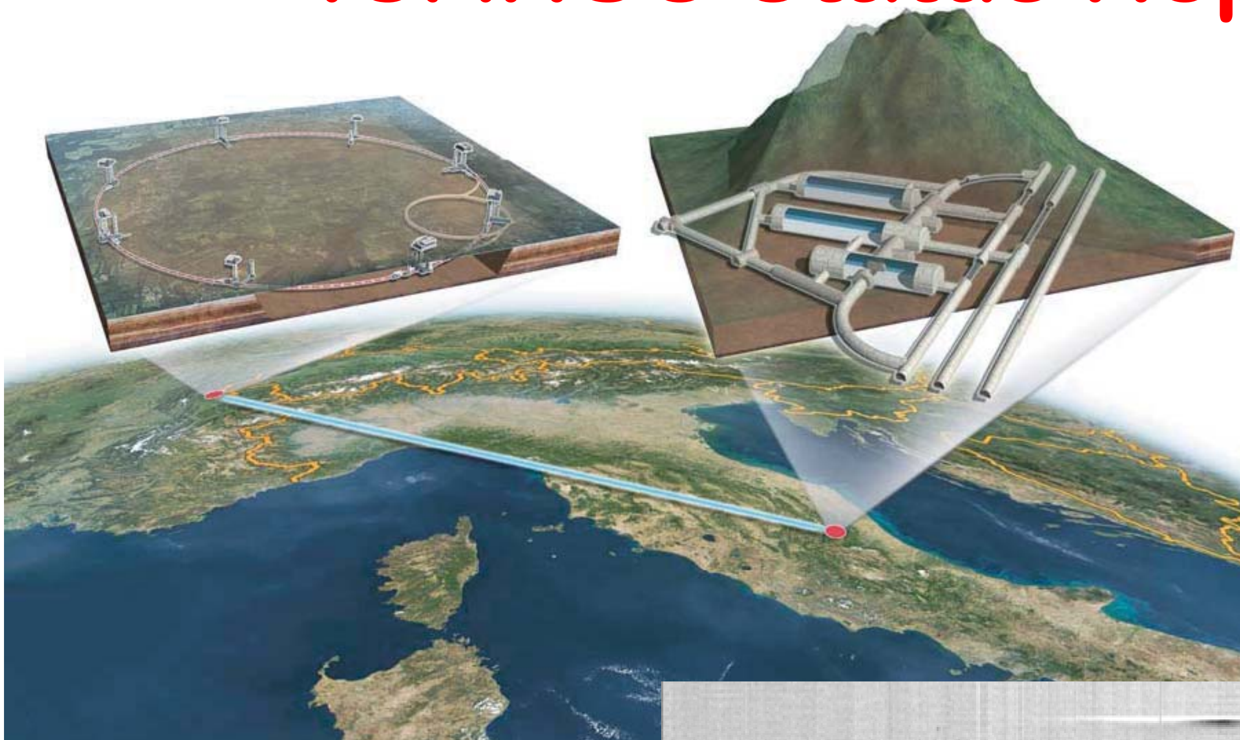
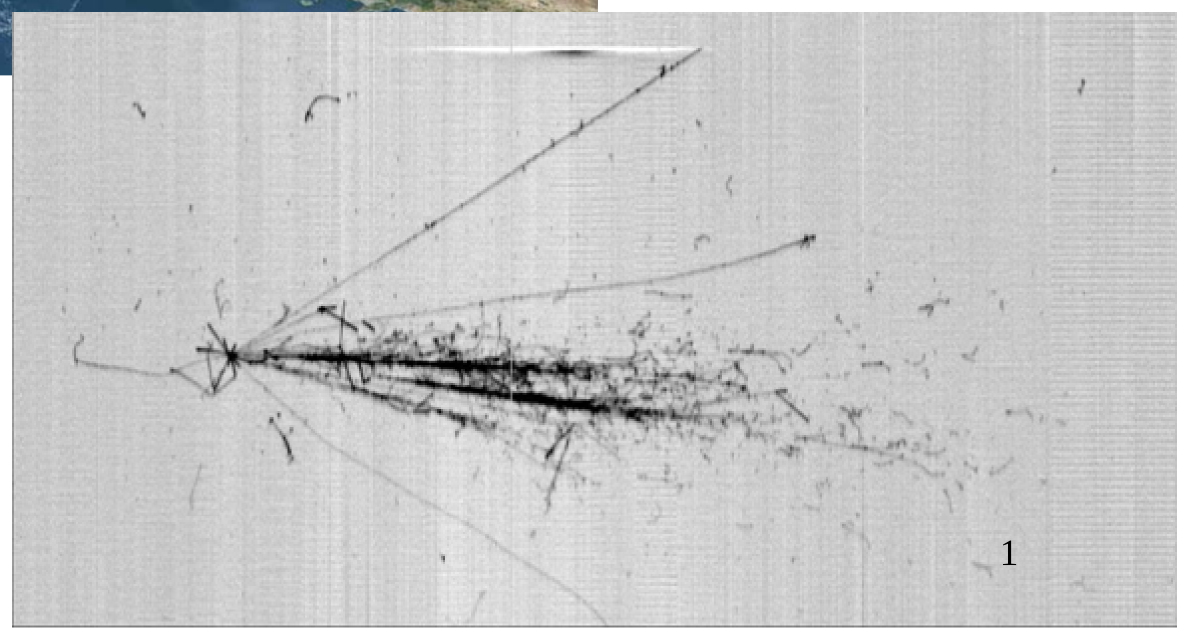
ICARUS Status Report





F. Varanini
for the ICARUS Collaboration

16th Lomonosov Conference
Moscow, 22 August 2013

The ICARUS Collaboration

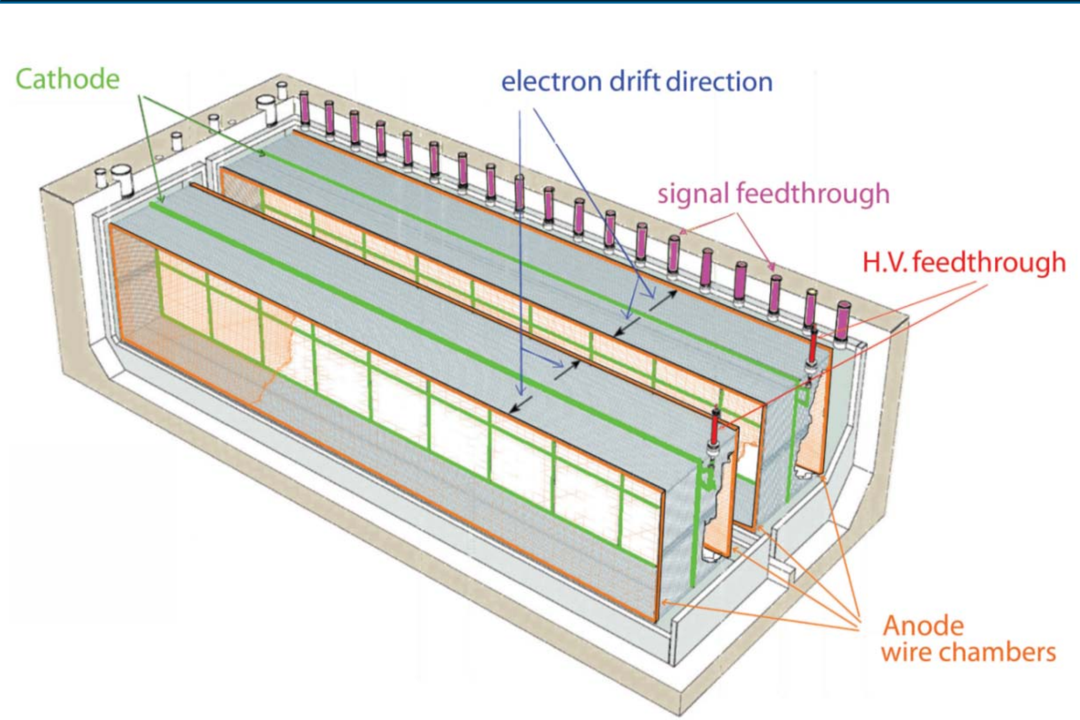
M. Antonello[a], B. Baibussinov[b], P. Benetti[c], F. Boffelli[c], A. Bubak[k], E. Calligarich[c], N. Canci[a], S. Centro[b], A. Cesana[f], K. Cieslik[g], D. B. Cline[h], A.G. Cocco[d], A. Dabrowska[g], D. Dequal[b], A. Dermenev[i], R. Dolfini[c], A. Falcone[c], C. Farnese[b], A. Fava[b], A. Ferrari[j], G. Fiorillo[d], D. Gibin[b], S. Gninenko[i], A. Guglielmi[b], M. Haranczyk[g], J. Holeczek[l], M. Kirsanov[i], J. Kisiel[l], I. Kochanek[l], J. Lagoda[m], S. Mania[l], A. Menegolli[c], G. Meng[b], C. Montanari[c], S. Otwinowski[h], P. Picchi[n], F. Pietropaolo[b], P. Plonski[o], A. Rappoldi[c], G.L. Raselli[c], M. Rossella[c], C. Rubbia[a,j,q], P. Sala[f], A. Scaramelli[f], E. Segreto[a], F. Sergiampietri[p], D. Stefan[a], R. Sulej[m,a], M. Szarska[g], M. Terrani[f], M. Torti[c], F. Varanini[b], S. Ventura[b], C. Vignoli[a], H. Wang[h], X. Yang[h], A. Zalewska[g], A. Zani[c], K. Zaremba[o].

