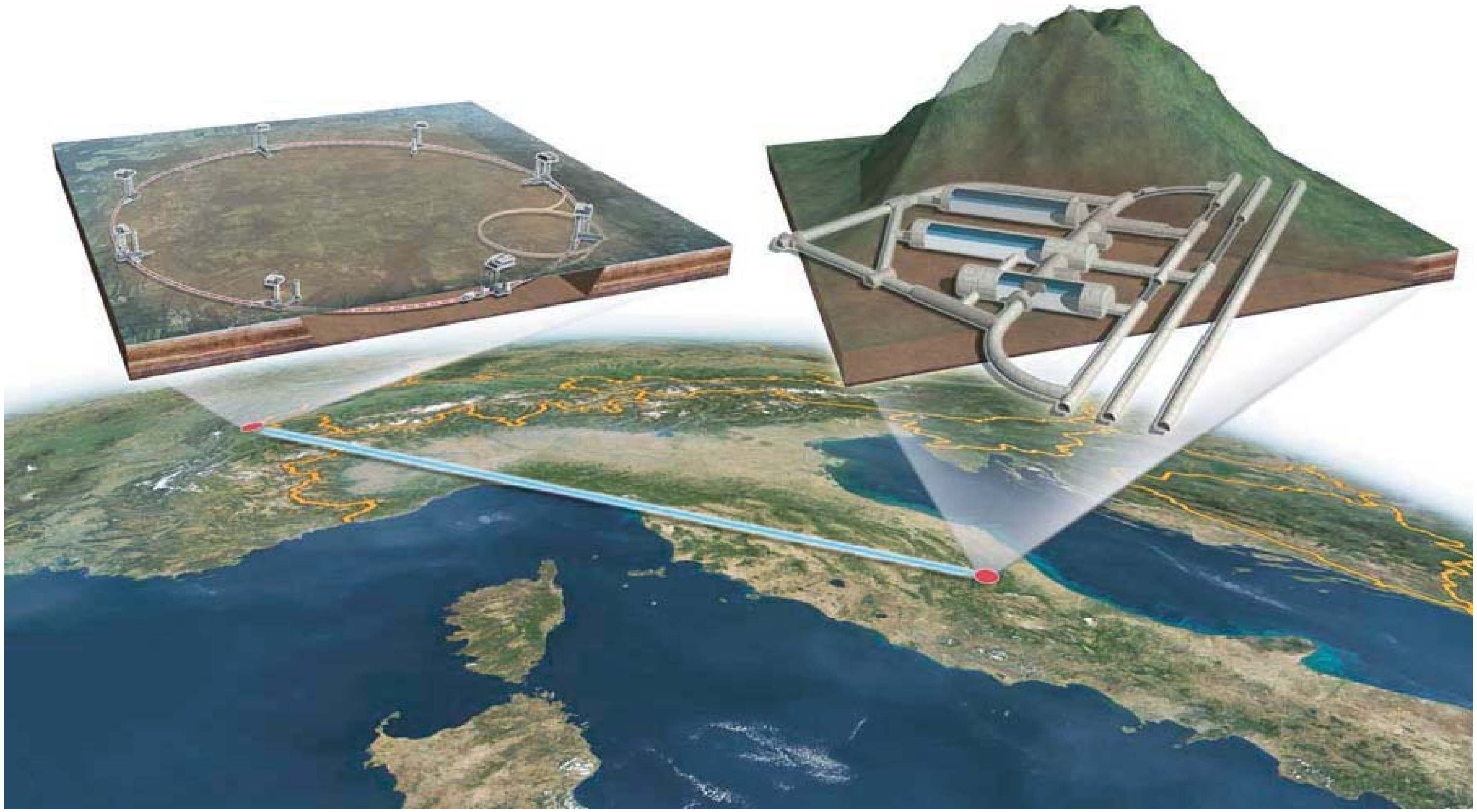
ICARUS and Status of Liquid Argon Technology



Blois, 31-05-2011

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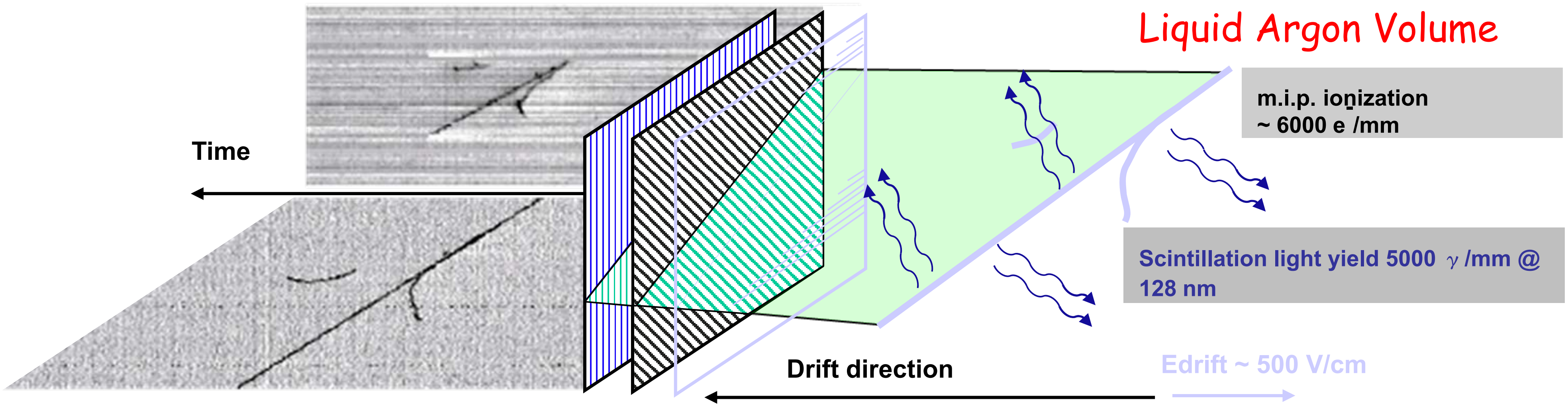
A powerful detection technique

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:

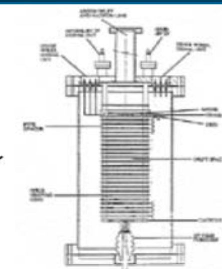
- continuously sensitive, self triggering
- high granularity (~ 1 mm)
- excellent calorimetric properties
- particle identification (through dE/dx vs range)



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).

The path to larger LAr detectors



CERN

24 cm drift wires chamber

1

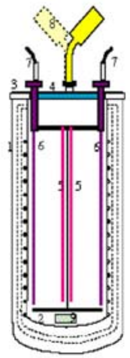
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

2

3 ton prototype

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

CERN

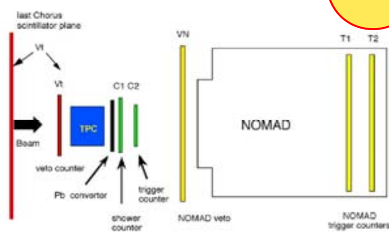


Laboratory work

3

CERN

50 litres prototype
1.4 m drift chamber



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

Icarus T600 experiment

2010 - … : Data taking with CNGS beam

4

10 m3 industrial prototype

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

Pavia

T600 detector

2001: First T600 module

Cooperation with industry
AirLiquide, Breme, Cinel, CAEN

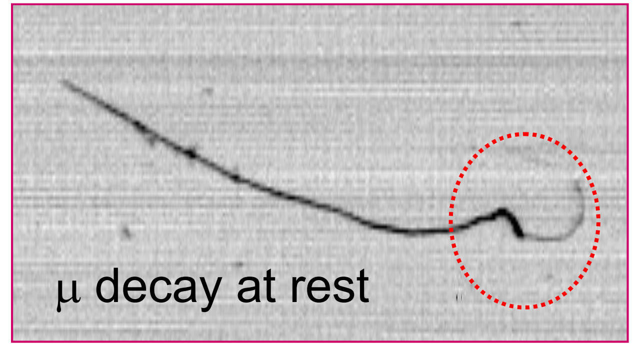
5

6

LNGS Hall-B

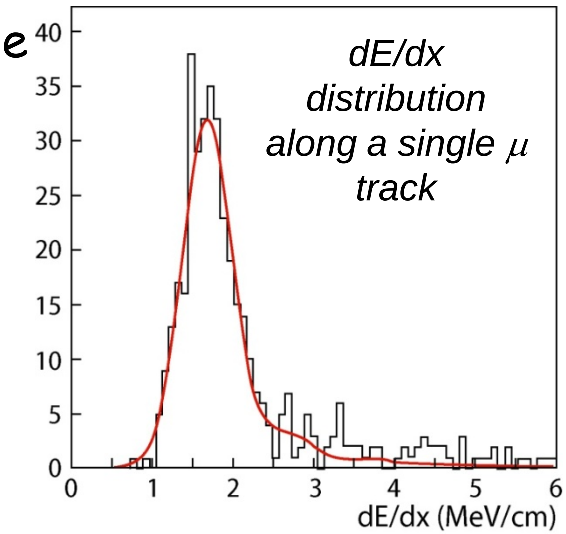
LAr-TPC performance

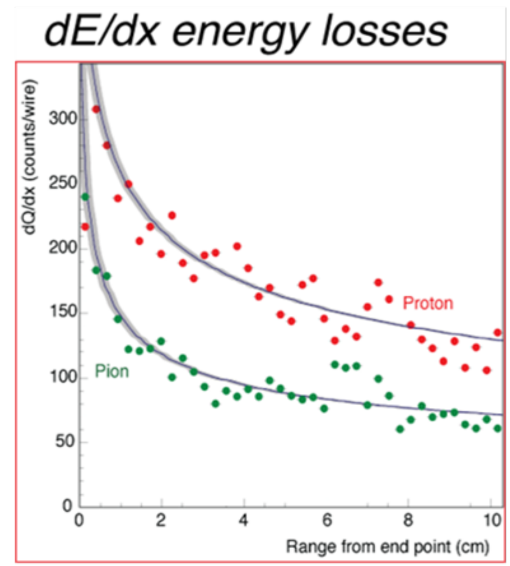
- Tracking device:
  - precise event topology ($s_{x,y}$ ~ 1mm, s_z ~ 0.4mm)
  - μ momentum measurement via multiple scattering: $\Delta p/p$ ~10-15% depending on track length and p
  - Total energy reconstruction by charge integration

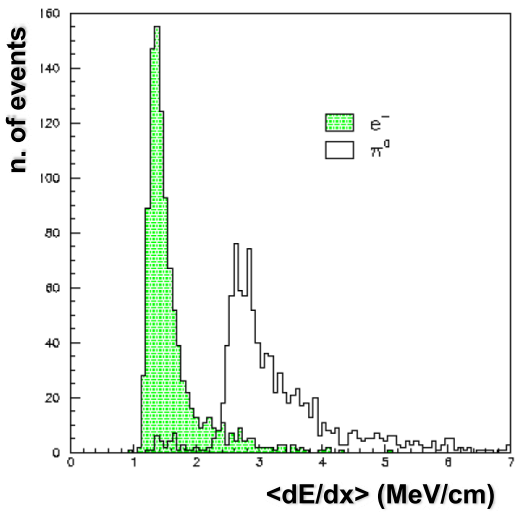


- Measurement of local energy deposition dE/dx:
  - e/μ separation (sampling at 1/50 X_0);
  - particle ID by means of dE/dx vs range

- 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.



