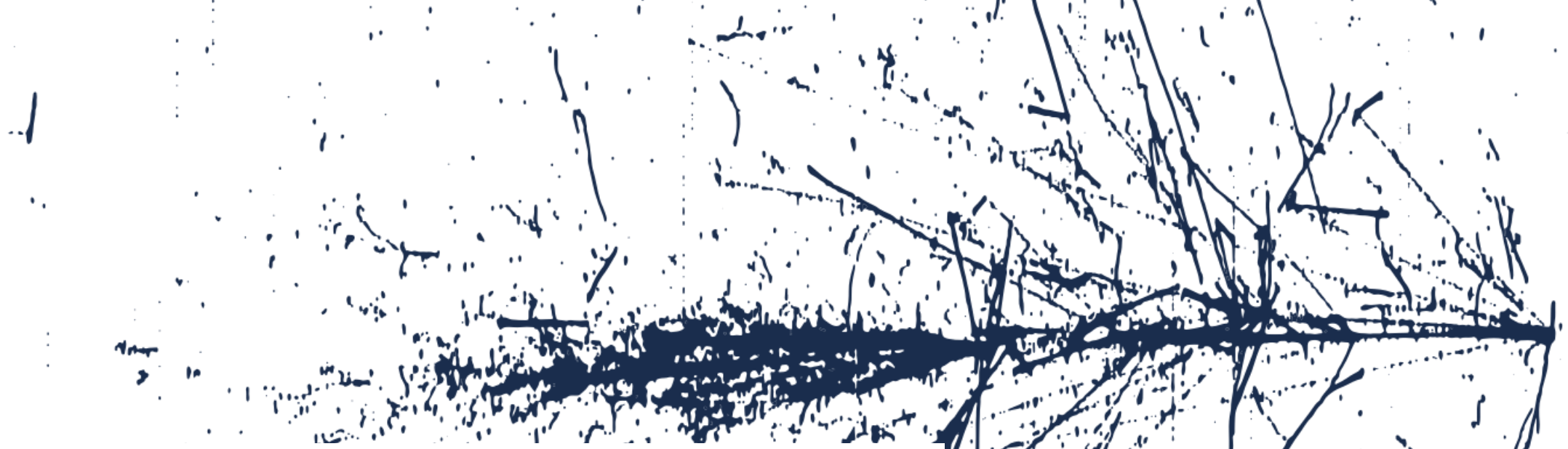
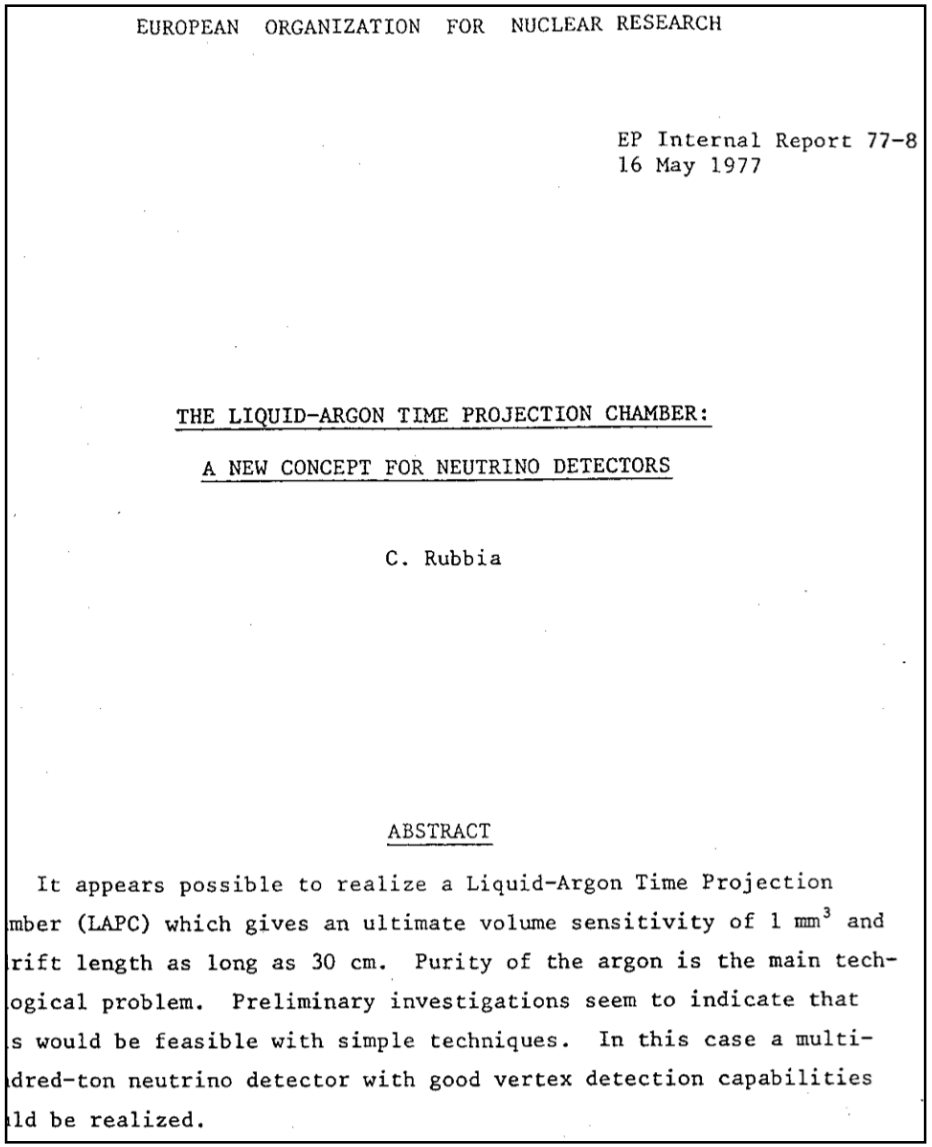


Carlo's Contribution to Neutrino Physics and Detector Technology

Prof. Antonio Zoccoli
INFN President

Istituto Nazionale di Fisica Nucleare

CERN, 18/10/2024



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection
mber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and
rift length as long as 30 cm. Purity of the argon is the main tech-
ogical problem. Preliminary investigations seem to indicate that
s would be feasible with simple techniques. In this case a multi-
dred-ton neutrino detector with good vertex detection capabilities
ld be realized.

Historical background

- Even before the experimental discovery of intermediate vector bosons at UA1, Carlo was thinking of how to remarkably improve neutrino physics
  - A growing and promising field

- Existing technologies (Water Cherenkov, Sampling massive detectors, massive bubble chambers) where either to light and slow to allow high precision statistics or incapable to provide details of the interactions

  - A new innovative technology was called for
  - **1977 proposal to build a Liquid Argon Time Projection Chamber**

1979 Group photo

Neutrino physics Today and LAr

- Leptons, and especially neutrinos, are not just mirroring the quark sector
  - They are remarkably light
  - They offer a rich and unique oscillation pattern, including possibly large CPV
  - They have only weak interactions

- Important questions or discoveries still ahead:
  - CPV in lepton sector, with interesting potential cosmological implications
  - Neutrino mass term (Dirac vs Majorana), with implications on Lepton Number violation
  - Is there a hidden “sterile” sector?
  - Is neutrino small mass connected to BSM physics through see-saw mechanism ?

→ To answer these questions we need next generation experiments with better technologies

→ LAr TPC, after decades of work, has become reality and offer unique opportunities

→ An important spin-off of the LAr TPC effort has been the development of double-phase liquid xenon and argon TPCs, widely used in dark matter search experiments

INFN

Liquid Argon Imaging Technology

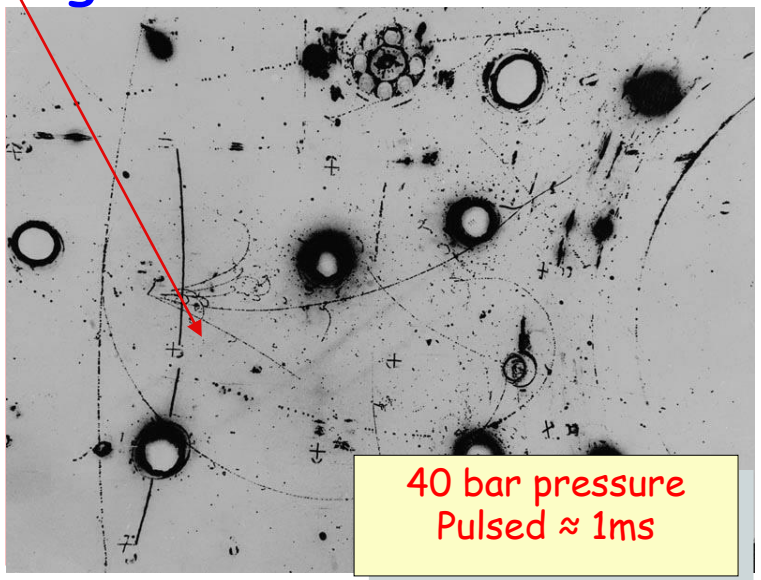
- Neutrino interactions are characterized by a very large number of potential events of different configurations and a large number of related channels which all need to be separately identified and accurately measured.
- The liquid Argon Imaging technology (LAr-TPC) is a new kind of detector, effectively an electronic bubble-chamber that Carlo has originally proposed at CERN [CERN-EP/77-08 (1977)], supported by the Italian Institute for Nuclear Research (INFN).
- Liquid Argon can be operated with very large sensitive masses, it is continuously sensitive, self-triggering, it provides three-dimensional views of ionising events, with particle identification from dE/dx, range measurements and multiple scattering.
- It acts also as a good homogeneous calorimeter of very fine granularity and high accuracy.
- Argon is inert, not flammable and it is operated safely even deep underground and without pressure or moving parts.

