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A Novel Cosmic Ray Tagger System for Liquid Argon TPC Neutrino Detectors

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Abstract: The Fermilab Short Baseline Neutrino (SBN) program aims to observe and reconstruct thousands of neutrino-argon interactions with its three detectors (SBND, MicroBooNE, and ICARUS-T600), using their hundred-ton scale Liquid Argon Time Projection Chambers to perform a rich physics analysis program, in particular focused on the search for sterile neutrinos. Given the relatively shallow depth of the detectors, the continuous flux of cosmic ray particles crossing their volumes introduces a constant background which can be falsely identified as part of the event of interest. Here we present the Cosmic Ray Tagger (CRT) system, a novel technique to tag and identify these crossing particles using scintillation modules which measure their time and coordinates relative to the internal events to the neutrino detector, with the intent of mitigating their effect in the event tracking reconstruction.

Keywords: neutrino detectors; particle identification methods; SiPM; background rejection

1. Introduction

The Fermilab Short Baseline Neutrino (SBN) program was proposed by three international collaborations to accomplish a wide spectrum of physics research. Once the program is completed, it will perform sensitive searches for ν_e appearance and ν_μ disappearance. It will also study the neutrino–argon cross-section with millions of interactions using the Booster Neutrino Beam (BNB) at Fermilab [1]. These studies are expected to solve the currently unexplained low energy event excess observed by MiniBooNE [2], which could be interpreted by theories that extend the Standard Model of Particles and Interactions with additional "sterile" neutrinos or the presence of a not-yet-observed electromagnetic background.

The program is composed of the currently running MicroBooNE detector, a 170 t (total mass) liquid argon (LAr) time projection chamber (TPC) with charge- and light-collection readout [3], located 470 m away from the BNB primary target. Besides this, the 112 t (total mass) Short Baseline Near

Detector (SBND) [4] and 600 t (total mass) ICARUS T-600 detector [5]—both LArTPCs—are respectively located at 110 m and 600 m away from the BNB target. The construction of the SBN detectors is expected to be completed in 2017. The MicroBooNE collaboration finished the commissioning of the detector in the Summer of 2015, and has already collected neutrino interactions corresponding to about 4.0×10^{20} protons on target [6]—more than half of the total expected for three years running.

Due to the shallow depth of the detectors' location ($\sim$6 m underground), these are continuously exposed to a flux of background cosmic ray particles. At ground level, the most abundant of these cosmic ray particles are muons, produced in the decay of pions and kaons [7].

In a typical neutrino–argon interaction in the LArTPCs, charged particles release their energy in the medium as described by the Bethe–Bloch formula. Due to the electric field present in the TPC, ionization electrons drift toward the anode, where they are collected and the energy and momentum of the secondary particles is reconstructed. At the same time, primary scintillation light coming from the argon atoms is read out by a system of photomultiplier tubes (PMTs) immersed in the LAr volume, providing timing information and an external trigger for the data acquisition (DAQ).

There exists a non-zero probability that a high-energy cosmic ray muon crossing the reconstructed volume is misidentified as part of the neutrino interaction. Each muon track is surrounded by tracks of electrons and positrons originating from bremsstrahlung of delta-electrons. For a 2.2 ms readout time window, it has been estimated that around eight muons cross the 2.33 m $\times$ 2.56 m $\times$ 10.37 m active volume of MicroBooNE [6].

The Cosmic Ray Tagger (CRT) system presented here detects cosmic ray muons and aims to measure their crossing time and coordinates relative to events internal to the TPC. It is a tool to mitigate the cosmic ray background in the MicroBooNE and SBND detectors, and to improve the statistical significance of the physics measurements. The CRT systems will enable the MicroBooNE and SBND experiments to efficiently remove cosmogenic related activity from beam neutrino datasets, and will allow precision detector response characterization and calibration utilizing tagged cosmic muons.

We report here on the design and construction features of the CRT basic modules, and present performance characterization test results.

2. Cosmic Ray Tagger System

The CRT system is composed of individual scintillator modules read out by silicon photomultipliers (see Section 2.1) with a maximum size of 4.1 m $\times$ 1.8 m $\times$ 2 cm, and a maximum weight of 174 kg. Smaller-sized modules—25% to 80% of the maximum size—will also be utilized to match to the specific geometry of the experiments at Fermilab. Spatial resolution better than 10 cm and muon detection efficiency higher than 95% are required by the system in order to achieve the desired background identification. Temporal resolution on the order of ns is also required to resolve crossing muons produced by beam neutrino interactions inside the 1.6 µs beam spill [1].

