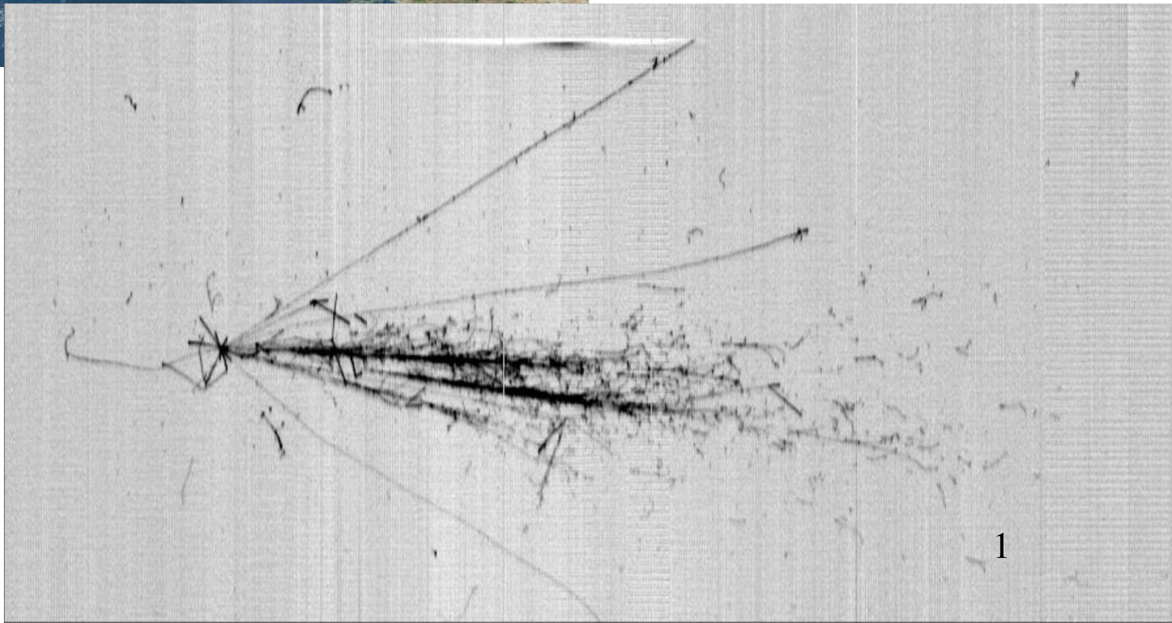
The ICARUS Experiment: latest results



C. Montanari
for the ICARUS Collaboration

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The ICARUS Collaboration

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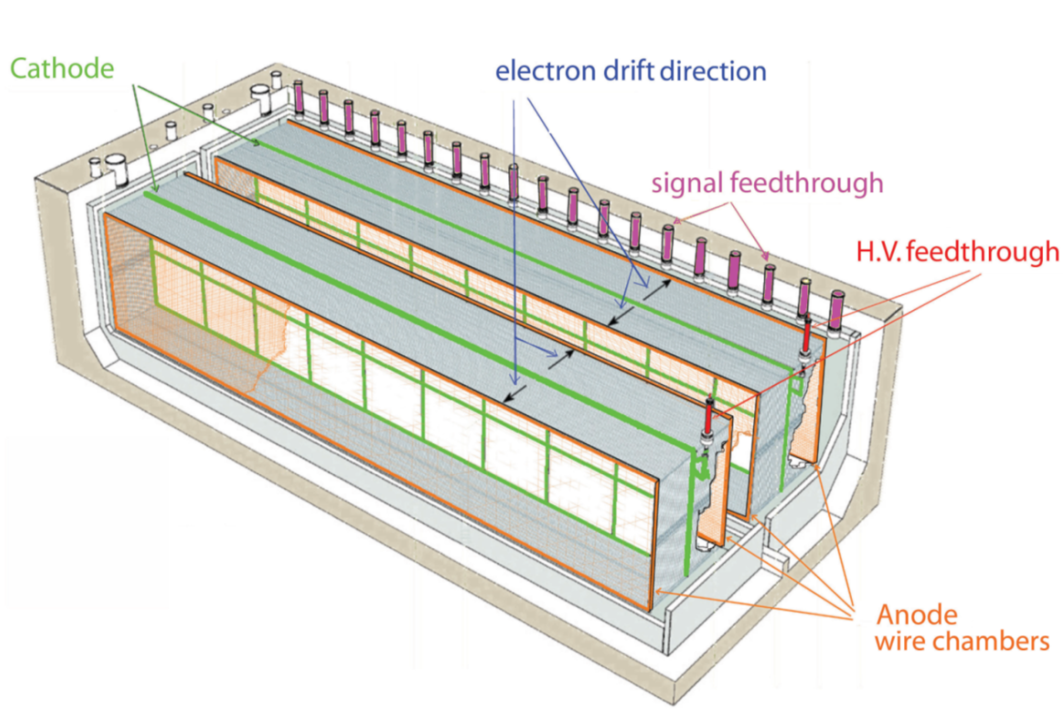
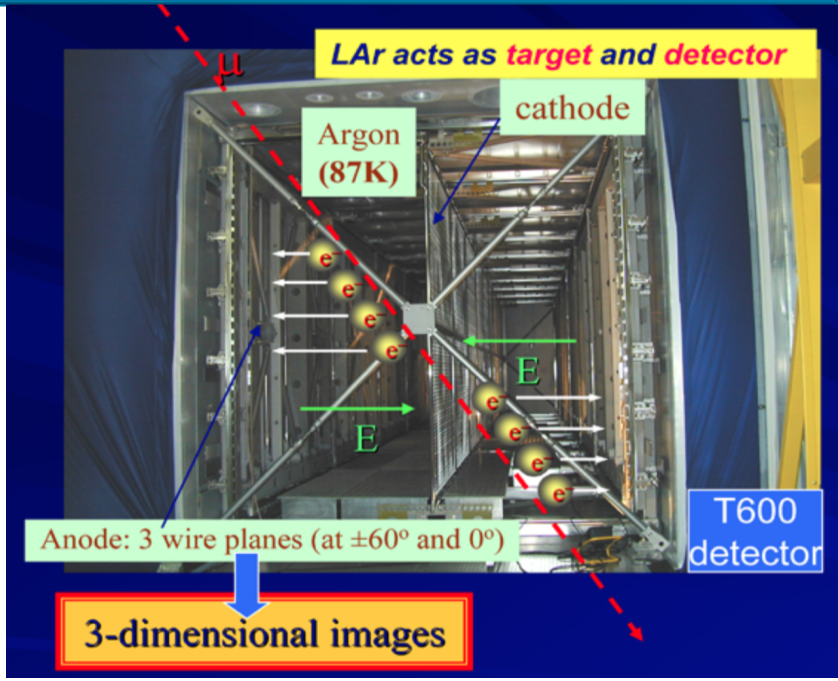
The ICARUS experiment

