Sterile Neutrino searches with the ICARUS detector

The 40th International Conference on High Energy Physics - ICHEP 2020

July 28th – August 6th 2020

Christian Farnese
INFN Padova

on behalf of the ICARUS collaboration
The present ICARUS Collaboration at SBN


On Leave of Absence from INFN Padova
On Leave of Absence from INFN Pavia

1. Brookhaven National Lab., USA
2. CERN, Switzerland
3. CINVESTAV, Mexico, USA
4. Colorado State University, USA
5. Fermi National Accelerator Lab., USA
6. INFN Bologna and University, Italy
7. INFN Catania and University, Italy
8. INFN Genova and University, Italy
9. INFN GSSI, L’Aquila, Italy
10. INFN LNGS, Assergi (AQ), Italy
11. INFN LNS, Catania, Italy
12. INFN Milano, Milano, Italy
13. INFN Milano Bic. and University, Italy
14. INFN Napoli, Napoli, Italy
15. INFN Padova and University, Italy
16. INFN Pavia and University, Italy
17. SLAC National Accelerator Lab., USA
18. Southern Methodist University, USA
19. Tufts University, USA
20. University of Houston, USA
21. University of Pittsburgh, USA
22. University of Rochester, USA
23. University of Texas (Arlington), USA

11 INFN groups, 10 USA institutions, 1 Mexican institution, CERN

Spokesman: C. Rubbia, GSSI
ICARUS T600: the first large Liquid Argon TPC (760 t of LAr)

- ICARUS-T600 LAr TPC is a high granularity uniform self-triggering detector with 3D imaging and calorimetric capabilities, ideal for $\nu$ physics. It allows to accurately reconstruct a wide variety of ionizing events with complex topology.
- Exposed to CNGS neutrino beam, ICARUS concluded in 2013 a very successful 3 years run at Gran Sasso INFN underground lab, collecting $8.6 \times 10^{19}$ pot event statistics, with a detector live time >93%, and cosmic ray events.

Two identical modules: 476 t total active mass:

- 2 TPC's per module, with a common central cathode: $E_{\text{Drift}} = 0.5 \text{ kV/cm}$, $\nu_{\text{Drift}} \sim 1.6 \text{ mm/\mu s}$, 1.5 m drift length;
- 3 "non-destructive" readout wire planes per TPC, $\approx 54000$ wires at $0^\circ, \pm 60^\circ$ w.r.t. horizontal: Induction 1, Induction 2 and Collection views;
- Ionization charge continuously read (0.4 $\mu$s sampling time);
- 8" PMT's, coated with TPB wls, for $t_0$, timing and triggering.
ICARUS results and search for an LSND-like effect

ICARUS run at LNGS allowed reaching several physics/technical results demonstrating the maturity of the LAr-TPC technology:

- An exceptionally low level ~20 p.p.t. [O₂] eq. of electronegative impurities in LAr; the measured e⁻ lifetime $\tau_{\text{ele}} > 15 \text{ ms}$ ensured few m long drift path of ionization e⁻ signal without attenuation;
- Demonstrated detector performance especially in $\nu_e$ identification and $\pi^0$ bkg rejection in $\nu_\mu$-$\nu_e$ study to unprecedented level;
- Performed a sensitive search for LSND-like anomaly with CNGS beam, constraining the LSND window to narrow region at: $\Delta m^2 < 1 \text{ eV}^2$, $\sin^2 2\theta \sim 0.005$ where all positive/negative experimental results can be coherently accommodated at 90% C.L., confirmed by OPERA.


ICARUS and the success of the LAr-TPC technology paved the way to the next generation long-baseline project: DUNE
Perspectives for sterile neutrino physics

- Different anomalies (from accelerator experiments LSND, MiniBoone, from reactors and from neutrino sources GALLEX/SAGE) have been collected in last years in neutrino sector despite the well-established 3-flavour mixing picture within Standard Model.
- Results hint to a new “sterile” flavour, described by large $\Delta m^2_{\text{new}} \sim eV^2$ and small mixing angle $\theta_{\text{new}}$, driving oscillations at short distance.
- The sterile neutrino scenario is far from understood and needs a definitive clarification.

- No evidence of oscillations in $\nu_\mu$ disappearance data (MINOS, IceCube)
- Recent reactor data (especially the recent results from Neutrino4) are intriguing but not conclusive...
- Tension between $\nu_e$ appearance and $\nu_\mu$ disappearance results. Measuring both channels with the same experiment will help disentangle the physics scenario.
- A comparison between far/near detector is crucial for any accelerator experiment, with a better control of backgrounds and systematics.

SBN satisfies these requirements: it could have a crucial role in solving the sterile neutrino puzzle!
The SBN project

- Three LArTPC detectors at different baselines from Booster neutrino beam searching for sterile $\nu$ oscillations measuring both appearance and disappearance channels.

- During SBN operations, ICARUS, as far detector, will also collect neutrinos from NuMI Off-Axis beam with a large $\nu_e$ component with $\sim 3 \text{ GeV}$ energy, providing $\nu$ interaction cross-section measurements in LAr and identification/reconstruction studies for the future long-baseline project DUNE.

