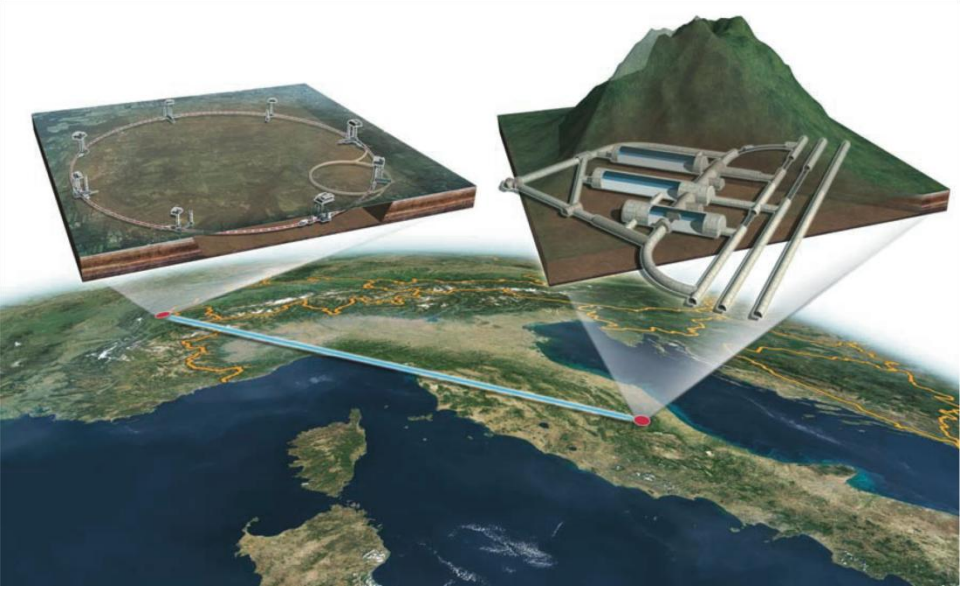
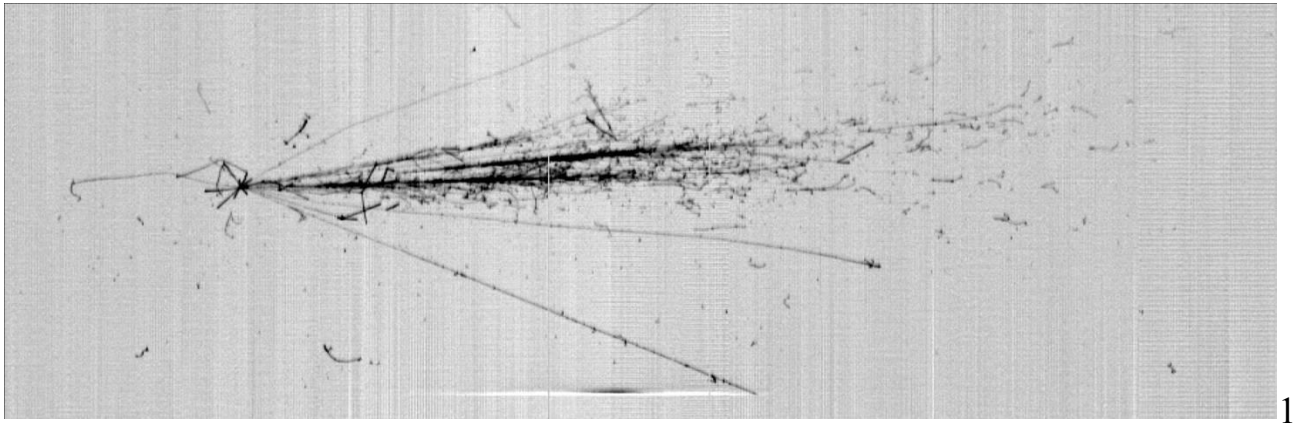
Status and early events from ICARUS T600



A. Guglielmi*

INFN – Padova

- ICARUS T600 LAr-TPC @ LNGS
- Detector commissioning
- First CNGS/cosmic-rays events



* On behalf of the ICARUS Collaboration

The ICARUS collaboration

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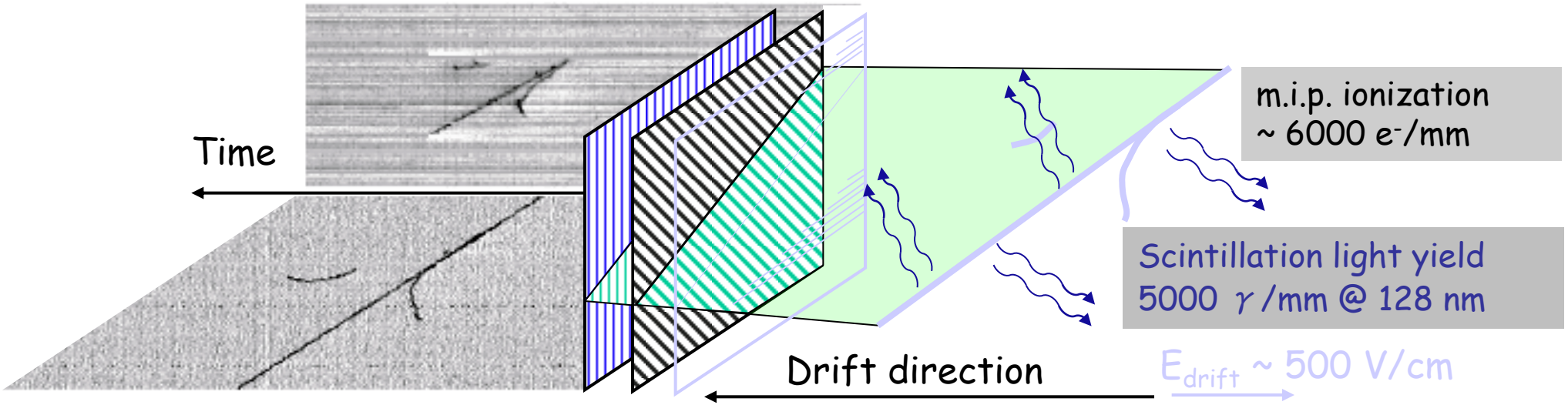
A powerful detection technique

The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)] first proposed to INFN in 1985 [ICARUS: INFN/AE-85/7] capable of providing a 3D imaging of any ionizing event ("electronic bubble chamber") with in addition:

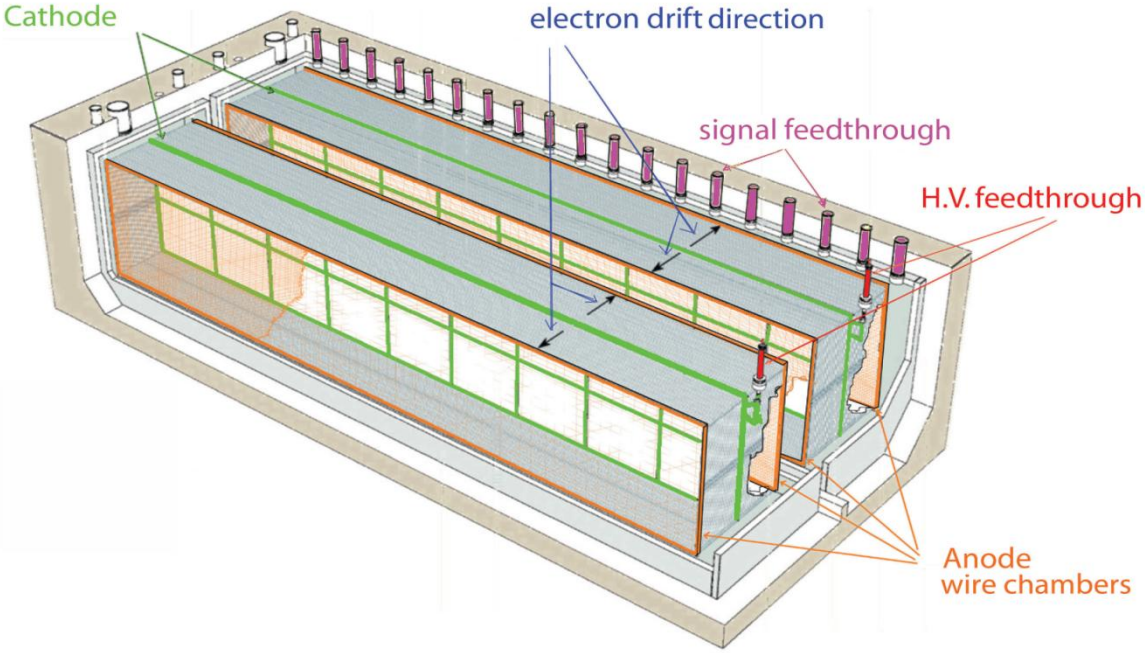
- continuously sensitive, self triggering
- high granularity (~ 1 mm)
- excellent calorimetric properties
- particle identification (through dE/dx vs range)

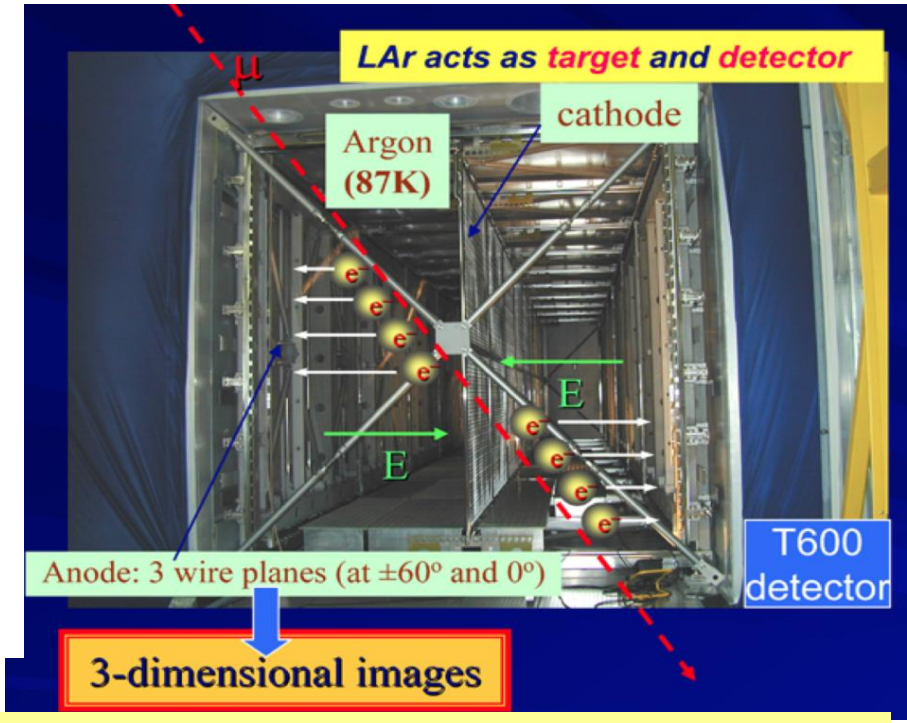


Electrons from ionizing track are drifted in LAr by E_{drift}. They traverse transparent wires arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by collection plane.

Key feature: LAr purity form electro-negative molecules (O_2, H_2O,CO_2).
Target: 0.1 ppb O_2 equivalent= 3 ms lifetime (4.5 m drift @ E_{drift} = 500 V/cm).

