Recent results from the ICARUS experiment

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Introduction

- Three years (May 2010 – June 2013) of continuous underground operation of the ICARUS detector in Hall B of the LNGS lab. resulted in plenty of high quality data, both from LNGS beam and cosmics.
- Such a long period allowed for detailed studies of all technical aspects of the detection technique, … and
- Development of advanced reconstruction algorithms.

June 27th: Detector decommissioning
July 25th: cryostat empty
740 ton (out of 760 tons) recovered
In this talk

• **ICARUS LAr TPC - detector performance**

• **Results:** search for the LSND/MiniBooNE anomaly, i.e. search for the oscillations $\nu_\mu \rightarrow \nu_e$ with LNGS beam

• **Conclusions**
The ICARUS Collaboration

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The ICARUS T600: the first LARGE LAr TPC

- 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, $\pm 60^\circ$
  - $\approx 54000$ wires, 3 mm pitch, 3 mm plane spacing
  - 20+54 PMTs, 8” $\varnothing$, for scintillation light:
    - VUV sensitive (128nm) with wave shifter (TPB)

Key feature: LAr purity from electro-negative molecules ($O_2$, $H_2O$, $CO_2$).
CNGS RUN (Oct 1st 2010 – Dec 3rd 2012)

- Detector live-time > 93%
- November 2011 and May 2012: timing measurement with bunched beam.
- PMT’s signal in coincidence with beam extraction → trigger

Collected $8.6 \times 10^{19}$ protons on target (pot)

LAr continuously filtered, max. charge attenuation at 1.5m: 17%

Natal WIN September 2013
ICARUS LAr-TPC performance

Total energy reconstr. 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 (0.02 $X_0$ samples)
- Particle identification by $dE/dx$ vs range

Low energy electrons:
$\sigma(E)/E = 11%/\sqrt{E(\text{MeV})} + 2%$

Electromagn. showers:
$\sigma(E)/E = 3%/\sqrt{E(\text{GeV})}$

Hadron showers:
$\sigma(E)/E \approx 30%/\sqrt{E(\text{GeV})}$

Data: $\nu_\mu$ CC energy deposit

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• Search for superluminal neutrinos (not in this talk):

3. Precision measurement of $\nu$ tof: JHEP 11 (2012) 049

• Search for „LSND“ anomaly (this talk):

2. Improved statistics result: arXiv:1307.4699
The LSND has observed an excess of anti-$\nu_e$ neutrino events in anti-$\nu_\mu$ beam: $87.9 \pm 22.4 \pm 6.0 (3.8\sigma)$

LSND anomalous production signal has been later partly confirmed by MiniBoone experiment.

MiniBooNE (PRL 110 (2013) 161801)
Event excess for $200 < E_{QE} < 1250$ MeV
- antineutrino: $78.4 \pm 28.5 (2.8 \sigma)$
- neutrino: $162 \pm 47.8 (3.4 \sigma)$, but the energy distribution of the excess is marginally compatible with a simple two neutrino oscillation
ICARUS search for LSND anomaly

**LSND**: $L/E=1 \text{ m/MeV}$

**ICARUS**: $L=730\text{km}$, $E_\nu \in [10,30] \text{ GeV}$, almost pure $\nu_\mu$ beam ($\nu_e \approx 1\%$)

$L/E \approx 36.5 \text{ m/MeV}$, i.e. fast oscillations as a function of $E_\nu$ averaging to

$$\sin^2(1.27\Delta m^2 L/E) \approx \frac{1}{2}$$

$$<P>_{\nu_\mu \rightarrow \nu_e} \approx \frac{1}{2} \sin^2(2\theta_{\text{new}})$$

A sterile neutrino signal would appear for ICARUS as an access of $\nu_e$ events.

$\nu_e$ CC event recognition becomes crucial, and possible due to unique Liquid Argon feature and our reconstruction algorithms.
ICARUS: e/γ separation and π⁰ reconstruction

- **MC**: single electrons (Compton)
- **MC**: e⁺ e⁻ pairs (γ conversions)
- **data**: EM cascades (from π⁰ decays)

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

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

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

\[ m_{\pi^0} = 127 \pm 19 \text{ MeV/c}^2 \]

\[ \theta = 28.0 \pm 2.5^\circ \]

\[ 1 \text{ m.i.p.} \]
\[ 2 \text{ m.i.p.} \]

\( M_{\gamma\gamma}: 133.8 \pm 4.4(\text{stat}) \pm 4(\text{syst}) \text{ MeV/c}^2 \)

- **LAr TPC**: very good e/γ separation
ICARUS: $\nu_e$ signal selection

• Visual selection of $\nu_e$ event candidates in the following fiducial volume for shower id: > 5 cm from walls and 50 cm downstream.

