M. Antonello

INFN - Laboratori Nazionali del Gran Sasso

XCVII Congresso Nazionale SIF
The ICARUS T600 Collaboration

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Outline

- LAr-TPC technology
- ICARUS T600 detector
- Preliminary results from run 2010
- CNGS run 2011 and physics perspectives
- Summary

For further details please attend ICARUS communications at this conference:
- E. Segreto, “Misura di contaminazioni residue in argon con uno spettrometro di massa” Later, this session
- D. Dequal, “Un trigger multilivello per LAr TPC” Later, this session
- M. Antonello, “Commissioning of the ICARUS T600 LAr TPC in the underground Gran Sasso Laboratory”, Aula 1.7 today 15:00-17:00
- E. Scantamburlo, “Attuale limite sulla purificazione dell'argon nei rivelatori LAr TPC”, Aula 1.7 today 15:00-17:00
- C. Farnese, “Misure di vita media degli elettroni nel rivelatore ICARUS-T600” Aula 1.6, tomorrow 09:00-13:00
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).
LAr-TPC as an “electronic bubble chamber”

**Gargamelle bubble chamber**

- **Medium**: Heavy freon
- **Sensitive mass**: 3.0 ton
- **Density**: 1.5 g/cm³
- **Radiation length**: 11.0 cm
- **Collision length**: 49.5 cm
- **dE/dx**: 2.3 MeV/cm

**ICARUS electronic chamber**

- **Medium**: Liquid Argon
- **Sensitive mass**: Many ktons
- **Density**: 1.4 g/cm³
- **Radiation length**: 14.0 cm
- **Collision length**: 54.8 cm
- **dE/dx**: 2.1 MeV/cm

**Properties**

- **Bubble diameter**: ~3mm (diffraction limited)
- **40 bar pressure**: Pulsed ≈ 1ms
- **LAr**: A cheap liquid (~1€/litre), vastly produced by industry

“Bubble” size: 3 x 3 x 0.3 mm³

- **No over-pressure**: Continuously sensitive
LAr TPC performances

- **Tracking device**
  - Precise event topology ($\sigma_{x,y} \sim 1\text{mm} \sigma_z \sim 0.4\text{mm}$)
  - Momentum measurement via multiple scattering: $\Delta p/p \sim 10$-$15\%$ depending on track length and $p$

- **Measurement of local energy deposition $dE/dx$**
  - Particle ID by means of $dE/dx$ vs residual range (stopping particles)
  - $e/\gamma$ separation (2% $X_0$ sampling)

- **Very good $e/\pi^0$ separation ($10^{-3}$)**
  - Using $e/\gamma$ separation, precise topology reconstruction at vertex and $\pi^0$ mass measurement

- **Total energy reconstruction of the events from charge integration**
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events over massive volumes

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**RESOLUTIONS**

- Low energy electrons: $\sigma (E)/E = 11\% / \sqrt{E (\text{MeV})} + 2\%$
- Electromagn. showers: $\sigma (E)/E = 3\% / \sqrt{E (\text{GeV})} + 1\%$
- Hadron shower (pure LAr): $\sigma (E)/E \approx 30\% / \sqrt{E (\text{GeV})}$
The path to massive liquid Argon detectors

1. CERN
   - 24 cm drift wires chamber

2. Laboratory work
   - 3 ton prototype
   - 10 m³ industrial prototype

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

4. LNGS
   - 1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

5. PAVIA
   - T600 detector
   - 20 m

Cooperation with industry
ICARUS T600
A novel instrument for neutrino physics

- 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
  - $\text{HV} = -75 \text{ kV}$ $\text{E} = 0.5 \text{ kV/cm}$
  - $v_{\text{drift}} = 1.55 \text{ mm/µs}$

- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - $\approx 53000$ wires, 3 mm pitch, 3 mm plane spacing

- PMT for scintillation light:
  - $(20+54)$ PMTs, 8" Ø
  - VUV sensitive (128nm) with wave shifter (TPB)
Front-end Electronics and DAQ

54000 channels

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

Gas

Decoupling Boards (32 ch.)

