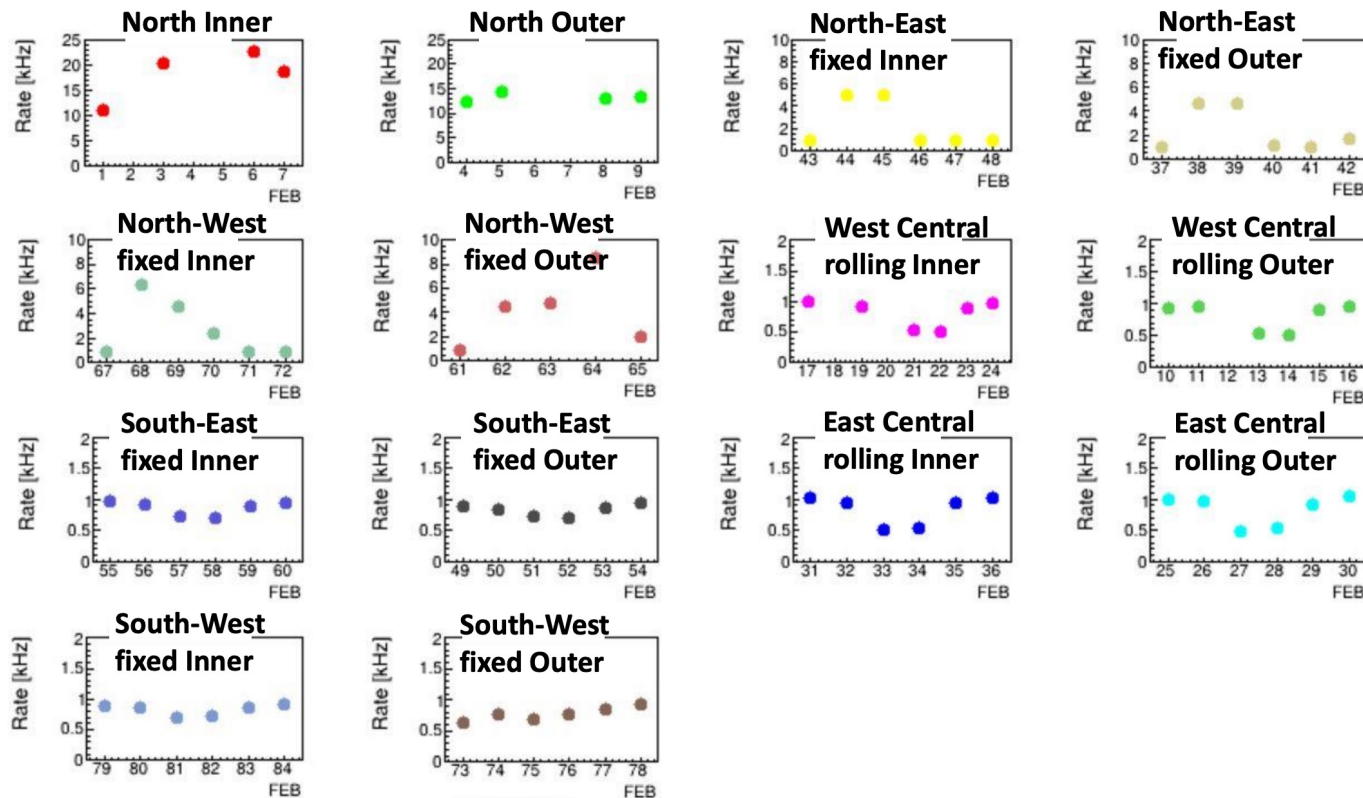
Run 2628, WW TPC: Max Track Drift Time



- Space charge effects (SCE) measured using anode-cathode-crossing cosmic muon tracks, looking at spatial distortions in drift direction.
- Same track sample used to measure drift velocity by maximum drift time of charge associated with tracks.

Early CRT commissioning

- 7 side CRT wall sections (5 installed even during the pandemic) integrated in the readout.
 - Implemented into standard DAQ for shifter-piloted runs.



High rates in some CRT components (generally near the cryogenic equipment). Investigations ongoing.

