

Analysis and Validation of PMT's Waveforms in ICARUS LArTPC Using Monte Carlo Simulations

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ICARUS (Imaging Cosmic and Rare Underground Signals) serves as the Far Detector in the Short Baseline Neutrino (SBN) program at Fermilab, playing a central role in investigating the potential existence of sterile neutrinos in the eV squared mass range.

The detector consists of two large Liquid Argon Time Projection Chambers (LArTPCs) with a total capacity of 760 tons of liquid Argon. A key component of the system is its array of 360 Photo-Multiplier Tubes (PMTs), which detect the scintillation light produced by charged particles in liquid Argon; the fast scintillation signal enables accurate event timing, triggering, and reconstruction.

Together with the TPC and CRT systems, the PMTs ensure precise interaction time measurements, which are crucial for distinguishing neutrino interactions from cosmic-ray backgrounds.

ICARUS uses Hamamatsu R5912-MOD PMTs, optimized for cryogenic temperatures, with high quantum efficiency, excellent timing resolution, low dark current (around 10 nA at 1500 V), and broad spectral sensitivity (300–650 nm). These characteristics are crucial for the efficient detection of scintillation light.

Analyzing the waveforms of PMT signals allows for a detailed comparison between experimental data and Monte Carlo simulations. This analysis is fundamental for improving the accuracy of neutrino event reconstruction, enhancing detector calibration, and optimizing the detector's performance for current and future operations.

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1. Introduction

Neutrino oscillations, where neutrinos change flavor during propagation, provide direct evidence for nonzero neutrino masses, challenging the Standard Model and extending its implications to cosmology. Recent anomalies, such as those observed in the LSND and MiniBooNE experiments [2, 3], suggest the existence of sterile neutrinos with a squared mass difference near $1eV^2$.

The Short-Baseline Neutrino (SBN) program at Fermilab aims to confirm or refute this hypothesis [1]; using three different LArTPC detectors (SBND Short-Baseline Near Detector, MicroBooNE and ICARUS T600), two of which along the Booster Neutrino Beam (BNB) [1], the program provides a comprehensive framework for short-baseline oscillation studies.

LArTPC technology enables high resolution 3D imaging and precise energy measurements, vital to distinguish the signal from the background and to measure neutrino cross sections [6]; strategic placement of the SBN detectors minimizes systematic uncertainties and enhances sensitivity to oscillation signals.

2. The ICARUS T600 Detector

The ICARUS T600 detector, is the world's largest LArTPC currently in operation. Each of the two cryostats houses 380 tons of liquid argon, with four Time Projection Chambers (TPCs) providing high-resolution 3D reconstruction of particle trajectories with 1 mm^3 precision [4, 5].

2.1 The Photomultiplier Tubes (PMTs): Light Detection and Timing Precision

The ICARUS detector is equipped with 360 photomultiplier tubes (PMTs) that play a crucial role in detecting scintillation light and providing precise timing information for event reconstruction [8]. The PMTs are Hamamatsu R5912-MOD models, specifically designed for cryogenic operation; they offer high quantum efficiency, excellent timing resolution, low dark current, and sensitivity to light in a broad spectral range (300–650 nm) [7]. The PMTs have two main functions:

- **Event Triggering:** PMT signals are used to generate triggers for the data acquisition system, with a majority logic scheme and in coincidence with the beam spill.
- **Timing Precision:** The PMTs provide precise timestamps (on the order of nanoseconds), crucial for correlating detected events with the neutrino beam and for rejecting cosmic-ray backgrounds.

To mitigate the cosmic-ray background, the detector integrates a cosmic-ray tagging (CRT) system [7]. Combined with the CRT and TPC, the PMTs enhance the overall event reconstruction capabilities of the detector, ensuring robust discrimination between signal and background [7].

