The Liquid Argon Time Projection Chambers: a conceptual overview and a review of practical implementations

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Major credits:
Claudio Montanari upon
Carlo Rubbia vision.

Also,
Flavio Cavanna,
Francesco Pietropaolo

Credits Ph. https://lbnf-dune.fnal.gov

Outline

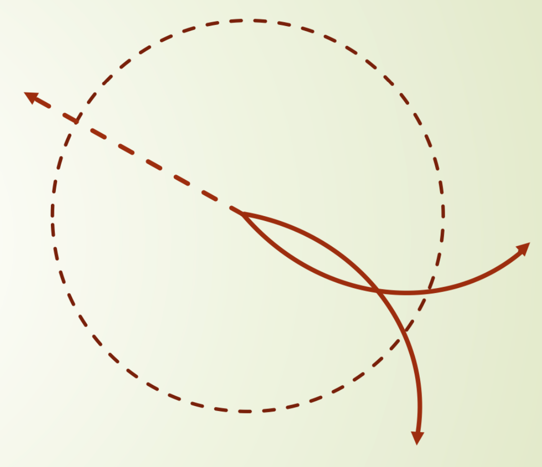
- Introductory concepts
- The Liquid Argon Time Projection Chamber (LAr TPC) technological development
  - Milestone1: Event imaging
  - Milestone 2: Liquid argon purification
  - Milestone 3: Detection of scintillation light in LAr
  - Performance of the LAr TPC
- Practical implementations
  - ICARUS Experiment at Gran Sasso Underground Laboratory (LNGS)
  - The MicroBooNE Experiment at Fermilab
  - The Short Baseline Neutrino Program at Fermilab
  - DUNE and the path towards, ProtoDUNE, ND-LAr
- Conclusions

Context

- Most interesting processes, in **High Energy Physics**, are characterized by extremely **low occurrence probabilities**. Most of the work of experimental particle physicists consists in devising and implementing strategies to produce and identify unambiguously the desired processes.

- Typically, such strategies are based on the definition of specific **characteristics** (signatures) that allow to discriminate the selected process from **backgrounds** that, quite frequently, have orders of magnitude larger probabilities (e.g.: competing processes produced by the same beams, events produced by environmental radiation like cosmic rays or materials radioactivity).

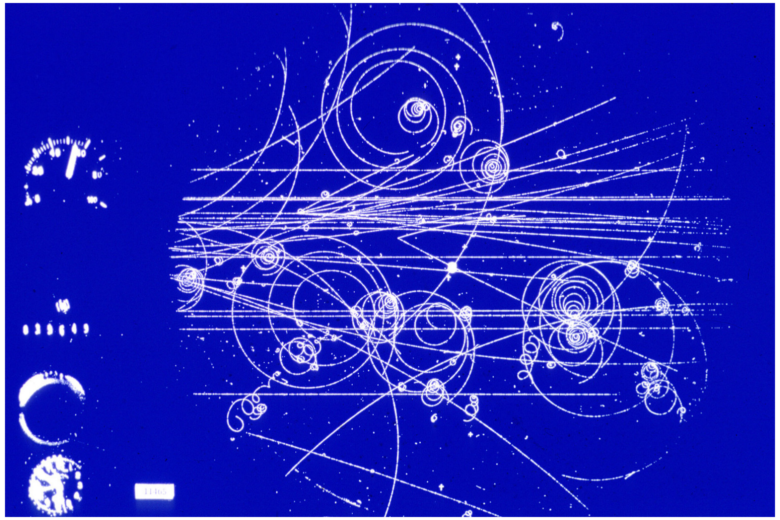
- **Imaging** techniques have played and continue to play a fundamental role in the implementation of our strategies, allowing to
  - display interactions topologies,
  - identify particles from their behaviors,
  - measure kinematical quantities, etc.



- A notable example was represented by the **bubble chamber**, operational in several different versions from the late 50's to the late 70's. Bubble chambers provided at the same time a **massive target** of substantial density with complete **imaging** and **reconstruction** of the events in it. Such unique characteristics allowed discoveries based on the complete reconstruction of single events (Ω^-) or on the identification of unexpected events (neutral currents in Gargamelle).

- However, bubble chambers have several drawbacks: they require high pressure and mechanical expansion, their sensitivity is limited to few **milliseconds** per operating **cycle** (typically once every few **seconds**), and they cannot be practically scaled beyond masses of **few tons**. These limitations make bubble chambers inapplicable to modern needs.

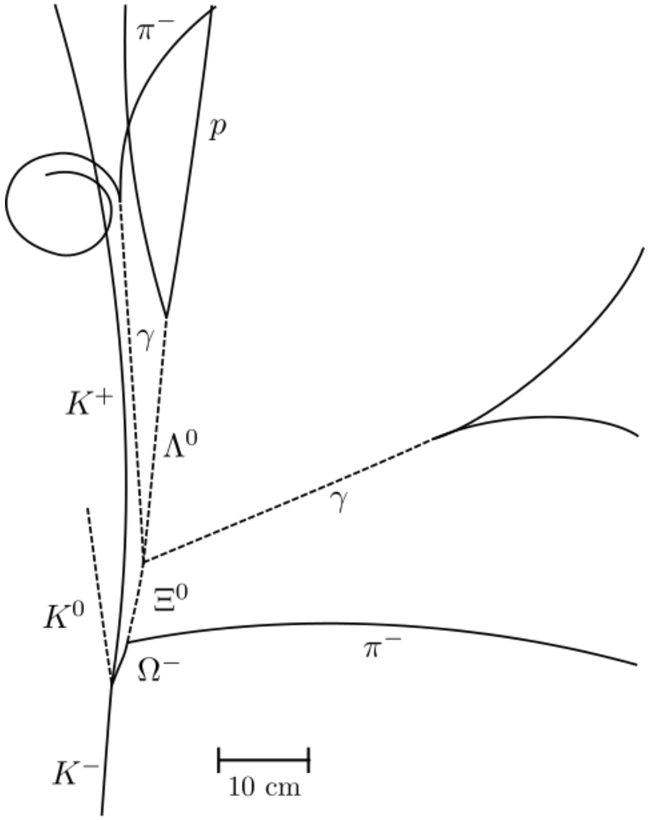
1960, CERN, 32 cm detector liquid hydrogen.
16 GeV $\pi^- + p \rightarrow \Lambda$



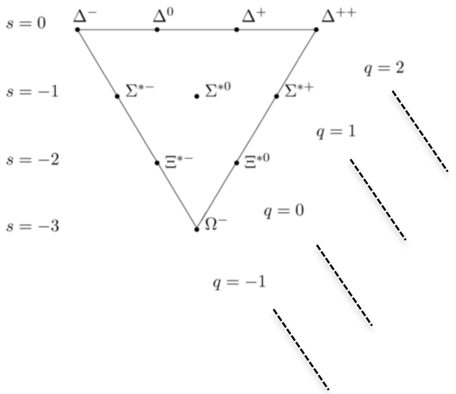
Credits: https://cds.cern.ch/record/39474

The Liquid Argon Time Projection Chamber (LAr TPC) was conceived and developed to match the imaging characteristics of bubble chambers, having neutrino physics and nucleon decay searches as primary research topics, and additional features.

Interlude



Ω^- was predicted in 1961 by
Gell-Mann & Ne'eman
via the Eightfold Way (SU_3 flavour)
as decuplet of spin 3/2 baryons



The first observed Ω^- baryon event at Brookhaven National Laboratory, adapted from original tracing, in 1964.
The tracks of neutral particles (dashed lines) are not visible in the bubble chamber.

K^- + proton -> $\Omega^- K^0 K^+$

The Ω^- decays into a π^- and a Ξ^0, which in turn decays into a Λ^0 and a π^0. The Λ^0 decays into a proton and a π^-.
The π^0 decays into two photons (γ), which in turn each create an e+e- pair.

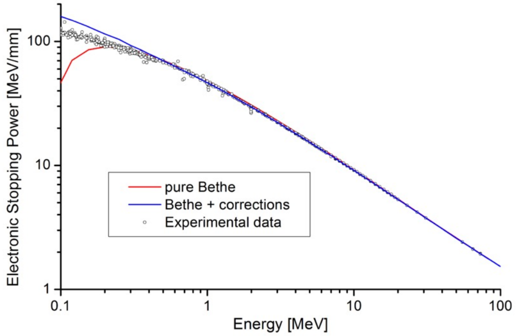
“Continuous” energy loss by charged particles

- Electrically charged particles crossing a material, loose energy in a “continuous” way by interacting with the electrons of the atoms of the material.
- The average amount of energy lost through this mechanism was first calculated by Bethe in1930. The formula was then refined over the years to assume the present analytical form:

$$-\left\langle\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\rho\frac{1}{\beta^2}\left(\frac{1}{2}ln\frac{2m_ec^2\beta^2\gamma^2W_{max}}{I^2}-\beta^2-\frac{\delta(\beta\gamma)}{2}\right)$$

$$dE = energy\ variation\ for\ a\ particle\ with\ \ charge\ z\\ crossing\ a\ material\ thickness\ dx$$

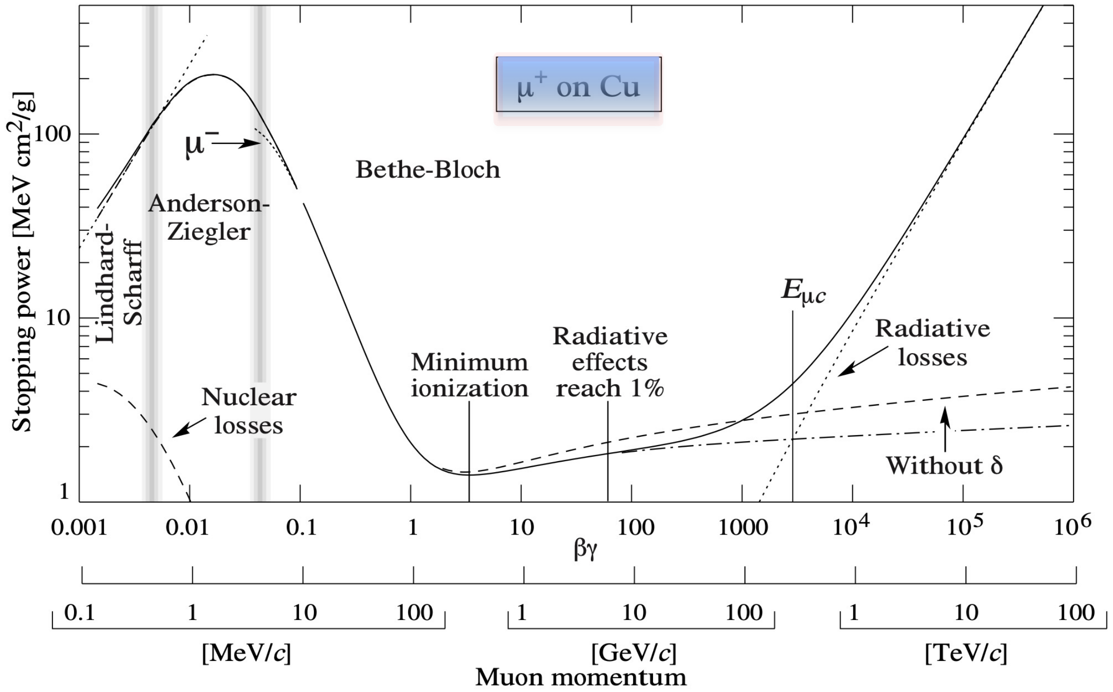
$$K = 4\pi N_A r_e m_e c^2\ ;z = projectile\ charge\ ;\ \rho = material\ density\ ;$$
$$W_{max} = \max energy\ transfer\ ; I = mean\ excitation\ energy\ ;$$
$$\boldsymbol{\delta(\beta\gamma) = density\ effect\ correction}$$



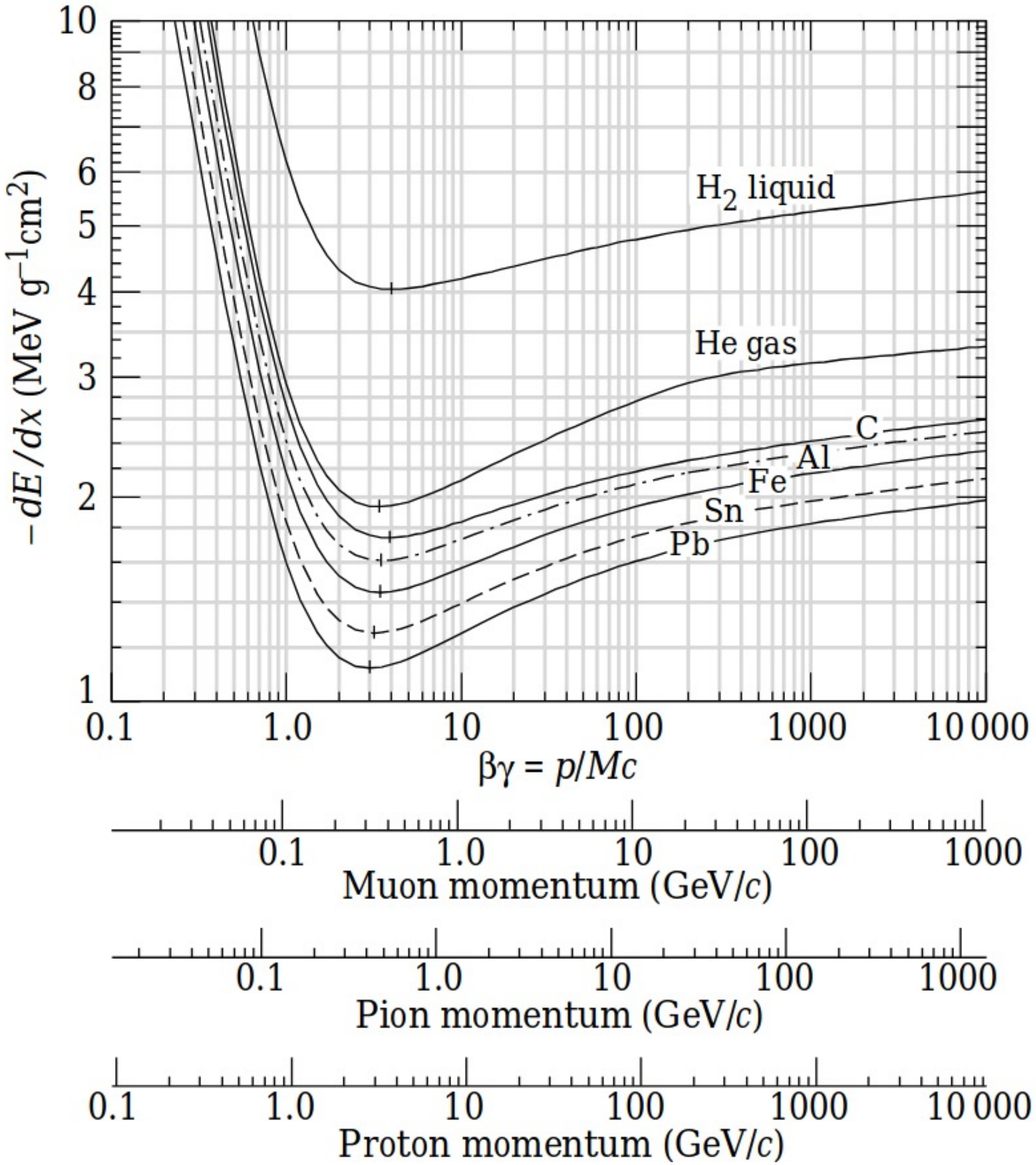
- The formula holds for moderately relativistic (*0.1 ≤ $\beta\gamma$ ≤ 1000*) massive (*M>>m_e*) particles.
- The energy lost in this way results into molecular/atomic excitation (eventually producing photons upon de-excitation), ionization and “heat” (at larger energies radiative contributions become relevant).

Credits: PDG at https://pdg.lbl.gov/2023/reviews/rpp2023-rev-passage-particles-matter.pdf

Energy loss of a charged particle as function of its momentum, for different materials



Stopping power (<-dE/dx>) for positive muon in copper



In practical cases, most relativistic particles (e.g., cosmic-ray muons) have energy loss rates close to the minimum, and are said to be minimum ionizing particles, or **mip**'s.

Active media

- **Materials** where ions, electrons, photons, phonons produced by the passage of charged particles can be efficiently transported and collected (in some way), can become **active** media, *id est* they can be used to produce an **electrical signal** as the result of the passage of the primary particles.

- Most detectors used in high energy particle physics can be grouped in two large categories:
  - Ionization based detectors
  - Scintillation based detectors

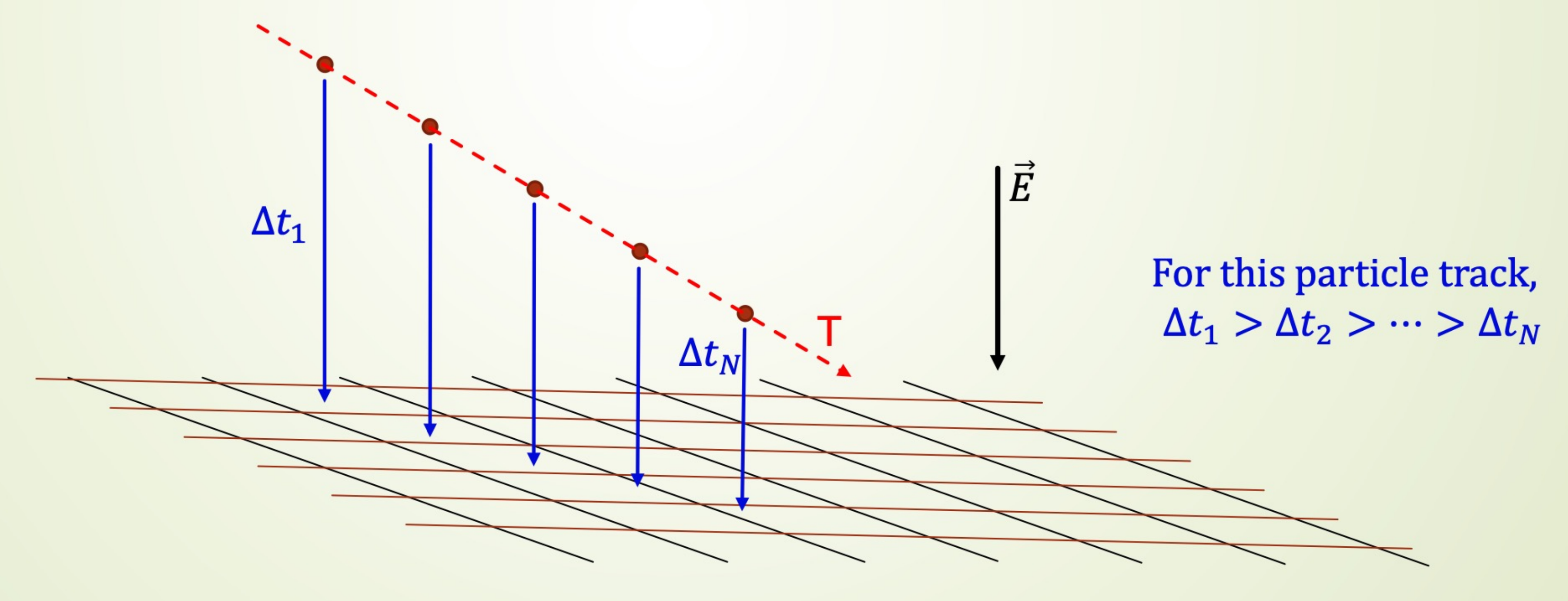
- Time projection chambers (**TPC**), in general, are ionization-based detectors.

- **Argon** is considered a very good active media both in **liquid** and **gas** phases, in view of the high ionization and scintillation yields and of the high mobility of unbound electrons.

  In the liquid phase, however, charge multiplication requires extremely high fields, until now impossible to realize in any practical application.

Interlude: TPC case

A gas ionization detector with 3D measurements (image), which makes use of the time of drift



For this particle track, $\Delta t_1 > \Delta t_2 > \cdots > \Delta t_N$

- Used in a cylindrical shape for collider experiments
- Huge Electric field and electron avalanche (gas amplification)
- Typical gas mixture: 90% noble gas and 10% gas quencher to ensure each discharge terminates

Its intrinsic limit: termic diffusion of electrons, which goes as square root of t

Liquid Argon as Radiation Detection Medium

➢ Atomic Mass	40 (spin 0)	
➢ Atomic Number	18	
➢ Density:	1.4 g/cm^3	
➢ Temperature LAr @ 1bar	-185.7 ºC (87K)	
➢ dE/dx (m.i.p.)	2.1 MeV/cm	
➢ Radiation Length	14 cm	
➢ Nucl. Coll. Length	80 cm	
➢ Electron's Mobility	**535 cm^2/V/s** →	**v_{drift} ≈ 1.5 mm/μs @ E=500 V/cm** 1.5 m/msec
➢ Ionization Potential	15.76 eV	
➢ W_{ion} (m.i.p.)	**23.6 eV** →	**≈ 8800 e^- Ar^+ pairs / mm**
➢ W_{ph} (m.i.p.)	**25.1 eV** →	**≈ 8400 γ / mm**
➢ λ(scintillation)	128 nm	
➢ τ(scintillation)	6 ns (30%) , 1.6 μs (70%)	
➢ Light Attenuation Length	0.8 m @ 128 nm	

Liquid Argon Time Projection Chamber (LArTPC)

	Water	He	Ne	Ar	Kr	Xe
Boiling Point [K] @ 1atm	373	4.2	27.1	87.3	120.0	165.0
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation Length [cm]	36.1	755.2	24.0	14.0	4.9	2.8
Scintillation [γ /MeV]	-	19,000	30,000	40,000	25,000	42,000
dE/dx [MeV/cm]	1.9		1.4	2.1	3.0	3.8
Scintillation λ [nm]		80	78	128	150	175

~40$/L ~2$/L ~0.5$/L ~700$/L ~3000$/L

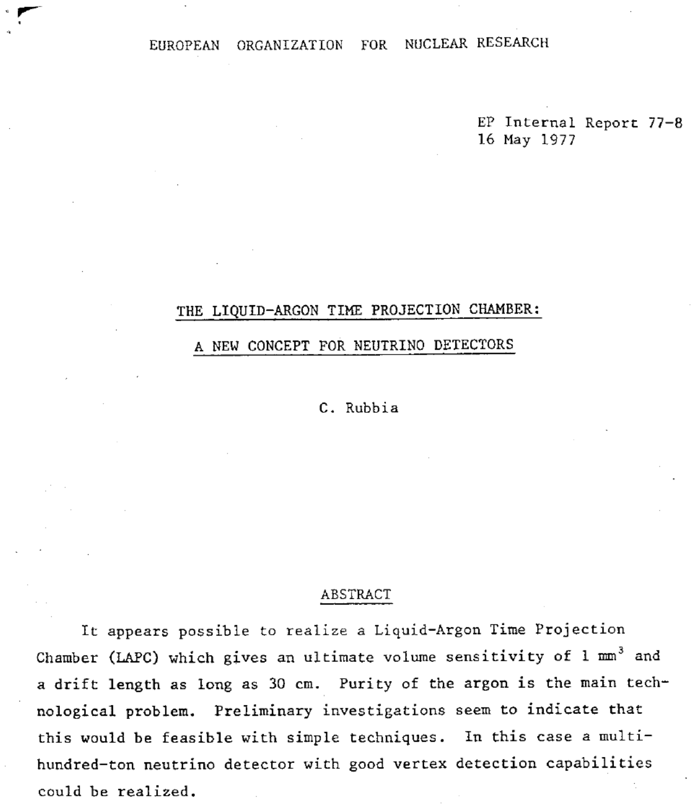
Liquid argon:
an excellent choice
for neutrino detectors

- Dense: 40% more dense than water
- Easily ionizable: 88,000 electrons/cm
- Highly scintillating: possible for photon detector system
- Very good dielectric properties: allow high-voltages in detector
- Long drift distance for ionization electrons (under high purity)
- Abundant & cheap: 1% of the atmosphere

The Lar TPC origin

- The idea of the LAr TPC technology was first proposed by Carlo Rubbia, as a new tool for neutrino physics in a seminal paper in 1977 (*C. Rubbia, The Liquid-Argon Time Projection Chamber: A New Concept For Neutrino Detector, CERN-EP/77-08 (1977)*).

Quoting this document, "*the original idea of Nygren (1974)*" for a so-called *"Time Projection Chamber (TPC)"* with a noble gas as **ionization** medium "*is extended to a liquefied noble gas - more specifically, liquid Argon - leading to what is"* thereafter *"called a Liquid-Argon TPC* (**LAr-TPC**). *Briefly, the idea consists of drifting the whole electron image of an event occurring in the noble liquid towards a collecting multi-electrode array which is capable of reconstructing the three-dimensional image (x,y,z) of the event from the (x,y) information and the drift time (t)"*.



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

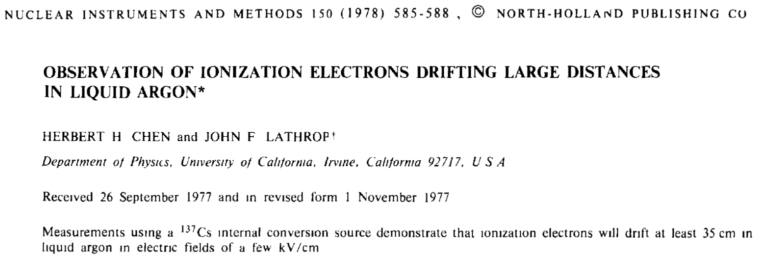
EP Internal Report 77-8
16 May 1977

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 Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.



NUCLEAR INSTRUMENTS AND METHODS 150 (1978) 585-588 , © NORTH-HOLLAND PUBLISHING CO

OBSERVATION OF IONIZATION ELECTRONS DRIFTING LARGE DISTANCES IN LIQUID ARGON*

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Received 26 September 1977 and in revised form 1 November 1977

Measurements using a ^{137}Cs internal conversion source demonstrate that ionization electrons will drift at least 35 cm in liquid argon in electric fields of a few kV/cm

- **Features of different experimental technologies are combined in a single device**
- **The liquid Argon is at the same time the active medium of the detector and the target of the experiment**

(ideal for detection and full reconstruction of rare events like neutrino interactions and nucleon decays).

The main limitation of the proposed technique was also clearly defined by C. Rubbia:
"*the purity of the Argon is the main technological problem. … electron lifetimes corresponding to residual Oxygen impurity content of about* 4×10^{-2} *ppm*" are reachable.
However, this limits "*the electron mean free path to about 30 cm. Clearly, Oxygen-free Argon is the central problem for the LAr TPC*".

Only after several years an effective, fast purification method became available !

Contaminants and Purification

The contaminants reduce the drift of the electrons
Major contaminants are, in order, Oxygen, Water, Nitrogen (not so electronegative)
Filters (currently in copper) are used during the filling and periodical re-circulation
(in Icarus a full recirculation is done in 5.5 days)
To reach a limit around 0.1-0.3 ppb

The average drift time of an electron is quoted in 1 msec for 0.3 ppb (Oxigen reference)
and it scales linearly (practically) with the percentage

Purification history

Ionization electrons must drift over distance of $\mathcal{O}$(m), ie drift times $\mathcal{O}$(ms), without substantial capture by electronegative impurities ⇒ limit on level of contamination [O_2-equiv] ≤ 100 ppt (part per trillion)

"The starting material is Argon gas which has a (typical) *impurity concentration of ≈ 0.1 ppm of Oxygen. The gas is passed through the* (filter) *cartridge to remove the Oxygen present … at a typical rate of 0.35 l of gas per second. The gas is then liquefied …"* [J. Bahcall, M. Baldo-Ceolin, D.B. Cline and C.Rubbia, **Phys.Lett B178**, (1986)]

The issue: At this rate it would take ~1000 yrs to purify&fill one DUNE module

The solution:

"Argon purification in the liquid phase" **[NIM A333 (1993), 567]**. *"we have shown that ultrapure liquid Argon can be obtained by direct purification of the liquid. The final purity corresponds to an electro-negative impurity concentrations below 0.1 ppb O_2 equivalent, equal to that obtained with similar procedures* (OXY reactant + molecular sieves) *purifying the gas phase. … The flows are almost three orders of magnitude (the ratio of the densities) higher. As a consequence, the problem of filling a large scale detector is much simplified (… few weeks for a kiloton sized detector)".*

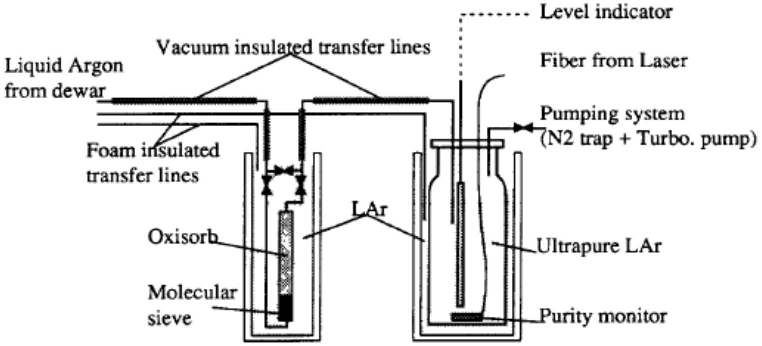
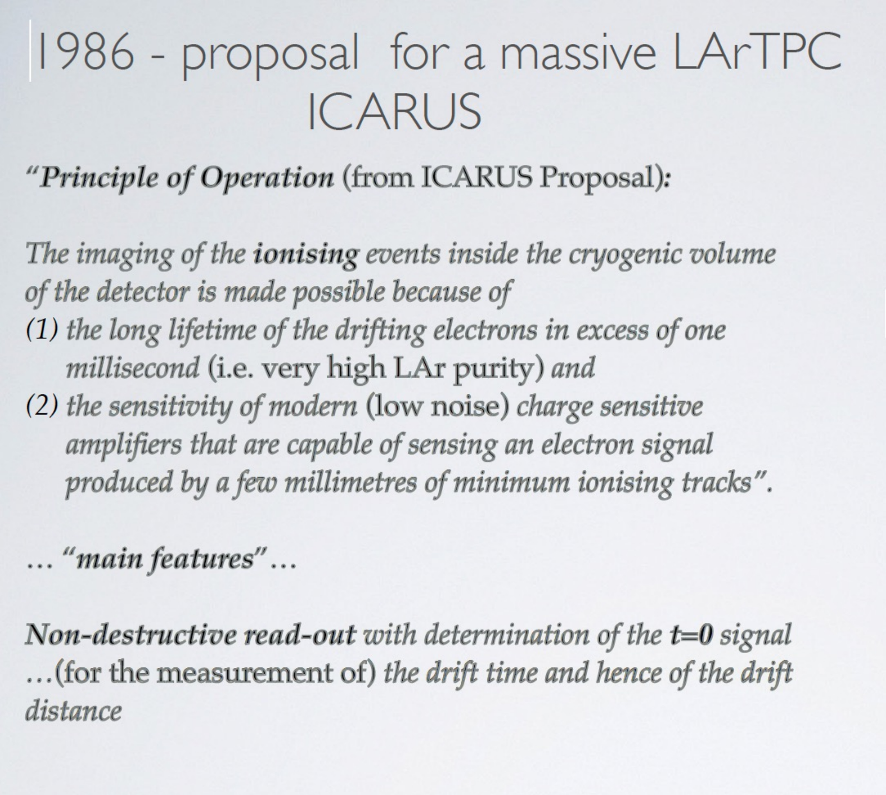


Fig. 1. Schematic view of the liquid phase argon purification system.

ICARUS proposal

Imaging **C**osmic **A**nd **R**are **U**nderground **S**ignals



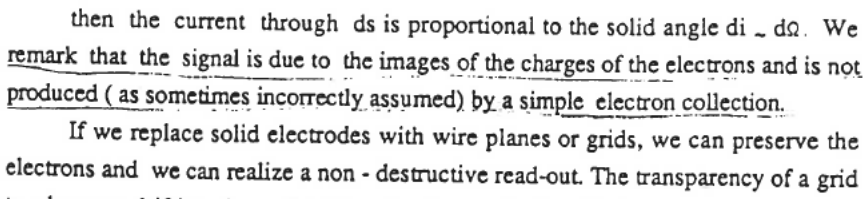
1986 - proposal for a massive LArTPC ICARUS

"*Principle of Operation* (from ICARUS Proposal):

The imaging of the ***ionising*** *events inside the cryogenic volume of the detector is made possible because of*
(1) *the long lifetime of the drifting electrons in excess of one millisecond* (i.e. very high LAr purity) *and*
(2) *the sensitivity of modern* (low noise) *charge sensitive amplifiers that are capable of sensing an electron signal produced by a few millimetres of minimum ionising tracks".*

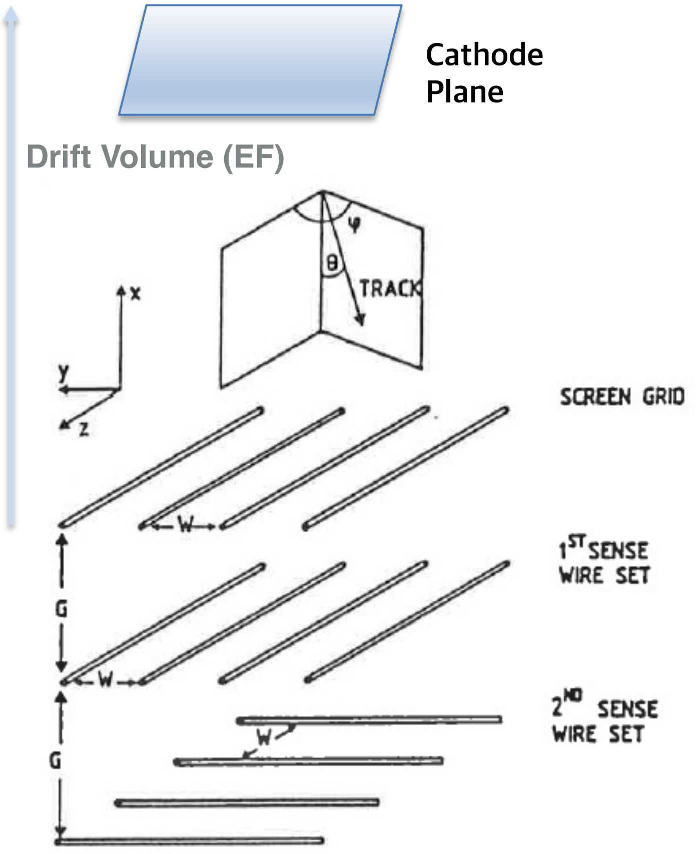
... "*main features*"...

Non-destructive read-out *with determination of the* ***t=0*** *signal* ...(for the measurement of) *the drift time and hence of the drift distance*



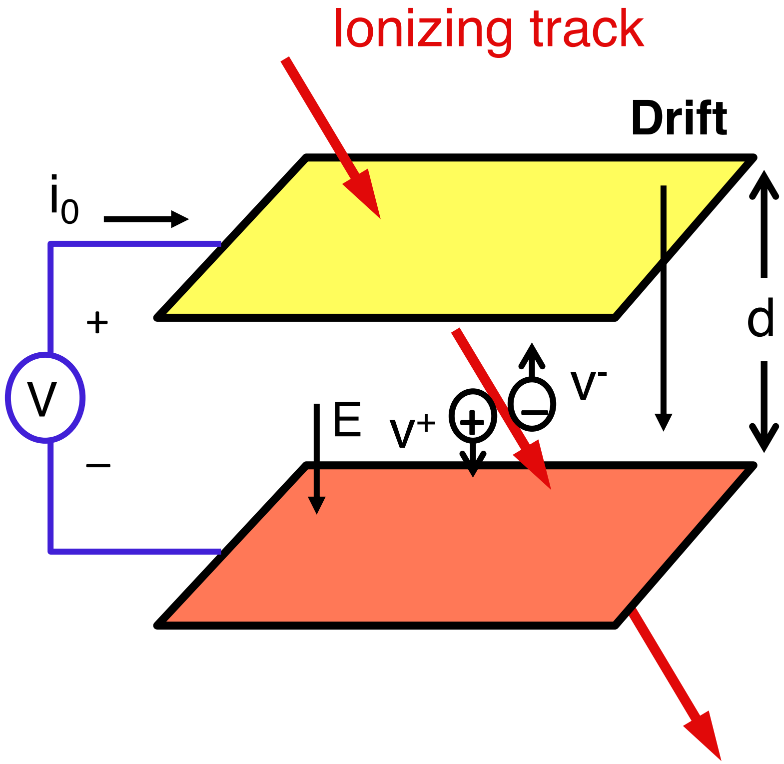
then the current through ds is proportional to the solid angle $di \sim d\Omega$. We remark that the signal is due to the images of the charges of the electrons and is not produced (as sometimes incorrectly assumed) by a simple electron collection.

If we replace solid electrodes with wire planes or grids, we can preserve the electrons and we can realize a non - destructive read-out. The transparency of a grid



GEOMETRY OF THE GRIDS AND REFERENCE FRAME

Signal in a non-multiplying medium



The “work” performed by the power supply that puts electrons and ions in movement is given by

$$dW = eE(v^+ + v^-)dt = Vi_0dt$$

From which the current and charge are

$$i_0 = \frac{e(v^+ + v^-)}{d} \quad ; \quad Q^{\pm} = \frac{e(d - x^{\pm})}{d}$$

Since $v^- >> v^+$, **electrons** current is dominant.

