ICARUS-T600: results from CNGS and future perspectives

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The ICARUS T600 detector

- Two identical modules
  - $3.6 \times 3.9 \times 19.6 \approx 275 \text{ m}^3$ each
  - Liquid Ar active mass: $\approx 476 \text{ t}$
  - Drift length = 1.5 m (1 ms)
  - $HV = -75 \text{ kV}$, $E = 0.5 \text{ kV/cm}$
  - $v$-drift = 1.55 mm/µs

- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at $0^\circ, \pm 60^\circ$
  - $\approx 54000$ wires, 3 mm pitch, 3 mm plane spacing
  - 20+54 PMTs, 8” Ø, for scintillation light:
    - VUV sensitive (128nm) with wave shifter (TPB)
The ICARUS detector in underground Hall B of LNGS

- CNGS (CERN $\nu$ to GranSasso beam)
  - $\nu_\mu$ NC and CC interactions
  - $\nu_\mu \rightarrow \nu_\tau, \tau \rightarrow e$
  - $\nu_\mu \rightarrow \nu_e, \theta_{13}$
  - $\nu_\mu \rightarrow \nu_e $ “LSND”
  - $\nu$ velocity

- Atmospheric $\nu$
- Proton decay
- Major milestone for future LAr detectors
ICARUS experiment: a major milestone for LAr-TPC

- 2010: Successful assembly and commissioning of ICARUS-T600, the first LARGE LAr-TPC at LNGS underground INFN Laboratory: high granularity imaging and resolution

March: detector and cryogenic completed
April-May: cooling and filling
May 27th: first CNGS neutrino

- 2011 -> now T600 taking data with CNGS beam &c-rays

Conversion distances
6.9 cm, 2.3 cm

Collection
Induction2

π⁰

close-up of two e.m. showers
LAr-TPC purification (< 60 parts per trillion O₂ equiv.)

- A main feature of the ICARUS R&D:
  - Highly efficient filters based on Oxysorb/Hydrosorb;
  - Ultra High Vacuum techniques;
  - Continuous purification by recirculation in liquid & gas

- $\tau_{\text{ele}} > 5 \text{ ms} \quad (\sim 60 \text{ ppt } [O_2]_{\text{eq}})$ corresponding to a free electron attenuation of 17% after 1.5 m (longest path length)

- 11 accidental purity stops until now. New pumps ready.
CNGS neutrino runs – summary

- **ICARUS T600 fully operational since Oct. 1\textsuperscript{st} 2010**

2010: Oct. 1\textsuperscript{st} ÷ Nov. 22\textsuperscript{nd}

- Detector live-time > 93% in November 2011 and May 2012: timing measurement with bunched beam.

2011: Mar. 19\textsuperscript{th} ÷ Nov. 14\textsuperscript{th}

- END CNGS data taking: 3 (17) December 2013

2012: March 23\textsuperscript{rd} ÷ now

- Detector live-time > 93% in 2011 and 2012

- November 2011 and May 2012: timing measurement with bunched beam.

- END CNGS data taking: 3 (17) December 2013
ICARUS and neutrino velocity


  - Arrival time determined using the prompt scintillation light signals (~ns resolution) and the accurate localization of each event w.r.t. PMT position.
  - 2011 bunched beam: 4 bunches/spill, 3 ns FWHM, 524 ns separation
  - 2012: New beam structure: 64 bunches, 3 ns width, 100 ns spacing. Four time distribution systems available in 2012.
    - Existing LNGS signal
    - Time stamping of ICARUS trigger with the high precision timing facility (HPTF) installed by Borexino at LNGS
    - Two timing distribution system over “White Rabbit” protocol operational @ LNGS/CERN under CERN respons.
      - Two independent GPS receivers
### Nu-tof data summary