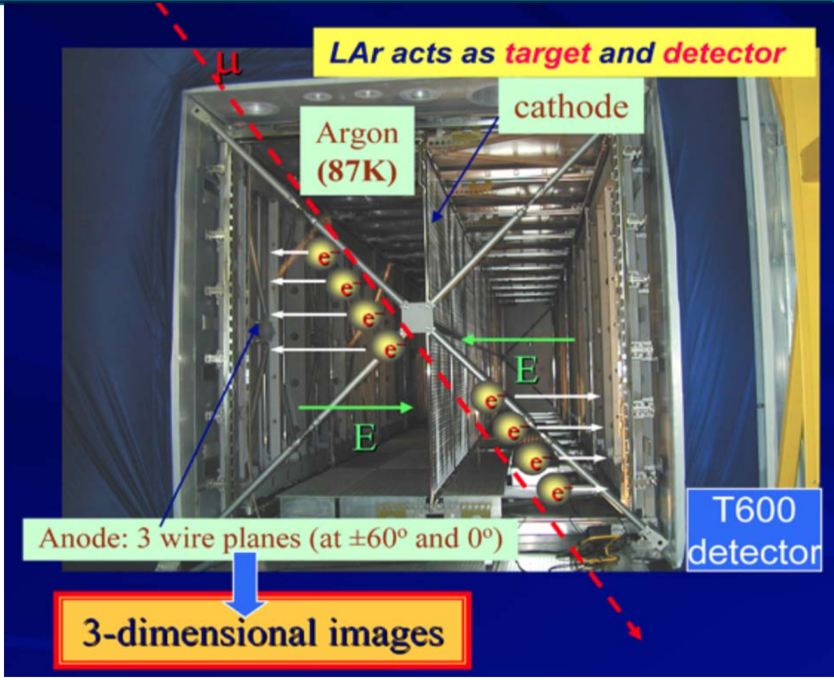
a Laboratori Nazionali del Gran Sasso dell'INFN, Assergi (AQ), Italy
b Dipartimento di Fisica e INFN, Università di Padova, Via Marzolo 8, I-35131 Padova, Italy
c Dipartimento di Fisica Nucleare e Teorica e INFN, Università di Pavia, Via Bassi 6, I-27100 Pavia, Italy
d Dipartimento di Scienze Fisiche, INFN e Università Federico II, Napoli, Italy
e Dipartimento di Fisica, Università di L'Aquila, via Vetoio Località Coppito, I-67100 L'Aquila, Italy
f INFN, Sezione di Milano e Politecnico, Via Celoria 16, I-20133 Milano, Italy
g Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Science, Krakow, Poland
h Department of Physics and Astronomy, University of California, Los Angeles, USA
i INR RAS, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
j CERN, CH-1211 Geneve 23, Switzerland
k Institute of Theoretical Physics, Wroclaw University, Wroclaw, Poland
l Institute of Physics, University of Silesia, 4 Uniwersytecka st., 40-007 Katowice, Poland
m National Centre for Nuclear Research, A. Soltana 7, 05-400 Otwock/Swierk, Poland
n Laboratori Nazionali di Frascati (INFN), Via Fermi 40, I-00044 Frascati, Italy
o Institute of Radioelectronics, Warsaw University of Technology, Nowowiejska, 00665 Warsaw, Poland
p INFN, Sezione di Pisa. Largo B. Pontecorvo, 3, I-56127 Pisa, Italy
q GSSI, Gran Sasso Science Institute, L'Aquila, Italy

The ICARUS experiment

- ICARUS is the first large volume LAr-TPC (760 tons) installed in Hall B of LNGS underground laboratory. It took data from May 2010 to June 2013 recording interactions from both CNGS ν beam and cosmic rays.
- "Electronic bubble chamber": excellent spatial resolution (~mm), homogeneous calorimetry, self-triggering detector.
- Important contributions to sterile neutrino search ($\nu_\mu \rightarrow \nu_e$) and neutrino velocity measurements
- A technological milestone towards future larger LAr-TPCs (tens of kt)

