ICARUS T600 experiment in the Gran Sasso underground laboratory

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on behalf of ICARUS T600 Collaboration
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● The ICARUS T600 detector.

● Physics perspectives.

● Preliminary results from data taken during run 2010.

● Event gallery and reconstruction.

● Summary.
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The detection technique

The **Liquid Argon Time Projection Chamber** (LAr-TPC), first proposed by C.Rubbia in 1977 [C.Rubbia: CERN-EP/77-08 (1977)] – is a powerful detection technique that can provide a 3D imaging of any ionizing event

- continuously sensitive, self triggering
- high resolution and granularity
- excellent calorimetric properties

Electrons from ionizing track are drifted in LAr by uniform electric field. They traverse the transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by the third collection plane.

**Key requirement:** LAr purity form electro-negative molecules ($O_2$, $H_2O$, $CO_2$), Target: 0.33 ppb $O_2$ equivalent = 1ms lifetime (1.5m drift @ $E_{drift} = 500$ V/cm).
ICARUS @ LNGS
A novel instrument for neutrino physics

- Two identical T300 modules (2 chambers for each module)
- LAr active mass 476t:
  - \((17.9 \times 3.1 \times 1.5\) for each TPC\)m\(^3\)
  - max drift length = 1.5m
  - \(E_{\text{drift}} = 0.5\text{kV/cm}, v_{\text{drift}} = 1.6\text{mm/\mu s}\)
  - HV = -75kV

- 3 readout planes/chamber at 0\(^\circ\), ±60\(^\circ\), 3mm plane spacing:
  - 53248 wires with length up to 9m, 3mm pitch
  - 2 induction planes, 1 collection

- PMT for scintillation light:
  - \((20 + 54)\) PMTs, 8” Ø
  - sensible to VUV scintillation light (\(\lambda = 128\text{nm}\)) by applying a wavelength shifter layer (TPB - tetraphenyl-butadiene)
Main technological challenge – to ensure and maintain a high LAr purity level. Electronegative contaminants (mainly O$_2$, H$_2$O and CO$_2$) attenuate ionization signal!

$\tau_{\text{ele}} \text{ [ms]} = 0.3/N \text{ [ppb O}_2\text{ equivalent]}$

currently: $\tau_{\text{ele}} \sim 6 \text{ [ms]}: \sim 50\text{ppt}$
CNGS – Cern project for a neutrino beam to Gran Sasso

\[ p + C \rightarrow \text{(interactions)} \rightarrow \pi^+, K^+, (\mu^+) \rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu \]

Energy distribution of \( \nu_\mu \) fluence

\[ <E> \sim 17\text{GeV} \]

\[ \nu_e/\nu_\mu \sim 0.8\% \]

\[ \bar{\nu}_e/\nu_\mu \sim 2.1\% \]

\[ \bar{\nu}_e/\nu_\mu \sim 0.07\% \]
The trigger system relies on the scintillation light signals provided by the internal PMTs and on the SPS proton extraction time for the CNGS beam.

For every CNGS cycle 2 proton spills, lasting 10.5μs each, separated by 50ms, are extracted from SPS machine.

The discrimination thresholds for the PMT sum signal have been set at ~90phe (West) and ~110phe (East), during a 60μs spill gate.

The residual 2.4ms delay is in agreement with the neutrino t.o.f. (2.44ms) taking into account the timing signal propagation delay to Hall B (~44μs)
ICARUS T600 physics potential

- **ICARUS T600**: major milestone towards realization of large scale LAr TPC detector.

- CNGS neutrino 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 event/year,
  - observation of $\nu_\tau$ events in the electron channel, using kinematic criteria,
  - search for sterile neutrinos in LSND parameter space (deep inelastic $\nu_e$ CC events excess).

