The ICARUS light detection system

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Table of contents

- Overview on the SBN Program and the ICARUS T600 detector
- The ICARUS light detection system
- New signal cables and their performance
  - Waveform shape analysis
  - Risetime analysis

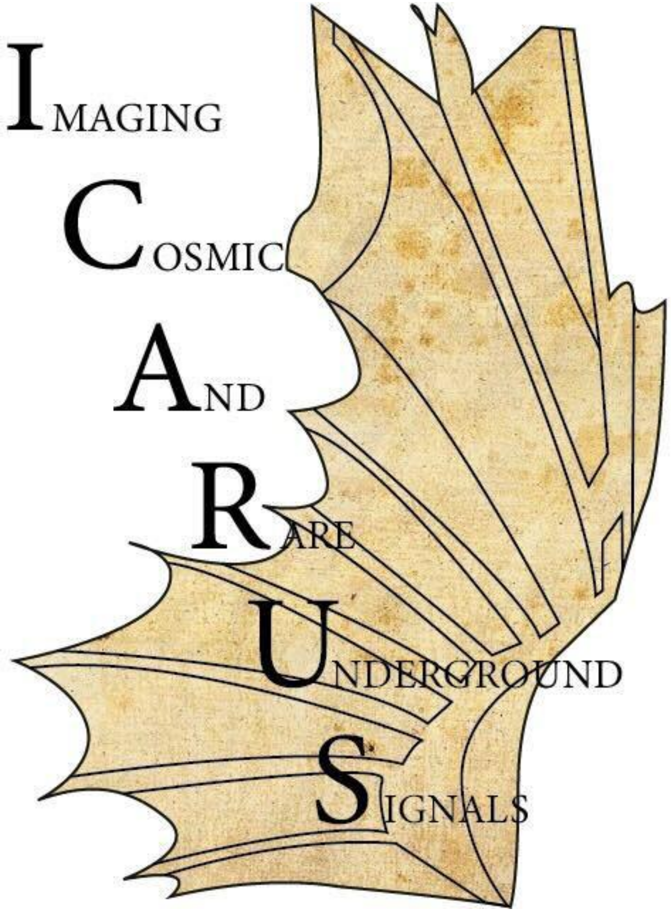
The SBN Program and the ICARUS T600 detector

The **Short-Baseline Neutrino Program** is an international short baseline neutrino oscillation experiment at Fermilab.

The **ICARUS T600** far detector is the **largest LAr-TPC ever used on a neutrino beam**, containing 760 tons of ultra-pure liquid argon of which 476 tons are the active mass of the detector.

The main goal of the ICARUS collaboration is to confirm or to reject the **possibility of a fourth sterile neutrino** in the O(1 eV^2) mass range.

- Additionally ICARUS studies the interaction of neutrinos such as the cross section between neutrino and argon.
- ICARUS also serves as R&D field for future large scale LAr-TPC projects, such as DUNE.



The ICARUS light detection system

The ICARUS light detection system consists in **360 8“ Hamamatsu R5912-MOD Photomultipliers** (PMTs), 90 in each TPC, sensitive to the argon scintillation photons thanks to a coating of tetraphenyl-butadiene (**TPB**) on the sensitive surface. The system has several fundamental tasks:

- Measure the **absolute timing** of each track (~1ns precision);
- **Localise the track** along the ~20m long detector with accuracy better than 1m;
- Take part in the **trigger** system and identify each interaction in coincidence with the neutrino beam spill, contributing to the rejection of ~10kHz cosmic background.

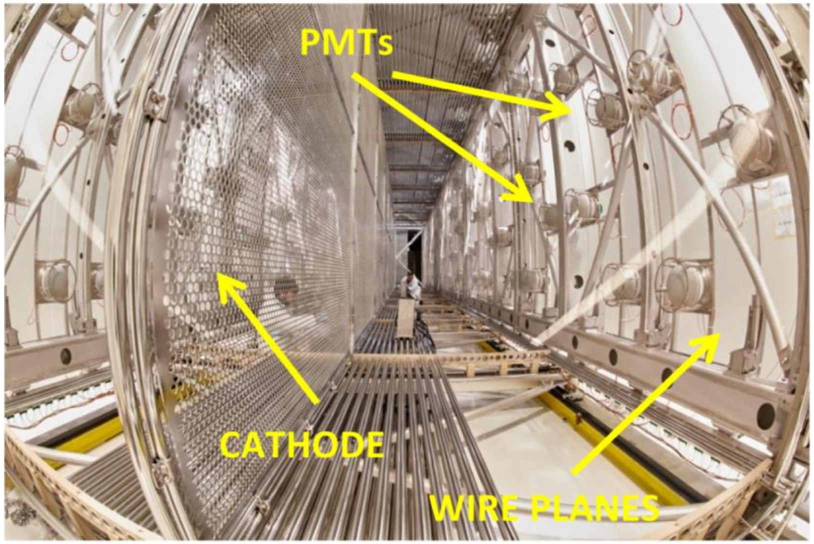
Picture of the insides of an ICARUS TPC; there are 90 PMTs in each TPC

The ICARUS light detection system

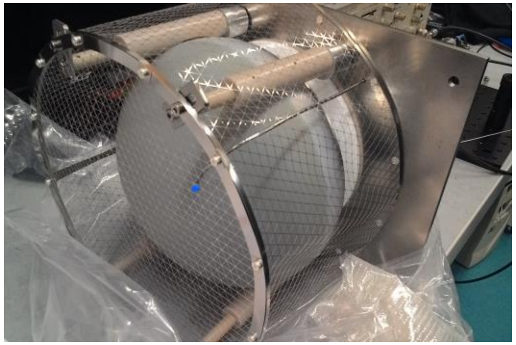
PMTs are mounted 5mm behind the charge collecting anode wire planes, in stainless steel grid cages to mitigate the induction of fake signals on the wires.

Additionally, the PMTs are complemented by a **laser calibration system**, which can send laser pulses into them. This allows the monitoring of the PMT performance and options like gain equalization among the PMTs.

Each PMT is connected to **two separate coaxial cables**: a supply HV cable and a signal readout cable, connected to the electronics to analyse the signal.



Picture of a PMT on its support with the optical calibration fiber



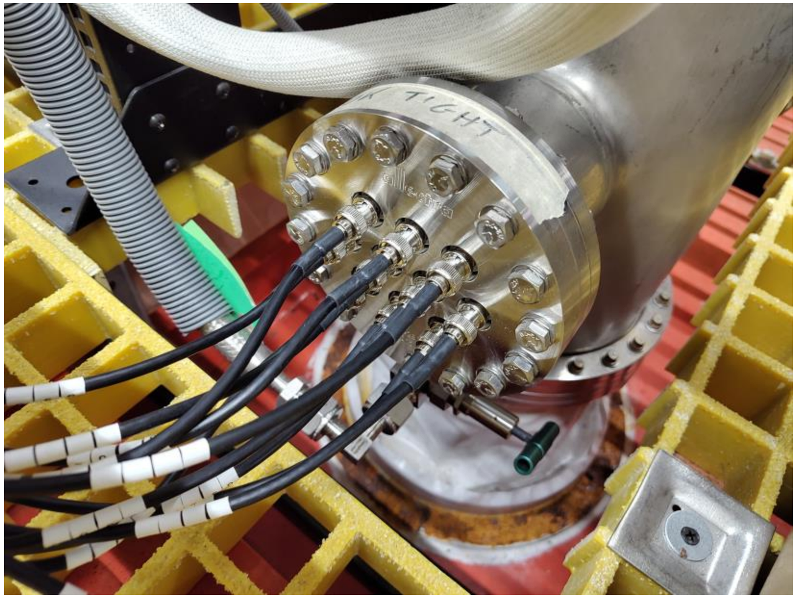
Picture of the insides of two adjacent ICARUS TPCs; the PMTs are located behind the anode wire planes

