ICARUS T600 results

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A powerful detection technique

The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)]

A 3D imaging of any ionizing event ("electronic bubble chamber"):

- continuously sensitive
- self triggering
- high granularity (~ 1 mm)
- excellent calorimetric properties
- particle identification (through dE/dx vs range)

Electrons from ionizing track are drifted in LAr by $E_{\text{drift}}$. They traverse two transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by collection plane.

Key feature: LAr purity form electro-negative molecules ($O_2$, $H_2O$, $CO_2$). Target: 0.1 ppb $O_2$ equivalent = 3 ms lifetime (4.5 m drift @ $E_{\text{drift}} = 500$ V/cm).
The path to larger LAr detectors

1. CERN
   - 24 cm drift wires chamber

2. 3 ton prototype

3. Laboratory work
   - CERN
   - 50 litres prototype
     - 1.4 m drift chamber
   - 1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4. Pavia
   - T600 detector
   - 2001: First T600 module

5. Cooperation with industry
   - AirLiquide, Breme, Cinel, CAEN
   - 10 m³ industrial prototype
   - 1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

6. LNGS Hall-B
   - 2010 - … : Data taking with CNGS beam

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LAr-TPC performance

- Tracking device:
  - precise event topology ($s_{x,y} \sim 1\text{mm}, s_z \sim 0.4\text{mm}$)
  - $\mu$ momentum measurement via multiple scattering: $\Delta p/p \sim 10-15\%$ depending on track length and $p$
  - Total energy reconstruction by charge integration

- Measurement of local energy deposition $dE/dx$:
  - $e/\mu$ separation (sampling at 1/50 $X_0$);
  - particle ID by means of $dE/dx$ vs range

- Good $e/\pi^0$ separation ($10^{-3}$) by means of $dE/dx$ in the first part of the track after the vertex. $\pi^0$ mass measurement.

**RESOLUTIONS:**

- Low energy electrons $\sigma(E)/E = 11\% / \sqrt{E(\text{MeV})} + 2\%$
- Electromagnetic showers $\sigma(E)/E = 3\% / \sqrt{E(\text{GeV})}$
- Hadronic showers $\sigma(E)/E \sim 30\% / \sqrt{E(\text{GeV})}$
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
  - $HV = -75 \text{ kV}$, $E = 0.5 \text{ kV/cm}$
  - $v_{drift} = 1.55 \text{ mm/µs}$

- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at $0, \pm 60^\circ$
  - 53248 wires, 3 mm pitch, 3 mm plane spacing

- PMT for scintillation light:
  - $(20+54)$ PMTs, 8” Ø
  - VUV sensitive (128nm) with wave shifter (TPB)
ICARUS T600 in LNGS Hall B

N₂ Phase separator  30 m³ LN₂ Vessels

N₂ liquefiers: 12 units, 48 kW total cryo-power

Apparatus activated on 27th May 2010
Optimization phase in summer 2010
Data taking in stable condition from 01st Oct. 2010
The presence of electron trapping polar impurities attenuates the electron signal.

Most of the contaminants freeze out spontaneously (87 K). Residuals: O\textsubscript{2}, H\textsubscript{2}O, CO\textsubscript{2}.

Recirculation/purification of both, the gas phase and the liquid phase (4 m\textsuperscript{3}/h, full volume recirculation in 6 days) to reduce the initial impurities concentration (Hydrosorb/Oxysorb™ filters).

Charge attenuation along track allows event-by-event measurement of LAr purity (Use of about 50 muon tracks without evident associated δ-rays and γ’s, day-by-day) (Pulse height for 3 mm m.i.p. ~ 15 ADC # (15000 electrons; noise r.m.s. 1500 electrons)
Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

\[
dN/dt = -N/\tau_R + k_L + k_D \exp(-t/\tau_D)
\]

- \(\tau_R\): recirculation time for a full detector volume
- \(k_D\): internal residual degassing rate assumed to vanish with a time constant \(\tau_D\)
- \(k_L\): total impurity leak rate and degassing rate
The trigger set-up is based on a controller crate, hosting a FPGA-board for signals processing, interfaced to a PC for data communication and parameter setting.

**Different trigger sources:**
- CNGS proton extraction time from "Early Warning" signal (80ms before spills)
- PMTs "Low Threshold" signal (~100phe)
- PMTs "High Threshold" signal (~1000phe)
- Test pulses for calibration
CNGS events timing w.r.t. CERN proton extraction time

Very narrow beam distribution: only 10 µs wide ≈ spill duration (10.5 µs)

Mean offset value (2.404 ms) in agreement with ν t.o.f. (2.437 ms) in view of ~ 40 µs fiber transit time from ext. LNGS labs to Hall B (8km)
ICARUS T600: major milestone towards realization of large scale LAr detector, but interesting physics in itself:

- CNGS $\nu$ events collection (beam intensity $4.5 \times 10^{19}$ pot/year, $E_\nu \sim 17.4$ GeV):
  - 1200 $\nu_\mu$ CC events/year;
  - $\sim 8$ $\nu_e$ CC events/year;
  - observation of $\nu_\tau$ events in the electron channel, using kinematical criteria;
  - search for sterile $\nu$ in LSND parameter space (deep inelastic $\nu_e$ CC events excess).