The ICARUS T600 detector

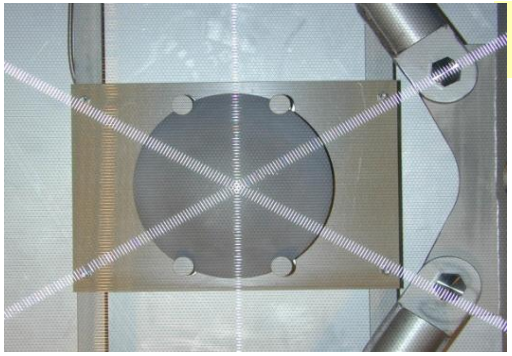




- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E= 0.5 kV/cm
  - v_{drift} = 1.55 mm/ μ s

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

Charge and light read-out



Three wire planes and a PMT

Wires before tensioning

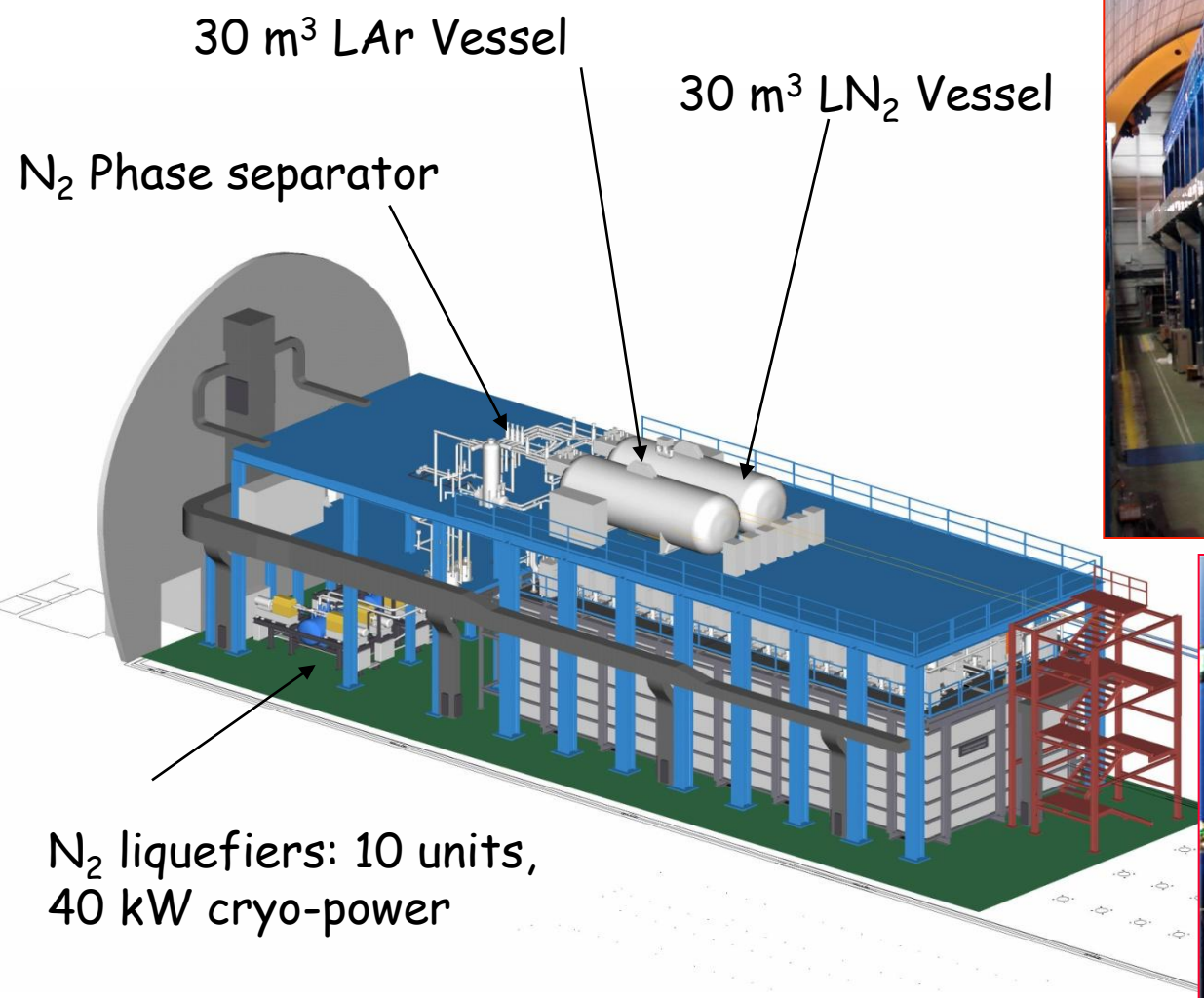
Purity Monitors

PMTs

Wall Position Meter

6	LAr purity monitors
16	LAr level meters
7	wire position meters
8	wall position meters
30	temperature probes

ICARUS T600 in LNGS Hall B



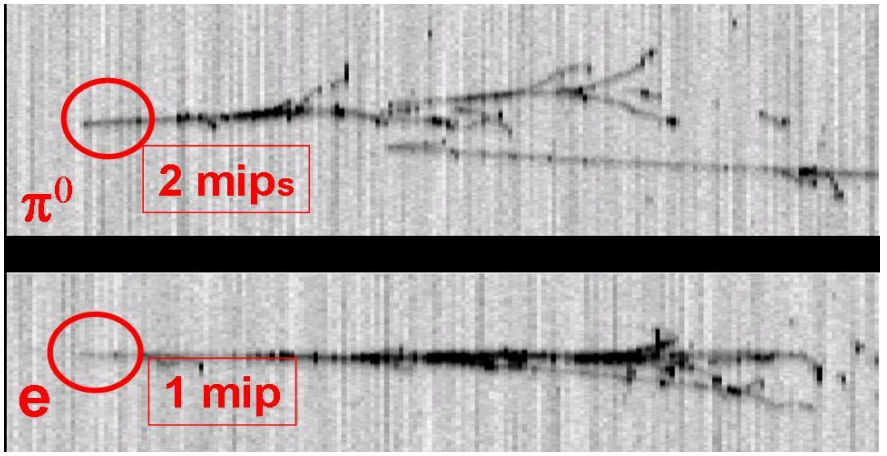
T600 cryostats layout

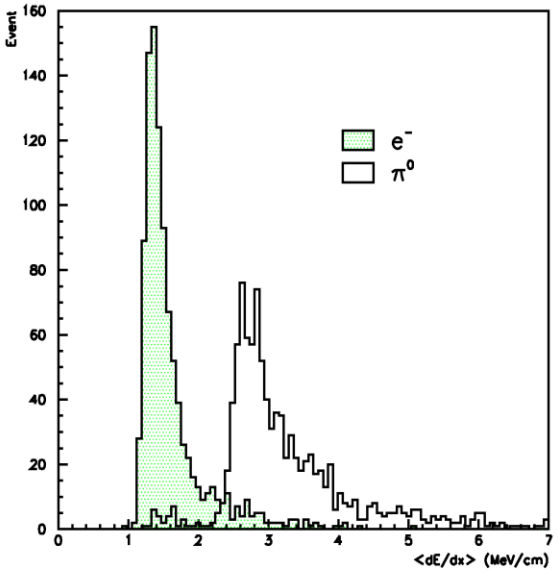
Electronics (54000 channels)

LAr-TPC performance

Fundamental for $\nu_\mu - \nu_e$ oscillation search!

- Tracking device
  - Precise event topology
  - Muon momentum via multiple scattering
- Measurement of local energy deposition dE/dx
  - e/γ separation (2% X_0 sampling)
  - Particle ID by means of dE/dx vs range
  - e/π^0 discrimination at 10^{-3}, 90 % electron ident. eff. by γ convertion from vertex, π^0 mass measurement and dE/dx.
- Total energy reconstruction of the events from charge integration
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events





RESOLUTIONS

Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$

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

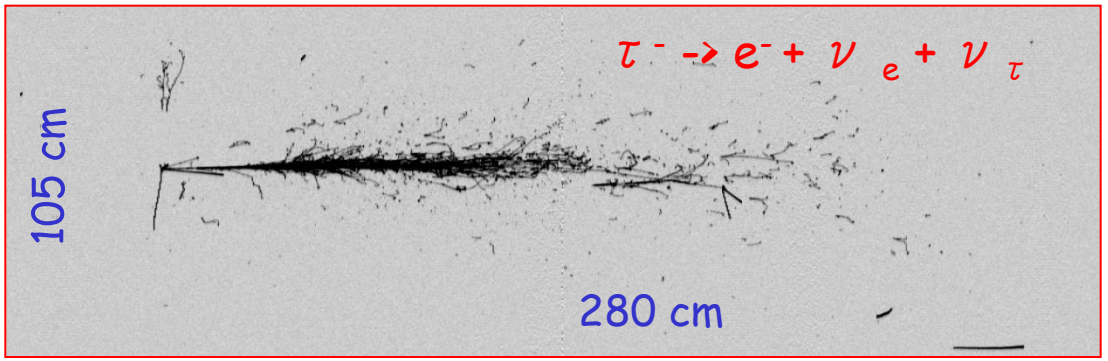
Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

Physics potentials of ICARUS T600

- T600 is a major milestone towards the realization of a much more massive multikton LAr detector, but it offers also some interesting physics in itself. The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, and e/π^0 separation allow "to see" events in a new way, w.r.t. previous/current experiments.
- The detector is collecting "bubble chamber like" CNGS events:
  - a beam related rate ≈ 1200 ev/year with 90 % efficiency of collection inside raw fiducial volume ≈ 480 t corresponding to ≈ 5000 beam related neutrino events for 18 10^{19} pot.
  - Search for $\nu-\tau$ decay with kinematical criteria.
  - Search for sterile neutrinos with deep e-like inelastic CC events in LSND parameter space with equivalent L/E.
- The T600 is also collecting simultaneously "self triggered" events:
  - ≈ 100 ev/year of individually recorded atmospheric CC cosmic rays.
  - Solar neutrino electron rates > 8 MeV.
  - A zero backgr. proton decay with 3 10^{32} nucleons for "exotic" channels.

CNGS2: searching for the ν_τ signature

- At the effective neutrino energy of 20 GeV and Δm^2 = 2.5E-3 eV^2, the expected $\nu\mu$ => $\nu\tau$ is 1.4%. Therefore for 5000 CNGS events in the T600 we expect 67 raw $\nu\tau$ events.

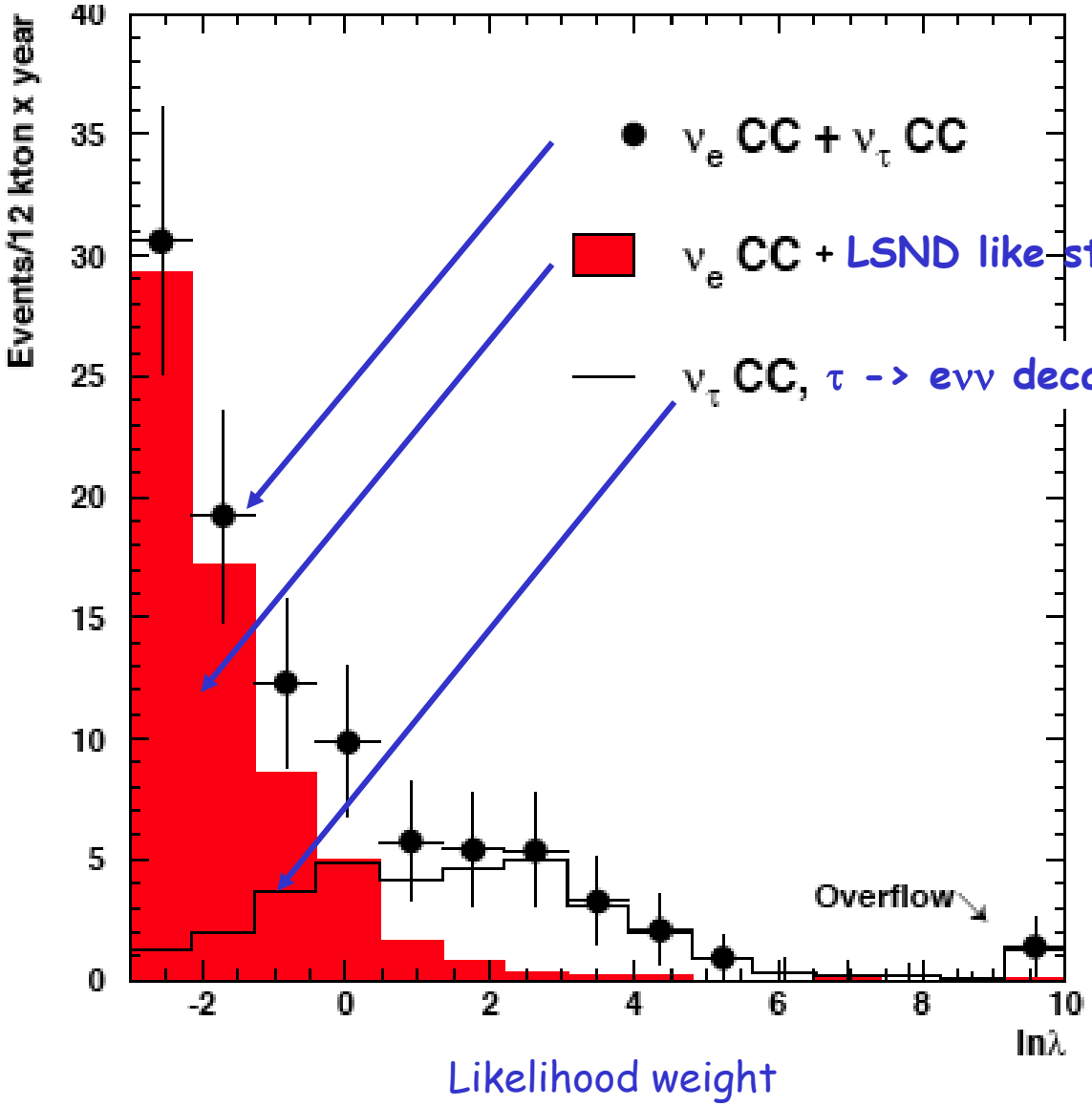


E_ν = 18.7 GeV

e^- =9.5 GeV
p_T = 0.47 GeV/c

- The branching ratio for τ => e$\nu\nu$ is 18%; hence we expect 12 electron deep inelastic events, in addition to the ≈ 12 intrinsic beam associated νe with energy <20 GeV. This is already "per-se" a significant effect, namely with 24 electron events observed vs. 12 ± 3.4 expected (3.5 s.d.).
- Events are characterised by a momentum unbalance because of neutrino emission and a relatively low electron momentum. Selection criteria suggest a sufficiently clean separation with kinematic cuts and efficiency of 50%.
- Therefore one should expect about 6 ± 2.5 unambiguous $\nu\tau$ => e$\nu\nu$ events.

