CERN

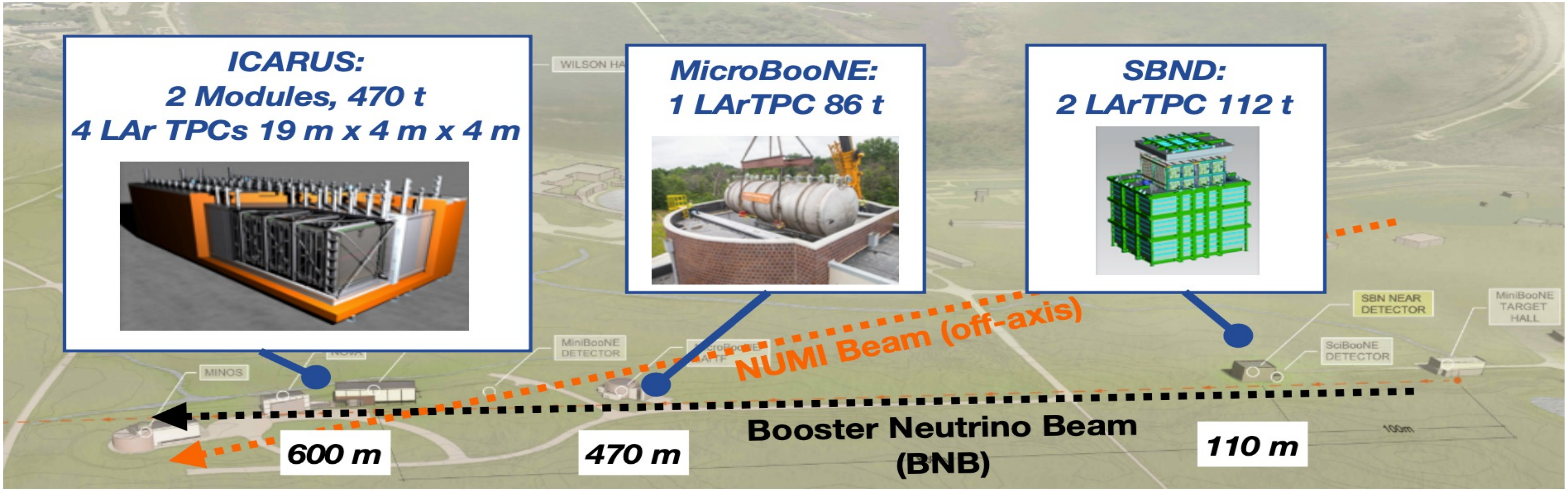
The light detection system of the ICARUS detector in the Short Baseline Neutrino Program

Marta Babicz for the ICARUS Collaboration

Imaging Cosmic And Rare Underground Signals

National Science Centre
Poland

Short Baseline Neutrino Program at Fermilab

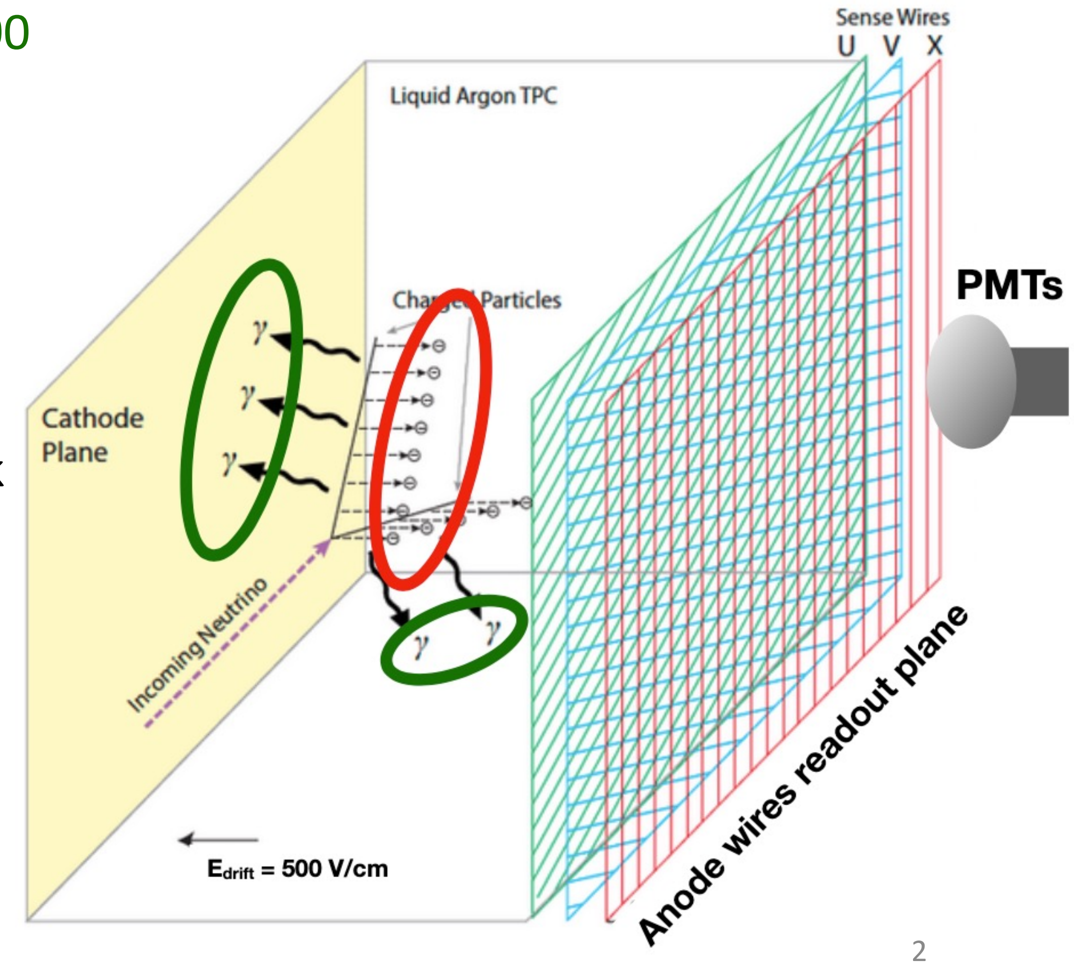


- **Designed to definitely solve the sterile neutrino puzzle**
- Three LArTPC detectors located on-axis of the Booster Neutrino Beamline (BNB)
- All detectors will make high-precision neutrino-Argon cross-section measurements
- Each detector will give valuable LArTPC operational experience for DUNE
- In addition, NuMI off-axis measurements will provide independent cross-check to BNB oscillation results and grant access to a rich Beyond the SM search program