- "Self triggered" events collection:
  - $\sim 80$ events/y of unbiased atmospheric $\nu$ CC;
  - zero background proton decay with $3 \times 10^{32}$ nucleons for “exotic” channels.
  - supernova explosion neutrinos (if any).
ICARUS fully operational for CNGS events recording in Oct. 1\textsuperscript{st} – Nov. 22\textsuperscript{nd}.

Trigger: photomultiplier signal for each chamber with low threshold discrimination at 100 phe, within 60 μs wide beam gate.

Oct. 1\textsuperscript{st} ÷ Nov. 22\textsuperscript{nd}: 8 \cdot 10^{18} (5.8 \cdot 10^{18}) pot delivered (collected). Detector lifetime up to 90% since Nov. 1\textsuperscript{st}.

Number of collected interactions compared with number of interactions predicted ((2.6 \nu CC + 0.86 \nu NC) \cdot 10^{-17}/pot), in the whole energy range up to 100 GeV, corrected by fiducial volume (424 tons) and DAQ dead-time.

Analyzed sample corresponds to 5.3 \times 10^{18} pot (corresponds to the 91% of statistics).

<table>
<thead>
<tr>
<th>Event type</th>
<th>Collected</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>\nu_\mu CC</td>
<td>108</td>
<td>115</td>
</tr>
<tr>
<td>\nu NC</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>\nu XC *</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>150</td>
<td>152</td>
</tr>
</tbody>
</table>

* Events at edges, with \mu track too short to be visually recognized: further analysis needed.

On overall statistics in agreement with expectations.
The first CNGS neutrino interaction in ICARUS T600

Collection view

Drift time coordinate (1.4 m)
Wire coordinate (8 m)

CNGS $\nu$ beam direction

$\nu_\mu$ CC

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Low energy CNGS neutrino interaction

Electron lifetime and quenching accounted for

Collection views (not to scale!)

Evis ~ 9 GeV

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CNGS CC neutrino interaction with $\pi^0$ production

Collection view

Wire coordinate (~3 m)

CNGS $v$ beam direction

Induction 1

Induction 2 view
CNGS CC interaction with both TPC signals

Wire coordinate (~5 m)

Collection right view

Electron drift 1.5m

Cathode (18 m)

Collection left view

CNGS v beam direction
Predicted number of collected interactions in the rock: 
$7.8 \times 10^{-17}$/pot
Analysis: 3D reconstruction and particle identification

- Complement of 2D reconstruction based on Polygonal Line Algorithm (PLA).
  
  [Link: http://www.iro.umontreal.ca/~kegl/research/pcurves/]

- 3D reconstruction: linking hit projections between views according to
  - drift sampling;
  - sequence of hits.

- Particle identification based on:
  - distance between nearby 3D hits: $d_x$
  - 3D hits and charge deposition: $dE/dx$

- Classify single $i^{th}$ point on the track
  $p_i : [E_k, dE/dx] \rightarrow \text{nnd}: [P(p), P(K), P(p), P(\mu)]$

- Average $M$ output vectors for the points
  $\text{NN} = S(\text{nnd})/M$

- Identify track as particle corresponding to $\text{max}(\text{NN})$
  Very high identification efficiency for $p, k, \pi+\mu$

- Energy reconstructed including quenching in simulation
LAr-TPC: powerful technique. Run 9927 Event 572

Total visible energy 4.5 GeV
Estimated $p_\nu \sim 12.3$ GeV/c

$p_\mu = 10.5 \pm 1.1$ GeV/c by multiple scattering

Primary vertex (A)
very long $\mu$ (1),
e.m. cascade(2),
pion (3).

Secondary vertex (B)
The longest track (5) is a $\mu$
coming from stopping k (6).
- $\mu$ decay is observed.

Conversion distances
6.9 cm, 2.3 cm

$M^{*}_{\gamma\gamma} = 125 \pm 15$ MeV/c$^2$

<table>
<thead>
<tr>
<th>Track</th>
<th>$E_{dep}$[MeV]</th>
<th>cosx</th>
<th>cosy</th>
<th>cosz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ($\mu$)</td>
<td>2701.97</td>
<td>0.069</td>
<td>-0.040</td>
<td>-0.997</td>
</tr>
<tr>
<td>2 ($\pi^0$)</td>
<td>520.82</td>
<td>0.054</td>
<td>-0.420</td>
<td>-0.906</td>
</tr>
<tr>
<td>3 ($\pi^-$)</td>
<td>514.04</td>
<td>-0.001</td>
<td>0.137</td>
<td>-0.991</td>
</tr>
<tr>
<td>Sec. vtx.</td>
<td>797.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>76.99</td>
<td>0.009</td>
<td>-0.649</td>
<td>0.761</td>
</tr>
<tr>
<td>5 ($\mu$)</td>
<td>313.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 (K)</td>
<td>86.98</td>
<td>0.000</td>
<td>-0.239</td>
<td>-0.971</td>
</tr>
<tr>
<td>7</td>
<td>35.87</td>
<td>0.414</td>
<td>0.793</td>
<td>-0.446</td>
</tr>
<tr>
<td>8</td>
<td>283.28</td>
<td>-0.613</td>
<td>0.150</td>
<td>-0.776</td>
</tr>
</tbody>
</table>

