ICARUS status and near future

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On Behalf of the
ICARUS Collaboration

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The ICARUS Collaboration


+ new WA104 members:


1CERN, Geneve, Switzerland
2Department of Physics, Catania University and INFN, Catania, Italy
3Department of Physics, Pavia University and INFN, Pavia, Italy
4Department of Physics and Astronomy, Padova University and INFN, Padova, Italy
5GSSI, Gran Sasso Science Institute, L’Aquila, Italy
6Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Science, Kraków, Poland
7INFN LNF, Frascati (Roma), Italy
8INFN LNGS, Assergi (AQ), Italy
9INFN Milano Bicocca, Milano, Italy
10Politecnico and INFN Milano, Milano, Italy
11INFN Napoli, Napoli, Italy
12Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
13Institute for Radioelectronics, Warsaw University of Technology, Warsaw, Poland
14Institute of Physics, University of Silesia, Katowice, Poland
15Institute of Theoretical Physics, Wroclaw University, Wroclaw, Poland
16National Centre for Nuclear Research, Warsaw, Poland
17Department of Physics, UCLA, Los Angeles, California, USA
18National Centre for Nuclear Research, Otwock, Swierk, Poland
19University of Pisa and INFN, Pisa, Italy

+ ICAR-US: 6 new US groups:
Colorado Univ., Pittsburgh Univ., SLAC, FNAL, Argonne, Los Alamos

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Anomalies in the neutrino sector

- Neutrino oscillations established a coherent picture with mixing of 3 physical $\nu_e, \nu_\mu, \nu_\tau$ with small mass differences $\Delta m_{31}^2 \sim 2.4 \times 10^{-3} \text{eV}^2$, $\Delta m_{21}^2 \sim 8 \times 10^{-5} \text{eV}^2$ and relatively large mixing angles, $\sin^2 2\theta_{13} \sim 10^{-1}$; but mass hierarchy, $\delta_{CP}$, $\nu$ mass values, Dirac/Majorana $\nu$?
- There are however a number of "anomalies" which, if confirmed experimentally, could hint at (at least) an additional 4th neutrino, with non-standard oscillations at small distances with $\Delta m_{\text{new}}^2 \sim 1 \text{eV}^2$, small $\sin^2 2\theta_{\text{new}}$:
  1. Observation of $\nu_\mu \rightarrow \nu_e$ excess signals from LSND, MiniBooNE at accelerators (LSND effect: $3.8\sigma$)
  2. Signal in anti-$\nu_e$ events detected from near-by nuclear reactors where the observed to predicted event rate is $R = 0.938 \pm 0.023$ and (3) from Mega-Curie $k$-capture calibration sources in solar $\nu_e$ experiments with $R = 0.86 \pm 0.05$;
- According to Planck measurement, Big Bang cosmology, at most one sterile $\nu$ is expected, $m < 0.4$ eV.
Evolution of LAr-TPC detectors

- Cherenkov detectors in water/ice and liquid scintillator detectors have been main technologies so far for neutrino and rare event physics. Unfortunately these detectors do not permit to identify unambiguously each ionizing track.

- As an alternative, the Liquid Argon Imaging technology (LAr-TPC), effectively an electronic bubble-chamber, was originally proposed by C. Rubbia in 1977 [CERN-EP/77-08], supported by Italian Institute for Nuclear Research (INFN).

- Thanks to ICARUS collaboration, LAr-TPC has been taken to full maturity with the T600 detector (0.6 kton) receiving CNGS neutrino beam and cosmic rays.