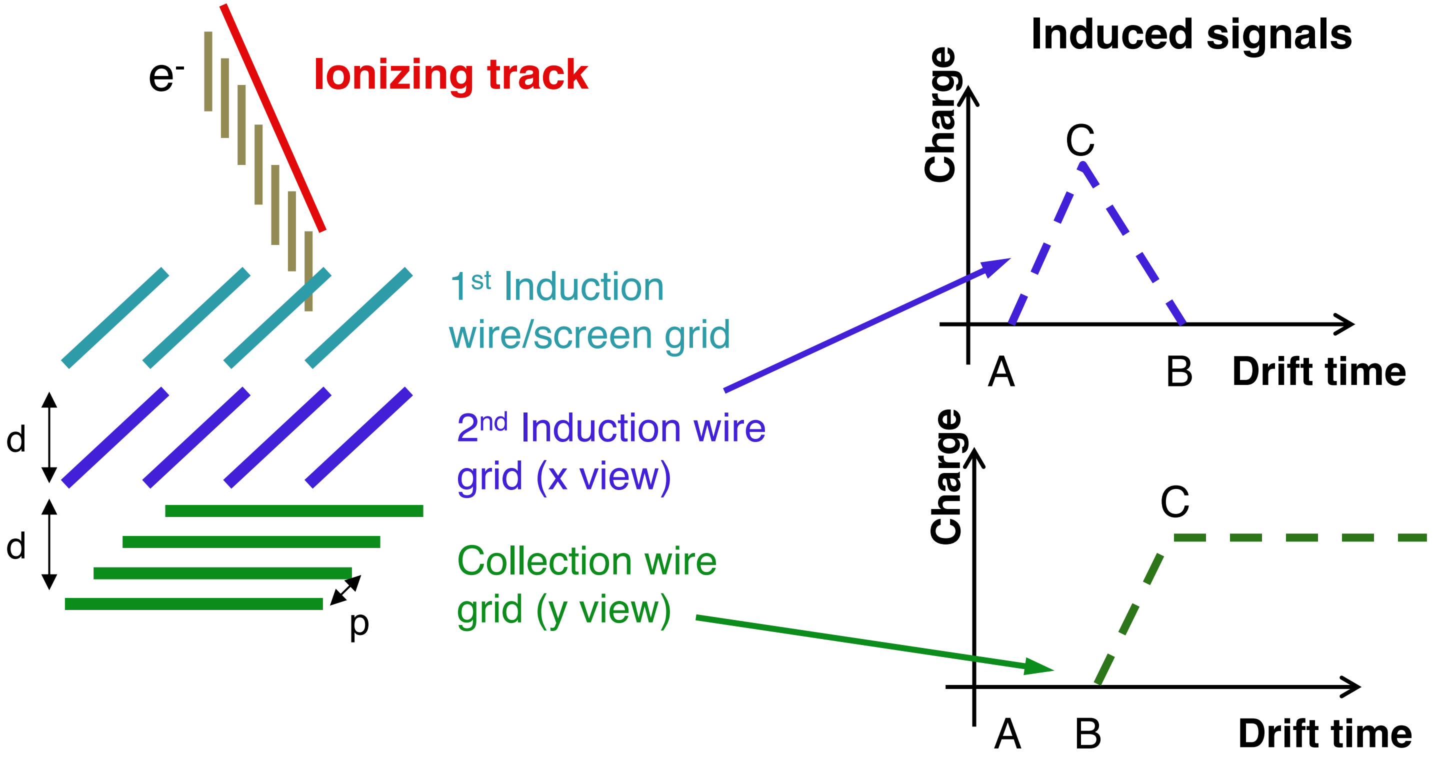
Typical values for 10,000 electrons and v^-=1.5 mm/μs @ E=500 V/cm are

$$i_0 = \frac{0.24}{d[cm]}\, nA \quad ; \Delta t = \frac{d}{v^-} = 6.6\, d[cm]\, \mu s$$

If a “grid” is inserted in the path of the electrons, the “work” changes sign upon traversal and so does the current and the total collected charge is zero.

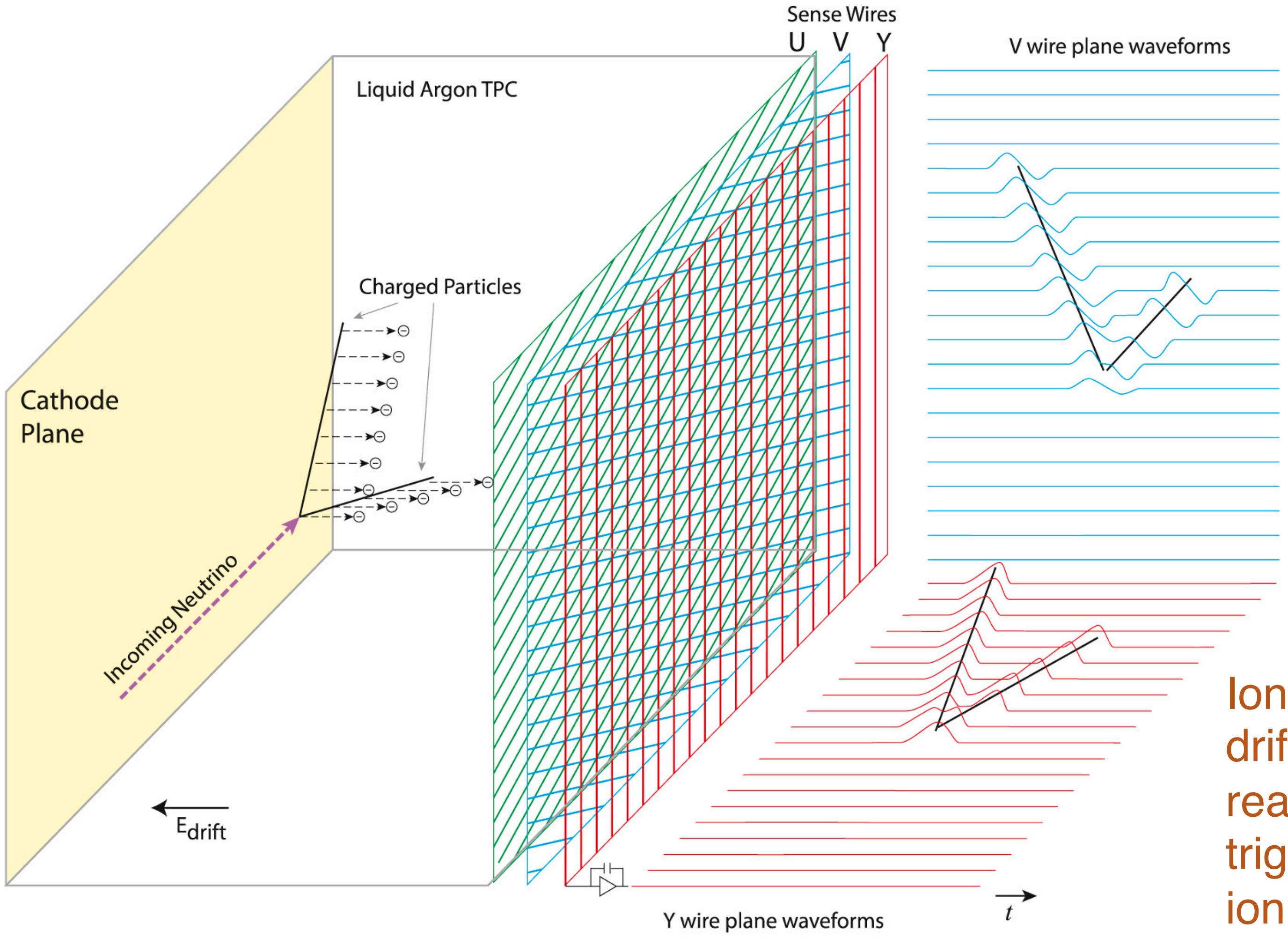
In case of multiple electrodes, the contribution to the “work” and therefore to the current, is proportional to the fractional field contribution at the point of the electron.

Non-destructive multiple readout of drifting electrons with wires



The drifting electron is traversing an arbitrary number of wire planes oriented in the direction of the required views. Each of them provides a “triangular” induction signal of maximum charge, equals to the electron charge. The electron charge is finally collected by the collection wire plane. The generated view of the event is the one seen by a camera at infinity with the optical axis in the direction of the wires.

Time Projection Chamber: principle of operation

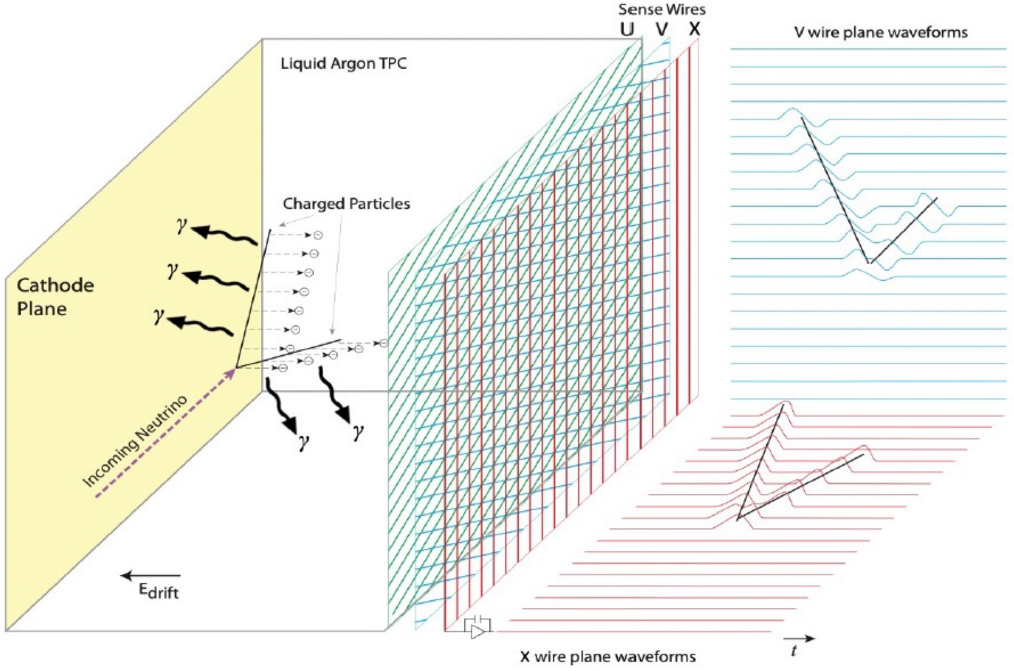


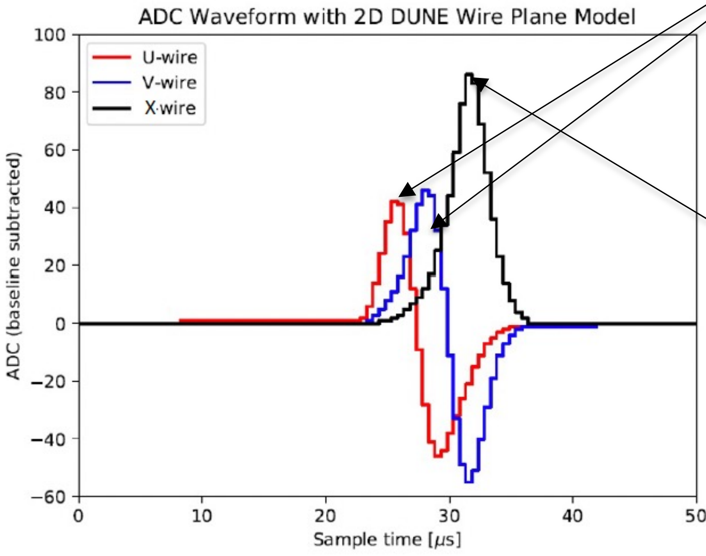
In a volume filled with an active medium (liquid or gas) a uniform **field** is established by means of a set of electrodes placed at the boundaries. In the typical structure of a LAr TPC these electrodes are:

1) a **cathode** plane;
2) an **anode** made of a grid or of parallel wires followed by two or more wire planes with different orientations;
3) a set of “race-track rings” at the other boundaries of the active volume set at a voltage appropriate to ensure a uniform field in the active region.

Ionization electrons produced in the active volume are drifted towards the wire planes to produce signals readout by electronics continuously recording. Upon a trigger, each wire plane provides a 2D (s,t) view of the ionization event. Multiple 2D views can be combined to obtain a 3D image of the event.

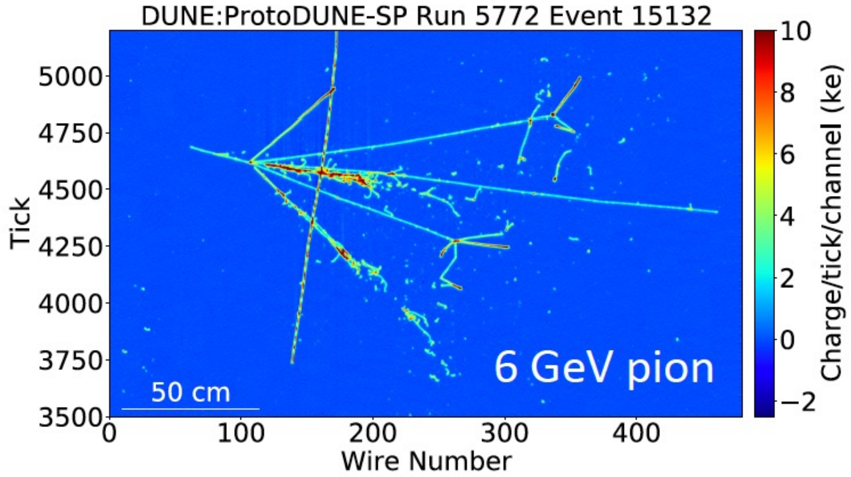
with also calorimetric measurements!





Induction planes

Collection plane



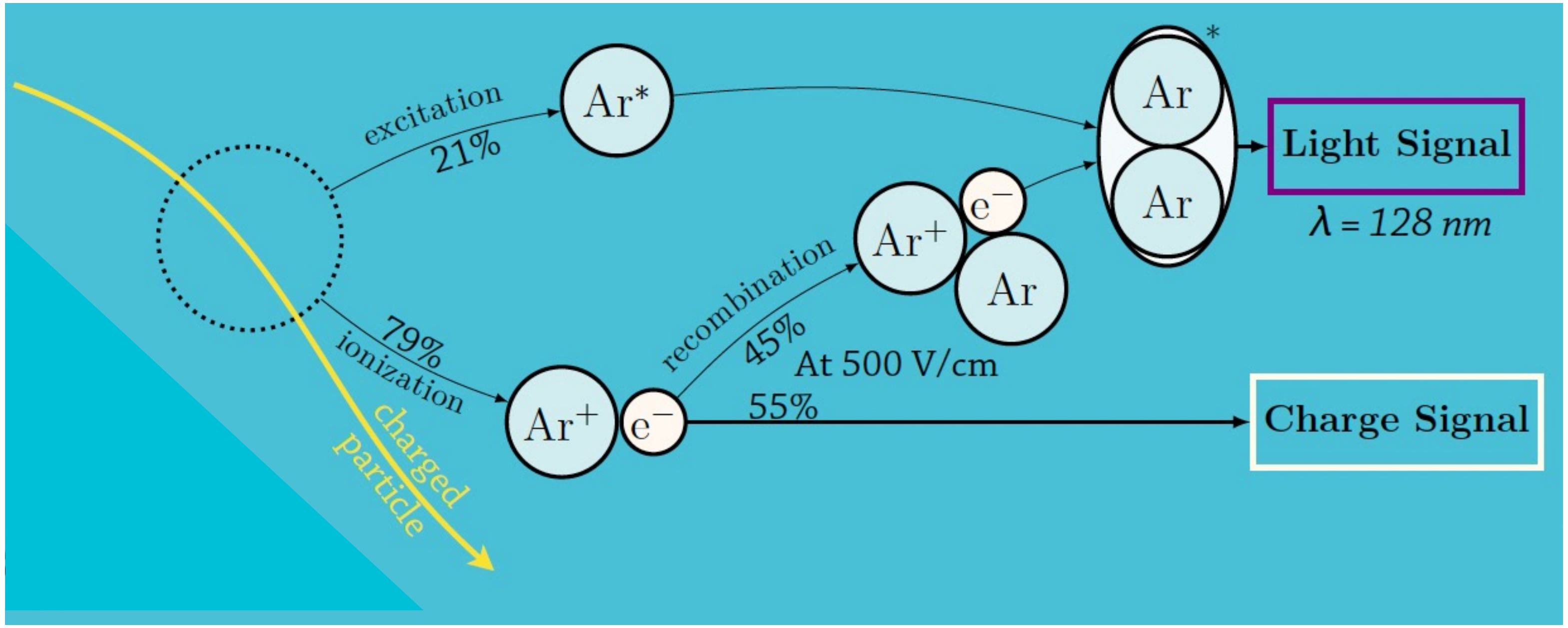
Primary detector technology for DUNE

- Detailed images of events
- Excellent spatial and calorimetric resolutions

Liquid Argon TPC

Charge particles excite and ionize LAr

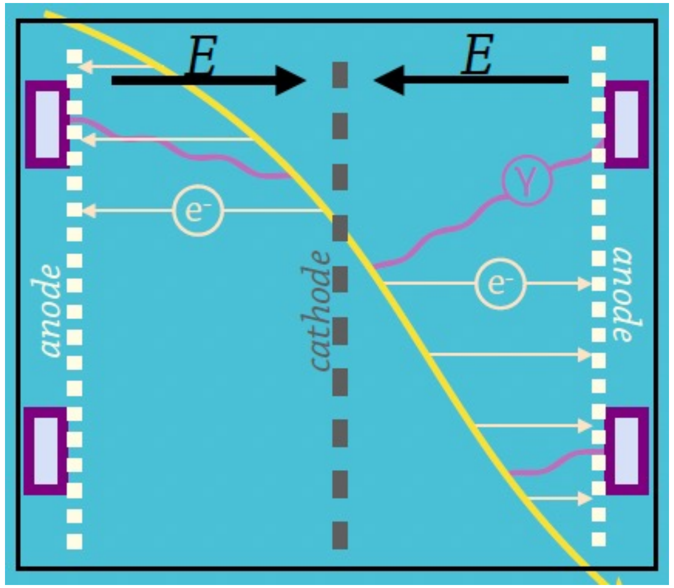
➔ Produces a charge & light signal
➔ An electric field suppresses the recombination
and allow to collect the e- at the anode



Collections ways

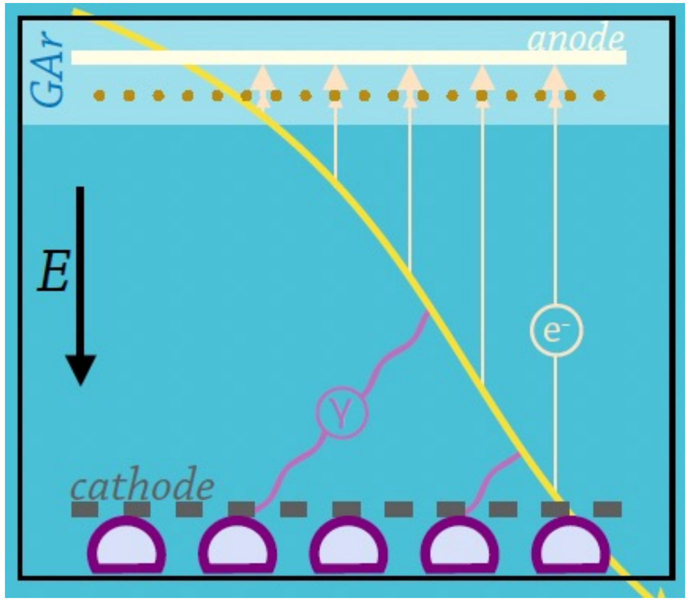
Different TPC designs to collect both signals

Single-Phase Horizontal Drift



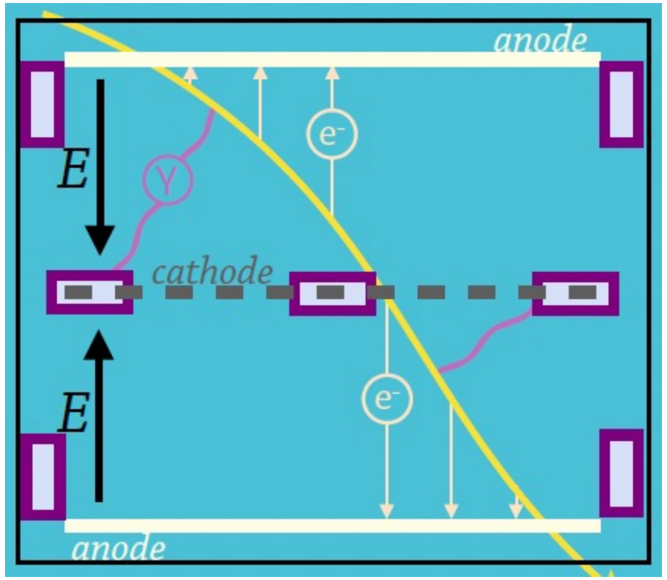
- ○ Two drift volumes
- ○ Anode made of wires
- ○ Light collected behind the anodes

Dual-Phase



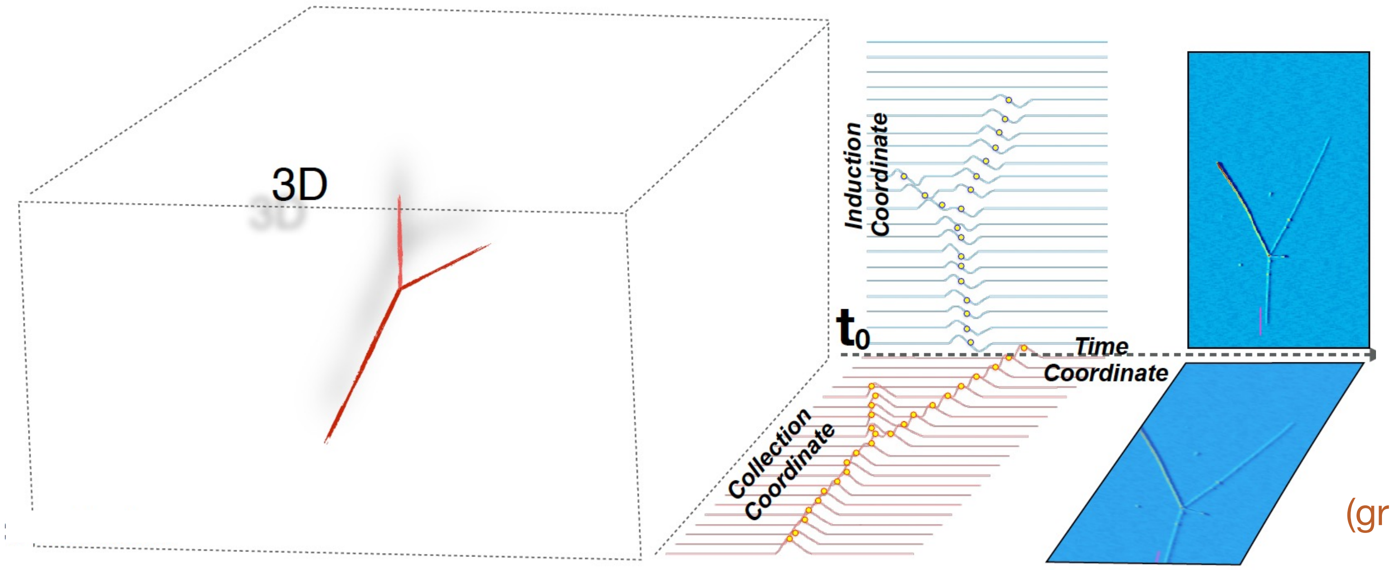
- ○ Single drift volume
- ○ Electron cloud amplified in gas argon layer with thick GEM
- ○ Anode made of PCBs
- ○ Light collected with PMTs below the cathode

Single-Phase Vertical Drift



- ○ Two drift volumes
- ○ Anode made of drilled PCBs
- ○ Light collected on the cathode and behind the field cage

LArTPC at work: Imaging and Energy reconstruction

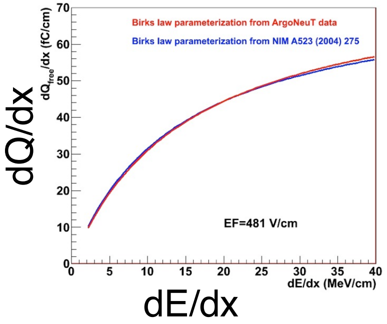


2D Image(s)
(graphic rendering)

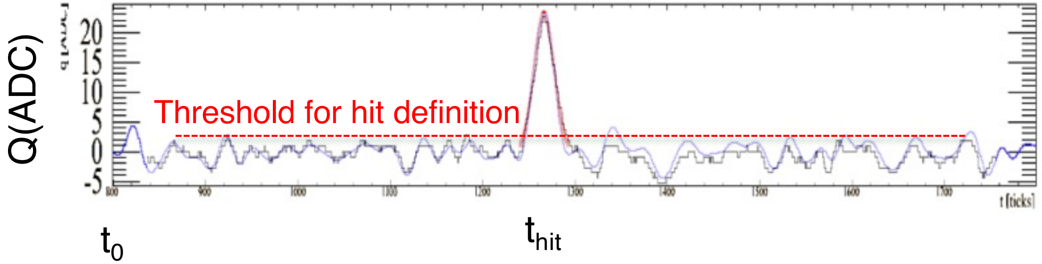
1. Hit coordinates (wire# and t_{hit}) ⇒ 2 x 2D ⇒ 3D image
2. Hit Amplitude ⇒ dQ Ionization Charge Deposited
3. Distance in space between hits ⇒ dx (track pitch)

4. dQ/dx ⇒ dE/dx ⇒ Particle Id

5. $\int_l \frac{dE}{dx} dx = Etot \Rightarrow$ Calorimetry

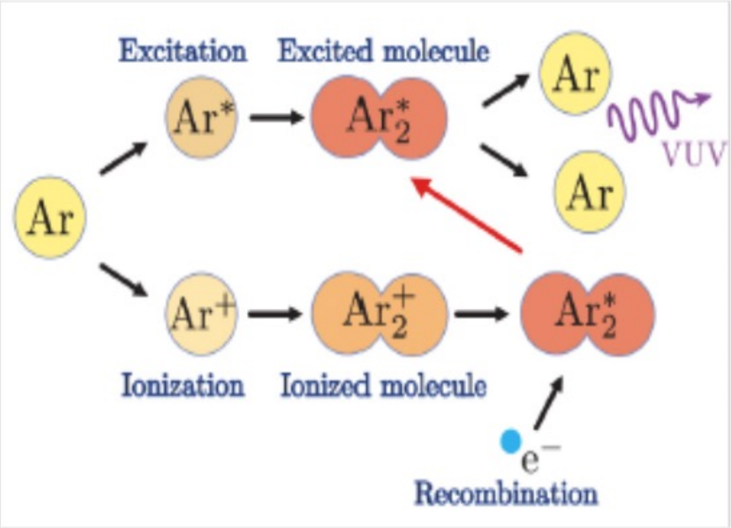


TPC wire Signal: find Hits



(real) TPC wire Signal

The t_0 issue



Need a fast signal to identify the time of the interaction (t_0)

Prompt scintillation light produced in LAr as part of the ionization process ideal for t_0 (and a lot more):

Need a ***Photo-Detector*** *embedded in the TPC structure*

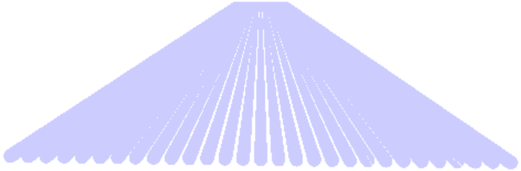
Ar Scintillation light is very abundant (40 k photons/MeV) but photon wavelength is in the VUV (128 nm)

Need wavelength-shifter (easiest solution)

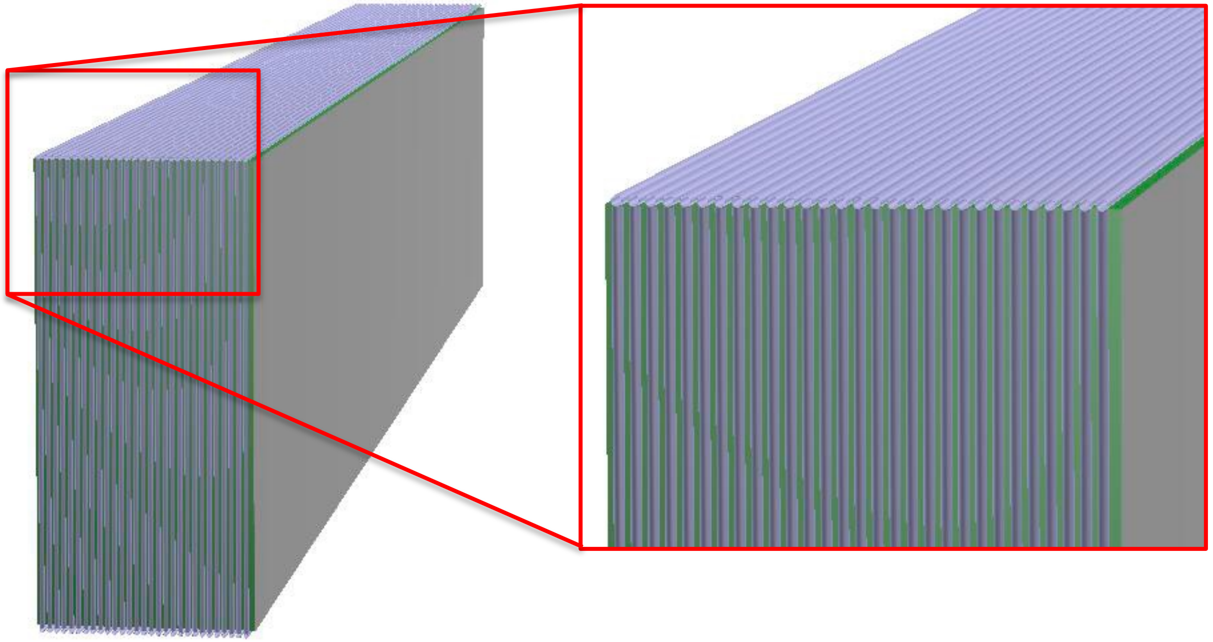
In the modern LArTPC technology - Light Detector (Photon Detection System) is becoming an important complement to the Charge Detector (TPC)

The Race-Track Rings (AKA Field Shaping Electrons)

The “Capacitor” has to be “infinite” not to have large distortions of the electrical field at its edges.
Thus, its boundaries must be closed by a a cage at the right potential.
The cage is given by track electrodes forming rectangular rings or strips.
The electrodes go from eg 75 KV to ground via a splitted power supply with resistive connectors (ICARUS, vacuum is needed) or via a distribution Power Supply (DUNE, SBND)



Race tracks at the bottom plane



Aluminium boxes against membranes

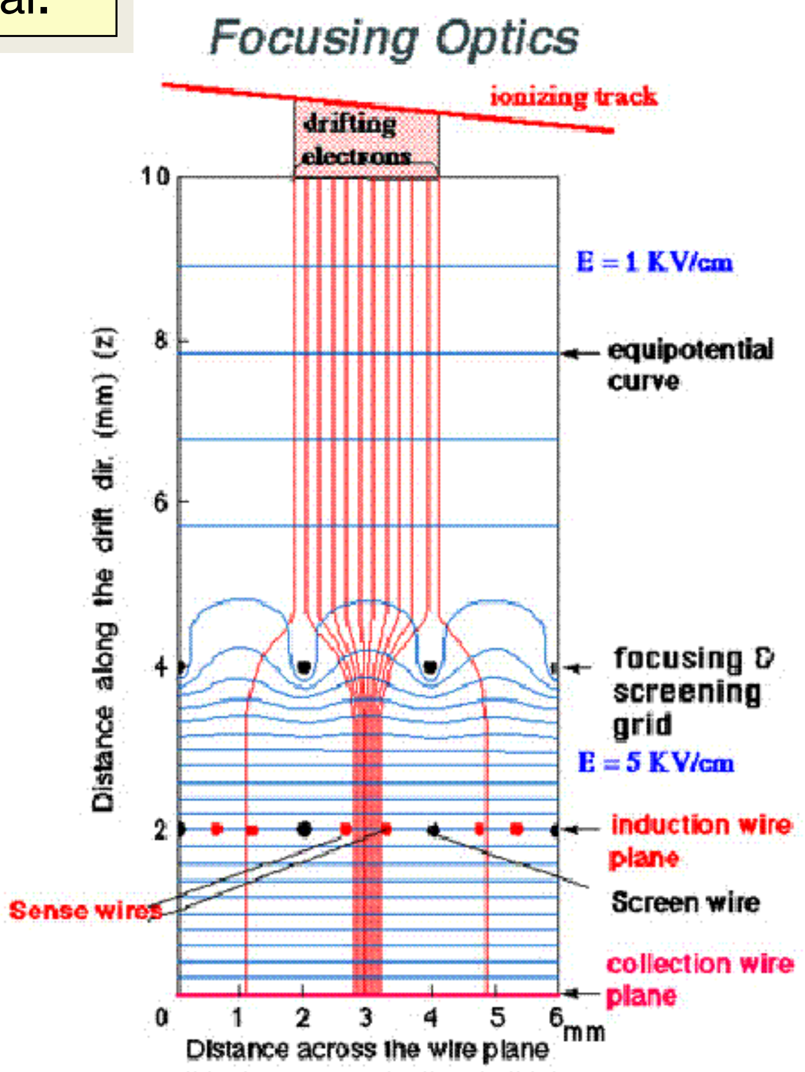
- Icarus choices the boxes since it is sufficiently small, DUNE will need to control and disperse the accumulated energy,
- Then, membranes have been chosen for DUNE (also to facilitate the detectors installations)
- That puts forwards a non-vacuum tightness, a much easier solution, that instead may sharpen problems with HV

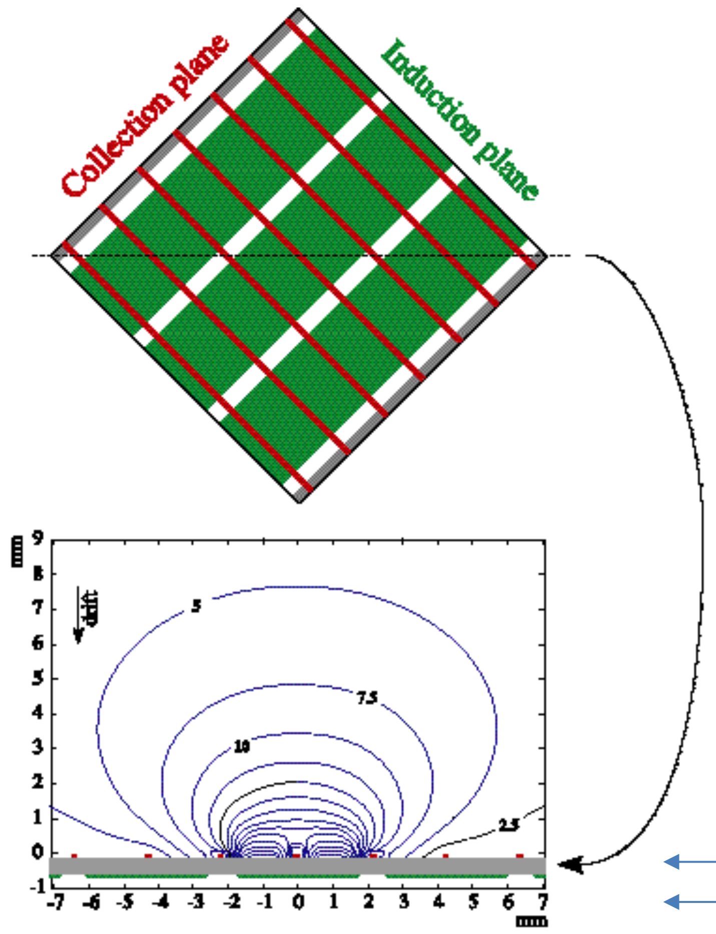
ICARUS: outside the Aluminium there are stainless boxes for containment.
Between the Aluminium and the Stainless there are screen exchangers for the cooling and foam pannels at closed cells,
During operations, the exchangers take away the heating.
A temperature gradient of 50 degree is acceptable.

The ICARUS system cannot work in DUNE which is too big. In DUNE the cooling system is internal to the membranes, done with calibrated tubes for liquid Argon leakage (nebulizers).

Practical readout configurations

Emilio Gatti et al.