- ICARUS T600 is the largest liquid argon TPC ever built (760 tons full volume, ≈ 500 tons sensitive). It is installed in Hall B of LNGS underground laboratory were it smoothly operated from May 2010 to June 2013 taking data both from CNGS ν beam and cosmic rays.
- Performing like an "electronic bubble chamber" it provides an uniform imaging and calorimetry of the sensitive volume with high granularity (~mm^3) and excellent space (≈mm) and energy resolution both for e.m. (≈ $3\%/\sqrt{E}$ (GeV)) and hadron showers (≈$30\%/\sqrt{E}$ (GeV)).
- It is self-triggering and it allows full 3D reconstruction of events from few MeV up to few tens of GeV.
- The LNGS run provided, so far, important contributions to sterile neutrino search ($\nu_\mu \rightarrow \nu_e$) and to neutrino velocity measurements. In particular the latest results of the search for a ν_e signal in the "LSND anomaly" region reduces the window of common agreement (90% CL) between ICARUS, KARMEN, LSND and MiniBooNE to a narrow region centered around (Δm^2 , $\sin^2(2\theta)$) = (0.5 eV^2 , 0.05)
- Long term underground operation of the T600 is widely considered as a major milestone towards next generation detectors (tens of ktons) for neutrino physics and rare events searches.

The ICARUS T600 detector



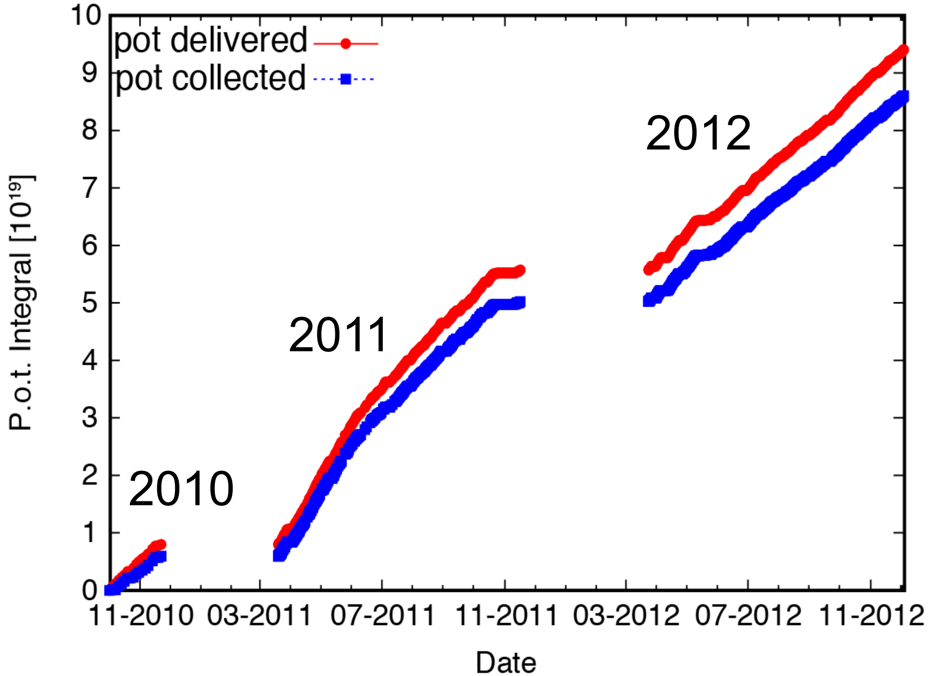


- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/µs

- 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)

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

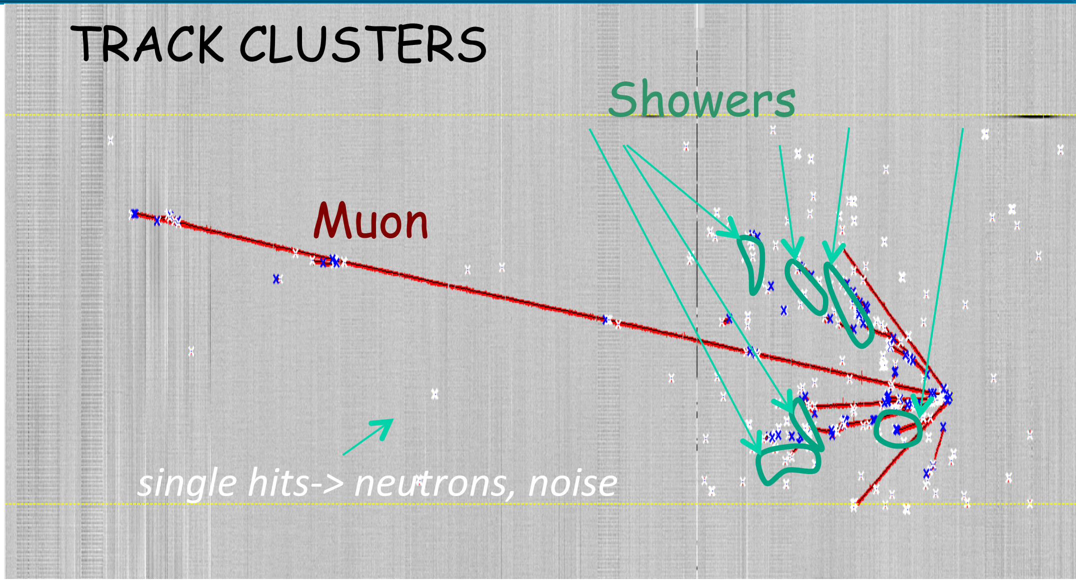


- First published physics results
  - Superluminal ν searches:
    1. Cherenkov-like e^+e^- emission: PL B711 (2012) 270
    2. neutrino tof measurement PL B713 (2012), 17
    3. neutrino tof precision measurement: JHEP 11 (2012) 049
  - Search for $\nu_\mu \rightarrow \nu_e$ "LSND/MiniBooNE" anomaly: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