The modules are produced at the Laboratory for High Energy Physics (LHEP) in Bern, and are shipped to Fermilab after a quality inspection. After assembly, modules and readout electronics (see Section 2.3) are tested for proper operation. These tests verify the full readout chain, characterize the efficiency of cosmic muon detection in each module, and verify the sensor response in each channel. The same tests were performed onsite at Fermilab with no observation of properties degradation after transportation.

Similar tagger designs have been used as muon vetoes in experiments such as the MINOS [8]. However, the novel use of silicon photomultipliers and high-elasticity optical adhesive presented here improve on both the robustness and simplicity of past designs.

2.1. Scintillator Module

Each scintillator module consists of a row of 16 mechanically-joined 10.8 cm wide scintillator strips (Figure 1) placed side by side in a protective aluminum casing. The thickness of the case walls is 2 mm; this provides the necessary mechanical stability. Strips are fixed within the module by a 0.1 mm thick double-sided adhesive layer. The gap between two adjacent strips in a module is kept below 0.2 mm. The length of the modules varies from 2.3 m to 4.1 m, for three different widths: 0.97 m, 1.75 m, and 1.81 m.

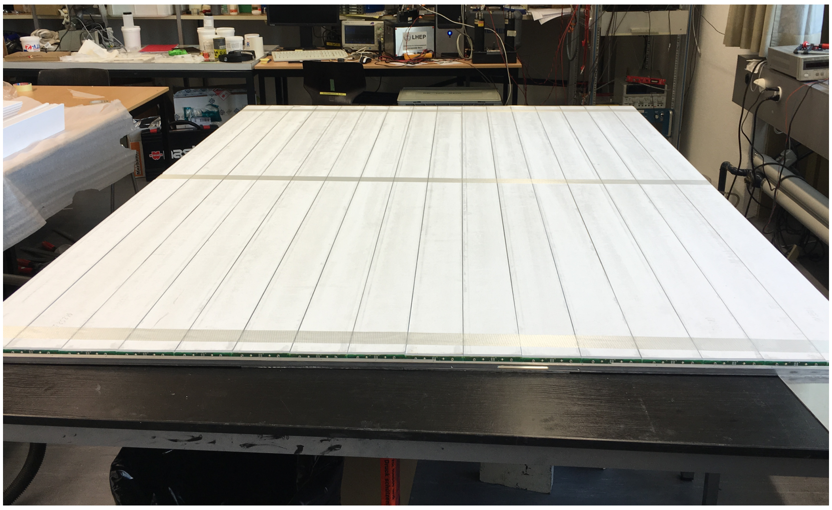
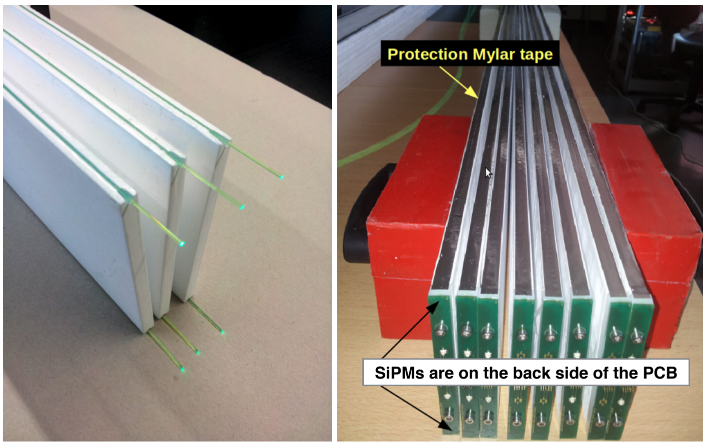


Figure 1. Scintillator module containing 16 scintillating strips. The external case is still to be mounted.

2.2. Scintillator Strip

Scintillating strips are extruded from a USMS-03 (USMS-03 by UNIPLAST Inc., Vladimir, Russian Federation) polystyrene-based mixture containing 1.5% diphenylbenzene (PTP) and 0.04% bis(5-phenyl-2-oxazolyl)benzene (POPOP). The surface of the strips is subjected to structural modification, resulting in the formation of a highly-reflective white layer (Figure 2a).



