The ICARUS detector for the Short Baseline Neutrino program at Fermilab

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Physics motivation

- In the last 20+ years, four anomalies have been observed in neutrino experiments at a short baseline (LSND, MiniBooNE, GALLEX/SAGE and reactor anomaly).
- These anomalies provided hints to indicate a fourth and non-weakly interacting (sterile) type of neutrino.
- Possible explanation by non-standard sterile neutrino states driving oscillation at $\Delta m^2 \approx 1\ eV^2$ and small $sin^2(2\theta)$ → interesting for astrophysics.

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_s\rangle \\ \vdots \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} & U^*_{e4} & \cdots \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} & U^*_{\mu 4} & \cdots \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} & U^*_{\tau 4} & \cdots \\ U^*_{s1} & U^*_{s2} & U^*_{s3} & U^*_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \vdots \end{pmatrix}$$

Formalism: mixing matrix for 3 active neutrinos extended with sterile neutrino(s) and additional mass term(s) in oscillation probabilities.

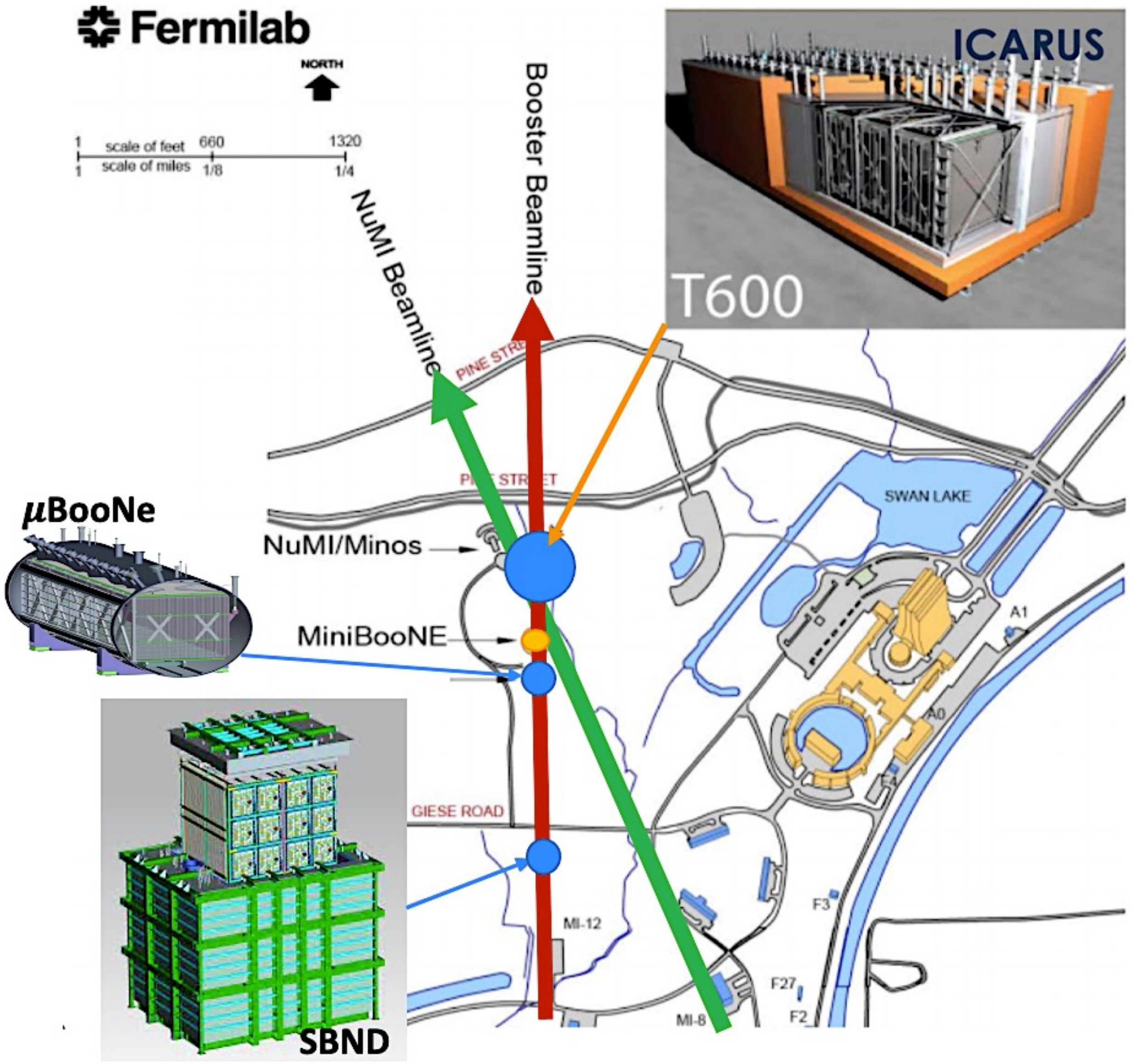
ν_s can be detected by observing oscillations with active neutrinos.