- Technical run with cosmic rays from Dec. 2012 to June 2013

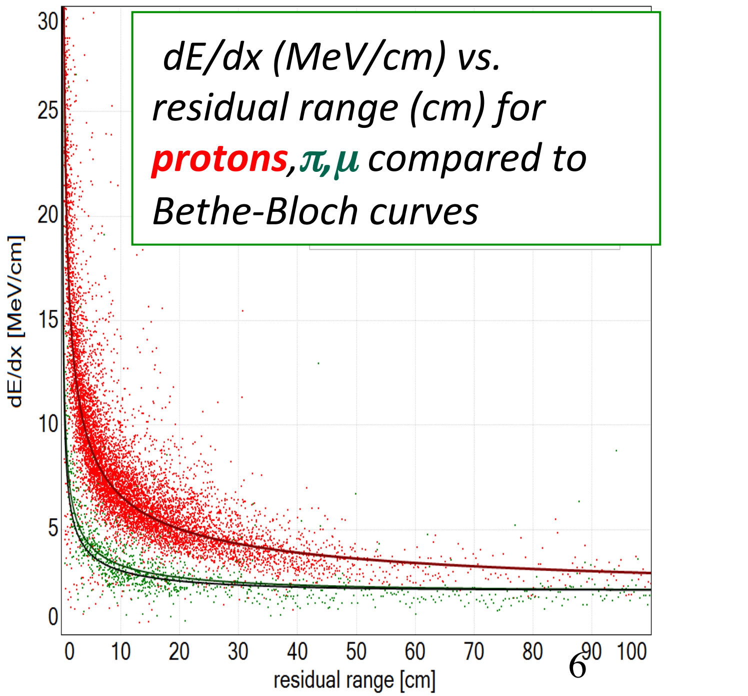
Full event reconstruction

- *Tracking:*
  - Automatic vertex and track identification
  - Precise (1 mm) 3D track reconstru
  - Non-contained muon momentum via multiple scattering

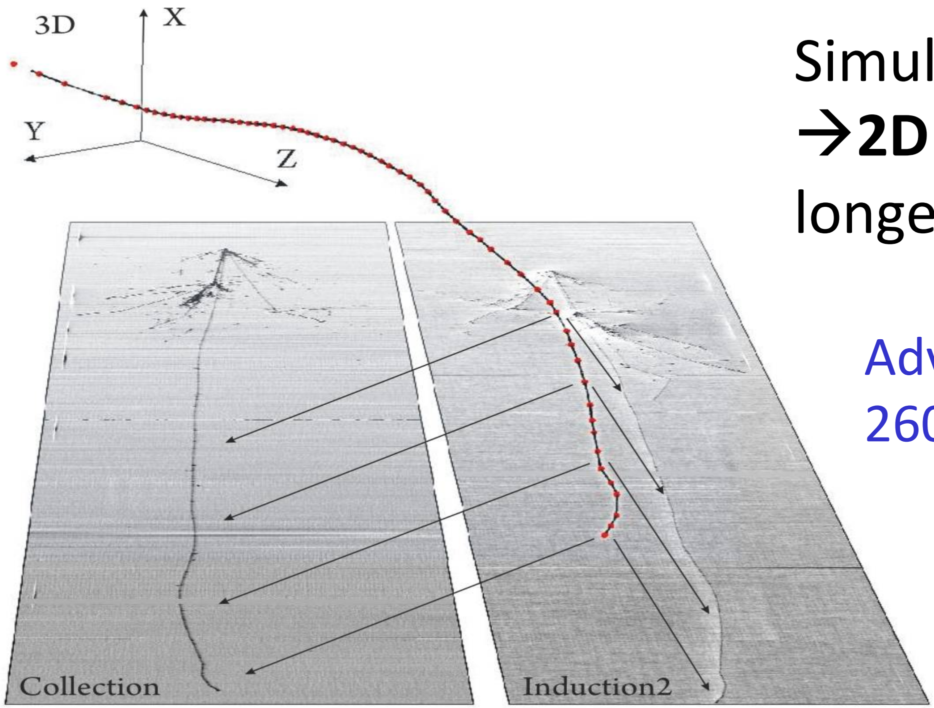


- *Measurement of energy deposition dE/dx:*
  - Excellent e/γ separation
  - Particle ID (dE/dx vs. range)

