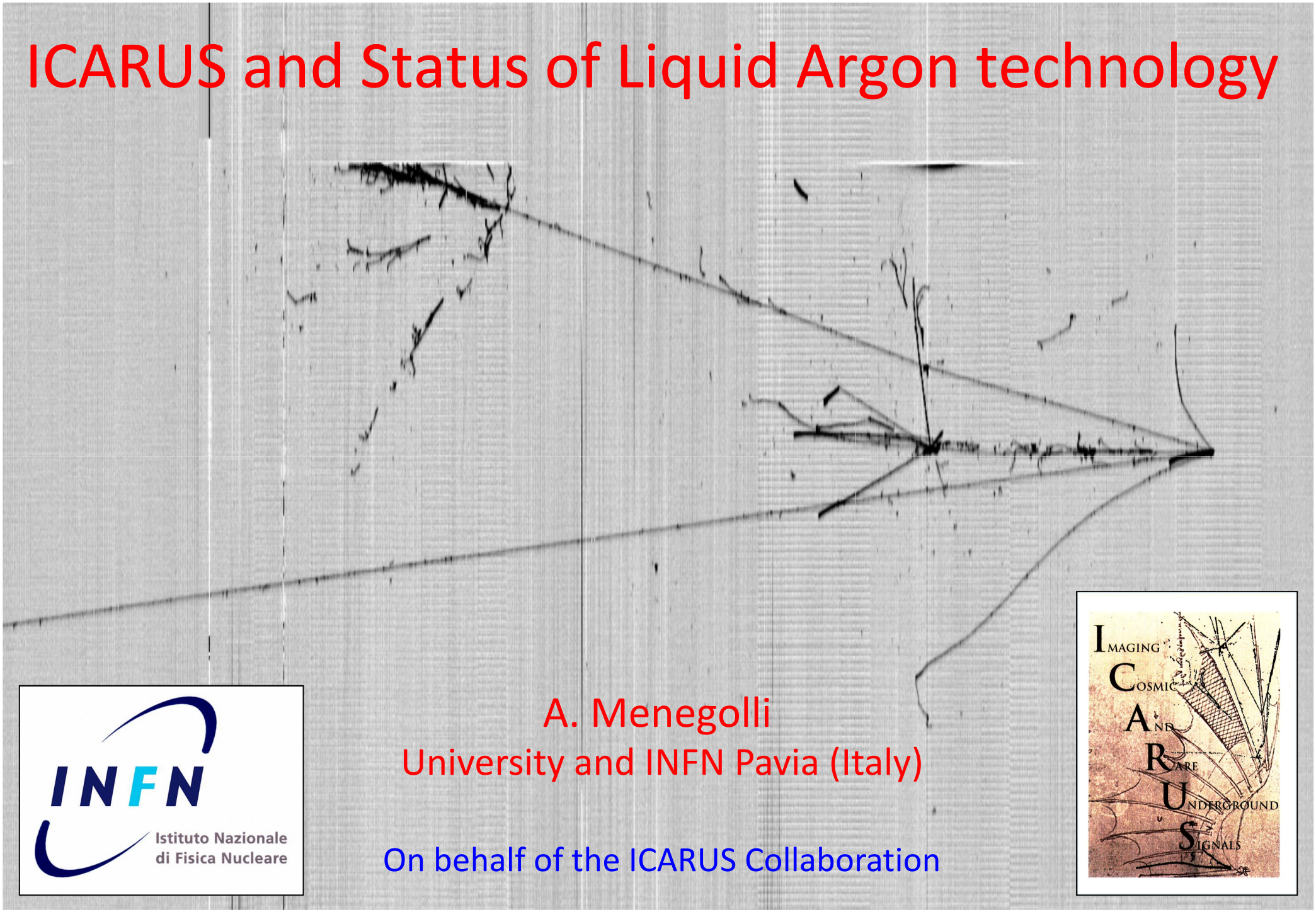
ICARUS and Status of Liquid Argon technology



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On behalf of the ICARUS Collaboration

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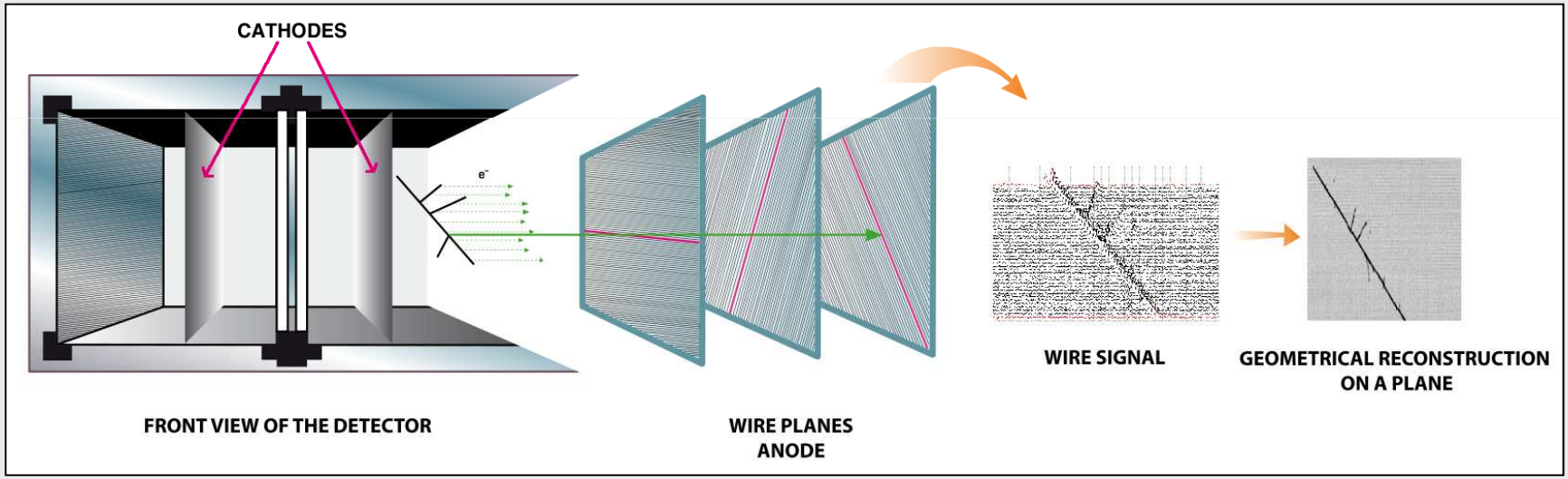
The detection technique

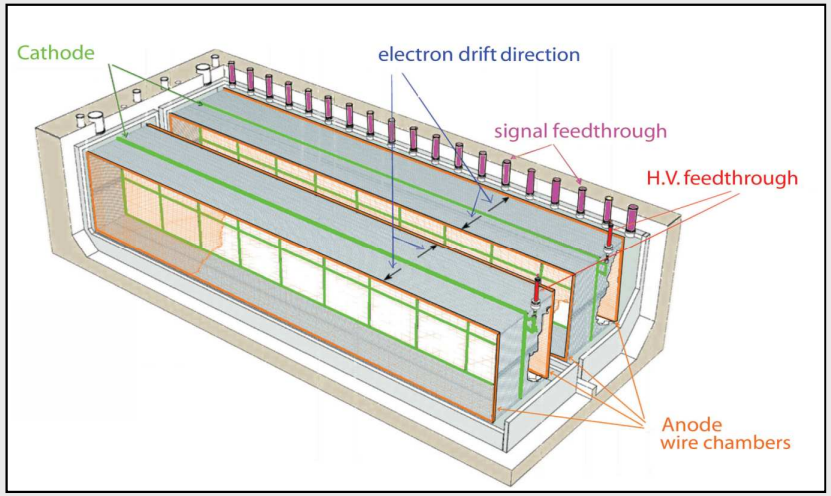
The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)] first proposed in 1985 [ICARUS: INFN/AE-85/7] is capable of providing a 3D imaging of any ionizing event (*electronic bubble chamber*) with in addition:

- Continuously sensitive, self triggering.
- High granularity (spatial resolution ≈ 1 mm^3)
- Excellent calorimetric properties.



Electrons from ionizing tracks are drifted in LAr by a uniform electric field. They traverse transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by a collection wire plane.