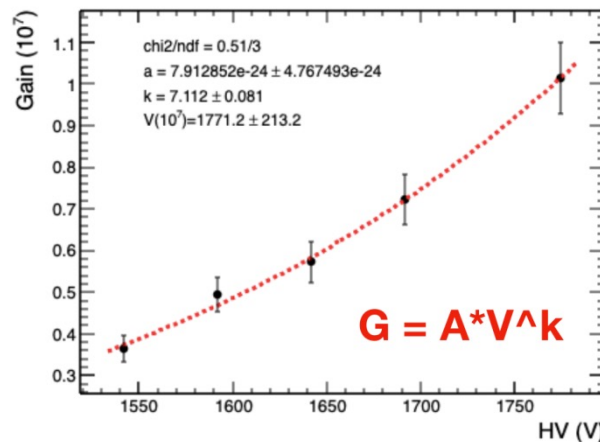
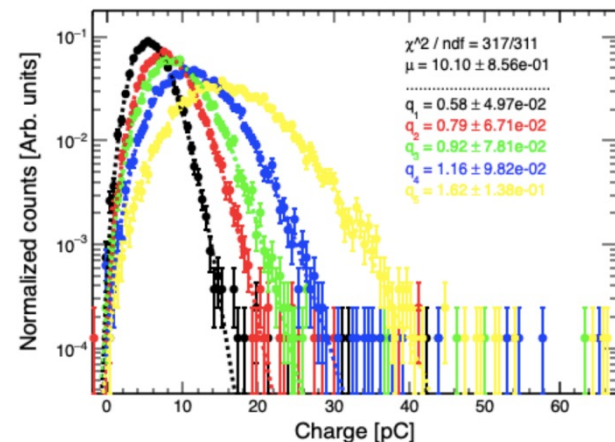
PMT calibration

- Calibration with laser system performed to find the nominal voltage for each PMT for getting a 10^7 gain in cryogenic environment.
- Signals recorded for 5 different voltages under the same illumination condition and data fitted with an analytical function to measure the released charge q .

$$S_i(x) = a_0 E_N(x, q_0, \sigma_0, \tau_0) + a_i \sum_{n=1}^{100} \frac{1}{\sqrt{2\pi n \sigma_i}} \frac{\mu^n e^{-\mu}}{n!} \exp\left(\frac{-(x - q_i n)^2}{2n \sigma_i^2}\right)$$

q_i : mean amplified charge at each dynode (depends on voltage)

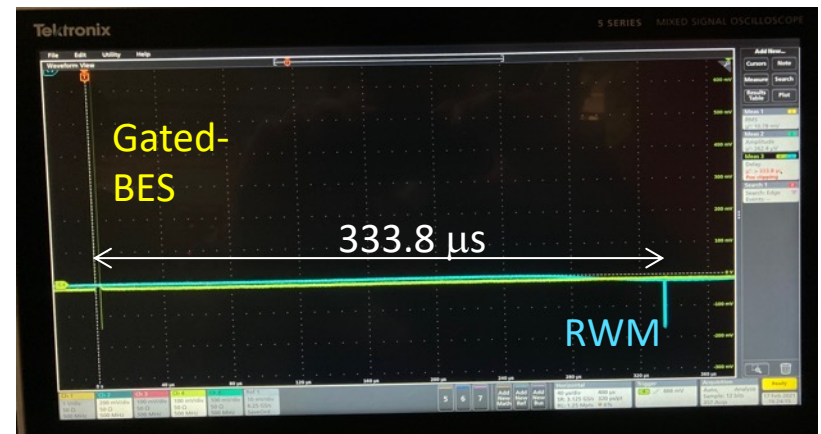
μ : Mean number of PE at Photocathode (Identical on same PMT)



- Results fitted with power law to get PMT gain vs. voltage curve.
- Nominal voltage at cryogenic temperature evaluated and set.

