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Review

The Long Journey of ICARUS: From the LAr-TPC Concept to the First Full-Scale Detector

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Abstract: The Liquid Argon Time Projection Chamber (LAr-TPC) technology was conceived at the end of the 1970s as a way to combine the excellent spatial and calorimetric performance of the traditional bubble chambers with the electronic read-out of the TPCs, obtaining the so-called "electronic bubble chambers". This technology was intended to be applied in particular to neutrino physics as an alternative to Ring Water Cherenkov detectors. The main technological issues of such an innovative technique were investigated from the very beginning within the ICARUS program, with staged R&D starting from prototypes of increasing mass to arrive, at the end of 1990s, at the largest LAr-TPC detector ever built at that time: ICARUS-T600, with almost 500 tons of active LAr. The successful operations of the ICARUS-T600 LAr-TPC in its more than twenty years of life, from the first run at surface in Pavia (Italy) in 2001 to the LNGS (Italy) underground run being exposed to the CNGS beam from CERN to Gran Sasso (2010–2013) and finally to the ongoing run at Fermilab (USA) for sterile neutrino searches (2020–), have demonstrated the huge potential of the LAr-TPC technique, paving the way to future larger LAr-TPCs detectors as DUNE.

Keywords: liquid argon detectors; time projection chambers; neutrino physics

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Citation: Menegolli, A. The Long Journey of ICARUS: From the LAr-TPC Concept to the First Full-Scale Detector. *Universe* **2023**, *9*, 74. https://doi.org/10.3390/universe9020074

Academic Editor: Lino Miramonti

Received: 16 December 2022
Revised: 23 January 2023
Accepted: 24 January 2023
Published: 30 January 2023

1. Introduction

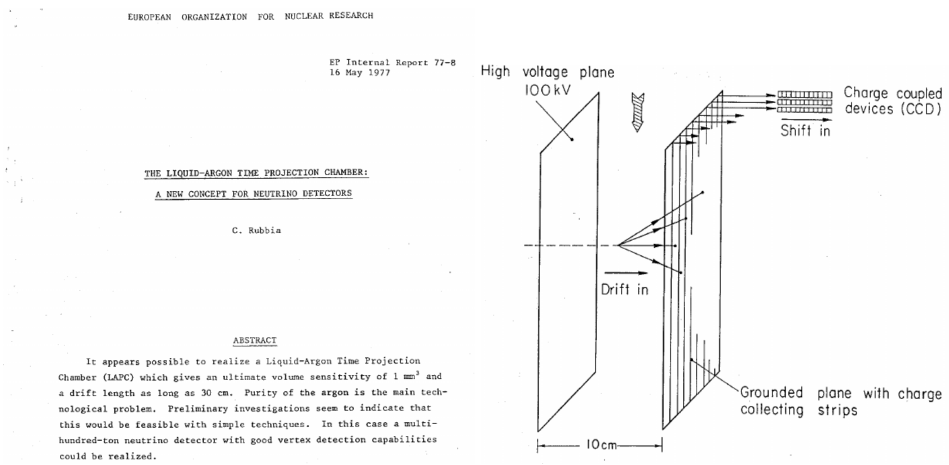
The technology of the Liquid Argon Time Projection Chamber (LAr-TPC), first proposed by C. Rubbia in 1977 [1], was conceived as a tool for completely uniform imaging with high accuracy of massive volumes. Indeed, the original idea was to combine the bubble chamber technology, allowing for high spacial resolution and 3D reconstruction of the tracks crossing a high density target such as Freon ($\rho \sim 1.5\ \mathrm{g/cm^3}$), with a continuous read-out of the signal, provided by a Time Projection Chamber detector with elevated sensor granularity. This is why LAr-TPCs were originally called *electronic bubble chambers*.

The LAr-TPC technology was from the very beginning developed within the ICARUS (Imaging Cosmic and Rare Underground Signals) program, targeting a broad number of studies of interest in the fields of neutrino and astro-particle physics. It should be remembered that at the beginning of the ICARUS developments (1980s), there was still no evidence of neutrino oscillations, and the main idea was to realize a detector mainly devoted to the physics of solar and atmospheric neutrinos, competing with the Ring Water Cherenkov detectors, which in those same years began to reveal anomalies in the sector of neutrinos from natural sources.

After the original proposal, the feasibility of this technology has been demonstrated by an extensive R&D program, which included many years of studies on small LAr devices allowing determining the main features of the liquid argon as a target and detector medium. Then, a phase of realization of increasing mass prototypes followed, allowing for a tuning of the technology in view of the realization, at the end of the 1990s, of the ICARUS T600 detector that, with its 760 tons of LAr, was the very first realization of a LAr-TPC detector at the ~kton scale.

2. LAr-TPC: First Concepts

The main idea to realize a LAr-TPC by C. Rubbia (see Figure 1) came together with the development of simple techniques [2–5] to obtain ultra-pure liquid argon with residual contamination of less than 1 ppb (O_2 equivalent). In this way, the ion–electron pairs produced after the passage of a charged track in the dense (ρ = 1.4 g/cm^3) LAr medium may travel undisturbed over macroscopic distances, of the order of several meters, when a uniform electric field is applied. A fraction of ion–electron pairs will not recombine, depending on the intensity of the field and on their density. Therefore, a drift is created following the lines of the field, with a current which is induced on any anodic electrode which is placed inside the LAr volume. The anode signal is then proportional to the current intensity, which is due to the flux of the electric field created by the charged particles crossing the electrode. Since the speed of the electrons is five orders of magnitude greater than that of the ions, basically only electrons contribute to the signal which is induced on the electrodes. The average number of electrons produced in LAr by a minimum ionizing particle (m.i.p.) is around 88,000/cm, with no amplification present close to the wires. Moreover, many electrons are recombining with ions, especially when the electric field intensity is low. This results in an extremely small signal. The problem is now overcome by using low noise FETs. Despite the small number of drift electrons, a huge advantage is obtained, since the electrons may induce a signal on subsequent electrodes if they are assembled as semi-transparent and parallel wire planes at the end of the LAr active volume, providing a three-dimensional read-out. If z is the coordinate along the electric field, with x and y being the coordinates on the wire planes, then z is given by a measurement of the drift time, provided that the t_0 = 0 time and the drift electron speed are both known.


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:
A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

Figure 1. Very first concept of a LAr-TPC by Carlo Rubbia in his CERN internal note of 1977.