Signal cable replacement

The **signal cable** connecting the PMT to the electronics can be divided into:

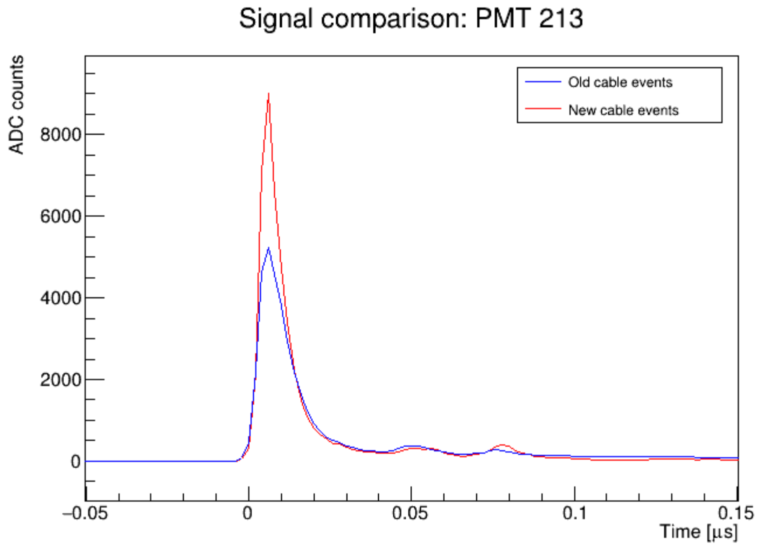
- a 7m section **inside** the detector, starting from the PMTs, along the mechanical structure of the detector up to the top of the detector into stainless chimneys;
- a section **outside** the detector, connecting the flanges on the chimneys to the electronics.

In August 2023, the 180 37m long RG316/U signal cables of the West module outside the detector were replaced by **new 28m WL-195N cables** to reduce deterioration effects observed on the signal.

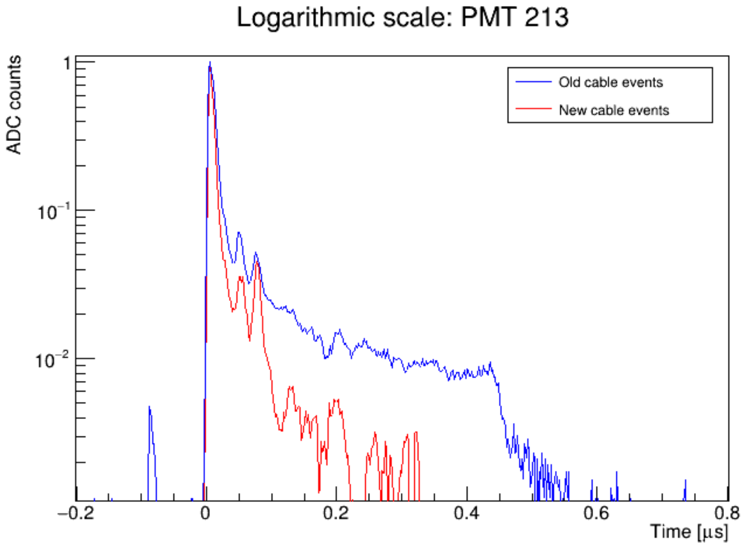


Picture of new WL-195N cables connected to the flange of one of the chimneys on the top of ICARUS West module

Signal waveform



Plot showing the waveform of a laser signal before and after the cable change



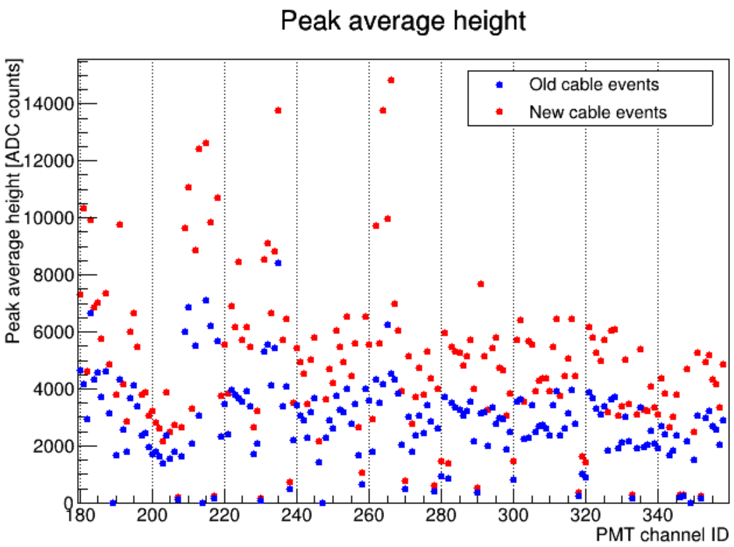
Normalised plot in logarithmic scale of the same waveform

The data in the following slides represents two distinct laser data collection runs before and after the cable change.

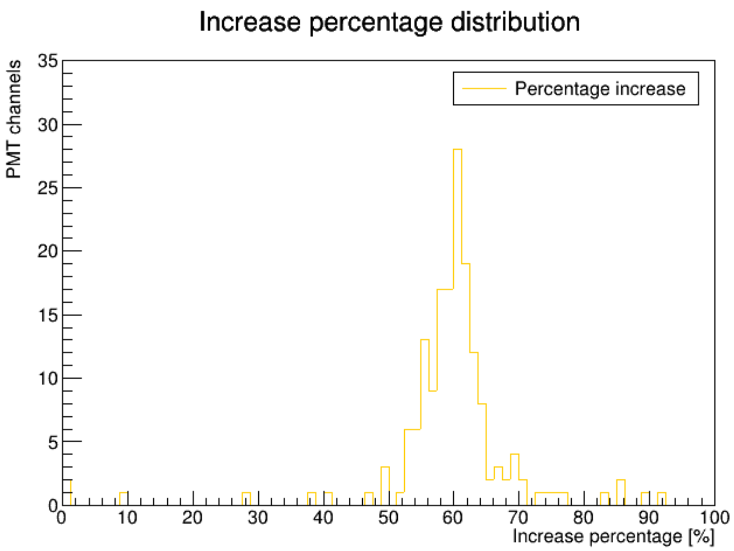
- The laser run has the purpose to measure gain differences on the same channel, since its intensity is kept the same.

After the cable change the signal has a visibly **larger amplitude**, and a larger fraction of the signal integral is concentrated in the peak instead of the tail (i.e. the signal has a **better resolution**).

Growth of signal amplitude (1000 events)



Plot showing the average signal amplitude of a laser signal before and after the cable change in each PMT



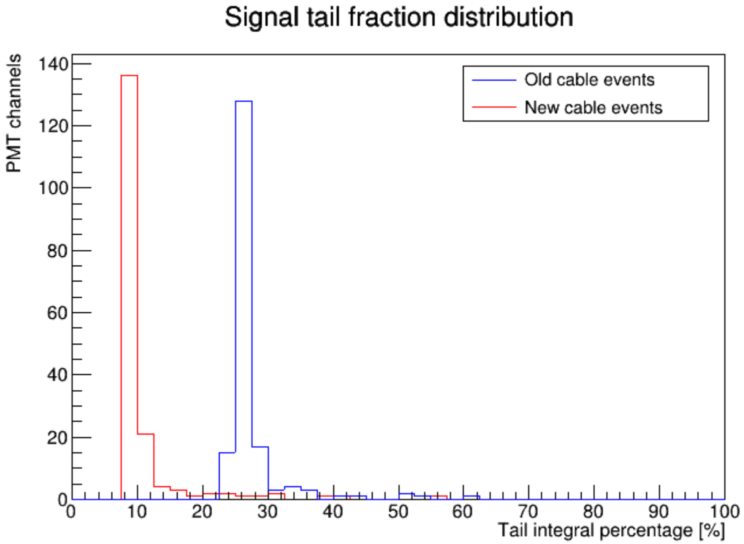
Plot of the distribution of the increase percentage

The amplitude of the signals increased successfully in every considered channel.

