Time calibration and synchronization of the scintillation light detection system in ICARUS-T600

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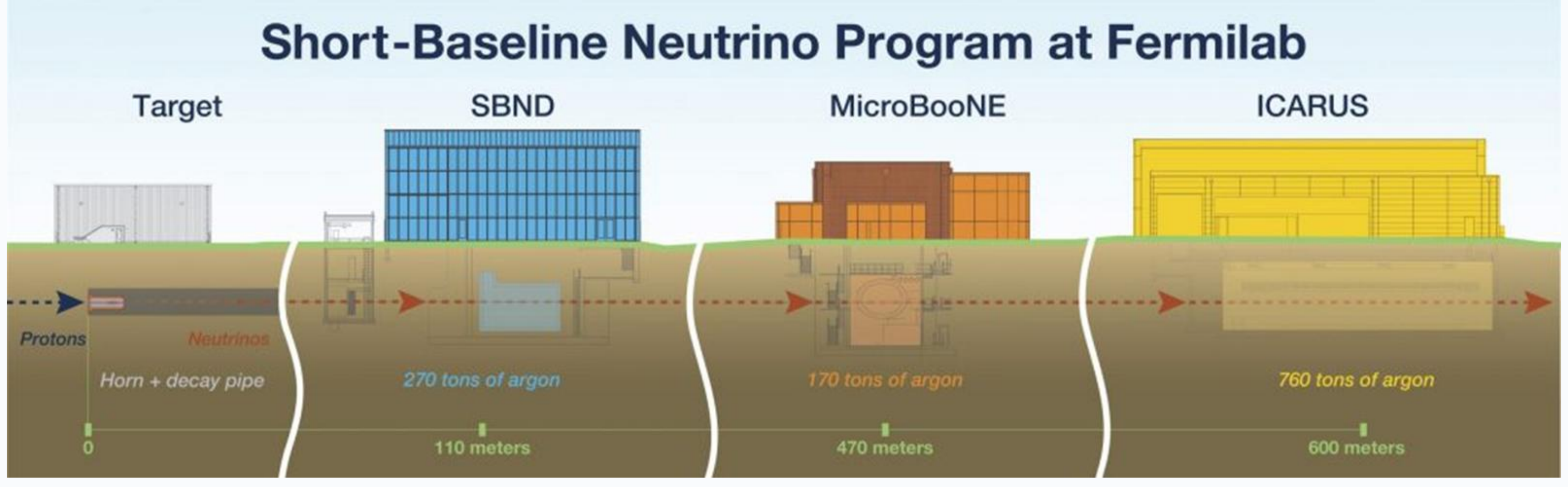
The ICARUS-T600 Liquid Argon (LAr) Time Projection Chamber (TPC) is presently used as a far detector of the Short Baseline Neutrino (SBN) program at Fermilab (USA) to search for a possible LSND-like sterile neutrino signal at $\Delta m^2 \sim 1$ eV^2 with the Booster Neutrino Beam (BNB).
A light detection system, based on 360 large area Photo-Multiplier Tubes (PMTs), has been realized for ICARUS-T600 to detect VUV photons produced after the passage of ionizing particles in LAr. This system is fundamental for the TPC operation, providing an efficient trigger and contributing to the 3D reconstruction of events. Moreover, since the detector is exposed to a huge flux of cosmic rays due to its shallow depths operations, the light detection system allows for the time reconstruction of events, contributing to the identification and to the selection of neutrino interactions within the BNB spill gate.
The correct time reconstruction of events requires the precise knowledge of the delay of each PMT channel and a good synchronization of recording electronics, this last based on fast sampling digitizers.