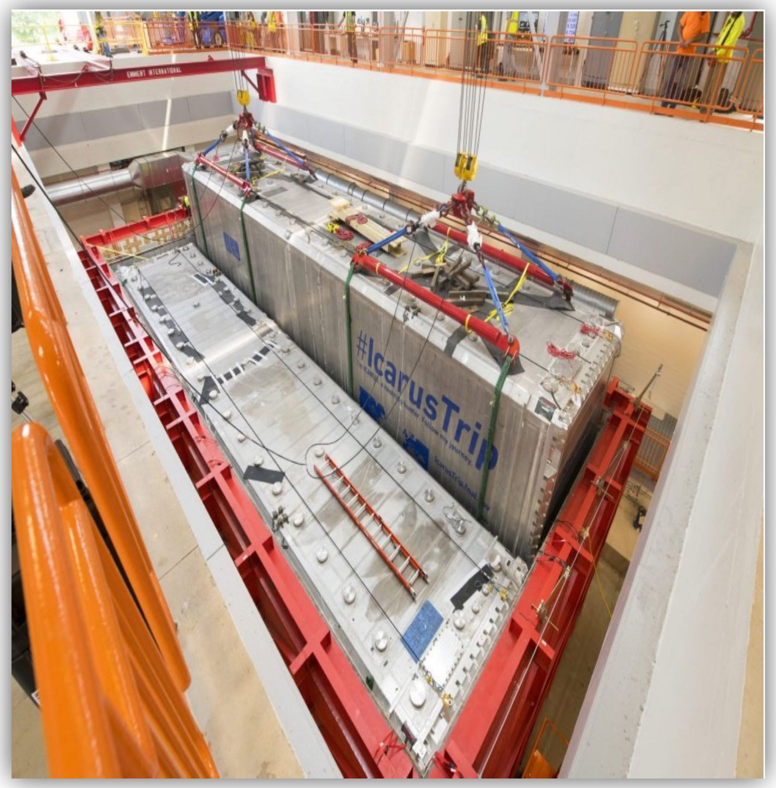
Liquid Argon TPC detection technique

Ideal detector for neutrino physics with excellent imaging and calorimetric capabilities allowing to reconstruct events with complex topologies

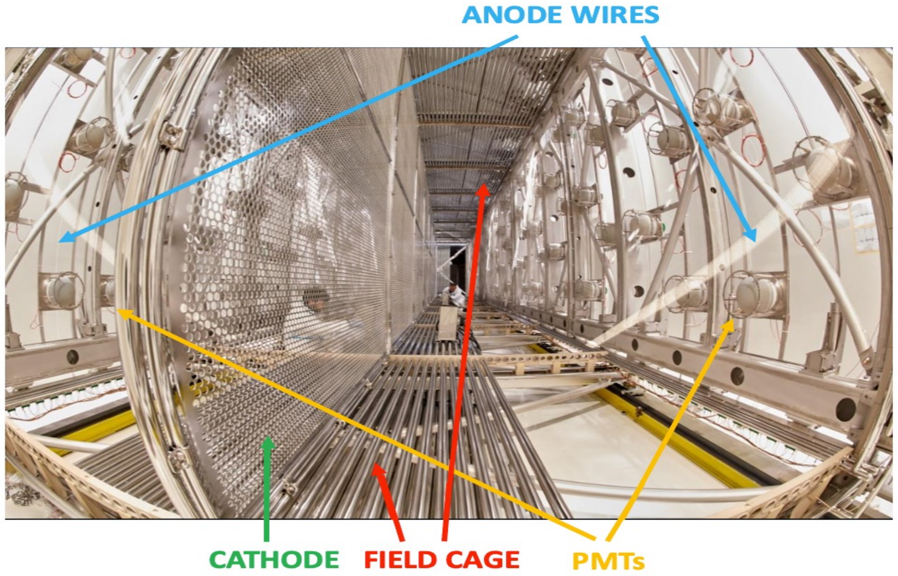
- **Scintillation light** (20000 γ/MeV at λ = 128 nm and E_D = 500 V/cm) detected by PMTs to provide the event time and trigger.
- **Ionization electrons** (42000 e^- / MeV) drifting in 1 ms towards readout sense wires.
- Combining wire coordinates at same drift time → 3D track reconstruction with **resolution of ~mm³**.
- **High energetic resolution**.
- **Possibility of building huge detectors** to compensate for very small cross-sections of neutrino interactions with matter.



ICARUS detector - first large LArTPC



- Each module contains two time projection chambers which have a common cathode.



- HV: 75 kV.
- Maximum electron drift length: 1.5 m.
- Maximum electron drift time: ~1 ms (500 V/cm).
- **360 8” PMTs coated with TPB (90 PMTs per TPC).**
- Cosmic Ray Taggers surround the cryostats with two layers of plastic scintillators ($\sim 1000\ m^2$).

- Two identical modules adjacent to each other.
- Dimensions of one module: 3.6 m × 3.9 m × 19.9 m.