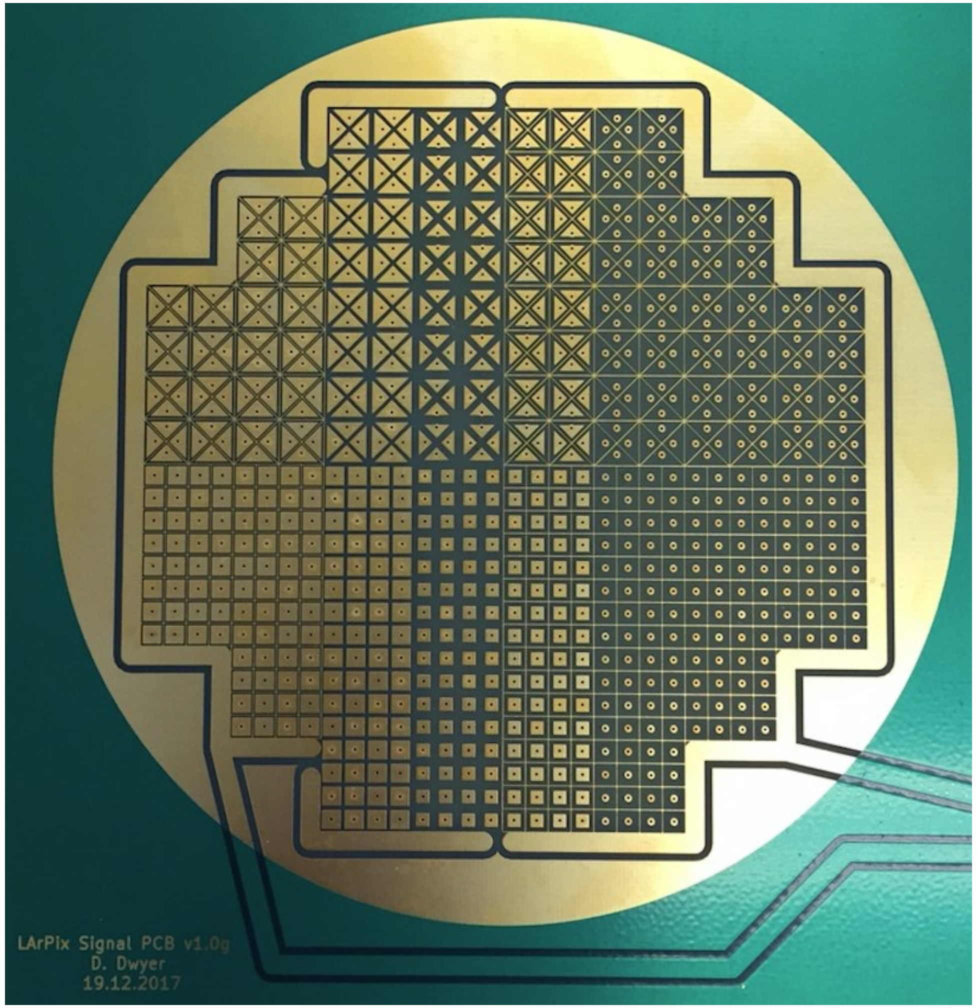


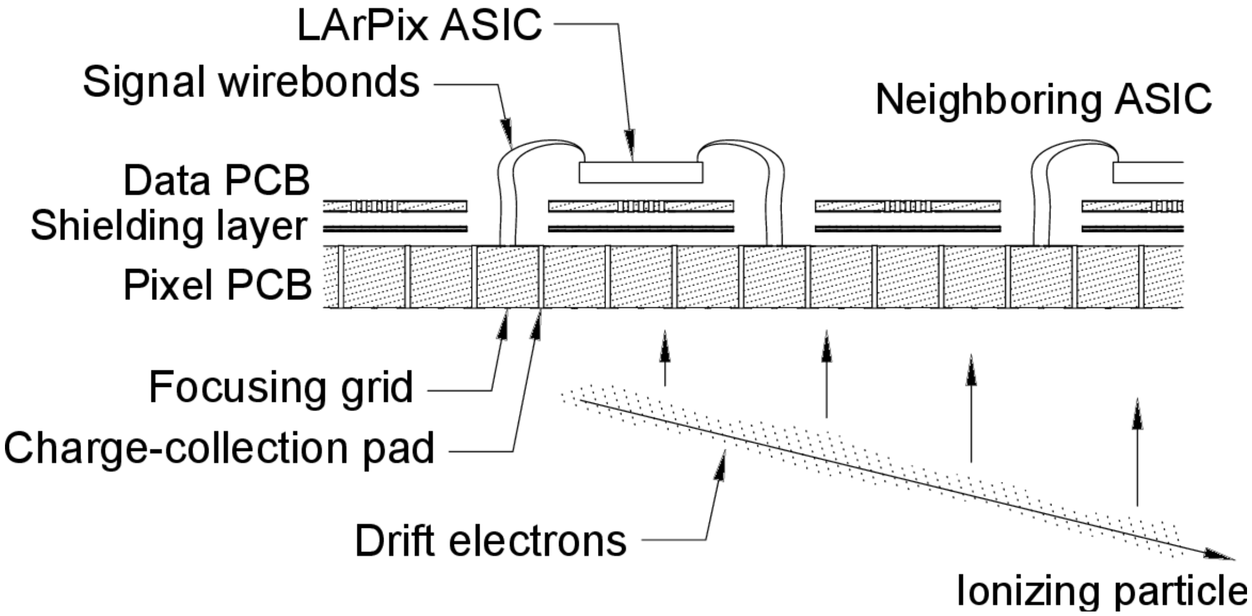
Collection “grid”

Induction “grid”

Multi-layer printed board technique

Pixelized readout





Calibrations

Different calibration systems:

- Icarus has no laser system implemented but the synchronized signal in optical fibers for the PMT
- Cosmics tracks are used for track calibration, charge efficiency, electron lifetime

- DUNE, system YAG with laser tracker (it depends on the quadratic of the beam intensity)

In summary

- The original idea, in later years, evolved in an experimental program for the development and realization of a large detector for neutrino studies and nucleon decay searches at the Gran Sasso underground Laboratory (LNGS): ICARUS (Imaging Cosmic And Rare Underground Signals).
- The development of the LAr TPC technology required **years of dedicated R&D**. Several milestones had to be reached to establish the necessary ground for the construction of a fully functional detector:
  - 1) Wire chambers construction and event imaging techniques;
  - 2) LAr purification;
  - 3) Determination of the absolute time of events through scintillation light detection.
- The R&D program culminated with the construction of the first large size LAr TPC: The ICARUS T600 detector. ICARUS T600 was first operated in 2001 at the assembly site, the INFN-Pavia Laboratory, for a 3 months long test run.

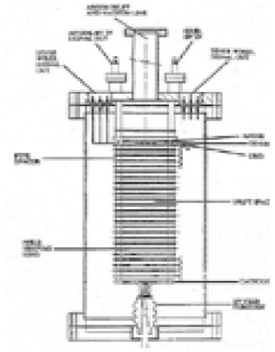
- After the successful test run of the T600 module in Pavia, Carlo Rubbia, in a seminar held at CERN on February 26, 2002, announced the coming of age of the LAr TPC and its availability for physics searches.

Many of the slides presented in this lecture are taken from that seminar.

After the ICARUS T600 test run

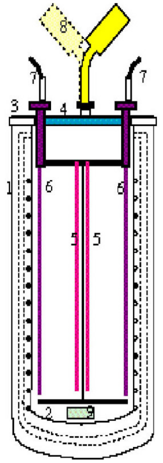
- After the successful test run, in Pavia, and the announcement at CERN in 2002, several initiatives, mostly in neutrino physics, started, taking the LAr TPC as reference technology:
  - LBNE in US and LAGUNA in Europe, which later merged in the present DUNE experiment, aiming at a long baseline, large mass, experiment to study CP violation, mass hierarchy, and other neutrino related topics and to search for proton decays, dark matter, and other rare events (large underground observatories).
  - MicroBooNE, at Fermilab, with the goal to elucidate the low energy excess of electrons neutrinos observed by the MiniBooNE experiment.
  - ProtoDUNE, at CERN: a large facility, with two large volume cryostats (≈ 500 m^3 each) equipped with LAr purification systems and a dedicated beam line, to test and validate components for the DUNE experiment.
  - ND-LAr, at Fermilab: with a highly modular design and pixelated readout, to serve as near detector for the DUNE experiment.
- ICARUS T600 detector was installed at LNGS, where, between 2010 and 2013, took data from the CERN to LNGS (CNGS) Long Baseline neutrino beam, from cosmic signals and searches for nucleon decays.
- At the end of LNGS run, ICARUS T600 was brought to CERN for some of upgrades allowing for operation at shallow depths, at high cosmic-rays flux. Starting from 2017 ICARUS T600 was re-installed at Fermilab, along the Booster neutrino beam line, where it has been operating since 2020 as Far Detector of the Short Baseline Neutrino (SBN) neutrino program, having as principal aim the clarification of the LSND anomaly in terms of a possible sterile massive neutrino.
- Construction of the SBN Near Detector (SBND), another large LAr TPC, is complete. SBND started operation at the beginning of 2024.

Milestone 1. LAR Imaging



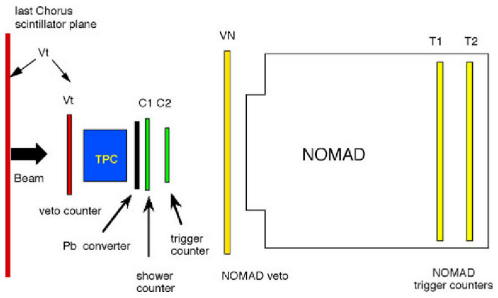
24 cm drift wires chamber

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



3 ton prototype

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



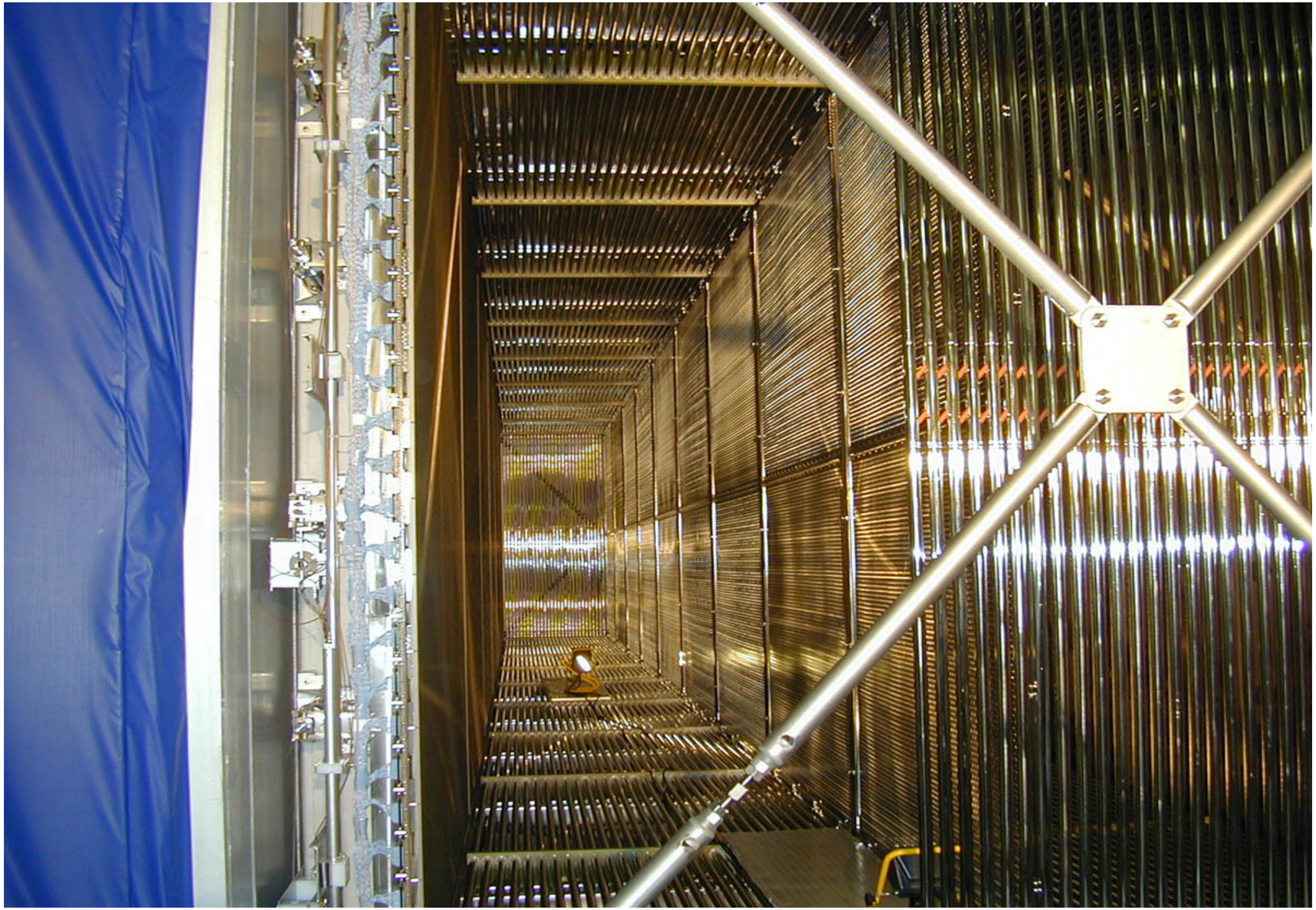
50 litres prototype
1.4 m drift chamber

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

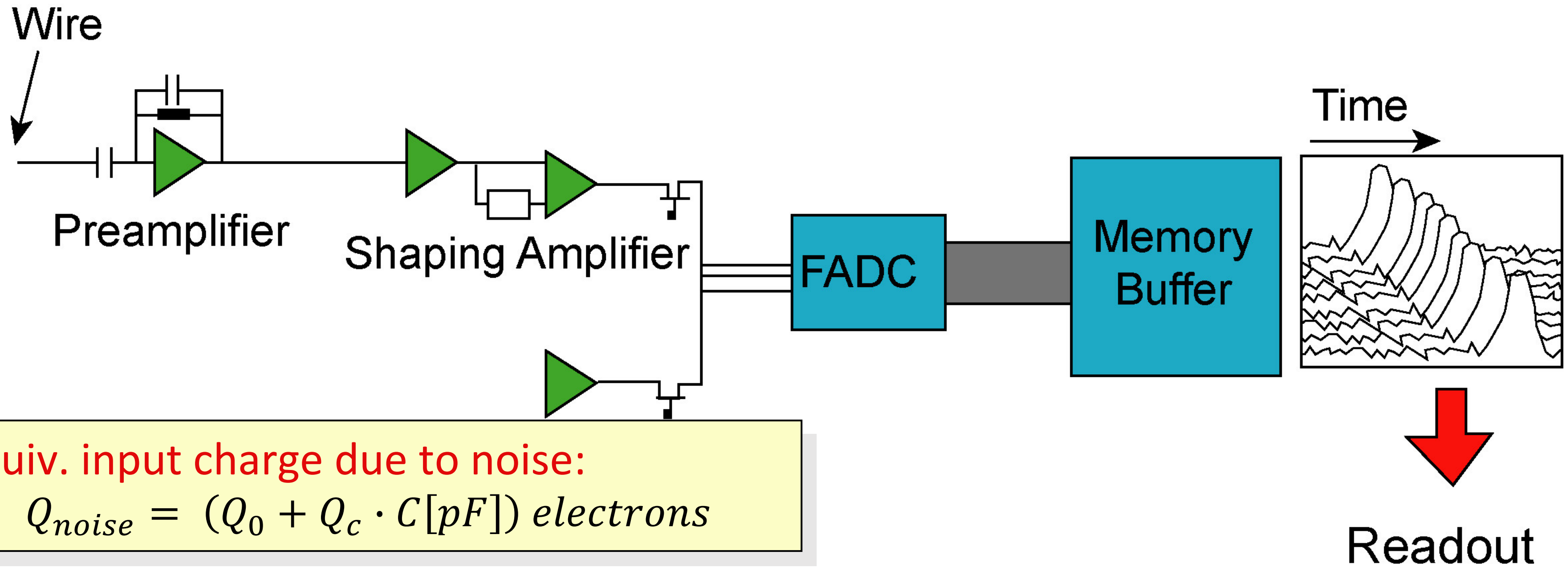
1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

The ICARUS T600 Detector: inner structure of a single gap



Method of the signal recording

- The collected charge is sensed by an ultra-low noise, FET charge sensitive pre-amplifier.
- The signal waveform from individual wires, after being further amplified, filtered and digitized, is continuously stored on a circular memory buffer.
  - The chamber is continuously sensitive
  - The *event* is contained in a time window, equal to the maximum drift time.
  - The event is “frozen” in the memory at the end off the readout

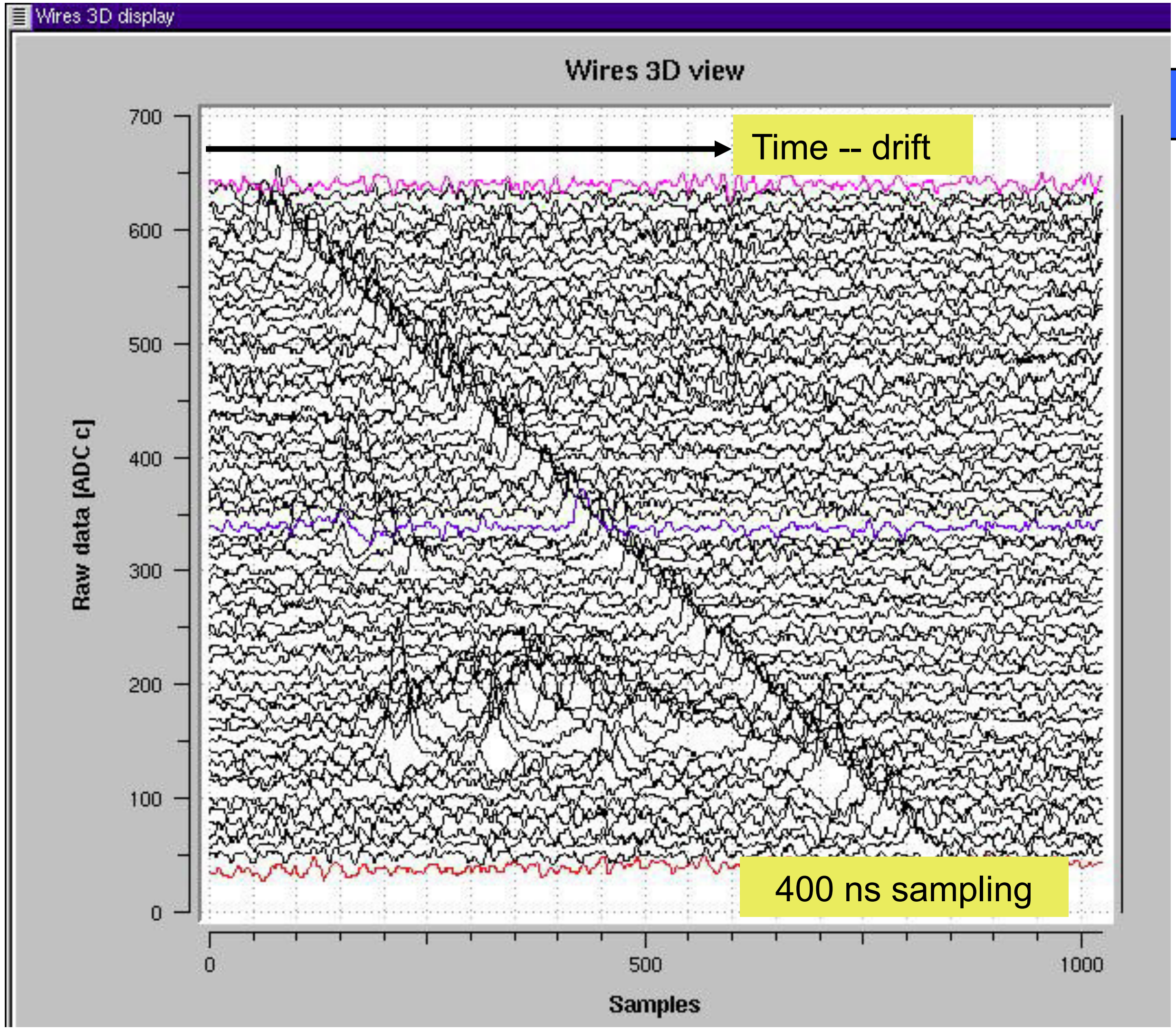


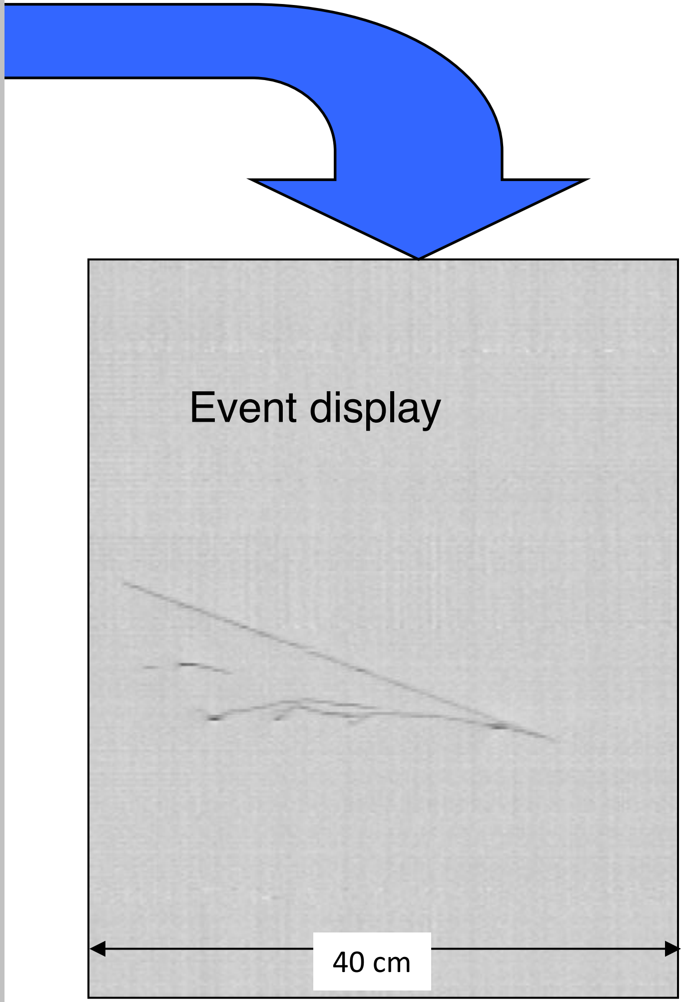
Equiv. input charge due to noise:

$$Q_{noise} = (Q_0 + Q_c \cdot C[pF])\ electrons$$

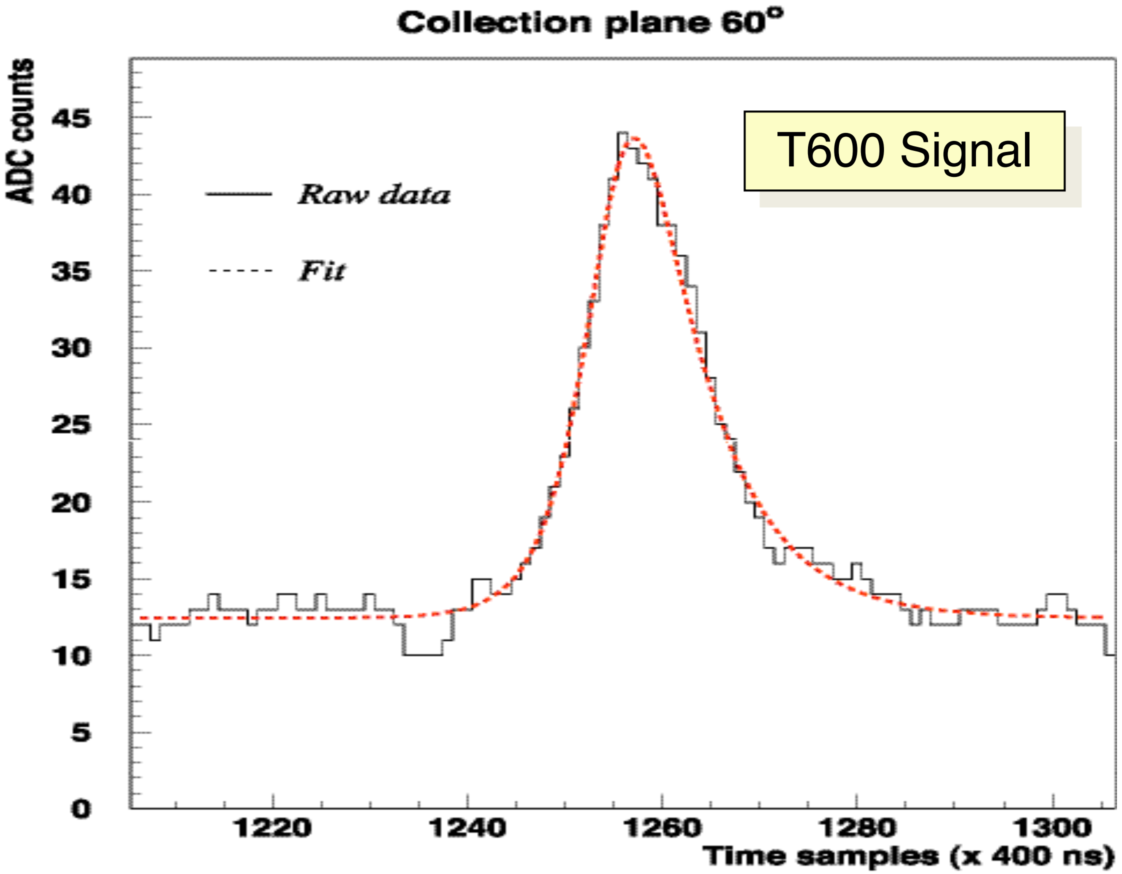
Principle of signal recording

Real Event from a
15 ton LAr Detector



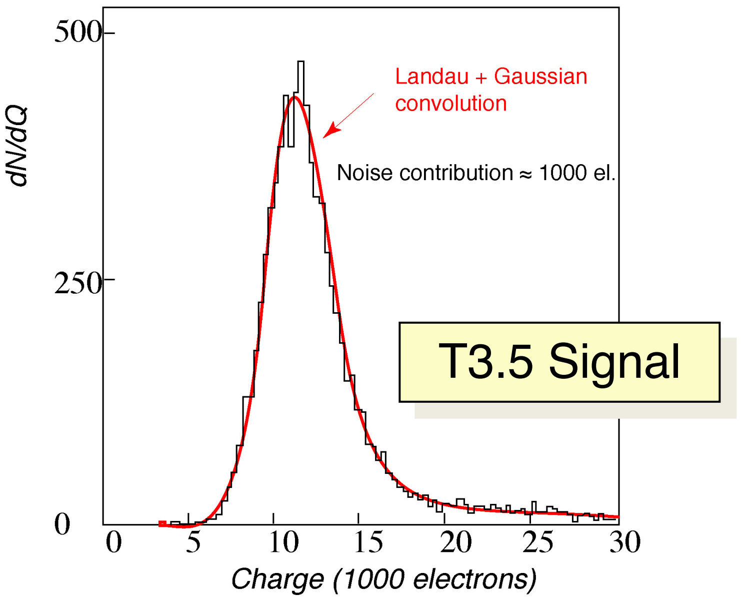


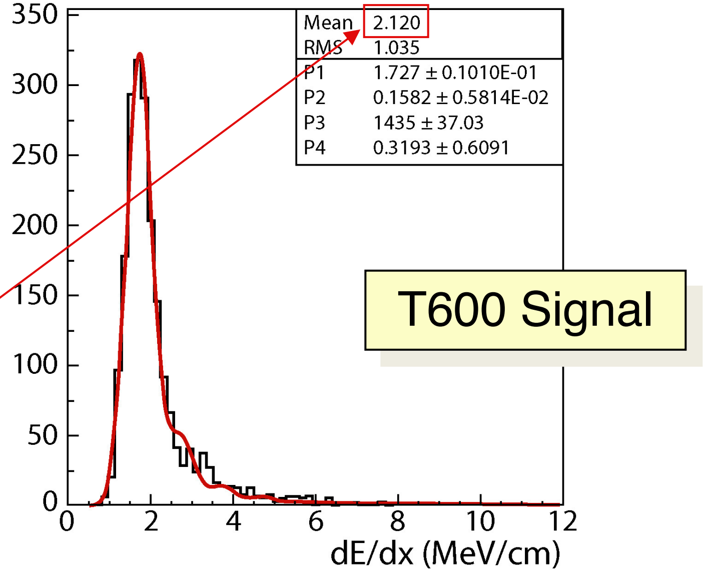
Single wire performance



Gross LAr masses
T3.5: 3.5 ton
T600: 740 ton

Charge distribution on 2 mm for m.i.p.





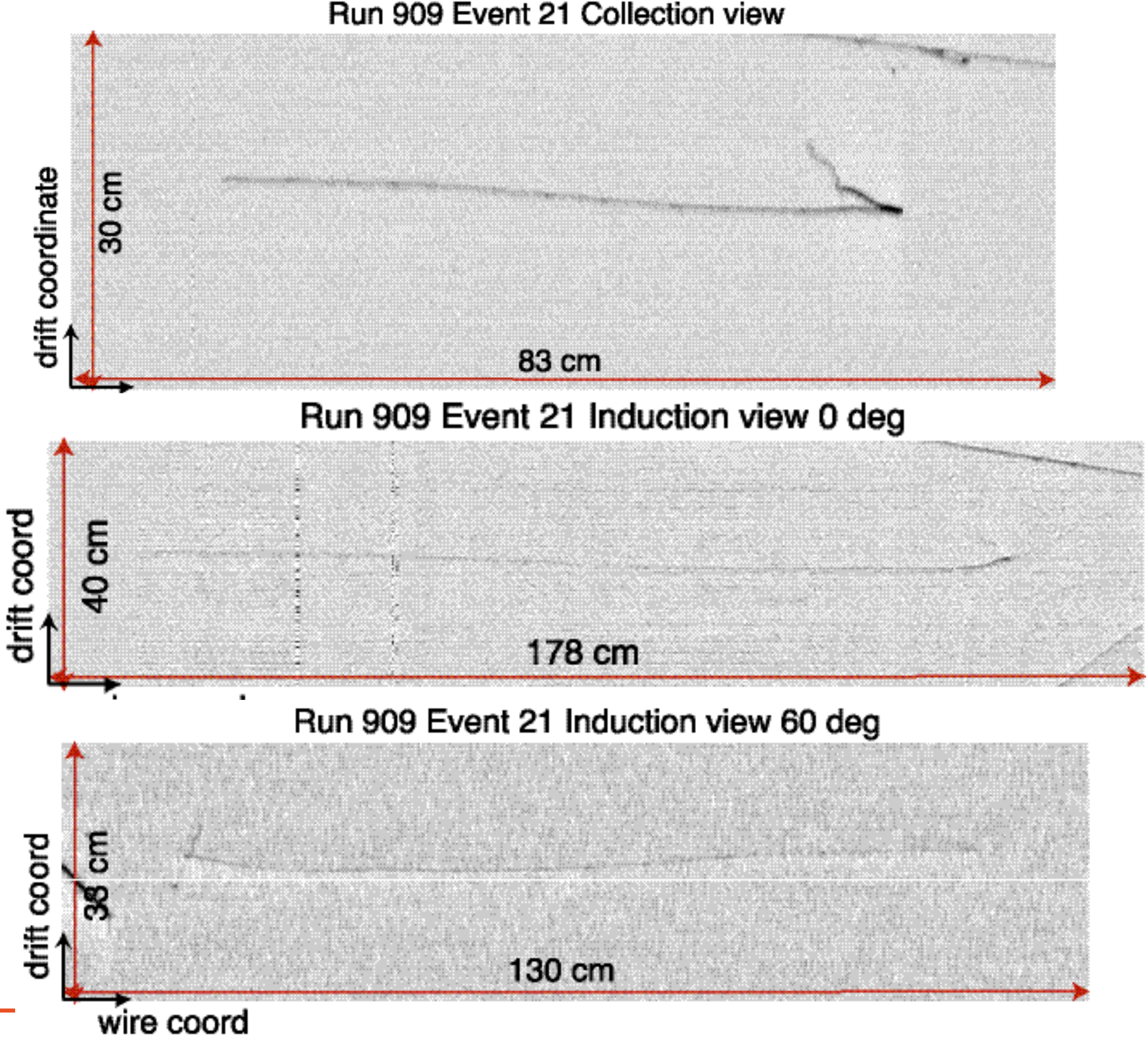
Reconstructed dE/dx:
2.12 MeV/cm

Multiple plane readout in ICARUS T600 (2001)

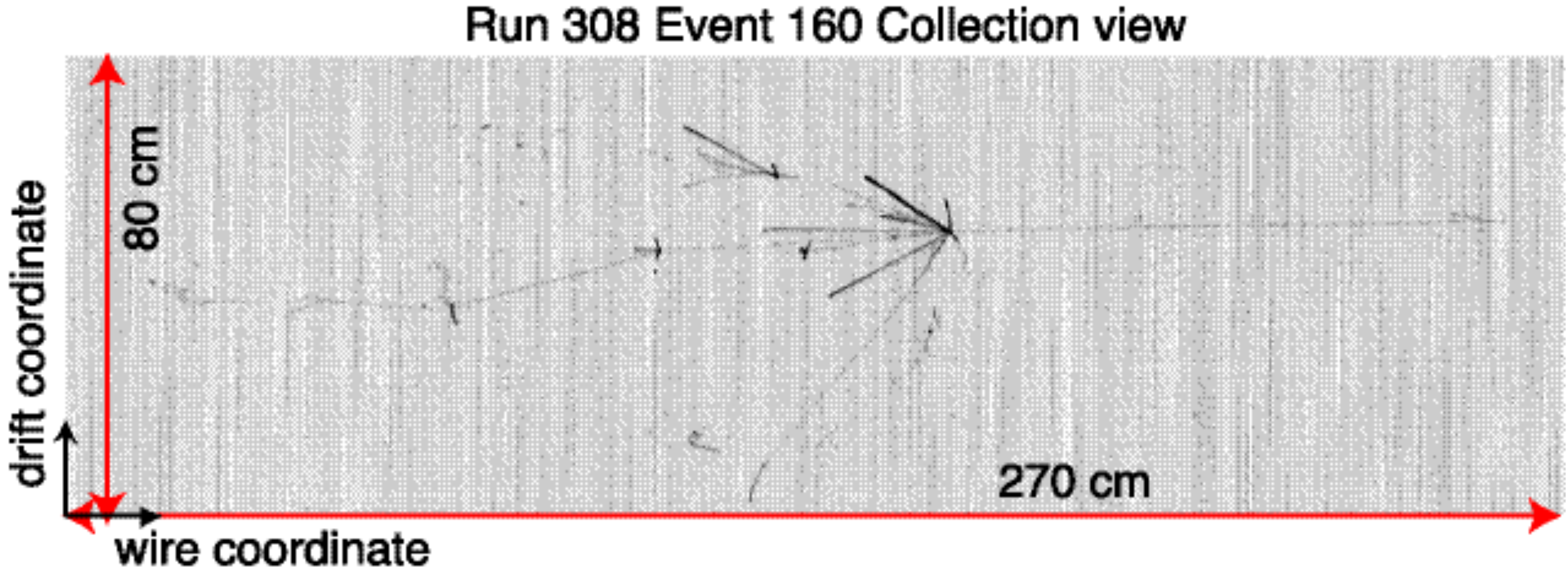
Collection (+60°)

Induction1 (-60°)

Induction2 (0°)

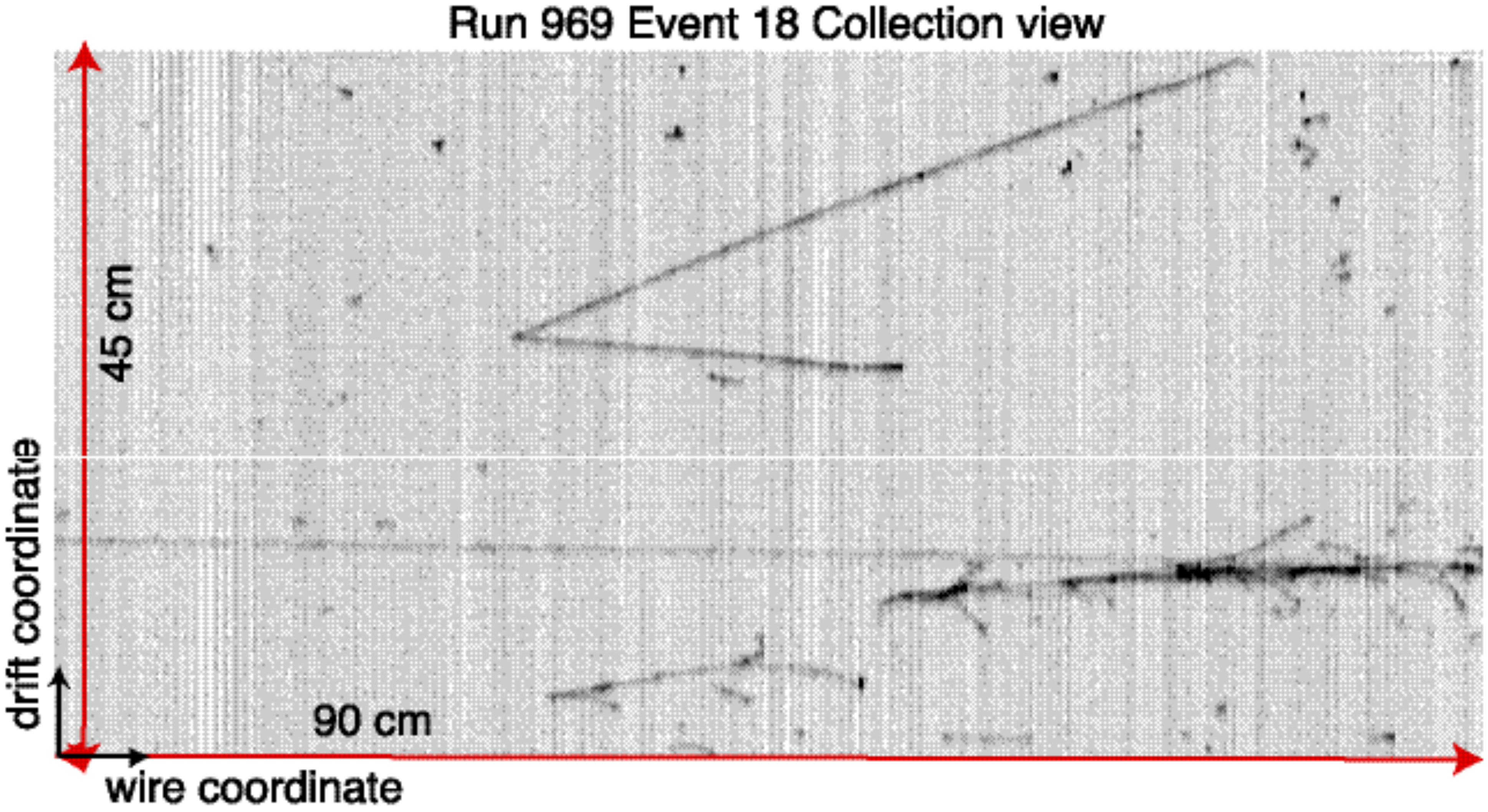


Hadronic interaction in ICARUS T600 (2001)

