The ICARUS T600 detector at LNGS underground laboratory

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on behalf of the

ICARUS Collaboration

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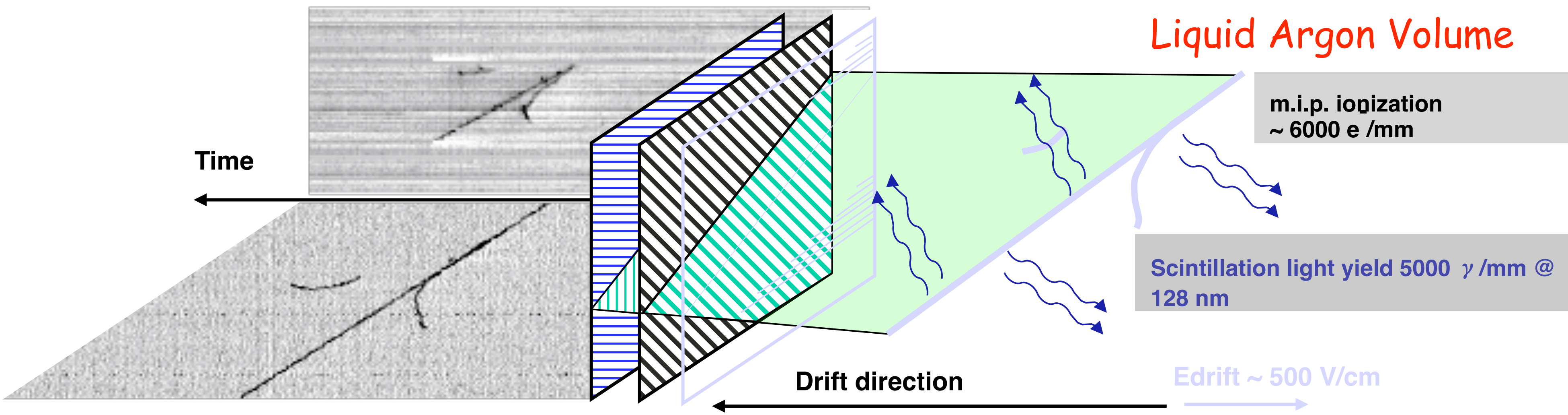
A powerful detection technique

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:

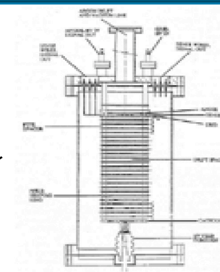
- continuously sensitive, self triggering
- high granularity (~ 1 mm)
- excellent calorimetric properties
- particle identification (through dE/dx vs range)



Electrons from ionizing track are drifted in LAr by E_{drift}. They traverse transparent wire 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).

ICARUS Milestones



CERN

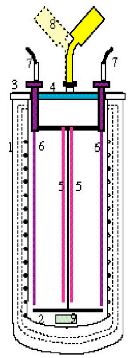
24 cm drift wires chamber

1

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

2

3 ton prototype



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

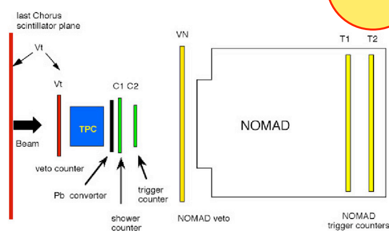
CERN

Laboratory work

CERN

50 litres prototype
1.4 m drift chamber

3



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

4

10 m^3 industrial prototype

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

Pavia

T600 detector

2001: First T600 module

5

Cooperation with industry and several companies

ICARUS T600 experiment

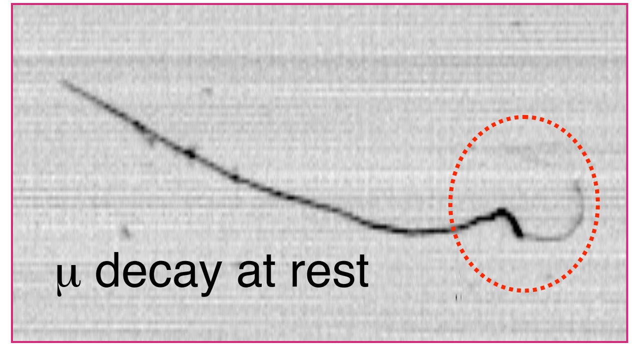
2010 - ... : Data taking with CNGS beam

6

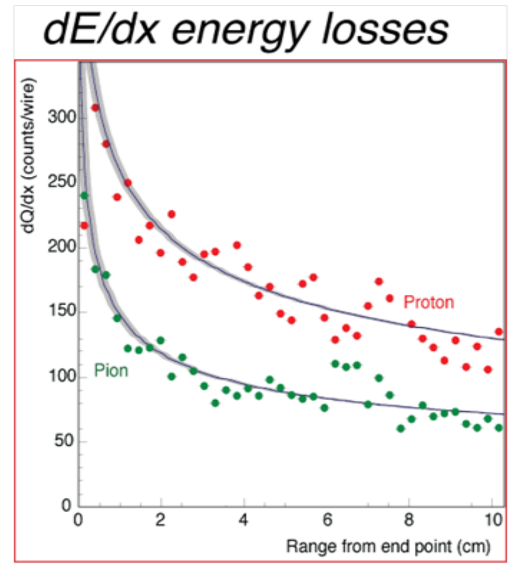
LNGS Hall-B

LAr-TPC performance

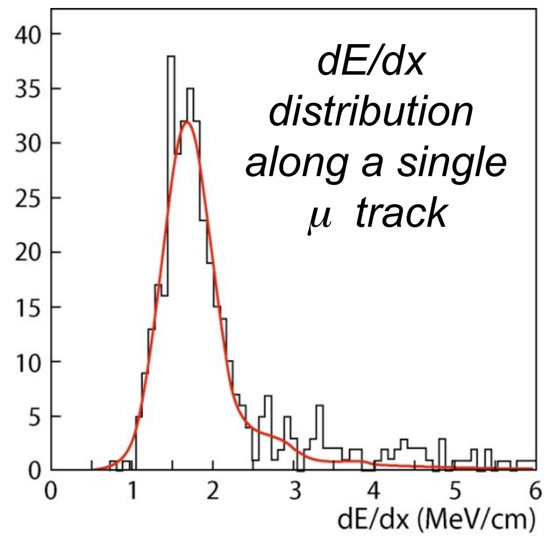
- Tracking device:
  - precise event topology ($s_{x,y}$ ~ 1mm, s_z ~ 0.4mm)
  - μ momentum measurement via multiple scattering: Δp/p ~10-15% depending on track length and p
  - Total energy reconstruction by charge integration

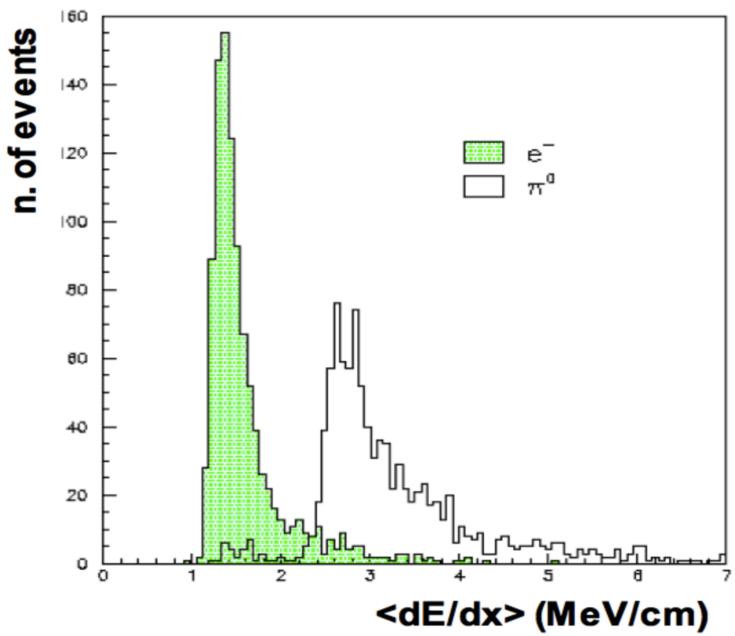


- Measurement of local energy deposition dE/dx:
  - e/γ separation (2% X_0 sampling);
  - particle ID by means of dE/dx vs range



- Good e/π^0 separation (10^{-3}) by means of dE/dx in the first part of the track after the vertex; π^0 mass measurement