3. The First Working ICARUS Prototypes

After the first feasibility studies, the newly formed ICARUS Collaboration proposed in 1985 [6] a multi-kton LAr-TPC to be operated in INFN underground Laboratori Nazionali del Gran Sasso (LNGS), with the aim of searching for extremely rare events, from the nucleon decay to neutrinos, in particular to solar neutrinos and relic Supernova neutrinos, and looking for possible signatures of neutrino oscillations. The first prototype built by the ICARUS Collaboration was a small LAr-TPC with a maximum drift of 24 cm, which was exposed to a 5 GeV pion beam to perform a number of tests to validate the new technique. A screening grid and two 8 × 8 cm^2 wire planes composed the wire chamber: in the first plane, a signal was induced, while the collection took place in the second one. Both planes were made of equally spaced steel wires, see Figure 2 (left). This layout allowed to create two-dimensional images of the ionizing events, the first coordinate being the position of the hit wires and the other one the drift time multiplied by the drift electron velocity. For the very first time, a number of achievements which would have been fundamental for the future development of the physics and technology of the LAr-TPCs were obtained [7–9]: a free electron lifetime exceeding several milliseconds, allowing for a drift of meters; very clean 2D images of ionizing events; study of the electron diffusion in LAr and of the effect of the electric field on the electron yield; evaluation of an energy resolution in the MeV range of the order of few percents, in agreement with measurements performed by other groups [10–12]; measurement of a spatial resolution along the drift coordinate of the order of 60 μm for 5 GeV tracks.

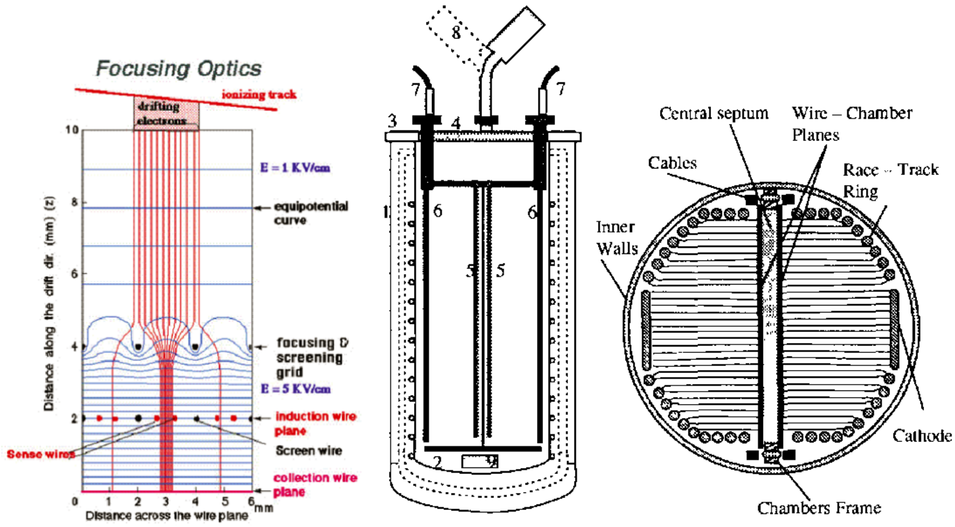


Figure 2. (**Left**): Electric field lines close to the wire chambers of the first small ICARUS LAr-TPC prototype. (**Center**): Sketch of the ICARUS 3 ton detector, with highlighted the outer vessel (1), the inner vessel (2), the annular flange (3), the circular flange (4), the wire chambers (5), the cathodes (6), the high voltage feed-throughs (7), the pre-amplifiers containers (8) and finally, the LAr purity monitor (9). (**Right**): Top view of the electric field lines along the drift region of the ICARUS 3-ton detector.

After this first achievement, the ICARUS Collaboration developed a staged program, including an initial phase of R&D, the construction and operation of a ∼0.2 kton detector dedicated to solar neutrino searches and a final multi-kton detector. As it will be shown, this strategy was later scaled down, with a final detector (ICARUS-T600) of about 760 tons of liquid argon. Nonetheless, a medium-scale prototype with a mass of 3 tons (2000 liters of LAr) [13,14] was first realized aiming to solve a number of technological problems, see Figure 2 (center and right), the most critical of which were:

- *Liquid argon purification*. This was ensured by using clean and non de-gassing materials for all inner instrumentation like feed-throughs flanges, cables, holders, etc. Feed-throughs had to be tight to avoid leaks between the clean argon and the outside.
- *Wire chambers*. The mechanics of the inner TPC had to grant a high precision, providing a non-destructive readout with different wire planes and a wire pitch of few millimeters, to be made unaffected by the thermal stress when going from room to cryogenic temperature.
- *Electronics*. The development of a low noise amplifier was necessary to obtain a good signal-to-noise ratio, given the absence of amplification inside the liquid argon.
- *Software*. A brand new software infrastructure, data management and reduction and track reconstruction algorithms were developed to cope with the large number of 3D digitized images.

The full 3 ton detector was assembled from January to May 199, while the first cosmic ray images were recorded in June 1991, see Figure 3. Experience gained with the 3 ton prototype showed for the first time that the LA-TPC technique was reliable at a reasonable detector scale, providing three-dimensional and high-resolution images of ionizing events, of the same quality as the bubble chamber ones. A number of important physical parameters of a LAr-TPC were studied, such as the free ion–electron yield, the recombination probability, the drift velocity, the diffusion coefficient and the free electron lifetime. In summary, the 3 ton prototype demonstrated that a novel type of detector was available for neutrino and rare events physics.