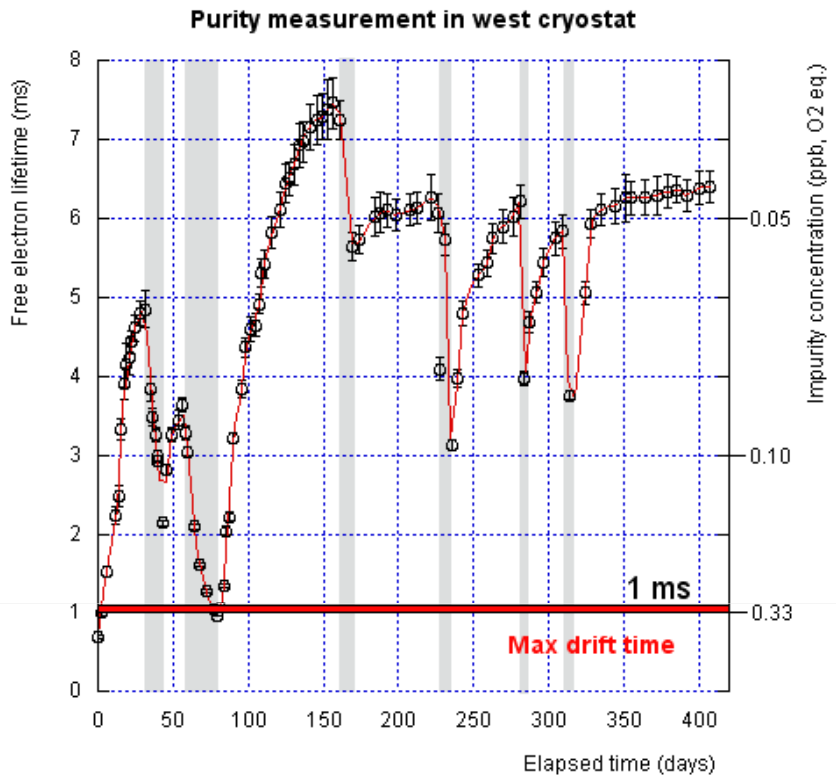
The ICARUS T600 detector

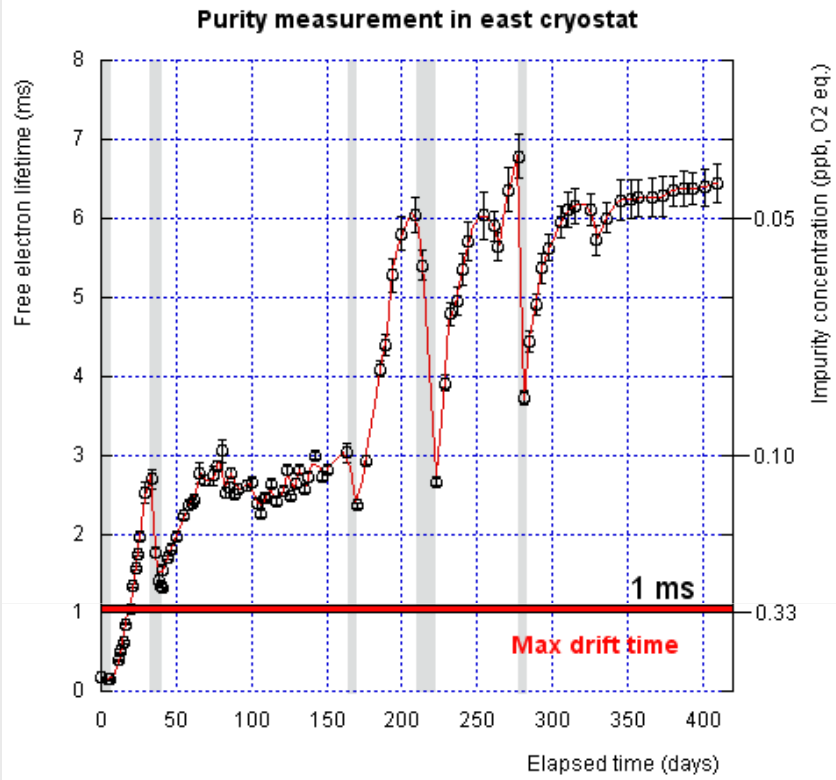


- Two identical T300 modules (two chambers per module)
  - Liquid Ar active mass: ≈ 476 t
  - (17.9 x 3.1 x 1.5 for each TPC) m^3
  - drift length = 1.5 m
  - $\mathbf{E}_{drift}$ = 500 V/cm ; $\mathbf{v}_{drift}$ = 1.589 mm/μs
- Three readout wire planes per chamber, at 0, ±60°, 3 mm plane spacing
  - ≈ 53.000 wires, 3 mm pitch
  - Two induction planes, one collection
- PMTs for scintillation light (128 nm)
  - 20+54 PMTs , 8" Ø
  - wave shifter (TPB)

Key feature: LAr purity form electro-negative molecules (O_2, H_2O, $C0_2$).
Target: 0.1 ppb 0_2 equivalent = 3 ms lifetime (4.5 m drift @ 500 V/cm).

LAr purity time evolution





Electronegative impurities can attenuate e^- signal: high purity is crucial!

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_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

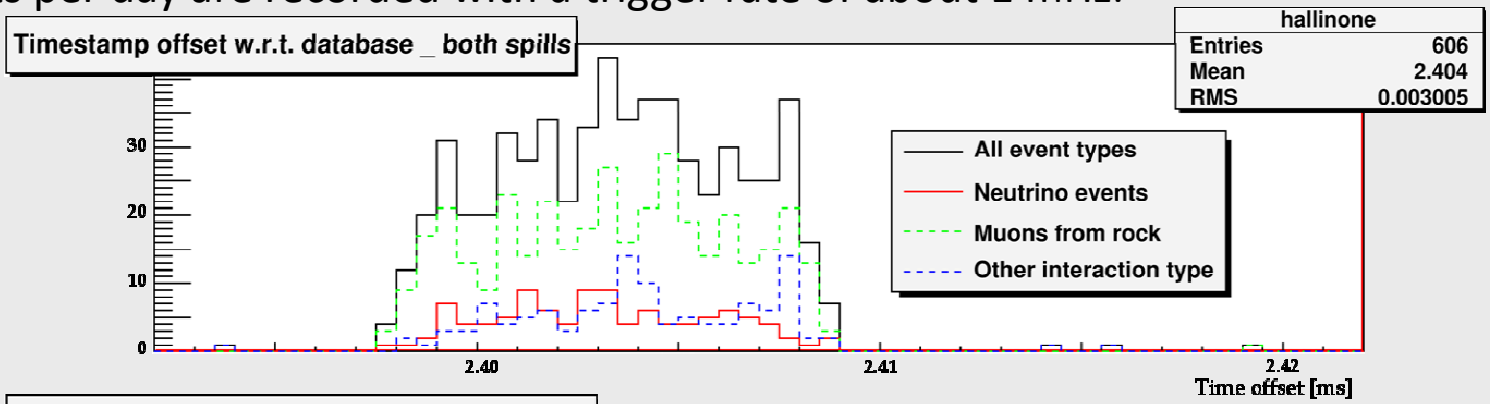
τ_R: 2 m^3/h corresponding to ≈ 6 day cycle time

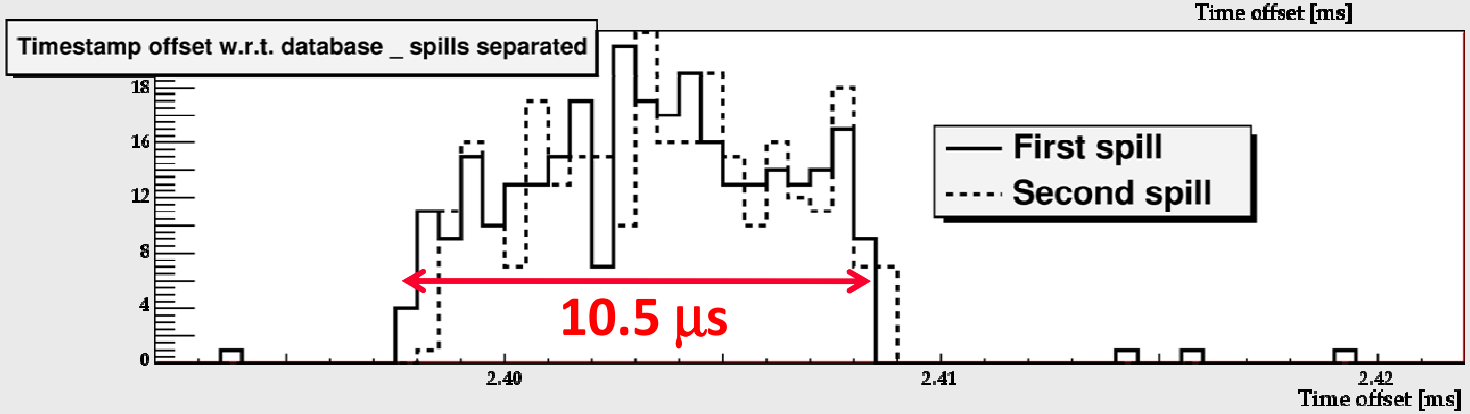
τ_{ele} [ms] = 0.3 / N[ppb O_2 equivalent]

Present value < 0.05 ppb (<u>6 ms lifetime</u>)

CNGS trigger

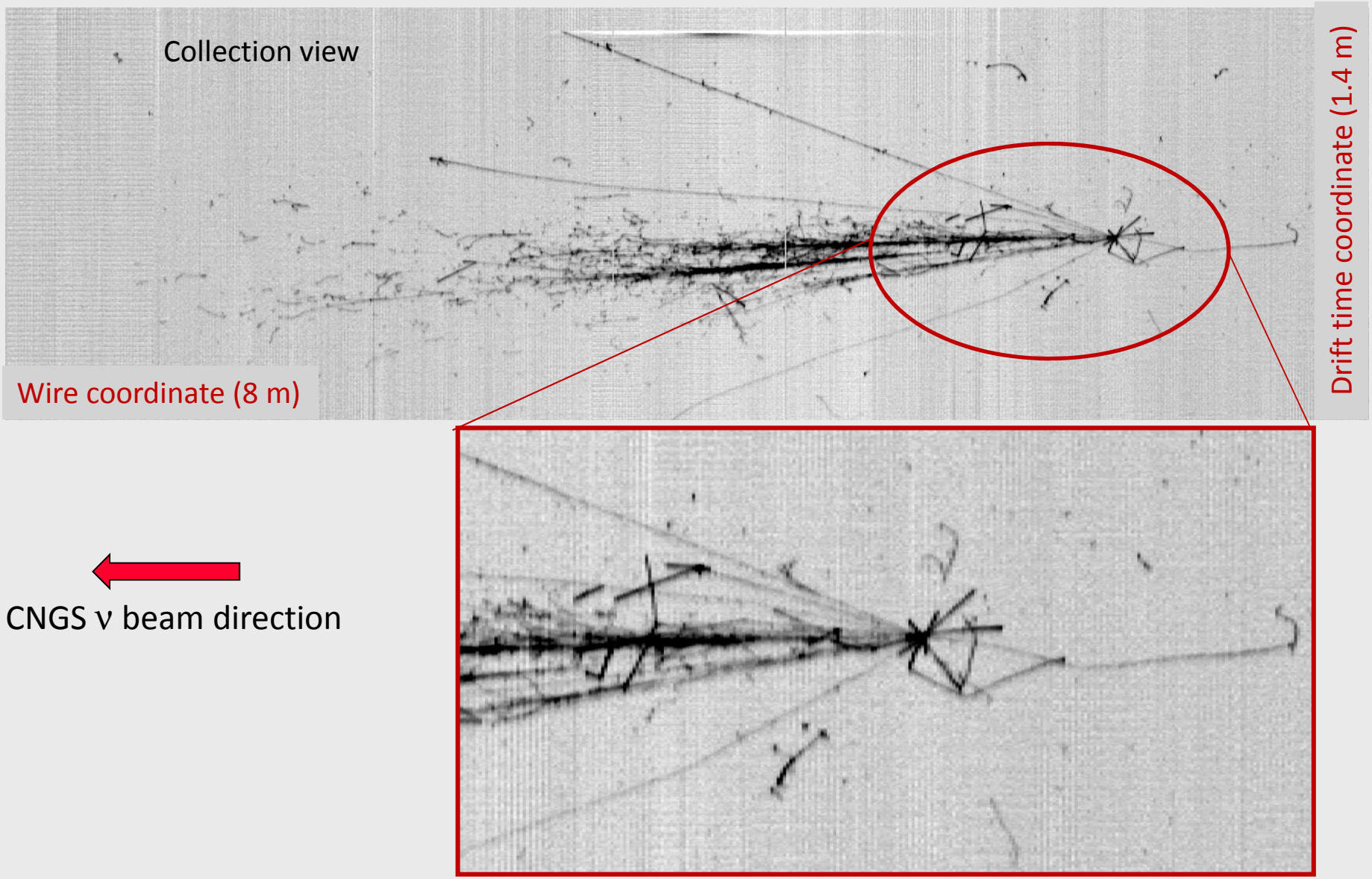
- At every CNGS cycle protons are extracted in 2 spills lasting 10.5 μs each, 50 ms apart. CNGS "Early Warning" signal sent 80 ms before the proton spill extraction, containing information on the time foreseen for the next extraction.
- Trigger: PMT analog sum signal for each chamber with low threshold discrimination at 100 phe, within 60 μs wide beam gate.
- 80 events per day are recorded with a trigger rate of about 1 mHz.





