# Status of the ICARUS Detector

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FNAL – INFN

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# Outline

- ✓ICARUS Collaboration
- ✓Detector status and stability
- ✓CRT Status
- ✓Liquid argon refill and LAr purity
- ✓Neutrino event gallery
- ✓Neutrino data taking
- ✓Commissioning status and plans
- ✓Initial neutrino physics
- ✓Conclusions

# ICARUS Collaboration at SBN

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11 INFN groups, 11 USA institutions, 1 Mexican institution, CERN

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3. CINVESTAV, Mexico
4. Colorado State University, USA
5. Fermi National Accelerator Lab., USA
6. INFN Bologna and University, Italy
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15. INFN Padova and University, Italy
16. INFN Pavia and University, Italy
17. SLAC National Accelerator Lab., USA
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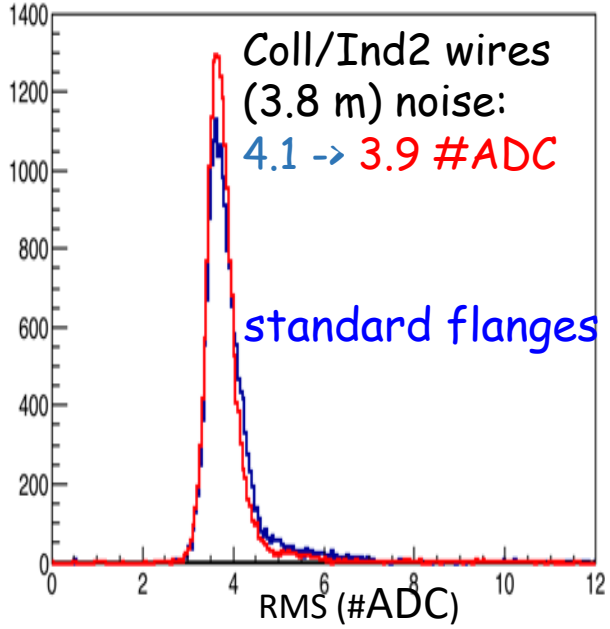
a On Leave of Absence from INFN Padova
b On Leave of Absence from INFN Pavia

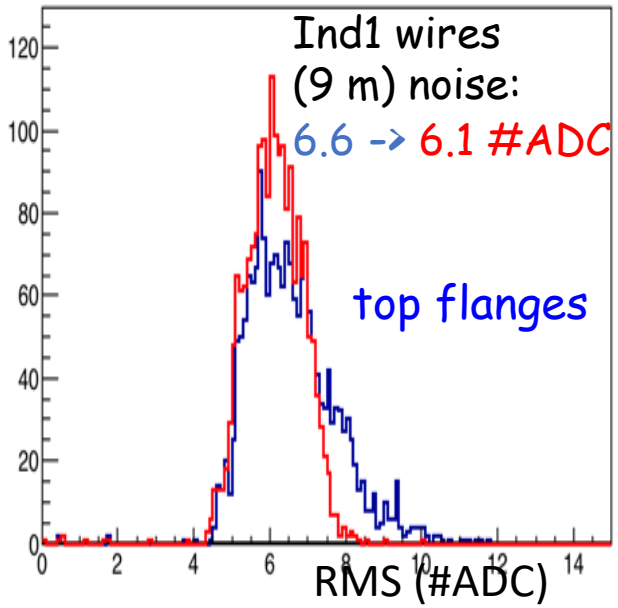
# Detector Status and Stability

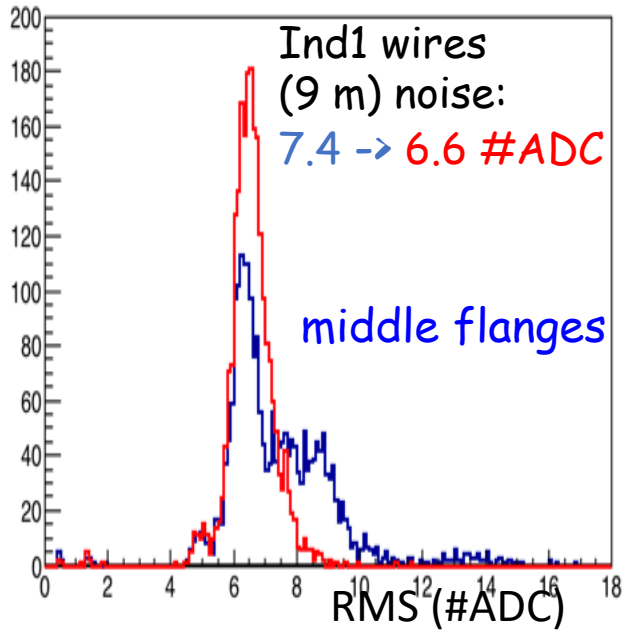
- ✓ Starting from September 2020, both the TPCs and the PMTs are running without significant interruptions or issues.
  - ✓ No major adjustments in the TPCs operating conditions have been made or are considered as necessary;
    - ✓ Interventions on some readout boards were successfully done, last December, to reduce the noise; additional interventions are planned, pending the possibly to travel from Italy, to extend the intervention to remaining boards.
  - ✓ PMTs operation is remarkably stable since their activation, in July 2020:
    - ✓ No PMTs have stop working, except from 3, that were not working from the beginning;
    - ✓ Few dead HV channels required the swap on available spare channels;
    - ✓ No significant drift in the operating parameters is observed;
    - ✓ First level calibration was performed in the summer and fine adjustment of the calibration is in progress.
  - ✓ Trigger system is still under commissioning;
- ✓ Networking has been upgraded to the final configuration with spare servers and connections;
- ✓ Slow controls are performing steadily and are continuously upgraded to add more components.

# TPC electronic noise mitigation

- ✓ ICARUS LAr-TPC has been recording cosmic tracks since its activation. AFTER LAr filling the electronic noise has increased by ~30% in all TPCs, well above expectations from LAr dielectric effect. However not preventing neutrino events collection.
- ✓ A test campaign on December '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

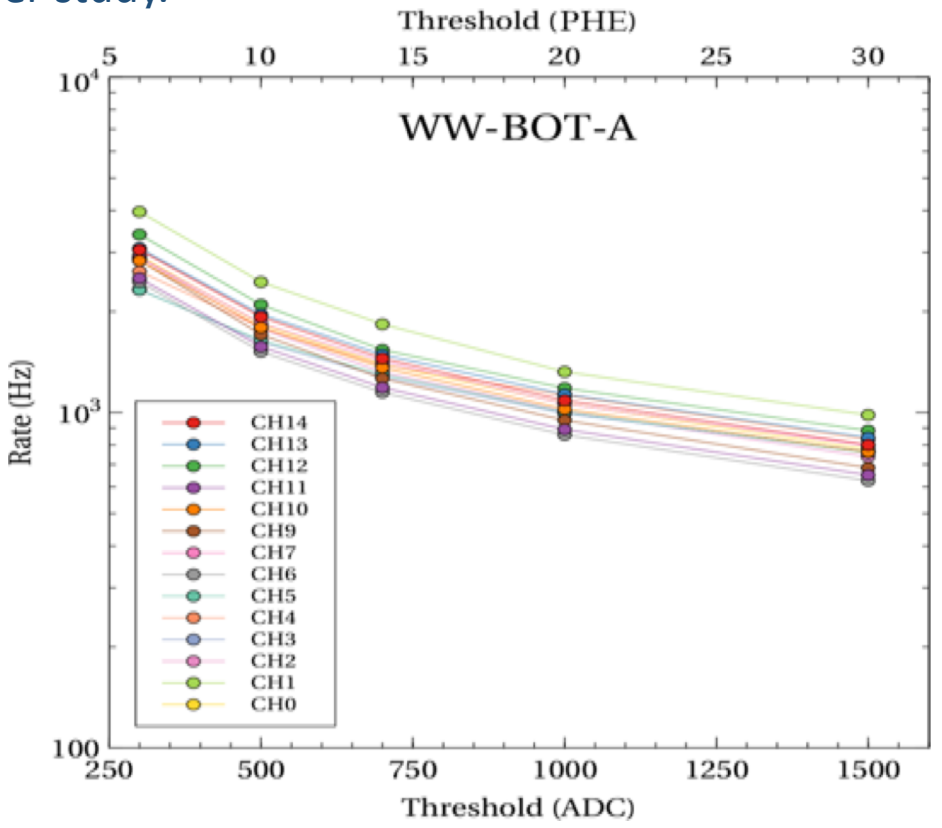
- ✓ Investigations performed at FNAL allowed to exclude potential noise sources, such as TT-Link trigger/clock, cathode HV, wire bias and test-pulse distribution systems: need of a deep investigation of coherent noise on all signal flanges... But extremely difficult to implement within the pandemic: a test-bench in Padova is studying this issue.

# Scintillation Light System status

- ✓ All PMTs were activated after the LAr filling: they are working correctly except 3 units located in 3 different TPCs, already marked as not-working during the vacuum test. The PMT system has been extensively employed for calibration purposes and now being integrated in the trigger system.
- ✓ PMT calibration activity is in progress to equalize the gain to G = $10^7$ using both Laser light pulses and single photoelectron (phe) from background (~50 kHz per PMT). PMT timing calibration is under study.
- ✓ The PMT HV system is remotely controlled by means of a GUI interface allowing PMT voltages monitoring and setting during regular shifts.
- ✓ PMT rates vs. the signal discrimination threshold have been measured:
  - ✓ Uniform behavior among different PMTs.
  - ✓ The recorded rates are being compared with expectation from MC simulation.

The light detection system shows an excellent stability.

Example of discrimination rates for 15 PMTs: threshold values are in ADC# (0.122 mV per ADC#) corresponding to 50 ADC#/phe (the signal discrimination refers to the prompt scintillation light emission).