- *Self triggered* events collection:
  - $\sim 80$ events/year of unbiased atmospheric $\nu$ CC,
  - zero background proton decay with $3 \times 10^{32}$ nucleons for exotic channels.
CNGS runs during 2010

ICARUS fully operational for CNGS events since October 1st 2010

October 1st to November 22nd 2010: 8x10^{18} (5.8x10^{18}) pot delivered (collected). Detector lifetime up to 90% since Nov. 1st.

<table>
<thead>
<tr>
<th>EVENT TYPE</th>
<th>COLLECTED</th>
<th>EXPECTED</th>
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</thead>
<tbody>
<tr>
<td>$\nu_{\mu}$ CC</td>
<td>114</td>
<td>129</td>
</tr>
<tr>
<td>$\nu_{\mu}$ NC</td>
<td>46</td>
<td>42</td>
</tr>
<tr>
<td>$\nu_{e}$ CC</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\nu$ XC*</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL</td>
<td>167</td>
<td>171</td>
</tr>
</tbody>
</table>

* Events at edges, with $\mu$ track too short to be visually recognized: further analysis needed.
Preliminary results of CNGS 2010 neutrino interactions

Calorimetric measurement of the deposited energy

![Graph showing calorimetric measurement of deposited energy with data and MC comparison.]

- MC: n=727; μ=8.917; σ=8.638;
- Data: n=105; μ=9.77; σ=9.797;
Preliminary results of CNGS 2010
muons interactions

- Zenithal and azimuthal distribution of muons from CNGS interactions in the Gran Sasso rocks

- Measurement of muons momentum from multiple scattering

The reconstructed average is $86.3\pm0.3$ degree, in fair agreement with expectations
Beam restarted on March 19\(^{th}\).

3.74x10\(^{19}\) (3.46x10\(^{19}\)) pot delivered (collected) up to August 28\(^{th}\).

Detector live-time improved (> 90%) due to more stable running conditions.

Trigger: PMT signal summed for each chamber (100 phe threshold), within 60\(\mu\)s beam gate
CNGS CC neutrino interaction with signal in both TPC chambers

Run 9802 Event 1054
15.10.2010, 19:12
\( \tau_e = 4599 \mu s \)
CNGS CC neutrino interaction in the rock

Predicted number of collected interactions in the rock:

$$7.8 \times 10^{-17} \text{ /pot}$$
CNGS NC neutrino interaction candidate

Run 9704 Event 693
16.09.2010, 22:12
\[ \tau_e = 2750 \mu s \]
CNGS CC neutrino interaction with $\pi^0$ production

Run 9927 Event 1462
14.11.2010, 12:53
$\tau_e = 6689 \mu s$

The total deposited energy $\sim 1$GeV
In the 2010 analyzed sample a $\nu_e$CC candidate has been identified, presumably coming from the intrinsic $\nu_e$ beam contamination.

This event has 45 GeV total energy with a single powerful e.m. shower at the vertex of about 37 GeV, and with a longitudinal profile peaking at the expected position (~88 cm).
ICARUS T600 TPC reconstruction performances

CASCADES:

➔ The total energy of the cascades is measured by charge integration with recombination correction.

Very good $e/\pi^0$ separation by means of $dE/dx$ in the first part of the cascade.
NC $\pi^0$ background rejected at 0.1% level while keeping 90% of $\nu_e$ CC.

ENERGY RESOLUTIONS:

Low energy electrons $\sigma(E)/E = 11\% / \sqrt{E(\text{MeV})} + 2\%$
Electromagnetic showers $\sigma(E)/E = 3\% / \sqrt{E(\text{GeV})}$
Hadronic shower (pure LAr) $\sigma(E)/E \sim 30\% / \sqrt{E(\text{GeV})}$

TRACKS:

➔ Momentum of high energy particles is measured via multiple scattering:
$\Delta p/p \sim 10-15\%$ depending on track length and $p$

➔ Stopping particles energy is measured by charge integration with recombination correction

➔ Stopping particle identification by means of $dE/dx$ vs $E$
ICARUS T600 spatial reconstruction