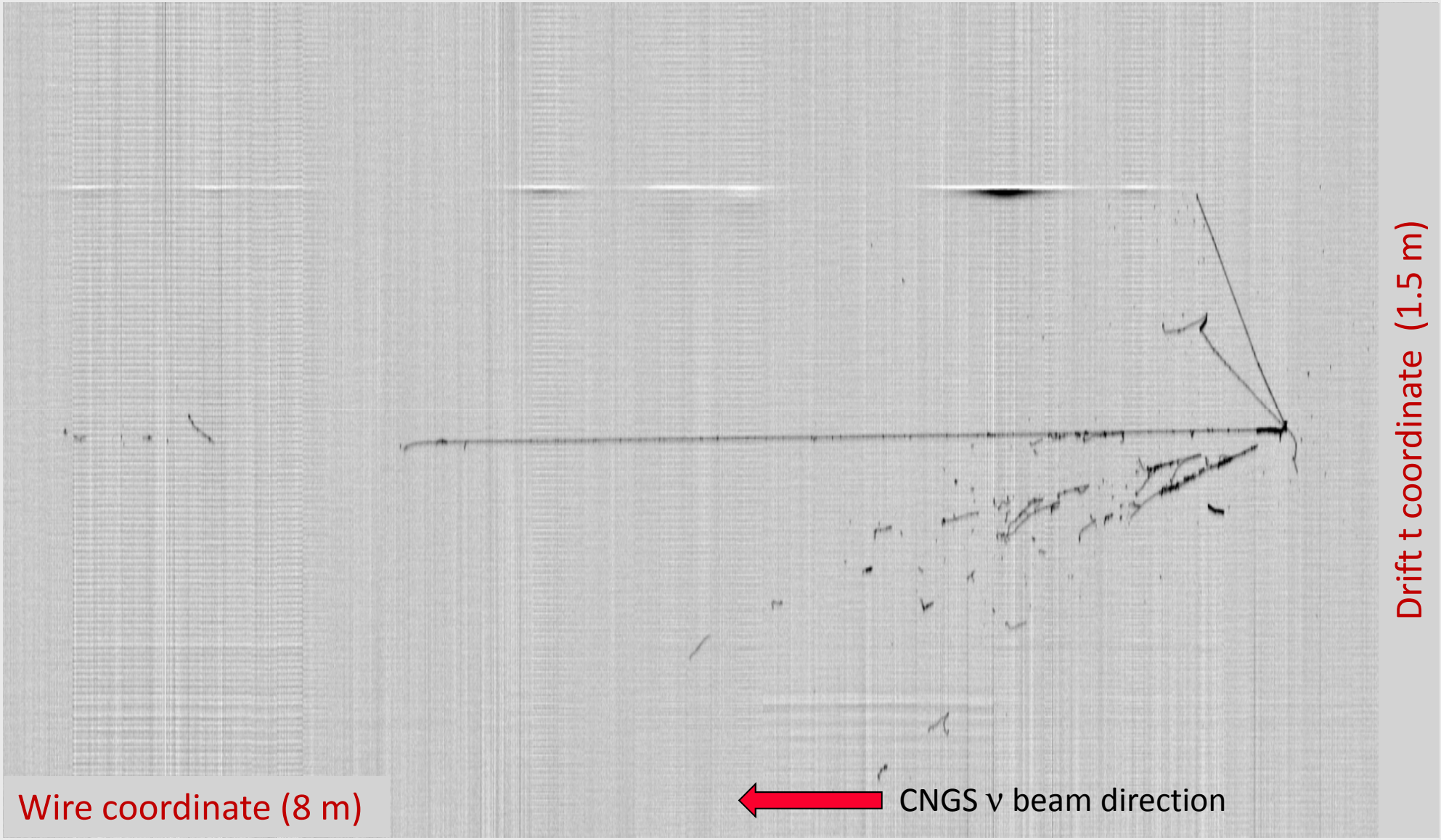
- Offset value (2.40 ms) in agreement with ν t.o.f. (2.44 ms) in view of 40 μs fiber transit time from external LNGS labs absolute clock to Hall B (8km).