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

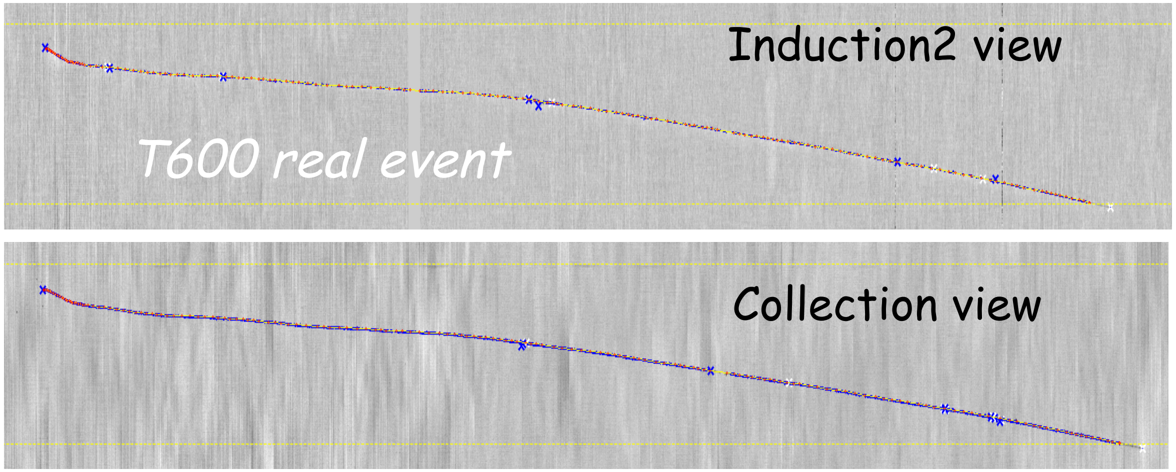


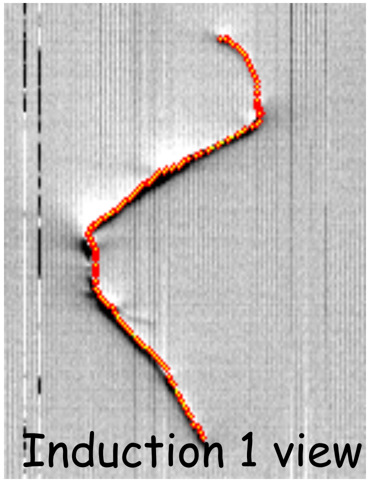
3D reconstruction (example of stopping μ)



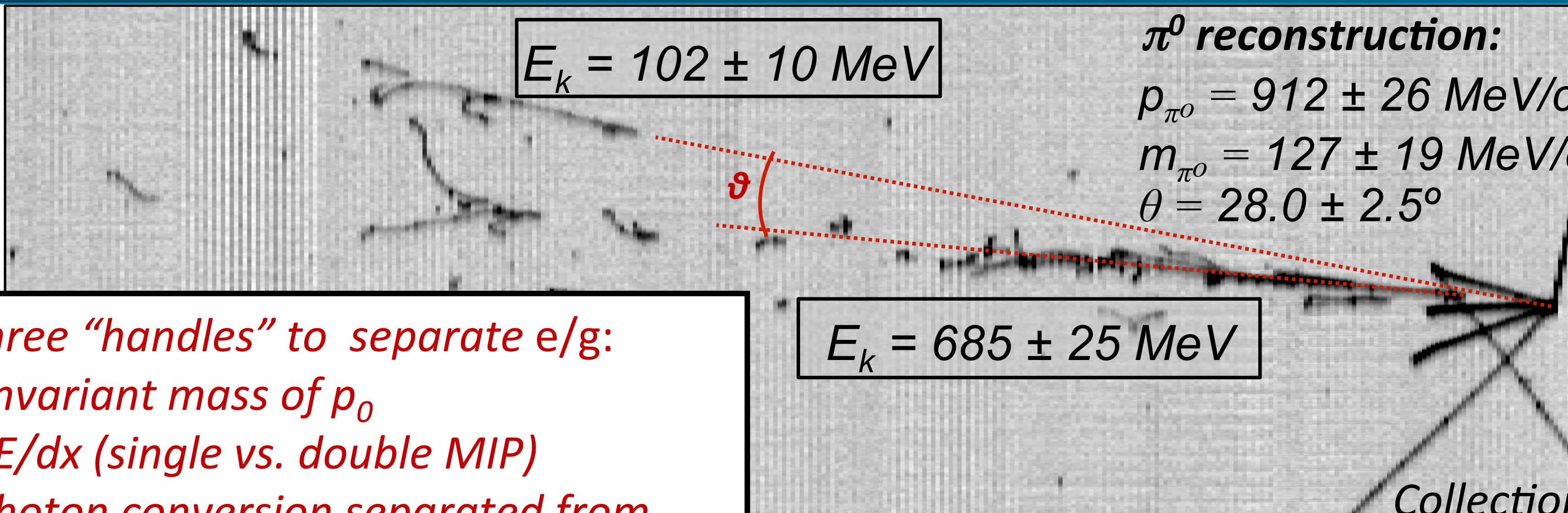
Simultaneous **3D** polygonal fit →**2D** hit-to-hit associations no longer needed