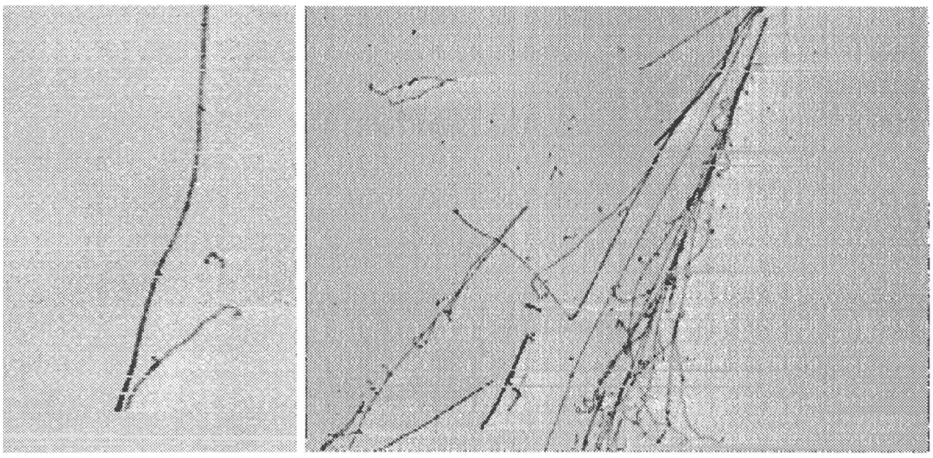


Figure 3. (**Left**): Stopping muon and subsequent decay electron track. The size of the image is $\sim$40 $\times$ 40 cm^2. The gap between the muon and the electron track is due to the 3 µs muon lifetime. (**Right**): Cosmic ray-induced shower.

The following step of the ICARUS R&D concerned the operation of small LAr-TPC prototype at the CERN-SPS neutrino beam, with the aim of recording a sizable sample of Quasi-Elastic $\nu_\mu + n \to p + \mu^-$ interactions, in order to gain experience with real neutrino events. For this reason, in 1997, the so-called ICARUS 50 liter LAr-TPC [15] was installed in the CERN hall 191 between CHORUS [16] and NOMAD [17] detectors to be successfully exposed to the 1997 CERN-SPS neutrino run, collecting more than 10^5 triggers. The detector structure consisted of a stainless steel cylindrical vessel with a 70 cm diameter and 90 cm height, whose upper side consisted of a vacuum tight flange housing the feed-throughs for liquid argon filling, high voltages and read-out electronics, see Figure 4 (left and center). Inside the main vessel, an ICARUS-type LAr-TPC was mounted. The TPC was a parallelepiped whose opposite horizontal faces (32 $\times$ 32 cm^2) acted as cathode and anode, while the side faces, 47 cm long, supported the field-shaping electrodes. The mass of the LAr-sensitive volume was 65 kg argon. The anodic read-out electrodes consisted in two parallel wire planes, at a distance of 4 mm, made of stainless steel wires, 100 µm diameter and 2.54 mm pitch: the plane closest to the active LAr volume operated in induction mode while the second collected the drift electrons. After the exposure to the CERN SPS neutrino beam, about 9000 charged current ν_μ events were identified, in agreement with the expectations. The quasi-elastic candidates amount to 350. An example of these events with a full 3D reconstruction is shown in Figure 4 (right). This was the very first time a LAr-TPC detector observed neutrino events, marking a breakthrough for this kind of technology.

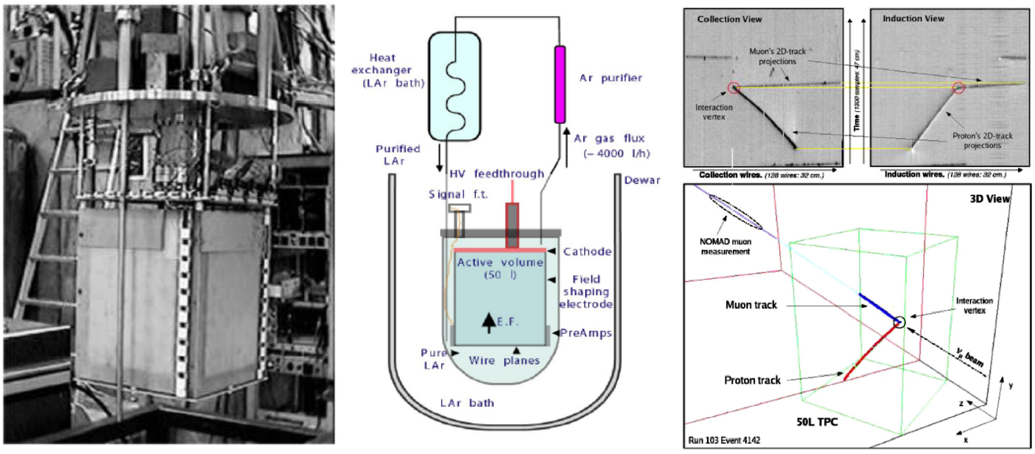


Figure 4. (**Left**): The 50 liters LAr-TPC detector mounted on its large feed-through flange. Center: Sketch of the overall apparatus. (**Right**): An example of Quasi-Elastic ν_{μ}CC event observed both in Induction and Collection wires planes, as well as its 3D reconstruction.

Despite the excellent results obtained by the first ICARUS prototypes, the scaling towards larger masses would need a major step, based on the transfer of the results obtained with a laboratory R&D to the industry. For this reason, the following, larger ICARUS prototype was built in 1997 in synergy with the Air Liquide cryogenics company [18]. The so-called 10 m^3 *module*, consisting of 14 tons of LAr, was intended as a intermediate size detector to test all the technical solutions which would have been implemented in the following larger-scale ICARUS-T600 module. The 10 m^3 detector was, in fact, a slice of one of the two modules of the T600 detector, being both the cryogenics systems and the inner TPCs replicas of the T600 ones. Additionally, as in the T600 case, the inner detector of the 10 m^3 included Photo-Multiplier Tubes (PMTs) for the detection of the prompt scintillation light (λ = 128 nm) emitted in LAr at the passage of ionizing particles [19]. The cryogenics, the Ar purification system and in general the performance of the inner detector were extensively tested at first in Pavia, with a number of cooling and filling tests successfully ending in July 1999. Then, a second test was performed at LNGS in the first half of 2000, see Figure 5 (left). The goal of this test was the study of the detector performance with a dedicated surface run to collect cosmic rays, see Figure 5 (right): all systems of the 10 m^3 detector have proven themselves to be fully operative and stable in a $\sim$100 days long-term run.