The first large scale underground detector

Bubble diameter ≈ 3 mm
(diffraction limited)

LAr is a cheap liquid (≈1CHF/litre), vastly produced by industry

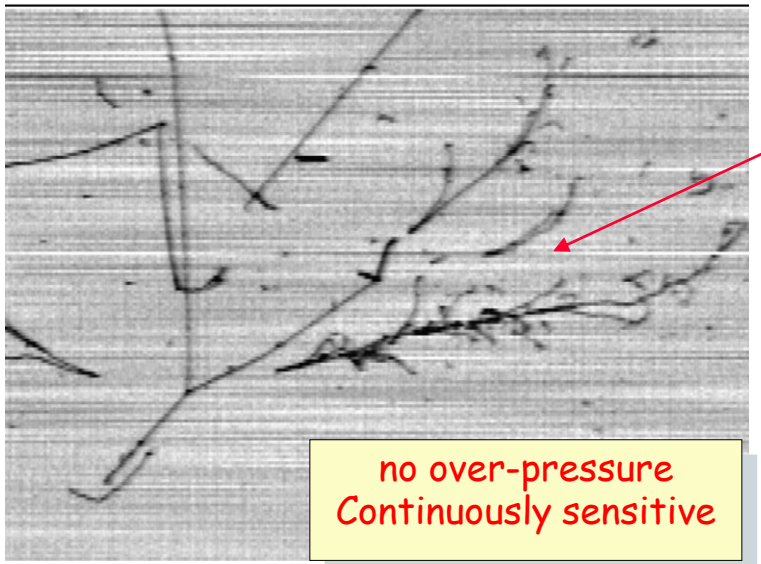
Gargamelle bubble chamber



40 bar pressure
Pulsed ≈ 1ms

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



"Bubble" size
3 x 3 x 0.3 mm3

no over-pressure
Continuously sensitive

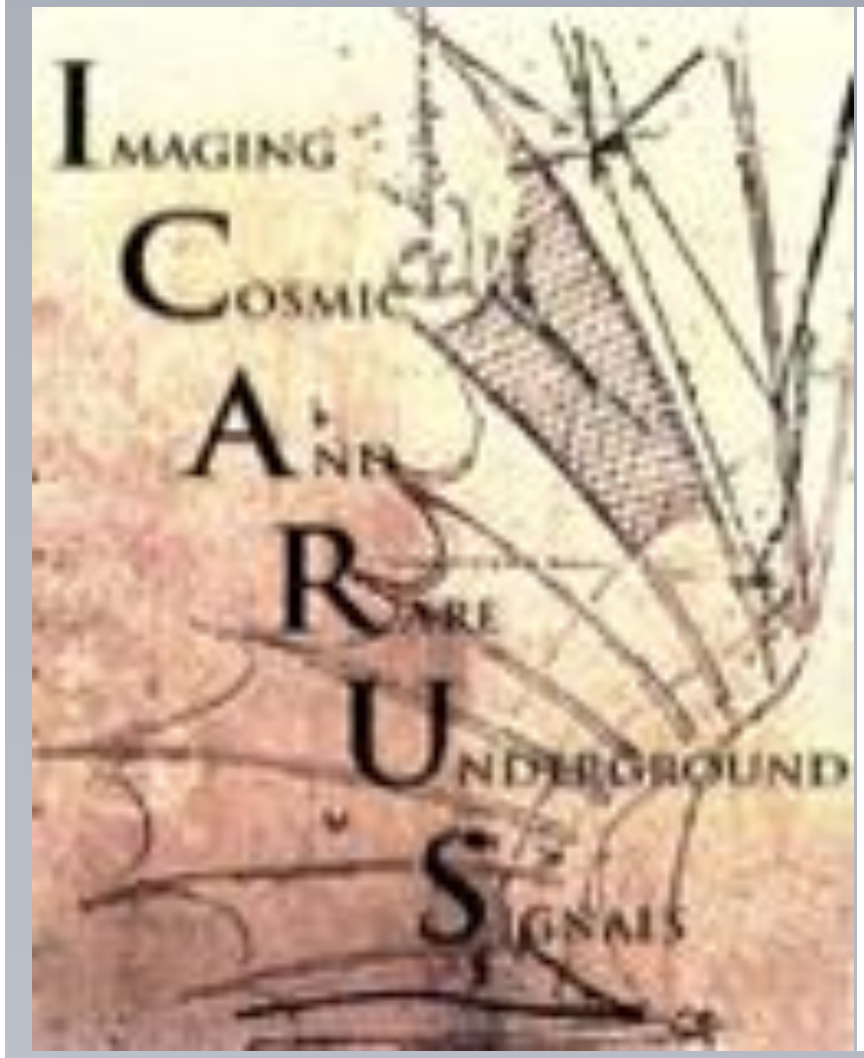
Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

→ *UV light*
Charge
Cerenkov light (if β>1/n)

1985

Imaging Cosmics And Rare Underground Signals

THE ICARUS PROPOSAL LNGS



SEARCHING FOR NEW UNDERGROUND PHENOMENA WITH HIGH RESOLUTION VISUAL TECHNIQUES AND MAGNETIC ANALYSIS

(ICARUS)

A PROPOSAL

FOR THE GRAN SASSO LABORATORY

CERN - Harvard - Milano - Padova - Roma - Tokyo - Wisconsin Collaboration

July 2, 1985

The Icarus long flight

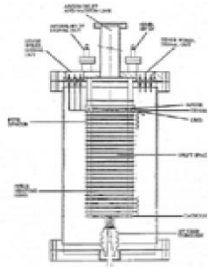
H. Matisse - Icarus

- 1977 conceptual idea
- 1985 ICARUS proposal
  - LNGS proposed by A. Zichichi in 1979, approved and financed in 1982, completed in 1987 [Science Fiction schedule today….]
- R&D in Pavia
  - 1987 First LAr TPC
  - 1991-1995 “small” (a few tons) scale demonstrators
  - 1997-1999 test beams @ CERN
  - 2001-2008 T600 modules in Pavia

- 2010-2013 Science with CNGS beam and cosmics @ LNGS
- 2014- Today, IcarUS is at Fermilab to study neutrino oscillations at high precision, after a careful refurbishment at CERN

The first large scale underground detector history

1



CERN

24 cm drift wires chamber

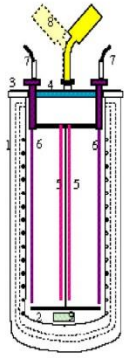
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

2

3 ton prototype

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

CERN

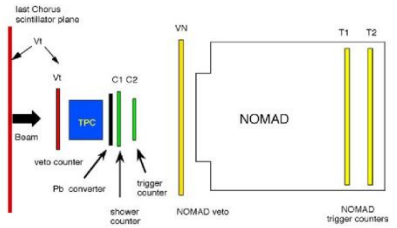


3

Laboratory work

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.

