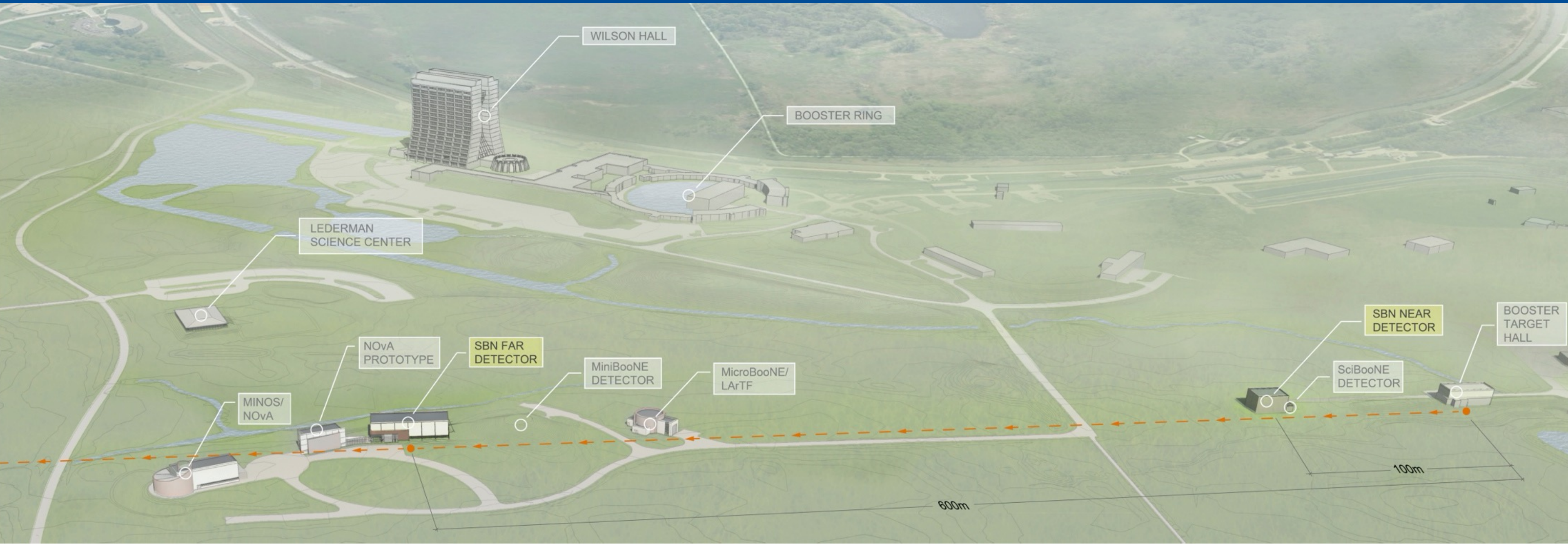
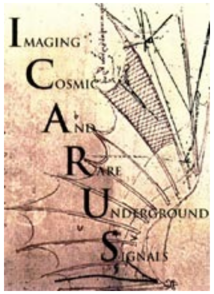


ICARUS detector
From activation to first data

A. Fava

Neutrino Seminar Series

Fermilab 05/19/22

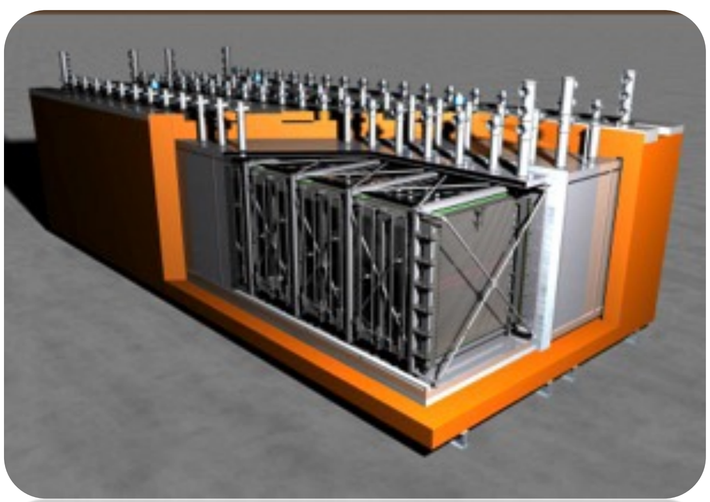


Outline

- Introduction
- Physics reach of ICARUS
- Technical status of the detector and its subcomponents
- Report of beam data taking
- Initial calibration studies
- Tuning of reconstruction

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



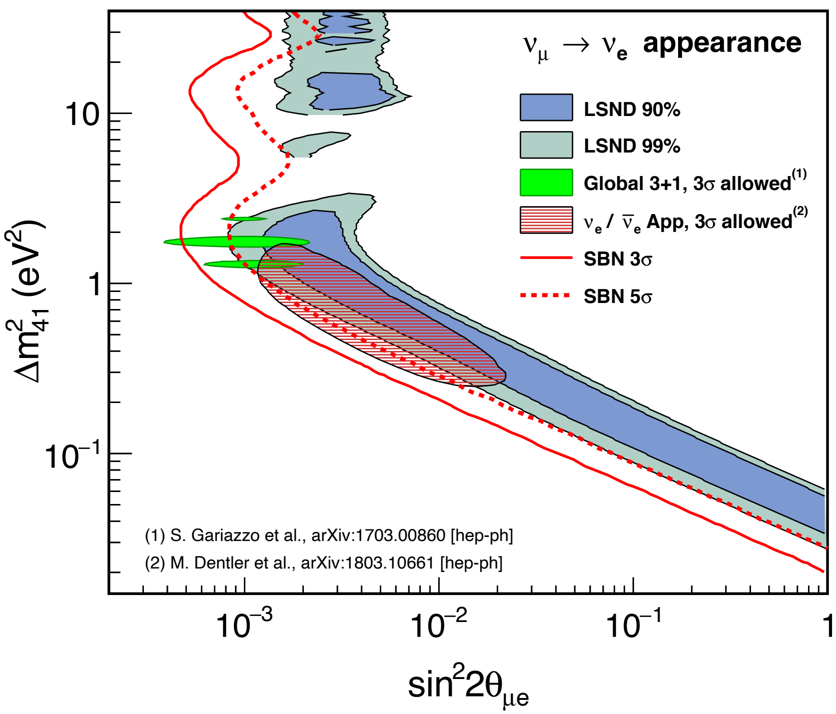
LAr-TPC detector:

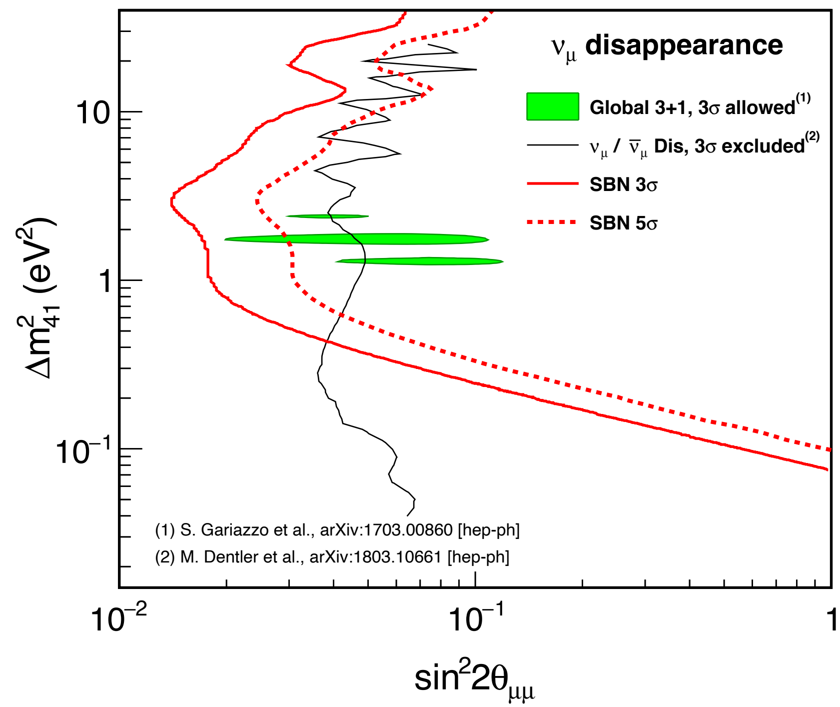
- 760 t of LAr, 476 t active mass, in two identical cryostats sitting side-by-side.
- 4 TPCs with 1.5 m drift and 3 wire planes.
- 360 8” PMTs coated with TPB.
- almost full Cosmic Ray Tagger (CRT) coverage.

Physics reach of ICARUS

SBN Program: sterile neutrino sensitivity

Annual Rev. Nucl. Part. Sci. 2019.69:363-387





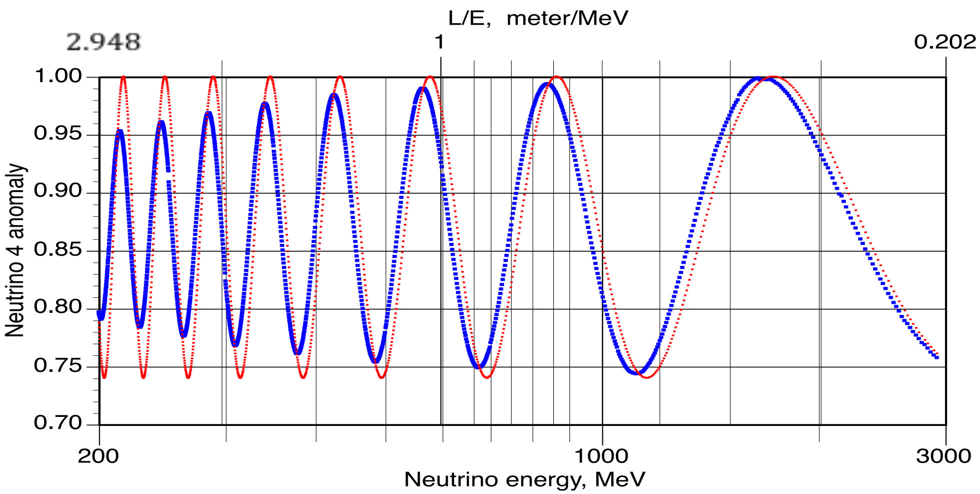
5σ coverage of the parameter area relevant to the LSND/MiniBooNE anomaly in 3 years (6.6 x 10^{20} pot).

1 order of magnitude beyond SciBooNE + MiniBooNE limits in 3 years (6.6 x 10^{20} pot). Probing the parameter area relevant to reactor and gallium anomalies.

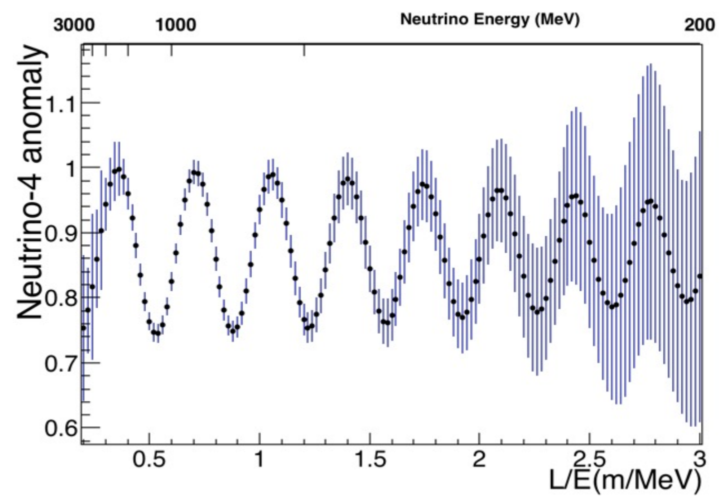
Unique capability to study appearance and disappearance channels simultaneously

Search for Neutrino-4 oscillation signal

- The Neutrino-4 collaboration claimed a reactor neutrino disappearance signal with a clear modulation with L/E ~ 1-3 m/MeV.
- ICARUS can confirm or refute the Neutrino-4 oscillation signal
  - disappearance of ν_μ from BNB, focusing on quasi-elastic contained ν_μCC interactions where the muon is at least 50 cm long (~11500 events in 3 months)
  - disappearance of the ν_e component in the NuMI beam, selecting quasi-elastic ν_eCC events with contained EM showers (~5200 events per year)



Expected Neutrino-4 disappearance signal for L averaged position (blue) and at center (red)

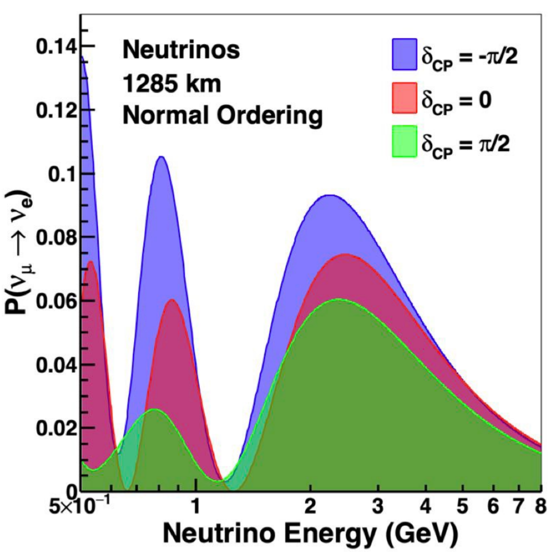


Survival oscillation probability in 3 years for Neutrino-4 best fit (only stats)

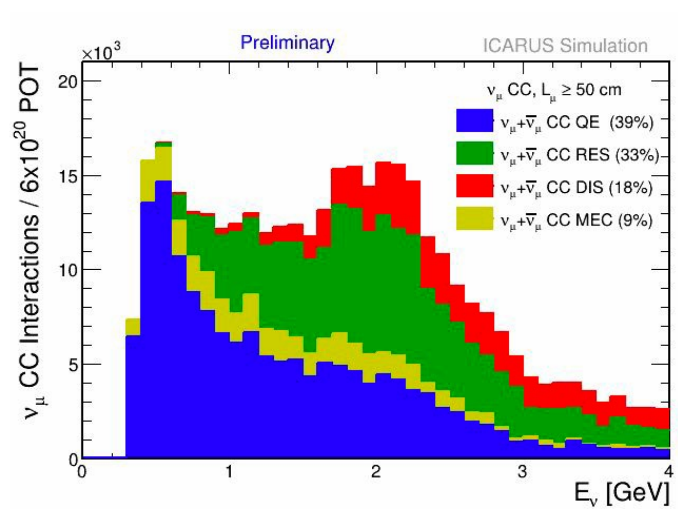
Physics searches with NuMI

- High statistics precision measurements of neutrino argon cross sections and tests of interaction models in the few hundred MeV to few GeV range, of use to SBN oscillation studies and DUNE
  - ~ 10^5 electron neutrino events/year
- Rich BSM searches: Higgs portal scalar, neutrino tridents, light dark matter, heavy neutral leptons, millicharged particles…