Adv.High Energy Phys. 2013 (2013) 260820





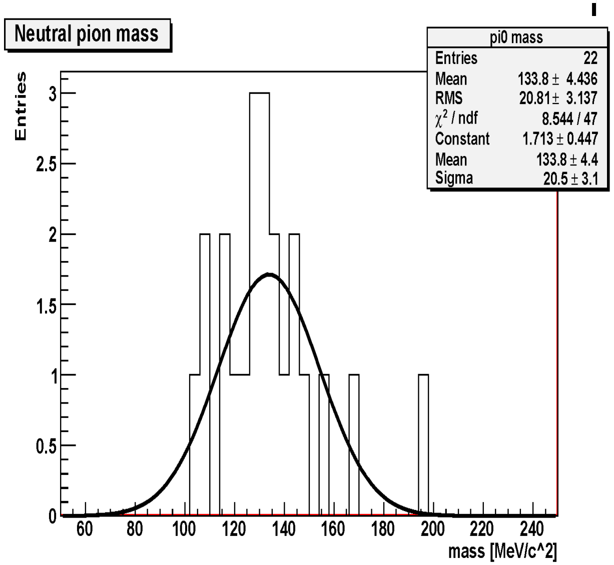
e/γ separation and π^0 reconstruction

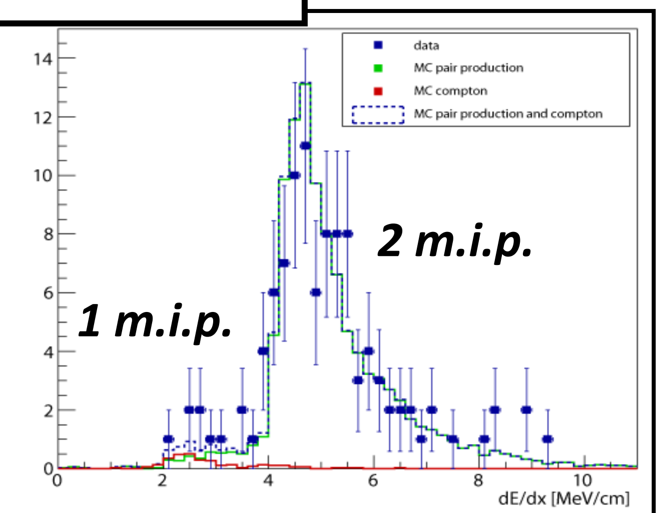


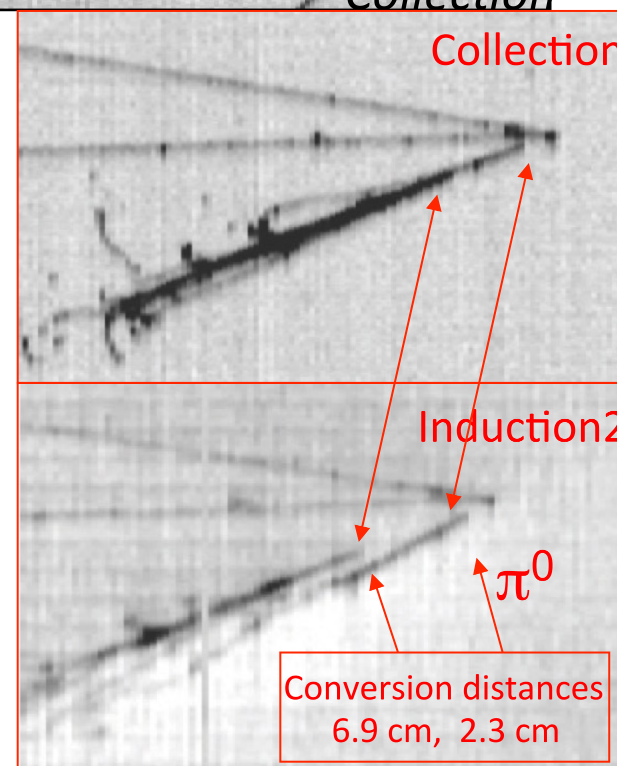
Three "handles" to separate e/g:

- invariant mass of p_0
- dE/dx (single vs. double MIP)
- photon conversion separated from primary vertex

$M\gamma\gamma$:133.8±4.4±4 MeV/c²







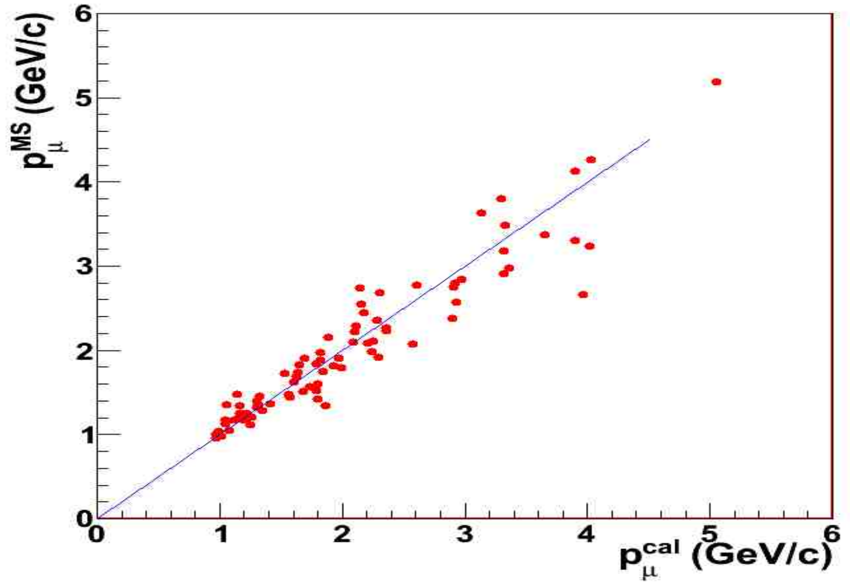
Unique feature of LAr
Crucial for ν_e physics

Muon momentum measurement via multiple scattering

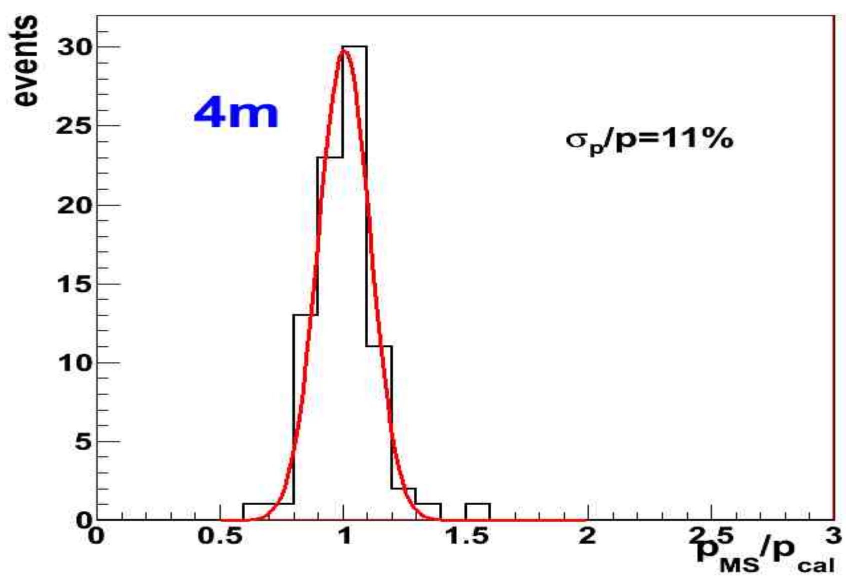
Key tool to measure momentum of non-contained muons: essential for ν_μ CC

- Measurement of p_μ with MS in LAr first proposed by C. Rubbia (1999)
- Method experimentally tested using stopping muons from CNGS ν_μ CC interactions in the rock upstream the T600.