Short Baseline Neutrino program at Fermilab

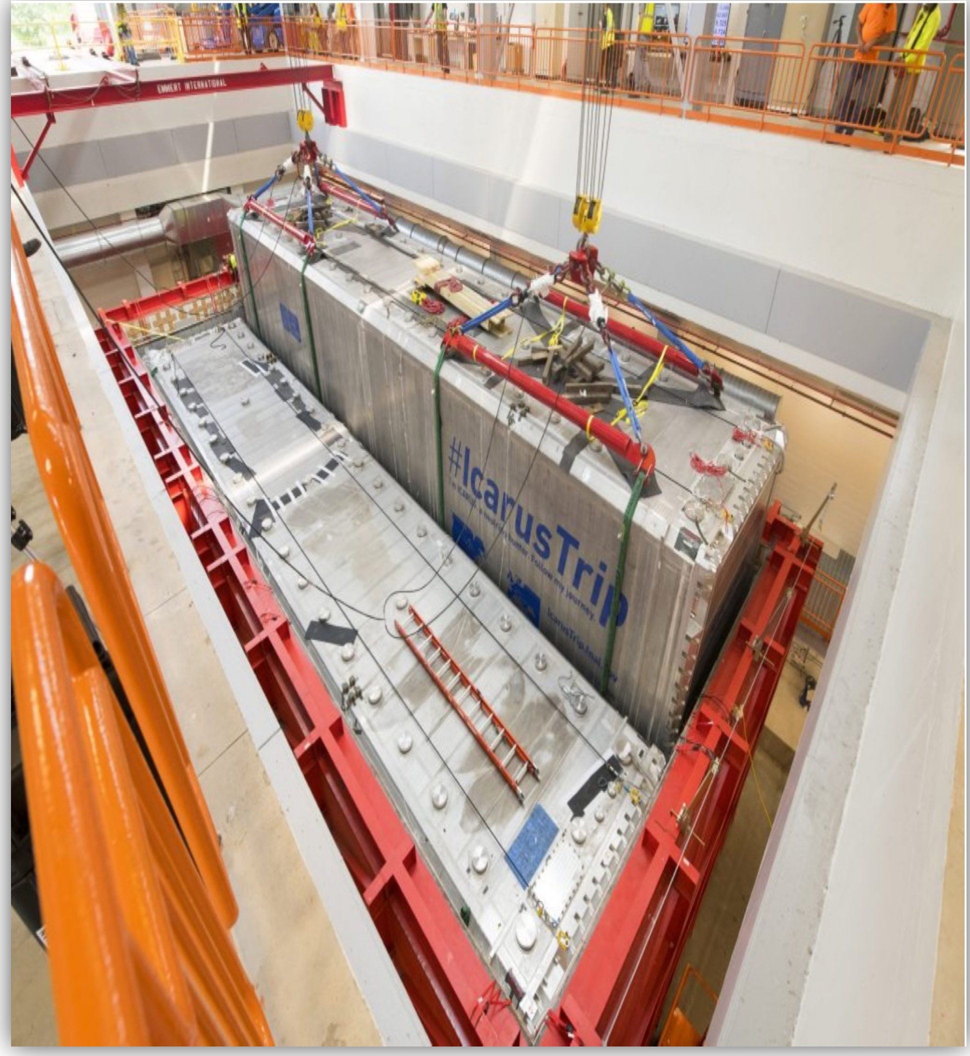
Program aimed at final check of LSND and MiniBooNE observations

- Use of three liquid Argon time projection chambers (LArTPCs) located at the Fermilab Booster Neutrino Beamline (BNB).
- Same detector technology: reducing systematic uncertainties to the % level.
- All the three detectors are on the surface and thus are exposed to a high cosmic background.
- **MicroBooNE's first low-energy excess results:**

  https://arxiv.org/pdf/2110.14080.pdf, https://arxiv.org/pdf/2110.14065.pdf, https://arxiv.org/pdf/2110.13978.pdf