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<tbody>
<tr>
<td>Classic</td>
<td>-1.73</td>
<td>0.74</td>
<td>2.3</td>
<td></td>
<td>2.75</td>
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<tr>
<td>HPTF</td>
<td>1.05</td>
<td>0.78</td>
<td>1.8</td>
<td></td>
<td>2.78</td>
</tr>
<tr>
<td>WR-2</td>
<td>1.30</td>
<td>0.78</td>
<td>1.5</td>
<td></td>
<td>2.13</td>
</tr>
<tr>
<td>WR-4</td>
<td>-0.42</td>
<td>0.78</td>
<td>2.0</td>
<td></td>
<td>2.27</td>
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<tr>
<td>Aver.</td>
<td>0.18</td>
<td>~0.69</td>
<td>1.30</td>
<td>1.8</td>
<td>2.17</td>
</tr>
</tbody>
</table>

(2011 result: +0.3 ± 4.9 ± 9.0 ns)

δt = tof$_c$ - tof$_ν$ = 0.18 ± 0.69 (stat.) ± 2.17 (syst.) ns

δ(v/c) = (v$_ν$ - c)/c = 0.7± 2.8 (stat.) ± 8.9 (syst.) $10^{-7}$

 đều mới nhất: 0.18 ± 0.69 (stat.) ± 2.17 (syst.) ns

δv/c = (v$_ν$ - c)/c = 0.7± 2.8 (stat.) ± 8.9 (syst.) $10^{-7}$

(final evaluation underway)

**Present result** (arXiv:1208.2629, under submission to JHEP)

Entries 25
Mean 0.18 ns
Error 0.69 ns
RMS 3.43 ns
The discovery of a Higgs boson at CERN/LHC has crowned the successful Standard Model (SM) and will call for a verification of the Higgs couplings to the gauge bosons and to the fermions.

Neutrino masses and oscillations represent today a main experimental evidence of physics beyond the Standard Model.

Being the only elementary fermions whose basic properties are still largely unknown, neutrinos must naturally be one of the main priorities to complete our knowledge of the SM.

Albeit still unknown precisely, the incredible smallness of the neutrino rest masses, compared to those of other elementary fermions points to some specific scenario, awaiting to be elucidated.

The astrophysical importance of neutrinos is immense.
“Sterile” neutrinos?

- **Sterile neutrinos** are a hypothetical type of neutrino that does not interact via any of the fundamental interactions of the Standard Model except gravity.
- Since per se they may not interact directly, they are extremely difficult to detect. If they are heavy enough, they may also contribute to dark matter.
- Sterile neutrinos may **mix with ordinary neutrinos** via a mass term. Evidence may be building up by “anomalies” observed by several neutrino experiments:
  - sterile neutrino(s) with $\Delta m^2 \approx 10^{-2} - 1$ eV$^2$ from $\nu_e$ observation in $\nu_\mu$ accelerator experiments (LNSD anomaly).
  - Neutrino disappearance may have been observed in nuclear reactors and very intense (megacurie) electron conversion neutrino sources with maybe comparable mass differences.
Sterile neutrinos?

- Sterile neutrino models
- 3+2 next minimal extension to 3+1 models
- 2 independent $\Delta m^2$
- 4 mixing parameters
- 1 Dirac CP phase allowing difference between neutrinos and antineutrinos

LSND anomaly: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation, described in 2-neutrino parameterization as (L=baseline)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta) \sin^2(1.27\Delta m^2 L / E)$$

Reactor anomaly: $\nu_e \rightarrow \nu_x \rightarrow$ reduction of $\nu_e$ flux $R$