• Energy cut: < 30 GeV (≈50% reduction on $\nu_e$ beam, but only 15% reduction of signal events.

**Selections for $\nu_e$ during visual scan:**

Single m.i.p. from vertex, al least 8 wires long ($dE/dx \leq 3.1$ MeV/cm, excluding $\delta$-rays), later developing into EM shower.

Minimum spatial separation (150 mrad) from other tracks coming from vertex, at least in one of 2 transverse views.

• visibility cuts: (3 independent scanners), leading to $0.74 \pm 0.05$ efficiency;

• no $\nu_e$-like events selected among NC simulated sample of 800 events.

• $\nu_\mu$ CC events identified by $L > 2.5$ m primary track without hadronic interaction
First result based on the analysis of 1091 \( \nu \) events (3.3 \( \times 10^{19} \) pot, 2010–2011 data, half the total statistic) published in Eur. Phys. J. C73 (2013).

Analysis presented here refers to 1995 \( \nu \) events (6.0 \( \times 10^{19} \) pot) expected number of \( \nu_e \) events:
- 5.7 \( \pm \) 0.8, due to the intrinsic \( \nu_e \) beam contamination,
- 2.3 \( \pm \) 0.5, due to \( \theta_{13} \) oscillations, \( \sin^2(\theta_{13}) = 0.0242 \pm 0.0026 \),
- 1.3 \( \pm \) 0.1, from \( \nu_\mu \rightarrow \nu_\tau \) oscillations with subsequent electron production, (3\( \nu \) mixing).

Total: 9.3 \( \pm \) 0.9 expected events.
Expected events, weighting for efficiency: 6.4 \( \pm \) 0.9 events.
In all events: single electron shower in the transverse plane clearly opposite to hadronic component

Example: 2 (out of 4) $\nu_e$ CC events observed in 1995 events

(a) \( \text{vis } E_{\text{tot}} = 11.5 \pm 1.8 \text{ GeV} \), \( p_t = 1.8 \pm 0.4 \text{ GeV/c} \)

(b) \( \text{vis } E_{\text{tot}} = 17 \text{ GeV} \), \( p_t = 1.3 \pm 0.18 \text{ GeV/c} \)
ICARUS results strongly limit the allowed parameters values for LSND anomaly indicating a narrow region $(\Delta m^2, \sin^2 2\theta) = (0.5 \text{ eV}^2, \ 0.005)$ where there is overall agreement (90% CL) among:

- the present ICARUS limit
- the limits of KARMEN
- the positive signals of LSND and MiniBooNE Collaborations

All limits are at 90% CL unless otherwise noted.
Within the present observation, our results is consistent with the absence of the LSND anomaly.

Weighting for efficiency, our limits on the number of events due to LSND anomaly are: 3.68 (90% CL) and 8.34 (99% CL).

which give the limits on oscillation probabilities:
\[ P(\nu_\mu \rightarrow \nu_e) \leq 3.4 \times 10^{-3} \text{ (90\% CL)}; \]
\[ P(\nu_\mu \rightarrow \nu_e) \leq 7.6 \times 10^{-3} \text{ (99\% CL)} \]
A small ~2% anti-neutrino event contamination is present in the CNGS beam → search for $\bar{\nu}_e$ appearance could be possible.

Anti-$\nu_\mu$ CC event rate is $(1.2 \pm 0.25)\%$ of $\nu_\mu$ CC for $E_\nu < 30$ GeV (from simulations).

In the limiting case in which the whole effect is due to $\bar{\nu}_\mu$, the absence of an anomalous signal gives a limit of 4.2 events (90% CL.).

Corresponding to $<P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)> \leq 0.32$

Or $\sin^2(2\theta_{\text{new}}) \leq 0.64$.

In case of MiniBoone best fit, ~12 events expected (5.4 signal +6.4 bgd)
ICARUS is the first large TPC operated underground.

ICARUS has been acquiring data without interruption for more than 3 years with both, CNGS beam and cosmics.

Efficient reconstruction algorithms for the tracks allow to resolve most of the events collected, down to their single components. Consequence of this is for example the accurate analysis of $\nu_e$ events, which allows for an investigation of sterile neutrino oscillations and a check on previous results (LSND anomaly).

No evidence of oscillation into sterile neutrinos is found in our measured L/E interval.
Thank you