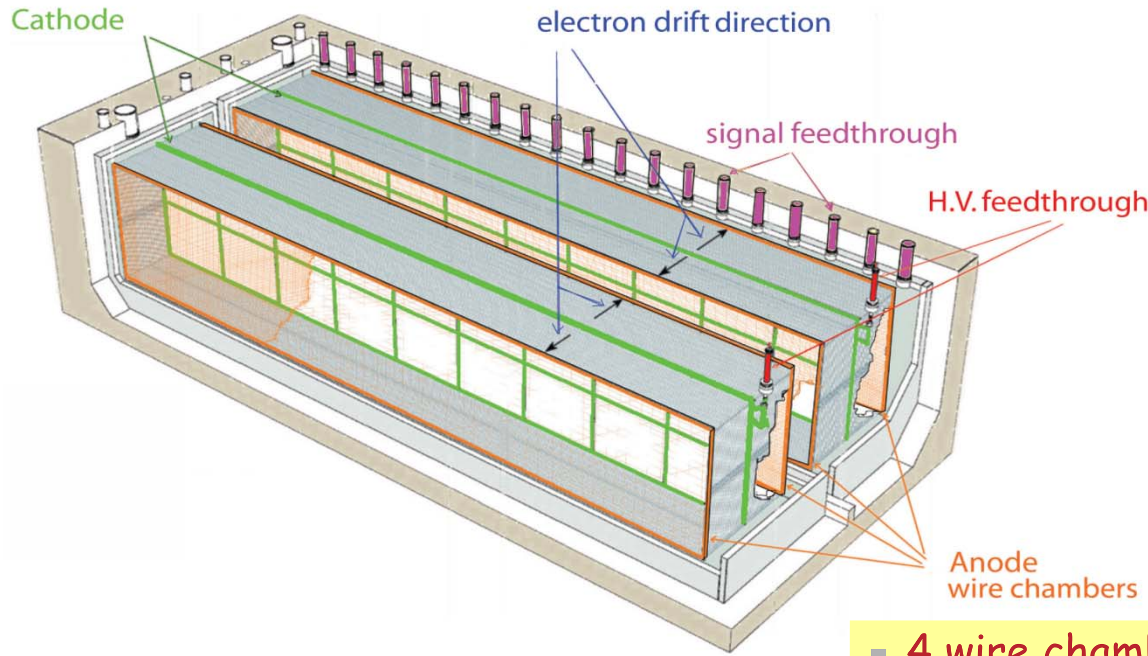


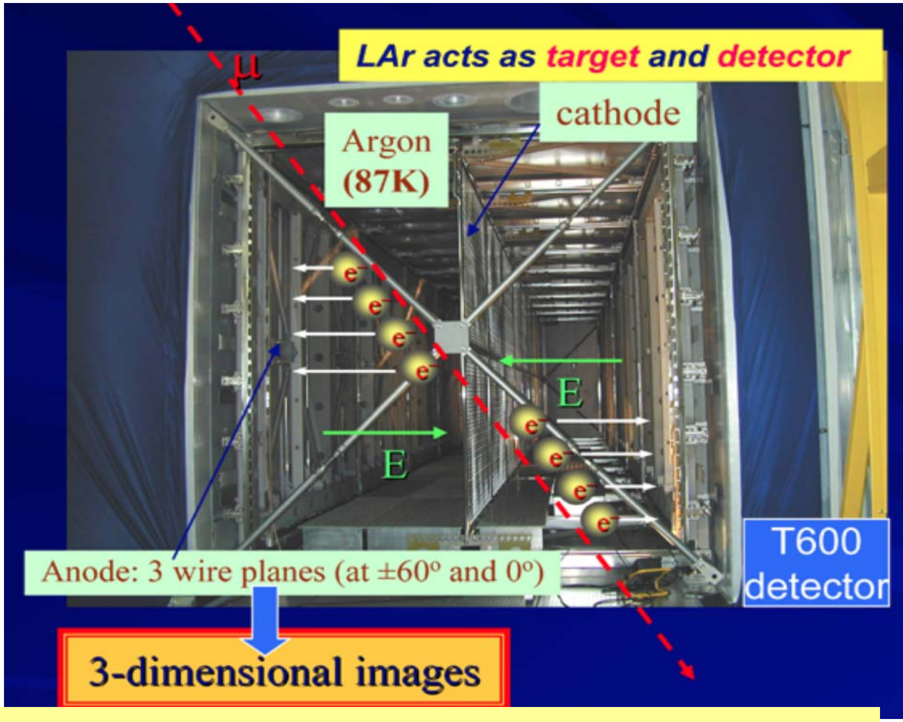


RESOLUTIONS:

Low energy electrons	$\sigma(E)/E = 11\% / \sqrt{E(MeV)}+2\%$
Electromagnetic showers	$\sigma(E)/E = 3\% / \sqrt{E(GeV)}$
Hadron shower (pure LAr)	$\sigma(E)/E \sim 30\% / \sqrt{E(GeV)}$

The ICARUS T600 detector

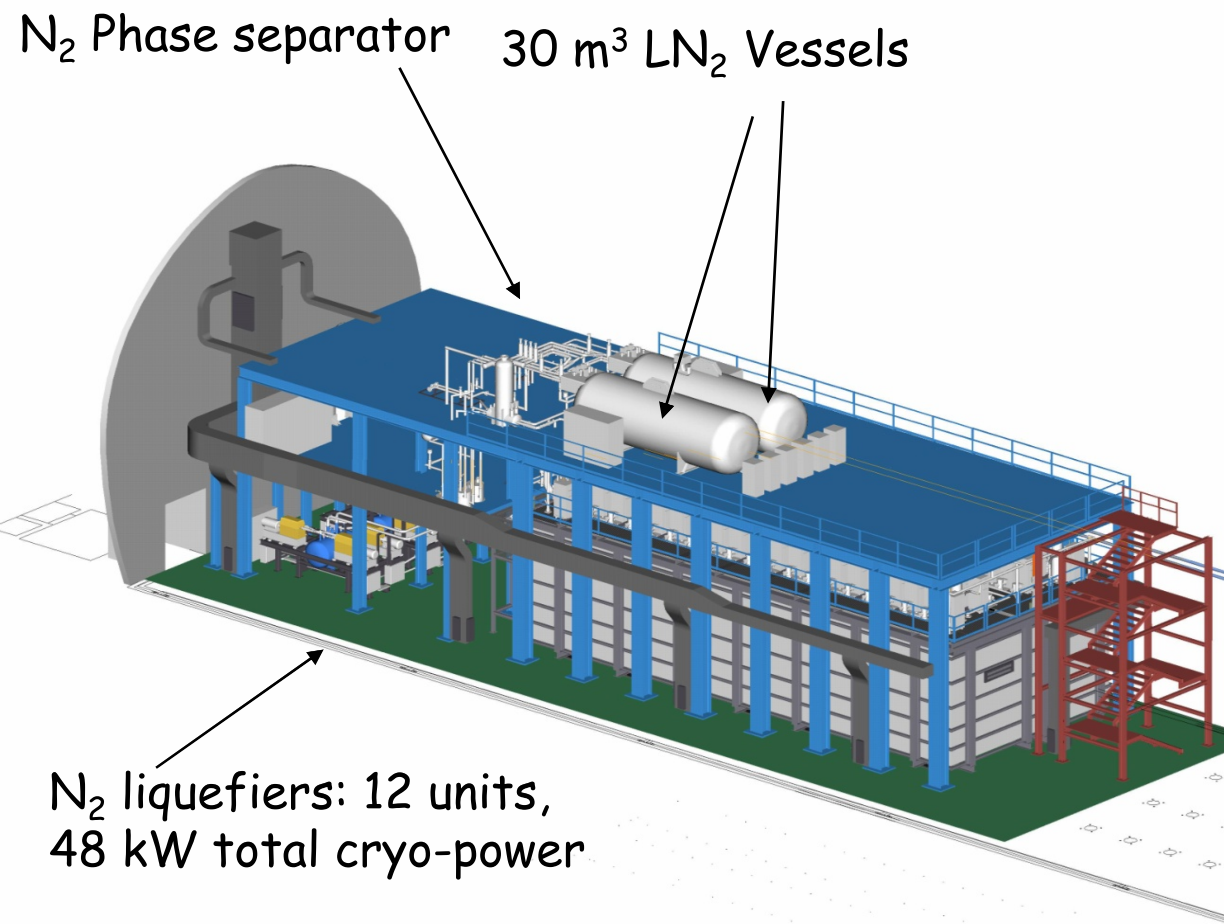




- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E = 0.5 kV/cm
  - vdrift = 1.55 mm/μs

- 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



Apparatus activated on 27th May 2010

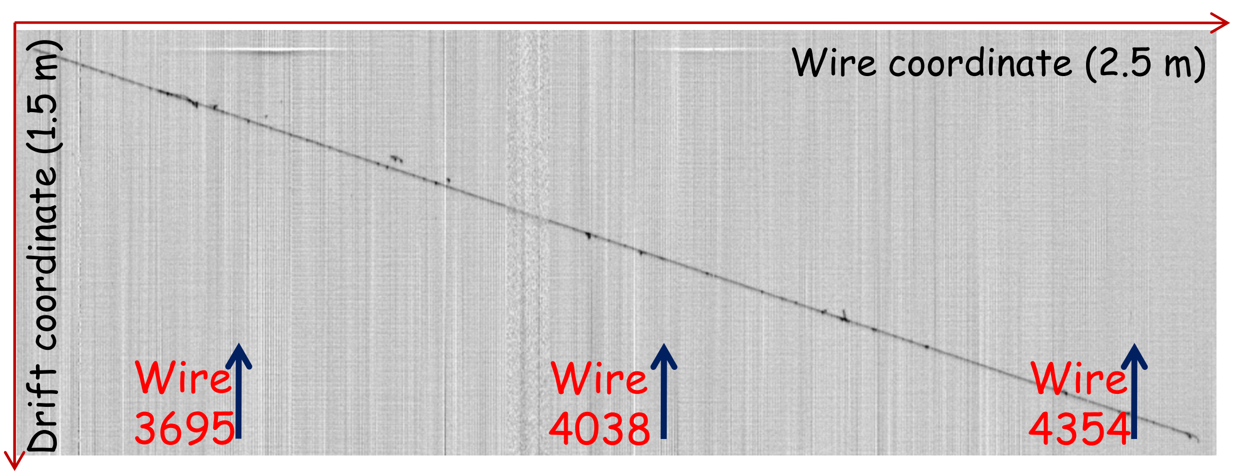
Optimization phase in summer 2010

Data taking in stable condition from October 1st 2010

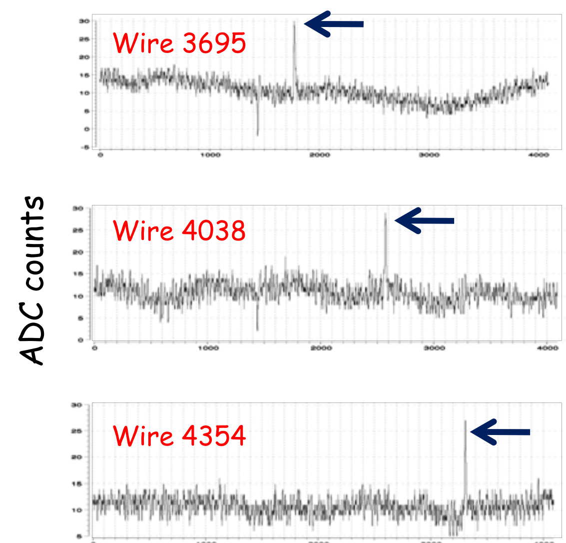
LAr purification and measurement in T600

- The presence of electron trapping polar impurities attenuates the electron signal as $\exp(-t_D/\tau_{ele})$ [τ_{ele} ~ 300 μs / ppb (O_2 equivalent)].
- Mostof the contaminants freeze out spontaneously (87 K) . Residuals: O_2, H_2O, CO_2.
- Recirculation/purification (100 Nm^3/h) of the gas phase to block the diffusion of the impurities from the hot parts of the detector and from micro-leaks; Recirculation/purification (4 m^3/h) of the bulk liquid volume to efficiently reduce the initial impurities concentration.