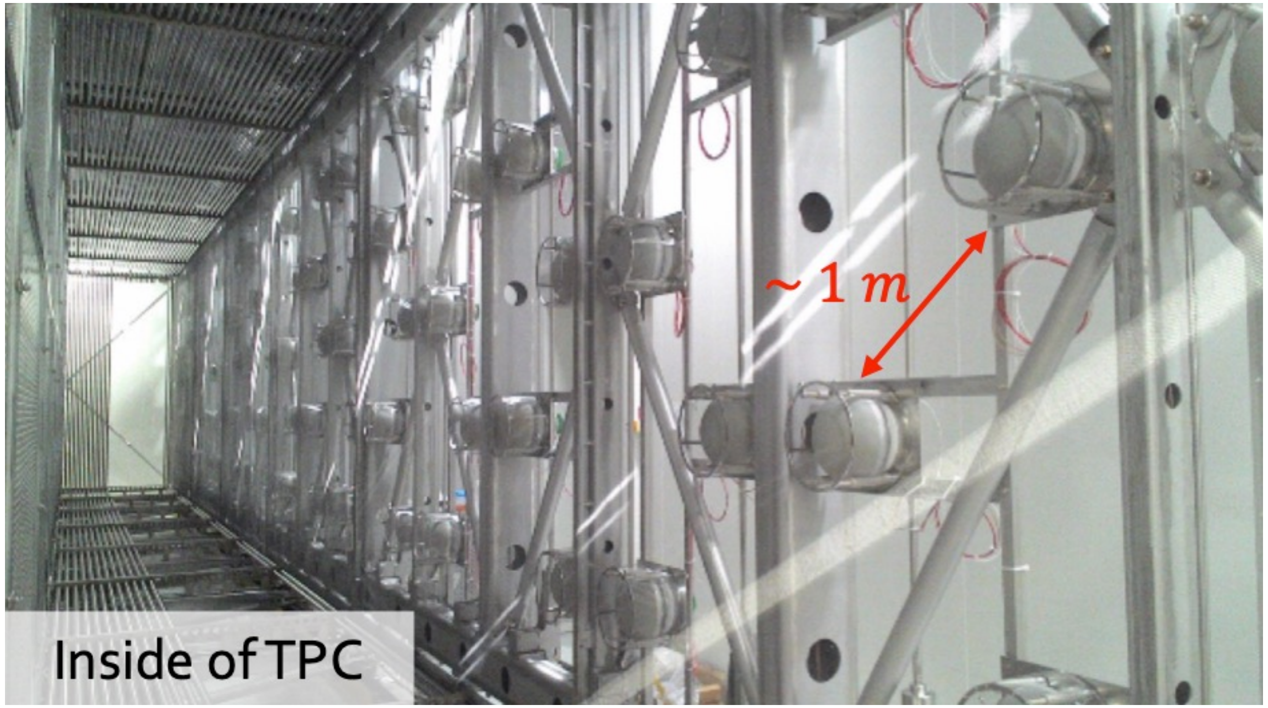
ICARUS began commissioning in 2020, and it already started the physics run

ICARUS light detection system

360 PMTs installed behind the wire planes allowing to:

8” Hamamatsu R5912-MOD

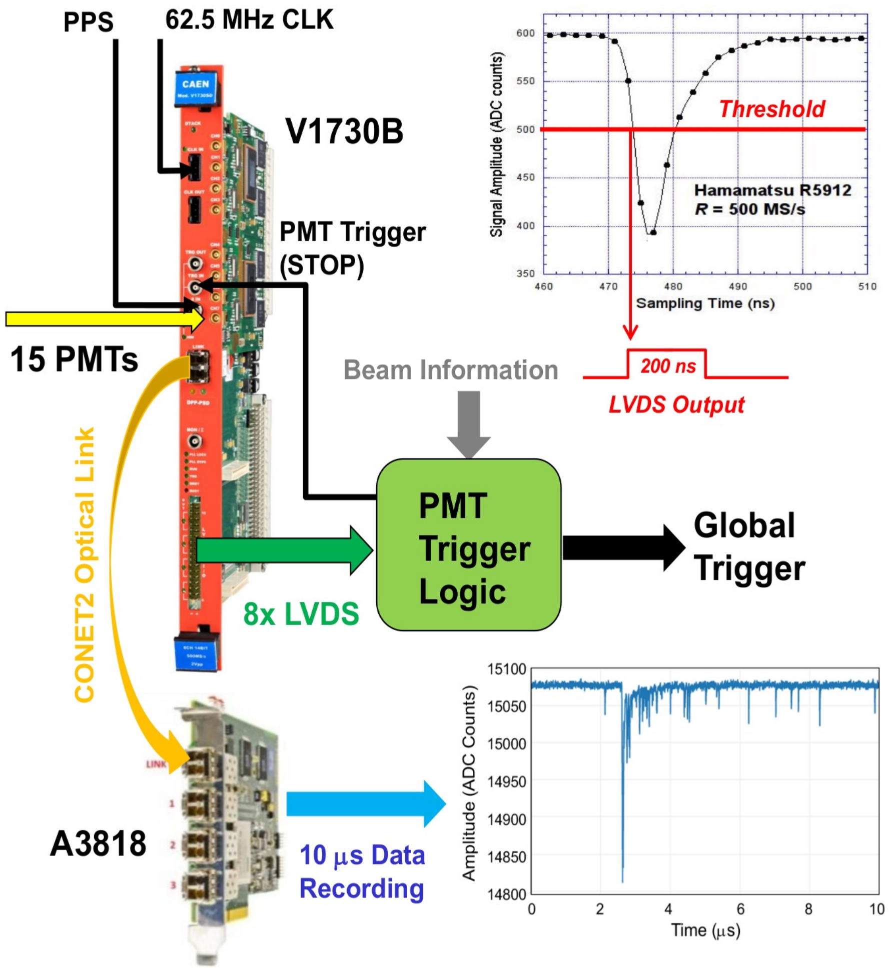
- Precisely identify the interaction time t_0 of ionizing events in the TPC, with $\sim ns$ time resolution.
- Localize events with spatial resolution better than 50 cm.
- Initial recognition of event topologies for the fast event selection.
- Generate a trigger signal for read-out sensitive to low energy events $\sim$100 MeV.