ICARUS T600 experiment

2010 - 2013 : Data taking with CNGS beam

4

Pavia

T600 detector

10 m^3 industrial prototype

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

Cooperation with industry and several companies

5

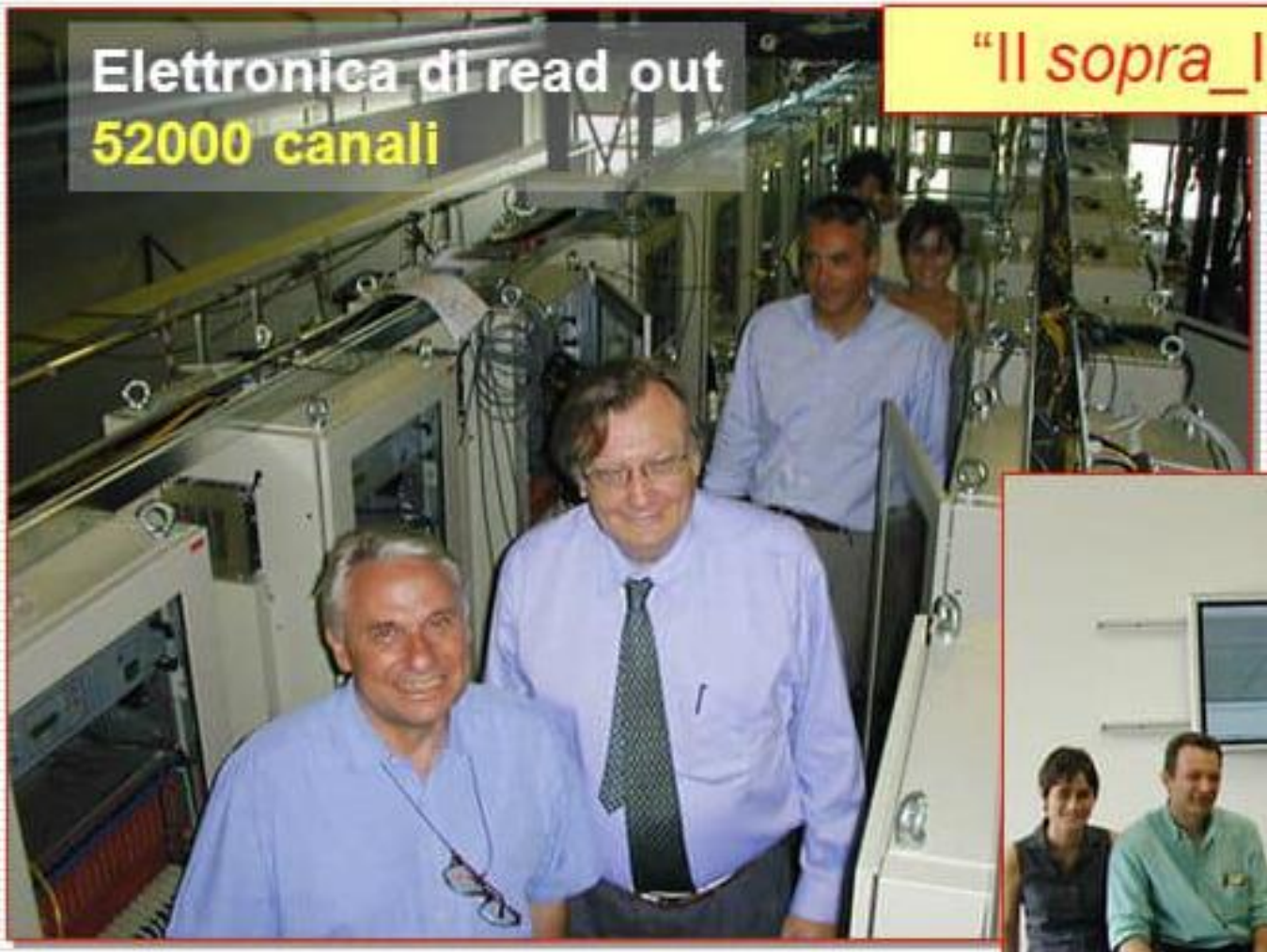
6

LNGS Hall-B

Nucl. Instrum. Meth. A 527 (2004) 329.

INFN

Test run.



"Il *sopra_luogo*"…

Agosto 2001

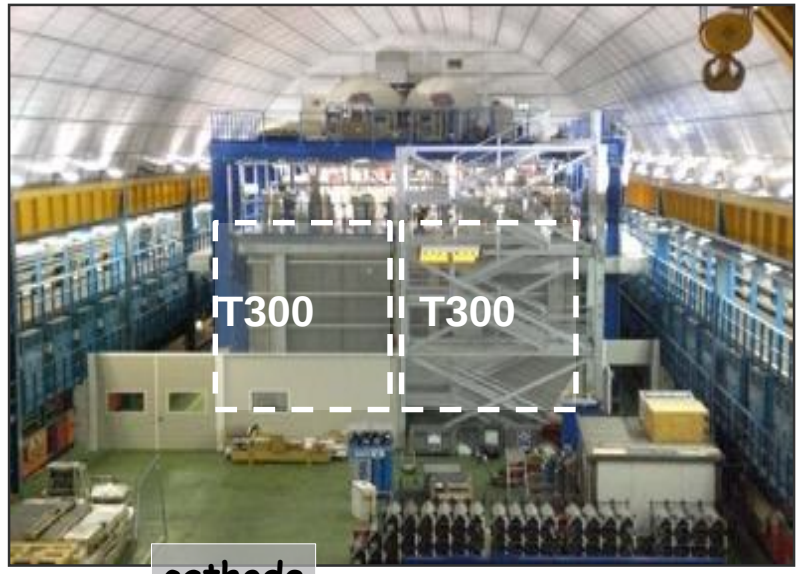
Le cosmiche interazioni…

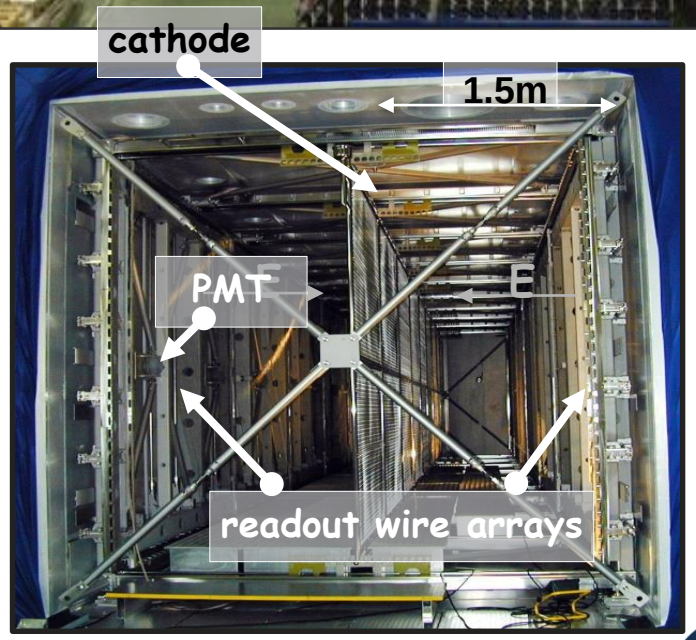
Pavia 2002

The first large scale underground detector:

2010-2013

- The first large-scale successful experiment ICARUS-T600, 0.76 kt ultra-pure LAr at LNGS exposed underground to CNGS and atmospheric νs
  - Tracking device: 3D event topology with $\Delta x \sim mm^3$, ionisation drifted undisturbed for meters with E_D= 0.5 kV/cm in pure LAr;
  - Full sampling homogeneous calorimeter: E measurement by charge signal integration;
  - Local dE/dx:remarkable e/γ separation, 0.02 X_0 sampling, X_0=14 cm, a powerful PID by dE/dx vs range.
  - Fast timing signal from scintillation light collected by TPB coated PMTS
- **Paving the way for Long Baseline experiments**



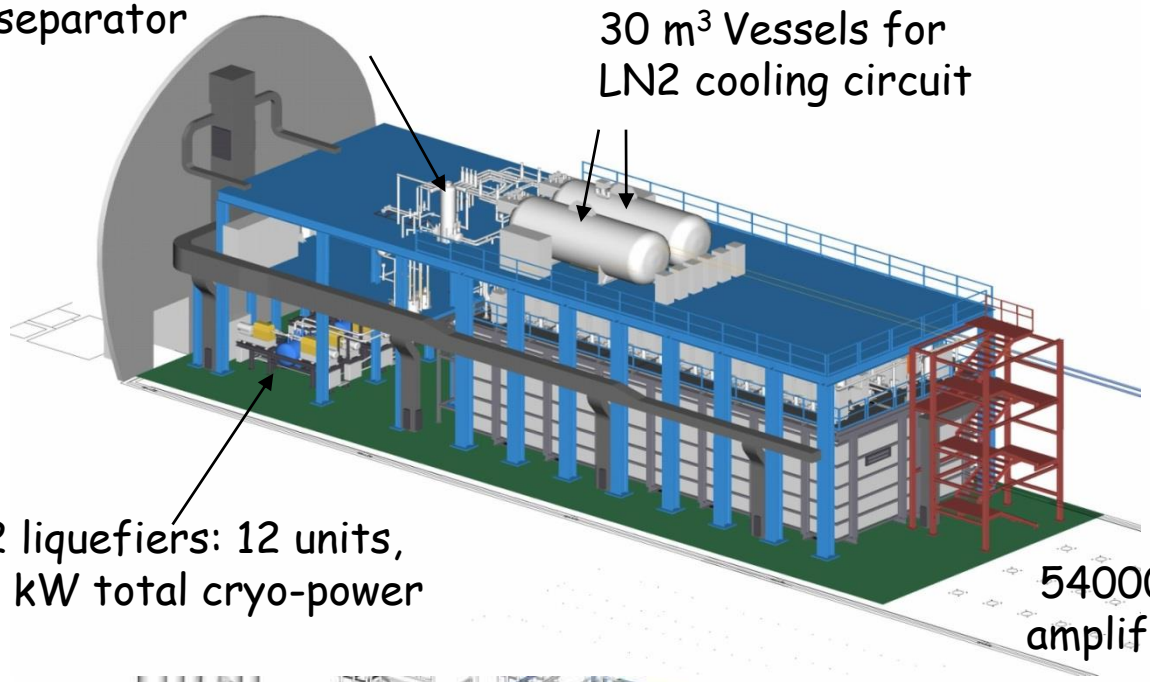


2011 JINST 6 P07011

ICARUS-T600 @ LNGS Hall B: 0.77 kton LAr-TPC

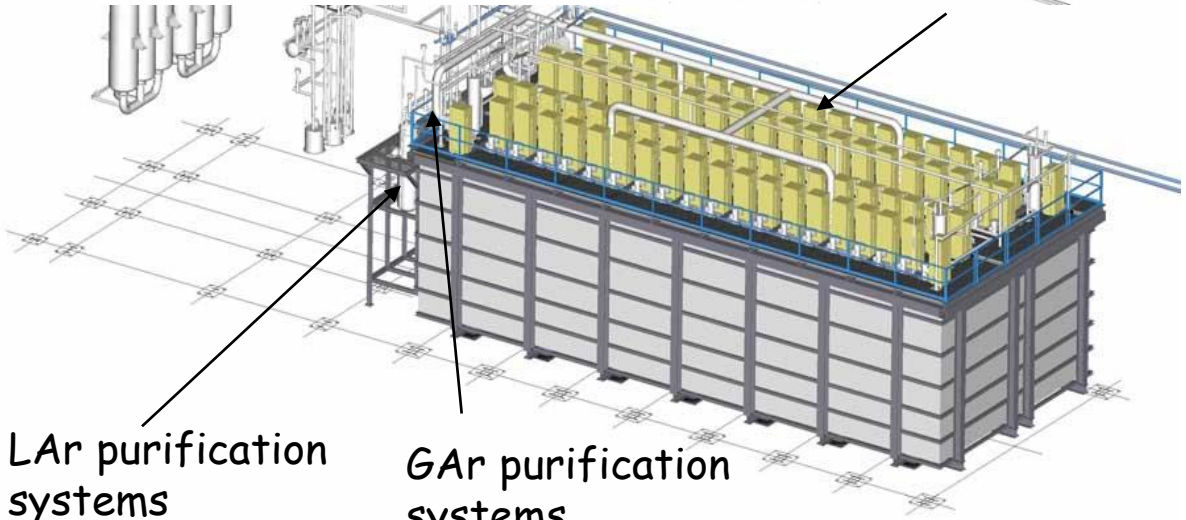
N2 Phase separator

30 m^3 Vessels for LN2 cooling circuit



N2 liquefiers: 12 units, 48 kW total cryo-power

54000 electronics channels (low noise charge amplifiers + digitizers, S/N > 10)