First CNGS ν interaction in ICARUS T600

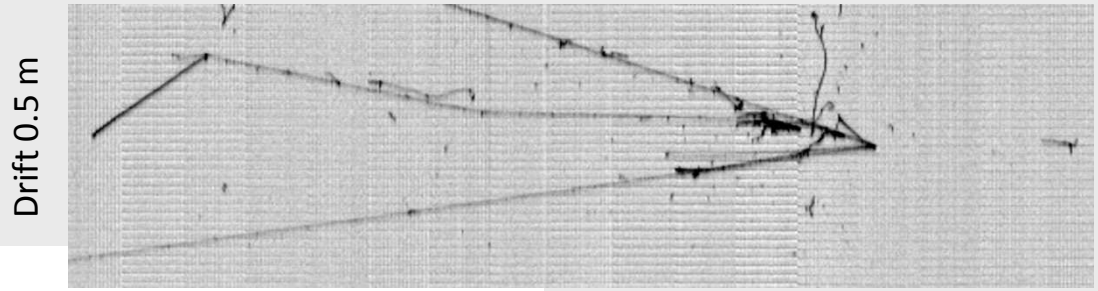


CNGS ν beam direction

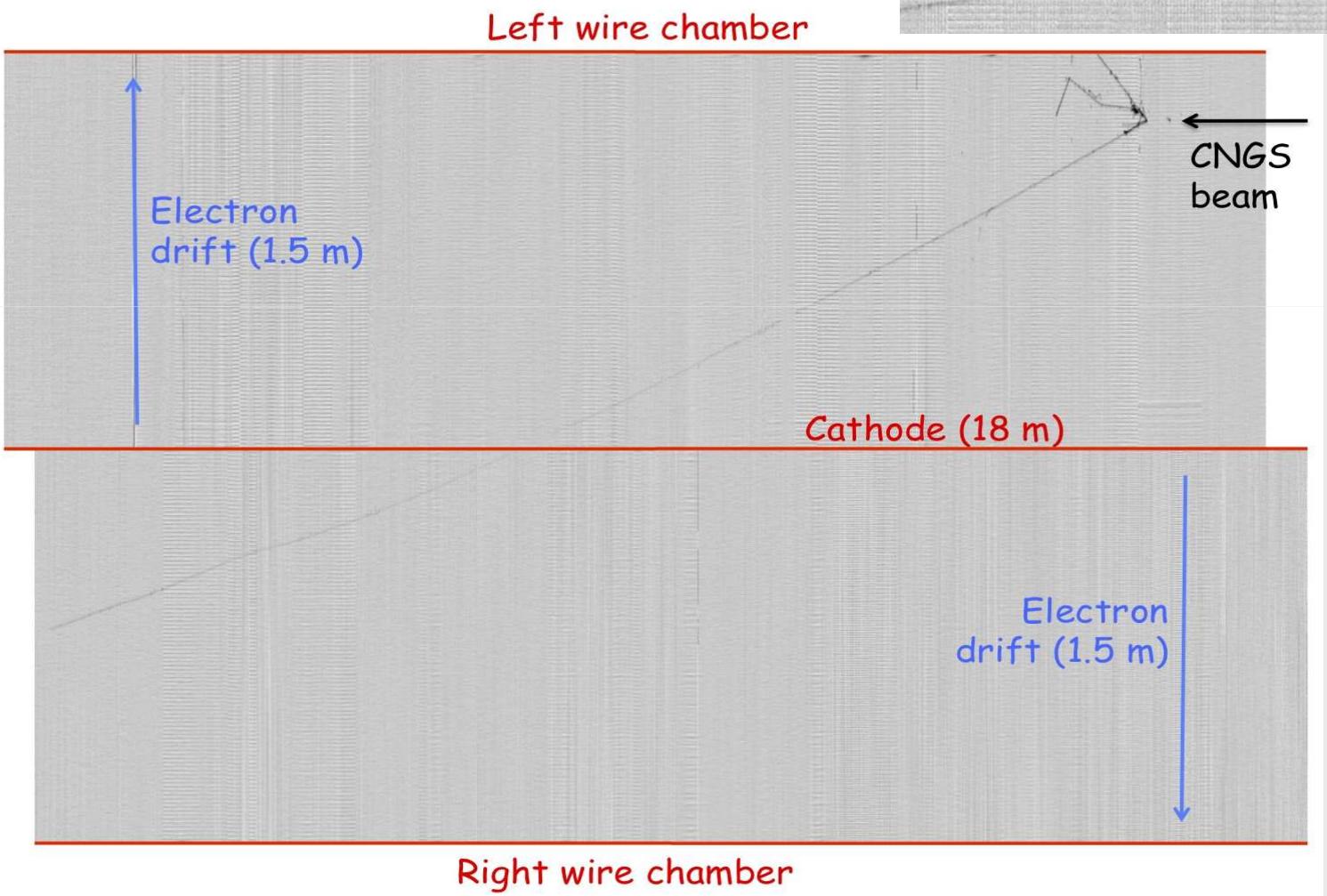
Another CNGS CC ν interaction



CNGS CC ν interaction with signal in both TPCs

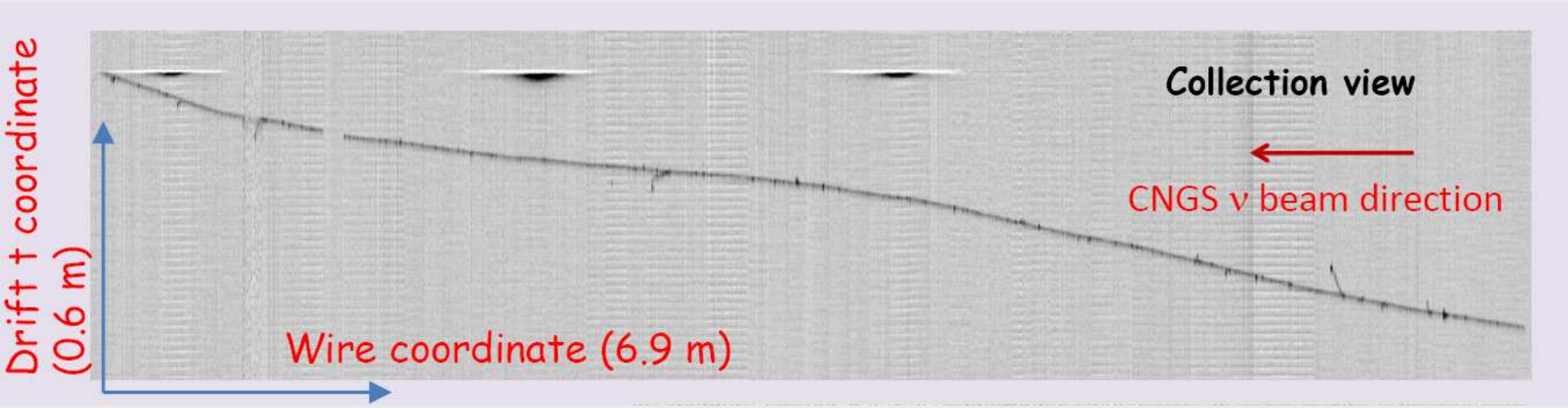


Wire coordinate 1.8 m

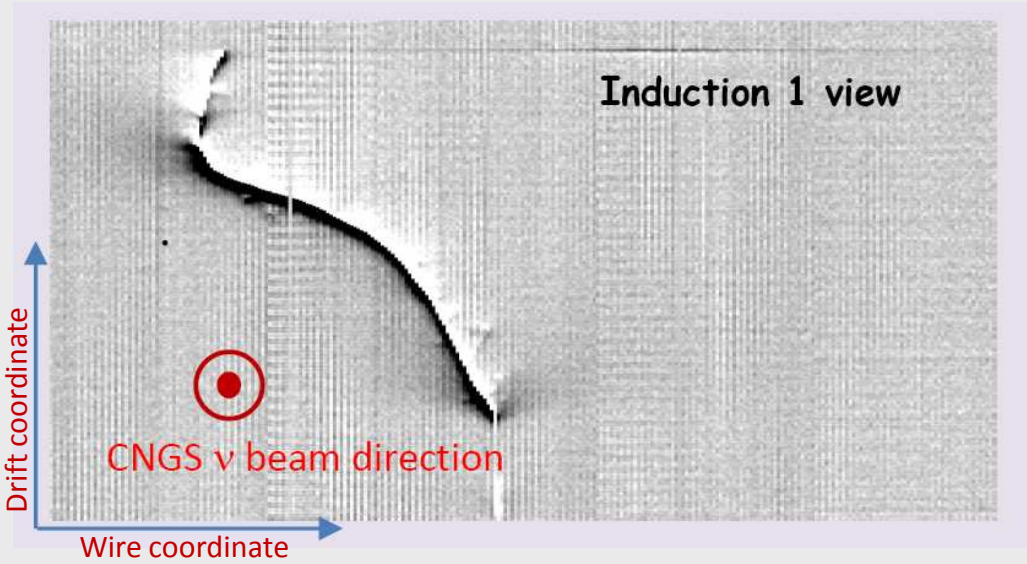


$E_{vis} \approx 9$ GeV

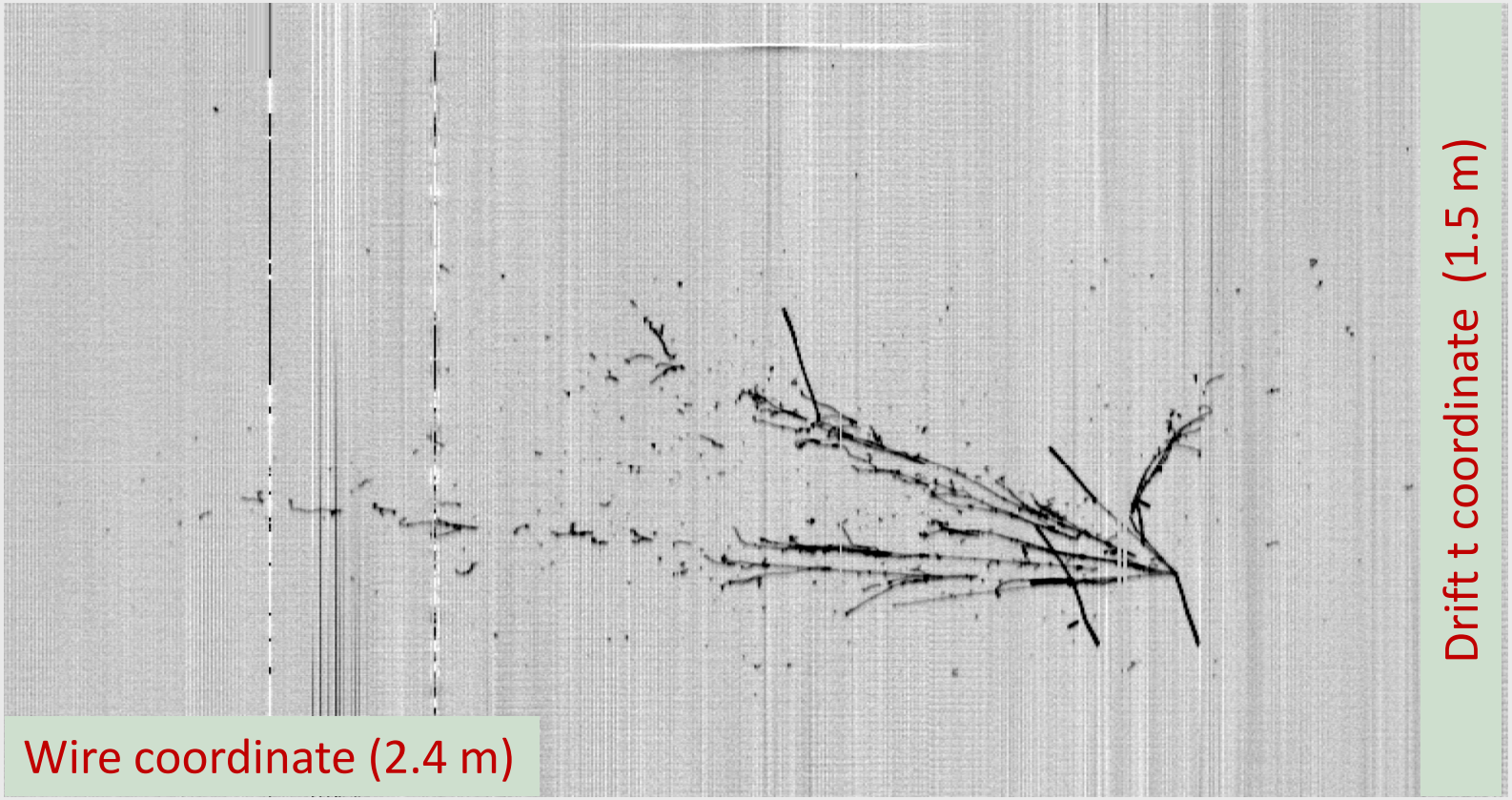
CNGS CC ν interaction in the rock surrounding Hall B