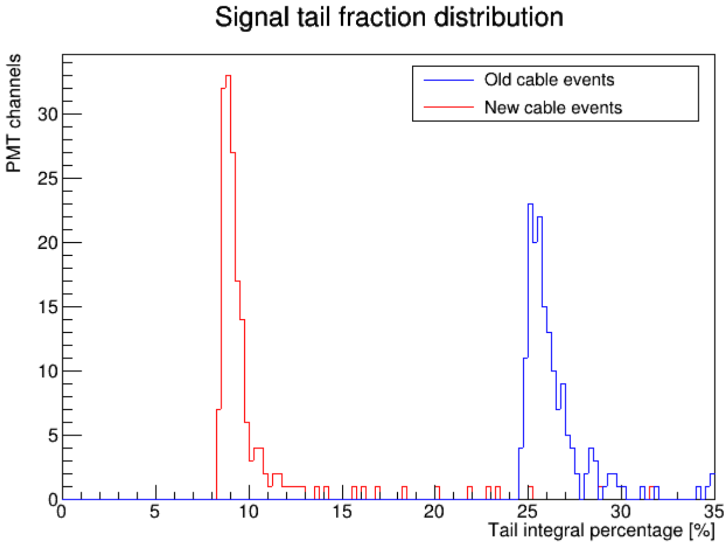
- High amplitude values risk the saturation of the signal, implying a potential loss of valuable data
- Low amplitude values are often due to misalignments of the calibration laser with respect to the photocathode in the PMT

After a gaussian fit of the distribution the result is an **average increase of the signal amplitude of 60±3 %**.

Charge distribution along the waveform (1000 events)



Plot showing the average percentage of the integral of the waveform in the tail



Focus of the previous plot in the region of interest

Looking at the fraction of the integral in the tail (80ns-1μs from the waveform startpoint) can tell how much the signal shape improves, since its value is related to the width of the waveform, therefore to the signal timing resolution.

- The integral of the waveform is directly proportional to the collected charge.

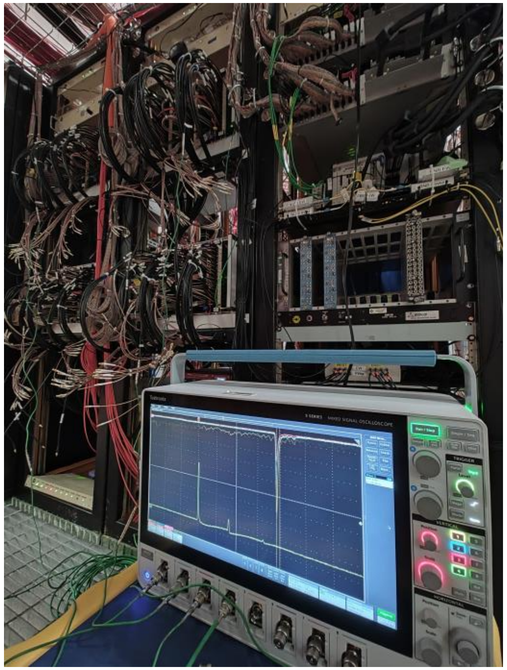
RG316/U

25.6±0.6%

WL-195N

8.9±0.3%

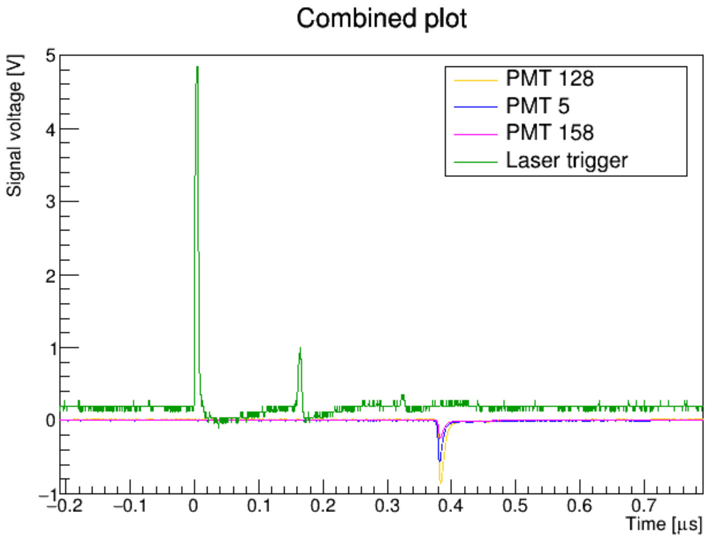
Risetime measurements: Hardware Procedure



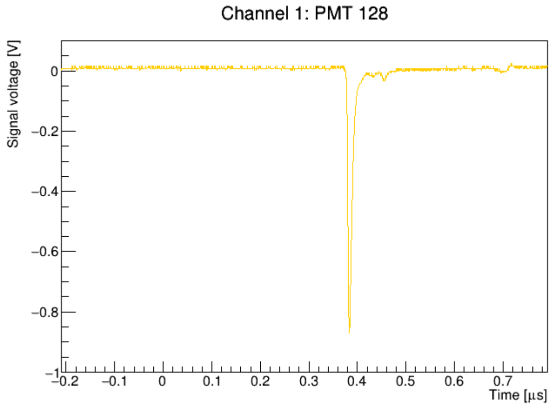
Picture of oscilloscope showing the laser pulses detected by the PMTs

- **3 PMTs** having distinct average laser signal amplitude from the West Cryostat were chosen: PMTs 128 (**Large** amplitude), 5 (**Medium** amplitude), 158 (**Small** amplitude)
- The output channels of the corresponding adders in the crates were connected to an oscilloscope
- The laser was connected to the oscilloscope and turned on to be used as the trigger
- **500 waveforms of signals coming from each PMT** using the WL-195N **new signal cables** were saved on a USB flash drive by the oscilloscope
  - Sampling rate: 6.25GHz, 160ps
- The 3 signal cables corresponding to the PMTs were temporarily replaced by the old RG316/U cables
- **500 signal waveforms** of each PMT were collected in the same manner using the **old cables**

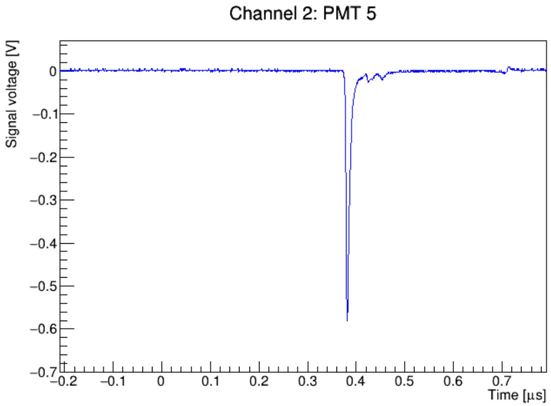
Risetime measurements: Signal waveforms



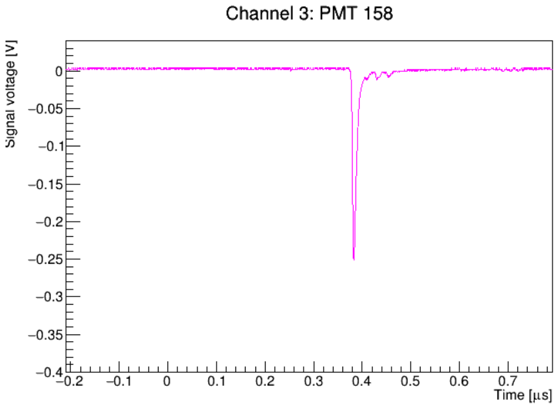
Plots of a sample of waveforms collected using new cables