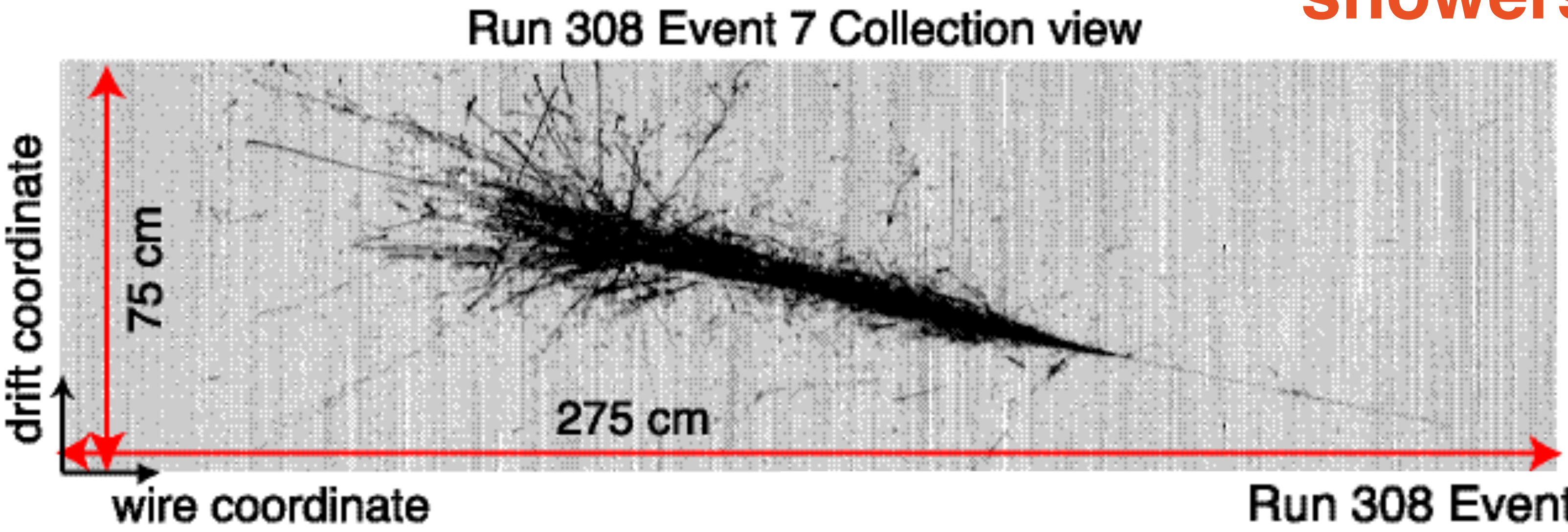


V_0 candidate in ICARUS T600 (2001)

A possible neutron interaction

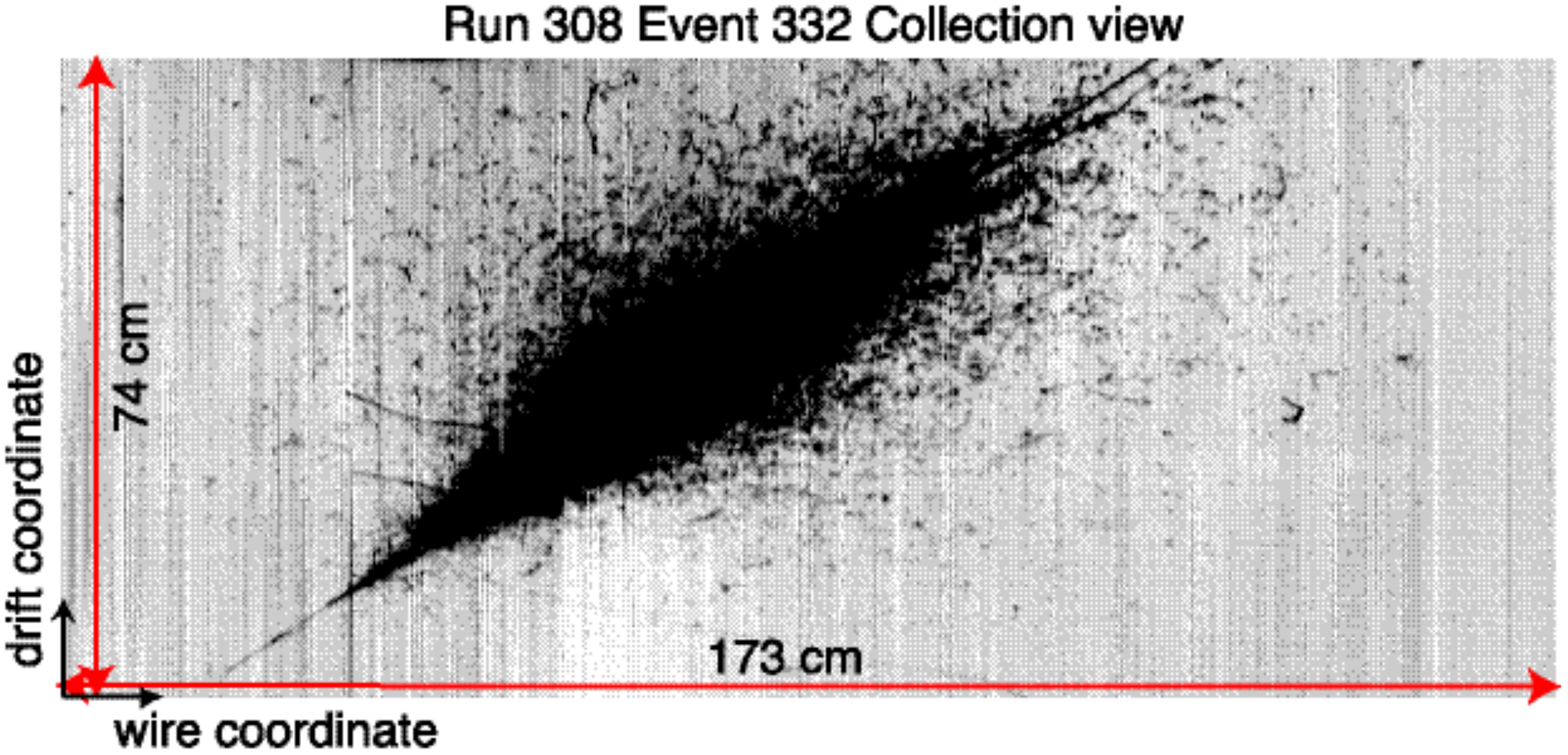


High energy cosmic ray showers in ICARUS T600 (2001)



Hadronic shower from p or π

Electromagnetic shower from μ

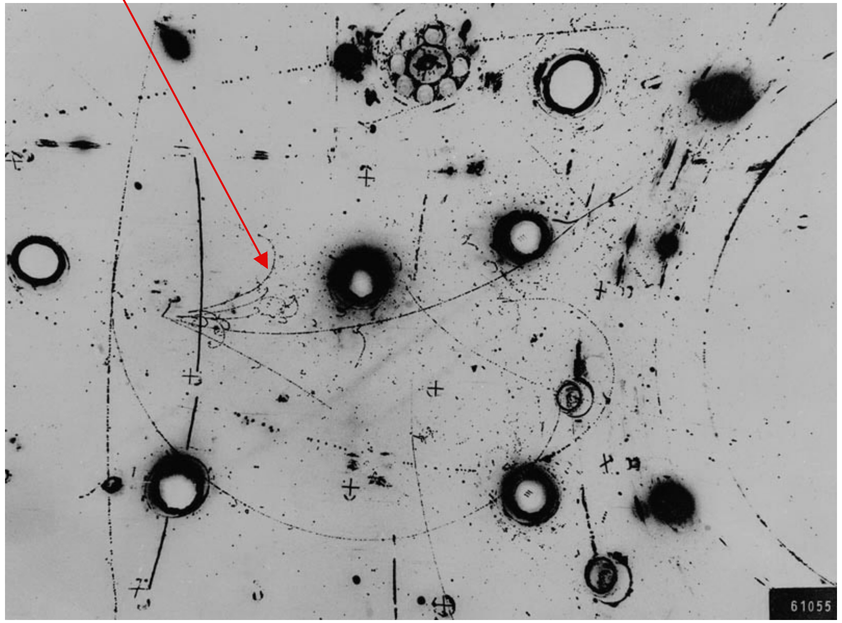


Thirty years later than…

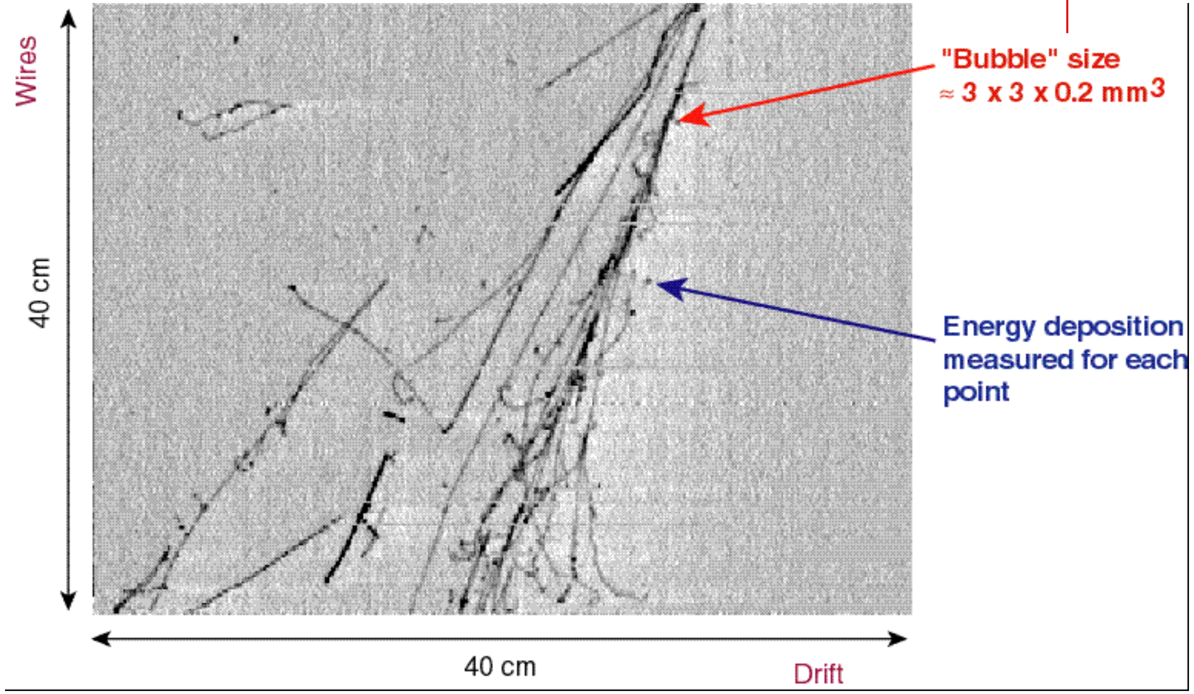
Bubble diameter ≈ 3 mm (diffraction limited)

LAr is a cheap liquid, vastly produced by industry

Gargamelle bubble chamber



ICARUS electronic chamber



"Bubble" size ≈ 3 x 3 x 0.2 mm^3

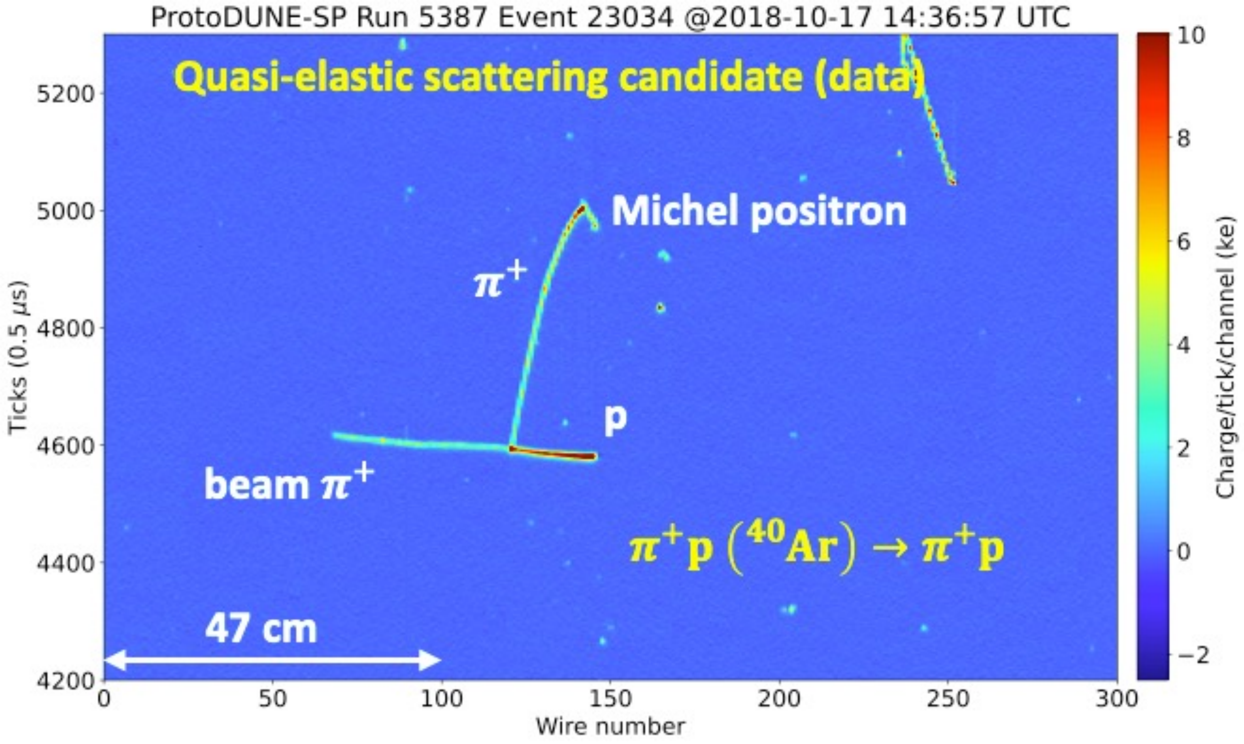
Energy deposition measured for each point

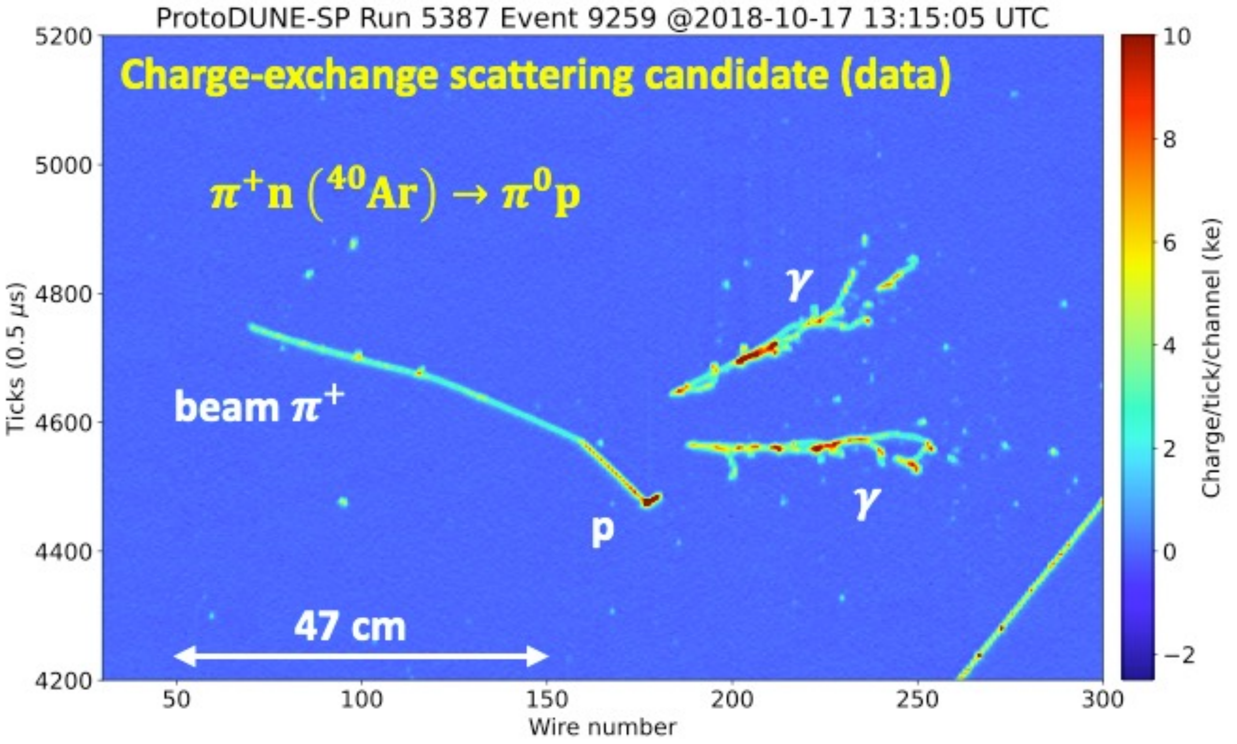
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

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

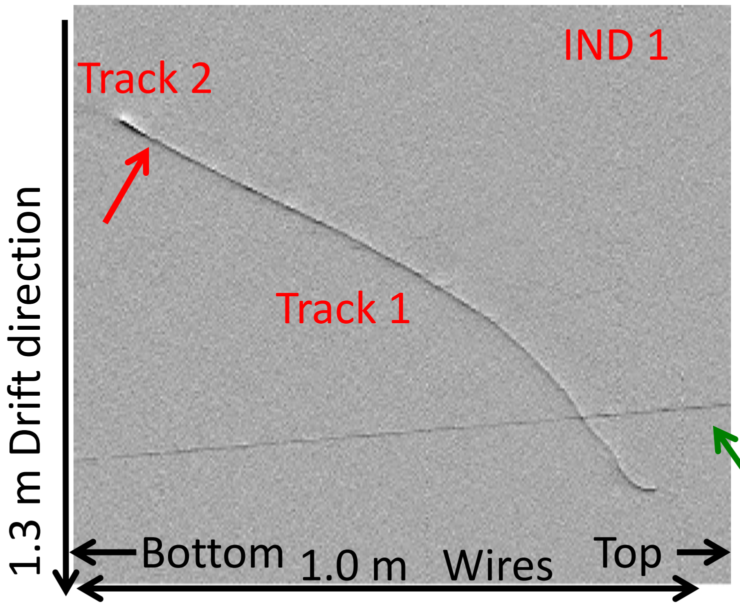
ProtoDUNE (2018-)

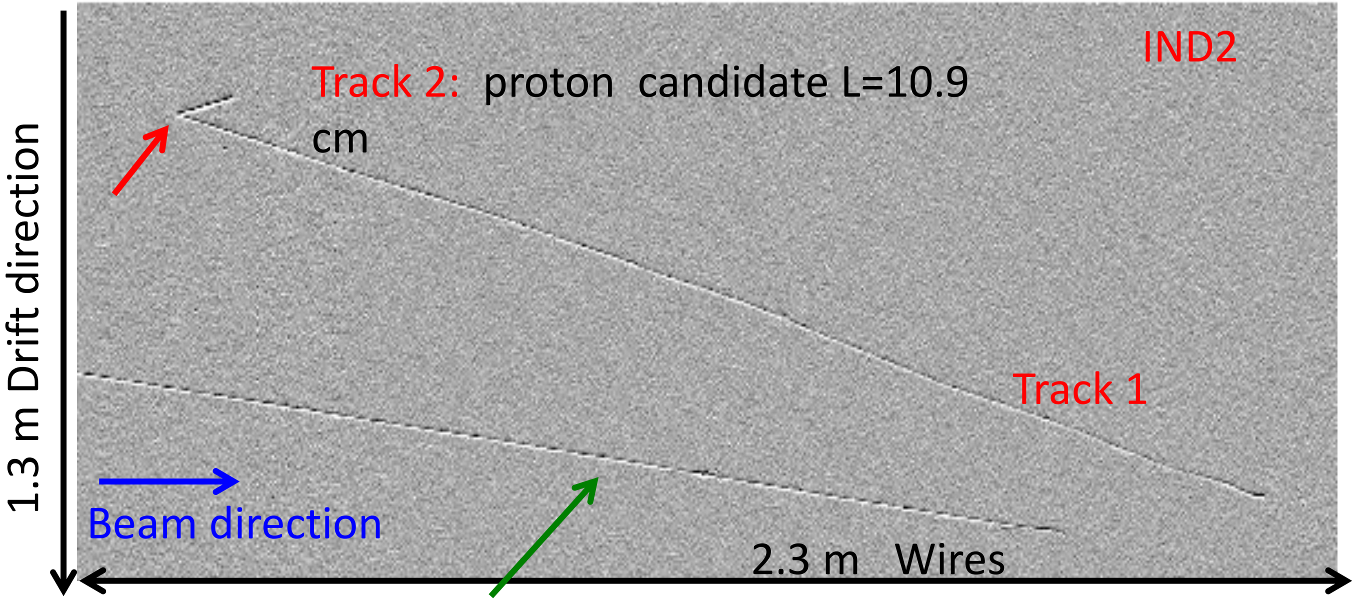
In ProtoDUNE all readout electronics, including the digital part is in LAr, directly attached to the wires. The input capacitance is significantly reduced, due to the absence of connecting cables → higher signal to noise ratio (≈ 40 for single wire signals from m.i.p.).





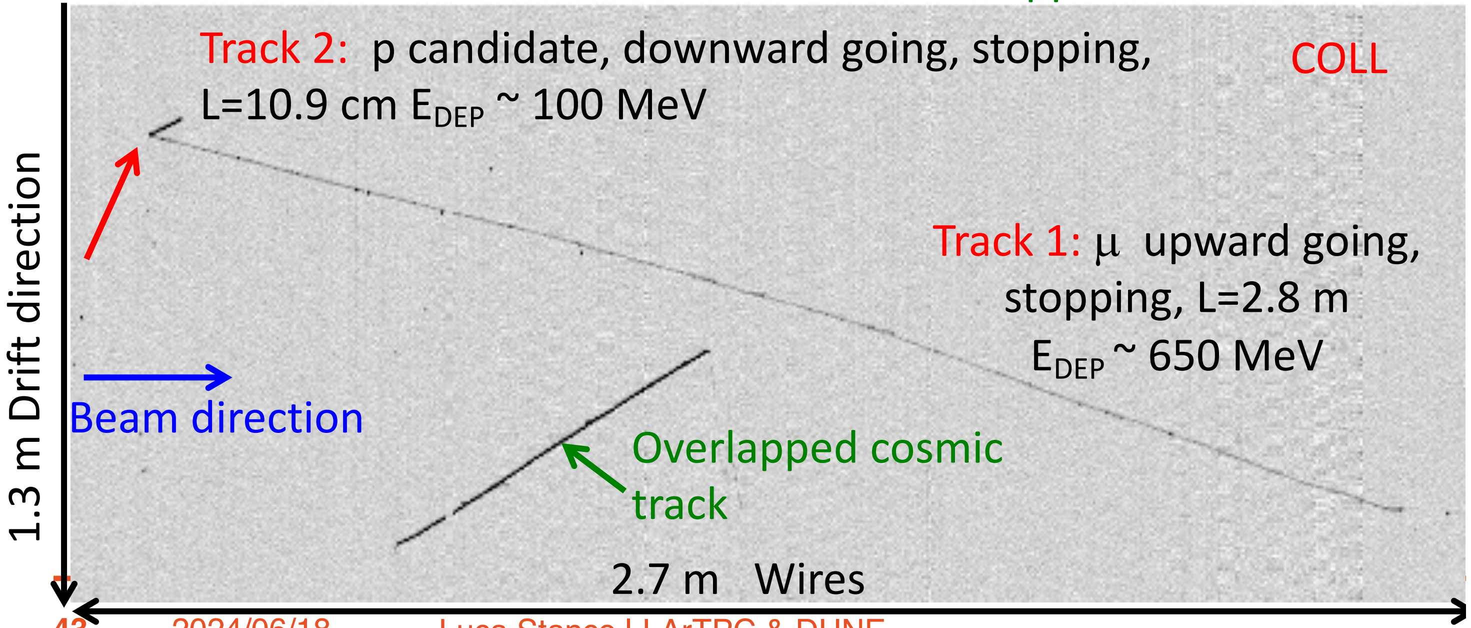
ICARUS/SBN-FD (2020-) BNB ν_μ CC candidate





Track 2: proton candidate L=10.9 cm

Overlapped cosmic track

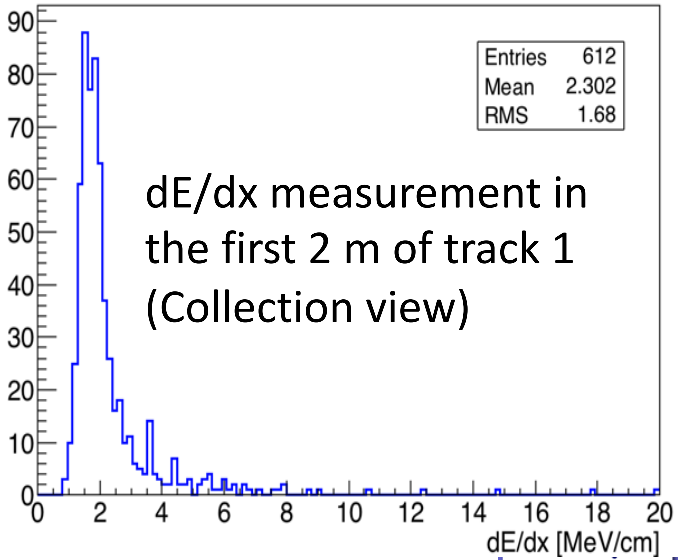


Track 2: p candidate, downward going, stopping, L=10.9 cm E_{DEP} ~ 100 MeV

Track 1: μ upward going, stopping, L=2.8 m E_{DEP} ~ 650 MeV

Overlapped cosmic track

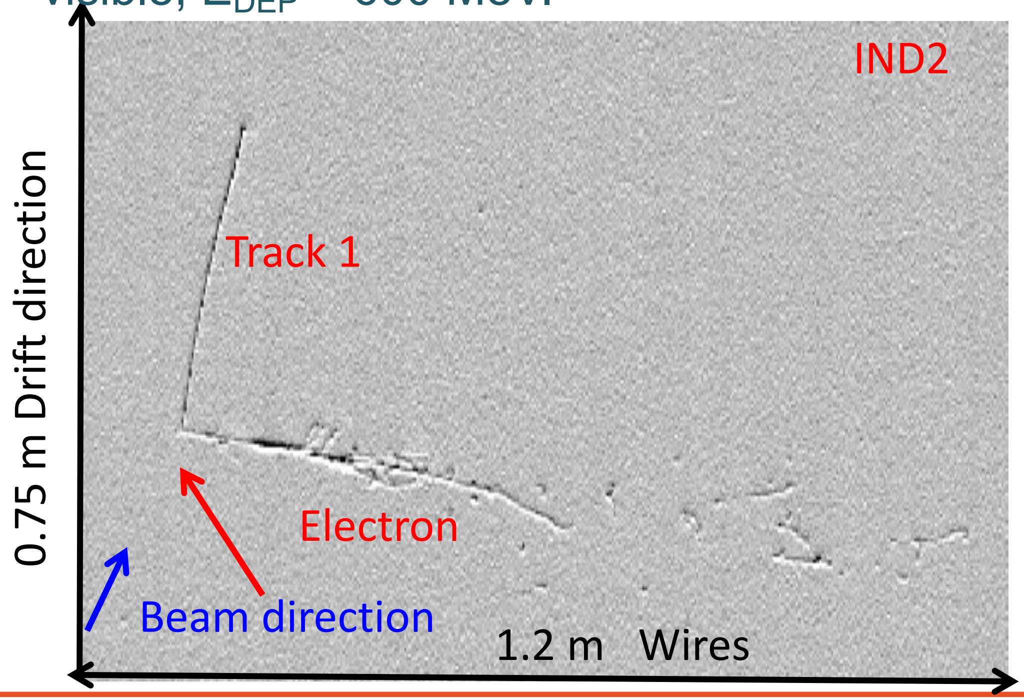
Total E_{DEP} ~ 750 MeV

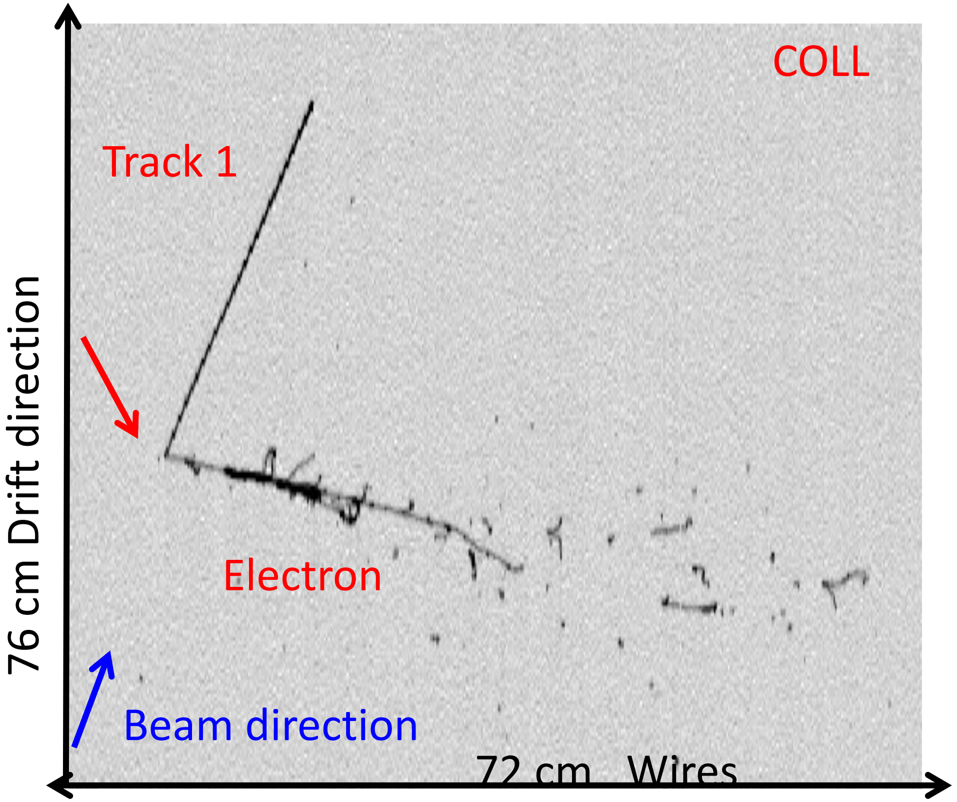


dE/dx measurement in the first 2 m of track 1 (Collection view)

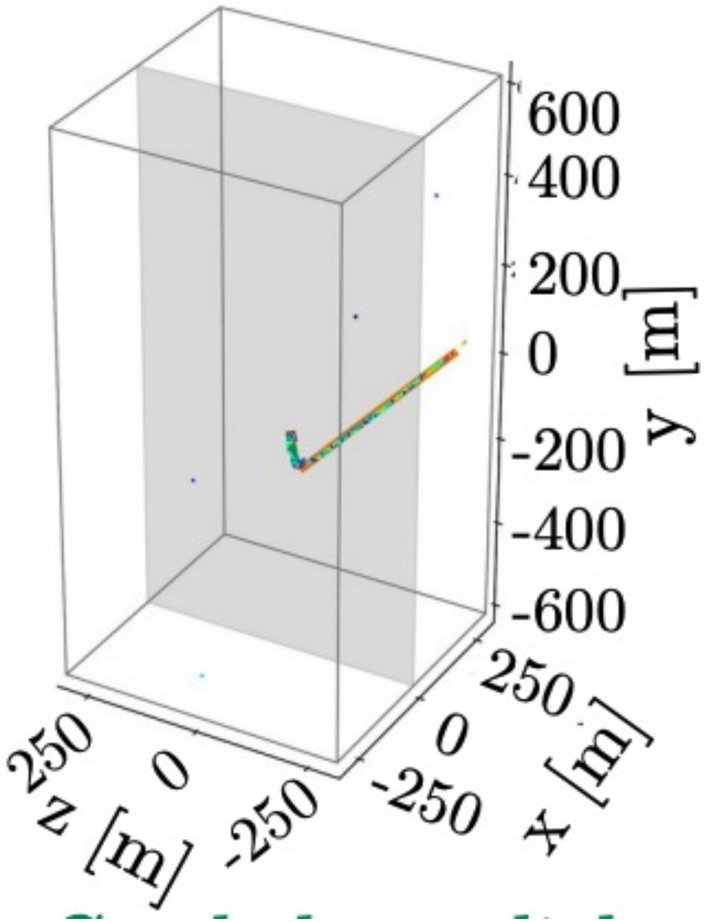
ICARUS/SBN-FD (2020-) ν_e CC candidate

- ✓ Contained Q.E. electron neutrino candidate with two particles at the primary vertex (indicated by red arrows), E_{DEP} ~ 800 MeV:
  - ✓ Track 1 is the upward going hadron track stopping inside L= 43 cm: proton or pion candidate;
  - ✓ The beginning of the electron shower is clearly visible, E_{DEP} ~ 600 MeV.

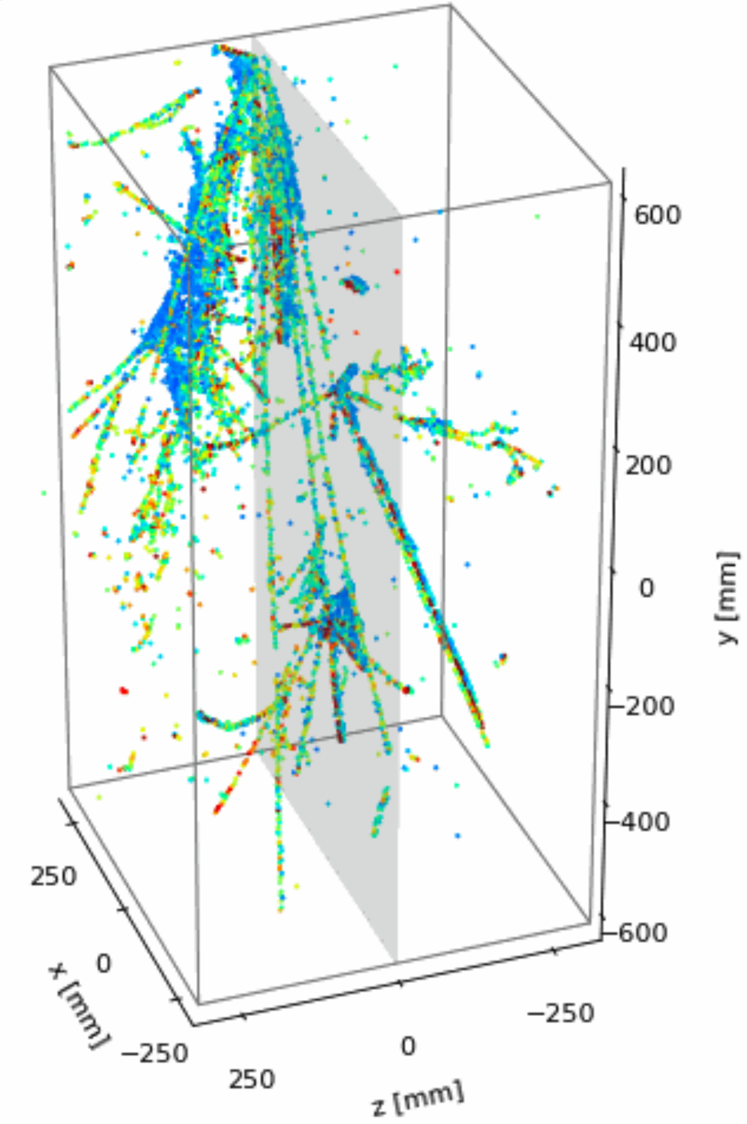




ND-LAr events from pixelated readout in prototype Module 0



Simulation

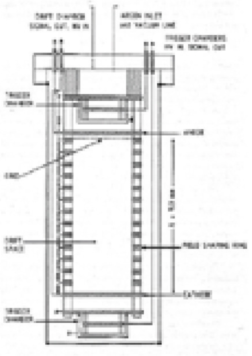


Data

Milestone 2: Lar Purity

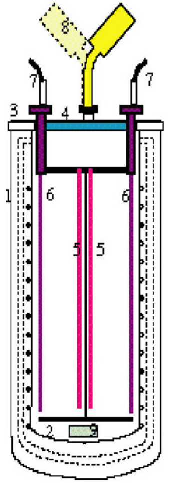
First purity monitor chamber

1987: First LAr Ultra-purification.
Measured Lifetime > 10 ms



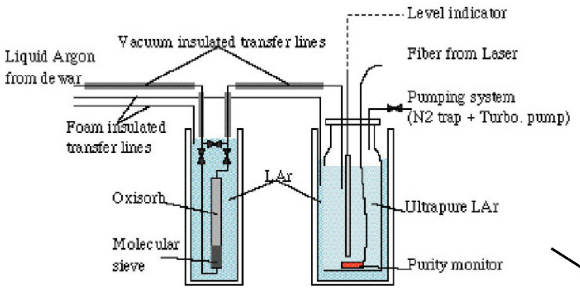
3 ton prototype

1991-1995: First demonstration on large masses. Argon recirculation in gas phase. Long duration test.



