PROCEEDINGS OF SCIENCE

The Short Baseline Neutrino Program at Fermilab

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The current status of the Short Baseline Neutrino (SBN) project at Fermilab is reviewed. While the installation of SBND is still in progress, ICARUS has taken its first neutrino data on beam: using both the Booster Neutrino Beam (BNB) and the Neutrino at the Main Injector (NuMI) beam. MicroBooNE has presently completed its data taking and is producing the world's first high statistics results on ν-Ar interactions, in both inclusive and exclusive channels. In parallel, the unexpected MiniBooNE "low energy excess" is under investigation, to search for sterile neutrinos. The physics potential for sterile neutrino searches at SBN will be outlined, with emphasis on the Neutrino-4 experiment and the possible ICARUS verification of this claim.

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[1] on behalf of SBN (Icarus, SBND, MicroBooNe collaborations)

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1. Introduction

Anomalies observed in short baseline (SBL) oscillation experiments in the last 20 years (see table 1), not fitting inside the standard model of 3-flavour neutrino mixing, may be explained by a 3+1 oscillation model with a sterile neutrino, where $\Delta m^2 \sim O(1eV^2)$ and $\sin^2(2\theta)$ is relatively small. Unluckily no model has so far been successful in fitting all experimental results at once.

Experiment	type	baseline, E_ν	mode	channel	CL
LSND [1]	DAR accelerator	$\sim$ 30 m, $\sim$ 30 MeV	appearance	$\overline{\nu}_\mu \mapsto \overline{\nu}_e$	3.8 σ
MiniBooNE [2]	SBL accelerator	$\sim$ 540 m, $\geq$ 500 MeV	appearance	$\nu_\mu \mapsto \nu_e$	4.5 σ
				$\overline{\nu}_\mu \mapsto \overline{\nu}_e$	2.8 σ
GALLEX/SAGE [3]	source - e capture	1.9 m, 0.6 m 0.8 MeV	disappearance	$\nu_e \mapsto \nu_X$	2.8 σ
Reactors [4]	β decay		disappearance	$\overline{\nu}_e \mapsto \overline{\nu}_X$	3.0 σ

Table 1: Main short-baseline experiments showing anomalies in the neutrino sector

The Fermilab Short-Baseline Neutrino program (SBN) [5] has been proposed in 2015 to give a definitive answer to the problem. The SBN program will have the unique possibility to exploit both ν_e appearance and ν_μ disappearance using the well known Booster Neutrino Beam (BNB) [1] and employing three detectors based on the common technology of Liquid Argon (LAr) TPC. As shown in figure 1, SBND is located at 100 m from the BNB target, followed by MicroBooNE at 470 m and Icarus at 600 m. BNB is a conventional horn-focussed ν_μ beam with an energy spectrum peaking at $\sim$ 700 MeV and with a well-known ν_e contamination ($\sim$ 0.5%), see the right panel of figure 1. While SBND will collect events from BNB at a rate of 0.25 Hz, Icarus will have a 0.03 Hz rate. Being at ground level, with a limited overburden, both detectors will have a sizeable rate of cosmics: around 0.03 Hz at SBND and 0.14 Hz at Icarus. The mitigation of this issue is one fundamental aspect of data taking for both experiments.