- ICARUS concluded in 2013 a very successful 3 years long run at LNGS, collecting $8.6 \times 10^{19}$ pot event with a detector live time $> 93\%$, recording $\sim 3000$ CNGS neutrinos (in agreement with expectations) and cosmic rays (0.73 kty).
Two identical modules

- 3.6x3.9x19.6 ~275 m$^3$ each
- LAr active mass: 476 t
- Drift length: 1.5 m (1 ms)
- $E=0.5$ kV/cm, $v_{\text{drift}} \sim 1.5$ mm/$\mu$s
- Sampling time 0.4$\mu$s (sub-mm resolution in drift direction)

Four wire chambers: 2 chambers/ module

- 2 Induction + 1 Collection readout wire planes per chamber; ~54000 wires, 3 mm pitch and plane spacing, oriented at $0^\circ, \pm 60^\circ$;
- Charge measurement on last Collection plane
- 20+54 8” PMTs for scintillation light detection:
  - VUV sensitive (128nm) with TPB wave shifter
The key features of LAr imaging: very long e-mobility

- Level of electronegative impurities in LAr must be kept exceptionally low to ensure ~m long drift path of ionization e− with very small attenuation.
- New industrial purification methods developed to continuously filter and re-circulate both in liquid (100 m³/day) and gas (2.5 volumes/hour) phases.
- Electron lifetime measured during ICARUS run at LNGS with cosmic μ’s: \( \tau_{\text{ele}} > 7 \text{ ms (} \sim 40 \text{ p.p.t. } [O_2] \text{ eq) } \rightarrow 12\% \text{ max. charge attenuation.} \)
- New pump installed on East cryostat since April 4th, 2013: \( \tau_{\text{ele}} > 15 \text{ ms (} \sim 20 \text{ p.p.t.)} \)

**ICARUS demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors ~5 m drift as required for LBNF/DUNE project**
ICARUS LAr-TPC performance

- **Tracking device:** precise ~mm$^3$ resolution, 3D event topology, accurate ionization measurement;
- **Global calorimeter:** total energy reconstruction by charge integration - excellent accuracy for contained events; momentum of non contained $\mu$ determined via Multiple Coulomb Scattering $\Delta p/p \sim 15\%$ in 0.4-4 GeV/c range;
- **Measurement of local energy deposition $dE/dx$:** remarkable $e/\gamma$ separation (0.02 $X_0$ sampling, $X_0=14$ cm; particle identification by $dE/dx$ vs range);
  - **Low energy electrons:**
    $\sigma(E)/E = 11\%/\sqrt{E(\text{MeV})} + 2\%$
  - **Electromagnetic showers:**
    $\sigma(E)/E = 3\%/\sqrt{E(\text{GeV})}$
  - **Hadron shower (pure LAr):**
    $\sigma(E)/E \approx 30\%/\sqrt{E(\text{GeV})}$

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- **dE/dx (MeV/cm) vs. residual range (cm) for protons, $\pi, \mu$** compared to Bethe-Bloch curves
- **dE/dx distribution for real and MC muon tracks from CNGS events**
Multiple Coulomb Scattering (MCS) is the only way to measure momentum of non-contained muons.

Algorithm validated on ~400 stopping muons: produced in $\nu_\mu$ CC interactions of CNGS neutrinos upstream of T600, and stopping/decaying inside the detector.

Stopping muons are an ideal subsample for validating MCS algorithm:
- Independent momentum measurement from calorimetry
- Momentum spectrum in a region of interest for future SB/LB neutrino experiments

Last meter of muon tracks not used for MCS measurement, in order to emulate case of escaping muons.
Muon momentum measurement algorithm

- Algorithm based on evaluation of $\theta_{\text{RMS}}$: average RMS of deflection angles (in Collection view), compared with expectations for a given $p$ (assuming Gaussian approximation of MCS)

- Three crucial ingredients:
  - Preliminary track cleaning, to avoid non-Gaussian tails (mainly $\delta$-rays)
  - Precise track-to-track estimation of measurement errors (essentially on drift coordinate $y$)
  - Track segmentation, optimized to enhance MCS contribution while reducing statistically the effect of errors

\[
\theta_{\text{RMS}} \div \frac{13.6\text{MeV}}{p} \sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}
\]

$\sigma_y \sim 0.7\text{ mm}$
Muon momentum measurement results

- Good agreement between MCS and calorimetric measurements
- Average resolution of ~15% on the stopping muon sample
- Resolution depends both on momentum and effective muon track length used for measurement