Charge attenuation along track allows event-by-event measurement of LAr purity
(Pulse height for 3 mm m.i.p. ~ 15 ADC # (15000 electrons; noise r.m.s. 1500 electrons)

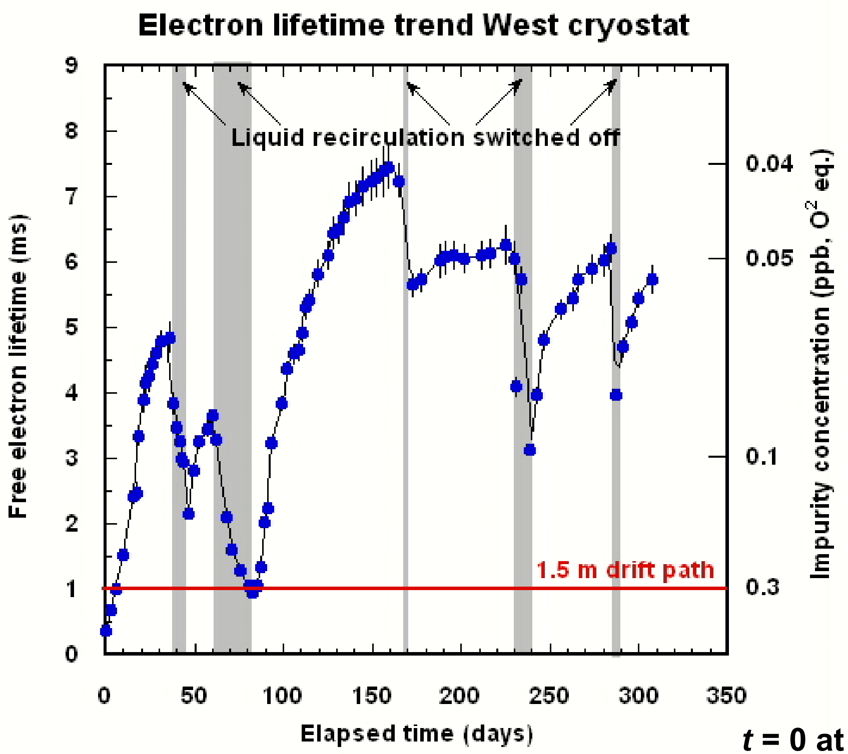


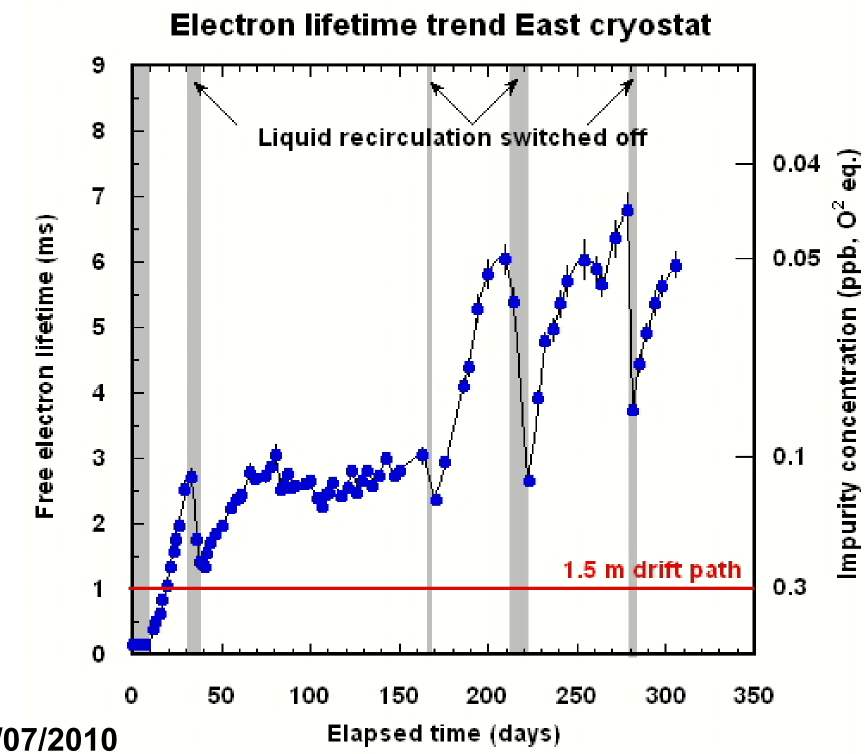
Run 10139 Event 8961 Collection view



Drift time (sampling = 0.4 ms)

LAr purity time evolution





t = 0 at 01/07/2010

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

$$dN/dt = -N/\tau_R + k + k_I \exp(-t/\tau_I)$$

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

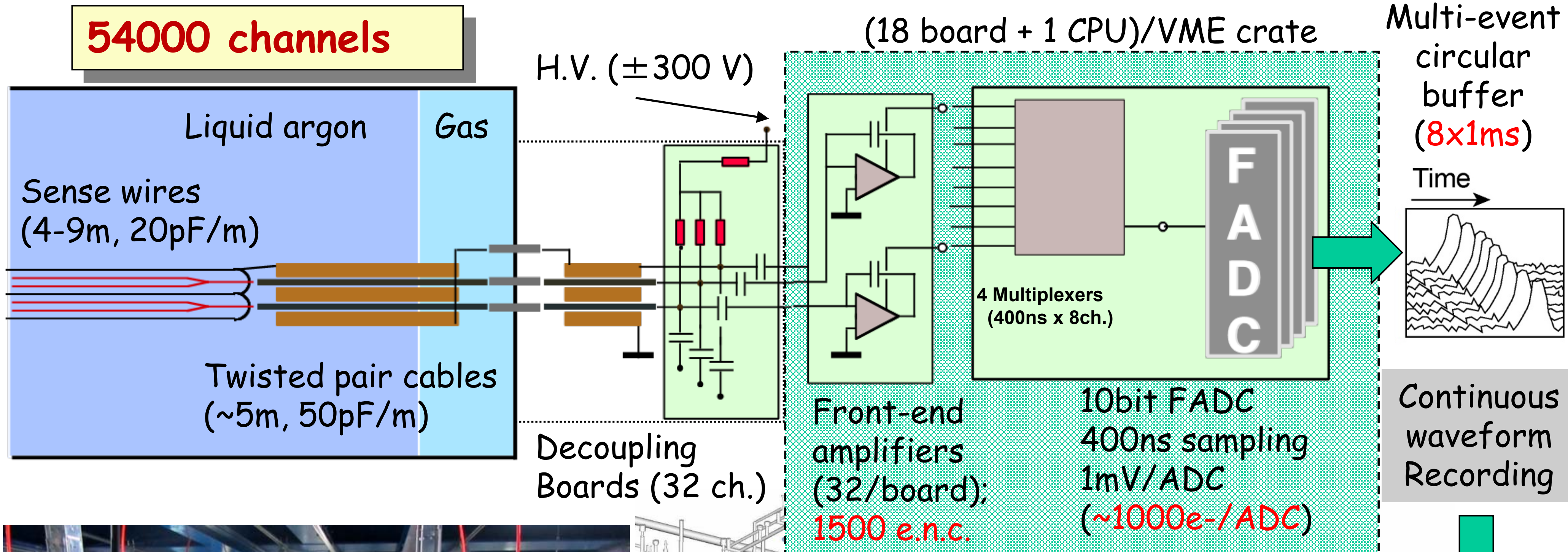
τ_R: recirculation time for a full detector volume

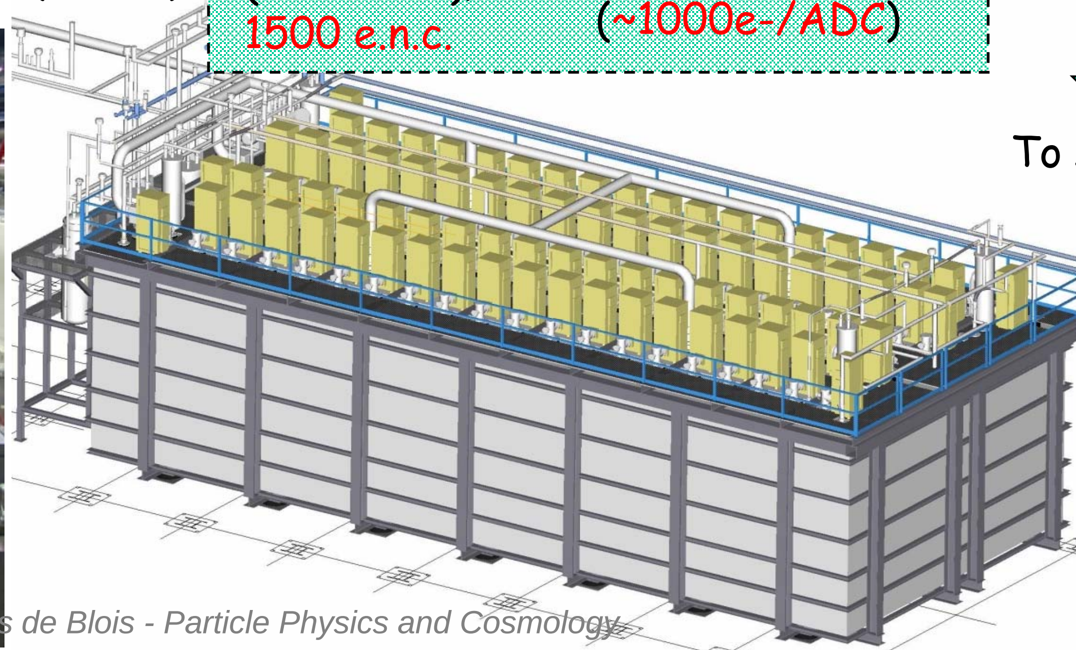
k_I and τ_I : related to the total degassing internal rate

