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

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Outline

- Introductory concepts
- The Liquid Argon Time Projection Chamber (LAr TPC) technological development
  - Milestone1: Event imaging
  - Milestone2: Liquid argon purification
  - Milestone3: 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
  - The path towards DUNE: 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, to identify particles from they behaviors, to measure kinematical quantities, etc..
- A notable example is 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).
- 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.
- 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, where additional features are required.

“Continuous” energy loss by charged particles

- Electrically charged particles, crossing a material, loose energy in a “continuous” way by interacting with the electrons of material’s atoms.
- The average amount of energy lost through this mechanism was first calculated by Bethe in the 1930’s. The formula was then perfected over the years to assume the present analytical form:

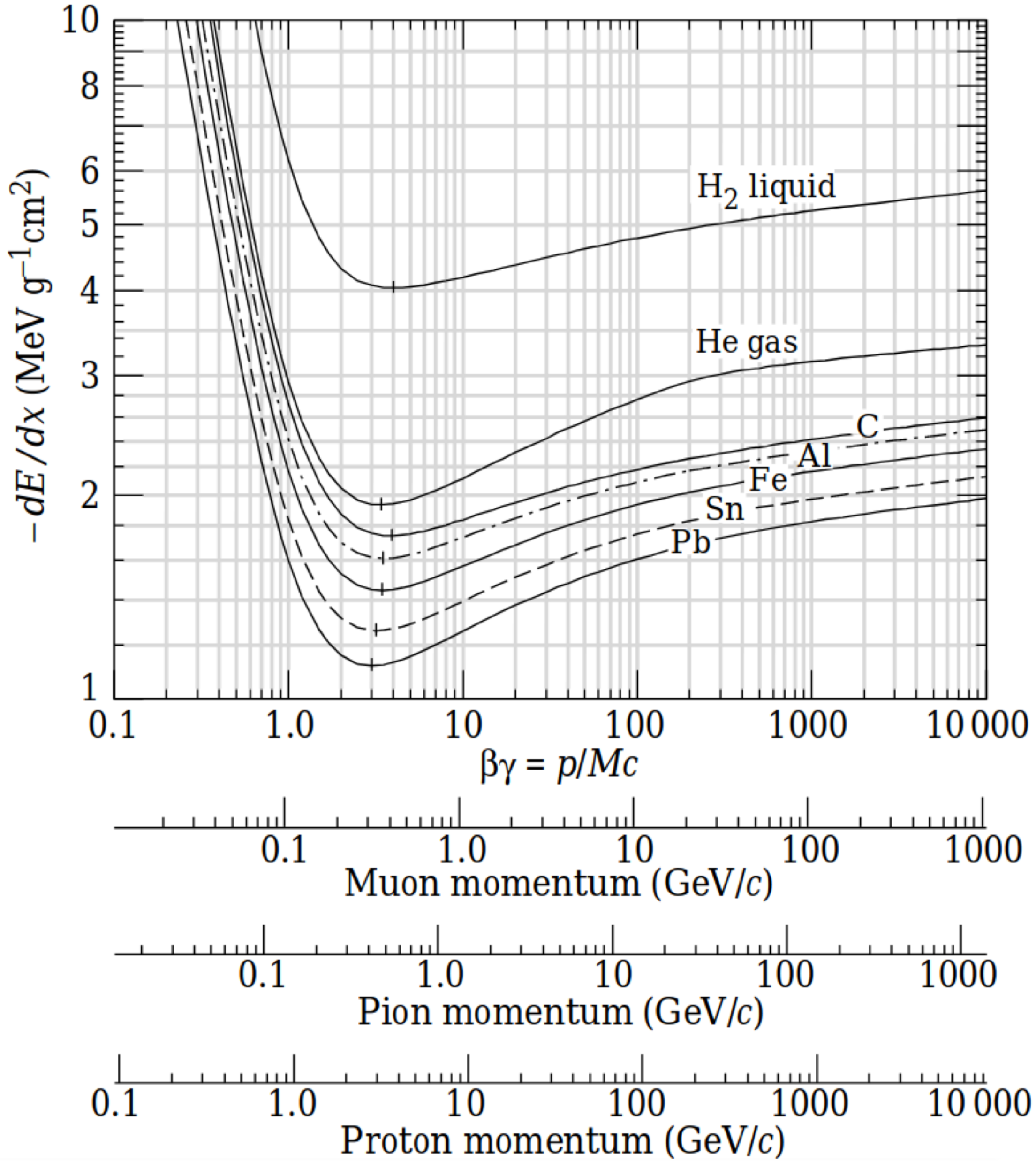
$$-\left\langle\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\rho\frac{1}{\beta^2}\left(\frac{1}{2}ln\frac{2m_ec^2\beta^2\gamma^2W_{max}}{I^2}-\beta^2-\frac{\delta(\beta\gamma)}{2}\right)$$

$K = 4\pi N_A r_e m_e c^2$; z = projectile charge ; ρ = material density ;
W_{max} = max energy transfer ; I = mean excitation energy ;
$\delta(\beta\gamma)$ = density effect correction
dE = energy variation for a particle with charge z crossing a material thickness dx

- The formula holds for moderately relativistic ($0.1 \leq \beta\gamma \leq 1000$) 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).

Active media

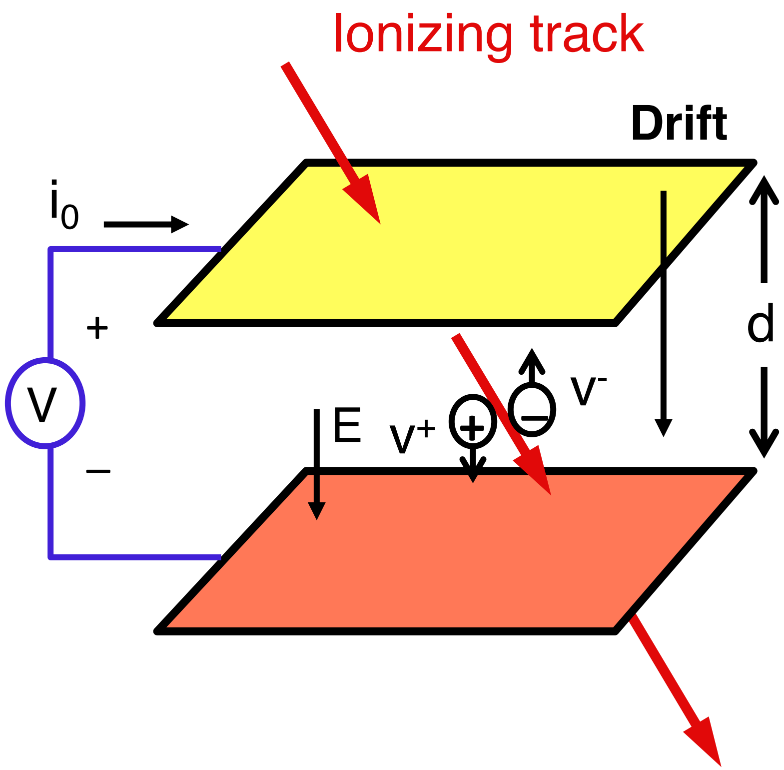
- Materials where ions, electrons, photons, phonons, produced by the passage or charged particles can be efficiently transported and collected (by some means) can become active media, in the sense that they can be used to produce an electrical signal as the result of the passage of the primary particles.
- Most detectors used in high energy particle physics can be grouped in two large categories:
  - Ionization based detectors
  - Scintillation based detectors
- Time projection chambers, 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.



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** →	**$v_{drift} \approx$ 1.5 mm/μs @ E=500 V/cm**
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	

Signals in a non-multiplying medium



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

$$dW = eE(v^+ + v^-)dt = V i_0 dt$$

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.

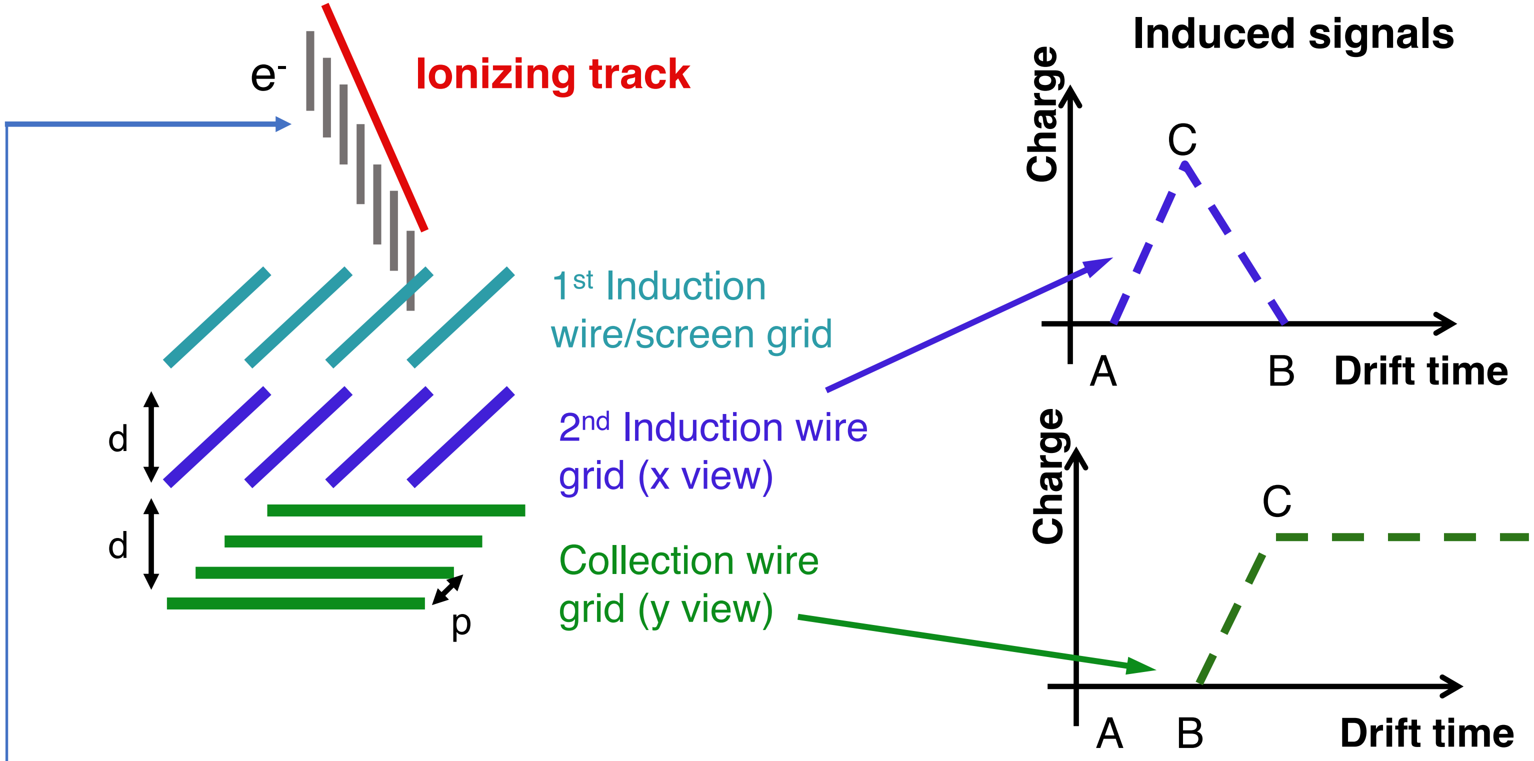
Typical values for 10000 electrons and v^-=1.5 mm/μs @ E=500 V/cm are

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

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 charge collected 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.

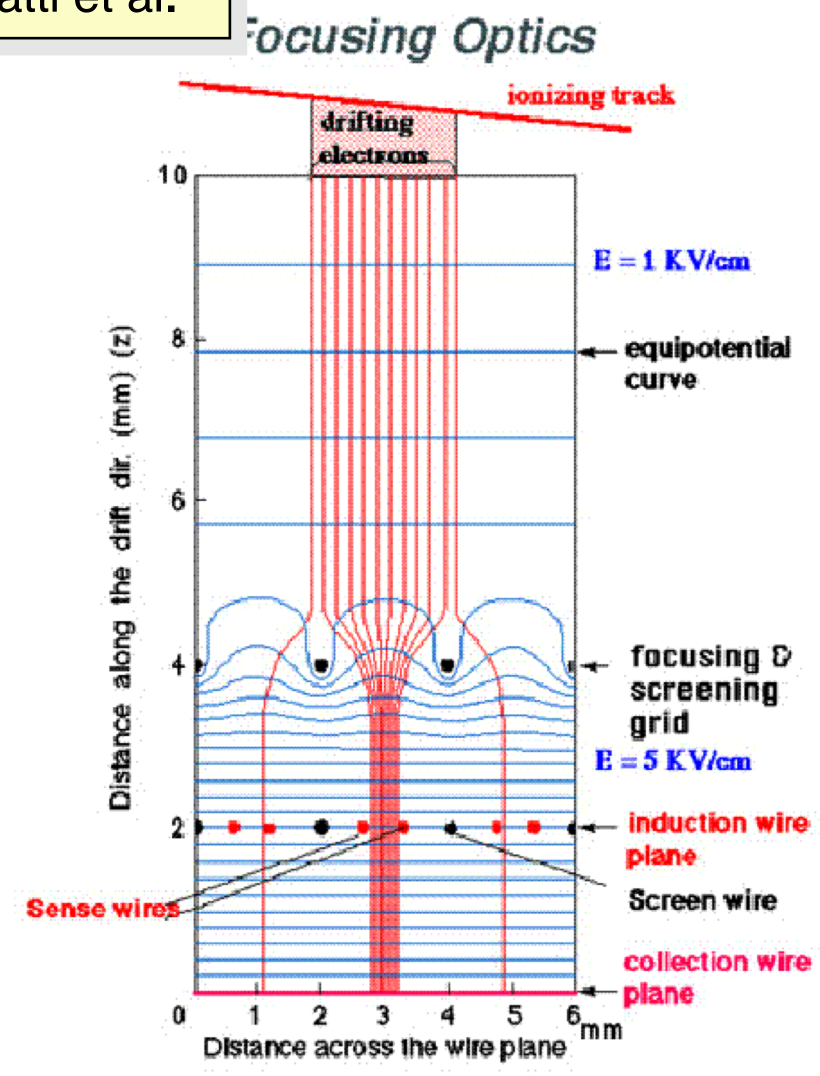
Non-destructive multiple readout of drifting electrons with wires

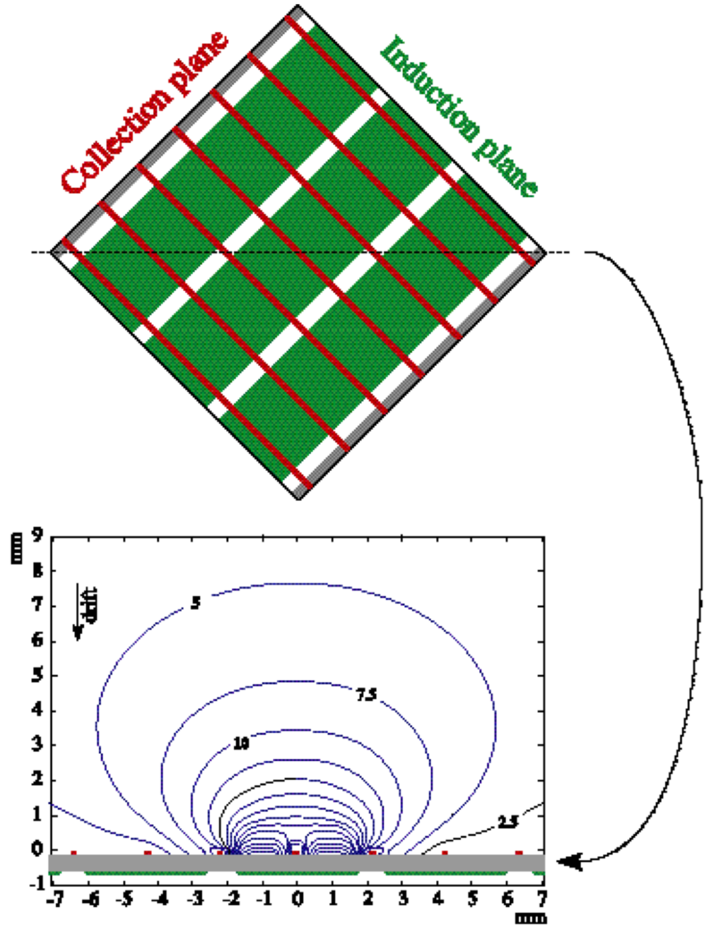


The drifting electron is traversing an arbitrary number of wire planes oriented in the direction of the required views. Each of them provides a “triangular” induction signal of maximum charge, equals to the electron charge. The electron charge is finally collected by the collection wire plane. The generated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

Practical readout configurations

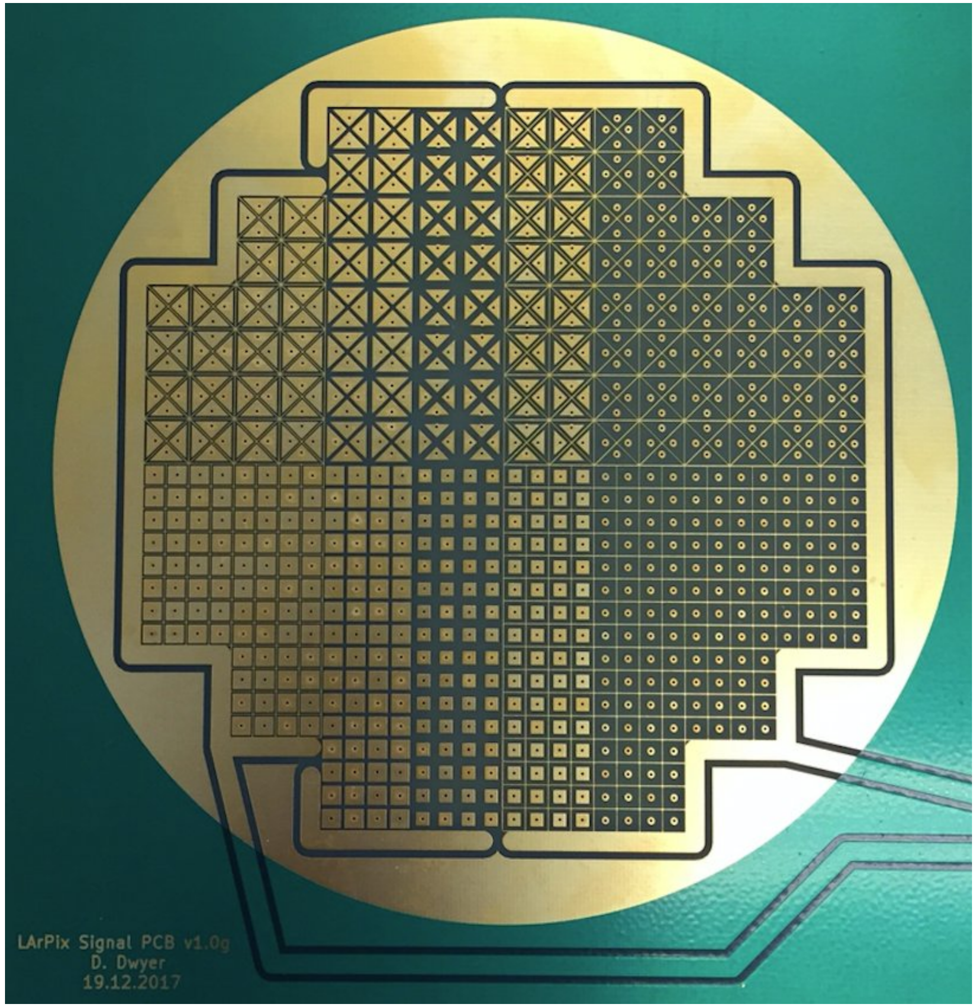
E. Gatti et al.

