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The ICARUS Collaboration

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* Spokesperson
• Liquid Argon TPC detection technique.
• ICARUS T600 detector performance and results.
  • CNGS events analysis
  • atmospheric neutrino candidates selection
  • sterile neutrino anomaly investigation
• Detector perspective: SNB programme at FNAL.
• Present: detector overhauling at CERN (WA104).
• Conclusions
LAr-TPC detection technique

- 2D projection for each of 3 wire planes per TPC
- 3D spatial reconstruction from stereoscopic 2D projections
- charge measurement from Collection plane signals
- Absolute drift time from scintillation light collection

CNGS νμ charge current interaction, one of TPC's shown
Four identical LAr-TPCs, successfully exposed to CNGS beam from Oct. 1st 2010 to Dec. 3rd 2012. In 2013 operation without CNGS beam. A total of $8.6 \times 10^{19}$ protons on target has been collected, with a remarkable detector live time $>93\%$.

In parallel cosmics have been studied with exposure of 0.73 kton year.

Key feature: LAr purity from electro-negative molecules (O2, H2O, CO2) to prolongate electron lifetime.

$\tau_e > 7\ ms$ ($\sim 40\ p.p.t.\ [O2]\ eq$),

$\tau_e > 15\ ms$ ($\sim 20\ p.p.t.$).
Energy reconstruction from charge integration

- Full sampling, homogeneous calorimeter with excellent accuracy for contained events

Tracking device

- Precise 3D topology and accurate ionization
- Muon momentum via multiple scattering

Measurement of local energy deposition $dE/dx$

- $e/\gamma$ remarkable separation ($0.02X_0 = 14\text{ cm samples}$)
- Particle identification by $dE/dx$ vs range

Energy resolution:

- Low energy electrons:
  \[ \sigma(E)/E = 11%/\sqrt{E}\text{ (MeV)} + 2\% \]
- E-M showers:
  \[ \sigma(E)/E = 3%/\sqrt{E}\text{ (GeV)} \]
- Hadronic showers:
  \[ \sigma(E)/E \approx 30%/\sqrt{E}\text{ (GeV)} \]
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.

The unique detection properties of LAr-TPC technique allow to identify unambiguously individual $e$-events with high efficiency.
Data collected in LNGS are being filtered by an automatic algorithm looking for interaction vertex and multi-prong event topology to select candidates for atmospheric neutrino interactions. The second filter looks particularly for E-M cascades in a search for electron like events.

Candidate events undergo additional visual scanning (~5% of total data sample)

6 $\mu$-like, and 4 e-like events within a sample of 24 observed atm. $\nu$ candidates have been identified so far in 49% of collected statistics (17±2 multi-prong $\nu$CC events are expected)

$\nu_\mu$ CC atm. candidate:

$E_{\text{dep}} \sim 630$ MeV

2.3 m muon track and 2 charged particle tracks leaving the neutrino interaction vertex
The first observed “LAr TPC” atmospheric \( \nu_e \) CC event

Deposited energy: \( \sim 2.1 \text{ GeV} \):

- E.m. shower (\( \sim 2 \text{ GeV} \)): clear single m.i.p from vertex;
- Identified short proton track (\( \sim 0.1 \text{ GeV} \)).

Automatic search for \( \nu_e \) CC with \( E_{\text{dep}} \) of the order of several GeV is feasible.
Downward-going, quasi-elastic event, deposited energy: \( \sim 240 \text{ MeV} \)

- \( \frac{dE}{dx} \) measured on the first wires (2.1 MeV/cm) corresponds to a m.i.p. particle
- One short proton track.

**ICARUS LAr TPC:** unambiguous identification and measurement capability of \( \nu_e \) interactions down to sub GeV energy range.
ICARUS searched for $\nu_e$ excess related to LSND-like anomaly on the CNGS beam (~1% intrinsic $\nu_e$ contamination, L/E$_{\nu} \sim 36$ km/GeV).

No excess was observed in $7.93 \times 10^{19}$ pot sample: $7\nu_e$ was observed, $8.5 \pm 1.1$ events was expected in absence of the LSND signal.

The estimated limit on the oscillation probability is: $P(\nu_\mu \rightarrow \nu_e) \leq 3.86 \ (7.76) \times 10^{-3}$ at 90 (99) % C.L.

including ICARUS results a very small region of sterile mixing parameters is still available at:

$\Delta m^2 \sim 0.5 \text{ eV}^2$, $\sin^2 2\theta \sim 0.005$

where all experimental results can be be accommodated at 90% CL.