3. Light collection: first preliminary DATA-MC comparison results

Scintillation light in liquid argon is produced by the deexcitation of molecular argon states (Ar_2^*) formed in the interaction of charged particles; we have $40000 \frac{\gamma}{\text{MeV}}$ with zero field and about $2.4 \times 10^4 \frac{\gamma}{\text{MeV}}$ with a $500 \frac{\text{V}}{\text{cm}}$ electric field. [4]. The scintillation light consists of two primary components:

- **Fast component:** Originating from the decay of singlet molecular states ($^1\Sigma_u^+$), it has a decay time of 6 – 7 ns and contributes 25 – 30% to total light.
- **Slow component:** Resulting from the decay of triplet molecular states ($^3\Sigma_g^+$), it has a decay time of 1.5 – 1.6 μs and contributes 70 – 75% to total light.

The Slow / Fast ratio is 3/1 only for mips.

These distinct decay times and contributions provide a natural temporal separation, which is crucial for identifying neutrino signals and rejecting cosmic-ray-induced background events [4, 5].

3.1 Waveform Analysis

The primary goal of this analysis was to compare the temporal and spatial characteristics of the waveforms generated by PMTs during data collection (Run 2) with those simulated in Monte Carlo (MC) models. The aim was to identify discrepancies, validate the detector's performance, and optimize the MC models to align more closely with experimental observations.

The analysis focused on two datasets of vertical cathode-crossing tracks: both MC and experimental data samples consisted of about 900 events selected, according to track-flash coincidences, and geometric constraints; tracks were required to satisfy range conditions in x and y coordinates and a barycentric alignment between tracks and scintillation flashes. Monte Carlo simulations generated

the events using realistic detector parameters, such as a PMT gain of 7.5×10^6 and a quantum efficiency of 7.3%.

The PMT signals were processed through several stages: the 12 brightest PMTs for each scintillation flash were identified, and their waveforms extracted. Waveforms were aligned in time and normalized to their peak amplitudes to allow for consistent comparisons across events, Fig. 1. The

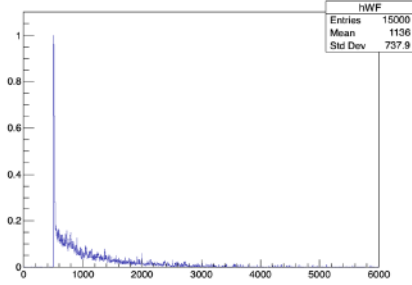


Figure 1: Typical waveform of an ICARUS PMT.

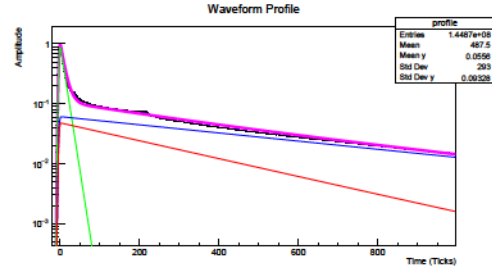


Figure 2: Fast, slow and intermediate components of the light.

average waveforms were obtained for both the data sets and the MC sets. The first fitting function was a sum of exponentials convoluted with a Gaussian, Eq.1, Fig. 2

$$f(t) = \sum_{j=f,i,s} \frac{A_j}{2\tau_j} \exp \left[\frac{1}{2} \left(\frac{\sigma}{\tau_j} \right)^2 - \frac{t - t_m}{\tau_j} \right] \left[1 - \operatorname{erf} \left(\frac{1}{\sqrt{2}} \left(\frac{\sigma}{\tau_j} - \frac{t - t_m}{\sigma} \right) \right) \right] \quad (1)$$

However, a better model of the PMT response waveform is obtained convolving Eq.1 with the average single photoelectron response (SPR).

3.1.1 Experimental Data

Experimental data analysis highlighted key features of the temporal structure of scintillation light. The measured decay times and relative contributions of the components are presented in

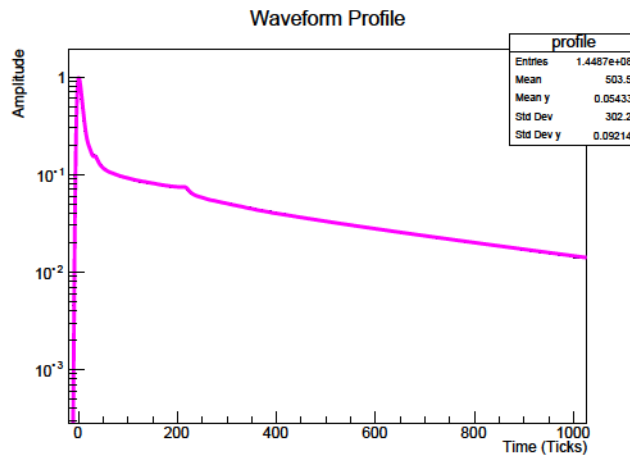


Figure 3: Fit results on Data profile.

