Sterile Neutrino searches with the ICARUS detector

Christian Farnese
INFN Padova

on behalf of the ICARUS collaboration

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M. Diwan, A. Timilsina, E. Worcester, M. Worcester
Brookhaven National Laboratory, USA

B. Behera, T. Boone, I. Caro Terrazas, C. Hilgenberg, J. Mueller, M. Mooney, H. Rogers,
D. Warner, R.J. Wilson
Colorado State University, USA

F.G. Garcia, M. Geynisman, S. Hahn, C. James, W. Ketchum, G. Lukhanin, S. Marcocci,
T. Nichols, A. Prosser, R. Rameika, R. Rechenmacher, A. Schukraft, A. Soha, D. Torretta,
P. Wilson, J. Zennamo, M. Zuckerbrot
Fermi National Accelerator Laboratory, USA

D. Cherdack
University of Houston, USA

V. Bellini, C. Petta, C. Sutera, F. Tortorici
INFN Sez. di Catania and University, Catania, Italy

C. Rubbia
INFN GSSI, L’Aquila, Italy

C. Vignoli
INFN LNGS, Assergi (AQ), Italy

R. Benocci, M. Bonesini, A. Falcone, M. Torti
INFN Sez. di Milano Bicocca, Milano, Italy

A. Cocco
INFN Sez. di Napoli, Napoli, Italy
The ICARUS Collaboration - 2

A. Braggiotti, S. Centro, C. Farnese, D. Gibin, A. Guglielmi, G. Meng, F. Pietropaolo, F. Varanini, S. Ventura
INFN Sez. di Padova and University, Padova, Italy

A. Menegolli, C. Montanari, A. Rappoldi, G.L. Raselli, M. Rossella, A. Scaramelli
INFN Sez. di Pavia and University, Pavia, Italy

V. Paolone, H. Su, A. Wickremasinghe
University of Pittsburgh, USA

SLAC National Accelerator Laboratory, Stanford, USA

H. Budd, K.S. MacFarland
University of Rochester, USA

J. Asaadi, A. Chatterjee, J. Yu
University of Texas (Arlington), USA

T. Coan
Southern Methodist University (USA)

O. M. Romagnoli
CINVESTAV-IPN (Mexico)

- **ICARUS Spokesman:** C. Rubbia, GSSI.
- **7 INFN groups, 9 USA institutions, 1 Mexico institution.**
Liquid Argon TPC: an “electronic bubble chamber”

- LAr-TPCs are ideal detectors for neutrino physics and nucleon decay:
  - 3D reconstruction with high (mm$^3$) spatial granularity
  - Homogeneous, full-sampling calorimetry for contained particles
  - Scintillation light can provide fast signals for timing/triggering
  - Electrons can drift for several meters (if Argon is sufficiently pure)
  - LAr is dense and cheap: very large masses (ktons) are realistic

- First proposed by C. Rubbia in 1977: long R&D at INFN and CERN culminated in first large-scale experiment: ICARUS-T600 at LNGS (2010)

- LAr physical parameters very similar to Freon of “classic” bubble chambers:

  **FREON:**
  - Density: 1.5 g/cm$^3$
  - Radiation length: 11.0 cm

  **LIQUID ARGON:**
  - Density: 1.4 g/cm$^3$
  - Radiation length: 14.0 cm
ICARUS-T600 at LNGS

- 2 identical modules: each is 19.6x3.6x3.9 m³, with active mass of 476 t (total 760 t)
- Drift distance 1.5 m and electric field 500 V/cm -> drift time ~ 1 ms
- 3 signal wire planes (2 Induction+Collection) with “non-destructive” wire readout
- Pitch and inter-plane distance both 3 mm; 400 ns sampling time; ~ 54000 total channels
- 74 (20+54) 8” PMTs with TPB wavelength-shifter coating

ICARUS was exposed to CNGS beam and cosmics for 3 years
Run confirmed expected performance and obtained important physics results
It proved the maturity of the LAr-TPC technique for large-scale experiments