(**a**) (**b**)

Figure 2. The scintillation light is collected by Kuraray Y-11 wavelength shifting fibers and transmitted to the strip end, where it is detected by Hamamatsu S12825-050P silicon photomultipliers (SiPMs) mounted in printed circuit board (PCB). (**a**) Scintillator strips with wavelength shifting fibers glued into grooves along the strip long edges; (**b**) the strip is covered by a high-reflectivity layer.

The scintillator has an emission maximum at 430 nm and a measured bulk attenuation length of longer than 7.5 cm. In order to provide efficient and uniform collection of the scintillation light, two wavelength shifting (WLS) fibers (Kuraray Y11(200)M, 1 mm diameter) are glued into two grooves in the long edges of each strip with a polysiloxane compound (Figure 2a). The wavelength absorption peak of the fibers is 430 nm with an emission peak at 476 nm. The high elasticity of the compound allows a displacement of the fiber along the strip without the risk of damaging its cladding. This in turn adds to the robustness of the assembled module. The modules can withstand moderate bending during transportation and manipulation without any appreciable deterioration of their properties. After gluing the fiber into the grooves, each strip is covered by a reflective aluminized Mylar tape to reduce photon losses and provide mechanical protection for the fibers as shown in Figure 2b.

At the read out end, the fibers are diamond-cut and fixed in dedicated plastic end-pieces. These end-pieces also provide precise alignment of the fiber with the photo-sensor. The opposite end of each fiber is coated with aluminium by evaporation in vacuum, forming a highly-efficient reflecting mirror which doubles the light collection efficiency. Hamamatsu S12825-050P [9] silicon photomultipliers (SiPMs) are used to collect the scintillation light from the opposite side of each fiber. The sensitivity wavelength peak of this SiPM is at 450 nm. Two SiPMs are used to read out one scintillation strip. Therefore, 32 photosensors are employed in one single module. Signals from the 32 SiPMs are sent to a front-end electronics board (FEB). Each FEB is mounted at the readout end of the modules and connected to the SiPMs via 1 mm thick coaxial cables. Signal processing is performed in the FEB and readout for storage or higher-level triggering.

2.3. Front-End Board Electronics

The CRT FEB is designed to serve 32 SiPMs from one module (16 scintillator strips). The FEB provides a bias voltage in the range of 40–90 V, individually adjustable for each of the 32 SiPMs. The FEB also provides a signal coincidence using an AND logic with the digitised signal of each pair of SiPMs from the same strip, with the possibility to trigger only on events that occurred in coincidence with another event in a different FEB or group of FEBs. Furthermore, the FEB is able to generate a timestamp taking an input reference with an accuracy of 1 ns. A detailed description of the FEB design and functionality can be found in [10].

2.4. Scintillator Plane

A scintillator plane consists of several scintillator modules arranged in two different layers and orthogonal directions, as shown in Figure 3. In this configuration, when a charged particle crosses the plane, it fires at least one strip per module.

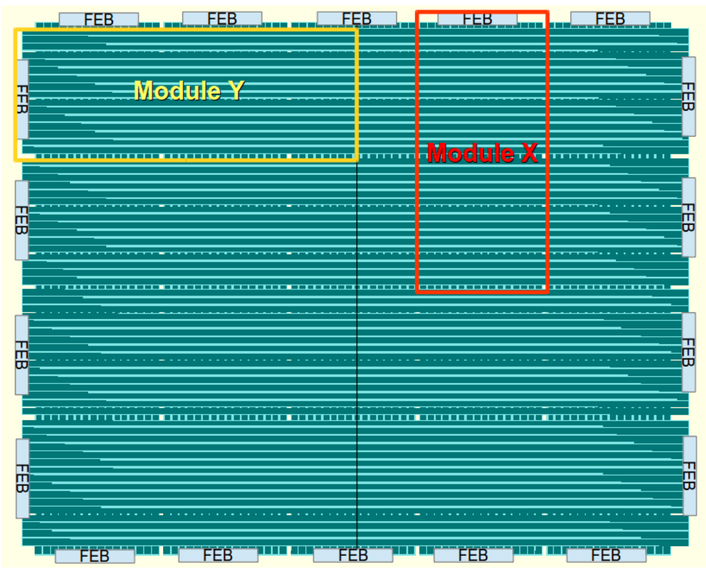


Figure 3. Cosmic ray tagger scintillator plane formed by two orthogonal layers of modules for X–Y coordinate reconstruction.