The ICARUS T600 detector

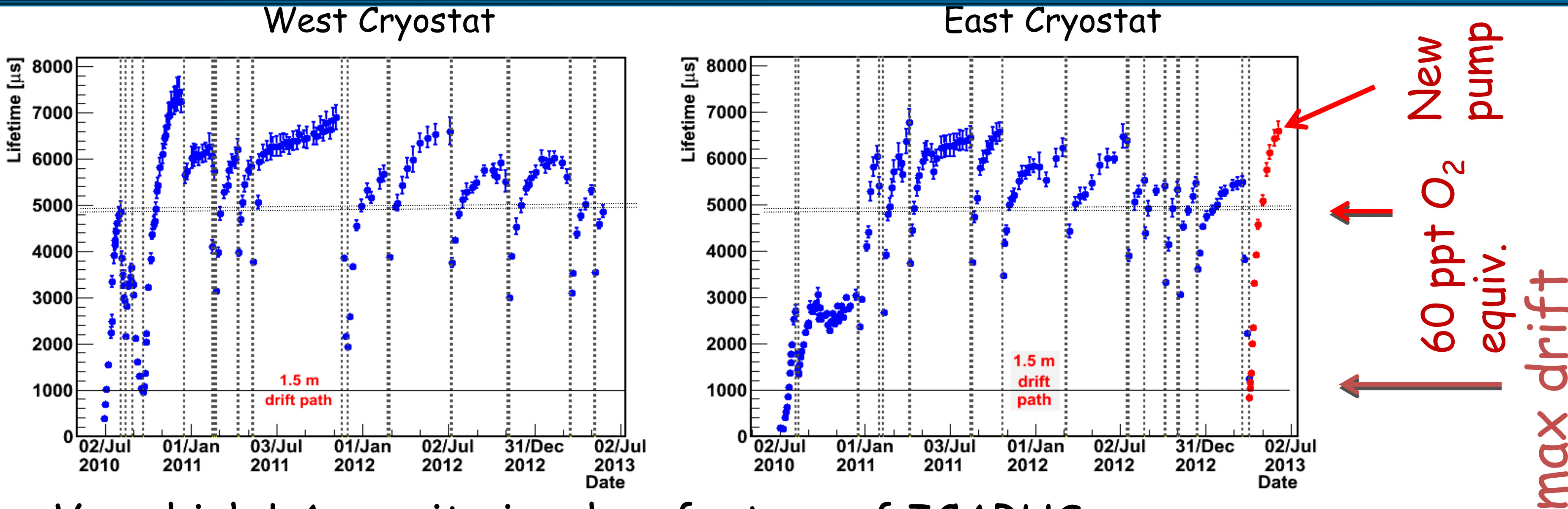




- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs

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

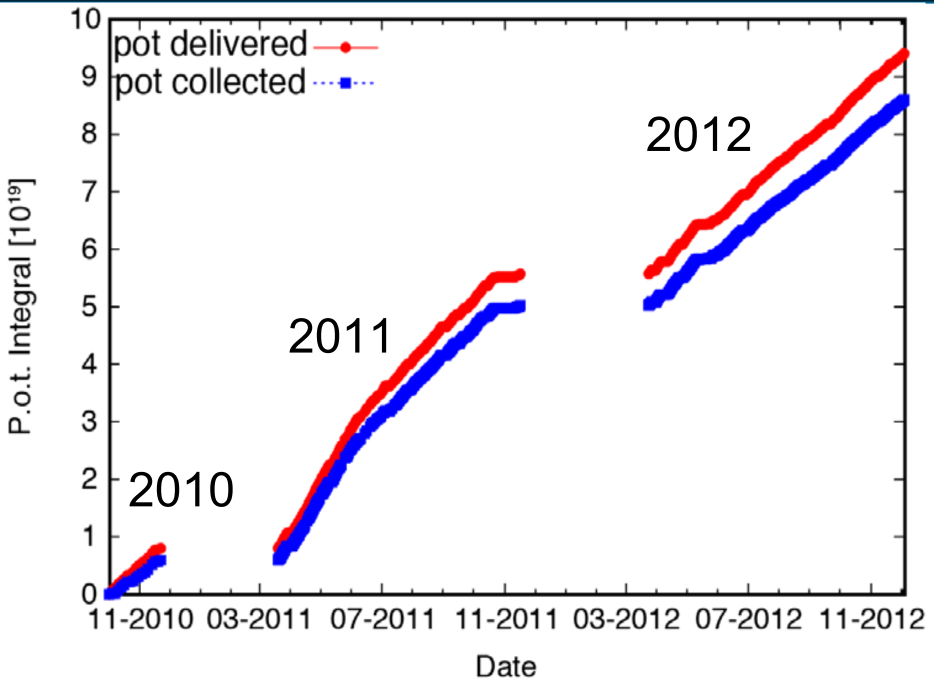
LAr purification



- Very high LAr purity is a key feature of ICARUS:
  - Highly efficient filters for O_2 and H_2O
  - Ultra High Vacuum techniques
  - Continuous purification by recirculation (gas and liquid phases).
- Free electron lifetime τ_{ele} > 5ms (~60 ppt $[O_2]_{eq}$) obtained in T600 (maximum charge attenuation at 1.5 m: 17%)
- τ_{ele} > 20ms obtained in ICARINO test facility: very promising for future detectors with larger drift length
- New non-immersed motor recirc. pump tested (Apr 2013): τ_{ele} > 7ms

Run with CNGS beam

- Exposed to CNGS ν beam from 1/10/2010 to 3/12/2012
- Total collected event statistics : 8.6 10^{19} pot with a detector live-time >93%
- Trigger based on PMT signals, in coincidence with proton extraction



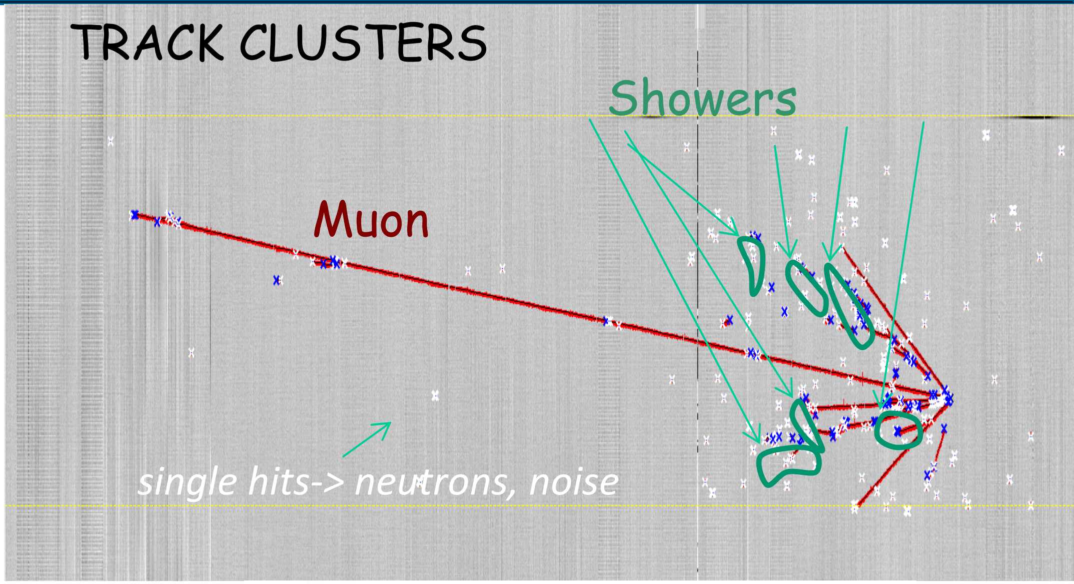
- First published physics results
  - Superluminal ν searches:
    1. Cherenkov-like e^+e^- emission: PL B711 (2012) 270
    2. neutrino tof measurement PL B713 (2012), 17
    3. neutrino tof precision measurement: JHEP 11 (2012) 049
  - Search for $\nu_\mu \rightarrow \nu_e$ "LSND/MiniBooNE" anomaly:
    1. Eur. Phys. J. C 73 (2013)
    2. New improved results: arXiv:1307.4699
- Technical run with cosmics from Dec. 2012 to June 2013

T600 decommissioning

- Data taking with cosmic rays stopped on June 27th: emptying started immediately after
- The emptying phase of two Cryostats ended on July 25th: 740 tons of LAr were recovered
- The Warming-up phase is ongoing; the dismantling of the cryogenic systems, read-out electronics and ancillary systems will start in September.
- The TPC chambers will be extracted and transported to CERN for the T600 refurbishing.