# CRT Status

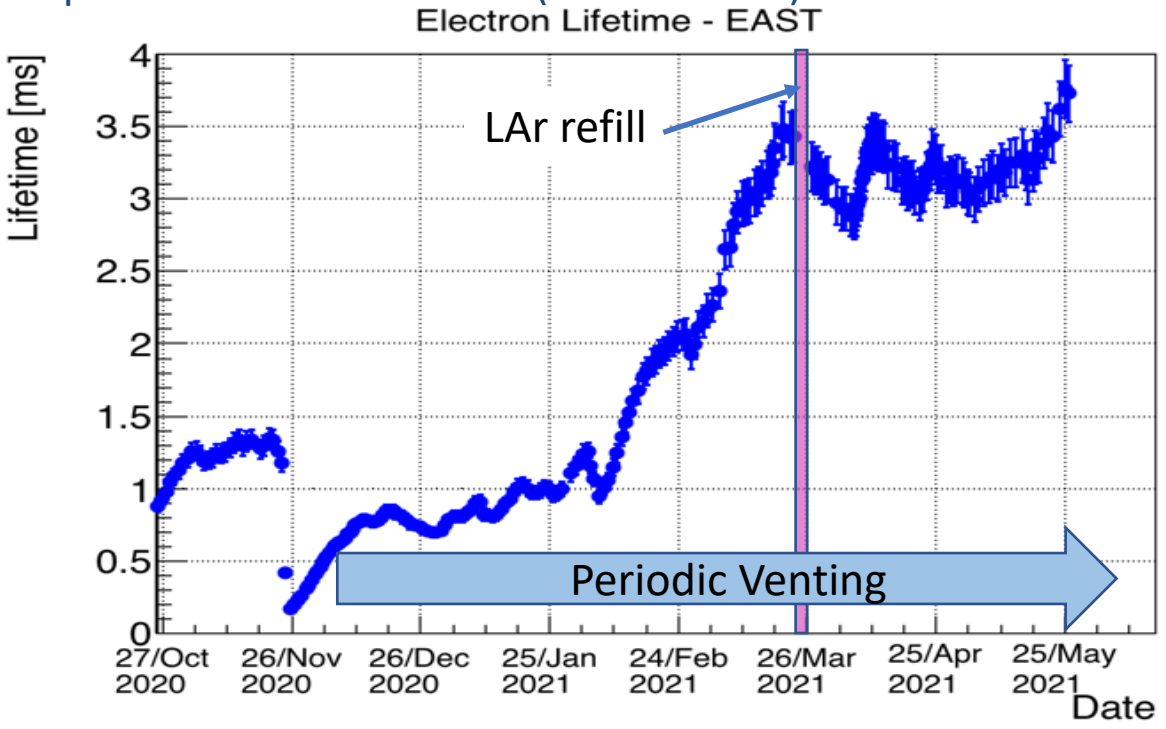
- ✓ Installation of the last wall of the side CRT has been completed, including the readout and cabling. Commissioning of the the last side CRT wall is starting.
- ✓ Top CRT arrived at Fermilab.
- ✓ Several ongoing activities: noise study on side CRT, side CRT Data/MC comparison, work on the CRT hits reconstruction

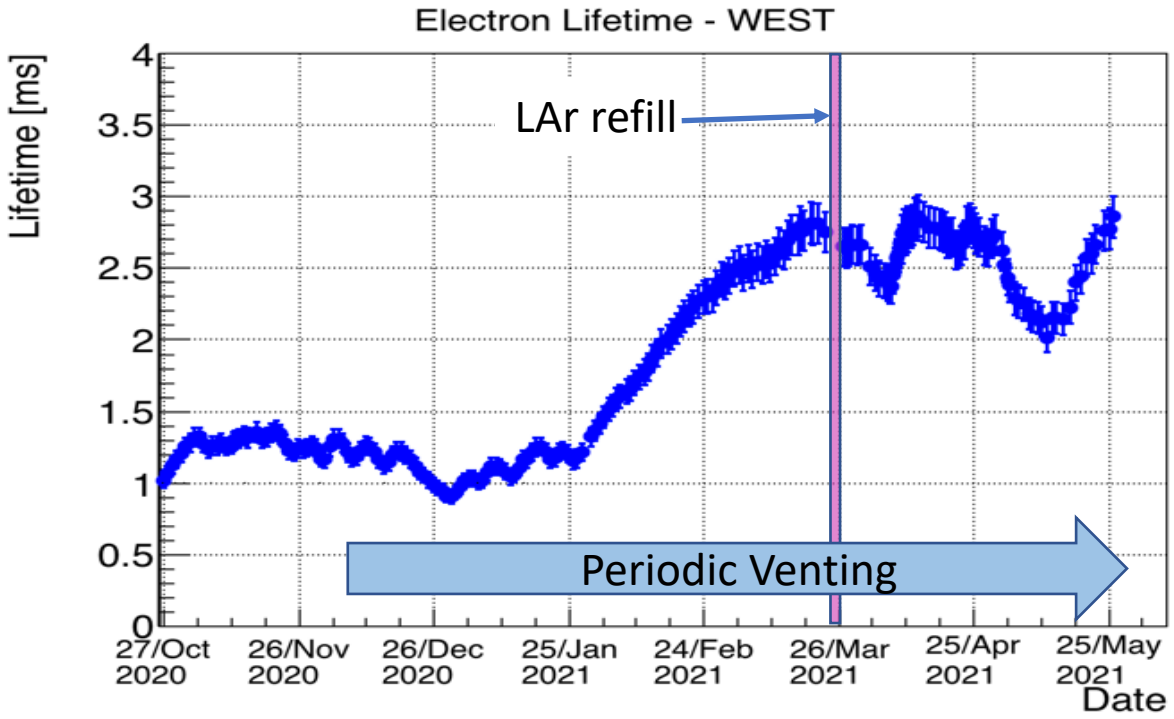
**South wall installed**

**Top CRT Modules at FNAL warehouse**

# Liquid argon refill and LAr purity

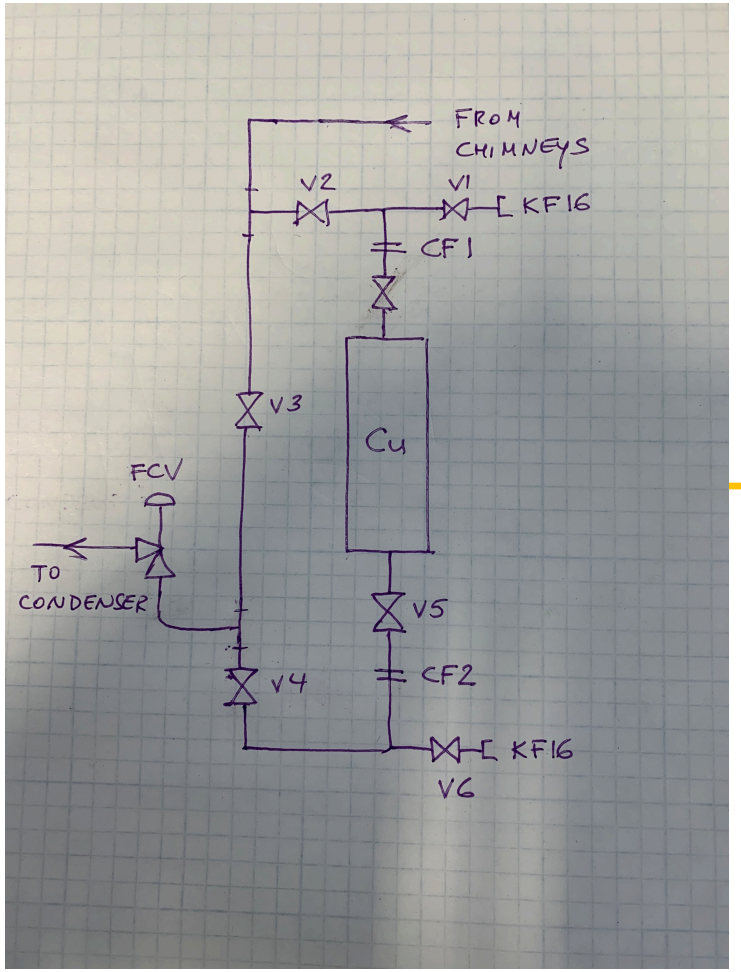
- ✓ ICARUS cryogenic system steady and well performing. All GAr filters re-generated and LN2 and LAr pumps maintained.
- ✓ The two South GAr recirculation units were modified, to increase performance. All 4 units performing well and steadily.
- ✓ LAr refill on March 24 (≈ 5000 liters) to bring the level 1.5 cm above the nominal level:
  - ✓ Smooth operation: ≈ 12 hours. No instabilities have been observed.
- ✓ April 7 to April 9: 1 day of continuous venting at 20 g/s/module and 2 days at 15 g/s/module to check the effect on the purity
- ✓ April 19: second LAr refill (≈ 2500 liters).