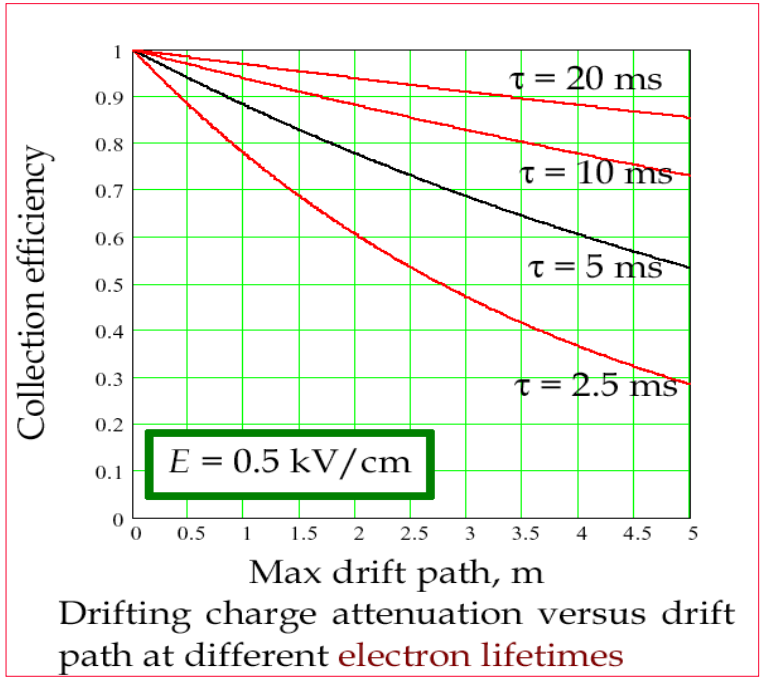
LAr purification systems

GAr purification systems

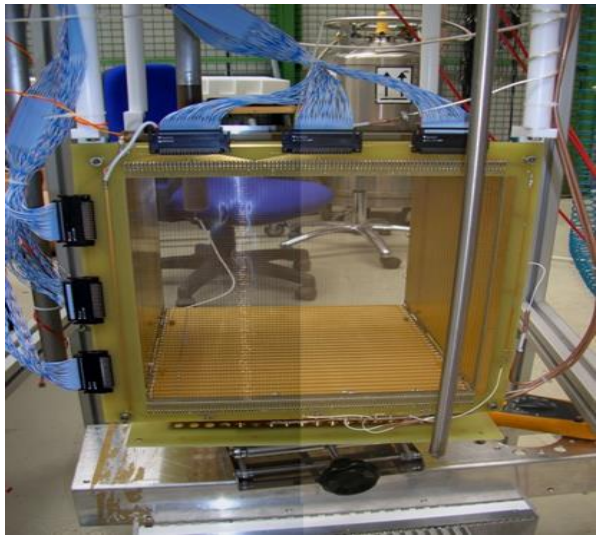
Results at LNGS 2010-2013

Long Electron Lifetime

- The main technological challenge of the LAr-TPC development is the sufficiently long free lifetime τ_{ele} of drifting electrons:
  - In the 2001 technical run in Pavia, τ_{ele} = 1.8 ms
- New industrial purification methods developed at an exceptional level: remnants of electronegative impurities (O2) have to be initially and continuously purified:
  - Extremely high τ_{ele} ≈21 ms (≈15 ppt molecular impurities) measured with cosmic μ's in a 50 litres LAr-TPC in INFN-Legnaro ICARINO.
  - Electron signal attenuation of ~10 % for a longest drift of 5 meters is obtained opening the way to exceptionally long drift distances.



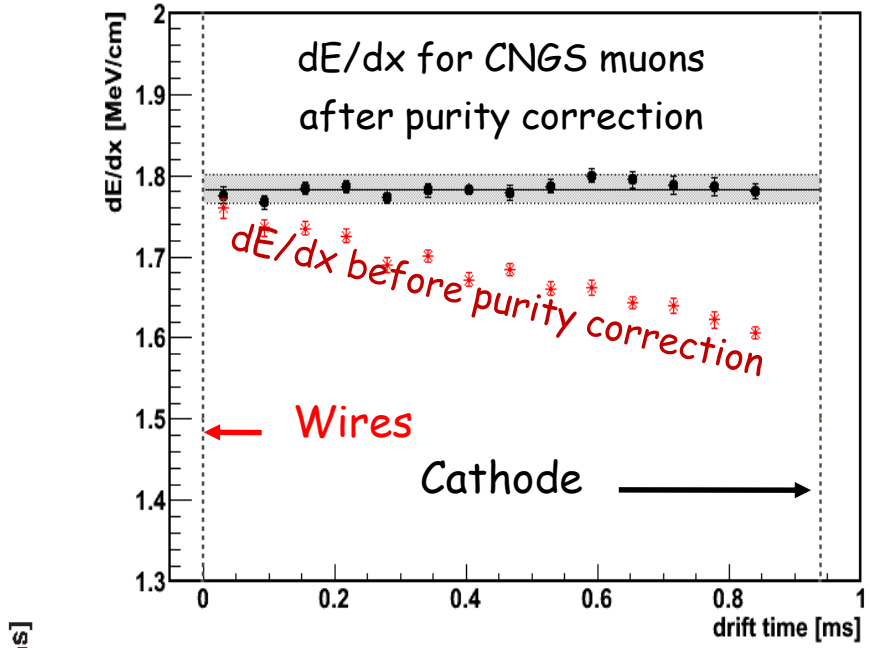
Drifting charge attenuation versus drift path at different electron lifetimes

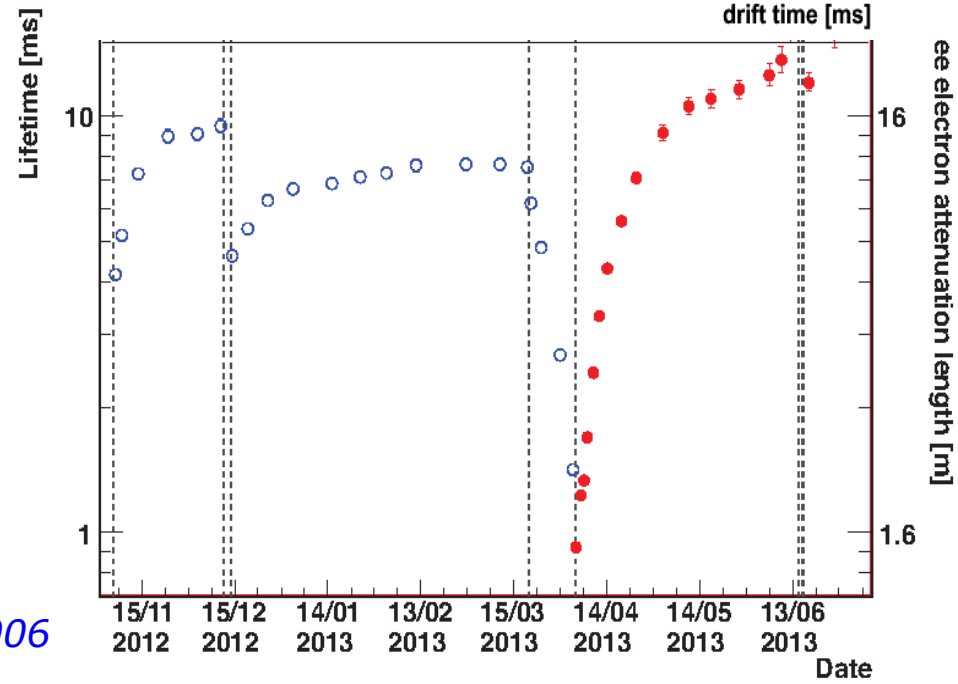


Results at LNGS 2010-2013

Lar purity

- Electron lifetime at LNGS studying the charge signal attenuation on cosmic μ's in the drift:
  - ∉ τ_{ele} > 7 ms (~40 p.p. trillion [O2] eq.)
  - 12% maximum charge attenuation on 1.5 m
- Cross check with muons from CNGS ν interacting in the upstream rock: dE/dx signal correctly reconstructed constant along the drift coordinate;
- Upgraded argon recirculation system: τ_{ele} > 15 ms !

