# The 600 Ton ICARUS detector at the LNGS

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Topics

1. R & D on ICARUS technology detector method
2. Installation of the T600 at the LNGS
3. Physics program: (a) high energy neutrons from CERN, (b) Search for exotic proton decay
4. Possible future plans to search for sterile neutrinos
5. As a prototype for multi-kiloton detector around the world

Summary

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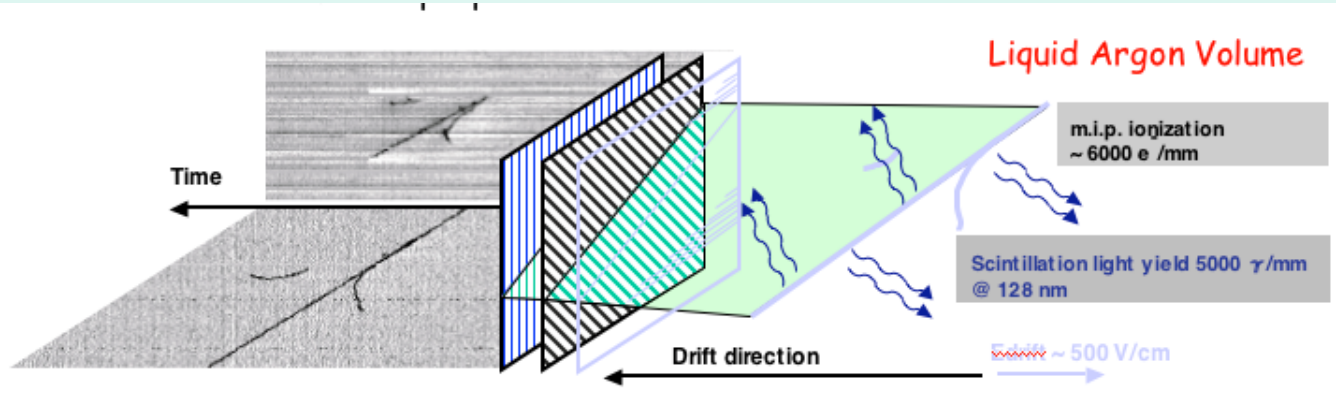
# A powerful detection technique

The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)] first proposed to INFN in 1985 [ICARUS: INFN/AE-85/7] capable of providing a 3D imaging of any ionizing event (''electronic bubble chamber'') with in addition:

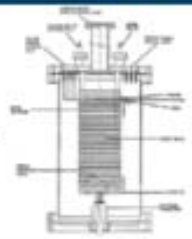
- continuously sensitive, self triggering
- high granularity (~ 1 mm)
- excellent calorimetric properties




Electrons from ionizing track are drifted in LAr by $E_{drift}$. They traverse 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 ($O_2$, $H_2O$,$C0_2$).
- Target: 0.1 ppb $O_2$ equivalent= 3 ms lifetime (4.5 m drift @ $E_{drift}$ = 500 V/cm).

# The path to larger LAr detectors



CERN

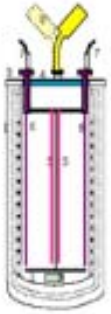
24 cm drift wires chamber

1

**1987**: First LAr TPC. Proof of principle. Measurements of TPC performances.

2

3 ton prototype



**1991-1995**: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

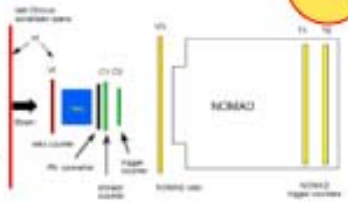
CERN

Laboratory work

3

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

10 m$^3$ industrial prototype

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

Icarus T600 experiment

**2010-...** : Datataking with CNGS beam

Cooperation with industry
AirLiquide, Breme, Cinel, CAEN

2001: First T600 module

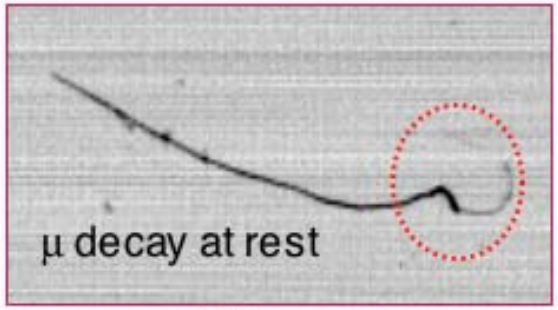
5

6

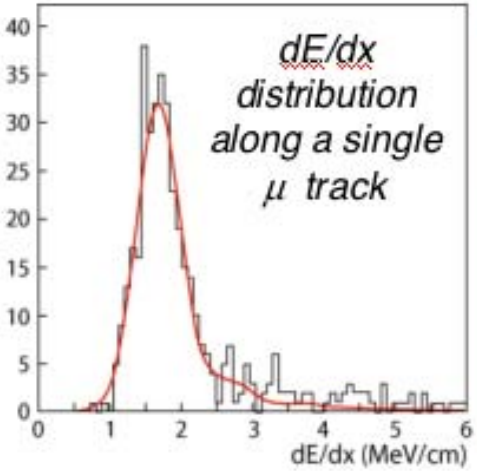
LNGS Hall-B

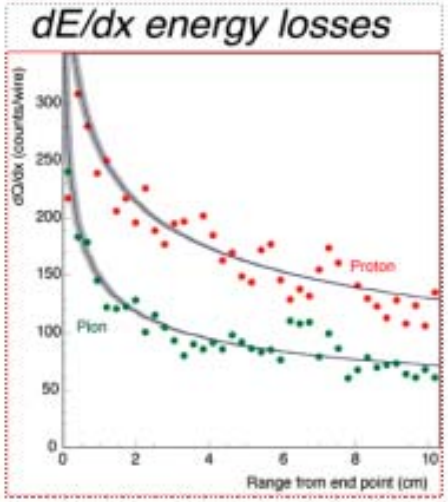
# LAr-TPC performance

- Tracking device:
  - precise event topology ($s_{x,y}$ ~ 1mm, $s_z$ ~ 0.4mm)
  - μ momentum measurement via multiple scattering: _p/p ~10-15% depending on track length and p




- Measurement of local energy deposition dE/dx:
  - e/≥ separation (2% $X_0$ sampling);
  - particle ID by means of dE/dx vs range




- Total energy reconstruction by charge integration:
  - full sampling, homogeneous calorimeter with excellent accuracy for contained events

RESOLUTIONS

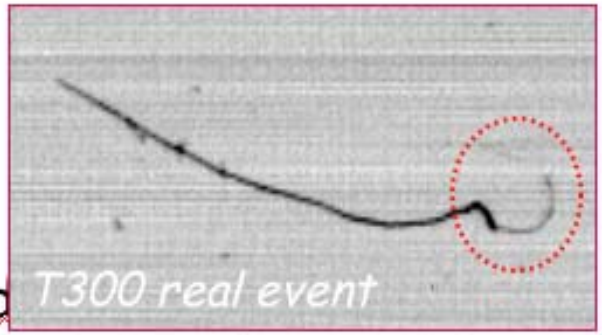
Low energy electrons: _(E)/E = 11% / √ E(MeV)+2%

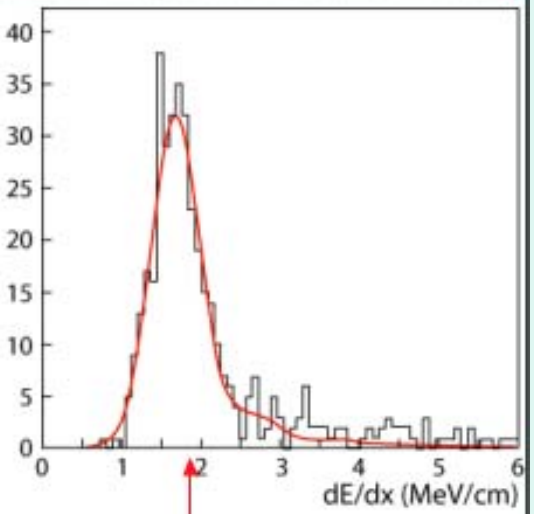
Electromagnetic showers: _(E)/E = 3% / √ E(GeV)