Liquid Phase purification

1994



10 m^3 industrial prototype

1998-1999: Ultra-pure LAr technique industrialization.
Forced LAr recirculation.

How far shall one drift?

- Detector **complexity grows** with the number of **electron collection** wire planes. Therefore, the distance over which electrons are made to drift should be as long as possible. Several **limitations** come into play;
  - ➔ The value of a **practical high voltage**. At the convenient drift field of 500 V/cm, in order to drift over 3 meters, 150 kV are required. The drift time over this distance is 1.85 ms.
  - ➔ The **diffusion of electrons**, which slightly blur the image, transforming a delta function into an approximately gaussian distribution:

$$\sigma(t) = \sqrt{2Dt}\ ; D \approx 5\ cm^2 s^{-1}$$
$$t = 2\ ms \ \Rightarrow\ \sigma \approx 1.4\ mm$$

  - ➔ The **electron attachment probability** during the drift time. In order to collect a significant electric signal, electrons must not become bound as ions, which have a much smaller v^-.The fraction of surviving free electrons is given by ($k^{(i)}$ = absorption rate for the i-th impurity of concentration $N^{(i)}$):

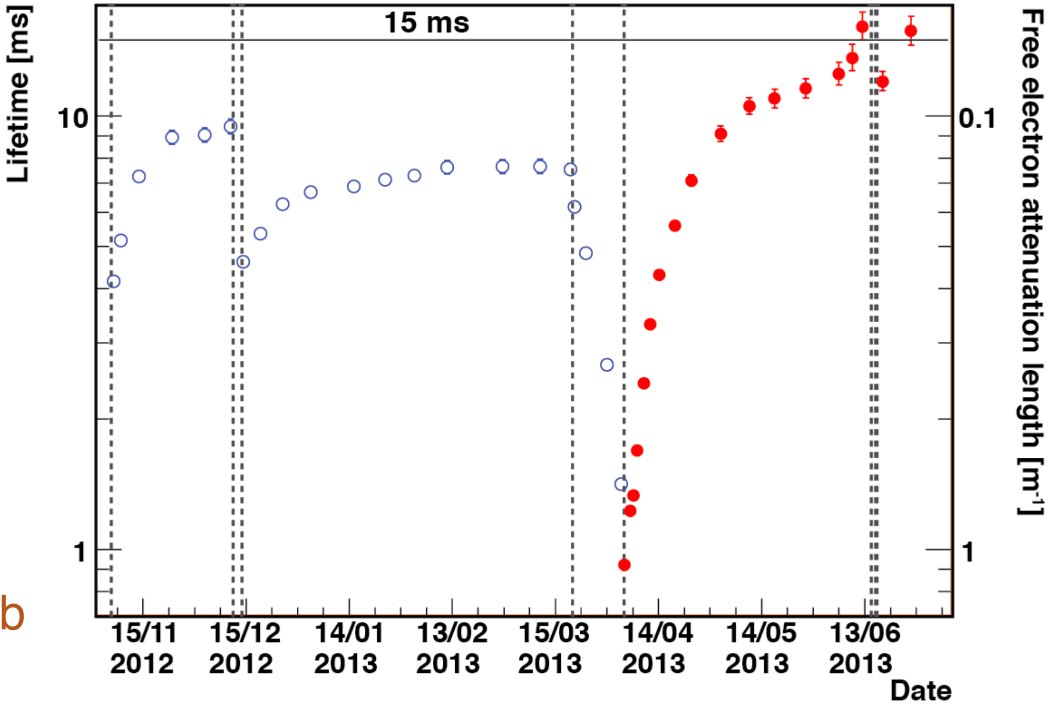
For $O_2\ , k \approx 10^{11} l\ mol^{-1} s^{-1}$

  - ➔ A concentration of **0.03 ppb Oxygen equivalent gives: τ = 10 ms**.
  - ➔ The present record, in terms of LAr purity, has been achieved in ProtoDUNE HD, with a maximum drift of 3.75 m, a maximum voltage of 175 kV and a maximum lifetime > 30 ms.

Free electron lifetime in Lar TPCs

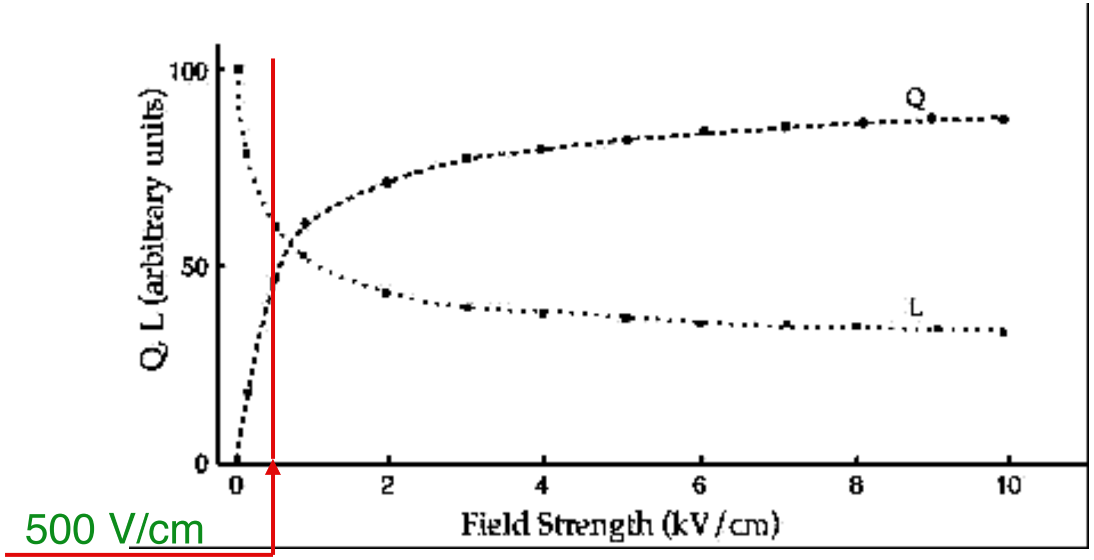
- The typical contamination in commercial LAr is O(0.2 ppm) for O_2 and O(0.5 ppm) for H_2O.
- A reduction of about 4 orders of magnitude is required to achieve long drift distances for large experiments.
- The **initial** removal of air and other impurities from the LAr volumes is achieved by vacuum pumping in ICARUS and by argon gas flushing in MicroBooNE and ProtoDUNE. The second solution was developed for very large volume detectors, where vacuum pumping is unpractical.
- In all LAr TPCs, LAr purity is achieved and **maintained** using the same scheme, developed for ICARUS:
  - Argon purification through a combination of chemical filters to remove H_2O and electro-negative impurities (O_2).
  - Continuous recirculation of the gas volume to minimize migration of impurities entering from the top, where feedthroughs and warm components (cables) are concentrated, in the sensitive LAr volume.
  - Continuous recirculation of the liquid volume, using circulation pumps.
- Very high free electron lifetimes have been achieved in all large detectors: ICARUS @ LNGS: > 15 ms; MicroBooNE @ Fermilab ≥ 9 ms; ProtoDUNE @ CERN > 30 ms.

Free electrons lifetime in ICARUS during operation at LNGS



The t=0 time mark

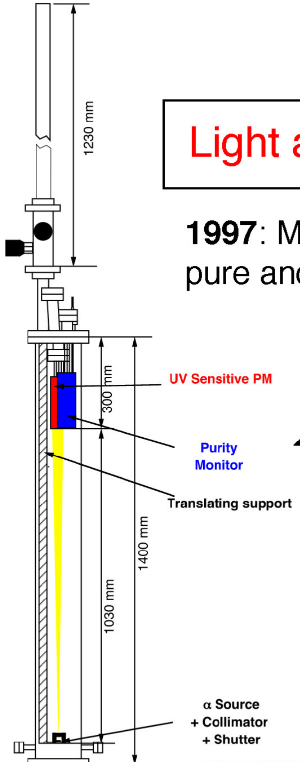
- For fully contained events,in a single wide gap, the longitudinal position requires the time of arrival of the event. This is called t = 0. It can be determined in a number of ways:
  - ➔ **Reading out the high voltage plane or, collectively, the first anodic plane**, for which the current flows from the start. However, the signal is small, although it applies to the whole event. A 3 m drift gives 1 nA for a deposition of 525 MeV.
  - ➔ Collecting the **scintillation light** naturally occurring in Argon.
    - ➔ λ = 128 nm ➔175 nm with Xe doping
    - ➔ Yield = $4x10^4$ photons / MeV @ 0 V / cm
    - ➔ $\lambda_{att} \approx$ 90 cm @ 128 nm; $\approx$ 180 cm @ 175 nm
    - ➔ Two time components: $\tau_S \approx$ 6 ns, and $\tau_L \approx$ 1.4 μs
    - ➔ Light yield is E- field dependent (Onsager)



500 V/cm

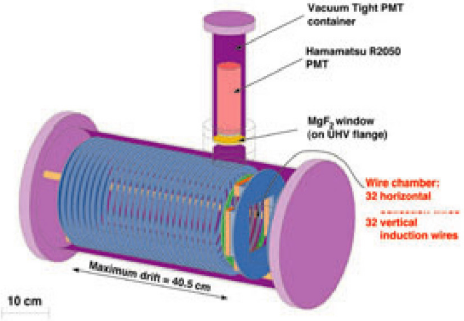
Electron recombination (E-dependent) contributes to scintillation light

Milestone 3: Scintillation in LAr



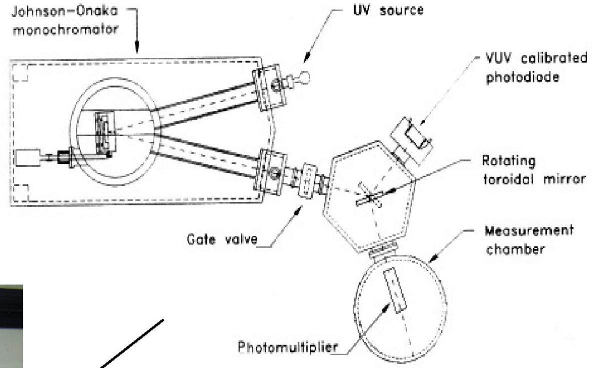
Light attenuation length

1997: Measurements in pure and Xenon doped LAR



30 litres prototype

1996: Scintillation light detection in coicidence with tracks in a LAr TPC. Proof of principle, efficiency measurements.



PMs and WLS

1999-2000: Wavelength shifters test and choice. Design and test of the final system for the T600

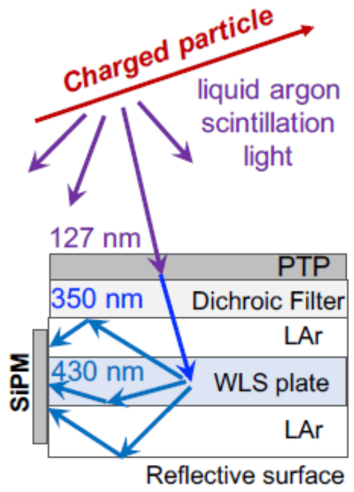
PM Choice and test

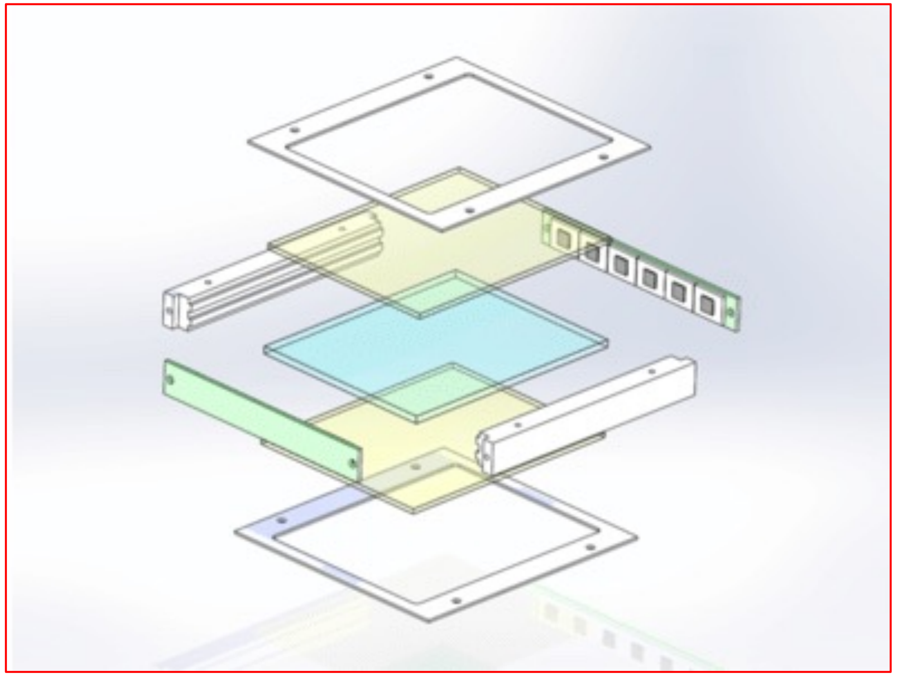
2000: Chosen Large size (8") PMs especially designed to work at cryogenic temperature. Performance and reliability tests.

Detection of scintillation light in LAr

- Detection of scintillation light in LAr required the development of special equipment:
  - Standard bi-alcali photomultipliers do not operate at cryogenic temperature, due to dramatic increase of the photocathode resistance → cryogenic PMTs have been developed with conductive coatings
  - LAr scintillation light has 128 nm wavelength → wavelength shifting is required to allow detection.
- In ICARUS, MicroBooNE and SBND scintillation light is detected using special 8” photomultipliers coated with Tetra-Phenyl-Butadiene.
- For DUNE, special light collecting devices, based on plastics, doped with different wavelength shifters, acting as dichroic filters and coupled to silicon photomultipliers have been developed (X-ARAPUCA).

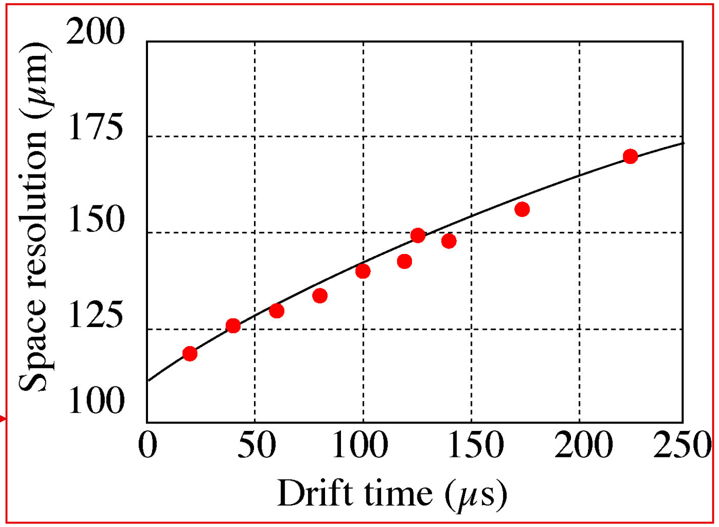
Principle of operation of an X-ARAPUCA

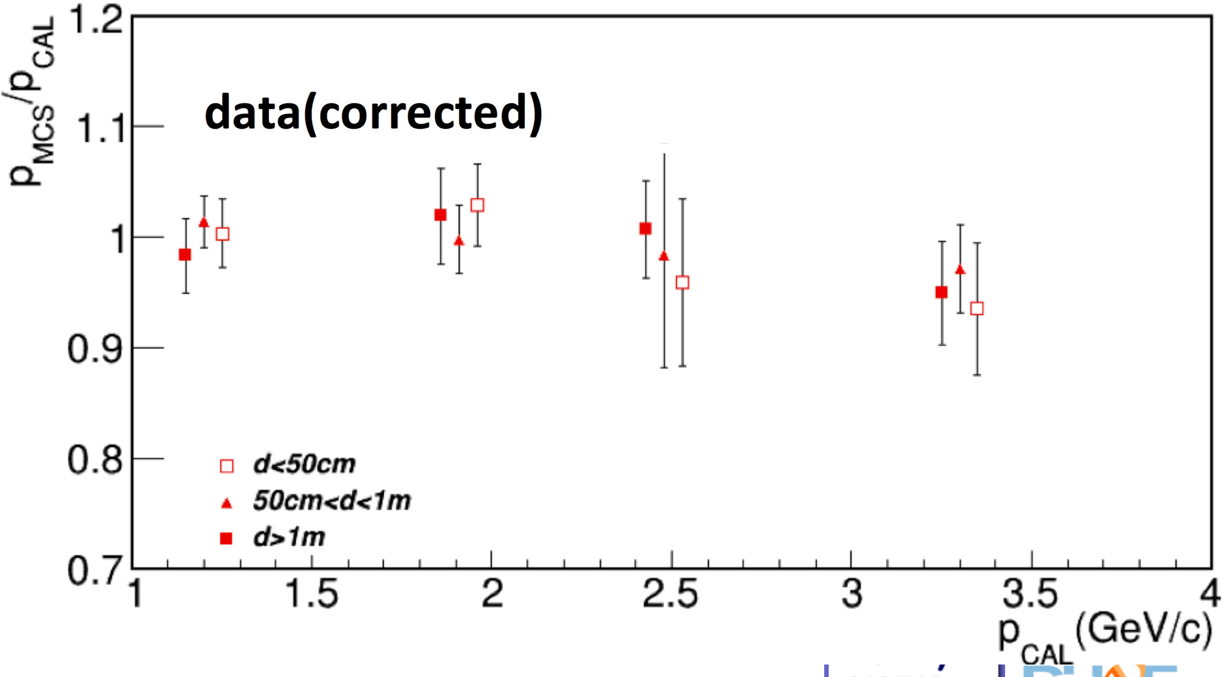




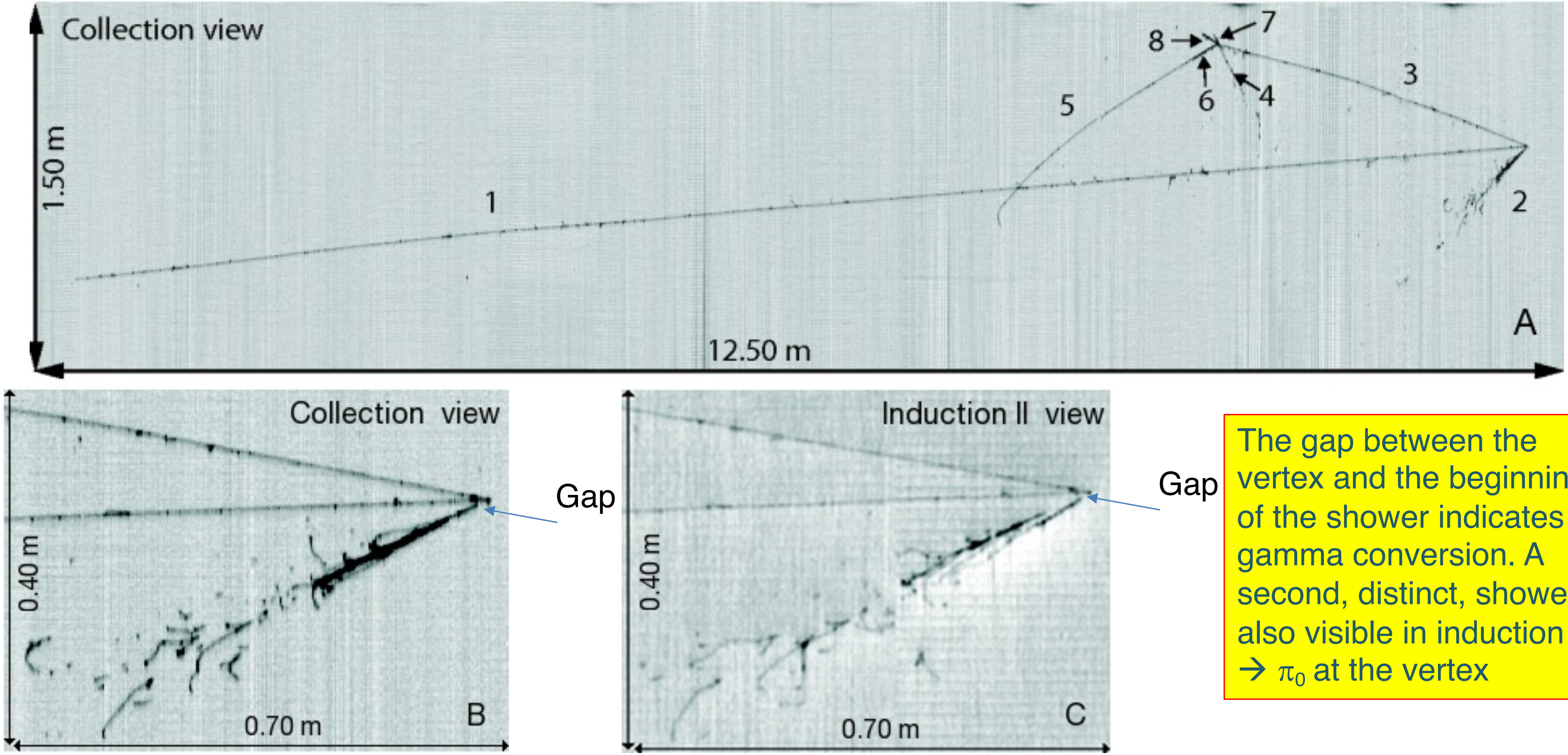
Detector's performance

- Self-triggering
- Continuously sensitive
- High granularity: wires pitch 2÷5 *mm*
    - Space resolution: $\sigma_{x,y} \approx 1\ mm$; $\sigma_z \approx 150\ \mu m$; along the drift coordinate $\sigma_z \approx 150\ \mu m$;
    - Highly accurate measurement of range, angles, multiplicity, etc.;
    - Multiple scattering → muon momentum measurement, approximately *±15 % @ 5 GeV* measured from stopping muons by ICARUS at LNGS





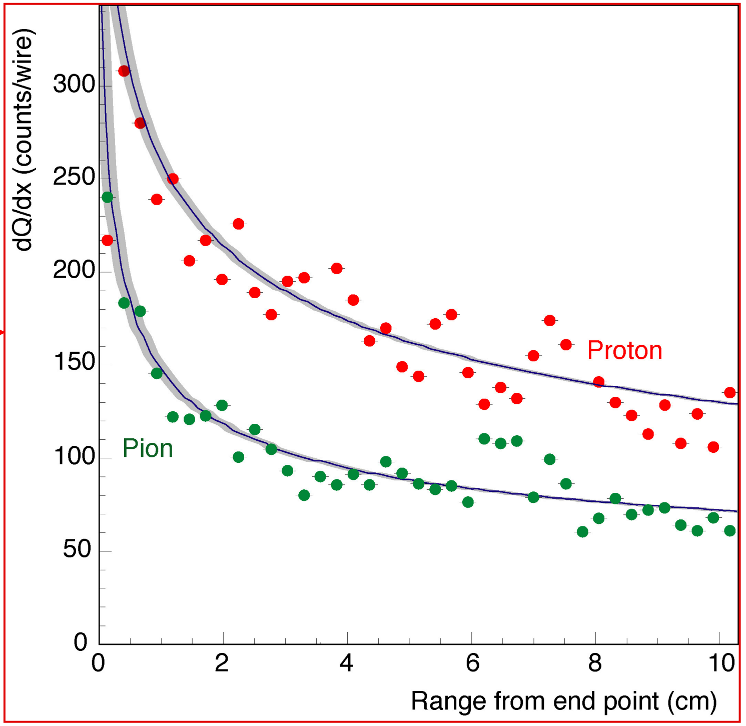
Detector’s performance (cont.) – ν_μ CC event@CNGS beam



The gap between the vertex and the beginning of the shower indicates a gamma conversion. A second, distinct, shower is also visible in induction 2 → π_0 at the vertex

Detector's performance (cont.)

- Measurement of local energy deposition:
    - Electron / gamma separation (3mm)
    - Particle ID by means of dE/dx vs range measurement
- Total energy reconstruction of the events from charge integration ➔ **excellent calorimeter** with high accuracy for relatively low energy, contained events.



RESOLUTIONS

Low energy electrons: $\sigma(E)/E = 7\% / \sqrt{E(\text{MeV})}$

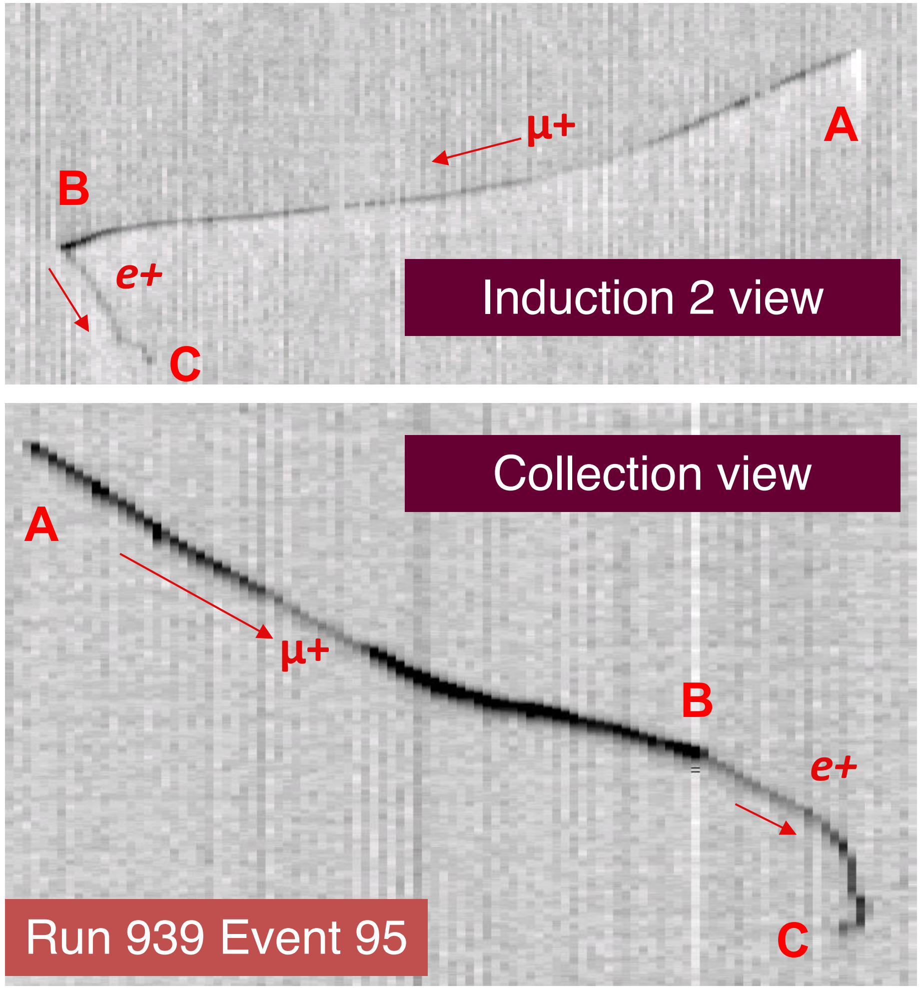
Electromagn. showers: $\sigma(E)/E = 3\% / \sqrt{E(\text{GeV})}$

Hadronic showers (pure LAr): $\sigma(E)/E = 16\% / \sqrt{E(\text{GeV})} + 1\%$

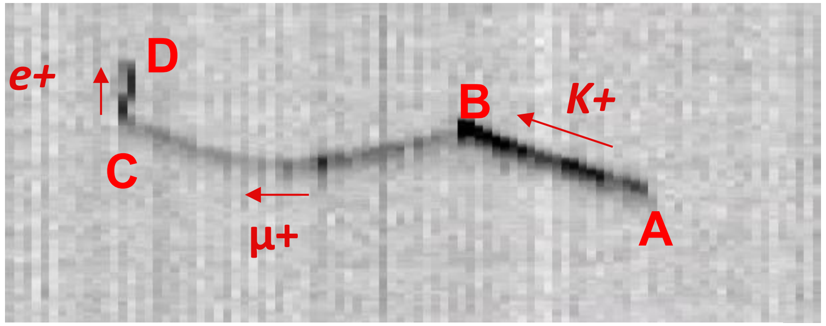
Hadronic showers (+TMG): $\sigma(E)/E = 12\% / \sqrt{E(\text{GeV})} + 0.2\%$

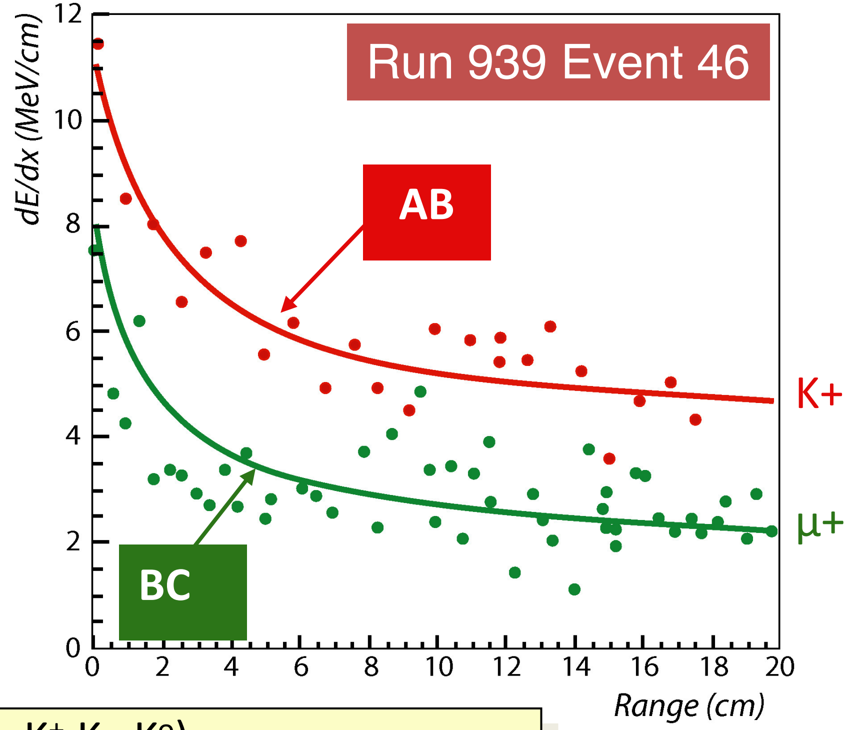
Detector’s performance (cont.)