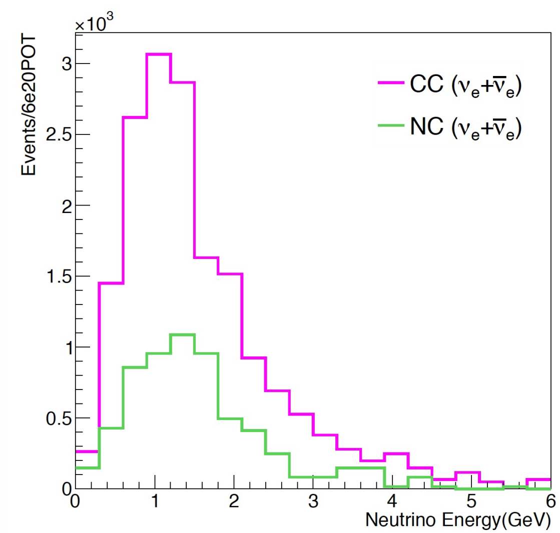
Oscillation probability at DUNE



ν_μ from NuMI at ICARUS



ν_e from NuMI at ICARUS



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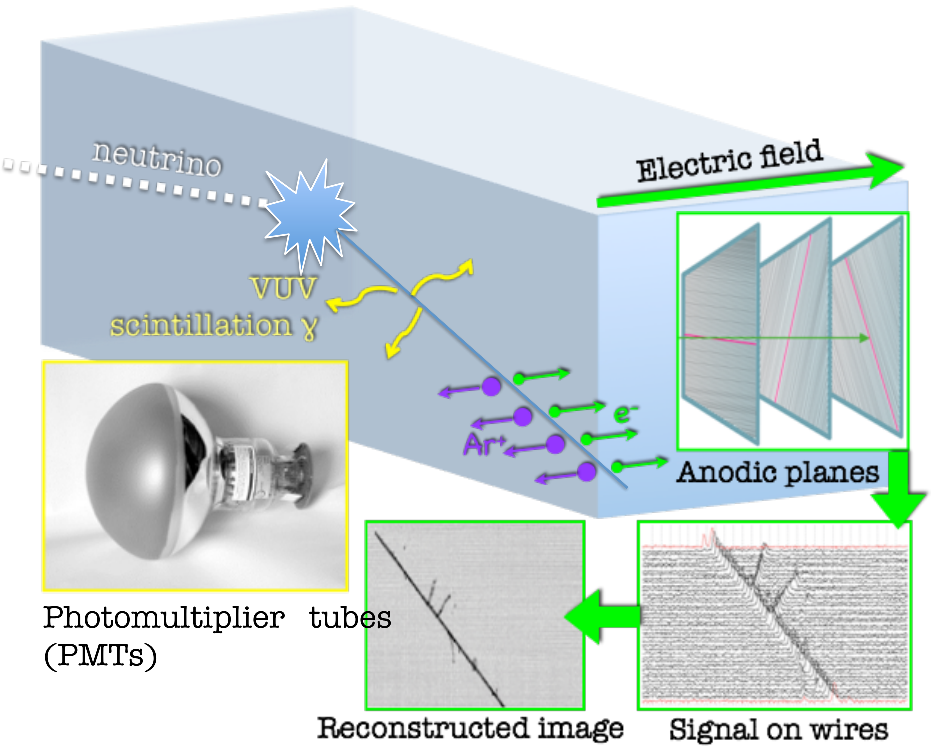
Technical status of the detector and its subcomponents

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.

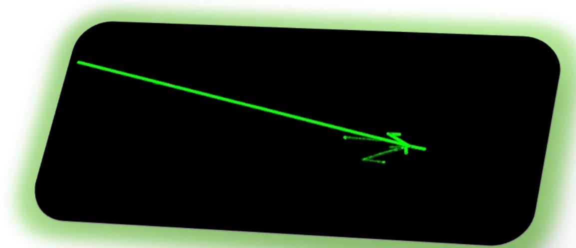
Ionisation electrons:

42000 e^-/MeV.

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

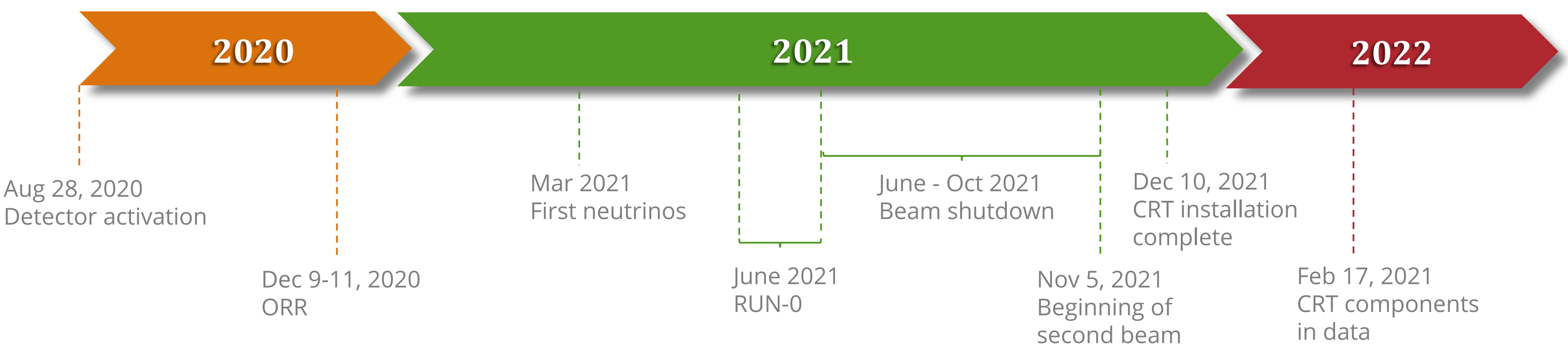
Response time = drift time (~ ms).

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



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).
- Very successful Operational Readiness Review (ORR) Dec 9-11 2020.
- Steady data taking with neutrino beams overnight and during weekends since mid March 2020, in parallel with commissioning activities during working hours. First BNB neutrino Full time (24/7) neutrino beam run May 31st - June 27th: "RUN-0".
- Installation, upgrades and commissioning during summer shutdown of the beams.
- 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 ongoing, close to completion.



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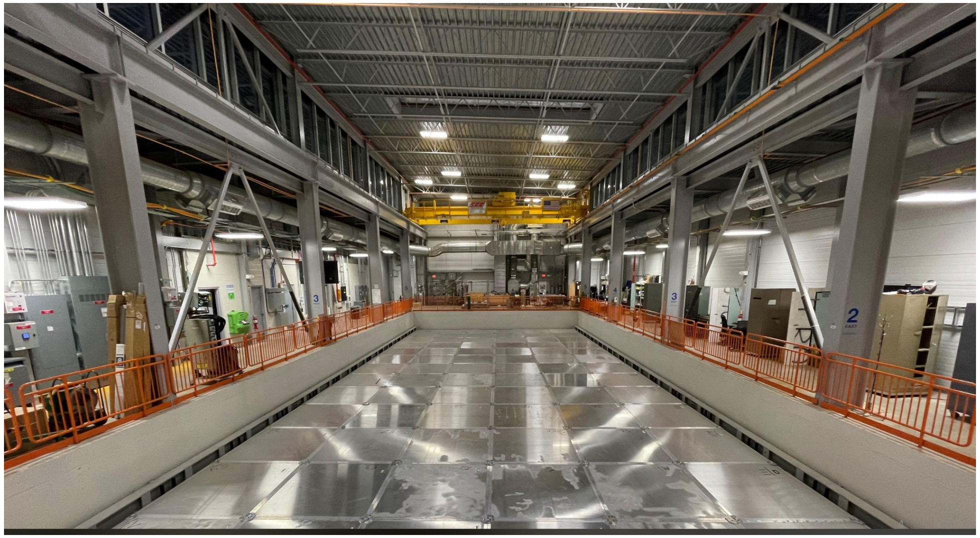
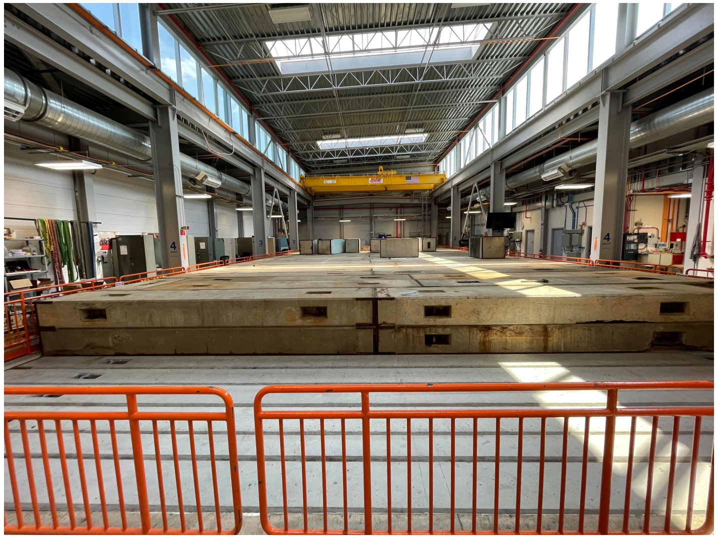
Evolution of the ICARUS detector

Sept 2020



Dec 2021



May 2022

Cryogenic system

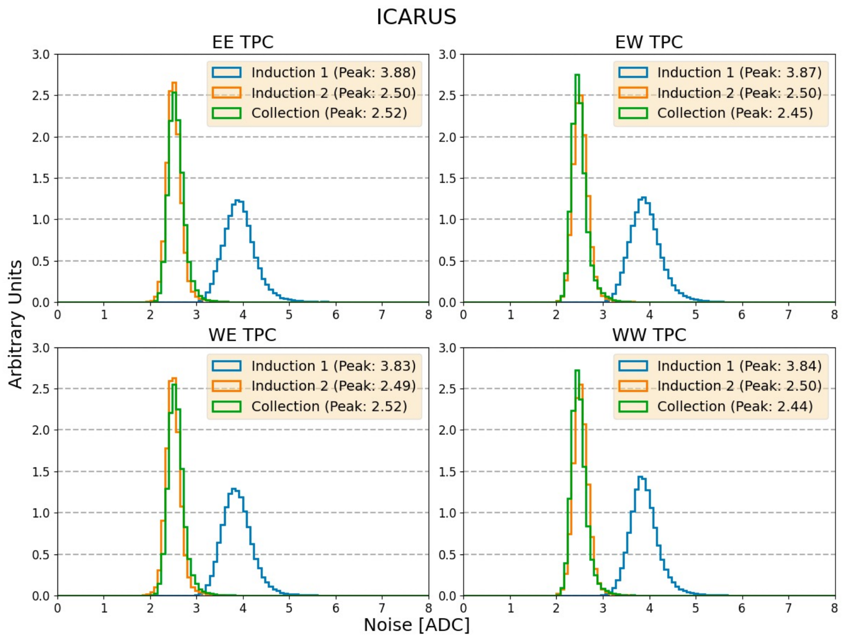
- Cryogenics/purification systems running steadily since detector activation. Some failures occurred with no impact on detector operation, thanks to the high level of redundancy. All functional parameters meet the design values.
- Substantial upgrades during 2021 summer shutdown, including improvement 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 next 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

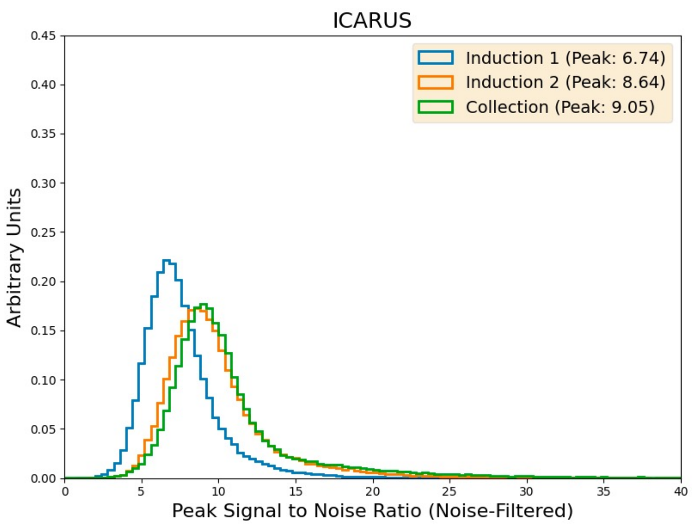
TPC readout electronics

- 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)



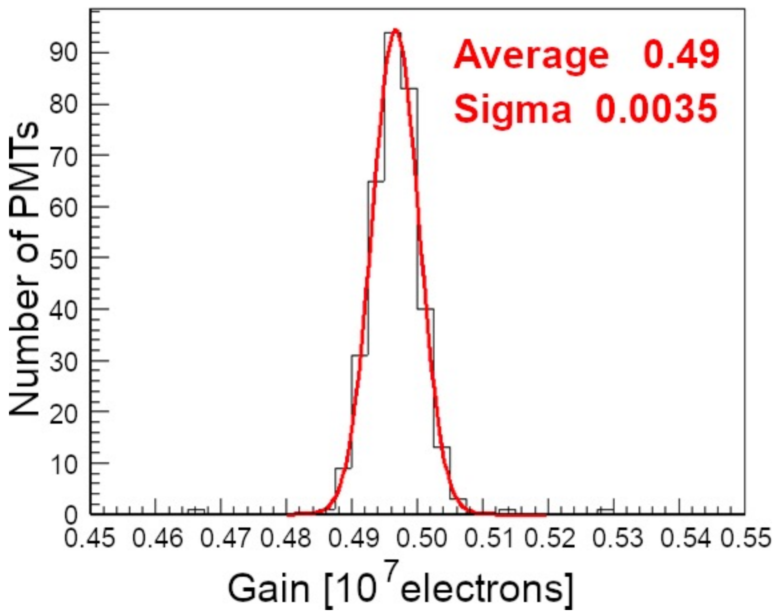
S/N after coherent noise removal



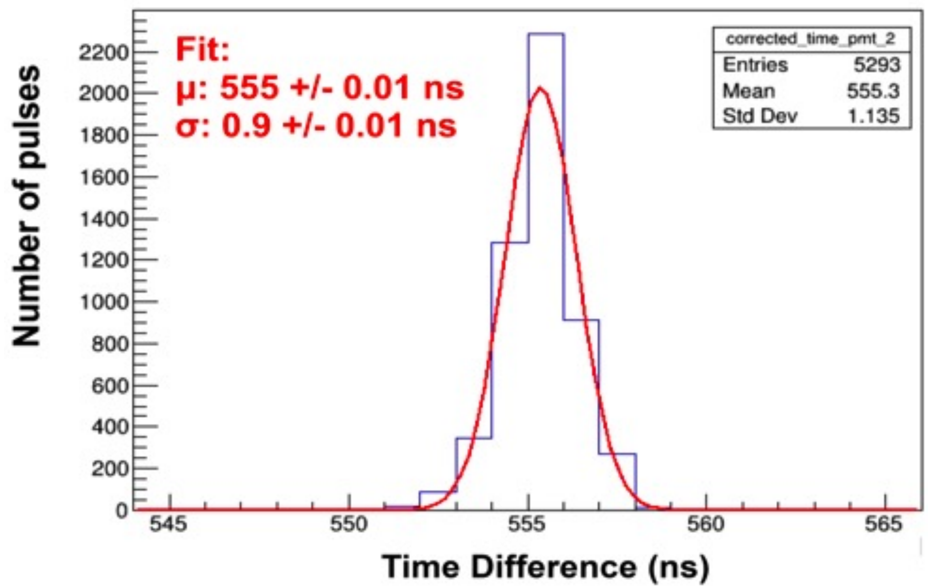
Scintillation light detection system

- 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



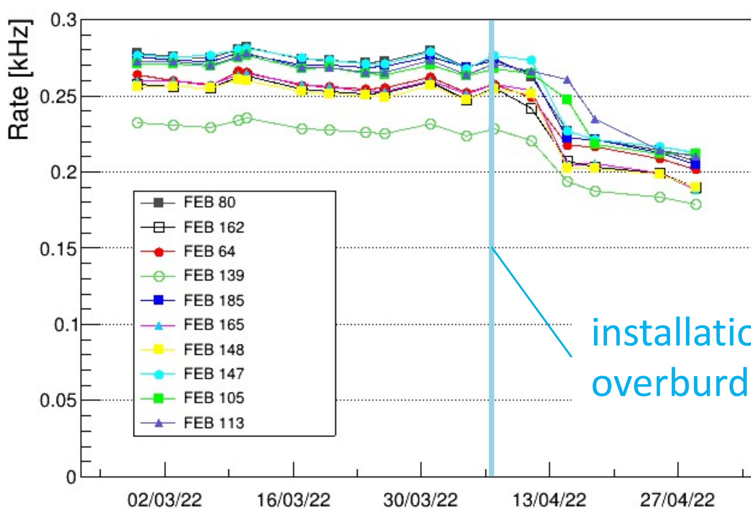
Distribution of time difference between PMT signals and trigger time