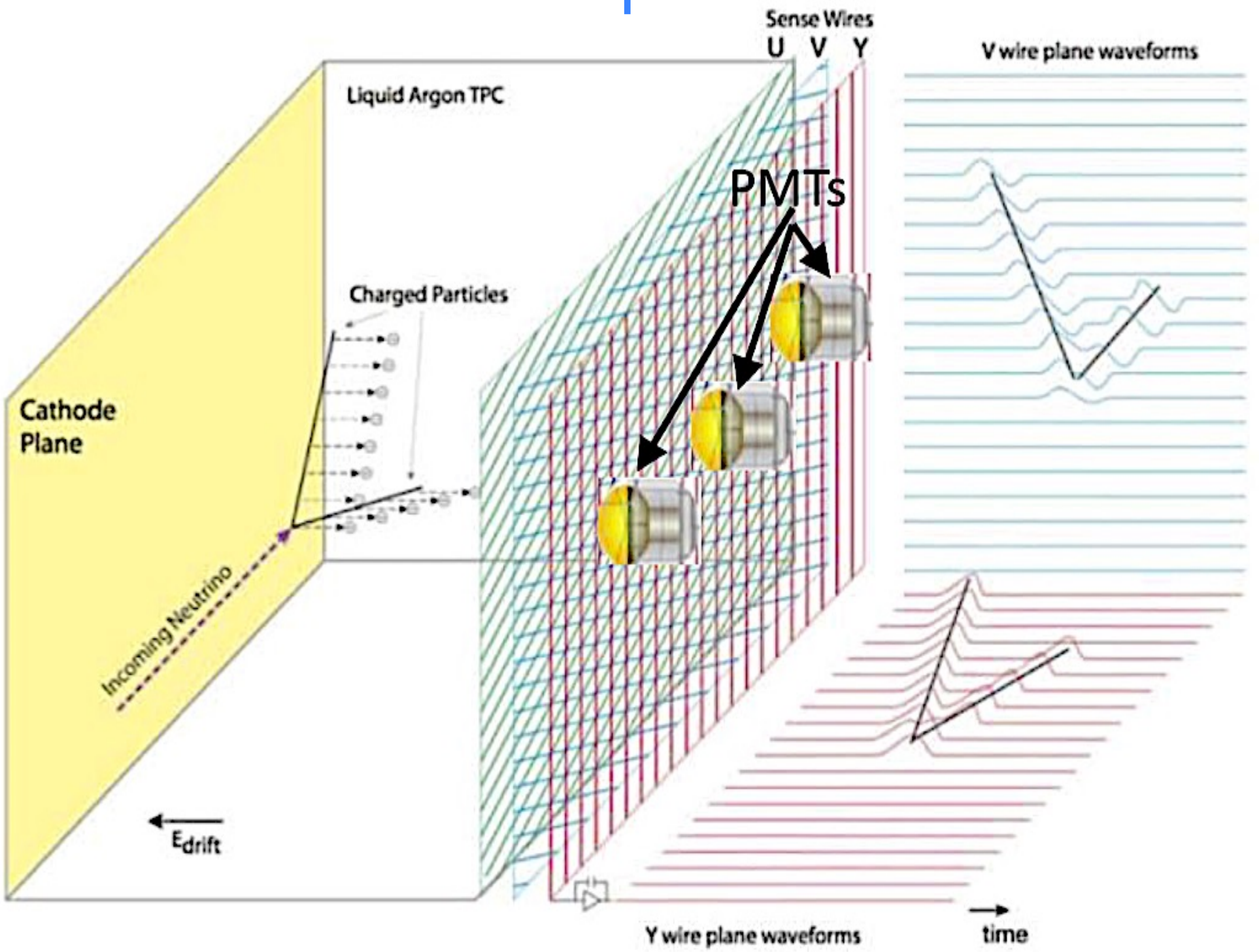
ICARUS T600 detector



- Two identical modules adjacent to each other.
- Dimensions of one module: 3.6 m × 3.9 m × 19.9 m.
- 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 ($\sim 1000\ m^2$).
- **ICARUS began commissioning in 2020, collected first neutrino data in June 2021 and continues data taking since November 2021.**

Liquid Argon TPC detection technique

- Scintillation light (fast signal) and ionisation charge (slow signal) → neutrino interaction time and 3D reconstruction of charged particles' tracks.
- Timing: scintillation light signal: ~6 ns, 1.6 μs; ionisation charge drift time: ~ms.
- High spatial and energetic resolution → accessing details of the final states in neutrino interactions.
- Possibility of building huge detectors to compensate for very small cross-sections of neutrino interactions with matter.

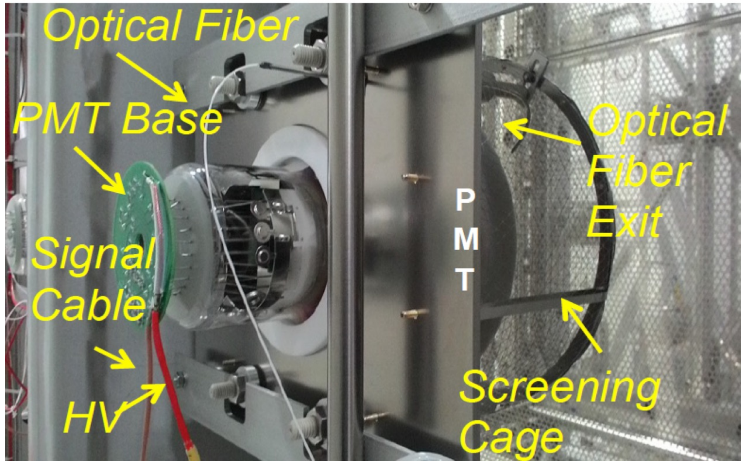


Detectors using the liquid Argon time projection technique: ICARUS, ArgoNeut, MicroBooNE, SBND, ProtoDUNE, DUNE.

The PMT light collection and trigger systems

Three tasks:

- identification of the time of occurrence (t_0) of each interaction,
- generation of a light-based trigger signal,
- initial recognition of event topologies for the fast event selection.



