ICARUS T600 – large LAr TPC

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(on behalf of the ICARUS Collaboration)

ICARUS Collaboration

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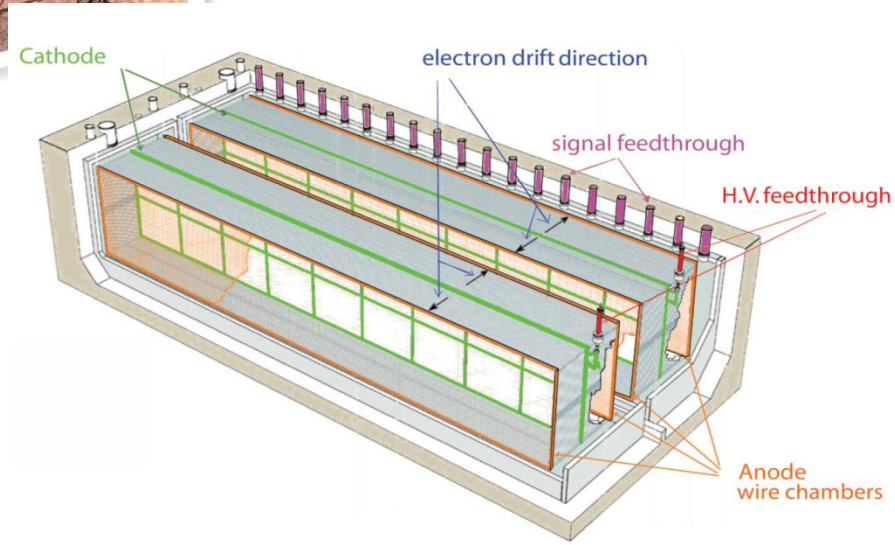
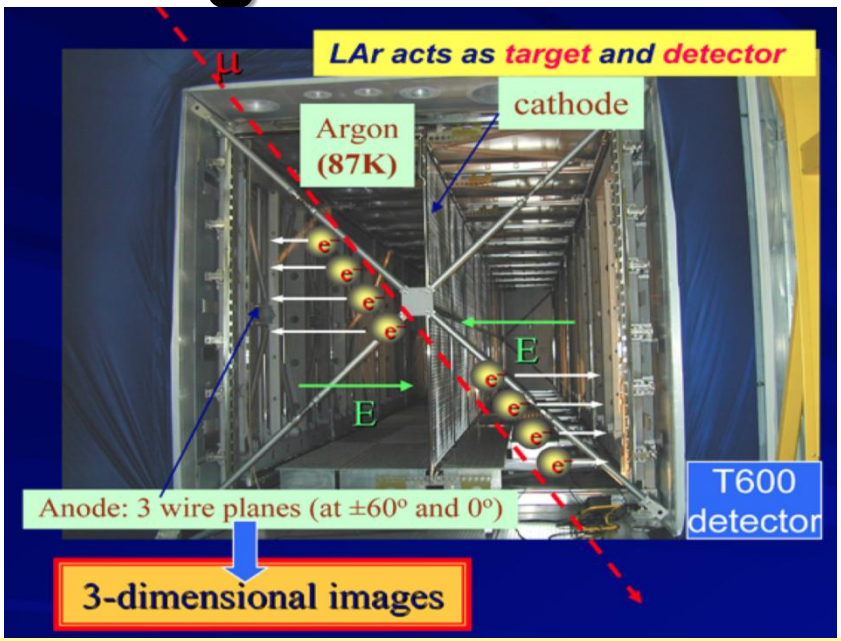
Introduction

- Three years (May 2010 – June 2013) of continuous and safe 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.
- A total of 8.6 x 10^{19} protons on target has been collected, with a remarkable detector live time > 93% (see next slide for related publications).
- Also atmospheric neutrinos have been studied with exposure to cosmic rays (0.73 kton year).
- In this talk a kind of summary of the ICARUS detector performance and obtained results will be presented.