1 – introduction

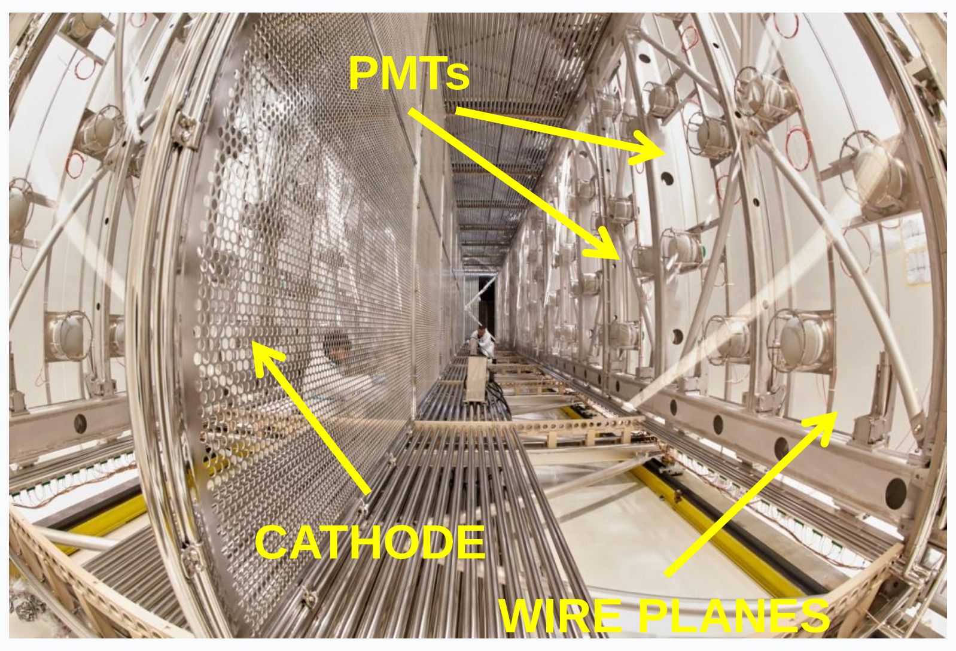
- ✓ Neutrino oscillation is a quantum mechanical phenomenon in which a neutrino created with a specific "lepton flavor" (electron, muon, tau) can later be measured with different lepton flavor.
- ✓ Despite the well established 3-flavour mixing picture within the Standard Model, anomalies at $\Delta m^2 \sim o(eV^2)$ have been observed in the last 20 years, all suggesting a possible existence of at least a fourth neutrino flavor, named "Sterile Neutrino".
- ✓ The SBN program at Fermilab has been proposed to provide a definitive clarification: Three detectors, all based on the Liquid Argon TPC technique and placed along the Booster Neutrino Beam (BNB) line, will investigate the possible presence of Sterile Neutrino States.



Thanks to the simultaneous study at different baseline of electron neutrino appearance and of muon neutrino disappearance channels, SBN will cover much of the oscillation parameters allowed by past anomalies, contributing to the resolution of the "neutrino sterile puzzle"

2 – The ICARUS T600 detector

ICARUS T600 detector is made of two identical cryostats, filled with about 760 t of ultra-pure liquid argon. Each cryostat houses two TPCs with 1.5 m maximum drift path, sharing a common central cathode made of punched stainless-steel panels. Charged particles interacting in liquid argon produce both scintillation light and ionization electrons. Electrons are drifted by a 500 V/cm electric field to the anode, made of three parallel wire planes. The electronics is designed to allow continuous read-out, digitization and independent waveform recording of signals from each wire allowing a full 3D reconstruction of tracks, with a spatial resolution of about 1 mm^3. Scintillation light is detected by photomultiplier tubes (PMTs) directly immersed in the liquid argon.