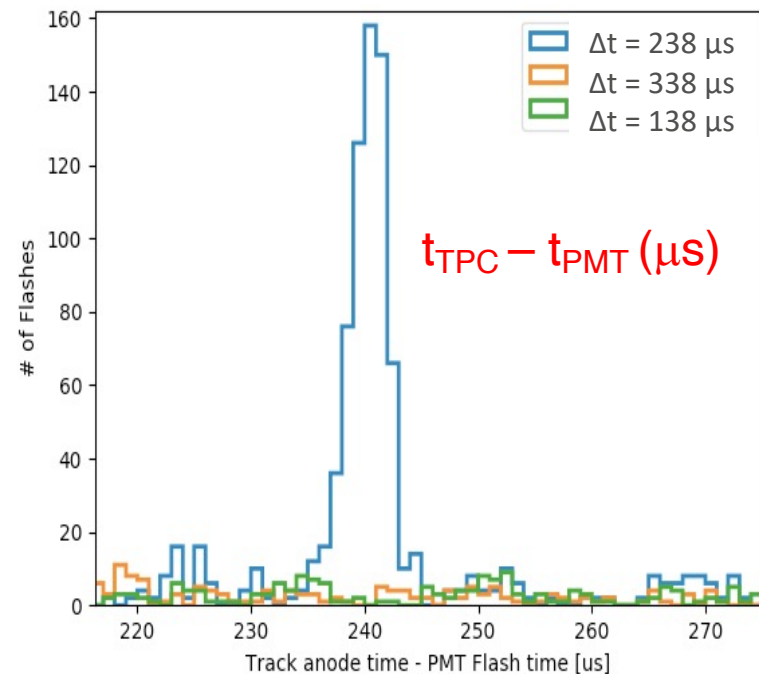
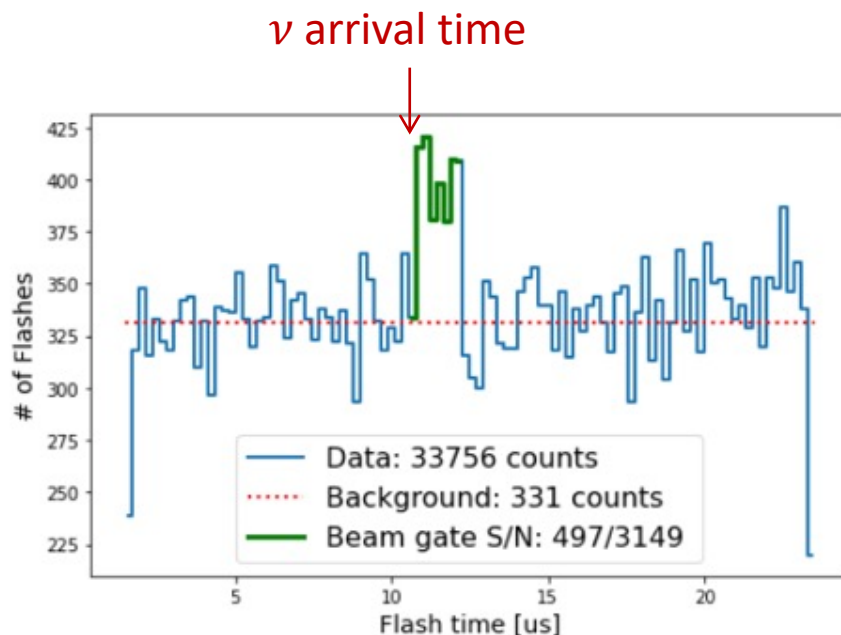
Initial activation of the trigger system

- Setup of an initial simplified trigger system aimed at verifying the correctness of the trigger chain and its functioning, as well as exercising the synchronization of the DAQ components.
In parallel with development/commissioning of full trigger.
- Two steps:
 - 1) “spill-only”, based on the BNB extraction signal (gated-BES) distributed via White Rabbit network (guaranteeing synchronization of nodes to better than 1 ns), to read-out both TPC and PMTs signals in the East cryostat;
 - 2) addition of scintillation light info by requesting ~ 10 PMT pairs in either PMT wall in the EAST cryostat inside a $1.6 \mu\text{s}$ BNB gate.
- Offset added to the gated-BES for the PMT trigger generation $\sim 335 \mu\text{s}$: time difference between gated-BES and neutrino extraction (RWM) signals + ν time of flight from MI-12 (beam target hall) to ICARUS.

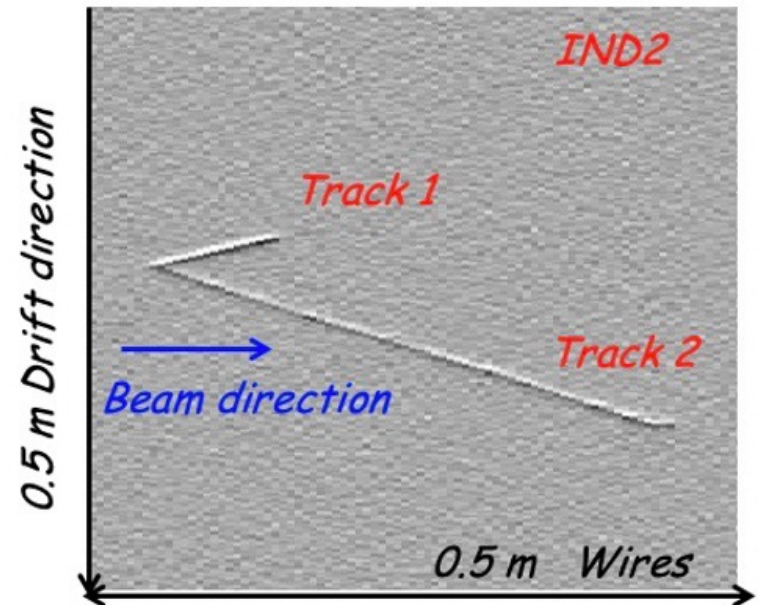
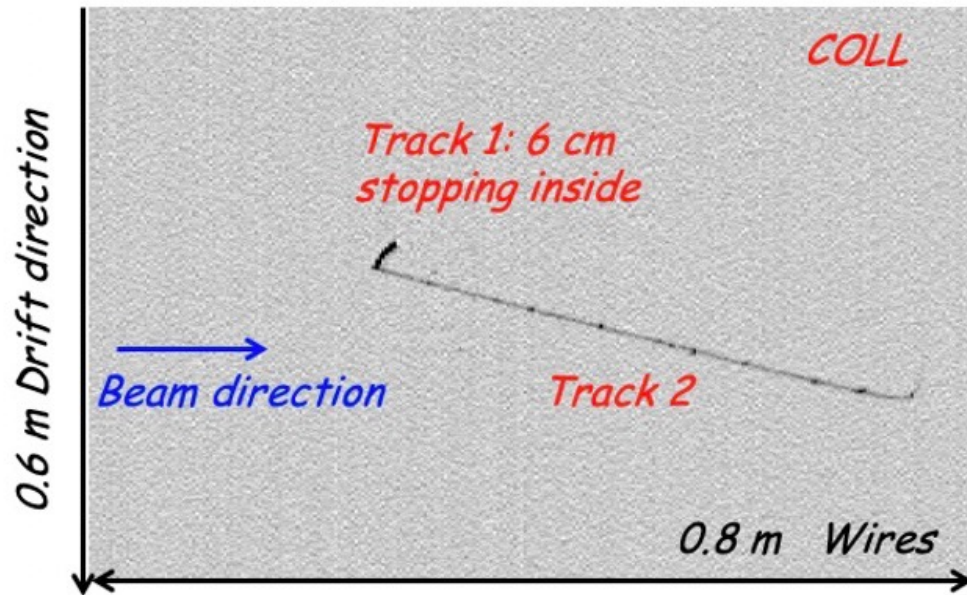