By using the relative intensities of the SiPMs corresponding to the same timestamp provided by the FEBs, the X–Y position of the particle crossing point can be computed (see Section 3). Two different scintillator planes allow a crossing particle to be tagged, providing an "interaction vector". This information can then be extrapolated to the reconstruction algorithm of the LAr TPC, discriminating any related event within the volume associated to the interaction vector that could be mistakenly identified as part of a neutrino interaction event.

The total number of scintillator modules to be built in Bern for the needs of the SBN program at Fermilab amounts to 215, for a total covering surface of 538 m^2.

3. Laboratory Tests

The first full-size 1.7 m $\times$ 5 m prototype CRT module was assembled and tested at LHEP in July–August 2015. Different studies were performed with this test module, providing useful information about the quality of the materials and the procedure for its construction. The same studies were conducted regularly on production modules (see Figure 4), obtaining similar performance results.

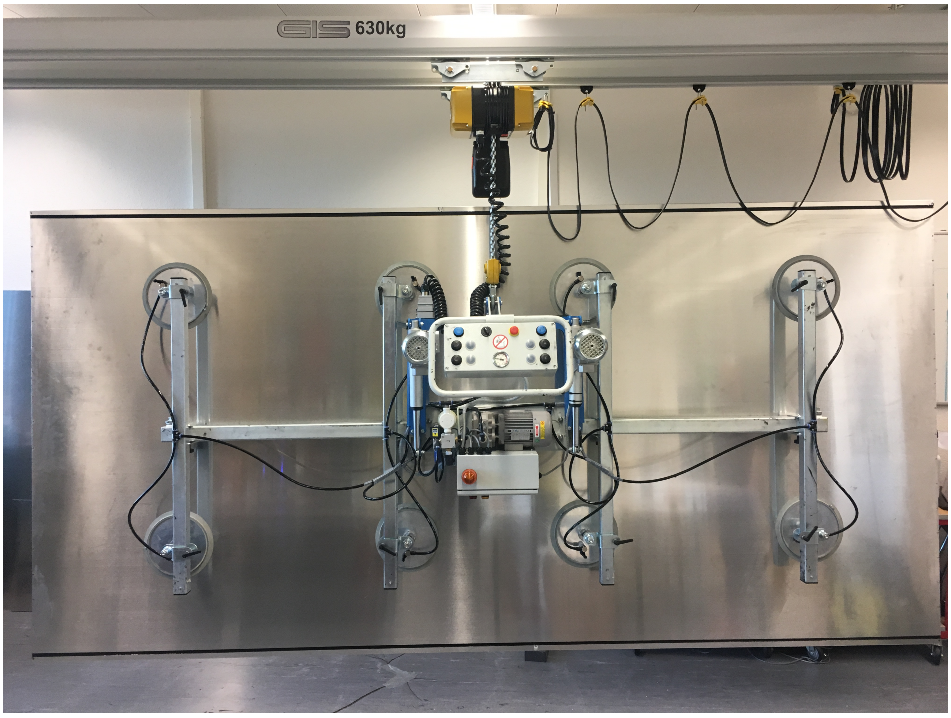
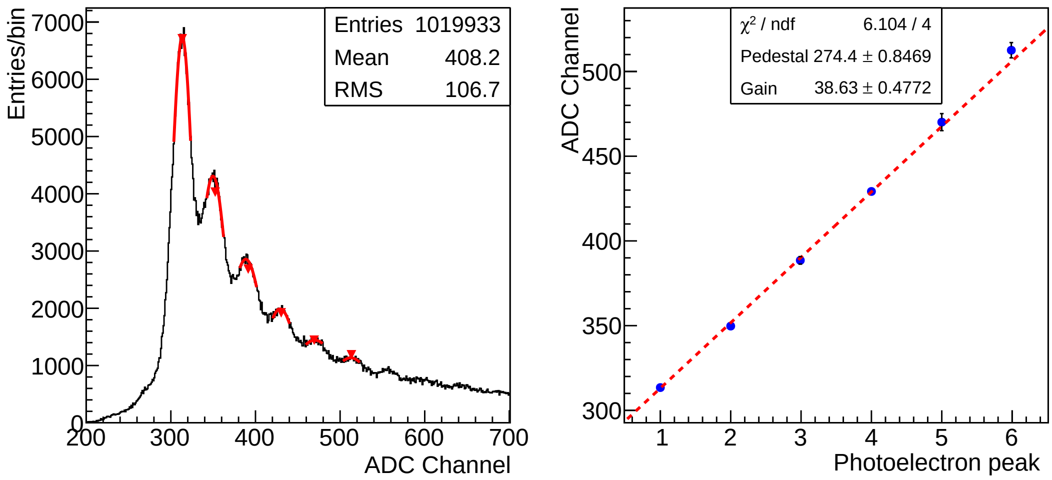