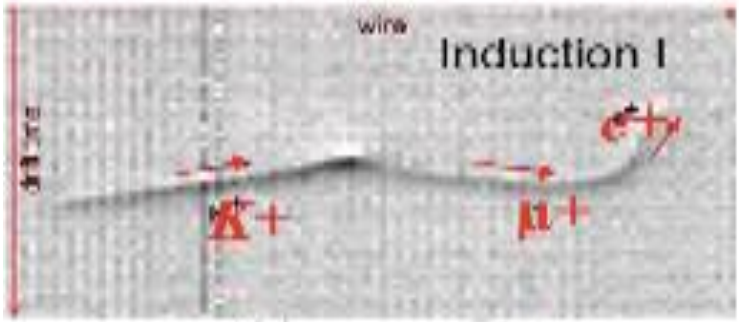


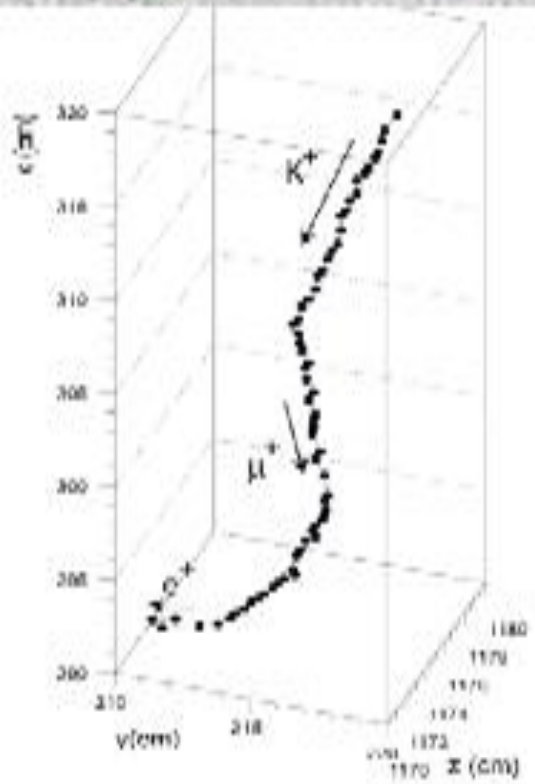


2014 JINST 9 P12006

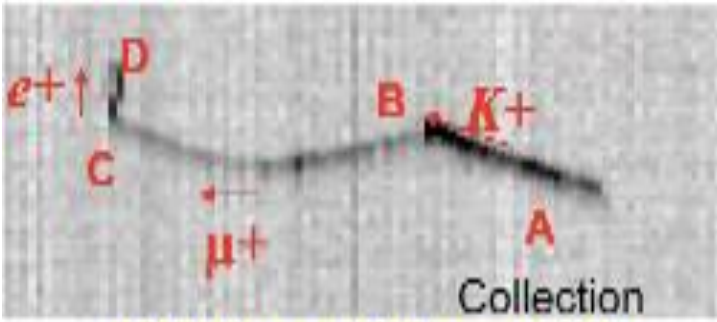
Results at LNGS 2010-2013

Particle Identification e.g. ($k^+ \rightarrow \mu^+ \rightarrow e^+$)





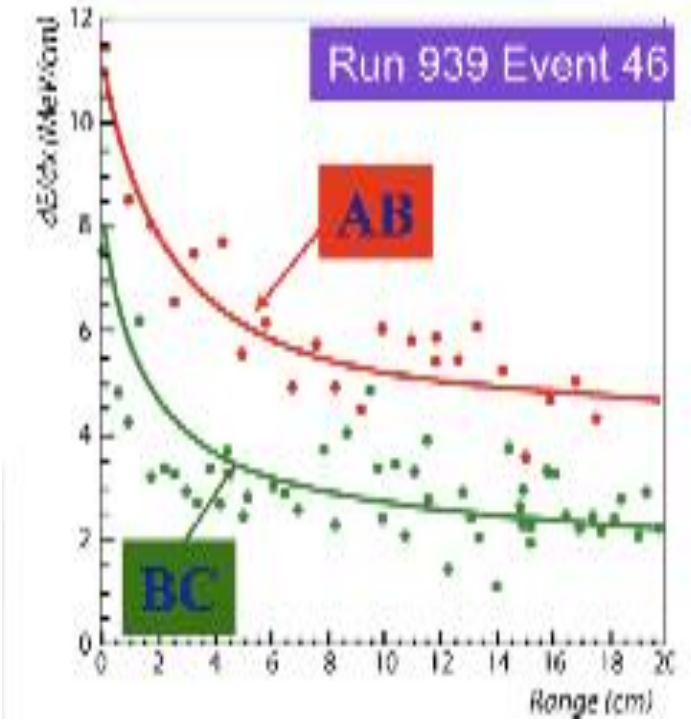
ICARUS EVENT



$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$

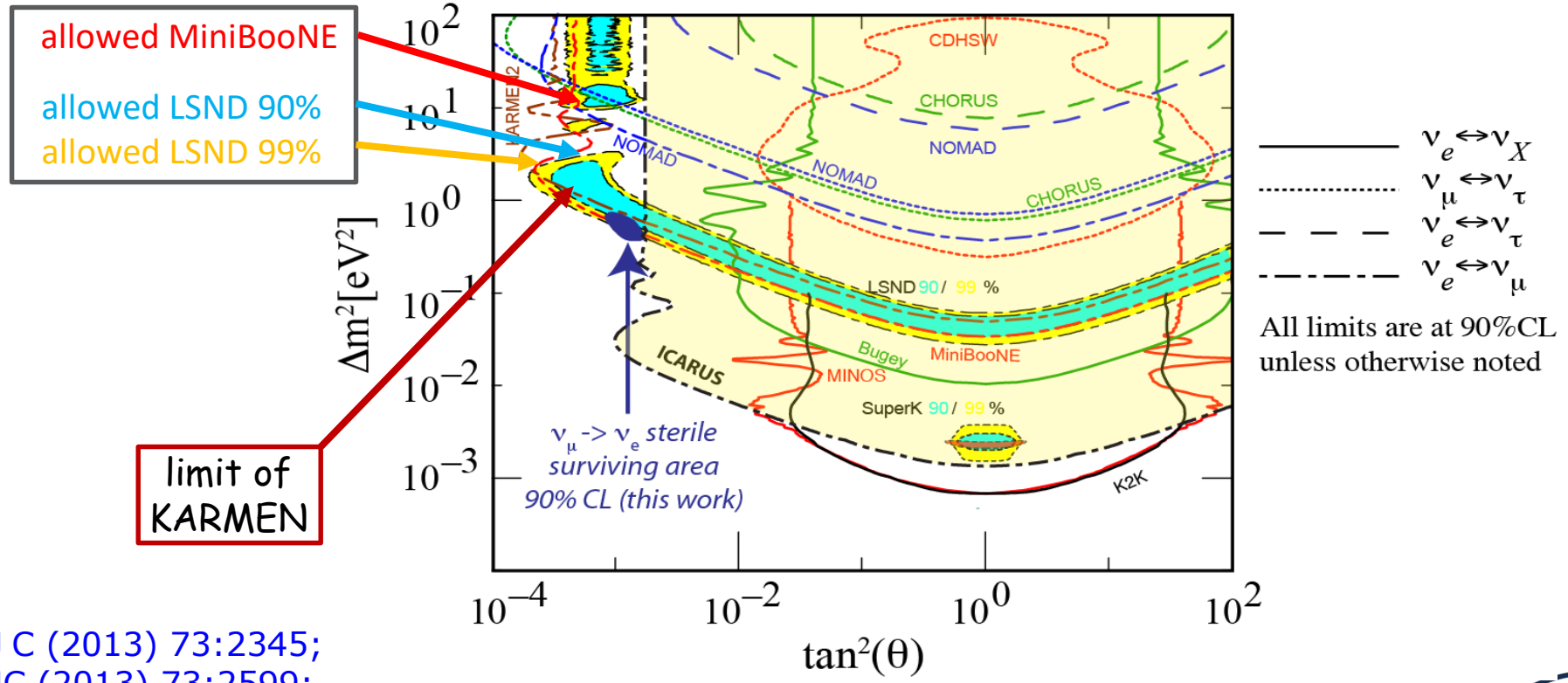
Efficient P.Id. (>90%), low misidentification, due to precise 3D reconstruction, dE/dx, range measurement:

- stopping power;
- recognition of secondary particle production after decay/interaction.



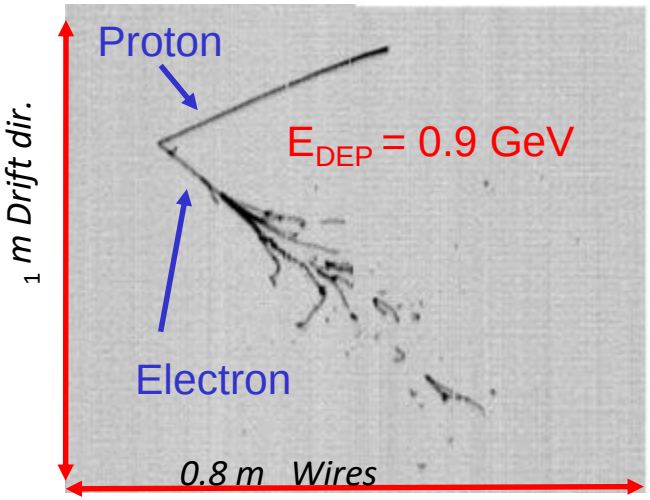
Probing LSND "anomaly"

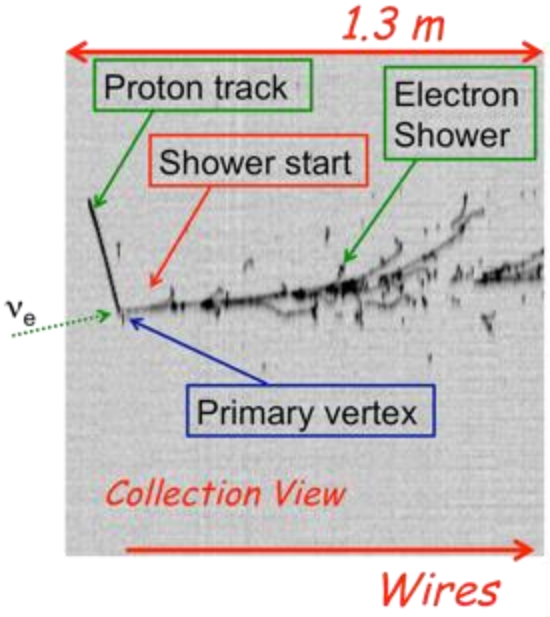
- Analysis on 7.93 x 10^{19} pot event sample provided the limit on the oscillation probability $P(\nu\mu \rightarrow \nu e) \leq 3.92\ (7.83) \times 10^{-3}$ at 90 (99) % CL.
  - ICARUS result indicates a very narrow region of the parameter space ($\Delta m^2 \approx 0.5$ eV2, $\sin^2 2\theta \approx 0.005$) where all experimental results can be accommodated at 90% C.L.