Some deviations for $p > 3.5 \text{ GeV}/c$ induced by non-perfect planarity of TPC cathode
Search for atmospheric $\nu$'s

- **Preparatory step:** automatic 3D reco of cosmic $\mu$'s
- **An algorithm** for filtering of interaction vertex and multi-prong event topology has been developed, complemented by visual scanning;
- **Work in progress:** 2 muon-like and 2 NC-like atmosphere $\nu$ candidates have been identified in 3 week data recording ($1\pm0.4\ \mu CC$, $1\pm0.4\ eCC$ and $0.4\pm0.2$ NC expected)

**Induction 2**

- **Collection**

**NC atm. candidate:** $E_{\text{DEP}} \sim 200\ MeV$
- 2 charged particles emerge from interaction vertex
- $\pi$ track: 63 cm (interacting and generating 2 protons)

**ν$\mu$ CC atm. candidate:** $E_{\text{DEP}} \sim 350\ MeV$
- $\mu$ and $p/\pi$ tracks are visible
- $\mu$ track candidate: 124 cm

~200 atm. $\nu$ expected for $0.73\ kt\ y$ exposure

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e/γ separation and π^0 reconstruction in ICARUS

\[ \pi^0 \] reconstruction:

\[ p\pi^0 = 912 \pm 26 \text{ MeV/c} \]
\[ m_{\pi^0} = 127 \pm 19 \text{ MeV/c}^2 \]
\[ \theta = 28.0 \pm 2.5^\circ \]

\[ E_k = 102 \pm 10 \text{ MeV} \]
\[ E_k = 685 \pm 25 \text{ MeV} \]

**Unique feature of LAr to distinguish e from γ and reconstruct π^0**

→ Negligible background from π^0 in NC and ν\_µ CC estimated from MC/scanning
\( \nu_e \) identification in ICARUS LAr-TPC

- The unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.

- The evolution of the actual \( dE/dx \) from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.
Search for LSND-like anomaly by ICARUS at LNGS

- ICARUS searched for $\nu_e$ excess related to LSND-like anomaly on the CNGS $\nu$ beam ($\sim 1\%$ intrinsic $\nu_e$ contamination, L/E$_{\nu}$ ~36.5 m/MeV)
- Analysis on $7.23 \times 10^{19}$ pot event sample provided the limit on the oscillation probability $P(\nu_{\mu} \rightarrow \nu_e) \leq 3.85 \ (7.60) \times 10^{-3}$ at 90 (99) % C.L.
- ICARUS result indicates a very narrow region of parameter space, $\Delta m^2 \sim 0.5 \text{ eV}^2$, $\sin^2 2\theta \sim 0.005$ where all experimental results can be accommodated at 90% CL

The result call for a definitive experiment on sterile neutrino to clarify all the reported neutrino anomalies
SBN experiment: 3 LAr-TPCs at FNAL
Booster beam ($E_\nu \sim 0.8$ GeV) for a definitive answer to sterile neutrino puzzle
SBN Sterile neutrino search at FNAL Booster $\nu$ beamline

- Joint ICARUS/SBND/MicroBooNE CDR received *Stage 1 Approval from FNAL PAC Jan 2015*. Three LAr-TPC’s at different distances from target: SBND (82 t active mass), MicroBooNE (89 t) and ICARUS (476 t) at 100, 470 and 600 m

- The experiment will likely clarify LSND/MiniBooNE, Gallex, reactor anomalies by precisely/independently measuring both $\nu_e$ appearance and $\nu_\mu$ disappearance, mutually related through

$$\sin^2(2\vartheta_{\mu e}) \leq \frac{1}{4}\sin^2(2\vartheta_{\mu x})\sin^2(2\vartheta_{ex})$$

- In absence of “anomalies”, 3 detector signals should be a close copy of each other for all experimental signatures. Intrinsic $\nu_e$ with a disappearance signal (if f.i. confirmed by reactors) may result in a reduction of a superimposed LSND $\nu_e$ signal: effects can be disentangled by changing intrinsic $\nu_e$ beam with different beam optics (horn/ decay tunnel length).