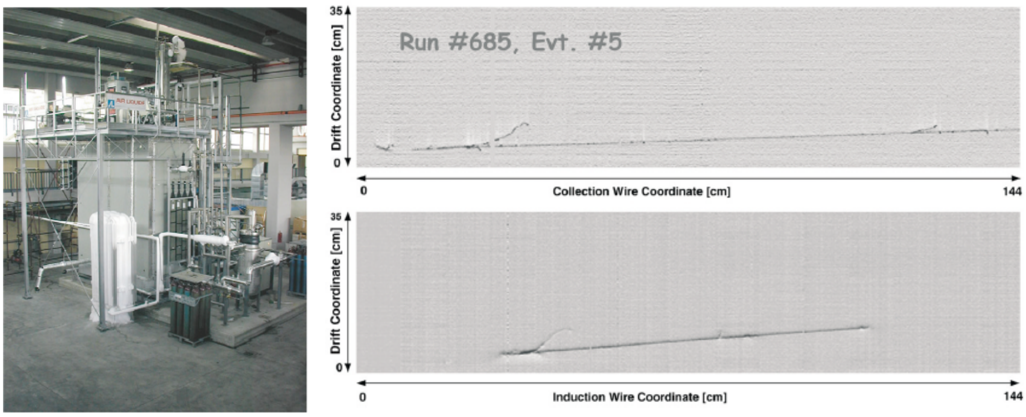


Figure 5. (**Left**): The 10 m^3 detector installed in an external lab at LNGS. (**right**): Cosmic muon crossing the LAr active volume recorded with the 10 m^3 detector at LNGS. A clear δ-ray originating from the muon track is also visible.

4. ICARUS T600 Pavia Surface Run

After the successful conclusion of the R&D on a smaller scale, the ICARUS project finally entered a new phase with the aim of the realization of a detector at industrial scale, a step needed for the realization of large volume detectors. The first realization of this kind was the already mentioned 10 m^3 prototype, which was operated with the aim of testing the final industrial solutions to be then implemented in what would have been the largest LAr-TPC detector ever built at that time: ICARUS-T600. The ICARUS-T600 detector was constructed in about four years in a dedicated laboratory in Pavia (Italy), allowing for a first test run held at surface in 2001 [20], see Figure 6 (left). This test proved the maturity of the adopted techniques in view of the following operations of the detector at LNGS underground laboratories. For the first time, all technical aspects of a such a large LAr-TPC detector were tested at the same time: cryogenics, LAr purification, TPC read-out, LAr scintillation light, electronics and DAQ. A large set of statistics on cosmic ray events was collected, allowing the tuning of the off-line tools for the event reconstruction and the extraction of information on selected physical quantities.

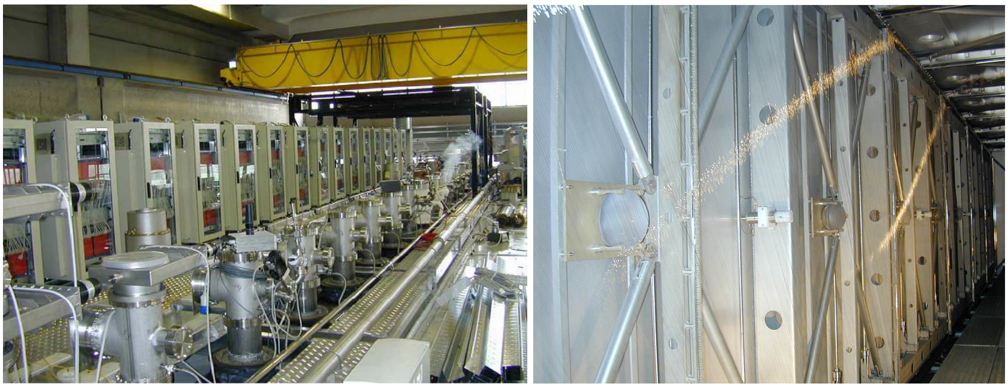


Figure 6. (**Left**): Top of one module of ICARUS-T600 in the Pavia surface laboratory, showing the disposition of the electronic racks for the one TPC and of the chimneys with the feed-through flanges for the other TPC. (**Right**): Inner detector of one module of ICARUS-T600, showing the wire chamber structure and the PMTs behind.

ICARUS-T600 was made up of two large and identical adjacent modules (so-called *T300*) with internal dimensions 3.6 × 3.9 × 19.6 m^3, filled with a total of 760 tons of liquid argon (476 tons of active argon). The dimensions and the shape of the modules were constrained by the requirement that the LAr containers had to be moved along the Italian highways into the LNGS laboratories and installed there. Each module housed two LAr-TPCs separated by a common central cathode with a maximum drift distance of 1.5 m, corresponding to $\sim$1 ms drift time for the nominal 500 V/cm electric drift field, see Figure 6 (right). The anode was made of three parallel wire planes, 3 mm apart, where the stainless-steel 100 μm wires were oriented on each plane at a different angle with respect to the horizontal direction: 0° (Induction 1), +60° (Induction 2) and −60° (Collection). The total number of wires installed in the T600 detector was 53248. By appropriate voltage biasing, the first two planes (Induction 1 and Induction 2) provided a non-destructive charge measurement, whereas the ionization charge was fully collected by the last Collection plane. A system made of the first large area (8″) PMTs, constructed to work at cryogenic temperatures, was also implemented to detect the Vacuum Ultra-Violet (VUV, λ = 128 nm) scintillation light emission in LAr, used for trigger and timing purposes: 74 9357FLA Electron Tubes PMTs were installed, 20 in the first ICARUS T600 module and 54 in the second one. All PMTs were made sensitive to the LAr VUV photons by coating the windows with a proper fluorescent wavelength shifter, the Tetra-Phenyl Butadiene (TPB).

The measurements and the experimental results of ICARUS-T600 in Pavia surface run demonstrated that it was actually feasible to master all technical issues related to the construction and operation of a large size LAr-TPC, within and sometimes beyond the design specifications [21–23]. Events collected with several trigger conditions, see Figure 7, were used to develop the first tools for semi-automatic reconstruction of events in LAr-TPC, as well as to define the performance of the detectors in terms of particle identification, spatial and energy resolution [24–27].