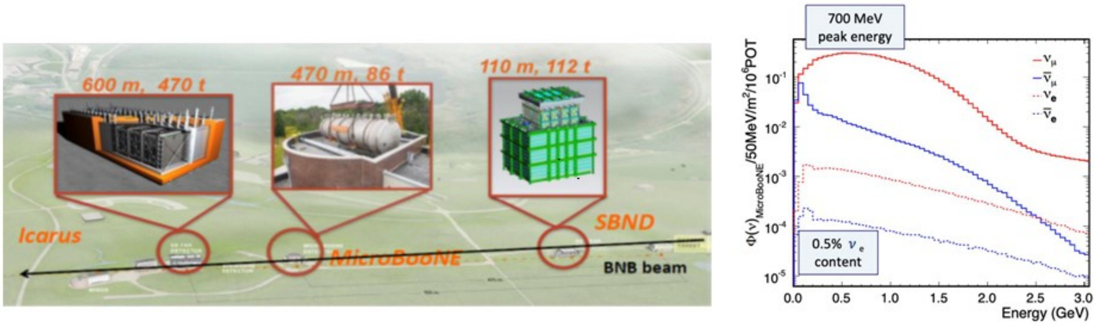

Figure 1: Left panel: layout of the BNB beamline at Fermilab. For the SBN program SBND will operate as near detector and Icarus as Far detector. Right panel: components of the BNB beam at Fermilab.

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[1] fluxes are well understood thanks to a detailed simulation [6] and the availability of 8.9 GeV/c p+Be data from the HARP experiment at CERN PS [7]

2. The SBN Physics Program

The SBN Physics Program was set up:

- to understand the nature of MiniBooNE "low energy excess", with MicroBooNE (Phase I);
- to search search for sterile neutrinos both in appearance and disappearance channels, using SBND as near and ICARUS as far detector (Phase II). The use of the same detector technology will greatly reduce the systematics errors, while the good ν_e identification capability of a LAr TPC will help to reduce backgrounds.
- pave the ground for future long-baseline experiments, as DUNE [8], by a further development of the LAr TPC technology and by a high-statistics measure of $\nu-$Ar cross sections in the few GeV region.

SBND will accumulate $\sim 7 \times 10^6$ ν_μ and 5×10^4 ν_e events in a 3-year run, to measure $\nu-$Ar cross sections in the DUNE energy range. ICARUS will collect $\sim 10^5$ events/year from the NuMI beam (off-axis) producing high statistics electron neutrino cross sections. Five sigmas sensitivities will be reached in the SBN program with 3-year data taking (6.6×10^{20} POT), to search for sterile neutrinos in appearance or disappearance channels, in the currently allowed parameter region. The expected sensitivities are shown in figure 2. In addition, a rich program of BSM searches will be performed, looking for neutrino tridents, dark matter, heavy leptons, Lorentz and CPT violations ...

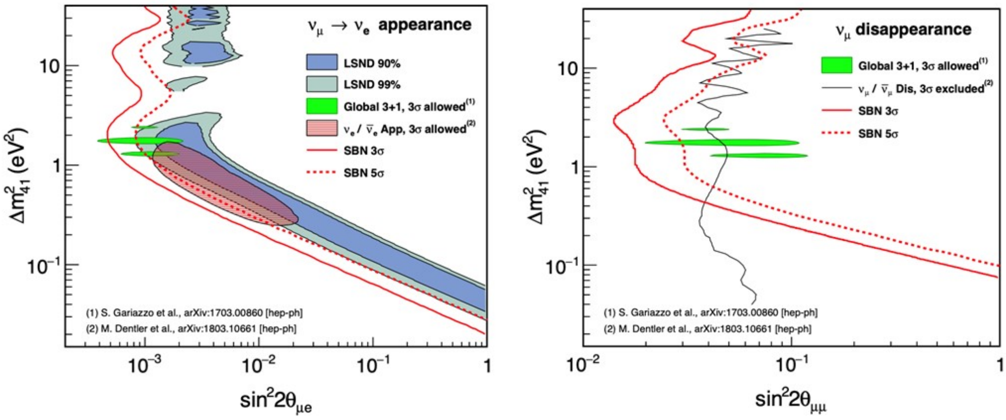

Figure 2: Expected sensitivities in the SBN program, in ν_e appearance (left) and ν_μ disappearance (right) modes, from reference [5]

The reactor Neutrino-4 experiment has recently shown evidence at 2.7 σ for an oscillatory pattern with best fit parameters $\Delta m^2_{N4} = 7.30$ eV^2, $\sin^2\theta_{N4} = 0.36$. [9]. Having a similar L/E ratio, ICARUS alone may provide a complete verification of this claim in less than one year, by using both the BNB and the NuMI beam [10]. About 11500 ν_μ CC events will be collected in 3 months of data taking at BNB and about 5200 ν_e interactions will be accumulated in 1 year of data taking at NuMI. Survival $\nu_\mu(\nu_e)$ probability are shown in figure 3, for the oscillation case. Neutrino-4 expectations are shown as black dotted line or blue continous line in the figure.