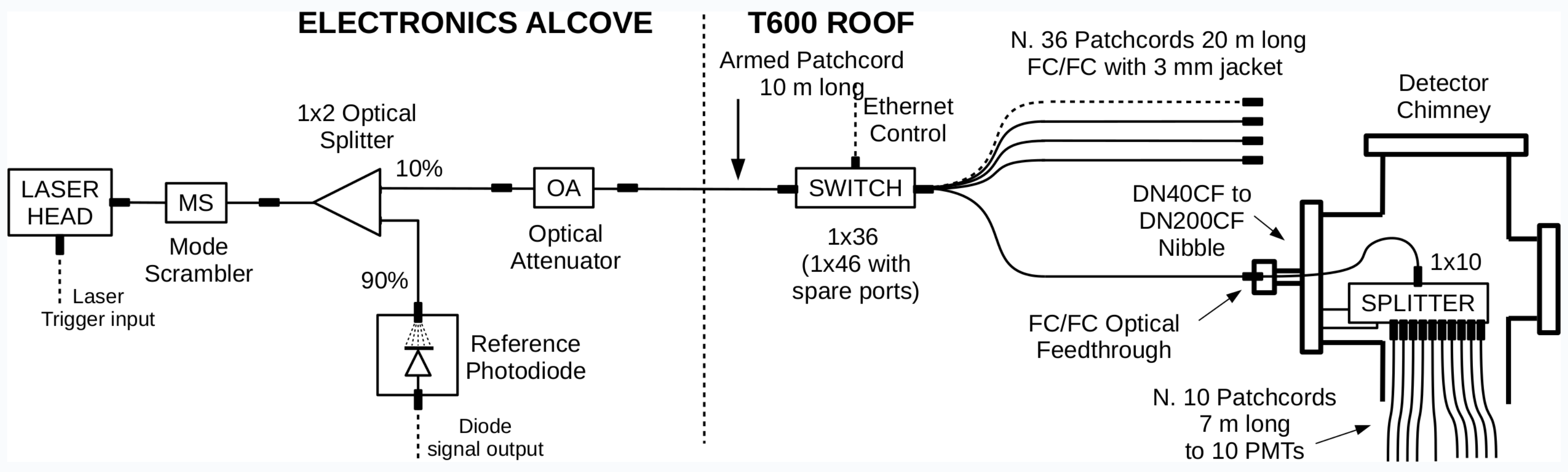
ICARUS at Fermilab is facing a more Challenging experimental condition (surface) than underground condition at LNGS: Large (~10 kHz) of cosmic ray events will be occurring continuously during the readout time window of T600 at SBN. To overcome the new experimental challenge, T600 underwent an intensive overhauling at CERN. One of the significant upgrade is on light detection system (PMTs)
See presentation: Status and perspective of ICARUS at the Fermilab Short-Baseline Neutrino Program

3 – The ICARUS T600 Ligh Detection System

Scintillation light emission in LAr is due to the radiative decay of excimer molecules Ar^{+2} produced by ionizing particles, releasing monochromatic VUV photons ($\lambda \approx 128$ nm) in transitions from the lowest excited molecular state to the dissociative ground state. The emitted light is characterized by a fast ($\tau \approx 6$ ns) and a slow ($\tau \approx 1.5$ µs) decay components. Their relative intensity depends on dE/dx, ranging from 1:3 for minimum ionizing particles, up to 3:1 for alpha particles. This isotropic light signal propagates with negligible attenuation throughout each TPC volume.

The realized light detection system features **360 Hamamatsu R5912-MOD 8" PMTs** deployed in groups of 90 devices behind each wire chambers. Since the PMT glass windows is not transparent to the scintillation light produced in liquid argon, each unit was coated with a proper wavelength shifter re-emitting in the visible. The PMTs were installed using dedicated mechanical supports.