ICARUS T600: first large LAr TPC

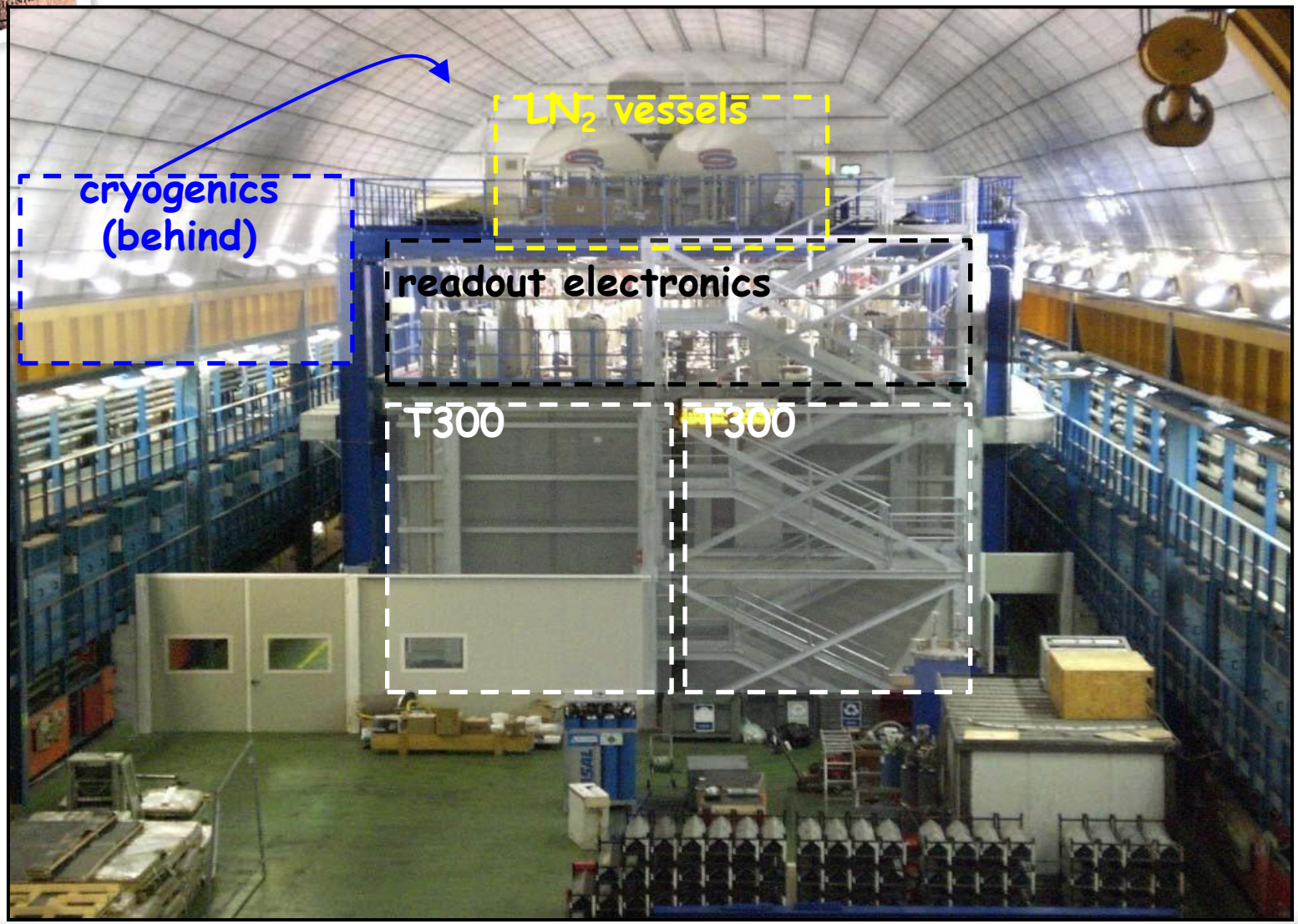




- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV sensitive (128nm) with wave shifter (TPB)

Key feature: LAr purity from electro-negative molecules (O_2, H_2O, CO_2).

ICARUS at Hall B of LNGS



ICARUS – published papers

- **Search for superluminal neutrinos:**

1. Cherenkov-like emission of e^+e^- pair: PL B711 (2012) 270
2. Measurement of neutrino tof: PL B713 (2012) 17
3. Precision measurement of neutrino tof: JHEP 11 (2012) 049

- **Search for „LSND" anomaly:**

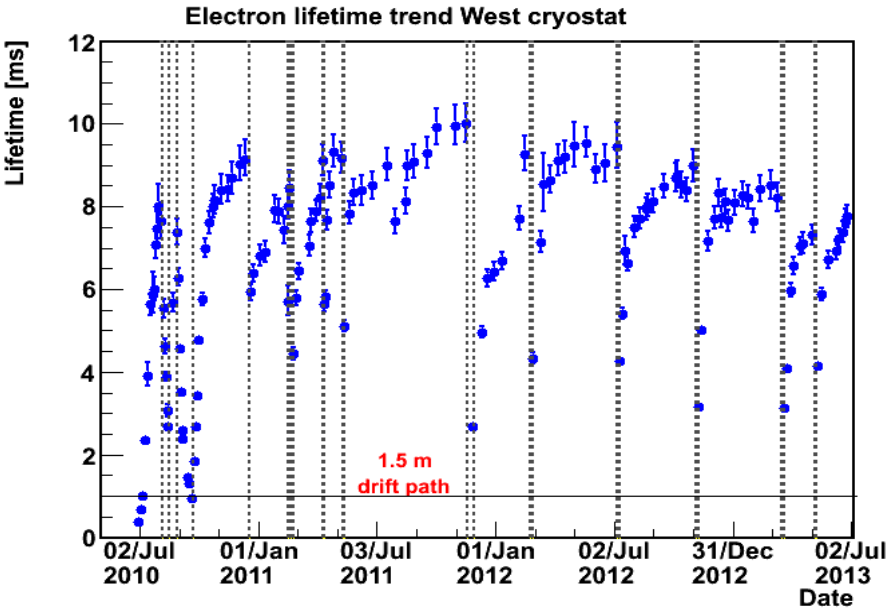
1. Limited statistics result: Eur. Phys. J. C73 (2013) 2345
2. Improved statistics result: Eur. Phys. J. C73 (2013) 2599.