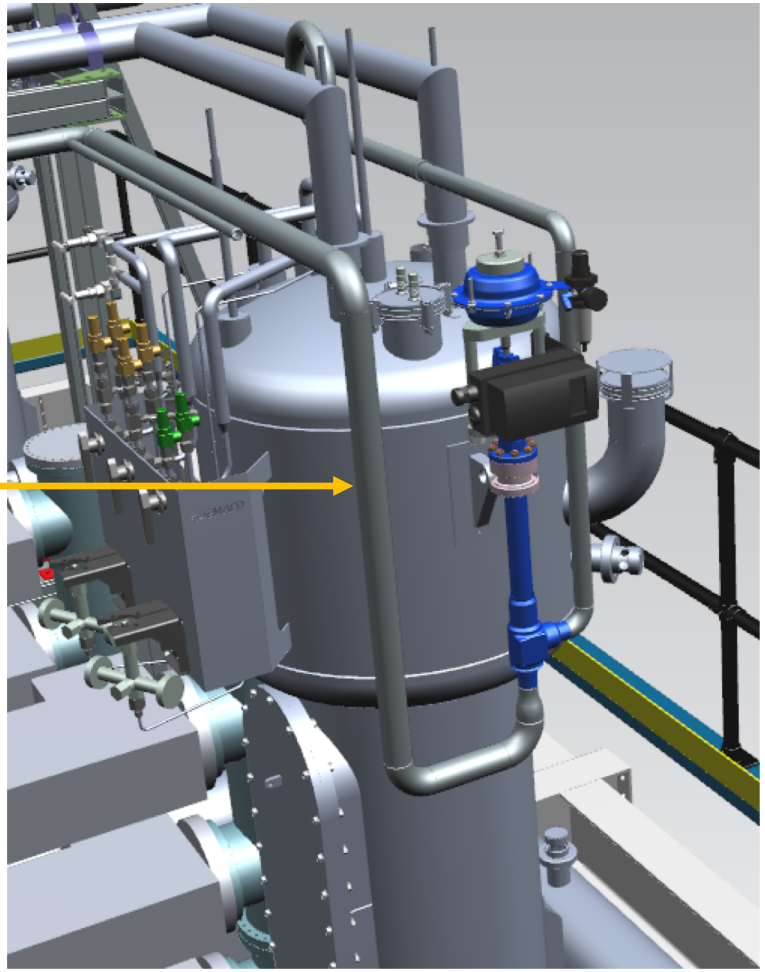


# Additional warm filters on the GAr collectors

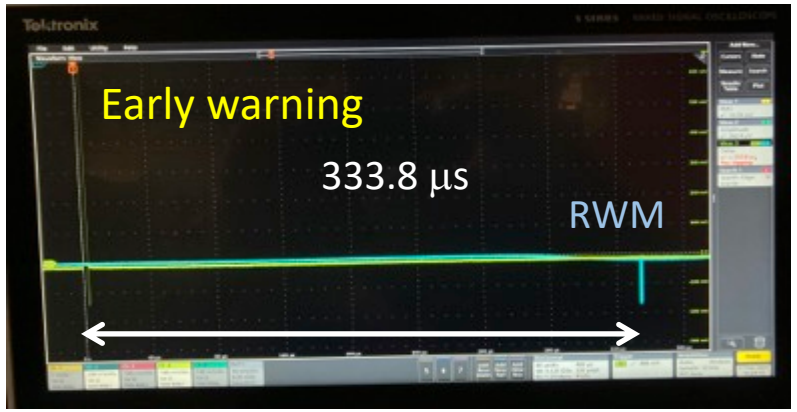
- ✓ The new cartridges have been constructed and tested at CERN.
- ✓ Delivery, from the vendor, of the mechanical filters that are to be installed at the two ends of the cartridges, has been delayed to the end of April.
- ✓ Parts for the modification of the argon gas collectors ar at Fermilab.
- ✓ Planning for modification is ongoing. Execution will be performed during the summer beam shutdown.



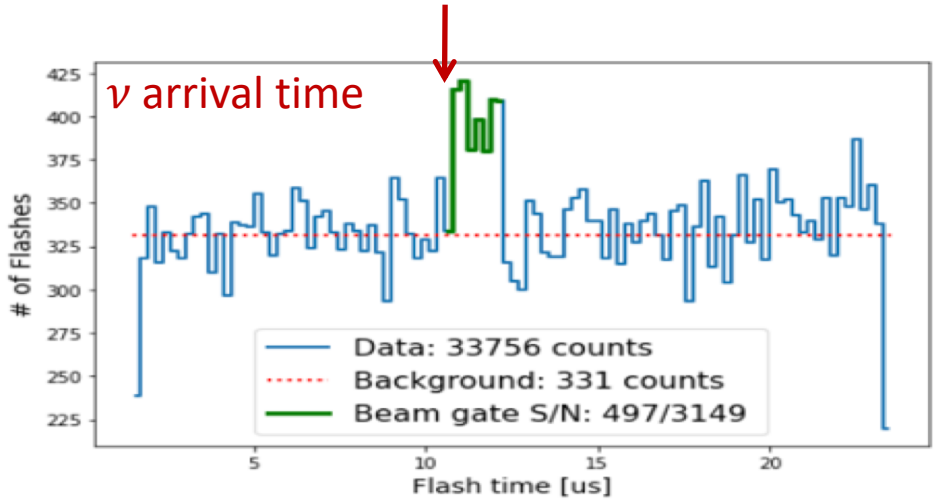



# Initial Trigger system activation: first Booster neutrino events

- ✓ DAQ event building was initially tested matching in time PMT signals and corresponding TPC track of cosmic muons traversing the full TPC drift.
- ✓ A two steps trigger deployment is taking place to verify the electronic chain/exercise DAQ in the EAST module, in parallel with the full trigger system development:
  1. "spill only – minimum bias trigger", based on BNB Early warning signal of p extraction distributed by White Rabbit ~0.33 ms in advance to read-out both TPCs and PMTs;
  2. Addition of scintillation light signals in coincidence with the BNB spill.
- ✓ Trigger timing set by PMT signals associated to 1.6 μs beam spill (νs + accompanying μs) in excess to cosmics: ~335 μs added to early warning to account also for $\nu$ tof from target.



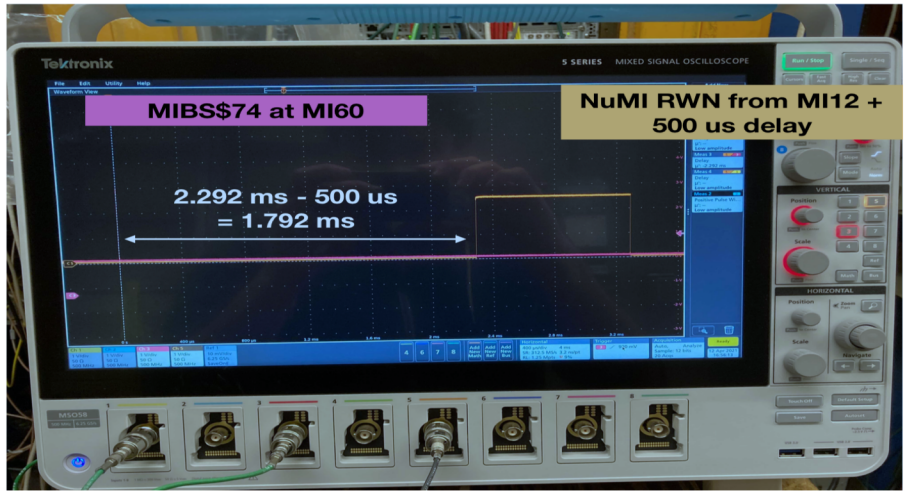

Time interval (scope) between Early warning signal and actual Booster p extraction measured by RWM counters at target.



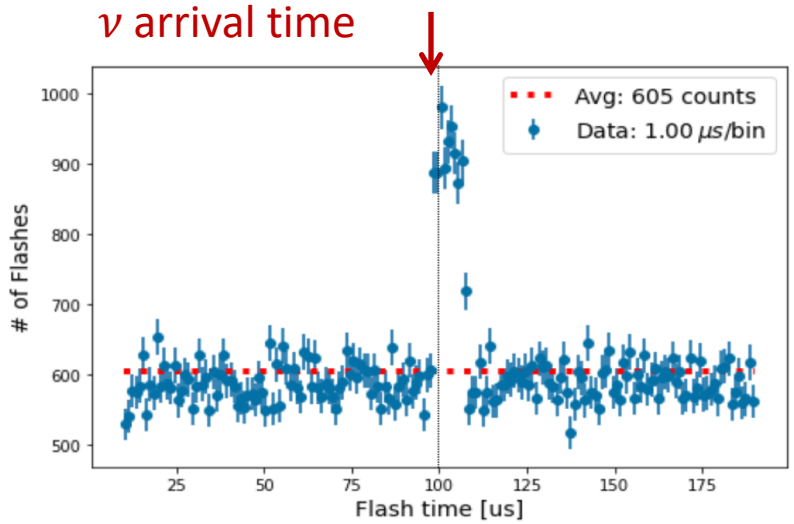

Time distribution of PMT light flashes (>10 fired PMTs in coincidence in left and right TPCs): beam event excess observed at expected $\nu$ arrival time.

# Initial Trigger system activation: NuMI beam

- ✓ NuMI Early warning signal of proton extraction spill (9.5 μs) is distributed by White Rabbit ~1.8 ms in advance. Procedure similar to commissioning of BNB:
  a) Time interval between Early warning signal (MIBS$74) and p extraction signal (RWM counters at target) has been measured at oscilloscope;
  b) 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 has been verified in a dedicated test run recording PMT signals only;
  c) Setup of minimum-bias NuMI trigger to record all ICARUS detector components (PMT, TPC and side CRT) at each p beam extraction.




Time interval (scope) between Early warning signal and the actual NuMI p extraction measured by RWM counters at target.

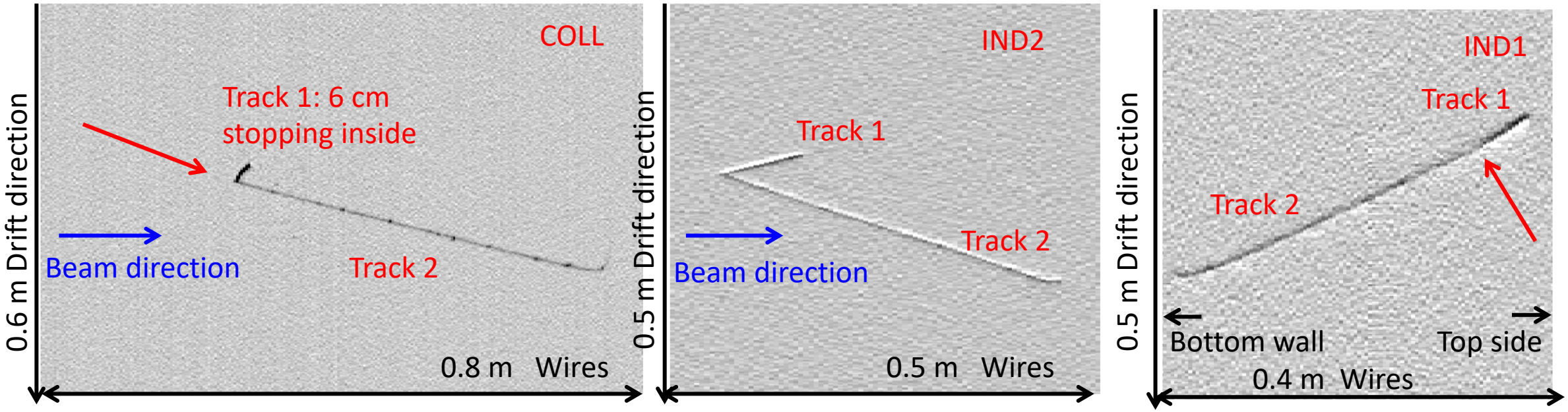



Time distribution of PMT light flashes: beam event excess observed at expected $\nu$ arrival time.