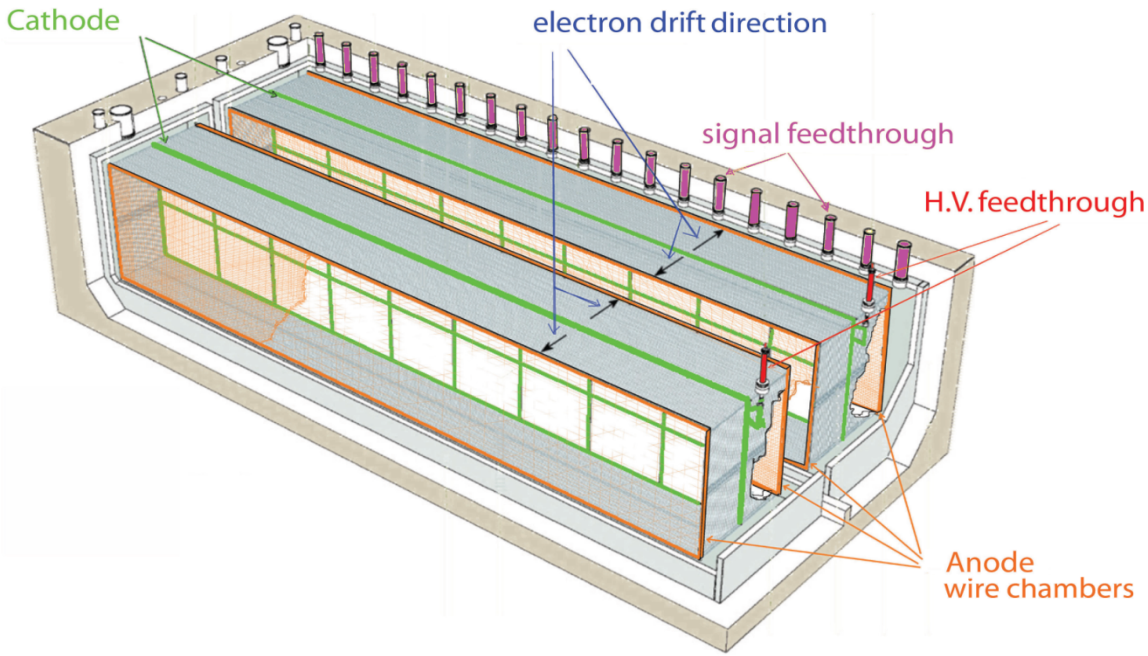


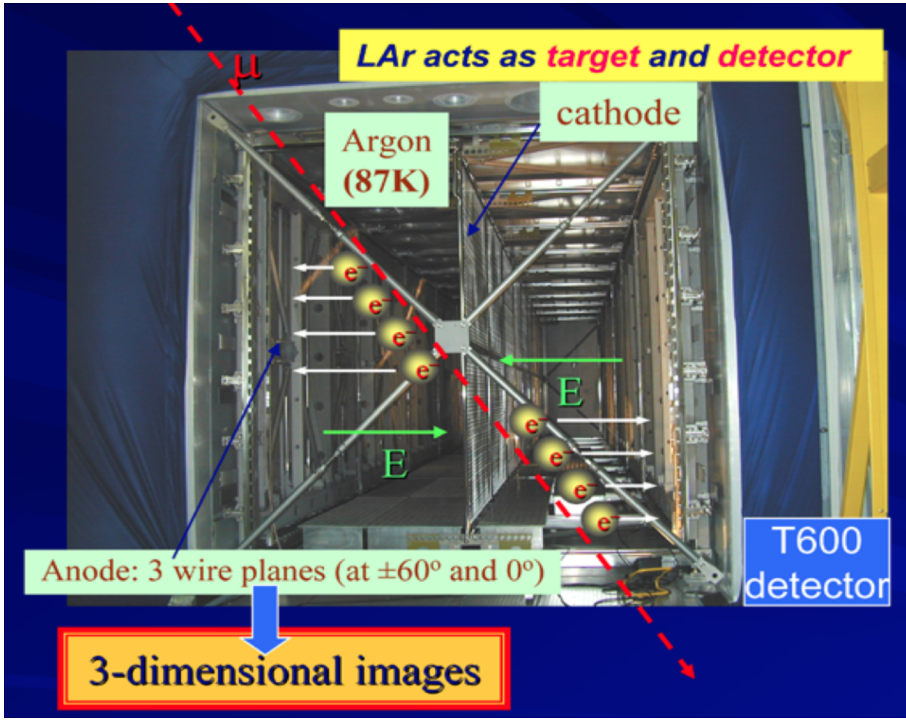


RESOLUTIONS

Low energy electrons:	σ(E)/E = 11% / √ E(MeV)+2%
Electromagnetic showers:	σ(E)/E = 3% / √ E(GeV)
Hadron shower (pure LAr):	σ(E)/E ≈ 30% / √ E(GeV)

The ICARUS T600 detector

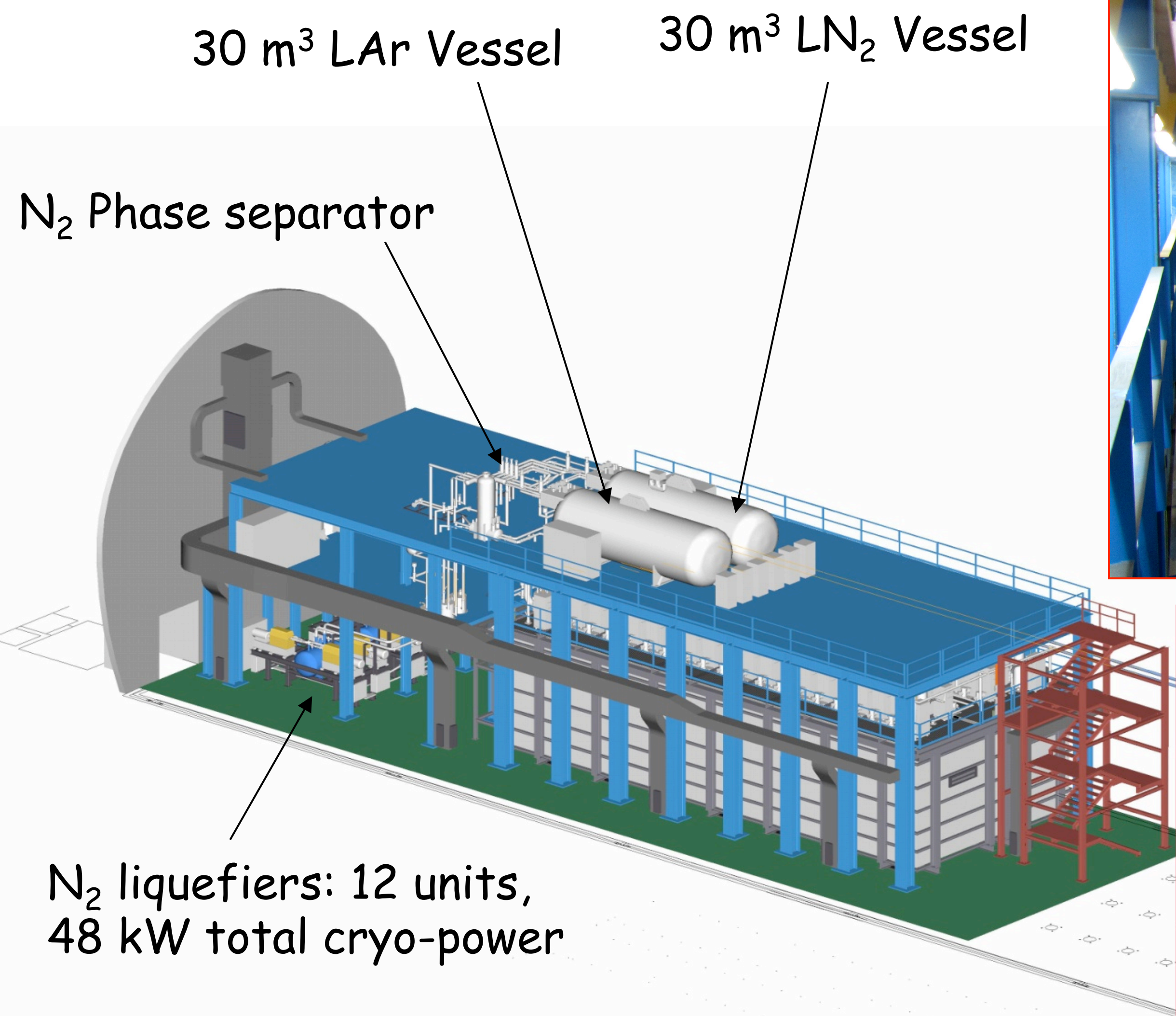


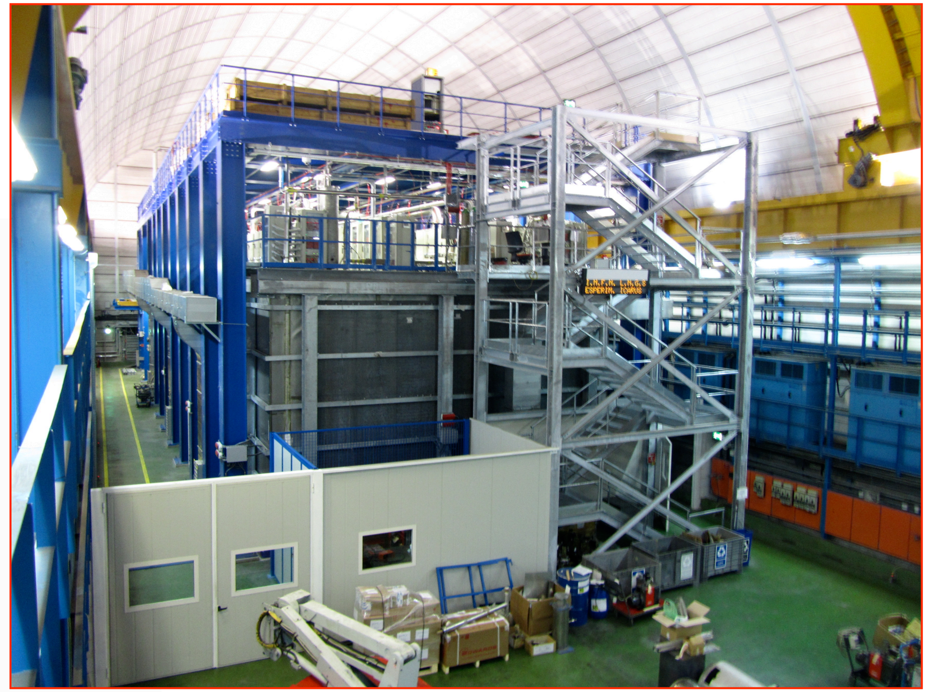


- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E = 0.5 kV/cm
  - vdrift = 1.55 mm/μs