Cosmic Ray Tagger (CRT)

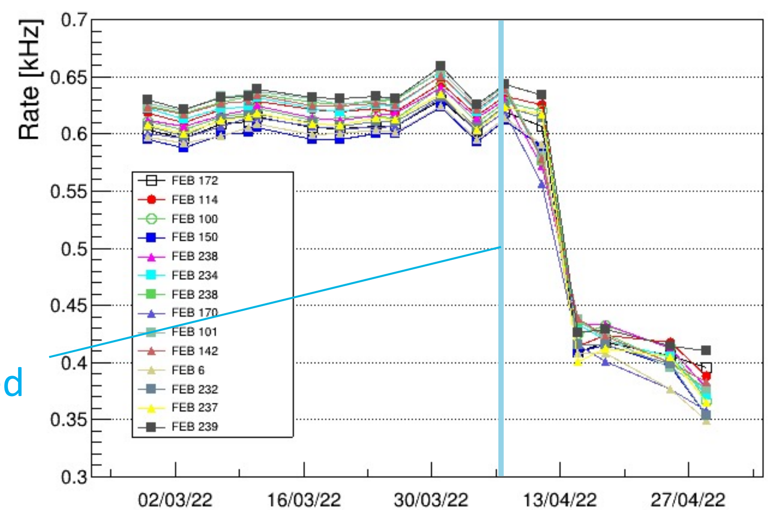
- Side and top CRT have been taking cosmic and neutrino data steadily with TPC and PMT systems, for one year for side CRT and three months for top CRT. Bottom CRT DAQ still needs to be integrated with the entire system.
- Rates without overburden for top CRT: 250/600 Hz for side/top. For side CRT, rates ~ few kHz, except for higher 20 kHz rate for North module, due to interference with cryogenic pumps.
- Rates with 1 m overburden for top CRT decreased to 200/400 Hz for side/top.

Rates for one vertical CRT module



installation of overburden started

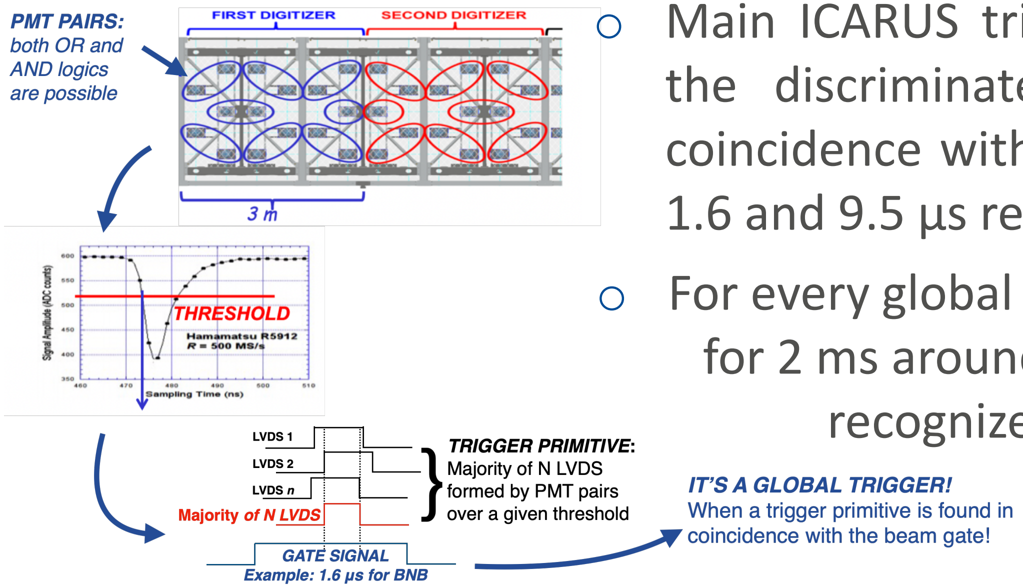
Rates for one horizontal CRT module



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.

Trigger and clock distribution system

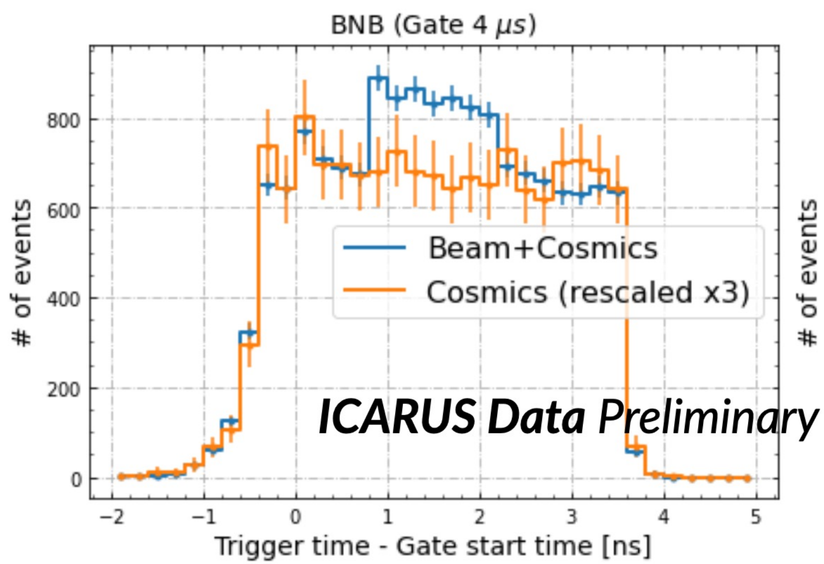


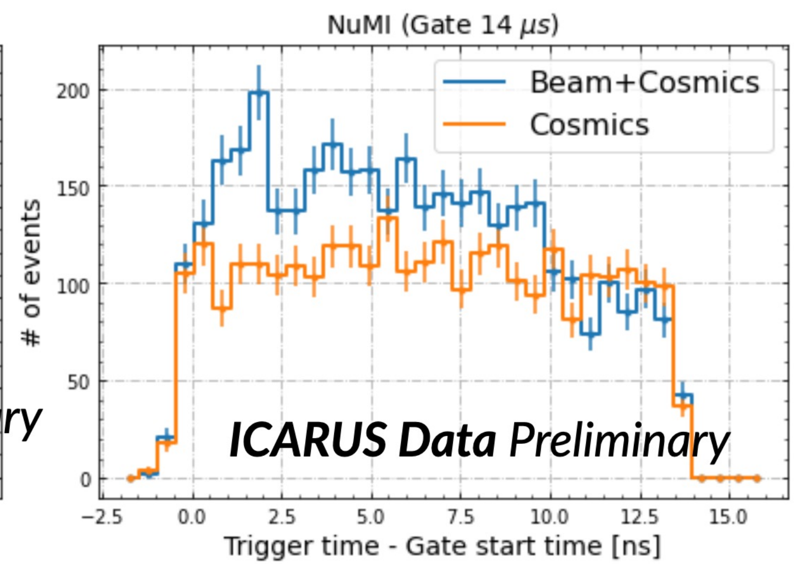
- Main ICARUS trigger signal generated by majority of the discriminated pairs of PMT signals (LVDS) in coincidence with the BNB and NuMI beam spill gates, 1.6 and 9.5 μs respectively.
- For every global trigger, light and CRT activity occurring for 2 ms around the trigger time are also recorded, to recognize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