Table 1 and are shown in Fig. 3.

Table 1: Measured scintillation light parameters in experimental data.

Component	Decay Time (τ)	Light Contribution (%)
Fast	10.0 ± 0.1 ns	29
Slow	1314 ± 0.4 ns	63
Intermediate	310 ± 1 ns	8

The results appear to confirm the presence of an intermediate component; the contributions and decay times appear consistent with theoretical predictions for the fast scintillation light components but the slow one is a little smaller.

3.1.2 Monte Carlo simulations

Monte Carlo (MC) simulations show some discrepancies compared to experimental data. Table 2 summarizes the decay times and relative contributions modeled in the MC simulations; the fit results are showed in Fig. 4 While the fast and slow components' contributions align

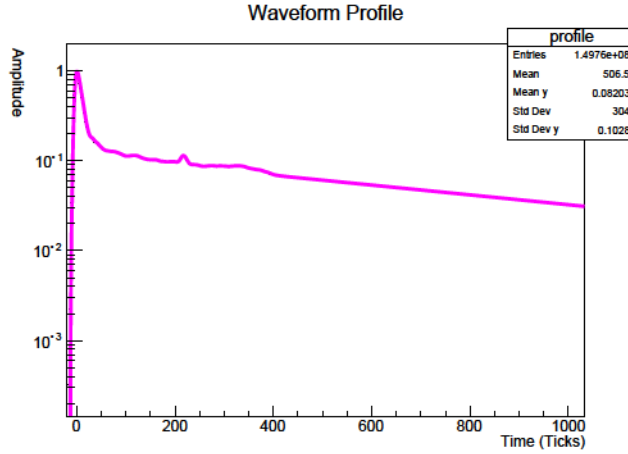


Figure 4: Fit results on MC profile.

Table 2: Scintillation light parameters in Monte Carlo simulations.

Component	Decay Time (τ)	Light Contribution (%)
Fast	14.6 ± 0.1 ns	24
Slow	1589 ± 0.2 ns	76
Intermediate	Not modeled	Not modeled

with expectations, the decay times show discrepancies, and the intermediate component is absent, indicating areas for improvement in the simulations.

4. Summary

The ICARUS T600 detector, plays a pivotal role in investigating the existence of sterile neutrinos and advancing our understanding of neutrino oscillations. With its advanced Liquid Argon

Time Projection Chambers (LArTPCs), Photomultiplier Tubes (PMTs), and Cosmic Ray Tagging (CRT) system, ICARUS demonstrates exceptional capabilities in high-resolution particle tracking, scintillation light detection, and background rejection.

A detailed analysis of the PMT waveforms confirms the detector's excellent performance in detecting and reconstructing neutrino interactions, validating its readiness for high-precision neutrino physics experiments. The scintillation light is accurately detected, characterized by well-established fast and slow components, with measured contributions and decay times closely matching theoretical predictions. The fast component provides timing precision, while the slow component dominates the light yield, ensuring robust temporal separation for signal identification.

Experimental data reveal minor discrepancies in decay times and light contributions, along with the observation of an intermediate component not accounted for in theoretical models. This highlights the need for further investigation into its origin. Meanwhile, Monte Carlo (MC) simulations reproduce the general features of the scintillation light but show significant differences: the decay times of the fast and slow components are overestimated, and the intermediate component is entirely absent. These findings point to areas for improvement in the modeling of the detector's response.

In summary, ICARUS has proven to be a powerful tool for neutrino physics, offering high sensitivity to neutrino interactions and laying the groundwork for future advancements in the SBN program.

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