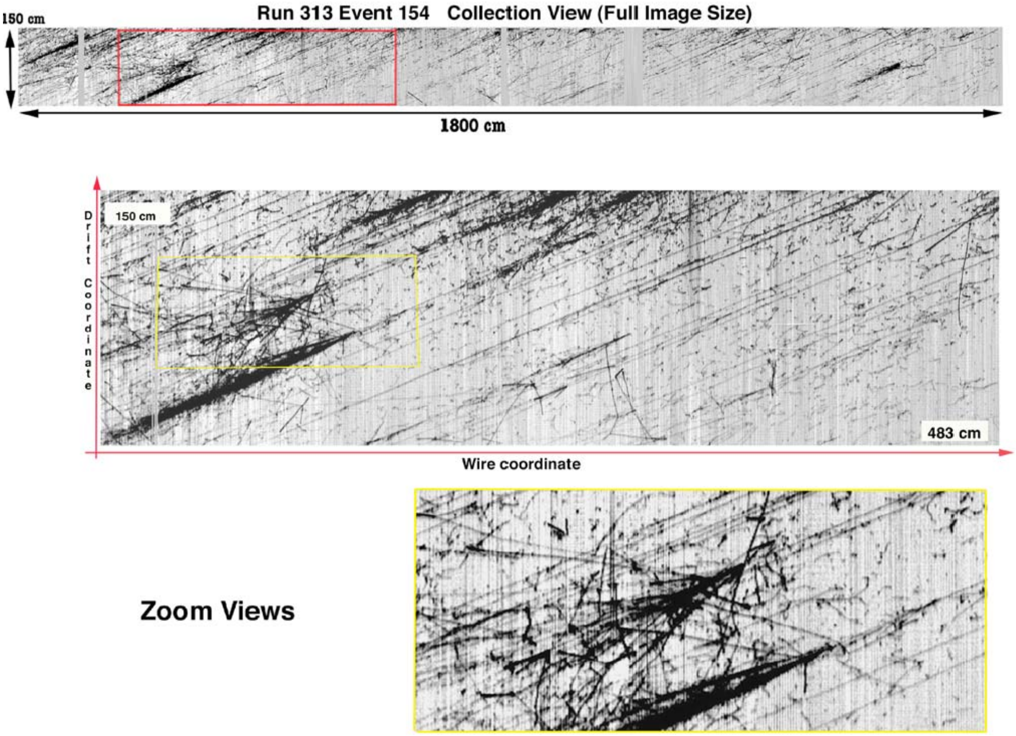


Figure 7. Example of an extensive air shower event collected by ICARUS-T600 in its surface run in Pavia, as seen in Collection view.

5. ICARUS T600 Operations at LNGS

After the Pavia surface test run in 2001, the detector was decommissioned and, in 2004, the two T300 modules were moved to their final site, in Hall B of LNGS laboratories (1400 m depth). The ICARUS T600 plant [28] and its dedicated technical infrastructures were installed in the Northern-end side of Hall B, see Figure 8.

The commissioning at LNGS was successfully and safely performed during the first half of 2010. Detection of the first events from the CNGS (CERN Neutrino to Gran Sasso) beam and of cosmic muons was already possible during the commissioning phase [29,30], soon after the cathode HV and the wire plane bias were provided. The detector smoothly reached optimal working conditions and took cosmic and CNGS neutrino beam data with extremely high liquid argon purity and high detector live-time, performing even beyond expectations. The ICARUS-T600 detector concluded in 2013 a very successful three-years-long run at LNGS collecting 8.6×10^{19} pot with a detector live time exceeding 93%, recording 2650 CNGS neutrinos, in agreement with expectations, and cosmic rays (with a total exposure of 0.73 kton/yr). In May 2012, the CERN-CNGS neutrino beam was also operated for two weeks with the proton beam made of bunches, few ns wide and separated by 100 ns. This beam structure allowed a very accurate time of flight measurement of neutrinos from CERN to LNGS on an event-by-event basis. The result was compatible with the simultaneous arrival of all events with speed equal to that of light [31–33] and demonstrated that a timing of the order of 1 ns was achievable with a LAr-TPC detector.

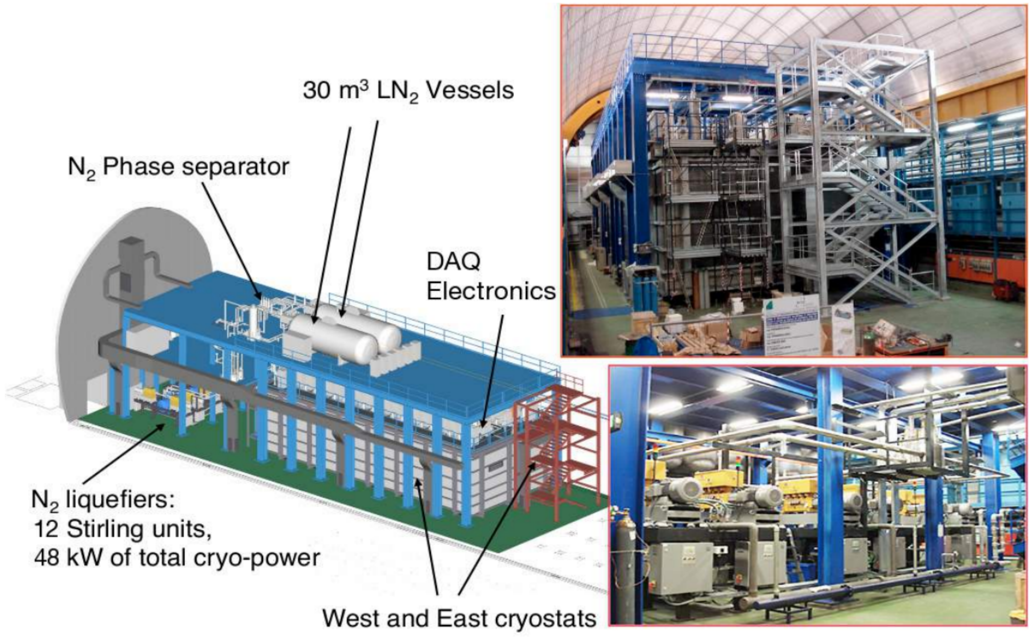


Figure 8. (**Left**): Schematic view of the whole ICARUS T600 plant in Hall B at LNGS. (**Right-top**): Detector plant. (**Right-bottom**): Details of the cryo-cooler plant.