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

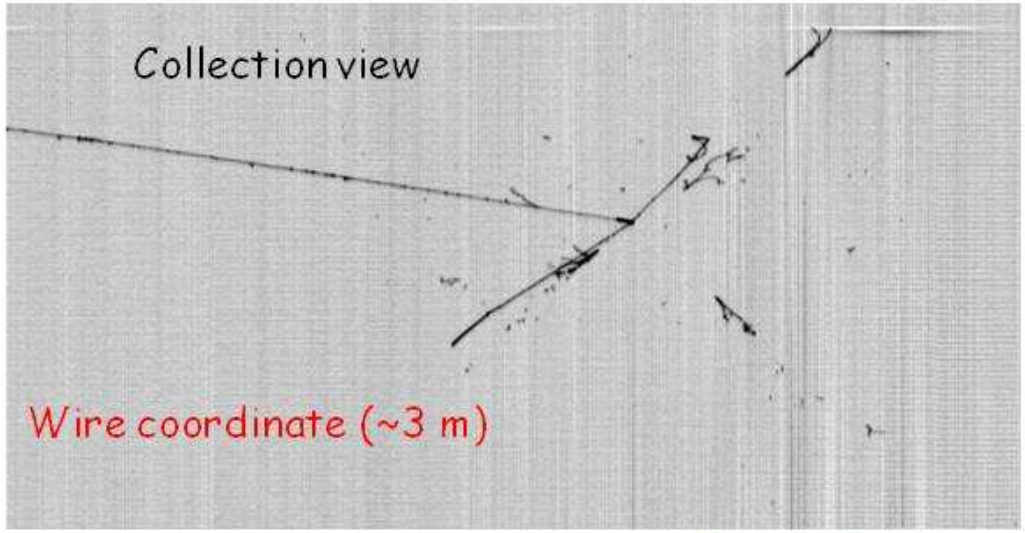


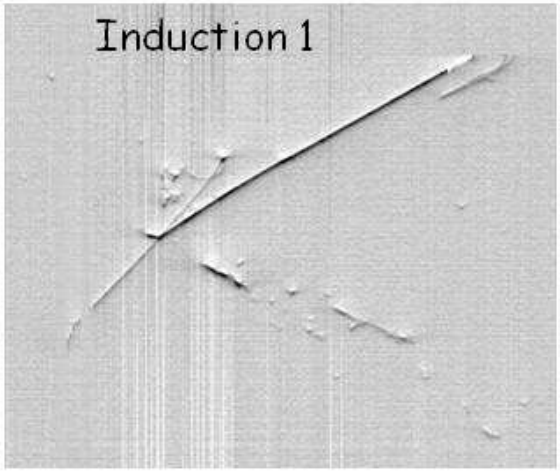
CNGS NC ν interaction



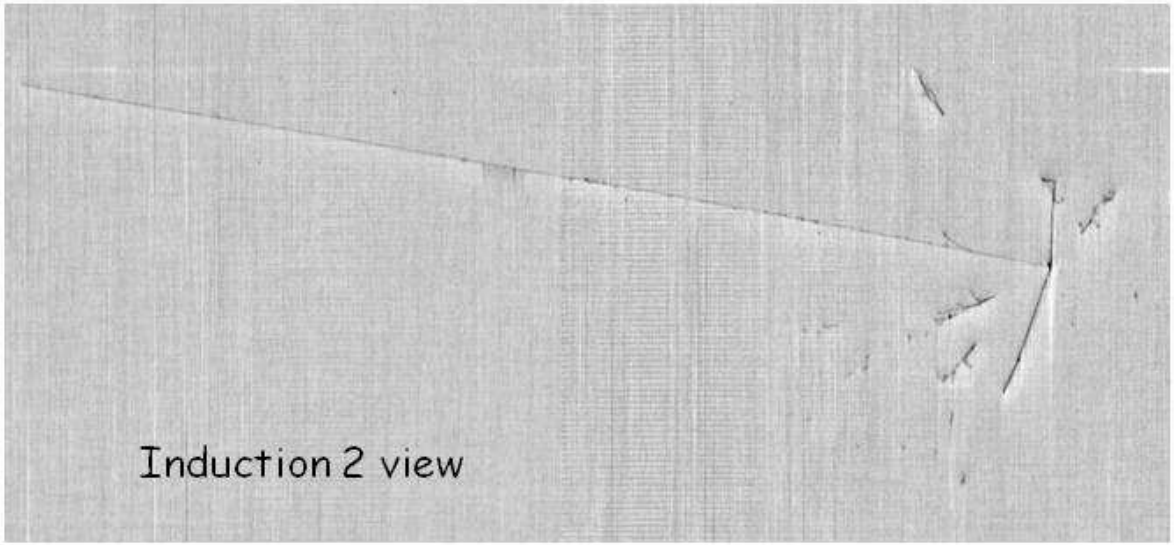
CNGS ν beam direction

CNGS CC ν interaction with π^0 production





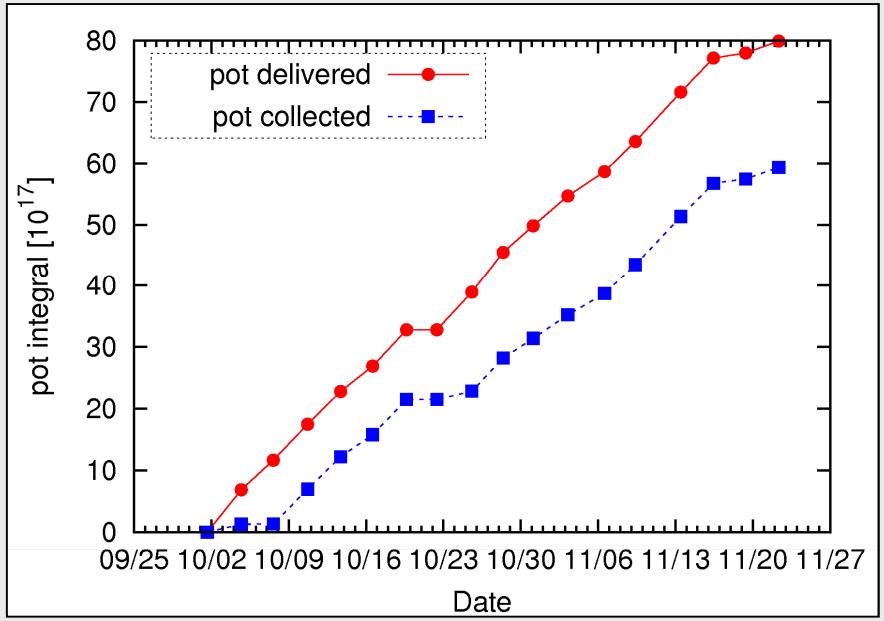
CNGS ν beam direction



Total deposited energy ≈ 1 GeV

CNGS run in 2010

- ICARUS fully operational for CNGS events recording since October, 1st.
- $5.9 \cdot 10^{18}$ pot collected (75% live time).
- Number of ν interaction within expectations.



Event type	Collected	Expected
ν_μ CC	114	129
ν NC	46	42
ν_e CC	1	1
ν XC (further analysis needed)	7	-
Total	167	171

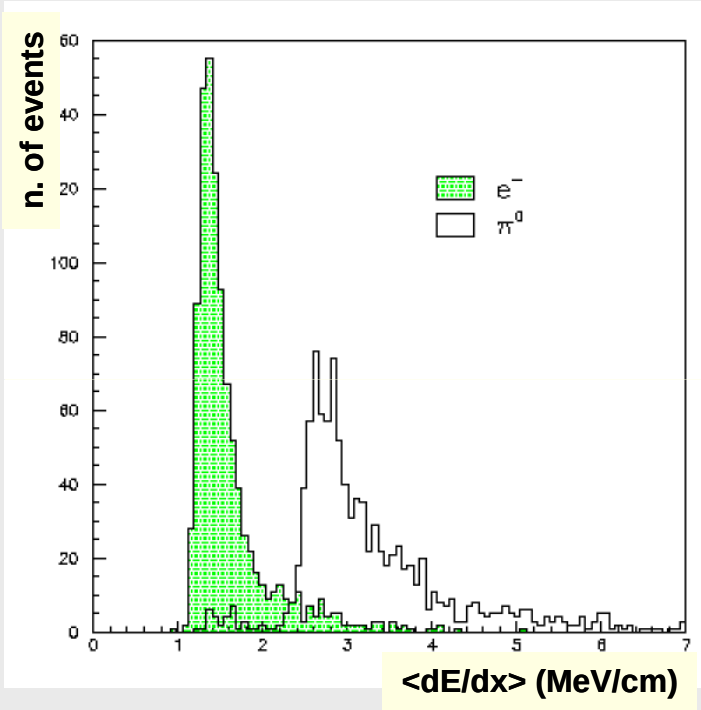
ICARUS T600 reconstruction performances

CASCADES:

- The total energy of cascades is measured by charge integration with recombination correction.

Very good e/π^0 separation by means of dE/dx in the first part of the cascade.

NC π^0 background rejected at 0.1% level while keeping 90% of ν_e CC



ENERGY RESOLUTIONS:

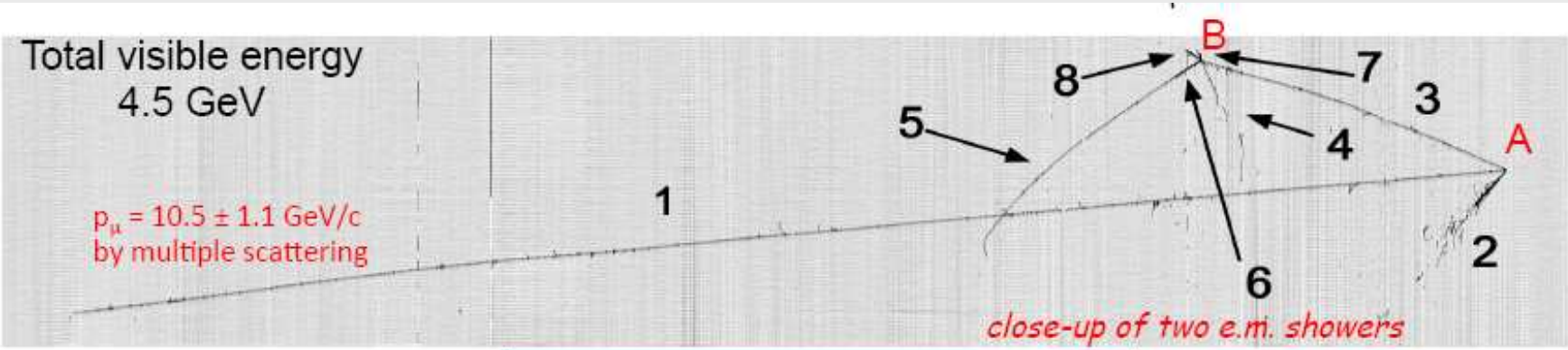
Low energy eletrons	$\sigma(E)/E = 11\%/\sqrt{E(MeV)} + 2\%$
Electromagnetic showers	$\sigma(E)/E = 3\%/\sqrt{E(GeV)}$
Hadron shower (pure Lar)	$\sigma(E)/E \approx 3\%/\sqrt{E(GeV)}$

TRACKS:

- Momentum of high energy particles is measured via multiple scattering: $\Delta p/p \approx$ 10-15% depending on track length and **p**.
- Stopping particles energy is measured by charge integration.
- Stopping particle identification by means of dE/dx vs E.