ICARUS paved the way to the next generation long-baseline project: DUNE
ICARUS reconstruction performances

- High electron lifetime: > 7 ms (impurity concentration < 40 ppt) over whole run. Crucial step towards future larger detectors
  
  **2014 JINST 9 P12006**

- Excellent spatial/calorimetric reconstruction. Accurate $dE/dx$ measurement with fine sampling (0.02$X_0$). Particle ID from $dE/dx$ vs. range
  
  **AHEP (2013) 260820**

- Momentum of escaping muons measured by multiple Coulomb scattering. Average ~ 15% resolution on stopping muons (0.5÷5 GeV/c)
  
  **JINST 12P04010**
e/\gamma\text{ separation and } \nu_e\text{ identification}

- $\nu_e$ CC event (electron-initiated EM showers) separation from NC background with $\pi^0$ ($\gamma$-initiated showers): crucial for oscillation physics
- LAr-TPC provides 3 handles:
  - Visual identification of $\gamma$ conversion gap
  - Reconstruction of $\pi^0$ invariant mass
  - $dE/dx$: calorimetric accuracy and fine sampling (2% $X_0$) allow measuring $dE/dx$ on each wire: single MIP corresponds to an electron.

**High-energy CNGS $\nu_e$ CC interaction:**

Evolution in Collection view from single m.i.p. to e.m. shower evident from $dE/dx$ (MeV/cm) on individual wires.
ICARUS search for sterile neutrinos

- ICARUS searched for sterile $\nu$ oscillations through $\nu_e$ appearance in the CNGS beam.
- L/E $\sim$ 36 km/GeV, far from LSND value $\sim$ 1 km/GeV. -> “sterile-like” oscillation was averaged out, canceling energy dependence.
- 7.9 $10^{19}$ pots analyzed ($\sim$2650 $\nu$ interactions).
- Expected $\sim$ 8.5±1.1 $\nu_e$ background events in absence of anomaly, mostly from intrinsic $\nu_e$ beam contamination.
- Estimated $\nu_e$ identification efficiency $\sim$74% with negligible background from misidentification.
- 7 events observed $\rightarrow$ no evidence of oscillation.
- Most of LSND allowed region is excluded – except for small area around $\sin^2 2\theta \sim 0.005$, $\Delta m^2 < 1$ eV$^2$.
- Similar result by OPERA with same CNGS beam and different detection technique.

Perspectives for sterile neutrino physics

- The sterile neutrino scenario is far from understood and needs a definitive clarification.
- Some “anomalies” from accelerators (LSND), reactor, neutrino sources, point out to flavour transitions in the $\Delta m^2 \sim 1\text{ eV}^2$ range.
- However, no evidence of oscillations in $\nu_\mu$ disappearance data (MINOS, IceCube).
- Tension between $\nu_e$ appearance and $\nu_\mu$ disappearance results. Measuring both channels with the same experiment will help disentangle.

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

ICARUS T600

FAR DETECTOR: T600 – 476 ton

MicroBooNE 89 ton

NEAR DETECTOR: SBND – 112 ton

L/Eν ~ 600 m / 700 MeV ~ O(1 m/MeV)

T600 also off-axis on NUMI beam: Asset for DUNE

NUMI beam (approximate)

BNB spectrum

ICARUS
The experiment will exploit 3 LAr-TPCs exposed to the FNAL Booster Neutrino Beam, with only ~ 0.5% $\nu_e$ contamination, at different distances from target: SBND, MicroBooNE and ICARUS at 110, 470, and 600 meters respectively.

The experiment is expected to clarify the sterile anomaly by precisely/independently measuring both $\nu_e$ appearance and $\nu_\mu$ disappearance.

Using the same detector technology for all the 3 detectors will greatly reduce the systematic errors: 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.