- Expected events Rates (Hz) at ICARUS:
<table>
<thead>
<tr>
<th></th>
<th>neutrinos</th>
<th>cosmics</th>
</tr>
</thead>
<tbody>
<tr>
<td>from Booster</td>
<td>0.03</td>
<td>0.11</td>
</tr>
<tr>
<td>from NuMI</td>
<td>0.014</td>
<td>0.08</td>
</tr>
</tbody>
</table>
SBN expected sensitivities for 3 years \((6.6 \times 10^{20} \text{ pot})\)

- Using the same detector technology for all the 3 detectors will greatly reduce the systematic errors: \textit{SBND} (near detector) will provide the “initial” beam composition and spectrum
- The great \(\nu_e\) identification capability of LAr-TPC will help reduce the NC background
- Thanks to the simultaneous study of the electron neutrino appearance and of the muon neutrino disappearance channels, SBN will cover much of the parameters allowed by past anomalies at >5\(\sigma\) significance

![Diagram](https://arxiv.org/pdf/1903.04608.pdf)
A new experimental challenge: a LAr-TPC on surface

ICARUS at FNAL is facing a more challenging experimental condition than at LNGS, requiring the recognition of $O(10^6)$ $\nu$ interactions amongst 11 KHz of cosmic rays.

- A 3 m concrete overburden will remove contribution from charged hadrons/$\gamma$'s.
- $\sim 11$ $\mu$ tracks will hit the T600 in 1 ms TPC drift window: associated $\gamma$'s represent a serious background source for $\nu_e$ search since $e$'s produced via Compton scatt./ pair prod. can mimic a genuine $\nu_e$ CC.

To face new experimental conditions, T600 underwent an intensive overhauling at CERN in the Neutrino Platform framework from 2015 to 2017, before shipping to US.

Several technology developments were introduced while maintaining the already achieved performance at LNGS run:

- new cold vessels, with a purely passive insulation;
- renovated LAr cryogenics/purification equipment;
- improvement of the cathode planarity
- upgrade of the PMT system: higher granularity and ns time resolution
- new faster, higher-performance read-out electronics;
Placement of ICARUS inside the warm vessel (August 2018)

Feedthrough TPC/PMT/laser flanges installation (December 2018)

All TPC readout electronics installed (May 2019) and tested

All cryogenics equipment installed, welded and tested (May 2019)
• Filling with Liquid Argon started on Feb 19\(^{th}\) and has been completed on Apr 19\(^{th}\) - 2020
• The Liquid and Gas recirculation for the Argon purification is also started

![Graph showing LAr Levels in the two T600 modules](image)

- Filter Regeneration
- Start Gas and Liquid re-circulation

- WEST Module
- EAST Module

**Filling Start: Feb 19**

**Filling Complete: Apr 19**
ICARUS@SBN exploits 360 PMTs (5% coverage, 15 phe/MeV). This system will allow to:

- Precisely identify the **time of occurrence** \( (t_0) \) of any ionizing event in the TPC with **ns timing resolution**
- Determine the event **rough topology** for selection purposes
- Generate a **trigger signal** for read-out
  - Sensitivity to low energy events (~100 MeV)
- **Localize events** with <50 cm spatial resolution

The system was completed in 2019 and is now ready for operation. The commissioning is in progress:

- Activation of all the 360 PMTs and calibration at LAr temperature

---

**RMS value of the waveforms from the digitizer boards**

Animesh Chatterjee, poster #240, poster session 4

New TPC readout electronics extensively tested on a 50 liter TPC@CERN:

- A front-end based on analogue low noise/charge sensitive pre-amplifier
- More compact layout both analog+digital electronics in a single flange
- Lower noise ∼1200 e- equivalent (∼20% S/N improvement w.r.t LNGS)
- Shorter shaping time ∼1.5 µs matching e- transit time between wire planes providing a better hit position separation

All the TPC readout electronics have been installed and Ten mini-crates have been continuously recorded to monitor the noise condition during the filling period:

- A steady increase of the noise level (after the removal of the observed coherent noise component) has been observed during the Liquid Argon filling, in agreement with the expected variation of the wire capacitance due to increase of the level of the Liquid Argon inside the detector
The Cosmic Ray Tagging system (CRT)

- Three subsystems (Bottom, Sides, Top) surrounding the cryostat with two layers of plastic scintillators \(\sim1000 \text{ m}^2\);
- Tags incident cosmic or beam-induced muons with high efficiency (95\%) giving spatial and timing coordinates of the track entry point;
- Reconstructed CRT hits are matched to activity in the LAr volume;
- Few ns time resolution allows measuring direction of incoming/outgoing particle propagation via time of flight;
- Commissioning of the two walls with cosmics is ongoing.
Reconstruction and analysis in SBN

- A detailed understanding of detector-related systematics and their correlation across near/far detectors will be crucial to SBN physics: common reconstruction tools and oscillation analysis are therefore fundamental.
- Starting from LNGS experience, neutrino event selection and reconstruction is being developed: the combined signals from TPC, PMTs and CRT will help rejecting background from cosmics.
- Promising results with the present stage of the reconstruction tuned for $\nu_e$ search: the $dE/dx$ at the beginning of the shower provide a $\sim 90\%$ electron identification efficiency and $\sim 90\%$ rejection of $\gamma$ in NC event for well reconstructed $\nu$ vertex.

**ICARUS Simulation**

6.6e20 POT

$\nu_{\mu} CC$ selection for contained events

$\nu_e$/e selection based on the $dE/dx$ at the beginning of the shower.

BNB $\nu eCC$ $(E_\nu=1.13$ GeV$)$ and overlapping cosmics

Normalized Events

Reconstructed Primary Track Momentum [GeV/c]
The ICARUS-T600 successful 3-year run at LNGS proved that LAr-TPC technology is mature and ready for large-scale neutrino physics experiments.

The SBN project at FNAL is expected to clarify the sterile neutrino puzzle, by looking at both appearance and disappearance channels with three LAr-TPCs.

After an extensive refurbishing, the ICARUS installation at FNAL in the SBN far site has been completed.

ICARUS cooling down, filling and cryogenics commissioning has been completed this May 2020 and the commissioning is starting.

ICARUS will see first neutrinos soon and the data taking for physics is expected by beginning of the next year!
Thank you!