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

H.V. (±300 V)

(18 board + 1 CPU)/VME crate

4 Multiplexers (400ns x 8ch.)

10bit FADC, 400ns sampling, 1mV/ADC (~1000e-/ADC)

Continuous waveform Recording

Multi-event circular buffer (8x1ms)

To storage

54000 channels

To storage
ICARUS T600 in LNGS Hall B

Apparatus activated on 27th May 2010, after commissioning
Optimization phase in summer 2010
Data taking in stable condition from October 1st 2010

M. Antonello talk, today

CNGS $\nu_\mu$ beam
$4.5 \times 10^{19}$ pot/yr
$\langle E_\nu \rangle \sim 17.4$ GeV
ICARUS T600: major milestone towards realization of large scale LAr detector.

Interesting physics in itself:

- **CNGS ν events collection** (beam intensity $4.5 \times 10^{19}$ pot/year, $E_\nu \sim 17.4$ GeV):
  - $1200 \nu_\mu$ CC event/year
  - $\sim 8 \nu_e$ CC event/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/yr of unbiased atmospheric $\nu$ CC
  - Zero background proton decay with $3 \times 10^{32}$ nucleons for “exotic” channels
Electronegative impurities (mainly $O_2$, $H_2O$) can attenuate $e^-$ signal: high purity is crucial!

Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

$$\tau_e [ms] = 0.3 / N[ppb \ O_2 \ equivalent]$$

Currently: $\tau_e > 6 [ms] : \sim 50 \ ppt \ !!!!$

$\tau_R$: recirculation time for a full detector volume
$k_I$ and $\tau_I$ : related to the total degassing internal rate
$k$ : related to the external leaks

$$dN/dt = -N/\tau_R + k + k_I \ exp(-t/\tau_I)$$

$\tau_R: 2 \ m^3/h \ (per \ cryostat) \ corresponding \ to \ \approx \ 6 \ day \ cycle \ time$
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.

PMT signals are summed over each of the 4 detector chambers. A “low threshold” of ~ 100 phe is used for discrimination.

For every CNGS cycle 2 proton spills, lasting 10.5\(\mu\)s each, separated by 50ms, are extracted from SPS machine. A 60\(\mu\)s acquisition gate is open in coincidence.

**Trigger logic & priorities:**

1. **CNGS + Low Threshold PMT** -> **CNGS neutrino events** ~ 1 mHz
2. **CNGS only** -> **online SW Trig on wires (hit)** (HW implemented soon for local trigger)
3. **Low Threshold PMT coincidence of 2 adjacent TPCs** -> **Mainly “cosmic” events** ~50mHz
CNGS runs during 2010

ICARUS fully operational for CNGS events since October 1\textsuperscript{st} 2010

October 1\textsuperscript{st} to November 22\textsuperscript{nd} 2010:
- $8.0 \times 10^{18}$ pot delivered
- $5.8 \times 10^{18}$ pot collected

Detector live-time up to 90% since November 1\textsuperscript{st}.

<table>
<thead>
<tr>
<th>EVENT TYPE</th>
<th>COLLECTED</th>
<th>EXPECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CC</td>
<td>115</td>
<td>129</td>
</tr>
<tr>
<td>$\nu$ NC</td>
<td>46</td>
<td>42</td>
</tr>
<tr>
<td>$\nu$ XC*</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL</td>
<td>168</td>
<td>171</td>
</tr>
</tbody>
</table>

• Events at edges: further analysis needed.

This sample kept as a training/control sample and to develop reconstruction and analysis tools.
### CNGS CC $\nu_\mu$ interaction

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_t$</td>
<td>201 [MeV/c]</td>
</tr>
<tr>
<td>$p_{\text{tot}}$</td>
<td>5.3 [GeV/c]</td>
</tr>
</tbody>
</table>

$E_{\text{dep tot}} = 2.4 \pm 0.2 \text{ GeV}$

$\mu, p = 5.1 \pm 1.0 \text{ [GeV/c]}$

- The conversion distances are: 41 cm, 7 cm.
- $M^*_{\gamma\gamma} = 122 \pm 16 \text{ MeV/c}^2$
- $p_{\pi^0} = 119 \text{ MeV/c}$
- $\pi^0, p = 208 \pm 11 \text{ [MeV/c]}$
- $\pi, p = 208 \pm 11 \text{ [MeV/c]}$
- $\text{range} = 29 \text{ cm}$

The decay of $\pi^0$ is observed.