Hadron shower (pure LAr): _(E)/E ≈ 30% / √ E(GeV)

# Summary of LAr TPC performances

- Tracking device
  - Precise event topology
  - Momentum via multiple scattering
- Measurement of local energy deposition d
  - e / $\gamma$ separation (2%$X_0$ sampling)
  - Particle ID by means of dE/dx vs range
- Total energy reconstruction of the events from charge integration
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events




dE/dx distribution along a single muon track

RESOLUTIONS

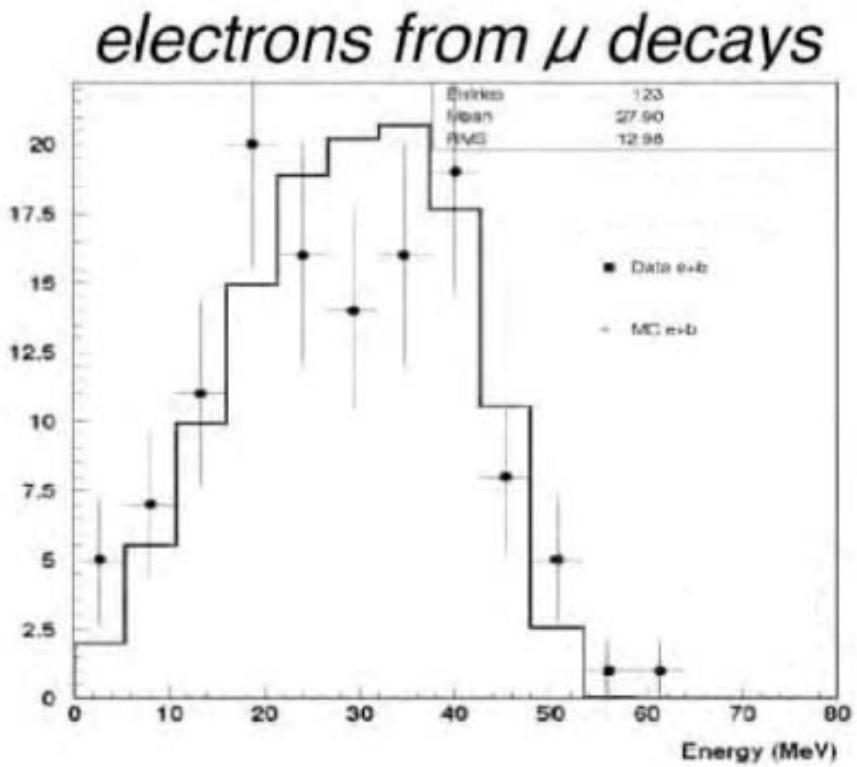
Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(\text{MeV})} + 2\%$

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

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

# Electrons from muon decay

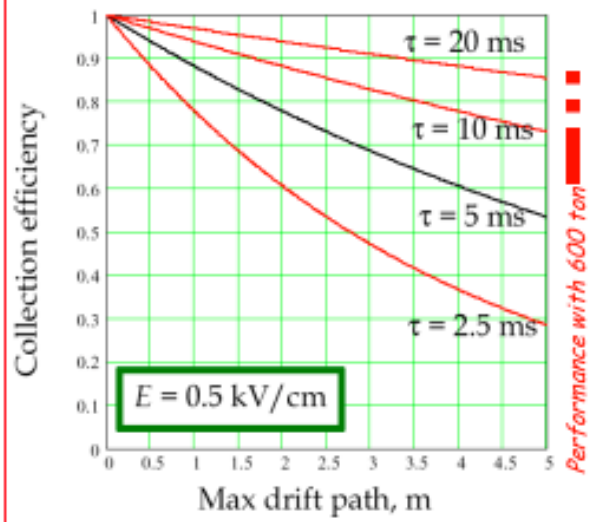
- Excellent resolution obtained from the measured decay electron spectrum (Michel parameter) from muon decays



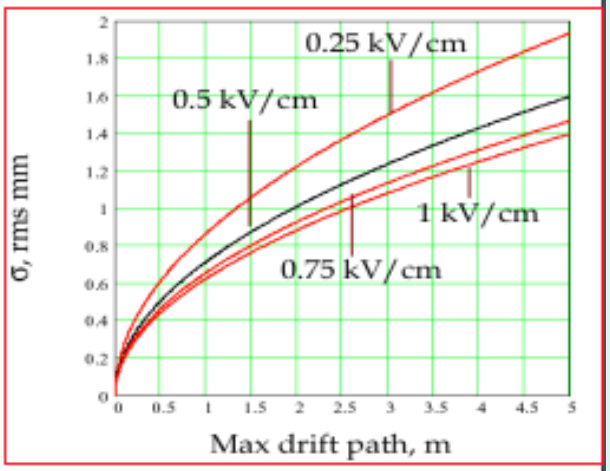
# The key feature of LAr imaging: very long e-mobility

- The main technological challenge of the development of the cryogenic liquid Ar chamber is the capability of ensuring a sufficiently long free electron lifetime.
- Indeed the free electron path in a liquid is ≈ 600 times shorter than in a gas. For instance 10 ms lifetime corresponds to a 30 ppt (t=trillion !) of Oxygen equivalent.
- At 500v/cm, a 5m drift length corresponds to a drift time of 3.1 ms (1.6 m/ms).
- The intrinsic bubble size (rms diffusion) is given by
- The values for 5m drift are $\langle\sigma_D\rangle \approx 1.1$ mm and $\sigma_{max} \approx 1.6$ mm , tiny with respect to the wire pitch (≥ 2mm).