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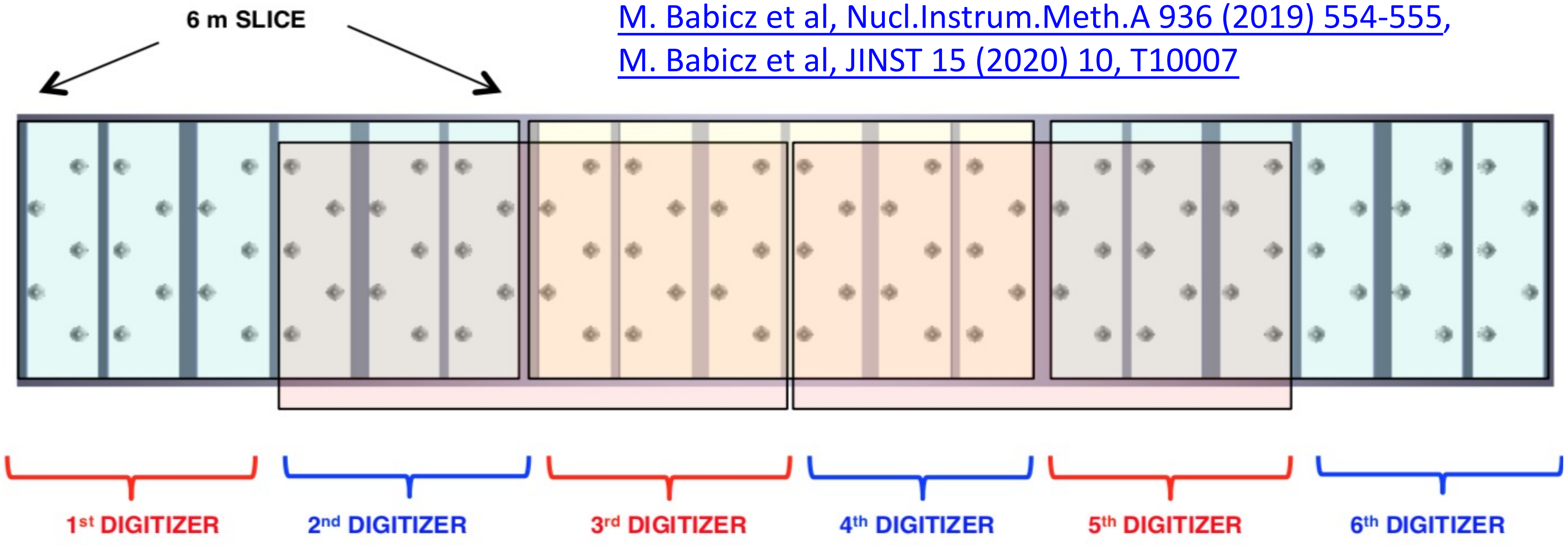
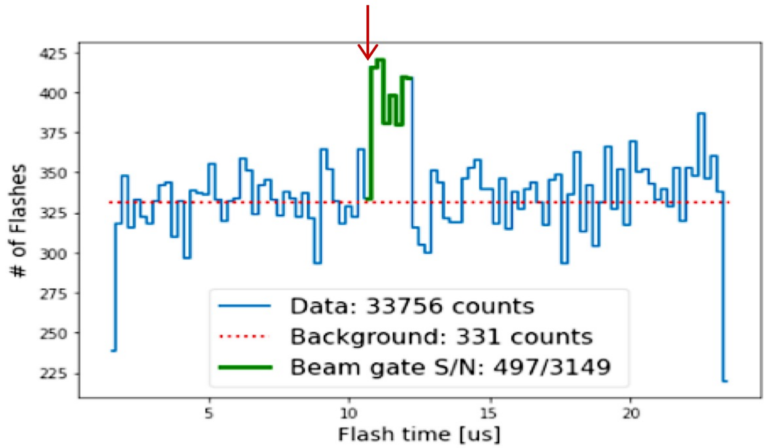
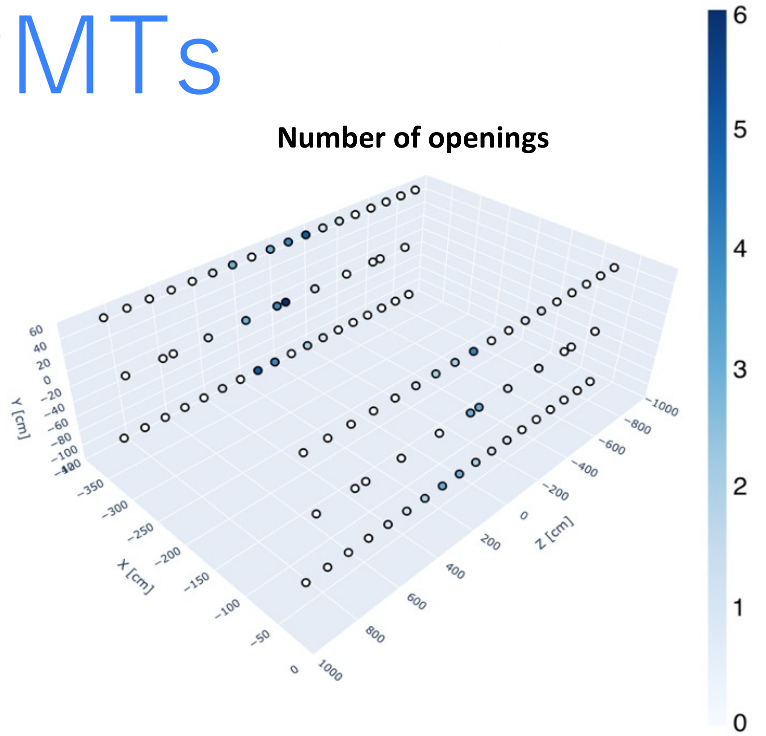