There is a need for a definitive experiment on sterile neutrinos to clarify observed neutrino anomalies. => SBN at Fermilab.
The SBN Collaborations – Institutions (July 2016)

**ICARUS**
- Argonne National Lab, USA
- Brookhaven National Lab, USA
- CERN, Switzerland
- Colorado State University, USA
- Fermi National Lab, USA
- INFN and University, Catania, Italy
- INFN GSSI, L’Aquila, Italy
- INFN LNGS, Assergi (AQ), Italy
- INFN Sez. di Milano Bicocca, Milano, Italy
- INFN Sez. di Napoli, Napoli, Italy
- INFN and University, Padova, Italy
- INFN and University, Pavia, Italy
- H. Niewodniczanski Inst. of Nucl. Phys., Polish Acad. of Science, Krakow, Poland
- Institute for Nuclear Research (INR), Institute of Physics, University of Silesia, Katowice, Poland
- Inst. for Radio-Electronics, University of Technology, Warsaw, Poland
- Los Alamos National Lab, USA
- Nat. Centre for Nucl. Research, Warsaw, Poland
- University of Pittsburgh, USA
- Russian Academy of Science, Moscow, Russia
- SLAC, USA
- Texas University at Arlington, USA

**MicroBooNE**
- University of Bern, Switzerland
- Brookhaven National Lab, USA
- University of Cambridge, UK
- University of Chicago, USA
- University of Cincinnati, USA
- Columbia University, USA
- Fermi National Lab, USA
- Illinois Institute of Technology, USA
- Kansas State University, USA
- Lancaster University, UK
- Los Alamos National Lab, USA
- University of Manchester, UK
- MIT, USA
- University of Michigan, USA
- New Mexico State University, USA
- Oregon State University, USA
- Otterbein University, USA
- University of Oxford, UK
- University of Pittsburgh, USA
- Pacific Northwest Nat. Laboratory, USA
- Princeton University, USA
- Saint Mary’s University of Minnesota, USA
- SLAC, USA
- Syracuse University, USA
- University of Texas at Arlington, USA
- Tübitak Space Tech. Research Inst., Turkey
- Virginia Tech, USA
- Yale University, USA

**SBND**
- Argonne National Lab, USA
- University of Bern, Switzerland
- Brookhaven National Lab, USA
- University of Cambridge, UK
- University of Campinas – UNICAMP, Brazil
- CERN, Switzerland
- University of Chicago, USA
- Columbia University, USA
- Federal Univ. of ABC – UFABC, Brazil
- Federal Univ. of Alfenas – UFAL, Brazil
- Fermi National Laboratory, USA
- Illinois Institute of Technology, USA
- Indiana University, USA
- Kansas State University, USA
- Lancaster University, UK
- University of Liverpool, UK
- Los Alamos National Lab, USA
- University of Manchester, UK
- University of Michigan, USA
- MIT, USA
- University of Oxford, UK
- Pacific Northwest National Lab, USA
- University of Pennsylvania, USA
- University of Puerto Rico
- University of Sheffield, UK
- Syracuse University, USA
- University of Texas, Arlington, USA
- University College London, UK
- Virginia Tech, USA
- Yale University, USA

27 US + 26 non-US Institutions
Short Baseline Neutrino Program at Fermilab

\[ \frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \approx \frac{600 \text{ m}}{700 \text{ MeV}} \sim \mathcal{O}(1 \text{ km/GeV}) \]

![Diagram showing various detectors and distances](image-url)

- Far Detector: ICARUS 476 t
- Near Detector: MiniBooNE 89 t
- Near Detector: MicroBooNE 89 t
- Near Detector: SBND 82 t

TARGET: 0.89 GeV BNB
The experiment will exploit 3 LAr-TPCs exposed to ~ 0.8 GeV FNAL Booster Neutrino Beam (BNB): SBND (82 t active mass), MicroBooNE (89 t) and ICARUS (476 t).

The SBN programme is expected to definitely clarify LSND/MiniBooNE, by independently measuring both $\nu_e$ appearance and $\nu_\mu$ disappearance channels.

Additionally ICARUS will be exposed to ~2 GeV neutrinos from NUMI off-axis beam. It can help to measure cross sections in LAr, and study CC/NC channels to improve neutrino identification algorithms. An asset for DUNE-LBNF project.
The LSND 99%CL region will be covered at $\sim 5\sigma$ level after 3 years of data taking ($6.6 \times 10^{20}$ pot) with positive focusing of BNB.

Example for

$\sin^2(2\theta)=0.013$

$\Delta m^2=0.43 \text{ eV}^2$
Facing a new situation: the LAr-TPC on the surface

- At shallow depth ~12 uncorrelated cosmic rays, depositing > 100 MeV, will occur in T600 fiducial volume, during 1 ms drift window readout: reconstructing track positions along the drift requires to associate to each element of TPC image the proper timing w.r.t. trigger.

- 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 large 4\( \pi \) Cosmic Rays Tagger of plastic scintillators surrounding the LAr volume, combined with timing information from internal scintillation light detectors, will unambiguously identify all cosmics entering the detector.