Figure 4. Full-size 1.8 m $\times$ 4.1 m production module during testing at the University of Bern.

Before data collection, the conversion gain of each individual photosensor must be accurately determined. The SiPMs from each scintillator strip are calibrated using ambient background gamma events which cross the module. From these events, the spectrum shown in Figure 5a is obtained. It corresponds to the analog to digital converted (ADC) signal associated with the avalanche charge produced by a different number of SiPM pixels. The conversion gain can be determined by fitting a Gaussian to the peaks and using the centroid position in a linear fit; an example is shown in Figure 5b. The bias voltage for each SiPM is individually adjusted in order to have a homogeneous response, achieving a spread in conversion gains within 5%.

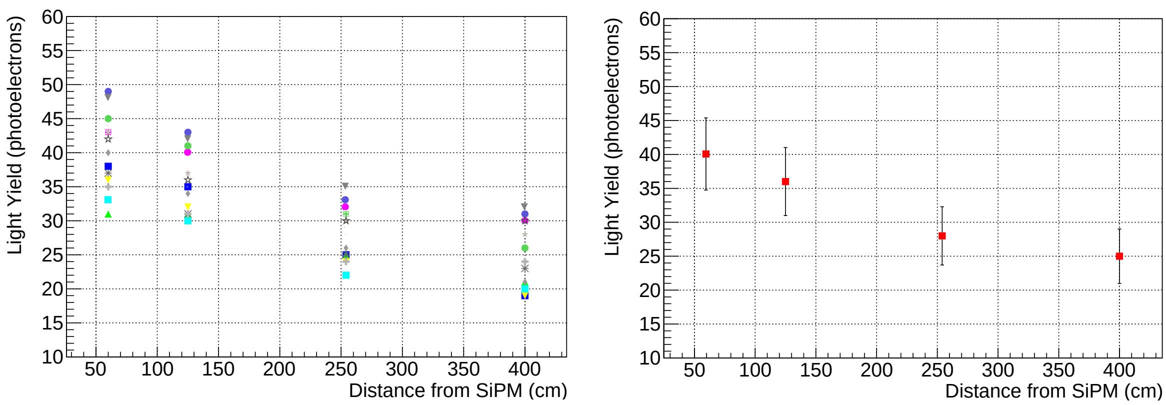


(**a**) (**b**)

Figure 5. (**a**) SiPM spectrum obtained with ambient gamma rays. Individual photoelectron peaks are fitted to a Gaussian; (**b**) number of ADC counts produced by different numbers of photoelectrons; a linear fit allows the conversion gain factor to be obtained.

The variation in the number of photoelectrons produced in the SiPMs (from now on light yield) for a relativistic muon traversing the 16 scinctillator strips of the module at different distances from the readout end was also measured. The interaction distance was determined with the aid of an external muon telescope composed of two scintillator paddles with PMTs as photodetectors. The results for each of the 16 strips are shown in Figure 6a, with Figure 6b showing the mean and the root mean square (RMS) of the spread at each point.

As one can see, the light yield follows an exponential behaviour which can be fitted to extract the attenuation length of the WLS fiber. Using the average response of the module, this was measured to be 6.88 ± 0.01 m, which is longer than the maximum module length of 4.1 m, hence ensuring sufficient light yield.



(**a**) (**b**)

Figure 6. Scintillator strip response to a traversing relativistic muon as a function of distance from the readout end. (**a**) Responses of the 16 individual strips from a module; (**b**) Mean and RMS of the data spread at each point.

The module detection efficiency for cosmic muons as a function of the distance from the readout end was measured using a trigger from the same muon telescope as described above. Detection efficiency is determined as the ratio between the number of muons detected by the telescope versus those detected by the module. Triggering of the module can only occur if the telescope is triggered, for which an efficiency above 90% has been estimated according to the expected muon flux. As shown in Figure 7, the efficiency is higher than 95% across the plane.