PMT electronics and data acquisition

24 CAEN V1730B digitiser boards (16-chanel, 14-bit, 500 Msa/s FLASH ADC):

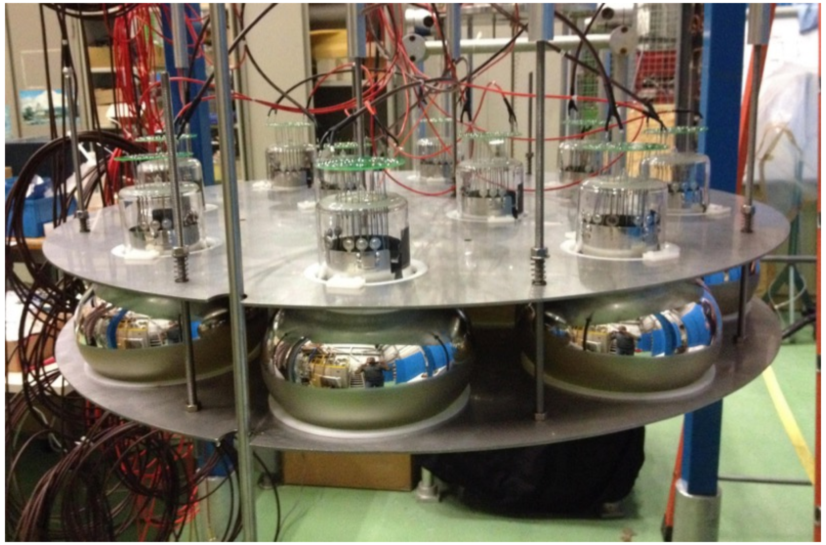
- Continuous read-out, digitisation and independent waveform recording of signals from 360 PMTs
- PMT signals sampled every 2 ns and recorded in 10 μs windows
- Trigger pulses generated by the Trigger System every time an interaction is recognised in the detector based on Beam information
- V1730Bs generate trigger request via Low Voltage Differential Signal outputs, indicating the presence of signals with amplitude overcoming digitally programmed thresholds
- LVDS outputs (one per PMT pair) are processed by an FPGA according to a predefined logic to activate (**Global Trigger**) the data acquisition

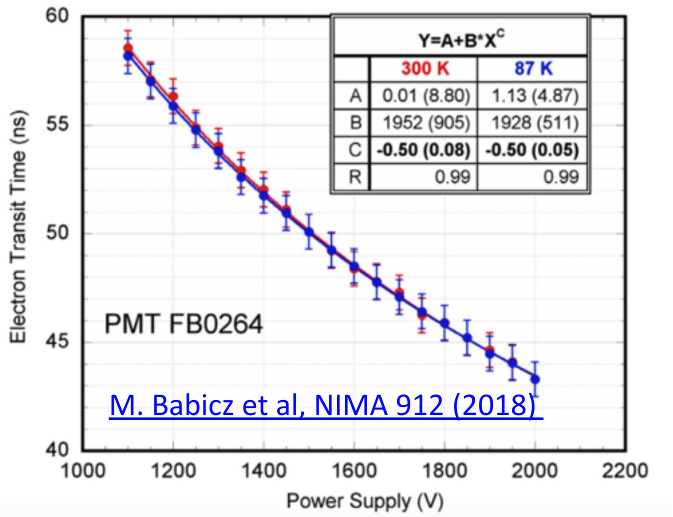


ICARUS PMT tests at CERN

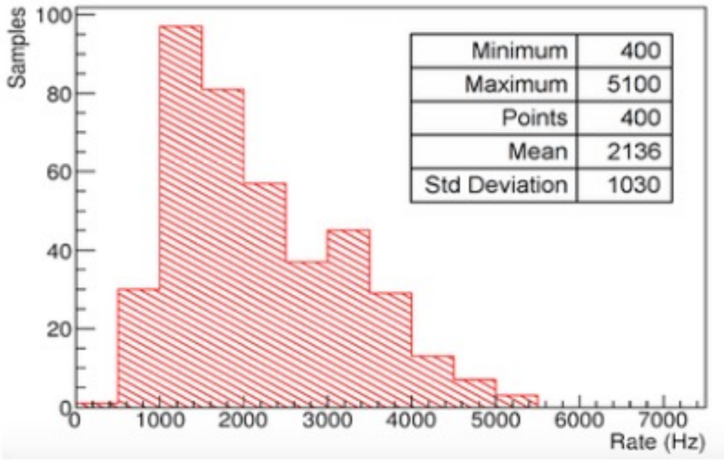
Fully characterized at CERN test-stand:

- Coated by evaporation of 0.21 ± 0.01 mg/cm^2 of TPB M. Bonesini, et al. JINST 12 P12020 (2018)
- Transit Time resolution ~1 ns, Dark rate < 5kHz, 12% uniform Quantum Efficiency *B. Ali-Mohammadzadeh et al 2020 JINST 15 T10007*
- Stable Gain of 10^7 at 87 K to detect down to Single Photoelectrons (SP) light *M. Babicz et al, 2018 JINST 13 P10030*

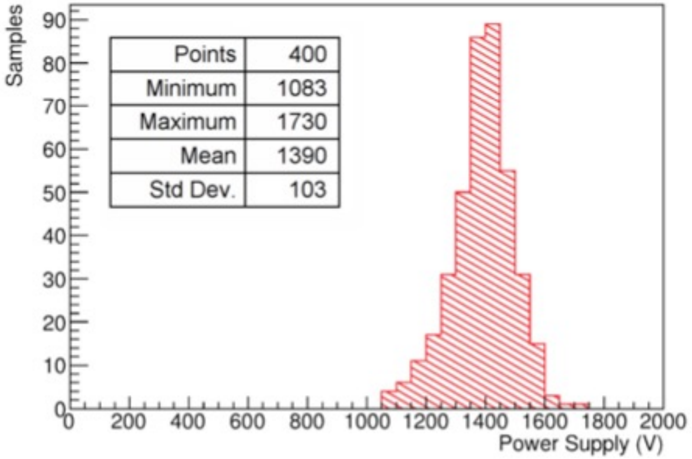




Electron transit time



The dark current rate.