Measurements with “spill-only” trigger

- Time of PMT light flashes (>5 fired PMTs within 150 ns window in coincidence in both left and right TPCs) in PMT readout window shows excess over the cosmic background rate at the expected ν arrival time.
- Anode-to-cathode cosmic μ tracks with unambiguously measured crossing time in the TPC image t_{TPC} found to match the corresponding time of PMT light signal t_{PMT} . Clear $\sim 2 \mu\text{s}$ peak in $t_{\text{TPC}} - t_{\text{PMT}}$ confirming the correct relative TPC - PMT timing.



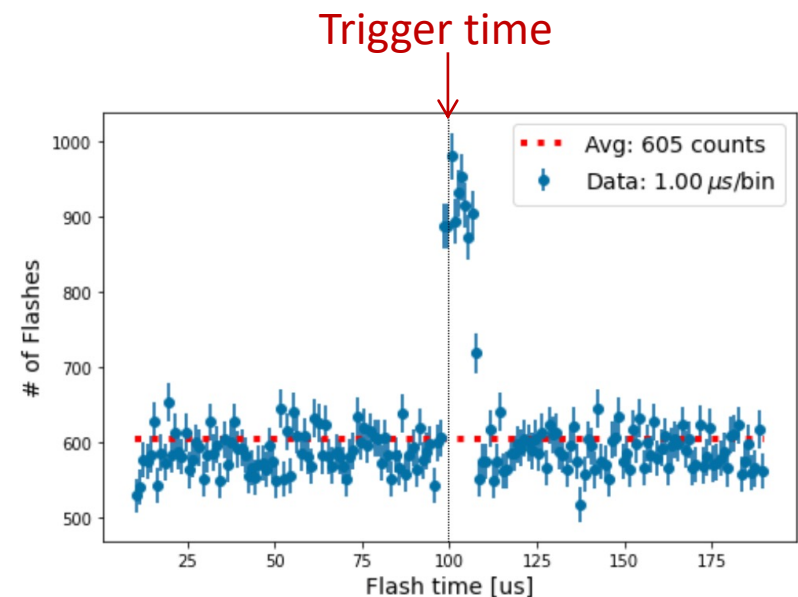
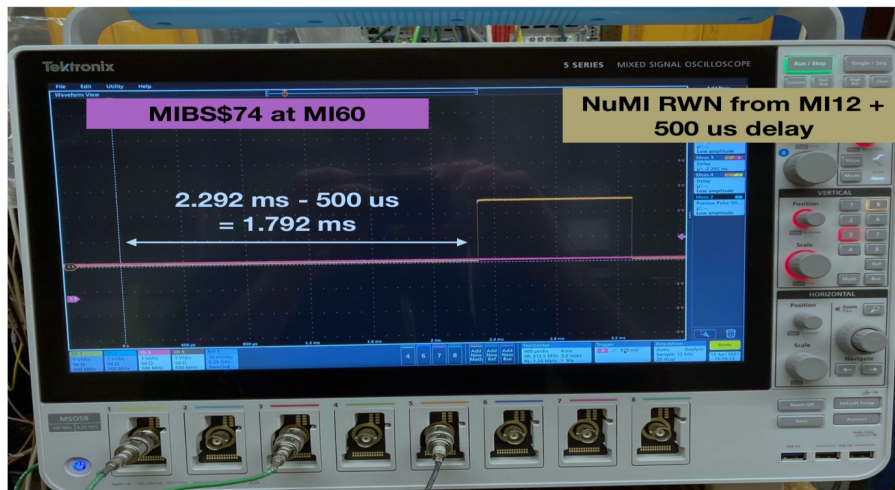
Example of BNB ν_μ CC candidate



