IL NUOVO CIMENTO **45 C** (2022) 19
DOI 10.1393/ncc/i2022-22019-6

Colloquia: SoUP 2021

The Cosmic Ray Tagger of the Short Baseline Neutrino program Far Detector at Fermilab

F. Poppi on behalf of the ICARUS Collaboration

INFN, Sezione di Bologna and Department of Physics and Astronomy, University of Bologna Viale Carlo Berti Pichat 6/2, 40127, Bologna, Italy

received 4 November 2021

Summary. — The Short Baseline Neutrino Program at Fermilab aims to discover, or definitely rule out, the existence of sterile neutrinos at the eV mass scale by means of Liquid Argon TPCs along the Booster Neutrino Beamline. In order to mitigate the background induced by cosmic muons, the Far Detector (ICARUS-T600) is instrumented with a 4π Cosmic Ray Tagger system. This paper focuses on the description of the cosmic ray tagger, its performance, its integration in the experiment and its role in the event reconstruction.

1. – Introduction

In recent years, several experimental anomalies in the neutrino sector have been reported which could hint at additional physics beyond the Standard Model. The anomalies were observed at accelerator neutrino beam experiments (LSND and MiniBooNE anomaly), nuclear reactor experiments (reactor neutrino anomaly and Neutrino-4 results) and radioactive MCi sources in solar neutrino experiments (Gallium anomaly) [1, 2], see table I. The observed anomalies are not consistent with the three neutrino mixing described by the Pontecorvo-Maki-Nakagawa-Sakata matrix. The unexpected oscillation pattern would imply the existence of one or more light sterile neutrino states.

The Short Baseline Neutrino (SBN) program at Fermilab aims to discover, or definitely rule out, the existence of sterile neutrinos at the eV mass scale by means of three Liquid Argon Time Projection Chambers (LAr TPCs) along the Booster Neutrino Beamline (BNB) (fig. 1) [3]. The Near Detector, SBND, is located at 110 m from the BNB target with an active mass of 112 t of liquid argon. MicroBooNE is 470 m from the BNB target and has an active mass of 87 t of liquid argon. The Far Detector, ICARUS T600, is placed 600 m from the BNB target with an active mass of 476 t of liquid argon. ICARUS is located $\sim 6^\circ$ off-axis the NuMI beam, hence it will also be exposed to its ν_e-rich off-axis component. The SBN program incudes the investigation of both the appearance and disappearance channels in neutrino and anti-neutrino mode. Over the 3 years beam

TABLE I. – *Neutrino anomalies summary.*

Experiment	Neutrino flux	Channel	Significance
LSND	DAR accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8 σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	4.5 σ 2.8 σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8 σ
Reactors (Neutrino-4)	β decay	$\bar{\nu}_e$ disappearance	3.0 σ (3.5 σ)

runs, the Far Detector will acquire $\sim$560000 ν_μ Charged Current (CC) events from the BNB, corresponding to an exposure of 6.6$\times 10^{20}$ POTs. From the NuMI beam, a rate of 4.3$\times 10^5$ ($\sim$3.7$\times 10^5$) CC events per year is expected for positive (negative) focusing.

2. – ICARUS-T600

The ICARUS detector consists of two adjacent modules of 3.6$\times$3.9$\times$19.9 m^3 filled with liquid argon. In each module, the argon volume is surrounded by a high voltage cathode surface on one side and an anode plane on the other. To obtain a 3-D image of the particles trajectories, three parallel planes of wires (horizontal, +60 and -60 degrees) are used. The ionization electrons are drifted by the $\sim$500 V/cm electric field and collected by the sensing wires on the anode plane. Scintillation light produced by LAr is collected by PMTs on each side of the modules providing fast timing and calorimetric information of the acquired events.

ICARUS-T600 was operated at the INFN Laboratori Nazionali del Gran Sasso (LNGS) where it collected $\sim$3000 neutrino events on the CNGS neutrino beam. The two TPC modules underwent a major overhauling at CERN and in 2017 they were shipped to FNAL.

At the time of writing, ICARUS-T600 concluded the "Run 0", dedicated to the commissioning phase of the detector. ICARUS took data both on BNB and NuMI, the first CC neutrino interactions have been observed and they are reported in fig. 2.

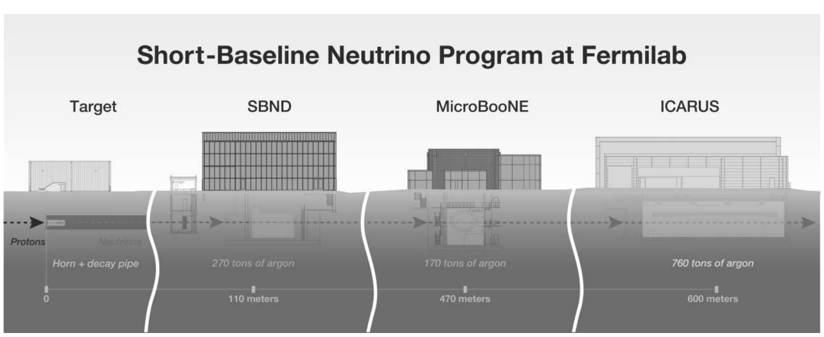


Fig. 1. – Illustration of the LArTPCs along the Booster Neutrino Beamline at Fermilab.