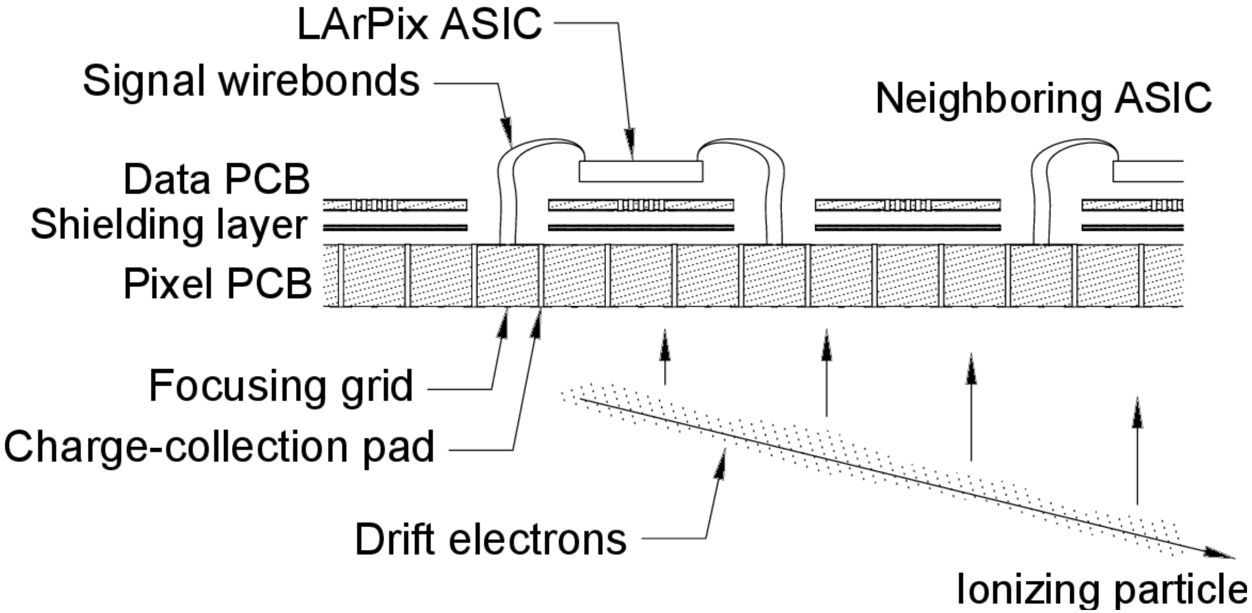




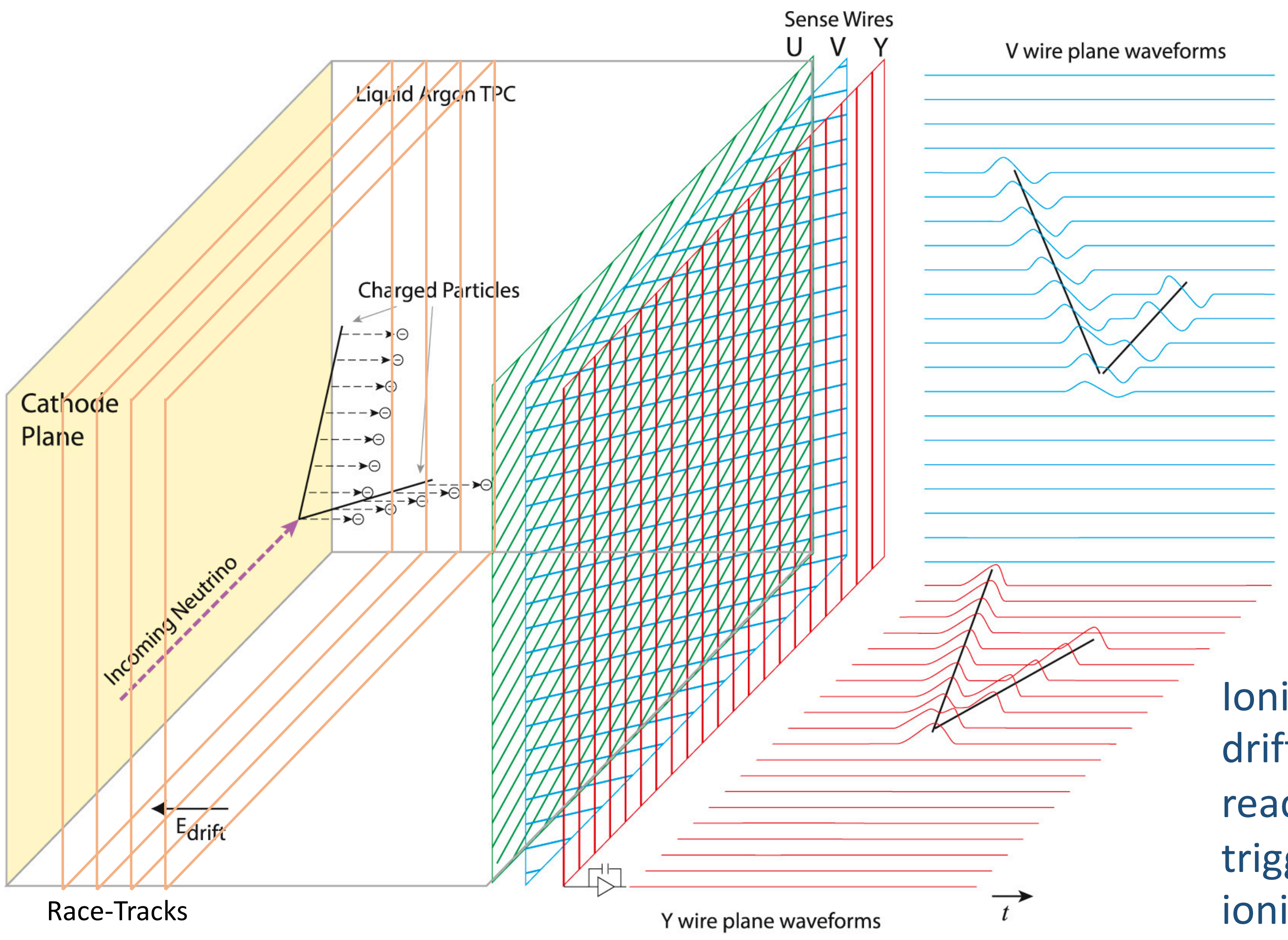
Multi-layer printed board technique

Pixelized readout





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 view of the ionization event. Multiple 2D views can be combined to obtain a 3D image of the event.

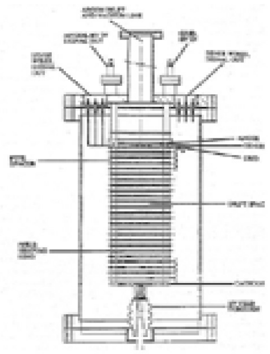
The LAr TPC

- 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)*).
- 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 searched 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 is planned to start operation at the beginning of 2024.

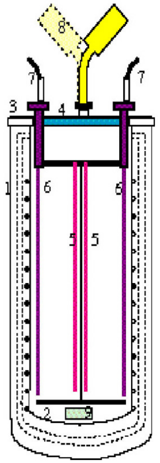
Milestone 1: LAr Imaging



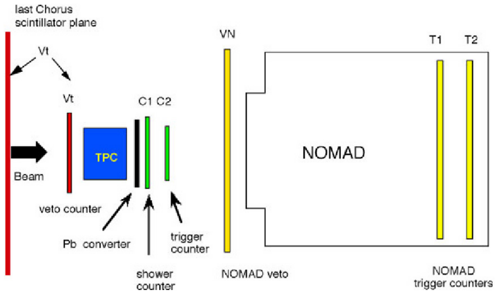
24 cm drift wires chamber

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.



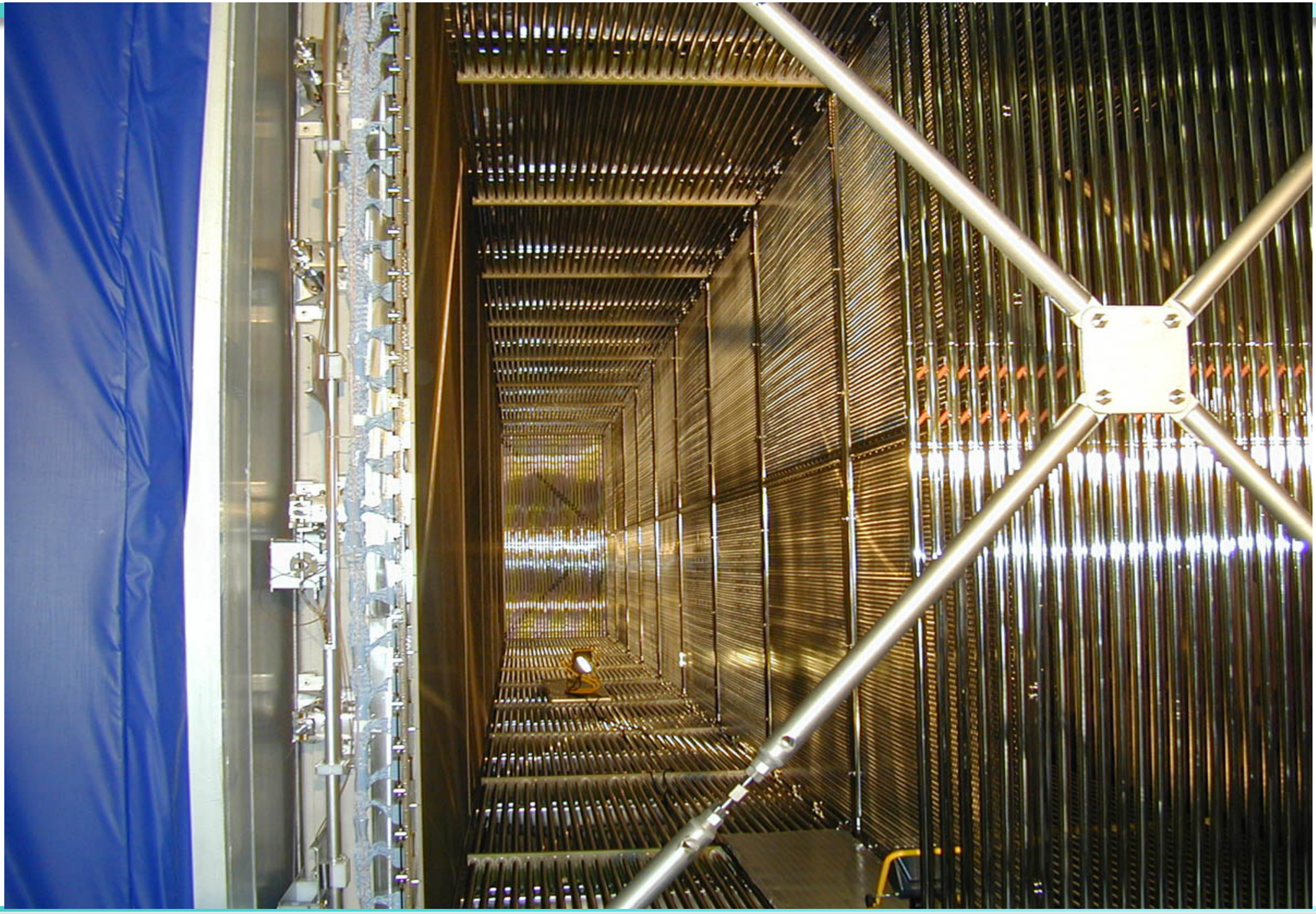
50 litres prototype 1.4 m drift chamber

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

$10\ m^3$ industrial prototype

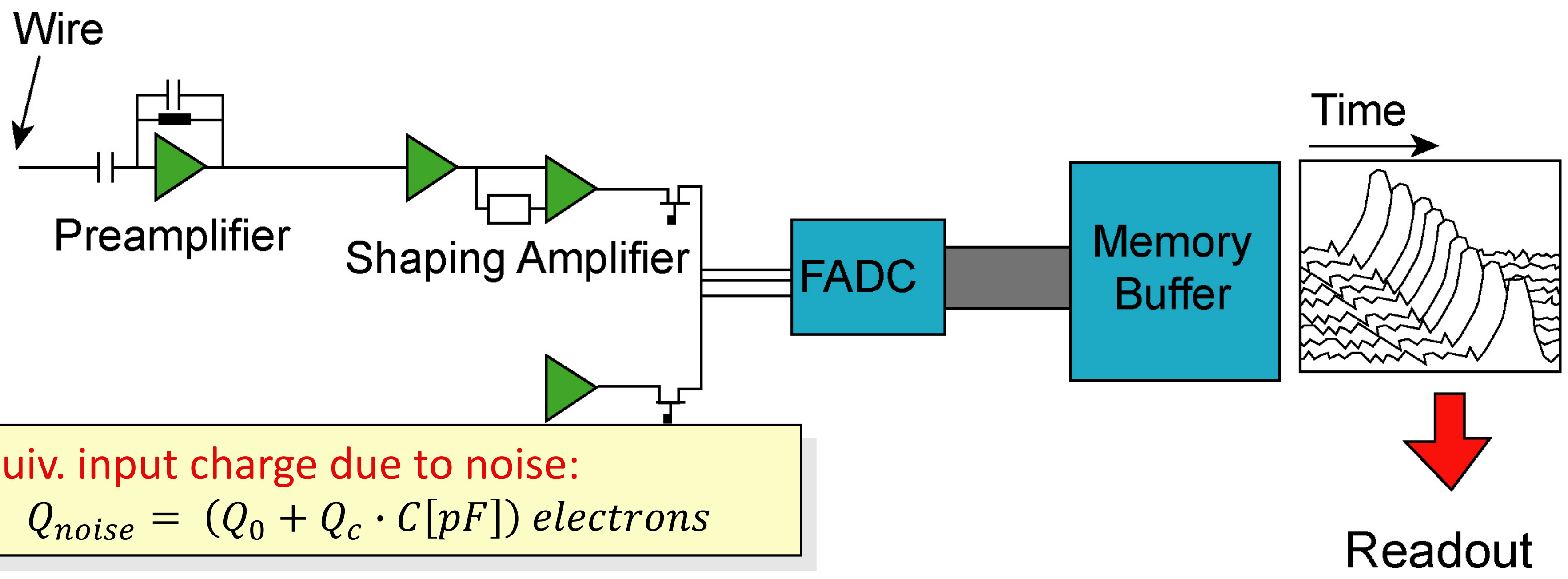
1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

The ICARUS T600 Detector: inner structure of a single gap



Method of signal recording

- The collected charge is sensed by a 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



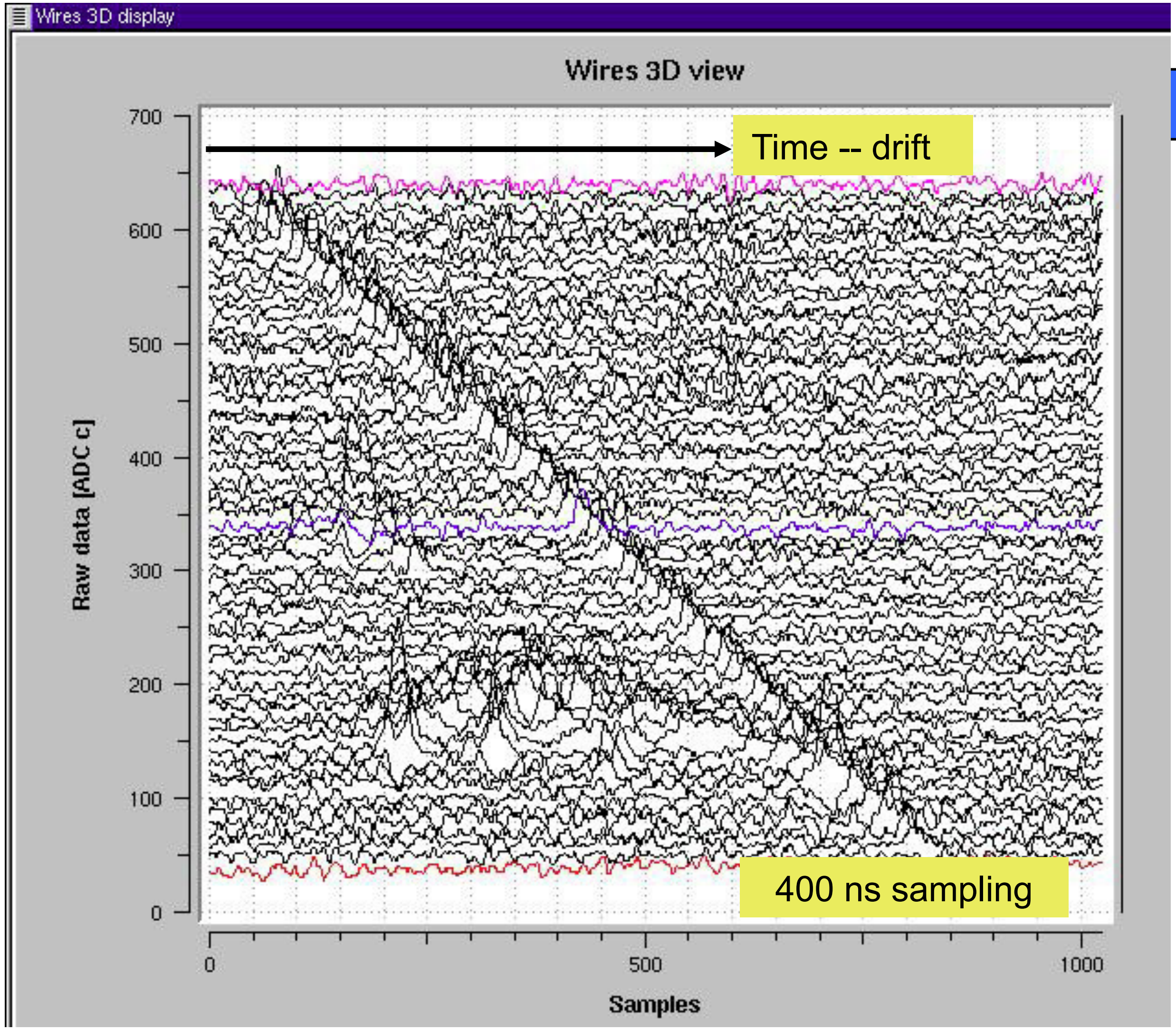
Equiv. input charge due to noise:

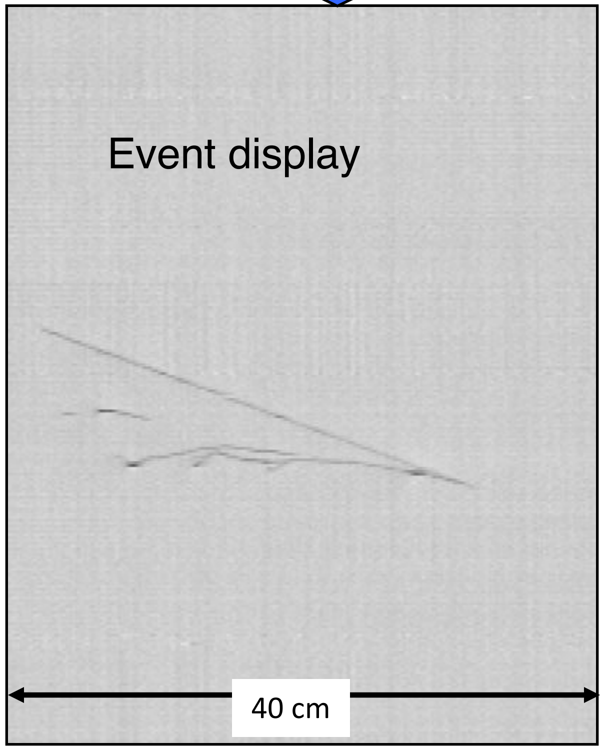
$$Q_{noise} = (Q_0 + Q_c \cdot C[pF])\ electrons$$