$$\sigma_D[mm] = 0.9\sqrt{T_D[ms]}$$

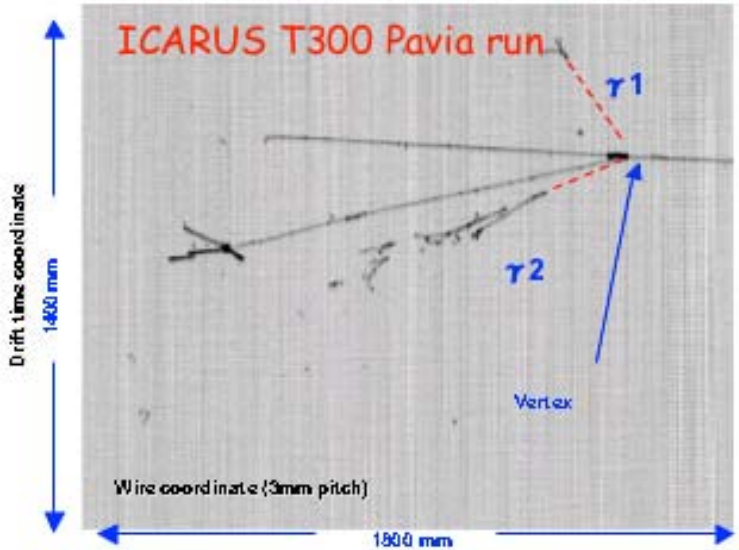



Drifting charge attenuation versus drift path at different electron lifetimes

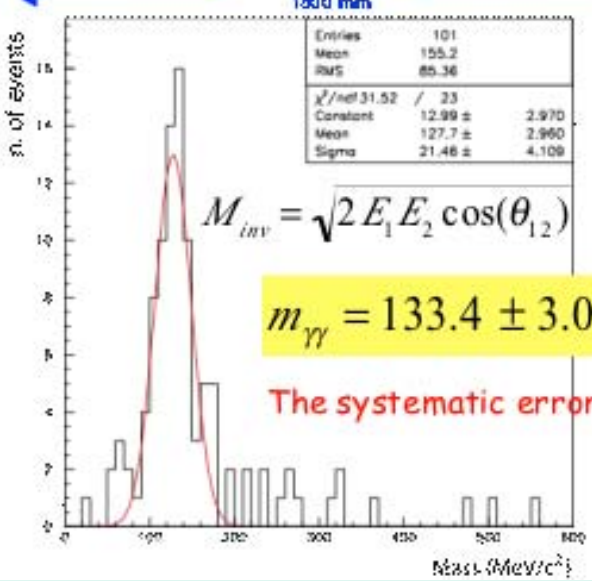


# electron - $\pi^0$ identification

## Reconstruction of $\pi^0$-showers



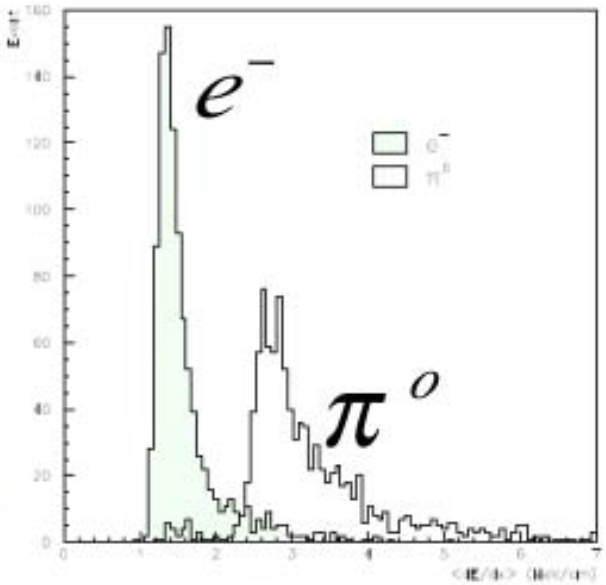

Electron shower events are extremely well identified experimentally, because of the ionization behaviour in the first cells after the vertex.



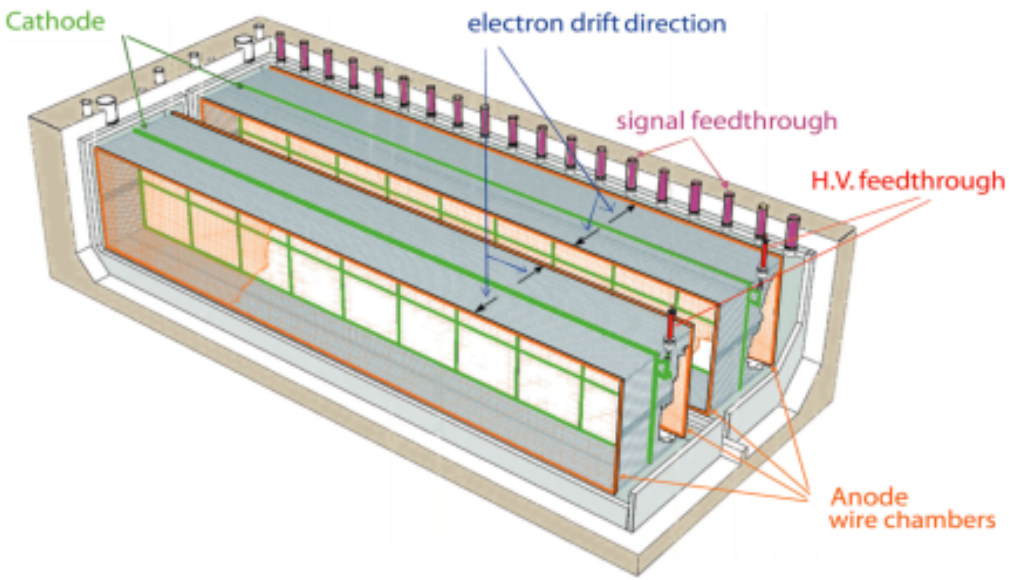

$$M_{inv} = \sqrt{2 E_1 E_2 \cos(\theta_{12})}$$

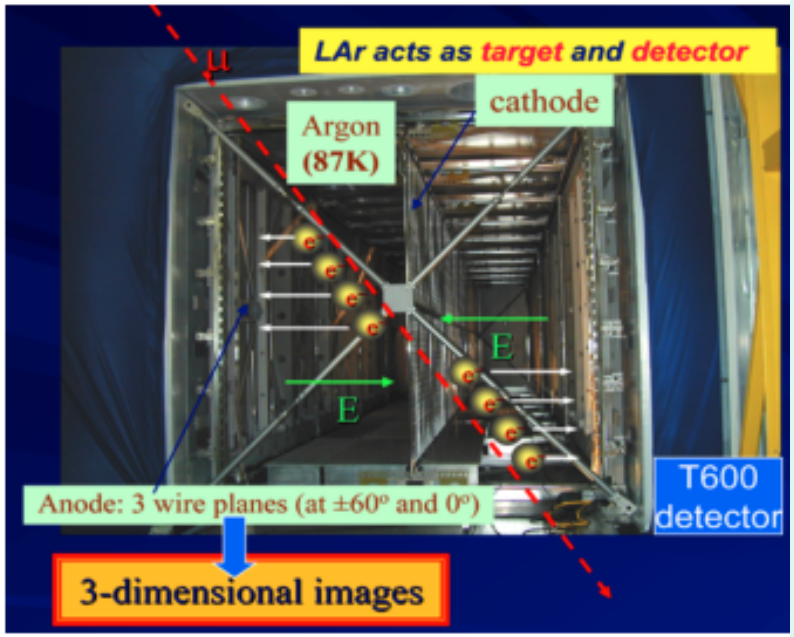
$$m_{\gamma\gamma} = 133.4 \pm 3.0(stat) \pm 4.0(sys)\mathrm{MeV/c^2}$$