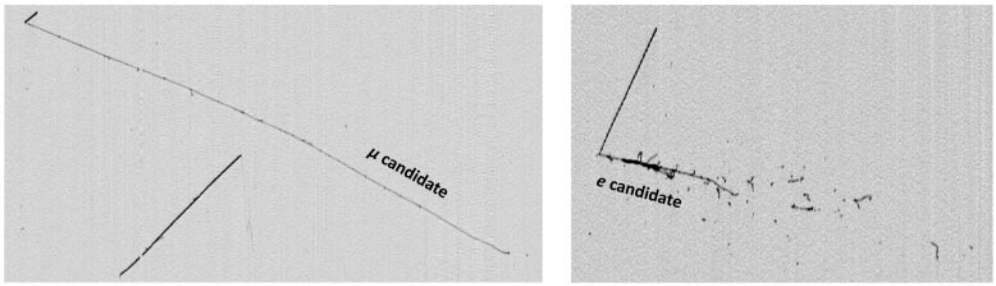


Fig. 2. – First neutrino interactions observed at the ICARUS Far Detector: (left) CC muon neutrino interaction from BNB, (right) CC electron neutrino interaction from NuMI.

3. – Cosmic ray induced background

ICARUS-T600 was first designed to operate in the low cosmic background environment of the LNGS, covered by 1400 m of Gran Sasso rocks. The SBN conditions are completely different: the detector will be covered by only a 3 m concrete overburden. ICARUS is thus exposed to a rate of ∼11 kHz cosmic muons events. During the 1 ms readout window of the TPC, ∼11 cosmic ray tracks are expected over the full T600 detector. Photons associated with cosmic muons represent a serious background for the ν_e appearance search, since electrons generated in LAr via Compton scattering or pair production can mimic a ν_e CC signal.

In order to mitigate the contribution of cosmic muon induced background, the TPC will be surrounded by a Cosmic Ray Tagging system (CRT), tagging the cosmic muons before they reach the TPC. The CRT will provide a 4π coverage with three different subsystems: Top, Side and Bottom CRT, with the Top CRT tagging more than 80% of the cosmic muon flux.

By crossing the CRT modules, cosmic or beam-induced muons are tagged and associated with a CRT hit providing spatial coordinates of the crossing particle and a time-stamp with ∼ns resolution. Exploiting the TPC information, tracks inside the LAr

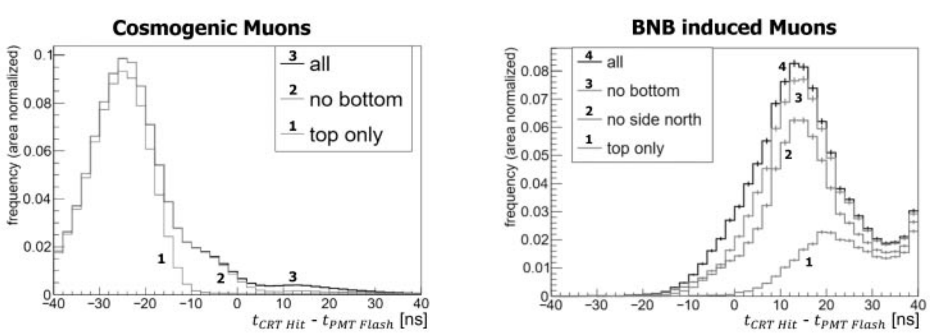
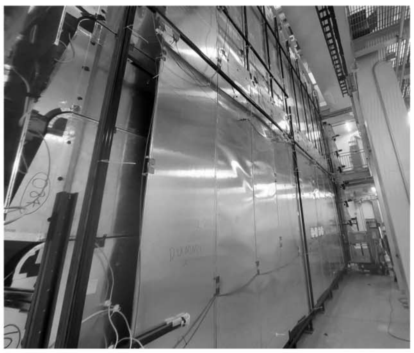


Fig. 3. – Simulation-based plots of the timing difference between CRT hits and PMT flashes for (left) cosmogenic muons and (right) BNB induced muons, considering the different CRT subsytem providing the CRT hit.