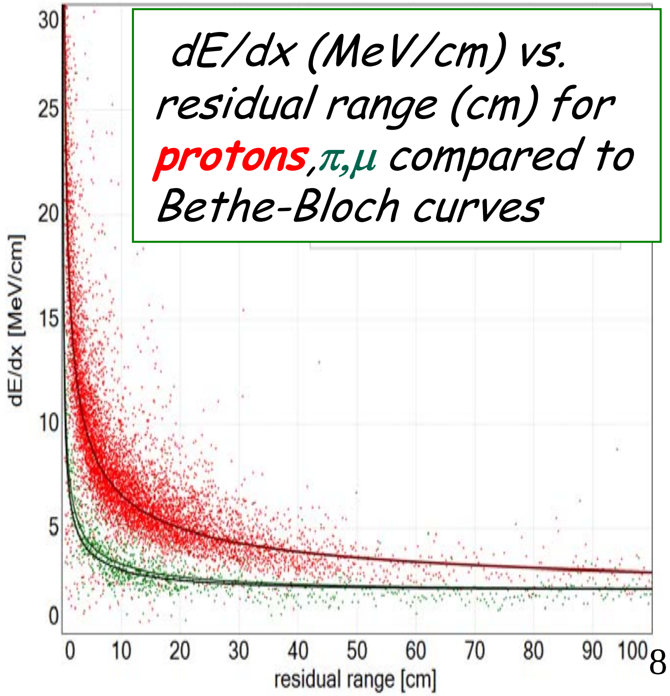
LAr-TPC reconstruction performance

- *Tracking:*
  - Automatic vertex and track identification
  - Precise (1 mm) 3D track reconstruction
  - Muon momentum via multiple scattering

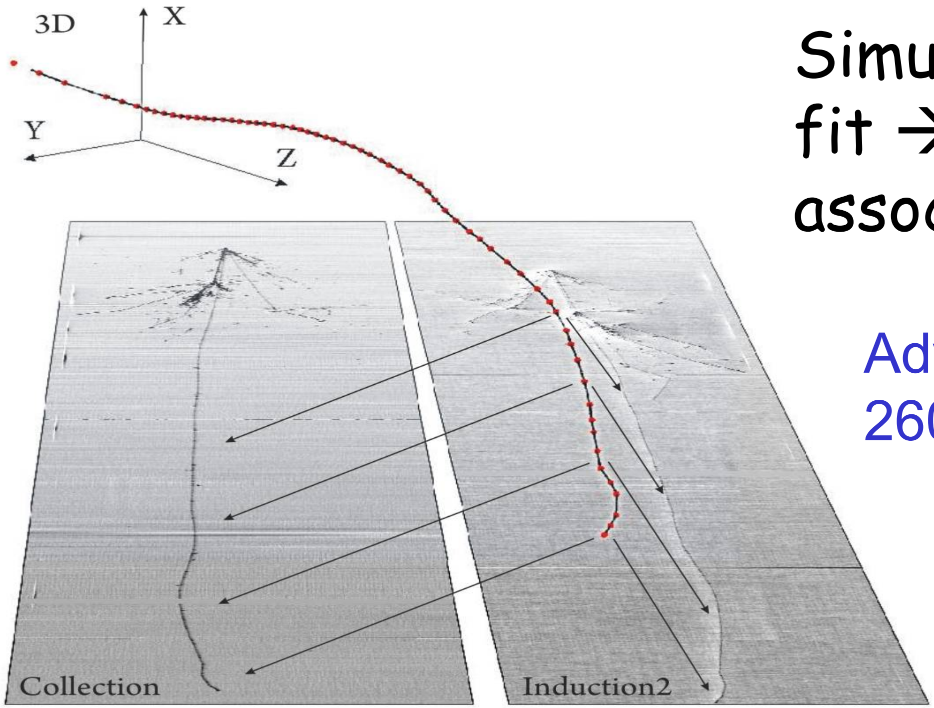


- *Measurement of energy deposition dE/dx:*
  - Good e/γ separation
  - Particle ID (dE/dx vs. range)

- *Total energy reconstruction of events from charge integration:*
  - Full sampling, homogeneous calorimetry with excellent accuracy for contained events



3D reconstruction (example of stopping μ)



Simultaneous **3D** polygonal fit →**2D** hit-to-hit associations no longer needed

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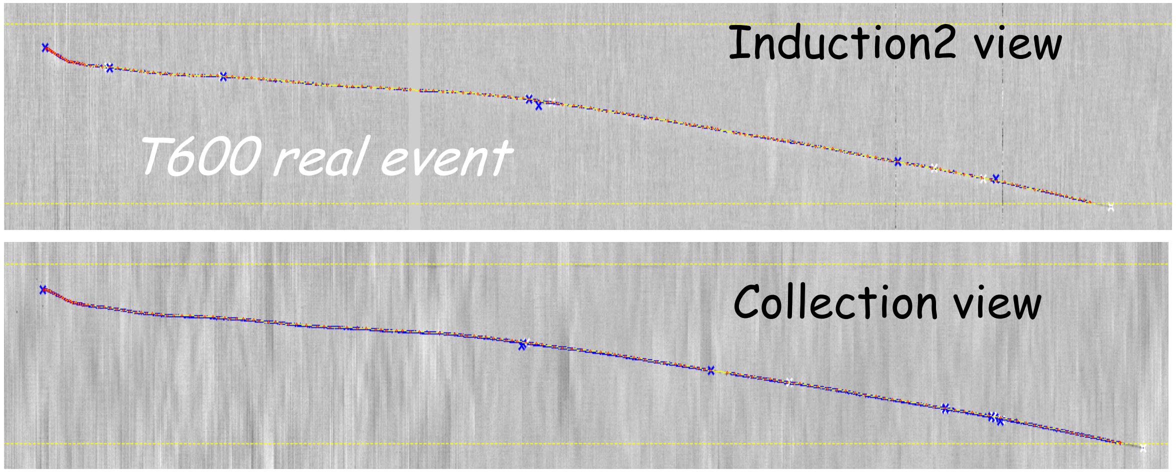
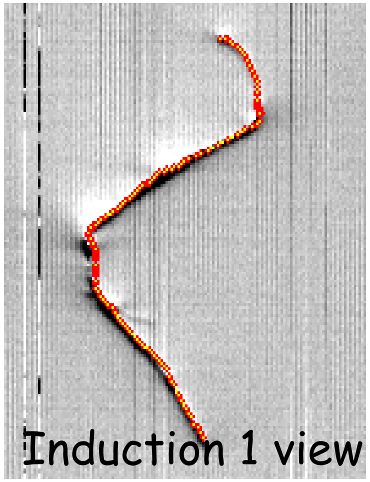
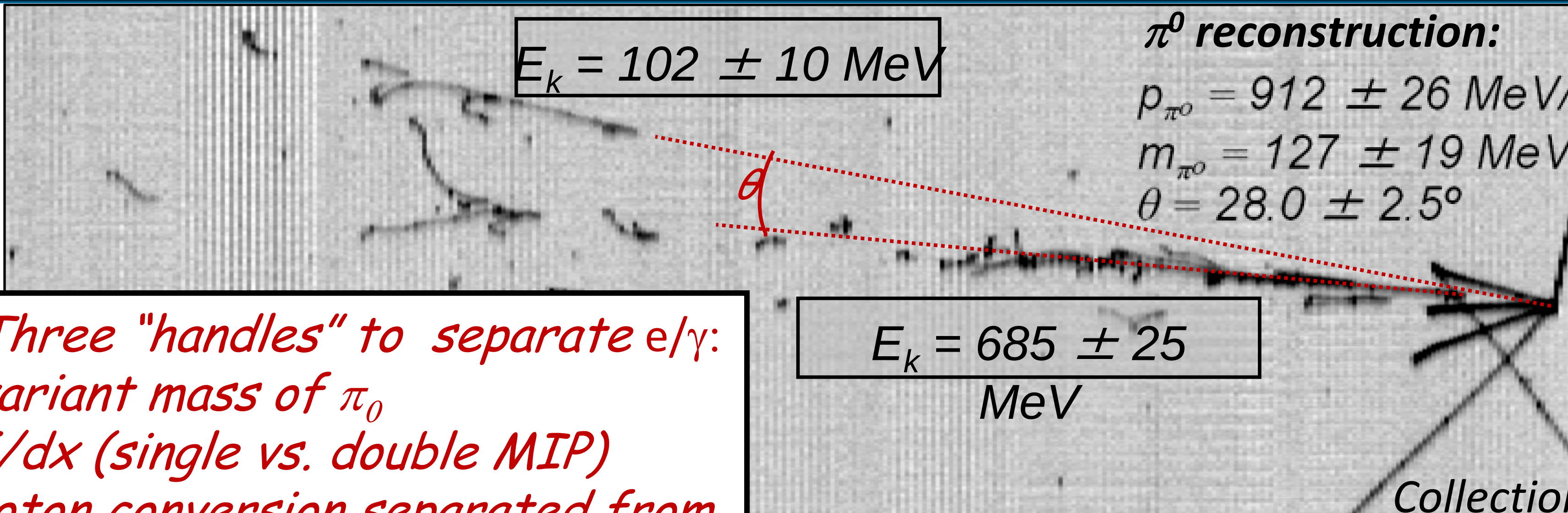