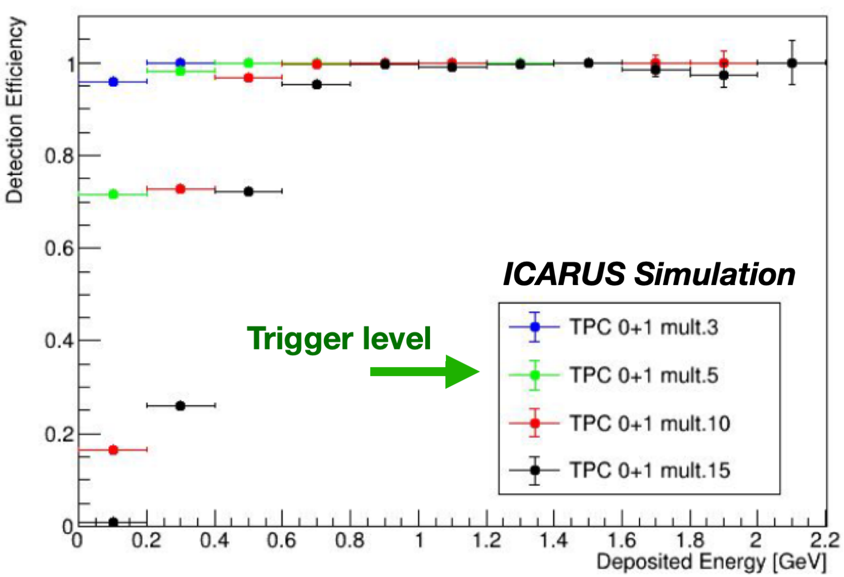




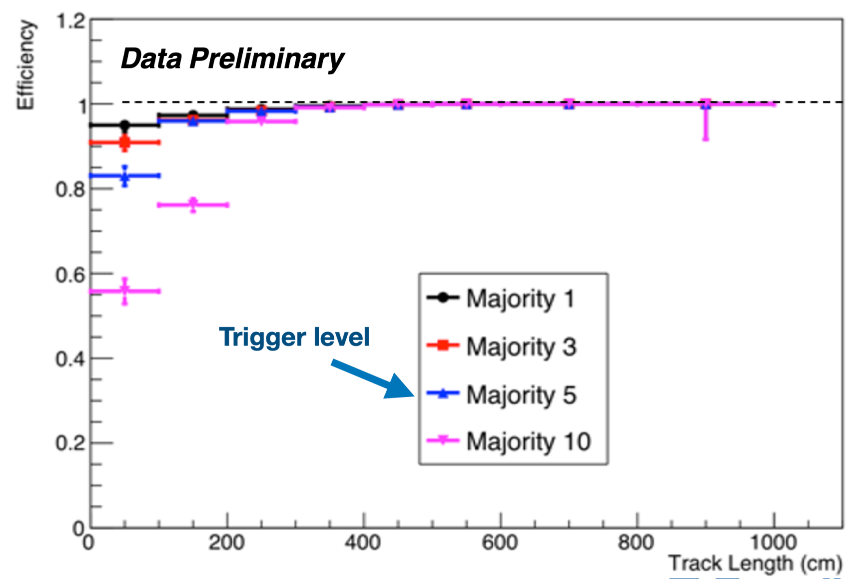
Trigger efficiency studies

- 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

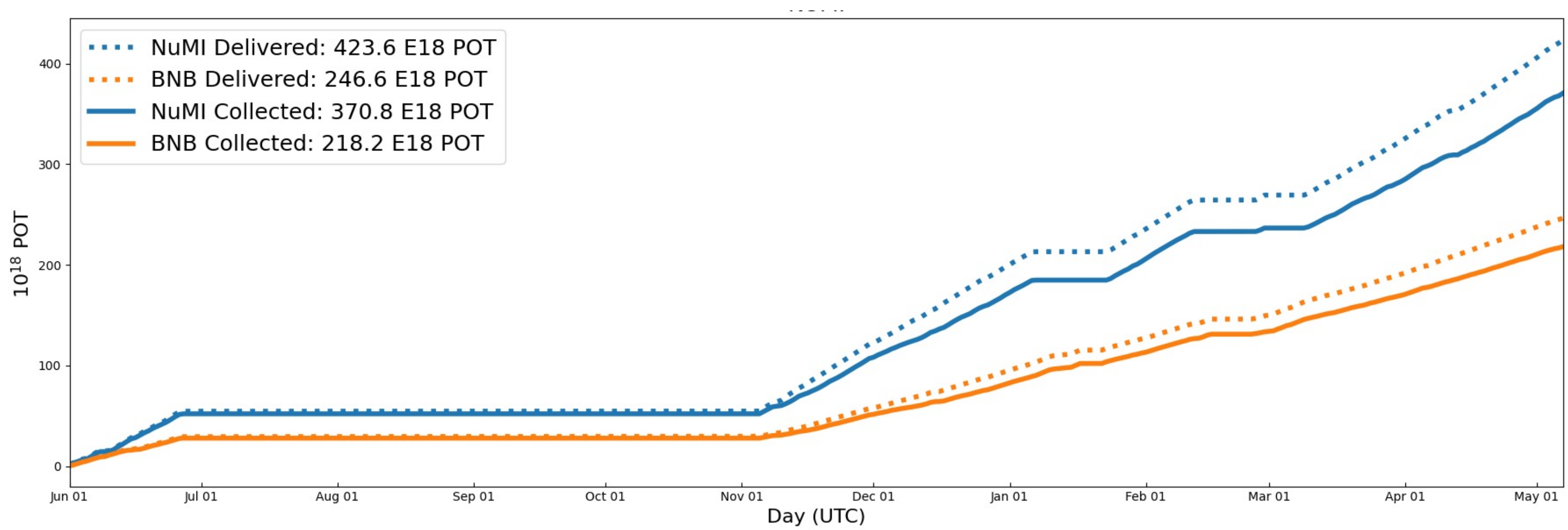


Trigger efficiency measured on crossing cosmic μ



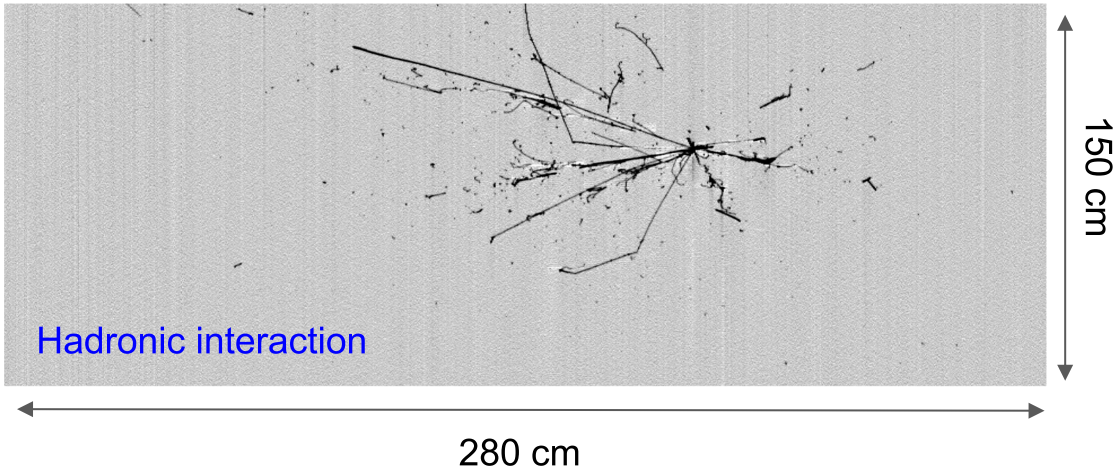
Report of beam data taking

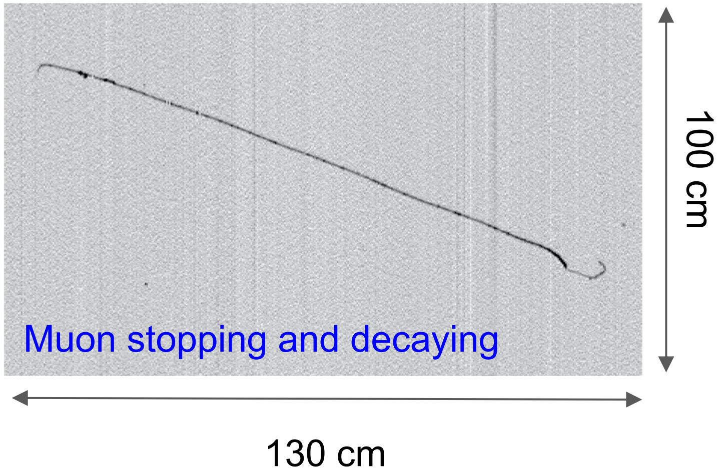
Data taking with BNB and NuMI beams

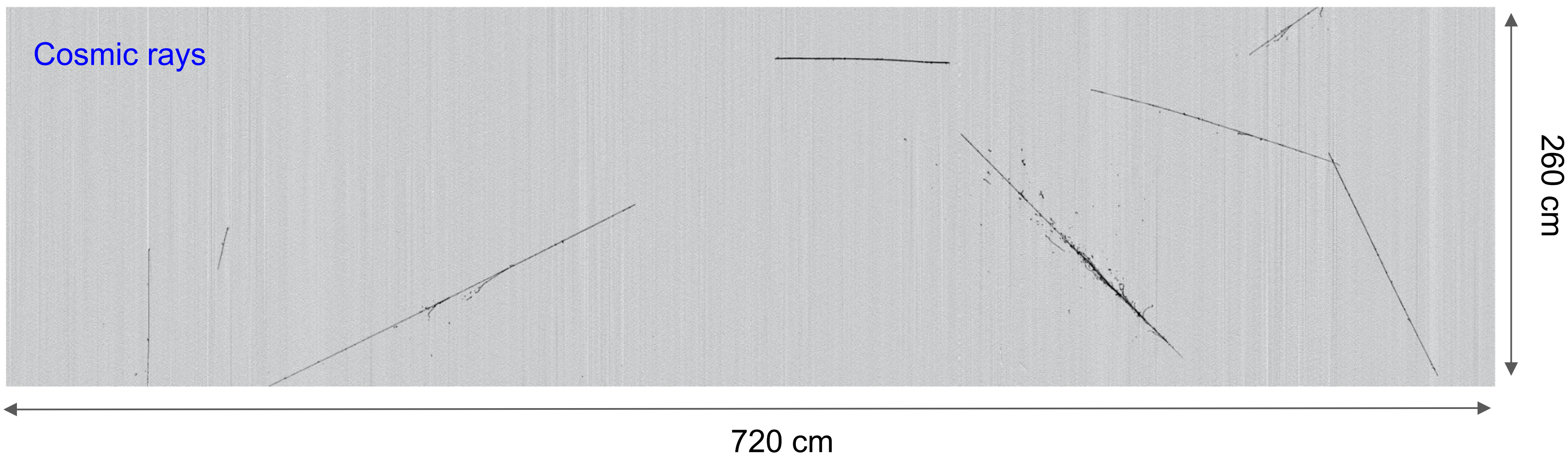


- Full time (24/7) neutrino beam run May 31st - June 27th 2021: "RUN-0".
  Part time (at least weeknights & full weekends) neutrino beam run since Nov 5th.
- Average intensity 4E12/50 E12 protons per pulse for BNB/NuMI.
- Overall 88% efficiency of beam data collection, despite several installation and commissioning activities.
- Data collected so far used for detector calibration / commissioning, not for SBN oscillation or NEUTRINO-4 analysis.

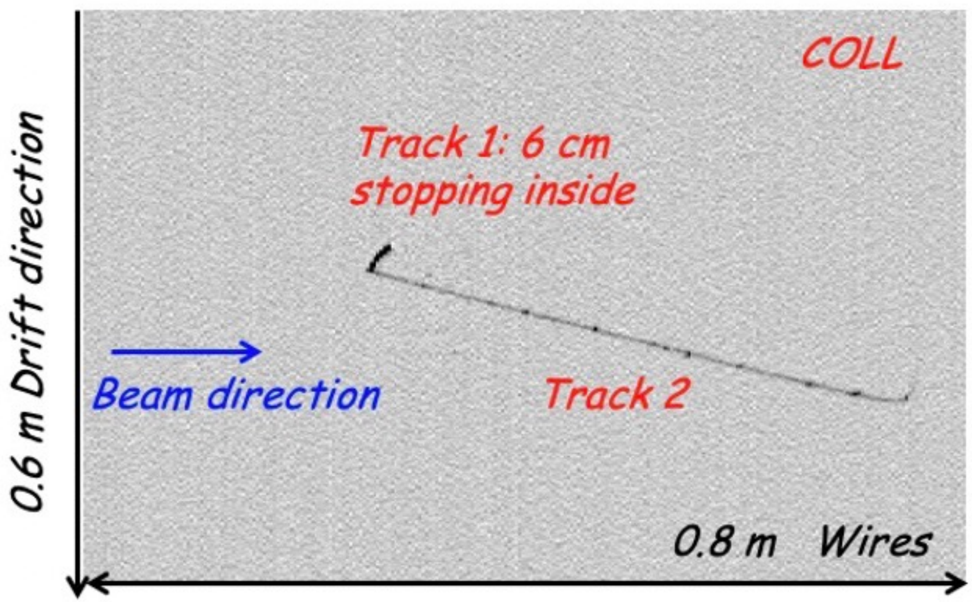
Sample event displays

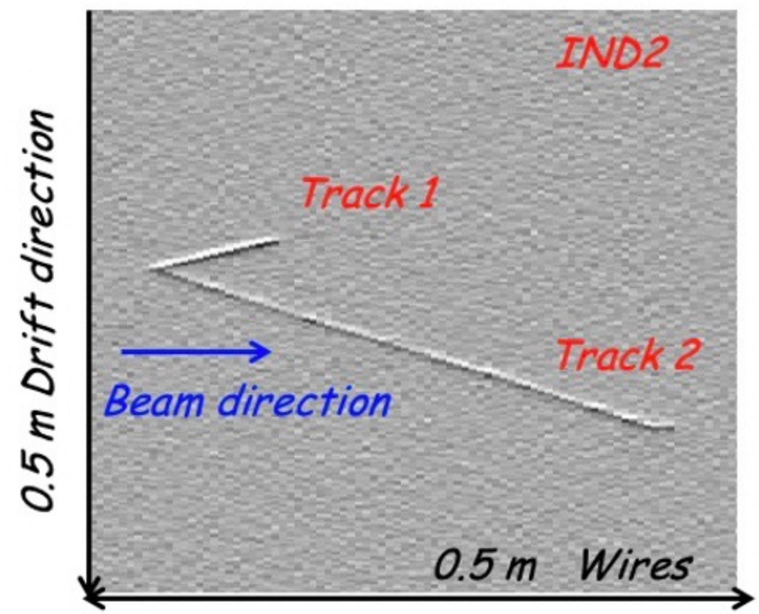






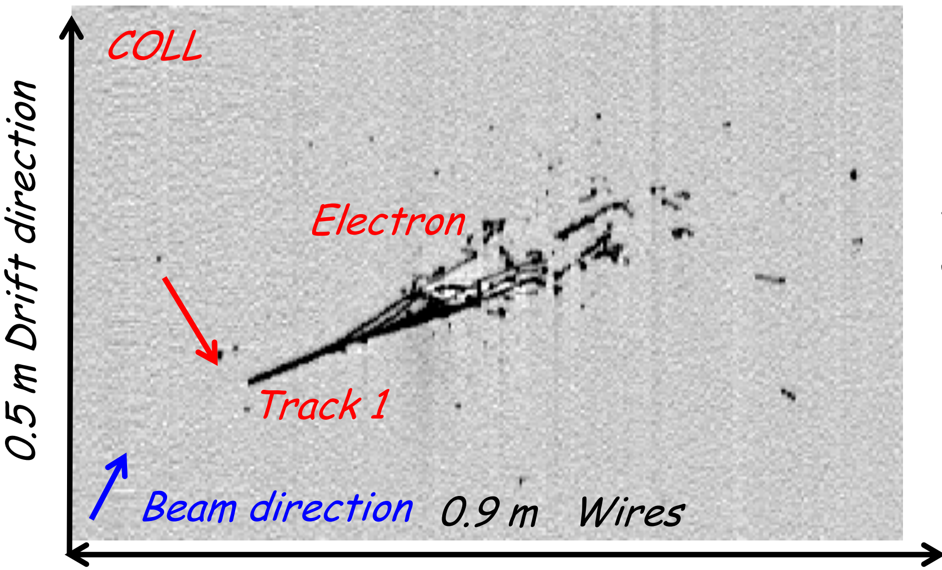
Example of BNB ν_μCC candidate

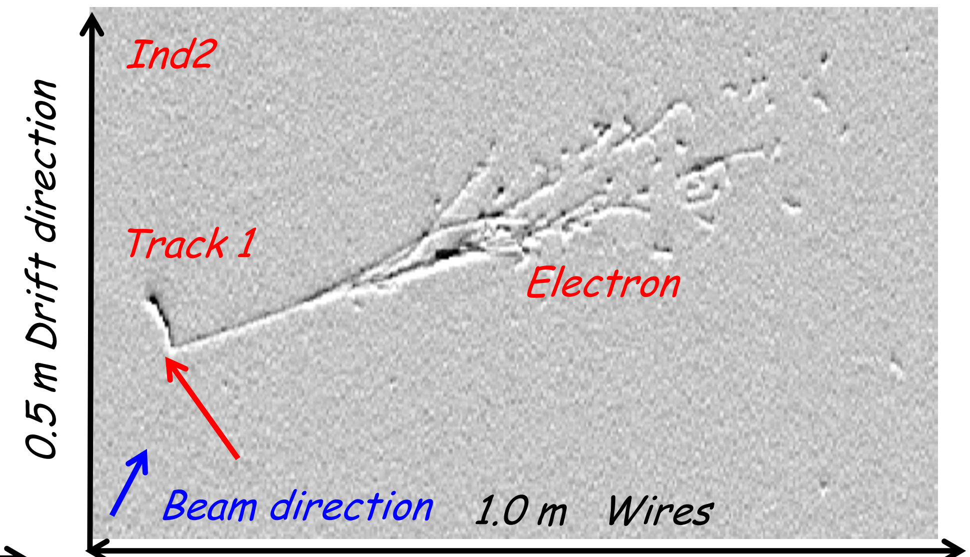




- QE ν_μCC candidate (run #4626, ev #227) in COLL and IND2 views.
- Vertex at 29 cm from the bottom wall. Two tracks produced, E_{DEP} ~ 170 MeV
  - Track 1 is the proton candidate with E_K ~ 70 MeV, stopping after L = 6 cm
  - Track 2 is likely the μ exiting on bottom wall after L = 51 cm.

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).

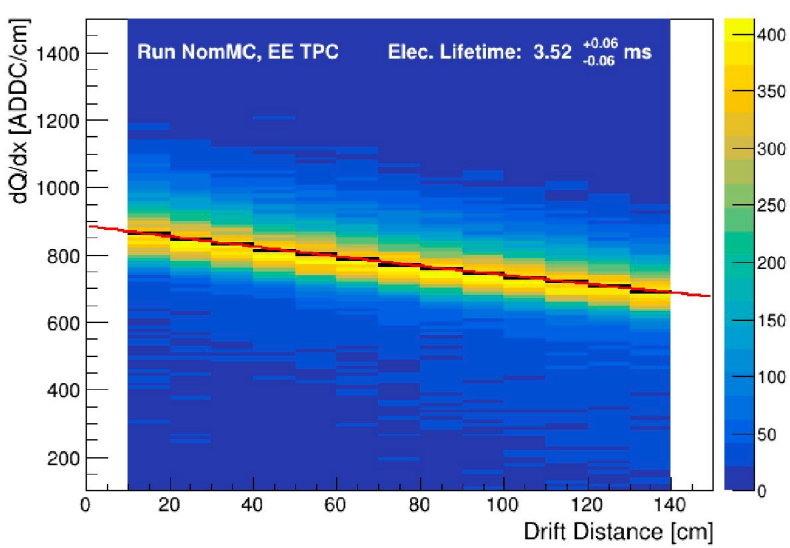
Initial calibration studies

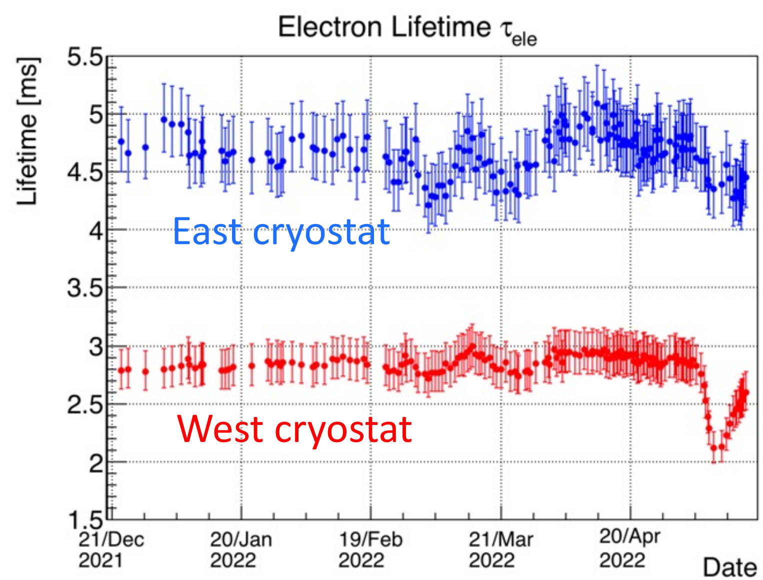
Electron lifetime (purity) measurement

- 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.

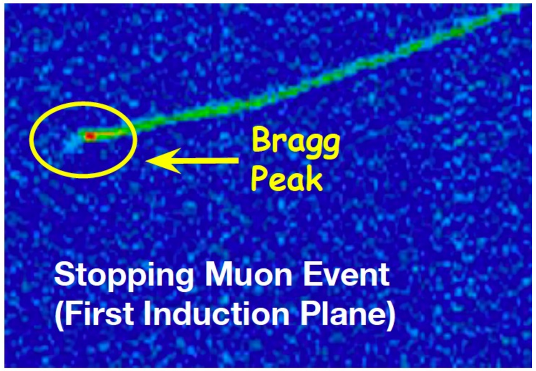
- Two complementary procedures developed and tested on MonteCarlo.
  - Method presently applied based on simplified physical signals and track reconstruction in 2D and measurement of the attenuation on each track. 7% total statistical + systematic uncertainty.