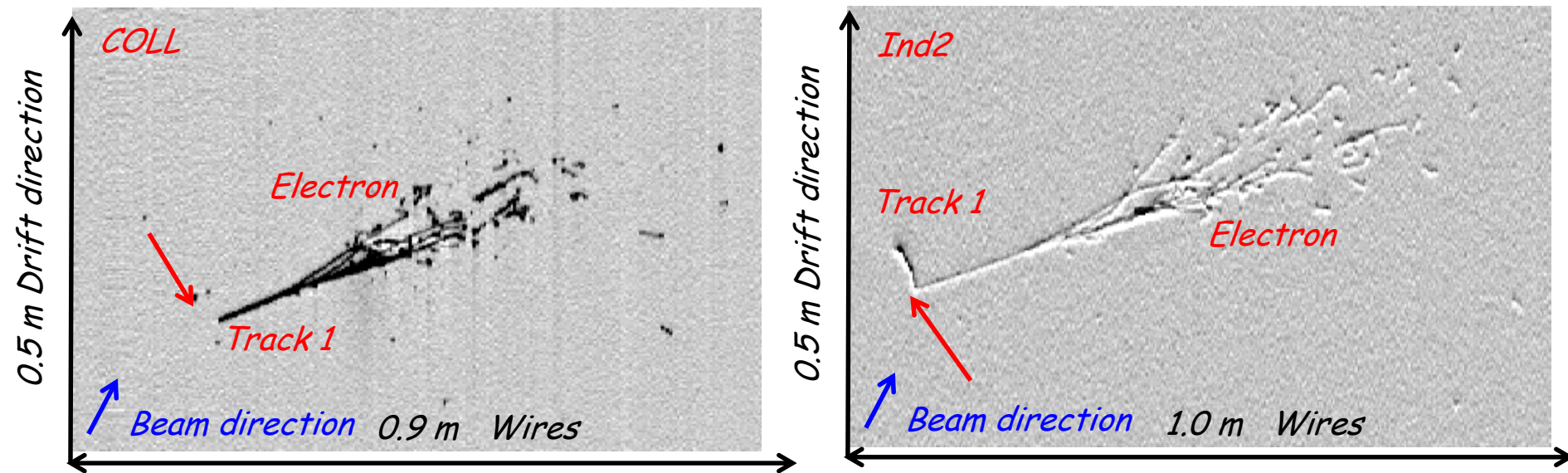
- QE ν_μ CC candidate (run #4626, ev #227) in COLL and IND2 views.
- Vertex at 29 cm from the bottom wall. Two tracks produced, $E_{\text{DEP}} \sim 170$ MeV
 - Track 1 is the proton candidate with $E_K \sim 70$ MeV, stopping after $L = 6$ cm
 - Track 2 is likely the μ exiting on bottom wall after $L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

Activation of the NuMI beam trigger

- Similar procedure adopted for NuMI:
 - 1) time interval between Early warning signal (MIBS\$74) and proton extraction signal (RWM counters at target) measured at oscilloscope;
 - 2) excess of PMT light flashes (>5 fired PMTs within 200 ns window in coincidence in both left and right TPCs) over the cosmic background rate at the expected time verified in dedicated test run recording only PMT components;
 - 3) setup of minimum-bias NuMI trigger to record all components (PMT, TPC and CRT) at each beam extraction.