The systematic error mostly due to the calibration



# The ICARUS T600 detector

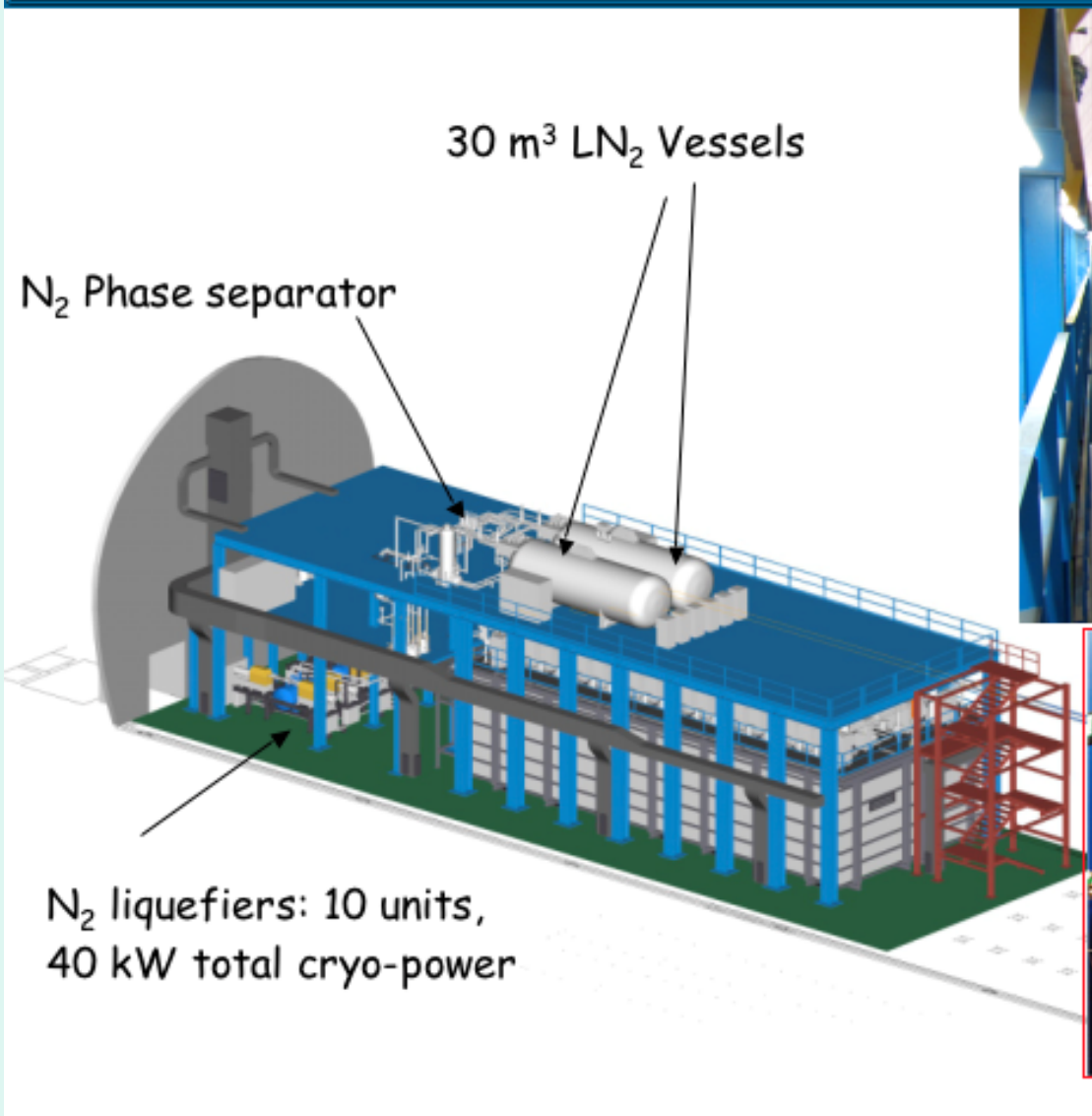


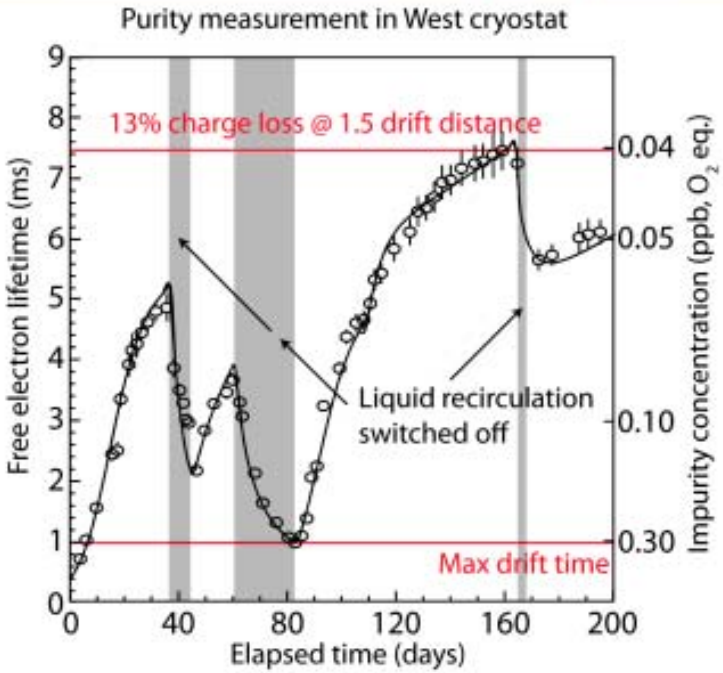

- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 $m^3$ each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E = 0.5 kV/cm
  - $v_{drift}$ = 1.55 mm/μs

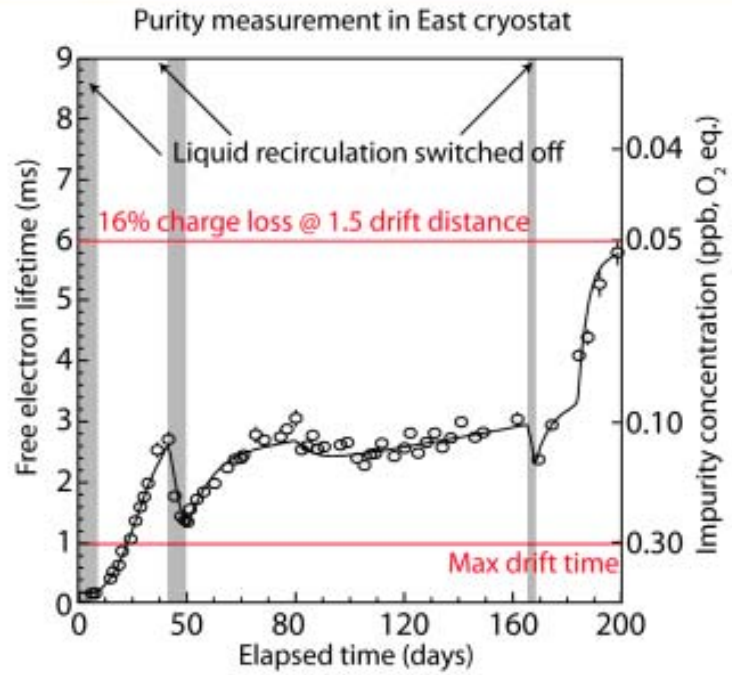
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- PMT for scintillation light:
  - (20+54) PMTs, 8" Ø
  - VUV sensitive (128nm) with wave shifter (TPB)

# ICARUS T600 in LNGS Hall B



# LAr purity time evolution




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

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

$\tau_{ele}$ [ms] = 0.3 / N[ppb $O_2$ equivalent]

$\tau_R$: 2 $m^3/h$ corresponding to ≈ 6 day cycle time

$\tau_R$: recirculation time for a full detector volume

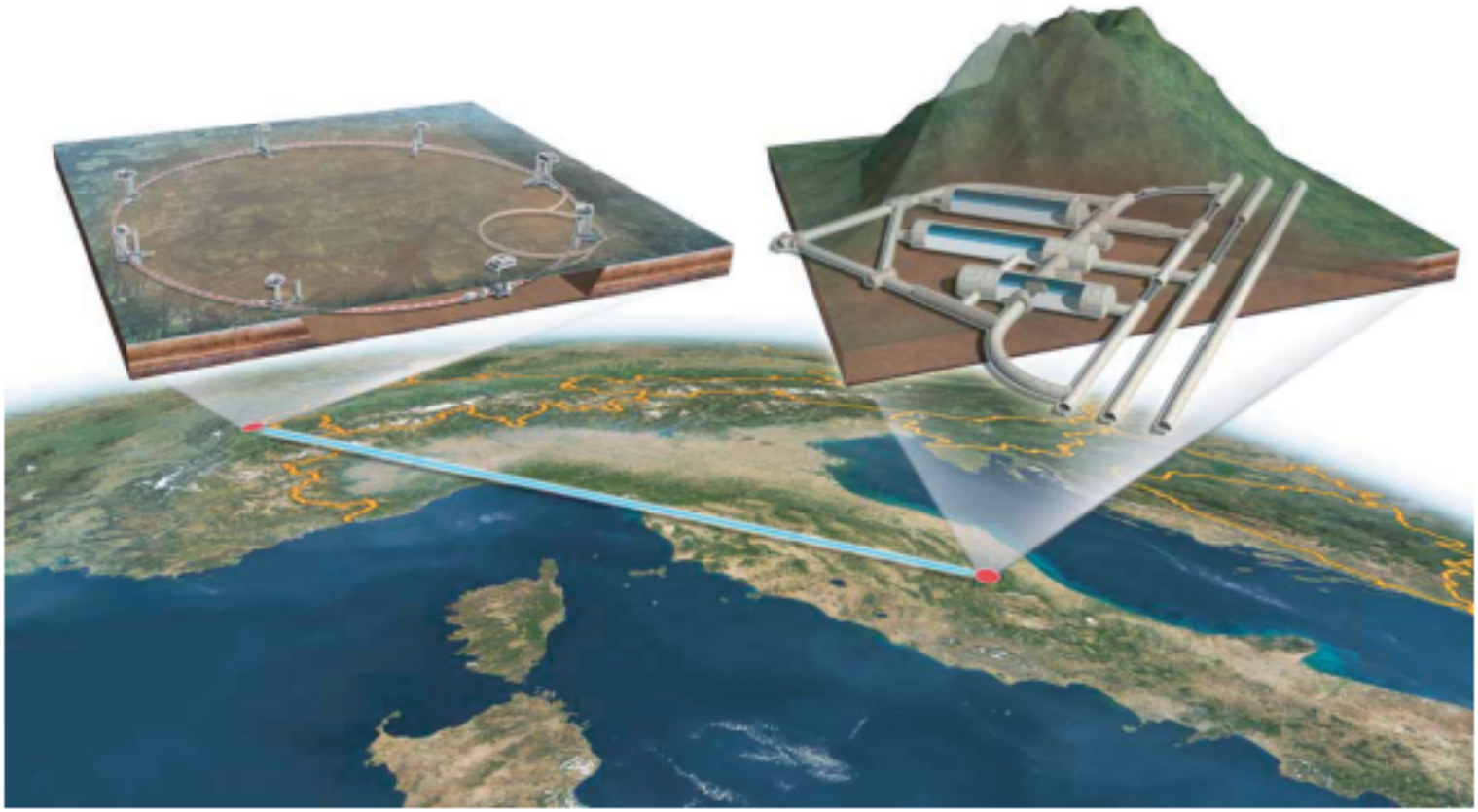
$k_I$ and $\tau_I$ : related to the total degassing internal rate