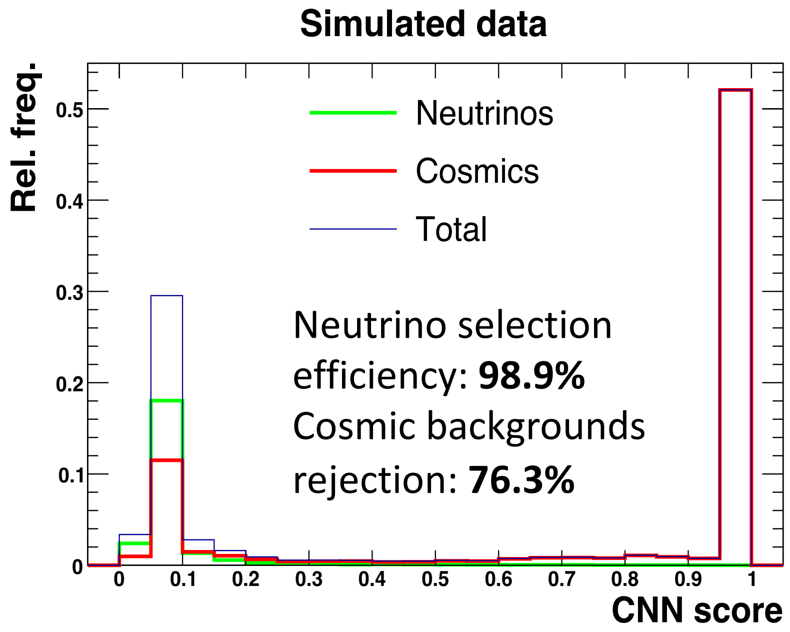
Excess of PMT light signal in correspondence with the 1.6 μs BNB gate observed.