k : related to the external leaks

τ_R: 2 m³/h (per cryostat) corresponding to ≈ 6 day cycle time

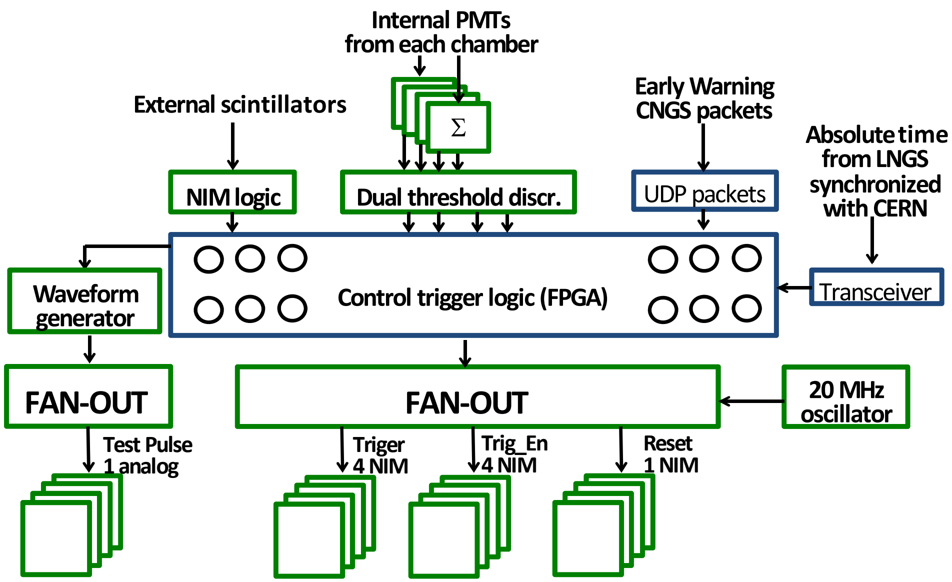
Front-end Electronics and DAQ





Trigger System

The trigger set-up is based on a controller crate, hosting a FPGA-board for signals processing, interfaced to a PC for data communication and parameter setting.

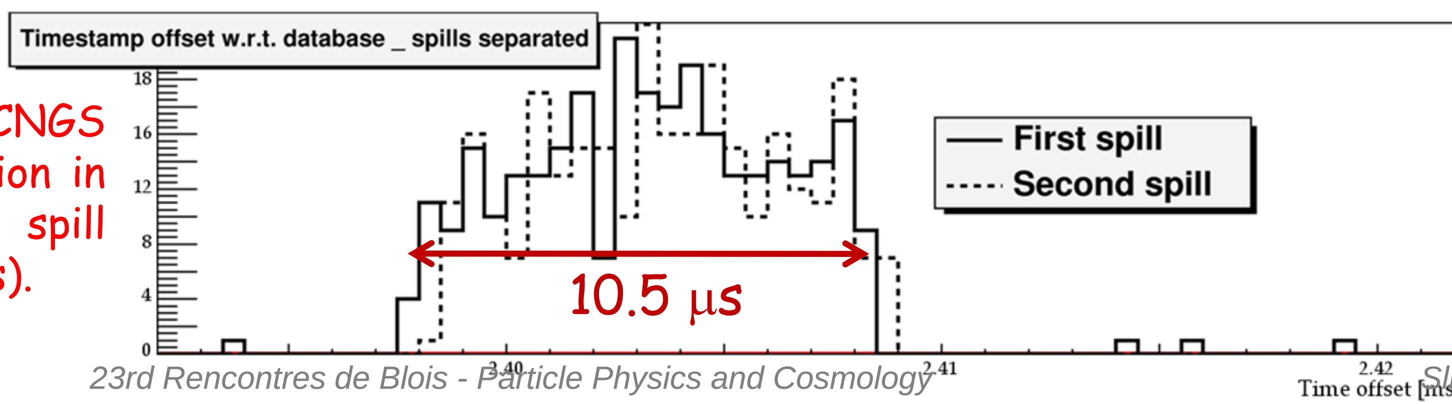


Different trigger sources:

- CNGS proton extraction time from "Early Warning" signal (80ms before spills)
- PMTs "Low Threshold" signal (~100phe)
- PMTs "High Threshold" signal (~1000phe)
- Test pulses for calibration
- Trigger on the charge (under test)

The absolute time stamp for the recorded events and the opening of the CNGS proton spill gate are evaluated by means of the signal from LNGS atomic clock.

Reconstruction of CNGS arrival time distribution in agreement with the spill time duration (10.5 μs).



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 $\rightarrow$ **events "seen in a new Bubble chamber like" way**.

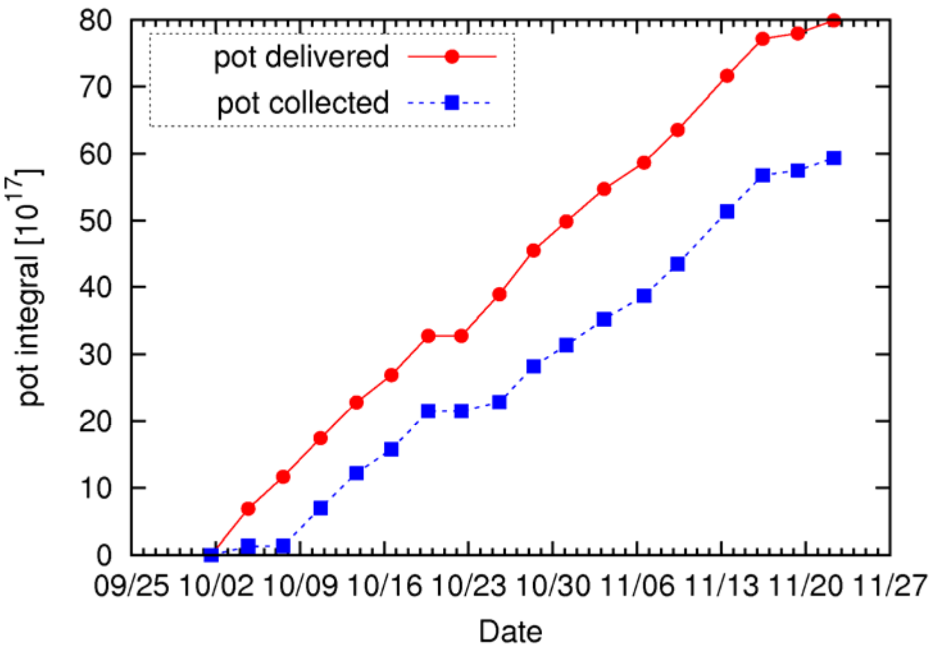
- CNGS ν events collection (beam intensity 4.5 10^{19} pot/year, E_ν ~ 17.4 GeV):
  - 1200 ν_μ CC event/year;
  - ~ 8 ν_e CC event/year;
  - observation of ν_τ events in the electron channel, using kinematical criteria;
  - search for sterile ν in LSND parameter space (deep inelastic ν_e CC events excess).

- "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.

CNGS run during 2010

- 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 ν CC + 0.86 ν NC) 10^{-17}/pot), in the whole energy range up to 100 GeV, corrected by fiducial volume (424 t) and DAQ dead-time.

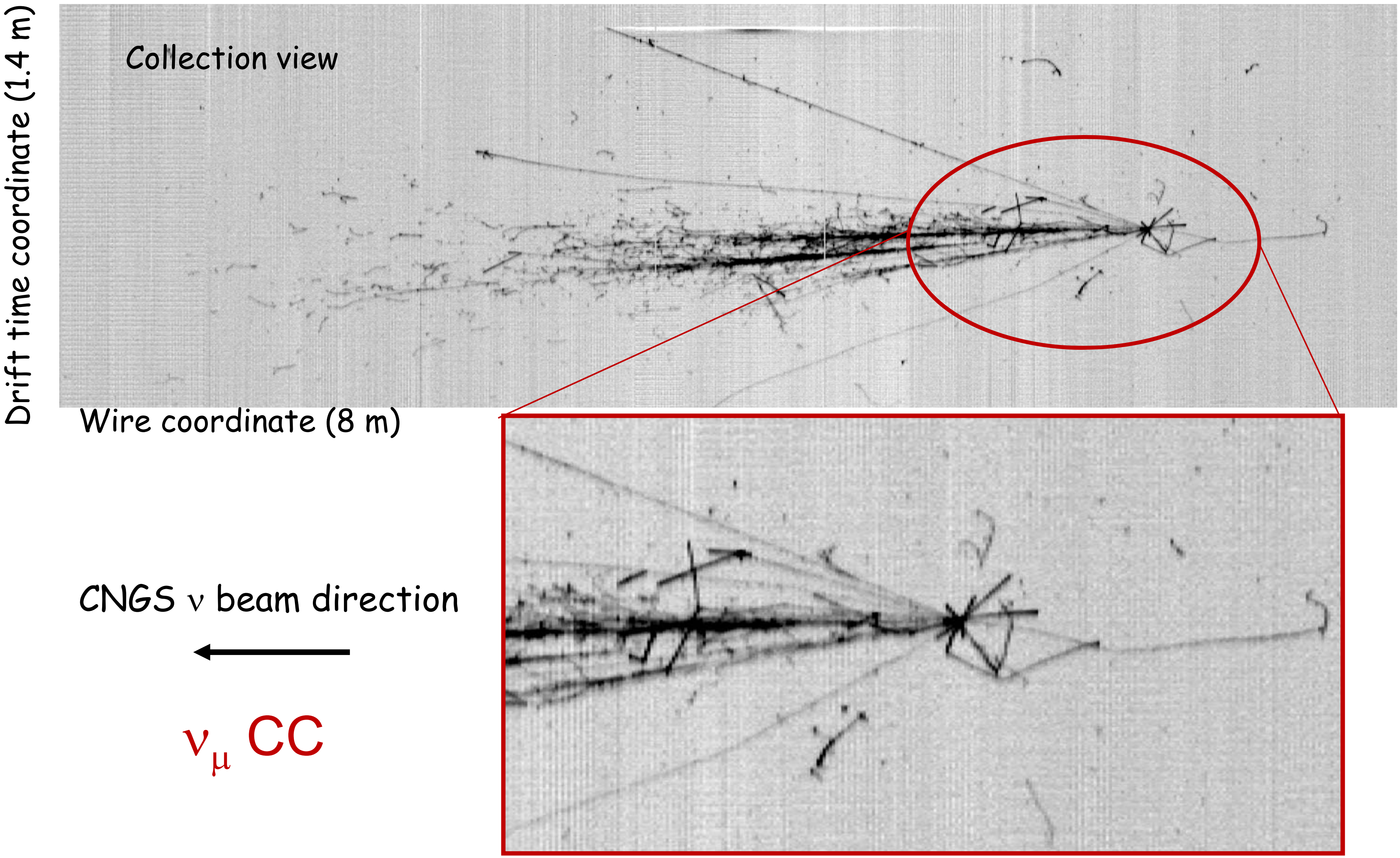
$5.3 \cdot 10^{18}$ pot = 91 % out of whole sample

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

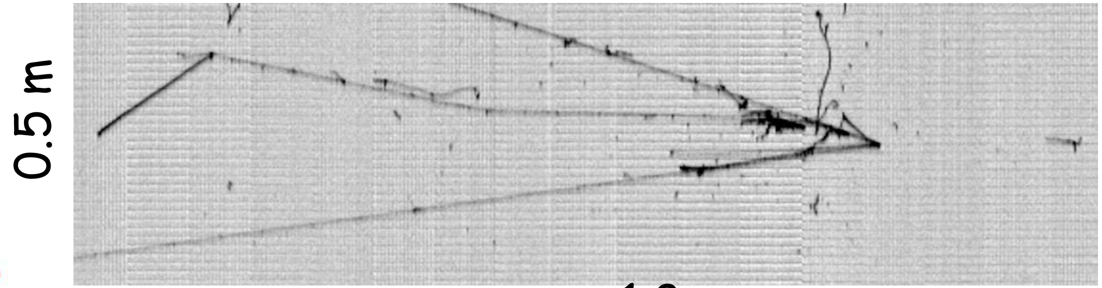
- Events at edges, with μ track too short to be visually recognized: further analysis needed.