Large amplitude channel

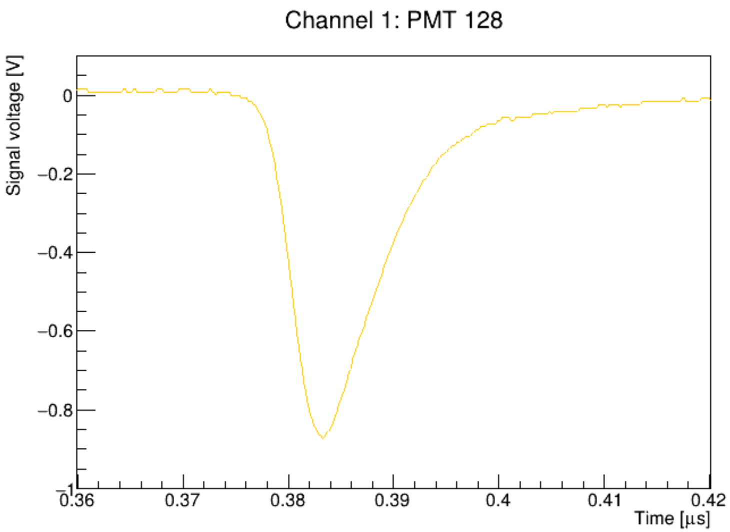


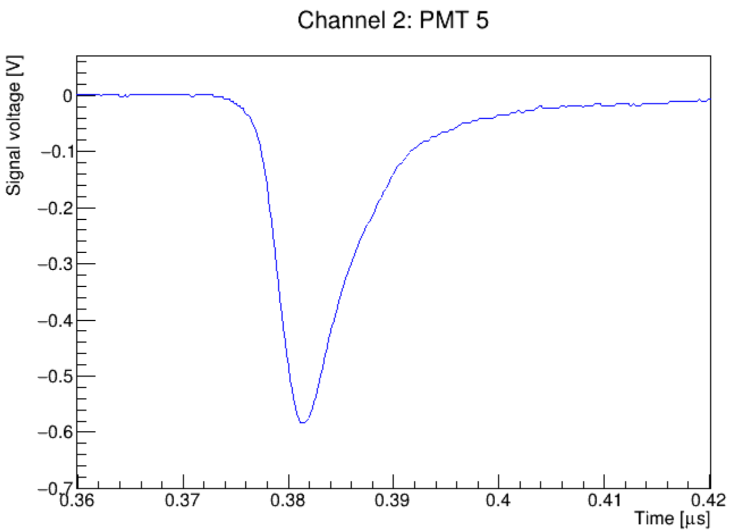
Medium amplitude channel

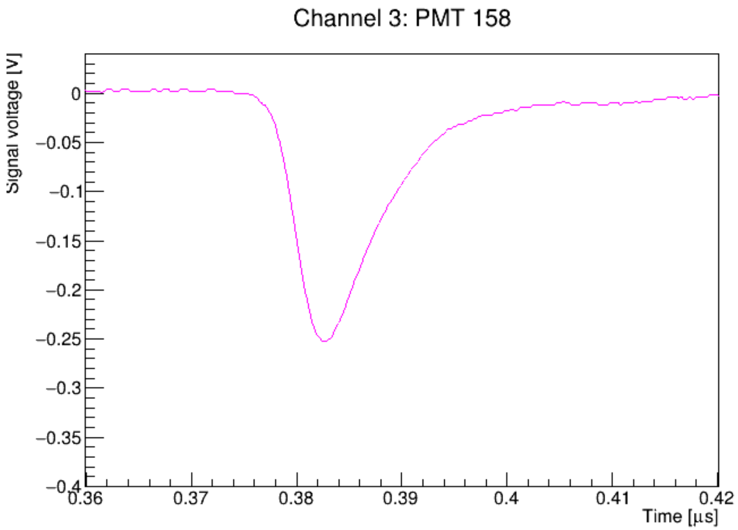


Small amplitude channel

Risetime measurements: Signal waveforms


Channel 1: PMT 128


Channel 2: PMT 5


Channel 3: PMT 158

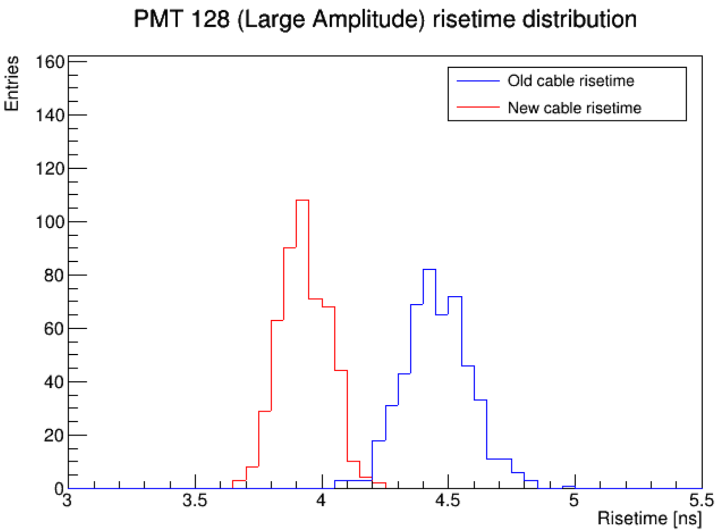
The reason why an oscilloscope was used instead of the DAQ system is the **sampling time** of the signal: a sampling time of 2 ns is not enough to describe the outline of the waveform having a risetime of few ns.

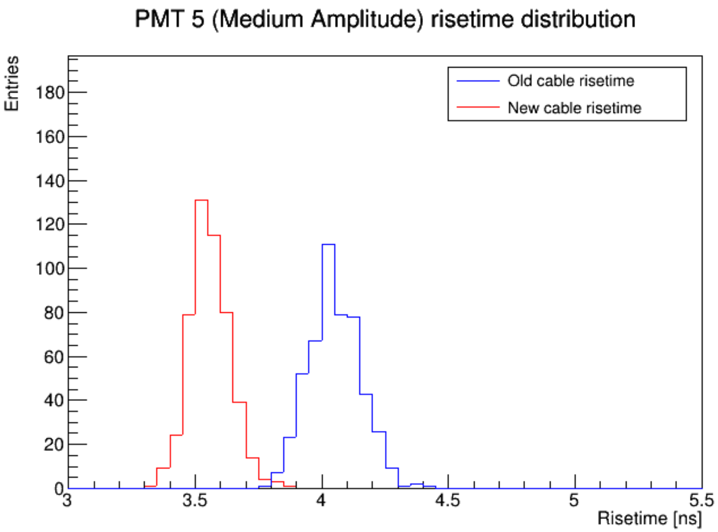
Enlargement of the previous waveforms

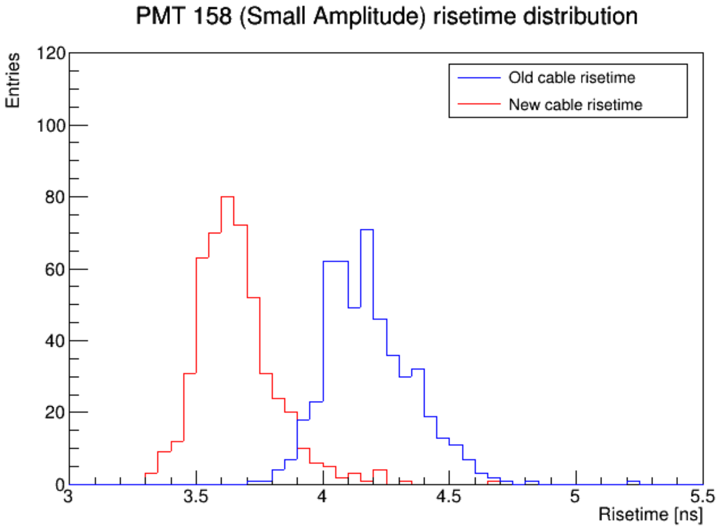
Risetime measurements: Analysis procedure

- **Risetime** was obtained from each waveform as the time between the timings at which the waveform reaches **10% and 90% of its maximum amplitude**
  - The exact timings were obtained using a linear relation between the point right before and the point right after the timing at which the amplitude is expected to reach 10%/90% of the amplitude
- The obtained risetime values were stored into histograms to compare the risetime of the signals using different cables in the same PMT

Risetime distribution







Despite the low statistics, the events distributions resemble a gaussian.