**Automatic tools to select, identify and reconstruct \( \nu \) events among the millions of events triggered by cosmics are mandatory.**
T600 overhauling at CERN (WA104)

- T600 detector has been moved to CERN for overhauling in the framework of CERN Neutrino Platform for LAr-TPC development for short/long baseline neutrino experiments (WA104 project).

- The activities are progressing, introducing technology developments:
  - Improvement of the cathode planarity;
  - New cold vessels with a purely passive insulation
  - Renovated cryogenics/LAr purification equipment;
  - Upgrade of the light collection system: 160 8” PMTs behind the wire planes (~5% photo-cathode coverage) to localise precisely the collected events in ~1.5 ms window;
  - New faster, higher performance read-out electronics.
SBN Programme Timeline

● **MicroBooNE:**
  ➢ Currently running - addressing the MiniBooNE anomaly.

● **ICARUS:**
  ➢ Overhauling of T600 is almost completed at CERN;
  ➢ Civil construction of far sites and buildings are progressing at FNAL;
  ➢ Installation and commissioning at FNAL in 2017, then start $\nu$ data taking.

● **SBND:**
  ➢ Begin of TPC assembly at FNAL in 2017, install into cryostat in 2018;
  ➢ Civil construction of near sites and buildings is also progressing;
  ➢ Begin commissioning in 2018.
Conclusions

- ICARUS is the largest, so far, LAr TPC. During 3 years of continuous and safe underground operation at LNGS, ICARUS collected high quality data resulting in new constrains on sterile neutrino searches. It also demonstrated capabilities of this detection technique.

- However, 50 years after their introduction by B. Pontecorvo, sterile neutrinos are still an open question in particle physics.

- After 20 years the LSND anomaly, suggesting sterile neutrino existence at ~eV scale is still surviving direct experimental tests.

- The SBN program at FNAL with three LAr-TPC detectors (SBND, MicroBooNE and ICARUS-T600) exposed to booster neutrino beam should sort out definitively the „sterile neutrino puzzle“. 

- Overhauling of the ICARUS T600 detector, towards SBN program, within the CERN/INFN ICARUS/WA104 project is progressing at CERN.
Thank you!

The Polish groups acknowledge the support of the National Science Center: Harmonia (DEC-2012/04/M/ST2/00775)
ICARUS: $e/\gamma$ separation and $\pi^0$ reconstruction

**LAr TPC:** very good $e/\gamma$ separation - important for rejection of NC background to $\nu_e$ events

**$\pi^0$ reconstruction:**
- $p_{\pi^0} = 912 \pm 26$ MeV/c
- $m_{\pi^0} = 127 \pm 19$ MeV/c$^2$
- $\theta = 28.0 \pm 2.5^\circ$

$E_k = 102 \pm 10$ MeV

$m_{\gamma\gamma} = 133.8 \pm 4.4$(stat)$\pm 4$(syst) MeV/c$^2$

**Neutral pion mass**

<table>
<thead>
<tr>
<th>Entries</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$133.8 \pm 4.43$</td>
</tr>
<tr>
<td>RMS</td>
<td>$20.81 \pm 3.137$</td>
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<tr>
<td>$\chi^2$/ndf</td>
<td>8.54/47</td>
</tr>
<tr>
<td>Constant</td>
<td>$1.713 \pm 0.447$</td>
</tr>
<tr>
<td>Mean</td>
<td>$133.8 \pm 4.4$</td>
</tr>
<tr>
<td>Sigma</td>
<td>$20.5 \pm 3.1$</td>
</tr>
</tbody>
</table>

$dE/dx [\text{MeV/cm}]$

**Conversion distances**
- 6.9 cm, 2.3 cm

**$\pi^0$ recontruction:**
- $E_k = 685 \pm 25$ MeV
SBN $\nu_\mu$ disappearance sensitivity

- High event rate and the correlation between all 3 LAr-TPCs allows extending sensitivity by **one order of magnitude** beyond present limits.

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

- To amplify the effect, one T300 module of ICARUS may be moved, at a later stage, to 1.5 km distance from the target.
T600 detector has been moved to CERN for overhauling in the framework of CERN Neutrino Platform for LAr-TPC development for short/long baseline neutrino experiments (WA104 project).

The activities are progressing, introducing technology developments while maintaining the already achieved performance:

- New cold vessels, with a purely passive insulation;
- Improvement of the cathode planarity;
- Renovated cryogenics/LAr purification equipment;
- Upgrade of the light collection system: 360 8'' PMTs behind the wire planes (~5% photo-cathode coverage) to localize precisely the collected events in ~ 1.5 ms window; a fast response - high time resolution, ~1 ns precision, is required for the rejection of cosmics by exploiting 2n/19ns bunched beam;
- New faster, higher performance read-out electronics.