During SBN operations, ICARUS will also collect ~ 2 GeV neutrinos from NuMI (Neutrino Main Injector) Off-Axis beam. This will be an asset for the future long-baseline project:

- $\nu$ interaction cross-section measurements and identification/reconstruction studies
- In particular, a large $\nu_e$ component with ~ 3 GeV energy (in the DUNE range)
SBN spectra and sensitivities for 3 years ($6.6 \times 10^{20}$ pot)

$\nu_e$ spectra (oscillation signal + backgrounds), Example for $\sin^2 2\theta = 0.013$ $\Delta m^2 = 0.43$ eV$^2$

$\nu_\mu$ spectra (oscillation modulation) for 3 years ($6.6 \times 10^{20}$ pot)
Example for $\sin^2 2\theta = 0.01$ $\Delta m^2 = 1.10$ eV$^2$

In absence of oscillations, spectra should be ~identical

$\nu_e$ appearance: LSND 99% CL region covered at 5 $\sigma$ level
3-5 $\sigma$ $\nu_\mu$ disapp. SBN sensitiv.

In absence of oscillations, spectra should be ~identical
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.
- ~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;
Upgrade of the light collection system

In shallow depth operation, the light collection system will allow to:

- Precisely identify the time of occurrence ($t_0$) of any ionizing event in the TPC
- Determine the event rough topology for selection purposes
- Generate a trigger signal for read-out

ICARUS@SBN exploits 90 PMTs per TPC (5% coverage, 15 phe/MeV) that provides:

- Sensitivity to low energy events (~ 100 MeV)
- Good spatial resolution (≤ 50 cm)
- ≈ ns timing resolution
- Possible cosmics identification by PMT space/time pattern

Timing/gain equalization will be performed with laser pulses

$\lambda = 405$ nm

FWHM < 100 ps

peak power ~ 400 mW
PMT tests at CERN

- All PMTs tested at room temperature in a dedicated dark room at CERN
- A subset of 60 PMTs tested immersed in LAr to compare the PMT performance in cryogenic environment to room temperature
- All PMTs illuminated with laser light pulses

PMTs were characterized individually at 300K and 87K:

- Gain
- Dark count rate
- Peak/valley ratio
- Uniformity of photocathode response

The gain reduction in LAr w.r.t. room temperature (up to a factor 10) will be compensated by a ~ 100 V increase in power supply voltage
Upgrade of the TPC read-out electronics

ICARUS electronics at LNGS was based on:

- “warm” low-noise front-end amplifier
- Multiplexed 10-bit ADC
- Digital VME module for local storage, data compression, trigger information

Performances proved adequate for track reconstruction and muon momentum measurement (Multiple Coulomb Scattering) \((S/N)_{\text{m.i.p.}} \sim 7\) in Collection, resolution \(\sigma_y \sim 0.7\) mm along drift

However, in view of the SBN program, some components were modernized and improved:

- Serial 12-bit ADC, fully synchronous in the whole detector
  \(\rightarrow \sim 20\%\) improvement in muon momentum resolution via MCS
- Serial bus architecture increases transmission rate to Gbit/s
- More compact layout: both analog+digital electronics hosted on a single flange

New electronics extensively tested on a 50-liter TPC@CERN

\textit{JINST 13 (2018) P12007}
The analog front-end shaping was also modified:

- Lower noise ~ 1200 e- equivalent (~20% S/N improvement w.r.t. LNGS electronics)
- Shorter shaping time (~ 1.5 µs for all planes) matching electron transit time between planes
- Drastic reduction of undershoot after large signals: better description of crowded vertex region

**Tests on 50-liter TPC at CERN:**

In particular, Induction 2 signal keeps bipolar shape (unlike in old front-end):

- Possible off-line integration with suitable LF filtering
- Allows calorimetric measurement in this plane too (with ~2 worse resolution than Collection)
- May improve νe identification efficiency by ~20%
ICARUS installation at FNAL - status

- T600 installed inside warm vessel in August 2018
- Installation of TPC/PMT feedthrough flanges and connectivity tests, completed by February 2019
- Leak tightness tests completed
- Top cold shields and top CRT support installed