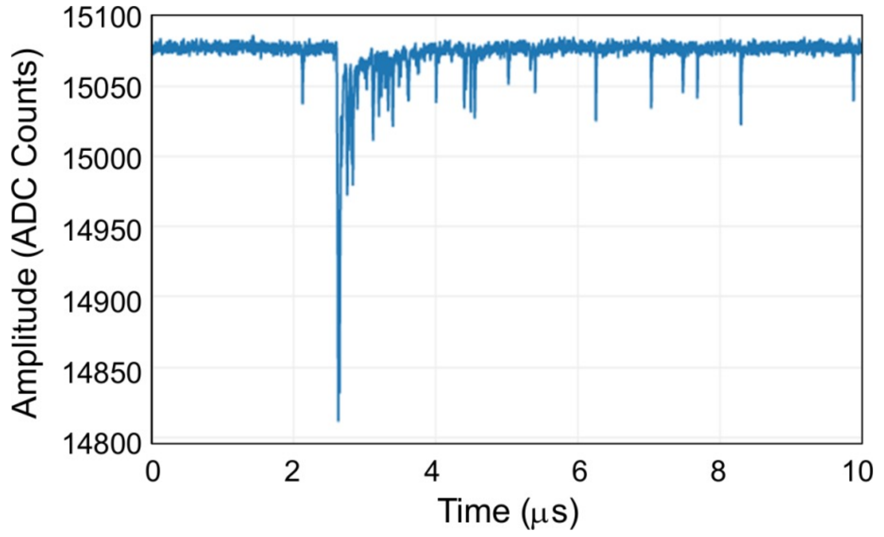


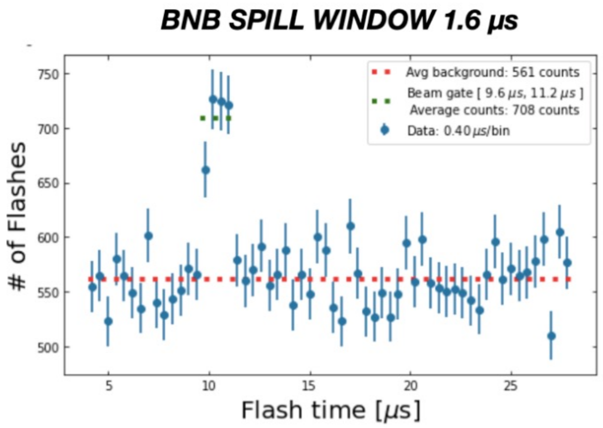
PMTs equalized **G=10^7** using the **Power Law** fitted from the 5 gains as function of the applied voltage.

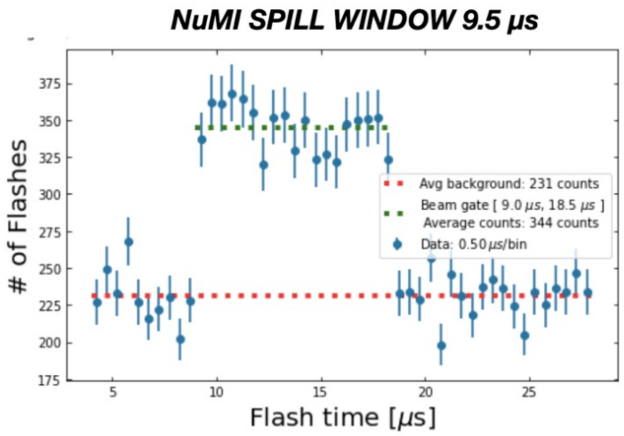
ICARUS PMTs at FNAL

- The light detection system was tested after the transportation at Fermilab before the cooling of the detector.
- 357 out of 360 working PMTs were found, with performances consistent with the test realised at CERN.
- The same number of working PMTs after filling the detector with LAr demonstrates the good low-temperature robustness of the adopted PMT model.
- Since its activation in 2019, the PMT system has been working smoothly.

A PMT signal recorded by the light detection system electronics with two decay components of the LAr scintillation light that can be identified.