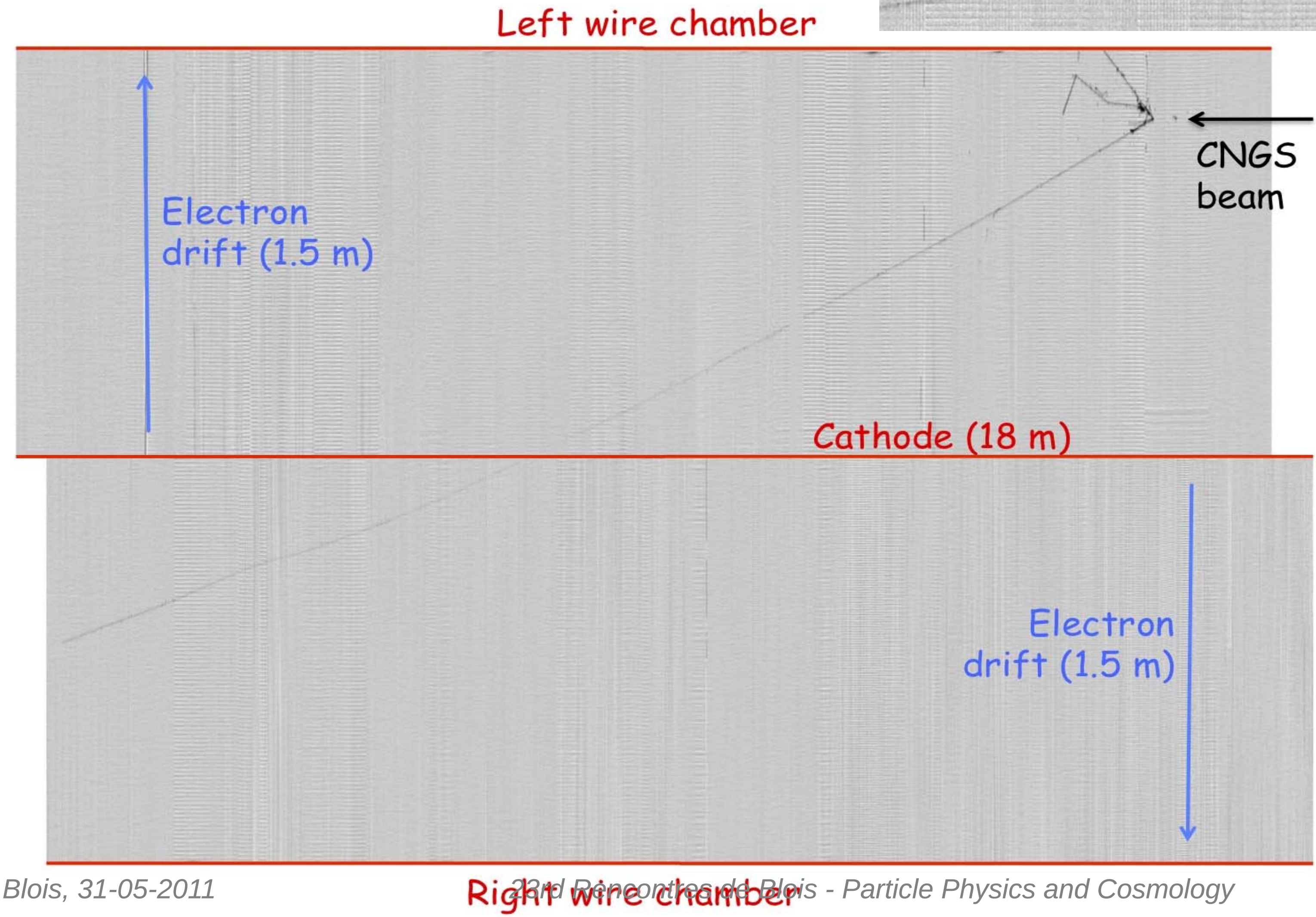
On overall statistics in agreement with expectations.

The first CNGS neutrino interaction in ICARUS T600



Low energy CNGS neutrino interaction

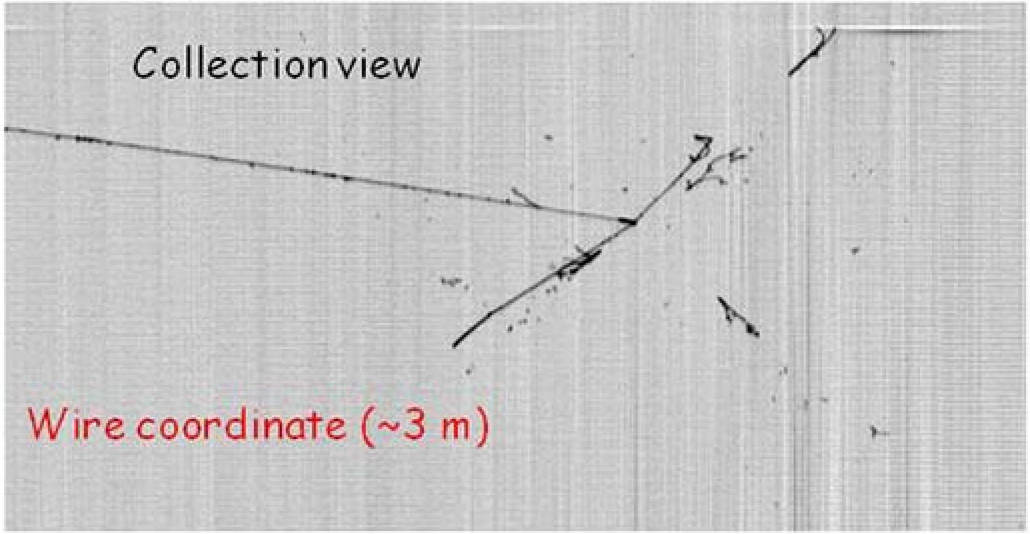


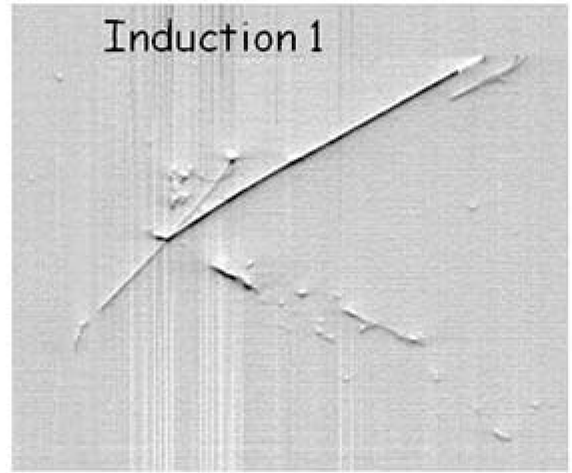


Evis ~ 9 GeV
Electron lifetime and quenching accounted for

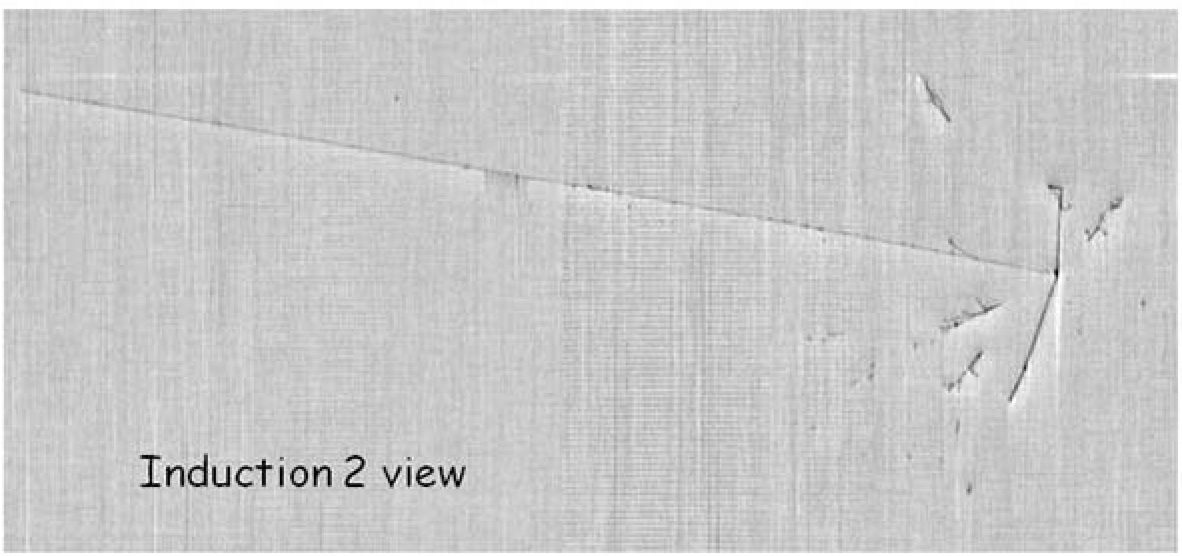
Collection views (not to scale!)