ν–e balanced events or ν–tau decays ?

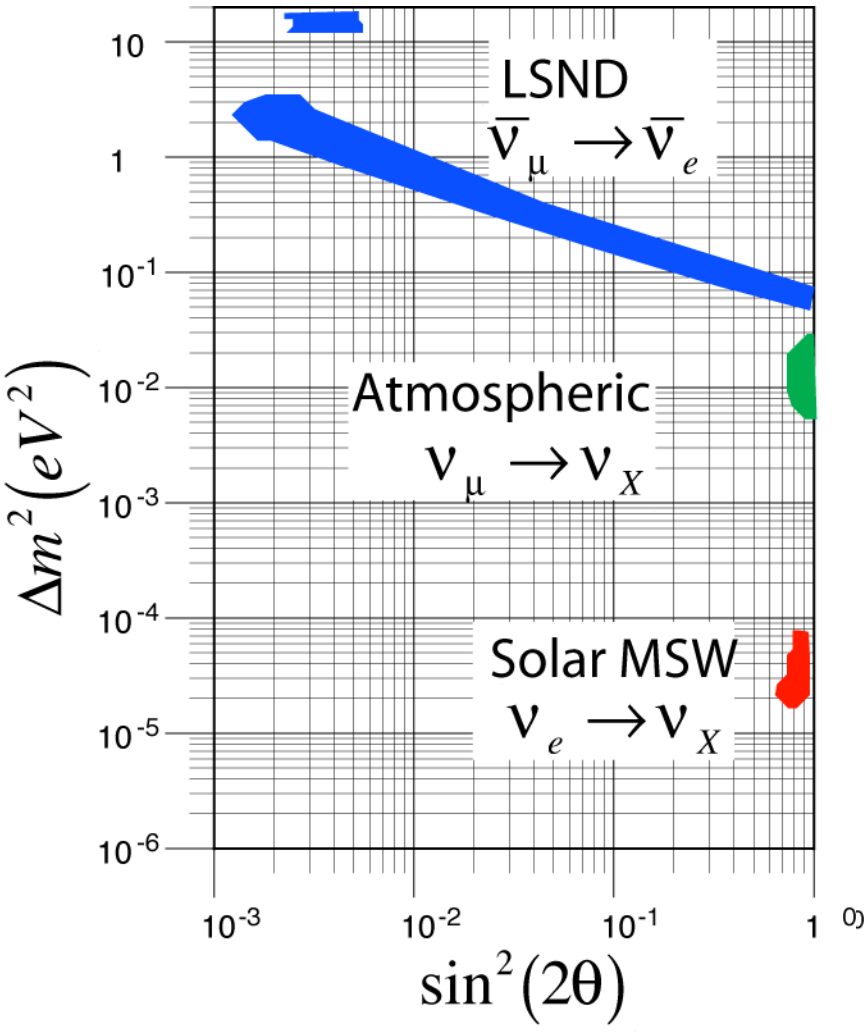


Likelihood distributions may separate an hypothetical sterile neu excess from the expected presence of τ –> eνν decays

How many neutrinos are present in nature ?

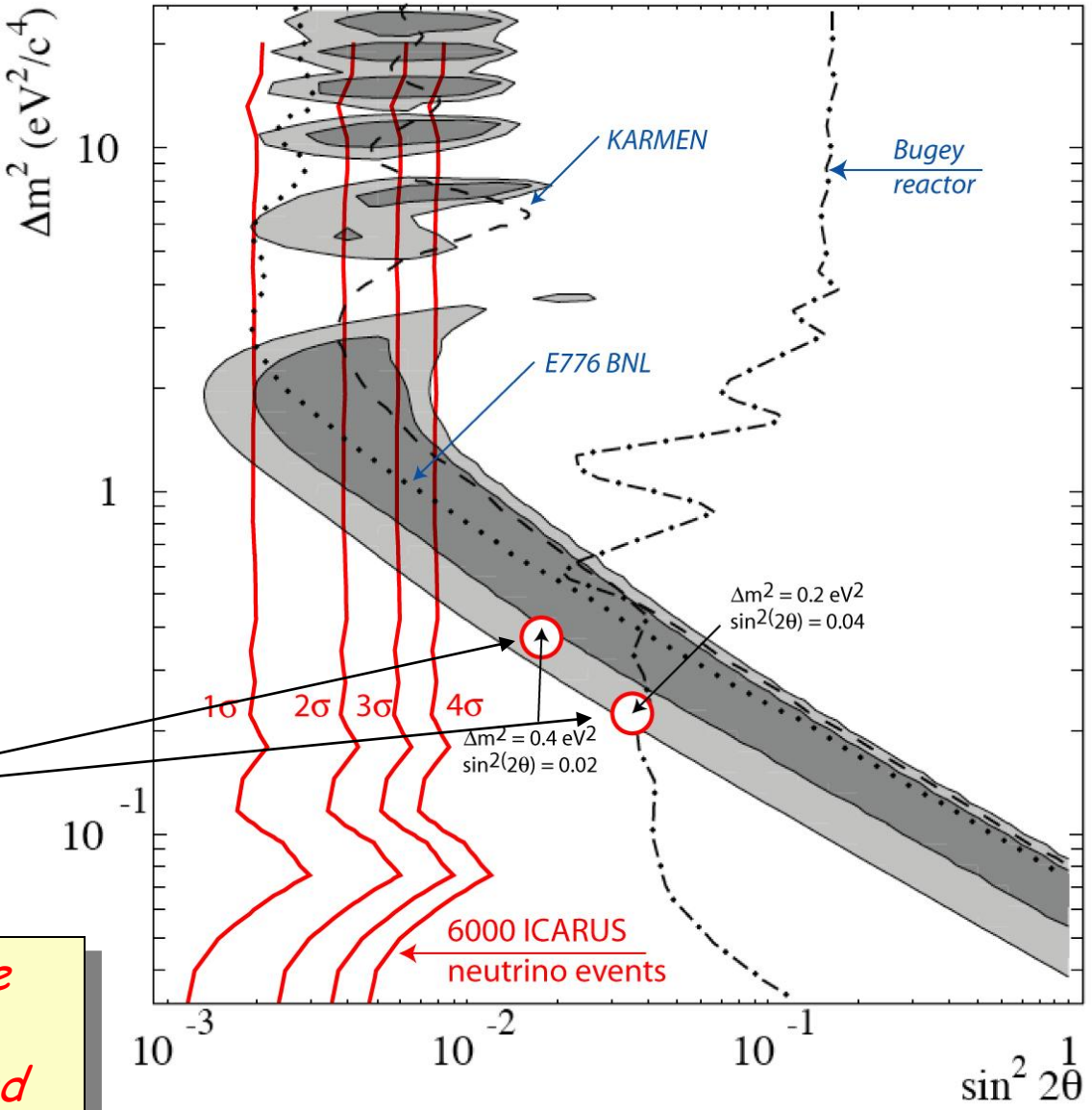
- According to the LEP result, three different neutrinos are coupled with Z-bosons.

  Consequently there are only 2 independent Δm^2.
- But the possibility of one or more additional, "sterile" kinds of neutrino — namely of neutrinos which do not participate in the weak interactions — is unaffected by these Z-boson-based measurements.
- The existence for such additional neutrino particles has been claimed by a Los Alamos experiment called LSND, in which they have been created through oscillations from ordinary neutrinos. ,
- It is possible that neutrinos are something very different than just a neutral counterpart of charged leptons and may couple to another segment of the Universe, the one of sterile neutrinos, which do not see fully ordinary electro-weak interactions but still introduce mixing oscillations with ordinary neutrinos.



Sterile (LSND) neutrino search

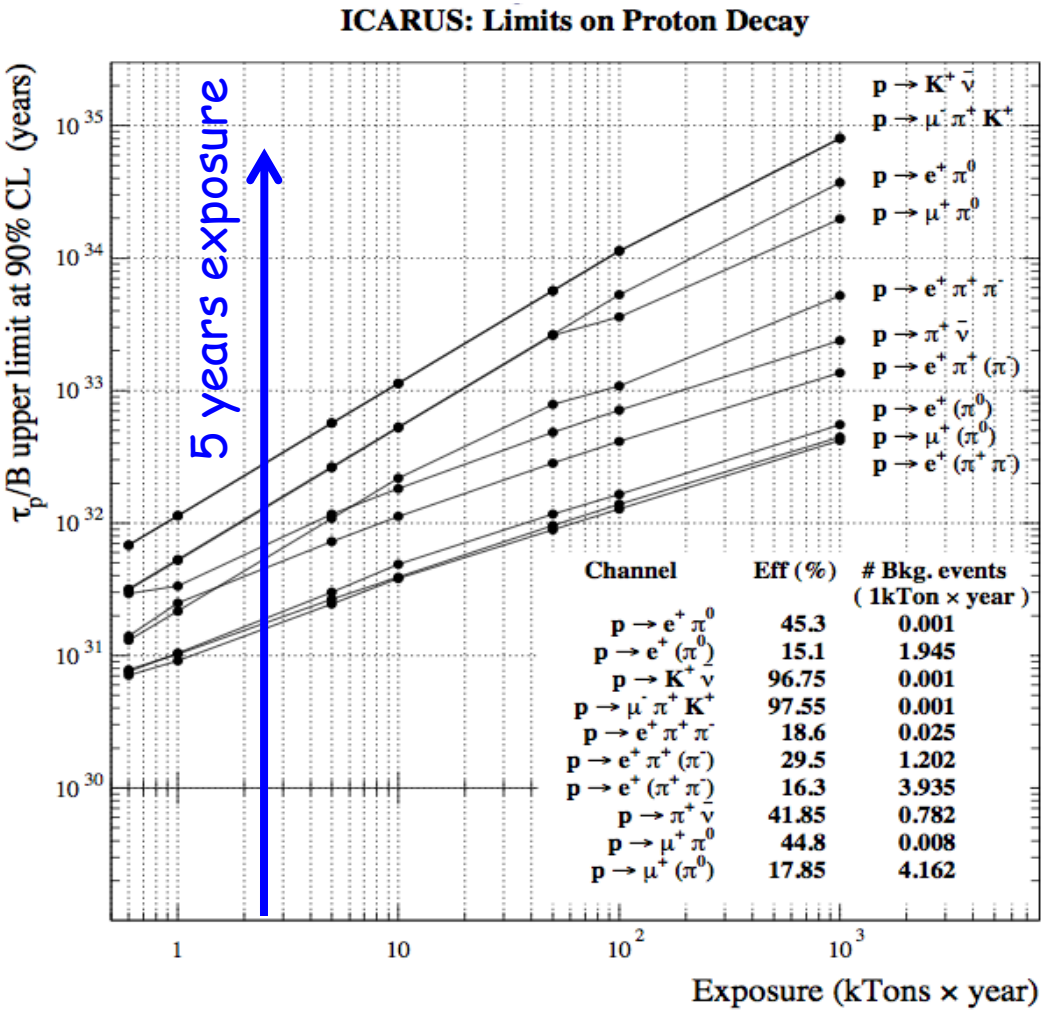
- Sensitivity region, in terms of Standard Deviations σ, for 6000 raw CNGS neutrino events. The potential signal is above the background generated by the intrinsic νe beam contamination, in the deep inelastic interval 10-30 GeV.
- The Δm^2 distribution extends widely beyond the LNSD and MiniBoone regions.
- Two indicated points are reference values of MiniBoone.



T600 at the CNGS offers an unique possibility of searching for sterile neutrinos, largely complementary and comparable to the Fermilab programme.