Principle of signal recording

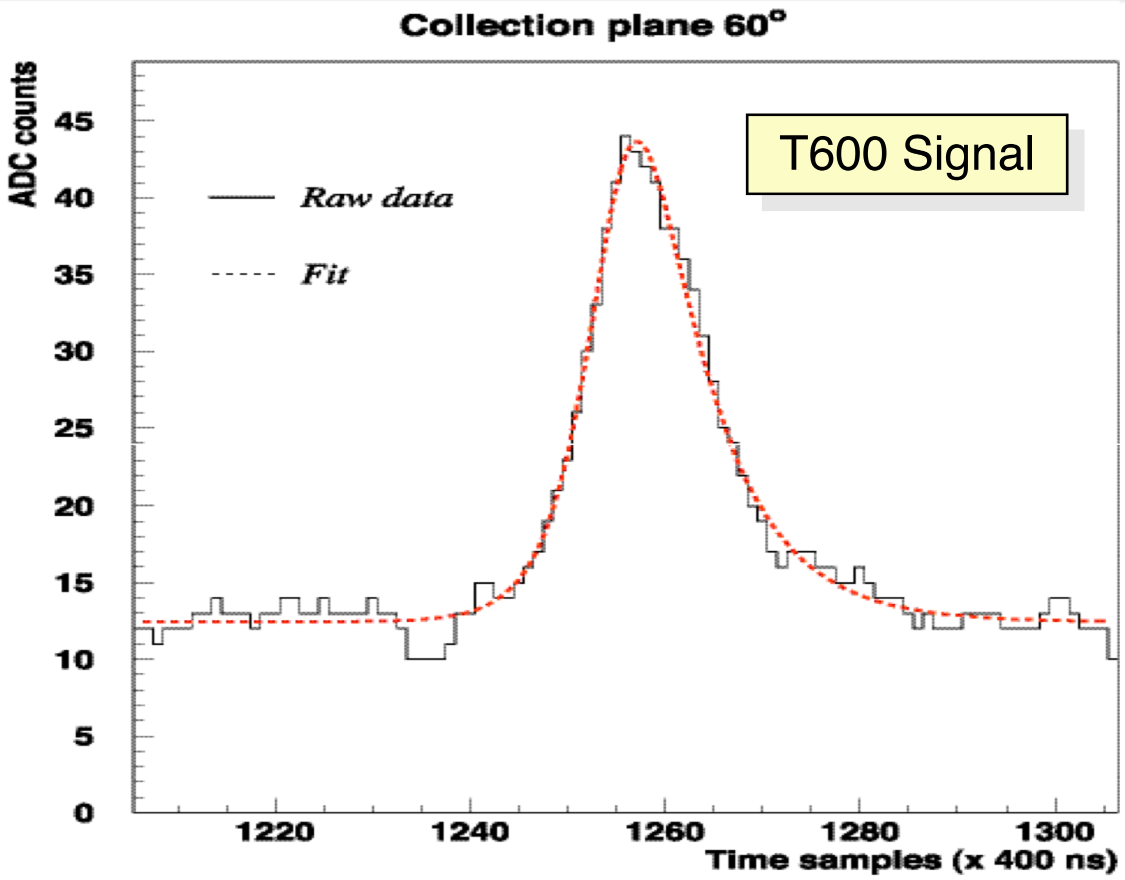
Real Event from a 15 ton LAr Detector

Raw Data



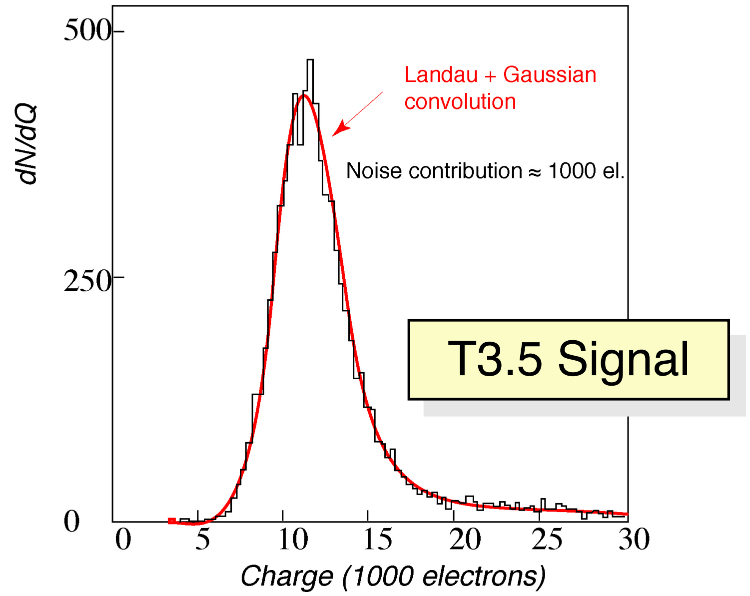


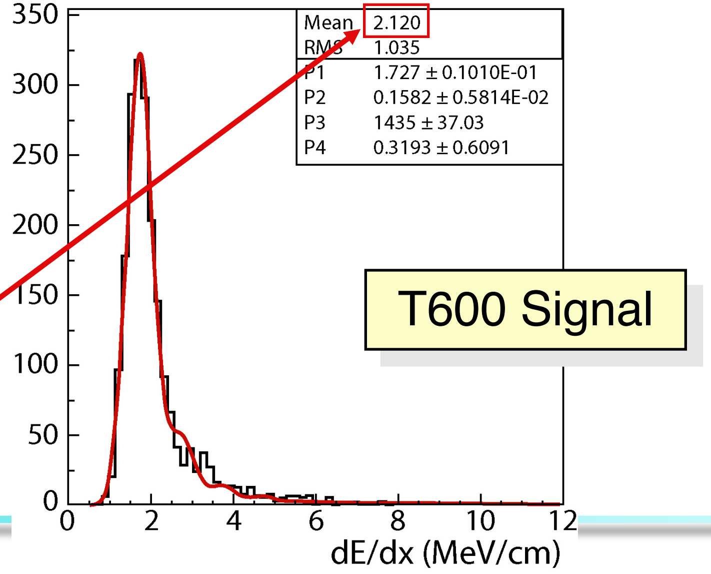
Single wire performance



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

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





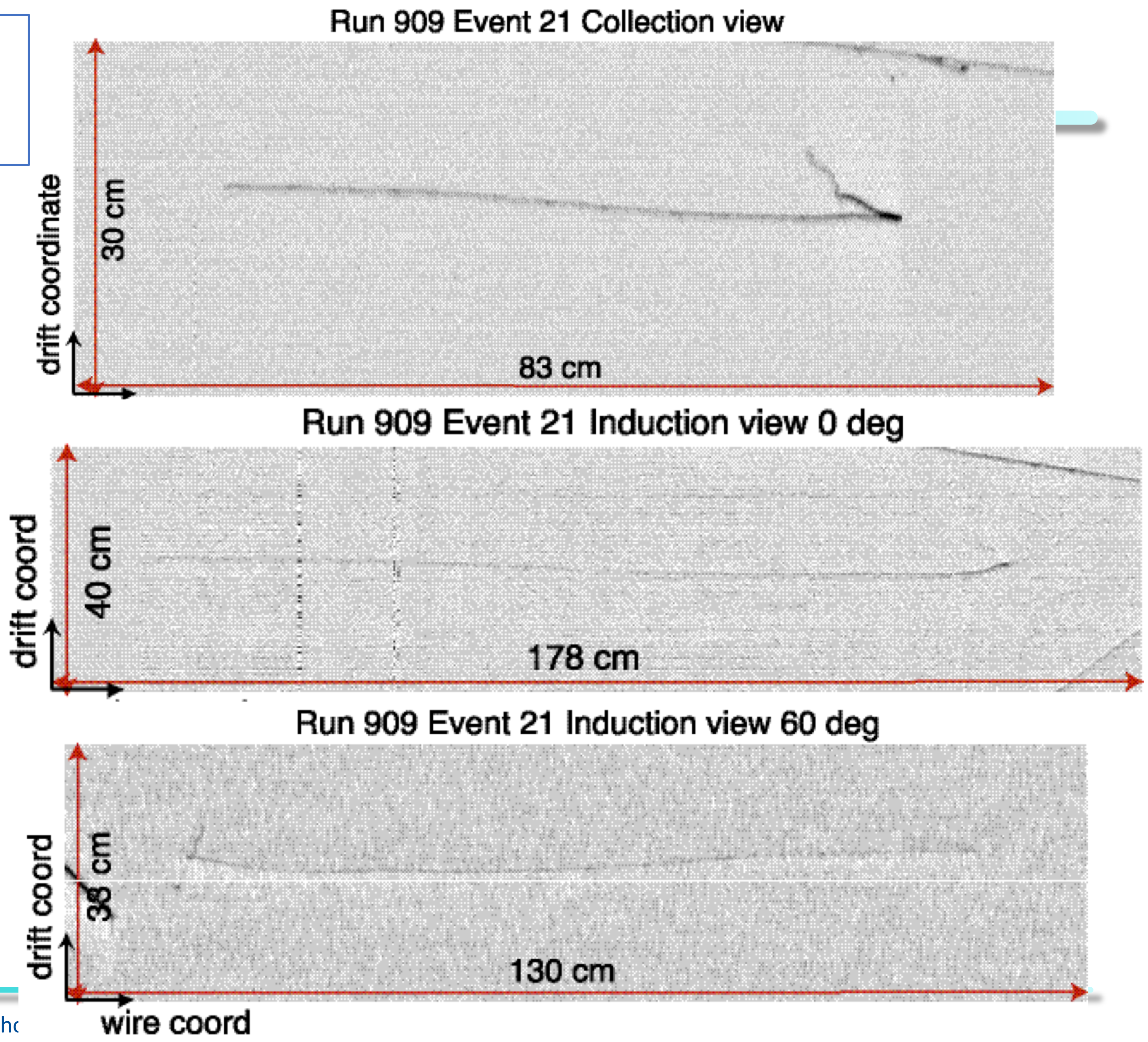
Reconstructed dE/dx: 2.12 MeV/cm

Multiple plane readout in ICARUS T600 (2001)

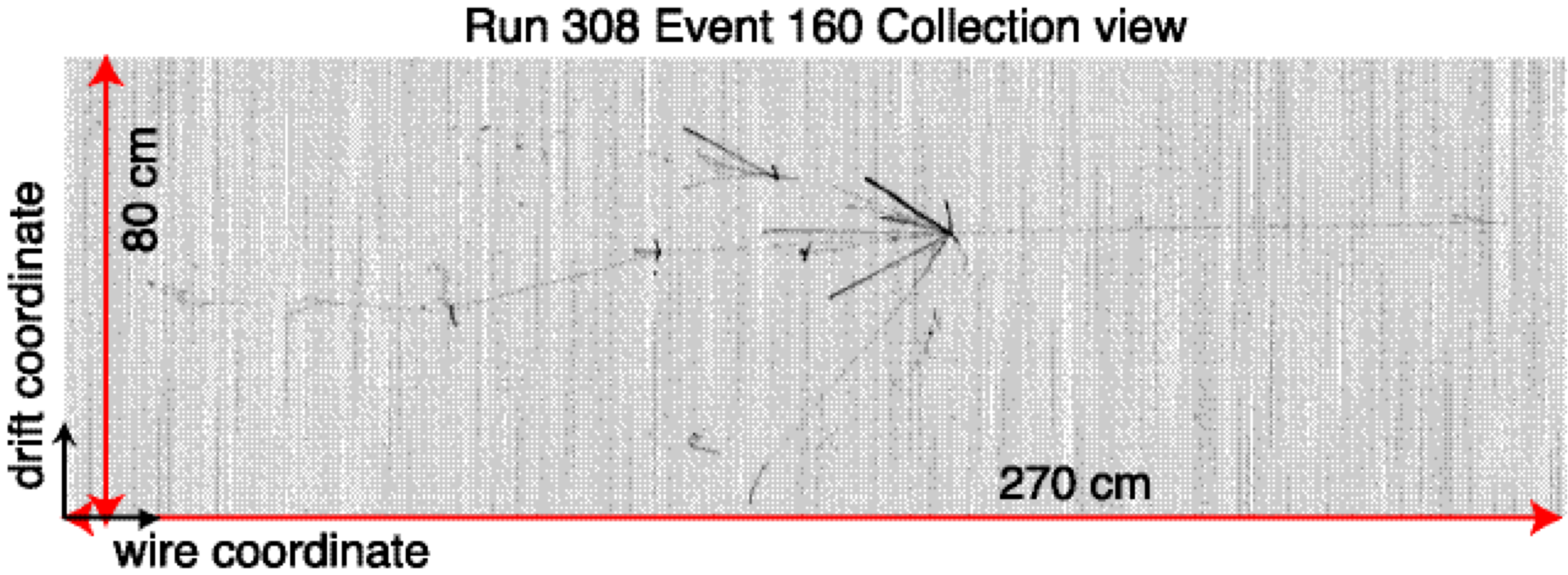
Collection (+60°)

Induction1 (-60°)

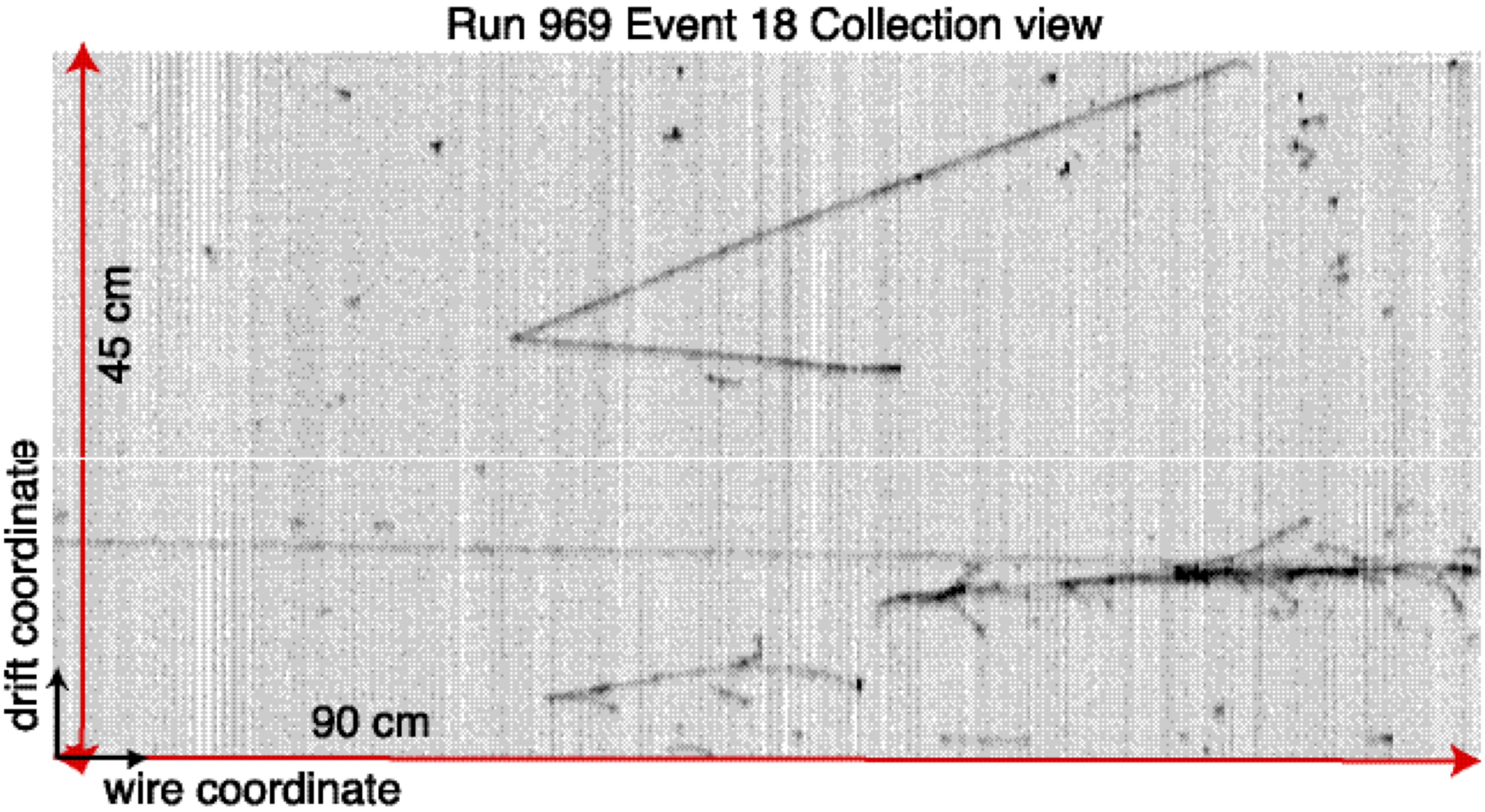
Induction2 (0°)



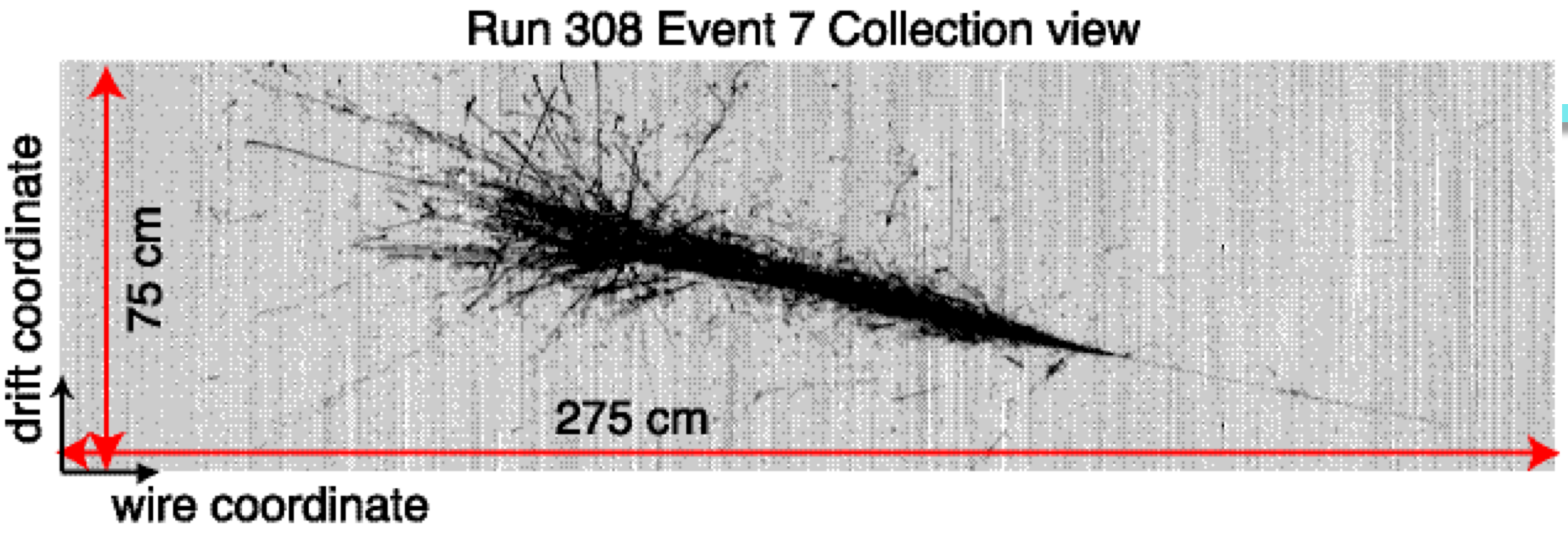
Hadronic interaction in ICARUS T600 (2001)

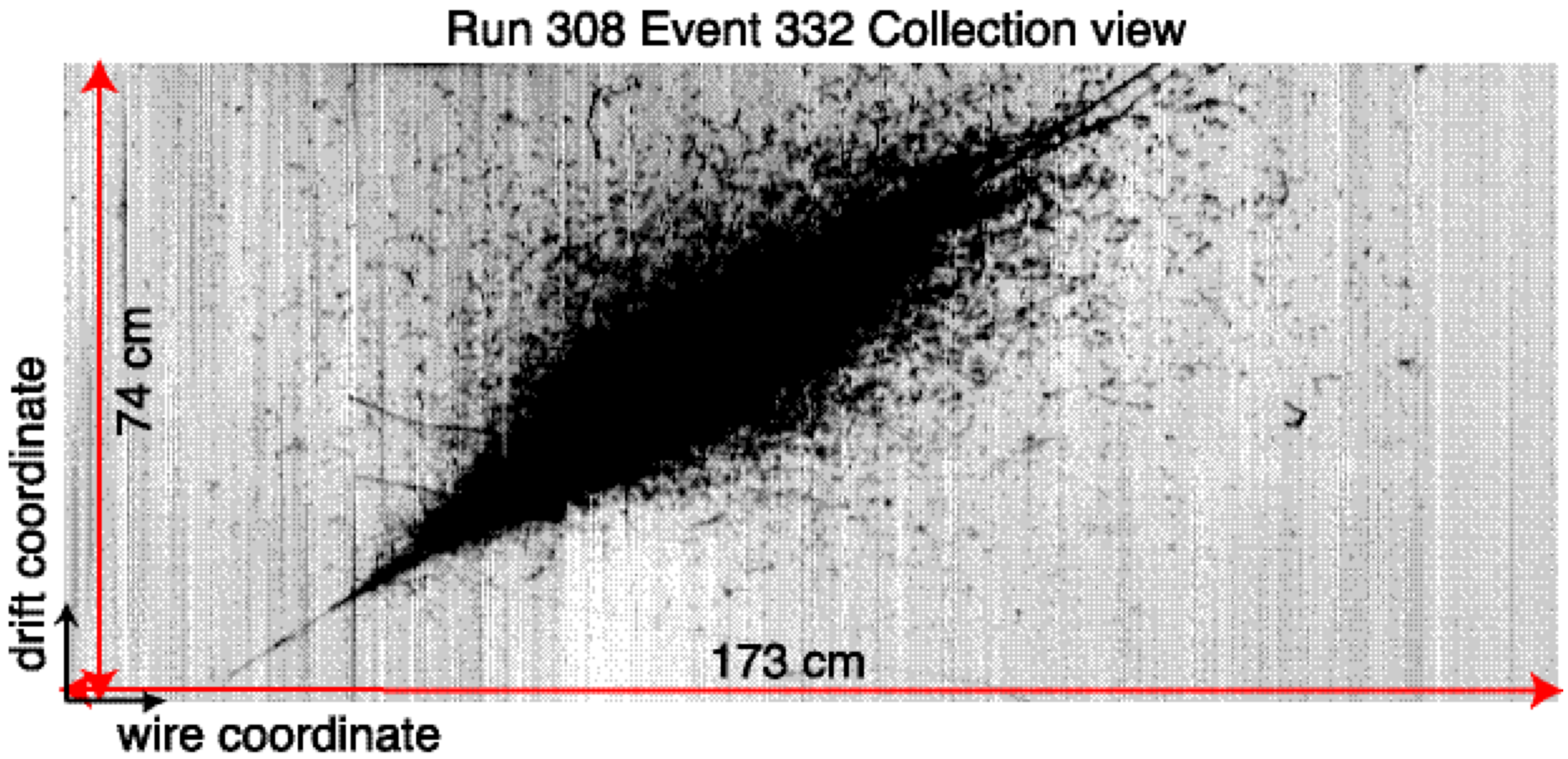


V_0 candidate in ICARUS T600 (2001)



High energy cosmic ray showers in ICARUS T600 (2001)



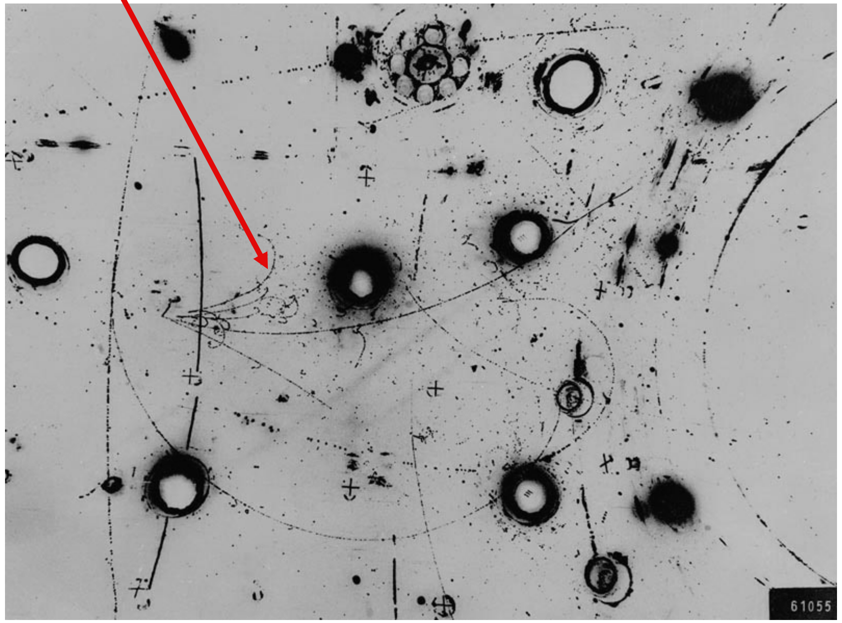


Thirty years later …

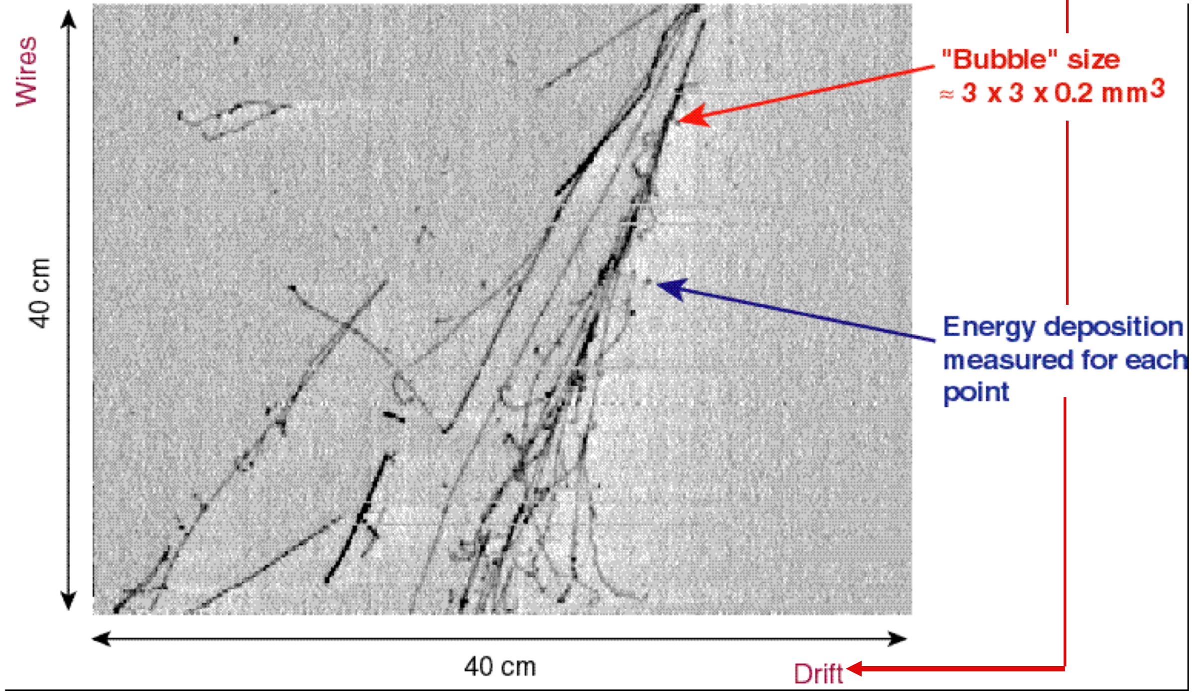
LAr is a cheap liquid, vastly produced by industry

Bubble diameter ≈ 3 mm (diffraction limited)