CNGS CC neutrino interaction with π^o production

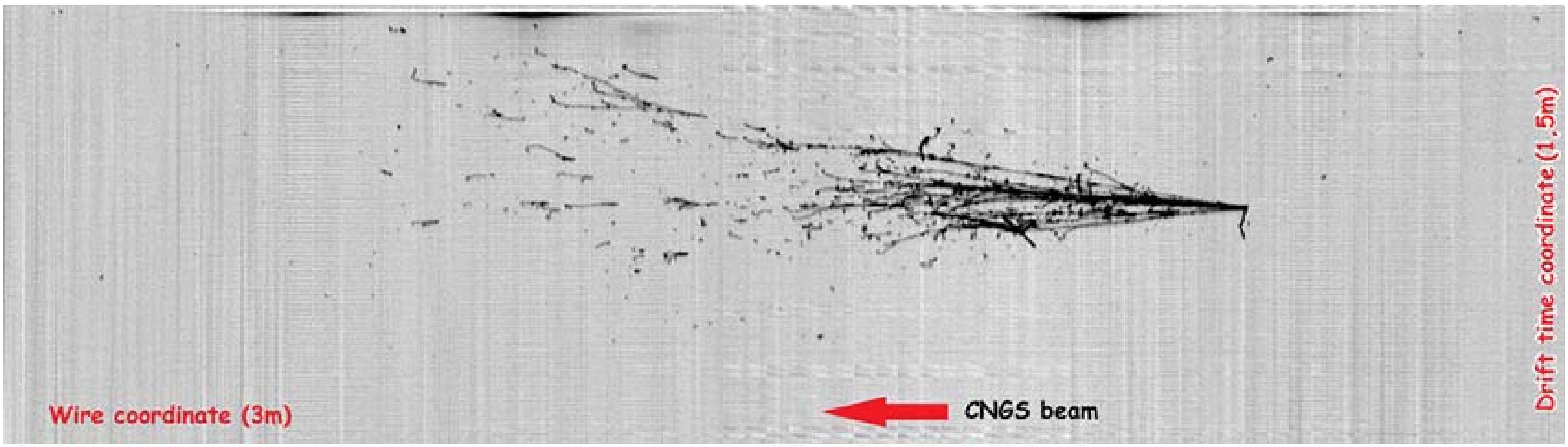




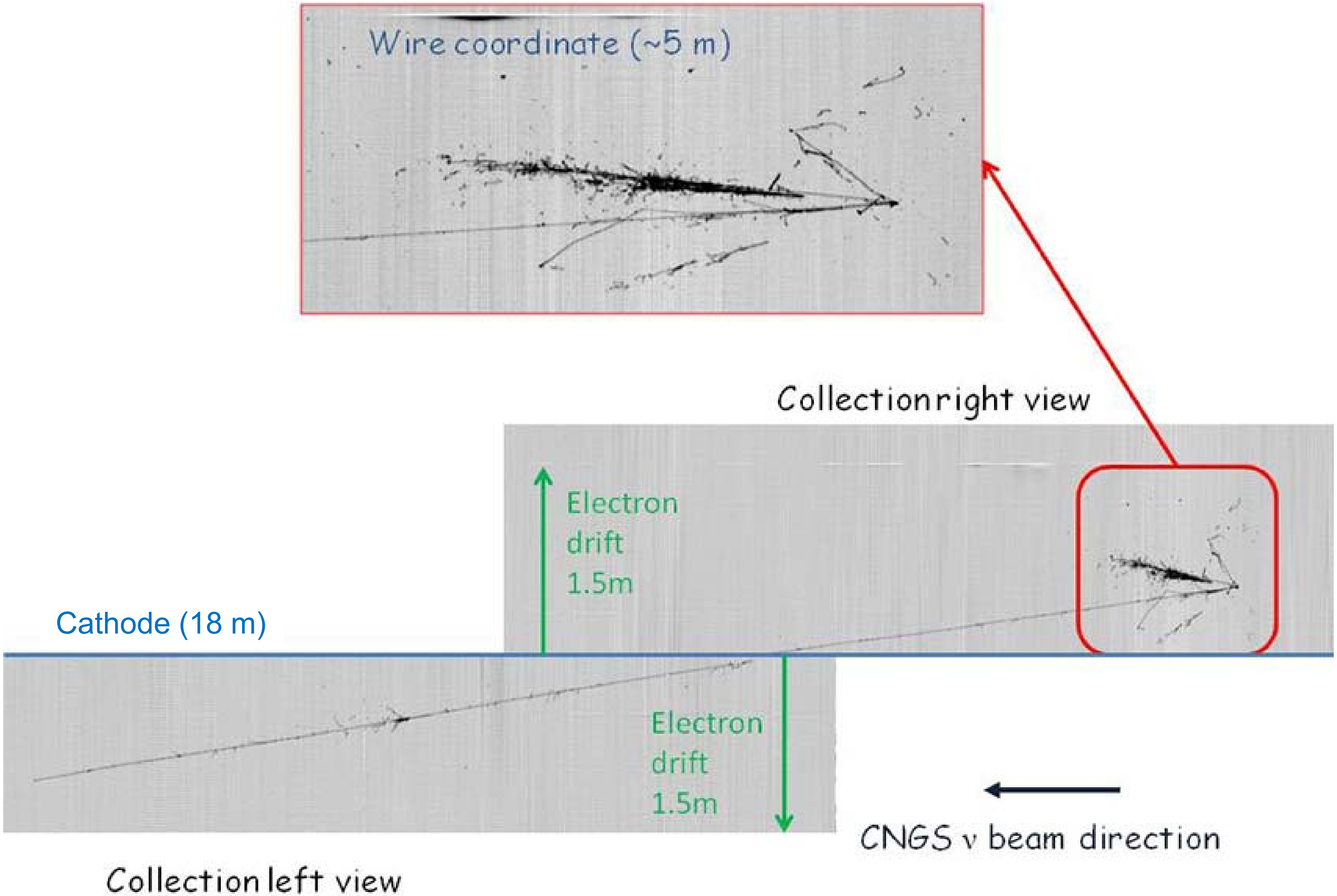
CNGS ν beam direction



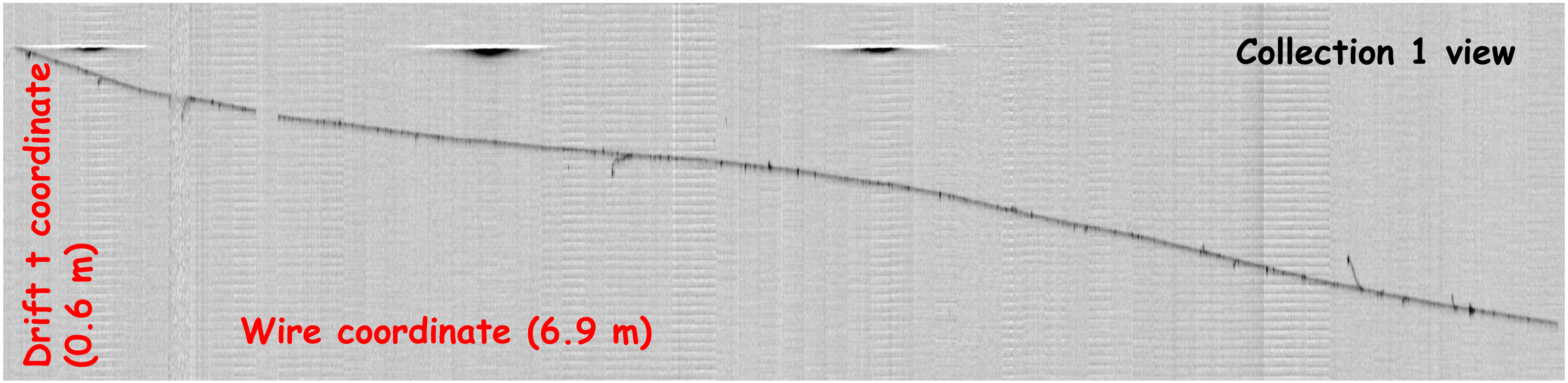
CNGS NC interaction

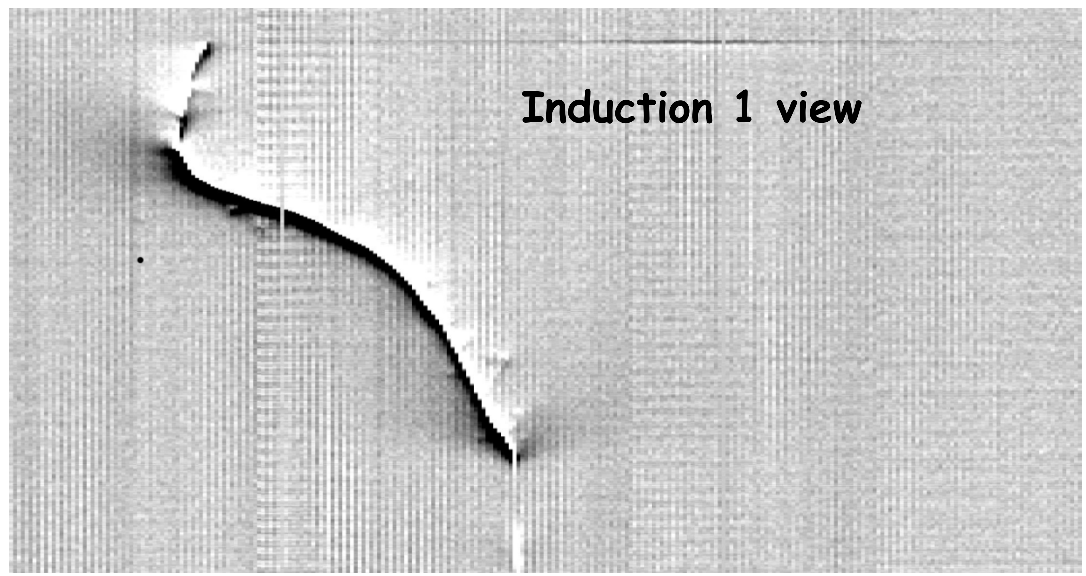


CNGS CC interaction with both TPC signal



CNGS ν interaction in the rock





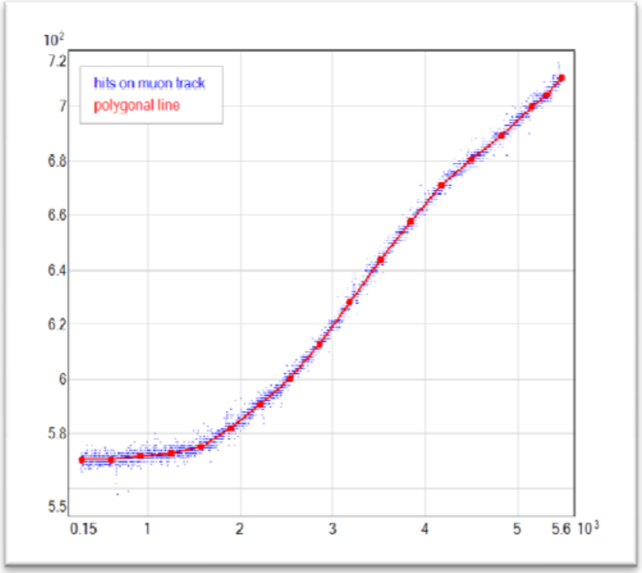
Predicted number of collected interactions in the rock:
$7.8\ 10^{-17}$/pot

Analysis: 3D reconstruction and 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.