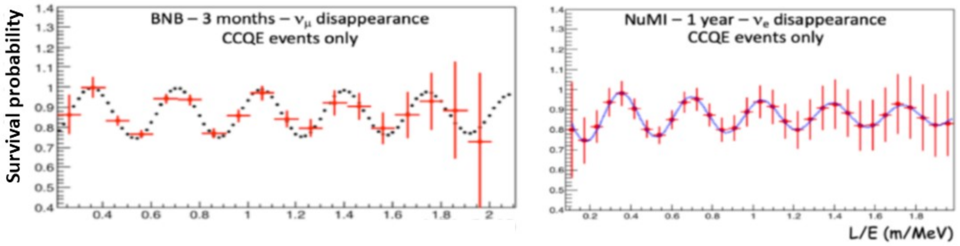

Figure 3: Left(right) panel: survival ν_μ (ν_e) probability for the Neutrino-4 anomaly and expected ICARUS measurement for 3 months (1 year) of BNB (NuMI) data taking.

3. Status of the SBN Program

The SBN detectors are based on the LAr TPC technology introduced by C. Rubbia in 1977 [11] and developed by the ICARUS Collaboration in the following years [12].

A LAr TPC is a kind of "electronic bubble chamber" that gives detailed images as shown in figure 4. As a figure of merit in the heavy freon bubble chamber "Gargamelle" the sensitive mass was 3 tons, compared to the 600 tons of ICARUS LAr TPC.

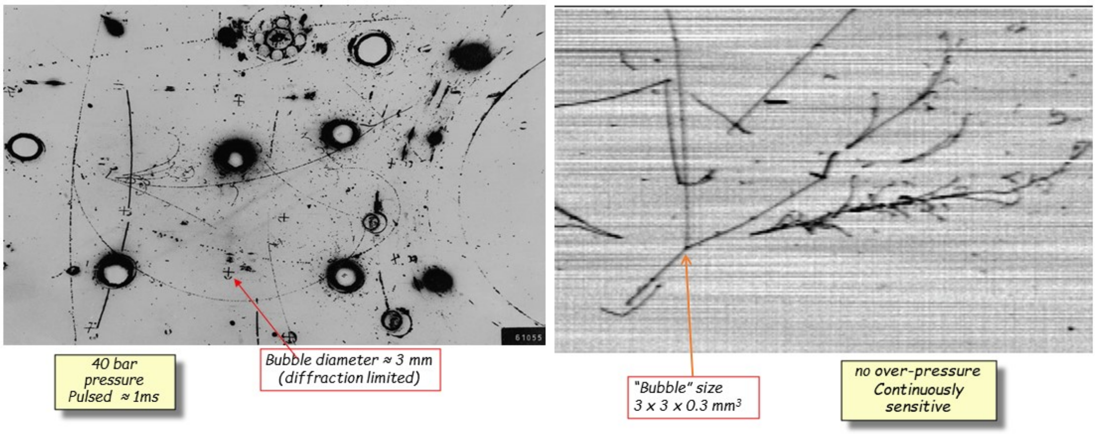

Figure 4: Images of two neutrino events as seen by the giant heavy freon bubble chamber "Gargamelle" at CERN (left side) and by ICARUS T600 (right side). "Bubble" sizes are similar.