k : related to the external leaks

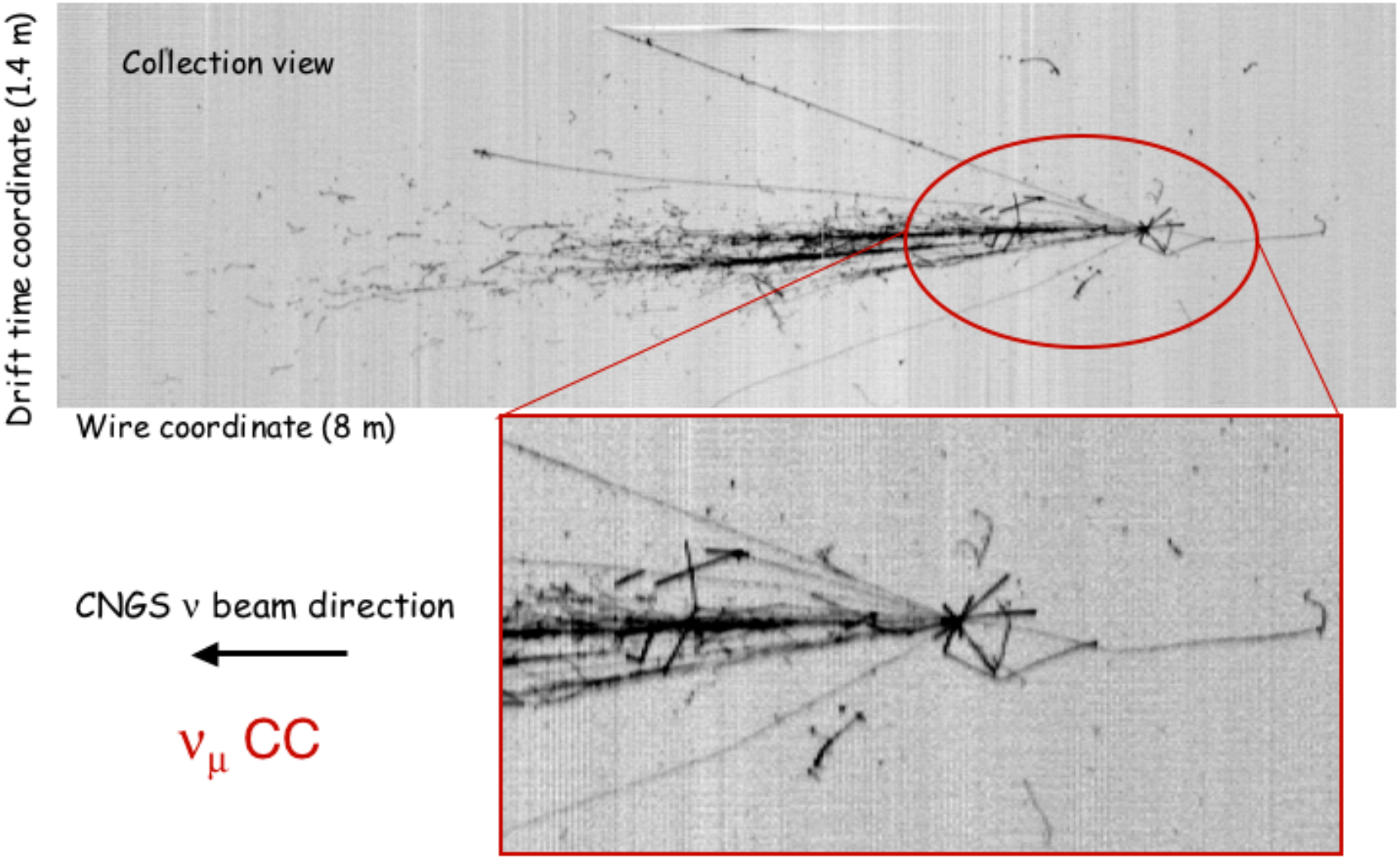
# ICARUS T600 physics potential

- ICARUS T600: **major milestone** towards realization of large scale LAr detector. Interesting physics in itself: unique imaging capability, spatial/calorimetric resolutions and $e/\pi^0$ separation → **events "seen in a new Bubble chamber like" way**.
- CNGS $\nu$ events collection (beam intensity 4.5 $10^{19}$ pot/year, $E_\nu$ ~ 17.4 GeV):
  - 1200 $\nu_\mu$ *CC* event/year;
  - ~ 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:
  - ~ 80 events/y of unbiased atmospheric $\nu$ *CC*;
  - zero background proton decay with 3 x $10^{32}$ nucleons for "exotic" channels.