Attenuation of ionization along μ track

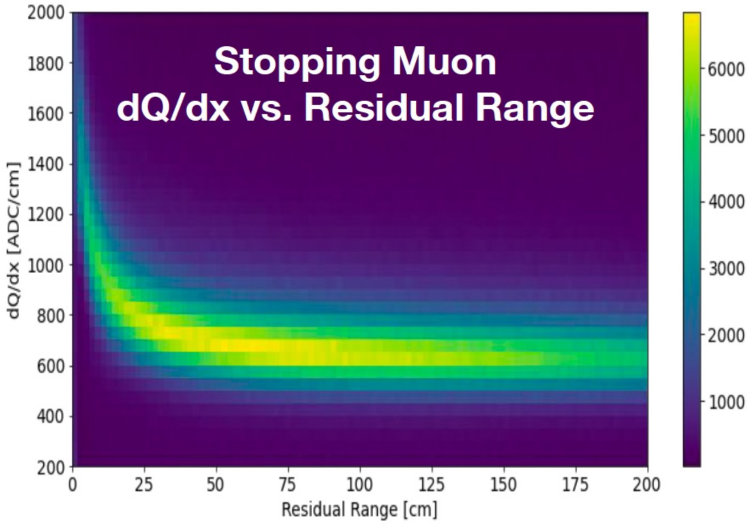


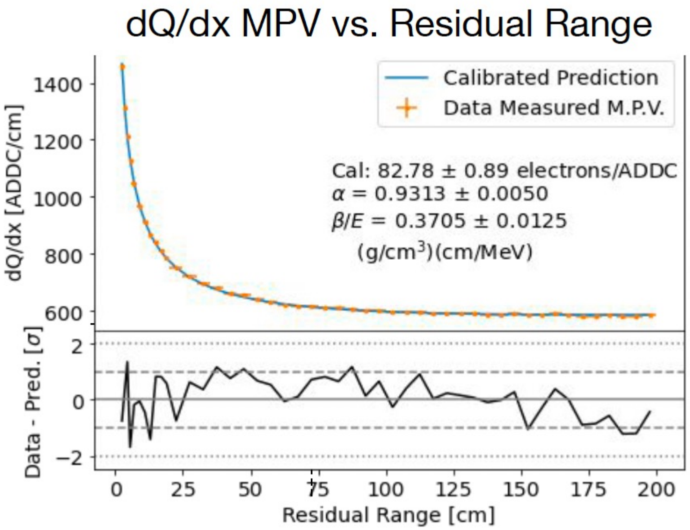


TPC wire signal gain calibration



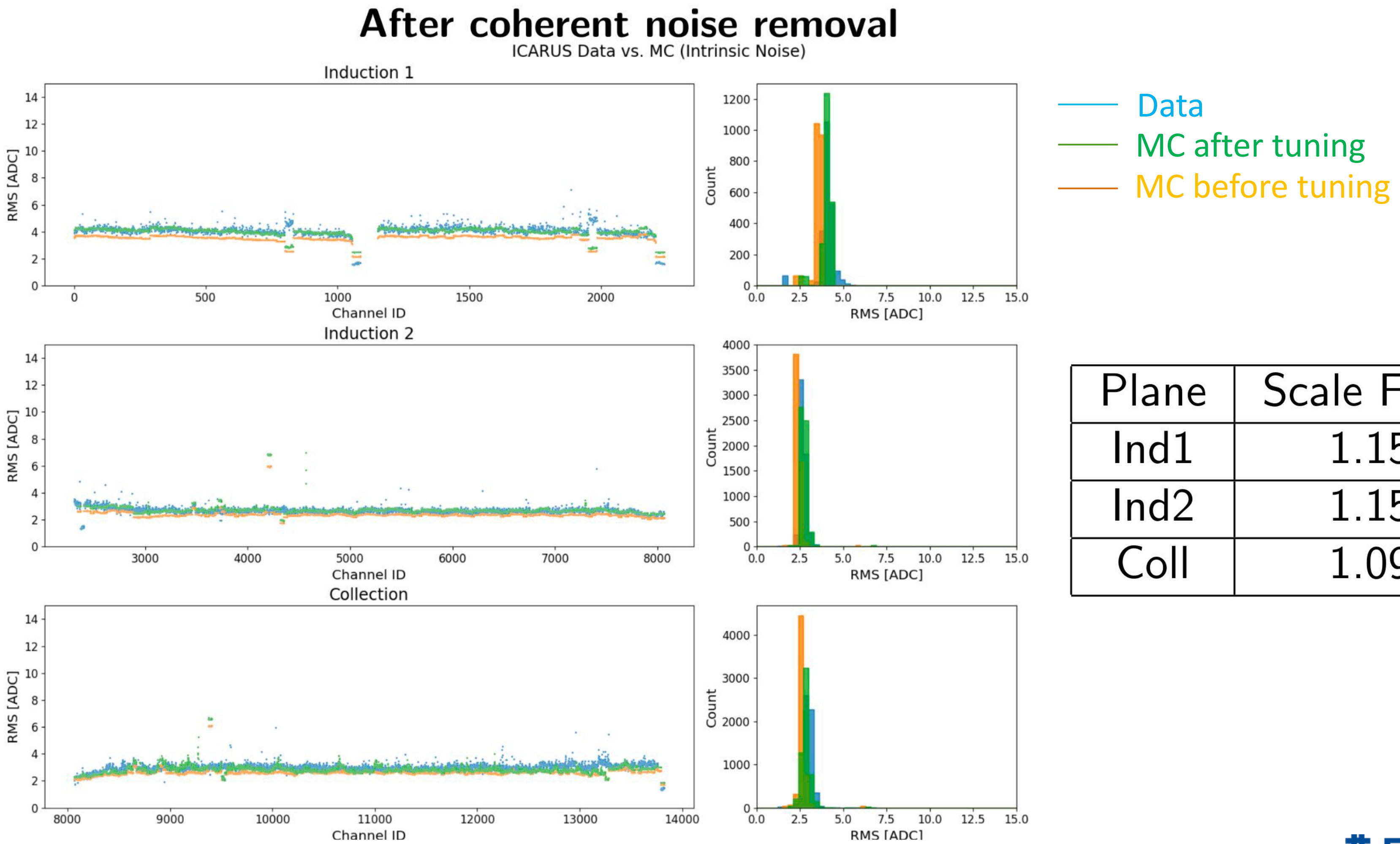
- Calibration chain based on the study of ionization vs residual range for cosmic μ crossing the cathode, stopping/decaying in the active LAr and identified by the reconstruction program.
- Goals: calibrate the absolute energy scale, equalize the individual wire electronic response, improve the modeling 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

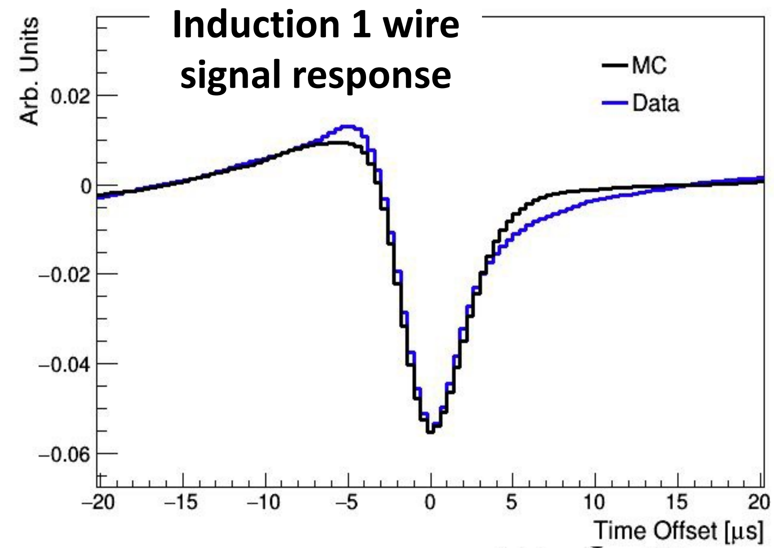
- Update to TPC noise model in simulation to better match data, applying scale factors scale factors plane by plane. Much better agreement.

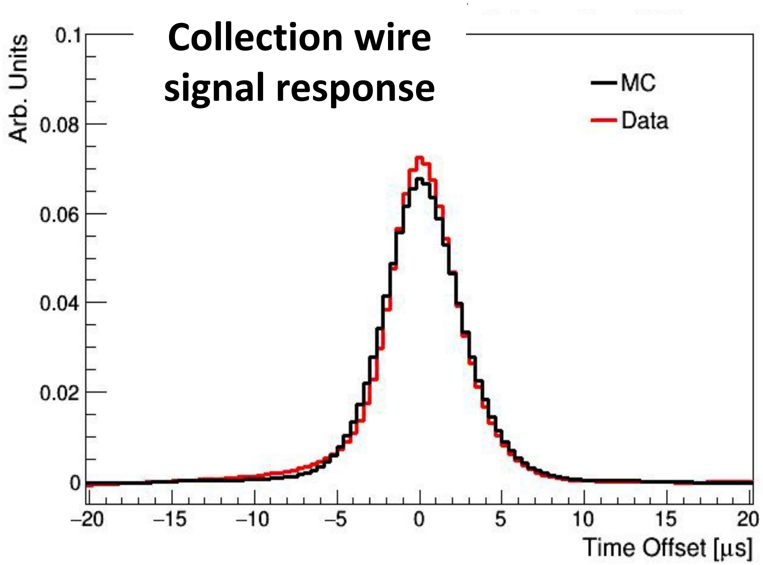


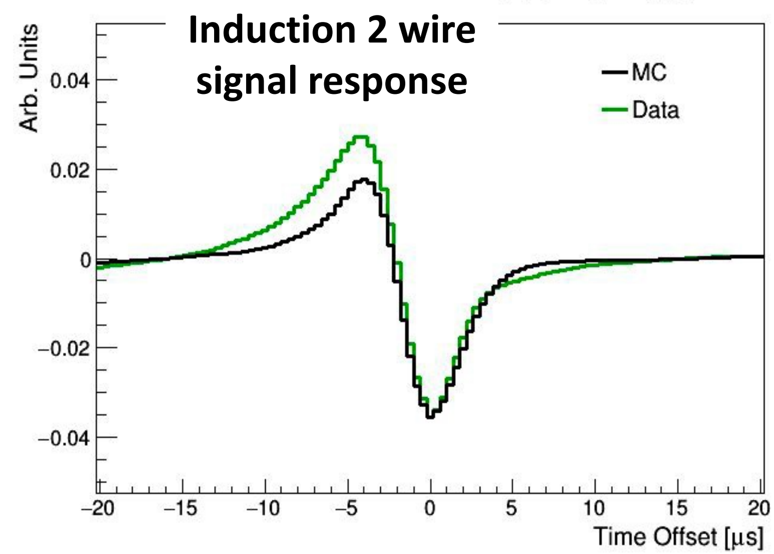
Plane	Scale Factor
Ind1	1.151
Ind2	1.152
Coll	1.096

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







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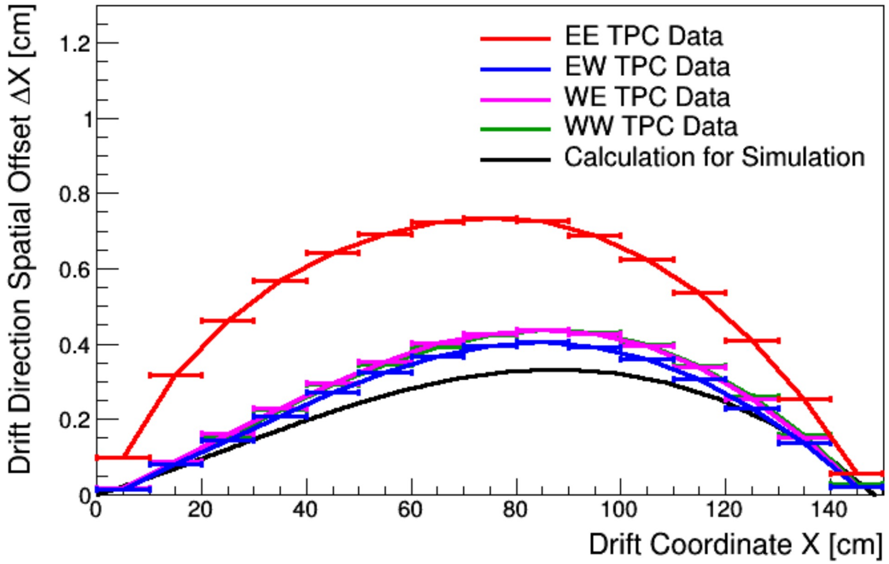
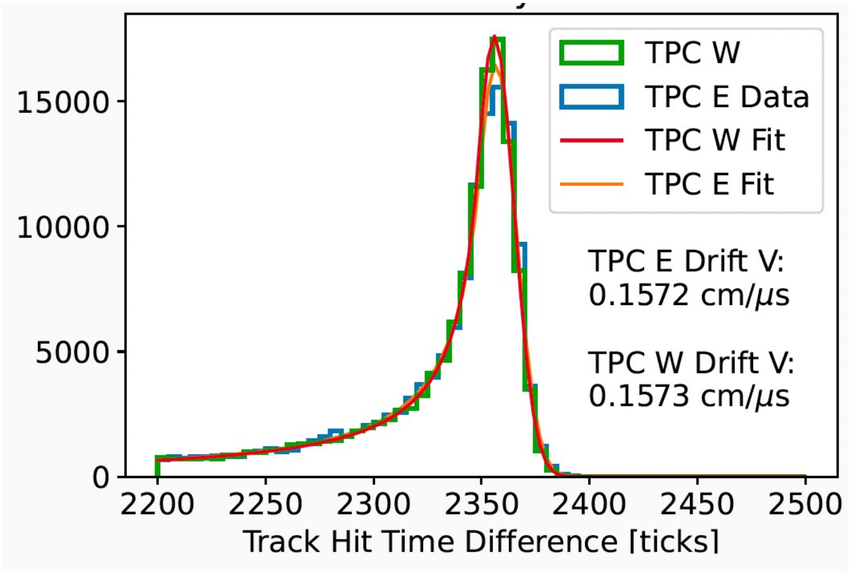
First look at TPC performance