Gargamelle bubble chamber



ICARUS electronic chamber

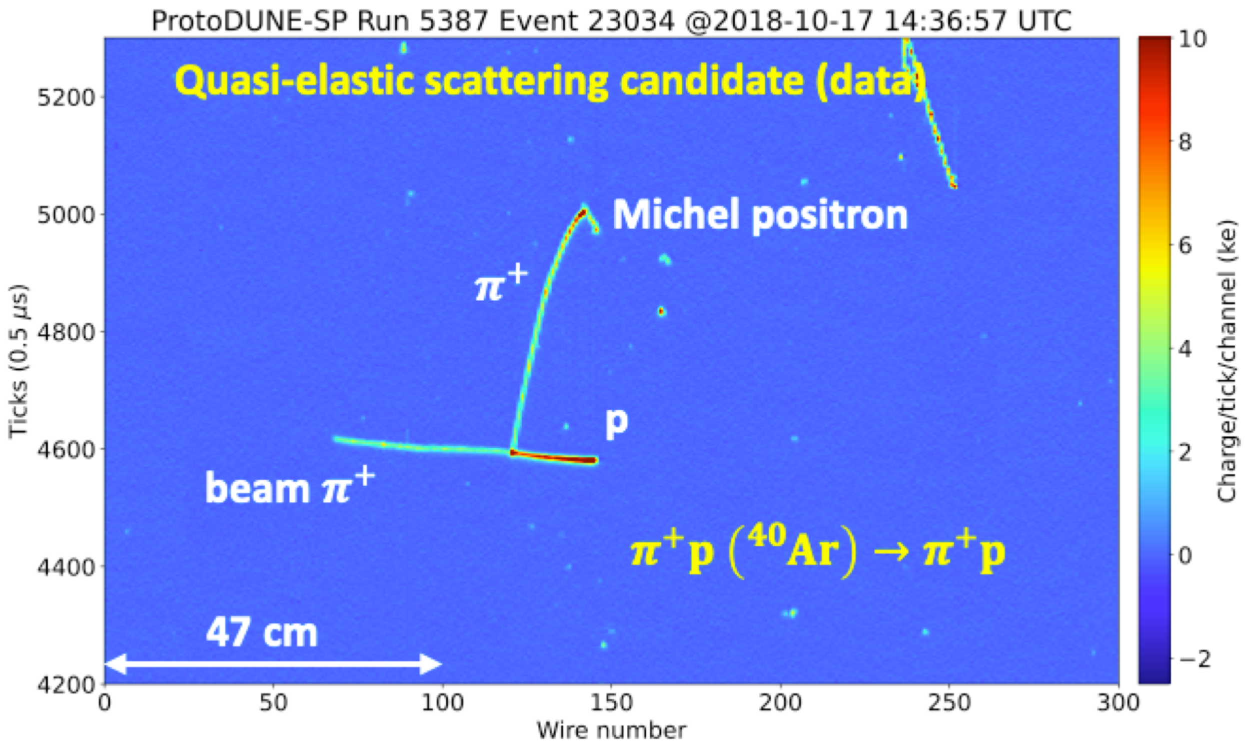


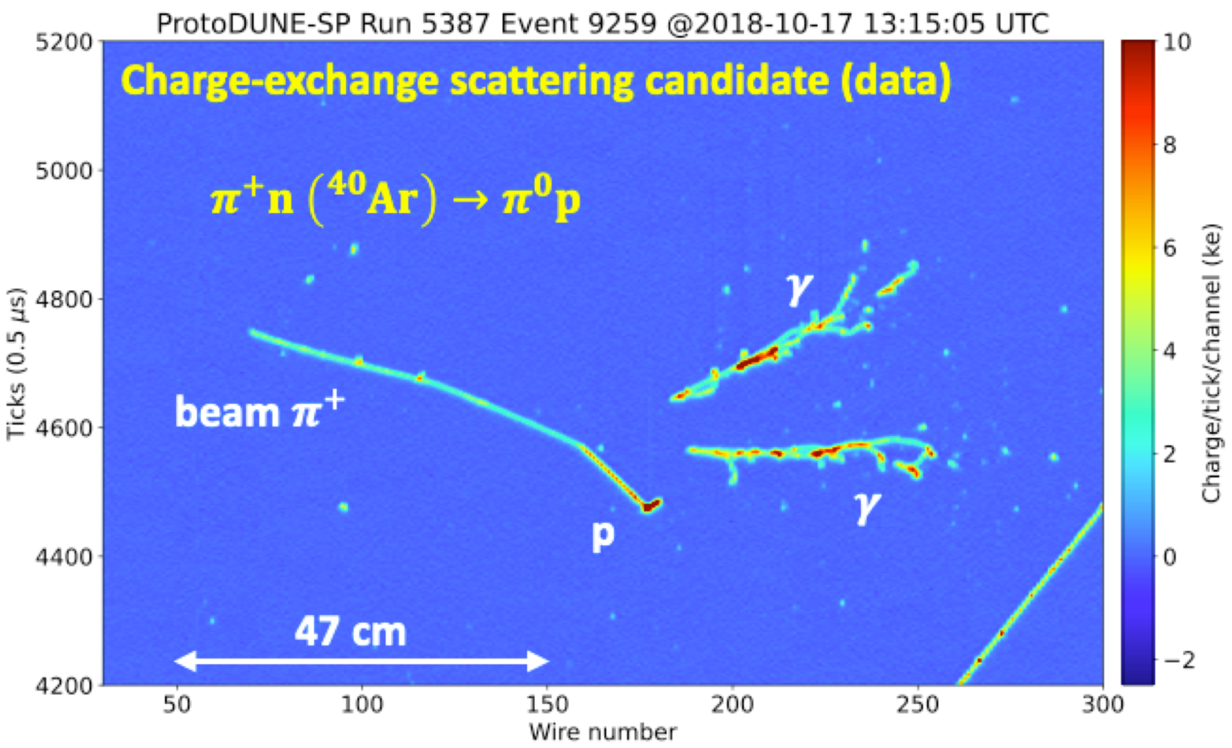
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

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

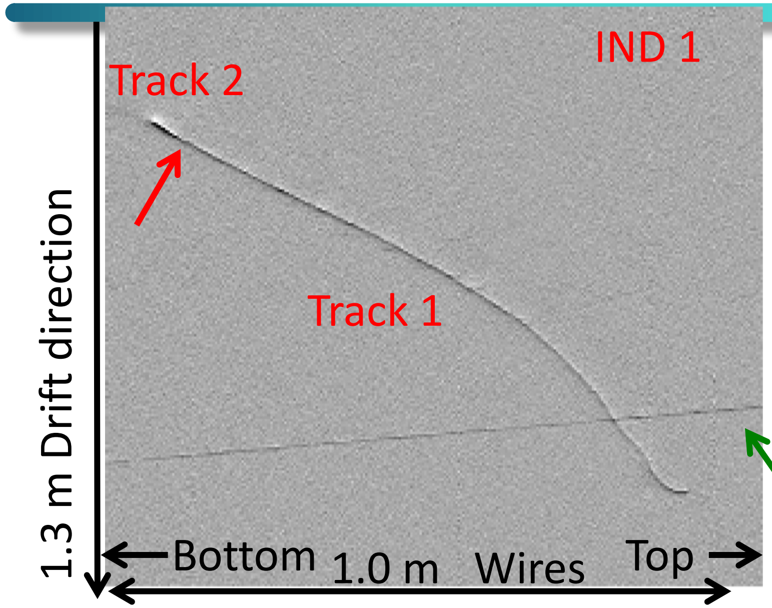
ProtoDUNE (2018-)

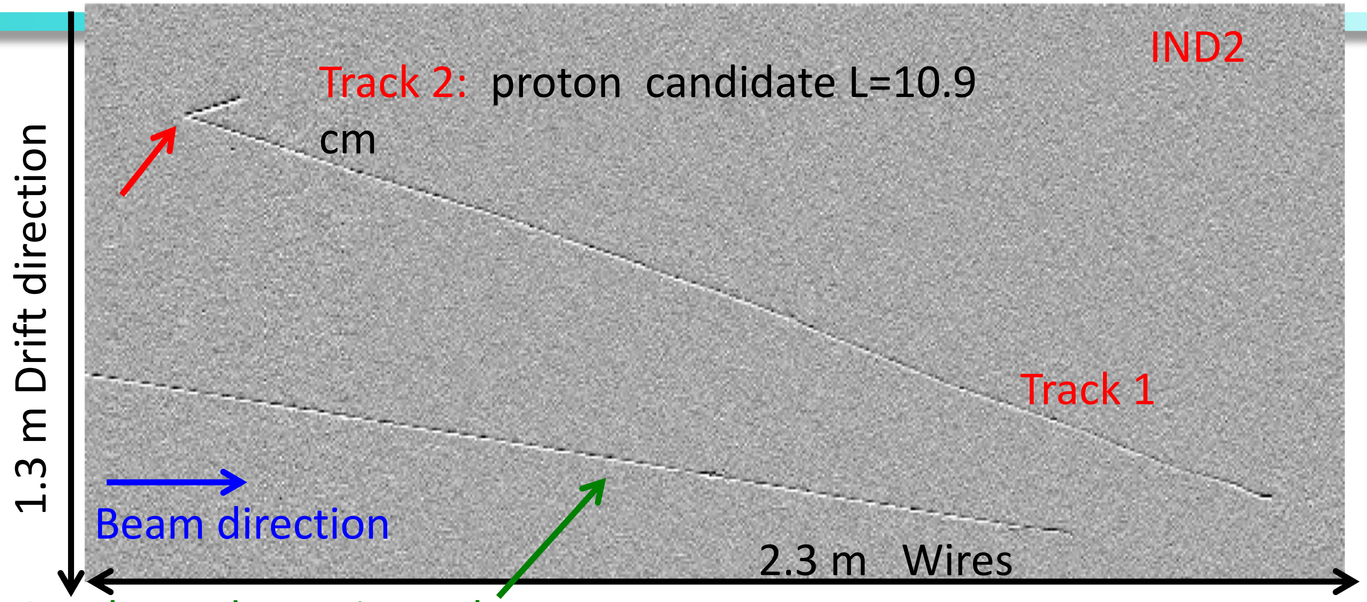
In ProtoDUNE all reaout electronics, including the digital part is in LAr, directly attached to the wires. The input capacitance is significantly reduced, due to the absence of connecting cables → higher signal to noise ratio (≈ 40 for single wire signals from m.i.p.).



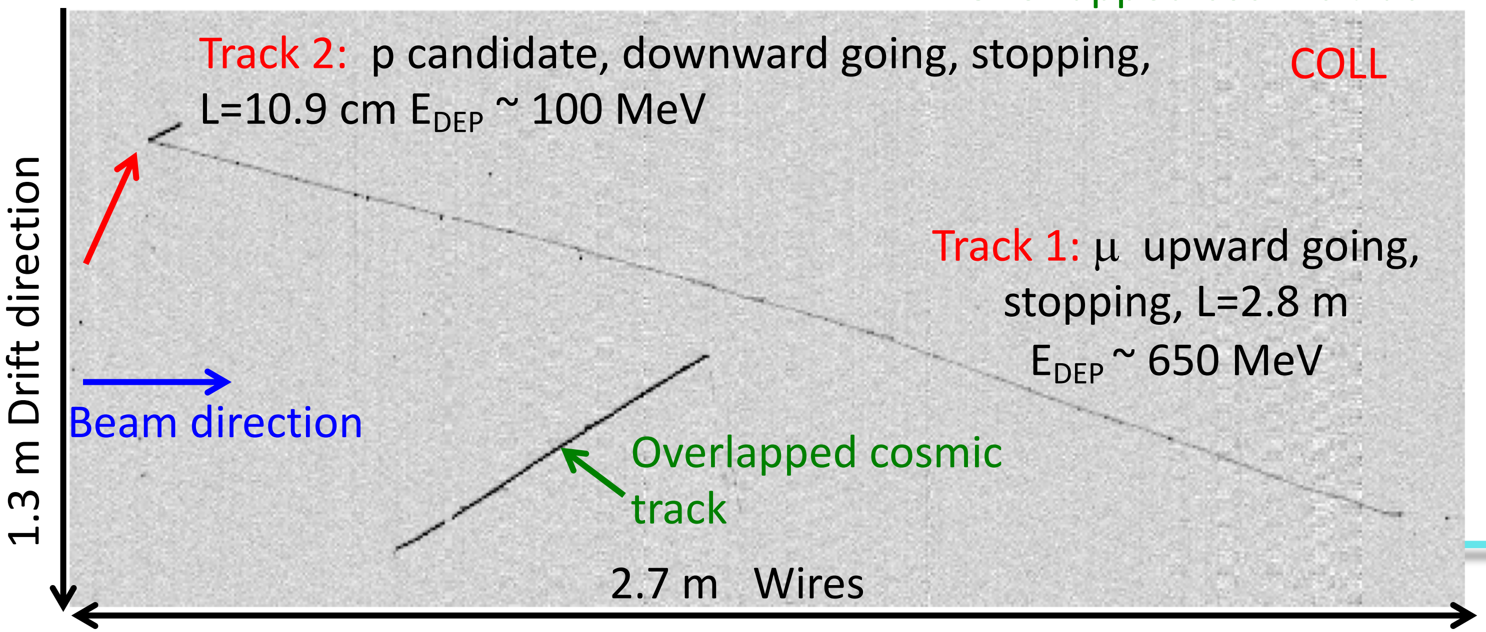


ICARUS/SBN-FD (2020-) – BNB ν_μ CC candidate

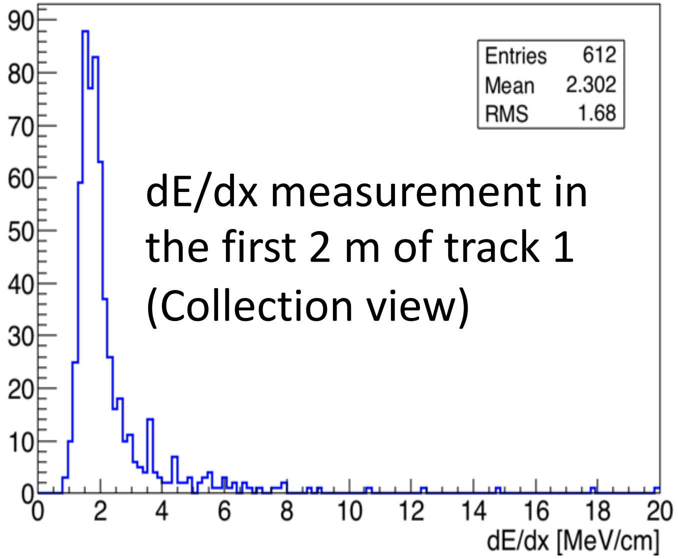




Overlapped cosmic track

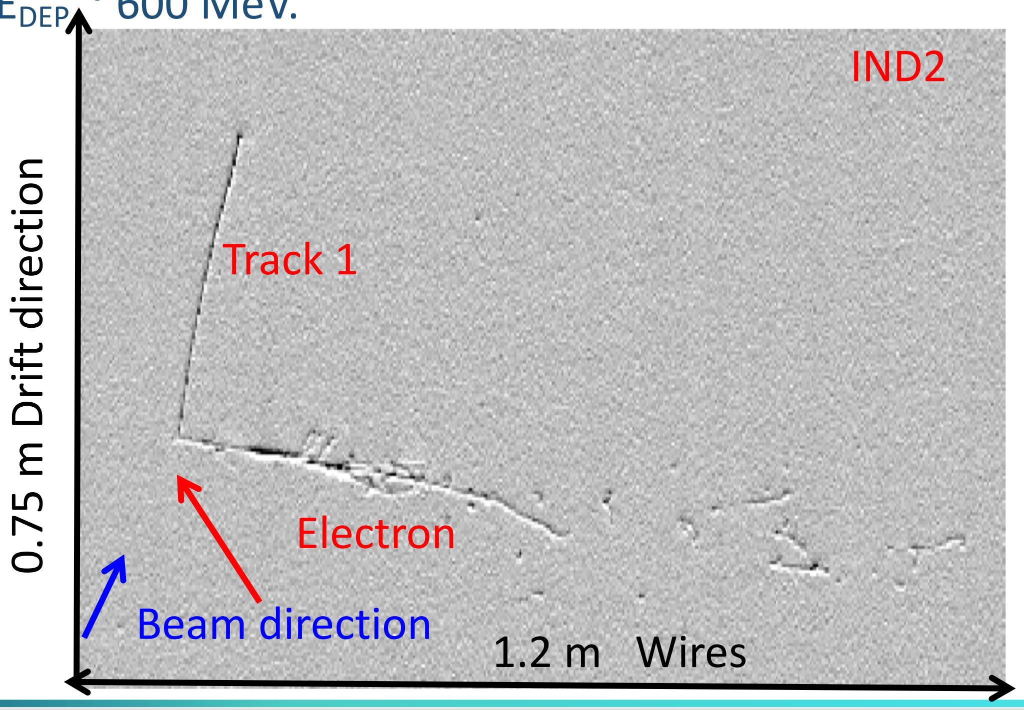


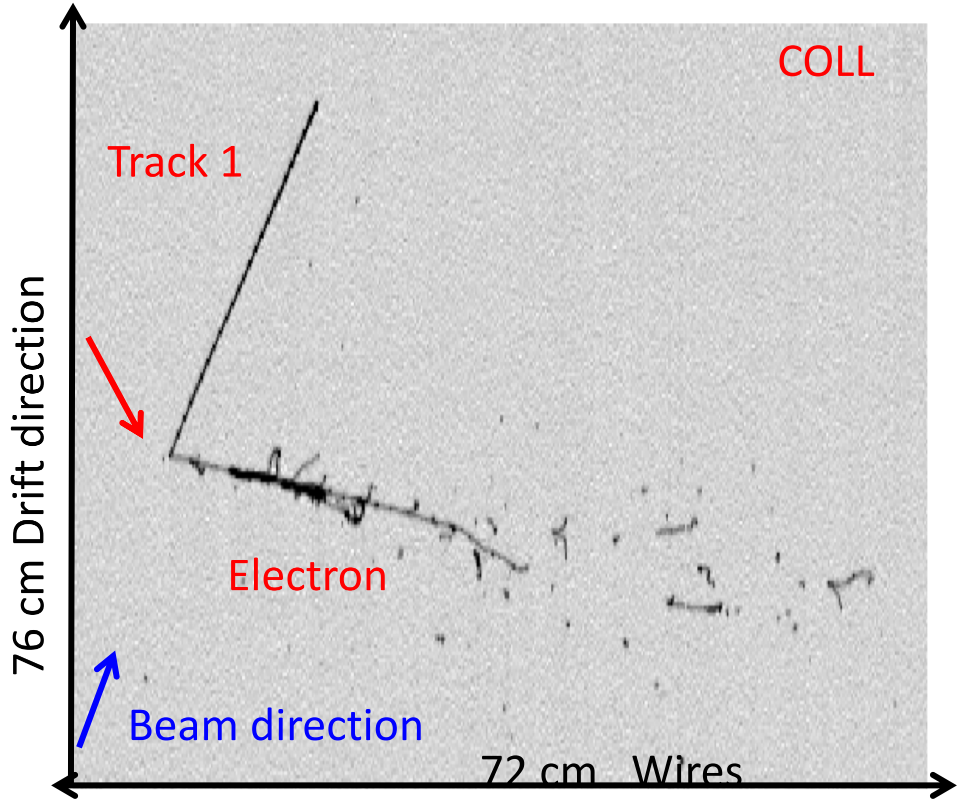
Total E_{DEP} ~ 750 MeV



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

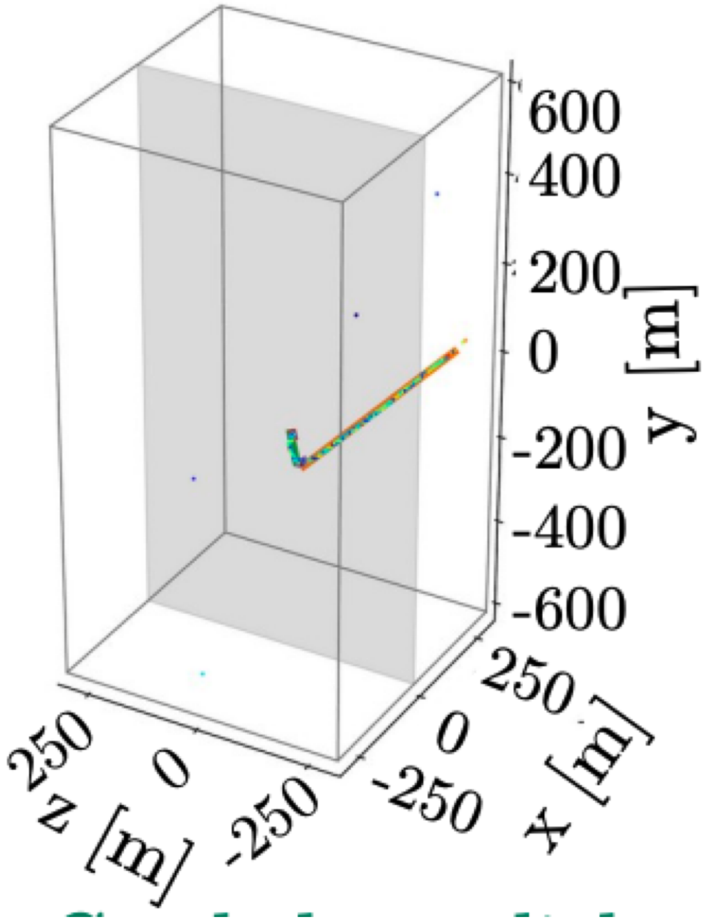
- ✓ Contained Q.E. electron neutrino candidate with two particles at the primary vertex (indicated by red arrows), E_{DEP} ~ 800 MeV:
  - ✓ Track 1 is the upward going hadron track stopping inside L= 43 cm: proton or pion candidate;
  - ✓ The beginning of the electron shower is clearly visible, E_{DEP}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



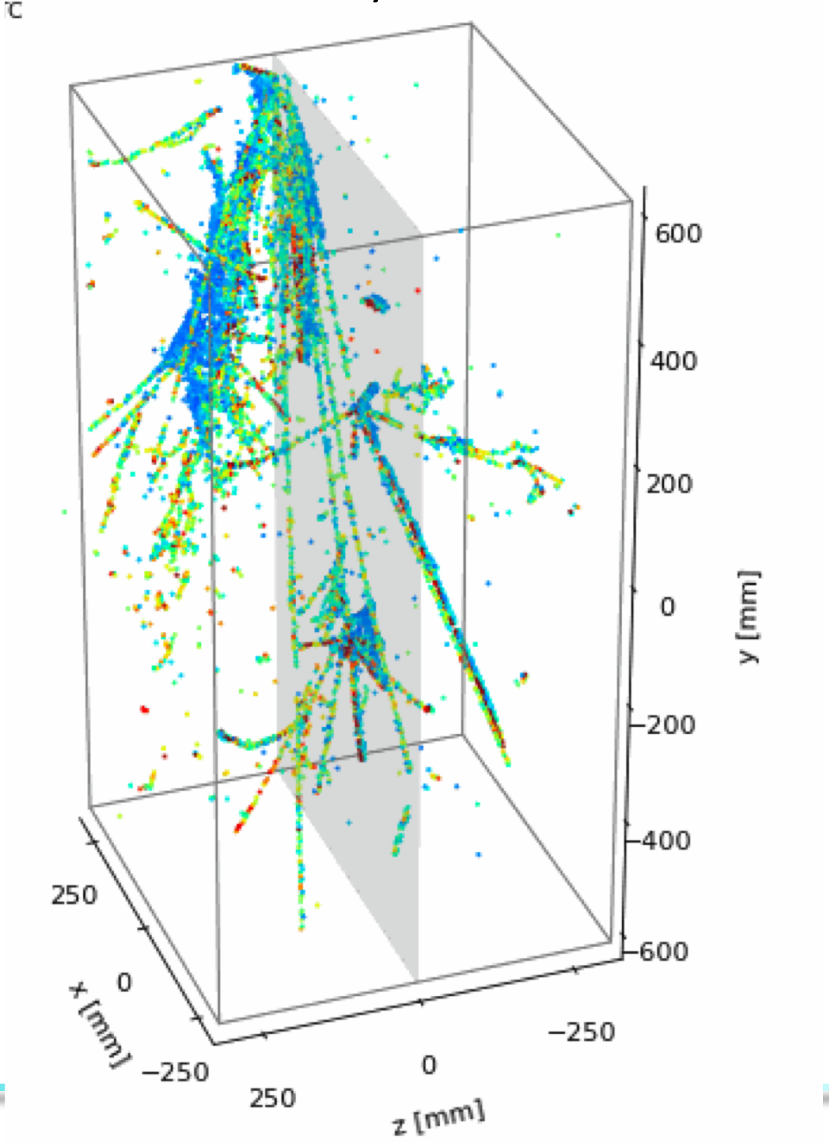


ND-LAr events from pixelated readout in prototype Module 0

Stopping muon



Cosmic rays showers



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, it requires 150 kV. 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 ($k^{(i)}$ = adsorption rate for the i-th impurity of concentration $N^{(i)}$):

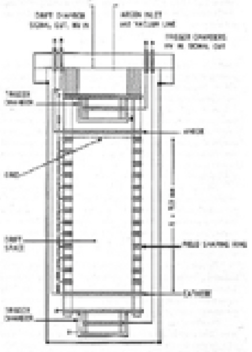
For $O_2\ , k \approx 10^{11} l\ mol^{-1} s^{-1}$

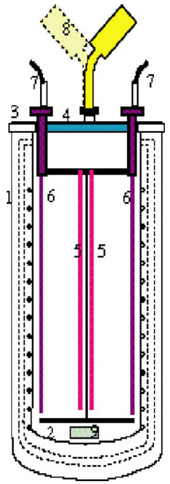
  - ➔ A concentration of 0.03 ppb Oxygen equivalent gives: τ = 10 ms.
  - ➔ The present record, in terms of LAr purity, has been achieved in ProtoDUNE HD, with a maximum drift of 3.75 m, a maximum voltage of 175 kV and a maximum lifetime > 30 ms.