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



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

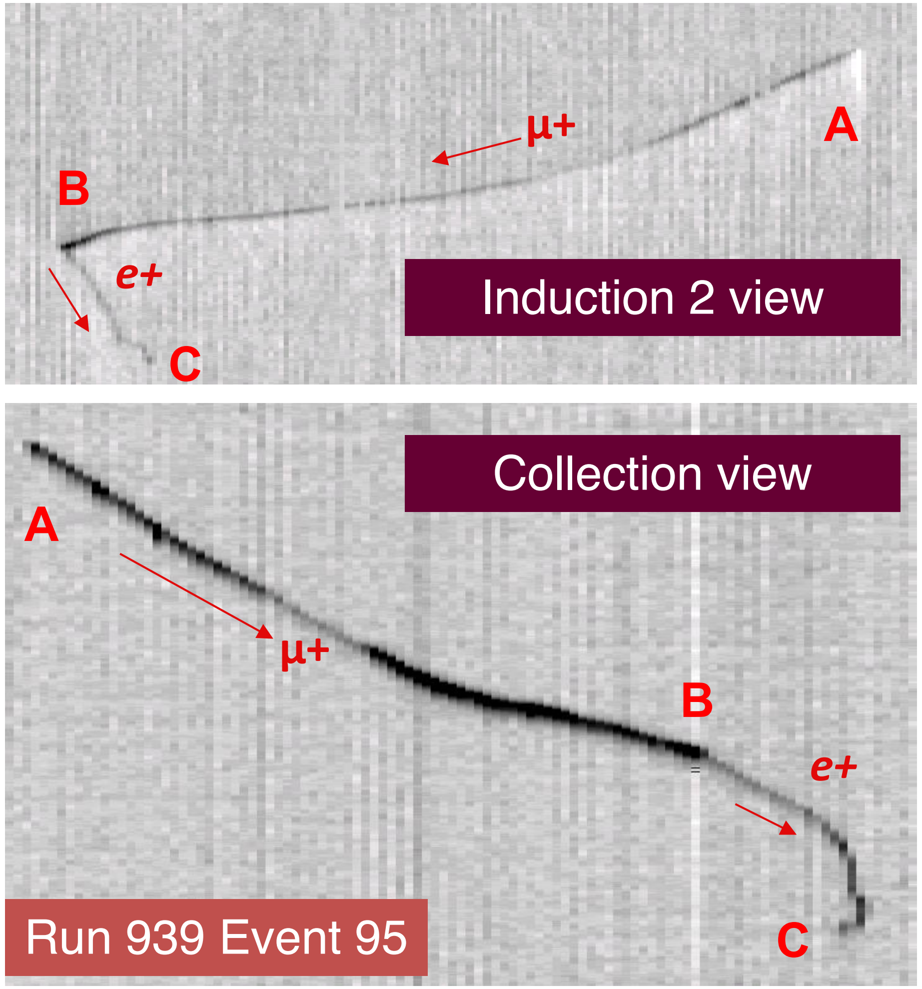




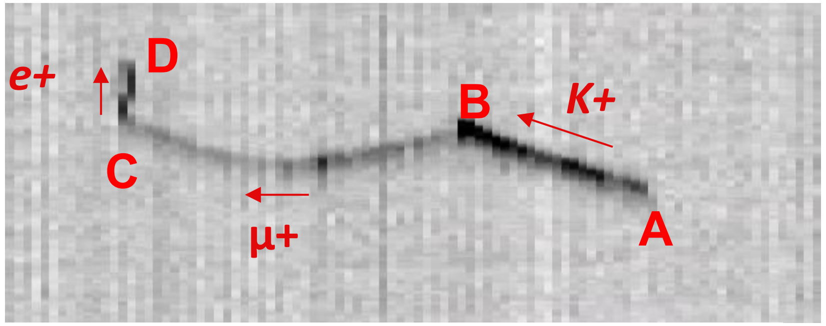
Particle identification by characteristic decay (μ^+,μ^-,K^+,K^-, K^o)

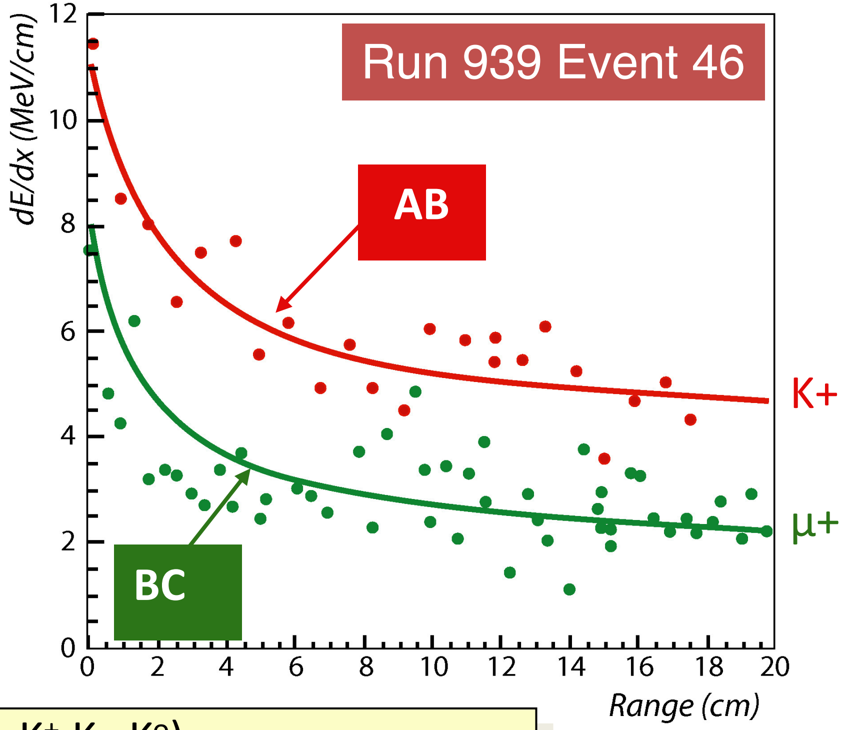
Reconstruction in 3D

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



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

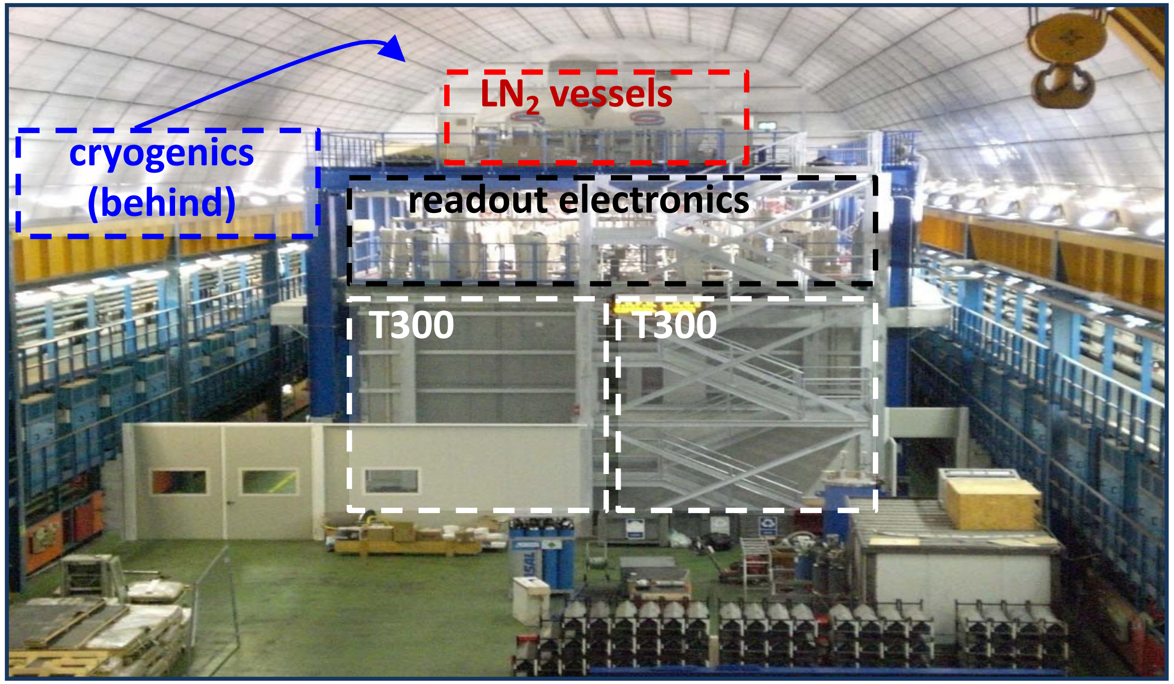


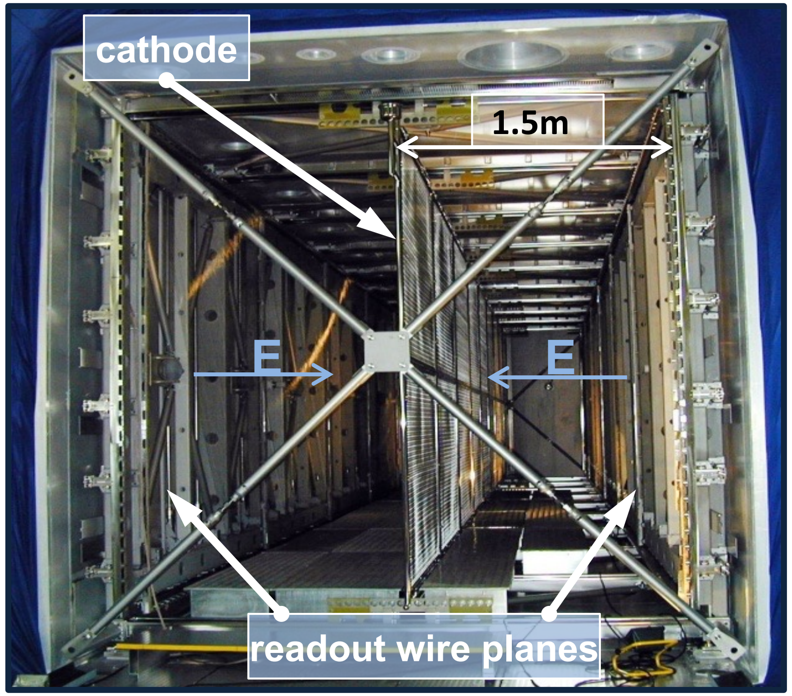


Particle identification by characteristic decay (μ^+,μ^-,K^+,K^-, K^o)

LAr implementations

The ICARUS T600 detector at LNGS-Italy (2010-2013)



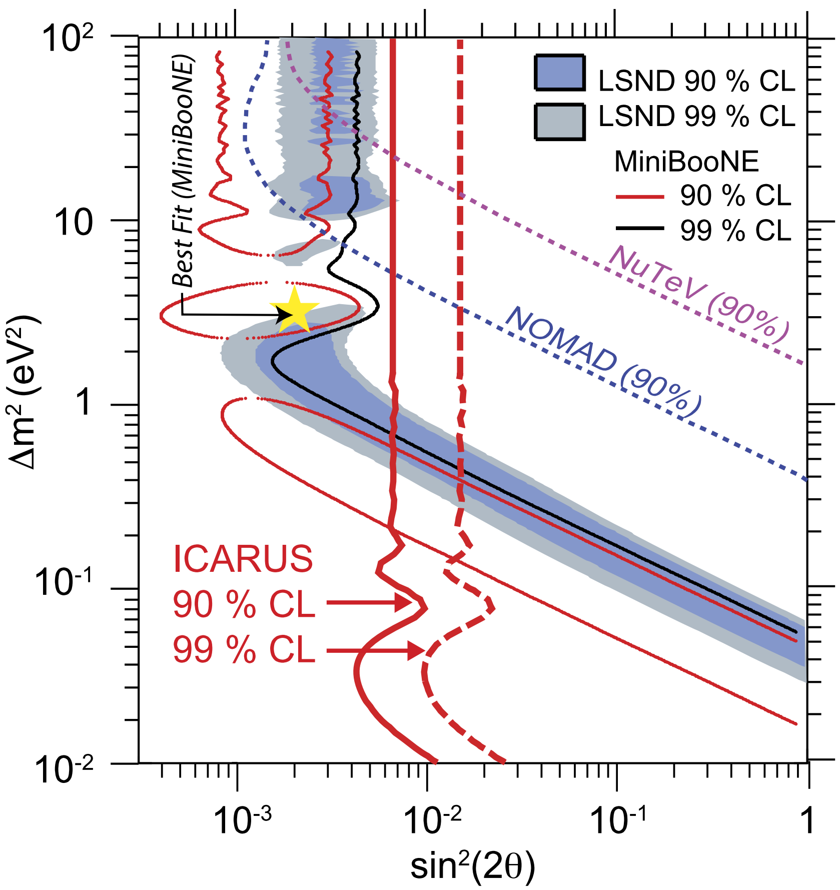


- Two identical modules
  - 3.6x3.9x19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV; E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
  - Sampling time 0.4μs (sub-mm resolution in drift direction)
- Wire chambers:
  - 2 chambers per module
  - 3 wire planes per chamber wires at 0,±60° (up to 9 m long)
  - Charge measurement on collection plane
  - ≈ 54000 wires, 3 mm pitch and plane spacing
- 20+54 8" PMTs for scintillation light detection:
  - VUV sensitive (128nm) with TPB wave shifter

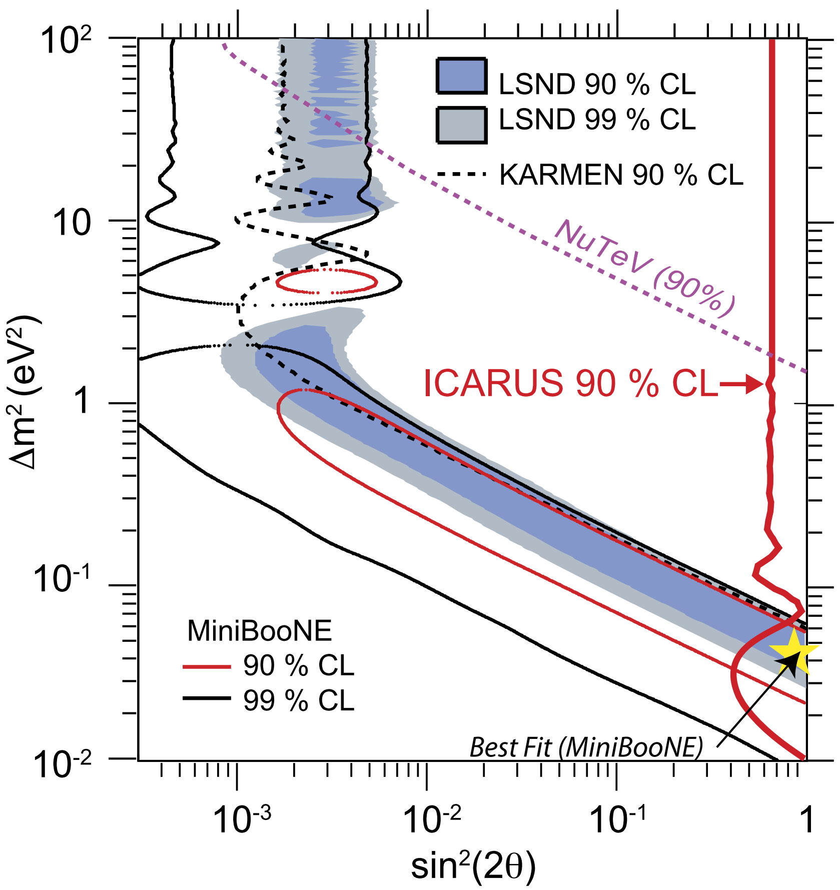
Physics with ICARUS in LNGS with CNGS

- Search for “LSND-like” anomaly in CNGS neutrino beam
- Exclusion of superluminal neutrino hypothesis
- Search for ν_τ in CNGS

Neutrino

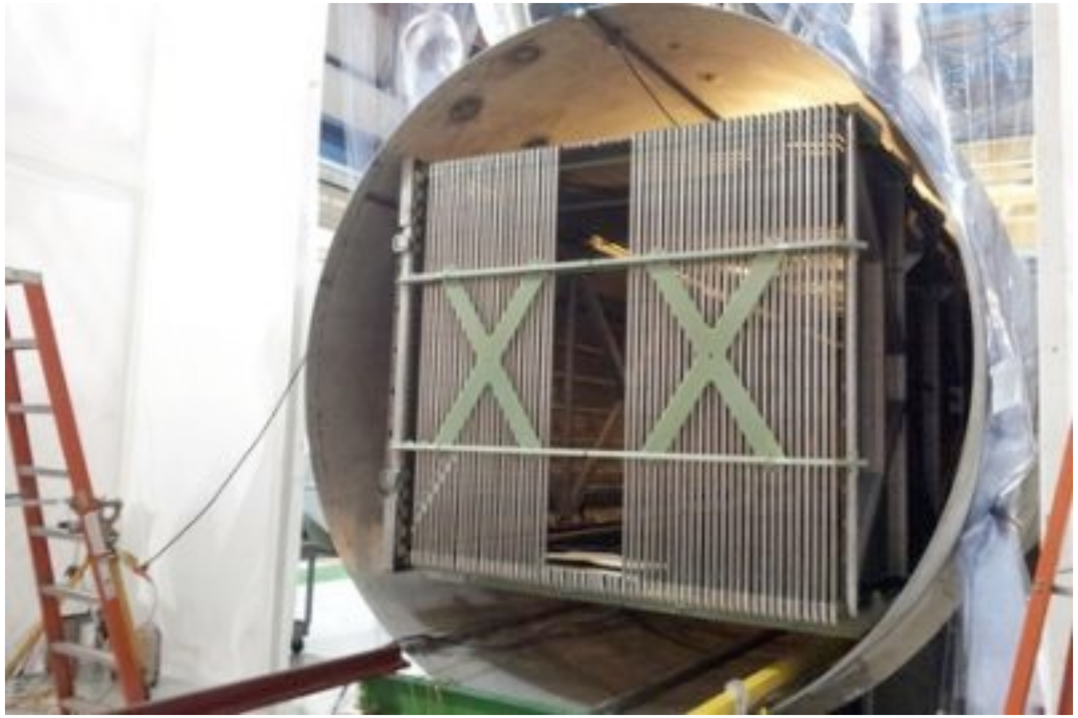


Antineutrino

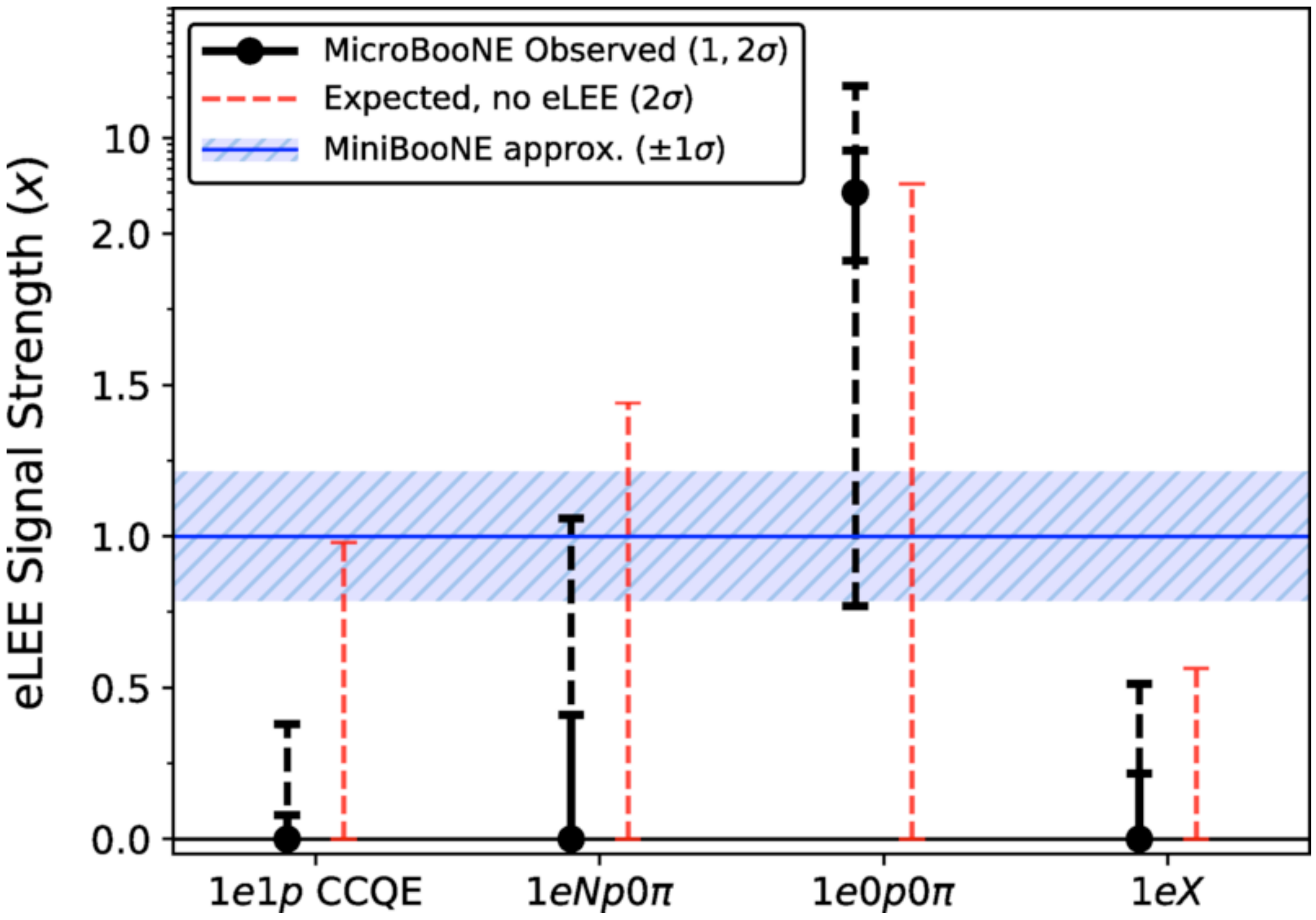


MicroBooNe (2015-2021)

- MicroBooNE is a large 170-ton liquid-argon time projection chamber (LArTPC) neutrino experiment located on the Booster neutrino beamline at Fermilab. The experiment first started collecting neutrino data in October 2015.
- MicroBooNE investigated the low energy excess events observed by the MiniBooNE experiment, measured low energy neutrino cross sections and investigated astro-particle physics.

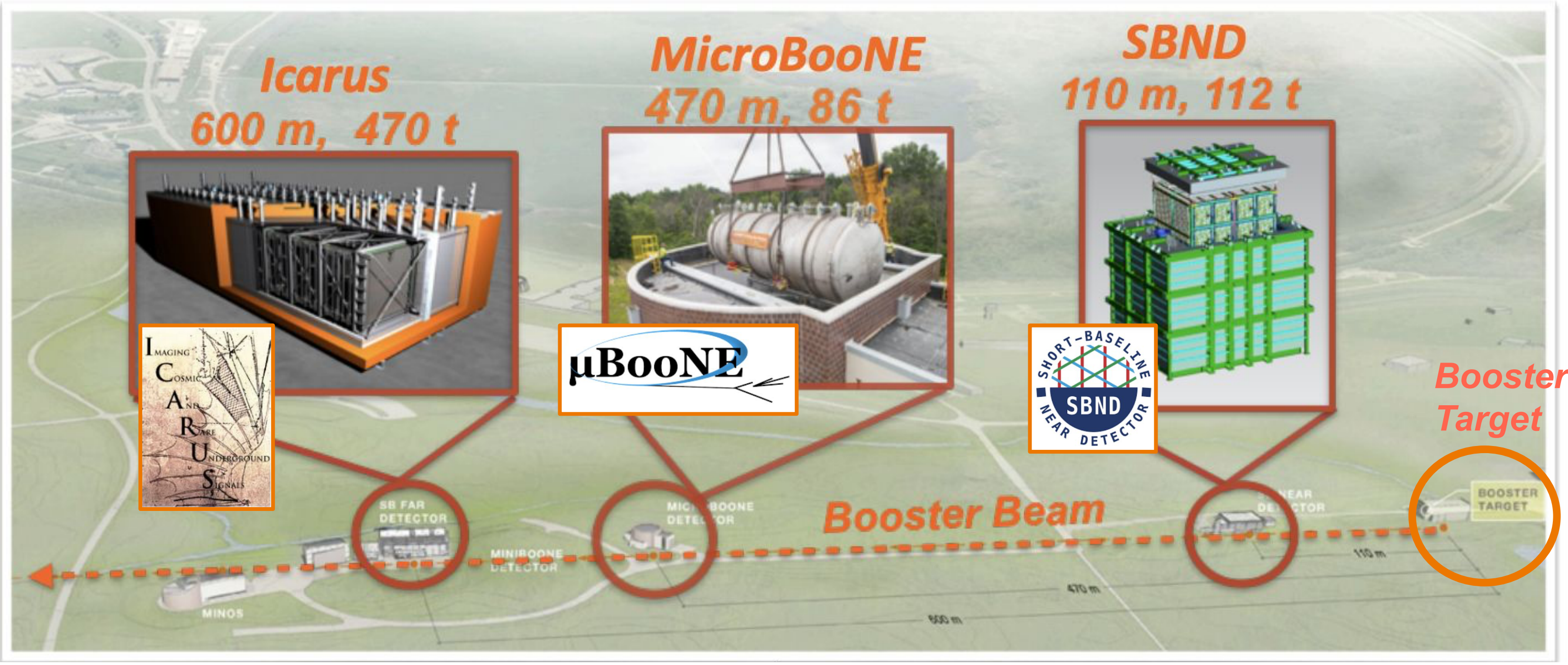


MicroBooNe: first results on Electron Low Energy Excess (eLEE)

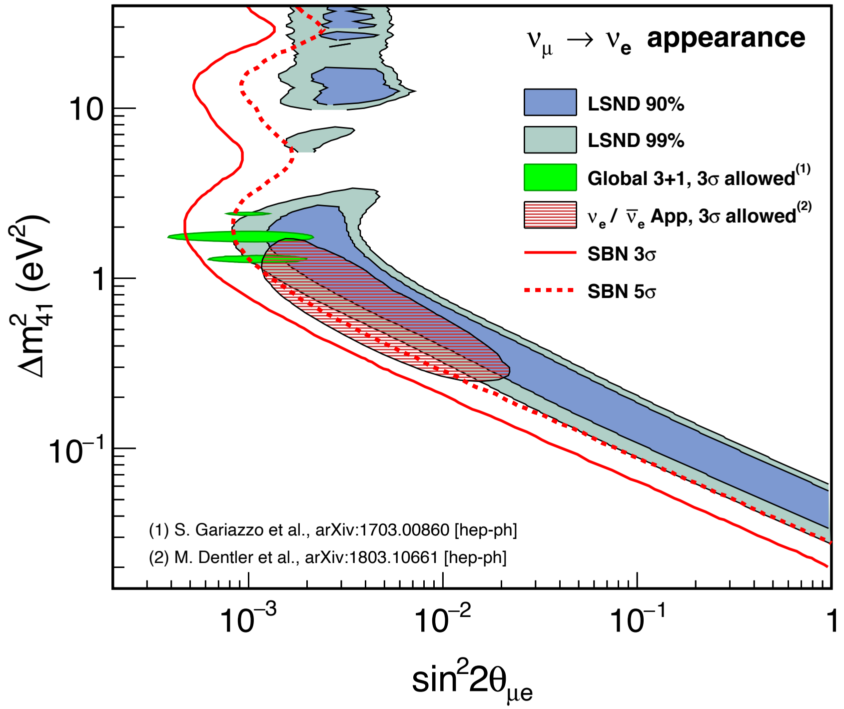


The Short Baseline Neutrino program at Fermilab (2020-)

- The experiment schematics is as follows:
  - A detector (SBND) positioned in proximity to the neutrino source provides information (composition and spectrum) of the non oscillated neutrino beam.
  - A second detector (ICARUS/SBNFD) measures the beam composition and spectrum at a distance from the neutrino source such as to provide a significant signal in case the LSND result is true (≈ 600 m).
  - A third detector (MicroBooNE), placed at an intermediate location (≈ 450 m) provides additional confirmation, in case of a positive signal, or increases the significance of a null result.
  - **Use of the same technology (LAr TPC) for the three detectors provides cancellation of systematic errors.**



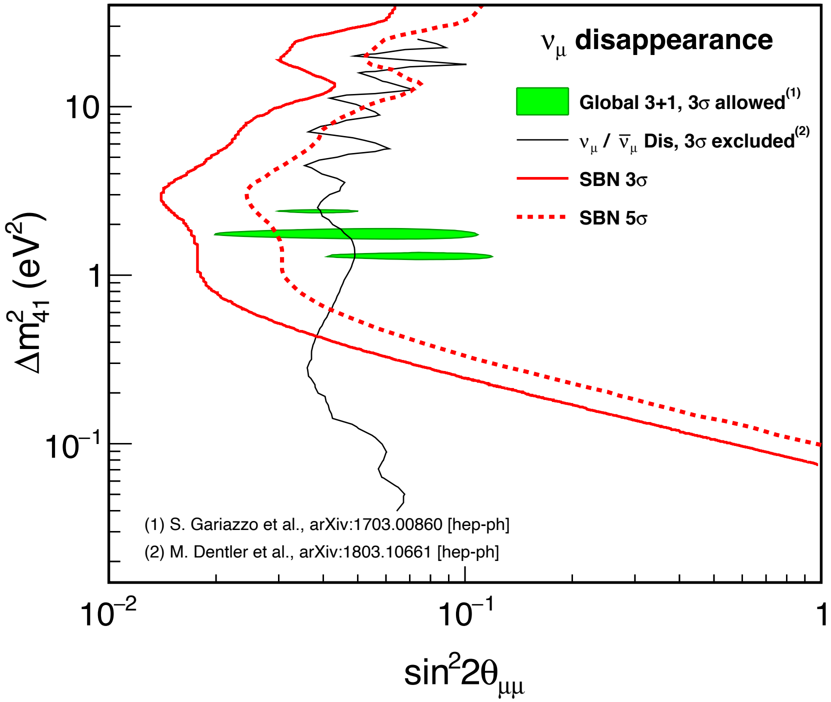
SBN program: sensitivity to “LSND-like” sterile neutrinos



(1) S. Gariazzo et al., arXiv:1703.00860 [hep-ph]

(2) M. Dentler et al., arXiv:1803.10661 [hep-ph]

5σ coverage of the parameter area relevant to the LSND/MiniBooNE anomaly in 3 years (6.6 x 10^{20} pot).



(1) S. Gariazzo et al., arXiv:1703.00860 [hep-ph]

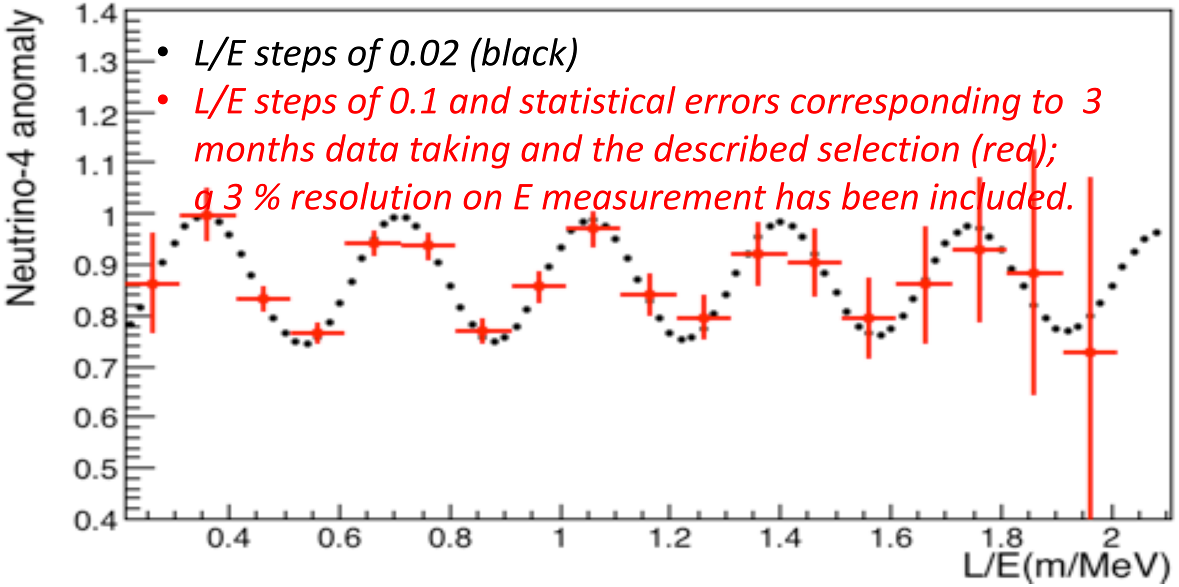
(2) M. Dentler et al., arXiv:1803.10661 [hep-ph]

1 order of magnitude beyond SciBooNE + MiniBooNE limits in 3 years (6.6 x 10^{20} pot). Probing the parameter area relevant to reactor and gallium anomalies.

Unique capability to study appearance and disappearance channels simultaneously

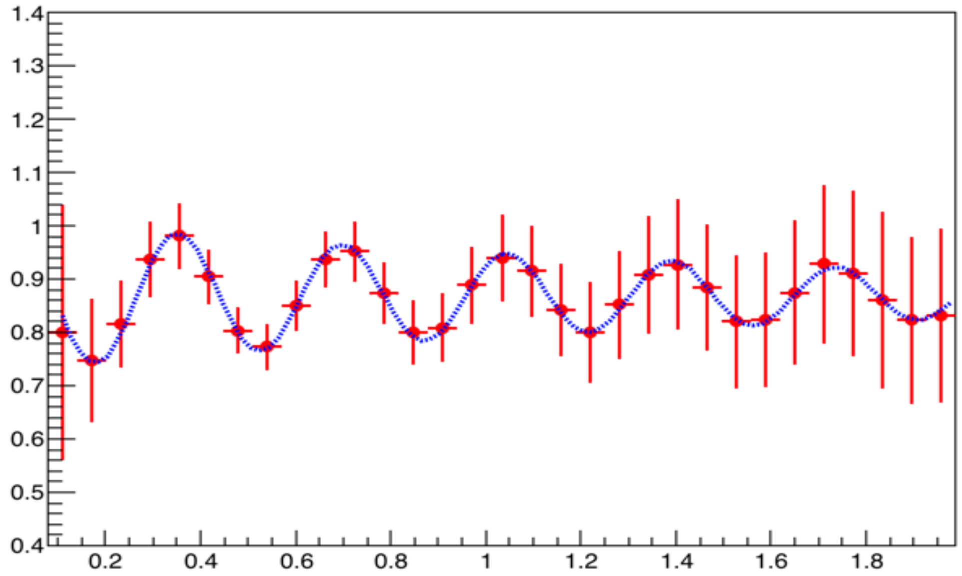
SBN program: ICARUS sensitivity to Neutrino4-like sterile neutrinos

BNB – 3 months – ν_μ disappearance
CCQE events only



- *L/E steps of 0.02 (black)*
- *L/E steps of 0.1 and statistical errors corresponding to 3 months data taking and the described selection (red); a 3 % resolution on E measurement has been included.*

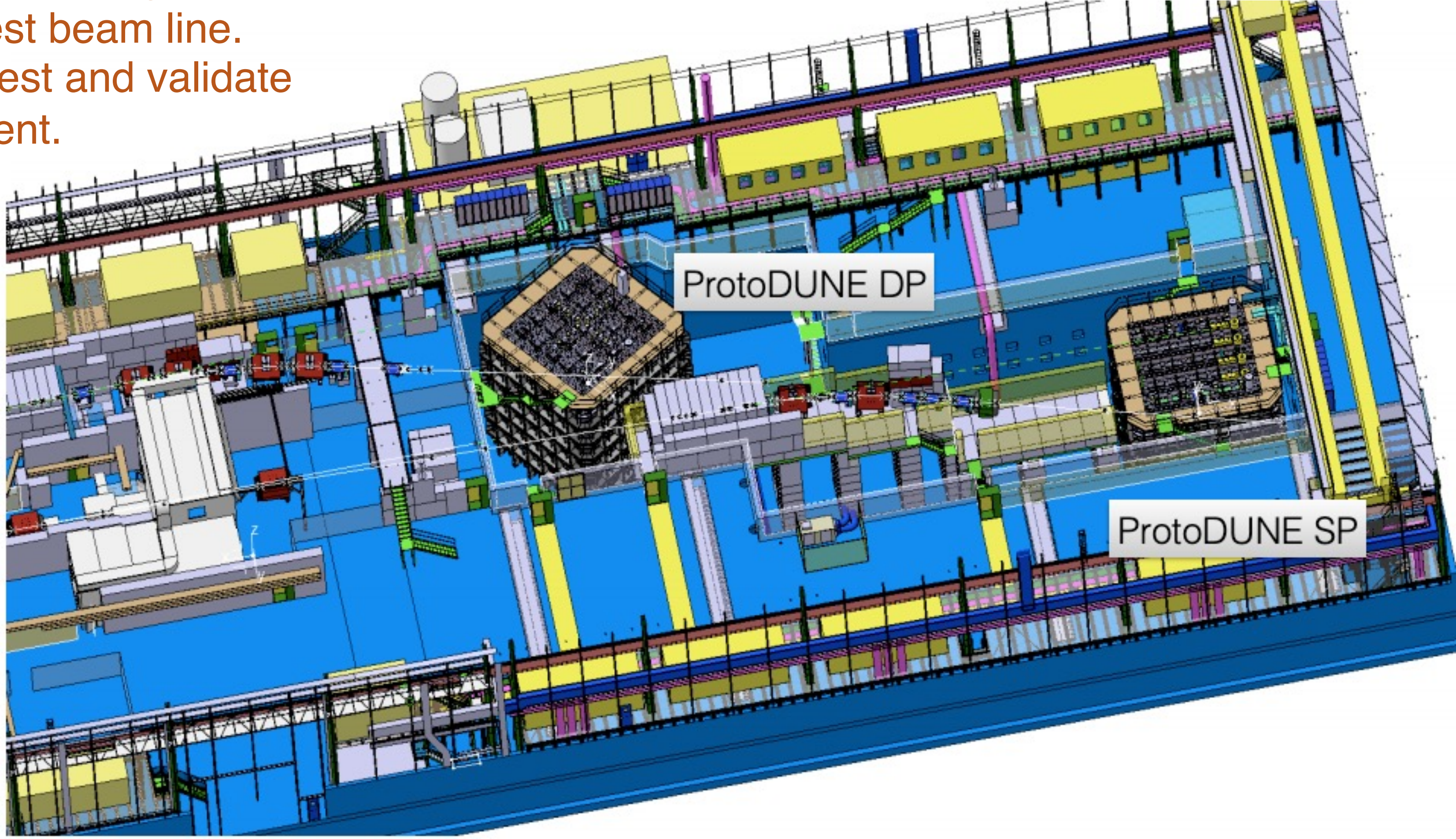
NuMI – 1 year – ν_e disappearance
CCQE events only



In addition to the search for sterile neutrinos, millions of neutrino events will be collected allowing for several measurements of great value, specifically for DUNE.

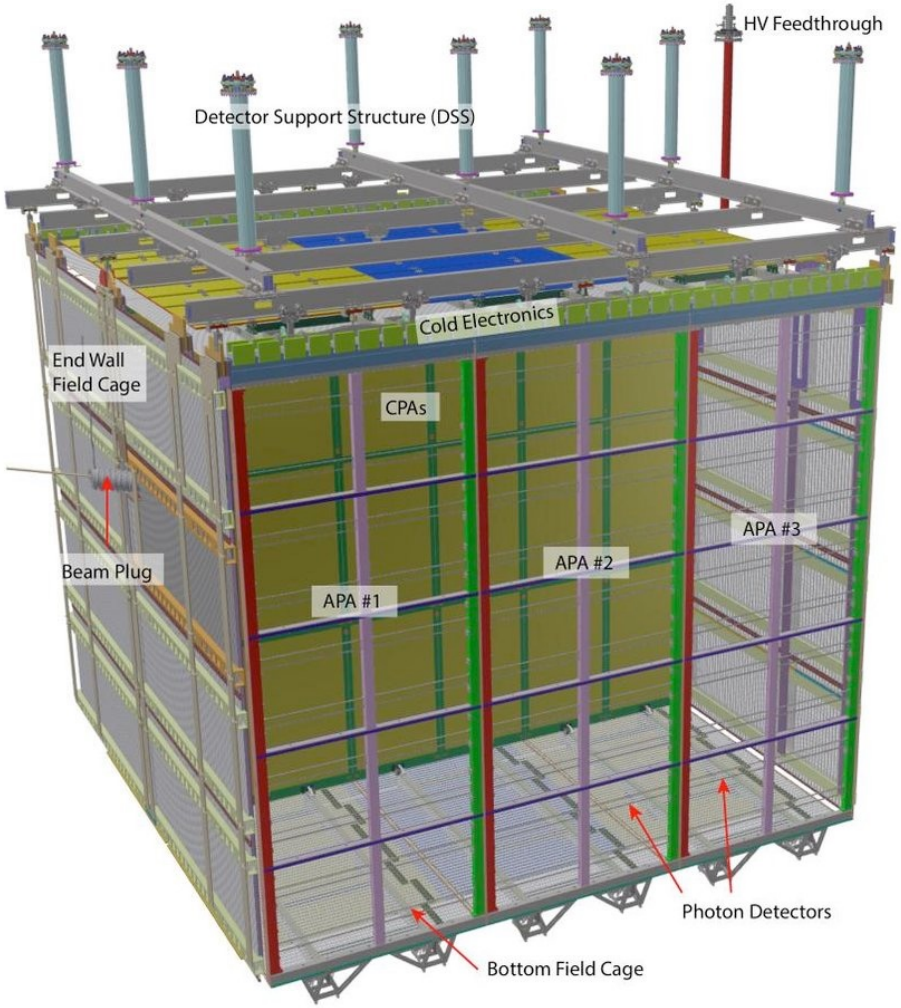
ProtoDUNE (2018-)

- ProtoDUNE, at CERN, is a large facility, with two large volume cryostats (≈ 500 m^3 each) build with the membrane cryostat technology and each equipped with LAr purification. The facility includes dedicated tertiary test beam line.
- The main goal of ProtoDUNE is to test and validate components for the DUNE experiment.
- One of two cryostat is being used for testing components of the first DUNE module, build with the more traditional structure: Horizontal Drift.
- The second cryostat is used to test components of the Vertical Drift version, to be used for the second DUNE module.