Feed-throughs installed on top

- PMT electronics and trigger being tested at cryogenic temperatures at CERN
- Installation of proximity cryogenics started in February
- Side CRT installation also ongoing
- Director’s Review in December 2018 recognized the great progress of SBN
ICARUS installation @FNAL

**Placement of ICARUS**
(August 2018)

**Chimneys installation**
(October 2018)

**Feedthrough installation**
(December 2018)

**Readout electronics**

**Power supply**

**Installing the readout electronics**
(May 2019)
Recent tests on the readout electronics

- All the feedthrough flanges and the mini-crates with the TPC wire read-out electronics (576 channels + optical links) has been installed
- A test of the full readout chain, from wires to DAQ, has been performed in April/May for all the mini-crates
  - Allowed to check readout and set baseline for future noise monitoring
  - Noise measured on random triggers and test pulses
  - Noise RMS ~1700 e-, not too far from ~1200 e- measured in CERN 50-liter setup: grounding conditions were still far from optimal

The successful readout test confirms the good performance of the full TPC electronics!
The Cosmic Ray Tagging system (CRT)

- Surrounds the cryostat with two layers of plastic scintillators: 1100 m²
- 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

**TOP:**
~ 400 m²: roof+angled parts
Will catch ~80% cosmic muons
2 strip layers (X+Y)
SiPM readout

**SIDES:**
~ 500 m² on four sides
Old MINOS veto modules
parallel strips
SiPM readout

**BOTTOM:**
~ 200 m², already installed
D-Chooz veto modules
2 parallel layers
PMT readout
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.

- ICARUS joined the LArSoft framework: mutual sharing of algorithms and tools and cross-check between different reconstruction approaches.

- Full simulation performed with realistic geometry and signals from all sub-detectors (TPC,PMT,CRT).

\[
\theta = 2^\circ, \quad \theta = 6^\circ
\]

angle between sim/reco direction for EM showers.

\[
\begin{array}{|c|c|c|}
\hline
\text{Entries} & 8897 \\
\text{Mean} & 0.05012 \\
\text{RMS} & 0.03964 \\
\text{Integral} & 8275 \\
\hline
\end{array}
\]

Electron lifetime (reco vs. sim)
ICARUS at LNGS was also exposed to atmospheric neutrinos (exposure ~0.74 kt year) for the first observation of atmospherics with a LAr-TPC.

14 events were found (8 $\nu_e$ CC + 6 $\nu_\mu$ CC) vs. 18 expected (taking into account triggering, filtering, and scanning efficiencies).

Very good benchmark for the forthcoming SBN experiment: similar energy/features. Useful to develop filtering and reconstruction tools.

- **Very alike to typical atmospheric $\nu_e$CC events @ LNGS**
  - Similar results hold for $\nu_\mu$CC interactions

**MC SBN $\nu_e$CC interactions**
- $\nu_e$CC
- $E_\nu$ = 1.26 GeV
- $E_{dep}$ = 1.2 GeV

**LNGS $\nu_e$ atmospheric event**
- Quasi-elastic $\nu_e$CC
  - $E_{dep}$ = 0.9 GeV.
- Proton identified by dE/dx.
- Electron identified by single m.i.p. before showering.
ICARUS at FNAL – plans and commissioning

- TPC/trigger electronics installation to be completed and tested by spring 2019
- PMT electronics installation also to be completed during the spring
- ICARUS expected to be ready to fill by August
- After cryogenics commissioning, cool down and filling, ICARUS T600 should be operational in the last quarter of 2019
- Commissioning of CRT, DAQ, trigger and slow controls will follow
- Data-taking for physics is expected by the end of this year
Conclusions

- The ICARUS-T600 successful 3-year run at LNGS proved that LAr-TPC technology is mature and ready for large-scale neutrino physics experiments.

- ICARUS searched for LSND-like anomaly via $\nu_e$ appearance in the CNGS beam. The negative result constrained significantly the allowed parameter region.

- 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, ICARUS is being installed as the SBN far detector at FNAL. Data taking expected in 2019, near detector in 2021.

- ICARUS will see first neutrinos by the end of this year!
Thank you