Milestone 2: LAr Purity

First purity monitor chamber

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



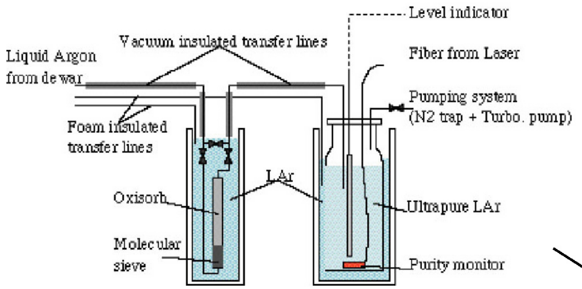


3 ton prototype

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

Liquid Phase purification

1994



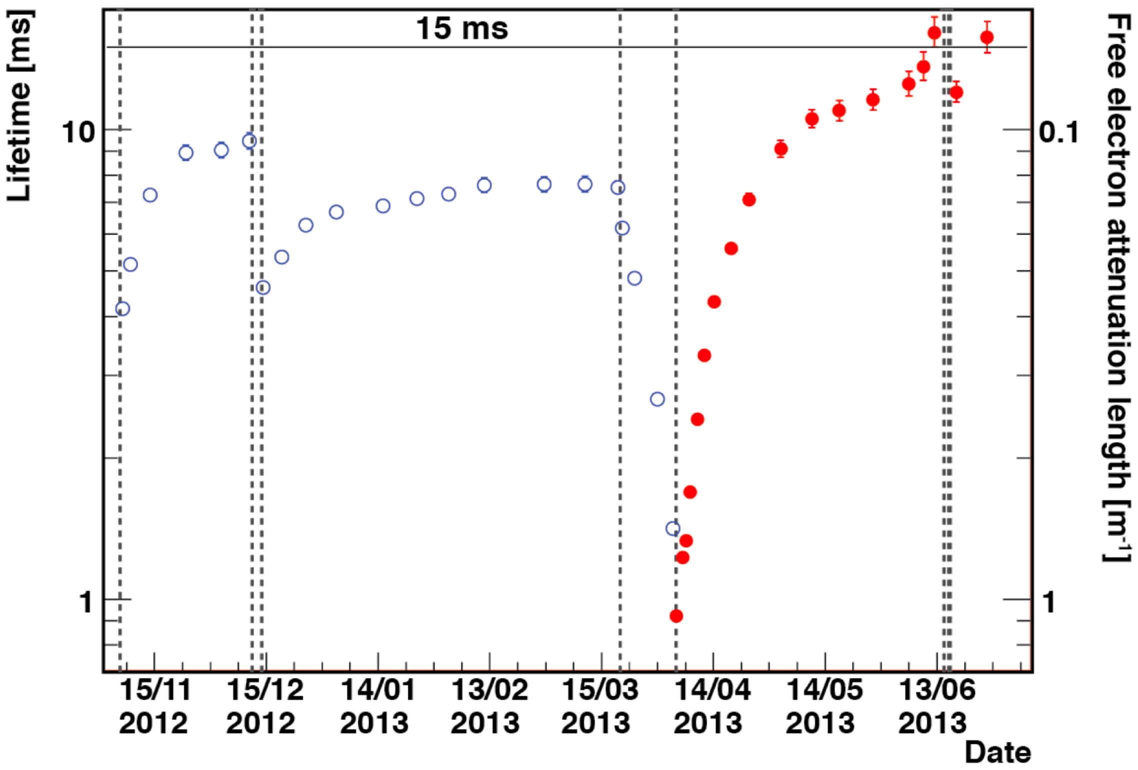
10 m^3 industrial prototype

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

Free electrons lifetime in LAr TPCs

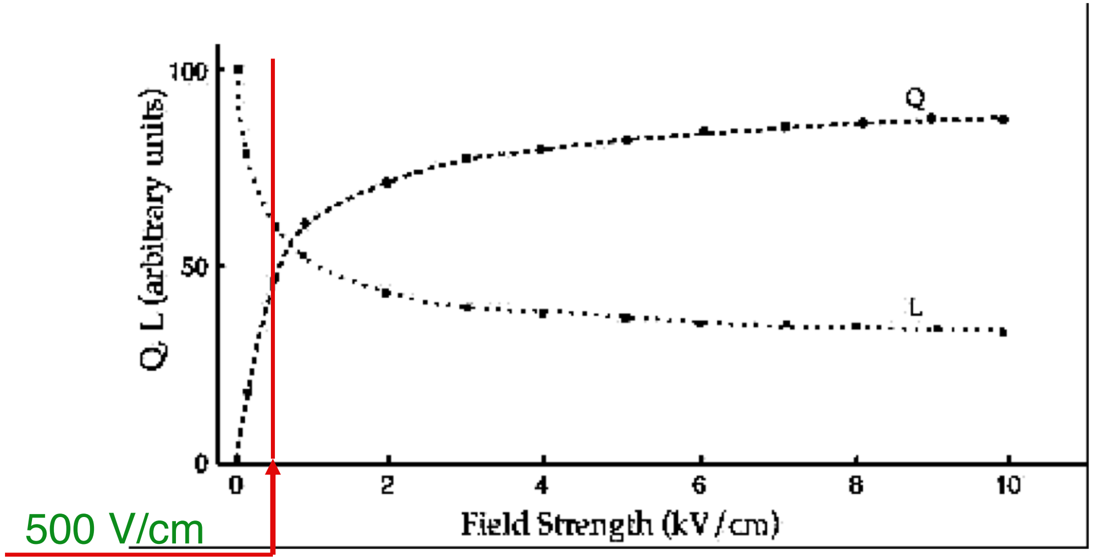
- The typical contamination in commercial LAr is O(0.2 ppm) for O_2 and O(0.5 ppm) for H_2O.
- A reduction of about 4 orders of magnitude is required to achieve long drift distances for large experiments.
- The initial removal of air and other impurities from the LAr volumes is achieved by vacuum pumping 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



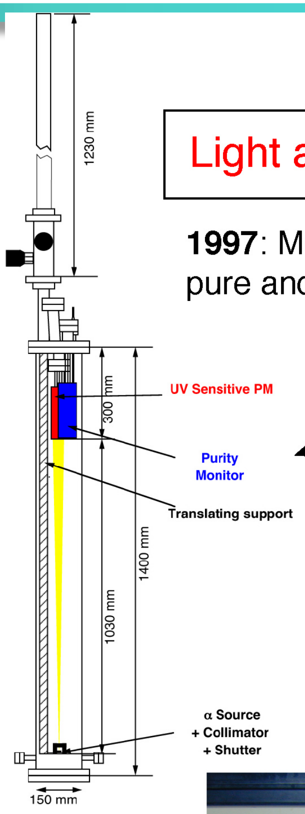
The t = 0 time mark

- 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
    - ➔ Y = 4×10^4 photons / MeV @ 0 V / cm
    - ➔ λ_{att} ≈ 90 cm @ 128 nm; ≈ 180 cm @ 175 nm
    - ➔ Two time components: τ_S ≈ 6 ns, and τ_L ≈ 1.4 µs
    - ➔ Light yield is E- field dependent (Onsager)



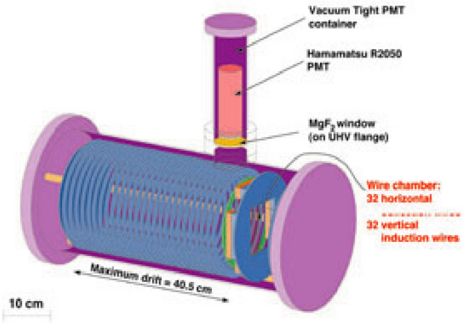
Electron recombination (E-dependent) contributes to scintillation light

Milestone 3: Scintillation in LAr



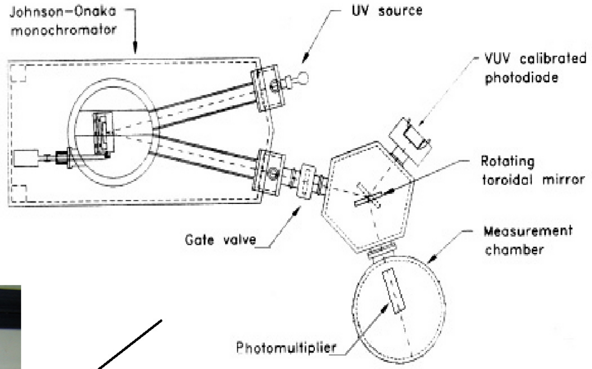
Light attenuation length

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

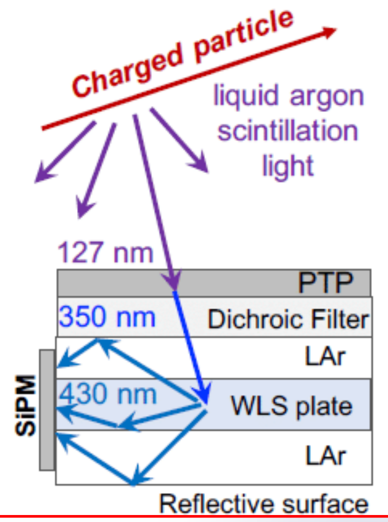
1999-2000: Wavelength shifters test and choice. Design and test of the final system for the T600

PM Choice and test

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

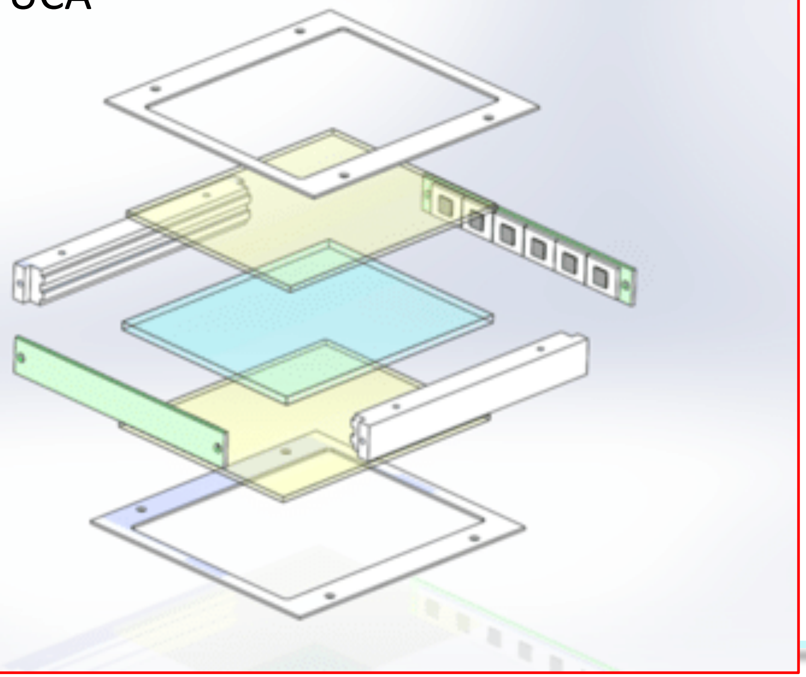
Detection of scintillation light in LAr

Principle of operation of an X-ARAPUCA



- 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).

X-ARAPUCA



Detection of scintillation light in LAr

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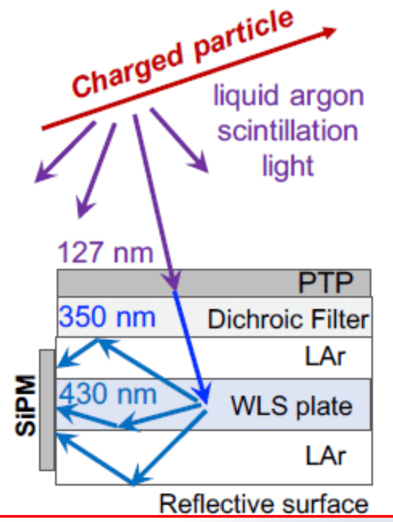
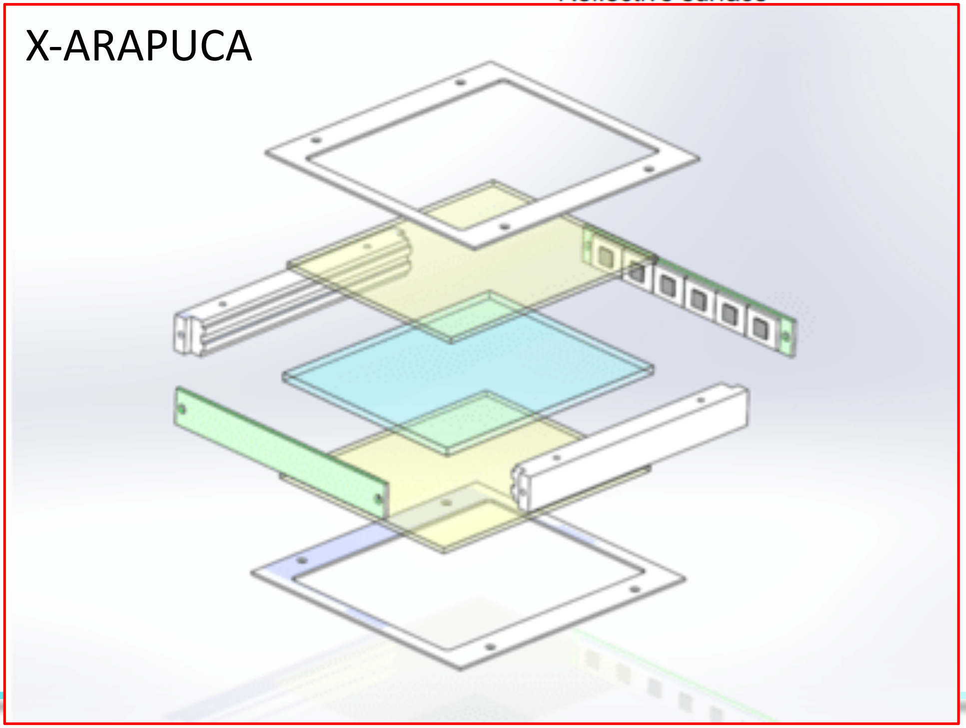
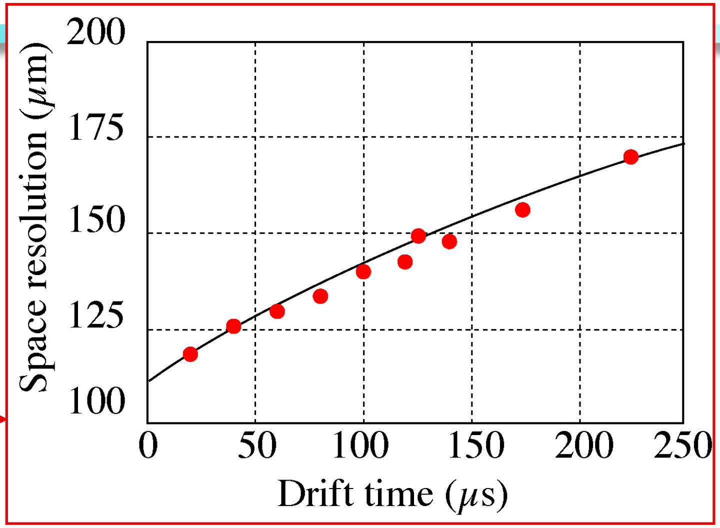
Principle of operation of an X-ARAPUCA

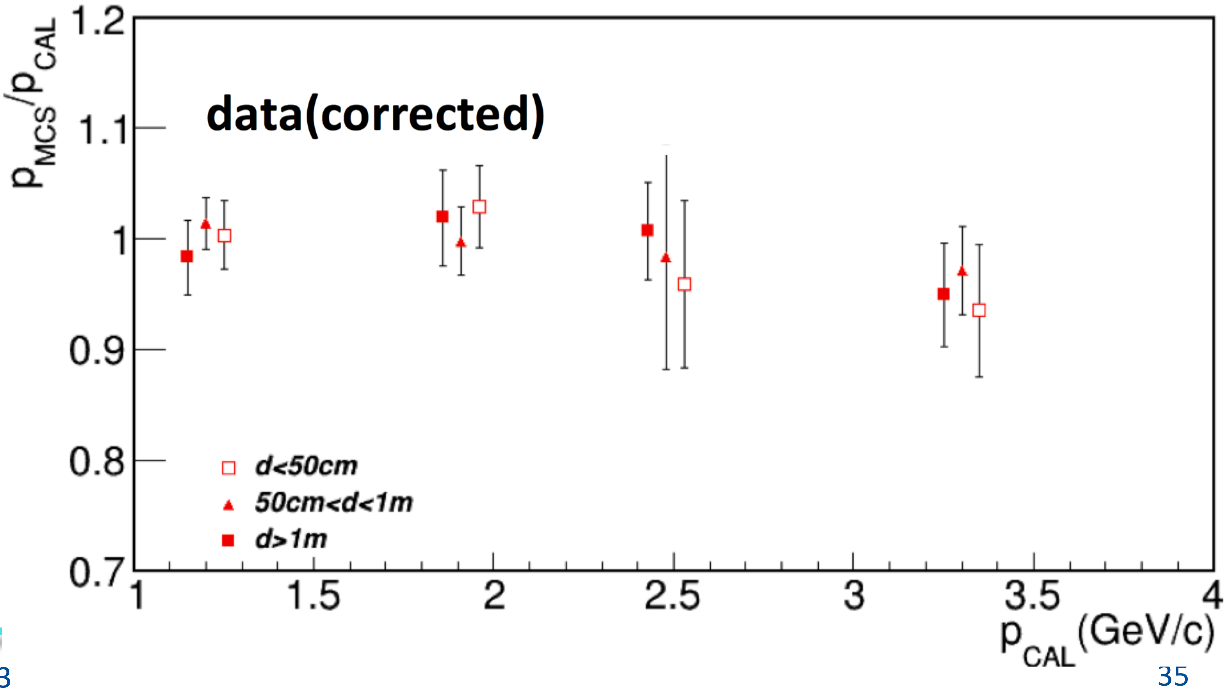




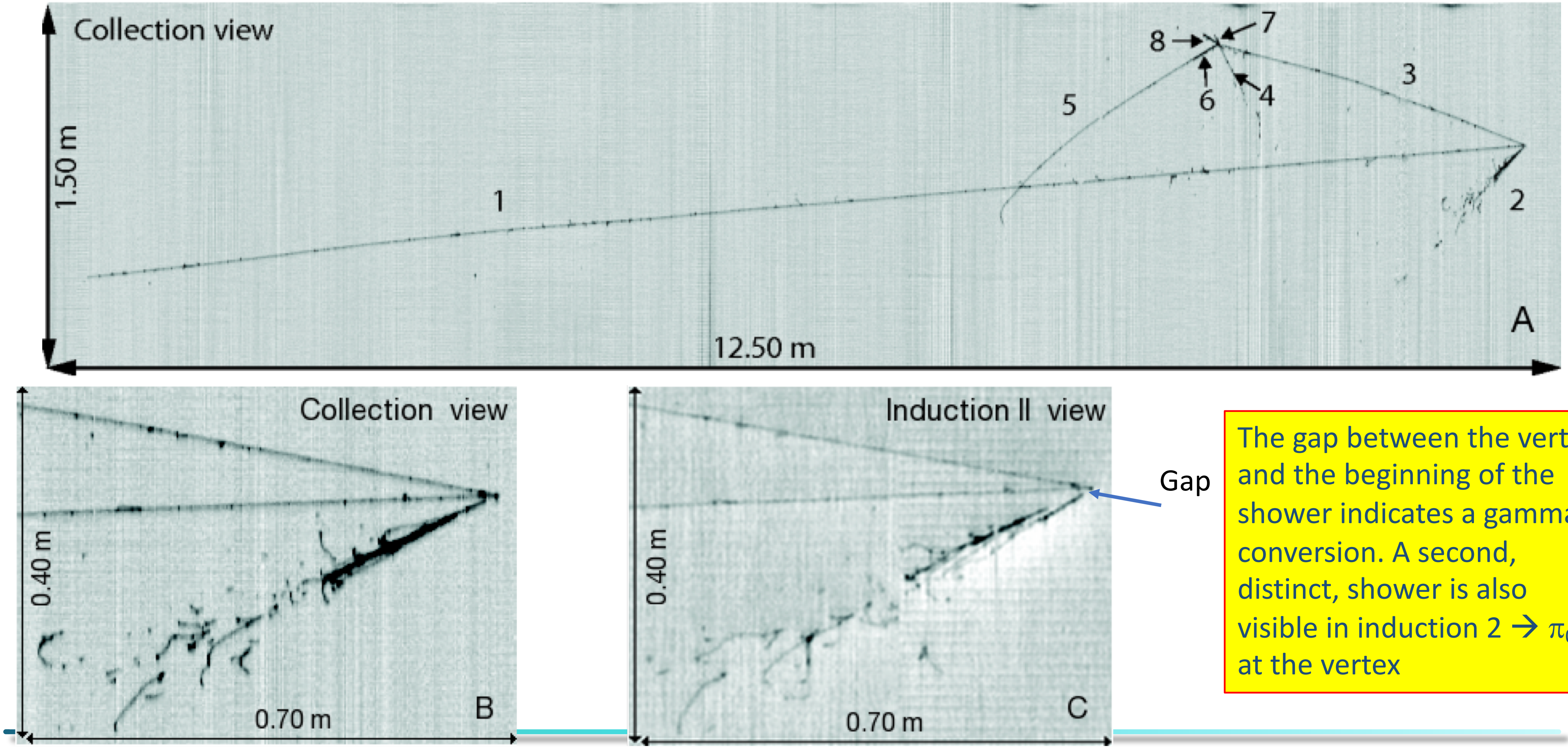
Detector's performance

- Self-triggering
- Continuously sensitive
- High granularity: wires pitch 2÷5 mm
  - Space resolution: $\sigma_{x,y} \approx 1\ mm$; sz ≈ 150µm ; 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





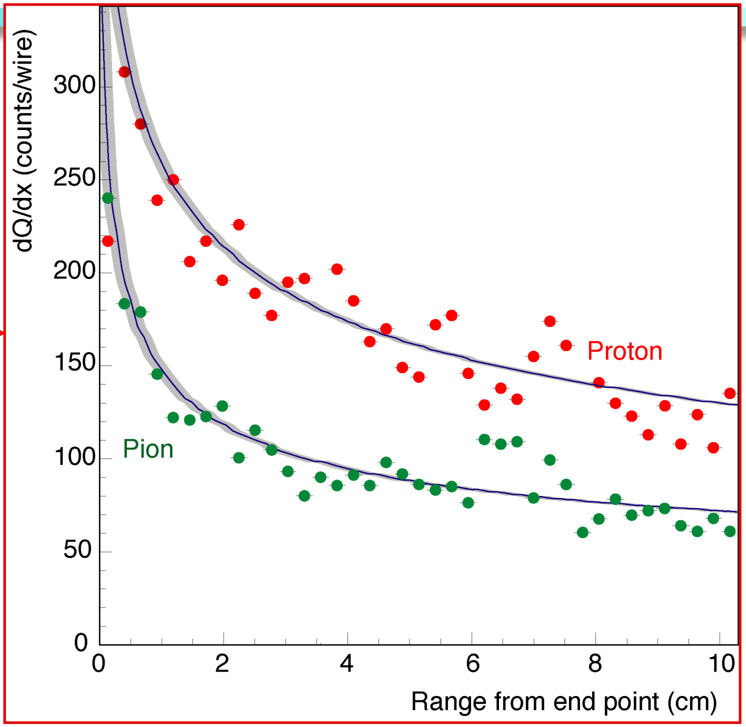
Detector’s performance (cont.) – ν_μ CC event @ CNGS beam



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.