Nucleon decay : single event capability

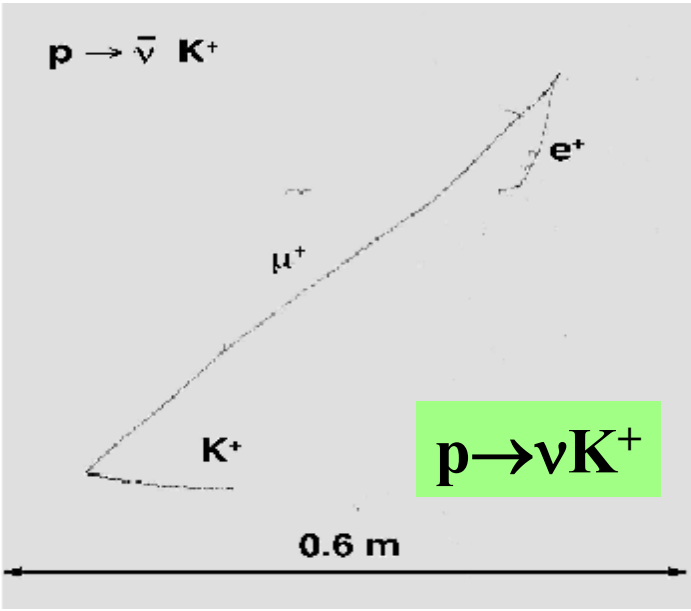
- LAr-TPC provides a much more powerful bkg rejection w.r.t. other techniques. It can perform a large variety of exclusive decay modes measurements in bkg free mode.
- In particular the T600 (*3 10^{32} nucleons*) is well suited for channels not accessible to Č detectors due to the complicated event topology, or because the emitted particles are below the Č threshold (e.g. $K^{\pm}$).
- *In few years exposure the T600 can improve limits on some "super-symmetric favored" exotic channels:*



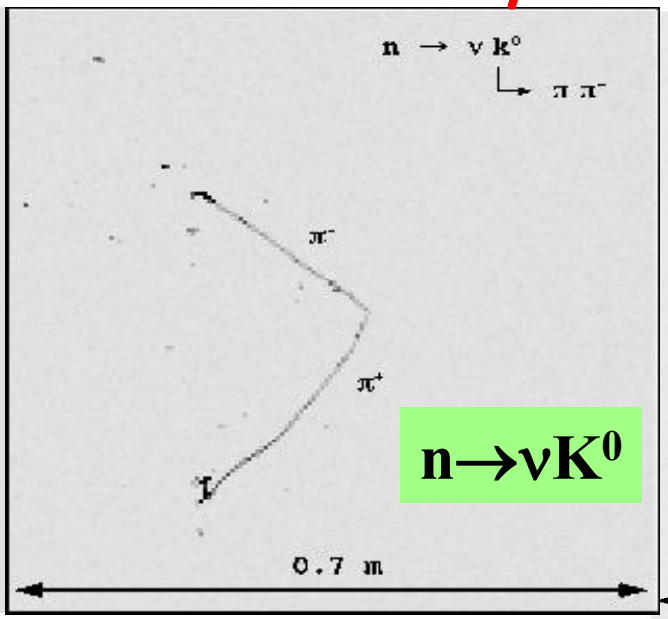
Channel	Eff (%)	# Bkg. events (1kTon × year)
$p \to e^+ \pi^0$	45.3	0.001
$p \to e^+ (\pi^0)$	15.1	1.945
$p \to K^+ \nu$	96.75	0.001
$p \to \mu^- \pi^+ K^+$	97.55	0.001
$p \to e^+ \pi^+ \pi^-$	18.6	0.025
$p \to e^+ \pi^+ (\pi^-)$	29.5	1.202
$p \to e^+ (\pi^+ \pi^-)$	16.3	3.935
$p \to \pi^+ \bar{\nu}$	41.85	0.782
$p \to \mu^+ \pi^0$	44.8	0.008
$p \to \mu^+ (\pi^0)$	17.85	4.162

Channel	90%CL-5y	(pdg 90%CL)
$p \to \nu \pi^+$	$1.1\ 10^{32}$	$(2.5\ 10^{31})$
$p \to \mu^- \pi^+ K^+$	$2.7\ 10^{32}$	$(2.5\ 10^{32})$
$n \to e^- K^+$	$3.2\ 10^{32}$	$(3.2\ 10^{31})$
$n \to \mu^+ \pi^-$	$1.5\ 10^{32}$	$(1.0\ 10^{32})$
$n \to \nu \pi^0$	$1.1\ 10^{32}$	$(1.1\ 10^{32})$

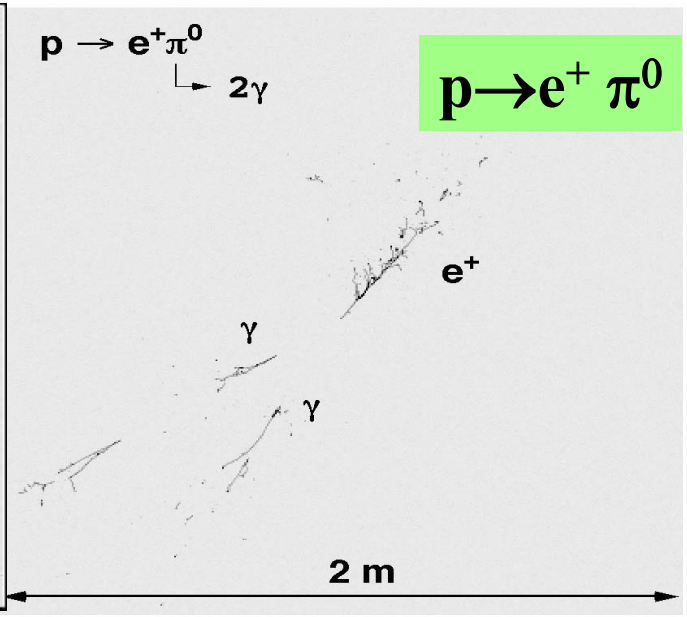
Nucleon decays



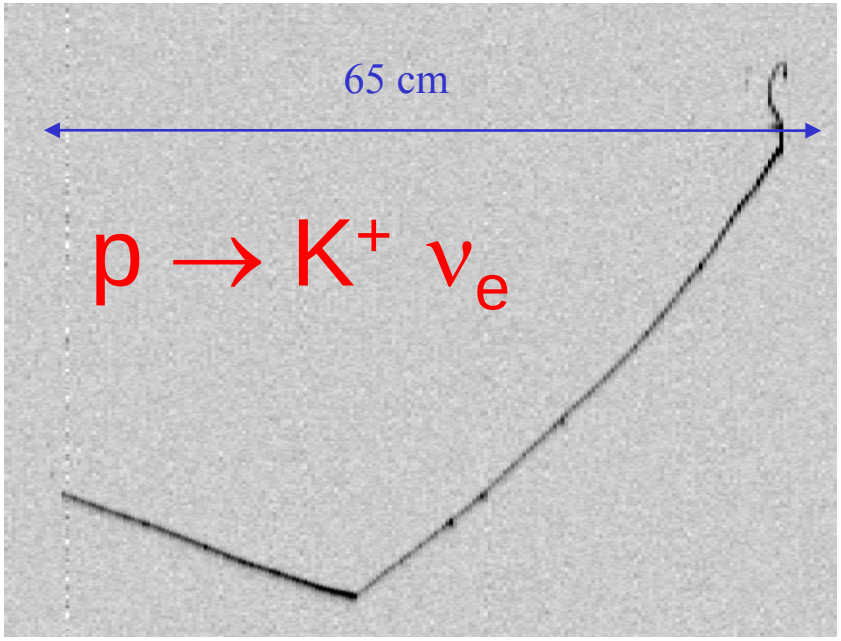
$p \rightarrow \nu K^+$



$n \rightarrow \nu K^0$



$p \rightarrow e^+ \pi^0$



ICARUS T600 start-up

Detector assembly completed by December 2009 including electronics and DAQ.

Cryogenic plant completed by March 2010 including deformation/temperature sensors of cryostat walls, overall process and control software.

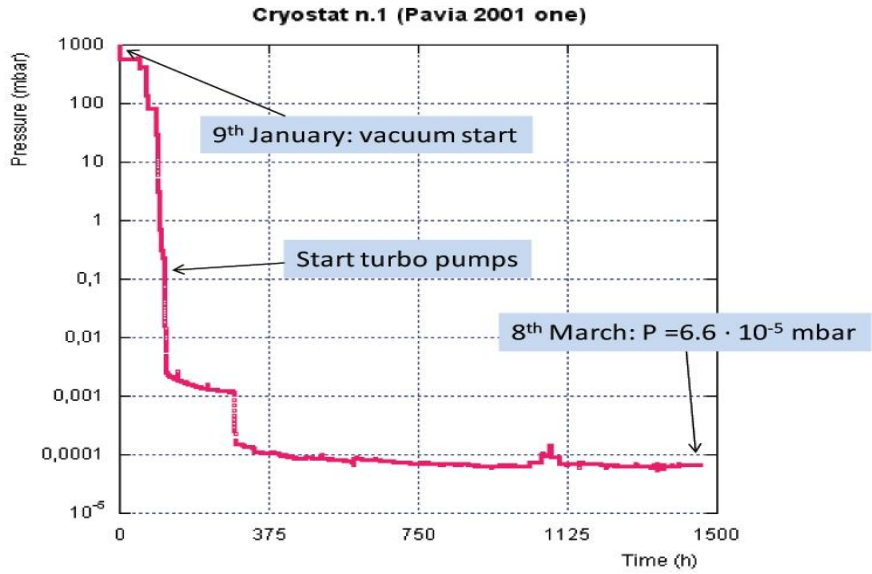
Start-up with leak-tests in April: all safety and technical requirements fulfilled.

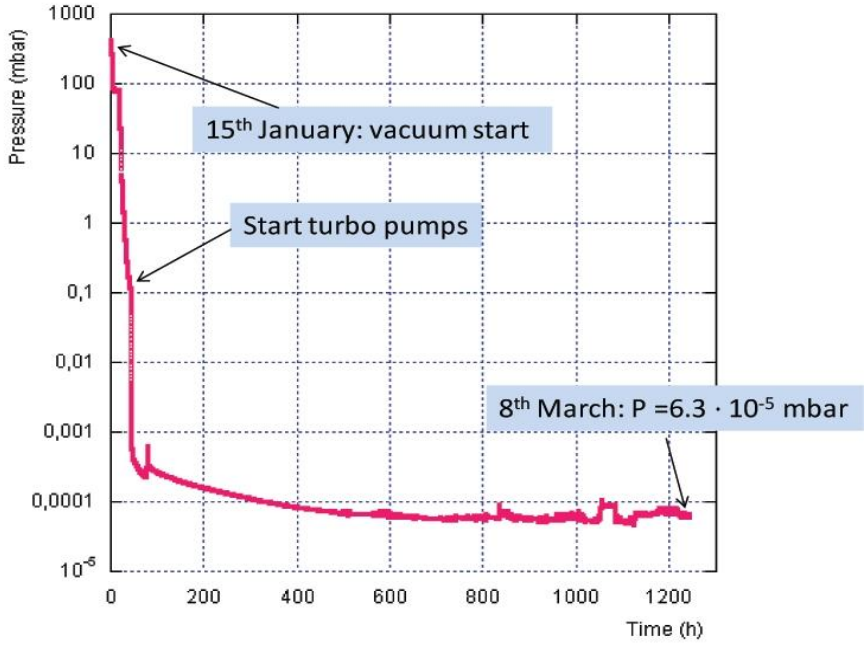
- Vacuum phase: the cryostats evacuation started on January 9th, 2010.
- Cooling phase: on April 14th the volume was filled with ultra-pure Argon gas, the liquid Nitrogen cool-down started on April 16th.
- Filling phase: on April 29th ultra-pure LAr was injected at a rate of ~2 m^3/hour. On May 18th both modules were completely full.
- T600 commissioning: on May 27th HV and wire biasing and PMT's were turned on the West Cryostat. At 12.24 the first muon crossing track was recorded. On June 1st the East cryostat was also turned on.

- On May 28th at 19.54 the first CNGS neutrino interaction was observed.

ICARUS vacuum and cooling phases

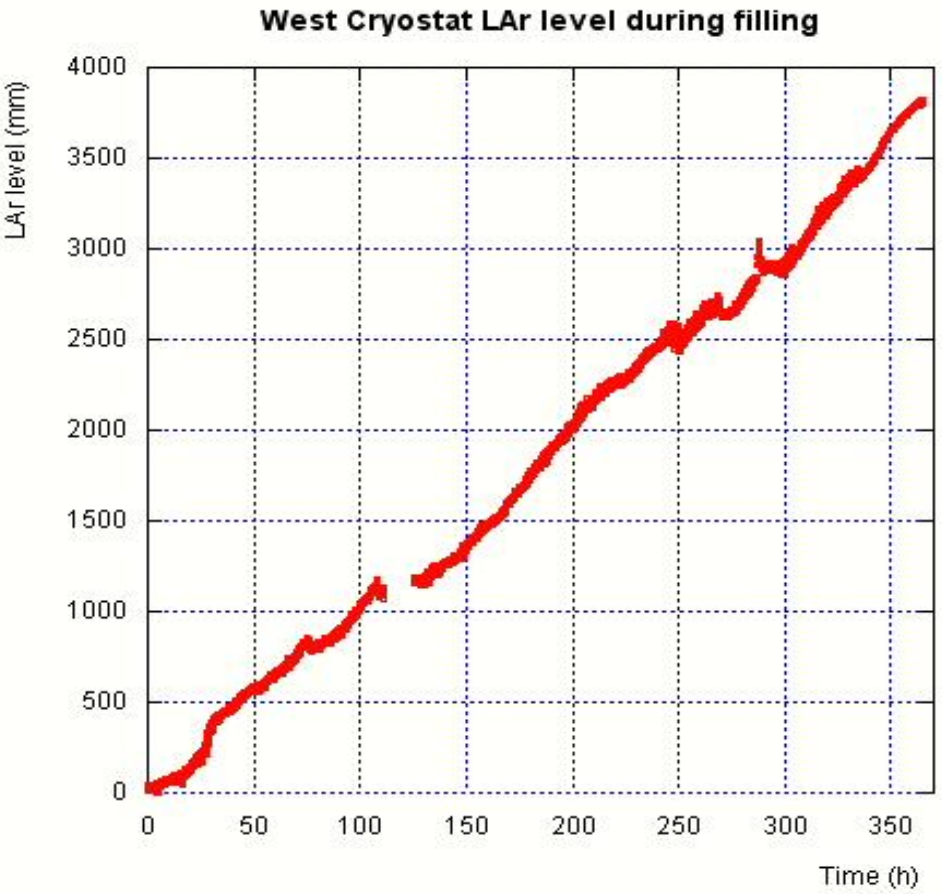
- January, 9th 2010: start of cryostats evacuation (turbo-pumps on at ~ 0.1 mbar).
- Mechanical deformations of the inner walls were continuously monitored during the whole vacuum phase .
- On April 14th: ultra pure Argon gas was loaded at +100 mbar pressure. Then the cooling of cryostats started, 10 Stirling compressors, 40 kW fully operative, and with the addition of liquid Nitrogen from the 30 m^3 storage. Periodic addition of Argon gas were performed, in order to maintain the correct overpressure in the process.
- On the 23th of April the LAr temperature (90 K) was reached at a average rate of about 1 K/hour, to minimize mechanical stresses.