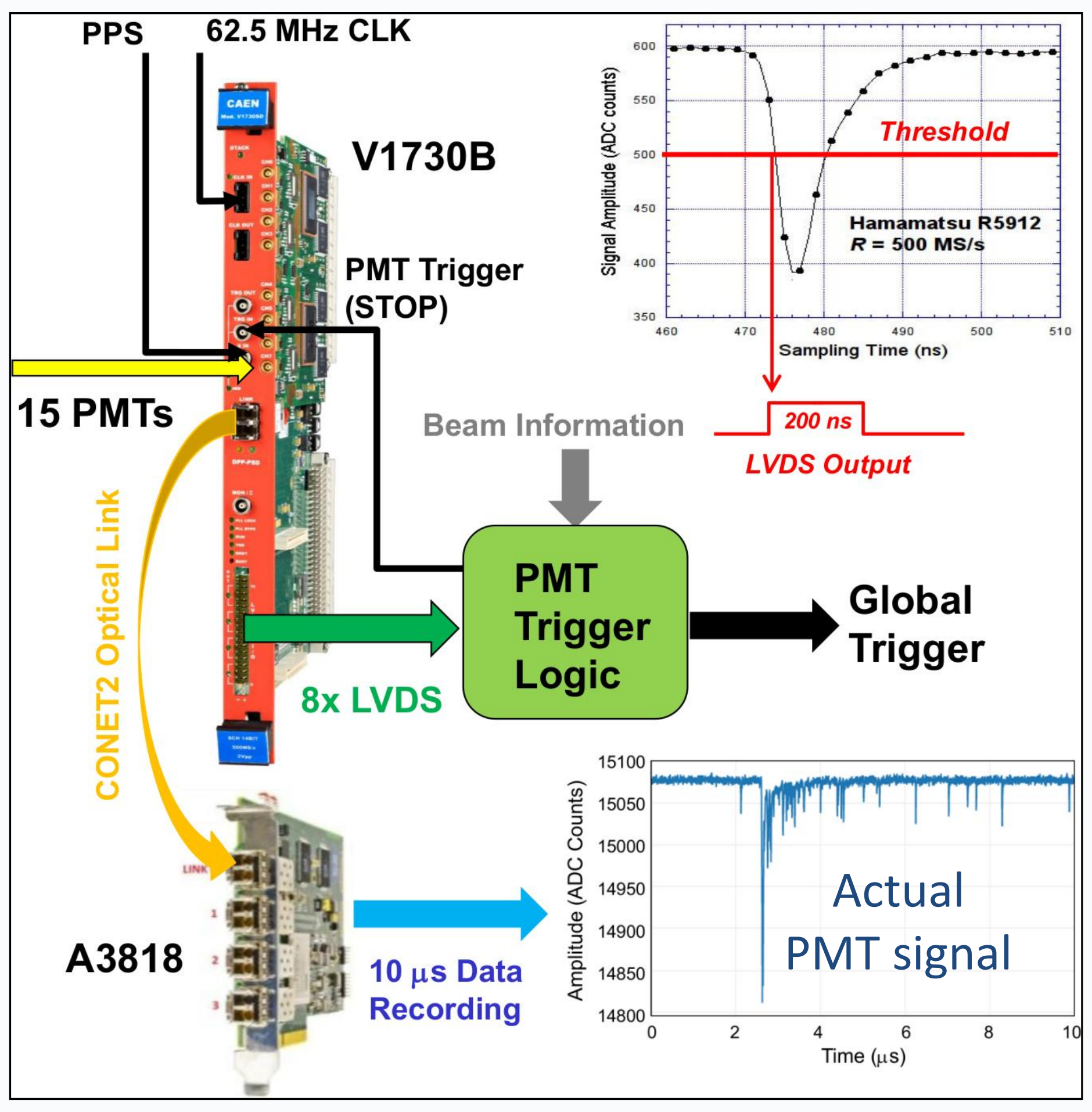
A fast-laser based calibration system has been developed for gain/time calibration, equalization and monitoring of each PMT channel. Laser pulses (λ=405m, FWHM 60 ps) are sent to each PMT (360) via a light distribution system.



4 – Description of PMT Electronics

PMT electronics is designed to allow continuous read-out, digitization and independent waveform recording of signals coming from the 360 PMTs of the light detection system. This operation is performed by **24 CAEN V1730B digitizers**. Each module consists of a **16-channel 14-bit 500-MSa/s FLASH ADC with 2 Vpp input dynamic range**. In each board 15 channels are used for the acquisition of PMT signals, while a channel is left for the acquisition of ancillary signals (trigger pulse, beam gate and RWM Resistive Wall Monitor). During the acquisition, data stream of each channel is continuously written every 2 ns in a circular memory buffer of 5kSa, corresponding to 10 µs, allowing the recording of both decay components of the LAr scintillation light.

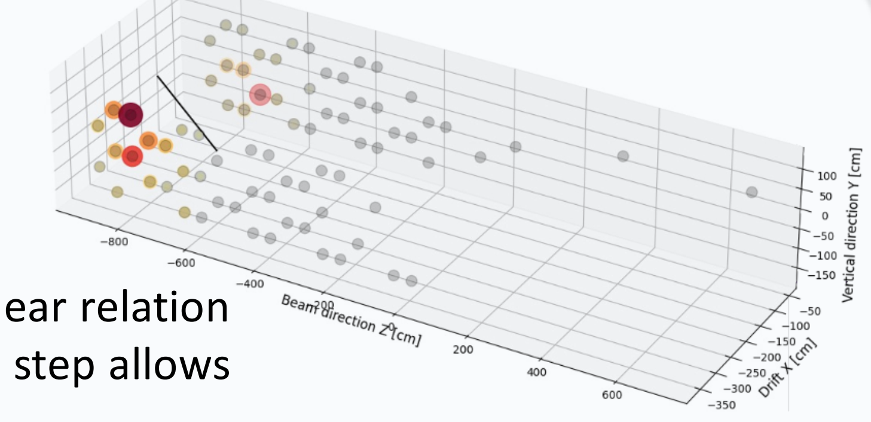
Data readout is performed by an optical link according to the CAENET protocol.