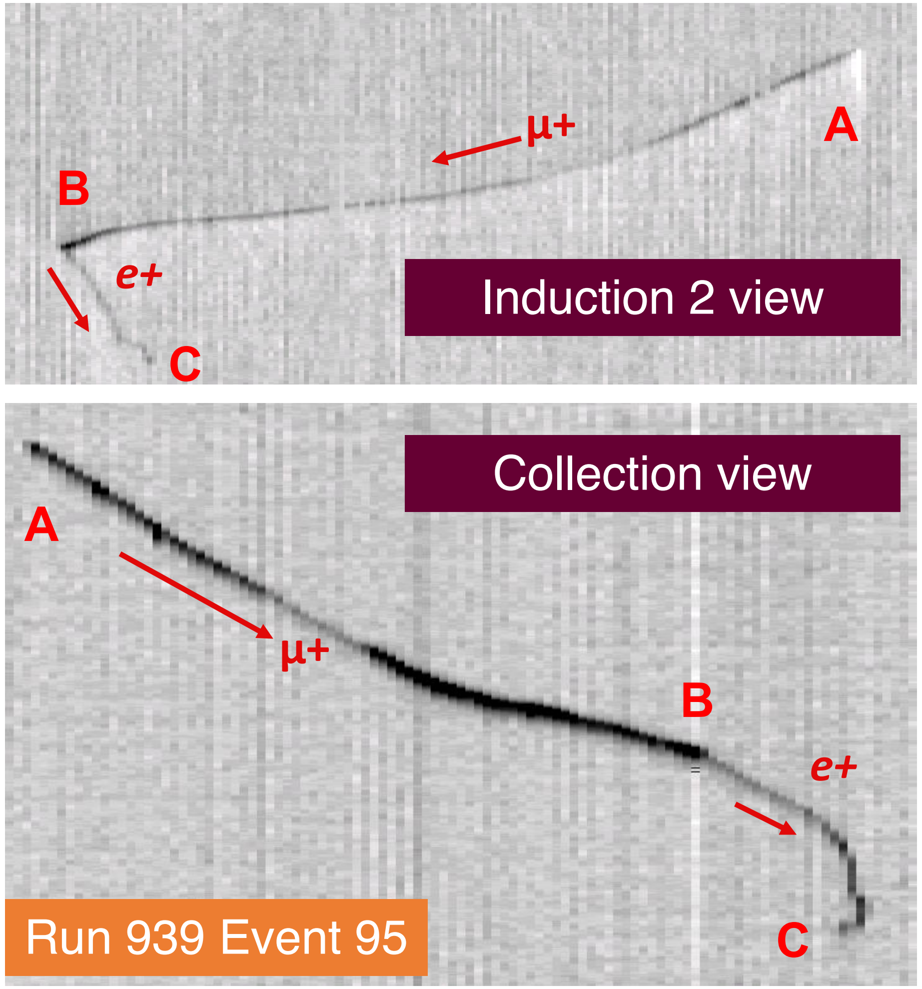


RESOLUTIONS

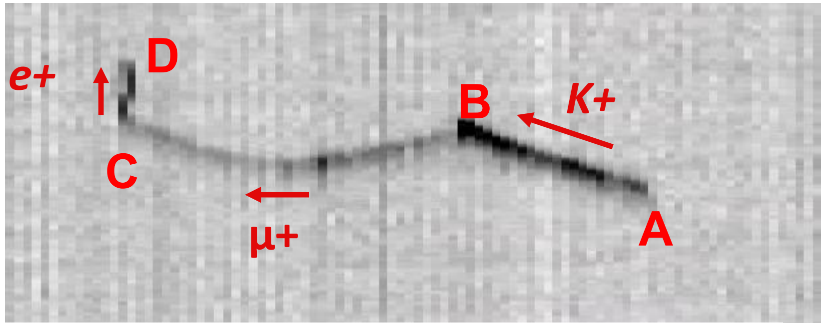
Low energy electrons:	σ(E)/E = 7% / √E(MeV)
Electromagn. showers:	σ(E)/E = 3% / √E(GeV)
Hadronic showers (pure LAr):	σ(E)/E = 16% / √E(GeV) + 1%
Hadronic showers (+TMG):	σ(E)/E = 12% / √E(GeV) + 0.2%

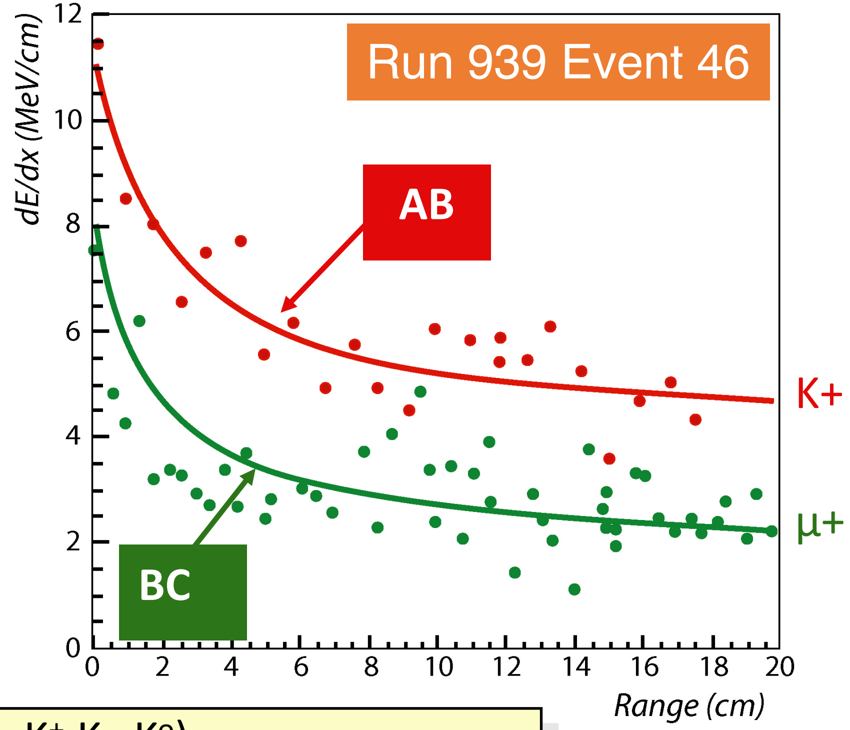
Detector's performance (cont.)

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



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

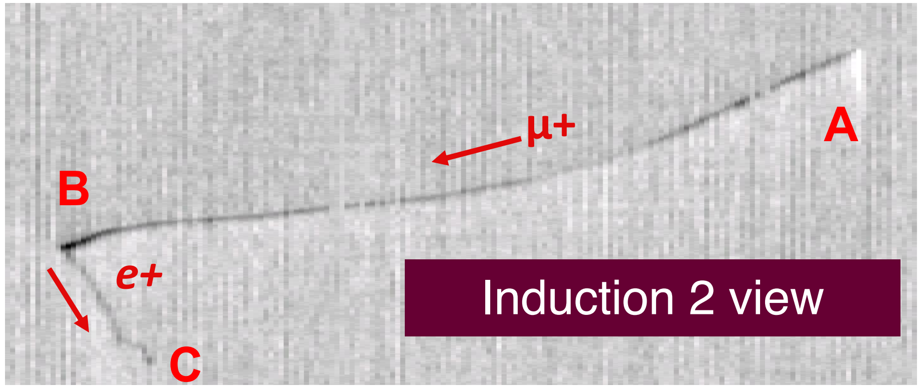


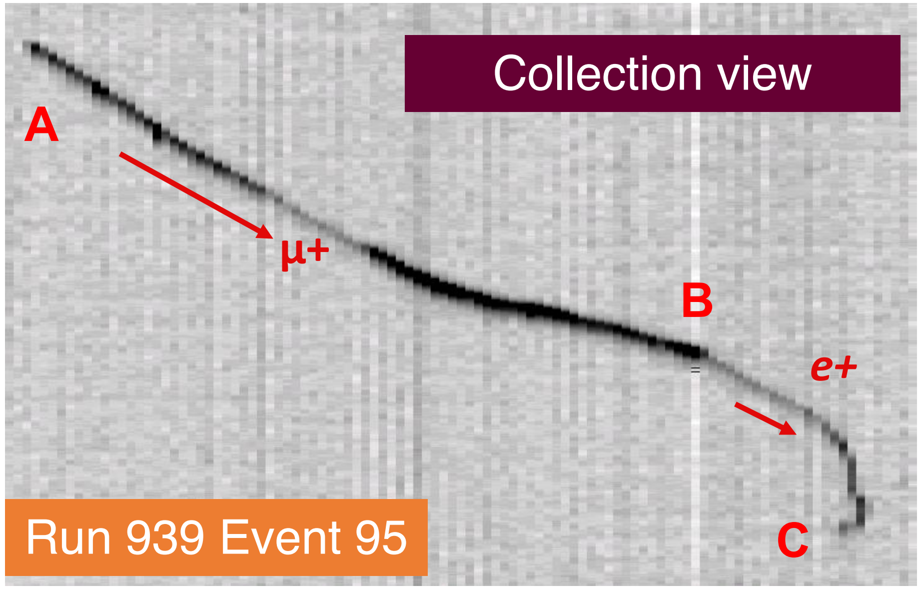


Particle identification by characteristic decay (μ^+,μ^-,K^+,K^-, K^o)

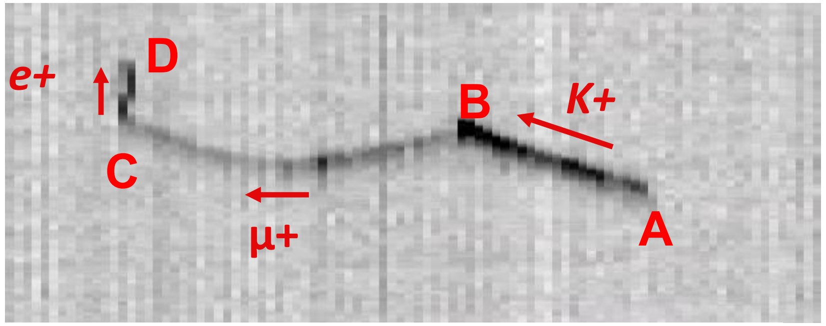
Reconstruction in 3D

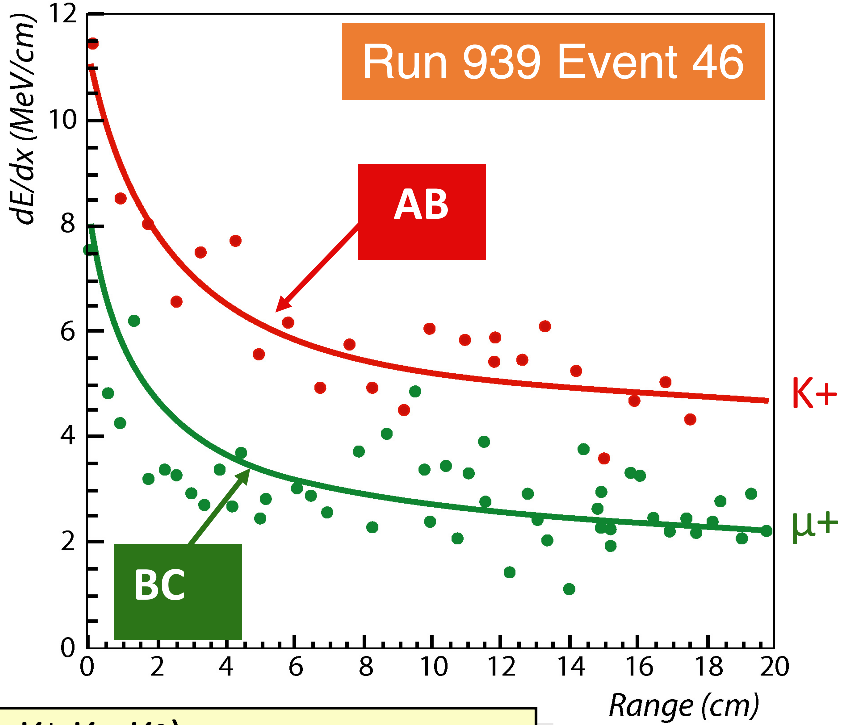
$\mu^+[AB] \rightarrow e^+[BC]$





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

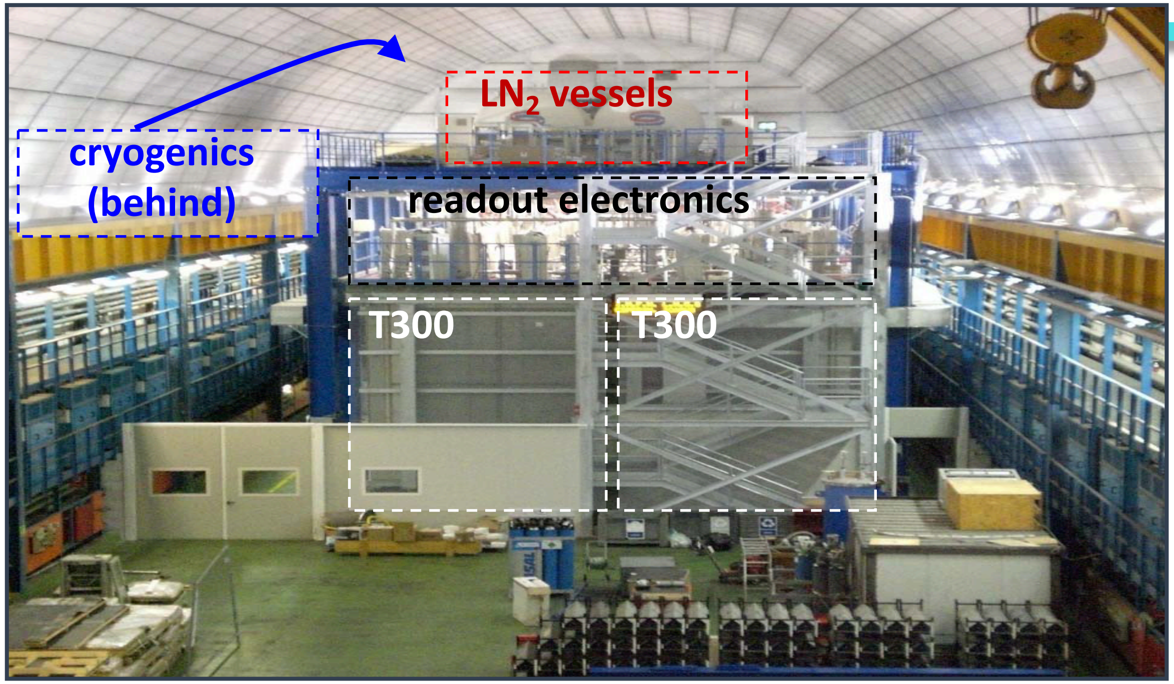


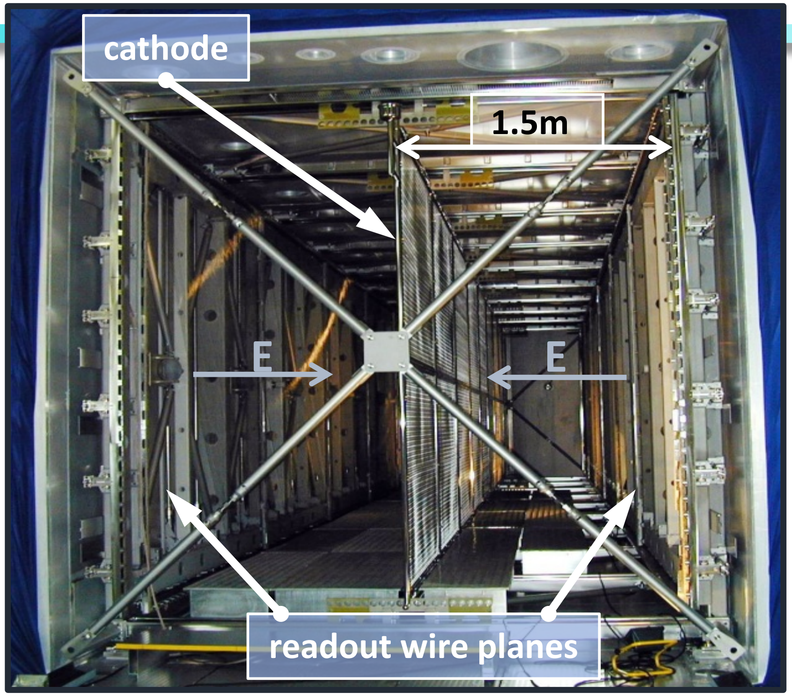


Particle identification by characteristic decay (μ^+,μ^-,K^+,K^-, K^o)

Practical Implementations

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

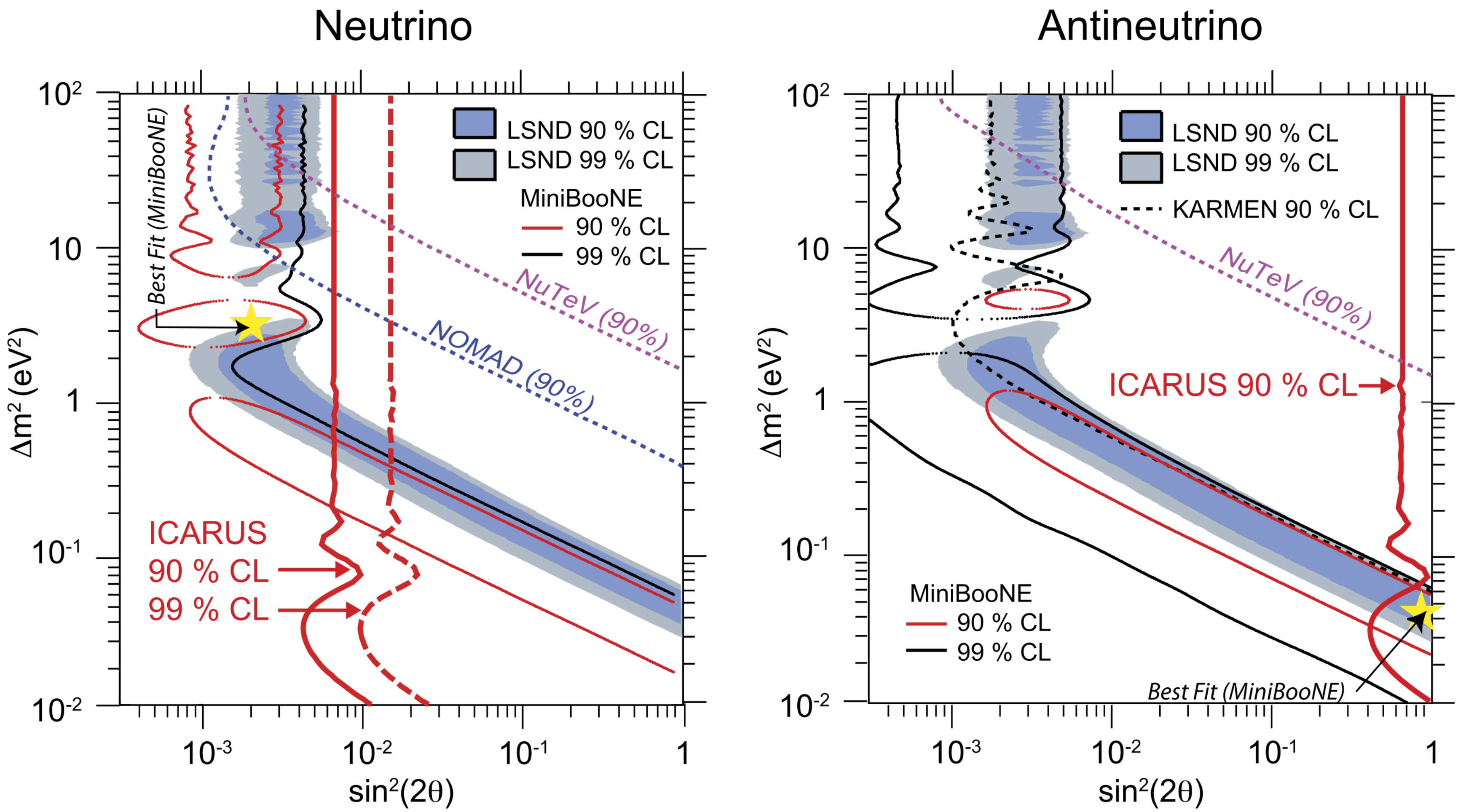




- Two identical modules
  - 3.6x3.9x19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV; E = 0.5 kV/cm
  - v-drift = 1.55 mm/µs
  - Sampling time 0.4µs (sub-mm resolution in drift direction)
- 4 wire chambers:
  - 2 chambers per module
  - 3 wire planes 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