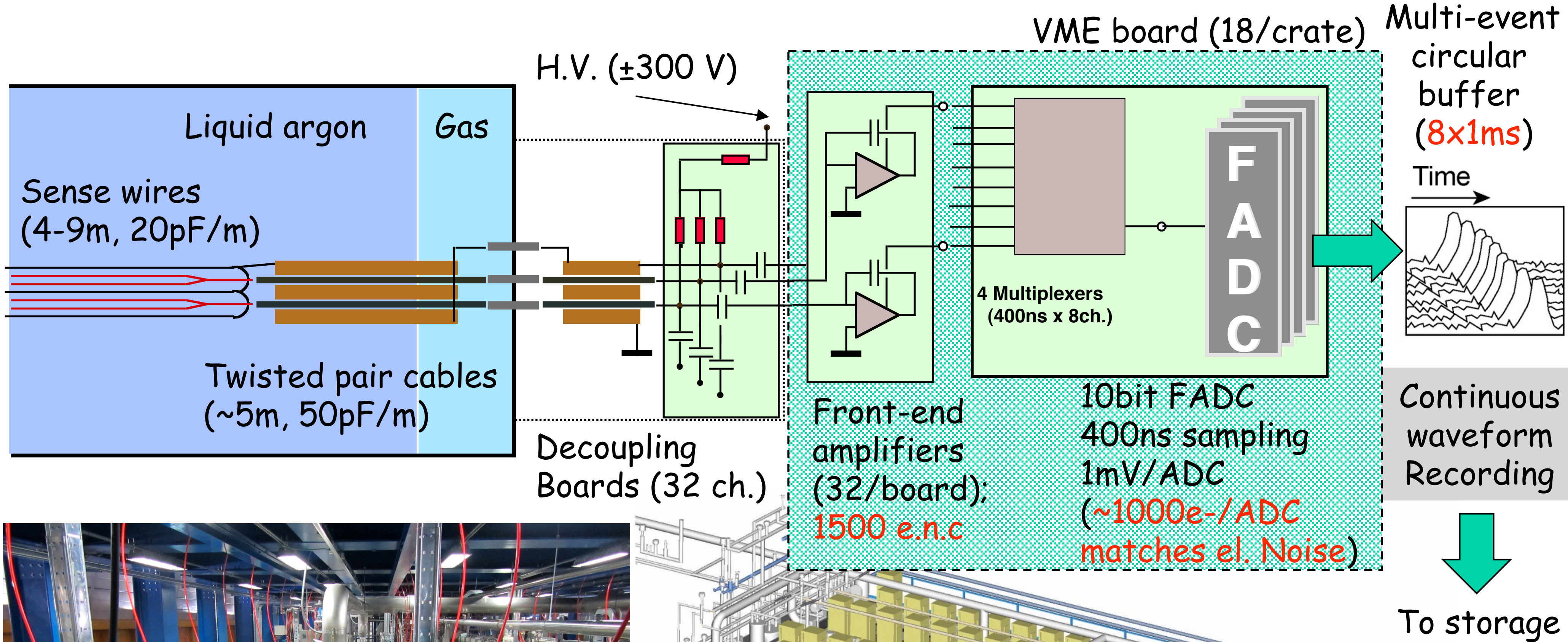
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- PMT for scintillation light:
  - (20+54) PMTs, 8” Ø
  - VUV sensitive (128nm) with wave shifter (TPB)

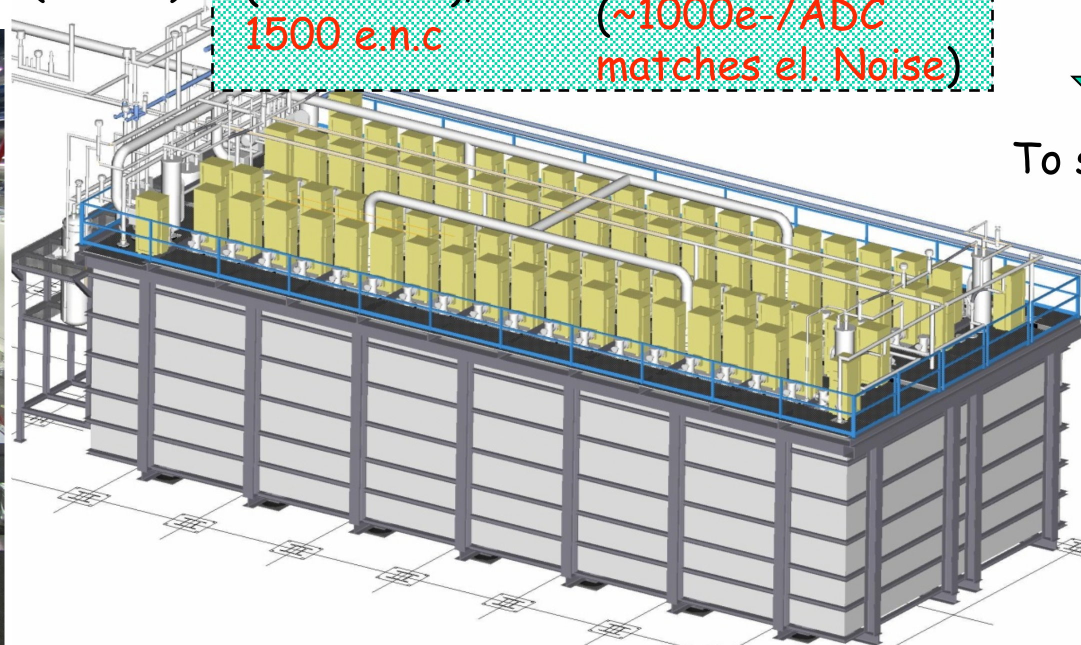
ICARUS T600 in LNGS Hall B





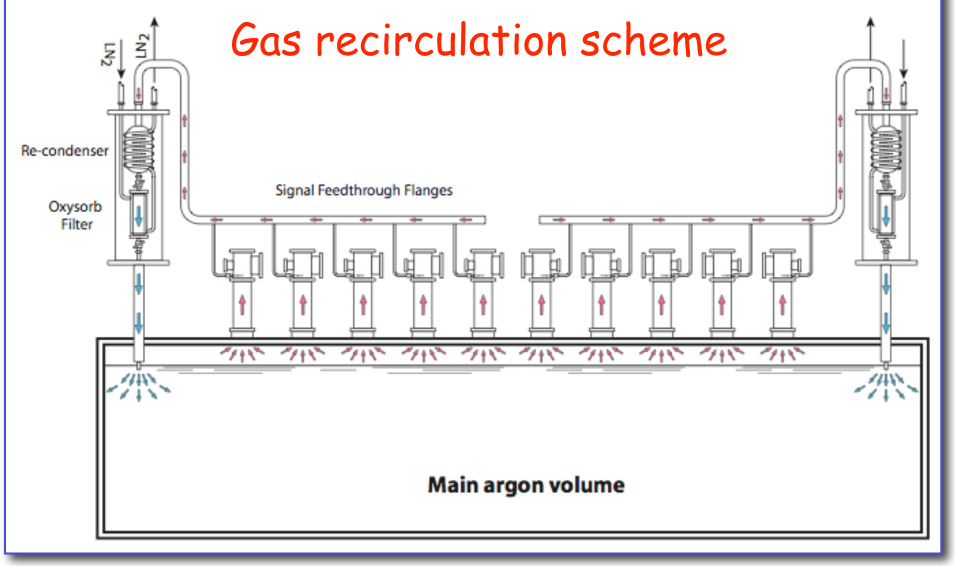
ICARUS front-end Electronics



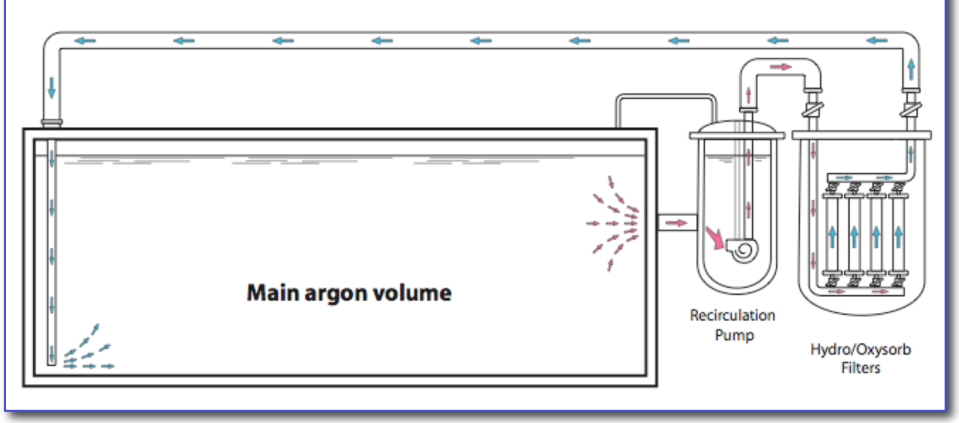


LAr Purification in T600

- The presence of electron trapping polar impurities attenuates the electron signal as $\exp(-t_D/\tau_{ele})$
- $\tau_{ele} \sim 300\ \mu s$ / ppb (O_2 equivalent).
- Because of temperature (87 K) most of the contaminants freeze out spontaneously. Main residuals: O_2, H_2O, CO_2.
- Recirculation/purification (100 Nm^3/h) of the gas phase (~40 Nm^3) to block the diffusion of the impurities from the hot parts of the detector and from micro-leaks on the openings (typically located on the top of the device) into the bulk liquid.
- Recirculation/purification (4 m^3/h) of the bulk liquid volume (~550 m^3) to efficiently reduce the initial impurities concentration (can be switched on/off).