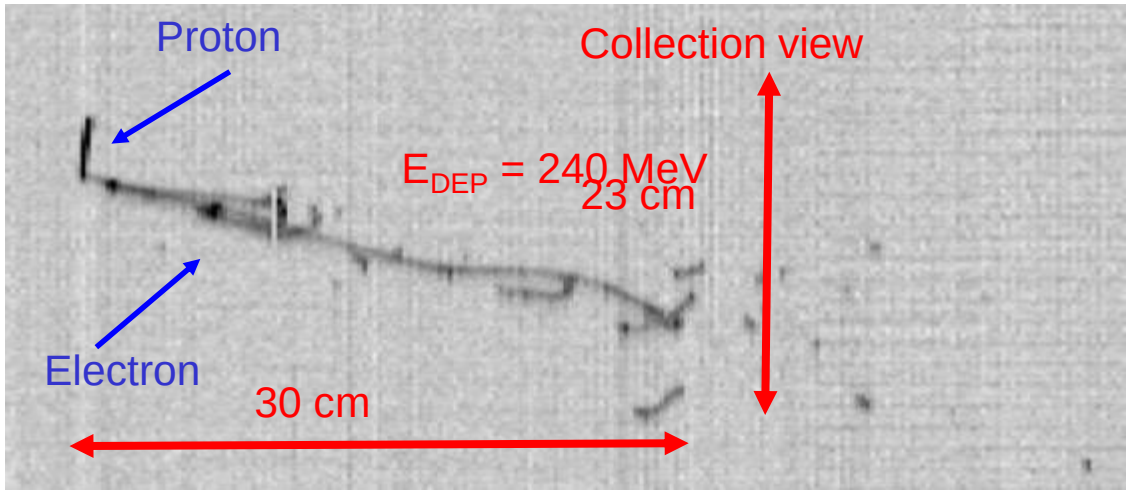
EPJ C (2013) 73:2345;
EPJC (2013) 73:2599;

First Atmospheric Neutrino In LAr





E_{DEP} = 2.12 GeV

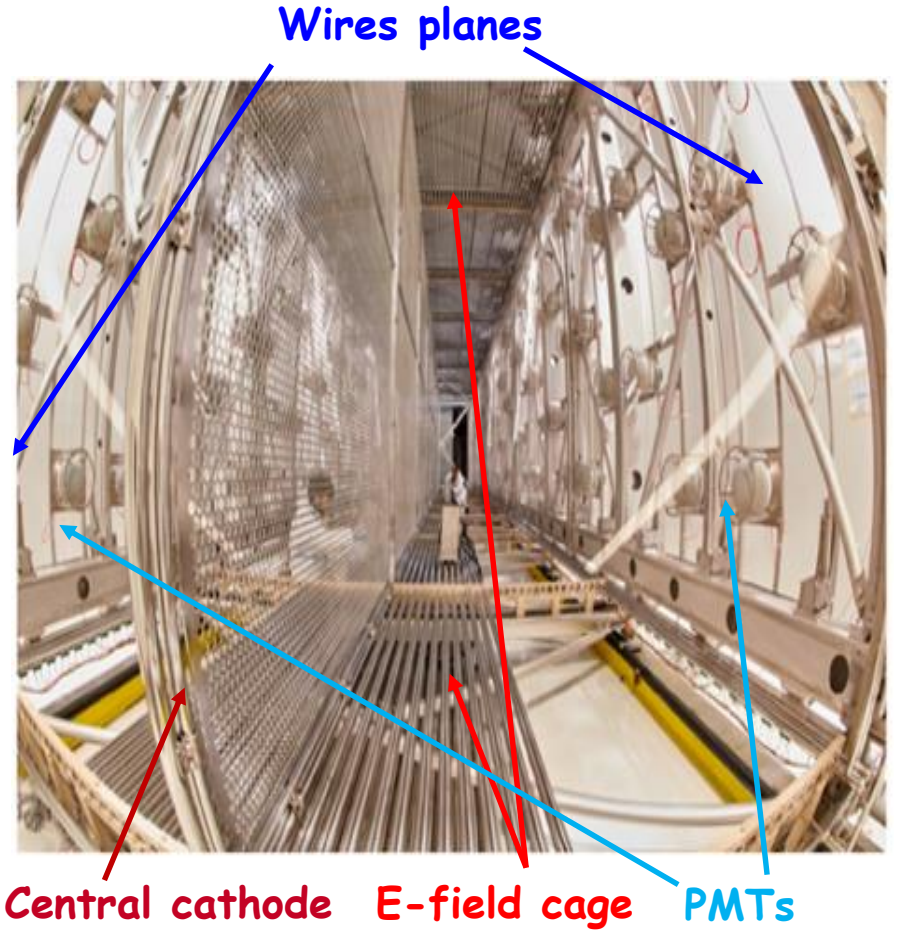


2019 Universe, 5, 17.

Crossing the Atlantic

IcarUS 2014-today

- ICARUS-T600 was overhauled at CERN in 2014-18 within the Neutrino Platform following a CERN-INFN Agreement. Main pojnts:
  - 2 modules, 2 TPCs per module with central cathode (1.5 m drift, E_D= 0.5 kV/cm);
  - 3 readout wire planes per TPC, in total 54000 wires at 0, ± 60^0, 3 mm pitch; new faster, higher-performance read-out electronics;
  - Upgraded light collection system: 360 8" PMTs, TPB coated detecting scintillation light by particles in LAr;
  - New cold vessels, purely passive insulation and refurbished cryogenics and purification equipment;
  - Surrounded by ~4π Cosmic Ray Tagger system, protected by ~3 m thick concrete overburden.

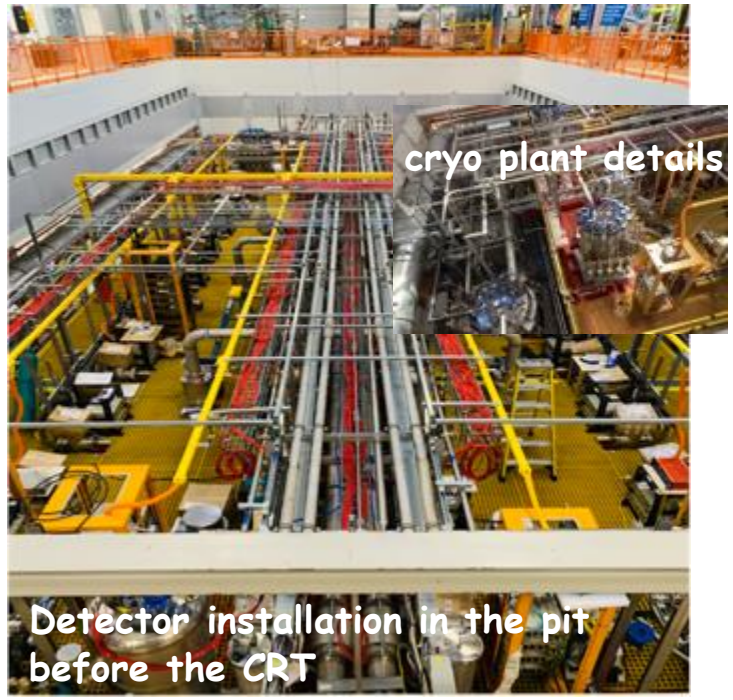


Structure of one module with 2 TPC chambers

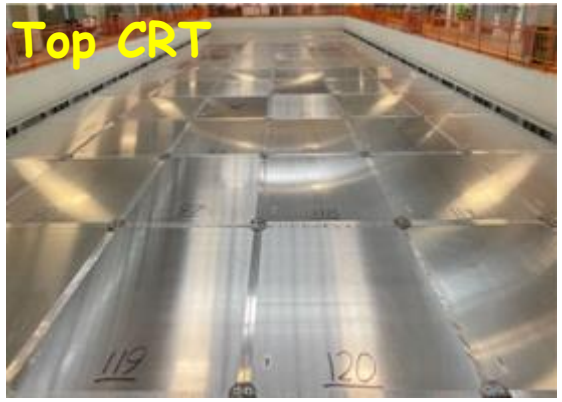
→ Importance of neutrino platform @ CERN !!!!