ICARUS-T600 at LNGS produced a large number of results which have been fundamental for the future developments of the LAr-TPC technology, demonstrating the feasibility of this technique, even in the challenging conditions of an underground laboratory. In the following, the main achievements of ICARUS-T600 from the operations at Gran Sasso are recounted:

- *Drift electron lifetime*. This was measured continuously and with high precision, using the residual cosmic rays crossing the detector at the rate of ∼3100 muons per day [34]. The lifetime was measured to be around 7 ms, corresponding to 40 ppt (O_2 equivalent) for most of the time, resulting in a 12% maximum charge attenuation. Moreover, at the end of the ICARUS physics run in 2013, a new re-circulation pump allowed to obtain the record electron lifetime of 15 ms, corresponding to ∼20 ppt.
- *Multiple scattering*. An innovative algorithm to measure the effect of the Multiple Coulomb Scattering (MCS) for charged-current muons exiting the detector was developed. It was validated with ∼400 muons produced in CNGS neutrino interactions in the rock upstream the Hall B and stopping inside the LAr active volume. The ability to measure the stopping muon momentum also through calorimetry (-dE/dx) allowed to have a benchmark for the MCS measurements, providing a momentum resolution $\Delta p/p \sim 15\%$ in the few-GeV energy range [35].
- *Atmospheric neutrino detection.* Atmospheric neutrinos were identified in ICARUS-T600 by inspecting the cosmic ray data collected with an overall exposure of 0.73 kton year, where ∼200 atmospheric neutrino events were expected. These kind of events, where selected using new methods for the automatic identification of the neutrinos, needed to filter out the overcoming cosmic tracks. Apart from the interest of the search itself, these methods demonstrated that automatic tools might be used to identify neutrinos having energies similar to the one expected from the Fermilab neutrino beams, in view of the following Short-Baseline Neutrino (SBN) program. The time needed for a visual event identification was effectively reduced, allowing to identify both ν_μCC and ν_eCC candidates [36]. An example of downward-going quasi elastic ν_eCC event is shown in Figure 9.
- *Search for LSND-like ν_e events in CNGS*. One of the major features of the ICARUS-T600 as a LAr-TPC, which makes this technology highly competitive with the Ring Water Cherenkov detectors for neutrino searches, is the capability in the electron/photon

separation through the measurement of the energy loss in the very first centimeters of the e.m. shower, which is developing in a liquid argon medium with a radiation length X_0 of ∼18 cm. In general, this allows a LAr-TPC to effectively reject the neutral current background to ν_e events. This feature was successfully applied to a sample of electron neutrinos collected in coincidence with the CNGS muon neutrino beam, where a small intrinsic contamination of ν_e was expected. The measurement was motivated by the possibility to search for anomalous $\nu_\mu \rightarrow \nu_e$ oscillations, hinting to the existence of sterile neutrino states, as reported by a number of past and present experiments at the accelerators like LSND [37] and MiniBooNE [38], and recently investigated by the MicroBooNE LAr-TPC [39]. Seven events were identified in ICARUS-T600 as ν_eCC candidates, in agreement with the 8.5 ± 1.1 events expected from the intrinsic CNGS beam ν_e component and a standard framework of three flavor mixing. ICARUS-T600 then provided a limit on the oscillation probability $P(\nu_\mu \rightarrow \nu_e) \leq 3.86 \times 10^{-3}$ at 90% CL [40,41], whose effect on the oscillation parameter space is shown in Figure 10. One of the seven ν_eCC candidates is shown in Figure 11 (top): the evolution from the single m.i.p. CC electron to the e.m. shower is evident by looking at the energy loss in the individual wires, see Figure 11 (bottom).

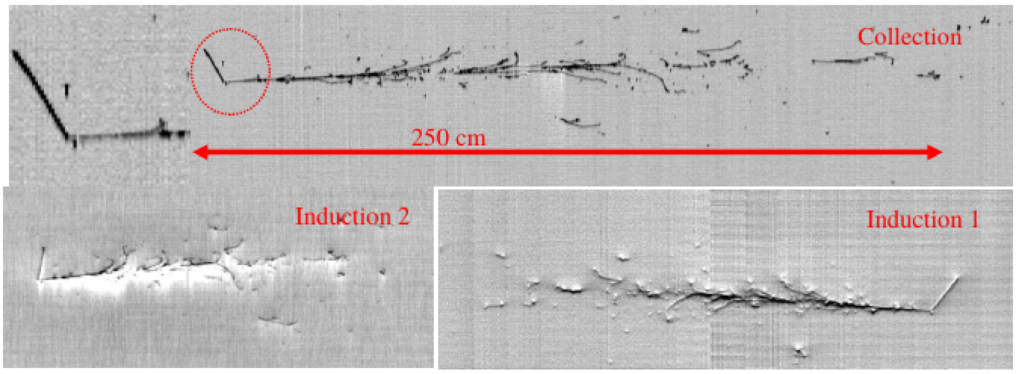


Figure 9. Example of a quasi elastic, downward-going atmospheric charged-current electron neutrino found in the scanned sample. A clear e.m. shower of 2 GeV is observed, while a 115 MeV kinetic energy proton emerges from the main interaction vertex as a single, highly ionizing track.

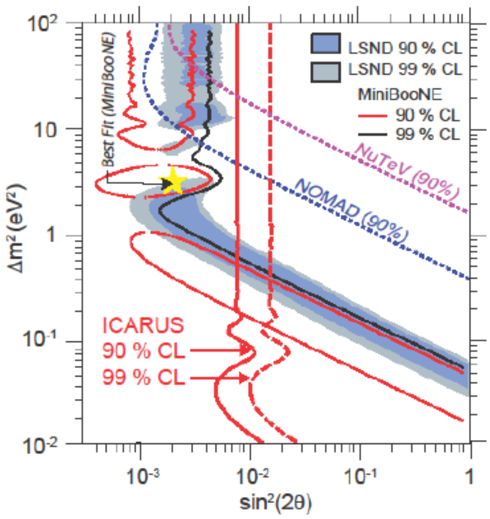


Figure 10. Δm^2 as a function of $\sin^2(2\theta)$ for a number of experiments searching for $\nu_\mu \rightarrow \nu_e$ anomalies, overlapped with the ICARUS-T600 90% (continuous red line) and 99% (dashed red line) exclusion limits. The best fit point of MiniBooNE [38] at that time (2013) is indicated with a yellow star.