Spatial distortions in drift direction due to space charge



Drift velocity in West cryostat



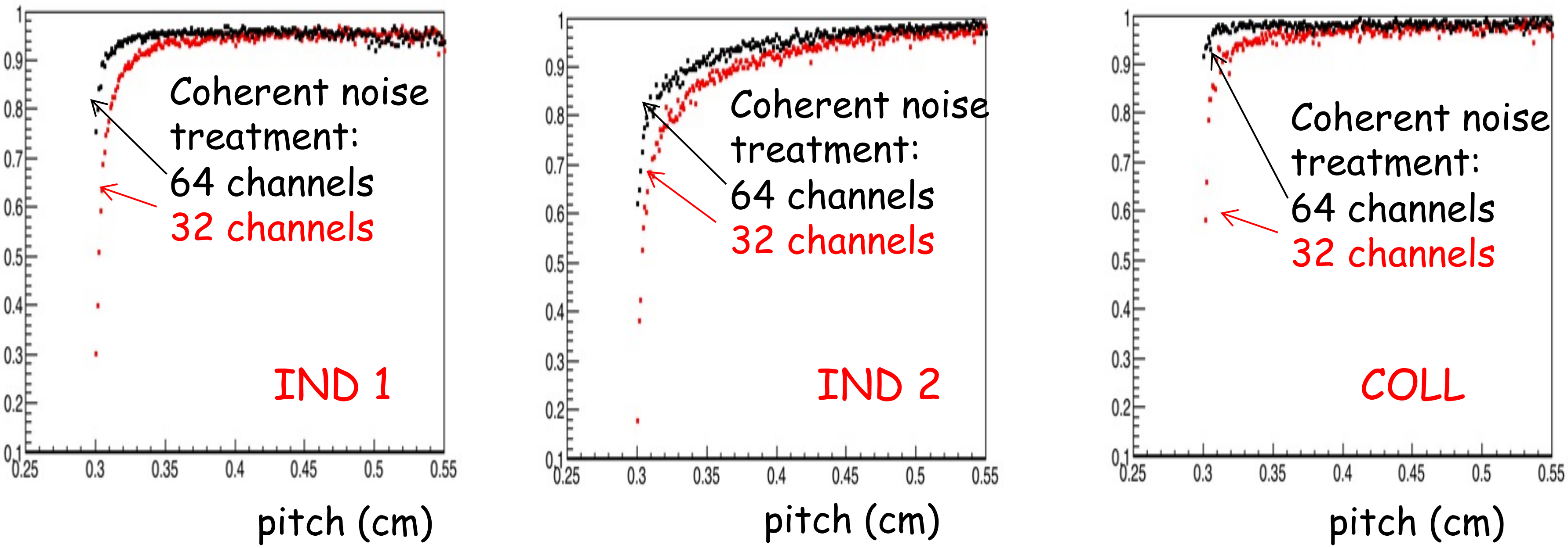
- Space charge effects (SCE) measured using anode-cathode-crossing cosmic muon tracks, looking at spatial distortions in drift direction. Good agreement with simulation, apart from one TPC where E field distortions associated with a possible field cage short are being investigated.
- Same track sample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

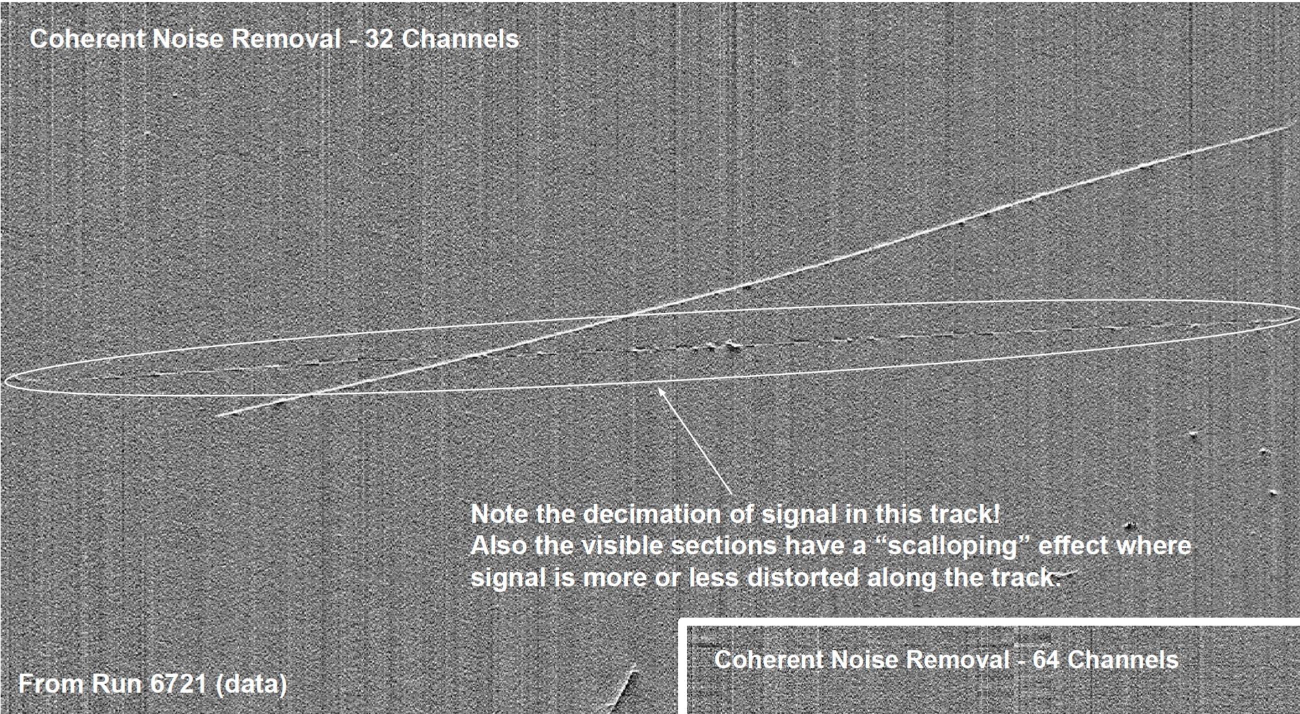
Tuning of reconstruction

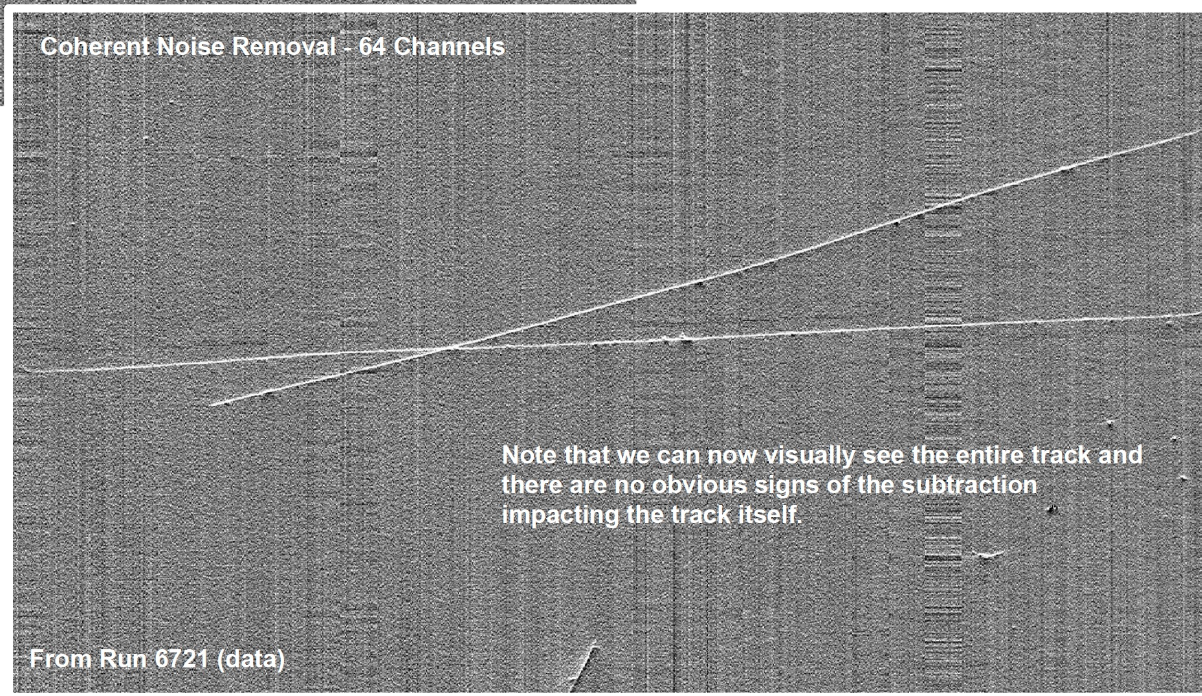
TPC signal reconstruction and coherent noise

- The track reconstruction algorithm is based on multi-steps: 1) pre-processing; 2) wire signals identification/reconstruction (hits); 3) track/shower reconstruction.
- The removal of the coherent component is now performed averaging over 64 channels (previously it was on 32 channels), with reduced impact on the wire signal.
- The efficiency to identify a signal on the wires was studied for the different wire planes with a sample of cosmic muon tracks crossing the cathode.

Wire signal identification efficiency for cosmic muons crossing the cathode (Data)



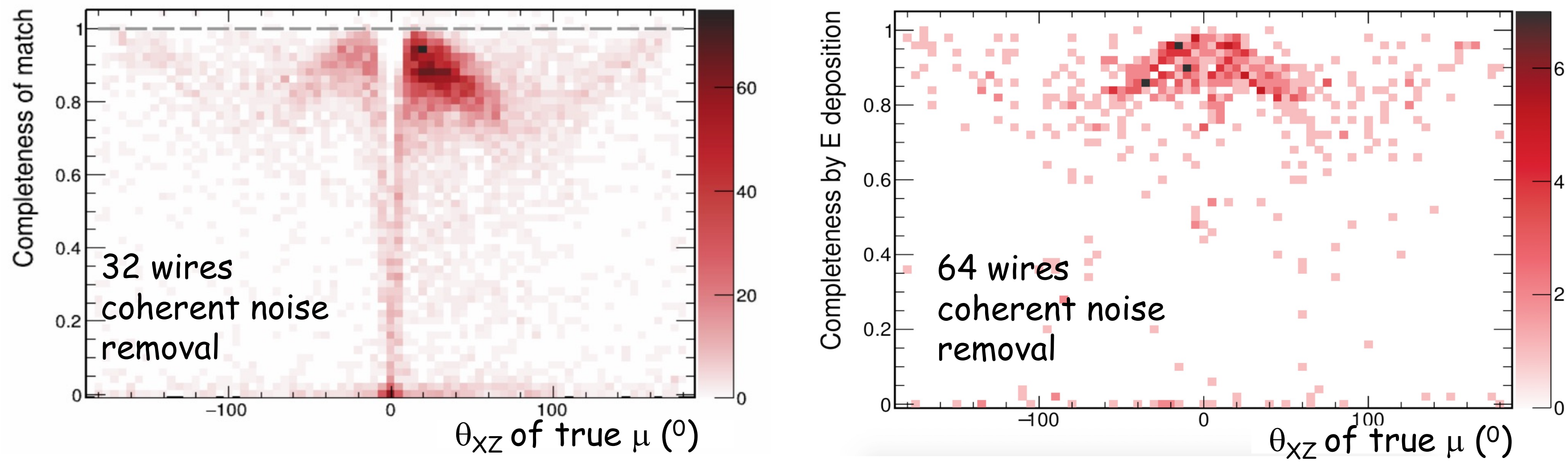

Coherent Noise Removal - 32 Channels
Note the decimation of signal in this track!
Also the visible sections have a "scalloping" effect where
signal is more or less distorted along the track.
From Run 6721 (data)


Coherent Noise Removal - 64 Channels
Note that we can now visually see the entire track and
there are no obvious signs of the subtraction
impacting the track itself.
From Run 6721 (data)

TPC signal reconstruction and coherent noise

- The removal of the noise component coherent can affect the signal, reducing the hit/track efficiency in particular for ~isochronous tracks (~perpendicular to the drift direction).

Reconstructed muons in simulated NuMI ν_μCC events



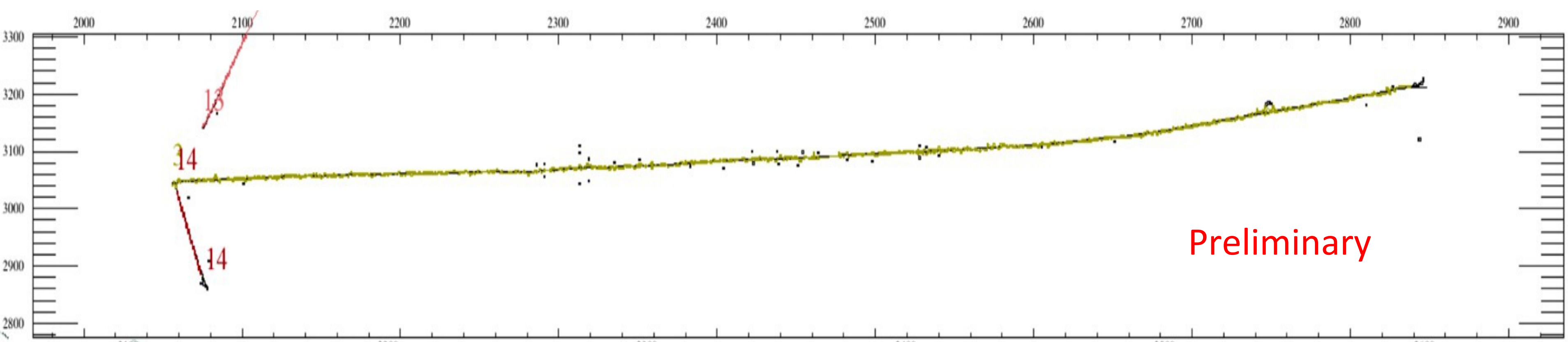
θ_{XZ}=angle from Z in XZ (drift-longitudinal axes) plane: 0^0 means along detector axis, +/- 90^0 means⊥to wire plane. Completeness = (#hits associated to the track)/(#of hits produced by the μ)

- The new treatment of the coherent noise allows to improve the reconstruction of ~isochronous tracks.
- From MC study ~80% of μs produced in ν_μCC with L_μ > 50 cm are correctly reconstructed, the same analysis should be applied to ν_μCCQE events.

TPC event reconstruction using Pandora

- Default reconstruction uses Pandora (https://github.com/PandoraPFA) – pattern recognition software suite with well-established LArSoft interface (for more info):
  - clusters the objects together into reconstructed particles in 3D by joining together info from the wire planes;
  - reconstructs vertex (common point where particles originate);
  - forms reconstructed particle hierarchy (parent/child particles)
  - classifies particles as track-like (e.g. μ, p, $\pi^{\pm}$, $K^{\pm}$) or shower-like (e.g. e, γ)
- Neutrino events found from visual scanning of a subsamples of collected data useful to investigate and test the automated software tools and compare MC/data performance.

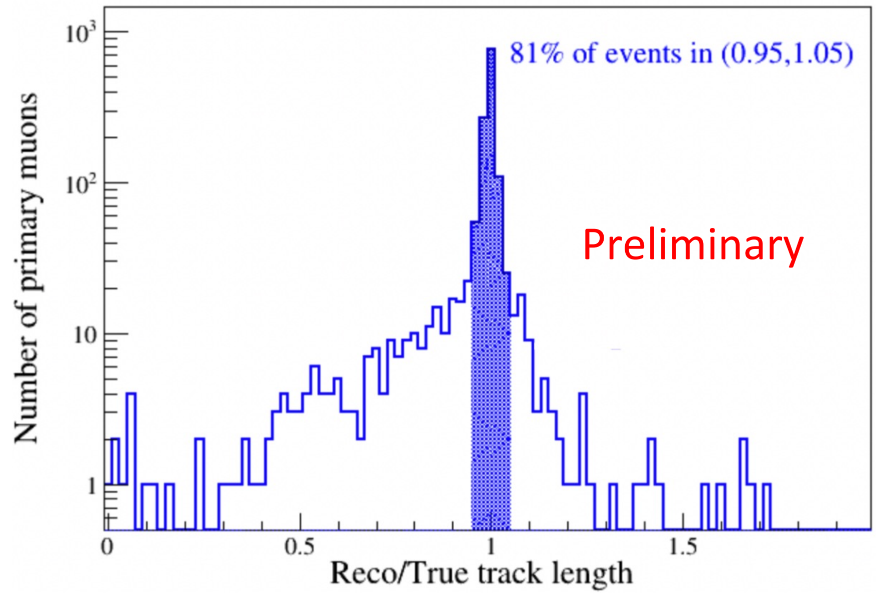
Sample data event selected by visual scanning with reconstruction overlaid



Reconstruction of TPC track length

- MC study of muon track reconstruction for $L_\mu > 50$ cm in NuMI events.