Comparison between the muon momentum measured by MS with the one obtained by calorimetry



Example of momentum measurement using only first 4 meters of μ track



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	-νμ ->νe CC	3.8 σ
MiniBoone	Short baseline	Neutrino beam	-νμ ->νe CC	3.4 σ
MiniBoone	Short baseline	Anti-Neutr. beam	anti-νμ ->νe CC	2.8 σ
Gallium	Electron capture	Source	ν disapp.	2.7 σ
Reactors	Fission	Beta decay	ν disapp.	3.0 σ

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 $\nu_e \approx 1\%$):
  - Difference w.r.t. LSND experiment:

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

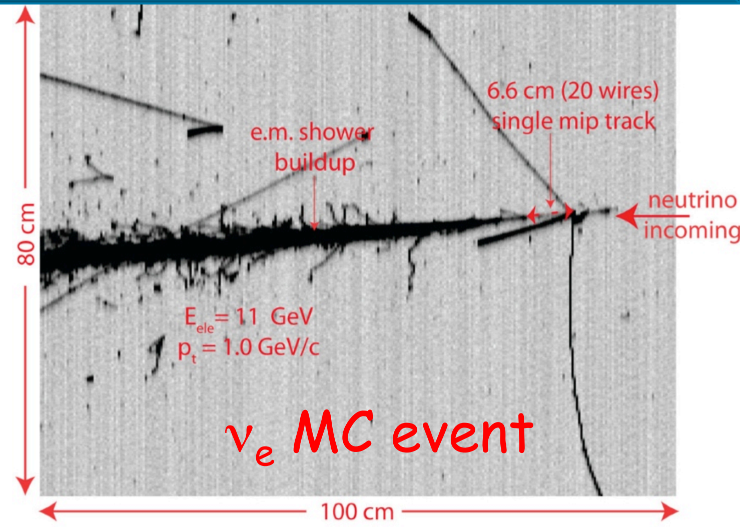
    LSND-like short distance oscillation signal averages to:

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

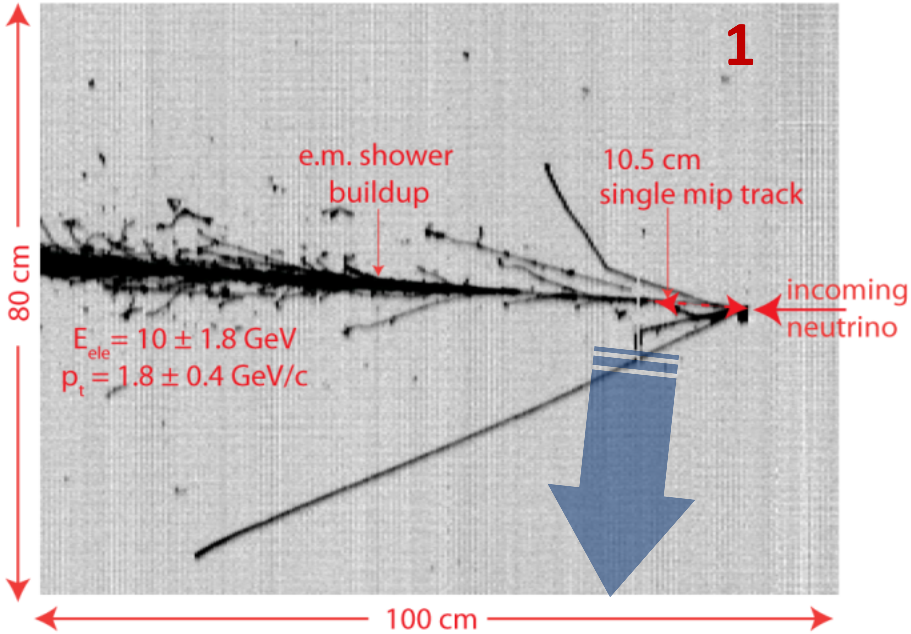
- POSITION AND ENERGY CUTS:
  - Primary vertex at > 5 cm from TPC walls (50 cm downstream) for shower identification
  - Visible energy <30 GeV (beam extends to higher E_ν), only 15% signal events rejected

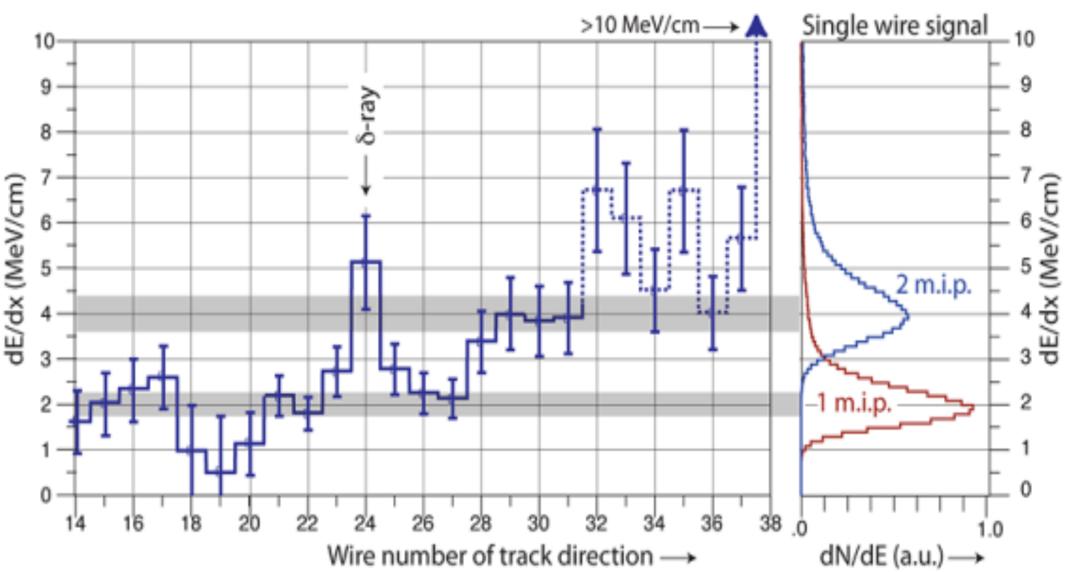


- ELECTRON SIGNATURE:
  - A charged track from primary vertex, m.i.p. on 8 wires, subsequently building up into a shower (very dense sampling: every 0.02 X_0)
  - Clear separation (150 mrad) from other ionizing tracks near the vertex in at least one of 2 transverse views
  - Electron efficiency studied 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 $\nu_\mu \rightarrow \nu_\tau$ 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