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Slide: 21
Atmospheric $\nu$ candidate

- Total visible energy: 887 MeV (including quenching and $e^{-}$ lifetime corrections).
- Out-of-time from CNGS spill AND angle w.r.t. beam direction: 35°.
Run 9392 Event 106

Total deposited energy: 887 MeV
Total reconstructed momentum: 929 MeV/c at about 35° away from the CNGS beam direction

<table>
<thead>
<tr>
<th>Track</th>
<th>$E_k$ [MeV]</th>
<th>Range [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (prob. $\pi$, decays in flight)</td>
<td>136.1</td>
<td>55.77</td>
</tr>
<tr>
<td>1</td>
<td>26</td>
<td>3.3</td>
</tr>
<tr>
<td>2</td>
<td>79.1</td>
<td>17.8</td>
</tr>
<tr>
<td>2a</td>
<td>24.1</td>
<td>10.4</td>
</tr>
<tr>
<td>2b</td>
<td>231.6</td>
<td>99.1</td>
</tr>
<tr>
<td>3</td>
<td>168</td>
<td>19.2</td>
</tr>
<tr>
<td>4</td>
<td>152</td>
<td>16.3</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>2.9</td>
</tr>
</tbody>
</table>

$2: \pi \rightarrow \mu \rightarrow e$

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2011 CNGS run

- ICARUS fully operational / data taking for CNGS events from 19th March.
- The detector lifetime above 90% with the new trigger/DAQ feature improvements.
- $2.16 \times 10^{19} \ (1.99 \times 10^{19})$ pot delivered (collected).
2011-2012 CNGS run: physics perspectives

- 2011-2012 run with dedicated SPS periods @ high intensity: expected $10^{20}$ pot.
- For $1.1 \times 10^{20}$ pot: 3000 beam related $\nu_\mu$ CC events expected in ICARUS-T600.

- 7 $\nu_e$ CC intrinsic beam associated events with visible energy < 20 GeV.
- 2011-2012 run with dedicated SPS periods @ high intensity: expected $10^{20}$ pot.
- For $1.1 \times 10^{20}$ pot: 3000 beam related $\nu_\mu$ CC events expected in ICARUS-T600.

- At the effective neutrino energy of 20 GeV and $\Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2$, $P(\nu_\mu \rightarrow \nu_\tau) = 1.4\%$.
- 17 raw CNGS beam-related $\nu_\tau$ CC events expected.
- $P(\tau \rightarrow e\nu\nu) = 18\% \Rightarrow 3$ electron deep inelastic events with visible energy < 20 GeV.

Background

- $\tau \rightarrow e\nu\nu$ events characterized by momentum unbalance (2$\nu$ emission) and relatively low electron momentum. Selection criteria suggest a sufficiently clean separation with kinematic cuts opening the possibility to identify 1-2 $\nu_\tau$ CNGS events in the next 2 years, only in this gold channel.

Signal

- Currently collected CC/NC data will be used to tune the selection criteria in order to optimize the sensitivity for $\tau$ search.
SIGNAL

\[ \nu_\tau + N \rightarrow \tau^- + X \]

\[ e^- \overline{\nu}_e \nu_\tau \ (BR \sim 17\%) \]

\[ \sum p_T \neq 0 \]

"missing"

\[ p_T^{\nu_e}, p_T^{\nu_\tau} \]

BACKGROUND

\[ \nu_e + N \rightarrow e^- + X \]

\[ (\nu_e \ CC) \]

Main part of the background

Flux contamination

\[ \sum p_T \approx 0 \]
The ICARUS experiment at the Gran Sasso Laboratory is so far the most important milestone for LAr TPC technology and acts as a full-scale test-bed located in an underground environment.

The successful assembly and operation of the ICARUS-T600 LAr-TPC demonstrate that the technology is mature.

The wide physics potentials offered by high granularity imaging and high resolution will be addressed already with the T600 detector:

- **Underground physics** (proton decay, atmospheric $\nu$, supernova, ...)
- **Long-baseline** neutrino oscillation physics

The T600 is presently taking data, recording cosmic and CNGS neutrino events in stable conditions since October 2010. Data analysis is on-going.

The detector will be exposed to CNGS beam in 2011-2012.
Thank you!
Front-end Electronics and DAQ

54,000 channels

Liquid argon
Sense wires (4-9m, 20pF/m)
Twisted pair cables (~5m, 50pF/m)

Gas

H.V. (±300 V)
Decoupling Boards (32 ch.)

Front-end amplifiers (32/board): 1500 e.n.c.

4 Multiplexers (400ns x 8ch.)
10bit FADC
400ns sampling
1mV/ADC (~1000e- /ADC)

Multi-event circular buffer (8x1ms)
Continuous waveform Recording
To storage

(GLA2011, J.Kisiel for ICARUS T600)