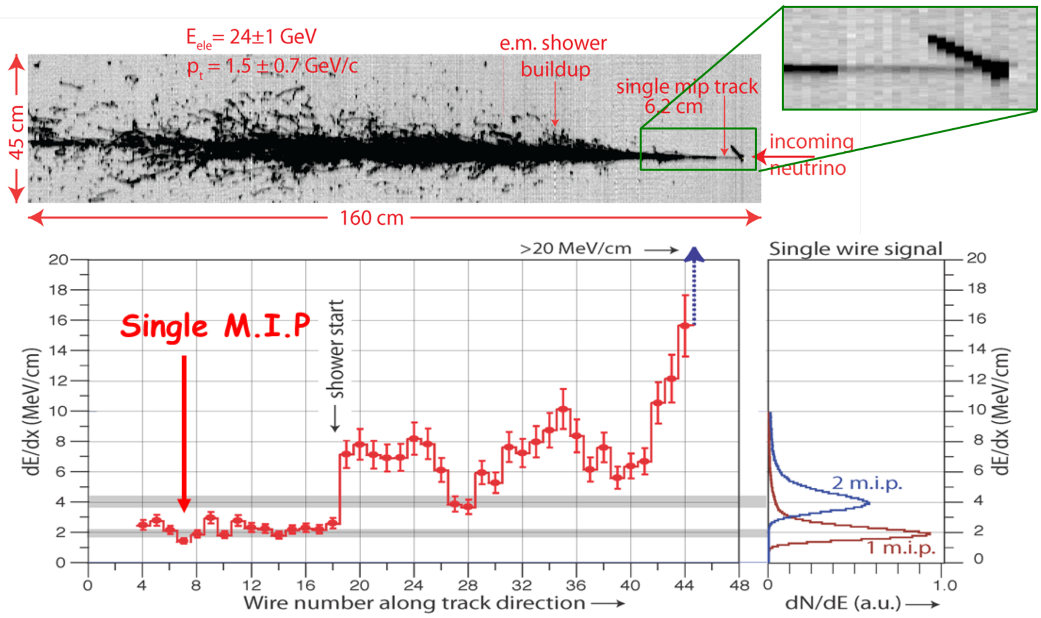


Figure 11. (**Top**): CNGS high energy ν_eCC candidate, with a CC electron resulting in a e.m. shower and a highly ionizing proton emerging from the main neutrino interaction vertex. (**Bottom**): Energy loss as a function of the evolution of the CC electron from a single track to an e.m. shower: the CC electron is a m.i.p. track for the first 6 cm, then the e.m. shower start its development.

The three years of safe and stable operation of the ICARUS-T600 detector in the challenging underground Gran Sasso environment marked an important milestone for the LAr-TPC technique. In particular, ICARUS-T600 proved the maturity of the technology in view of its scalability to masses of several ktons, as the ones foreseen by future neutrino programs, with drift distances of many meters, such as the DUNE experiment [42].

6. ICARUS at Fermilab within the SBN Project

The idea to extend the life of the ICARUS-T600 detector beyond the LNGS run came soon after the results obtained by the ICARUS Collaboration in the search for LSND-like ν_e events with the CNGS beam, as already shown in Section 5. Indeed, it was immediately understood that a Short-Baseline ($\sim$1 Km) neutrino experiment with a low-energy ($\sim$1 GeV) neutrino beam would have granted a perfect experimental environment to definitively clarify the results of LSND, searching for sterile neutrinos with $\Delta m^2 \sim 1$ eV^2. For this reason, an experimental program called Short Baseline Neutrino (SBN) [43] was set up in 2015, with the idea of using three LAr-TPC detectors deployed along the Booster Neutrino Beam (BNB) [44] at Fermilab National Laboratories (FNAL). The near detector (SBND), with an active mass of 112 tons, is being located 110 m from the BNB target. The MicroBooNE detector, which took data with BNB since 2015 with its 89 tons active mass, is located at 470 m. The far detector is the ICARUS-T600, which was installed in a dedicated building placed at 600 m from the BNB target after a campaign of overhauling. The detector positions along the beam line are optimizing the sensitivity to neutrino oscillations, while minimizing the impact of the uncertainties coming from the flux systematics. The total exposure will be 6.6×10^{20} protons on target in SBND and ICARUS-T600 and 13.2×10^{20} protons on target in MicroBooNE. With this exposure, SBN is expected to cover the LSND 99% C.L. allowed region at $>5\sigma$ level above $\Delta m^2 = 0.1$ eV^2 and $>4.5\sigma$ everywhere, see Figure 12. Results from ICARUS-T600 at LNGS (see Section 5) were already excluding at more than 5σ the LSND region at $\Delta m^2 < 0.1$ eV^2. A full description of all the backgrounds and systematics can be found in the SBN proposal [43].

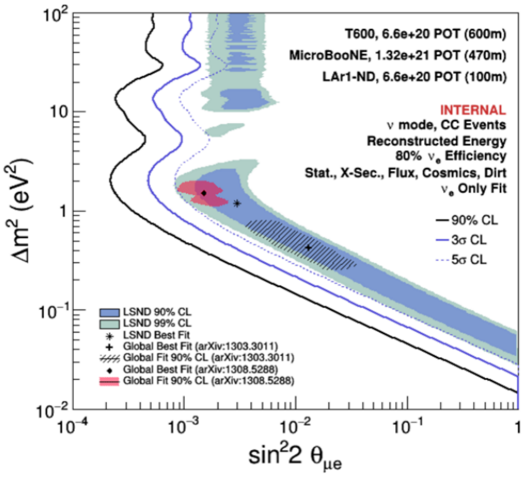


Figure 12. Sensitivity of the SBN Program to $\nu_\mu \rightarrow \nu_e$ oscillation signals.

Additionally, being located 6° off-axis along the NuMI beam [45], ICARUS-T600 is collecting a large event sample from the ν_e NuMI component in the 0÷3 GeV energy range, allowing to perform precision measurements of neutrino–argon cross section, to test interaction models in the few hundred MeV to few GeV energy range—extremely useful both for SBN oscillation analysis and for the future DUNE experiment—as well as to search for Physics Beyond the Standard Model (Higgs portal scalar, neutrino tridents, light dark matter, heavy neutral leptons, etc.) Finally, ICARUS can either confirm or exclude the recent Neutrino-4 Short Baseline reactor oscillation signal ($\Delta m^2 \sim 7$ eV^2 and $\sin^2 2\theta \sim 0.36$) [46] by measuring disappearance of ν_μ from BNB, focusing on contained Quasi Elastic (QE) ν_μ CC interactions (∼11,500 events in three months) and disappearance of ν_e from NuMI beam, selecting contained QE ν_e CC candidates (∼5200 events per year).