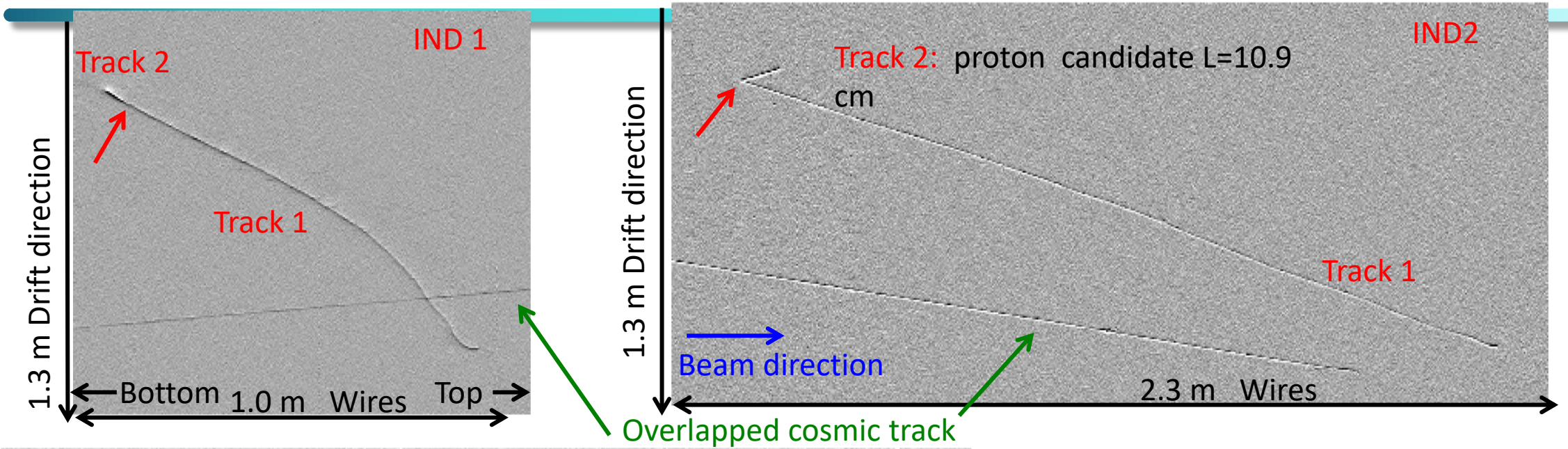
# BNB QE νμ CC candidate, e- lifetime τ ~ 1 ms

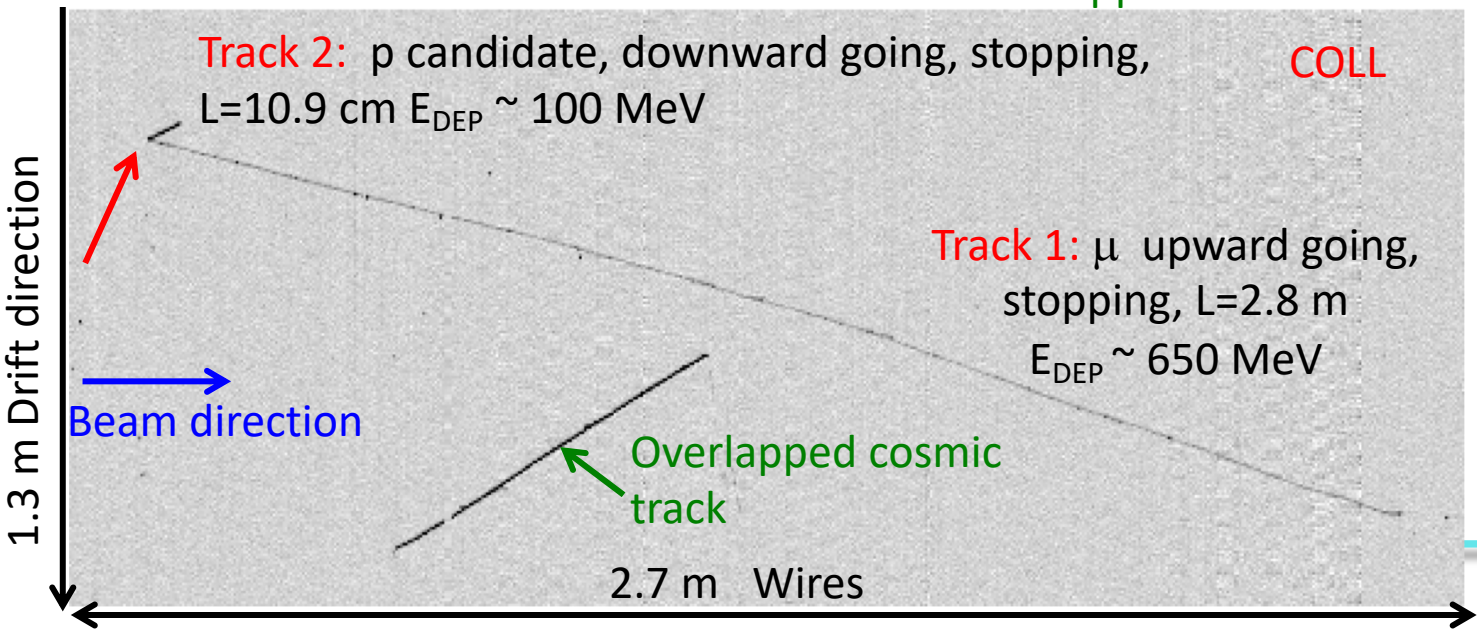
- ✓ Vertex (red arrows) is located at 29 cm from bottom. Two tracks are produced (total $E_{DEP}$ = 170 MeV):
  - ✓ Track 1 upward going, stopping inside L= 6 cm: proton candidate, $E_K$ ~ 70 MeV from range.
  - ✓ Track 2 downward going, exiting on bottom, L= 51 cm: possible μ candidate, $E_{DEP}$ ~100 MeV.

Interaction vertex recognized also in Induction1 view by dE/dX. Note the bipolar signal shape by the new electronics in Induction2 wires relative to e- transit from Induction1 to Collection wire planes.