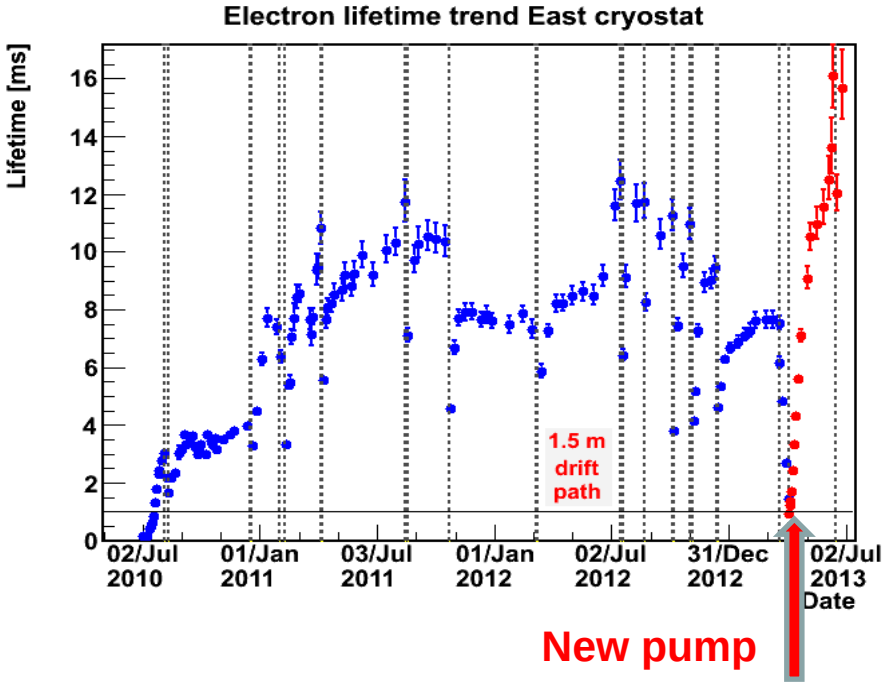
- **„Technical" aspects of the experiment:**

1. Underground operation: JINST 6 (2011) P07011
2. 3D reconstruction: Adv. High Energy Phys. (2013) 260820
3. Trigger system: JINST 9 (2014) P08003
4. Electron lifetime: JINST 9 (2014) P12006

ICARUS: LAr purity

- Operation of large TPC (~ 1 kton LAr, 1.5 m drift → 1 ms electron drift time) requires to reach and maintain very high level of LAr purity.
- In ICARUS detector it was achieved with use of commercial filters and liquid/gas recirculation (LAr continuously filtered).

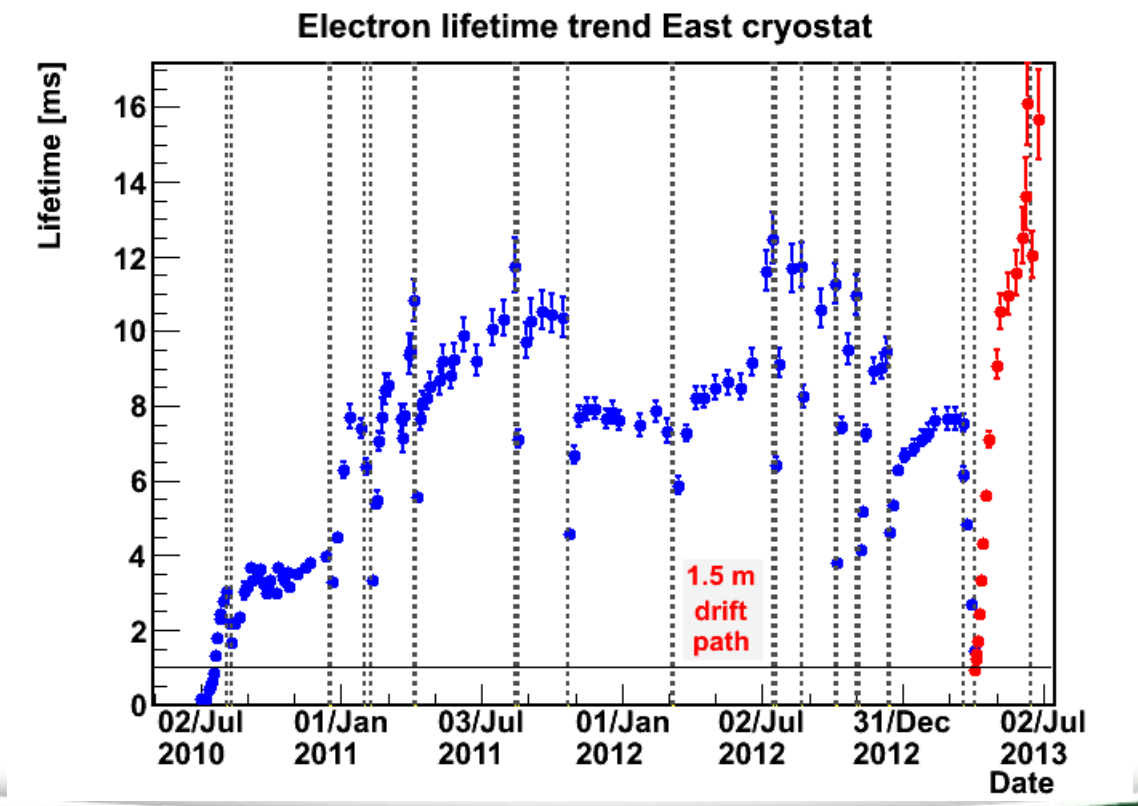




Average purity level ~60 ppt (O_2 equivalent) → Max. charge attenuation at 1.5m: 17%

ICARUS: LAr purity – new pump

- A new high-performance pump has been installed on East cryostat near run-end.
- Electron life time exceeded 16 ms, value so far reached only in small size prototypes → important for future very large LAr detectors (drift distance ~ 5 m).