3.1 Phase I: MicroBooNe

MicroBooNE is currently the world's longest running LAr TPC: from 2015 on. With a mass of 170 tons of liquid Argon (87 tons active volume), it consists of a TPC with 2.5 m drift, a system of 32 8" PMTs coated with TPB and a top/side cosmic ray tagger (CRT) to reject cosmics. It has presently completed its physics run, with more than 33 published papers. It has produced the world's first high statistics precision studies of ν-Ar interactions, in both inclusive and exclusive final states [13]. In addition, it is investigating the unexpected MiniBooNE excess ($> 3\sigma$ statistical and systematics combined) at lower energies of neutrino interactions producing final states electrons or photons. The two possibilities may not be discriminated by a Cherenkov detector as MiniBooNE, in contrast with MicroBooNE that uses a different technology and thus has the possibility to assess if these events are due to ν_e charged current interactions, see reference [14] for more details. Unfortunately, due to its surface location, MicroBooNE has very limited capabilities in non-accelerator ν physics.

3.2 Phase II: SBND+Icarus

Phase II of the SBN program will use both SBND as near detector and ICARUS as far detector to study SBL neutrino oscillations. With a mass of 260 tons of LAr (112 tons active mass) SBND is made of 2 TPCs with 2m drift, a light detection system based on 120 8" PMTs (96 coated with TPB) and 192 X-ARAPUCA photon traps instrumented with SiPMs and a 4π CRT. One central cathode plane assembly (CPA) divides the TPC active volume ($5 \times 5 \times 4m^3$) in two drift volumes. The readout is based on two anode planes assemblies (APA), made of 3 wire planes each (vertical, ±60°) with a wire pitch $\sim$ 3 mm, see figure 5 for details. Behind APAs, 24 photon detection modules (PDS) are placed. Each is made of 5 PMTs and 8 X-ARAPUCA modules. Every side of the detector will be covered by planes of extruded scintillator strips, making the CRT. In regards to the installation at Fermilab, PMTs and X-ARAPUCAs have been tested and delivered, TPC installation is under way as well as CRT and cryostat/cryogenics and will be finished by 2022.

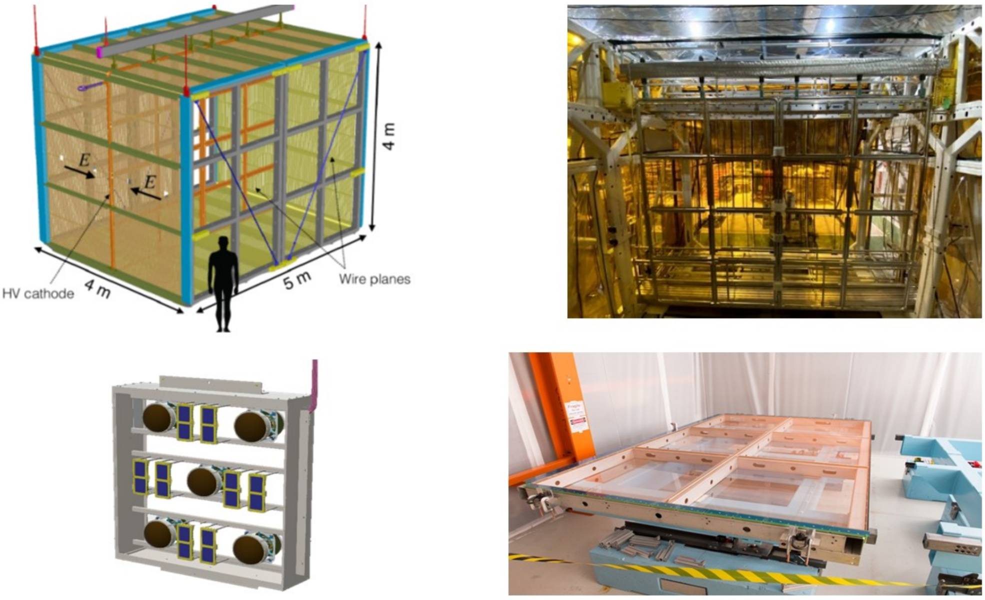

Figure 5: Left panel: layout of the SBND TPCs (top), layout of one PDS module (bottom). Rght panel: cathode plane assembly (CPA) recently installed (top); first APA plane on-site (bottom)