Requires good spatial reconstruction

Full reconstruction of a typical CNGS CC ν_μ event



Primary vertex (A):

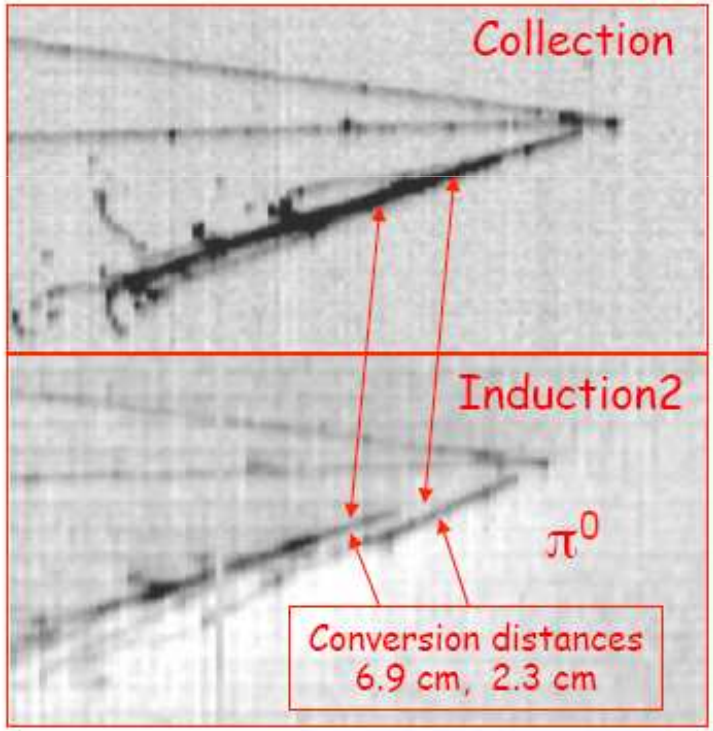
(1) long muon (uncontained)

(2) e.m. Cascades

(3) pion

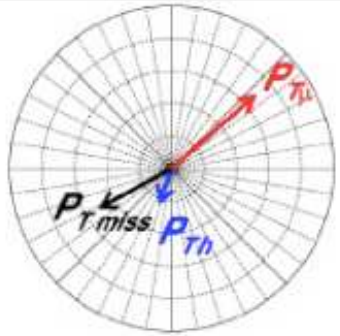
Secondary vertex (B):

the longest track (5) is a μ coming from stopping kaon (6). The μ decay is also observed



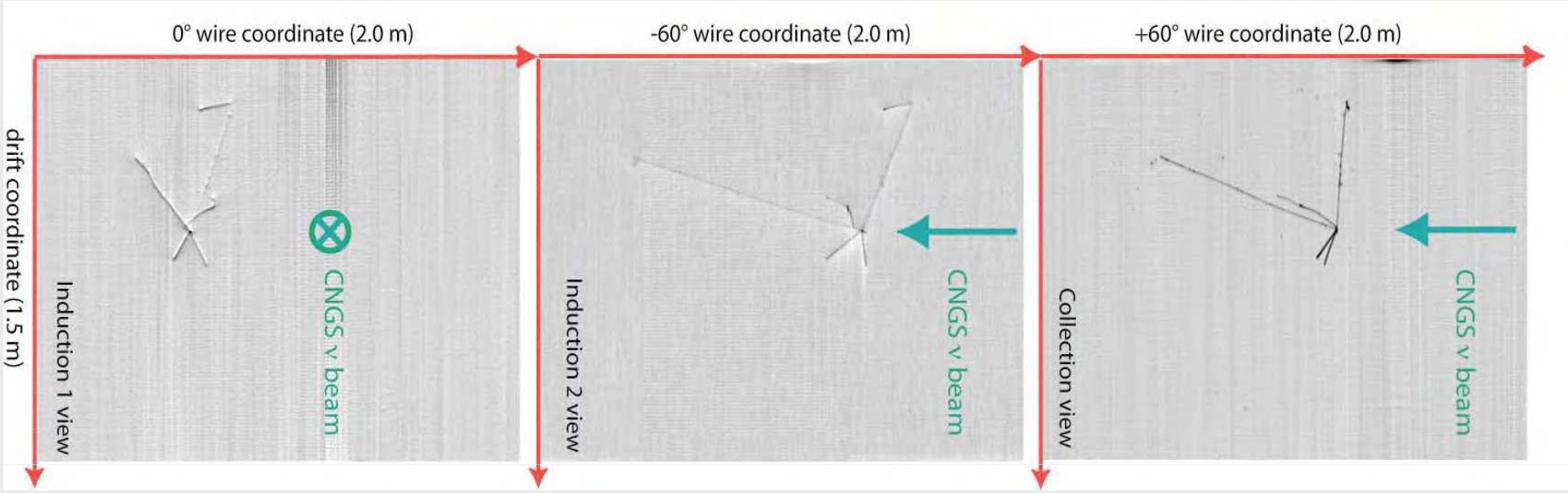
$M^*\gamma\gamma$ = 125±15 MeV/c²

Total transverse momentum is consistent with Fermi distr.