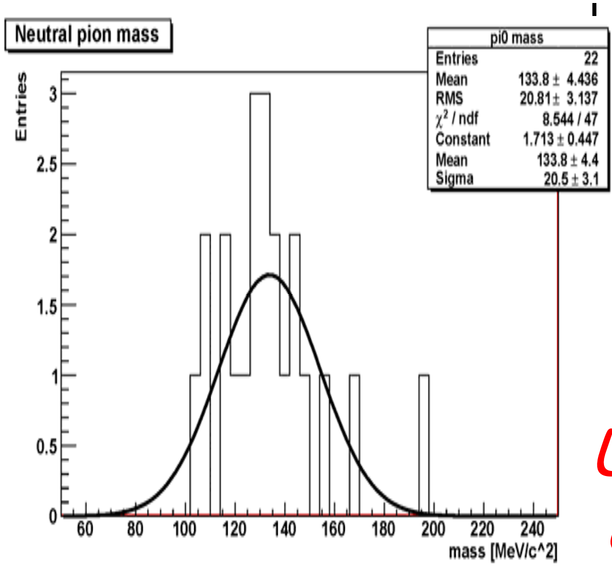
e/γ separation and π^0 reconstruction

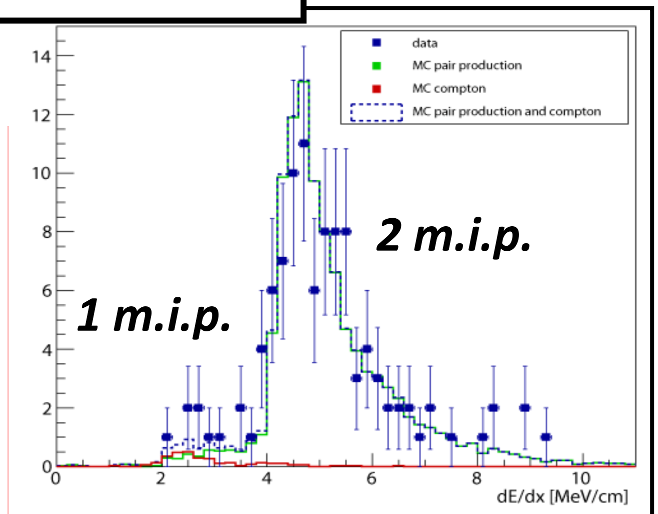


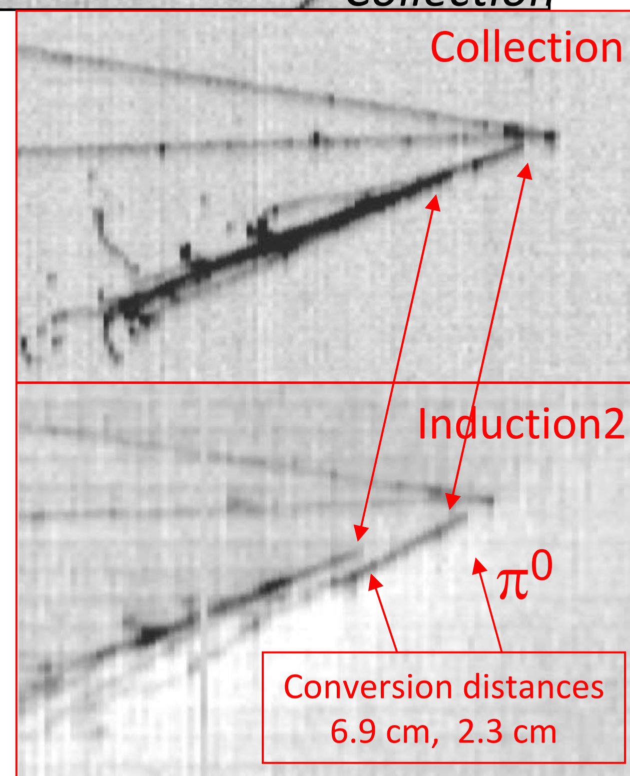
Three "handles" to separate e/γ:

- *invariant mass of π_0*
- *dE/dx (single vs. double MIP)*
- *photon conversion separated from primary vertex*

$M\gamma\gamma$:133.8±4.4±4 MeV/c²







Unique feature of LAr
Crucial for ν_e physics

Muon momentum measurement via multiple scattering

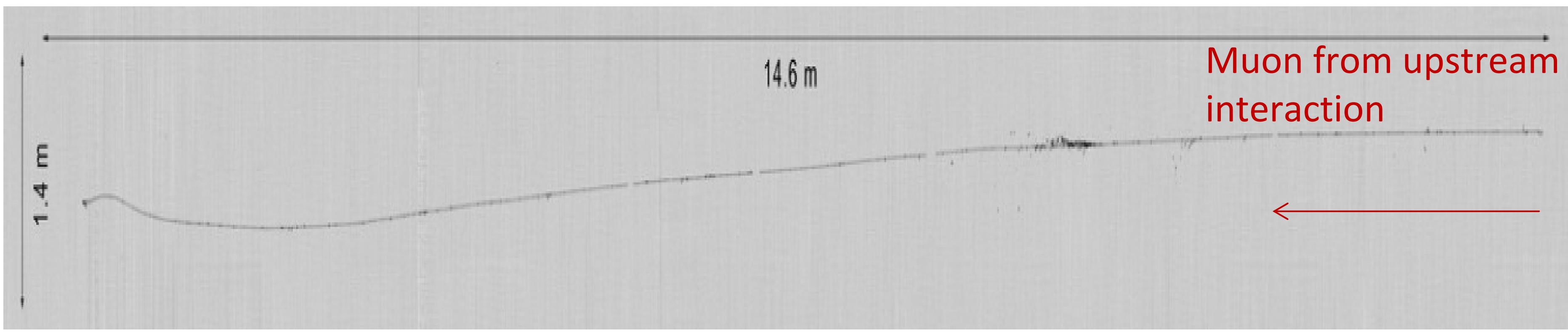
Key tool to measure momentum of non-contained muons: essential for ν_μ CC

- Measurement of p_μ with MS in LAr first proposed by C. Rubbia (1999)
- Muon track is well measured (3 mm sampling) -> it is possible to separate momentum-dependent MS deflections from fake scattering due to measurement error on position.
- Current implementation:
  - Accurate, automatic track cleaning from δ rays and crossing tracks.
  - Tracks are split into "segments", optimized to enhance MS contribution w.r.t. errors (estimated event-by-event)
  - "$\chi^2(p)$" built from angles between consecutive segments permits to estimate muon momentum and errors.

CNGS stopping muons

- Single muons from CNGS neutrino interactions in upstream rock, stopping in the detector
  - Momentum range (0.5ô 4 GeV/c) is perfectly matched to future long and short baseline experiments
- p_μ precisely known from calorimetry (~1% resolution, <1% bias).