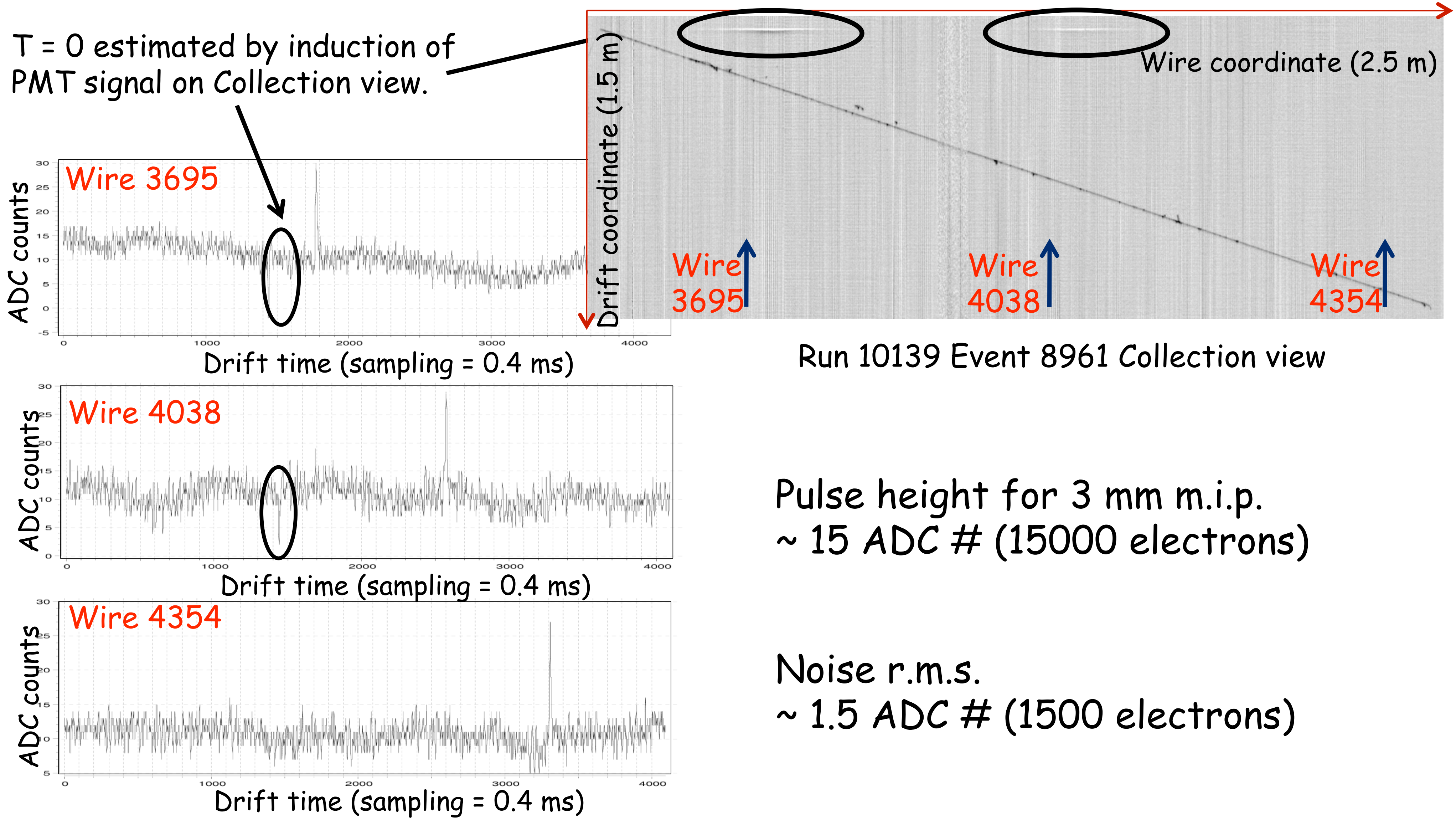
Gas recirculation scheme



Liquid recirculation scheme

LAr purity measurement with muon crossing tracks

Charge attenuation along track allows event-by-event measurement of LAr purity.

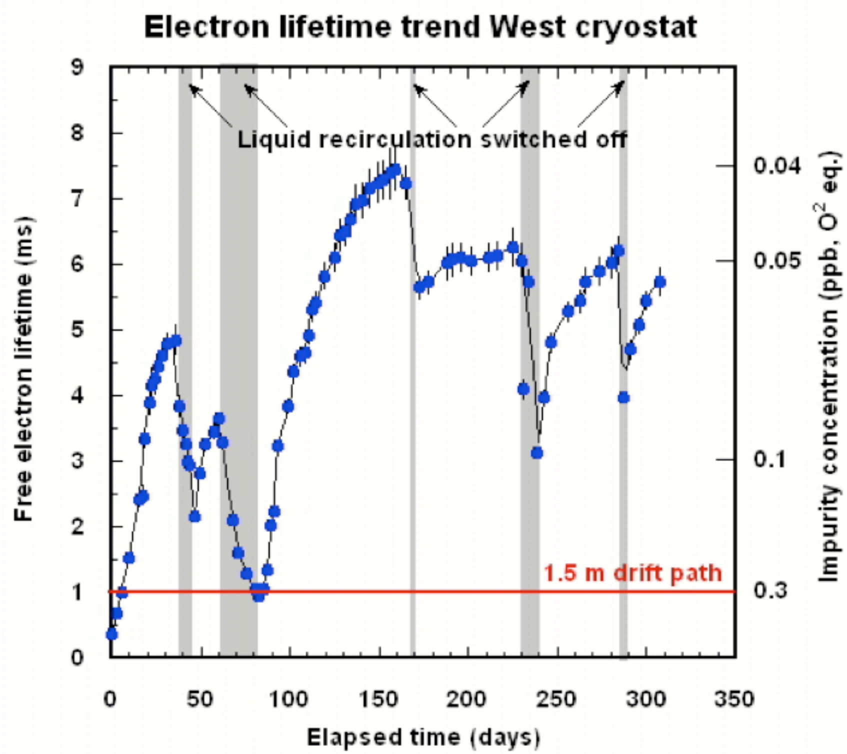


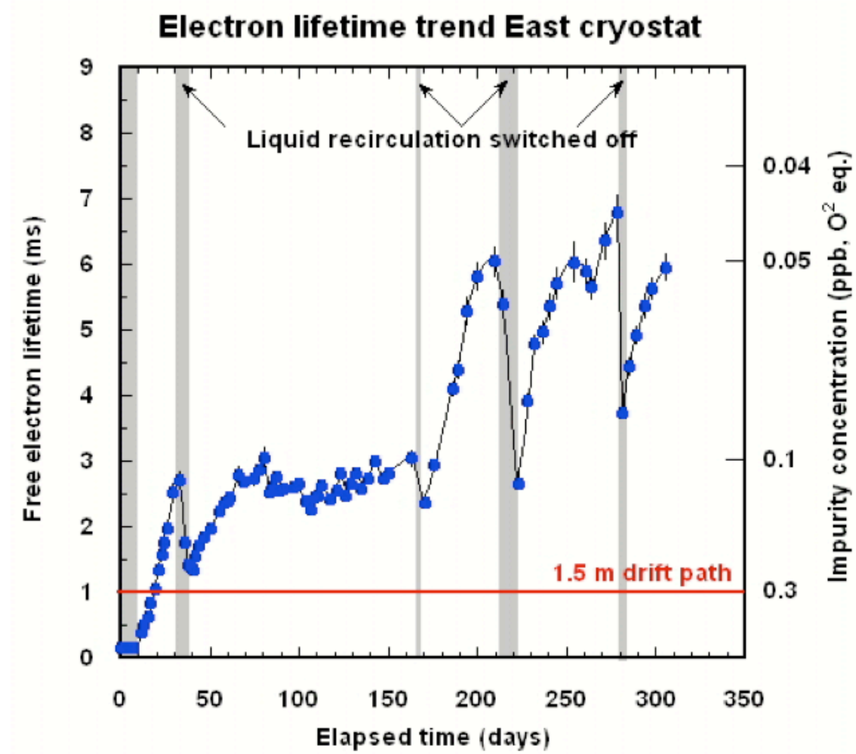
Run 10139 Event 8961 Collection view

Pulse height for 3 mm m.i.p.
~ 15 ADC # (15000 electrons)

Noise r.m.s.
~ 1.5 ADC # (1500 electrons)

LAr purity time evolution





Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

$$dN/dt = -N/\tau_R + k_I + k_D \exp\left(-t/\tau_D\right)$$

τ_R: *recirculation time for a full detector volume*
k_D *and* τ_D : *related to the total degassing internal rate*
k_I : *totally impurity leak rate and degassing rate*

τ_R: *2 m^3/h per half module corresponding to ≈ 6 day cycle time*

τ_{ele} [ms] = 0.3 / N[ppb O_2 equivalent]

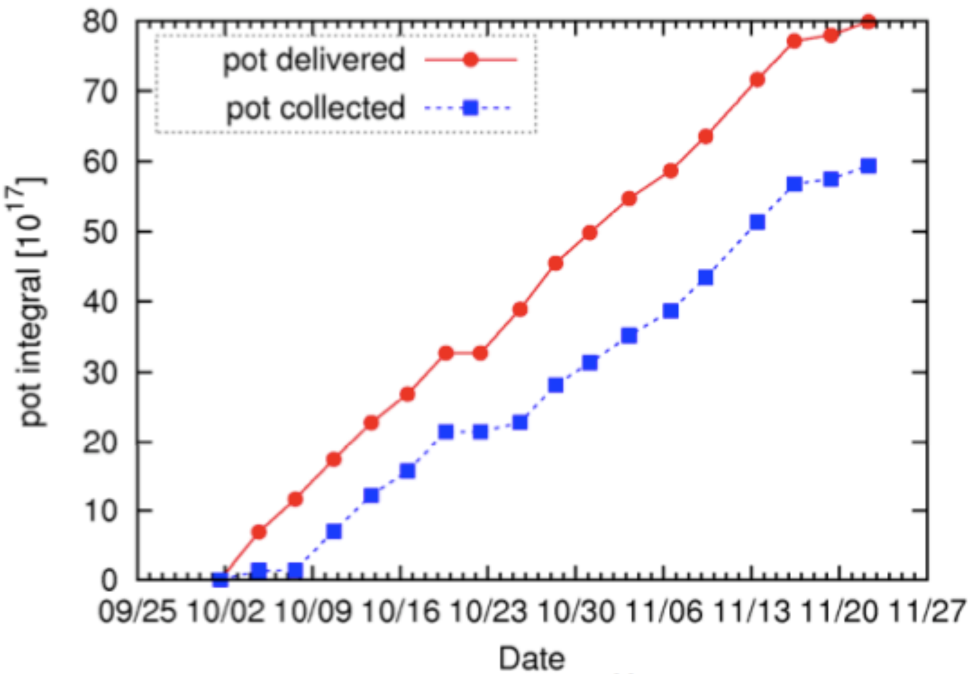
ICARUS T600 physics potential

- ICARUS T600: **major milestone** towards realization of large scale LAr detector. Interesting physics in itself: unique imaging capability, spatial/ calorimetric resolutions and e/π^0 separation → **events "seen in a new Bubble chamber like" way**.
- CNGS ν events collection (beam intensity 4.5 10^{19} pot/year, E_ν ~ 17.4 GeV):
  - 1200 ν_μ CC event/year;
  - ~ 8 ν_e CC event/year;
  - observation of ν_τ events in the electron channel, using kinematical criteria;
  - search for sterile ν in LSND parameter space (deep inelastic ν_e CC events excess).
- "Self triggered" events collection:
  - ~ 80 events/y of unbiased atmospheric ν CC;
  - zero background proton decay with 3 x 10^{32} nucleons for "exotic" channels.