ICARUS filling phase

- From April 29th the four gaseous re-circulations are operating at maximum speed of >20 Nm^3/h each (>24 l/h of LAr, ~2 kWatt).
- Cryostats filling was performed with 47 trucks during 2 weeks, for a total amount of 610511 l of LAr. The filling rate was more than 1 m^3/hour/cryostat during the whole period.
- On May 18th LAr level reached in both cryostats is 3825 mm, i.e. 65 mm from internal top, enough to completely cover HV electrodes.
- 8 Stirling machines out of 10 are operating (32 KWatt) smoothly.

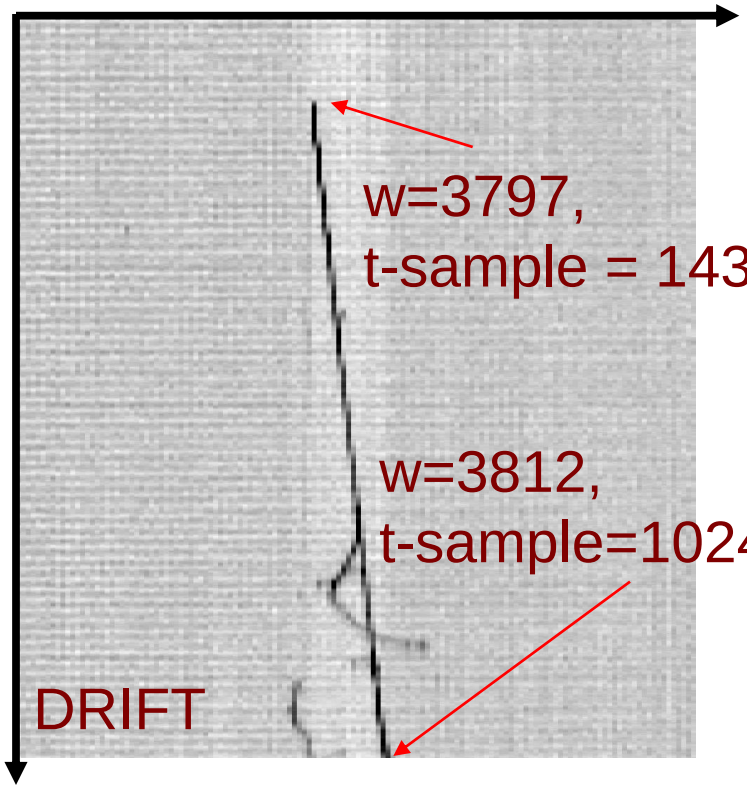


ICARUS detector commissioning

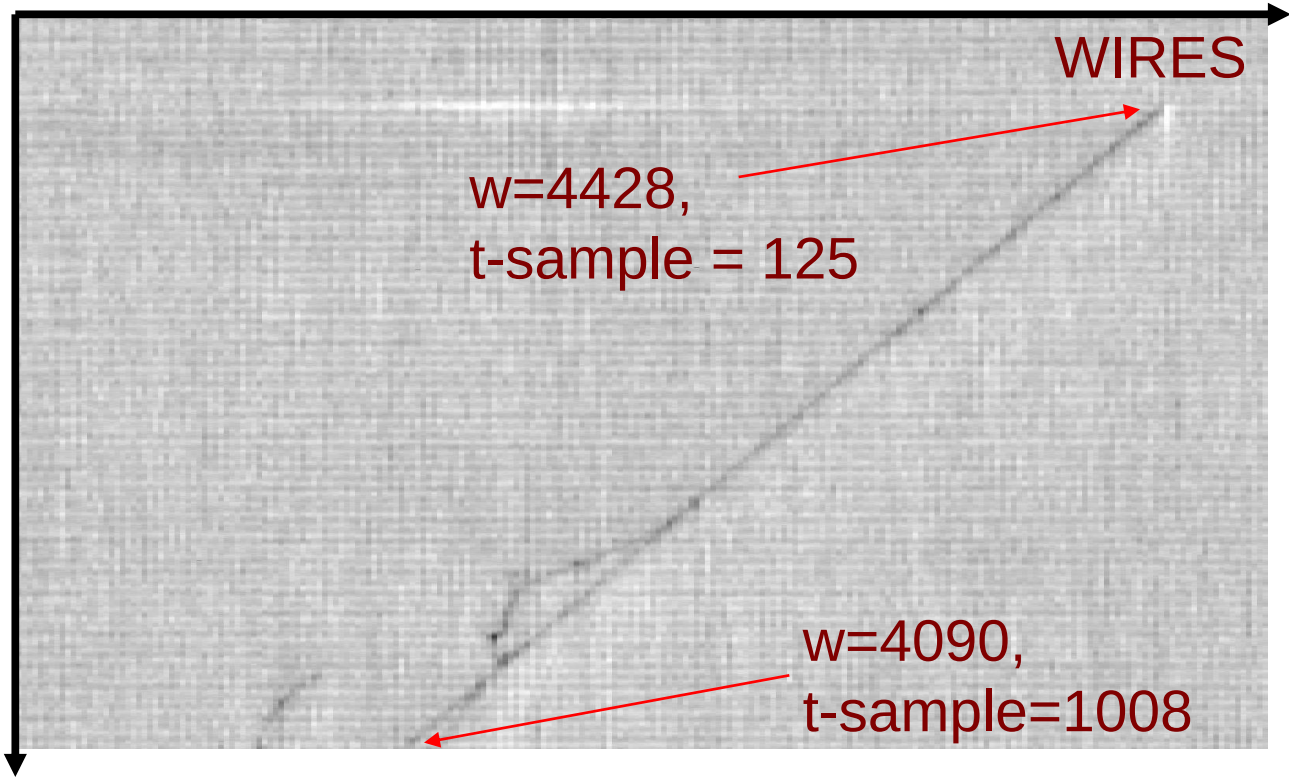
- On May 20th, activation of West cryostat started.
  - Cathode HV suppliers were turned on: the -75 kV nominal power was reached, showing a stable current.
  - PMTs: good signal from 19 over 21 internal photomultipliers (the remaining two are under investigation). Electronics for PMTs' signal discrimination and trigger logic is under optimization.
  - On May 27th, nominal values applied to wire biasing at (-220, 0, +280 V) without any problem (low and stable current).
  - At 12.14 h the first ionization track was recorded and visualized by DAQ; during the night the firsts horizontal muons crossing the cryostat West and pointing back to CERN were recorded (nu int. in upstream rock).
  - On May 28th at ~19.54 the first CNGS neutrino interaction was observed.
  - Muon tracks are presently used to evaluate electron lifetime in real time (present trigger rate: ~ 15 events/hour/cryostat).
- On June 1st the East cryostat was also turned on without problems.