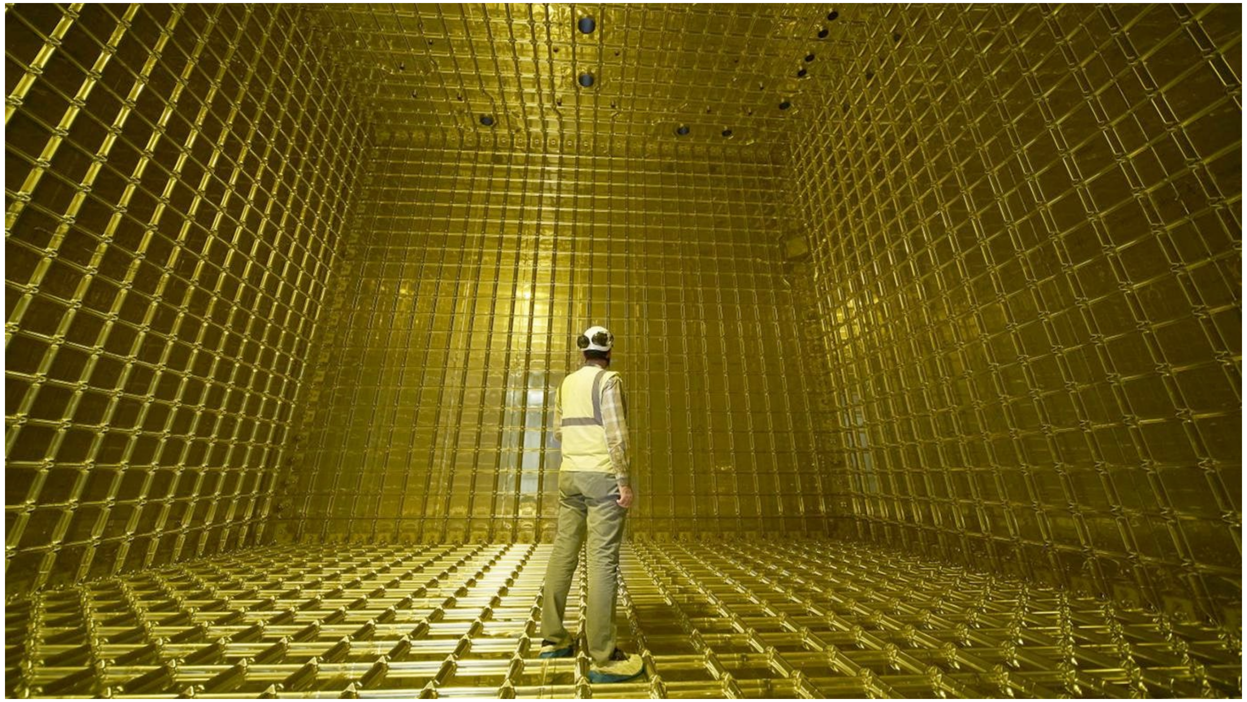


ProtoDUNE (2018-)

ProtoDUNE Horizontal Drift

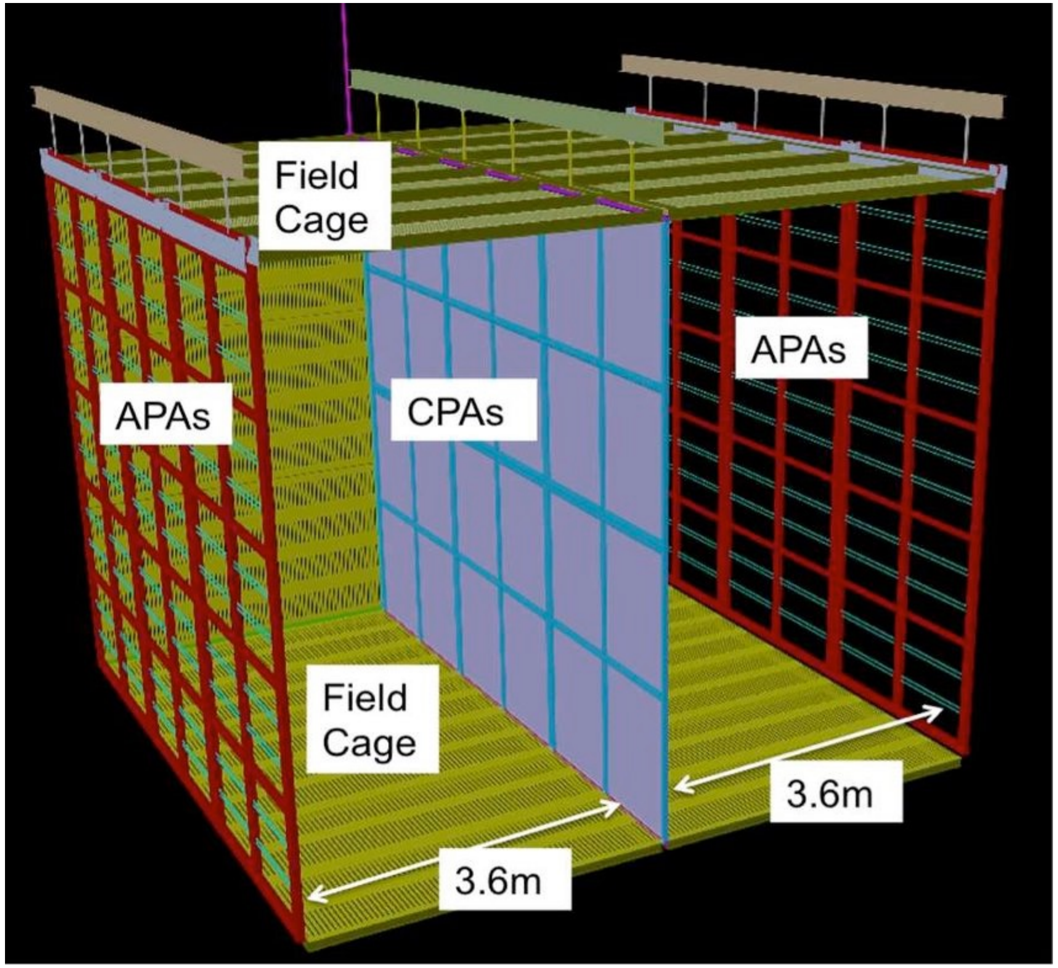


Membrane cryostat (new concept!)

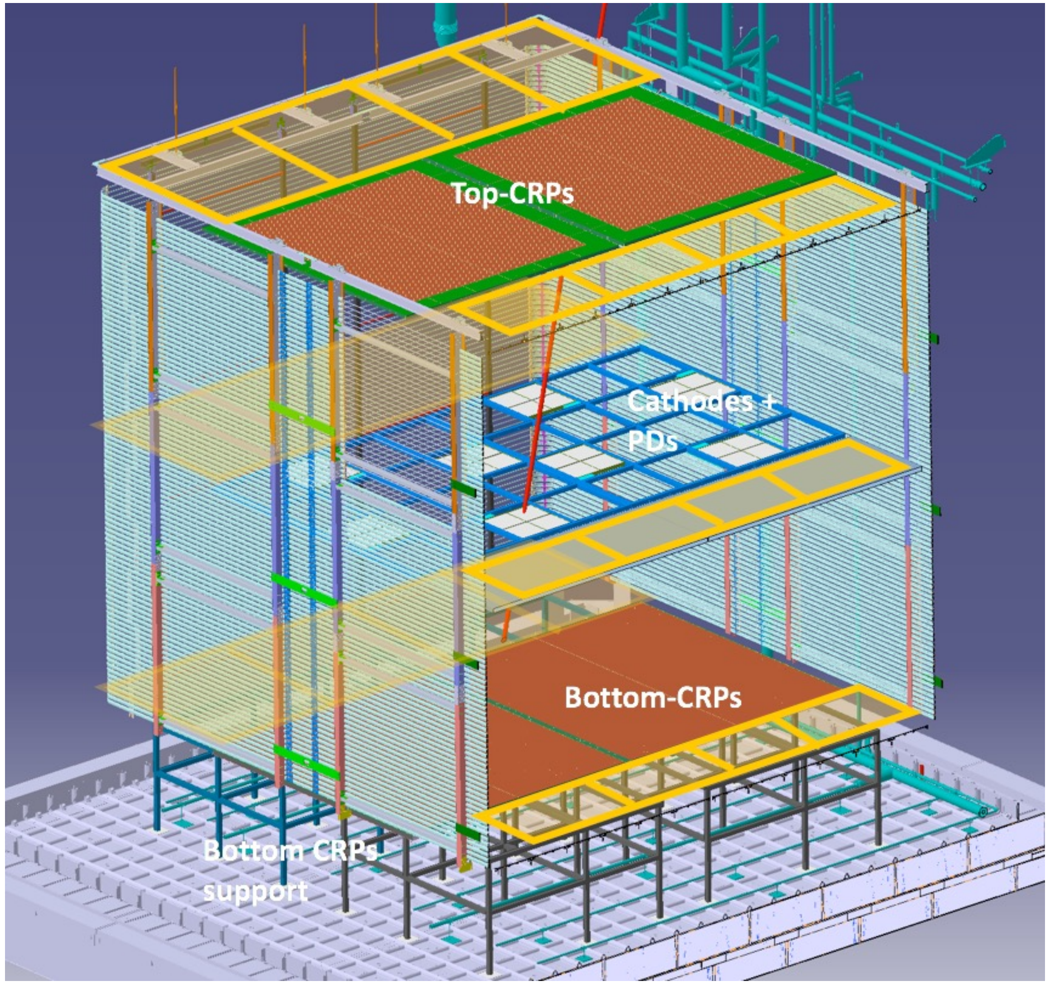


ProtoDUNE

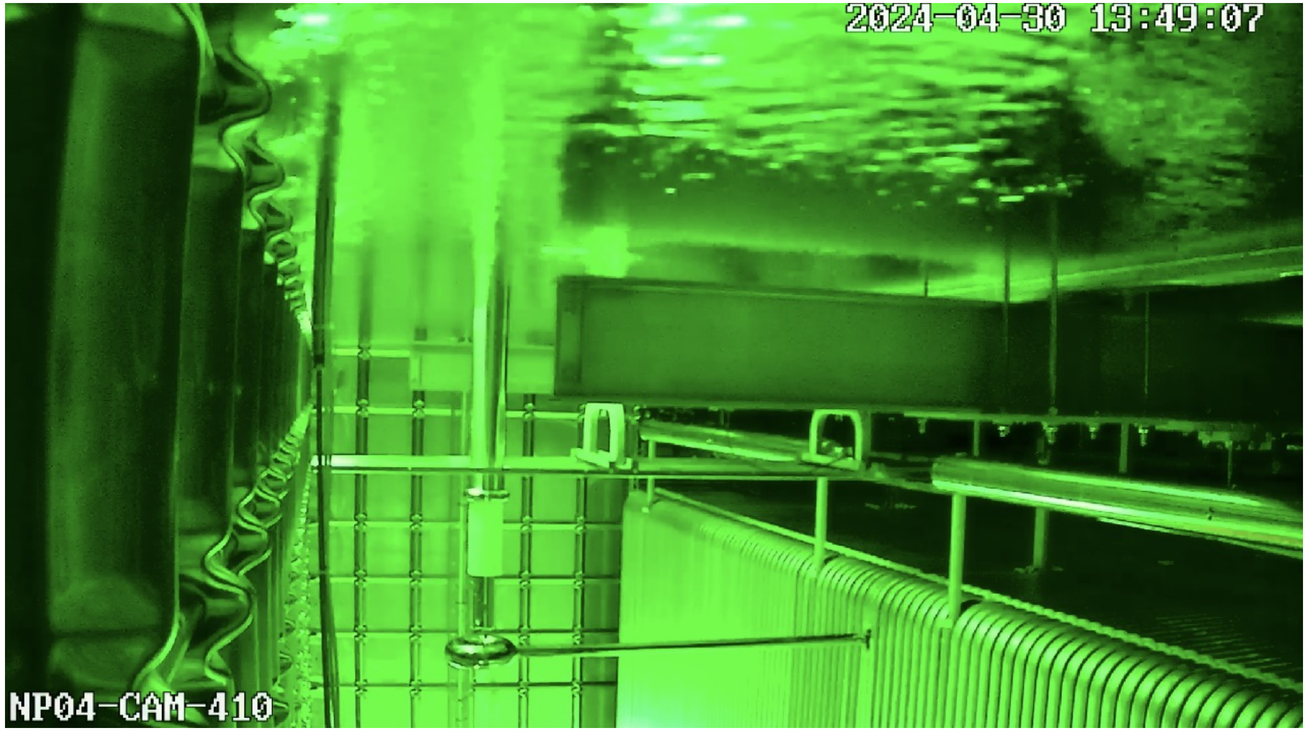
ProtoDUNE **Horizontal** Drift



ProtoDUNE **Vertical** Drift



ProtoDUNE-HD activities highlights



Detector filling complete on April 30th, 2024

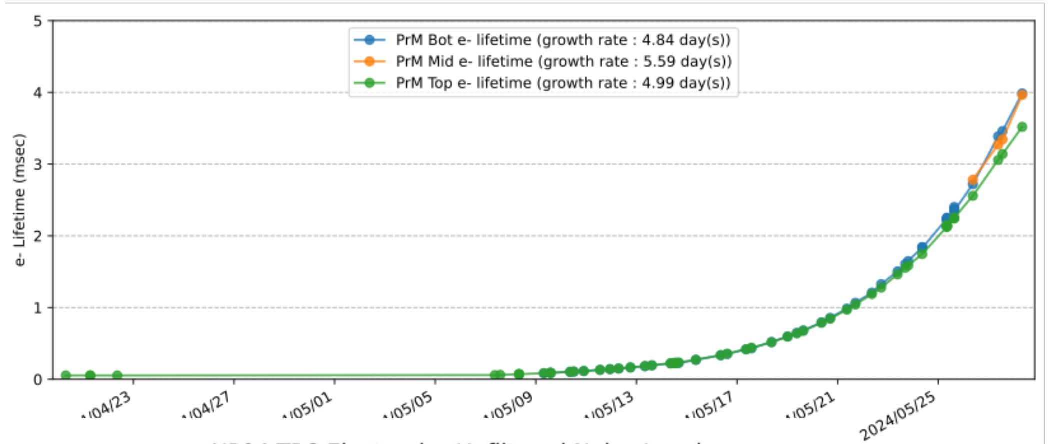
ProtoDUNE-HD cont.

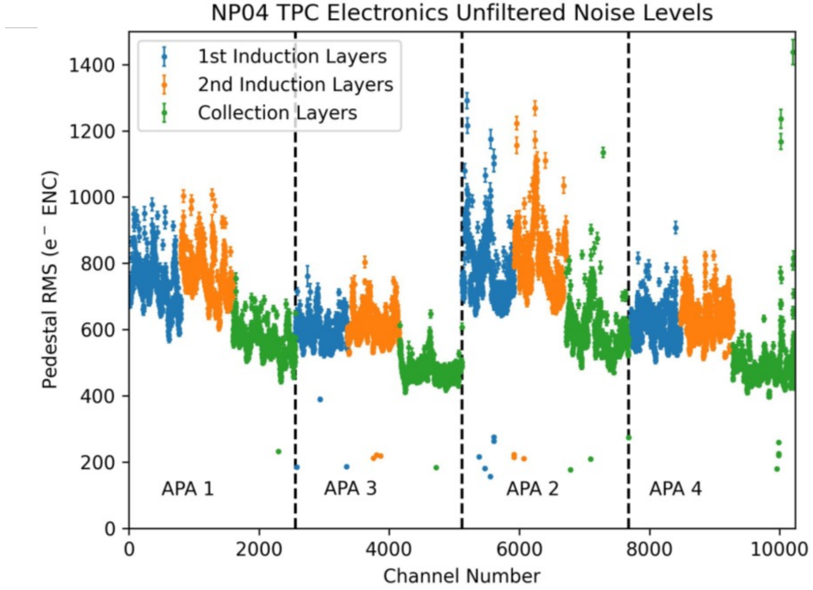
- Electron lifetime above 10 msec (still improving)

- Good Electronics noise performance (some small coherent noise sources still under investigation)

- Stable HV system performance (>99.9%) – up to 180 kV
(no regular streamer events seen in ProtoDUNE-SP-I)

- Purity >30msec

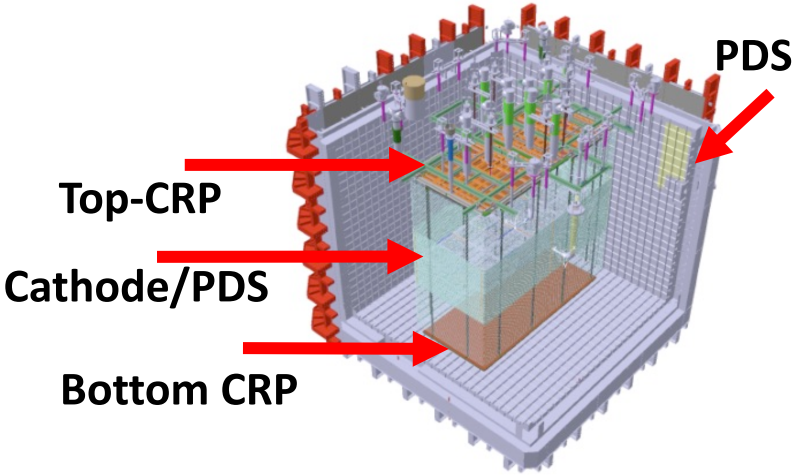




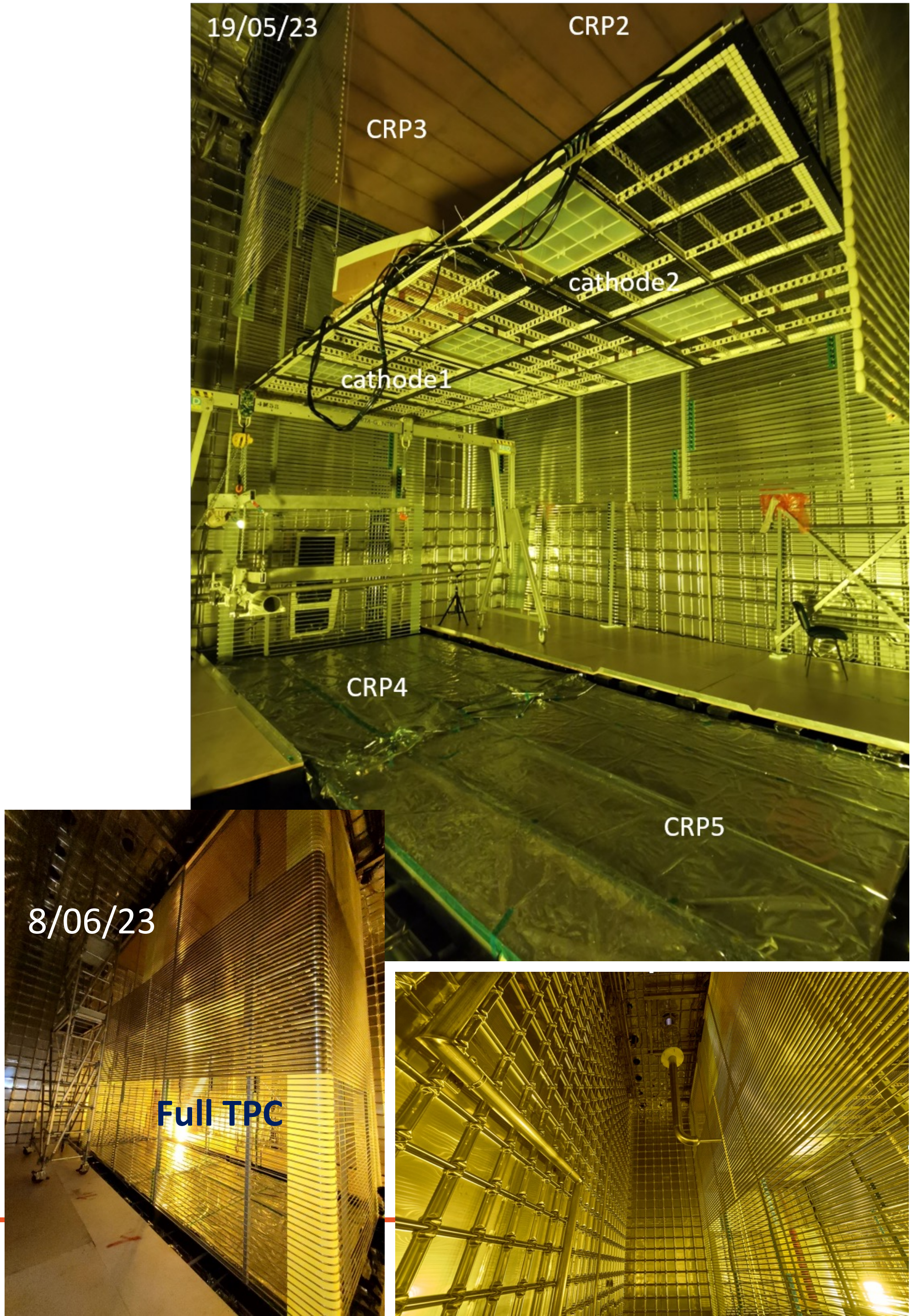
ProtoDUNE-VD activities: Highlights

Vertical Drift TPC installation completed 9 June 2023

- top and bottom CRPs,
- top and bottom drift electronics,
- field cage, HV extender and cathode
- PDS modules in cathode and walls (except for 2 near TCO)

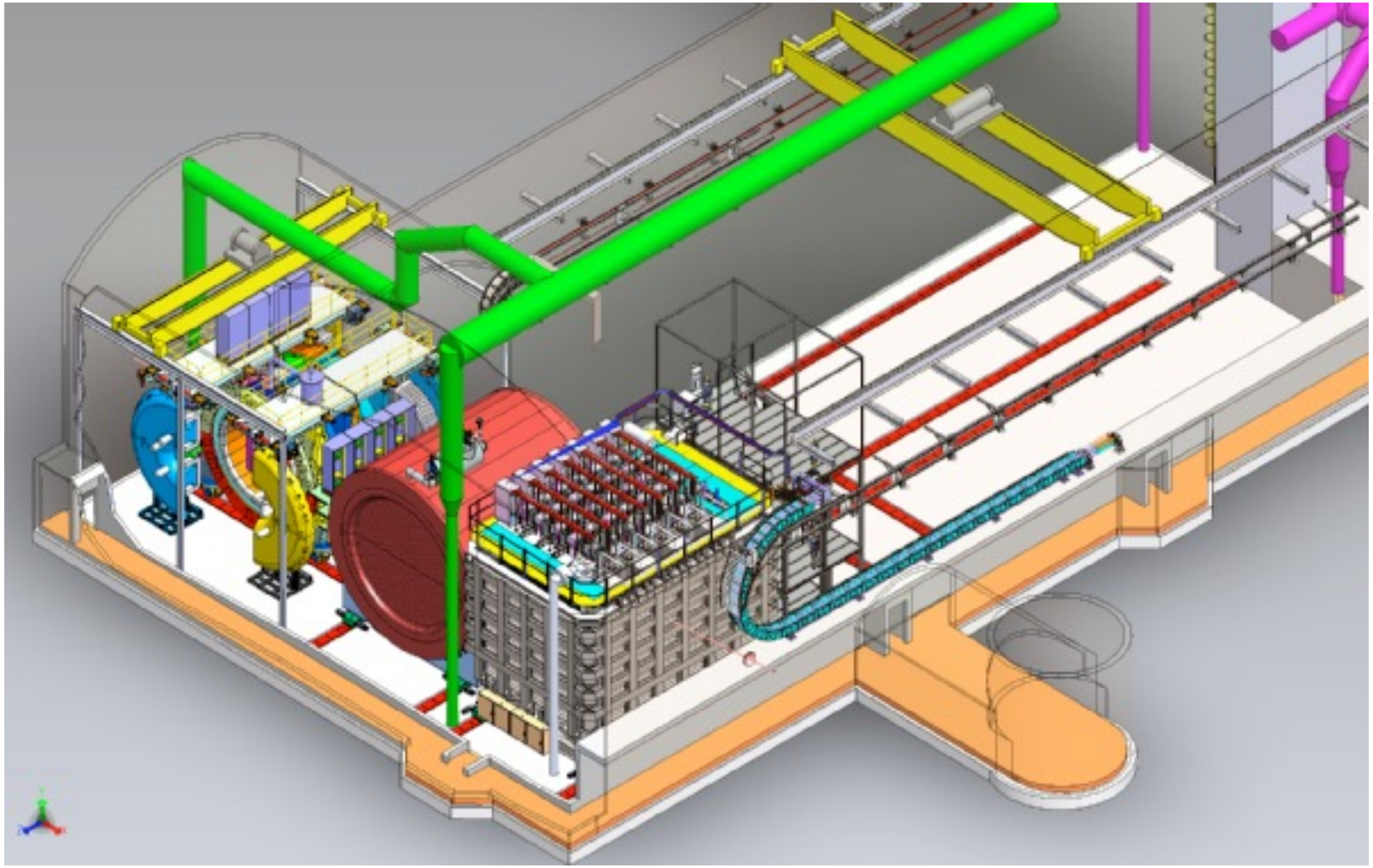


- 2 top CRP (#2-3)
- 2 cathodes (8 x-Arapuca)
- 2 bottom CRP (#4-5)
- 8 membrane x-Arapuca
- 70% transparent field cage

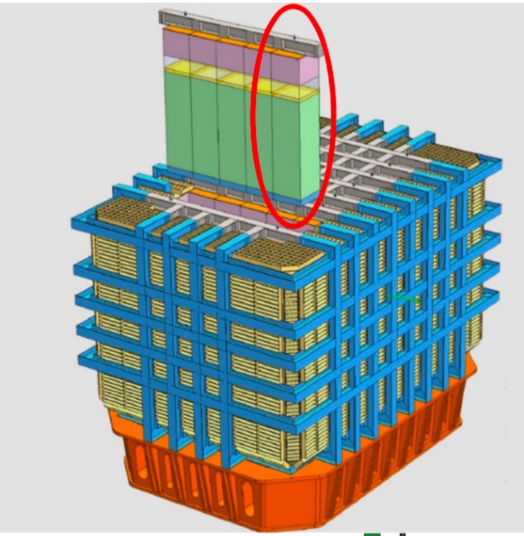


ND-Lar at DUNE

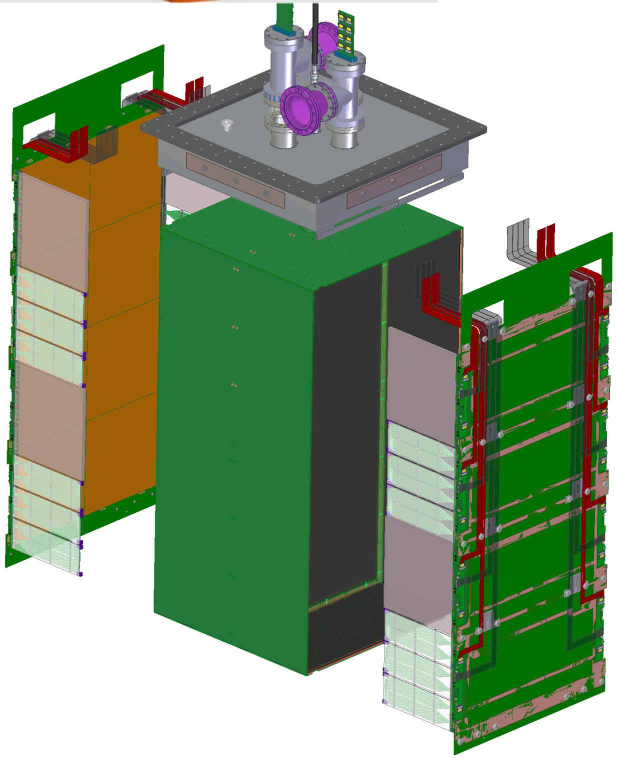
ND-LAr is one of three detectors to be installed at Fermilab at the beginning of the DUNE's neutrino beam line.
Operating in conjunction with the magnetic spectrometer (TMS) will constrain systematic errors due to event selection and reconstruction in the far detector.



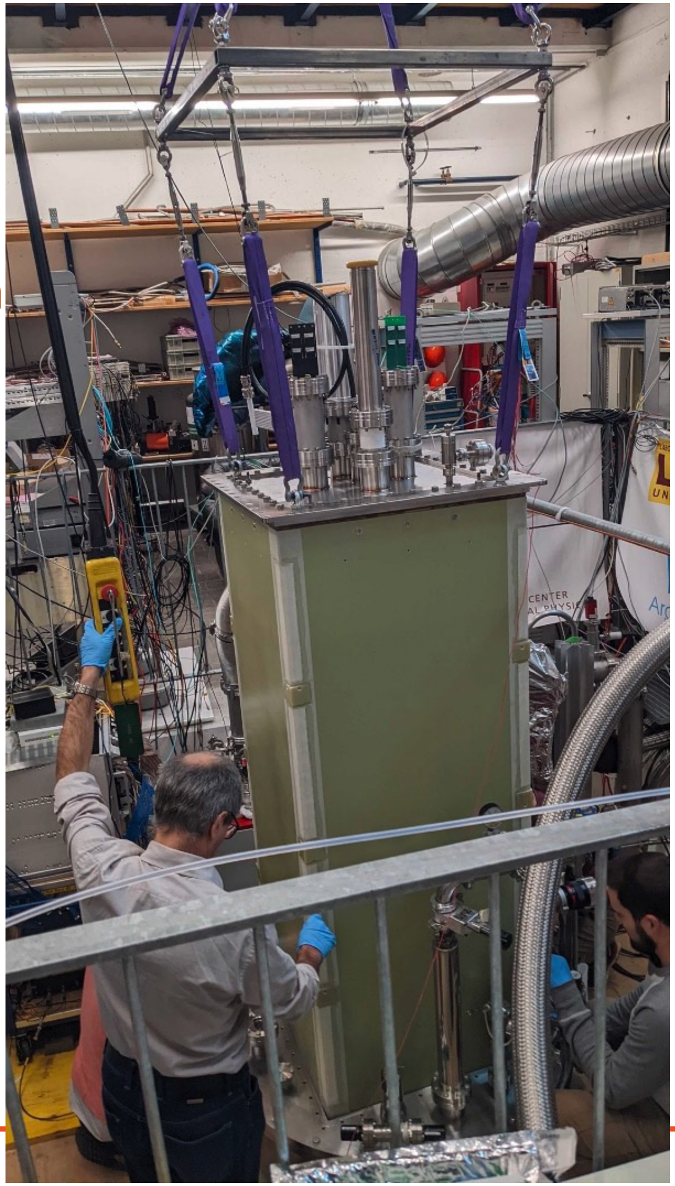
ND-Lar prototyping (for DUNE)



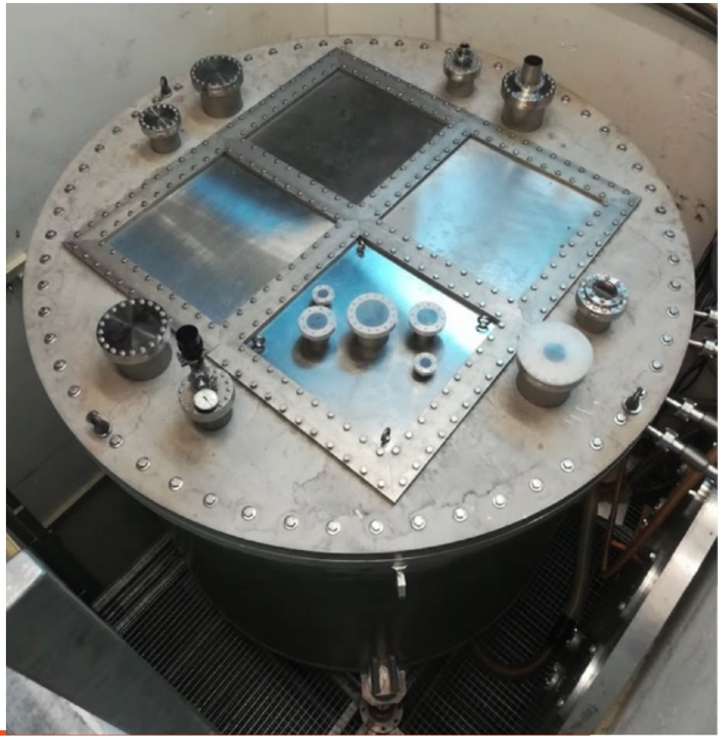
Modular construction:
1 x 1 x 3 m^3 modules
35 modules (7 x 5)
Total active mass = 130 ton
0.5 m maximum drift



Module prototype in Bern



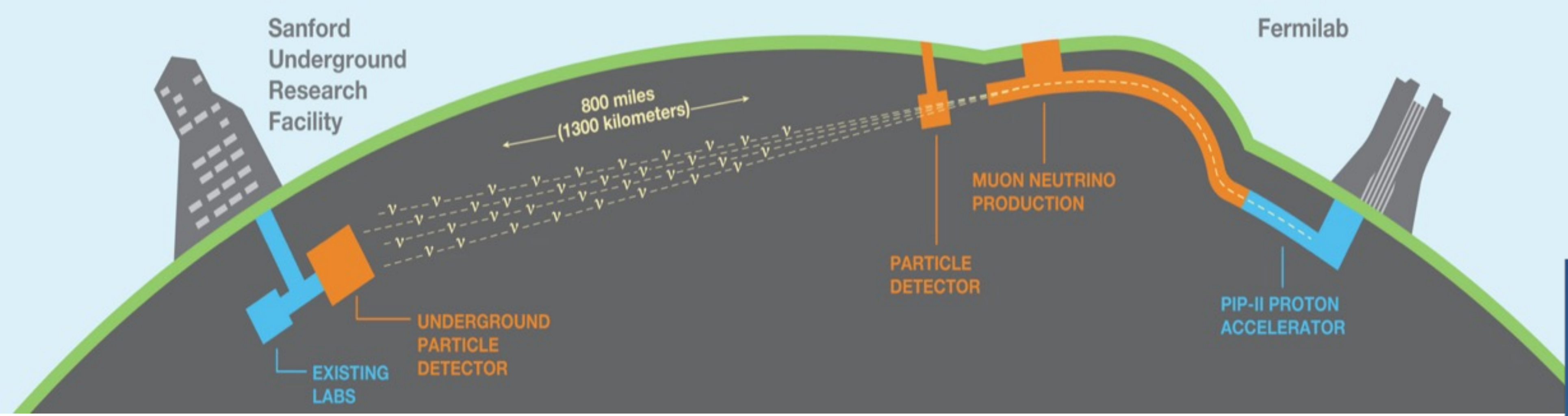
2 x 2 Demonstrator at Fermilab



DUNE experiment

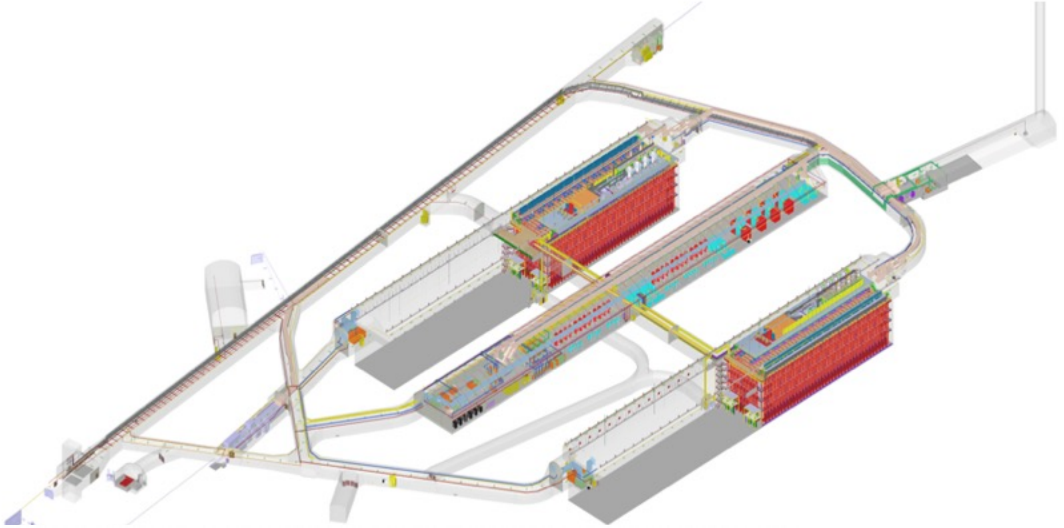
Next generation long baseline neutrino experiment: 1300 km from Fermilab to SURF (SD), 4300 m water equivalent depth (1500 m)

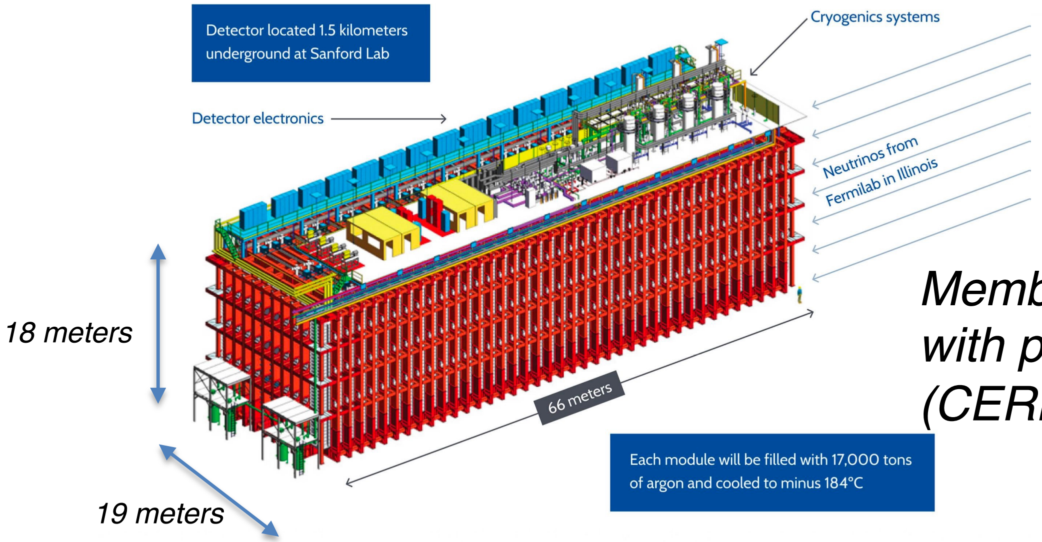
- *Very intense wide band ν_μ & anti-ν_μ beam (0.5 – 7 GeV): 1.2 MW, upgradable to > 2 MW*
- *Two detectors location, Near/Far, giant liquid argon TPC detector as far detectors (> 40 kt fiducial mass)*
- *A worldwide Collaboration: 1400+ people, 200+ institutions w/ CERN, 34 countries*