Preliminary results of first CNGS 2010 run

- ICARUS fully operational for CNGS events recording in Oct. 1st – Nov. 22nd.
- Trigger: photomultiplier signal for each chamber with low threshold discrimination at 100 phe, within 60 μs wide beam gate.

Oct. 1st ÷ Nov. 22nd: $8 \cdot 10^{18}$ ($5.8 \cdot 10^{18}$) pot delivered (collected). Detector lifetime up to 90% since Nov. 1st.



Number of collected interactions compared with number of interactions predicted (($2.6\ \nu$ CC + $0.86\ \nu$ NC) 10^{-17}/pot), in the whole energy range up to 100 GeV, corrected by fiducial volume (424 t) and DAQ dead-time.

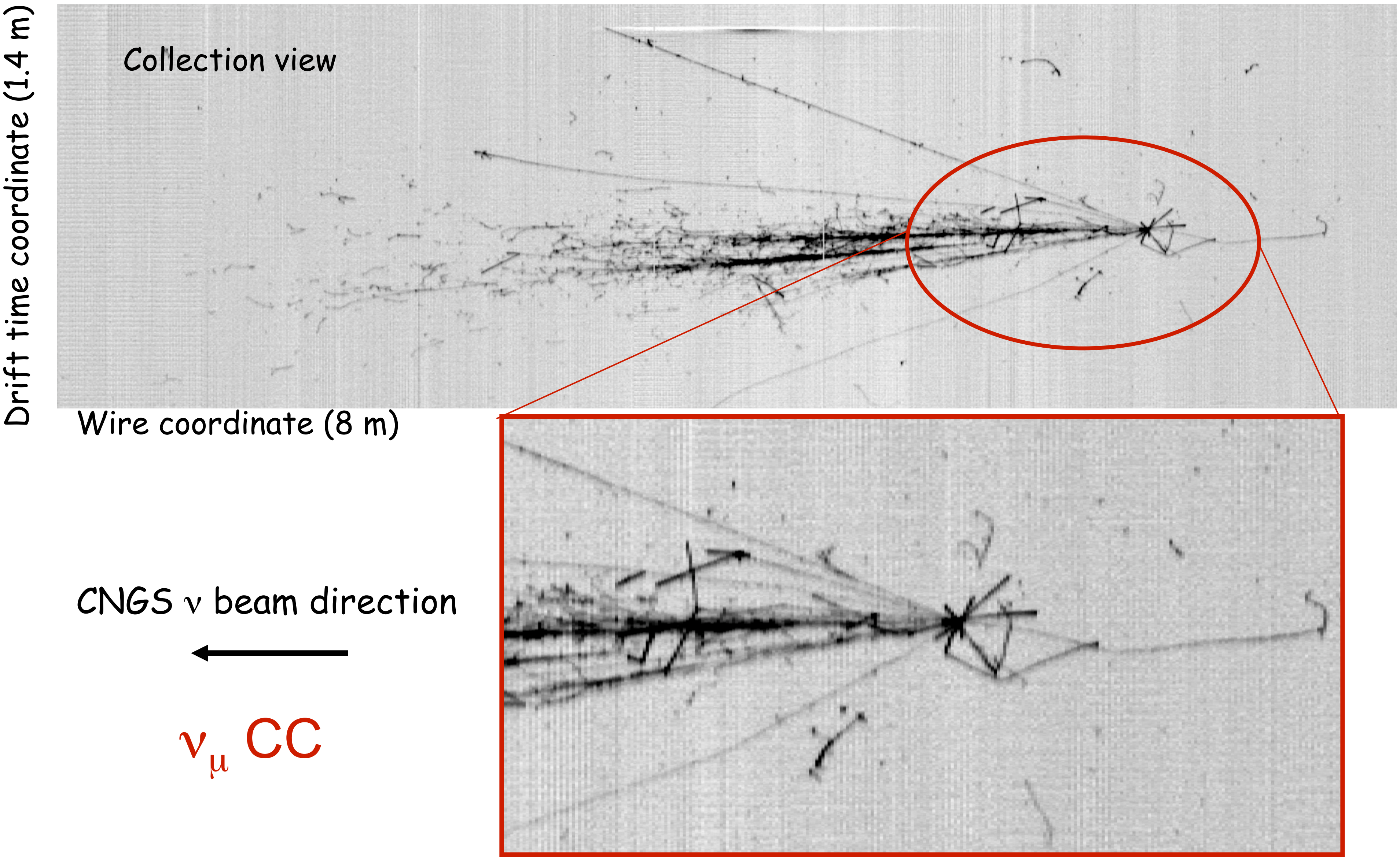
$5.3 \cdot 10^{18}$ pot = 91 % out of whole sample

Event type	Collected	Expected
ν_μ CC	108	115
ν NC	36	37
ν XC *	6	-
Total	150	152

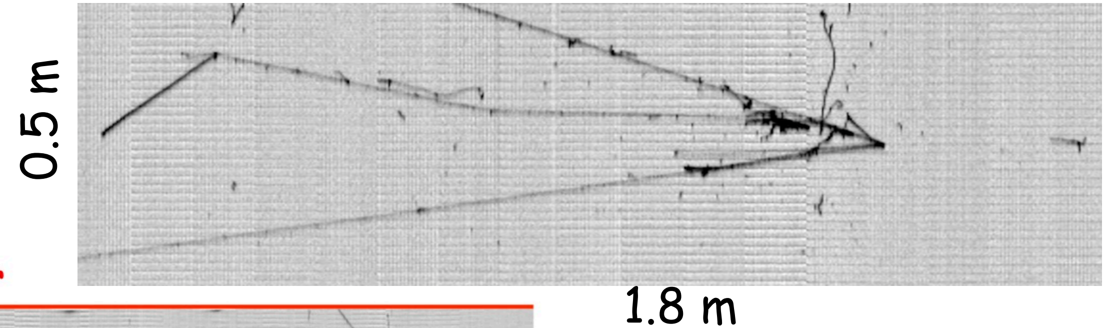
- Events at edges, with μ track too short to be visually recognized: further analysis needed.

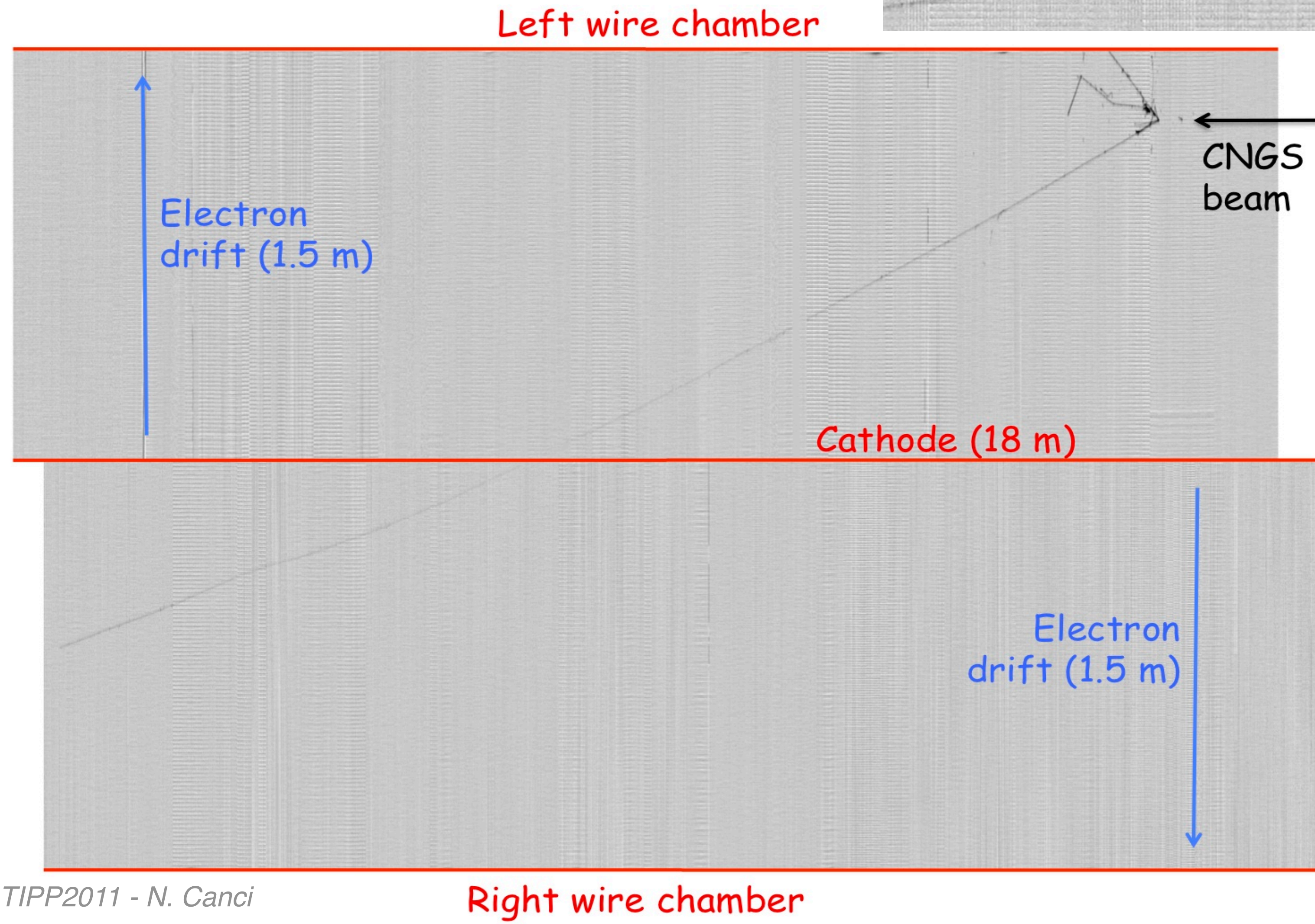
On overall statistics in agreement with expectations.