-> Direct validation of MS with real data

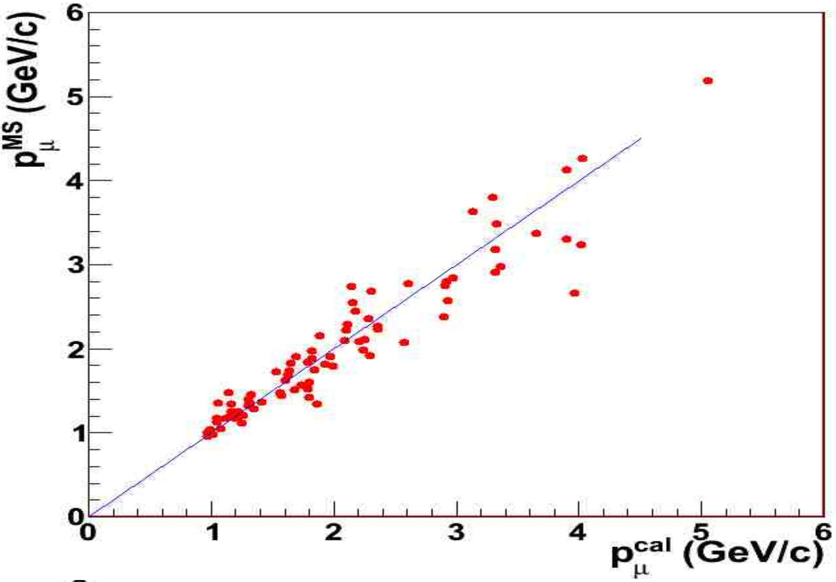


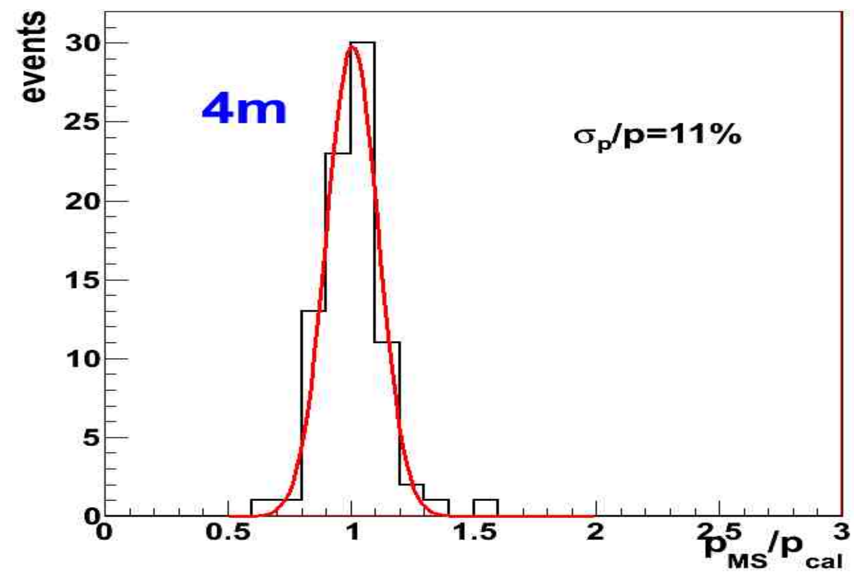
- 129 muons analyzed (length>2.5m to ensure correct muon identification)

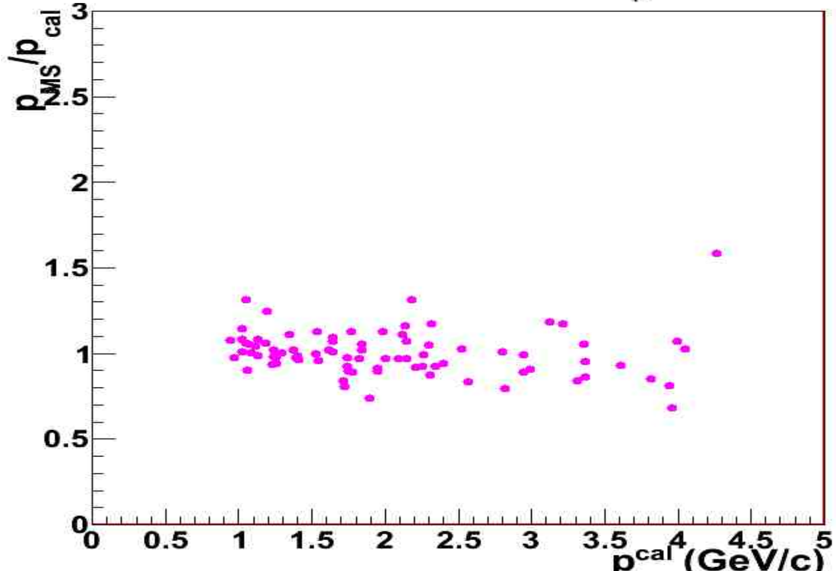
Extension to much more complex/higher energy CNGS ν_μCC events: ongoing evaluation/correction of possible detector effects

Preliminary results are encouraging

MS vs. calorimetry comparison







- Example of momentum measurement using only first 4 meters of μ track
- Good resolution over the full muon momentum range
- Higher statistics study is ongoing

Muon momentum measurement by MS is possible with a resolution ≈ 10% in the range of interest for future experiments

The sterile neutrino puzzle

- Significant evidence of $\nu_\mu \rightarrow \nu_e$ transitions from LSND experiment, with L/E~ 1 m/MeV. MiniBoone results do not fully confirm or rule out LSND.
- LSND's most likely interpretation (if confirmed) is the existence of (at least) a 4th neutrino flavor, with $\Delta m^2 \approx 10^{-2} \div 1$ eV^2
- In recent years, many hints to (anti-)neutrino oscillations in a similar L/E range

Anomaly	*Source*	*Type*	*Channel*	*Significance*
LSND	Short baseline	Decay at rest	$-\nu_\mu \to \nu_e$ CC	3.8 σ
MiniBoone	Short baseline	Neutrino beam	$-\nu_\mu \to \nu_e$ CC	3.4 σ
MiniBoone	Short baseline	Anti-Neutr. beam	anti-$\nu_\mu \to \nu_e$ CC	2.8 σ
Gallium	Electron capture	Source	ν disapp.	2.7 σ
Reactors	Fission	Beta decay	ν disapp.	3.0 σ
Cosmology	Big bang WMAP	No of neutrino		$\approx 2\ \sigma$

ICARUS-T600 is addressing the LSND claim for a large fraction of parameter space

LSND effects in ICARUS

- Search for $\nu_\mu \rightarrow \nu_e$ appearance in CNGS beam neutrinos
- CNGS peaked in 10-30 GeV energy range (beam associated ν_e ~1%):
- Difference w.r.t. LSND experiment:

L/E ≈ 36.5 m/MeV in ICARUS (≈ 1 m/MeV at LSND).

LSND-like short distance oscillation signal averages to:

$\sin^2(1.27\Delta m^2_{new} L/E) \approx \frac{1}{2}$ and $\langle P \rangle \nu_\mu \rightarrow \nu_e \approx \frac{1}{2} \sin^2(2\theta_{new})$

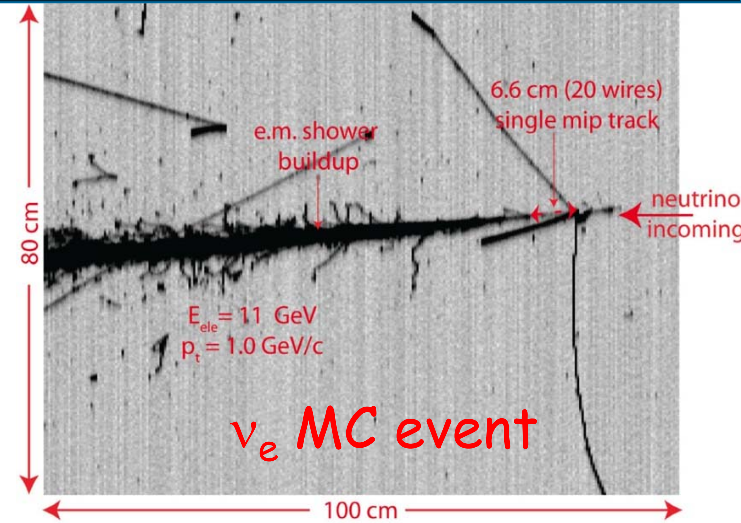
- In the ICARUS L/E region, contributions from standard neutrino oscillations are not too relevant, unlike other LBL experiments i.e. MINOS, T2K.