RUN 9064 EVENT 29

COLLECTION VIEW



INDUCTION 2 VIEW

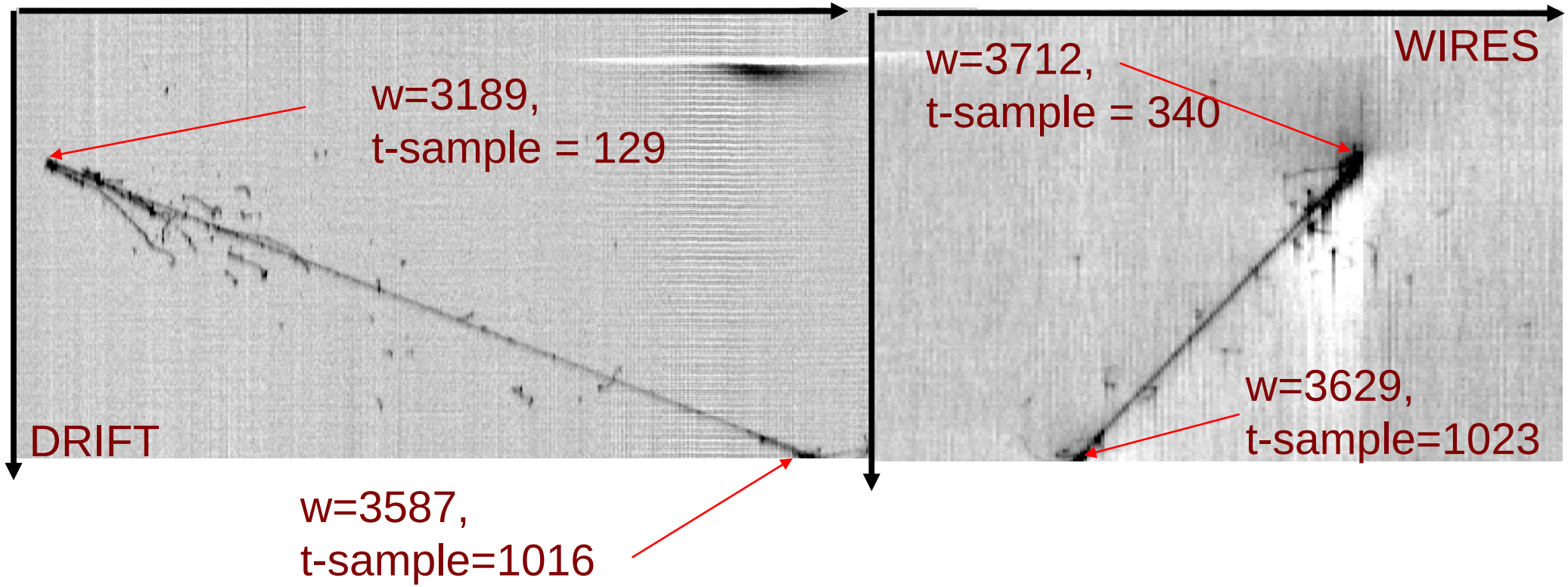


Track length in Collection view ~ 55 cm

RUN 9064 EVENT 61

COLLECTION VIEW

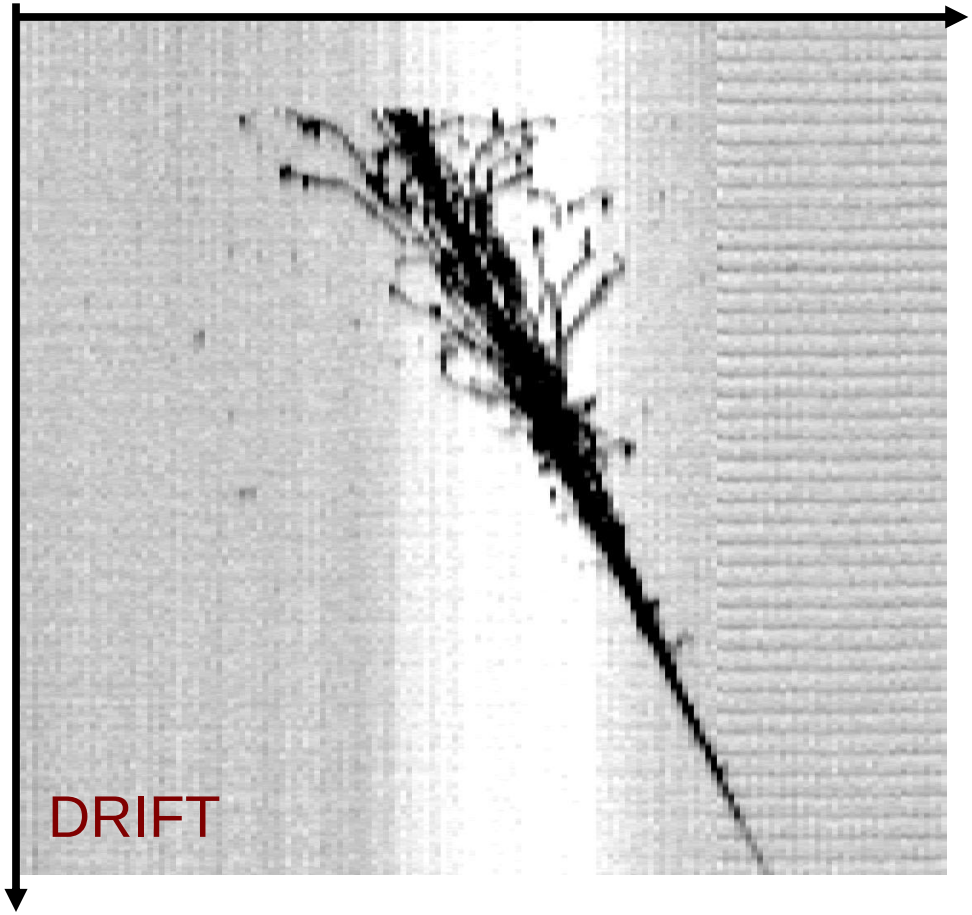
INDUCTION 2 VIEW



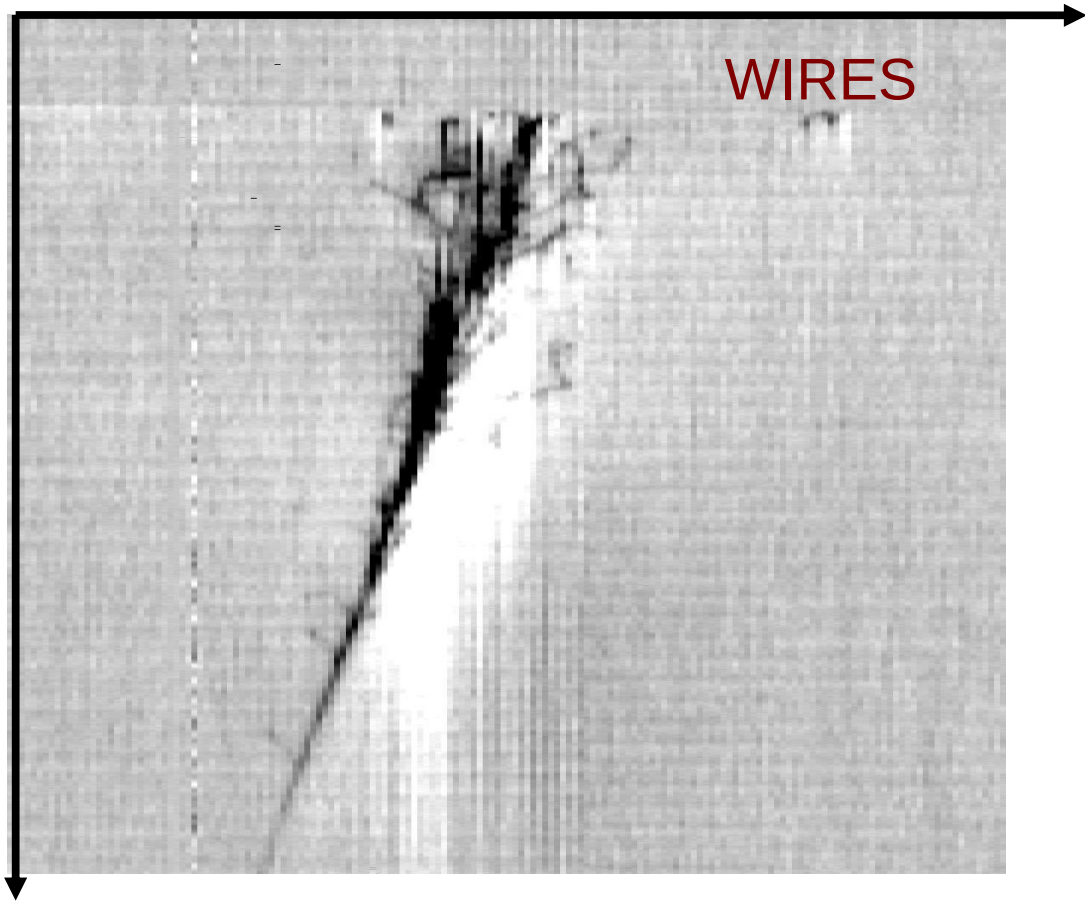
Track lenght in Collection view ~ 130 cm

RUN 9064 EVENT 164

COLLECTION VIEW



INDUCTION 2 VIEW

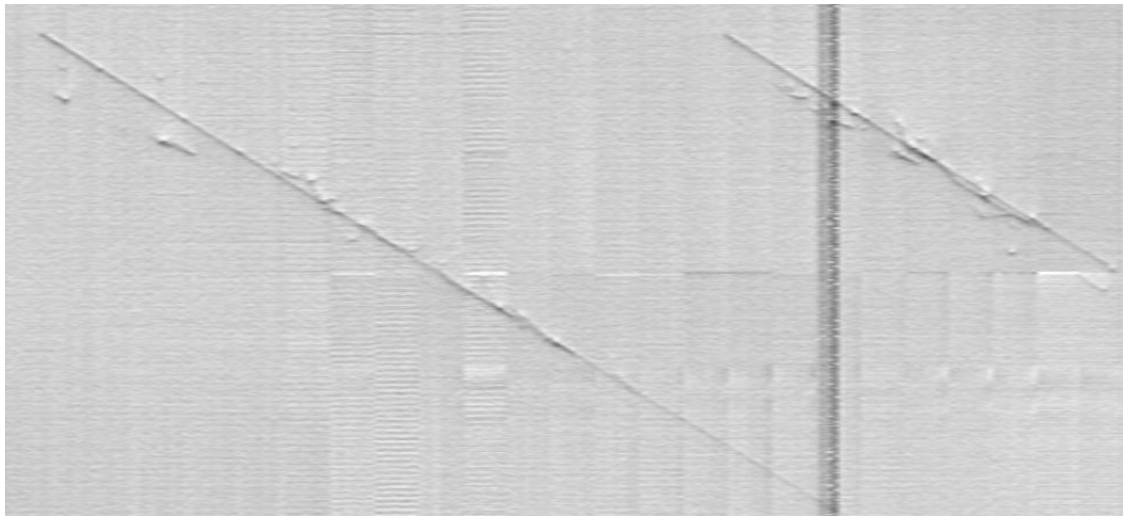


Δw_{coll}=66, Δw_{ind2}=46, Δt-sample = 900

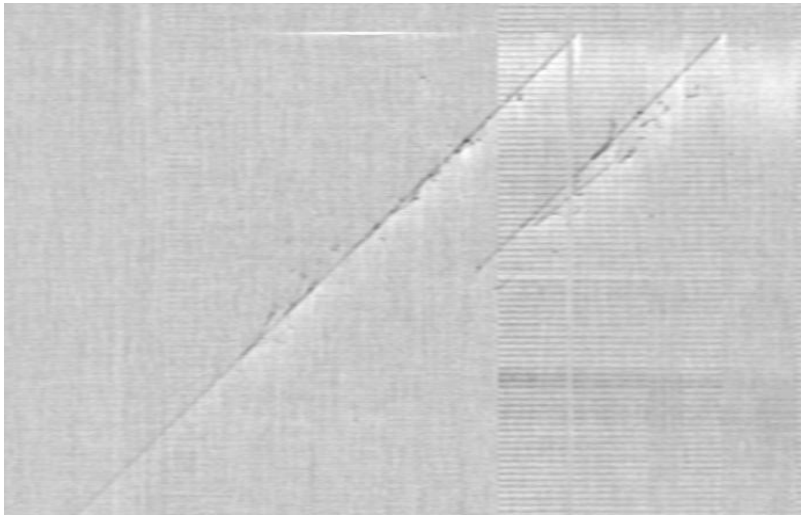
Three views at 60°

Drift time coordinate (1.5 m)

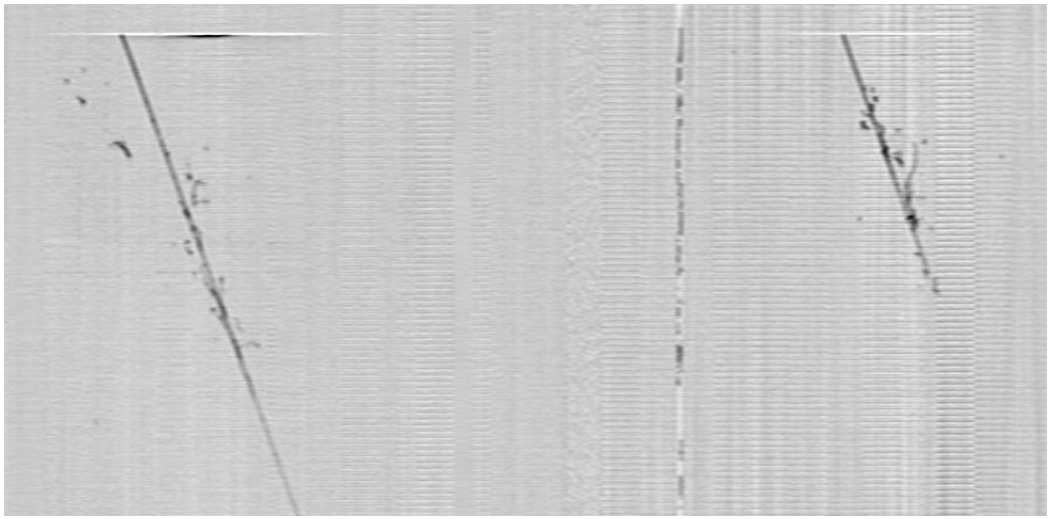
Induction 1 view (0°)



Induction 2 view (+60°)



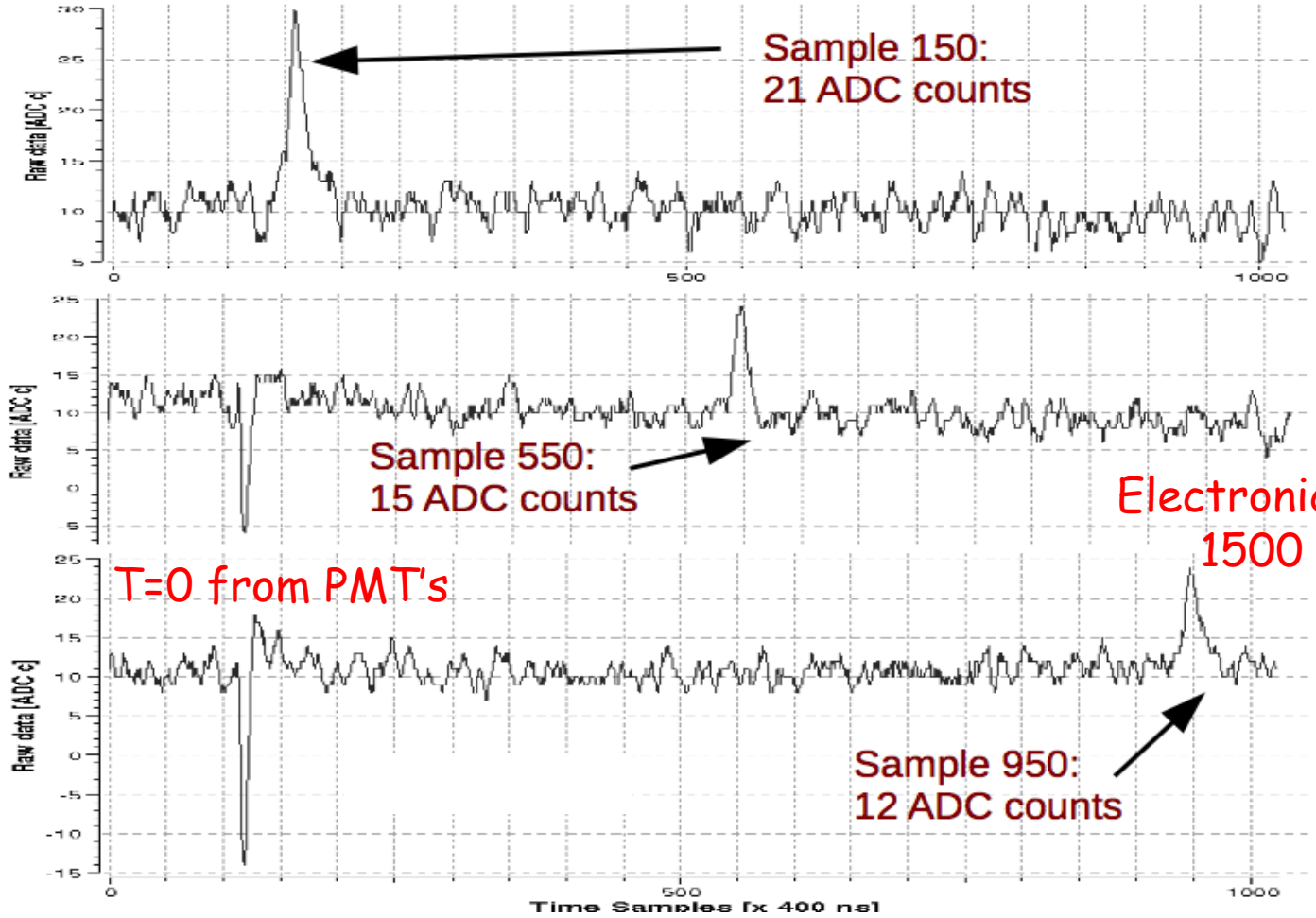
Collection view (-60°)