The new signal cable has overall a lower risetime.

Risetime distributions of the 2 cables

Risetime measurements: Some numerical values

	Old cables risetime	New cables risetime	Difference
PMT 128 (Large)	(4.5 ± 0.1) ns	(3.9 ± 0.1) ns	(-11.8 ± 0.7) %
PMT 5 (Medium)	(4.0 ± 0.1) ns	(3.56 ± 0.08) ns	(-12.2 ± 0.5) %
PMT 158 (Small)	(4.2 ± 0.2) ns	(3.6 ± 0.1) ns	(-13.0 ± 0.8) %

Results obtained from gaussian fits of the distributions

No clear relation between signal amplitude and risetime can be deduced from this data, more PMTs having different amplitudes would be necessary.

The **risetime** in the new cables was **reduced between 11% and 13%** compared to the old cables

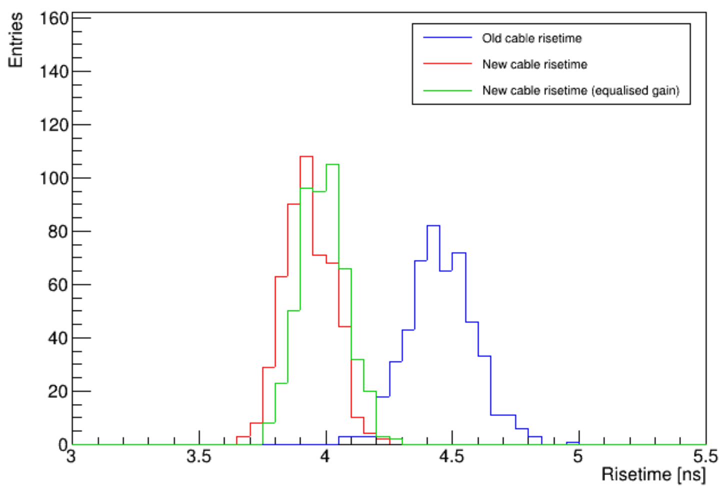
This result is consistent with the fact that the signal waveform shape improved, having a larger fraction of the integral in the peak.

Risetime measurements: Before and after gain equalisation

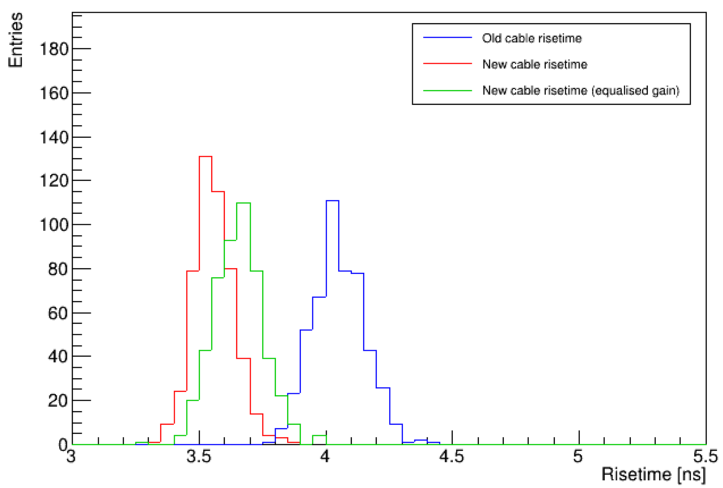
- Additional 500 waveforms were collected using the new cables from the same PMT channels **after a first equalization of the PMT gains**, that was carried out in the West cryostat in September 2023
  - The gain equalization aims to equalize the signals coming from interactions occurring inside the TPC; therefore this does not mean that the laser amplitudes are equalized to the same value, considering there are misaligned optical fibers not pointing directly towards the photocathode
- The risetime values were stored into histograms and compared with the risetime values of the signals collected before the equalization of the gains

Risetime distribution: Before and after gain equalisation

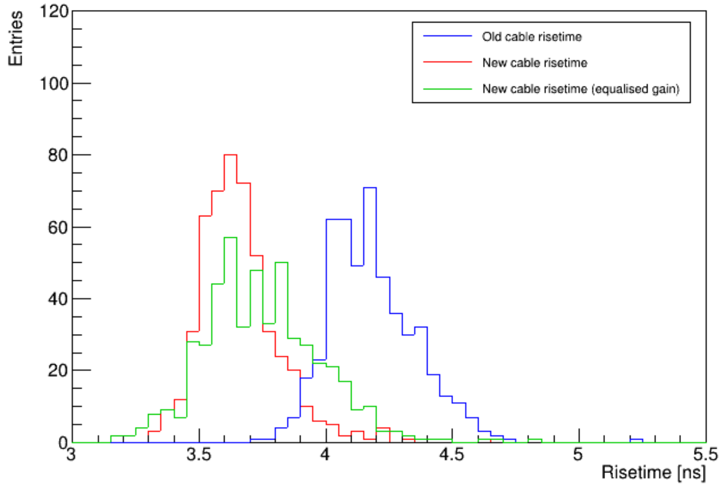
PMT 128 (Large Amplitude) risetime distribution



PMT 5 (Medium Amplitude) risetime distribution



PMT 158 (Small Amplitude) risetime distribution



The distribution did not change much adjusting the gain of the PMTs.

The PMT158 distribution looks very dispersed compared to before.

Risetime distributions of the 2 cables + risetime distribution of new cable after gain equalisation

Risetime measurements: Before and after gain equalisation

	Risetime pre-equalisation	Risetime post-equalisation	Compatibility
PMT 128 (Large)	(3.9 ± 0.1) ns	(3.99 ± 0.09) ns	0.43σ
PMT 5 (Medium)	(3.56 ± 0.08) ns	(3.7 ± 0.1) ns	0.79σ
PMT 158 (Small)	(3.6 ± 0.1) ns	(3.7 ± 0.2) ns	0.42σ

Results obtained from gaussian fits of the distributions

Applying a Z-test between the risetime mean values before and after the equalisation of the gains, the obtained result tells that the **two values are compatible** between each other, meaning that **the gain adjustment does not lead to a significant change in the risetime** of the signal.

Conclusions

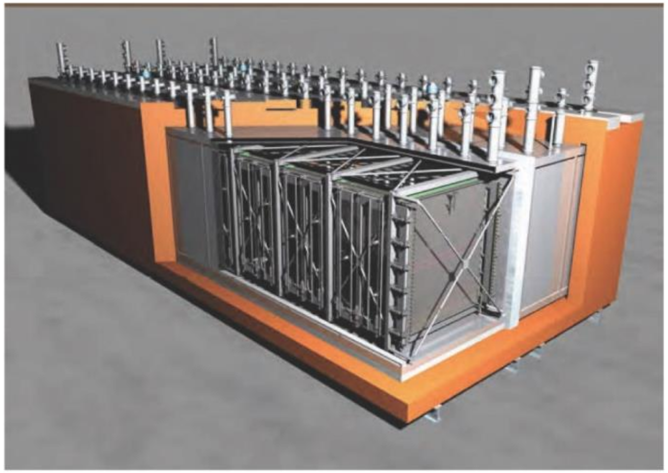
The ICARUS **light detection system** exploits the argon scintillation light to **locate neutrino interaction events in space and time** in the detector.

After the change of the signal cables the signal **waveform shape improved** in both amplitude and time resolution.

The adjustment of the PMT gains for the **equalization does not lead to a drastic variation of the risetime** of the signal.