The DUNE Far detector complex

- Four independent detector modules
- Main detector technology:
  Single phase LAr-TPC modules,
  ~17 kt total Ar mass each module (62x14x15 m3):
  - **FD #1**: SP LAr-TPC,
    Horizontal Drift (HD), operational by 2030
  - **FD #2**: SP LAr-TPC,
    Vertical Drift (VD): operational by 2029
  - **FD #3**: SP LAr-TPC,
    technology VD as baseline
  - **FD #4**: Ongoing R&D
    for Module of Opportunity

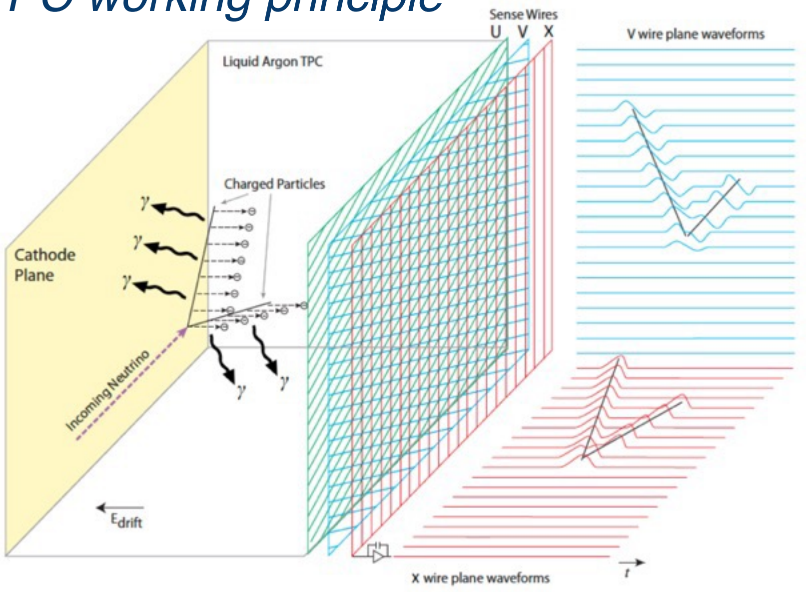




Membrane cryostat with passive insulation (CERN/GTT design)

The Single Phase Lar-TPC

TPC working principle



- Ionization electrons [~5 fC/cm] drift to the anode in pure LAr & uniform E-field (~500 V/cm)
  - Few mm pitch and ~MHz sampling frequency
  - 3D via multiple 2D view (wire# vs drift time)
  - high imaging capabilities → kinematic reconstruction with mm-scale spatial resolution
  - Intrinsically excellent Calorimetry and Particle Identification (dE/dx) capability
- Prompt scintillation light (@128 nm)
  - T = 0, trigger, calorimetry

LAr as radiation detection medium

Dense: 40% more than water

- Abundant primary ionization: 42 000 e-/MeV
- High electron lifetime if purified à long drifts
- High light yield: 40k γ/MeV
- Easily available: ~1% of the atmosphere
- Cheap: \$2/L (\$3000/L for Xe, \$500/L for Ne)

Technological challenges

- LAr continuous purification << 0.1 ppt O_2 eq. (>> 3 ms electron lifetime) for long drift
- Imaging & anode planes
- Very low noise front end amplifiers to detect ~ fC primary charge deposition
- Large area photon detectors sensitive to 128 nm wave length
- HV system to provide uniform/stable E-field in large drift volume

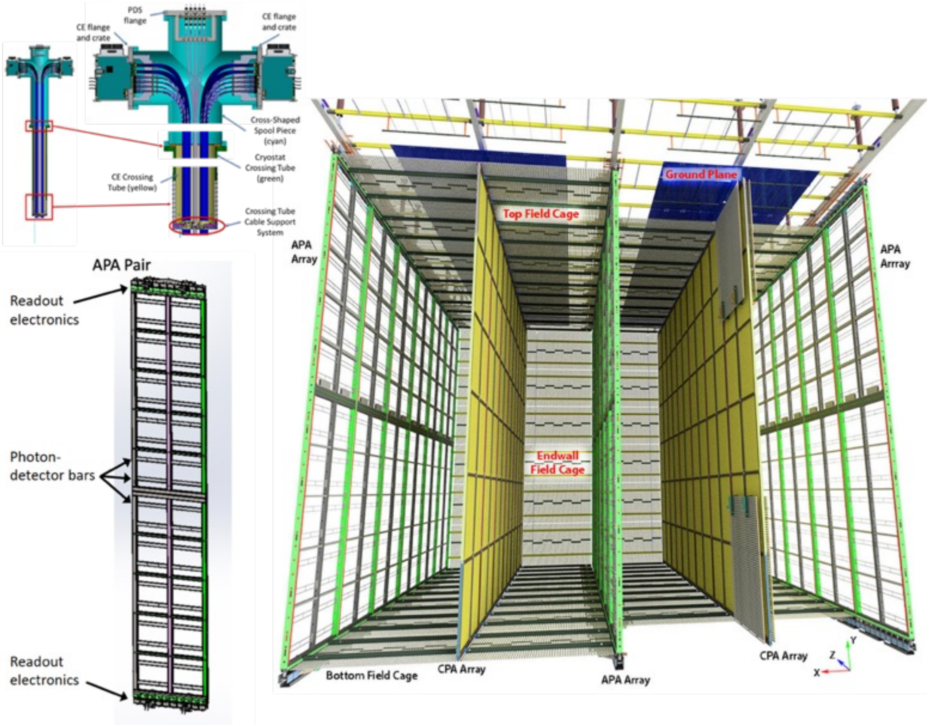
Pioneered by ICARUS and adopted in present and next generation neutrino experiment (µBoone, SBND, DUNE)

- DUNE: scaling to multi-kt size

FD1- LAr-TPC Horizonthal Drift technology

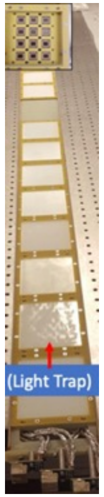
Alternated Anode and Cathode Plane Assemblies (APA/CPA) – 4 drift regions

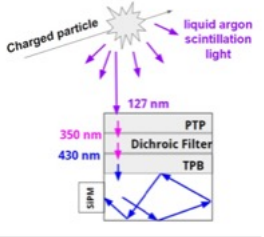
- ❖ Segmented: 4 drift volumes, Drift distance: 3.5 m
- ❖ Electric field = 500 V/cm (HV = -175 kV)
- ❖ High-resistivity CPAs to prevent fast discharges
- ❖ Anode: 150 APAs (6x2.3 m2) 4 wire planes each Grid, 2x Induction, Collection
- ❖ Wire pith ~ 4.7 mm
- ❖ Full cryogenic readout chain (analogue FE + Digitizer)



Photon Detectors:

- ❖ X-ARAPUCA SiPM based light traps integrated into APA frame





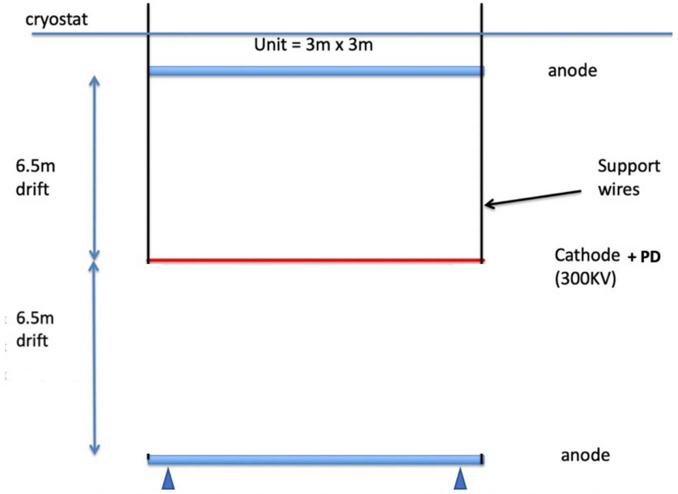
Module-0 in ProtoDUNE NP04 in 2022. Final validation of

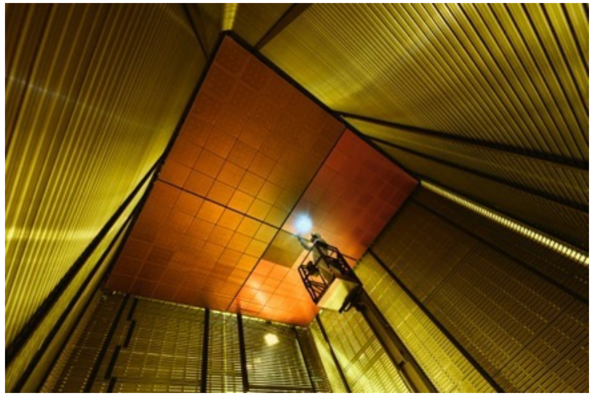
- ➢ Components production
- ➢ Assembly procedures
- ➢ Detector performance and stability

FD2 Vertical Drift concept and motivation

Capitalizing on the important R&D done in the last 4 years with the Proto-DUNE, new solutions emerged for the FD2 project:

- LAr purity in ProtoDUNE's is outstanding
  - allows longer drift path (6-7m)
- Charge readout electronics in ProtoDUNE demonstrated excellent S/N (>30).
  - No need of multiplication in gas phase.
- The Vertical drift layout is simpler to construct.
  - More efficient use of LAr volume
  - reduce schedule and financial risks
- Lightweight CRP support developed for DP well suited for immersed PCB anodes (SP)
  - Xe-doping improves the photon budget
  - Allow more uniform light detection over long distance.

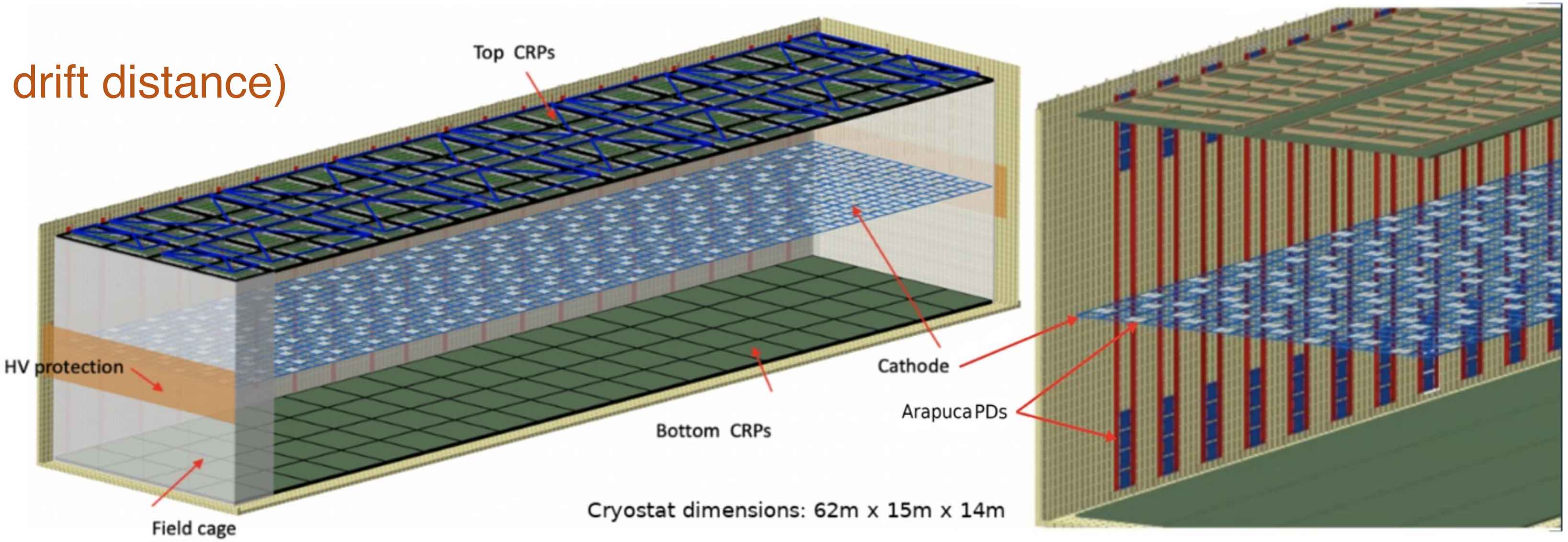


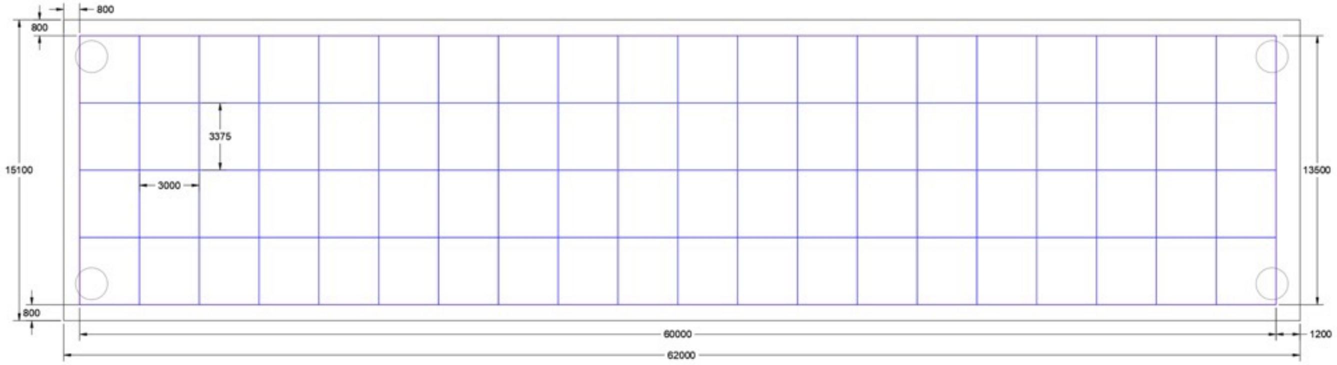


FD2 Vertical Drift layout

- CRP= 3x3.375 m2 readout units (anode)
- Modularity manly driven by max size transportable underground
- 2 drift regions (6.25 m drift distance)

TDR posted to arXiv:2312.03130 , accepted by JINST

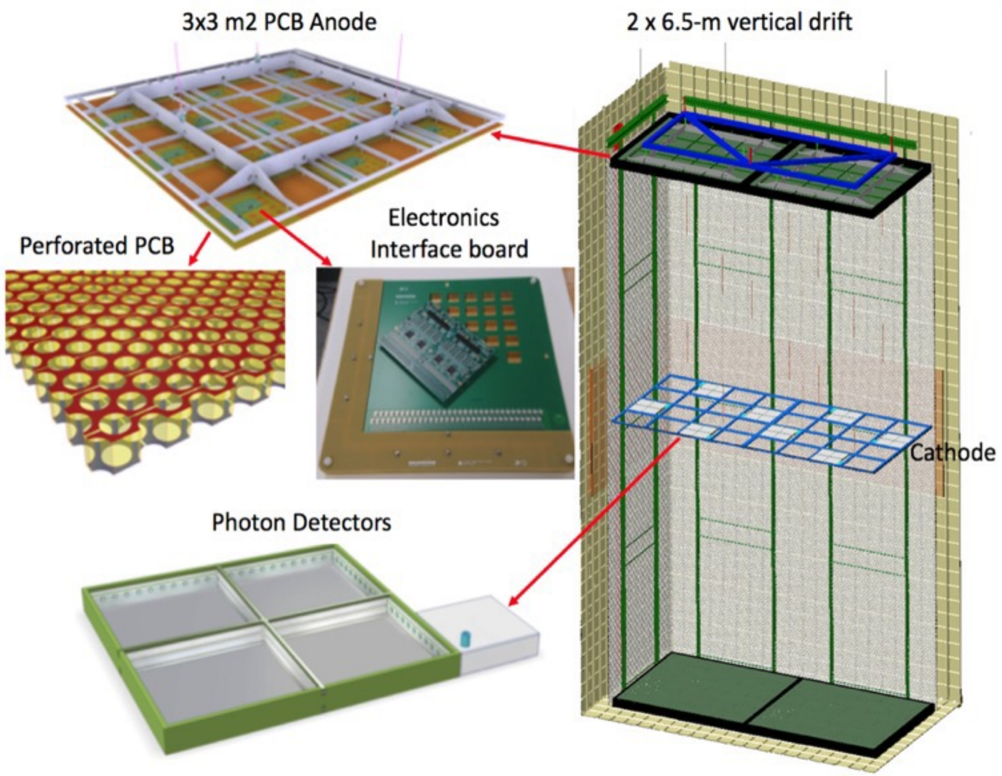




- 160 CRP units (80 on top, 80 on the bottom)
- Drift active volumes 2*5'265 m3 = LAr 14.74 Ktons
- Photon detectors on cathode and cryostat walls (up to 14% coverage)

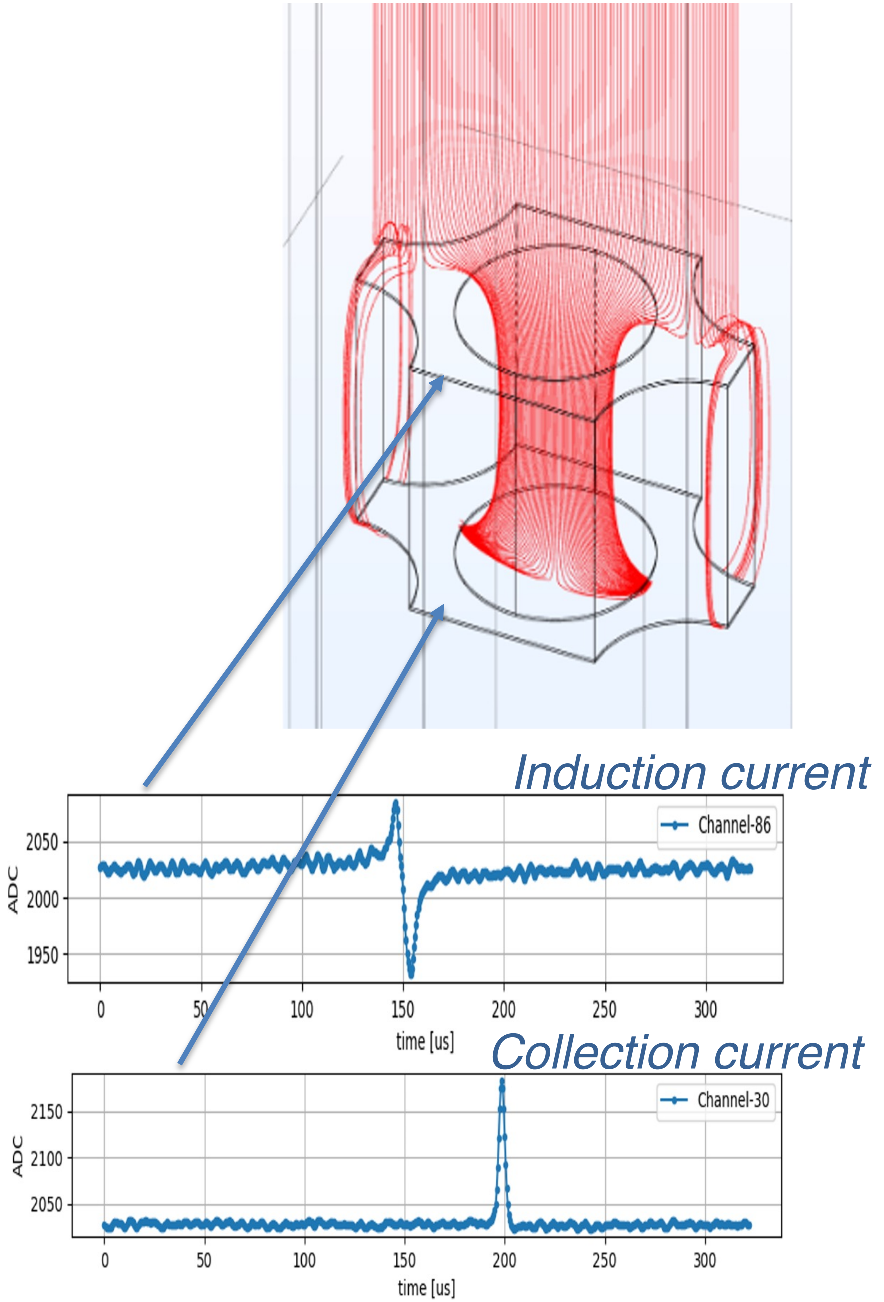
Main Vertical Drift detector components

- Designed to maximize active volume:
  - Readout units close to LAr surface and cryostat floor.
  - Cathode at middle height: better HV stability due to LAr hydrostatic pressure → closer distance to cryostat walls
  - 6.5 m drift , 450 V/cm , 300 kV on Cathode
- **Perforated PCB's** with segmented electrodes (strips) as readout units with integrated electronic interfaces
  - Good planarity (lightweight) and robust
  - Optimizable strip orientation, pitch, length
  - PCB modularity defined by strip readout length (S/N) and PCB drilling machines
- Modular supporting structures for readout planes
  - Derived from CRP design of DP
  - Incorporates cathode hanging system
- Single field cage surrounding entire active volume
  - derived from DUNE-DP design



VD: Basics and signal shapes

- Working principle
  - Electron trajectories are focused into 2D holes not in a “slice” like for wires. Focusing can be repeated on stacked PCBs for multiple readout views.
- PRO:
  - Electric and weighting fields in the hole is more uniform.
  - Bipolar shape of induction signal is asymmetric with benefit for visibility of large dip angle tracks because “cancellation effects” are reduced
  - Induction signal is intrinsically larger than with wires and less blurred because the weighting field is confined to a single strip and not distributed on several wires
  - 3 views possible: PCB stack (preferred), multilayer, charge sharing
- CONS:
  - focusing EF ratio is high (> ratio of hole area to full area --> DV ~ kV)
  - Capacitance of strips (PCB dielectric constant and strip width) 4 to 6 times higher than wires at the same pitch: higher electronic noise compared to same length wire

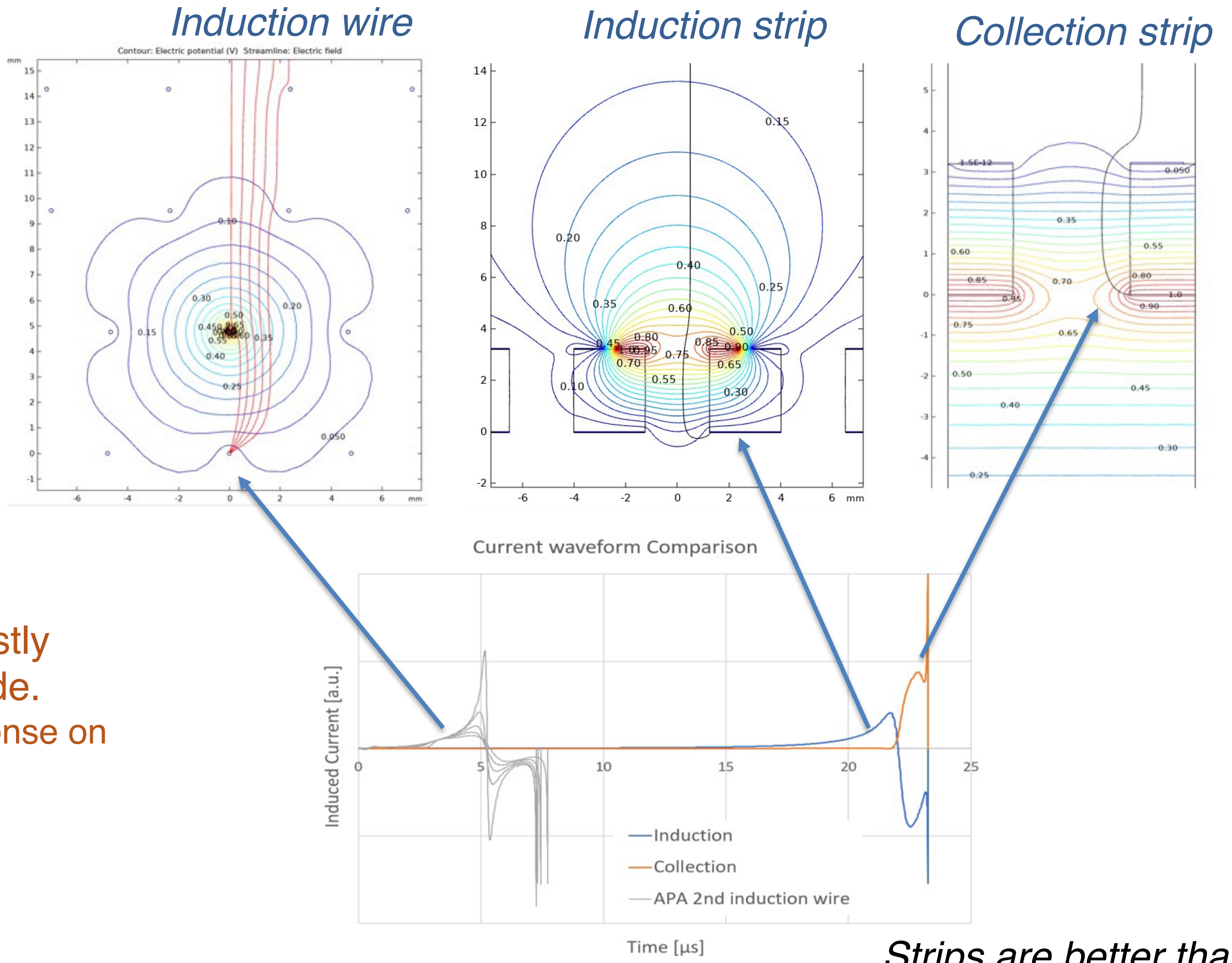


Induction current

Collection current

Wires vs Strips signal comparison

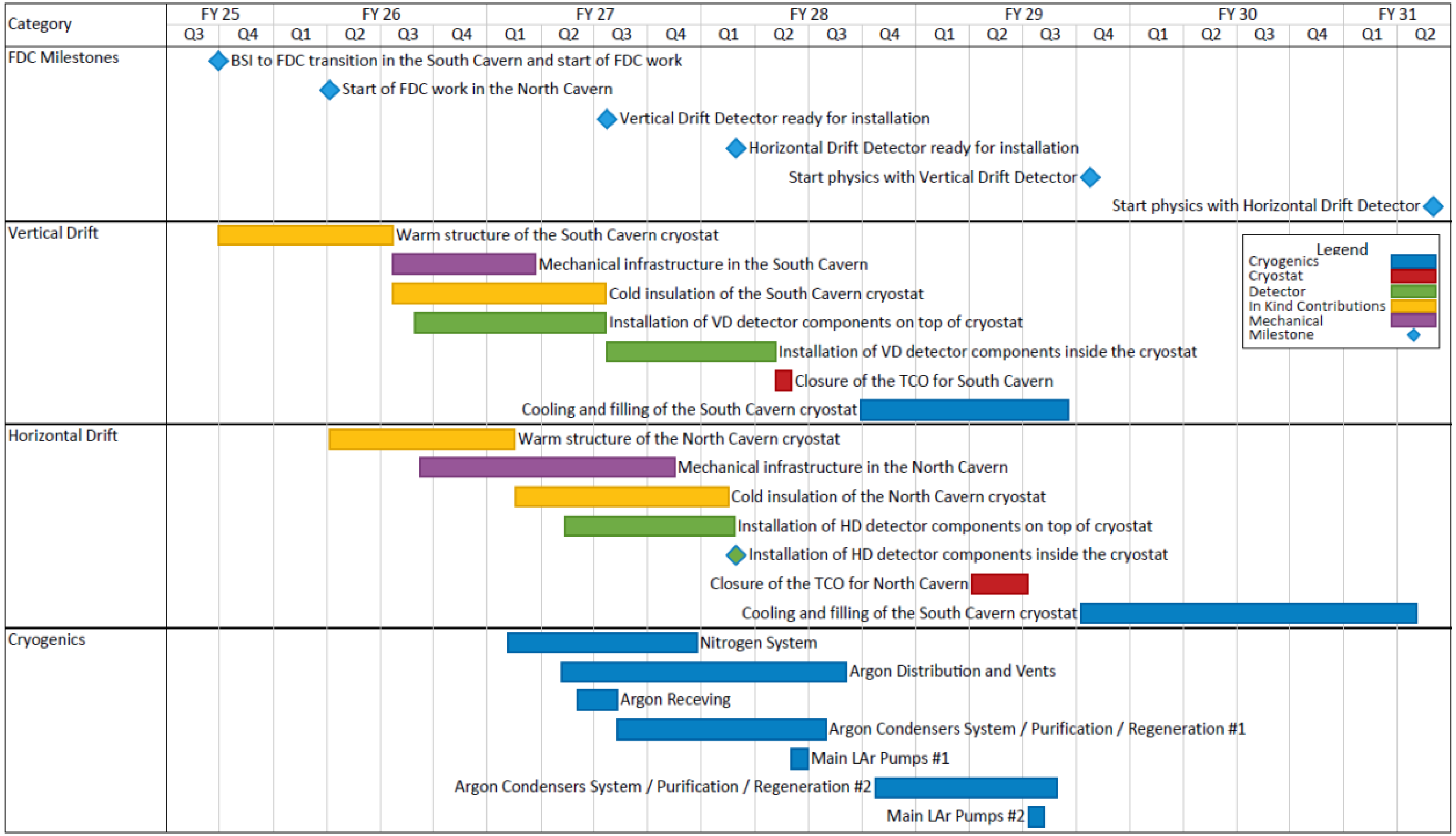
- Weighting potential used to derive induction current:
  - much more uniform in the case of strips vs wires



- The signal is less dispersed, mostly concentrates on a single electrode.
  - More uniform calorimetric response on all readout planes
  - Less blurred imaging

Strips are better than wires…

DUNE Far detectors schedule



Conclusions

- An introduction to the LAr TPC technology has been given here, together with an accounting of the several milestones that had to be reached to bring it from the initial conception, in 1977, to technical maturity, in 2001.
- ICARUS has been, for most of those many years, and with the untiring drive and great insights of Carlo Rubbia, the experimental and collaborative environment in which these efforts have found space, support, focus and, ultimately, success. CERN and, dominantly, INFN, have been the major supporters of the technological development.
- Following the announcement, in February 2002 at CERN, of the successful completion of the R&D phase and of the availability of the first large LAr TPC, the ICARUS T600 detector, many other initiatives have been born, having the LAr TPC as reference detector. The LAr TPC has continued to evolve thanks to the drive of these new initiatives.
- Only those initiatives related to neutrino physics have been acknowledged in this lecture. Others, focusing on low energies, dark matter searches, dedicated R&D, etc, have not been considered, certainly not for lack of importance, but, rather, for lack of time.
- ICARUS is taking data now, joined this year by SBND, on sterile neutrino searches at Fermilab's Booster and NuMI neutrino beams.
- In the near future, DUNE is receiving most of the attentions, with the extremely ambitious program both in terms of LAr scale and physics searches.

Backup

Argon purification in the liquid phase

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 333, Issues 2–3, 1 September 1993, Pages 567-570

Argon purification in the liquid phase

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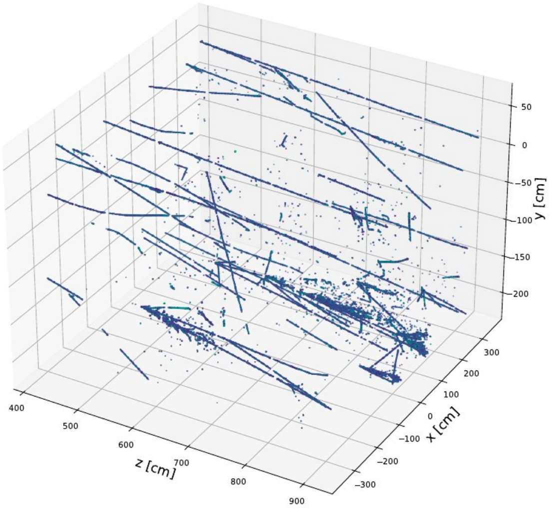
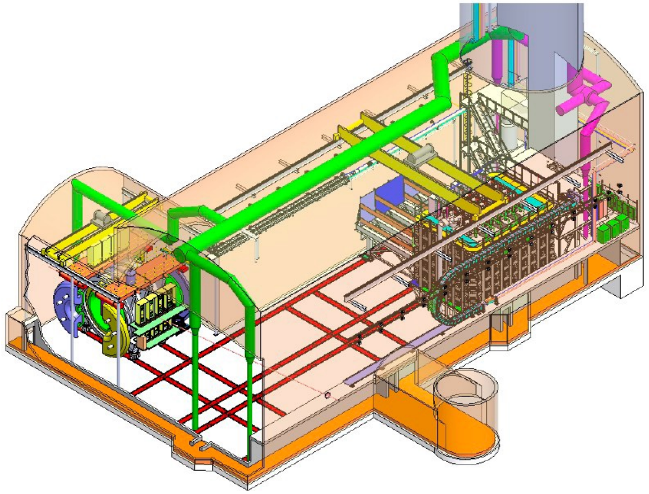
https://doi.org/10.1016/0168-9002(93)91209-6

Abstract

In the R&D programme for the ICARUS experiment, we have developed a practical procedure to purify liquid argon in the liquid phase. Extreme purity is obtained, corresponding to an electronegative impurity concentration below 0.1 **ppb** of 0_2 equivalent. This corresponds to an electron lifetime in the range of several milliseconds equivalent to attenuation length of a few metres. The

ND-Lar, Lar-TPC at the Near Site of DUNE

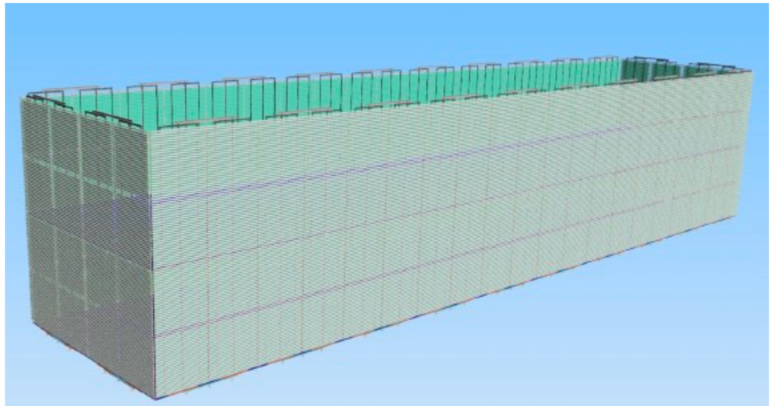




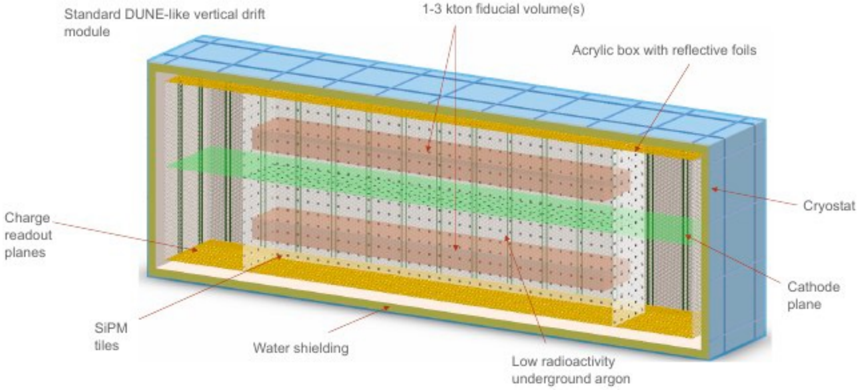
- ND is a (movable) LArTPC + muon spectrometer, and a (fixed) magnetized tracker + calorimeter
- Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
- Same target, same technology → inform predictions of reconstructed E_ν in Far Detector
- Neutrino pile-up → modular design with pixelated, natively 3D readout to isolate activity from individual neutrinos

DUNE, Far site, 3rd and 4th modules

APEX for FD3



Possible FD4 Module of Opportunity (SLOMO)



- Vertical Drift module is the baseline design for Phase II FD modules
- Pursuing low-hanging improvements to light collection for FD3, including Aluminum Profiles with Embedded X-ARAPUCA, essentially integrating light detectors into field cage
- FD4 is the “Module of Opportunity”, and more ambitious designs are being considered, including a very low background module, additional Xe doping, pixel readout, and non-LAr technologies