CNGS neutrino interactions in ICARUS T600



Low energy CNGS neutrino interaction

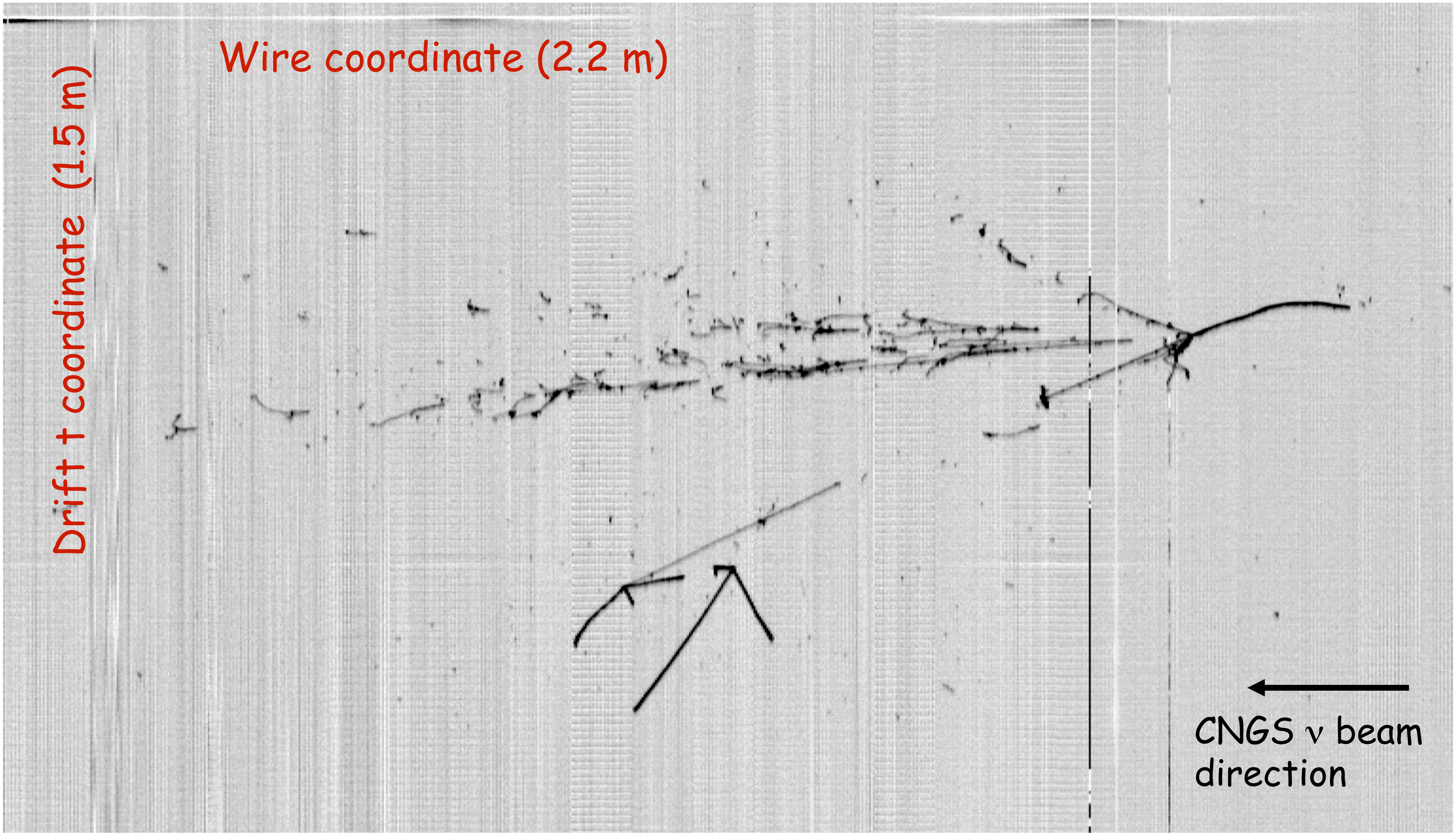




Evis ~ 9 GeV
Electron lifetime and quenching accounted for

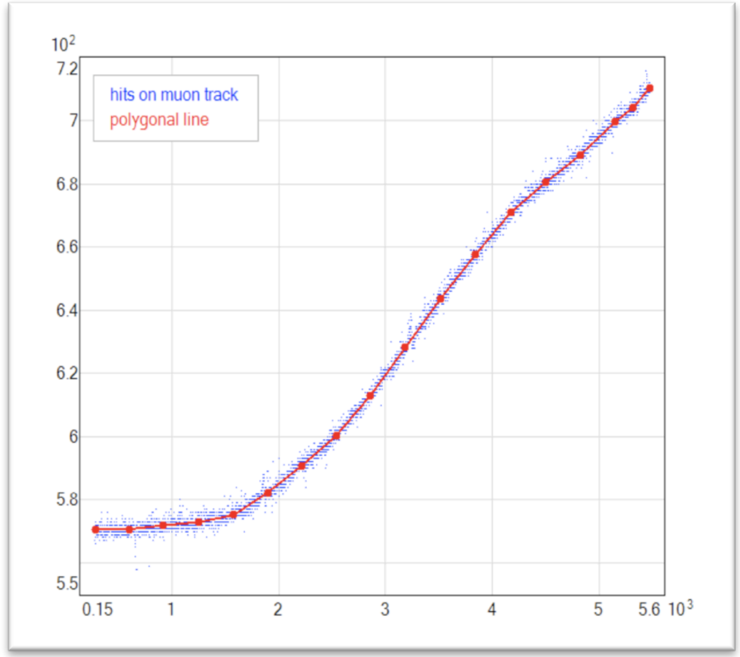
Collection views (not to scale!)

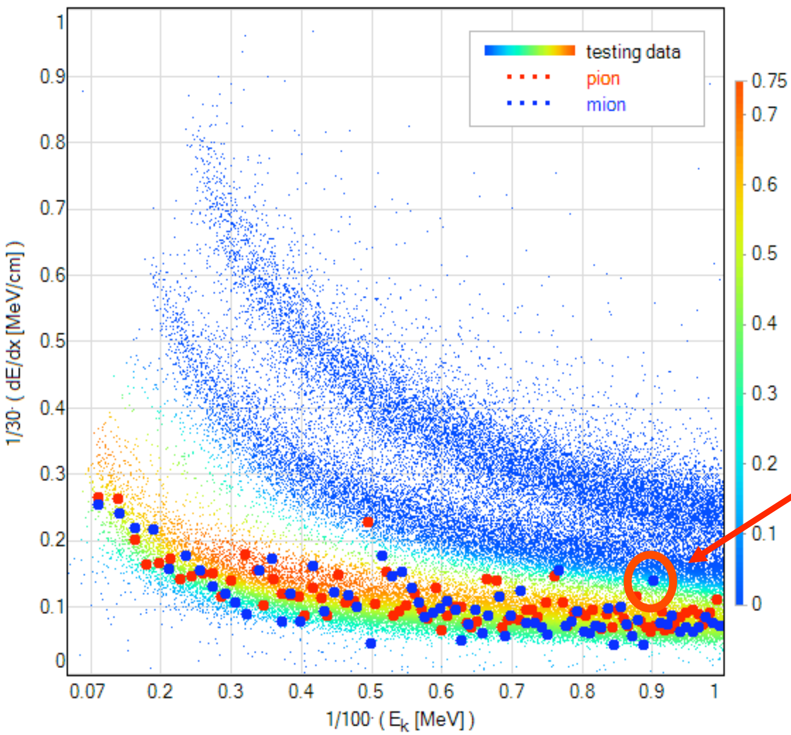
CNGS NC interaction



3D reconstruction and (nn) particle identification

- Complement of 2D reconstruction based on Polygonal Line Algorithm (PLA).
  http://www.iro.umontreal.ca/~kegl/research/pcurves/
- 3D reconstruction: linking hit projections between views according to
  - drift sampling;
  - sequence of hits.