# ICARUS and Status of Liquid Argon Technology

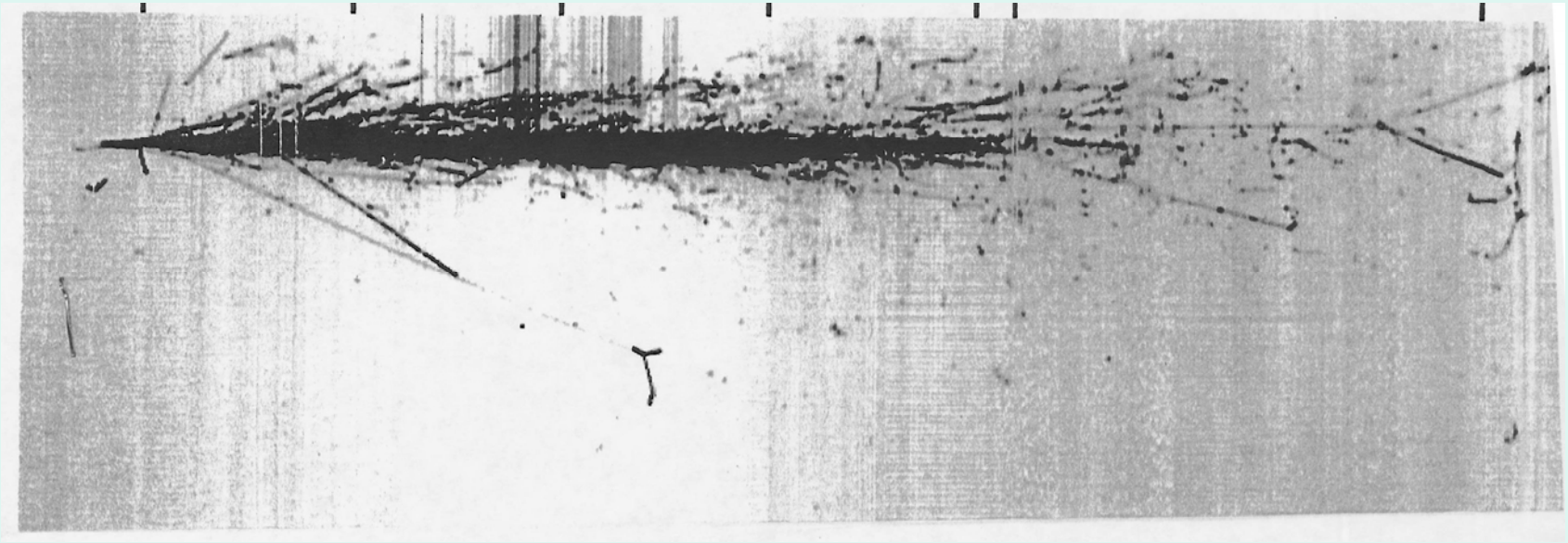


# CNGS neutrino interactions in ICARUS T600



# ICARUS 9839/1274

**CERN beam→**



**Candidate for a $\nu_e$ interaction**

# Preliminary results of first CNGS 2010 run

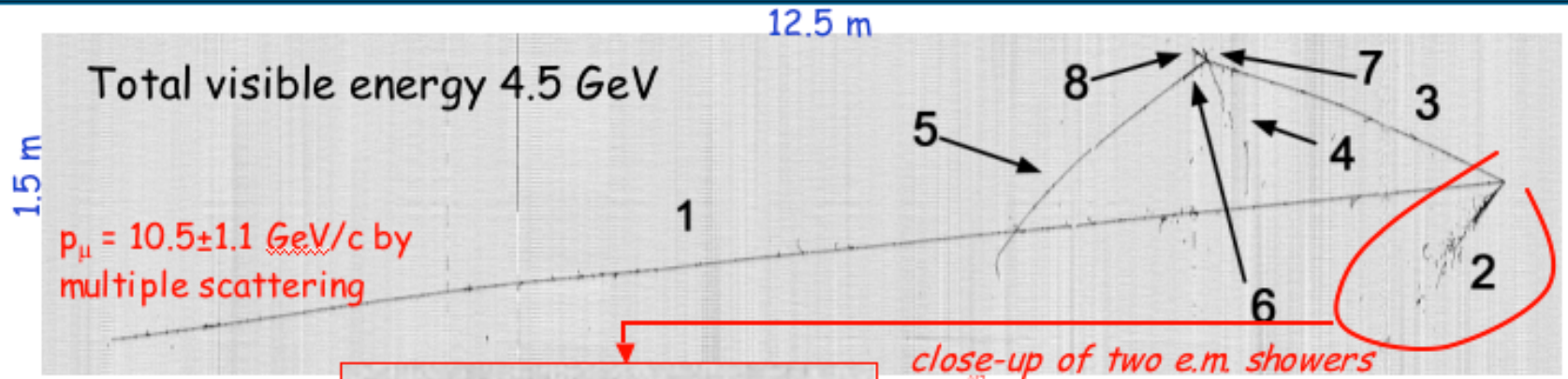
- Analyzed sample: 1494 CNGS triggers, i.e. $4.54 \cdot 10^{18}$ pot = 78 % out of whole sample. Classified by visual scanning into fiducial volume of 434 t.
- Number of collected interactions compared with number of interactions predicted ((2.6 $\nu_\mu$ CC + 0.86 $\nu_\mu$ NC) $10^{-17}$/pot), in the whole energy range up to 100 GeV, corrected by fiducial volume and DAQ dead-time.

| Event type | Collected | Expected |
|---|---|---|
| $\nu_\mu$ CC | 94 | 98 |
| $\nu_\mu$ NC | 32 | 31 |
| $\nu_\mu$ XC * | 6 | - |
| Total | 132 | 129 |

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

On overall statistics in agreement with expectations.

# LAr-TPC: powerful technique. Run 9927 Event 572



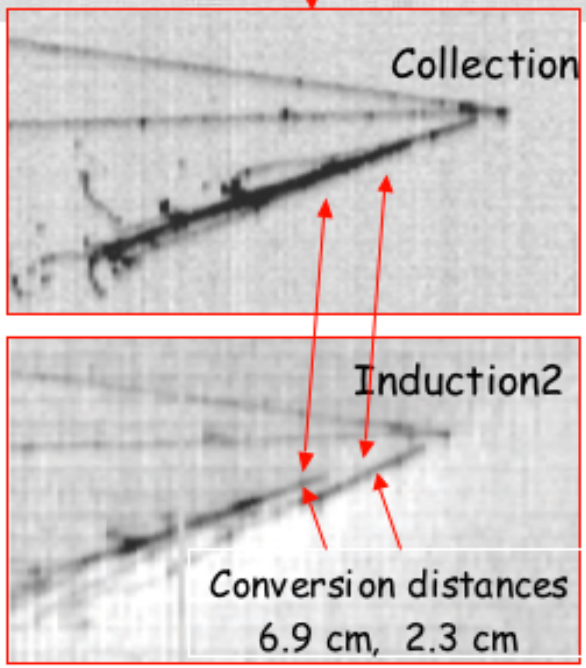

*close-up of two e.m. showers*

*Primary vertex (A)*

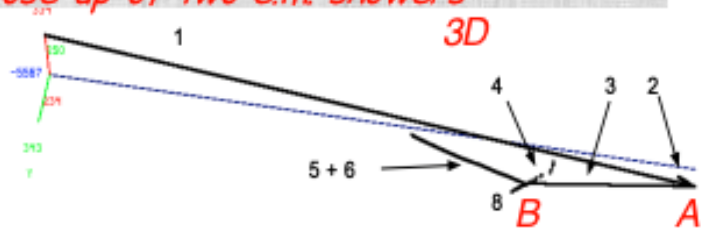
very long μ (1), e.m. cascade(2), pion (3).

*Secondary vertex (B)*

The longest track (5) is a μ coming from stopping k (6). - μ decay is observed.