- The unique detection capabilities of LAr-TPC technique allows to identify individual ν_e events with high efficiency.

New results presented here refer to 1995 ν interactions (6.0 10^{19} pot statistics).

Selection of ν_e events

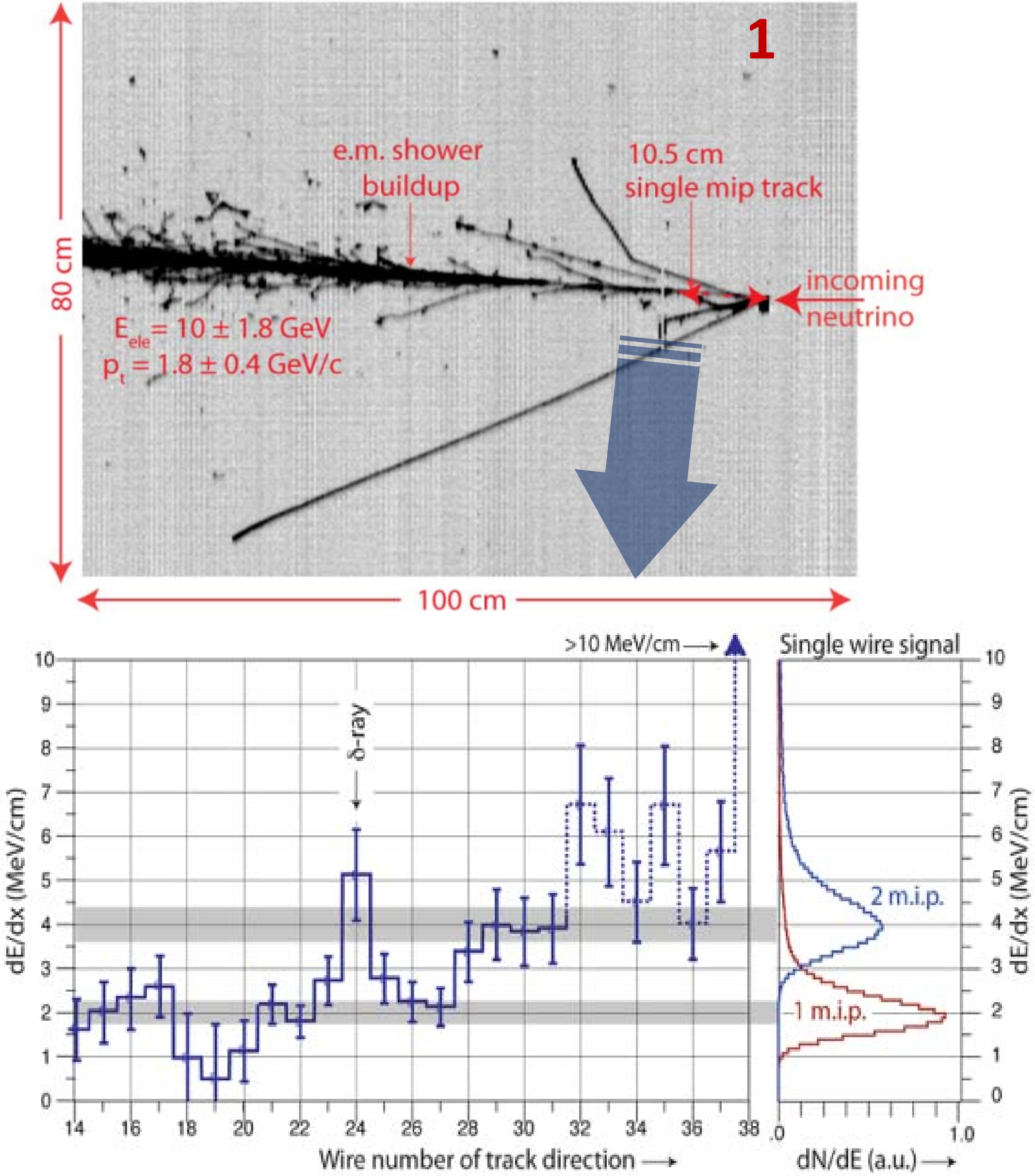
- **POSITION AND ENERGY CUTS:**
  - Primary vertex at > 5 cm from TPC walls (50 cm downstream) for shower identification
  - Visible energy <30 GeV (beam extends to higher E_ν), only 15% signal events rejected



- **ELECTRON SIGNATURE:**
  - A charged track from primary vertex, m.i.p. on 8 wires, subsequently building up into a shower (very dense sampling: every 0.02 X_0)
  - Clear separation (150 mrad) from other ionizina tracks near the vertex in at least one of 2 transverse views
    - Electron efficiency studied with a sophisticated simulation: h=0.74±0.05. (for intrinsic ν_e background, η' = 0.65±0.06 due to harder spectrum)

The expected number of e- events from intrinsic ν_e beam, θ_{13}~9^0 and $\nu_\mu - \nu_\tau$ oscillations is 6.4±0.9

4 ν_e events observed on 1995 neutrinos



Reconstruction:

(1) E_{tot} = 11.5 ± 1.8 GeV, p_t = 1.8 ± 0.4 GeV/c

(2) E_{tot} = 17 GeV, p_t = 1.3 ±0.18 GeV/c

(3) E_{tot} = 27 ± 2.0 GeV, p_t = 3.5 ± 0.9 GeV/c

(4) E_{tot} = 14 ± 1 GeV, p_t = 1.2 ±0.2 GeV/c

In all events: single electron shower clearly opposite to hadronic component in the transverse plane