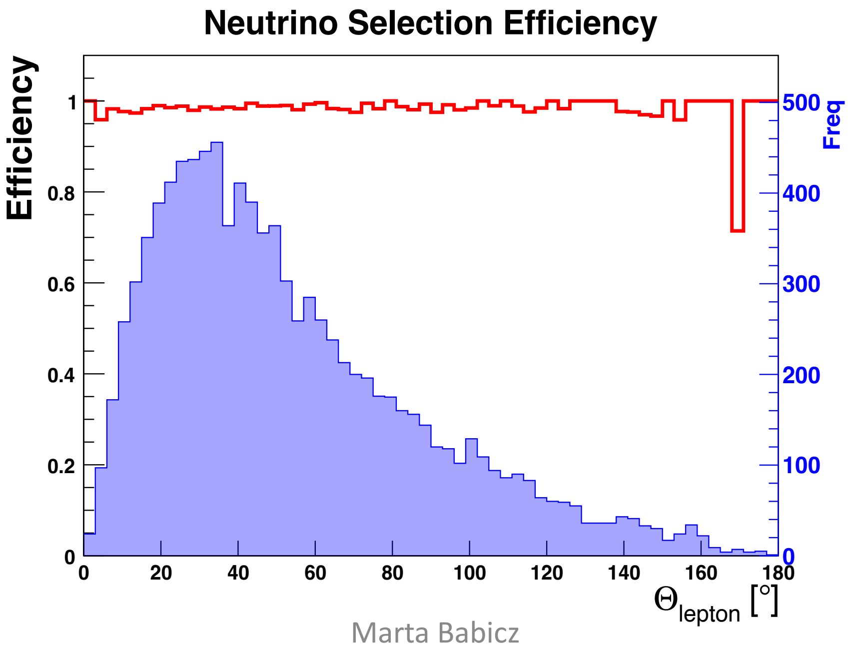


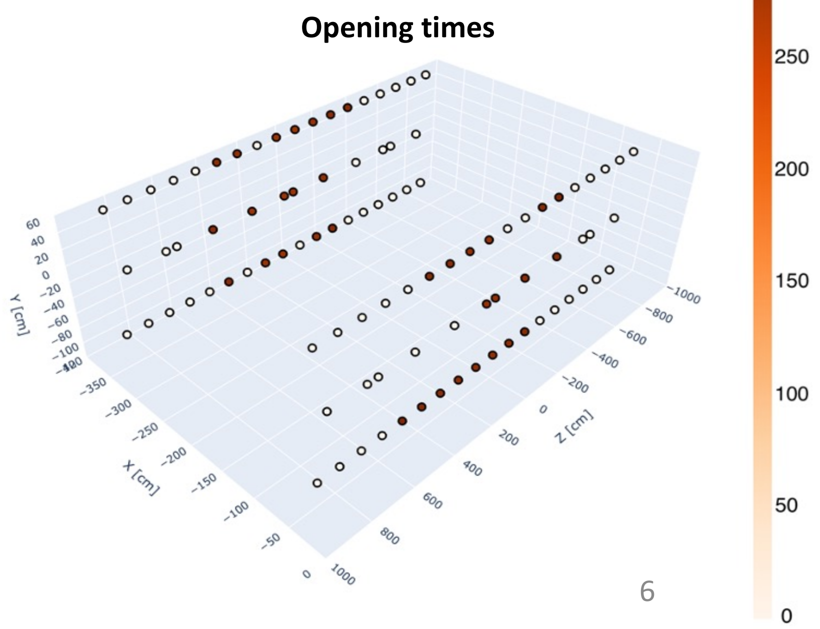
Event filtering in ICARUS using PMTs

- Within the BNB spill window we expect over three times more cosmic background than neutrino interactions.
- The aim of the filter is to reduce this background using the information available from the PMTs at the trigger level.
- The triggered PMT data represented as images is fed into a Convolutional Neural Network (CNN) to further discriminate between cosmics and neutrino interactions.