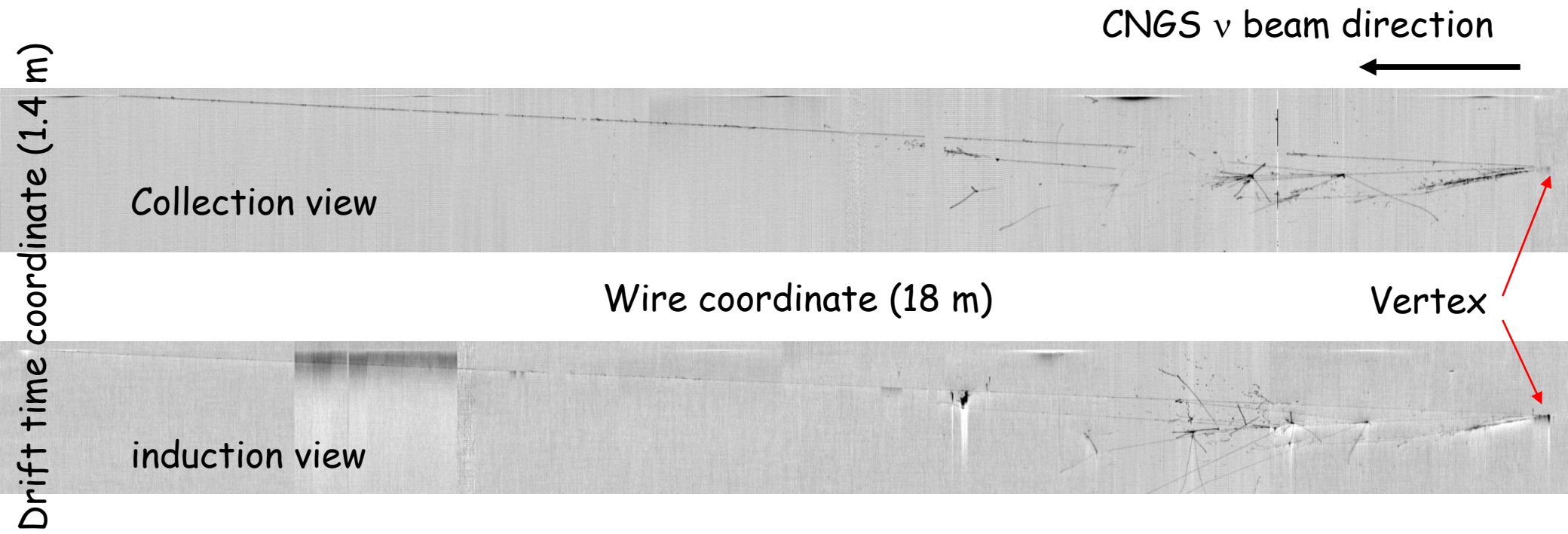
- Helps solving ambiguities and improve space resolution.
- Useful when a track runs parallel to a given wire direction (too few wires hit for 3D reconstruction)

LAr purity measurement

- Only the gaseous re-circulation/purification system is active
- On-line measure with charge attenuation along single muon crossing tracks
- Starting electron lifetime: T_{ele} ~ 650 μs, steadily increasing

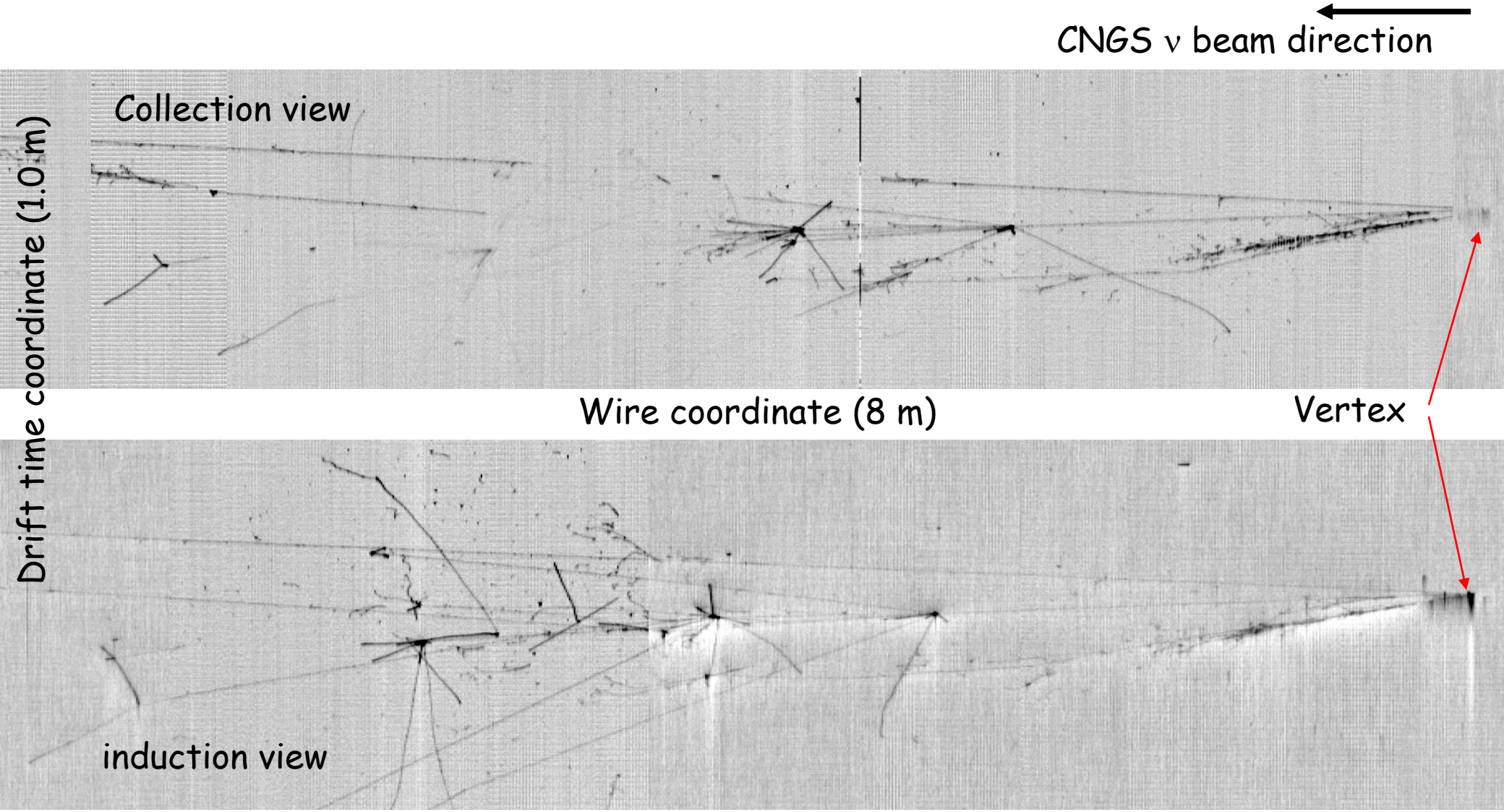


The first CNGS neutrino interaction in ICARUS T600

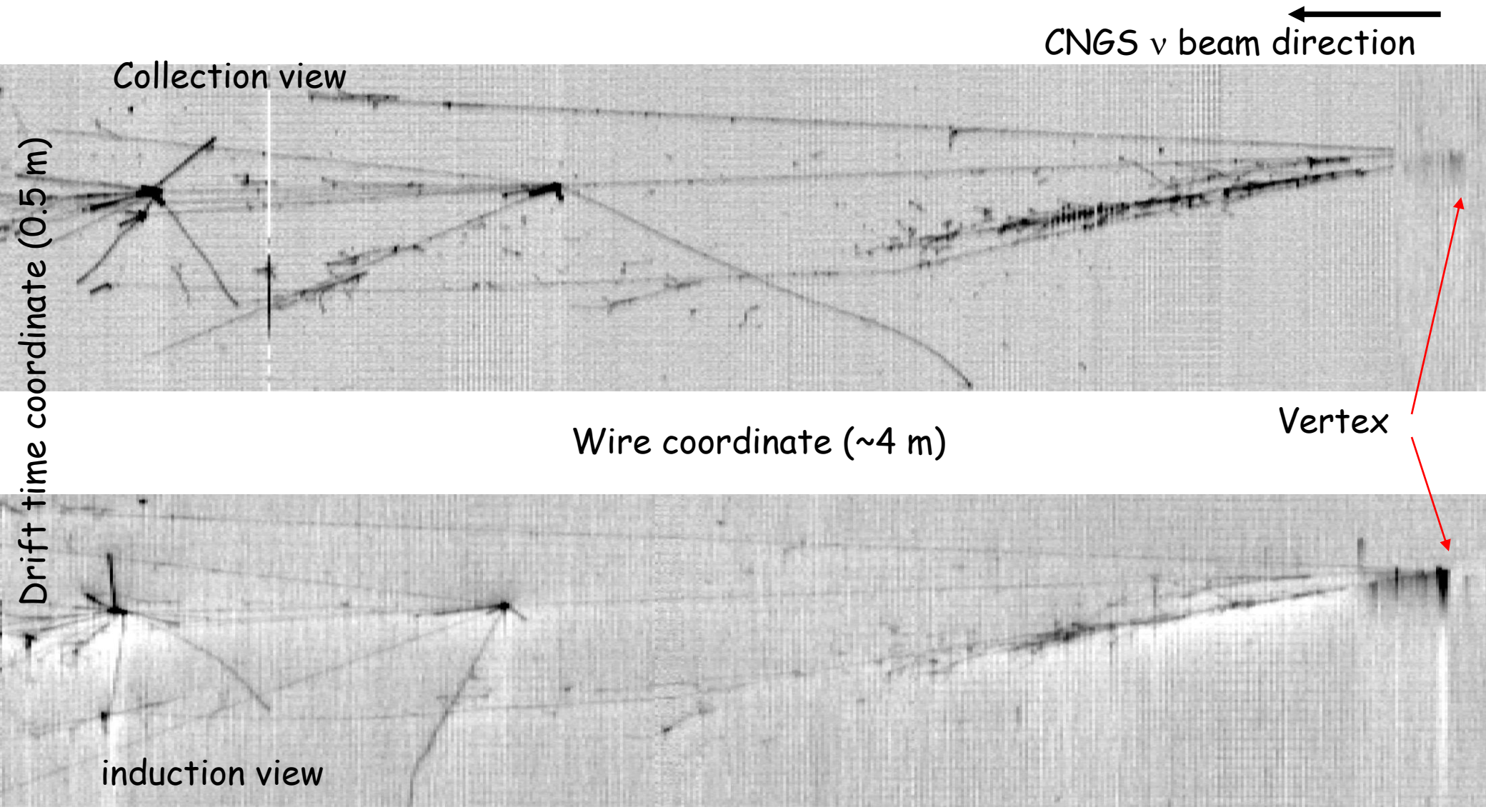


- Leading muon (crossing horizontally the whole cryostat)
- Two charged particle tracks undergoing hadronic interactions
- Two γ converting at 14 and 16 cm from vertex (π^0?)
- Vertex not fully visible in collection view, due to locally wrong wire biasing