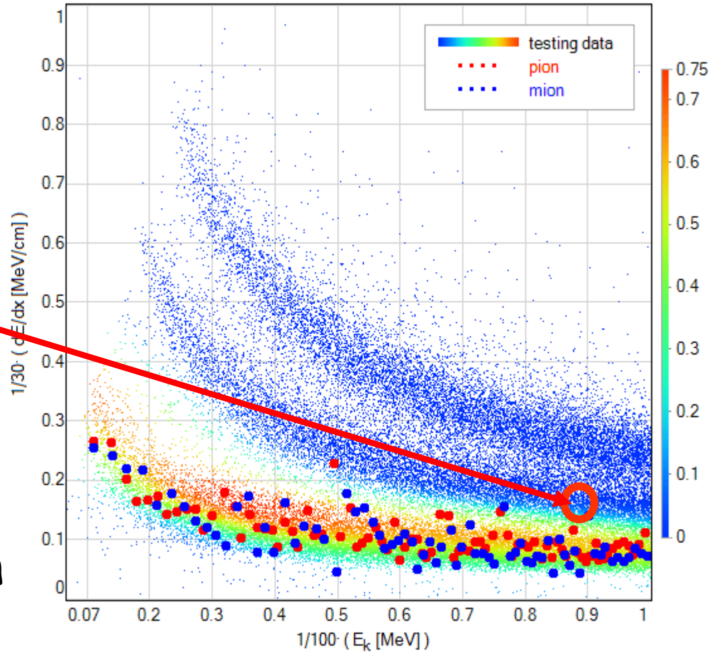


- Particle identification based on:
  - distance between nearby 3D hits: dx
  - 3D hits and charge deposition : dE/dx
- Classify single i^{th} point on the track

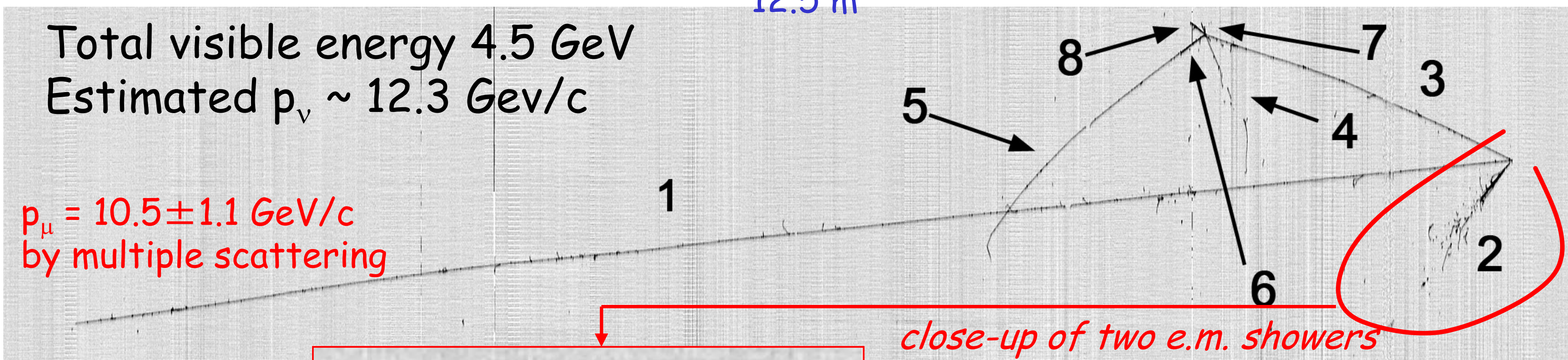
  p*i* : [Ek, dE/dx] → nn*i* : [P(p), P(K), P(p), P(μ)]
- Average M output vectors for the points

  NN = S(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

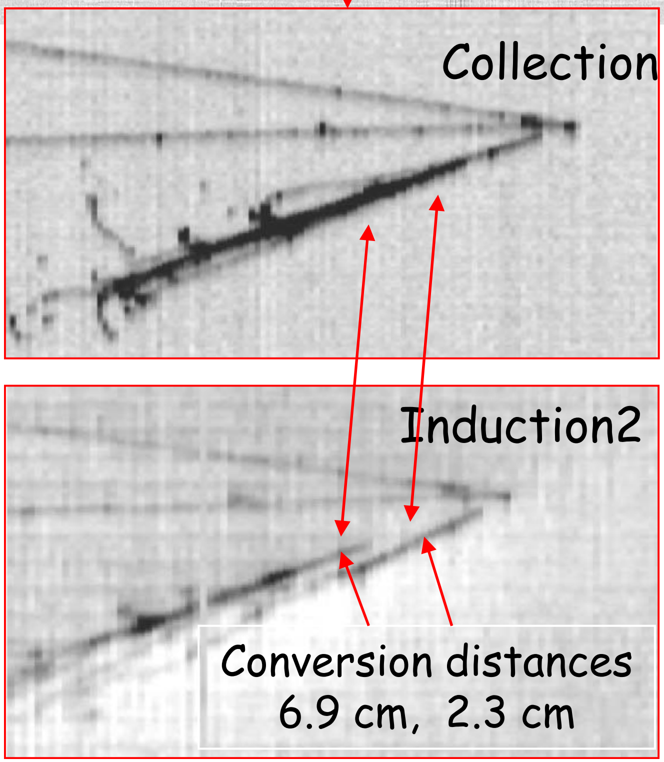


Primary vertex (A)

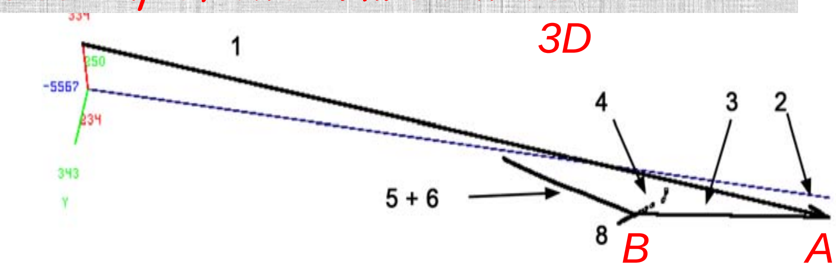
very long μ (1), e.m. cascade(2), pion (3).

Secondary vertex (B)

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

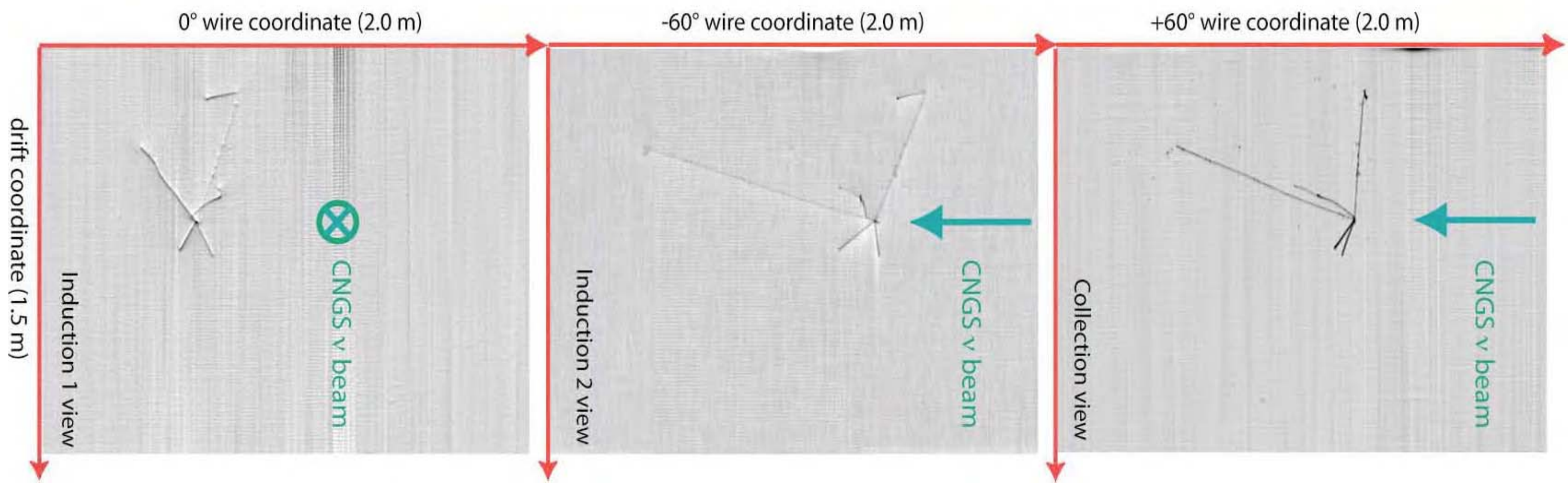


$M^*_{\gamma\gamma}$ = 125±15 MeV/c²



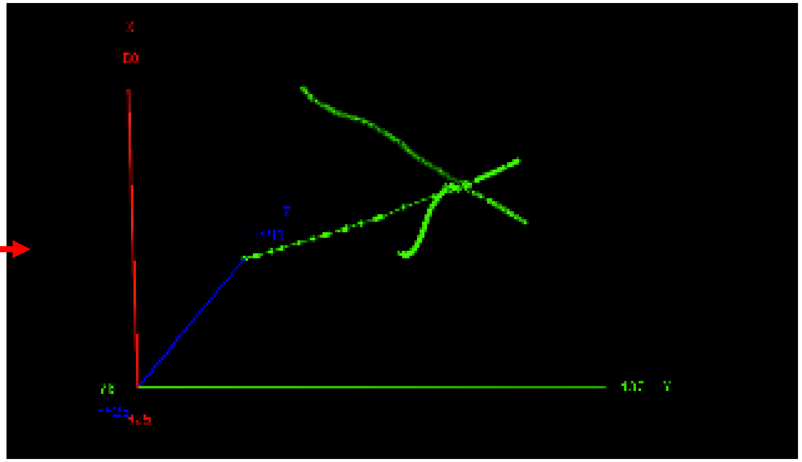
Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2 (π^0)	520.82	0.054	-0.420	-0.906
3 (π)	514.04	-0.001	0.137	-0.991
Sec.vtx.	797.			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