The definitive equalisation of all the PMT gains to a proper value will be performed before the starting of the new regular data taking with the neutrino beams.

The replacement of the rest of the signal cables is planned to be done in early October 2023.



ICARUS T600 Detector schematic with both modules and the common insulation surrounding the detector

Thank you for your attention

References

- ICARUS-WA104, LAr1-ND and MicroBooNE Collaborations, *A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam*, ArXiv:1503.01520v1
- B. Ali-Mohammadzadeh, et al., *Design and implementation of the new scintillation light detection system of ICARUS T600*, J. Instrum. 15 (2020) T10007
- ICARUS Collaboration, *The scintillation light detection system of ICARUS-T600, Hardware implememtation and early results,* Nuclear Inst. and Methods in Physics Research, A 1046 (2023) 167685
- ICARUS Collaboration, *The electronic set-up for the scintillation light detection system of ICARUS-SBN at Fermilab,* Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167871
- ICARUS Collaboration, *ICARUS at the Fermilab Short-Baseline Neutrino Program - Initial Operation*, arXiv:2301.08634v1

Backup slides

Short-Baseline Neutrino Oscillation Experiments

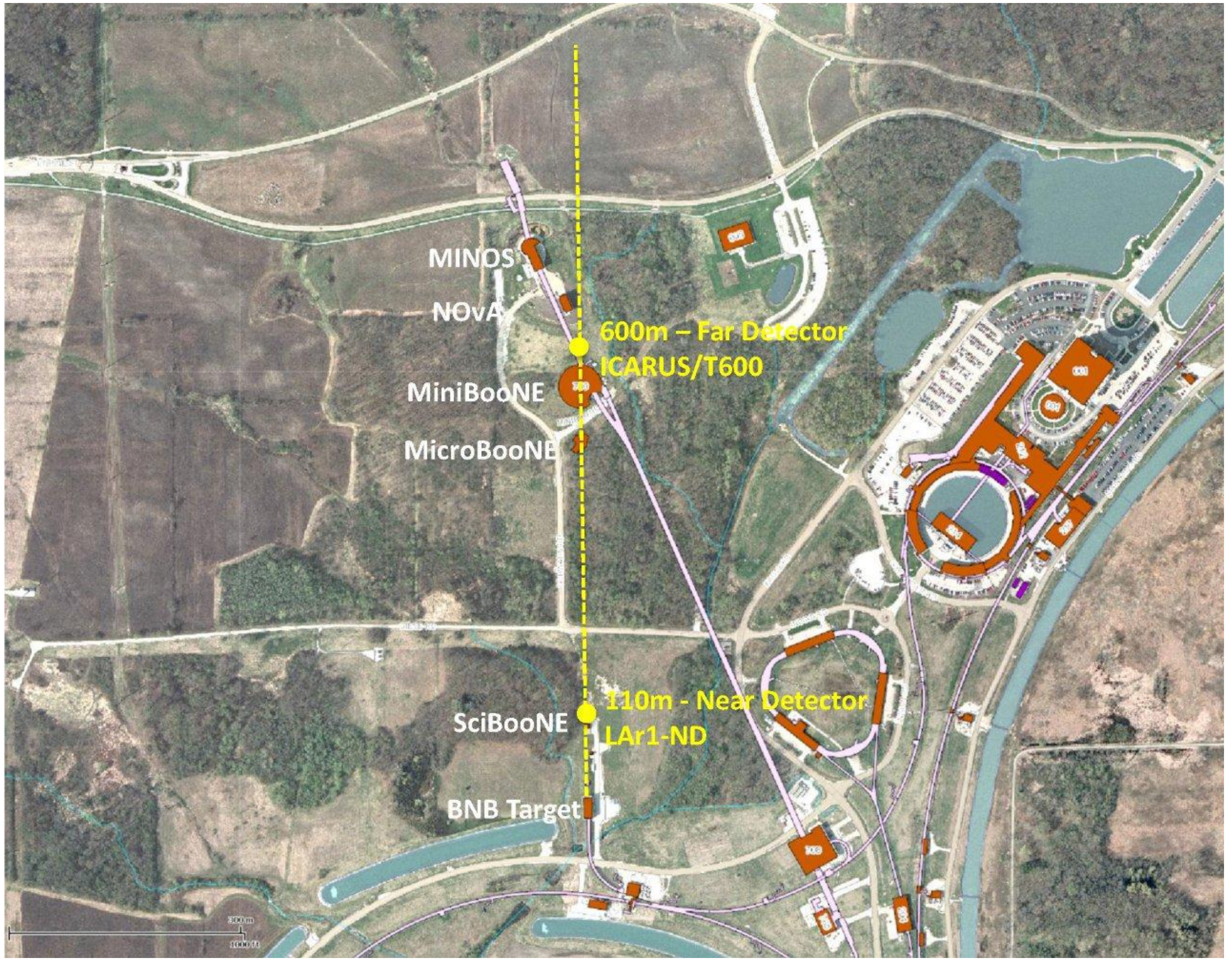
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Neutrino oscillations in 2 flavor oscillation limit
($[\Delta m^2] = eV^2$, $[L] = m$, $[E_\nu]$=MeV)

In order to observe and study neutrino oscillations the argument of the second sine function must be O(1).

Short Baseline neutrino oscillation experiments are characterised by a relatively small L value (O(10^2m), 600m at SBN considering ICARUS) therefore a relatively high Δm^2 value (O(eV^2)) considering E_ν to be around O(GeV) (0.8GeV by BNB, 0-3GeV by NuMI at Fermilab).

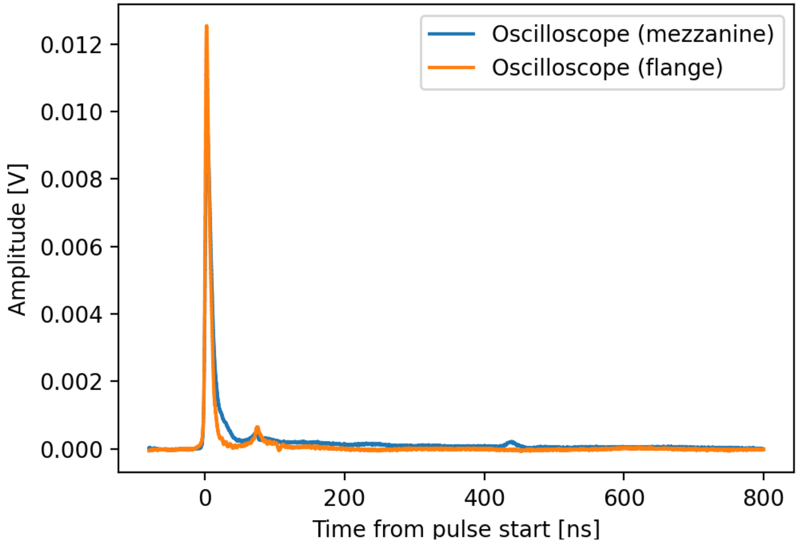
SBL experiments	SBN program
L = O(10^2m)	L = 600m
E_ν = O(GeV)	E_ν = 0 – 3GeV
Δm^2 = O(eV^2)	Δm^2 = O(eV^2)

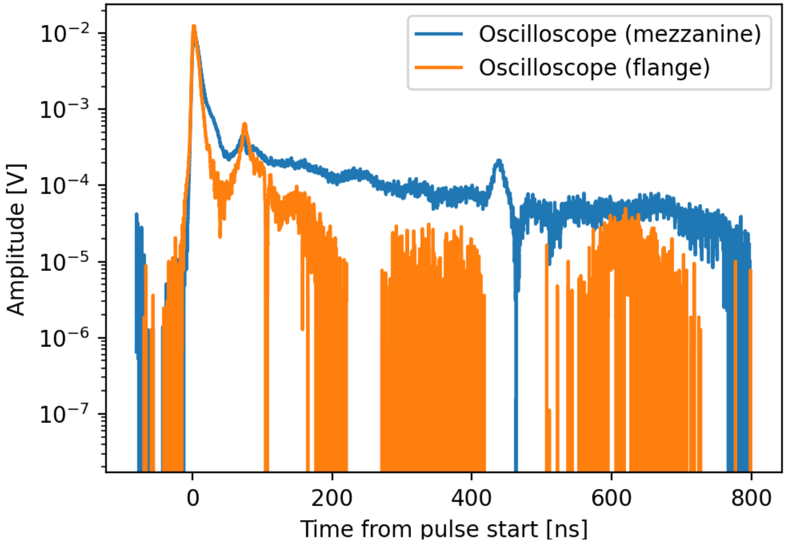


Map of the Fermilab neutrino area, showing the approximate position of the various detectors and the two beam axis

(BNB in yellow, NuMI in pink)

Signal deterioration in the old cables





ICARUS 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 is performed by 24 CAEN V1730B digitizers (15 PMT/digitizer, 6 digitizers/TPC).