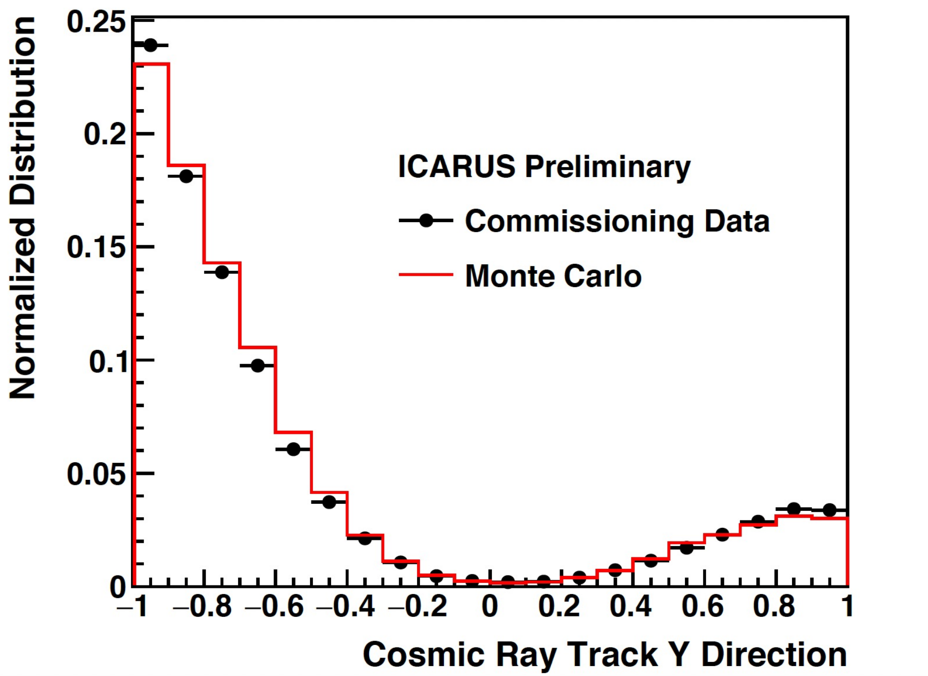
Comparison of reconstructed and true μ track length on NuMI MC

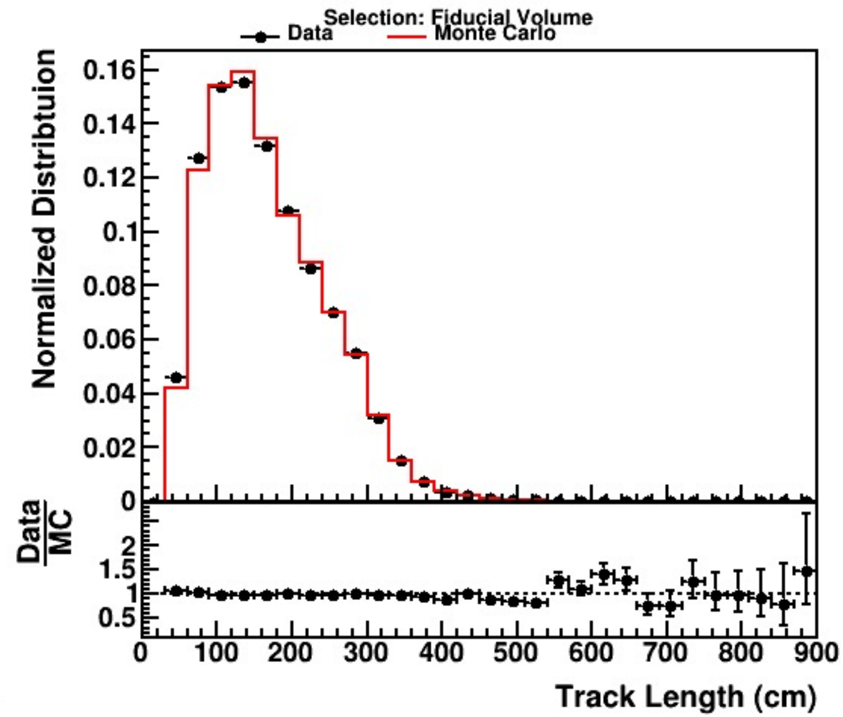


- Pathological cases have been identified and need further studies: split tracks, missing hits, very low purity/ completeness, etc.
- Important to: (1) understand how often it happens, (2) have a tagged set of events with which to study improvements, (3) identifying further issues that need to be solved.
- Track reconstruction will improve as the understanding of the detector progress, yet already sufficiently robust to allow for tracks to be used in calibration

Track reconstruction: data/MC comparison

- Comparison of cosmic events reconstructed in data and MC. Several reconstructed quantities have been studied to understand the features of the reconstruction.



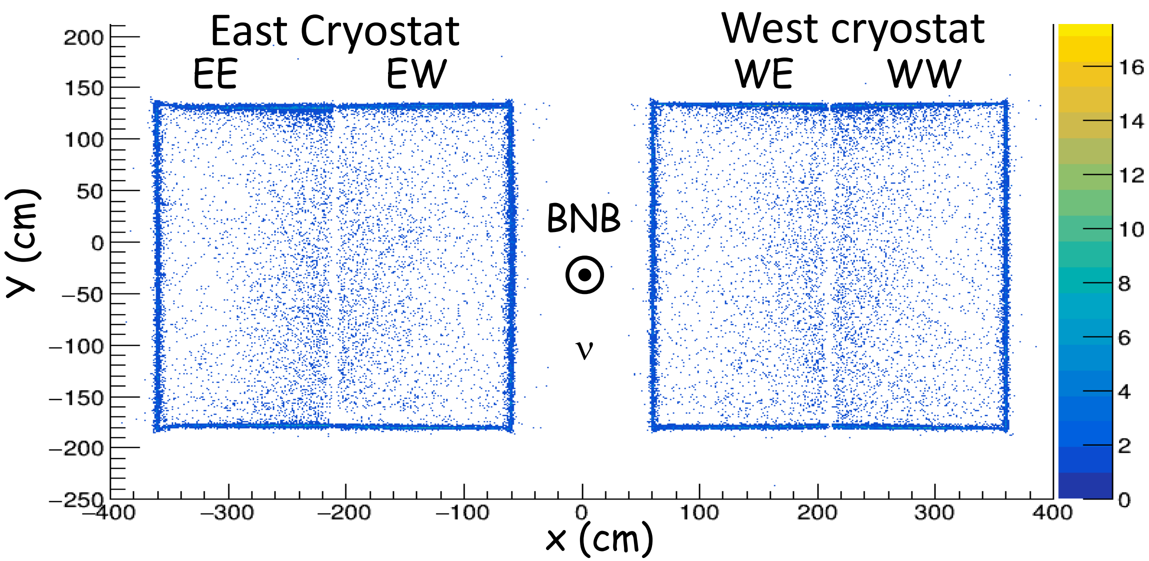


- Ongoing parallel study of shower reconstruction in cosmic rays for data and MC.
- Next steps include identifying pathologies in the reconstruction and investigate data/MC discrepancies.
- Preliminary indications of good end to end processing chain for both data and simulation.

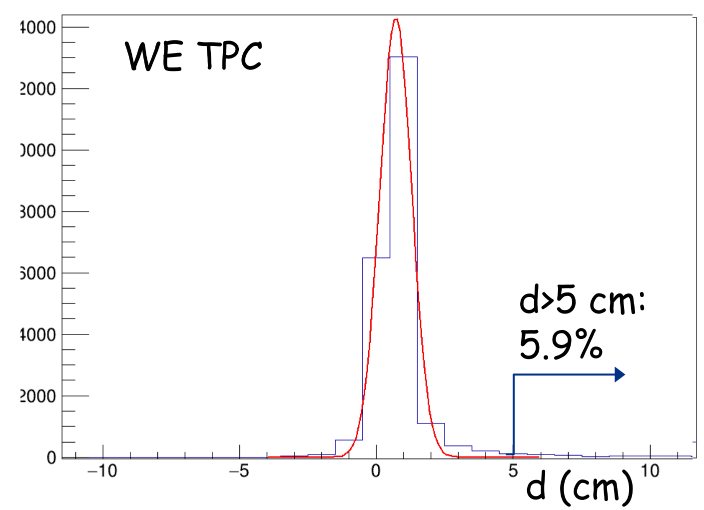
Event containment condition

- Large sample of cosmic muons passing through the cathode and fully reconstructed in 3D.
- The initial and final 3D point of the μ tracks are distributed as expected at the detector boundaries and can be exploited to define a condition for contained tracks based on the minimal distance d from the active volume walls.

Entry and exit points of cosmic muons crossing the detector



Distance of the μ entry point from the detector walls

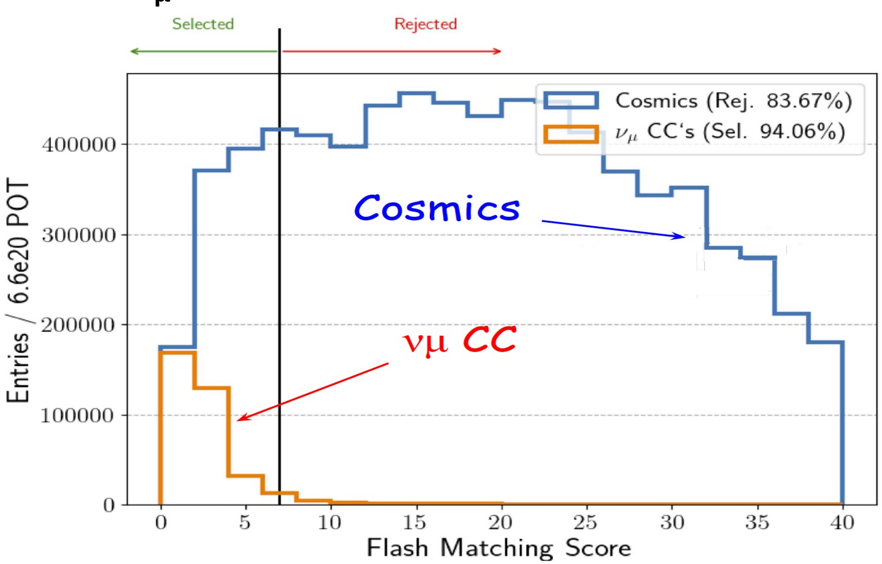


- Promising approach to reject cosmic tracks crossing the border of the TPC, accounting for the actual performance of track reconstruction: d > 5 cm -> factor ~18 suppression.
- Additional study is ongoing to understand/fix bad reconstruction of entry/exit points

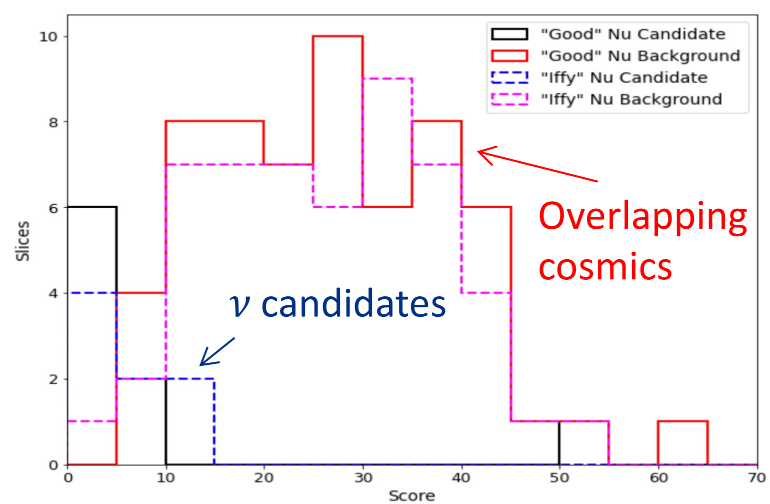
PMT light signal – TPC event association

- The agreement between the light signals of PMTs firing in coincidence in 100 ns ("flash") and the reconstructed TPC event is quantified by a "flash score" based on
  - weighted barycenter of light signals and barycenter of deposited TPC charge;
  - dispersion of fired PMTs around the light barycenter;
  - sharing of the total detected light between the two PMT walls in each cryostat.
- The score is small (large) for correlated (uncorrelated) PMT and TPC reconstructed events, as determined in MC and verified in collected data.

MC BNB ν_μCC interactions and random cosmic overlays

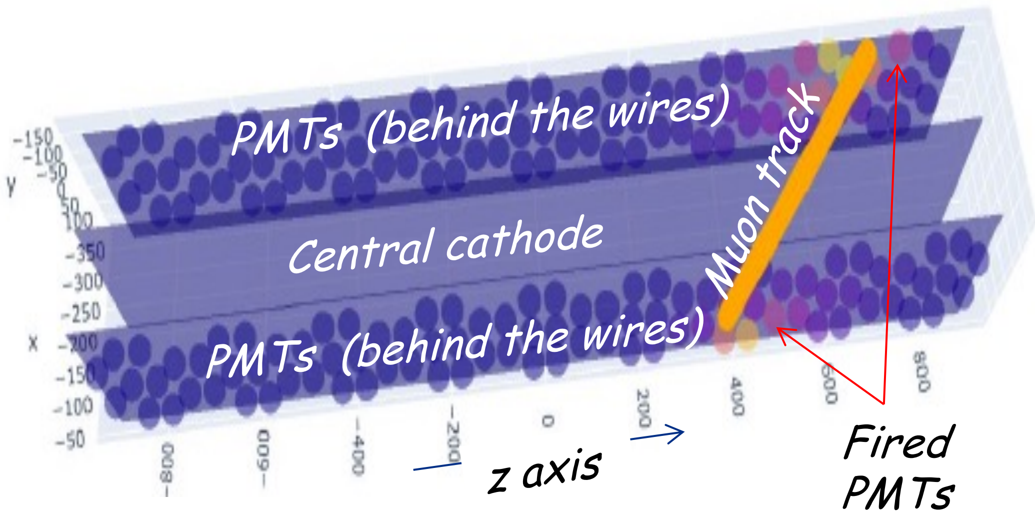


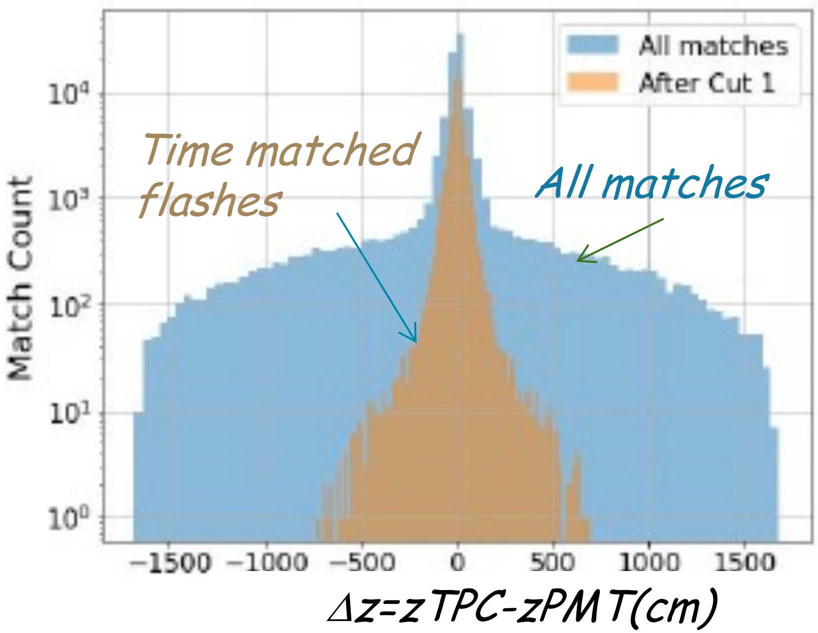
Flash matching in Data

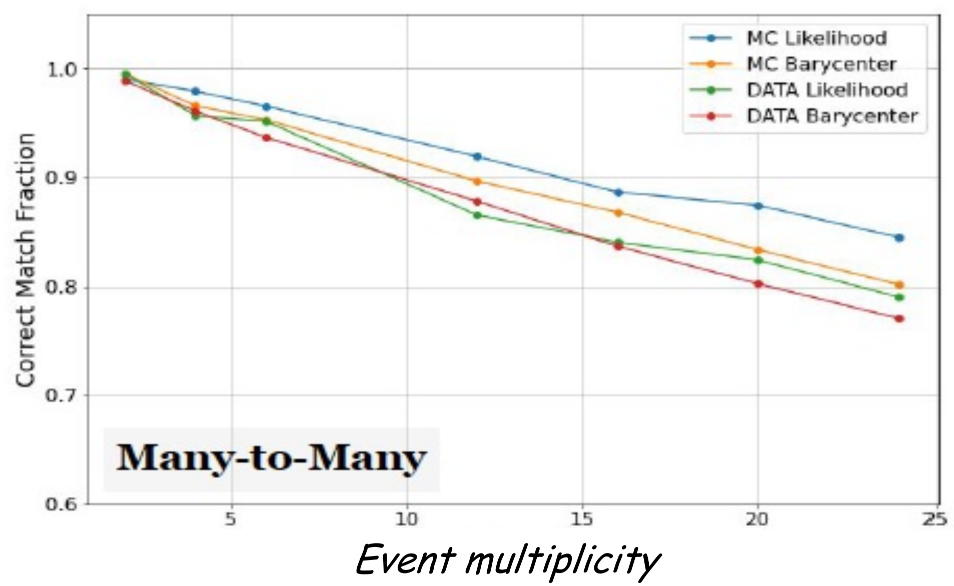


PMT-TPC association for cathode crossing μ in data

- Study on cathode crossing μ data
- Simplified approach: light and track barycenter compared along the z axis. Good association within Δz~1m.
- For better association: likelihood function that fully exploits the fired PMT/TPC signals after further tuning of PMT signal reconstruction.