- During its SBN operations, ICARUS will collect also $\sim 2$ GeV $\nu_e$CC events with NUMI Off-Axis beam, an asset for the long baseline LAr project at FNAL.
  - accurate determination of cross sections in LAr;
  - experimental study of all individual CC/NC channels to realize algorithms to improve the identification of neutrino interactions.
\[ \nu_\mu \rightarrow \nu_e \] appearance sensitivity

- Expected exposure sensitivity of \( \nu_\mu \rightarrow \nu_e \) oscillations for 3 years - \(6.6 \times 10^{20}\) pot BNB positive focusing (6 years for MicroBooNE).

Example for
\[ (\sin^2(2\theta) = 0.013 \quad \Delta m^2 = 0.43 \text{ eV}^2) \]

In absence of oscillations, the spectra should be copies of each other.

The LSND 99\% CL region is covered at \(\sim5\sigma\) level.
- High event rates/correlations between 3 LAr-TPC’s will allow extending sensitivity by one order of magnitude beyond present limit.

- However for $\Delta m^2 < 0.5 \text{ eV}^2$
  $\nu_\mu$ disappearance at 600 m will be limited at lowest $\nu$ energy bins (0.2-0.4 GeV).

- In order to amplify the effect we may move at a later stage one ICARUS T300 module to 1500 m distance.
Facing a new situation: the LAr-TPC near the surface

- At shallow depth ~12 uncorrelated cosmic rays will occur in T600 during 1 ms drift window readout at each triggering event.
- This represents a new problem compared to underground operation at LNGS: the reconstruction of the true position of each track requires precisely associating to each element of TPC image the occurrence time with respect to trigger time.

Moreover, $\gamma$'s associated with cosmic $\mu$'s represent a serious background for the $\nu_e$ appearance search since electrons generated in LAr via Compton scattering/ pair production can mimic a $\nu_e$ CC genuine signal.

- A $4\pi$ Cosmic Rays Tagger (total surface ~ 1200 m$^2$) of plastic scintillators around the LAr active volume will unambiguously identify all cosmic ray particles entering the detector providing timing/position to be combined with the TPC reconstructed image.
WA104 Project at CERN: overhauling of the T600

- INFN has signed a MoU for **WA104 project at CERN** for T600 overhauling in the framework of CERN Neutrino Platform for LAr-TPC development for short/long baseline neutrino experiment

- T600 is being upgraded introducing technology developments **while maintaining the already achieved performance**:
  - new cold vessels, with a purely passive insulation;
  - refurbishing of cryogenics / purification equipment;
  - a cathode with better planarity;
  - upgrade of the light collection system;
  - new faster, higher-performance read-out electronics.

- **Common items for ICARUS and other SBN LAr-TPCs**: muon tagging systems to be designed/constructed; tools for event reconstruction have to be developed

*The detector is expected to be transferred to FNAL before end 2016 for installation, commissioning and start of data taking (end 2017).*
**Upgrade of the light collection system**

- **Main requirements for the refurbished light detection system:**
  - High detection coverage, to be sensitive to low $E_\nu$ deposition (~100 MeV)
  - High detection granularity, to localize events and unambiguously associate the collected light to deposited charge;
  - Fast response - high time resolution, to be sensitive to timing of each event in the T600 DAQ windows (~1 ms); a ~1 ns precision is advisable to exploit the 2ns/19ns bunched beam structure.

- The present T600 light detection system can be extended to 90 PMT per TPC, (5% area coverage). ~15 phe/MeV allowing to efficiently trigger LE events.

- Neural Networks can provide a clear cosmic muon identification (~2% wrong ID)
Exposed in Hall B of the Gran Sasso underground Lab. to CNGS neutrino beam from CERN, the ICARUS T600 neutrino experiment with 760 ton of highly purified LAr has successfully completed a three years physics program at LNGS. Together with all previous test beam runs, this allowed the definitive assessment of detection capabilities of LAr-TPC technology.