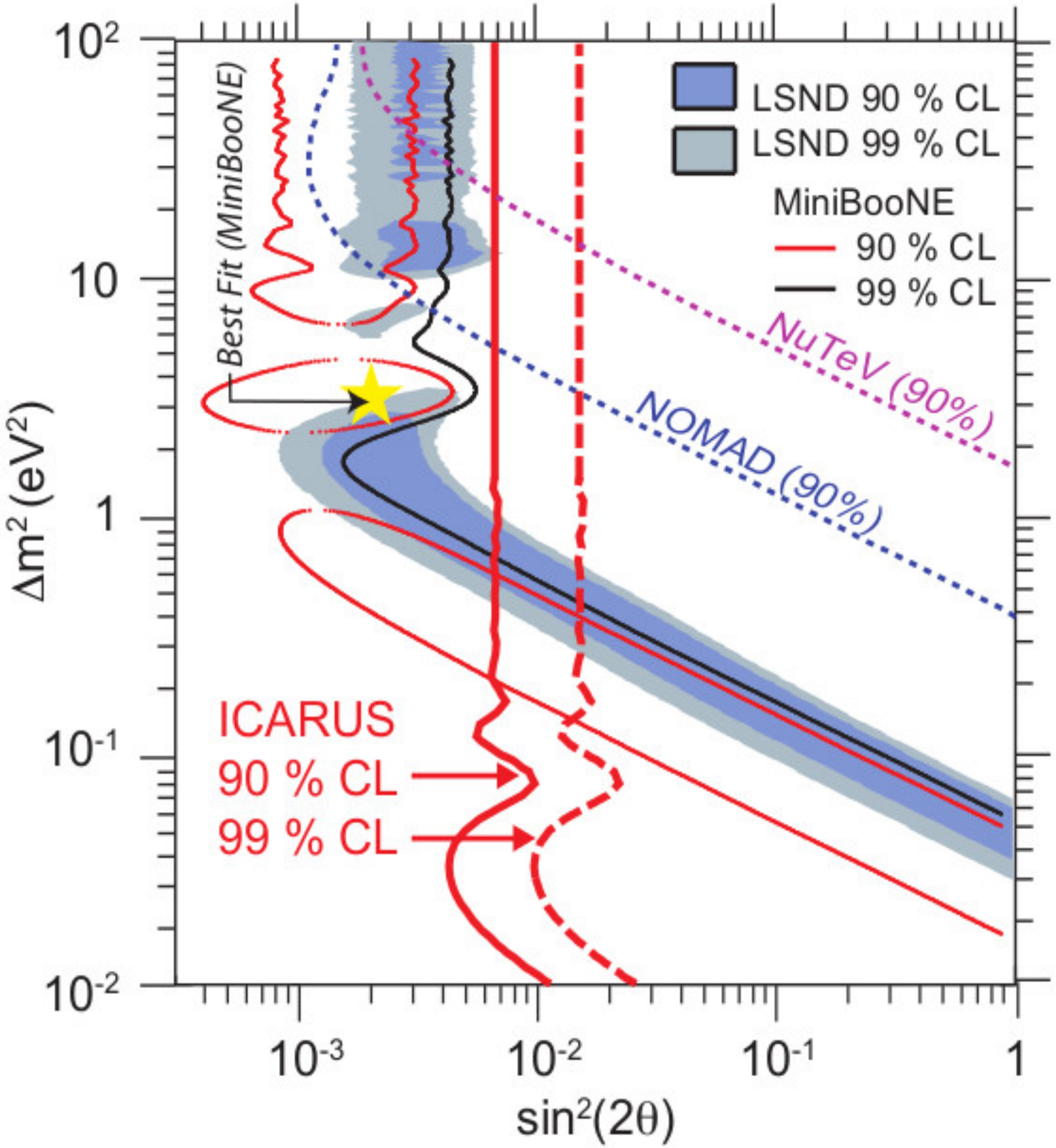
(3) E_{tot} = 27 ± 2.0 GeV,
p_t = 3.5 ± 0.9 GeV/c