Example of NuMI ν_e CC candidate

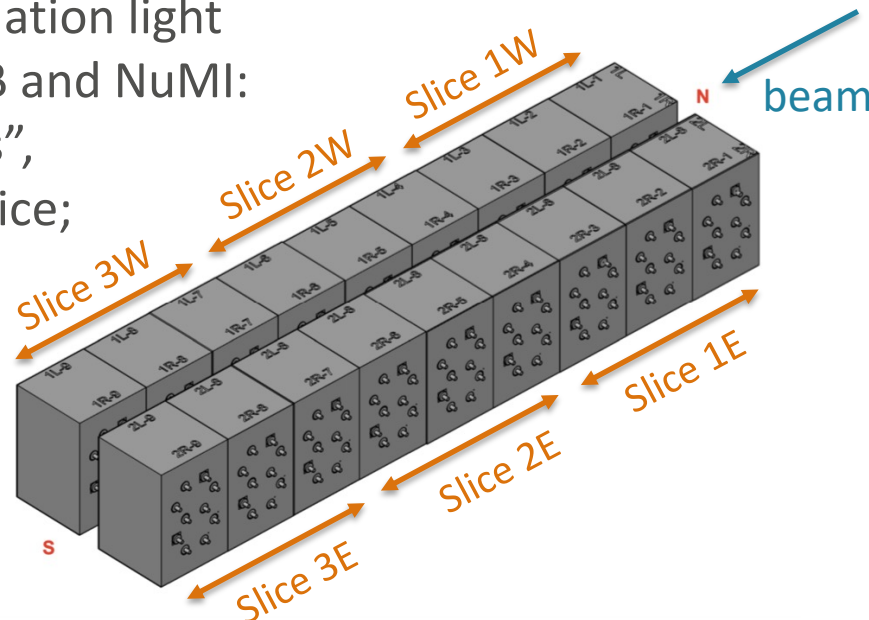


- QE electron neutrino candidate with two particles at the primary vertex (indicated by red arrows):
 - Track 1 is the upward going proton candidate stopping inside $L = 13$ cm
 - The electron shower is downward going: the beginning of the shower is clearly visible in particular in Induction 2 view (in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

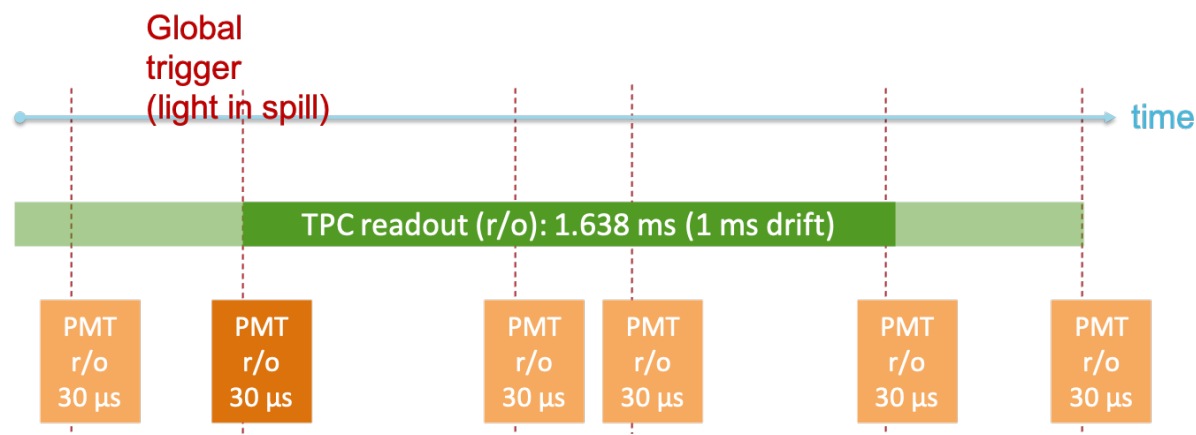
First beam trigger based on scintillation light

- Activation of beam trigger requesting scintillation light in coincidence with beam gate, for both BNB and NuMI:

- PMTs in each cryostat grouped in 3 "slices", 6m size along beam direction, 60 PMTs/slice;
- request of signal $\gtrsim 10$ phe in at least 10 pairs of adjacent PMTs in at least one slice.

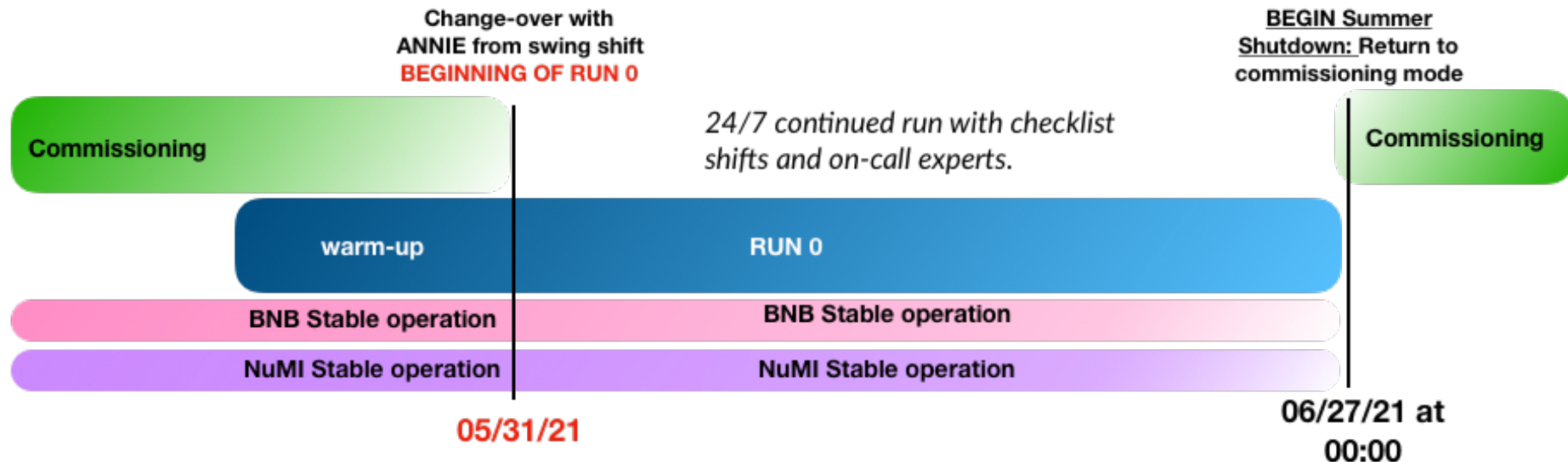


- PMT waveforms readout at any scintillation light activity in 2 ms around the beam gates. Allows recording of information on cosmics during TPC drift time for offline matching of light and charge.