$$R = 1 - \sin^2(2\theta) \sin^2(1.27\Delta m^2 L / E)$$

Reactor and "LSND" $\Delta m^2$ are compatible
Over-all evidence is mounting…

### Combined evidence
\[
(3.8 + 3.8 + 2.7 + 3.0 + 2.0) \text{ S.D} \]

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Source</th>
<th>Type</th>
<th>Channel</th>
<th>Significance</th>
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<tbody>
<tr>
<td>LSND</td>
<td>Short baseline</td>
<td>Decay at rest</td>
<td>-νμ →νe</td>
<td>3.8 σ</td>
</tr>
<tr>
<td>MiniBoone</td>
<td>Short baseline</td>
<td>Neutrino beam</td>
<td>-νμ →νe</td>
<td>3.0 σ</td>
</tr>
<tr>
<td>MiniBoone</td>
<td>Short baseline</td>
<td>Anti-Neutr. beam</td>
<td>anti-νμ →νe</td>
<td>1.7 σ</td>
</tr>
<tr>
<td>Gallium</td>
<td>Electron capture</td>
<td>Source</td>
<td>ν disapp.</td>
<td>2.7 σ</td>
</tr>
<tr>
<td>Reactors</td>
<td>Fission</td>
<td>Beta decay</td>
<td>ν disapp.</td>
<td>3.0 σ</td>
</tr>
<tr>
<td>Cosmology</td>
<td>Big bang WMAP</td>
<td>No of neutrino</td>
<td></td>
<td>≈ 2 σ</td>
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</table>
The present experiment looks for the a LSND like $\nu_\mu \to \nu_e$ signal from the CNGS $\nu_\mu$ beam at 730 km and $10 \leq E_\nu \leq 30$ GeV.

Allowed LSND and MiniBooNE signals

\[
\mathcal{P}(\nu_\mu \to \nu_e) = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L /E)
\]
LAr TPC performance

- Tracking device
  - Precise 3D topology and accurate ionization
  - Momentum via multiple scattering
- Measurement of local energy deposition $dE/dx$
  - $e/\gamma$ remarkable separation ($0.02 X_0$ sample)
  - Particle identification by $dE/dx$ vs range
- Total energy reconstruction of the events from charge integration
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events

RESOLUTIONS

Low energy electrons:  $\sigma(E)/E = 11\% / \sqrt{E\text{(MeV)}} + 2\%$
Electromagn. showers:  $\sigma(E)/E = 3\% / \sqrt{E\text{(GeV)}}$
Hadron showers:  $\sigma(E)/E \approx 30\% / \sqrt{E\text{(GeV)}}$

Multiple Scattering check on long CNGS stopping muons
$\frac{p_{MS}}{p_{calo}}$
$\sigma \approx 16\%$

Points: Data $dE/dx$ vs residual range compared to Bethe-Bloch curves
NEW: Simultaneous 3D polygonal fit → 2D hit-to-hit associations no longer needed

μ \rightarrow e \quad \text{NEW: Simultaneous 3D polygonal fit → 2D hit-to-hit associations no longer needed}
Example of data: kaon decay in a CNGS event

- Kaon track
- Muon track

Corresponding PID patterns

Collection view

- CNGS beam
- Left chamber. Induction 2 view
- Right chamber. Collection view

Residual range (cm)

dE/dx (MeV/cm)

Kaon track
Muon track

Primary vertex

Cathode

Pion
Kaon
Muon

~90 cm, 325 MeV
~54 cm, 147 MeV
~13 cm, 27 MeV

Collection view
$E_{k16a} = 102 \pm 10 \text{ MeV}$

$E_{k16b} = 685 \pm 25 \text{ MeV}$

$p_{\pi^0} = 912 \pm 26 \text{ MeV/c}$

$M_{\pi^0} = 127 \pm 19 \text{ MeV/c}^2$

$\theta = 28.0 \pm 2.5^\circ$

$\pi^0$ showers identified by:
- 2$\gamma$ conversion separated from primary vertex
- Reconstruction of $\gamma\gamma$ invariant mass
- Ionization in the first segment of showers

From CNGS Real Data

d$E$/d$x$ of the initial part of low E showers
d$E$/d$x$ from a single long stopping muon ($p=1.8\text{GeV/c}$),

Most Probable $dE$/d$x$ in agreement with expect. Signal/noise from Landau+ Gaussian $\approx 10$
CNGS facility delivers an almost pure $\nu_\mu$ beam peaked in the range $10 \leq E_\nu \leq 30$ GeV (beam associated $\nu_e$ about 1/2%). The signature of the $\nu_\mu \rightarrow \nu_e$ signal is observed visually.

Present sample: 1091 neutrino events from 2010 and 2011.