$127 \pm 11 \text{ [MeV]}$

$110.6^\circ \pm 2.5^\circ$

$44 \pm 6 \text{ [MeV]}$
CNGS CC $\nu_\mu$ interaction

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

$p_\mu = 10.5\pm1.1$ 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

$M^{\gamma\gamma}_* = 125\pm15$ MeV/c$^2$

Total transverse momentum
$\sim 250$ MeV (consistent with Fermi momentum)
Neutrino energy reconstruction for CNGS $\nu_\mu$ CC events

- **Calorimetric reconstruction:**
  - "raw" deposited energy compared with MC for CNGS CC interactions (2010 data)

- **Total measured energy of 2010 $\nu_\mu$ CC:**
  - Lepton and hadronic jet reconstructed separately
  - $\mu$ momentum via multiple scattering
  - Hadron energy from calorimetric measurement $\oplus$ MC corrections for non containment/non compensation.

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**PRELIMINARY!!!**

Calibrations: to be checked

-- DATA: $<E> = 25.4 \pm 2.0$ GeV
93 collected events

-- MC: $<E> = 26.1 \pm 0.5$ GeV

$<E> = 11.5$ GeV
$<E_{MC}> = 12.0$ GeV

---
A 2010 $\nu_e$ CC candidate presumably coming from intrinsic $\nu_e$ beam contamination. This event has 45 GeV of total energy with a single powerful 37 GeV e.m. shower at vertex with a longitudinal profile peaking at the expected position (~88 cm).
CNGS NC event
with $\eta$ particle created at the primary vertex

Run 9962 Event 2276
$t_0 = 1439$, $v_{\text{drift}} = 1.589 \text{ mm}/\mu$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.

$E_{\text{dep},\pi} = 137 \pm 12 \text{ MeV}$
$E_{\text{dep},e} = 35 \pm 3 \text{ MeV}$
$E_{\text{dep}} = 172 \pm 15 \text{ MeV}$

$\tau_e = 7163 \mu$s

$E_{\text{dep},\pi} = 1884 \pm 41 \text{ MeV}$

$E_{\text{dep}} = 242 \pm 15 \text{ MeV}$

Conversion angle: $44.5 \pm 2.5^\circ$

$\pi \rightarrow \mu \rightarrow e$
CNGS NC event (1)

Deposited energy is 1.07 GeV

<table>
<thead>
<tr>
<th>TRACK</th>
<th>$E_{dep}$[MeV]</th>
<th>$p$ [MeV/c]</th>
<th>range[cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(π)</td>
<td>157±13</td>
<td>261±15</td>
<td>49</td>
</tr>
<tr>
<td>2(π)</td>
<td>119±10</td>
<td>217±12</td>
<td>51</td>
</tr>
<tr>
<td>3(π)</td>
<td>882±75</td>
<td>1011±76</td>
<td>135</td>
</tr>
<tr>
<td>4(π)</td>
<td>325±28</td>
<td>443±29</td>
<td>7</td>
</tr>
<tr>
<td>5(p)</td>
<td>203±17</td>
<td>650±30</td>
<td>25</td>
</tr>
<tr>
<td>6(p)</td>
<td>140±12</td>
<td>531±24</td>
<td>24</td>
</tr>
<tr>
<td>7(p)</td>
<td>95±8</td>
<td>433±19</td>
<td>8</td>
</tr>
<tr>
<td>8(p)</td>
<td>69±6</td>
<td>366±16</td>
<td>7</td>
</tr>
</tbody>
</table>

Run 9814 Event 1012
$t_0 = 1439$, $v_{drift} = 1.589$ mm/µs
$\tau_e = 7163$ µs
## CNGS NC event (2)

**Deposited energy is 1.37 GeV**

<table>
<thead>
<tr>
<th>TRACK</th>
<th>$E_{dep}$ [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(π)</td>
<td>141±12</td>
<td>243±14</td>
<td>50</td>
</tr>
</tbody>
</table>
\[ E_{k16a} = 102 \pm 10 \text{ MeV} \]
\[ p_{16a} = 195 \pm 12 \text{ MeV/c} \]

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

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

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

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

The conversion distances are:
6.2cm, 66.8cm
The capability to identify/reconstruct NC interactions and distinguish them from $\nu_e$ CC events is a key issue which identifies LAr-TPC as the ideal candidate for the next generation of neutrino oscillation experiments willing to study $\nu_\mu \rightarrow \nu_e$ appearance.