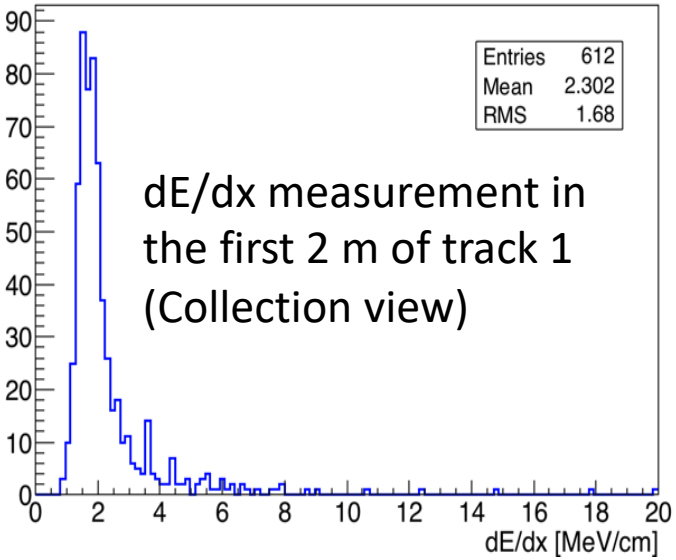


# BNB contained QE νμ CC candidate, e- lifetime τ ~ 1.2 ms

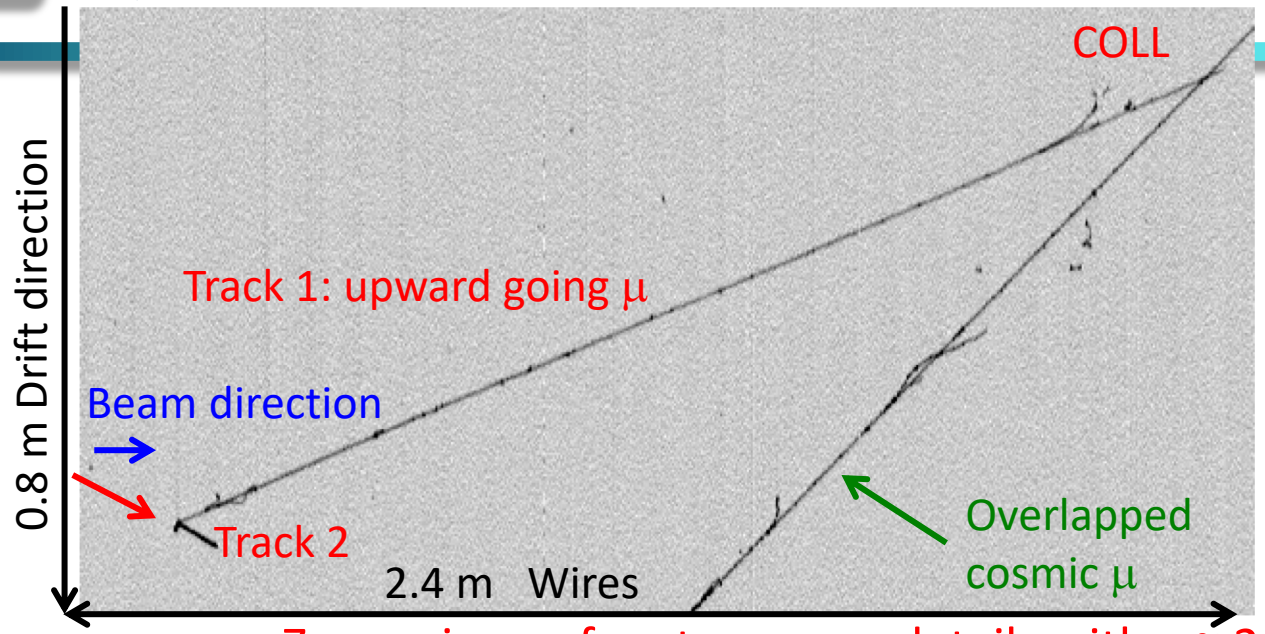



Total $E_{DEP}$ ~ 750 MeV

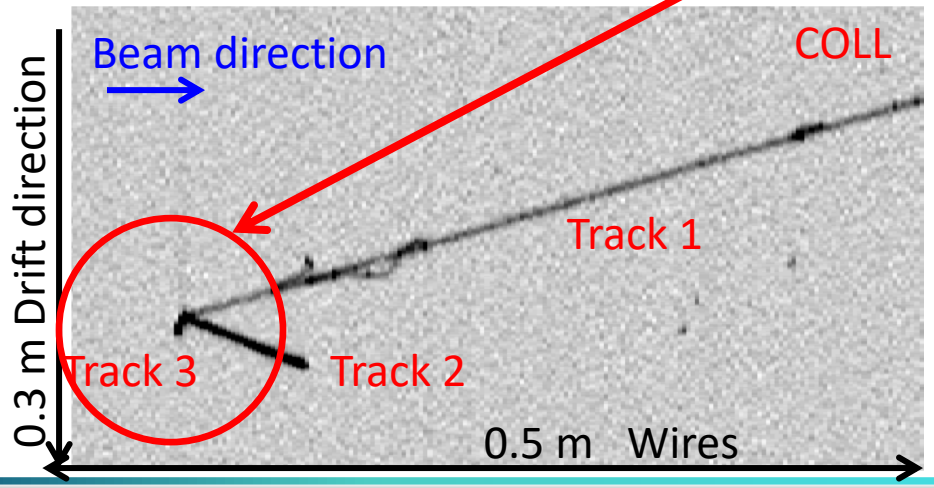


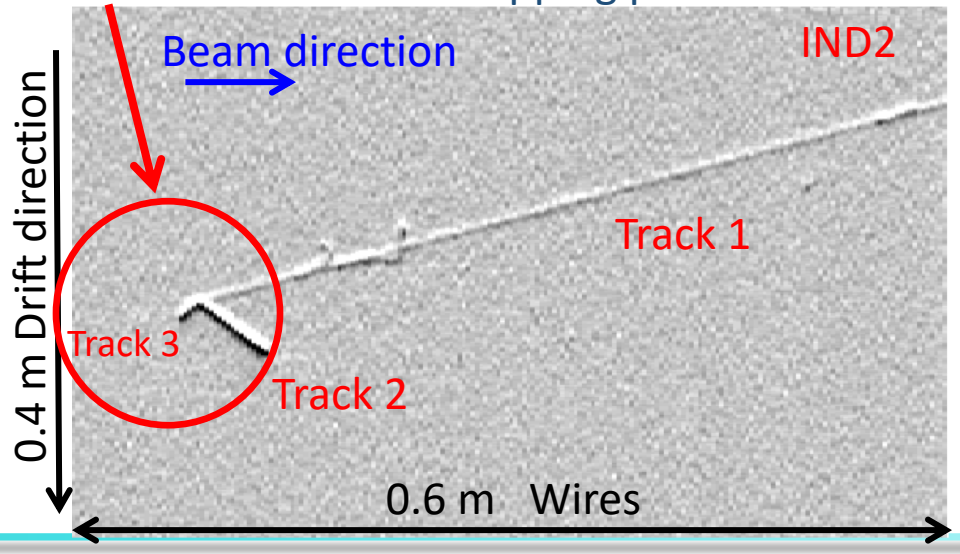
# νμ CC candidate, e- lifetime τ ~ 2.7 ms



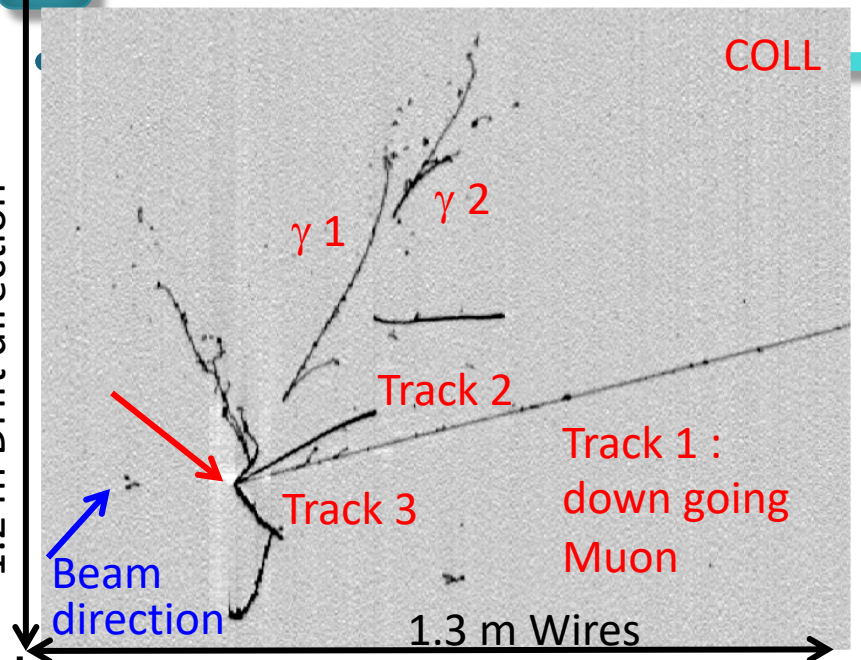

- ✓ Three particles produced at vertex, located at center of the TPC (red arrow and circles):
  - ✓ Track 1 μ candidate crossing the cathode and exiting through top wall L= 5.5 m, ~2 GeV/c momentum as evaluated by MCS;
  - ✓ Track 2 downward going stopping proton candidate L=10 cm, $E_K$ ~ 110 MeV;
  - ✓ Track 3 (visible in the zoom) downward going stopping proton candidate L= 2 cm.

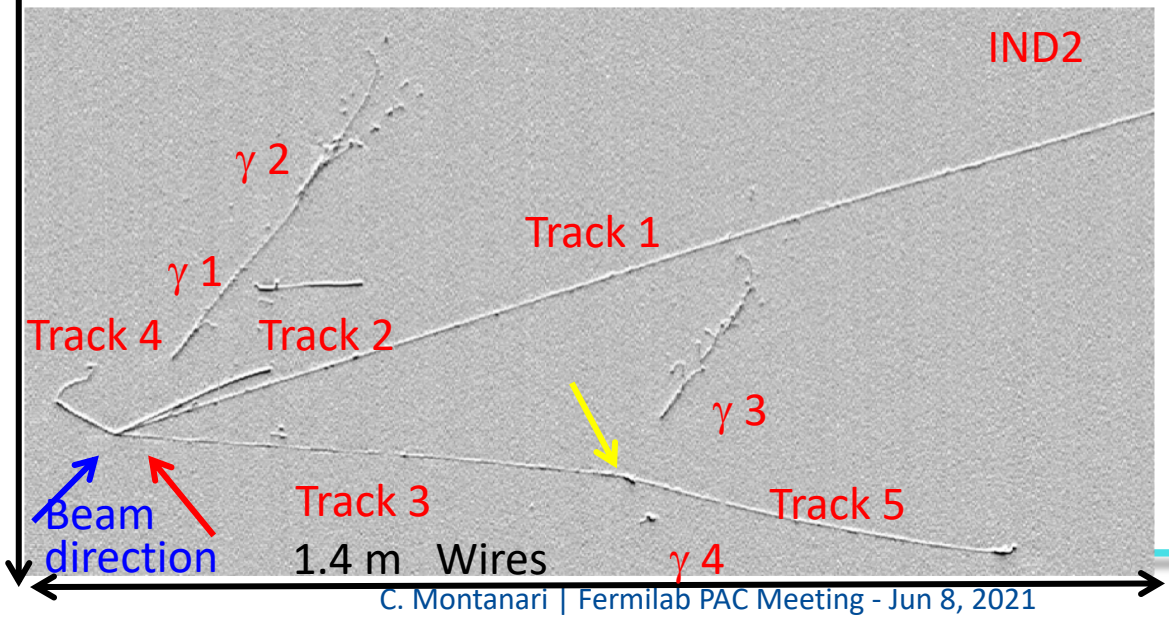
Zoom views of vertex: more details with τ ~ 2.7 ms !



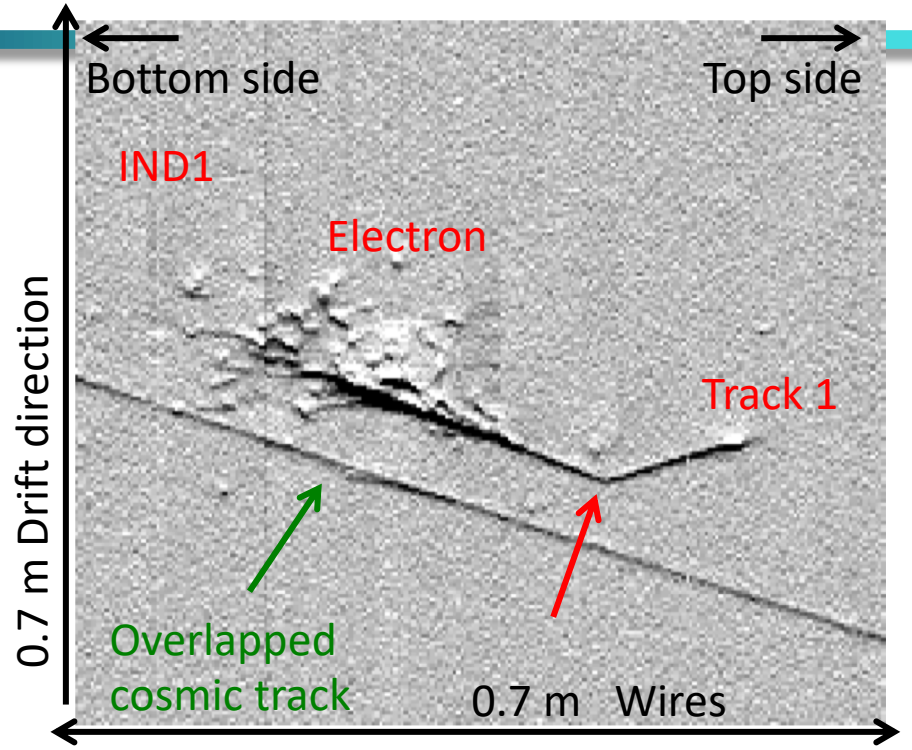
# NuMI νμ CC candidate, e- lifetime τ ~ 3.2 ms