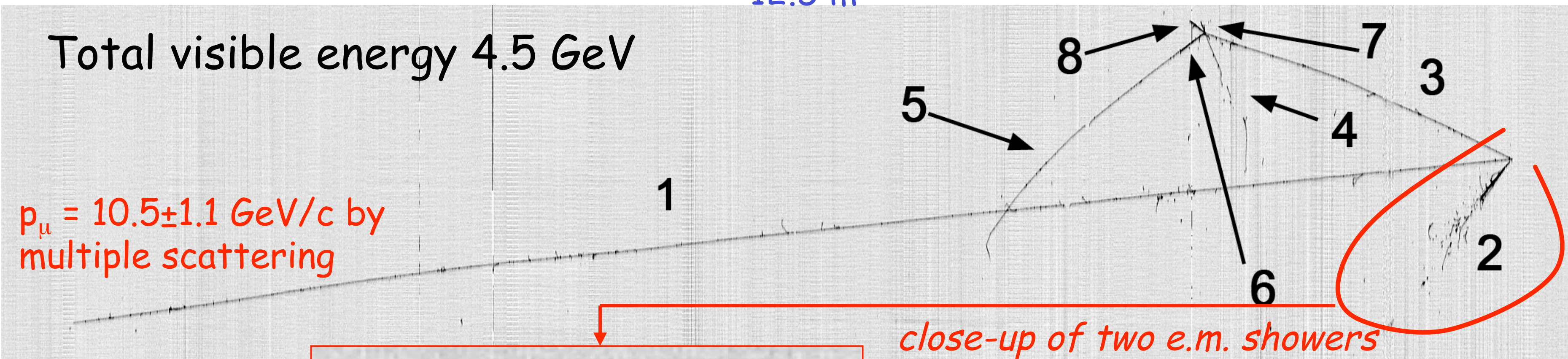


- **Particle identification** based on:
  - distance between nearby 3D hits: dx
  - 3D hits and charge deposition : dE/dx
- Classify single i^{th} point on the track

  $\mathbf{p}_i$: [E_k, dE/dx] $\rightarrow$ $\mathbf{nn}_i$: [P(p), P(K), P(p), P(μ)]
- Average M output vectors for the points
  NN = $S(\mathbf{nn}_i)/M$
- Identify track as particle corresponding to max(**NN**)

  very high identification efficiency for p, K, π^+, μ
- Energy reconstructed including quenching in simulation

LAr-TPC: powerful technique. Run 9927 Event 572

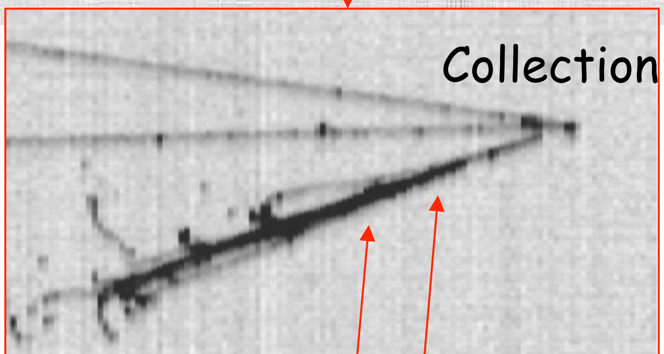


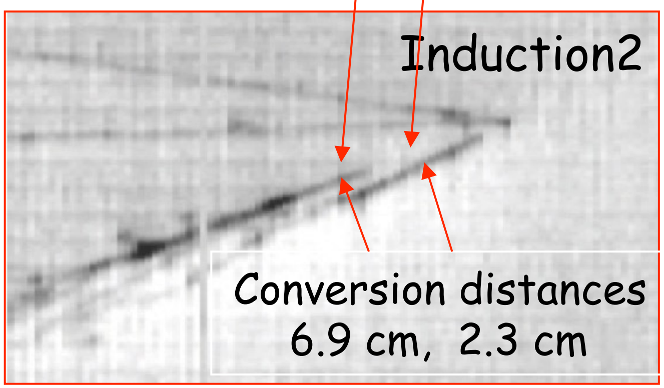
Primary vertex (A)

very long μ (1), e.m. cascade(2), pion (3).

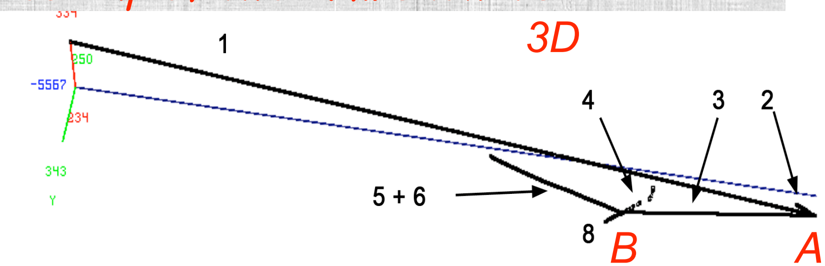
Secondary vertex (B)

The longest track (5) is a μ coming from stopping k (6).
- μ decay is observed.



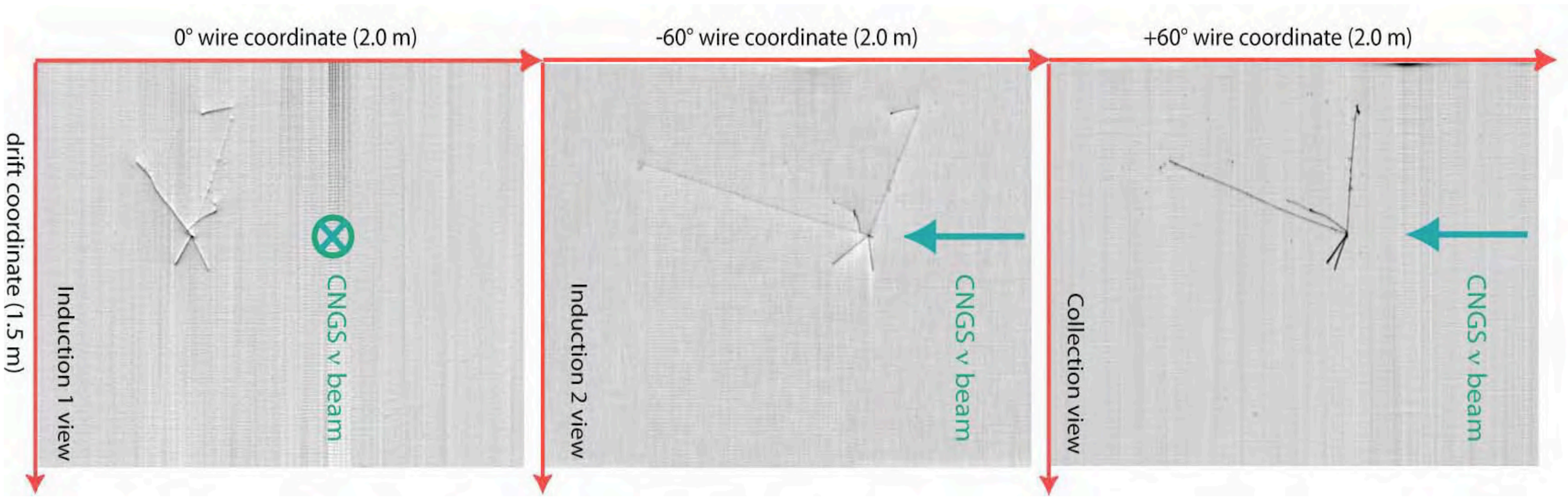


$M^*_{\gamma\gamma}$ = 125±15 MeV/c^2

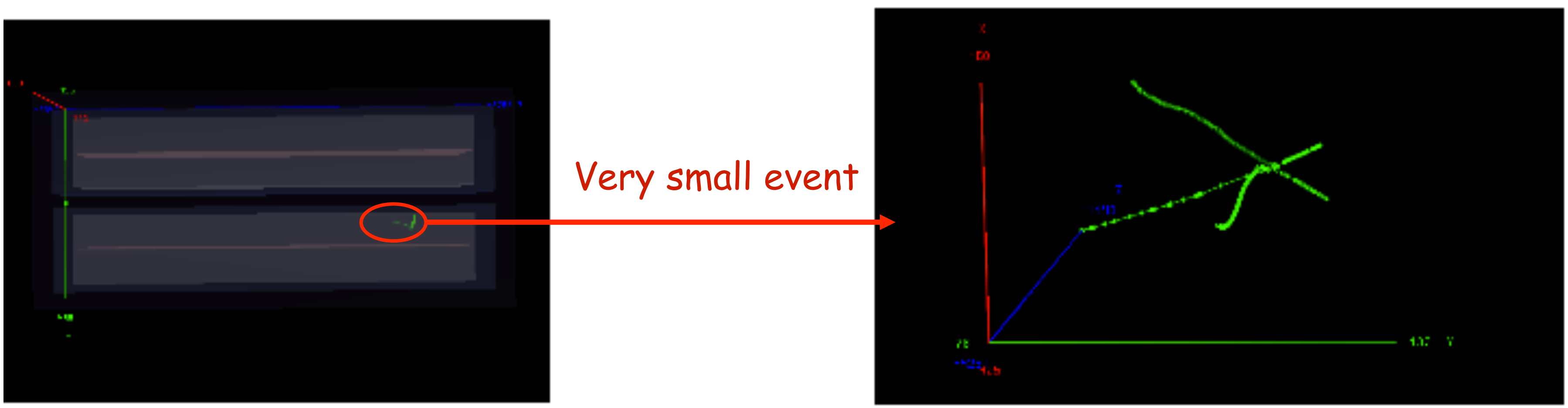


Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2 (π^0)	520.82	0.054	-0.420	-0.906
3 (π)	514.04	-0.001	0.137	-0.991
Sec.vtx.	797.			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

Atmospheric ν candidate



- Total visible energy: 887 MeV (including quenching and e⁻ lifetime corrections).
- Out-of-time from CNGS spill AND angle w.r.t. beam direction: 35°.



2011-2012 CNGS run: physics perspectives

- 2011-2012 run with dedicated SPS periods @ high intensity: expected 10^{20} pot.
- For 1.1 10^{20} pot: 3000 beam related ν_μ CC events expected in ICARUS-T600.

Background: 7 ν_e CC intrinsic beam associated events with visible energy < 20 GeV.

Signal:

- At the effective neutrino energy of 20 GeV and $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$, $P(\nu_\mu \rightarrow \nu_\tau) = 1.4\%$
- 17 raw CNGS beam-related ν_τ CC events expected
- $P(\tau \rightarrow e\nu\nu) = 18\% \Rightarrow$ 3 electron deep inelastic events with visible energy < 20 GeV.

- $\tau \rightarrow e\nu\nu$ events characterized by momentum unbalance (because of 2ν emission) and relatively low electron momentum. Selection criteria suggest a sufficiently clean separation with kinematic cuts and efficiency ~ 50%, allowing to detect 1-2 ν_τ CNGS events expected in ICARUS T600 in next 2 years.