Atmospheric ν candidate

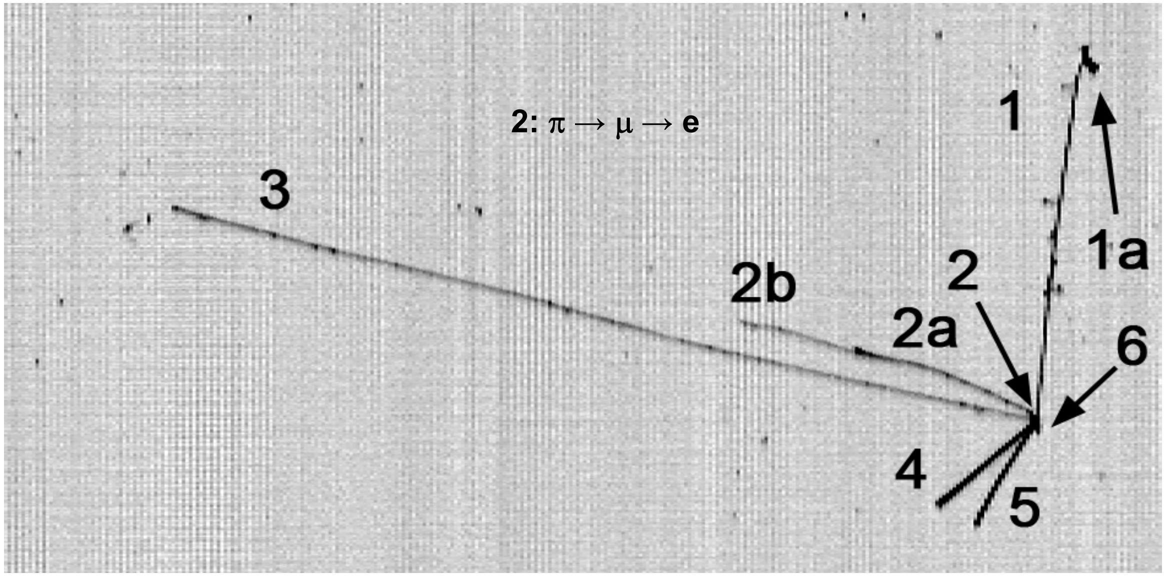


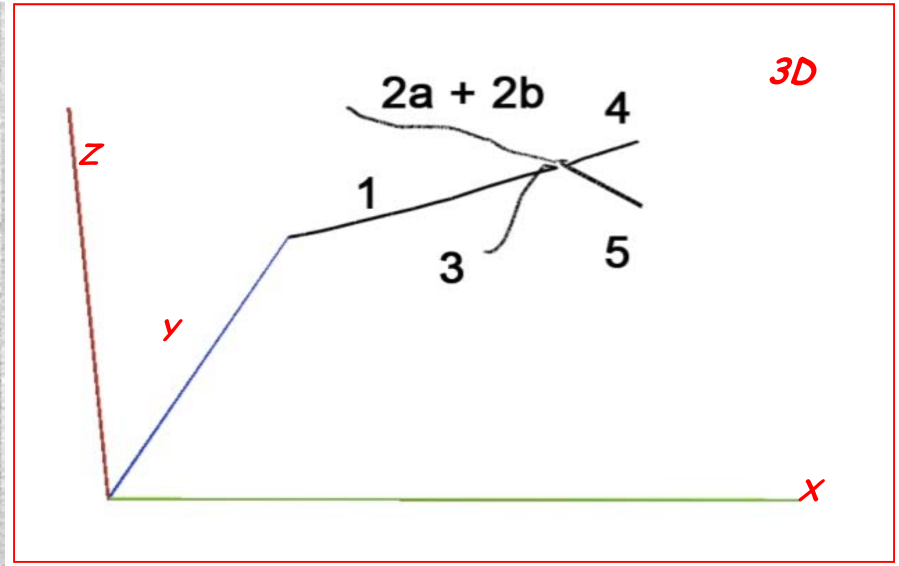
- Total visible energy: 887 MeV (including quenching and e^- lifetime corrections).
- Out-of-time from CNGS spill AND angle w.r.t. beam direction: 35° .

Very small event



Run 9392 Event 106



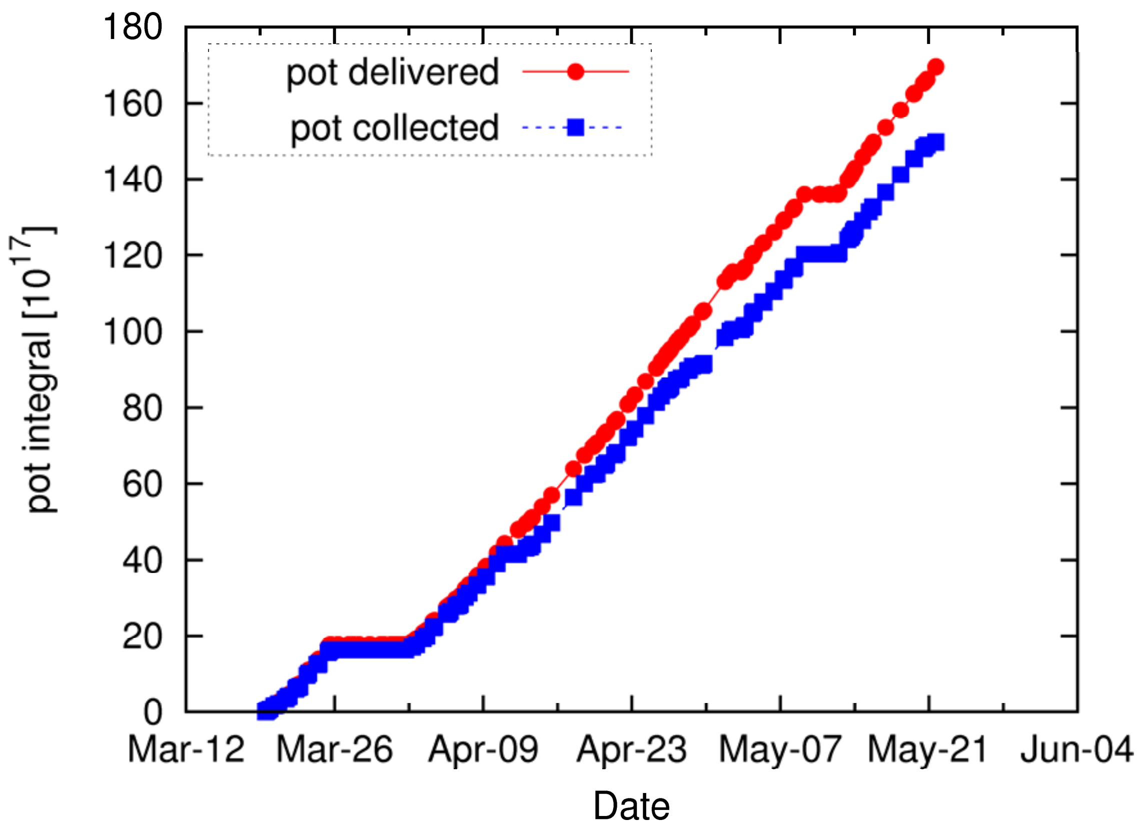


Track	E_k [MeV]	Range [cm]
1 (prob. π, decays in flight)	136.1	55.77
2 (π)	26	3.3
2a (μ)	79.1	17.8
2b **(e)**	24.1	10.4
3 (μ)	231.6	99.1
4 **(p)**	168	19.2
5 **(p)**	152	16.3
6 (?) (merged with vtx)		2.9

- Total deposited energy: 887 MeV
- Total reconstructed momentum: 929 MeV/c at about 35° away from the CNGS beam direction

2011 CNGS run

- ICARUS fully operational / data taking for CNGS events from 19th March.
- The detector lifetime above 90% with the new trigger/DAQ feature improvements.
- $1.7 \cdot 10^{19}$ ($1.5 \cdot 10^{19}$) pot delivered (collected) up to 23th May.



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.

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

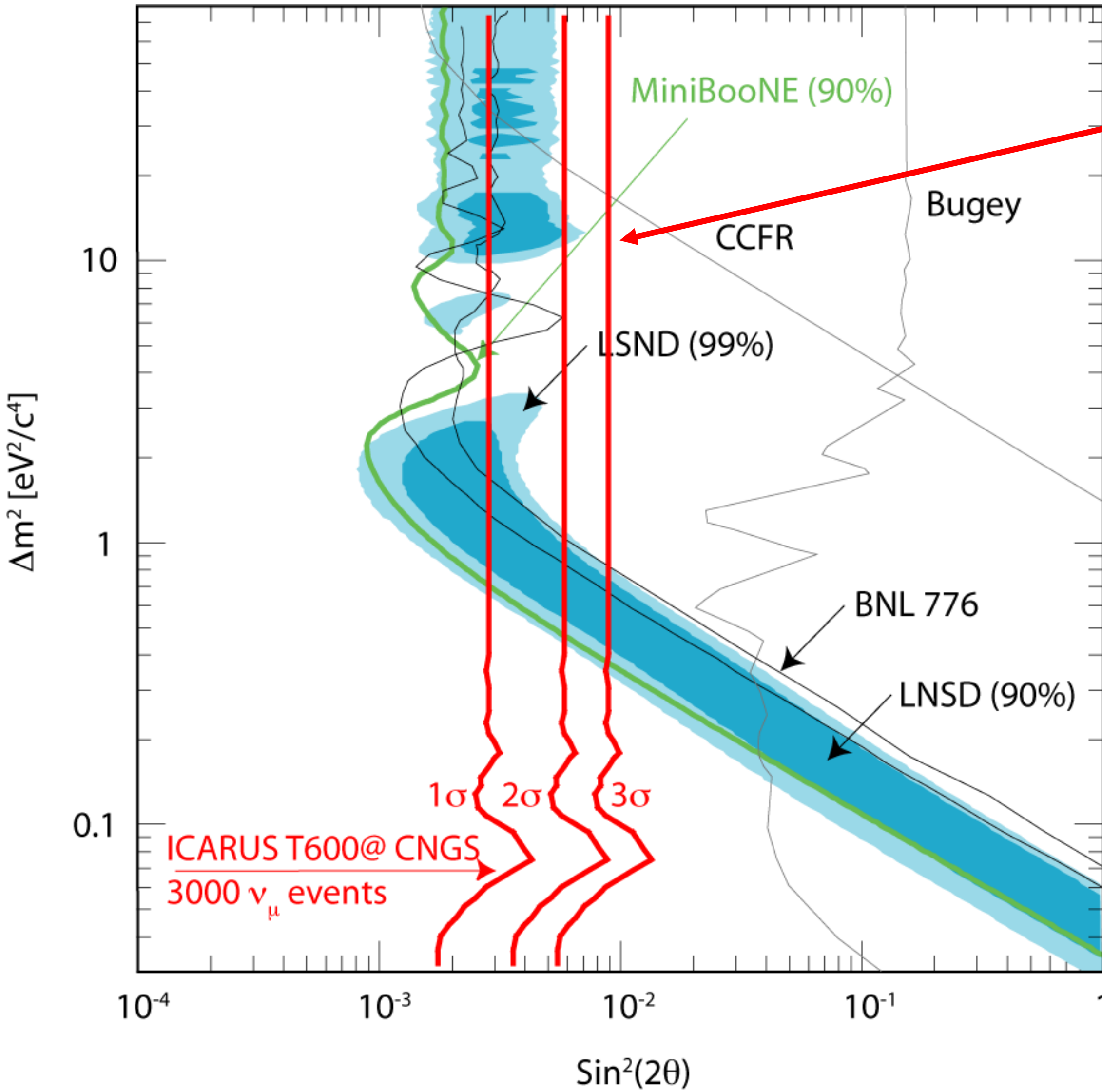
Background

- 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.

Signal

- $\tau \rightarrow e\nu\nu$ events characterized by momentum unbalance (2ν emission) and relatively low electron momentum. Selection criteria suggest a sufficiently clean separation with kinematic cuts opening the possibility to identify 1-2 ν_τ CNGS events in the next 2 years, only in this gold channel.
- Currently collected CC/NC data will be used to tune the selection criteria in order to optimize the sensitivity for τ search.

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.

Beyond ICARUS T600

- The operation of the T600 demonstrates the large number of important milestones which have been achieved in the last several years, opening the way to the development of new line of modular elements, which may be progressively extrapolated to the largest conceivable LAr-TPC sensitive masses. Based on the T600 experience, the ICARUS collaboration has proposed a next generation LAr-TPC in tens of kt scale: the MODULAr project (*Astroparticle Physics 29 (2008) 174).*
- The novelty of the ICARUS LAr-TPC technology is offering interesting alternatives for the T600, after CNGS2 runs during 2011 and 2012.
- A sensitive search of sterile neutrinos with the CERN-PS refurbished neutrino beam has been proposed to clarify the LSND-MiniBooNE-Gallium-Reactor anomalies (CERN-SPSC-2011-012; SPSC-M-773), based on a dual LAr-detectors at different distances. The ICARUS T600 is available, being transportable by design.

Conclusions

The ICARUS experiment at the Gran Sasso Laboratory is so far the most important milestone for LAr TPC 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 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, atmospheric ν…)
  - 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 running for the 2011-2012 CNGS high intensity exposure with important additional improvements on trigger and data streaming in order to fulfill the wide physics programme.
- A sensitive search of sterile neutrinos with the CERN-PS appears at present the most interesting evolution of the T600 after the CNGS2 run.


Thank you !