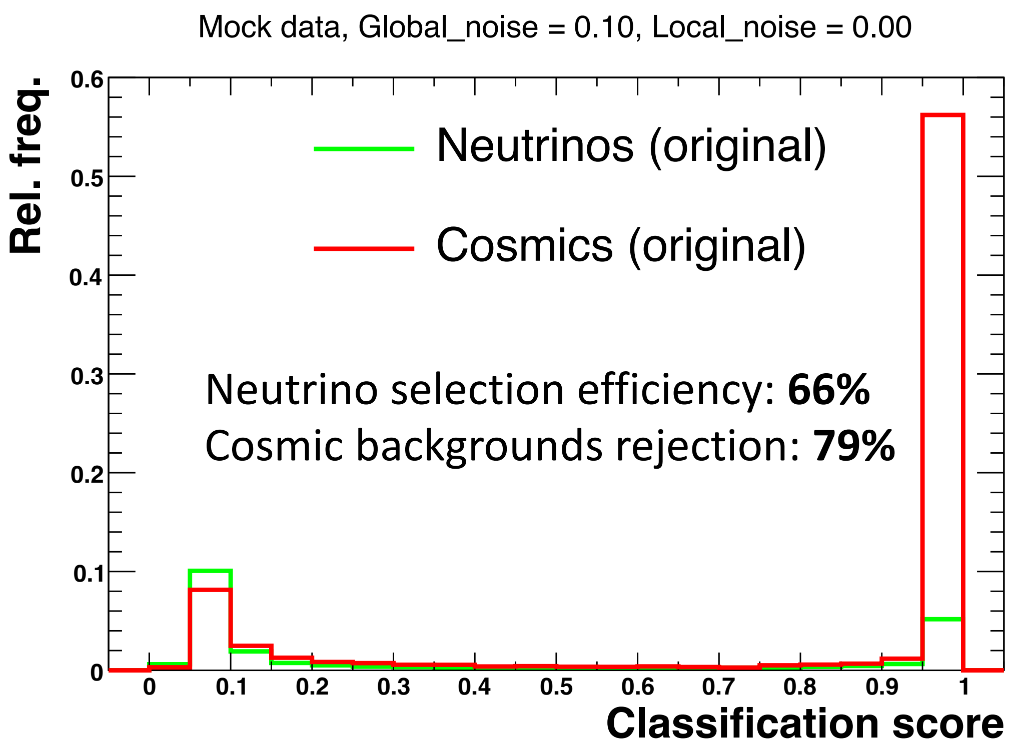




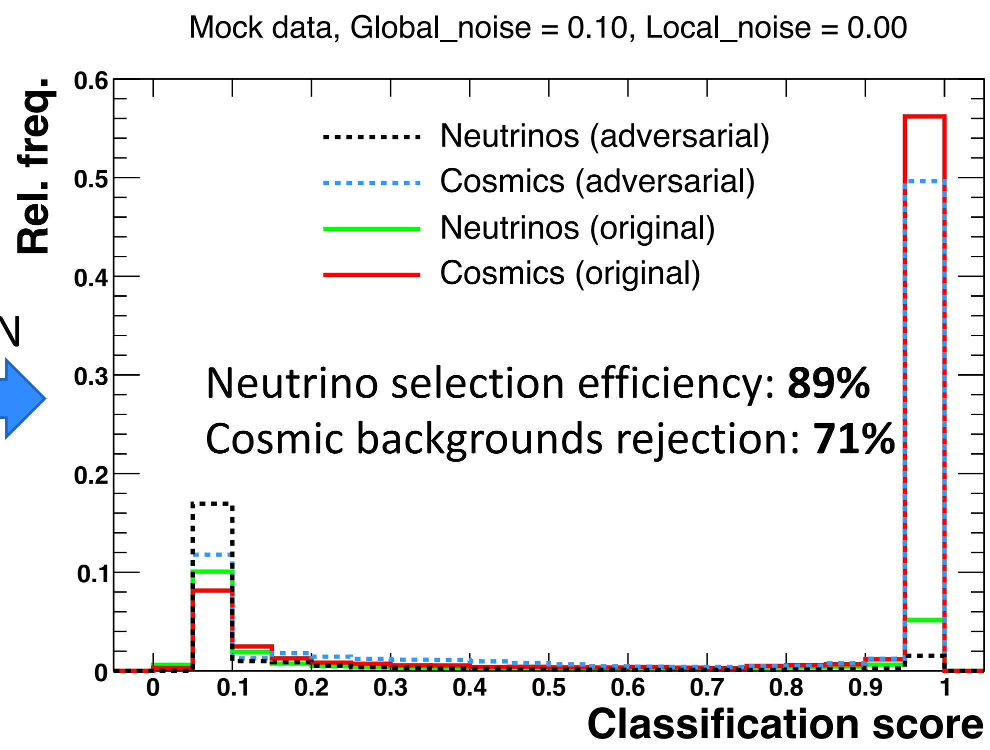


Reducing the simulation bias

- 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.
- 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 (publication soon).**



After DANN



Conclusions

- The SBN program should finally clarify the sterile neutrino hypothesis to explain the anomalies observed by LSND and MiniBooNE.
- The ICARUS light detection and trigger systems are essential for the detector operation on a surface with a large cosmic muon background.
- A CNN-based event filter to separate neutrino interactions from cosmic backgrounds has been developed using the PMT information to reduce this background further.
- Current ICARUS simulation shows that the filter based on DANN successfully rejects the vast majority of the cosmic background while efficiently selecting neutrino interactions.
- The event filter is being implemented as a part of the ICARUS production workflow and its output can become the input to higher level analyses.

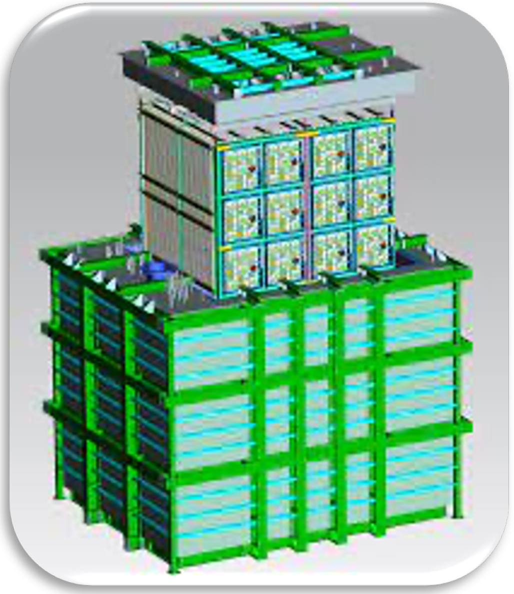
Backups

Mitigation of the cosmic background in the ICARUS

- By a twofold strategy which includes:
  - 3 m concrete overburden.
  - realization of ~4 π Cosmic Ray Tagger detector encapsulating the TPCs.
- CRT surrounds the cryostat with two layers of plastic scintillators (~1000 m^2) .
- However, software reduction of the background is also needed, especially now due to the delays in installation of the top CRT and concrete overburden installation.

SBN liquid Argon detectors

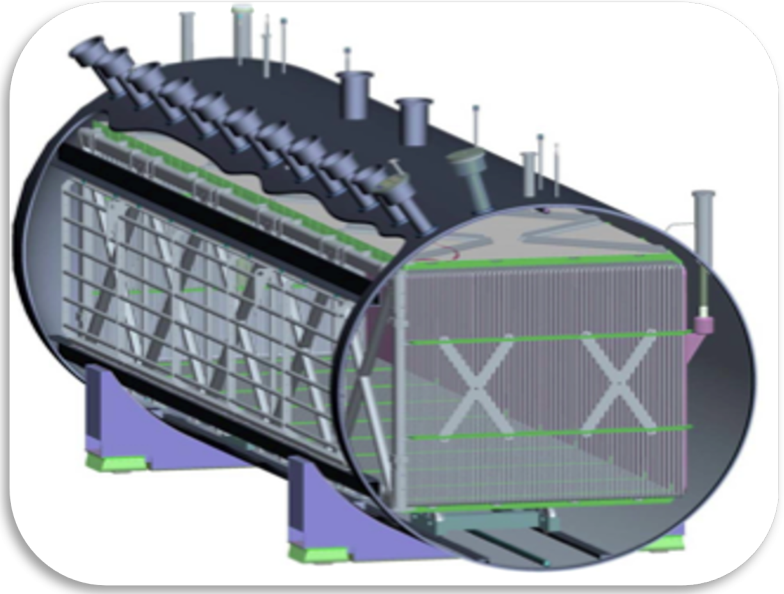
SBND



construction/installation

- 110 m from ν production
- 112 ton active volume
- 2 TPCs with 2 m drift
- 128 8” PMTs (96 coated with TPB), 192 X-ARAPUCA modules, TPB coated reflector foils on the cathode