Crossing the Atlantic

IcarUS 2014-today

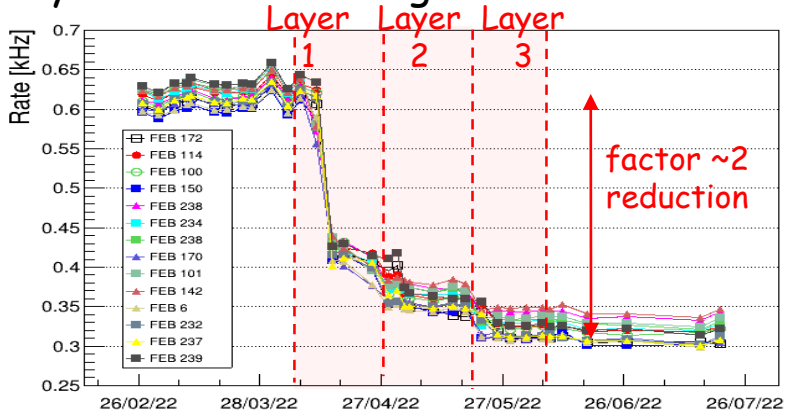


- The Cosmic Ray Tagger (CRT) encloses the detector: a double layer of scintillator bars (~10^3 m^2) tagging incoming cosmics with ~95% efficiency.



- Cosmic γ's and neutrons are suppressed by ~3 m concrete overburden on top of CRT.

Cosmic rays reduction during the overburden installation



Crossing the Atlantic

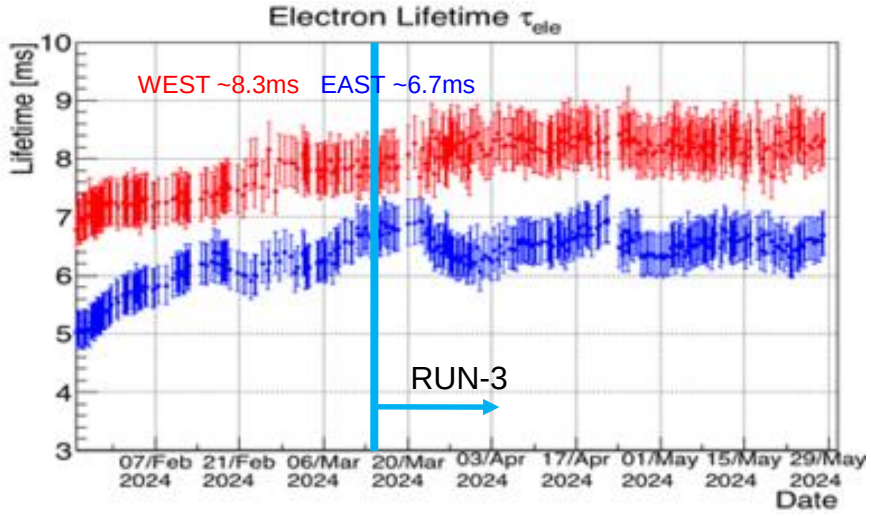
IcarUS 2014-today

Crossing the Atlantic

IcarUS 2014-today

Data Taking @ FNAL

- June 2022: start of data taking for physics
  - Data acquisition largely successful, currently with >97% data taking efficiency;
  - The cryogenic and purification system performed smoothly keeping resic impurities in LAr at ~ 40 p.p.t. of [O2]equi
    - The free electron drift lifetime τ_{ele} ~7-8 ms, results in an almost full track detection efficiency in the whole 1.5 m drift (Δt ~ 1 ms).

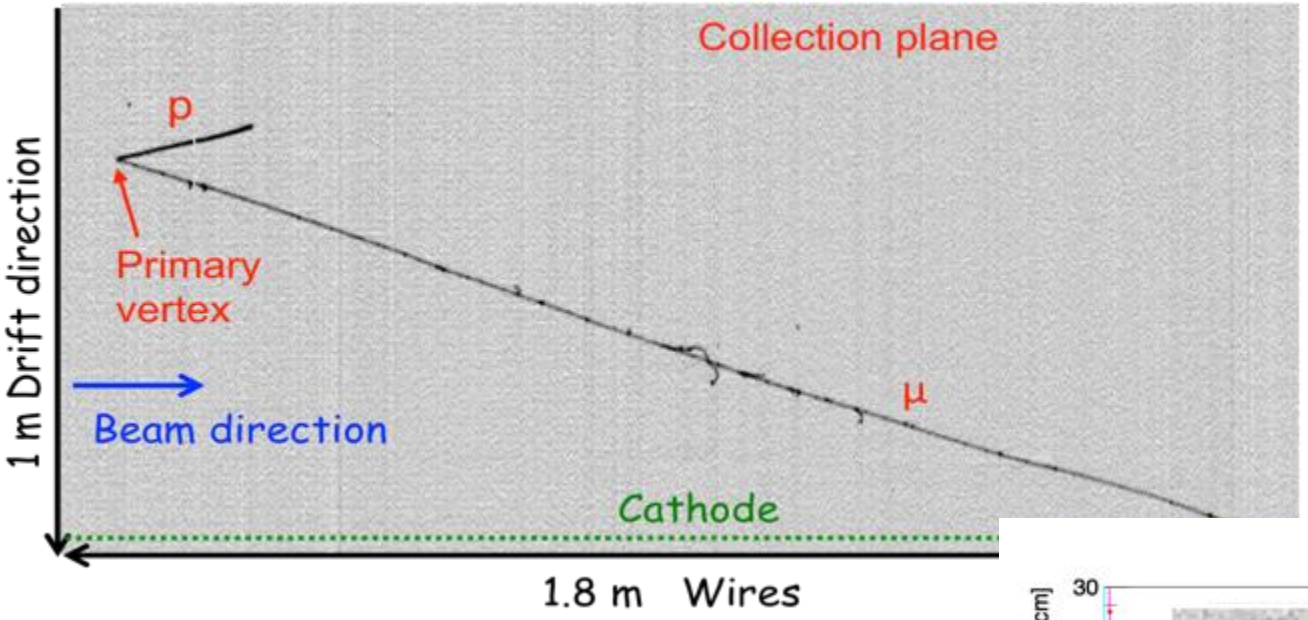


Collected Protons on target (PoT)	BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1 (Jun-Jul 22)	0.41 10^{20}	0.68 10^{20}	-
RUN-2 (Dec 22-Jul 23)	2.05 10^{20}	2.74 10^{20}	-
RUN-3* (Mar 15 -July 11, 2024)	1.36 10^{20}	-	2.82 10^{20}
TOTAL	3.82 10^{20}	3.42 10^{20}	2.82 10^{20}

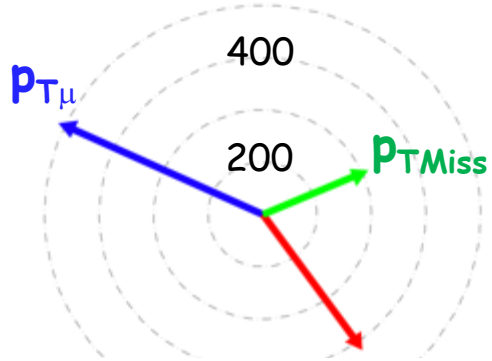
Crossing the Atlantic

IcarUS 2014-today

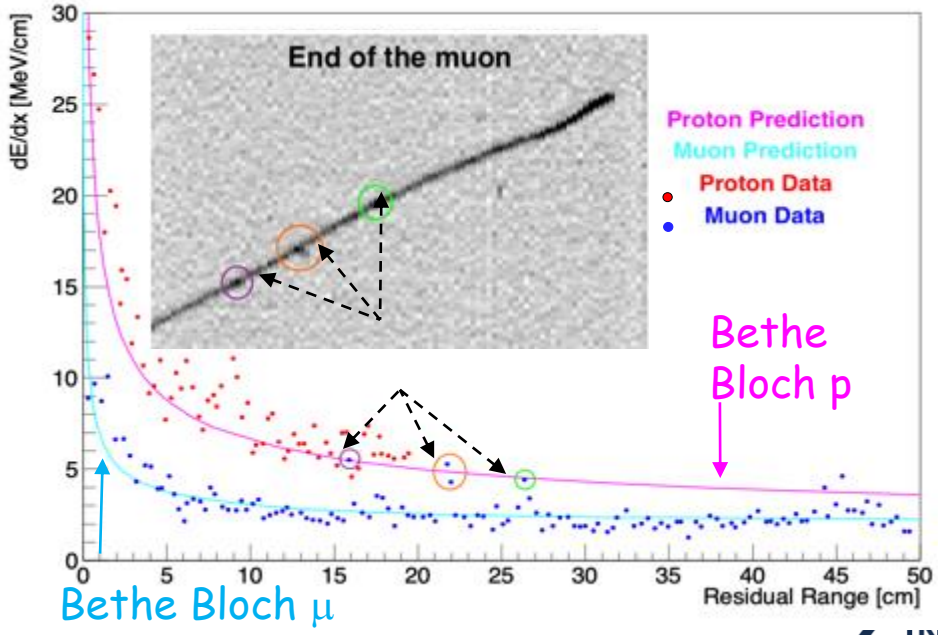
Full Reco with automatic selection

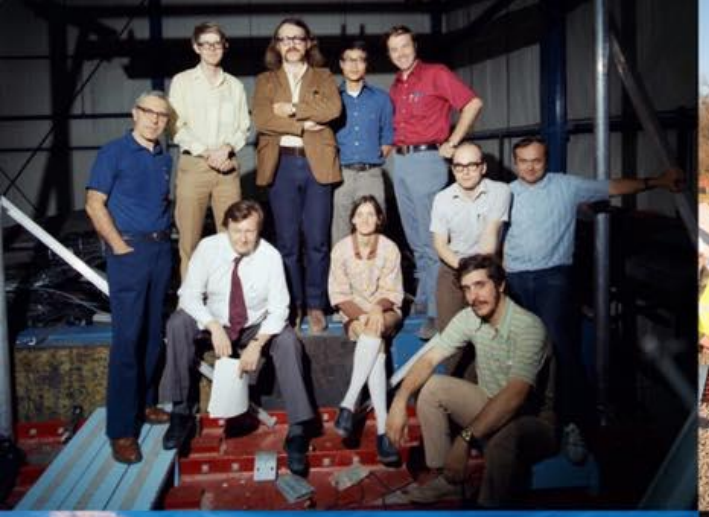


Momentum in the transverse plane (MeV/c)