Conclusions

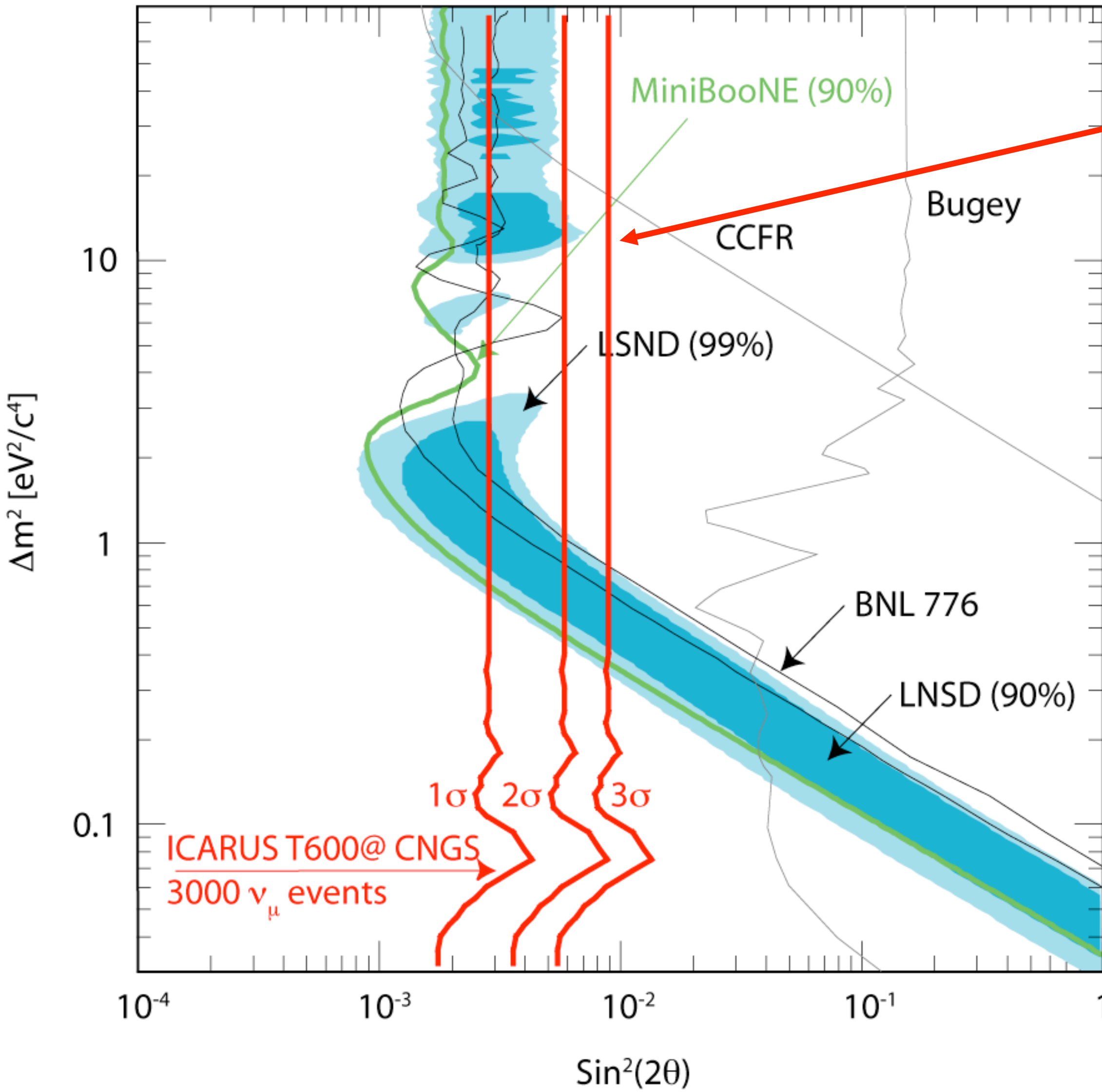
Cryogenic noble liquids and Argon in particular have recently regained a strong interest in the scientific community.

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.

- The successful assembly and operation of the ICARUS-T600 LAr-TPC demonstrate that the technology is <u>mature.</u>
- 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, atmospheric ν, supernova, …)
  - Long-baseline neutrino oscillation physics
- The T600 is presently taking data, recording cosmic and CNGS neutrino events in stable conditions since October 2010. Data analysis is on-going.
- The detector is ready for the 2011-2012 CNGS high intensity exposure.

The ICARUS Experiment: Back up Slides

Sterile neutrino search with ICARUS T600



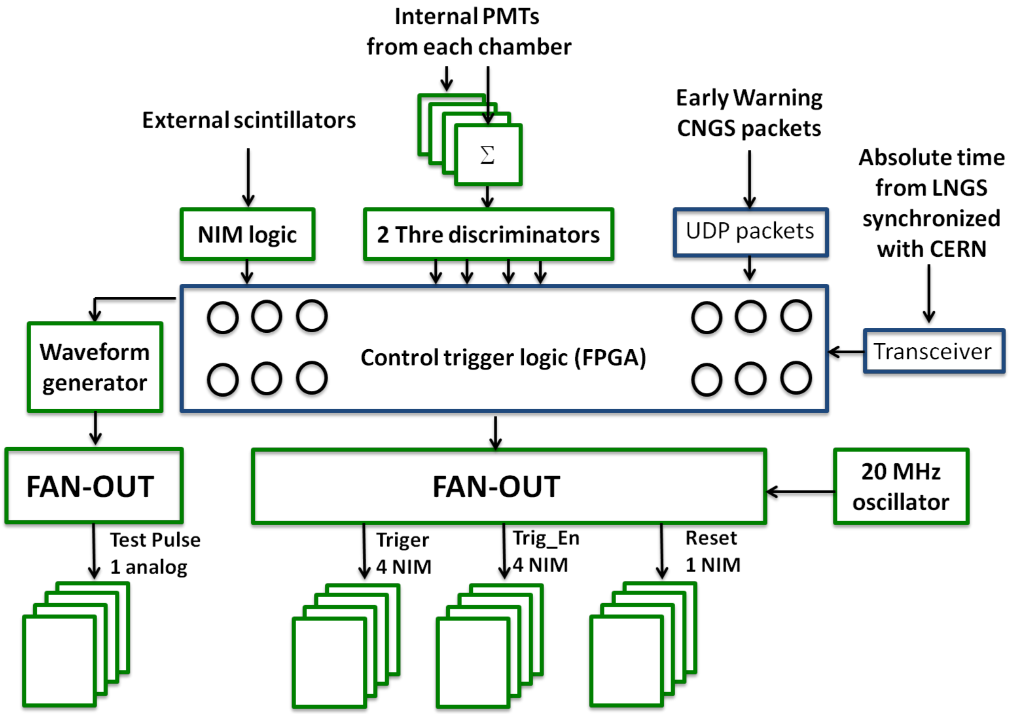
$\nu_{\mu} \rightarrow \nu_e$ appearance search in T600 in LNSD parameter space

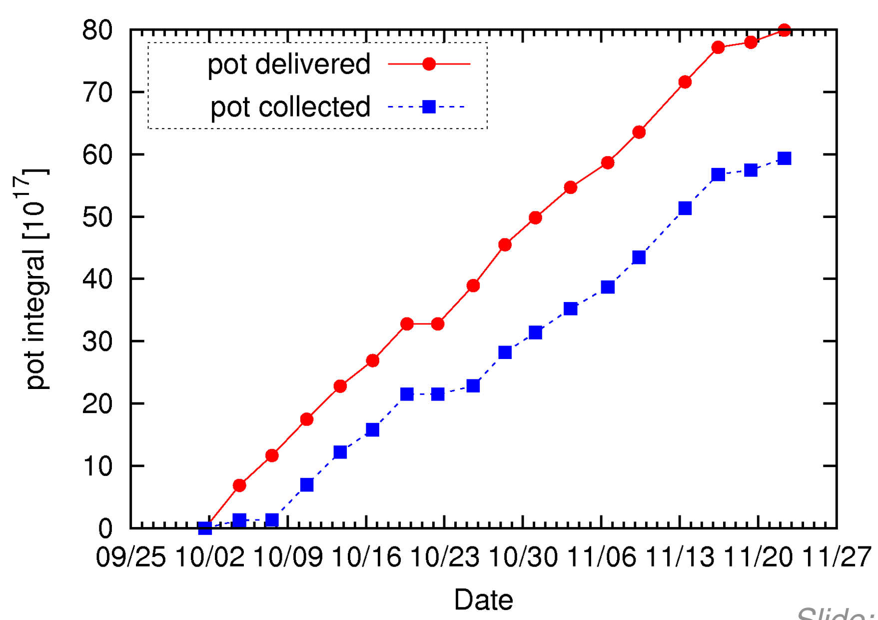
- Sensitivity region, in terms of standard deviations, for 3000 raw CNGS muon neutrino events.
- The potential signal is above the background generated by the intrinsic ν_e beam contamination, in the deep inelastic interval 10-30 GeV.
- Largely complementary to the Fermi-lab program in terms of energy and baseline.

CNGS run during 2010

- ICARUS fully operational for CNGS events recording in Oct. 1st – Nov. 22nd.
- At every CNGS cycle 2 spills lasting 10.5 μs each, 50 ms apart; ppp = 2.1 10^{13}.
- CNGS "Early Warning" signal sent 80 ms before the proton spill extraction, containing information on the time foreseen for the next extraction.
- Trigger: photomultiplier signal for each chamber with low threshold discrimination at 100 phe, within 60 μs wide beam gate.

Oct. 1st ÷ Nov. 22nd: 8 · 10^{18} (5.8 · 10^{18}) pot delivered (collected). Detector lifetime up to 90% since Nov. 1st.





A CNGS ν_μ interaction with time coincidence

CNGS ν beam direction