The T600 detector has now been moved to CERN for a significant overhauling in view of the SBN neutrino experiment on the FNAL Booster and NUMI beams based on three detectors at different baselines (near: SBND, mid: MicroBooNE, far: ICARUS).

The experiment is expected to start data taking by end 2017 aiming to the definitive clarification of the LSND signal in terms of $\nu$ oscillations ($\nu_e$ appearance). It will also provide a significant amount of data in the energy range of interest for the next Long Baseline experiment.

A second phase is also under consideration with a fourth LAr detector at a longer distance ($\geq 1500$ m) extending the sterile $\nu$ search to lower $\Delta m^2$ as indicated by cosmology ($\nu_\mu$ disappearance).
Neutrino masses and oscillations represent today a main experimental evidence of physics beyond SM. Being the only elementary fermions whose basic properties are still largely unknown, $\nu$s are naturally one of the main priorities to complete our knowledge of SM.

The incredible smallness of $\nu$ masses compared to other elementary fermions points to some specific scenario awaiting to be elucidated.

$\nu$s: the most abundant massive particles in the Universe: $336 \, \text{v/cm}^3$
ICARUS-T600 @ LNGS Hall B: 0.77 kton LAr-TPC

- N2 Phase separator
- 30 m³ Vessels for LN2 cooling circuit
- N2 liquefiers: 12 units, 48 kW total cryo-power
- 54000 electronic ch, low noise charge amplifiers + digitizers, S/N > 10
- LAr purification systems
- GAr purification systems
ICARUS: summary of collected data with CNGS

- A total sample of 2650 $\nu$ interactions corresponding to $7.93 \times 10^{19}$ over $8.6 \times 10^{19}$ pot collected has been filtered, scanned & preliminarily analyzed.
- Distributions of collected neutrinos and of beam related $\mu$s normalized by $10^{17}$pot statistics and DAQ efficiency: 3.4 vs 12 $\mu$s events on average.

Data are consistent within 6% with MC predictions for corresponding exposure.
● Main requirements for the refurbished light detection system:
  Ø High detection coverage, to be sensitive to low $E\nu$ deposition in the TPC (~ 100 MeV) and to reject $^{39}$Ar background;
  Ø High detection granularity, to localize events/ unambiguously associate the collected light to deposited charge;
  Ø Fast response - high time resolution, to be sensitive to time and evolution of each event in the T600 DAQ windows (~ 1.5 ms); a ~1 ns precision is advisable to exploit the available 2ns/19 ns bunched beam structure.

● The present T600 light detection system can be easily extended with additional 8” PMTs with TPB wavelength shifter, up to 90 devices per TPC.

● The photo-cathode coverage corresponds to 5% of the wire plane area. ~ 15 (11) phe/MeV are collected at 1.5 (3) m drift allowing to trigger low energy events with fairly high threshold and PMT multiplicity.
An upgraded electronics

- Architecture of ICARUS electronics is based on analogue low noise “warm” front-end amplifier, a multiplexed 10-bit 2.5 MHz AD converter and a digital VME module for local storage, data compression & trigger.
- A signal to noise ratio > 10 and ~ 0.7 mm single point resolution were obtained in LNGS run, resulting in precise spatial event reconstruction and muon momentum by multiple scattering.
- Some limitations: asynchronous sampling of channels within 400 ns sampling-time slightly affecting MCS measurement, data throughput mainly due to VME.
- Some relevant ongoing changes/improvements:
  - Serial ADCs (10-12 bits, one per channel) in place of the multiplexed ones;
  - Synchronous sampling of all channels (400 ns sampling time) of whole detector;
  - Digital part contained in a single, high performance FPGA per board, that handles signal filtering, organizes information provided by the serial ADCs;
  - Housing/ integration of electronics onto detector; serial bus with optical links for faster transmission.

From 595 to 10 liters