There are differences with respect to LNSD experiment:
- $L/E_\nu \sim 1$ m/MeV at LNSD, but $L/E_\nu \approx 36.5$ m/MeV at CNGS
- A LNSD-like short distance oscillation signal averages to $\sin^2(1.27 \Delta m^2_{\text{new}} L / E) \sim 1/2$ and $\langle P \rangle_{\nu_\mu \rightarrow \nu_\tau} \sim \frac{1}{2} \sin^2(2\theta_{\text{new}})$

Expected conventional $\nu_\mu \rightarrow \nu_e$ the same energy range and fiducial volumes:
- 3 events due to the intrinsic $\nu_e$ beam contamination
- 1.3 events due to $\theta_{13}$ oscillations:
- 0.7 events of $\nu_\mu \rightarrow \nu_\tau$ oscillations with electron production.

The total is therefore of 5 expected events.
The detection of events has been widely simulated by a very sophisticated Montecarlo emulation, reproducing in every detail the actual signals from the wire planes. The agreement between MC and observed events has been excellent.

An “electron signature” has been defined by presence of a single minimum ionizing relativistic electron track:

- of sufficient length from the vertex, subsequently building up into a shower; very dense sampling: every $0.02 \times_0$ !!!!
- clearly separated from other ionizing tracks near the vertex in at least one of the two transverse views.

Visibility cuts reduce the probability of identification an electron tracks to $\eta = 0.74 \pm 0.05$. In a good approximation $\eta$ is independent of the shape of the energy spectrum.

The number of expected events with visible $\nu_\mu \rightarrow \nu_e$ is then 3.7.
Calibration from CNGS muons

- dE/dx of individual 3 mm track segments reconstructed in 3D, after removing δ rays and e.m. cascades
- Excellent agreement between real and simulated data

Comparison MC and actual data

MC: \( \mu = 2.37 \text{ MeV/cm}; \text{ rms} = 1.37 \)
Data: \( \mu = 2.32 \text{ MeV/cm}; \text{ rms} = 1.31 \)

Muon tracks from CNGS CC interactions

Comparison of the predicted (full MC) and detected deposited energy spectrum from CC CNGS events (green : sperluminal nu)
Typical Montecarlo generated event from the ICARUS simulation program with $E_\nu=11$ GeV and $p_t=1.0$ GeV/c. Only the vertex region is shown.
Two CC events have been observed in data sample, with a clearly identified electron signature:

(a) total energy = 11.5 \pm 1.8 \text{ GeV}, P_t = 1.8 \pm 0.4 \text{ GeV/c}

(b) Total visible energy = 17 \text{ GeV}. P_t = 1.3 \pm 0.18 \text{ GeV/c}

In both events the single electron shower in the transverse plane is clearly opposite to the remaining of the event.
• The ICARUS experiment is presently compatible with the absence of a LSND anomaly. The limits due to the LSND anomaly are respectively 3.41 (90% CL) and 7.13 events (99% CL)

• Given the sample of 627 $\nu_\mu$ - CC events, the limits to the oscillation probability are:
  
  \[
  P_{\nu_\mu\rightarrow\nu_e} \leq 5.4 \times 10^{-3} \quad (90\% \text{ CL})
  \]
  
  \[
  P_{\nu_\mu\rightarrow\nu_e} \leq 1.1 \times 10^{-2} \quad (99\% \text{ CL})
  \]

• The exclusion area is shown for the plot $\Delta m^2 - \sin^2(2\theta)$. At small $\Delta m^2$ ICARUS strongly enhances the probability with respect to the short baseline experiments.

With $(\Delta m^2 - \sin^2(2\theta)) = (0.11 \text{ eV}^2, 0.10)$ as many as 30 events should have been seen
The ICARUS result excludes a substantial fraction of the MiniBooNE curves corresponding to lines from 1 to 5. The origin of the L/E$_\nu > 1$ (low energy) excess observed by MiniBooNE may need further clarification.
The present result strongly limits the window of opened options for the LSND anomaly, reducing the remaining effect to a narrow region centered around $(\Delta m^2 - \sin^2(2\theta)) = (0.5 \text{ eV}^2 \text{ and } 0.05)$ where there is an over-all agreement (90 % CL) between