The ICARUS T600 decommissioning process started in June 2013 at LNGS, with the cryostat emptying phase lasting less than one month in a safe and smooth way. A warming-up phase followed, that brought the cryostats to room temperature in about one month. The T600 dismantling started in September 2013 and globally lasted about 10 months. After it was concluded, the cryostats were opened to recover the internal TPC detectors and the cryogenic plant and electronics to be re-used in future projects. The movement of the two T600 modules to CERN was completed in 2014 to allow for a complete overhauling of all the ICARUS-T600 TPCs, preserving most of the existing operational equipment, while upgrading some components with up-to-date technology in view of the non-underground operation at Fermilab (CERN WA104/NP01 project).

ICARUS-T600 operations at Fermilab are held in a much different environment than LNGS, the detector being deployed at shallow depths. As a consequence, cosmic rays may constitute a non-negligible background, especially for neutrino electron detection. This is mostly due to cosmic muons crossing the LAr volume, generating an electromagnetic shower faking a pure ν_e event. Moreover, neutrino-like events can be also mimicked by primary cosmic neutrons or photons. A number of improvements had then to be implemented to cope with these background sources, namely:

- A layer of 2.85 m concrete overburden placed on top of the detector to remove all primary photons and to effectively reduce the neutron background by a factor ∼200. The muon component is reduced by the overburden by ∼25%;
- A ∼4π segmented Cosmic Ray Tagging (CRT) detector surrounding ICARUS-T600, composed by two layers of plastic scintillators arranged in XY configuration, with a total surface of ∼1100 m^2. The CRT is expected to tag about 95% of cosmic muons entering in the detector;
- A brand new LAr VUV scintillation light detection system, made of 90 Hamamatsu R5912-MOD (8″) PMTs in each TPC [47,48], see Figure 13 (left). This system is characterized by a ∼1 ns time resolution and a detection capability of very low energy

events, below 100 MeV, being effective in tagging neutrino events in coincidence with the beam spill, while rejecting the cosmic ray events occurring out of time. PMTs are equalized in gain and calibrated in time by using a dedicated laser system illuminating the PMT windows through an optical fiber [49];

- New TPC electronics, designed and optimized for the ICARUS-T600 shallow depths operations, with an improvement of the performance of the system in terms of signal-to-noise ratio. The integration of advanced electronic components also allowed to reduce costs and volumes with respect to the LNGS configuration [50,51].

After its overhauling at CERN, the detector was moved to Fermilab in 2017 and then installed in the newly built SBN far detector building between 2018 and 2020, see Figure 13 (right). After a vacuum phase needed to clean up the internal volume, green light was given for the subsequent filling with liquid argon in February 2020. The filling phase proceed smoothly until April 2020, when the nominal LAr level was reached and all detector subsystems were activated. In parallel, the liquid argon purification started in order to quickly reach a level of purify allowing for a drift electron lifetime of a few milliseconds as done at LNGS. The liquid argon purity in both ICARUS-T600 modules is continuously monitored thanks to a real time analysis of the attenuation of the charge signal as a function of the drift coordinate along cosmic muon tracks crossing the entire drift, from the cathode to the wire planes. After a phase of commissioning, a stable trigger system has been realized, based on the coincidence of the scintillation light signal as detected by the PMTs with the BNB and NuMI beam spills [52]. This allowed to almost immediately collect and then reconstruct the first neutrino candidate events both from BNB and NuMI beams, examples of which are shown in Figure 14: one of the first BNB ν_μCC candidates, shown in Figure 14 (left) is a Quasi Elastic event recognized from a primary vertex generating two tracks, the first being a short, highly ionizing proton, the second a longer muon stopping in the active volume and characterized by an energy loss compatible with a m.i.p. particle. A remarkable example of an electron neutrino event from NuMI beam is finally shown in Figure 14 (right), where a clear e.m. shower produced by the primary electron is seen.

Figure 13. (**Left**): Deployment the upgraded ICARUS-T600 PMT system behind a wire plane of one of the four TPCs during the overhauling activities at CERN. (**Right**): Status of the ICARUS-T600 plant at Fermilab before the beginning of the cryogenic commissioning in 2020.

The ICARUS-T600 detector is presently taking data smoothly, being exposed to both BNB and NuMI beams within the SBN program at Fermilab, aiming for a sensitive search of sterile neutrino states. ICARUS will help in solving a puzzle that dates back to the end of the 1990s with the first hints coming from LSND experiment. Despite the difficulties encountered in the years of the COVID-19 pandemic, the activation, commissioning and operation of ICARUS-T600 at Fermilab have been very successful, allowing for the recording of the first neutrino events and eventually the beginning of data taking for physics in mid-2022.

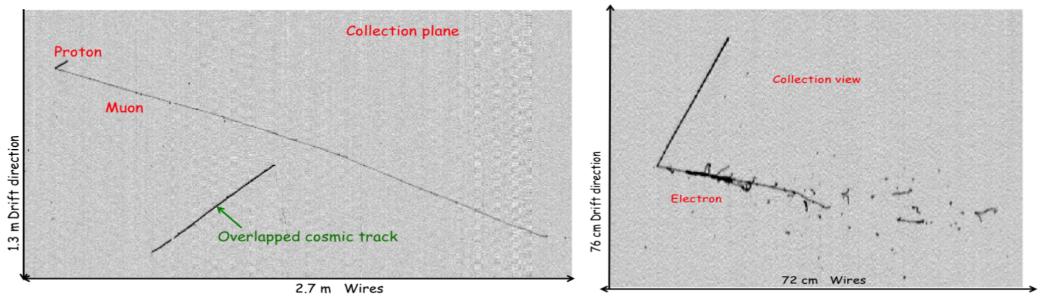


Figure 14. (**Left**): A fully contained ν_μCC quasi-elastic event from the BNB beam. (**Right**): An electron neutrino event from the NuMI beam.

7. Conclusions

The ICARUS program dates back almost 40 years, with a constant development from the first small prototypes of few hundred cm^3 in volume to the largest realization of the ICARUS-T600 detector (760 tons of liquid argon). Despite the long time needed to get to a full operative detector with a mass of the order of 1 kton for neutrino oscillation physics, it has to be remarked that the successful operations of ICARUS-T600, in Pavia first and then at LNGS, paved the way for the development of a large community of neutrino physicists and technologists rapidly converging around newest LAr-TPC projects, in particular at Fermilab. Remarkably, the ICARUS-T600 detector is still part of these projects within the SBN program, also thanks to a very fruitful collaboration between INFN, CERN and Fermilab.

Funding: This research received no external funding

Conflicts of Interest: The authors declare no conflict of interest.

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