ICARUS LAr TPC: performance

Total energy reconstr. from charge integration

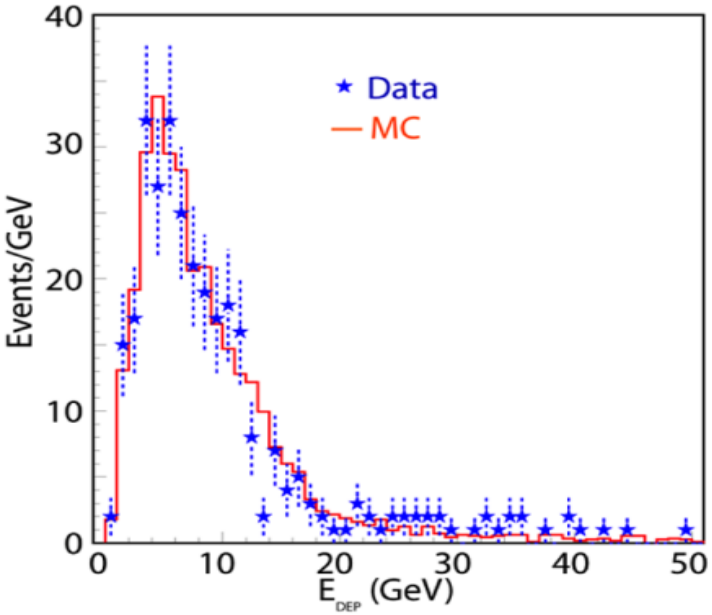
- Full sampling, homogeneous calorimeter with excellent accuracy for contained events

Tracking device

- Precise 3D topology and accurate ionization
- Muon momentum via multiple scattering

Measurement of local energy deposition dE/dx

- e/γ remarkable separation (0.02 X_0 samples)
- Particle identification by dE/dx vs range



Low energy electrons:

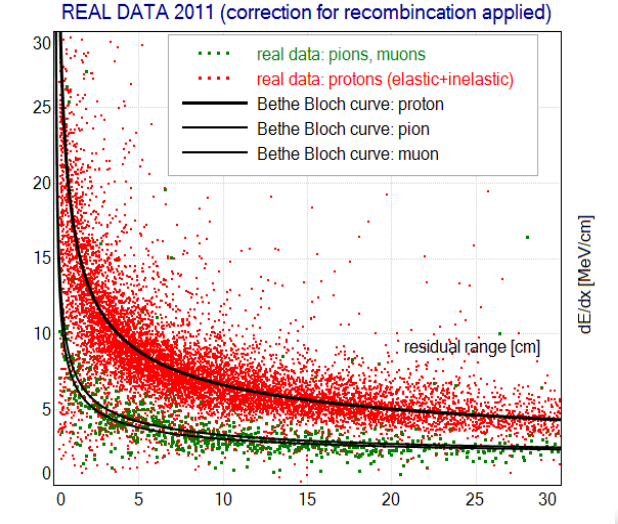
$\sigma(E)/E = 11\%/\sqrt{E(MeV)} + 2\%$

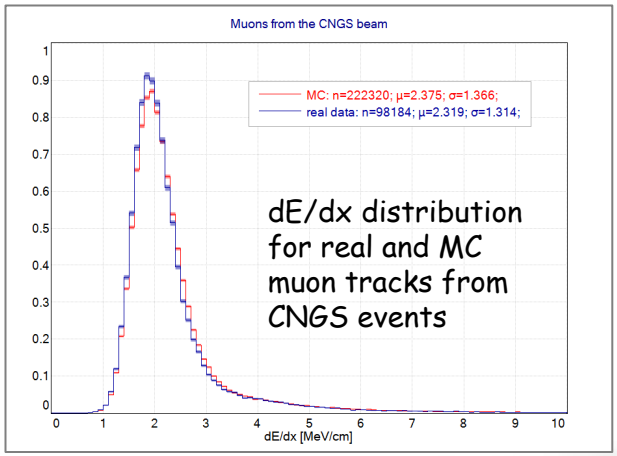
Electromagn. showers:

$\sigma(E)/E = 3\%/\sqrt{E(GeV)}$

Hadron showers:

$\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$





ICARUS: search for LSND anomaly

- The LSND has observed an excess of anti-ν_e nuetrino events in anti-ν_μ beam: 87.9 ± 22.4 ± 6.0 (3.8σ), later partly confirmed by MiniBooNE with both ν_μ/anti-ν_μ beams: $\Delta m^2_{new} \approx 10^{-2} \div 1\ eV^2$ implied.