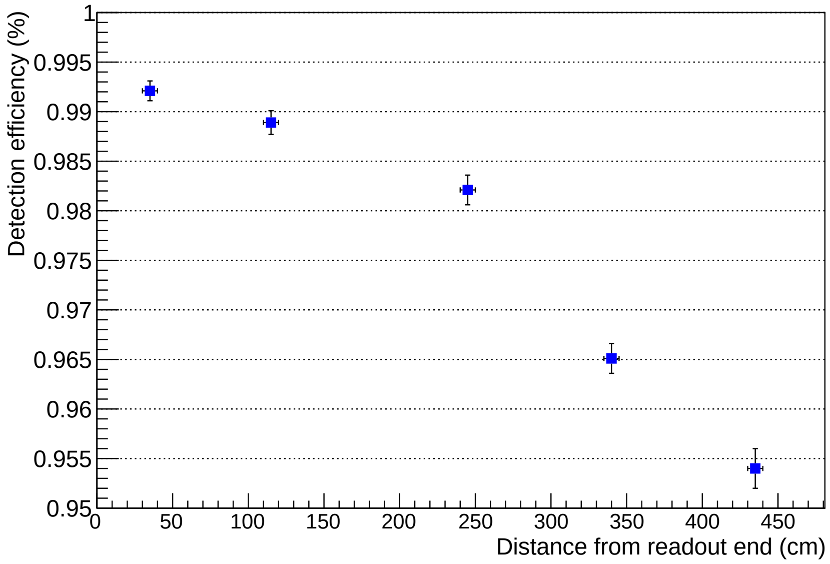


Figure 7. Detection efficiency for cosmic muons as a function of the interaction distance from the readout end.

The time resolution of the module is determined mainly by two factors: the resolution of the FEB time stamp generator, and the spread of the photon's path inside the scintillator strip and the WLS fiber. The FEB time stamp generator is composed of a coarse counter working at the clock frequency of 250 MHz, and a delay-chain interpolator [10]. For each event, the FEB is capable of recording two independent time stamps w.r.t the positive flank on LEMO inputs. The resulting resolution is illustrated in Figure 8 for events arriving 100 ns after a reference signal; it is equal to 1.3 ns RMS.

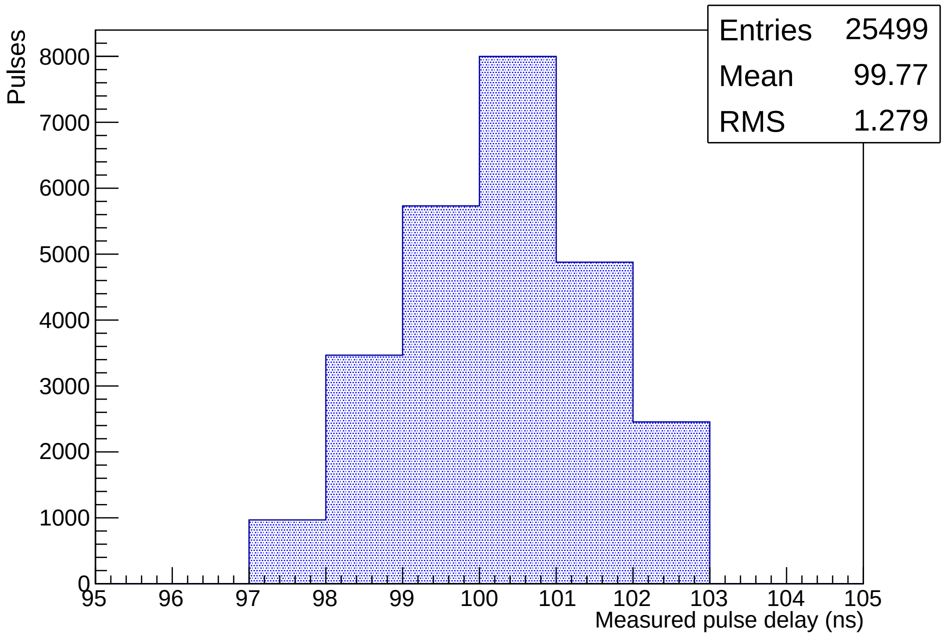
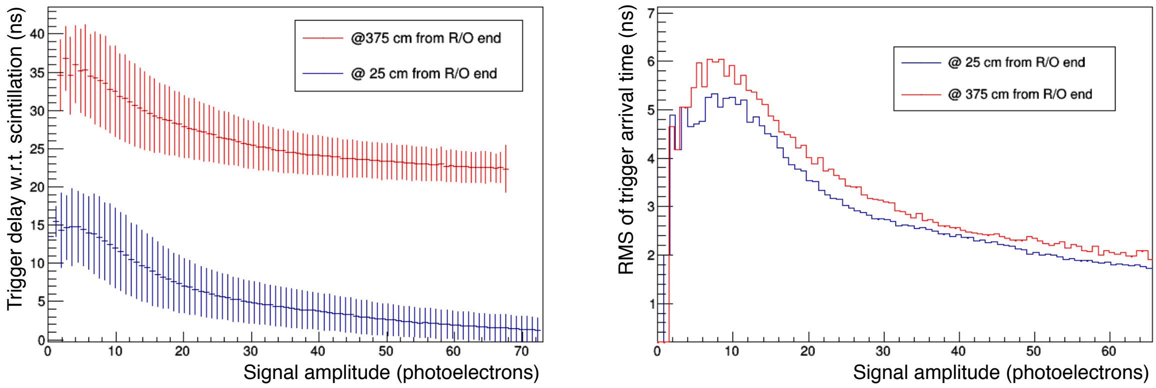