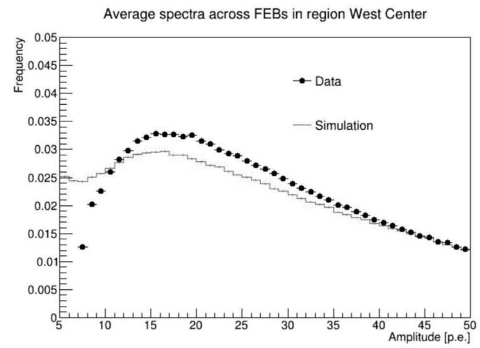


Fig. 4. – Left: picture of Side CRT modules after installation and testing. Right: preliminary comparison between commissioning and simulated data of the signal amplitude spectra for some of the Side CRT modules. The difference between the two spectra is due to collected data not corrected yet for single channel calibration.

volume can be associated with CRT Hits. The $\mathcal{O}$(few ns) timing resolution of the CRT hit can be compared with the fast PMT flash signal inside the TPC, allowing to determine if the muon particle was exiting or entering the TPC (fig. 3).

4. – Cosmic Ray Tagging system

The Bottom CRT system is composed of modules reused from the Double Chooz experiment. The modules consist of two layers of 32 parallel scintillator strips, each 5 cm wide. The readout is performed by a 64-pixel multi-anode PMT. In summer 2017 bottom CRT modules were installed underneath the warm vessel, they will be integrated in the common DAQ in the upcoming months.

The Side CRT is composed of scintillator bars previously used on the MINOS experiment. Each Side CRT module consists of 20 parallel scintillator strips. The scintillation light is readout by one Silicon PhotoMultiplier (SiPM) at each side. Modules have a double layer X-X configuration, with the exception of the upstream wall, which has an X-Y configuration. The Side CRT system has been fully installed and it is undergoing the final steps of the commissioning phase, see fig. 4. In this preliminary stage, single channel calibration of the Side CRT is not yet implemented, this introduces differences with the predicted amplitude spectra that will be resolved in the commissioning phase.

The Top CRT will provide a coverage of 400 m^2. It is composed of 123 modules deployed horizontally (84 modules) and vertically (39 modules) on the top side of the ICARUS detector. The modules are hodoscopes consisting of two orthogonal layers of eight 23 cm wide scintillator bars each, encased in 1.86×1.86 m^2 aluminum boxes. The scintillator bars used in the top (bottom) layer are 10 (15) mm thick. An illustration of the Top CRT assembly is provided in fig. 5. The scintillation light is collected by two WaveLength-Shifting (WLS) fibres per bar, each read out at one end by a SiPM, while the other end is mirrored. The signals coming from the SiPMs are collected by a commercial Front-End Board (FEB) and they are processed by the trigger logic. In order

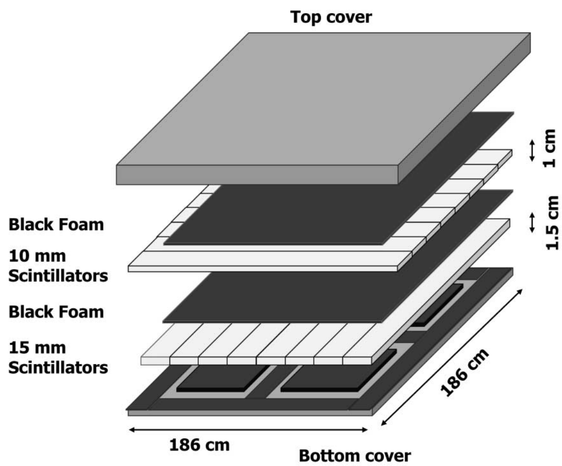


Fig. 5. – Illustration of the Top CRT module design, consisting of two orthogonal layers of eight scintillator bars each encased in an aluminum box.

for a muon to be acquired by the FEB it has to cross at least one scintillator bar per layer and the signals generated by both SiPMs have to be above a 1.5 Photo-Electrons (PE) threshold. The CRT hits are reconstructed with position and timing resolution of 23×23 cm^2 and $\sim$2 ns, respectively.

The Top CRT modules were built and tested at INFN-LNF, they will be installed in fall 2021 and then commissioned.

5. – Conclusion

The SBN Far Detector at Fermilab is undergoing its commissioning phase, the first neutrino interactions were observed both on the BNB and NuMI beams. In order to mitigate the cosmic ray induced background, the LAr TPC will be surrounded by a cosmic ray tagger system. Once the CRT will be fully commissioned, it will be integrated in the full ICARUS DAQ system, providing the cosmic rejection tool needed for the background discrimination.

REFERENCES

[1] Giunti C. and Lasserre T., *Annu. Rev. Nucl. Part. Sci.*, **69** (2019) 1.
[2] Serebov A. P. and Samoilov R. M., *JETP Lett.*, **112** (2020) 4.
[3] MicroBooNE, LAr1-ND and ICARUS-WA104 Collaborations, *A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam*, arXiv:1503.01520 (2015).