ICARUS has an active mass of 476 tons of liquid Argon. It was refurbished at CERN in the framework of the WA104 program [15]. Cold vessels and a purely passive insulation were installed; a new scintillation light detection system (based on 360 PMTs coated with TPB) was provided; a new TPC readout electronics was implemented and cryogenics and LAr purification systems were refurbished. The present installation status of the ICARUS cryogenic system at Fermilab, on the top of the detector, is shown in figure 6. Aside the top CRT, installation activities in ICARUS are completed, with latest adjustments during COVID-19 restricted operations. Since March 17th 2020

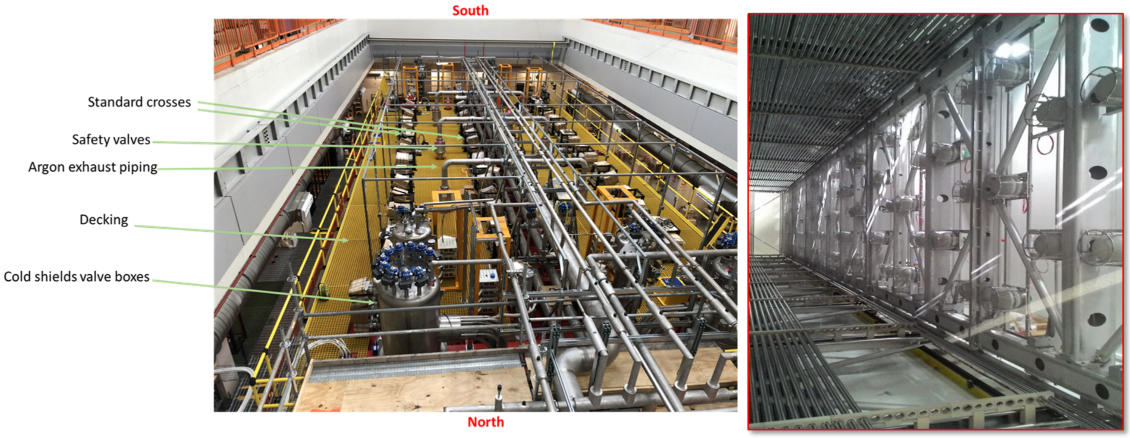

Figure 6: Left: layout of the cryogenics for ICARUS at Fermilab. Right: PMTs after the planes of readout wires. For more details see [16].

the detector is operated with 24/7 remote shifts and a minimal presence in situ. One of the main problems in ICARUS data-taking is its installation at shallow depth, with a limited overburden. ICARUS will thus be exposed to a continuos flux of cosmic rays, containing high-energy muons that may be misidentified as part of a neutrino interaction. To mitigate this problem, two handles are available: a 4π CRT surrounding ICARUS TPCs and the timing in coincidence with the beam spill, from the PMTs system. The 3m overburden, on the top of ICARUS, will absorb more than 99% of the incoming photons and hadrons. The CRT system is composed of a bottom, a side and a top CRT. Each is made of two layers of plastic scintillators, partly recuperated from Double CHOOZ and MINOS. The CRT will provide informations on incoming muons by their detection and measurement of crossing time and coordinates. Preliminary results are shown in reference [17].

The new light detection system [18] is based on 360 8" R5912-MOD photomultipliers, installed behind the TPCs wires, as shown in figure 6. The PMTs' coating with TPB allows the detection of the prompt scintillation light from LAr at 128 nm. The system will allow ICARUS to identify the time of occurrence (t_0) of any ionizing event in the TPC with $\sim$ 1 ns timing resolution, localize events with $\leq$ 50 cm spatial resolution and determine their rough topology and generate a trigger signal for readout. Together with the beam bunched structure, this will allow an efficient rejection of the cosmics background. PMTs' equalization of gain and timing is performed with a laser system, flashed on each PMT by a dedicated fiber system [19].