Figure 8. Accuracy of the front-end electronics board (FEB) time stamp generator.

The spread in the photon arrival time from the point where scintillation happened to the SiPM is measured with a 400 nm pulsed laser set to 60 ps pulse width. The beam was illuminating the middle of the scintillator strip, between the two fibers. This measurement was made with the laser beam entering at 25 cm, and again at 375 cm from the SiPMs. The laser was triggered by a T0 reference signal, which was also sent to the FEB. The time registered at the FEB as event time represents the delay between the laser pulse and the signal at the SiPM. The beam was gradually attenuated to a level where the SiPMs registered only a few photoelectrons. In Figure 9, a summary of the results is shown. The two curves in Figure 9a illustrate signal arrival delay for the two beam entry points. Using the average values for both distributions, the photon propagation delay was measured to be 6.1 ± 0.7 ns/m. The dependence of the RMS on the signal amplitude for both 25 cm and 375 cm from the readout end is shown in Figure 9b.

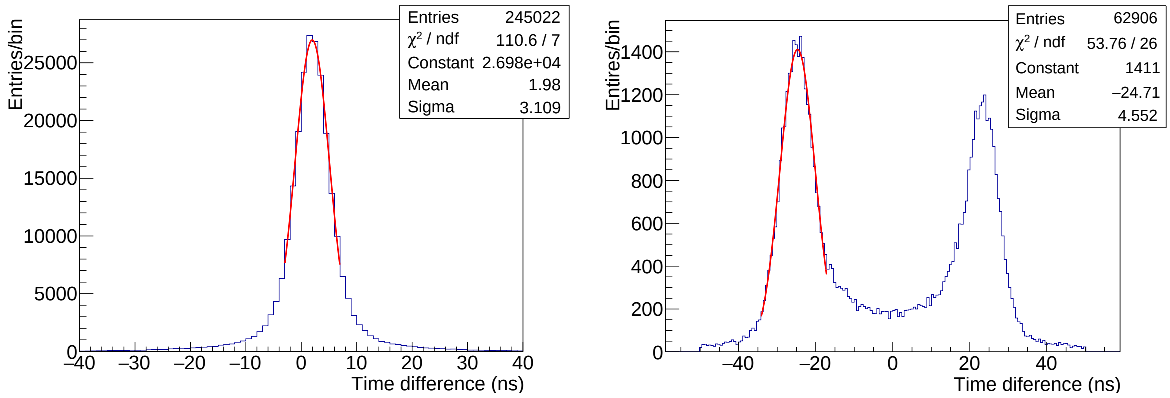


(**a**) (**b**)

Figure 9. (**a**) Arrival time and (**b**) its uncertainty for the photons in Cosmic Ray Tagger (CRT) scintillator strips as a function of signal amplitude at a threshold of 2.5 photoelectrons. The effective photon propagation delay is 6.1 ± 0.7 ns/m. R/O: read out.