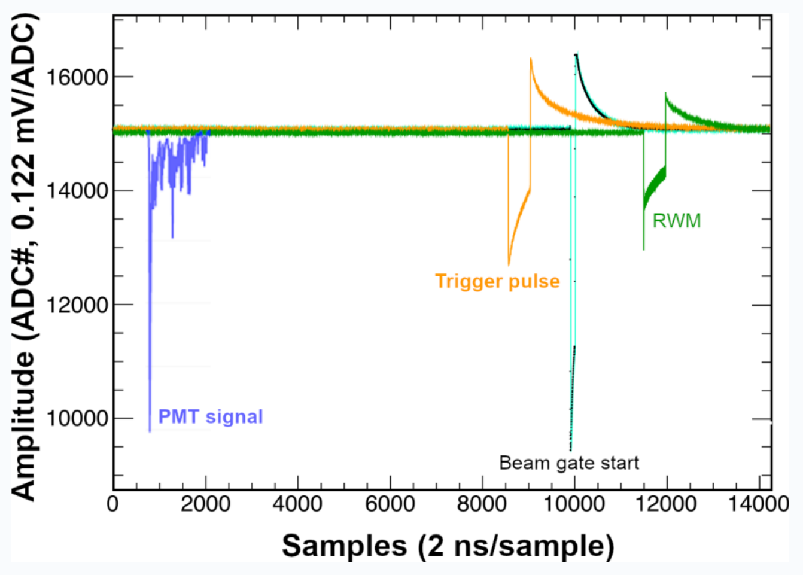
When a board receives an external trigger request (STOP), the active buffers are frozen, writing operations are moved to the next available buffers and stored data are available for download via optical link. Trigger pulses are generated by the ICARUS Trigger System every time a ionizing interaction is recognized in the detector on the base of information coming from neutrino beams and other apparatus. To this aim, **V1730B boards generate trigger-request logical patterns through 8 programmable LVDS (Low Voltage Differential Signal) outputs** showing the presence of signals with amplitude overcoming digitally programmed thresholds. LVDS outputs (one for each PMT pair) are processed by an FPGA according to a Majority logic to produce a Global Trigger when it occurs during a beam gate. The Global Trigger activates the acquisition of TPC wires and PMTs.

5 – Timing and synchronization

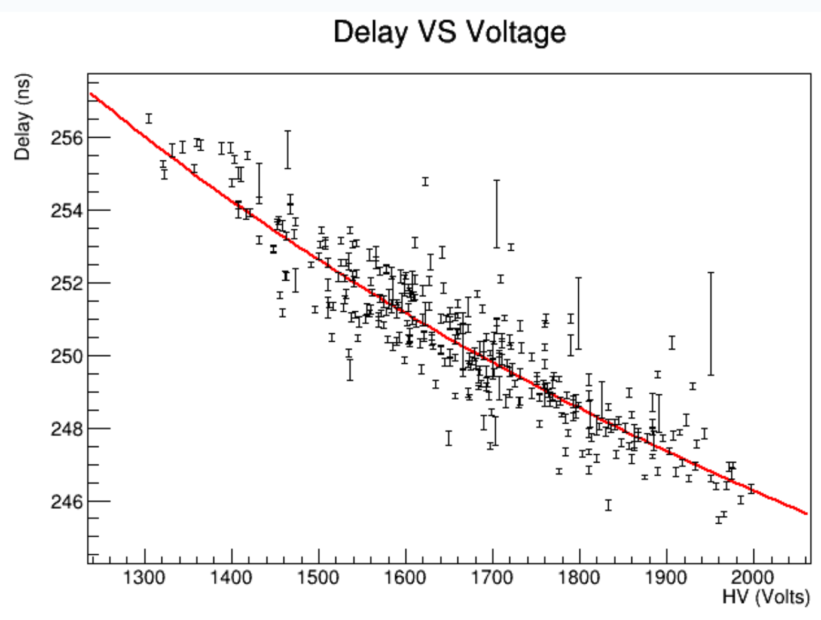
The correct identification and selection of neutrino events requires the precise time reconstruction of each interaction inside the detector with a < 1 ns precision. This can be accomplished by exploiting the fast response of the scintillation light, once the light detection system is correctly timed and synchronized with the TPC and the BNB spill gate. Timing and synchronization of the light detection system is carried out by performing three timing corrections at different stages on the optical data flow:



1) **Hardware correction** – PMT signals are recorded in "fragments" of 10 µs. The header of each fragment contains a 16 ns resolution counter called Trigger Time Tag (TTT). A PPS (Pulse Per Second) is sent to each digitizer by the trigger electronics to perform every second a synchronized reset of the TTT counters. To remove the internal jitter between different boards, the trigger pulse, the leading edge of the beam gate and the Resistive Wall Monitors (RWM) signal (which is matched with the beam profile) are also recorded for each event in dedicated channels to realign and synchronize off-line the time of each PMT pulse with the neutrino beam spill.



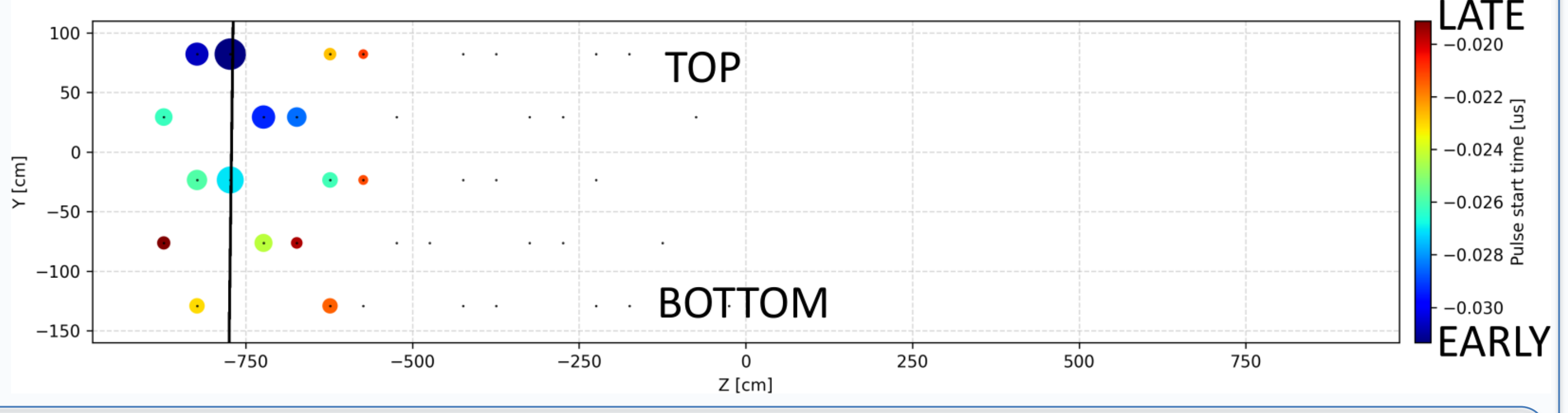
2) **Laser correction** - Laser pulses are sent to each PMT via a light distribution system. This allows to correct for the differences in the PMT transit time and readout delays (e.g. cable delays), resulting in a O(1ns) resolution.



Distribution of the PMT transit time and readout delays as a function of the PMT voltage from the laser measurement.

3) **Cosmic rays correction** - PMT delays are equalized by using the expected linear relation between vertical position and time for downward-going cosmic muons. This step allows to correct some laser uncertainties and improves the resolution to < 1 ns.

For each PMT, we consider the total light collected (SIZE) and start time (COLOR) from vertical cosmic muons, extracting a linear relationship between vertical coordinate and time.



RESULTS – The timing improvements from each correction are highlighted by considering downward-going muons and the resulting time residual for every PMT, which is defined as the time difference between the recorded signal in each tube and the expected signal time given the PMT vertical coordinate.
The final correction reduces the uncertainty on the temporal reconstruction of the signal below 1ns, allowing the precise time reconstruction of each event occurring in ICARUS T600 and the association of neutrino events with the bunched structure of BNB.