LSND: L/E=1 m/MeV

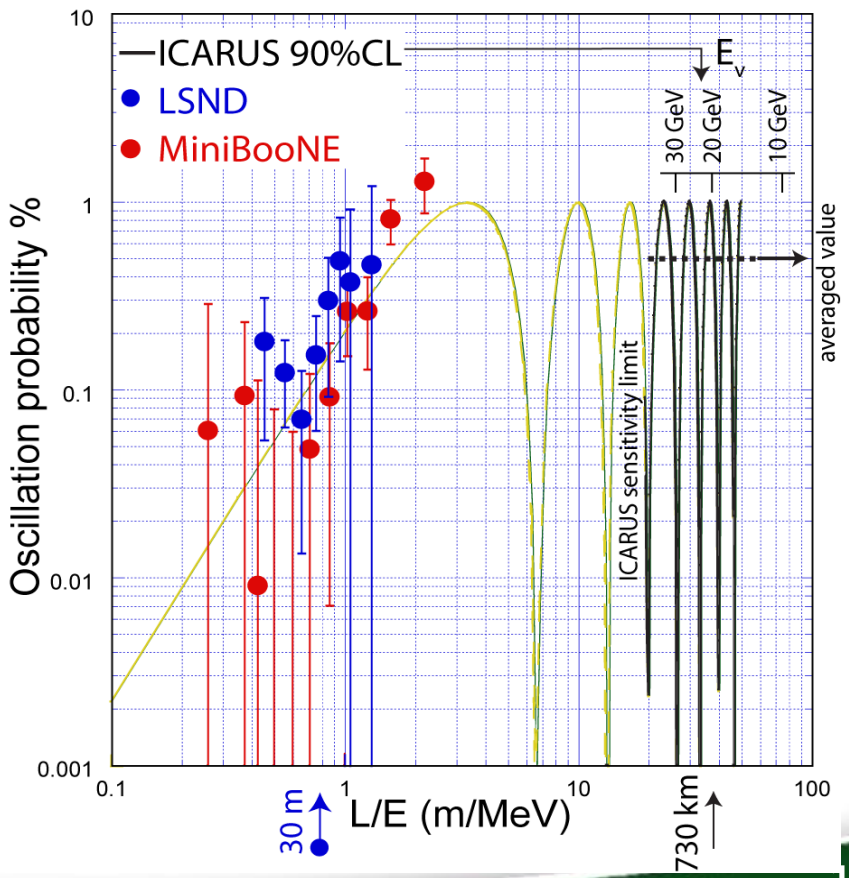
ICARUS: L=730km, $E_\nu \in [10,30]$ GeV, almost pure ν_μ beam ($\nu_e \approx 1\%$) L/E ≈ 36.5 m/MeV, i.e. fast oscillations as a function of E_ν averaging to

$$\sin^2(1.27\Delta m^2 L/E) \approx ½$$

$$\langle P \rangle_{\nu_\mu \to \nu_e} \approx ½ \sin^2(2\theta_{new})$$

A sterile neutrino signal would appear for ICARUS as an excess of ν_e events.

ν_e CC event recognition becomes crucial, and possible due to unique LAr feature.



ICARUS: ν_e signal selection

• Visual selection of electron neutrino 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 ν_e beam, but only 15% reduction of signal events.

Signal events selection criteria:

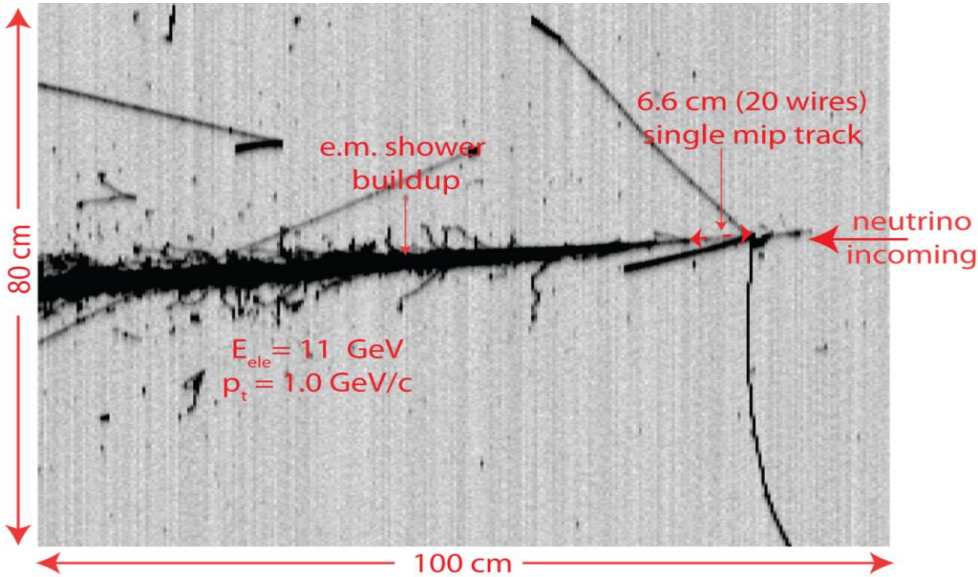
• Single m.i.p. from vertex, al least 8 wires long (dE/dx ≤ 3.1 MeV/cm, excluding δ-rays), later developing into EM shower.