The other major issue in ICARUS data taking is the Argon purity level, that affects the electron drift lefeime τ_D. As shown in figure 7 in RUN0 τ_D reached up to $\sim$ 4.5(3) ns in the EAST (WEST) cryostat, allowing efficient signal detection over the full LAr volume. This was due to improvements on poor performing GAr recirculation units and periodic venting (3 times/day). Further improvements are expected from the installation of new higher capacity GAr filters.

4. ICARUS RUN0 with BNB and NuMI beamlines

During RUN0, up to end of July 2021, ICARUS has taken data with the following goals:

- certify the readiness of the detector for physics quality data, operating as primary BNB user;
- verify the possibility to run the detector in remote mode 24/7, with a limited on-site presence;

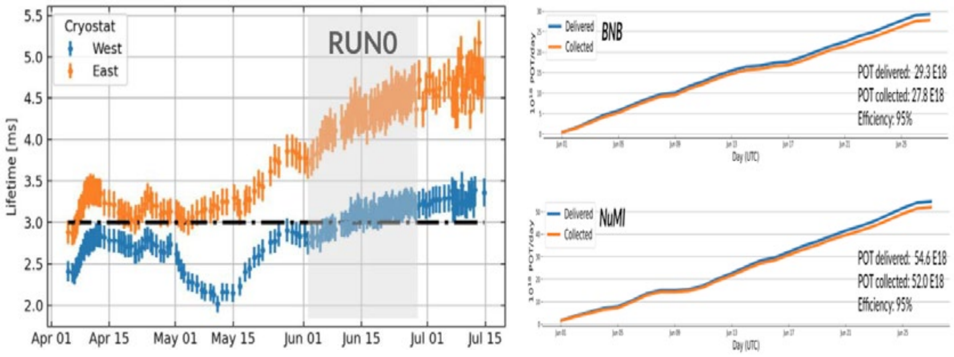

Figure 7: Left panel: measured electron drift lifetime during ICARUS RUN0. Right panel: delivered and collected data during RUN0 from the ICARUS detector.

- test DAQ for different triggers for both BNB and NuMI beam;
- accumulate data samples of good quality to tune neutrino and cosmics event reconstruction.

Two main triggers we used to collect BNB and NuMI events: a Minimum Bias Trigger, where data were recorded for every beam spill and a “Majority trigger” using pairs of discriminated PMT signals in coincidence with the beam spill gate. As shown in figure 7 about 27.8×10^{18}(52.0×10^{18} POT were collected from BNB (NuMI) beams with an efficiency $\sim$ 95%. As examples of the commissioning of ICARUS in RUN0, figure 8 shows the results of the PMTS’ gain equalization using the laser system and single photoelectrons from the background [2] and of the measurement of space charge effects (SCE) using anode-cathode-crossing cosmic muons, looking at distortions in the drift direction.

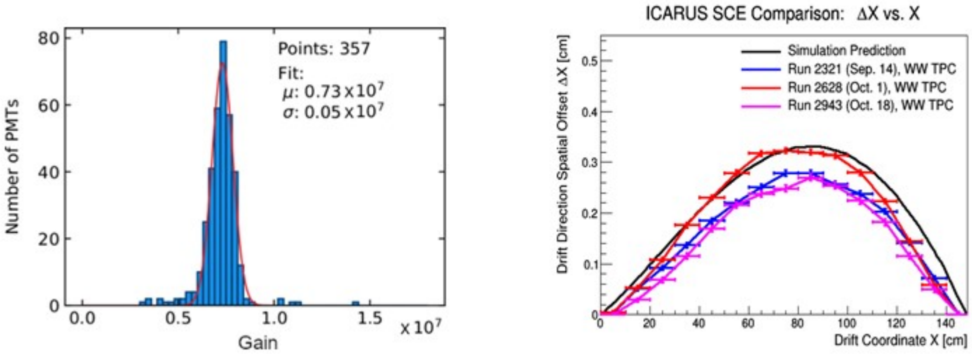

Figure 8: Left panel: Distribution of PMTs’ gains after the equalization procedure. Right panel: measurement of SCE for the ICARUS TPC.