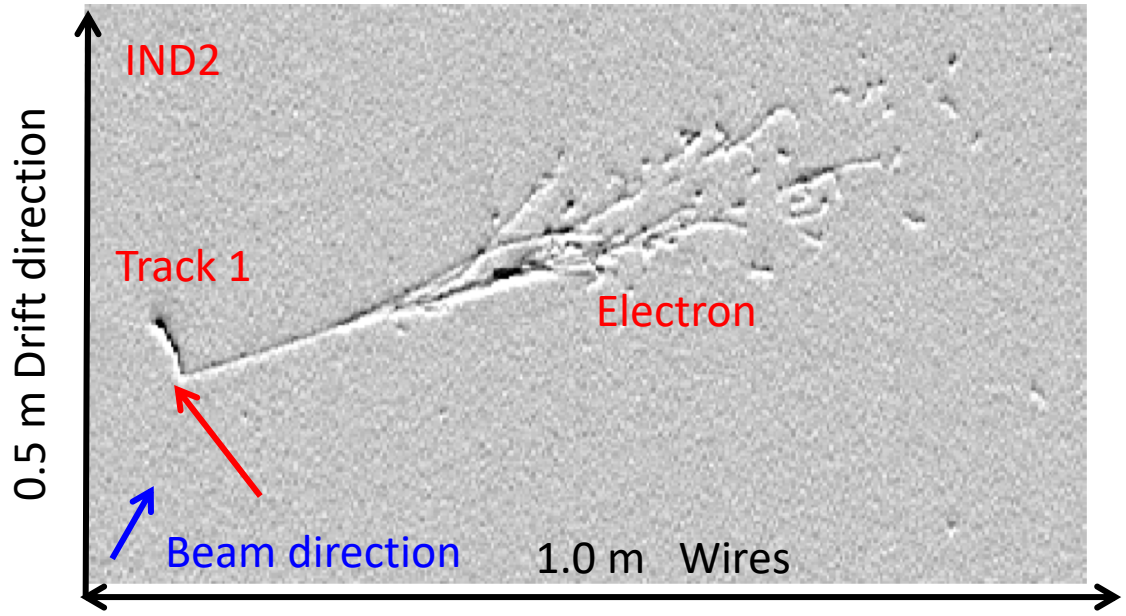



- ✓ Five particles produced at the primary vertex (indicated by red arrows), $E_{DEP}$ ~ 2.5 GeV:
  - ✓ Track 1: downward going μ, crossing the cathode and exiting downstream, L= 4.2 m, p~ 1.3 GeV/c by MCS;
  - ✓ Track 2: upward going *p* candidate, L=31 cm;
  - ✓ Two photons $\gamma_1$, $\gamma_2$ are pointing to the primary vertex, $E_1$ ~ 200 MeV, $E_2$~ 240 MeV and converting at 18 cm, 58 cm distance respectively;
  - ✓ Track 3: hadron that produce a secondary vertex (marked by the yellow arrow) where a short proton, another hadron (Track 5) and two photons $\gamma_3$, $\gamma_4$ are also clearly visible;
  - ✓ Track 4: charged pion with visible Michel electron produced in the π -> μ -> e decay chain.

# NuMI νe CC QE candidate, e- lifetime τ ~ 3.2 ms

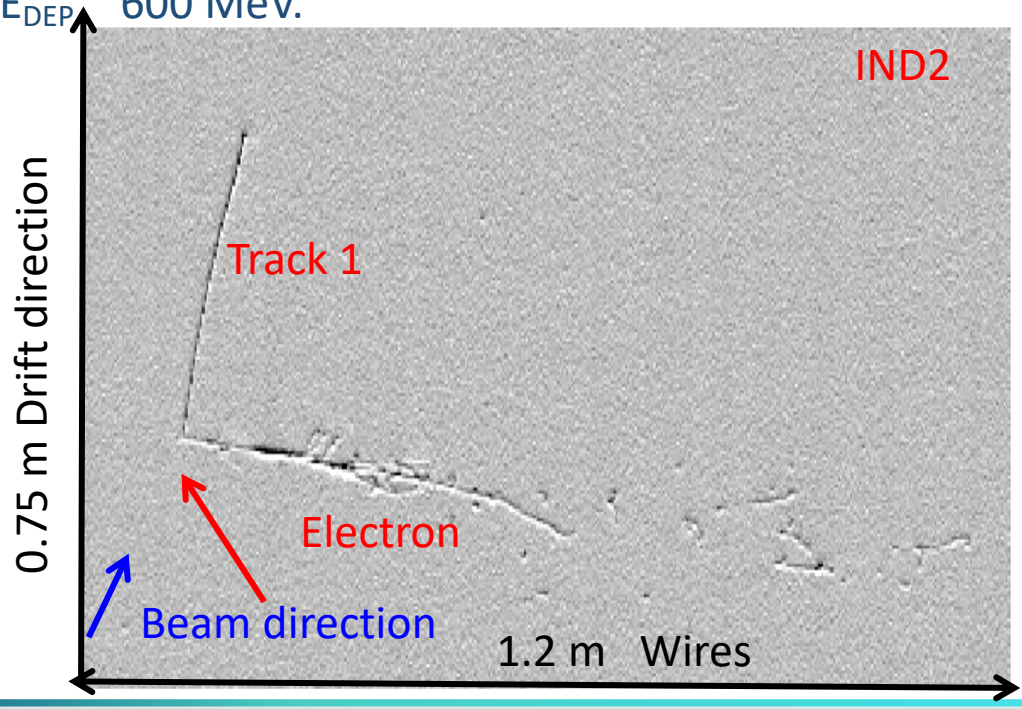


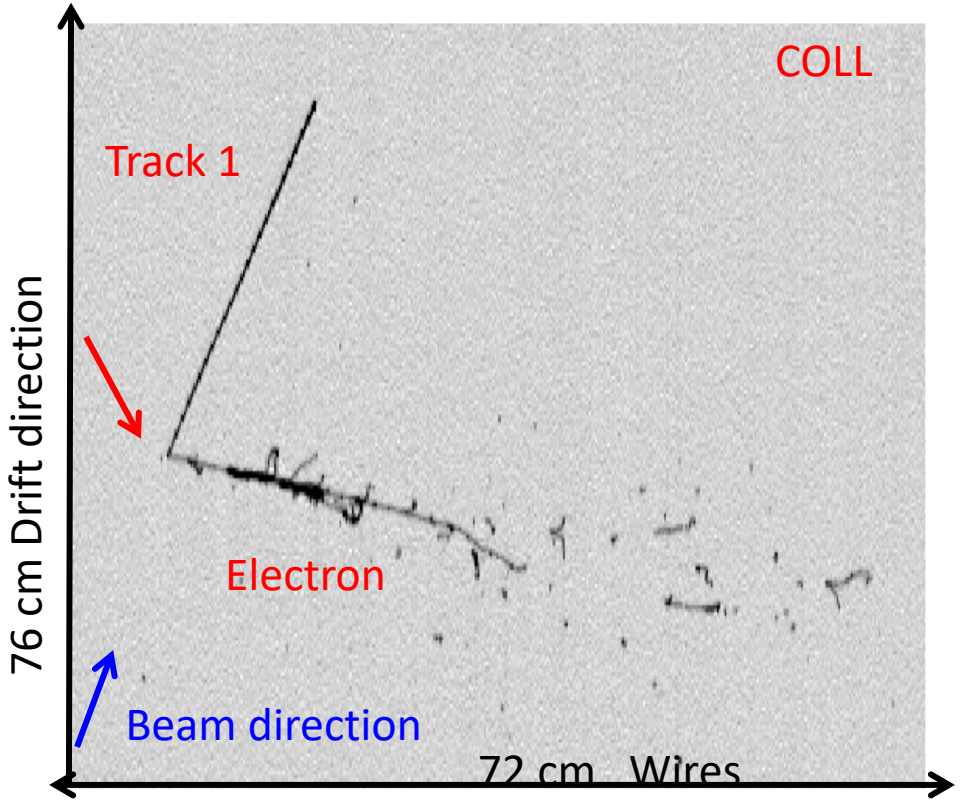




- ✓ QE electron neutrino candidate with two particles at the primary vertex (indicated by red arrows), $E_{DEP}$ ~ 870 MeV:
  - ✓ Track 1 is the upward going proton candidate stopping inside L= 13 cm;
  - ✓ The electron shower is downward going: the beginning of the shower is clearly visible in Induction1,2 views (in Collection the *e* and track 1 are overlapped).

# NuMI νe CC QE candidate, e- lifetime τ ~ 3.2 ms

- ✓ Contained Q.E. electron neutrino candidate with two particles at the primary vertex (indicated by red arrows), $E_{DEP}$ ~ 800 MeV:
  - ✓ Track 1 is the upward going hadron track stopping inside L= 43 cm: proton or pion candidate;
  - ✓ The beginning of the electron shower is clearly visible, $E_{DEP}$ ~ 600 MeV.



# First Neutrino data taking

- ✓ **The advancement in the detector commissioning process, the reached nominal free electrons lifetime and the detector operational stability recognized at the last ICARUS Collaboration meeting (March 16-17, 2021) allowed to initiate the ICARUS data taking collecting steadily neutrino beam events with the full PMTs + TPCs and lifetime > 2.7 ms:**
  - ✓ Since end of March BNB neutrinos has been initially collected overnight with minimum bias trigger (beam only gate: data are collected for every spill). Commissioning activities (trigger development, PMTs calibration, CRT, ...) taking place during the day. NuMI beam trigger has been added in the second half of April.
  - ✓ The delivered POT number is monitored spill-per-spill.
  - ✓ This running mode has been proven very stable. Average run duration is > 9 h.
  - ✓ Raw data are written to tape. A simple light filter is used to down-select events that contain light activity in coincidence with the BNB 1.6 μs spill gate for higher level processing (e.g TPC reconstruction): reduction factor in the data load ~1/30.
  - ✓ Collected events are used to setup the software infrastructure for data processing/storage and workflow management.