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

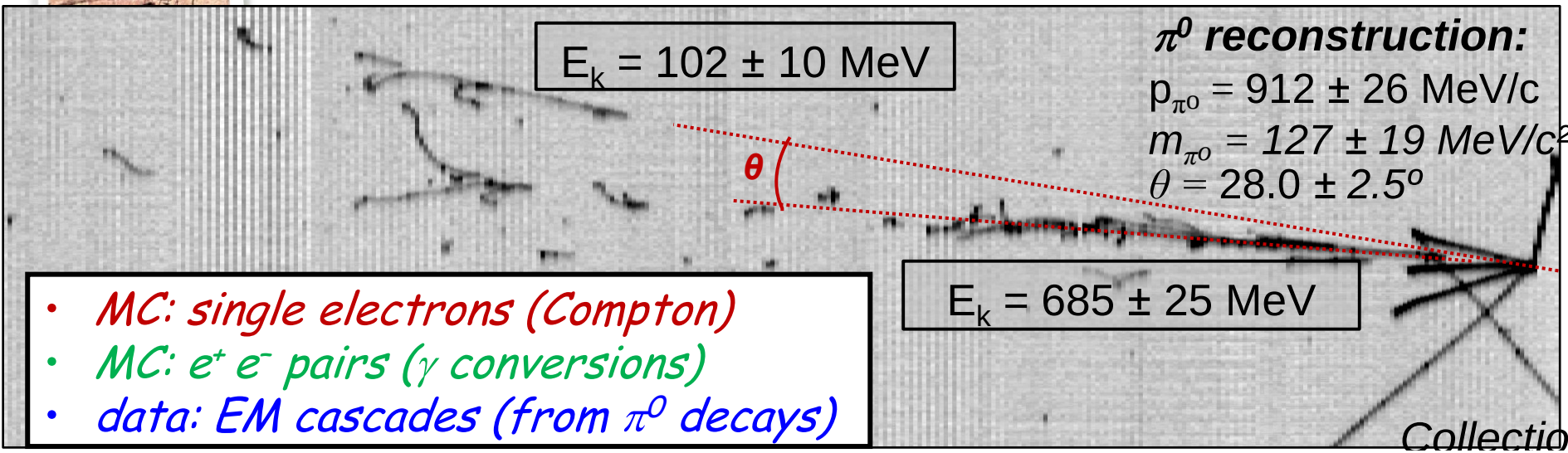
• visibility cuts: (3 independent scanners), leading to 0.74 ± 0.05 efficiency;

•No ν_e-like events selected among NC simulated sample of 800 events.

• ν_μ CC events identified by L > 2.5 m primary track without hadronic interaction



ICARUS: e/γ separation



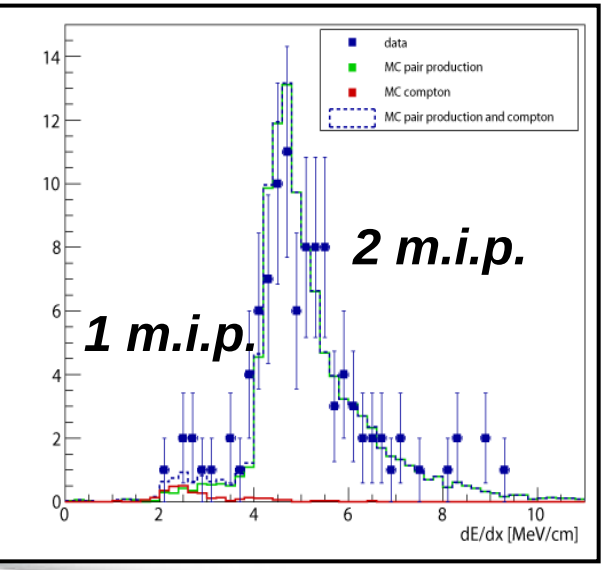
π^0 reconstruction:

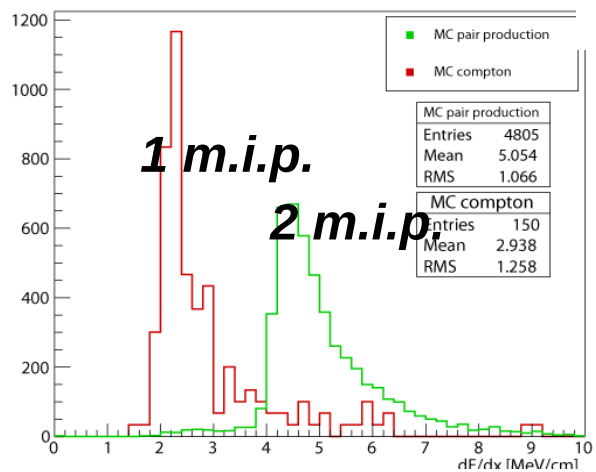
p_{π^0} = 912 ± 26 MeV/c

m_{π^0} = *127 ± 19 MeV/c²*

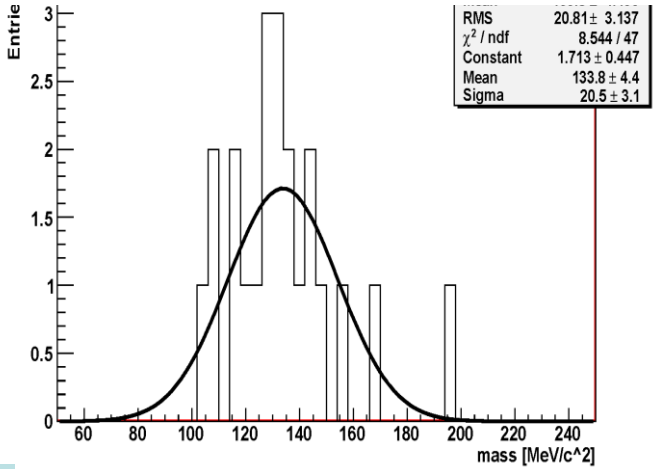
θ = 28.0 ± 2.5°

- *MC: single electrons (Compton)*
- *MC: $e^+ e^-$ pairs (γ conversions)*
- *data: EM cascades (from π^0 decays)*





Mγγ:
133.8±4.4(stat)±4(syst) MeV/c²



LAr TPC: very good e/γ separation

Data sample and event rate

- Analysis presented here is based on 2450 neutrino events corresponding to **7.23×10^{19} pot** (84% of fully collected statistics).

- Previously published result (Eur. Phys. J. C73 (2013) 2599) was based on 1995 neutrino interactions (6.0×10^{19} pot).