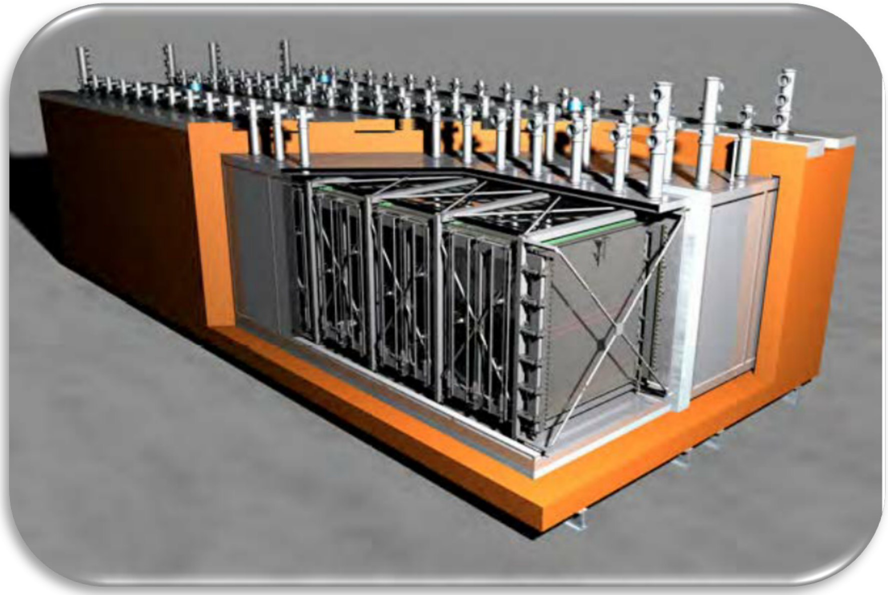
μBooNE



physics run completed

- 470 m from ν production
- 87 ton active volume
- 1 TPC with 2.56 m drift length
- 32 8” PMTs on acrylic support coated with TPB

ICARUS

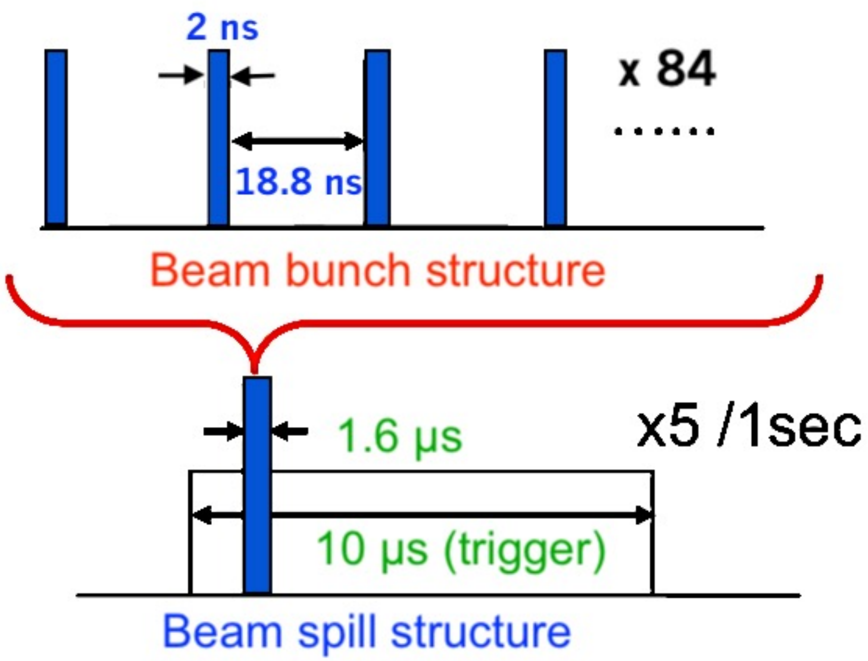


start data taking

- 600 m from ν production
- 476 ton active volume
- 4 TPCs with 1.5 m drift length
- 0.95 ms drift time at 500 V/cm
- **360** 8” PMTs coated with TPB

ICARUS event rates

1. BNB: 5×10^{12} POT/spill extracted in $\sim1.6\ \mu s$, 5 Hz repetition rate
   - **1 in-spill physical event over 35 spills ($\sim$ 0.15 Hz) expected inside ICARUS (E >100 MeV).**



2. Within the BNB spill window we expect over three times more cosmic ray backgrounds than neutrino interactions.
3. NuMI: 6×10^{13} POT/spill extracted in $\sim9.5\ \mu s$, 0.75 Hz repetition rate
   - **1 in-spill physical event over $\sim$ 5 spills ($\sim$ 0.17 Hz) expected inside ICARUS.**