The ICARUS detector recorded its first muon and electron neutrinos, thus demonstrating its excellent detection capabilities. About 254 ν_μ CC and 15 ν_e CC candidates were selected and visually scanned during this run. Examples of charge current (CC) quasi-elastic (QE) candidates from BNB and NuMI beams are shown in figure 9. The top panels of figure 9 show a picture of a

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[2] after equalization the spread of PMTs’ gains is reduced to $\sim$ 7% from an initial value $\sim$ 17%, obtained using preliminary calibrations at room temperature

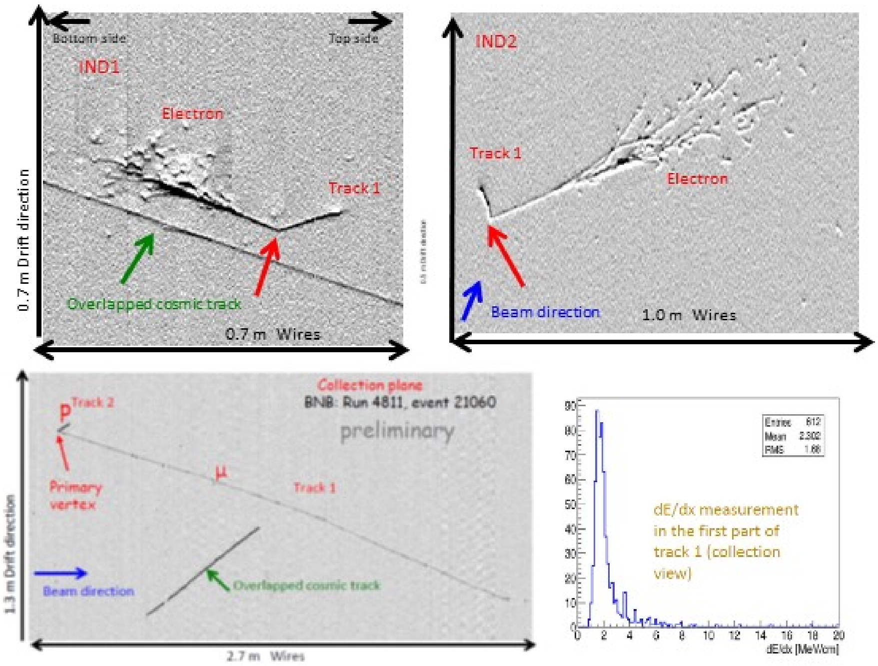

Figure 9: Examples of CC QE neutrino events, collected during RUN0 at Fermilab. Top: NuMI ν_e CC candidate; bottom: BNB contained ν_μ candidate. Red arrows point to the primary vertex.

NuMI QE CC $\nu_e p \mapsto pe$ event. Track 1 is the forward going proton candidate stopping inside 13 cm. The e.m. shower from the electron candidate ($E_{dep} \sim 650$ MeV) is going downward. The left bottom panel of figure 9 shows instead the image of a BNB CC QE $\nu_\mu n \mapsto p\mu$ event. Track 1 is the muon candidate stopping after 2.8 m, with a deposited energy $E_{dep} \sim 650$ MeV, while track 2 is the proton candidate stopping after 10.9 cm, with $E_{dep} \sim 100$ MeV. The shower beginning is clearly visible.

5. Conclusions

The SBN program at Fermilab is progressing well, with MicroBOONE now producing high statistics measurements of $\nu-$Ar cross sections and getting closer to release the first results on the low energy excess of MiniBooNE, with 6×10^{20} POT.

ICARUS was activated in August 2020 and is currently taking data.

Assembly and installation of SBND detector are progressing and will finish by 2022.

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