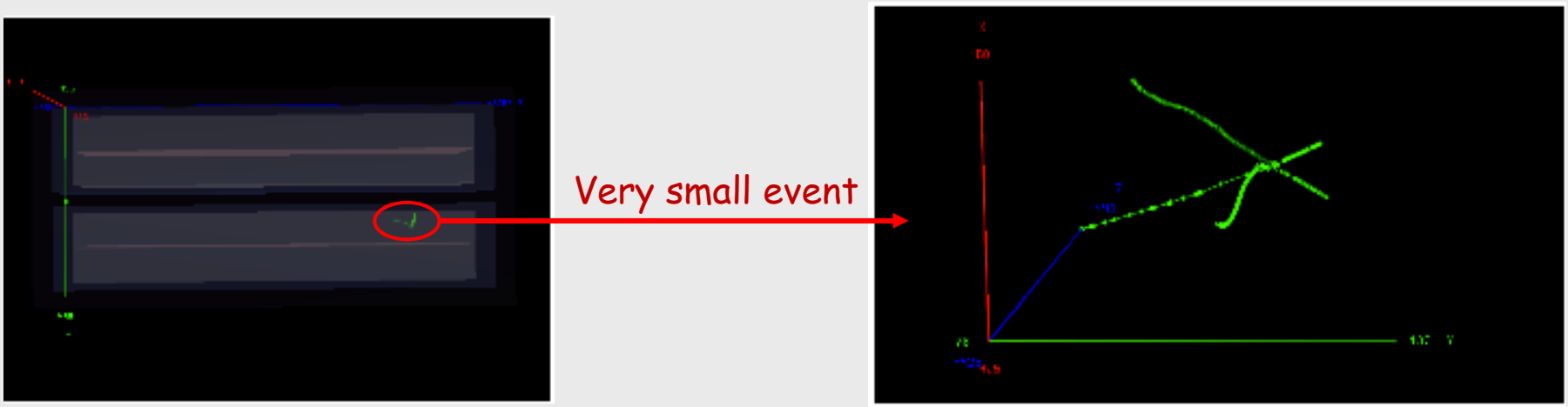


P_T unbalance ~ 250 MeV

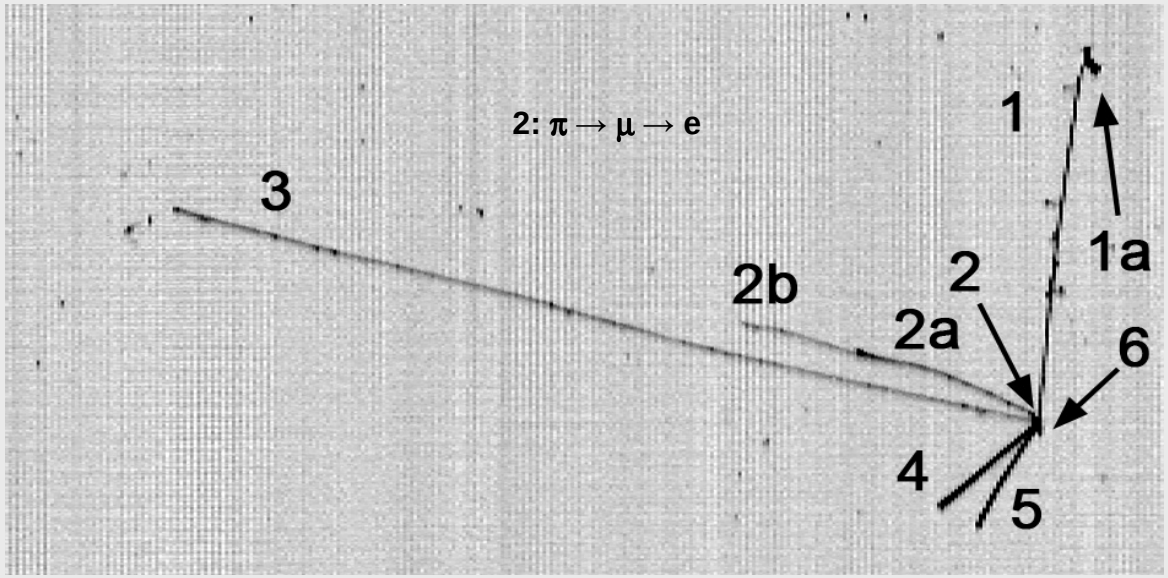
Low energy ν interaction

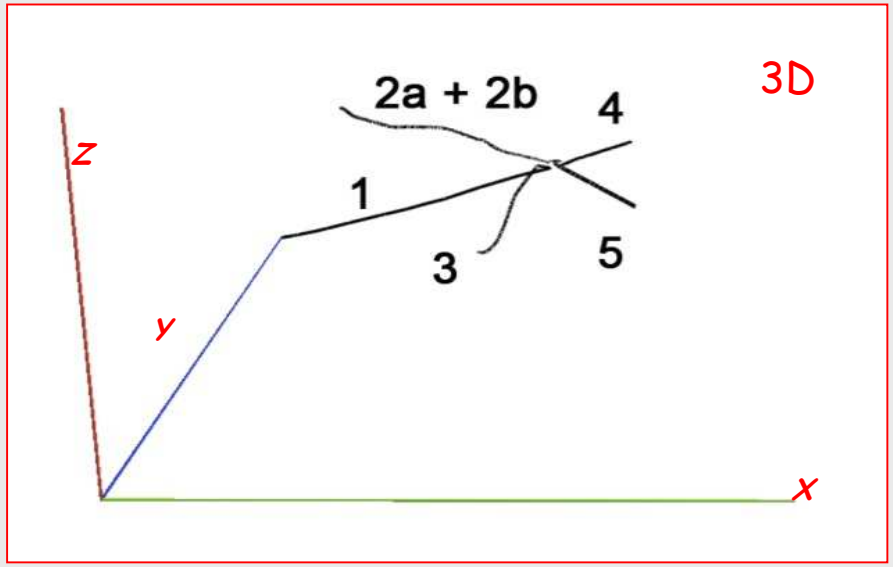


Total visible energy: 887 MeV (including quenching and e^- lifetime corrections).



Atmospheric neutrino candidate

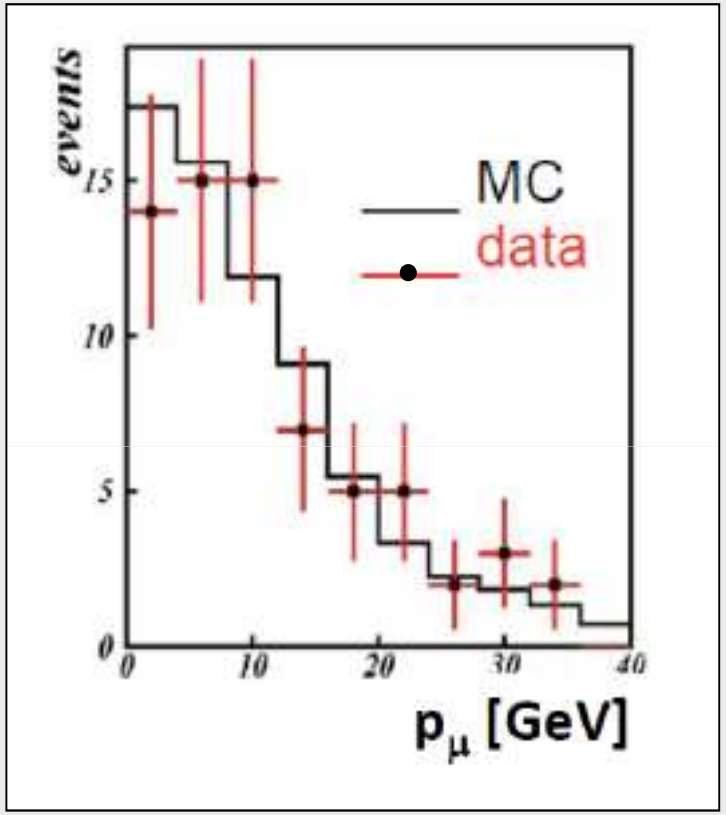




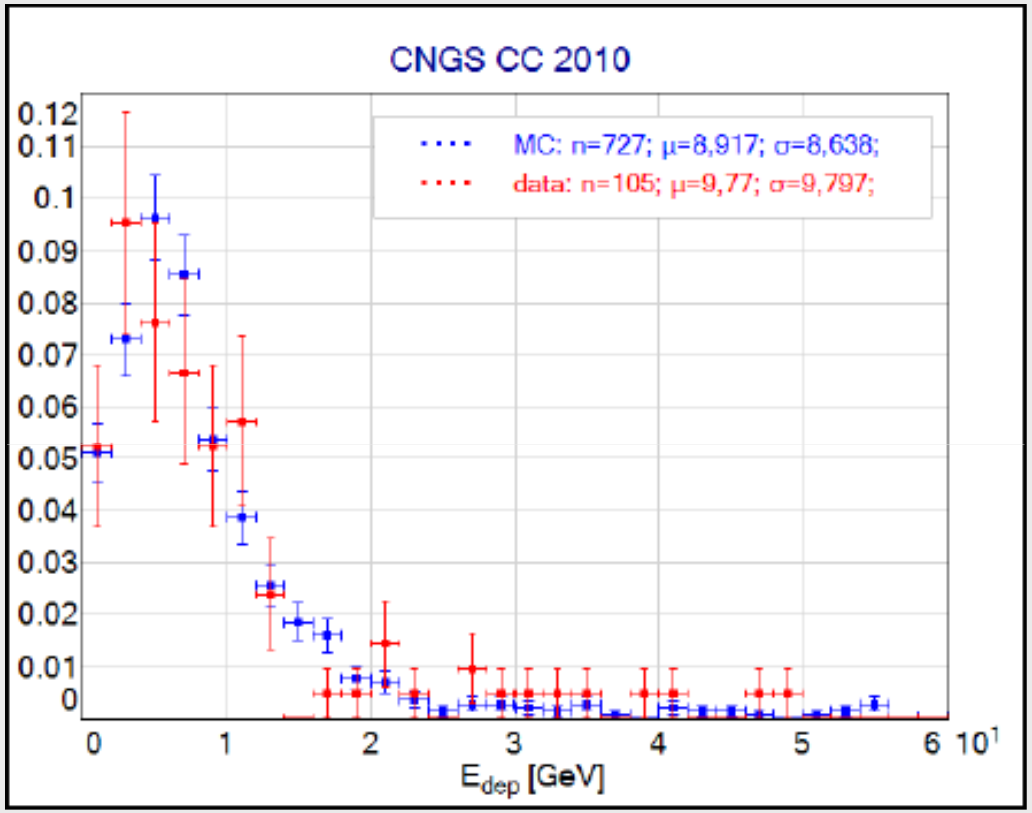
Track	E_k [MeV]	Range [cm]
1 (prob. π, decays in flight)	136.1	55.77
2 (π)	26	3.3
2a (μ)	79.1	17.8
2b (e)	24.1	10.4
3 (μ)	231.6	99.1
4 (p)	168	19.2
5 (p)	152	16.3
6 (?) (merged with vtx)		2.9

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

Preliminary results of CNGS 2010 CC ν interactions



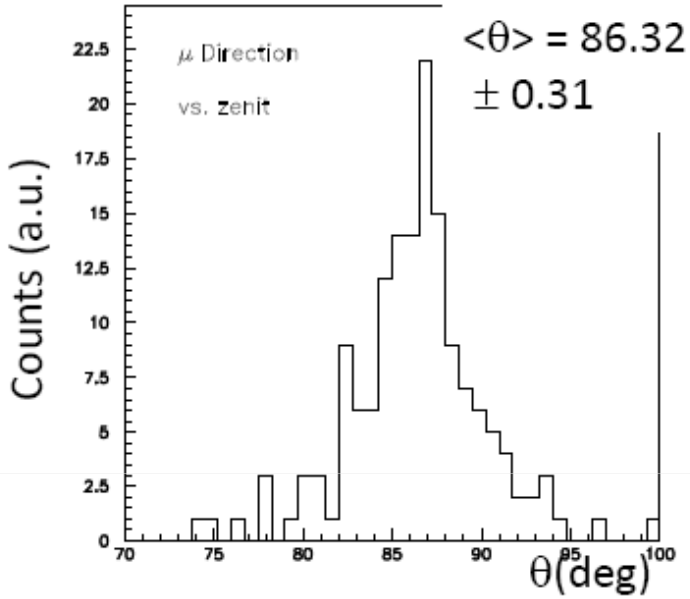
Measurement of muon momentum from multiple scattering



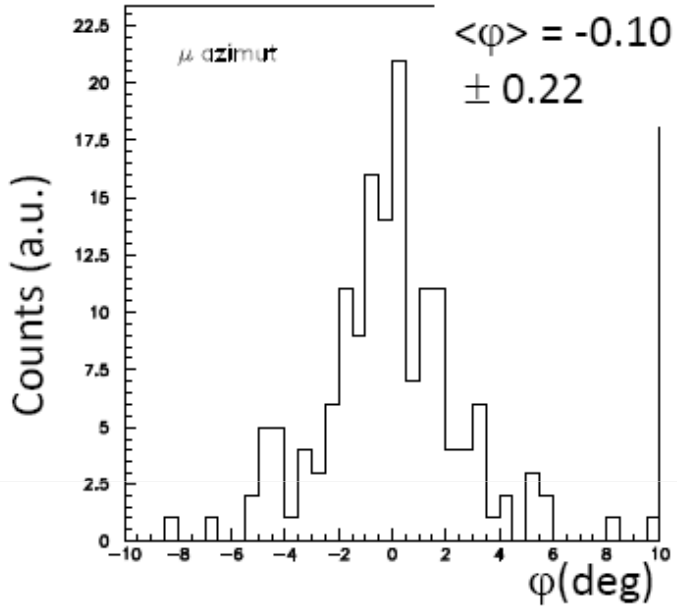
Calorimetric measurement of the deposited energy