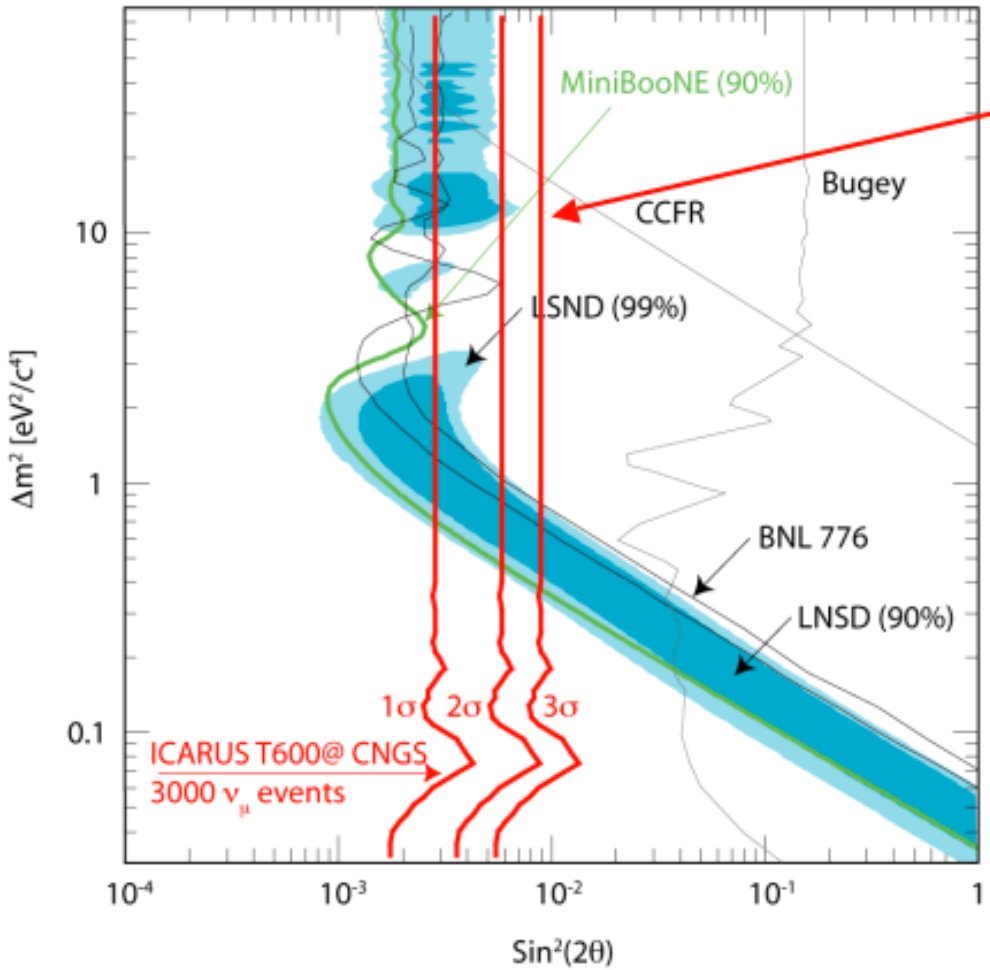



$M^*_{\gamma\gamma}$ = 125±15 MeV/$c^2$




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

# Sterile neutrino search with ICARUS T600

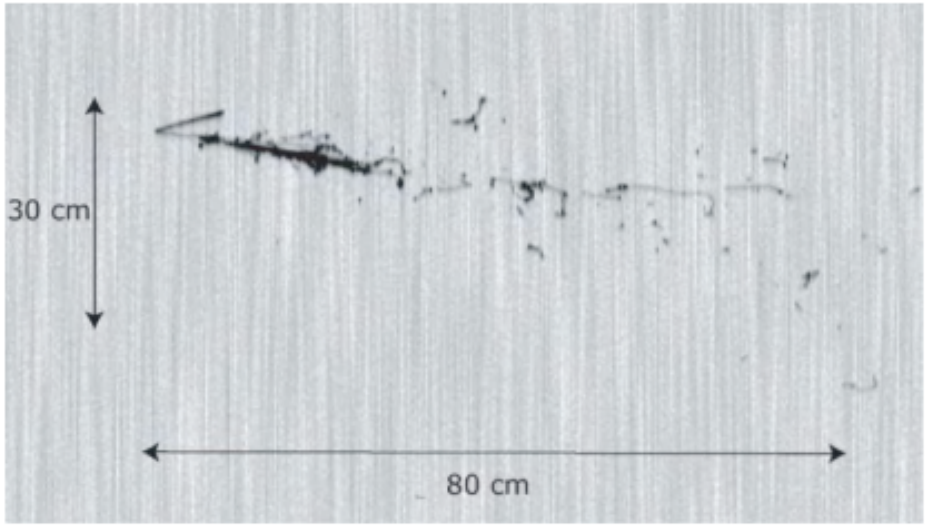



$\nu_\mu \rightarrow \nu_e$ appearance search in T600 in LNSD parameter space

- Sensitivity region, in terms of standard deviations, for 3000 raw CNGS muon 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.
- Largely complementary to the Fermi-lab program in terms of energy and baseline.

# $\nu_e$ CC interaction at ~ 1.5 GeV

- At these energies, electron identification and energy reconstruction of $\nu_e$ interactions is ensured with ~5 $X_0$ ($X_0$=14cm) longitudinal cut and ~2 $X_0$ side cut of the sensitive volume are performed, corresponding to a fiducial volume of ~ 80 % of the active one.



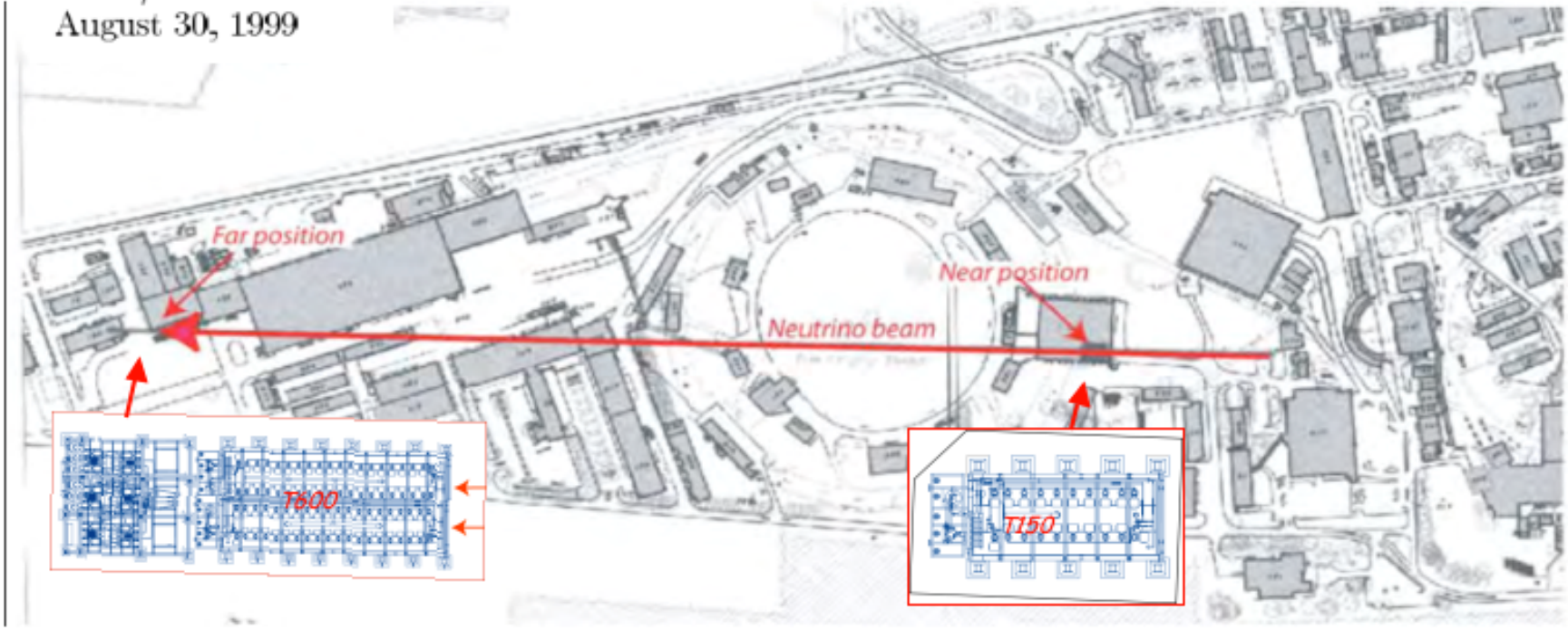

$\pi^0$ from NC are rejected by photon vertex identification, invariant mass reconstruction and dE/dx measurement: the expected $\pi^0$ mis-interpretation probability is 0.1 %, with $\nu_e$ detection efficiency of 90 % within the fiducial volume.

With these fiducial cuts, the expected $\nu_e$ energy resolution is around 14 %

# Two LAr-TPC detectors at the CERN-PS neutrino beam

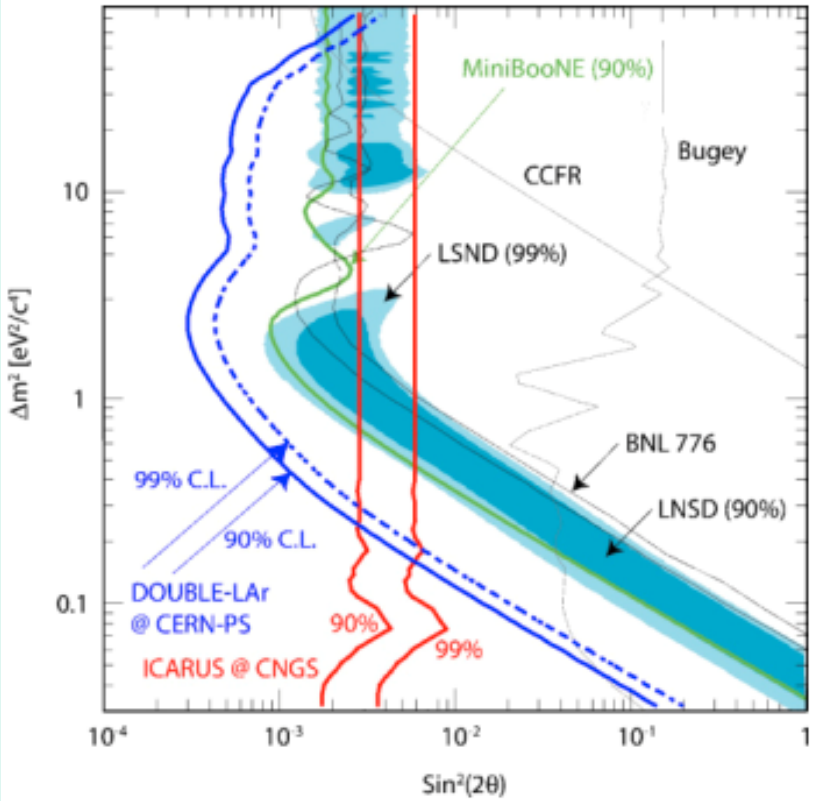
CERN-SPSC/99-26
SPSC/P311
August 30, 1999