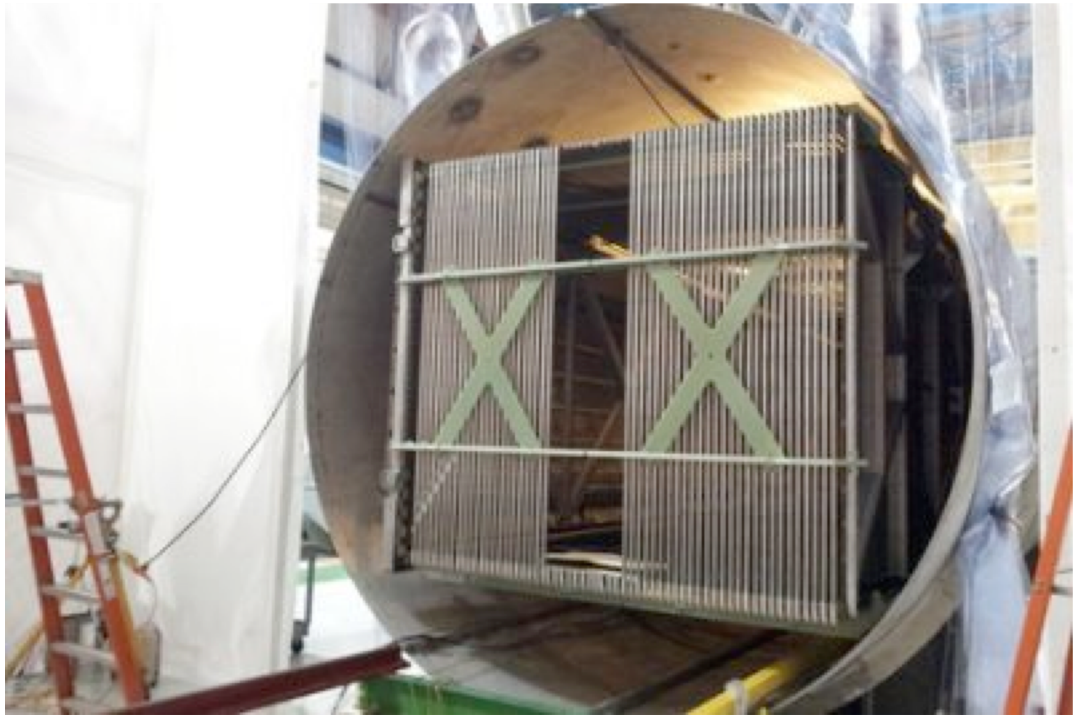
Physics with ICARUS in LNGS and with CNGS

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

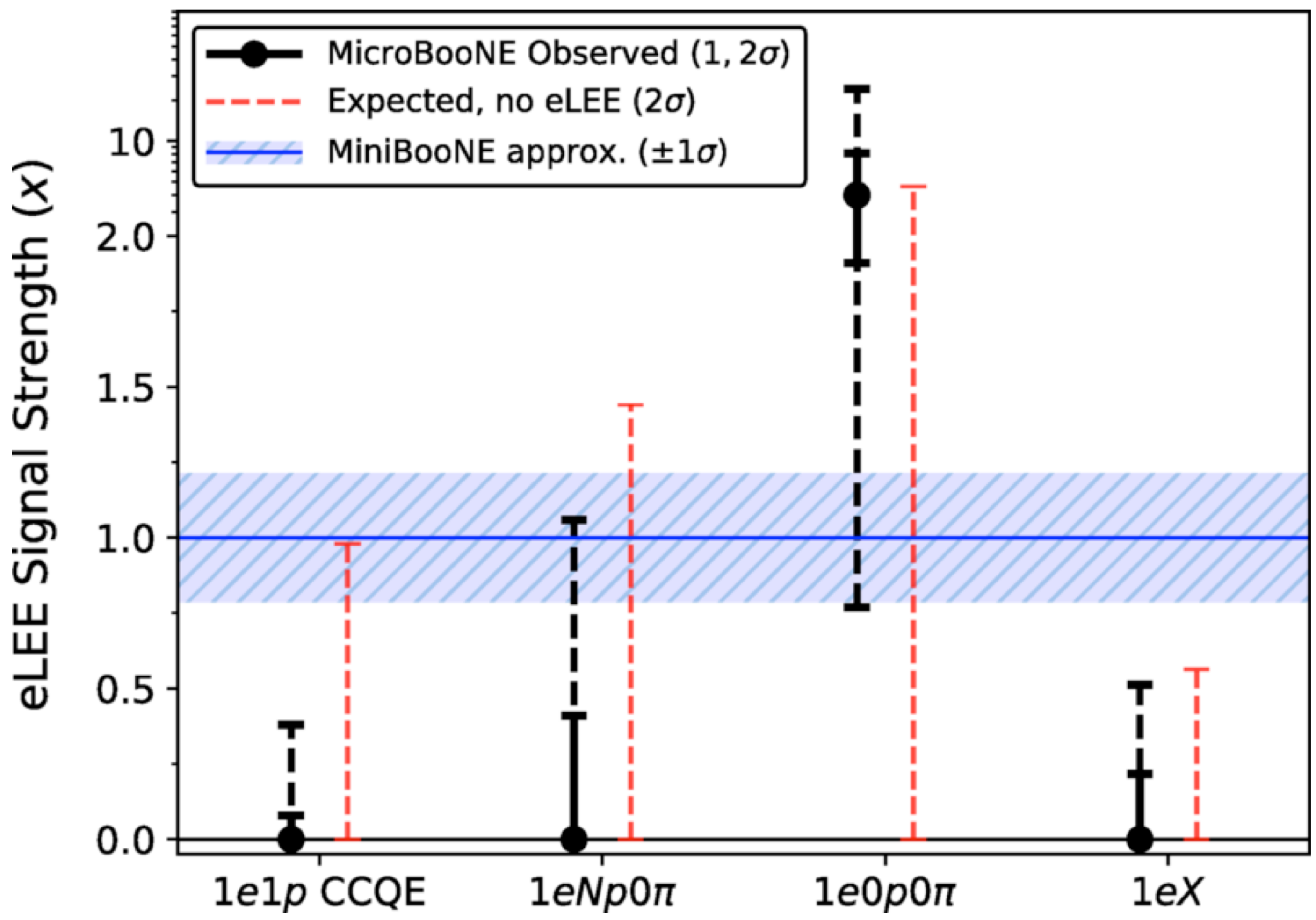


MicroBooNE (2015-2021)

- 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.

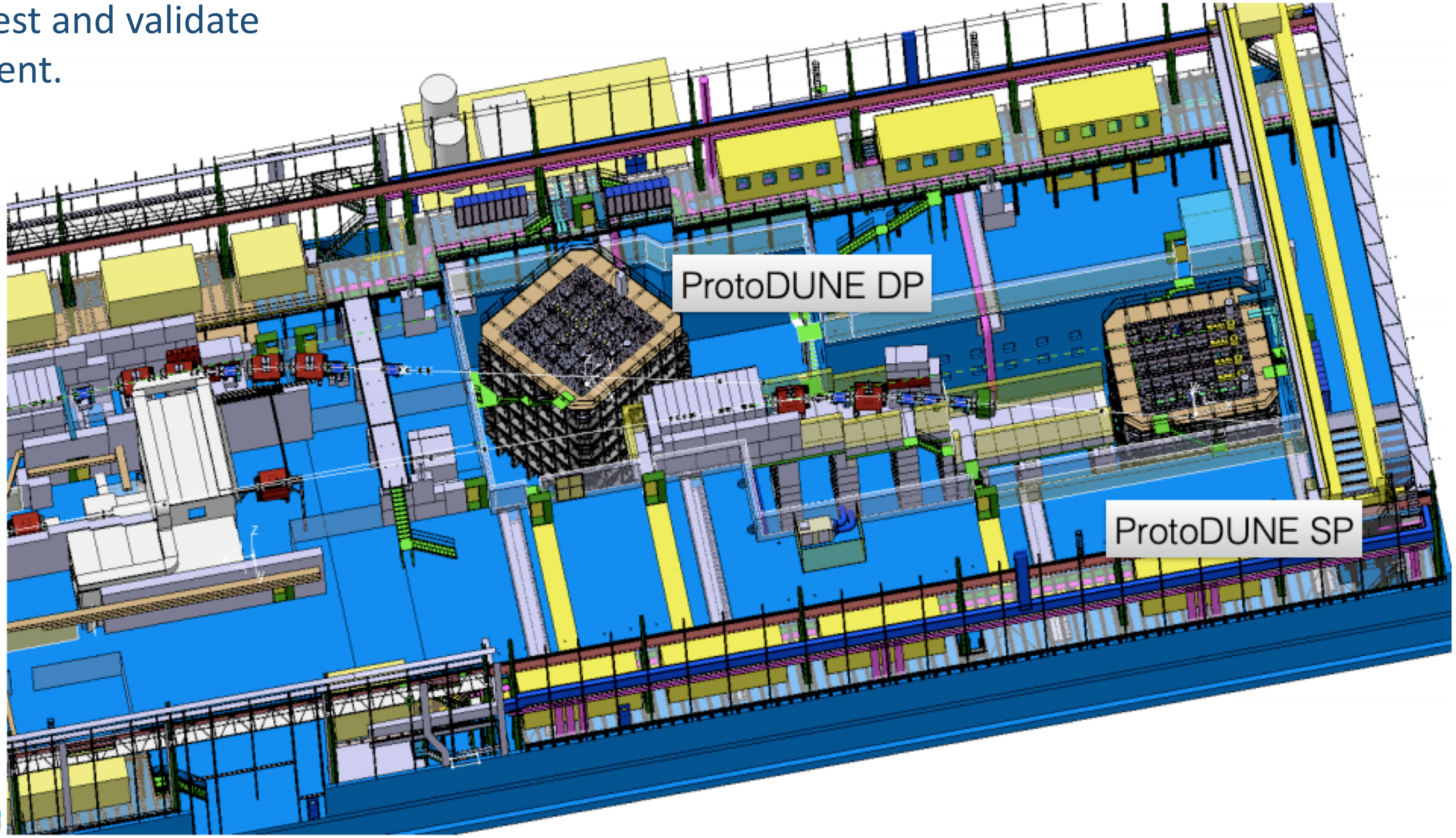


MicroBooNE: first results on Electrons Low Energy Excess (eLEE)



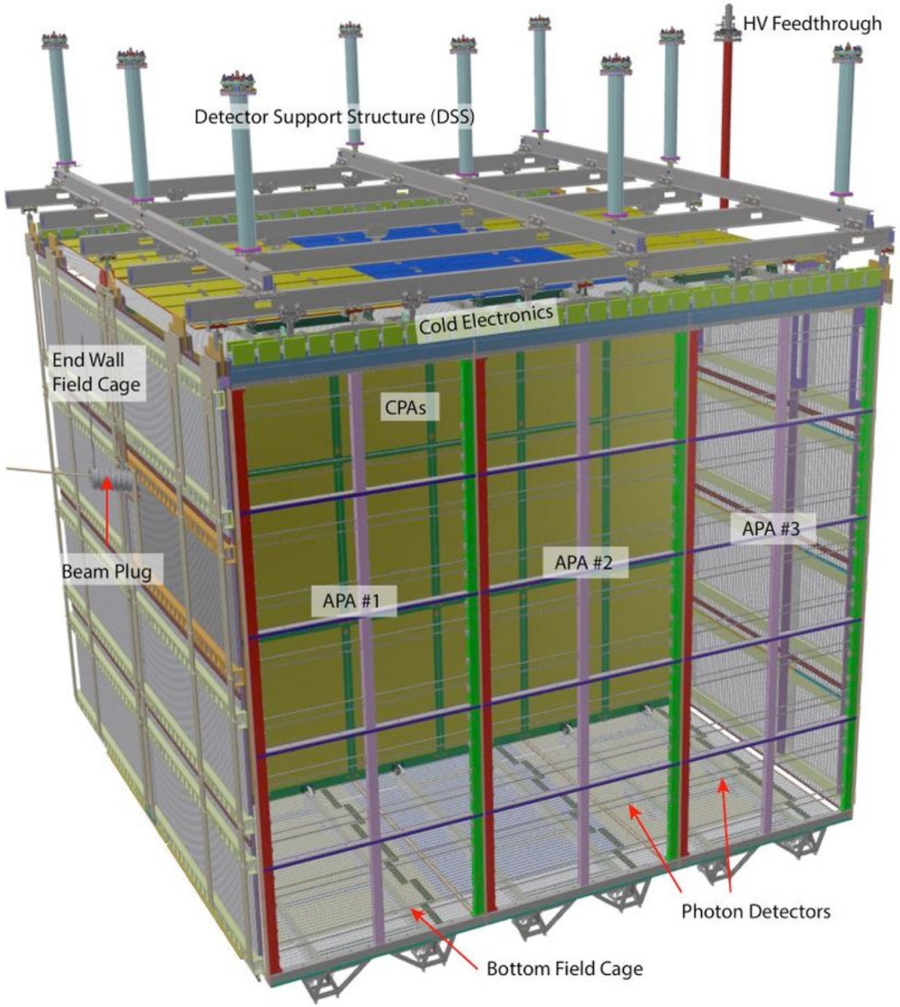
ProtoDUNE (2018 -)

- 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.

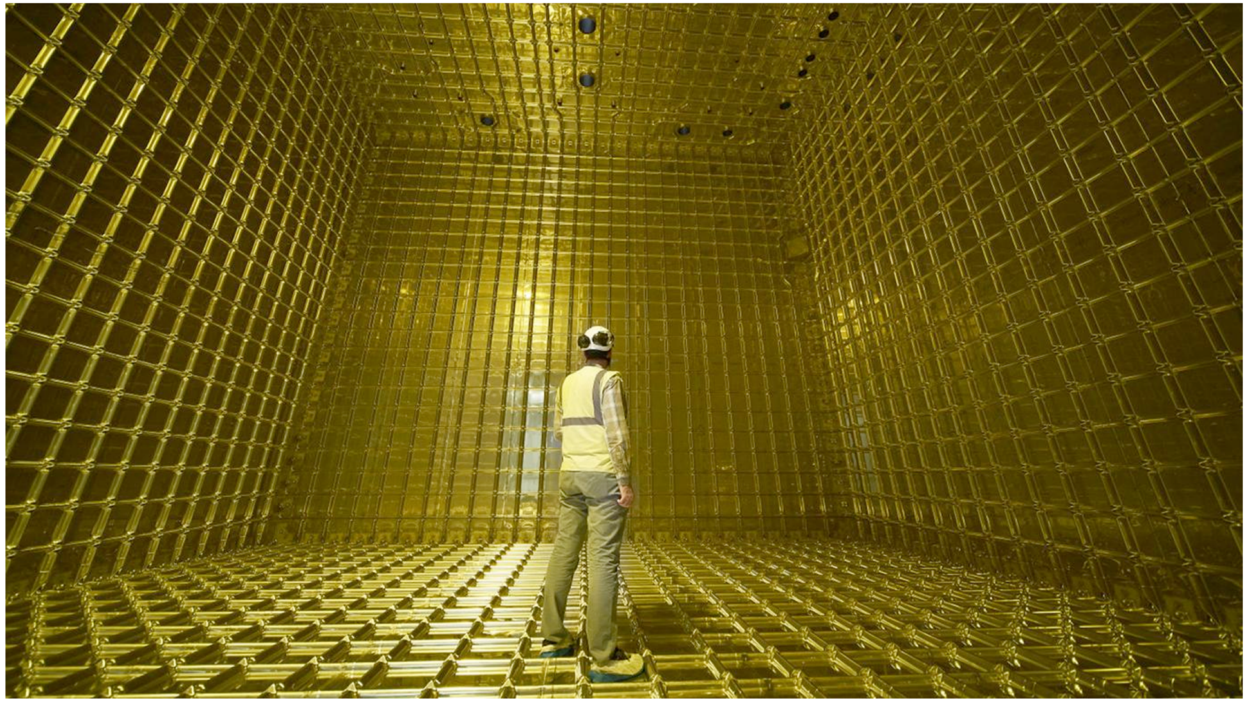


ProtoDUNE (2018-)