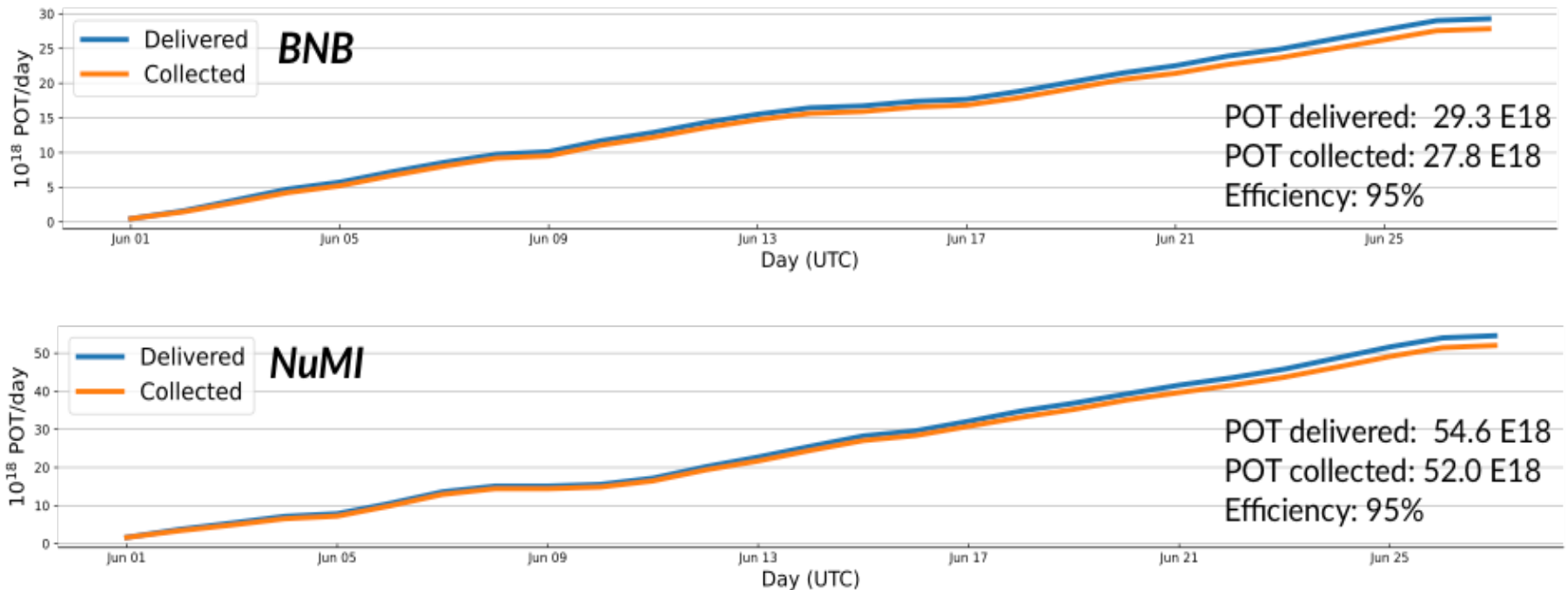


First ICARUS data run

- Goals of the ICARUS RUN-0:
 - Certify the readiness of the detector for physics quality data with TPC and PMT and operate as primary BNB user in stable mode and with minimal downtimes
 - Accrue a good quality data samples to tune the reconstruction of neutrino and cosmic candidates, perform dedicated detector and trigger efficiency studies, improve the calibration, and tune the simulation.
- 1 month of stable operation for both NuMI and BNB.