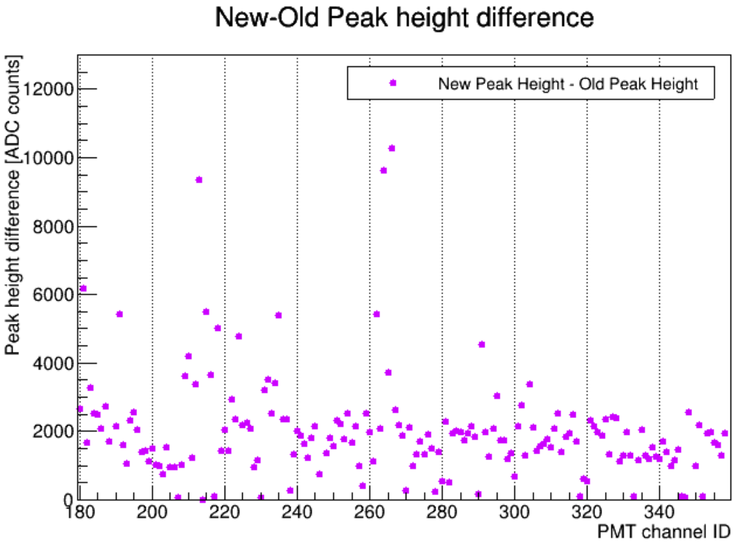
- Each channel generates an internal trigger request when recording a pulse higher than a programmable threshold
- Logical OR combination between adjacent channel, each digitizer outputs 8 low-voltage differential signals (LVDS)
- LVDS signals are processed by the ICARUS T600 trigger electronics to produce a detector Global Trigger when an interaction occurs inside a beam gate

Each channel has 1024 consecutive buffers, corresponding to recording 10μs with a 2ns sampling time.

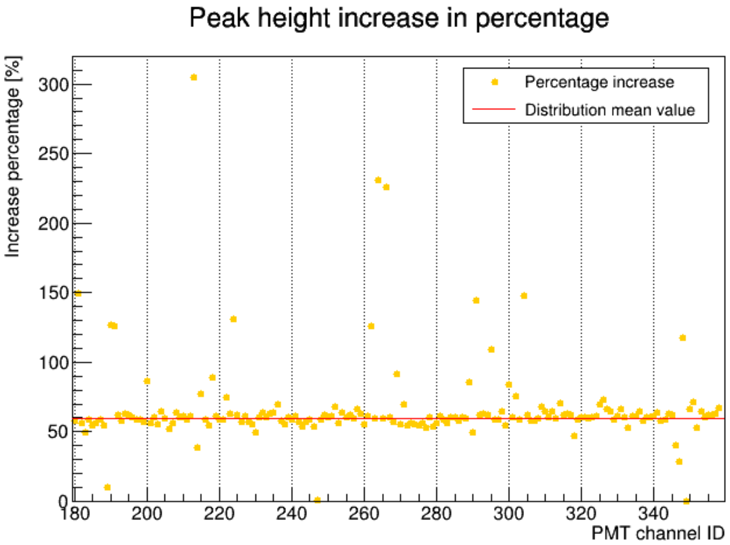
BNB and NuMI beams

BNB	**NuMI**
ICARUS on beam axis	ICARUS off beam axis
Beam from Booster Accelerator (8 GeV protons)	Beam from Main Injector (120 GeV protons)
1.6 μs beam spill	9.5 μs beam spill
ν_μ rich beam	ν_e rich beam

Additional amplitude-related plots

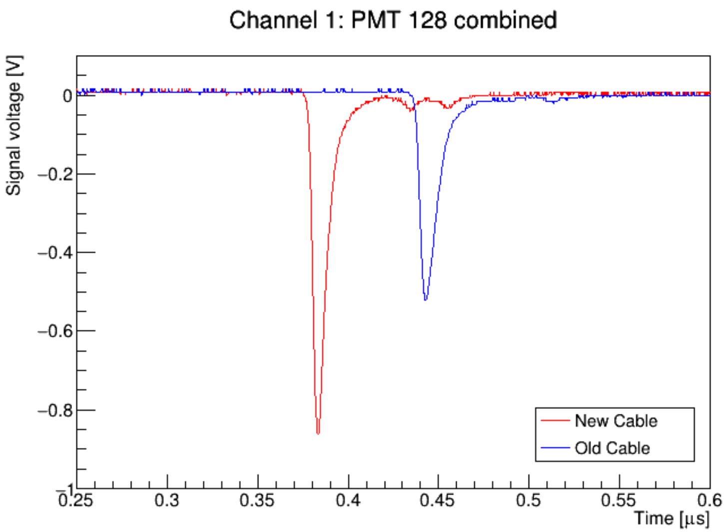


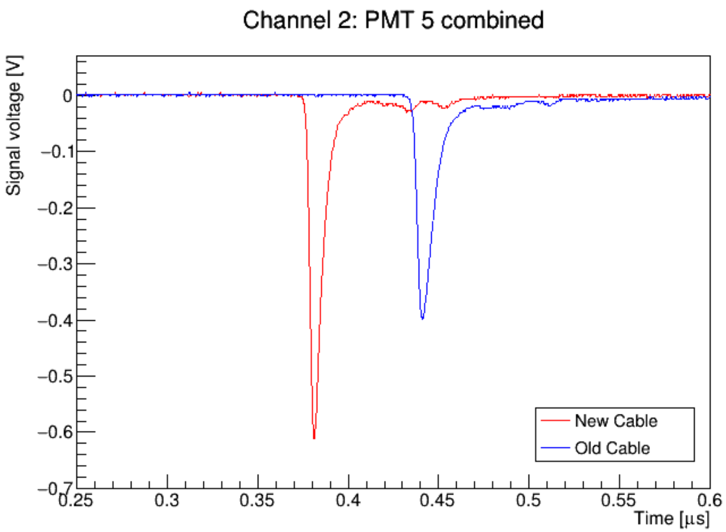
Difference between the average new cable and average old cable signals in each PMT