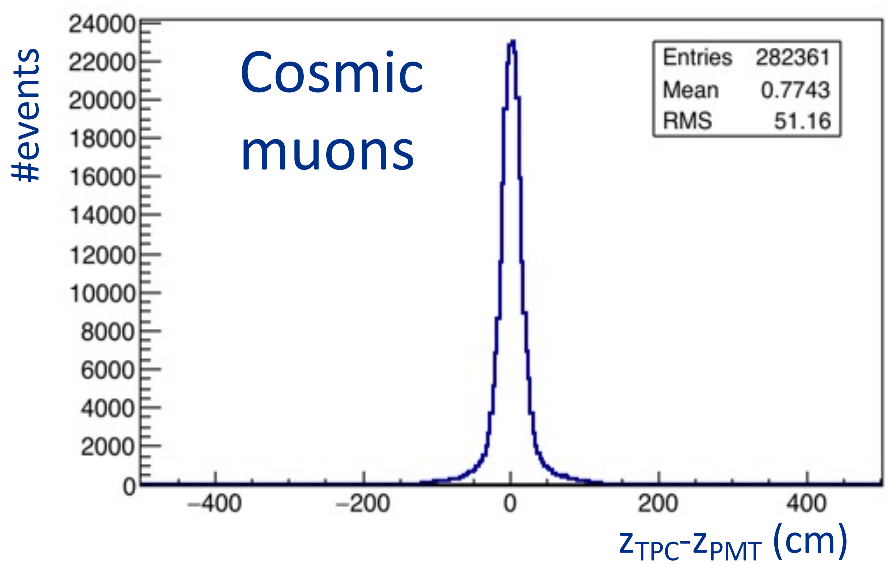


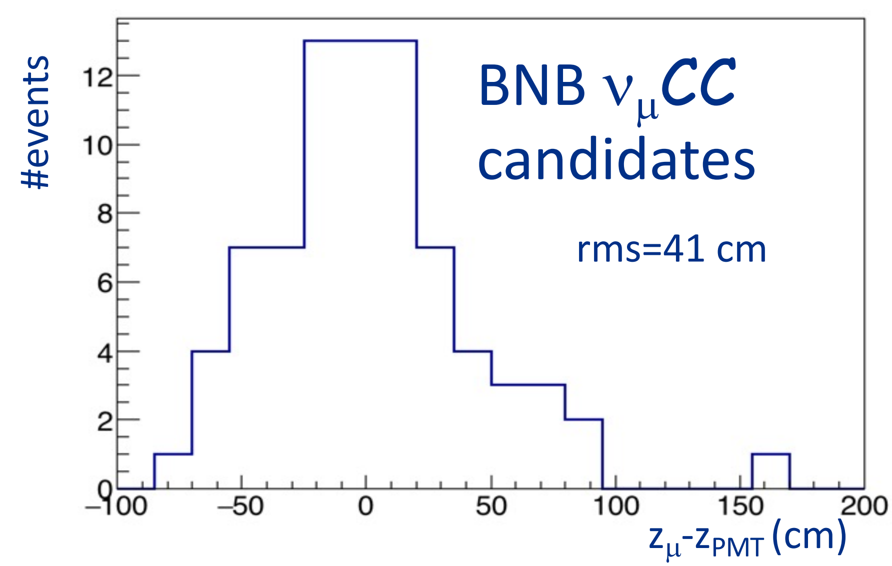




Longitudinal localization of the event with the light

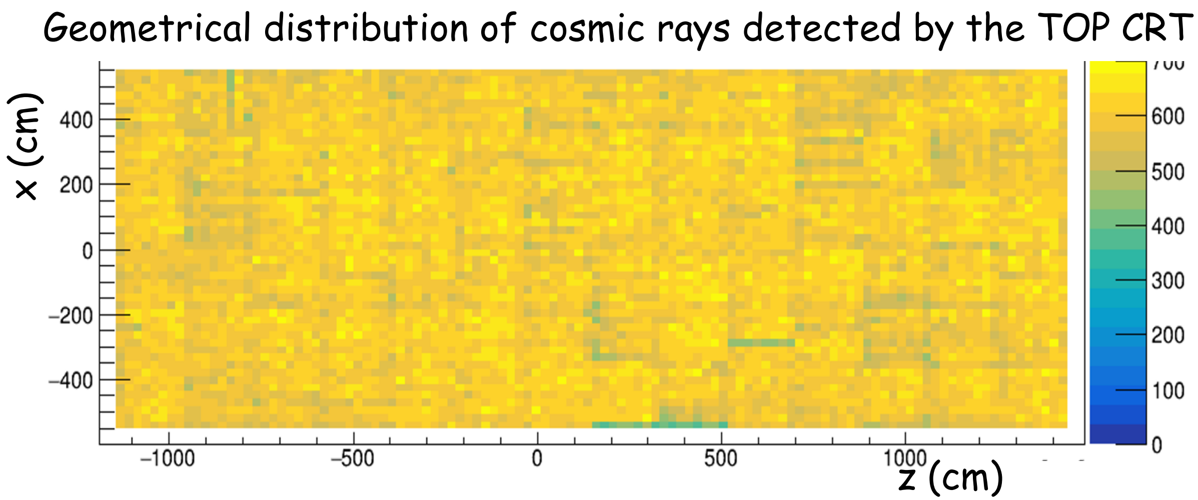
- A validation of the simple algorithm comparing the track and the light barycenter (z_{TPC}, z_{PMT}) was performed with cosmic muons in the RUN0 dataset (docdb 23574 and 23665).
- A similar study was performed on a set of 78 BNB ν_μCC candidates with L_μ > 50 cm identified by scanning: the average 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.

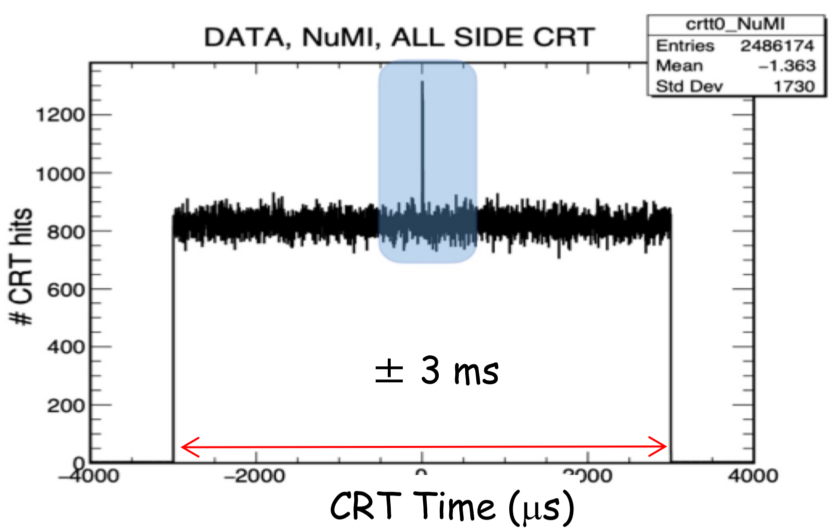


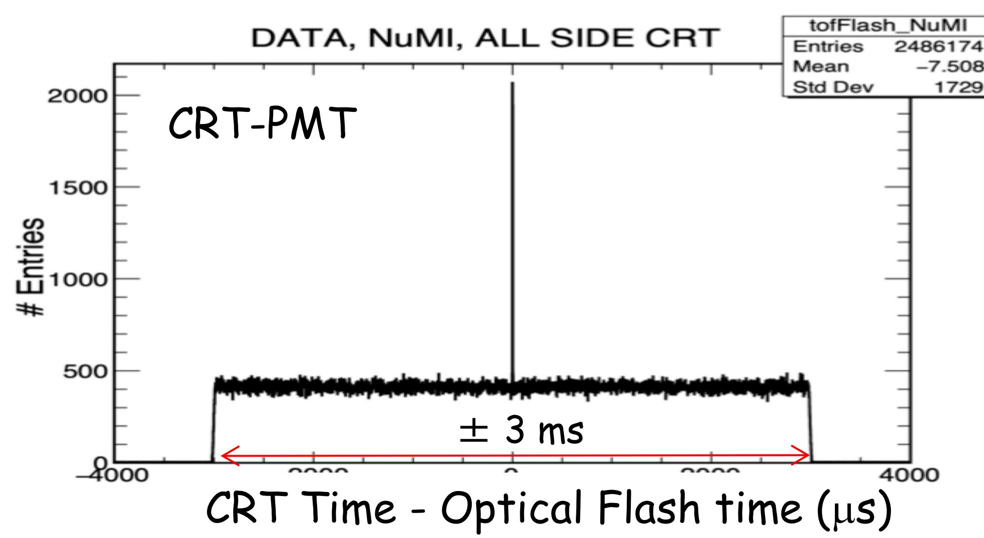


CRT reconstruction

- Validation of the time reconstructed by the CRT. Initial studies confirm the match of side CRT and PMT in events collected triggering only on the NuMI beam spill. The detailed study of the time resolution is ongoing.

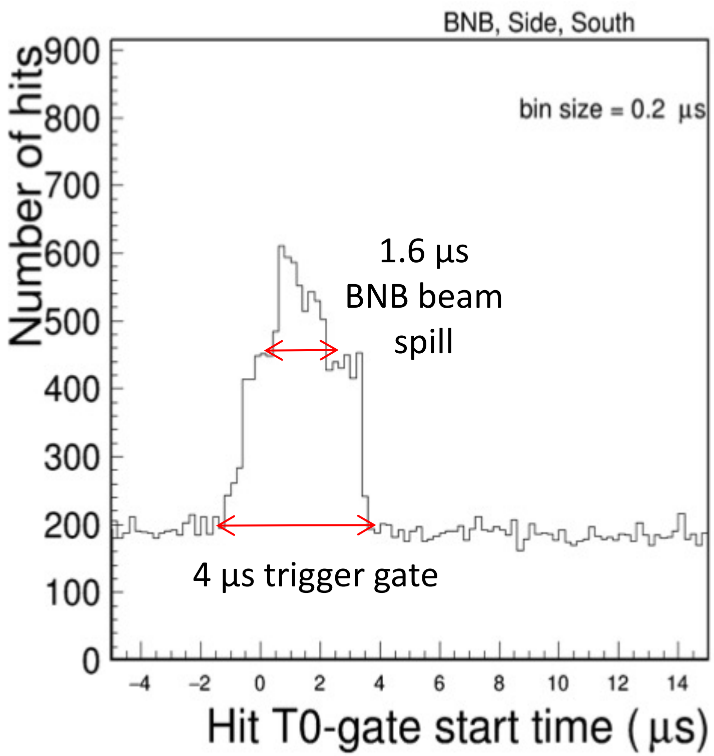


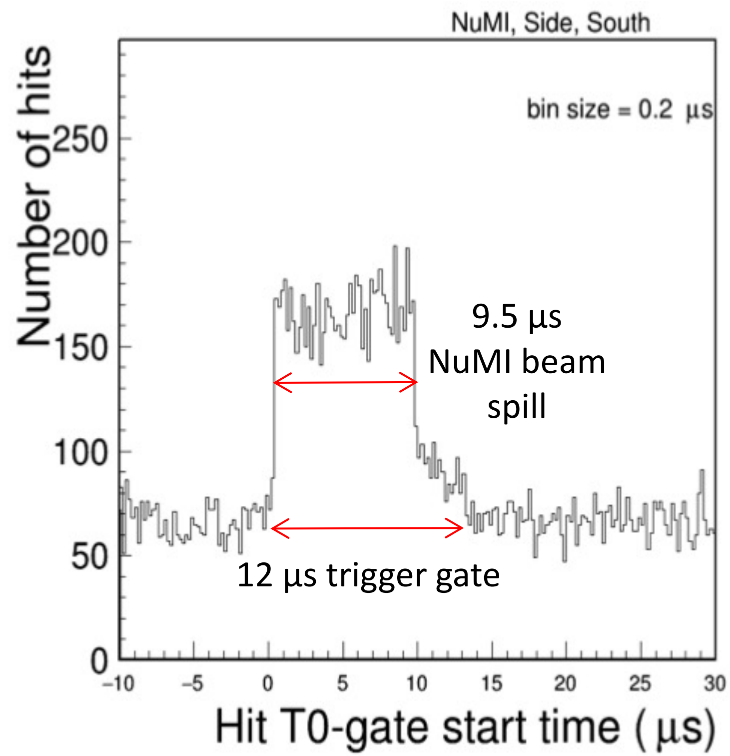




CRT reconstruction

- Side CRT time reconstruction relative to the gate start time





- Coincidence gate windows were extended to 4 μs (BNB) and 12 μs (NuMI).
- Excess of CRT activity during the gate is due to trigger bias, the beam activity is visible as a further activity during the 1.6 μs/9.5 μs beam spill arrival time for BNB/NuMI

Summary

- The ICARUS detector has operated steadily since its activation, on August 28th 2020. From the technical standpoint most subcomponents have met, if not exceeded, the expected performance.
- Installation and commissioning are approaching completion, with just a few blocks of concrete overburden left to be deployed.
- A full time (24/7) neutrino beam run was carried out for one month in 2021 before the summer shutdown of the beams, to assess the status of the detector operation before installing the top CRT and the overburden. A part time (at least weeknights & full weekends) neutrino beam run is ongoing since Nov 5th.
- The data collected so far with both cosmic rays and neutrinos from both 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!