- the present ICARUS limit,
- the limits of KARMEN and
- the positive signals of LSND and MiniBooNE collaborations
- When compared to the other long baseline results (MINOS and T2K) ICARUS operates in a $L/E_\nu$ region in which the contributions from standard neutrino oscillations are not yet too relevant.
- Unique detection properties of Lar-TPC permit to identify unambiguously individual electron events with high efficiency.
In order to investigate the surviving LSND/MiniBooNE ($\Delta m^2 - \sin^2(2\theta)$) region, the ICARUS LAr detector will be moved to CERN, at much shorter distances (300 m and 1.6 km) and lower neutrino energies. This will increase the events rate, reduce the over-all multiplicity of the events, enlarge the angular range and therefore improve substantially the electron selection efficiency.

The experimental set-up will include a FAR and a NEAR detectors, identical except for dimensions.

In absence of oscillations, apart some beam related small spatial corrections, the two spectra at different distances should a precise copy of each other, independently of the specific event signatures and without any Monte Carlo comparison.

Magnetic spectrometers (NESSIE collab.) will be installed in far and near position for $\nu_\mu$ disappearance searches.

This will presumably permit a definitive clarification of the “LSND anomaly” in all the available oscillation channels in the same experiment.

ICARUS-NESSIE proposal, SPSC-P-347, arXiv:1208.0862
New neutrino facility in North Area

100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe \( l \approx 100 \text{m} \)

Interchangeable \( \nu \) and \( \bar{\nu} \) focussing.

Near position (330m)
- 150t LAr-TPC detector
- To be build anew + magnetic spectrometer

Far position (1600 m)
- ICARUS-T600 detector + magnetic spectrometer
**Expected signals for LSND/MiniBooNE anomalies**

- Event rates for the near and far detectors given for $4.5 \times 10^{19}$ pot. ($\approx 1$ year)
- The oscillated signals are clustered below 6 GeV of visible energy

### Event Rates

<table>
<thead>
<tr>
<th></th>
<th>NEAR (neg. foc.)</th>
<th>NEAR (pos. foc.)</th>
<th>FAR (neg. foc.)</th>
<th>FAR (pos. foc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + \bar{\nu}_e$ (LAr)</td>
<td>35 K</td>
<td>54 K</td>
<td>4.2 K</td>
<td>6.4 K</td>
</tr>
<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$ (LAr)</td>
<td>2030 K</td>
<td>5250 K</td>
<td>270 K</td>
<td>670 K</td>
</tr>
<tr>
<td>$\sin^2(2\theta)=0.02$, $\Delta m^2=0.4$ eV$^2$</td>
<td>590</td>
<td>1900</td>
<td>360</td>
<td>914</td>
</tr>
<tr>
<td>$\nu_\mu$ (LAr+NESSiE)</td>
<td>230 K</td>
<td>1200 K</td>
<td>21 K</td>
<td>110 K</td>
</tr>
<tr>
<td>$\nu_\mu$ (NESSiE)</td>
<td>1150 K</td>
<td>3600 K</td>
<td>94 K</td>
<td>280 K</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ (Lar+NESSiE)</td>
<td>370 K</td>
<td>56 K</td>
<td>33 K</td>
<td>6.9 K</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ (NESSiE)</td>
<td>1100 K</td>
<td>300 K</td>
<td>89 K</td>
<td>22 K</td>
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<tr>
<td>Disapp.. test point</td>
<td>1840</td>
<td>4700</td>
<td>1700</td>
<td>5000</td>
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Exploring all channels

Expected sensitivity in the **appearance** channels for the proposed experiment: $\nu_\mu$ beam (left) and anti-$\bar{\nu}_\mu$ (right) for $4.5 \times 10^{19}$ pot (1 year) and $9.0 \times 10^{19}$ pot (2 years) respectively. LSND allowed region is fully explored in both cases.

Expected sensitivity in the **disappearance** channels for the proposed experiment: $\nu_\mu$ and anti-$\bar{\nu}_\mu$ (right, 3y) Left: $\nu_e$ 1 y
Thank you!