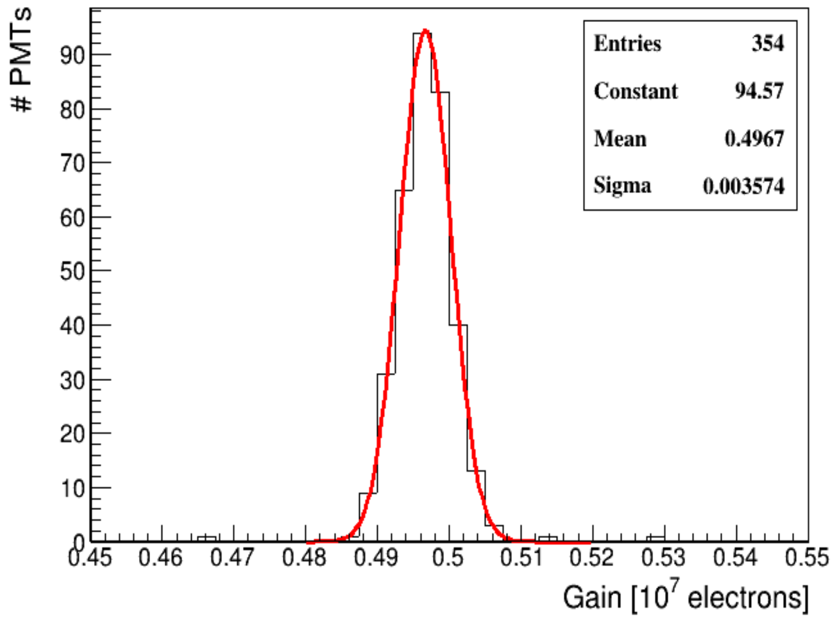


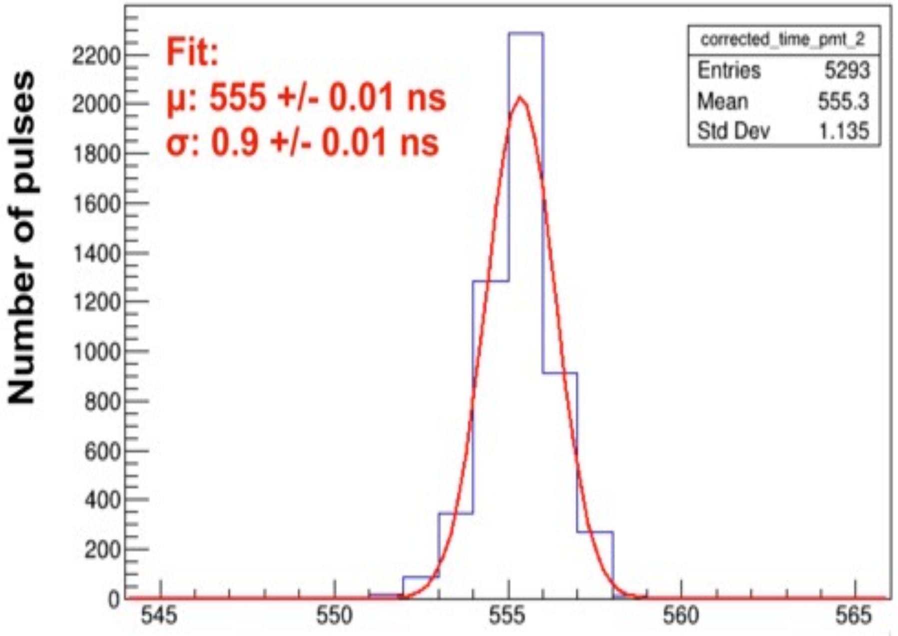
- ICARUS acquires data regularly using the light information at the trigger level, contributing to the selection of genuine neutrino interactions while rejecting the cosmic background.

Gain and timing calibration at FNAL

Fast laser-based calibration system allows for gain/time calibration, equalization, and monitoring of each PMT channel.

- PMT gain equalized at $\sim 0.5 \times 10^7 \pm 1\%$ with $\lambda \sim 405\ nm$ laser and measuring the 4 mV PMT response to background single photoelectrons



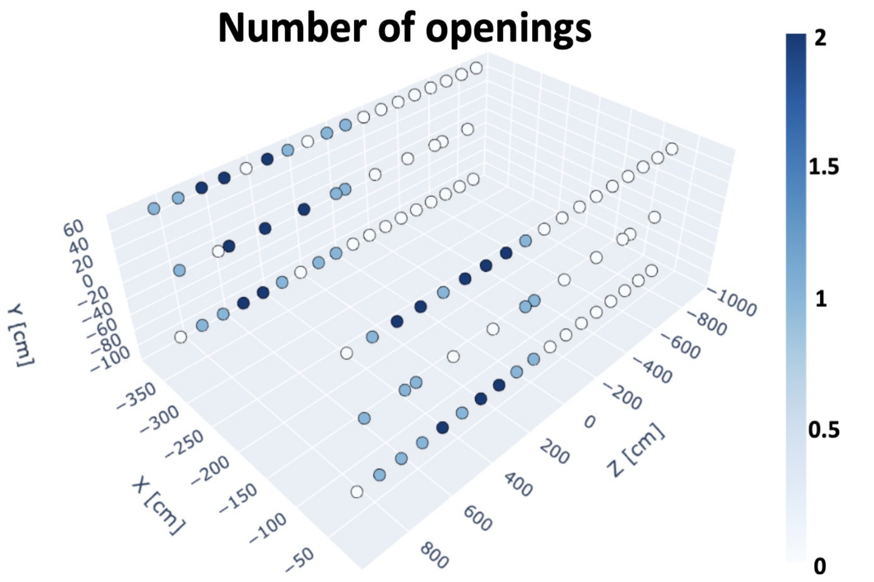


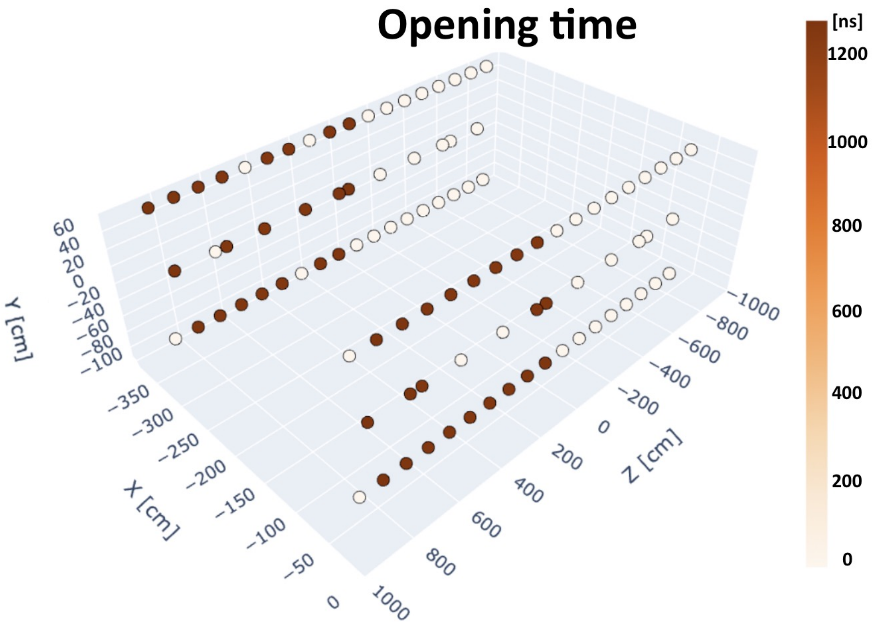
$$\Delta T = T_{PMT} - T_{Trigger}\ (ns)$$

- PMT time response equalised by the laser to trigger signal with 1 ns resolution allowing to perfectly determine the time of collected events

Proposal for event filtering in ICARUS using PMTs

- Within the BNB spill window we expect about four times more cosmic background events than neutrino interactions at the trigger output.
- Aim of the filter: distinguish cosmic background from neutrino events using the information available from the PMTs.
- The triggered PMT timing data represented as images is fed into a **Convolutional Neural Network** (CNN) to further discriminate between cosmic and neutrino interactions.
- Openings = which PMTs have signals exceeding a predefined threshold.
- Opening time = at what time that signal was recorded with respect to the start of the beam window.