The first CNGS neutrino interaction: hadronic showering

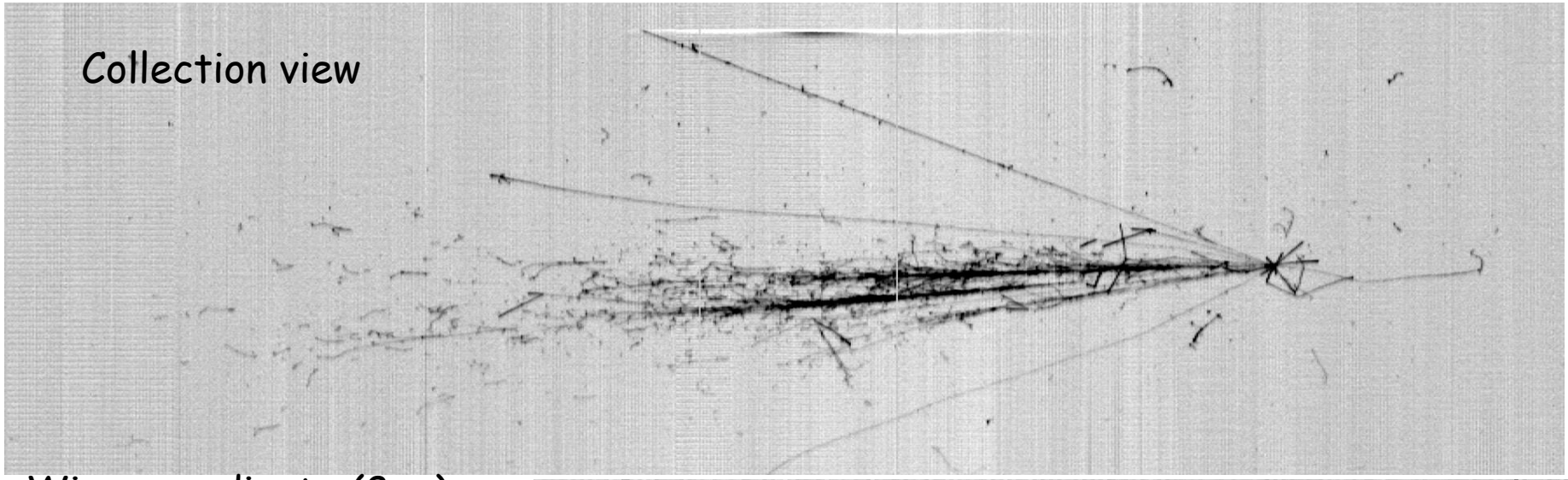


The first CNGS neutrino interaction: vertex and e.m. showers



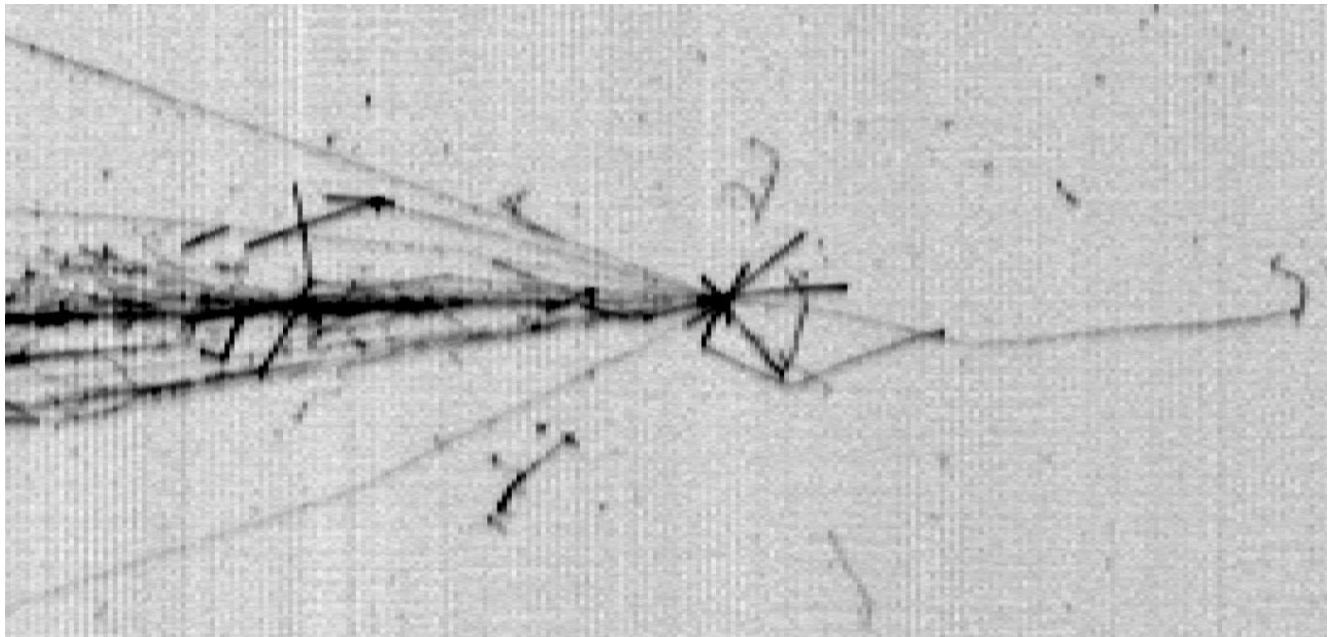
The second CNGS neutrino interaction in ICARUS T600

CNGS ν beam direction

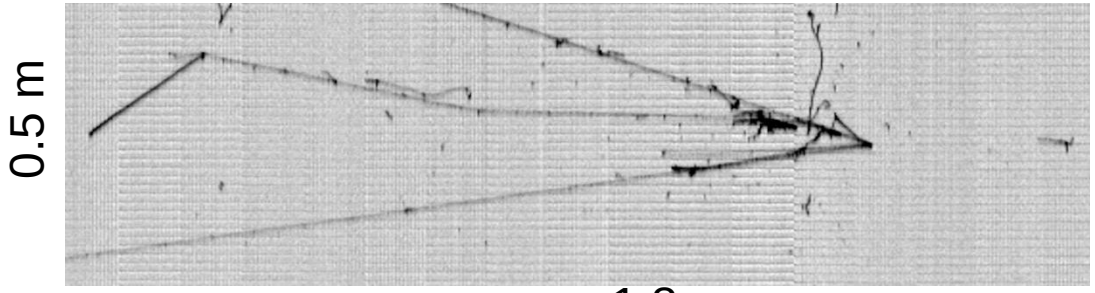


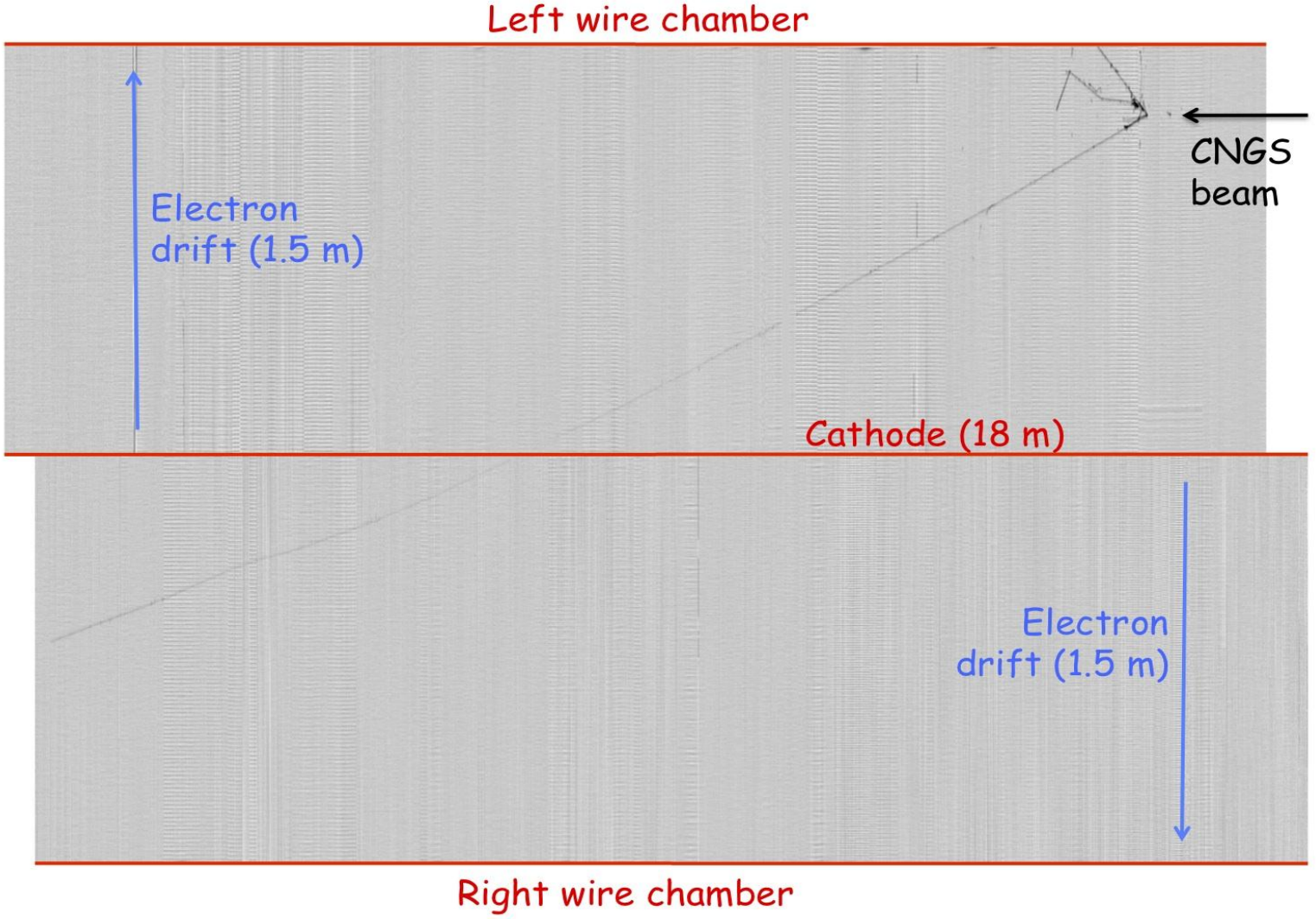
Drift time coordinate (1.4 m)

Wire coordinate (8 m)



Low energy CNGS neutrino interaction

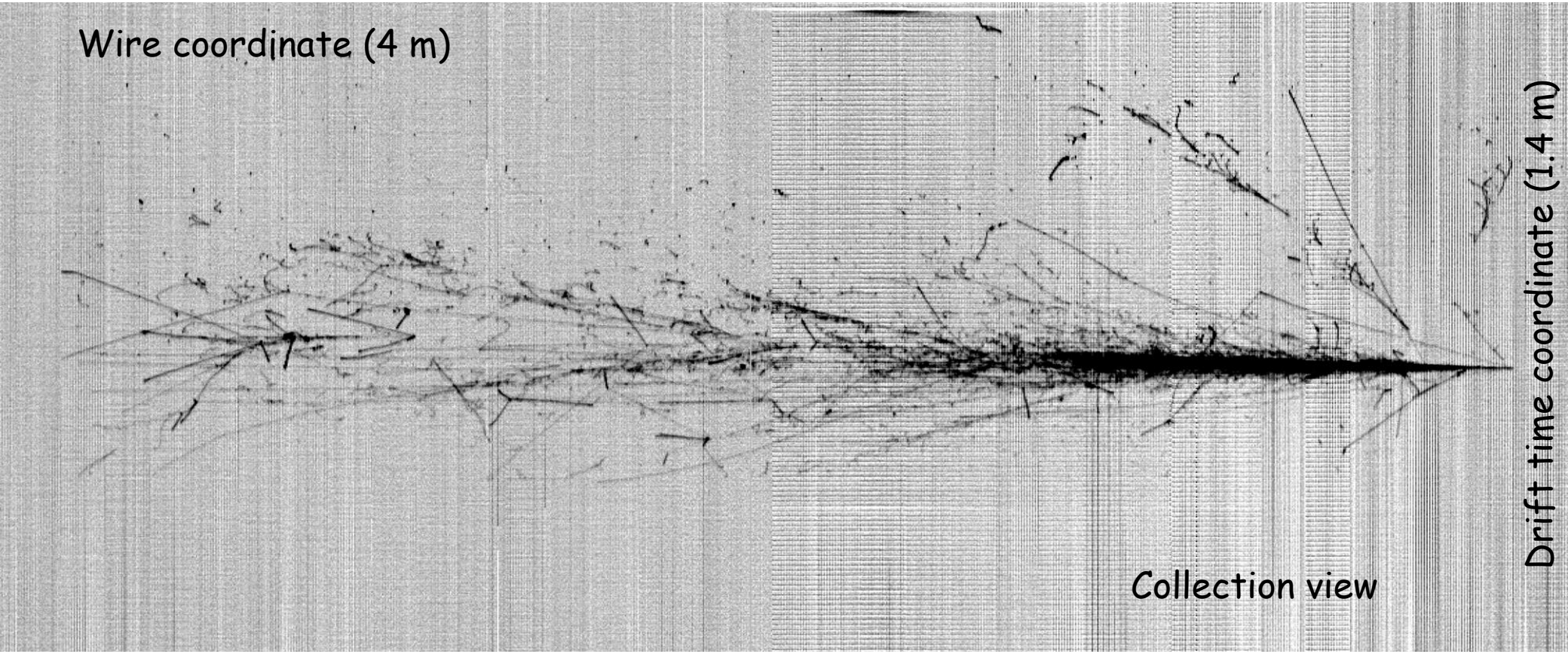




E_{vis} ~ 9 GeV
Electron lifetime and quenching accounted for

Collection views (not to scale!)

CNGS neutrino interaction



Conclusions: *The Renaissance of the "Bubble chamber" neutrino physics*

Cryogenic noble liquids and Argon "in primis" have recently regained a strong interest in the scientific community.

- The successful assembly and operation of the ICARUS-T600 LAr-TPC demonstrate that the technology is mature.
- The wide physics potentials offered by high granularity imaging and extremely high resolution will be addressed already with the T600 detector:
  - Underground physics (proton decay, solar, supernova, …)
  - Long-baseline, high precision neutrino physics
- The T600 is presently taking data, smoothly reaching optimal working conditions. Neutrino interactions have been observed. Data analysis already on-going.
- The ICARUS experiment at the Gran Sasso Laboratory is so far the most important milestone for this technology and acts as a full-scale test-bed located in a difficult underground environment.