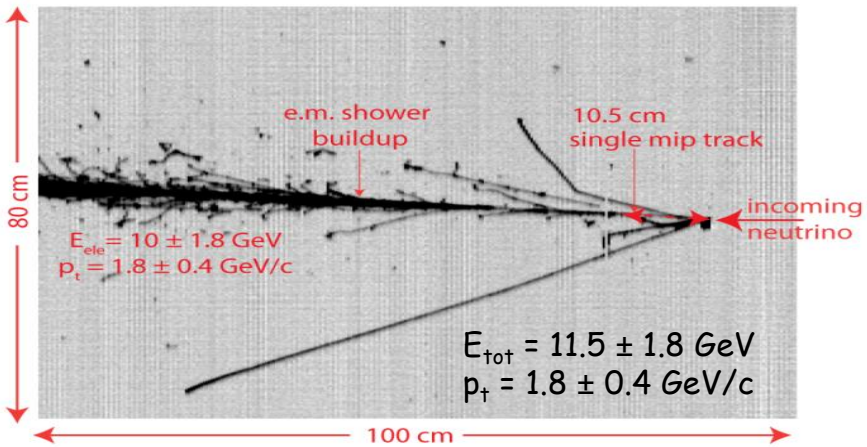
- Expected number of ν_e events in this sample:
  - 7.0 ± 0.9 due to the intrinsic electron neutrino beam contamination.
  - 2.9 ± 0.7 due to θ_{13} oscillations, $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$.
  - 1.6 ± 0.1 from $\nu_\mu \rightarrow \nu_\tau$ oscillations with subsequent e production.

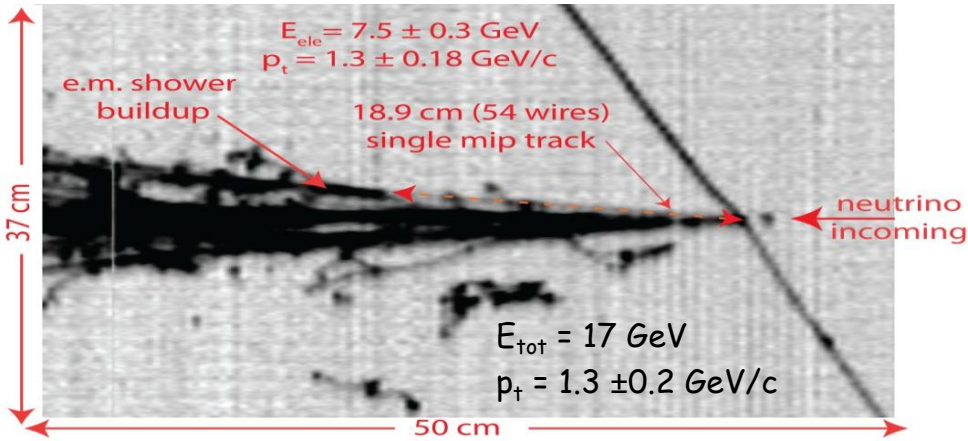
- Total number of expected events: 11.5 ± 1.2, which reduces to **7.9 ± 1.0**, when accounting for recognition efficiency (systematics only).

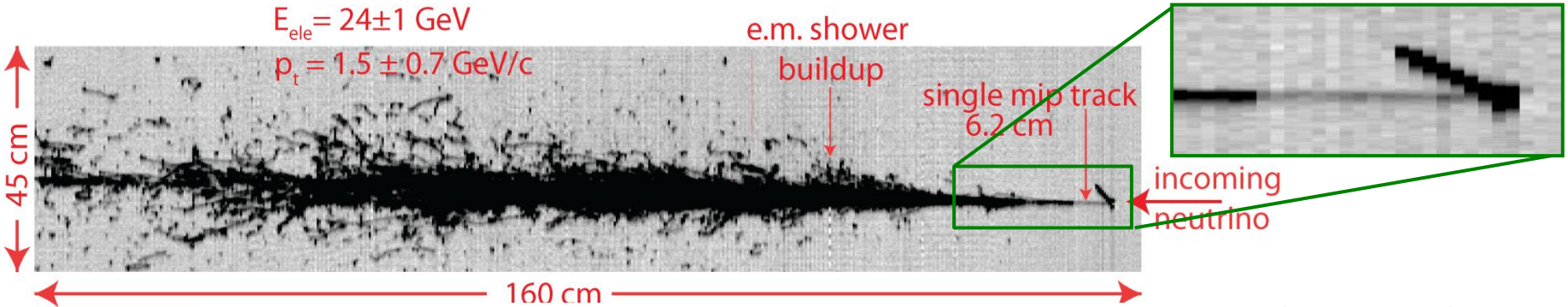
- **6 electron neutrino events have been identified** $\rightarrow$ compatible with expectations (probability to observe ≤ 6 ν_e events is ~33%).