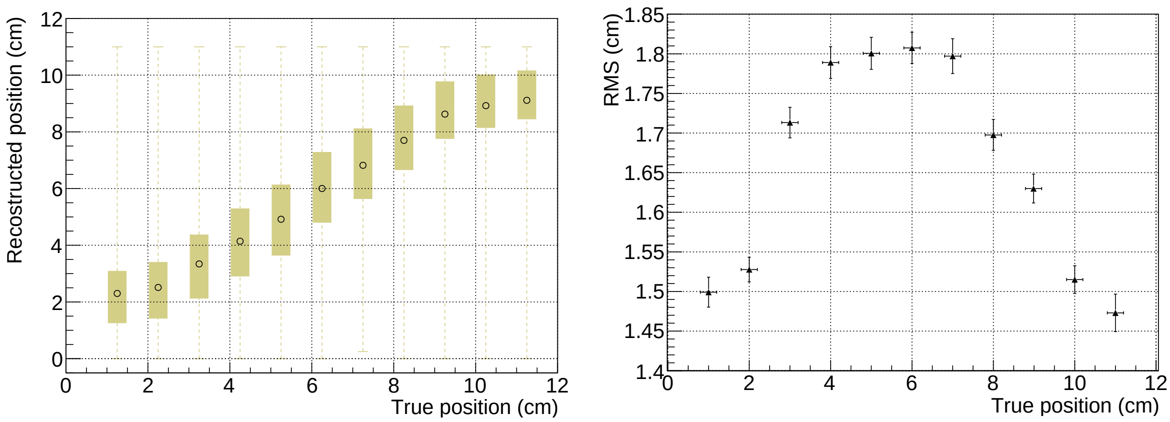
The difference between the triggers time produced in two modules, in various configurations, was measured using crossing muons. Figure 10 shows results for the two modules triggering in coincidence; Figure 10a shows results from an adjoining module configuration, and Figure 10b with a separation of 7.3 m between modules. Directionality for crossing muons can be extracted from the right plot as positive or negatives measured times. The mean values of the trigger time differences correspond with delays introduced by the length of cabling used in each setup, 2 ns and 25 ns, respectively, while time resolution for the timestamp generation of the event can be extracted from their sigmas, 2.2 ns RMS and 3.2 ns RMS, respectively.

Each scintillator strip is equipped with two WLS fibers and two SiPMs, one on each edge. This configuration enables the reconstruction of the position of a particle that hits the strip by measuring the relative intensities registered by the SiPMs. Measurements were made with cosmic muons entering normal to the plane at different transverse positions in the strip at 0.5 m from the readout end. The muon's true position was constrained with two scintillator counters working as a telescope in coincidence with the FEB of the module. Figure 11a shows the reconstructed hit coordinate versus its true position. Figure 11b shows the RMS of the difference between the reconstructed and true coordinates as a function of the true coordinate.



(**a**) (**b**)

Figure 10. Trigger time difference distributions for two modules configuration with (**a**) 0 cm and (**b**) 7.3 m distance separation between them. Mean values correspond to delays introduced by the length of cabling used in each setup, 2 ns and 25 ns. The sigma values correspond to the trigger time resolution.



(**a**) (**b**)

Figure 11. (**a**) Position of hit derived as the weighted average of signals from left and right SiPMs; (**b**) RMS of the difference between the derived coordinate and the true one. The derived coordinate is corrected using the dependence in the left plot.

4. Summary

We have presented a scintillator-based Cosmic Ray Tagger (CRT) system designed, built, and characterised in Bern. The purpose of the CRT is to mitigate a dominant background of cosmic muons crossing the detectors of the Short Baseline Neutrino (SBN) program at Fermilab.

The SBN program will study ν_e appearance and ν_μ disappearance, as well as neutrino-argon cross-sections. Tagging cosmic muon interactions would reduce the ν_e-like backgrounds, improving the detectors' ability to identify and reconstruct neutrino interactions.

The CRT system utilises a novel approach for the construction of a scintillator-based tracking detector. Details of the construction—including materials, photosensors, and other relevant technologies—have been presented.

Characterisation of the individual modules of the CRT system has shown the spatial resolution to be 1.8 cm, with a timing resolution of 1 ns. The tagging efficiency was measured to be greater than 95% across the the entire surface of each module. Quality assurance tests have shown the same performance across all modules built so far. These results show that the CRT system meets the design requirements for accurately identifying crossing muons in both position and time with respect to events inside the LArTPCs.

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

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