ProtoDUNE Horizontal Drift

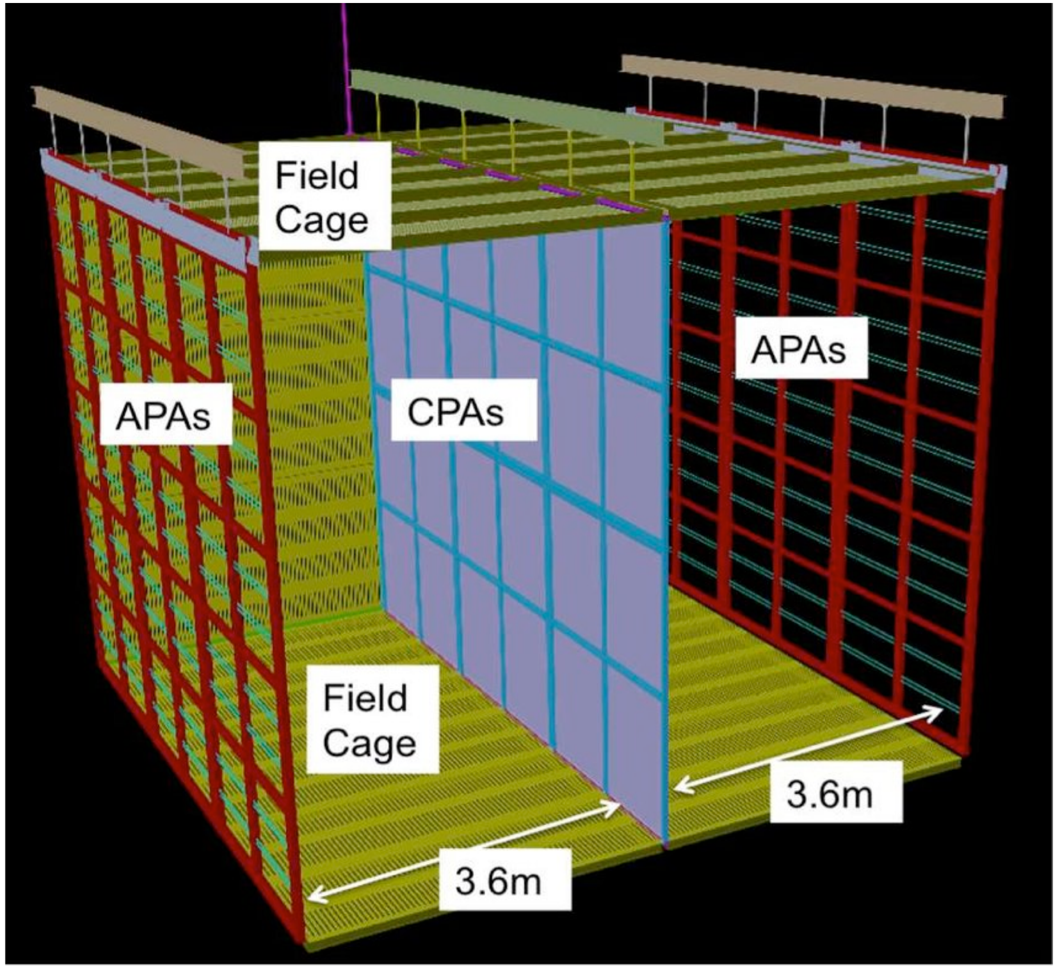


Membrane cryostat

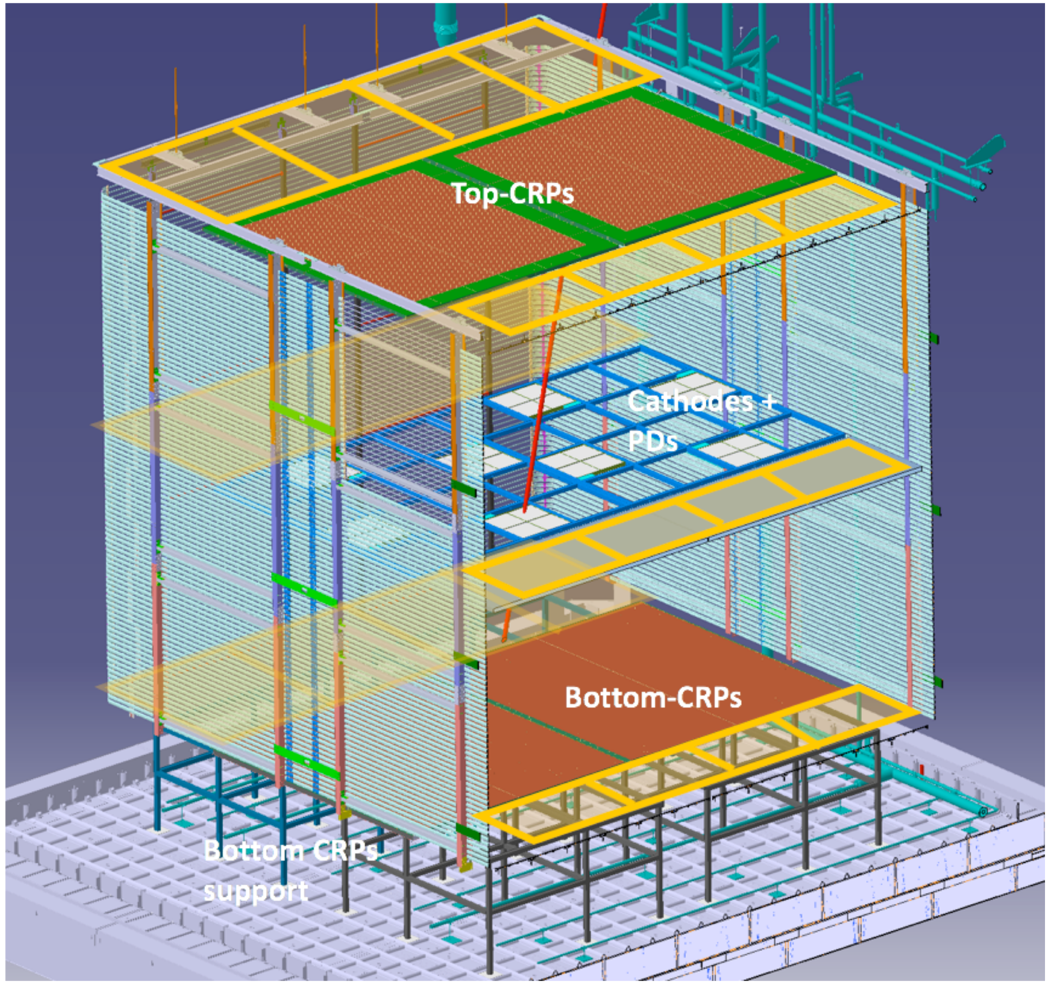


ProtoDUNE

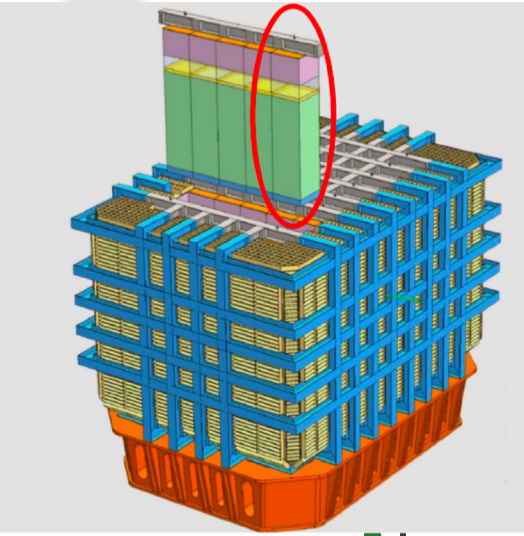
ProtoDUNE Horizontal Drift



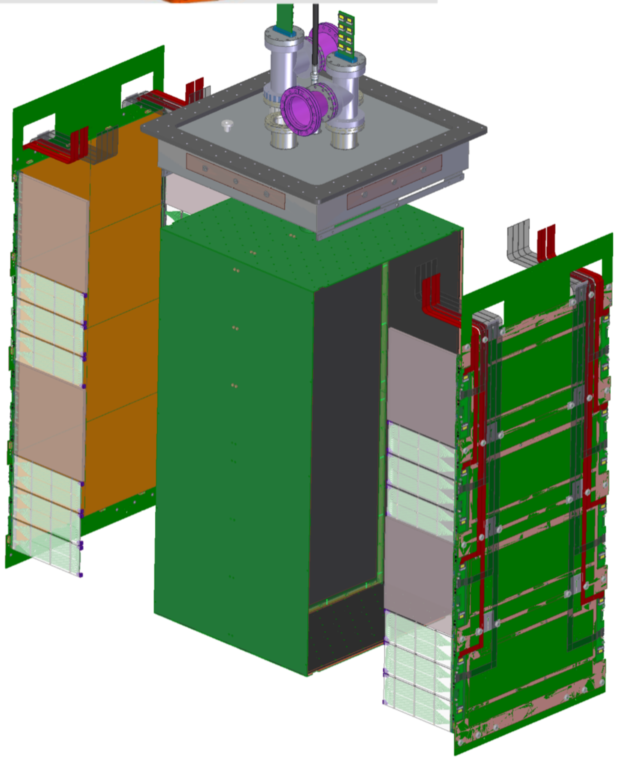
ProtoDUNE Vertical Drift



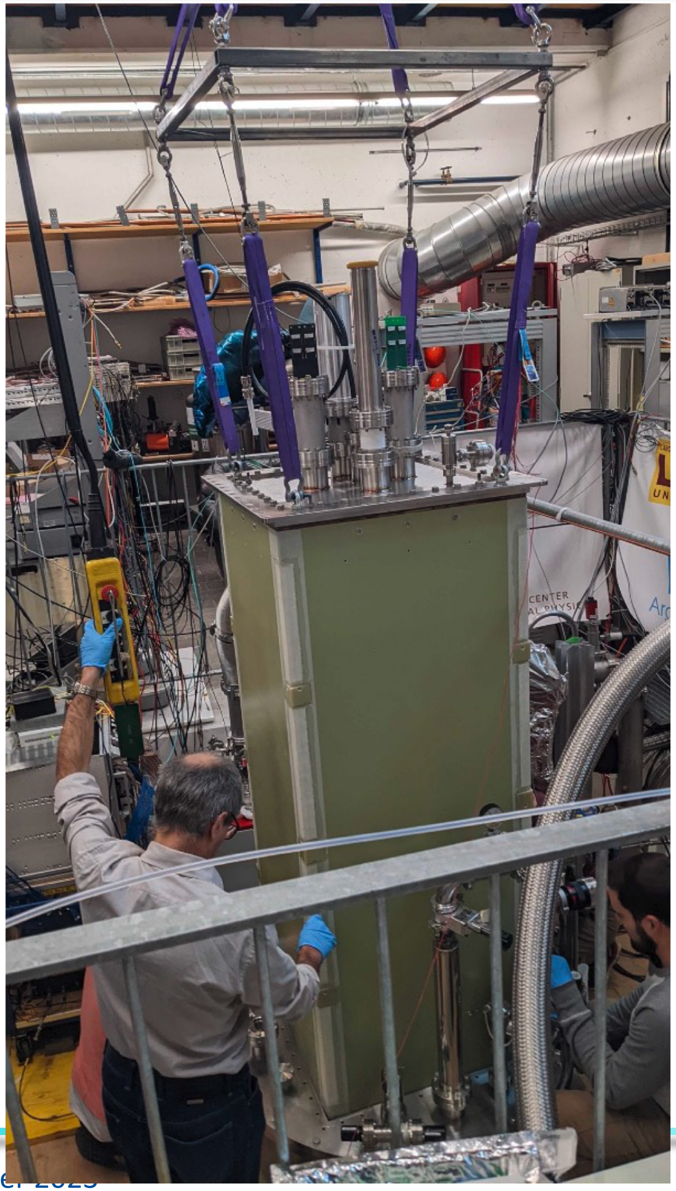
ND-LAr (prototyping)



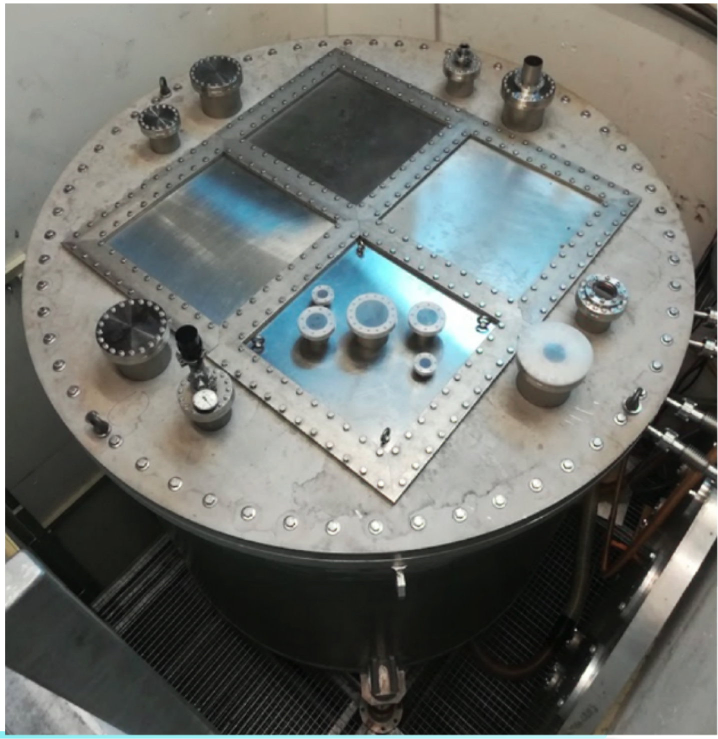
Modular construction:
1 x 1 x 3 m^3 modules
35 modules (7 x 5)
Total active mass = 130 ton
0.5 m maximum drift



Module prototype in Bern

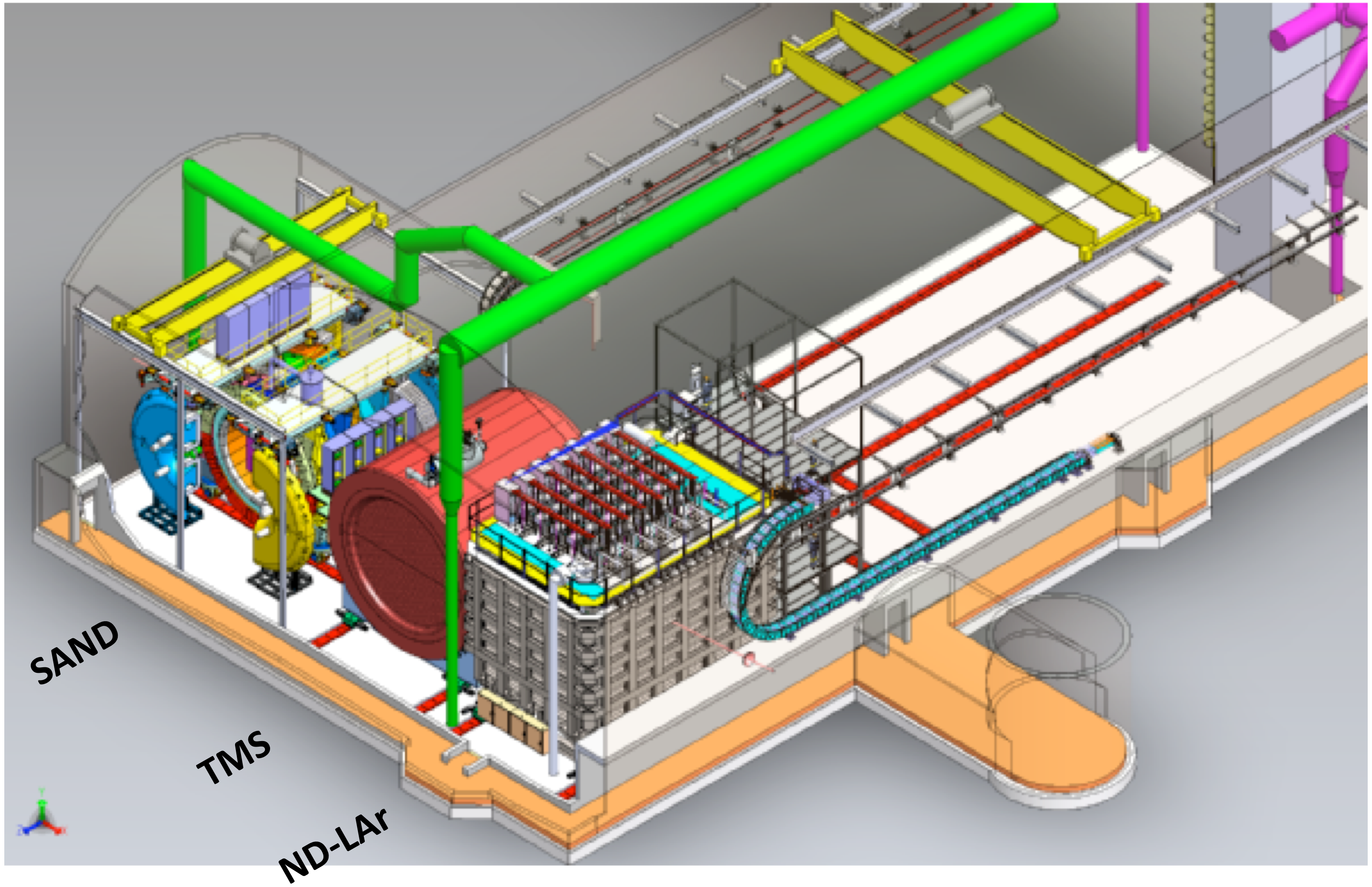


2 x 2 Demonstrator at Fermilab



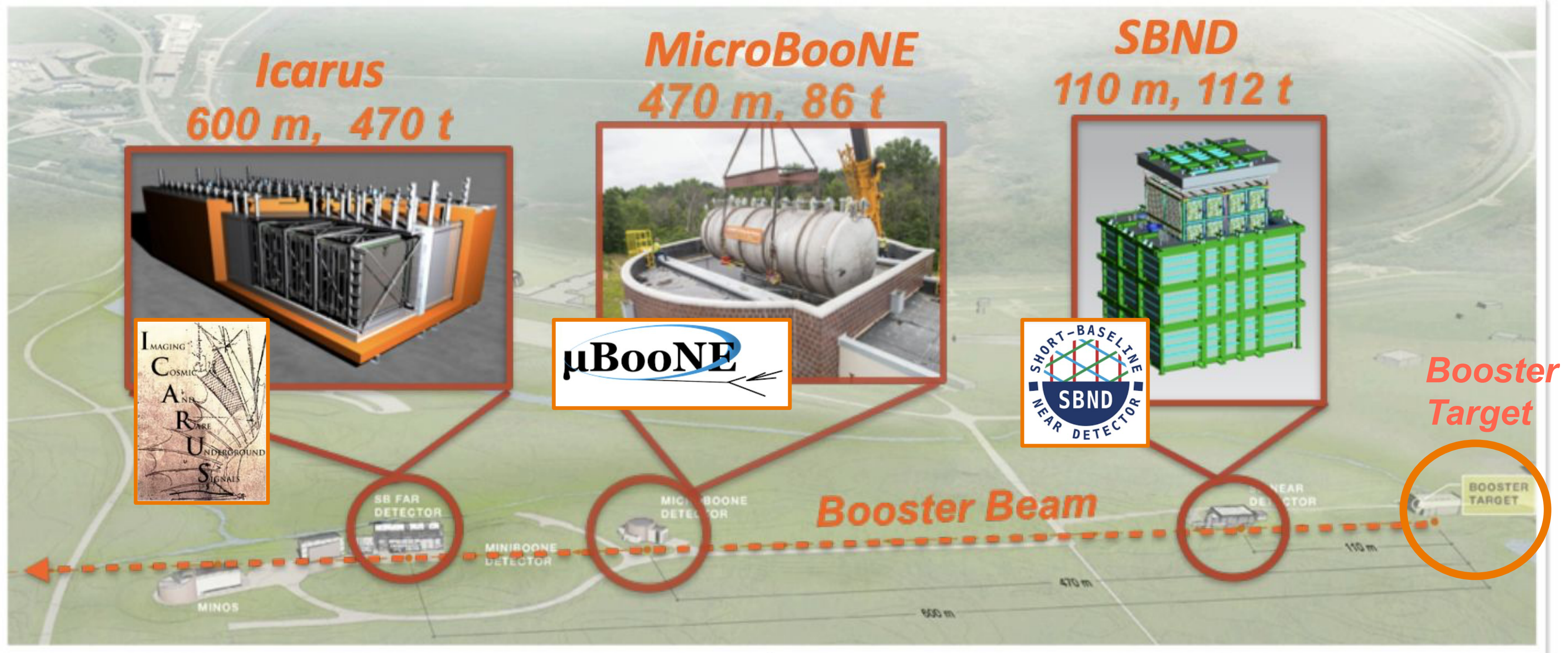
ND-LAr

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.

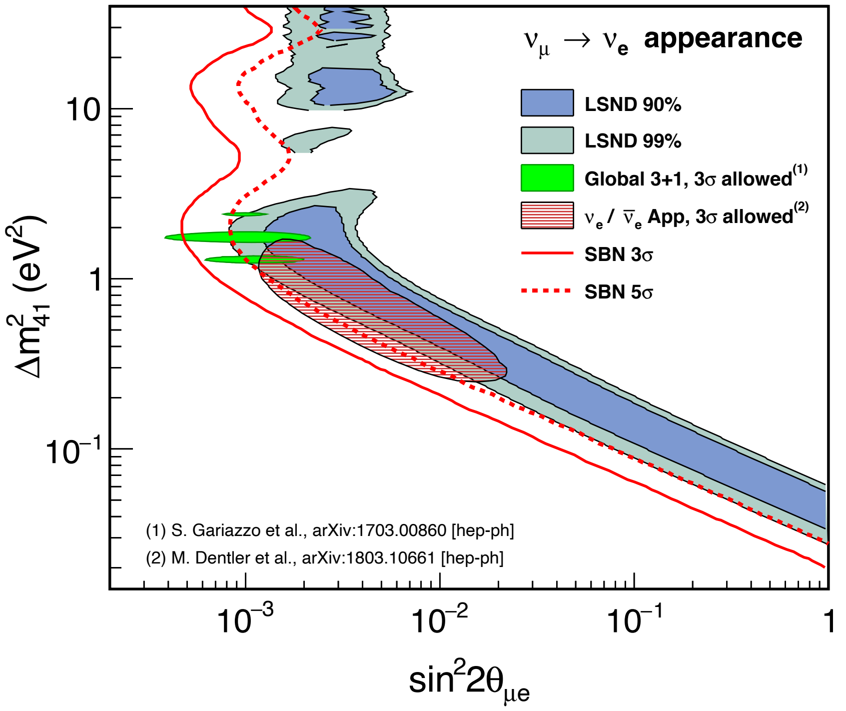


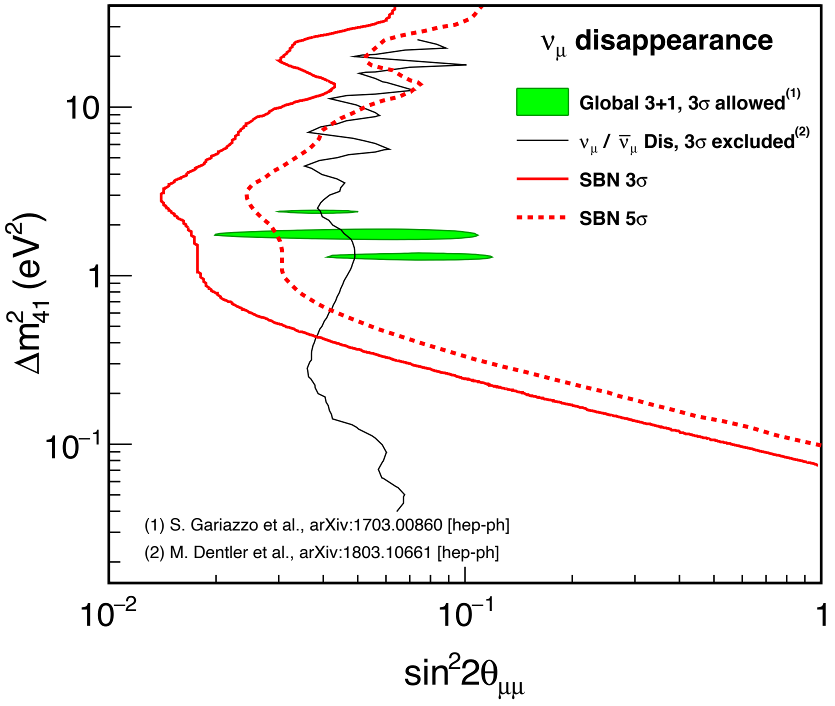
The Short Baseline Neutrino Program at Fermilab (2020-)

- 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





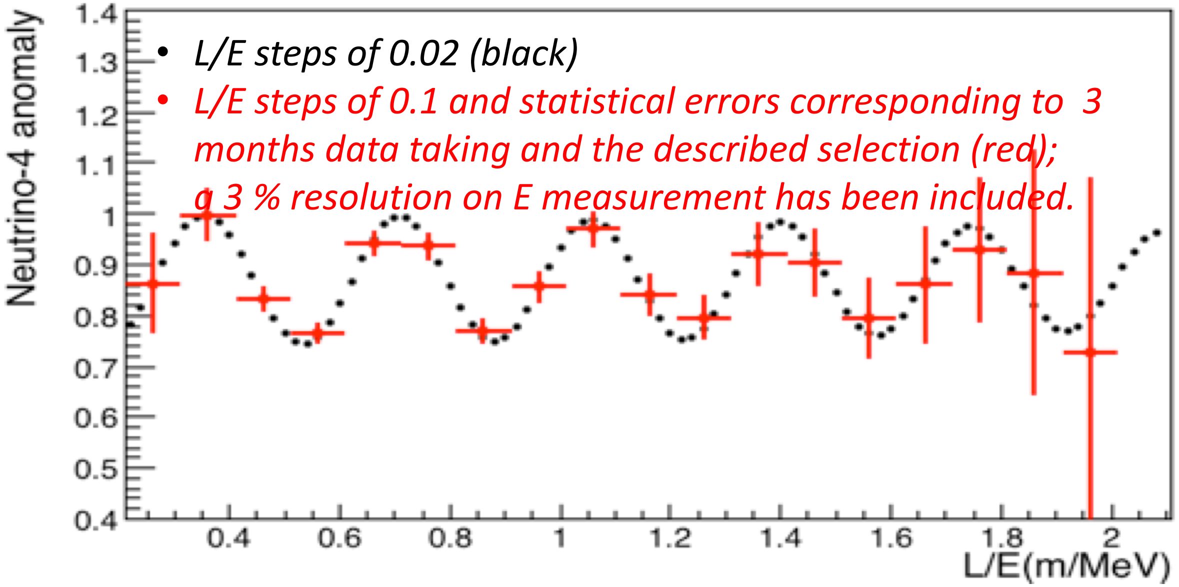
5σ coverage of the parameter area relevant to the LSND/MiniBooNE anomaly in 3 years (6.6 x 10^{20} pot).

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.

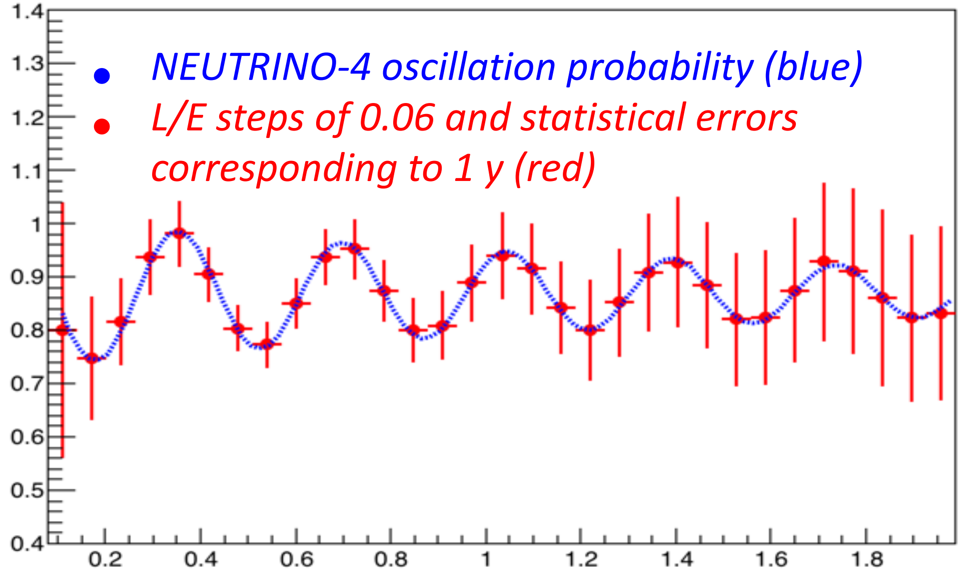
Unique capability to study appearance and disappearance channels simultaneously

SBN program: ICARUS sensitivity to Neutrino4-like sterile neutrinos

BNB – 3 months – ν_μ disappearance
CCQE events only



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, in particular for DUNE.

See the dedicated lecture from Luca Stanco

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.
- In the future, DUNE receives most of the attentions, with the extremely ambitious program both in terms of scale and physics searches.
- ICARUS is taking data now, to be joined soon by SBND, on sterile neutrino searches at Fermilab's Booster and NuMI neutrino beams.