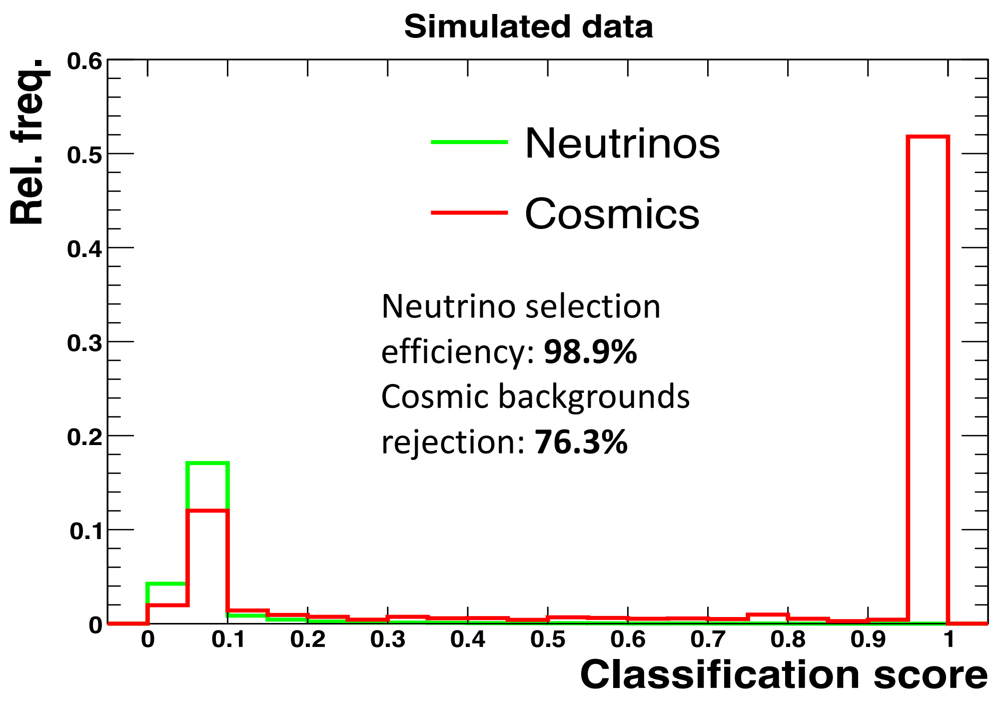


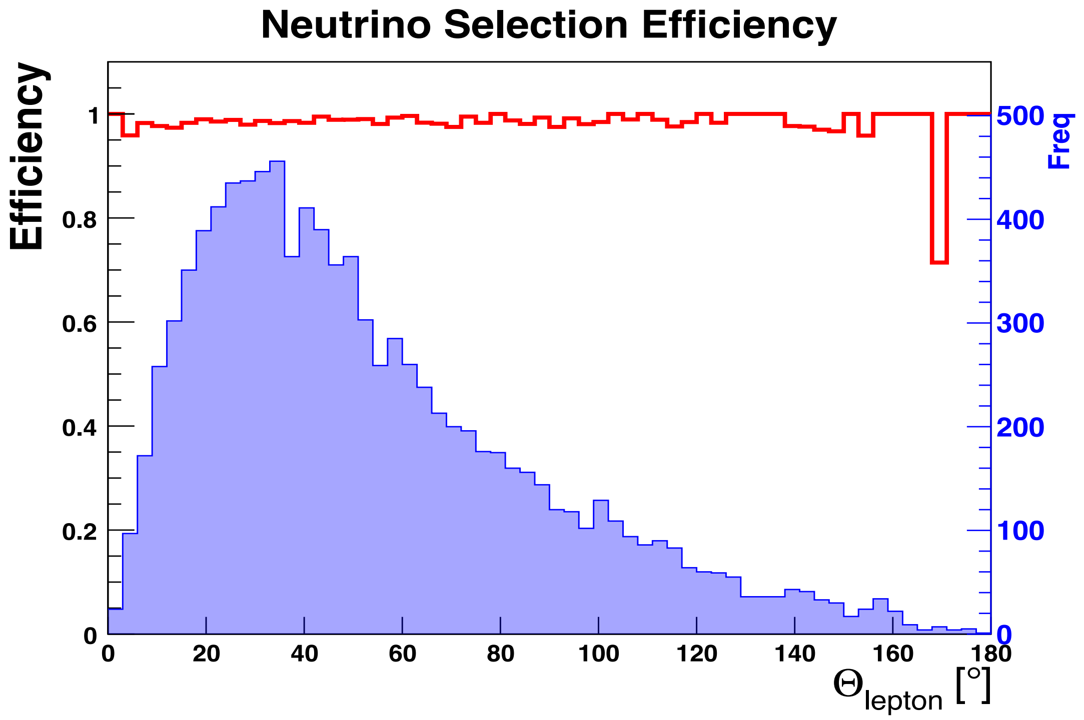


Proposal for event filtering in ICARUS using PMTs

- Once trained, the output of the CNN is a score for each event between 0 (neutrino-like) and 1 (cosmic-like).
- The charged-current selection efficiency is found to be flat (i.e., unbiased by kinematics) in various tested observables.