Beam detection efficiency

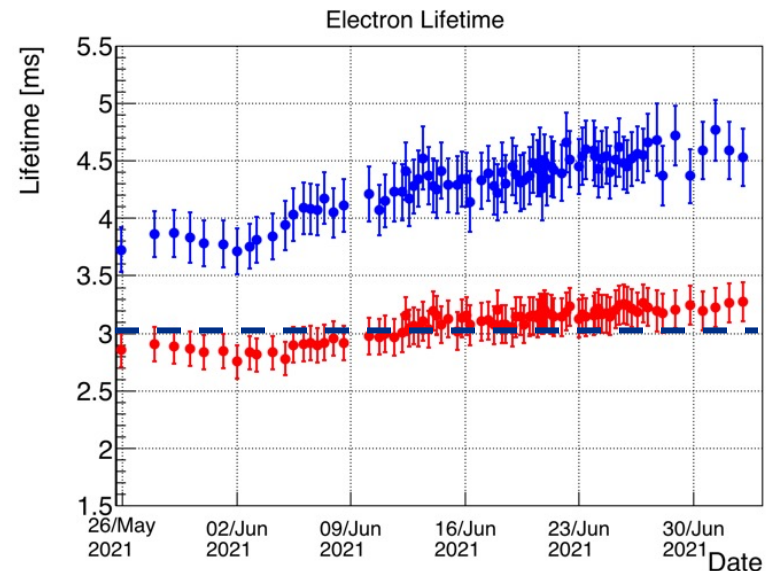
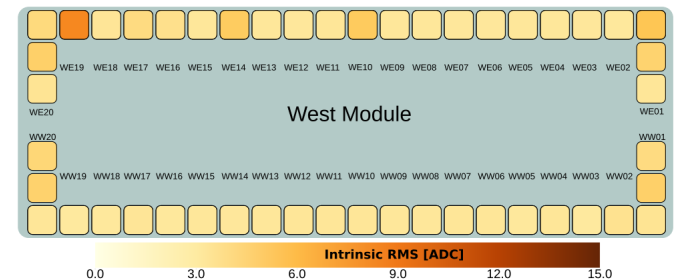
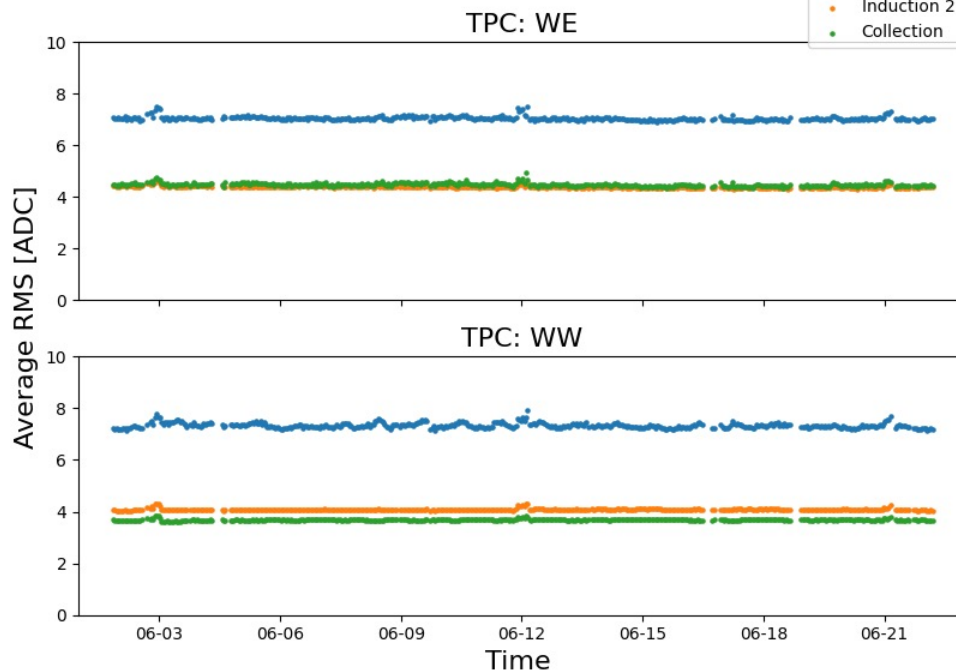


- Efficiency of beam detection, measured as ratio between collected and delivered pot (proton on target) in excess of 95% for both beams.
- All episodes of unplanned interruption of data taking investigated and lessons learned informing improvement of the operation procedures.

Monitoring of detector status and data quality

- TPC noise stable for the entire duration of the detector data run.
- Electron lifetime above the reference values for both cryostats and compatible with the 3D reconstruction of charge signal.

Noise in West Cryostat for Run 0



Commissioning activities during the summer

- **Detector upgrades:**
 - Installation and activation of the TOP CRT
 - Upgrades of the PMT HV systems, installation of the Adders (modules that produce the analogue sum of PMT waveforms , and full recalibration of the system
 - Further mitigation of TPC noise sources external to the cryostats
 - DAQ upgrades to improve multi-PMT acquisition and integration with trigger
 - Improvements of the trigger system, including better synchronization of timing of the detector sub-components and fixing of bugs observed during RUN0
- **Shifts:** the experience was overall good during RUN0, but some critical points emerged
 - Simplify the shifter's experience and improve the documentation
 - Discussion to add shadow shifts, backup shifters, and recognition of experts contribution is in progress
- **Reconstruction and analysis:**
 - the quality of the data collected is sufficient to work on calibration studies and the tuning of the reconstruction targeting a simple ν_μ CC selection
 - Trigger efficiency studies will also continue during the summer in support of the improvements planned