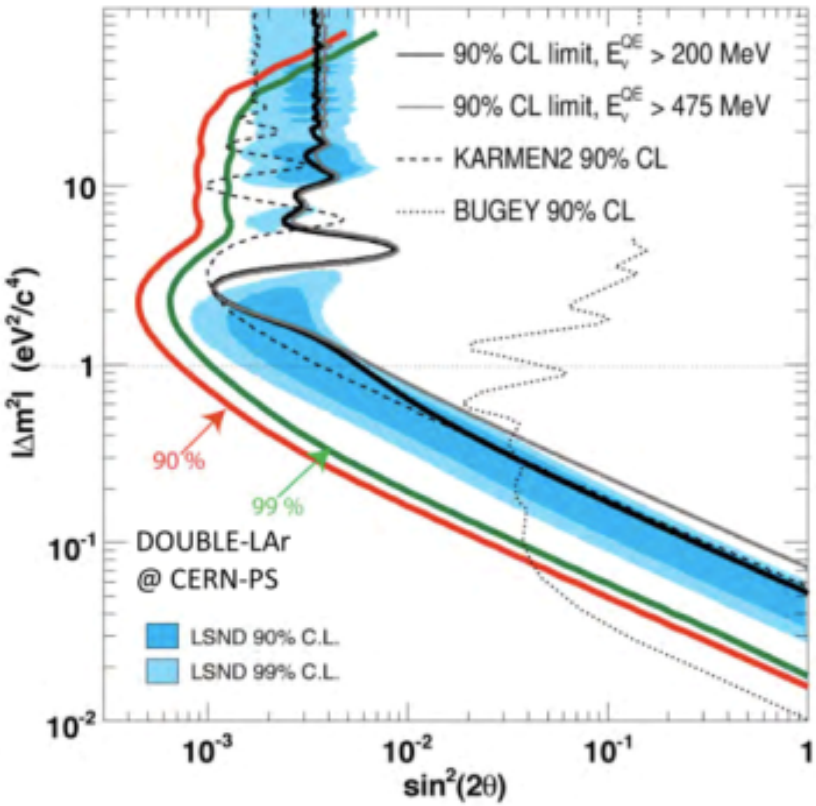
SEARCH FOR $\nu_\mu \rightarrow \nu_e$ OSCILLATION
AT THE CERN PS




Two positions are foreseen for the detection of the neutrinos
The far (ICARUS-T600) location at 850 m from the target: L/E ~ 1 km/GeV;
The additional detector and new location at a distance of 127 m from the target: L/E 0.15 km/GeV

# Comparing LSND sensitivities *(arXiv:0909.0355)*



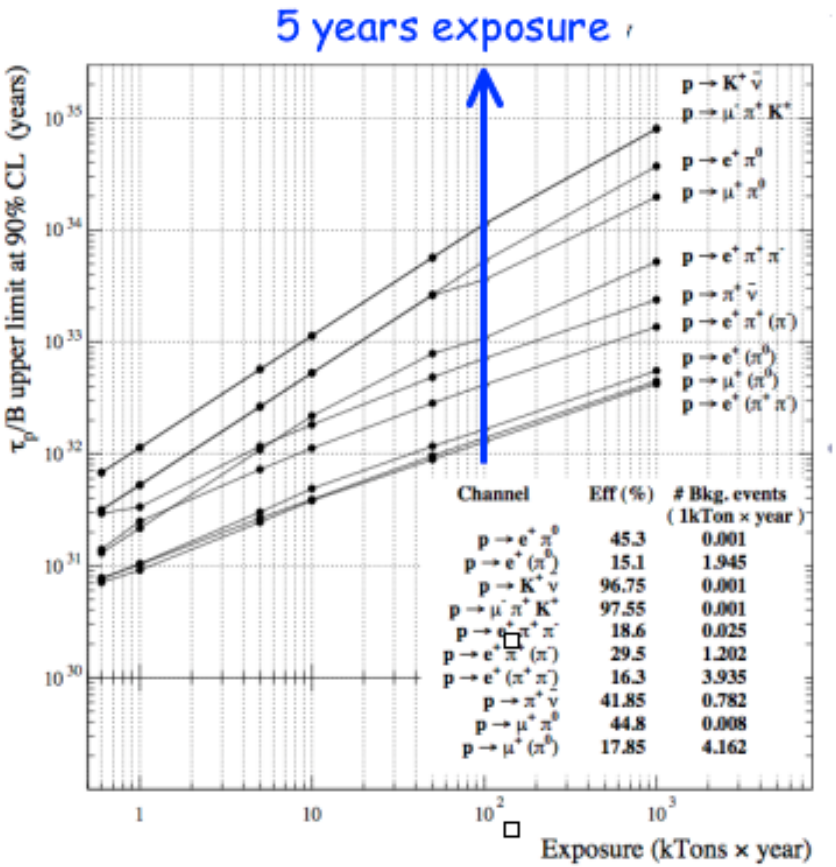




Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (left) for 2.5 $10^{20}$ pot (30 kW basic option) and twice as much for anti-neutrino (right). The LSND allowed region is fully explored both for neutrinos and anti-neutrinos. The T600 expectations from one year at LNGS are also shown.

# Nucleon decay expectations

- LAr-TPC provides a much more powerful bkg rejection w.r.t. other techniques. It can perform a large variety of exclusive decay modes measurements in bkg free mode.
- With *1.2 $10^{34}$ nucleons*, MODULAr is well suited for channels not accessible to _ detectors due to the complicated event topology, or if the emitted particles are below the _ threshold (e.g. $K^+$)

| Channel | 90% CL-5y | (pdg 90% CL) |
|---|---|---|
| $p \to \nu \pi^+$ | $4.4\ 10^{33}$ | $(2.5\ 10^{31})$ |
| $p \to \mu^- \pi^+ K^+$ | $1.1\ 10^{34}$ | $(2.5\ 10^{32})$ |
| $n \to e^- K^+$ | $1.3\ 10^{34}$ | $(3.2\ 10^{31})$ |
| $n \to \mu^+ \pi^-$ | $6.0\ 10^{33}$ | $(1.0\ 10^{32})$ |
| $n \to \nu \pi^0$ | $4.4\ 10^{33}$ | $(1.1\ 10^{32})$ |




| Channel | Eff (%) | # Bkg. events (1kTon × year) |
|---|---|---|
| $p \to e^+ \pi^0$ | 45.3 | 0.001 |
| $p \to e^+ (\pi^0)$ | 15.1 | 1.945 |
| $p \to K^+ \nu$ | 96.75 | 0.001 |
| $p \to \mu^- \pi^+ K^+$ | 97.55 | 0.001 |
| $p \to e^+ \pi^+ \pi^-$ | 18.6 | 0.025 |
| $p \to e^+ \pi^+ (\pi^-)$ | 29.5 | 1.202 |
| $p \to e^+ (\pi^+ \pi^-)$ | 16.3 | 3.935 |
| $p \to \pi^+ \nu$ | 41.85 | 0.782 |
| $p \to \mu^+ \pi^0$ | 44.8 | 0.008 |
| $p \to \mu^+ (\pi^0)$ | 17.85 | 4.162 |