- Two particles: 3.8 m long stopping muon and ~20 cm track stopping proton, total deposited energy ~1.1 GeV;
- Total momentum at 8^0 from the beam ax
- Total transverse momentum ~200 MeV/

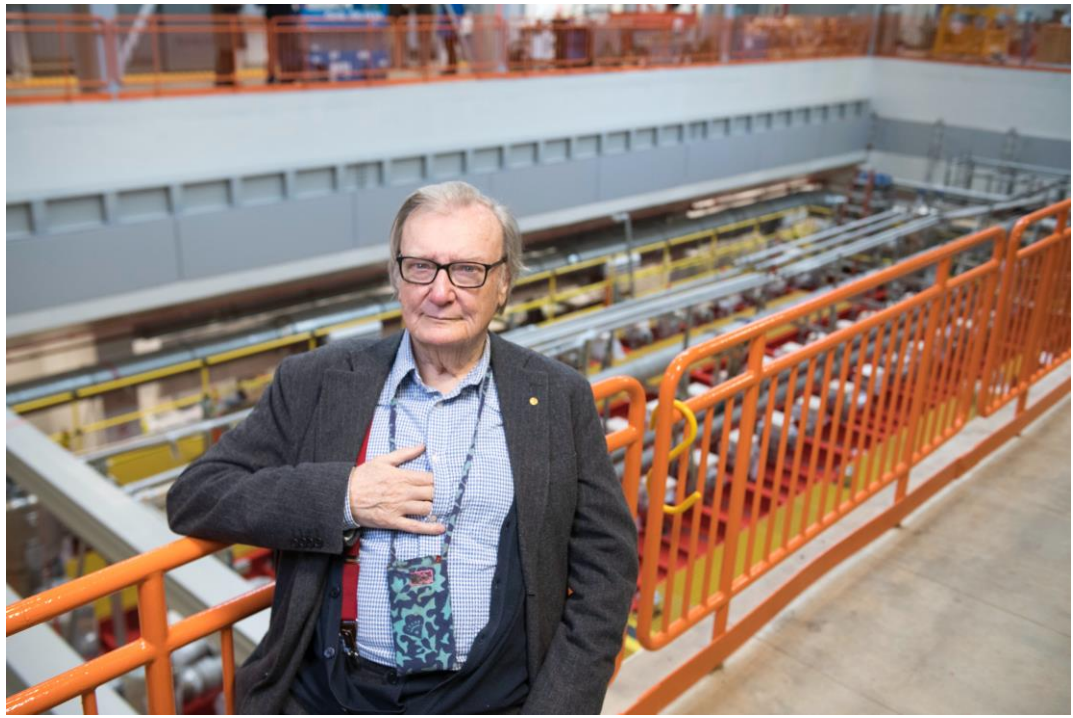





Fermilab

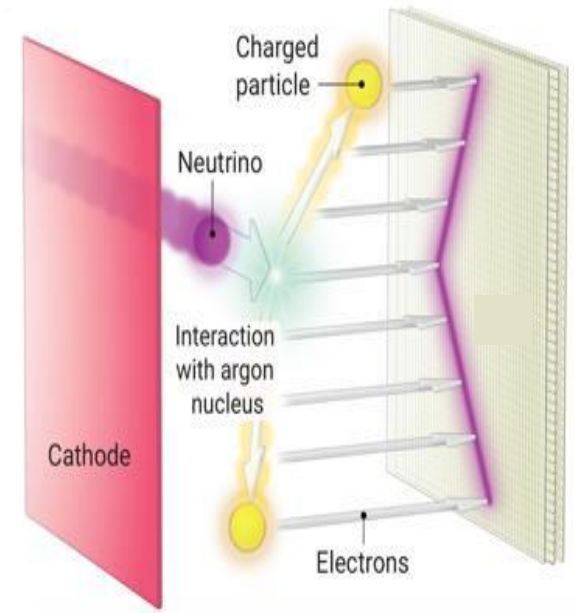

ICARUS
averaged

deflection angle θ and
from χ² of the fit:
MS angle
detector
resolution



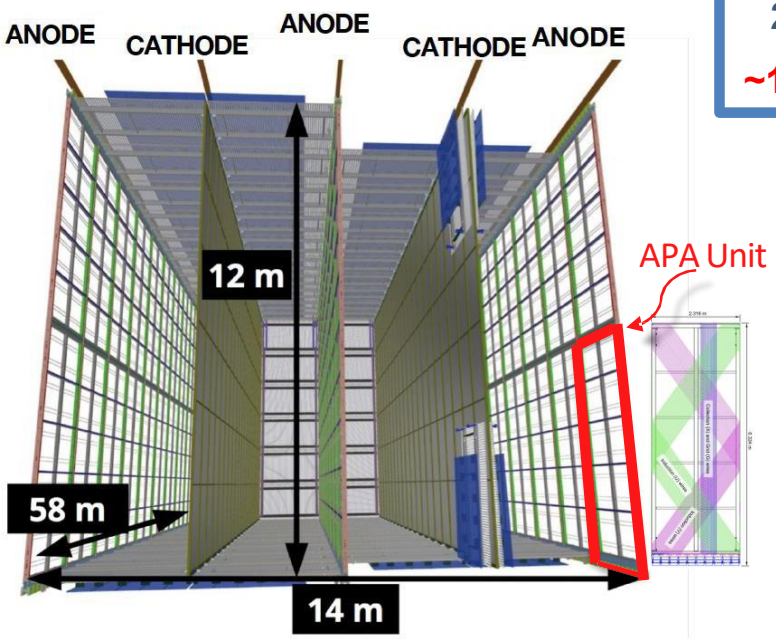
The ICARUS Legacy

LAr TPC technology



Liquid Argon TPC (C. Rubbia, 1977) is the technique with the best particle imaging capability at kton scale:

FD1-HD «Horizontal drift» (ICARUS concept, wires)



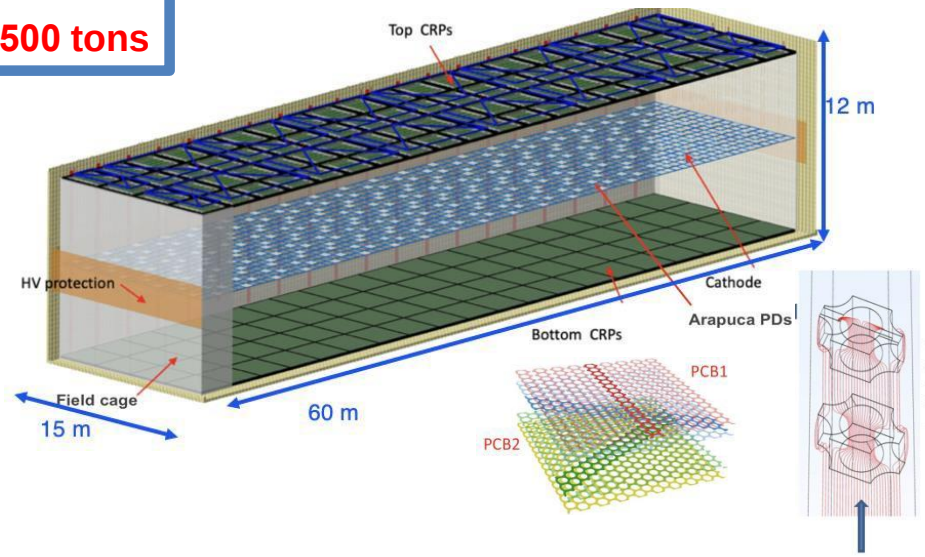
- 150 Anode Plane Assemblies (APAs)
- 384,000 readout wires
- Anode-Cathode 3.5 m drift;
- 500 V/cm field; cathode at -180 kV;
- 6000 photon detection system (PDS) channels

BOTH:

28’500 m³

~17’500 tons

FD2-VD «Vertical drift» (Simpler, no wires)



- Charge Readout Planes : perforated PCB’s with segmented electrodes (strips)
- CRPs at the top and bottom
- Cathode (-300 kV) in the middle
- two 6.5 m drift chambers 450 V/cm field

Concluding remarks

- The seminal 1977 idea and the long R&D effort in Pavia, CERN and LNGS has brought a brand new technology to maturity
- ICARUS at LNGS has been the first large scale LAr TPC with full reco capability, large mass, sufficient purity for large drift operations
- ICARUS is a key element of the current Short Base Line program at Fermilab
  - It has the capability to “close” the LSND / Neutrino-4 anomalies or achieve a major discovery
- The future of LAr TPCs is DUNE and DUNE would not be there without Carlo!


Thank you Carlo !!

Crossing the Atlantic

IcarUS 2014-today

Data Taking @ FNAL

A nice neutrino event with CC and a stopping proton