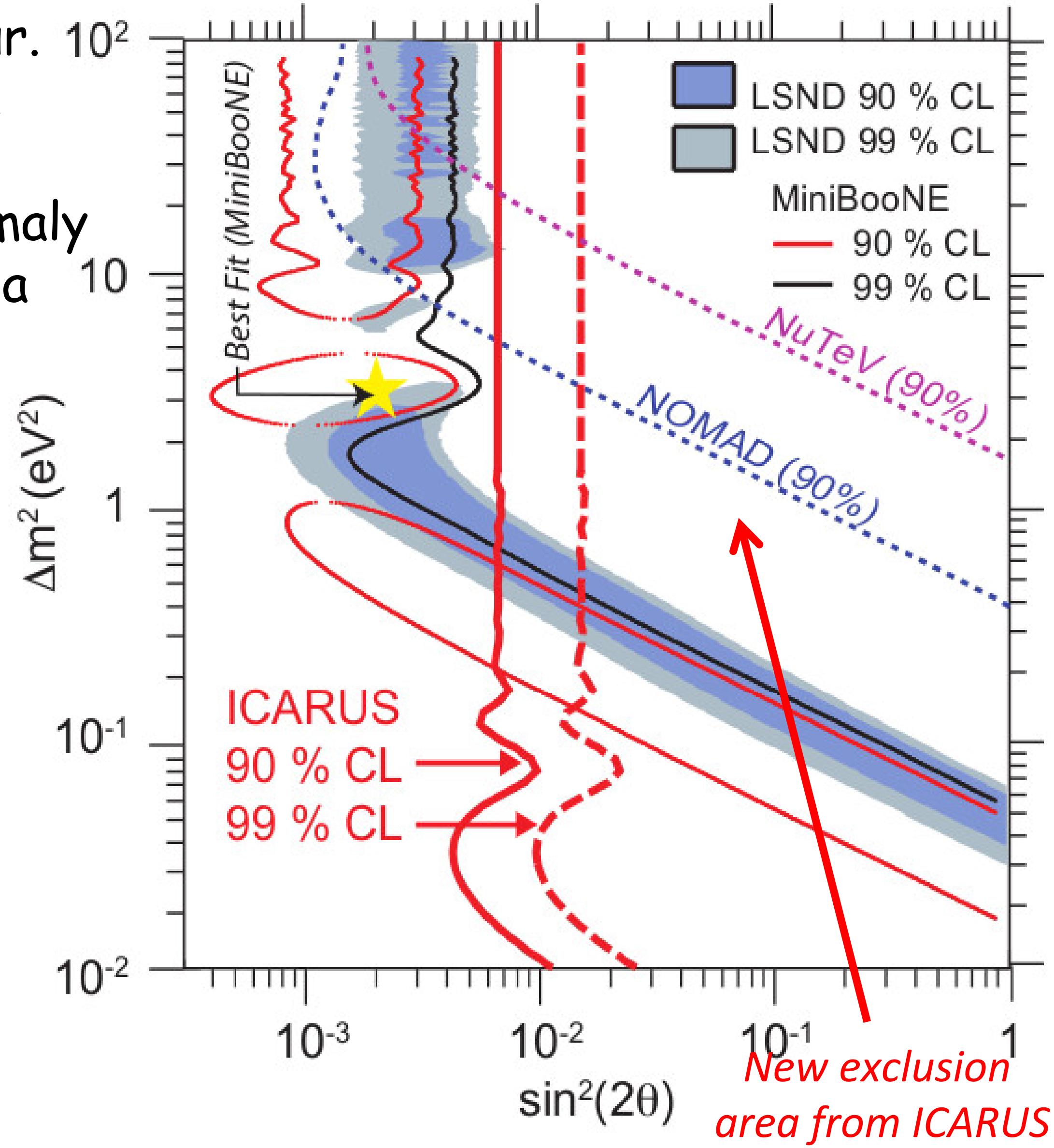
Results on LSND-like anomaly

- The first ICARUS result (Eur. Phys. J. C 73) based on 1091 ν interactions (3.3 10^{19} pot) ruled out most of LSND anomaly parameter region, indicating a narrow region around ($\Delta m^2 \sin^2 2\theta$)=(0.5 eV^2-0.005) where all results are compatible.
- New updated analysis with almost doubled statistics ⇒ in total 6.0 x 10^{19} pot and 1995 n events
- Limits on number of events:

  3.7 (90% CL) 8.3 (99% CL)

- Limits on oscillation probability:

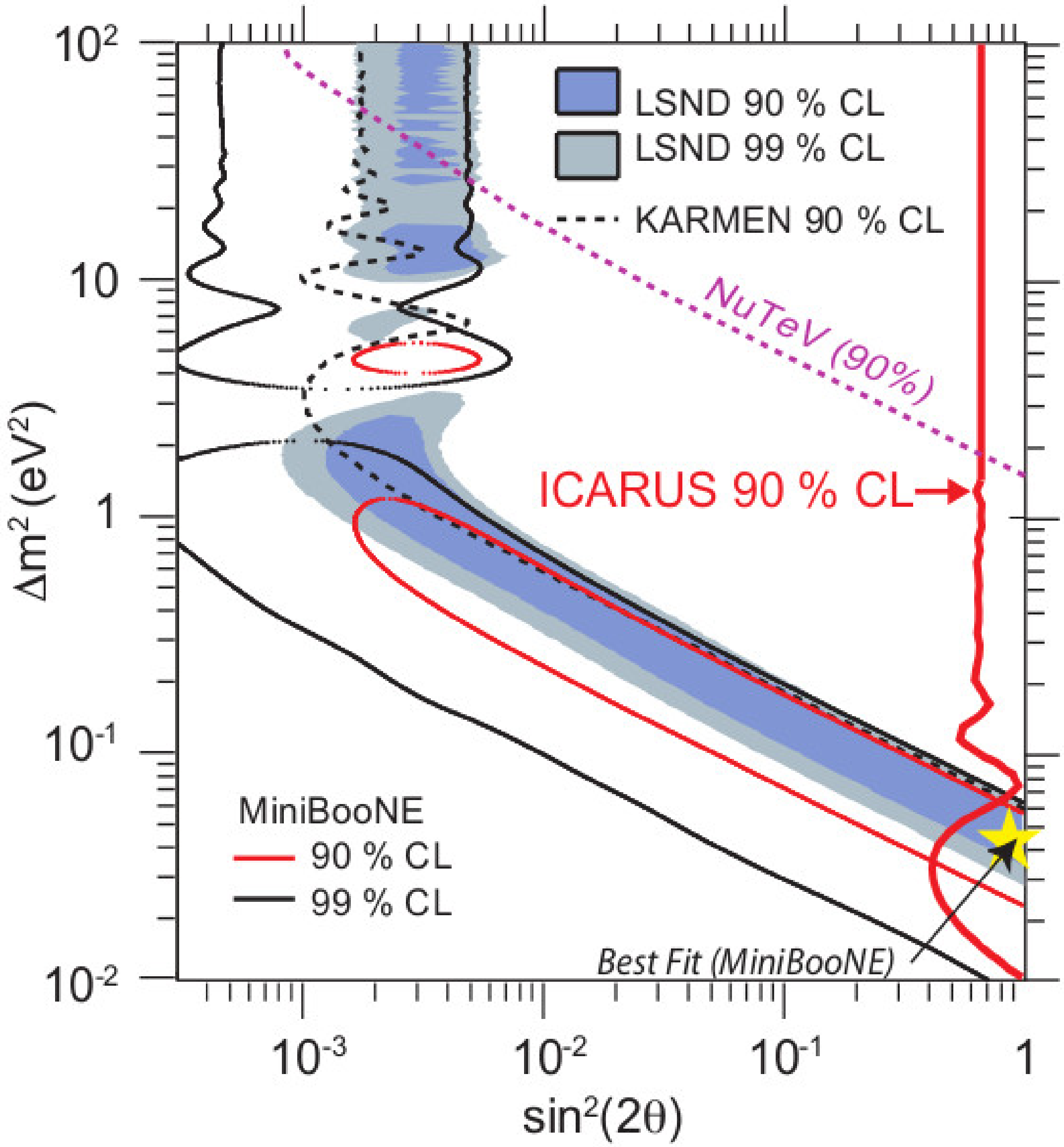
  $P_{\nu\mu\rightarrow\nu e} \leq 3.4\ 10^{-3}$ (90% CL)
  $P_{\nu\mu\rightarrow\nu e} \leq 7.6\ 10^{-3}$ (99% CL)



arXiv:1307.4699

Search for antineutrino oscillation

- A test of "LSND-like" antineutrino oscillation can be performed using the anti-ν_μ contamination in the CNGS beam (2%); search for appearance of anti-ν_e (signature is identical to ν_e)
- The absence of an anomalous anti-ν_e excess gives a limit of 4.2 events @90% C.L.
- Large $\sin^2 2\theta$ solutions in LSND/MiniBOONE antineutrino parameter space are excluded.



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Outlook and conclusions

- ICARUS-T600 just ended 3-year run at LNGS with CNGS ν beam
- The successful long-term operation of a large LAr-TPC in an underground lab paved the way for a promising future of this detector technique
- Analysis of the full collected CNGS sample and cosmic data is ongoing; first physics results have been published (LSND anomaly, neutrino velocity)
- Detector decommissioning is ongoing; the T600 will soon be moved to CERN for refurbishing and further R&D activity with test beams
- Partnership with LBNE project ensures a long-term future for LAr-TPC technology

THANK YOU!