Conversion distances from primary vertex:
- 71.2 cm
- 13.7 cm
- 41.8 cm
- 17.4 cm

Initial ionizations (~2 mip):
- 5.1 MeV/cm
- 6.1 MeV/cm
- 3.1 MeV/cm
- 4.4 MeV/cm

$\pi^0$ showers clearly identified, invariant mass reconstructed, conversion vertex identified, initial ionization consistent with 2 mips.
Reconstruction of $\mu$ from CNGS $\nu$ interactions in the rock

Reconstruction of muon direction (from rock $\nu$): agrees with expectations

$\theta = 86.7^\circ$, $\varphi = 0^\circ$
### Cosmic $\nu$ event candidate

**Track**
- 1 (prob. $\pi$, decays in flight)
- 2 ($\pi$)
- 2a ($\mu$)
- 2b (e)
- 3 ($\mu$)
- 4 (p)
- 5 (p)
- 6 (?) (merged with vtx)

<table>
<thead>
<tr>
<th>Track</th>
<th>$E_k$ [MeV]</th>
<th>Range [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>136.1</td>
<td>55.77</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>79.1</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td>24.1</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>231.6</td>
<td>99.1</td>
</tr>
<tr>
<td>3</td>
<td>168</td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>152</td>
<td>16.3</td>
</tr>
<tr>
<td>5</td>
<td>152</td>
<td>2.9</td>
</tr>
<tr>
<td>6</td>
<td>152</td>
<td></td>
</tr>
</tbody>
</table>

- **Total deposited energy:** 887 MeV
- **Total reconstructed momentum:** 929 MeV/c at about 35° away from the CNGS beam direction
Cosmic events calorimetric reconstruction

- Physical events identified using an automatic filter procedure optimized to reject fake triggers:
  - The output of the visual scan used to validate the automatic algorithm for event pre-selection and noise rejection
  - For cosmic (and other) events: 99% efficiency with a rejection of empty events at the $10^{-3}$ level.

- Identification of the region containing the events (only in the Collection view at the moment) and energy estimation taking into account of electron lifetime and quenching corrections.

- Same filter applied to MC cosmic events: for the energy spectrum we take into account the efficiency of the PMTs estimated from real data.

\[
\begin{align*}
\text{E}_{\text{dep}} \text{ of cosmic events} \\
\text{MC: } \langle E \rangle = 0.949 \text{ GeV} \\
\sim 3300 \text{ events} \\
\text{Real: } \langle E \rangle = 1.005 \text{ GeV} \\
\sim 281000 \text{ collected events}
\end{align*}
\]
CNGS runs during 2011

- Beam restarted on March 19th.
- Trigger: PMT signal summed for each chamber (100 phe threshold), within 60µs beam gate
- 3.9x10^{19} (3.7x10^{19}) pot delivered (collected) up to September 12th.

- Detector live-time improved (> 93%): more stable running conditions.

Dead time not intrinsic to DAQ + trigger!

Data Analysis: WORK IN PROGRESS
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.

- $\tau \rightarrow e\nu\nu$ 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.

- Currently collected CC/NC data will be used to tune the selection criteria in order to optimize the sensitivity for $\tau$ search.
Beyond ICARUS T600: Search for sterile neutrino

Several recent anomalies point out to oscillations with $\Delta m^2 > \sim eV^2$:

- $\nu_e$ and anti-$\nu_e$ appearance at accelerators (LSND, MiniBoone) $\rightarrow$ arXiv:1007.1150 etc.
- anti-$\nu_e$ disappearance (~6%) at reactors after re-evaluation of reactor fluxes (+ 3%) $\rightarrow$ arXiv:1101.2755v4
- Disappearance of $\nu_e$ (~14%) from Mega Curie radioactive sources in Gallium solar neutrino experiments (GALLEX, SAGE) ($\Delta m^2 > 1.5 eV^2$, $0.02 < \sin^2 2\theta < 0.23$ at 99.7 C.L.) $\rightarrow$ arXiv:1006.3244
- Cosmological data (WMAP) not excluding 4th neutrino state.