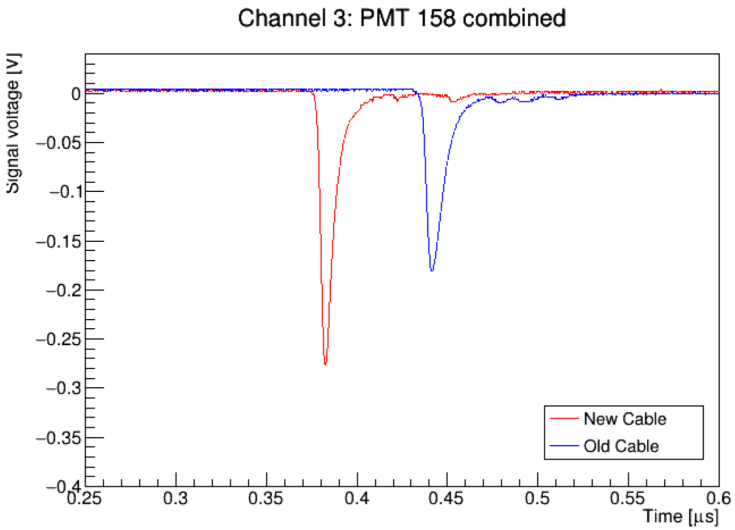


Plot showing the average percentage increase in height in each PMT

Risetime measurements: Signal waveforms


Channel 1: PMT 128 combined

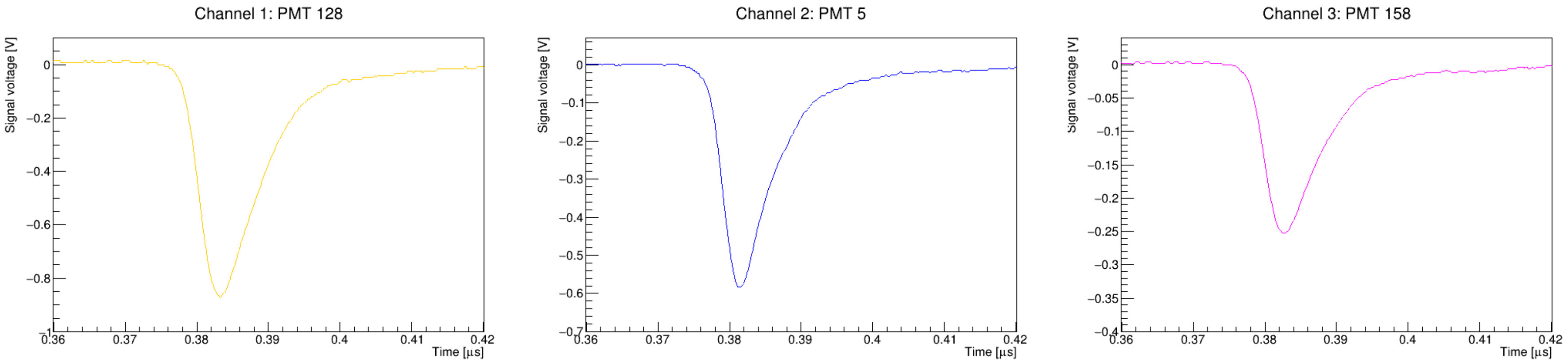

Channel 2: PMT 5 combined


Channel 3: PMT 158 combined

The new cable is 9 m shorter therefore the new signal arrives to the digitizers earlier than the old signals.

Comparison of the signal arrival timings

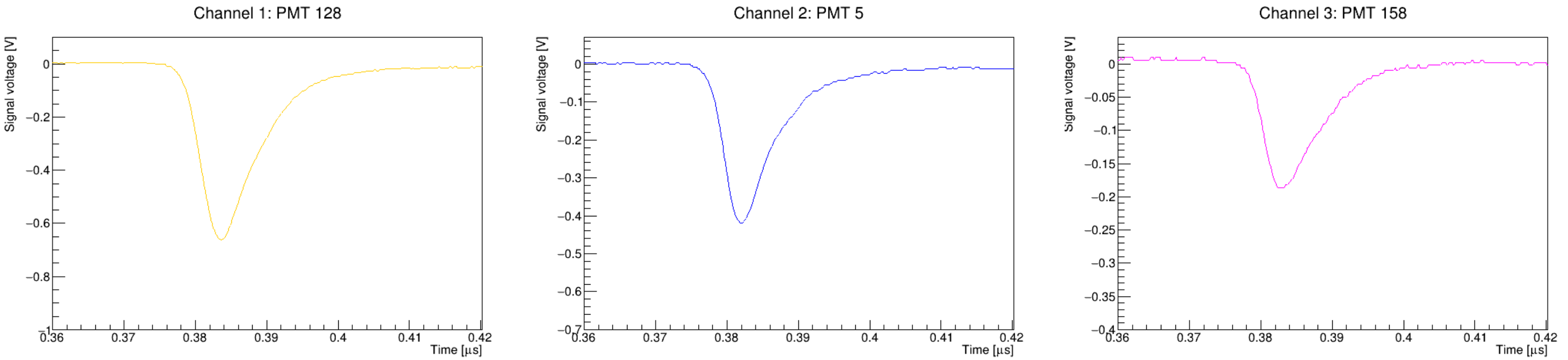
Risetime measurements: Signal waveforms


Channel 1: PMT 128

Channel 2: PMT 5

Channel 3: PMT 158

Waveforms before gain equalisation

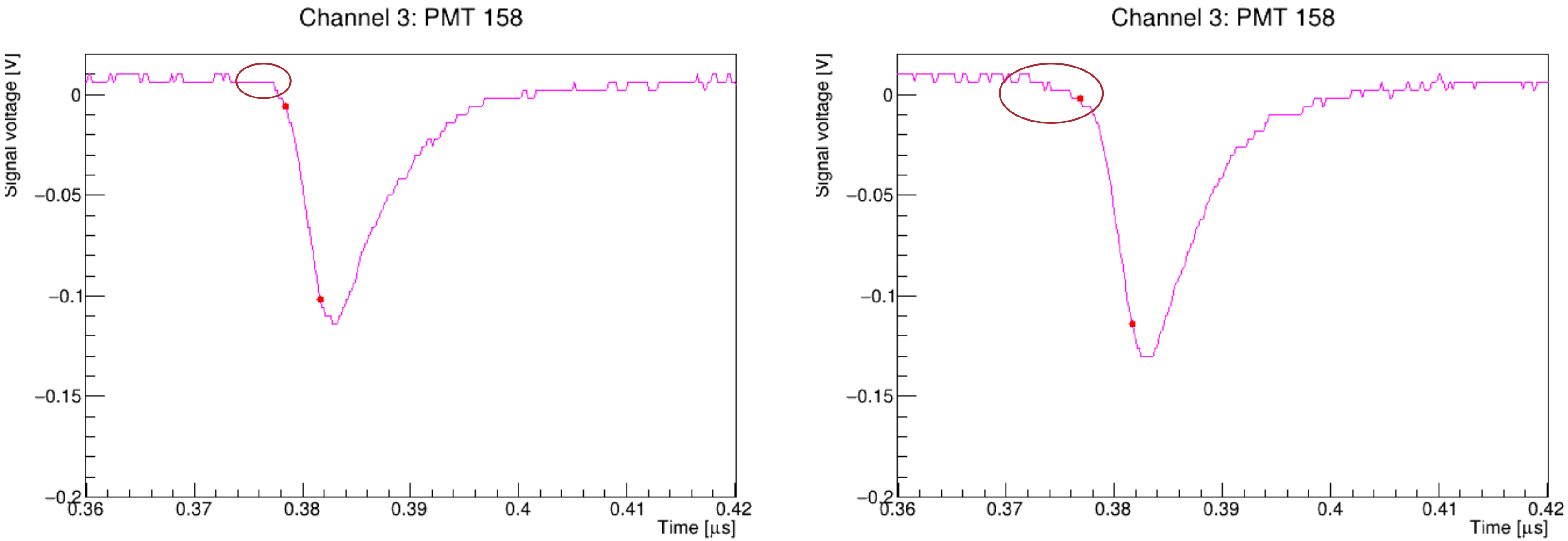

Channel 1: PMT 128

Channel 2: PMT 5

Channel 3: PMT 158

Waveforms after gain equalisation

Risetime: Dispersed values signal waveforms



Comparison of two waveforms at the opposite extremes of the risetime distribution

The reason why the risetime distribution is so **spread out** is the occasional **presence of a small slope before the spike** of the waveform which leads the algorithm on finding the **startpoint slightly off** the mean value.

This could be a consequence of the small amplitude of the waveform and a resulting bigger influence of the baseline fluctuations on the waveform and risetime calculation algorithm, which would otherwise be negligible.