- ✓ **Since May 30th, we started full time (24/7) neutrino beam run:**
  - ✓ Run coordination is active with A. Scarpelli as Run Coordinator and A. Fava as Deputy;
  - ✓ ICARUS is now the primary BNB user.

| Beam | Neutrinos interactions per spill | Data collected on disk | | |
|---|---|---|---|---|
| | | # of spills | POT ( E20 ) | Time (H:M:S) |
| BNB | 1/180 | 6821856 | 0.25 | 452:39:42 |
| NuMI | 1/15 | 428380 | 0.18 | 178:58:09 |

# Getting ready for the physics run in October

- ✓ The present neutrino run will continue until the summer shutdown to be restarted with the first physics run in October.
- ✓ Collected data are being analyzed and used for the tuning of the event reconstruction software tools:
  first results will be presented at summer conferences.
- ✓ During the summer shutdown:
  - ✓ Commissioning activities (calibrations, trigger development, ...) will be restarted with cosmic ray data.
  - ✓ Upgrades of the PMTs HV system and interventions on the TPC readout electronics (noise reduction) are planned.
  - ✓ Upgrade of the GAr recirculation system (insertion of warm filters with $H_2O$ removal) will be implemented.
  - ✓ Main installation activity will be the installation and commissioning of the Top CRT to be followed by the installation of the overburden.
  - ✓ Deploy a stable data processing, storage and related workflow.
  - ✓ Complete the automatic data transfer by RUCIO system from FNAL to CNAF (Italy), at present in preparation with FNAL and CNAF Computing Centers support. A suitable book-keeping database exploiting run metadata will be also prepared.

# Top CRT Installation

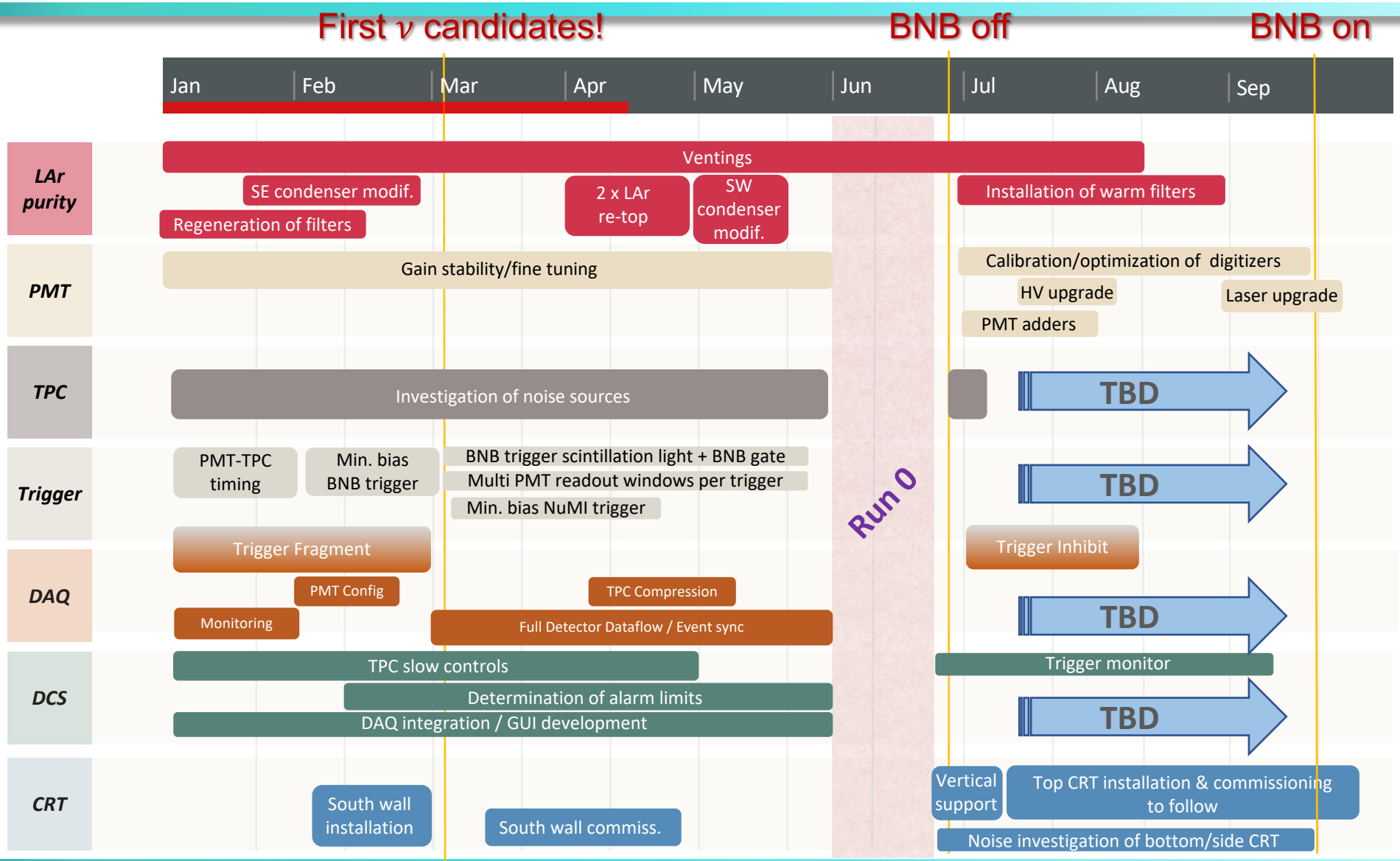
- ✓ CRT modules delivered from CERN and stored in the warehouse.
- ✓ Mounts for vertical modules:
  - ✓ The mount design has been modified for more rigidity and easier CRT module installation;
  - ✓ Installation requires grinding and welding above the detector
  - ✓ Delay the primary installation until summer shutdown to avoid conflict with beam run.
- ✓ Module installation planning:
  - ✓ ICARUS has identified 22 INFN collaborators (engineers, physicists and technicians) to come to Fermilab in teams to perform the CRT installation over a period of ~ 4 months;
  - ✓ Support from PPD and ND technicians;
  - ✓ Preparing for first team of four in July.
- ✓ Need to make sure installation does not interfere with detector commissioning or cryogenics work.

- ✓ Installation Schedule:
  - ✓ May-early July: modify and install vertical mounts (FNAL)
  - ✓ July: vertical modules (INFN+FNAL)
  - ✓ July-Aug: support beams, fire protection, and lighting (FNAL + subcontractors)
  - ✓ Aug-Oct: horizontal modules (INFN+FNAL)
  - ✓ Oct-Nov: commissioning (collaboration)

# ICARUS Overburden

- ✓ Start overburden installation *after* the Top CRT is commissioned to the point that no CRT module needs to be swapped
  - ✓ Current expectation - we reach this point in late October 2021
- ✓ Overburden consists of three layers of concrete blocks:
  - ✓ Bottom layer: 42” tall x 18” wide custom blocks that bridge the pit and carry the load of layers above, procurement of approximately $600k (budgetary quote Dec 2015)
  - ✓ Middle and top layers: 36” tall each using standard shield blocks mined from decommissioned Fermilab facilities – stacked west of the MINOS building.
- ✓ Procurement process started:
  - ✓ Bidding to obtain firm offers – both $ and delivery times
  - ✓ Bid package submitted to Fermilab procurement in early May
    - ✓ Includes option of SBND blocks (delivery ~ 1 year later)
  - ✓ Goal to have bids returned by end June
  - ✓ Commitment of funds in August to meet current timeline
- ✓ Expected delivery/installation timeline:
  - ✓ Start block delivery when CRT commissioned
  - ✓ Receive and install 10 blocks/week implies 6 weeks to install first layer
    - ✓ Blocks installed as they are delivered
  - ✓ Need an additional month to install layers 2 and 3

# High-level planning of commissioning activities



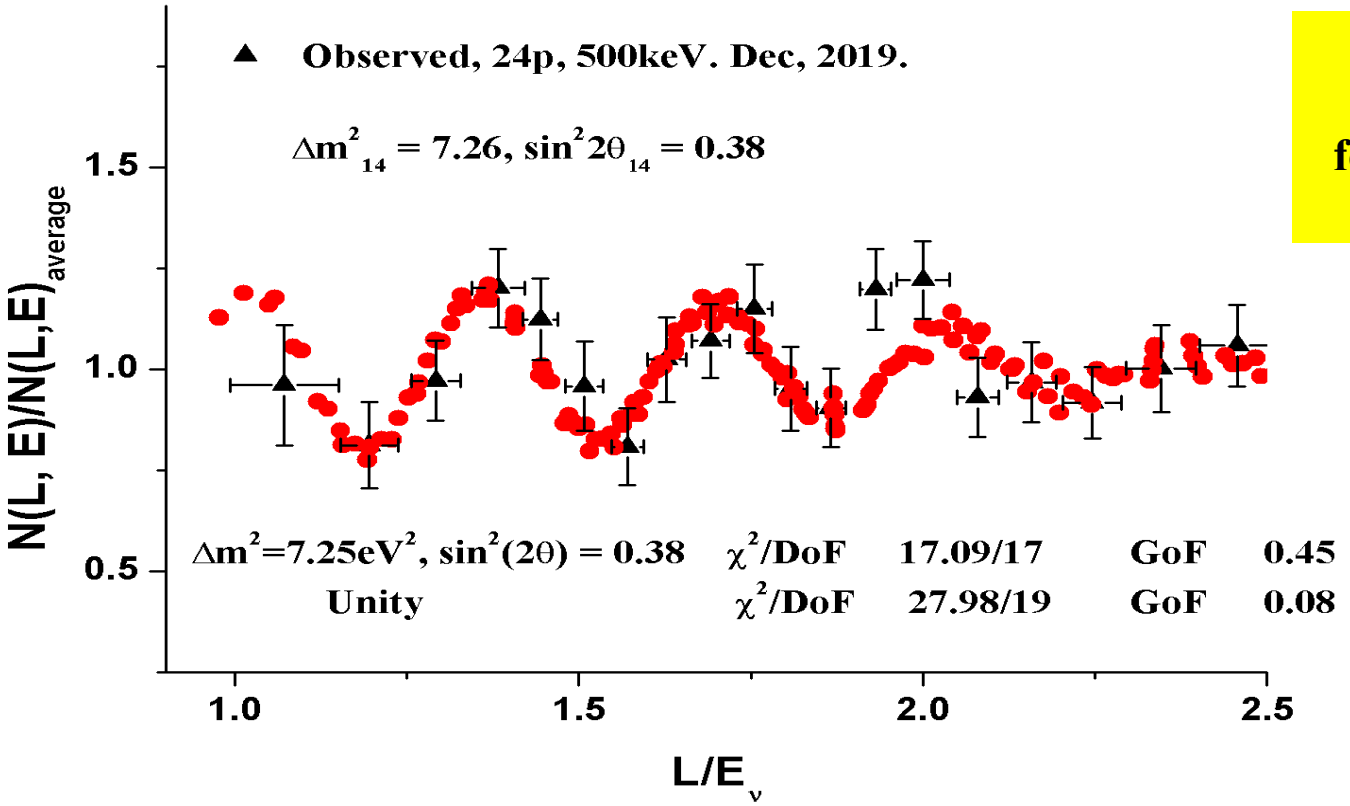
# Initial neutrino physics: addressing the NEUTRINO-4 claim