M. Babicz S. Alonso-Monsalve, S. Dolan *PoS ICRC2021 (2021) 1075*



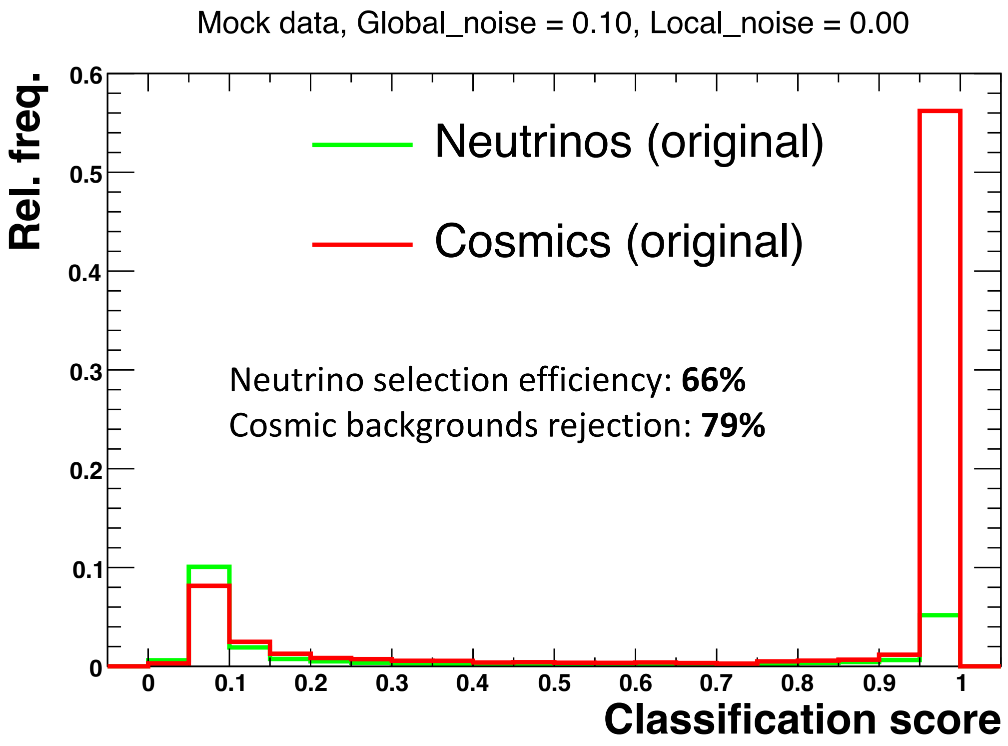


Domain Adversarial Neural Network

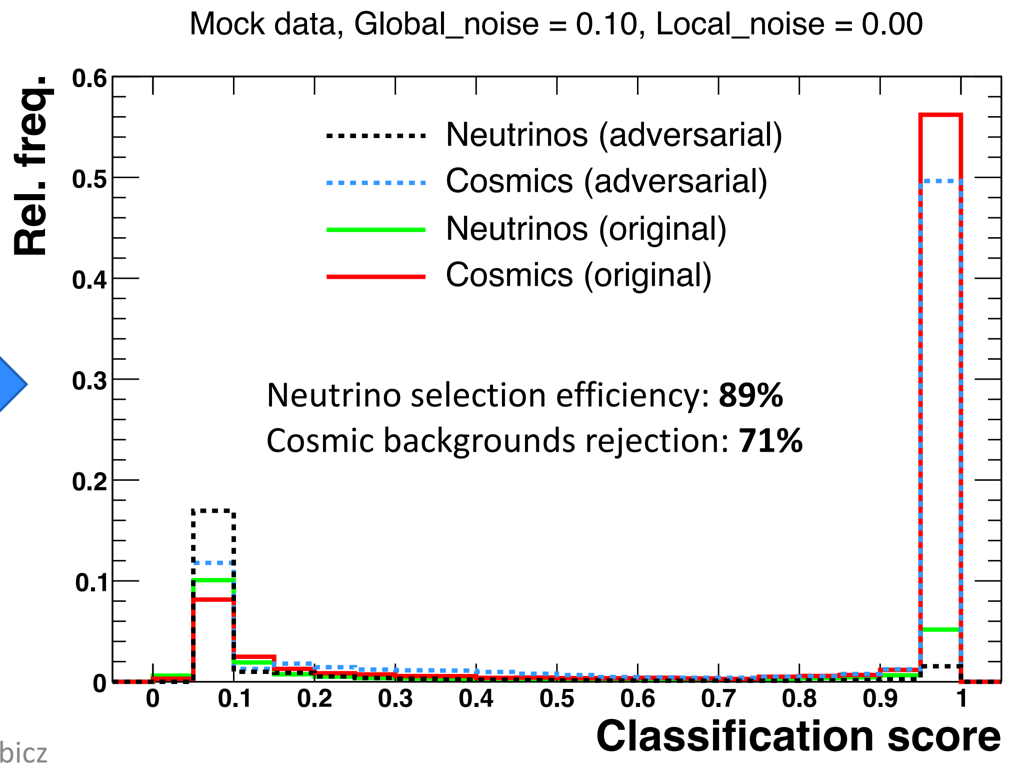
- CNN algorithms trained on simulation, but applied to real data, face uncertainties due to imperfect modelling.
- To test this, mis-modelling bias (as global/local noise) was introduced to the simulation.

M. Babicz et al *Phys.Rev.D* 105 (2022) 11, 112009

- To mitigate the simulation dependence, the Domain Adversarial Neural Network (DANN) has been introduced instead of CNN.
- Improvement of neutrino selection efficiency while keeping the cosmic rejection factor at a similar level was obtained.



After DANN



Conclusions

- The SBN program at Fermilab is expected to clarify the sterile neutrino puzzle.
- The ICARUS light detection is a fundamental part of the detector allowing the precise timing and interpretation of a TPC event.
- Tests and evaluation of the PMTs' performance at CERN proved to fulfil the requirements of the SBN program.
- The light detection system of ICARUS is fully operational, allowing the detector to take data regularly.
- A CNN-based event filter to separate neutrino interactions from cosmic background has been developed using the PMT information to reduce this background further.
- Current ICARUS simulation shows that the filter based on Domain Adversarial Neural Network successfully rejects most of the cosmic background while efficiently selecting neutrino interactions.
- The event filter can be implemented as a part of the ICARUS production workflow and its output can become the input to higher level analyses.