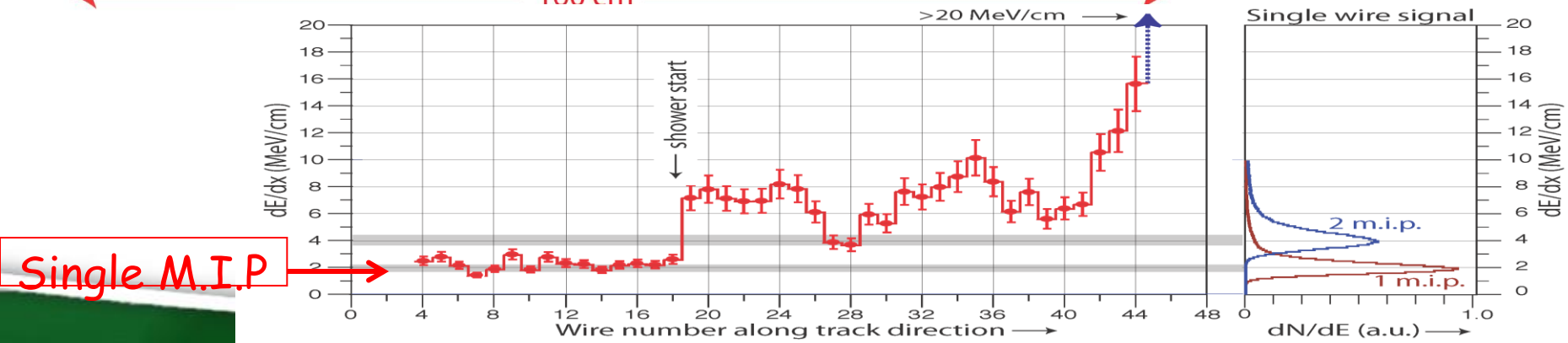
- **No evidence of oscillation** into sterile neutrinos was found in the analysed sample.

Examples: 3 out of 6 CC ν_e events









ICARUS: no LSND-type signal

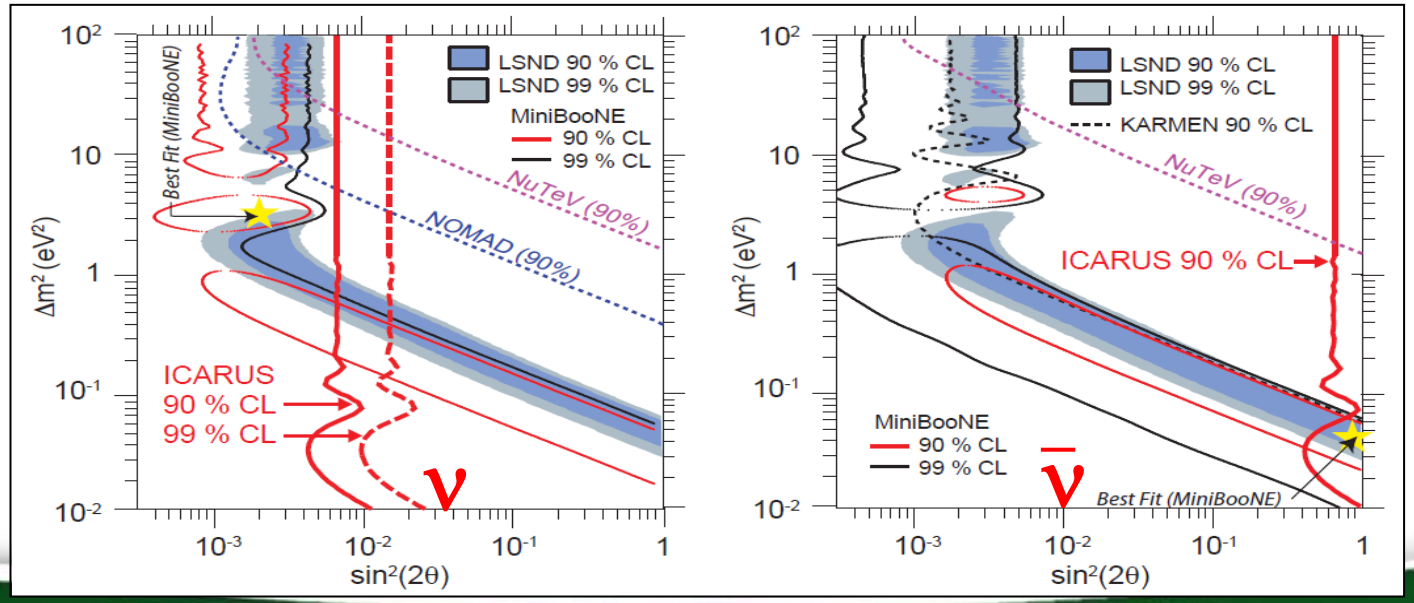
ICARUS new limits, weighted for efficiency, on neutrino events due to LSND anomaly are: 5.2 (90 % C.L.), or 10.3 (99 % C.L.), with the following limits on the oscillation probability:

$$P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3} \text{ (90 \% C.L.)}$$

$$P(\nu_\mu \rightarrow \nu_e) \leq 7.60 \times 10^{-3} \text{ (99 \% C.L.)}$$

In case the effect is only due to anti-ν_μ (CNGS beam contamination ~2%), the derived oscillation probability is: $P(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e) \leq 0.32$ (90 % C.L.), corresponding to 4.2 ev.

Only a narrow region of overall agreement between different experiments remains, centered around $\Delta m^2 \approx 0.5\ eV^2$, $\sin^2 2\theta \approx 0.005$.



Conclusions

- ICARUS is the first LAr large TPC operated underground.

- ICARUS has been acquiring data without interruption for more than 3 years with both CNGS beam and cosmics, proving the maturity of this detection technique → important for next generation experiments.

- Efficient reconstruction algorithms allow to resolve most of the events collected, down to their single components. As an example analysis of electron neutrino events has been shown. No evidence of oscillation into sterile neutrinos is found in measured L/E interval.

- For the detector future

See talk by Maurizio Bonesini Wednesday, Dec. 17 See talk by