- ✓ As already presented by C. Rubbia at December '20 PAC meeting, the ICARUS early search will be focused on CC QE events $\nu\mu + n \rightarrow \mu^- + p$ with BNB and $\nu e + n \rightarrow e^- + p$ with NUMI beam, the $\mu$ and e-shower being contained in the active LAr:
  - ✓ The additional request $L\mu > 50$ cm for a better $\mu$ identification would result in ~ 11500 $\nu\mu$CC QE events *in 3 months data taking* with BNB;
  - ✓ In one year data taking with NuMI ~5200 $\nu$eCC QE will be collected.
- ✓ The study of these events, complemented by a similar sample of beam-off events, would allow to observe a clear modulation in the L/E as predicted by Neutrino-4.
- ✓ In parallel the study of $\nu e$, $\nu\mu$ events collected off-axis from NuMI will allow to optimize the neutrino reconstruction/identification as well as to measure their interaction cross sections in LAr in an energy range of interest for the DUNE program. Moreover the exploitation of the 120 GeV NuMI beam will allow also an initial search for sub-GeV Dark Matter, exploring a range of parameters of present models.
- ✓ The necessary resources for data storing and processing for 2021-2023 had been required (13.7 PB and 14.4 CPU MHr for '21 and 17.7 PB and 20.8 CPU MHr for'22).

# NEUTRINO-4 reactor signals

✓ Data have been collected for 3 years until June 2019, followed by background measurements until January 2020: 720 days reactor “on” and 417 days reactor “off”, with 87 reactor cycles.

**All data 2016 -2019 + background 20119**




**The period of oscillation for neutrino energy 4 MeV is 1.4 m**

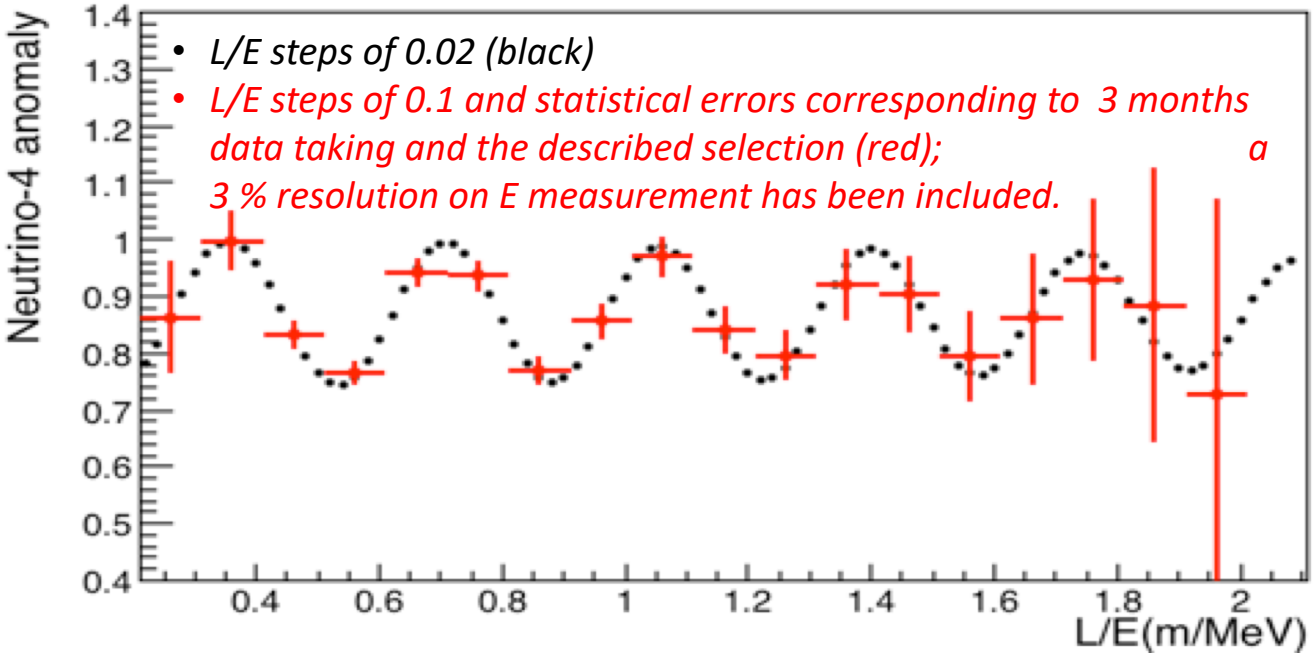
A.P.Serebrov, et al.
JETP Letters,
Volume 109,
Issue 4, pp 213–221.

arxiv:1809.10561

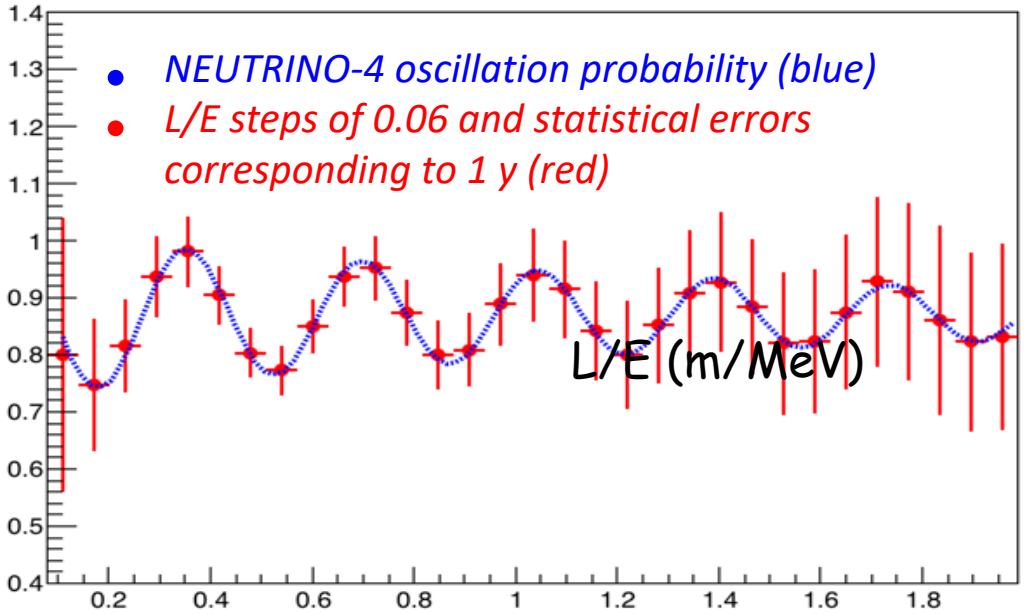
✓ Second experiment in preparation, NEUTRINO-6, with two additional detectors, aiming to improve the sensitivity by a factor 3.

# ICARUS sensitivity to NEUTRINO-4 signal

BNB – 3 months – νμ disappearance
CCQE events only




NuMI – 1 year – νe disappearance
CCQE events only



# The analysis for early ICARUS data

- ✓ An initial automatic event selection will be based on:
  - ✓ (1) a sum of signals from the PMT 's above threshold and
  - ✓ (2) the absence of signals from the CRT over its ~4π surface, occurring within few ns.
- ✓ The pattern recognition tools prepared within the common SBN software reconstruction Group allow tagging the neutrino interaction candidates.
- ✓ All connected vertices of two joining tracks will be searched inside the 1 ms drift image — one for a high dE/dx stopping proton and the other either for a stopping μ (for Booster) or a single e-showering (for NUMI).
  All other tracks in the 3-D 1 ms time window will be discarded
- ✓ Ongoing developments in the common SBN software reconstruction framework look promising in extending the proton identification capability to low energy, beneficial for this initial analysis.

  Same procedure will be applied to a test sample of collected beam-off events.
- ✓ Raw data will be pre-processed and converted into a more flexible analysis format separately for beam on and beam off.
- ✓ Both raw and pre-processed data will be replicated at CNAF.

# Additional considerations about the overburden in ICARUS

- ✓ The present CORSIKA simulation does not include the $E_k$< 50 MeV component of primary cosmic rays which could impact the detector performance.
- ✓ An estimate of the effect of the low energy component for ICARUS only has been recently obtained with a Fluka standalone cosmic rays simulation which includes:
  1) AMS2+Bess primary spectrum;
  2) solar activity modulation;
  3) geomagnetic cosmic flux modulation;
  4) spherical geometry with US standard atmosphere.

  (energy threshold set at 0.3 MeV for all particles, apart neutrons, $10^{-5}$ eV).
- ✓ This simulation predicts *in absence of overburden*:
  - ✓ The CRT single layer count rate would ~ double while the two layer coincidence would increase by ~ 50%;
  - ✓ ~1.3 kHz of additional cosmic ray interactions depositing > 100 MeV in the ICARUS LAr active volume;
  - ✓ ~18000 neutron events > 200 MeV in the 211 s exposure, failing the CRT, i.e. roughly 10% of the expected NC from BNB.

# Conclusions

- ✓ Both the detector and the cryogenic systems are running very steadily since several months.
- ✓ The free electrons lifetime is now at the level of 3 ms and it is stable.
- ✓ The advancement in the detector commissioning process and the reached detector operational stability recognized at the last ICARUS Collaboration meeting (March 16-17, 2021) allowed to initiate the ICARUS data taking collecting steadily neutrino beam events with the full PMTs + TPCs:
  - ✓ Neutrino beam data (BNB and NuMI) have been taken regularly since the end of March;
  - ✓ Since end of May a full time neutrino beam run is taking place: ICARUS is now the primary BNB user.
- ✓ Installation of the Top CRT and of the overburden is needed in order to fulfil the requirements for sterile neutrino search:
  - ✓ The side CRT is completely installed and commissioned. The top CRT modules have arrived at Fermilab;
  - ✓ Installation of the Top CRT is currently planned to take place during the summer shutdown, to be followed by the installation of the overburden at the beginning of the next neutrino run;
  - ✓ Procurement of the overburden is presently on hold, waiting for the approval of Fermilab management. Further delays in the procurement will result in loss of data for the sterile neutrino search.