- **2D tracks reconstruction** on different views
  - hit finding $\rightarrow$ ADC pulse position (drift time) and charge reconstruction (Collection)
  - forming 2D objects (tracks, cascades) from hit

- **3D reconstruction**: complement of 2D tracks reconstruction
  - based on Polygonal Line Algorithm (PLA)
  - the procedure of sorting hits along 2D tracks independently in each view
  - As a result of the **PLA application**
    - PLA-FIT through hits of a track both hits and hit projections to the fit are sorted along the track
Particle identification is based on:
- \( \frac{dE}{dx} = f(E) \) dependency
- reconstructed 3D track segments: dx
- charge deposition on the track segment: dE

Theoretical \( \frac{dE}{dx} (E) \) curves
Fully reconstructed CNGS NC event interaction with \( \eta \) created in the primary vertex

Run 9962 Event 2276

\[ t_0 = 1439, \nu_{\text{drift}} = 1.589 \text{ mm/\mu s} \]
\[ \tau_e = 7163 \mu s \]

\[ M^*_{\gamma\gamma} = 512 \pm 39 \text{ MeV} \]
\[ p_\eta = 2066 \text{ MeV/c} \]
\[ p_t = 722 \text{ MeV/c} \]

The conversion distances are: 26 cm, 12 cm.
Example of fully reconstructed CNGS NC neutrino interaction

**Run 9814 Event 1012**

- $t_0 = 1439$, $v_{\text{drift}} = 1.589 \text{ mm/\mu s}$
- $\tau_e = 7163 \mu s$

Deposited energy is 1.07 GeV
**Example of fully reconstructed CNGS NC neutrino interaction**

Deposited energy is 1.37 GeV

<table>
<thead>
<tr>
<th>TRACK</th>
<th>$E_{\text{dep}}$ [MeV]</th>
<th>$p$ [MeV/c]</th>
<th>range [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9(p)</td>
<td>110±9</td>
<td>467±20</td>
<td>13</td>
</tr>
<tr>
<td>10(K)</td>
<td>120±10</td>
<td>365±17</td>
<td>9</td>
</tr>
<tr>
<td>11(μ)</td>
<td>161±14</td>
<td>573±27</td>
<td>53</td>
</tr>
<tr>
<td>12(e)</td>
<td>26±2</td>
<td>27±2</td>
<td>11</td>
</tr>
<tr>
<td>13(p)</td>
<td>151±13</td>
<td>553±26</td>
<td>11</td>
</tr>
<tr>
<td>14(p)</td>
<td>142±12</td>
<td>535±24</td>
<td>12</td>
</tr>
<tr>
<td>15(pi)</td>
<td>141±12</td>
<td>243±14</td>
<td>50</td>
</tr>
</tbody>
</table>
Example of fully reconstructed CNGS NC neutrino interaction

\[ E_{k16a} = 102 \pm 10 \text{ MeV} \]
\[ p_{16a} = 195 \pm 12 \text{ MeV}/c \]

\[ E_{k16b} = 685 \pm 25 \text{ MeV} \]
\[ p_{16b} = 809 \pm 25 \text{ MeV}/c \]

\[ p_{\pi^0} = 912 \pm 26 \text{ MeV}/c \]
\[ m_{\pi^0} = 128 \pm 20 \text{ MeV}/c^2 \]

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

The conversion distances are:
6.2cm, 66.8cm
ICARUS T600 @ LNGS is taking data with CNGS beam since October 2010.

The successful assembly and operation of the LAr-TPC is the experimental proof that this technique is well-suited for large scale experiments.

The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, allow to reconstruct and identify events in a new way with regard to previous/current experiments.

The 2011-2012 run with CNGS $\nu_\mu$ beam will allow to possibly detect few $\nu_\tau$ appearance events. Interesting physics perspectives also for solar and atmospheric neutrinos, sterile neutrino and proton decay.

The ICARUS experiment at the Gran Sasso Laboratory is so far the major milestone towards the realization of a much more massive LAr detector.