(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

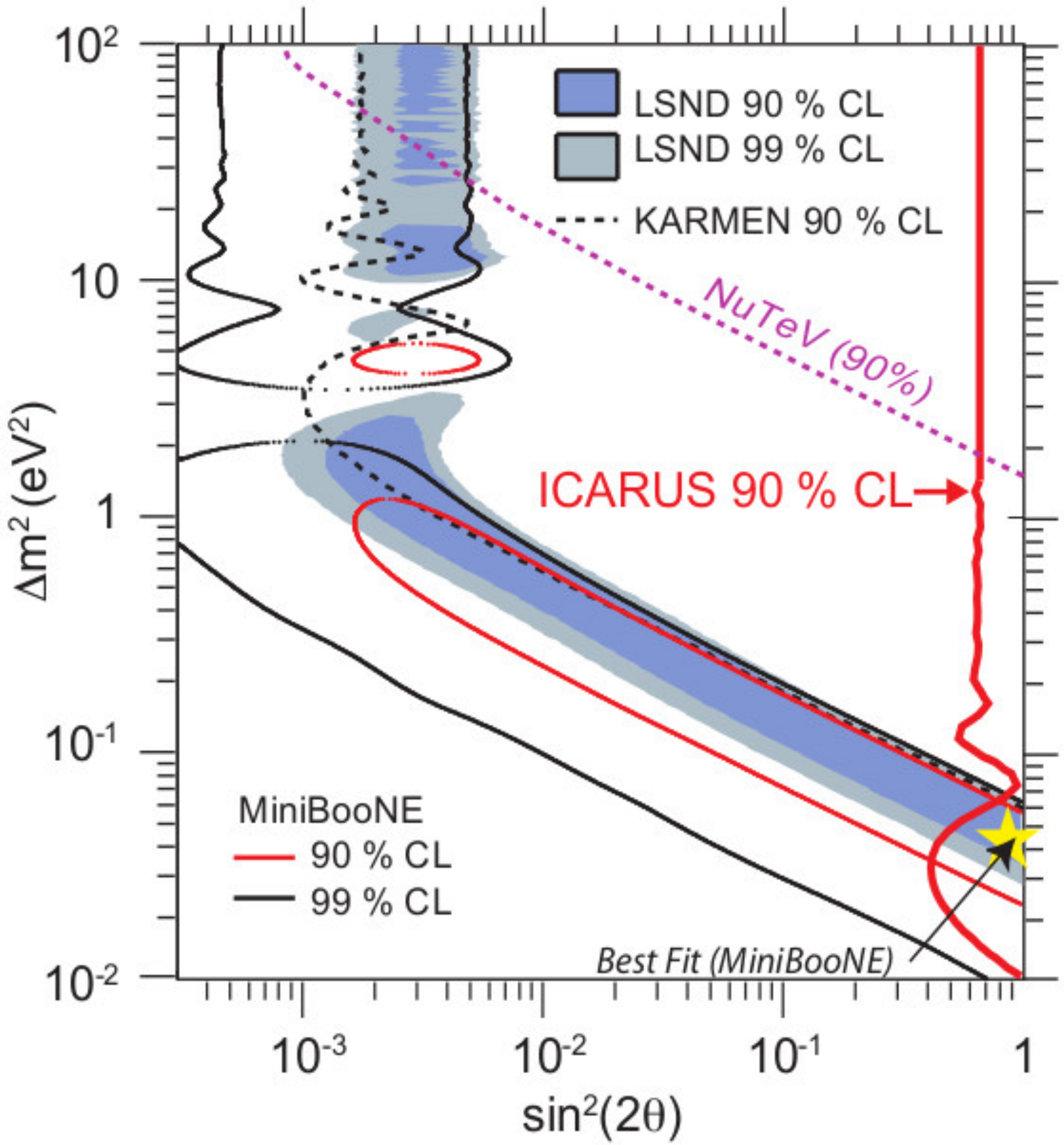
- The first ICARUS result (Eur. Phys. J. C 73) based on 1091 ν interactions (3.3 10^{19} pot) ruled out most of LSND anomaly parameter region, indicating a narrow region around ($\Delta m^2 \sin^2 2\theta$)=(0.5 eV^2-0.005) where all results are compatible.
- New updated analysis with almost doubled statistics ⇒ in total 6.0 x 10^{19} pot and 1995 ν events
- Limits on number of events: 3.7 (90% CL) 8.3 (99% CL)
- Limits on oscillation probability:
  $P_{\nu\mu \to \nu e} \leq 3.4\ 10^{-3}$ (90% CL)
  $P_{\nu\mu \to \nu e} \leq 7.6\ 10^{-3}$ (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.



arXiv:1307.4699

The LAr-TPC technology challenges

- Implementation of the LAr-TPC technology poses several very specific and demanding challenges:
  - Ultra-high LAr purification: electronegative contaminants concentration < 0.1 ppb (O_2 equiv. , depending on the chosen maximum drift length) has to be reached and maintained.
  - Mechanical precision and stability of the wires chambers: no wire has to broke due to the thermal stresses occurring during the cool down to LAr temperature.
  - Low noise, stable and reliable front-end electronics: no charge multiplication occurs in LAr. The typical signal, with 3 mm wires pitch, is 15000 electrons that has to be continuously recorded with a signal to noise > 10/1.
  - Highly reliable HV system: at a drift field of 500 V/cm, the voltage required to supply the field cage is 50 kV / meter. The system has to satisfy very strict requirements in terms of stability and reliability as a discharge could damage a large fraction of the readout electronics.

The LAr-TPC technology challenges (cont.)

- Highly stable and performing cryogenic system: capable to keep the LAr temperature very uniform and to guarantee continuous operation over several years.
- Safety: underground operation of a large and complex cryogenic device with large quantities of cryogenic liquids poses very severe requirements in terms of safety and reliability.

From T600 to the multi-kton scale

- Having successfully implemented fully industrial solutions for the above mentioned issues, the T600 represents the natural starting point for the developments required for new multi-kton devices.
- Modularity is an obvious choice. Already in 2008 we developed a preliminary design of 5 ktons units based on the evolution of the T600 (project ModuLAr). The ModuLAr design is very similar to the one currently proposed for LBNE.
- The T600, now being de-commissioned at LNGS, will be transported to CERN where it will be overhauled and put again in operation.
- A new smaller unit, about one quarter of the T600, T150, will be built implementing evolutionary solutions especially developed in view of future larger detectors. It will also be used, on appropriate beams, to precisely measure the LAr-TPC characteristics in the energy range (0 to few GeV) of interest for future neutrino experiments.
- Both the T600 and the new T150 will be then operated as far and near detector on a neutrino/anti-neutrino beam either at CERN or at Fermilab collecting a large number ($\geq 10^6$) of events on a short baseline and also appropriate for the future LBNE experiment.

Next neutrino activities

- Following the deliberation of the European Strategy Group for Particle Physics (March 16, 2013):
  CERN should develop a neutrino programme to pave the way for a substantial European role in future long — baseline experiments.
  Europe should explore the possibility of major participation in leading long — baseline neutrino projects in the US and Japan.
- A CERN project, spanning across the boundaries of the various CERN departments and groups, is now created *with the mandate to foster collaboration with all partners mentioned above and to create an effective research platform, supported by CERN, for a future neutrino research activity involving European partners.*
- The Italian ICARUS teams are joining the LBNE Collaboration; an agreement has already been co-signed.
- In addition to a *definitive clarification of sterile neutrino*, the R&D programme in LAr may pave the way to the ultimate realization of the LNBE detector for instance with:
  - An accurate determination of cross sections in Argon
  - The experimental study of all individual CC and NC channels
  - The realization of sophisticated algorithms capable of the most effective identification of the events.

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. A new T150 detector will also be built implementing new solutions in view of large scale future generation detectors.
- Italian ICARUS teams are joining the LBNE Collaboration for the realization, in the long range, of a multi-kton detector at Homestake for neutrino studies and rare phenomena searches.

THANK YOU!