$\nu$ knowledge still incomplete: definitive experiment needed.
$\nu$ LAr-TPC experiment at a CERN-PS refurbished $\nu$ beam can be the solution
A dual LAr-TPC detector at CERN-PS

- Two strictly identical LAr-TPC to search for both $\nu_\mu \rightarrow \nu_e$ LSND signal (appearance) and $\nu_e \rightarrow \nu_x$ reactor anomaly (disappearance) in Far and Near positions.
- Cross sections and experimental biases canceling out in the comparison because of $\nu_e$ identical spectra and same LAr-TPC technique of the two detectors.

Re-use old TT7 tunnel/cavern to house primary beamline, target station
Proton beam to be provide by CERN PS

- “Far” detector, 850 m L/E~1 km/GeV: ICARUS T600 transported to CERN BEBC Hall in after CNGS program, ensuring new operation soon;
- “Near” detector bg. 181, 127 m L/E~0.15 km/GeV: to be constructed anew (2 years), as much as possible identical to the T600 but with a mass of 150 t
Comparing LSND and MiniBooNE sensitivities (*arXiv:0909.0355*)

Expected sensitivity for proposed experiment exposed at CERN-PS neutrino beam (left) for $2.5 \times 10^{20}$ pot (30 kW basic option) and twice as much for anti-neutrino (right). LSND allowed region is fully explored both for $\nu$ /anti-$\nu$. 
Sensitivity to $\nu_e$ disappearance anomalies

- Sensitivities (90% CL) in the $\sin^2(2\theta_{\text{new}})$ vs. $\Delta m^2_{\text{new}}$ for an integrated intensity of $2.5 \times 10^{20}$ pot (30 kW average CERN/PS beam intensity), a fully dedicated (90 kW) neutrino beam and a 270 kW curve. They are compared (red) with “anomalies” of reactor + Gallex/Sage experiments. 1% overall + 3% bin-to-bin systematic uncertainty is included (for 100 MeV bins).
ICARUS T600 @ LNGS is taking data with the CNGS beam in stable conditions since October 2010.

The unique imaging capability of ICARUS and its spatial and calorimetric resolutions allow to reconstruct and identify events in a new way w.r.t. previous and current experiments.

The 2011-2012 run with CNGS $\nu_\mu$ beam will allow to possibly detect few $\nu_\tau$ appearance events.

Interesting perspective also for atmospheric neutrinos, sterile neutrinos and proton decay.

The successful assembly and operation of ICARUS T600 is the experimental proof that this technique is suitable for large scale experiments.

LAr-TPC can be employed to solve the “sterile neutrino puzzle”: a novel search with a refurbished $\nu$ beam at the CERN-PS is being proposed (after the ICARUS T600 exploitation @ LNGS).
Thank you!
Backup slides
Identification of the nature of particles is obtained by studying the event topology and the energy deposition per track length unit as a function of the particle energy for muons/pions, kaons and protons.

**Particle identification is based on:**
- \( \frac{dE}{dx} = f(E) \) dependency
- reconstructed 3D track segments: \( dx \)
- charge deposition on the track segment: \( dE \)
Polygonal 3D Line Algorithm

- Initialization
- Projection
- Vertex optimization
- Convergence?

\[ G(v_i) = \frac{1}{n} \Delta_n(v_i) + \lambda \frac{1}{k + 1} P(v_i) \]

- Local squared distance to hits
- Local angle penalty term

Segment number \( k \) exceeds \( c \cdot n \) where \( c \) is a given threshold and \( n \) is the track hits number: longer tracks usually are more straight.

http://www.iro.umontreal.ca/~kegl/research/pcurves
Nucleon decay: single event capability

- LAr-TPC provides a much more powerful bkg rejection w.r.t. other techniques, a large variety of exclusive decay modes measurements bkg free.

- ICARUS-T600 ($3 \times 10^{52}$ nucleons) well suited for channels not accessible to Č detectors due to complicated event topologies, or because the emitted particles are below threshold (e.g. $K^\pm$).

- In few years exposure the T600 can improve limits on some “super-symmetric favored” exotic channels:

<table>
<thead>
<tr>
<th>Channel</th>
<th>90%CL-5y</th>
<th>(pdg 90%CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow n p^*$</td>
<td>$1.1 \times 10^{32}$</td>
<td>$(2.5 \times 10^{31})$</td>
</tr>
<tr>
<td>$p \rightarrow n r p^<em>K^</em>$</td>
<td>$2.7 \times 10^{32}$</td>
<td>$(2.5 \times 10^{32})$</td>
</tr>
<tr>
<td>$n \rightarrow e^- K^+$</td>
<td>$3.2 \times 10^{32}$</td>
<td>$(3.2 \times 10^{31})$</td>
</tr>
<tr>
<td>$n \rightarrow \mu^+ \pi$</td>
<td>$1.5 \times 10^{32}$</td>
<td>$(1.0 \times 10^{32})$</td>
</tr>
<tr>
<td>$n \rightarrow \nu \pi^0$</td>
<td>$1.1 \times 10^{32}$</td>
<td>$(1.1 \times 10^{32})$</td>
</tr>
</tbody>
</table>
Sensitivity region, in terms of standard deviations $\sigma$, for 6000 raw CNGS neutrino events. The potential signal is above the background generated by the intrinsic $\nu_e$ beam contamination, in the deep inelastic interval 10–30 GeV.

The $\Delta m^2$ distribution extends widely beyond the LNSD and MiniBoone regions.

Two indicated points are reference values of MiniBoone.

*T600 at the CNGS offers an unique possibility of searching for sterile neutrinos, largely complementary and comparable to the Fermilab programme.*
• The present proposed experiment could determine both the mass difference and the value of the mixing angle.
• Very different and clearly distinguishable patterns are possible, depending on the values in the \((\Delta m^2, \sin^2 2\theta)\) plane.
• The intrinsic \(\nu_e\) background is also shown.
Event rates for the near and far detectors given for $2.5 \times 10^{20}$ pot (30 kW beam power) for $E_\nu < 8$ GeV. The oscillated signals are clustered below 3 GeV of visible energy.

<table>
<thead>
<tr>
<th></th>
<th>$\nu$ focus</th>
<th></th>
<th>$\bar{\nu}$ focus</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FAR</td>
<td>NEAR</td>
<td>FAR</td>
<td>NEAR</td>
</tr>
<tr>
<td>Fiducial mass</td>
<td>500 t</td>
<td>150 t</td>
<td>500 t</td>
<td>150 t</td>
</tr>
<tr>
<td>Distance from target</td>
<td>850 m</td>
<td>127 m</td>
<td>850 m</td>
<td>127 m</td>
</tr>
<tr>
<td>$\nu_\tau$ interactions</td>
<td>$1.2 \times 10^6$</td>
<td>$18 \times 10^6$</td>
<td>$2.0 \times 10^5$</td>
<td>$2.3 \times 10^6$</td>
</tr>
<tr>
<td>QE $\nu_\tau$ (or $\bar{\nu}_\tau$) interactions</td>
<td>$4.5 \times 10^5$</td>
<td>$66 \times 10^5$</td>
<td>87000</td>
<td></td>
</tr>
<tr>
<td>Events/Burst</td>
<td>0.17</td>
<td>2.5</td>
<td>0.03</td>
<td>0.3</td>
</tr>
<tr>
<td>Intrinsic $\nu_\tau + \bar{\nu}_\tau$ from beam</td>
<td>9000</td>
<td>120000</td>
<td>2000</td>
<td>29000</td>
</tr>
<tr>
<td>Intrinsic $\nu_e + \bar{\nu}_e$ (E. &lt; 3 GeV)</td>
<td>3900</td>
<td>54000</td>
<td>880</td>
<td>13000</td>
</tr>
<tr>
<td>$\nu_e$ oscillations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta m^2 = 2. eV^2; \sin^2 2\theta = 0.002$</td>
<td>1194</td>
<td>1050</td>
<td>230</td>
<td>58</td>
</tr>
<tr>
<td>$\Delta m^2 = 0.4 eV^2; \sin^2 2\theta = 0.02$</td>
<td>2083</td>
<td>2340</td>
<td>330</td>
<td>115</td>
</tr>
<tr>
<td>$\Delta m^2 = 0.064 eV^2; \sin^2 2\theta = 0.96$</td>
<td>3350</td>
<td>1250</td>
<td>465</td>
<td>140</td>
</tr>
<tr>
<td>$\Delta m^2 = 4.42 eV^2; \sin^2 2\theta = 0.0066$</td>
<td>2980</td>
<td>25050</td>
<td>490</td>
<td>3220</td>
</tr>
</tbody>
</table>
Predicted number of collected interactions in the rock:

$7.8 \times 10^{-17}$/pot
CNGS CC neutrino interaction with signal in both TPC chambers

Cathode (18m)

Collection right view

Electron drift 1.5m

Collection left view

Run 9802 Event 1054
15.10.2010, 19:12
$\tau_e = 4599\mu s$
CNGS NC neutrino interaction candidate

Run 9704 Event 693
16.09.2010, 22:12
$\tau_e = 2750\,\mu\text{s}$

- Drift time
- Wire coordinate (~3m)
- CNGS beam direction
- Drift coordinate (1.5m)
CNGS CC neutrino interaction with $\pi^0$

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

The total deposited energy $\sim 1\,\text{GeV}$
CNGS – Cern project for a neutrino beam to Gran Sasso

Proton beam → (interactions) → \( \pi^+, K^+, (\mu^+) \) → (decay in flight) → \( \mu^+ + \nu_\mu \)

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

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

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

\[ \nu_\mu/\nu_\mu \sim 2.1\% \]

\[ \nu_e/\nu_\mu \sim 0.07\% \]
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 10.5 µs each, separated by 50 ms, are extracted from SPS machine.

The discrimination thresholds for the PMT sum signal have been set at ~100 phe, within a 60 µs spill gate, open in coincidence with the proton extraction.

80 events per day recorded with a trigger rate of about 1 mHz.

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

- A low PMT discrimination threshold required to maximize the efficiency detection of low energy cosmic events.

- Efficient reduction of spurious signals: coincidence of PMTs sum signals of 2 adjacent chambers in the same module (50% cathode transparency).

- A trigger rate of about 20 mHz per cryostat has been achieved leading to ~100 cosmic events/hour collected on the full T600 with only 6% of events classified as empty by visual scanning (160 events/hour predicted by Monte Carlo).

- This difference is due to PMT’s HV biasing/signal read-out that does not allows full collection of scintillation light. Only prompt photons (about 30-40% of the total) can be exploited for trigger signal generation.
CNGS $\nu_\mu$ CC events calorimetric reconstruction

- Besides “full” track and event reconstruction, T600 events can be reconstructed in a calorimetric way.
- Lepton and hadronic part reconstructed separately.
- Hadronic part corrected for non-compensation/non-containment (based on MC).

**First step:** deposited energy compared with MC in CC interactions

**Second step:** muon momentum reconstructed via multiple scattering

<table>
<thead>
<tr>
<th>Energy Deposition (GeV)</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>30</td>
</tr>
<tr>
<td>0.02</td>
<td>20</td>
</tr>
<tr>
<td>0.03</td>
<td>10</td>
</tr>
</tbody>
</table>

- MC: $n=727; \mu=8.917; \sigma=8.638$
- Data: $n=105; \mu=9.77; \sigma=9.797$

\[\langle E\rangle = 11.5 \text{ GeV} \quad \langle E_{MC}\rangle = 12.0 \text{ GeV}\]
Neutrino energy reconstruction for $\nu_\mu$ CC events

- Total measured energy of the 2010 $\nu_\mu$ CC events:
- $\mu$ momentum from multiple scattering
- hadron energy from calorimetric measurement $\oplus$ MC corrections for non containment and non-compensation.

DATA: $\langle E \rangle = 23.1 \pm 2.0$ GeV ~ 80 collected events

MC: $\langle E \rangle = 26.1 \pm 0.5$ GeV

PRELIMINARY!!!
Calibrations: to be checked