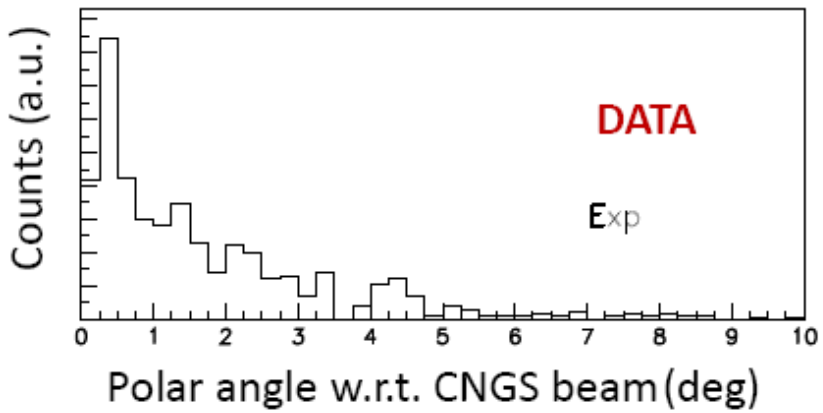
Reconstruction of muons from ν interaction in the rock

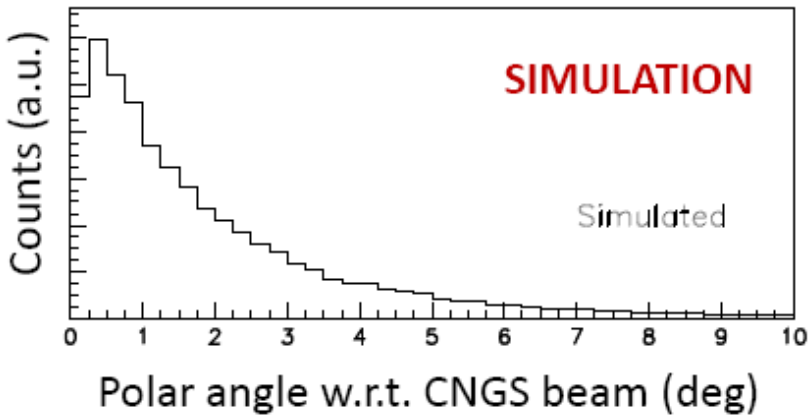
Direction of muons w.r.t. the vertical:



Muon azimuth:

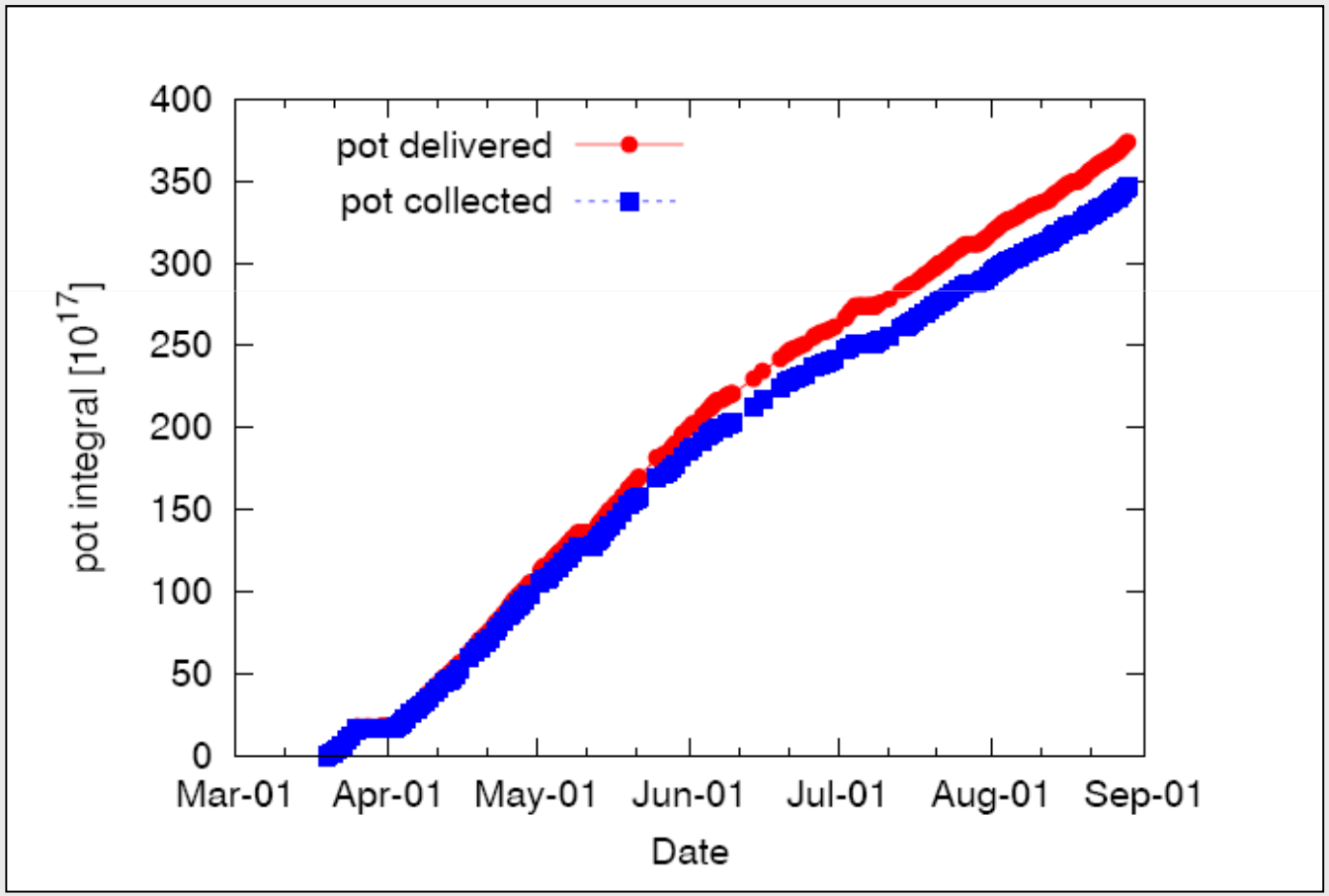




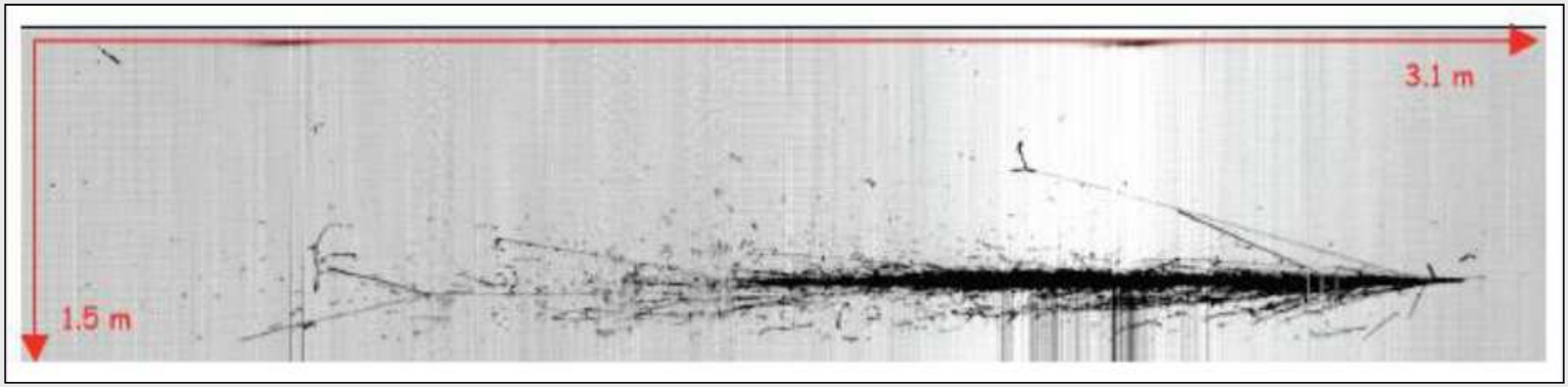


2011 CNGS run

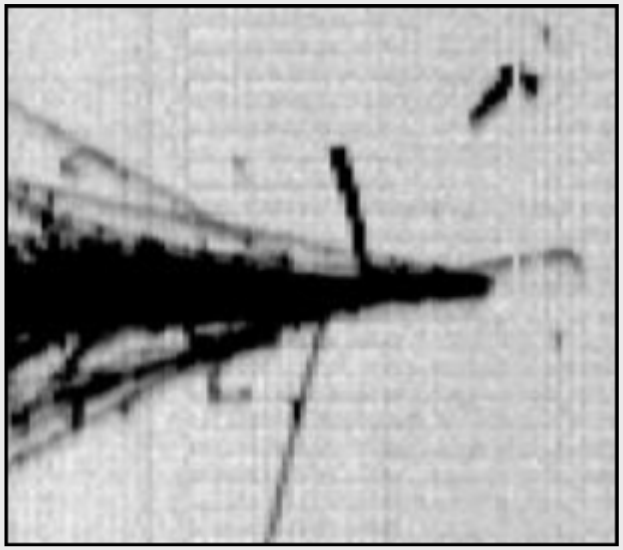
- Beam restarted from March, 19th .
- Detector live time above 92% due to more stable run conditions
- $3.46 \cdot 10^{19}$ ($3.74 \cdot 10^{19}$) pot delivered (collected) up to August, 28th .



2011 run CC ν_e event candidate



- Total deposited energy 45 GeV.
- Single high energy EM shower (37 GeV) measured by charge integration, partially overlapped to hadronic jet.



ICARUS T600 physics potential (2011-2012 CNGS run)

- 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.

- 2011-2012 run with dedicated SPS periods @ high intensity (10^{20} pot, $E_\nu \approx 17.4$ GeV).

- For $1.1 \cdot 10^{20}$ pot: <u>3000 beam related ν_μ CC events</u> expected in ICARUS T600.

- 7 ν_e CC intrinsic beam associated events with $E_{vis} < 20$ GeV $\rightarrow$ **BACKGROUND**;
- 17 ν_τ raw CC events assuming $P(\nu_\mu \rightarrow \nu_\tau) = 1.4\%$ ($\Delta m^2 = 2.5 \cdot 10^{-3}$ eV^2, $E_\nu = 20$ GeV);
- $P(\tau \rightarrow e\nu\nu) = 18\% \rightarrow$ 3 electron deep inelastic events with visible energy < 20 GeV $\rightarrow$ **SIGNAL**:

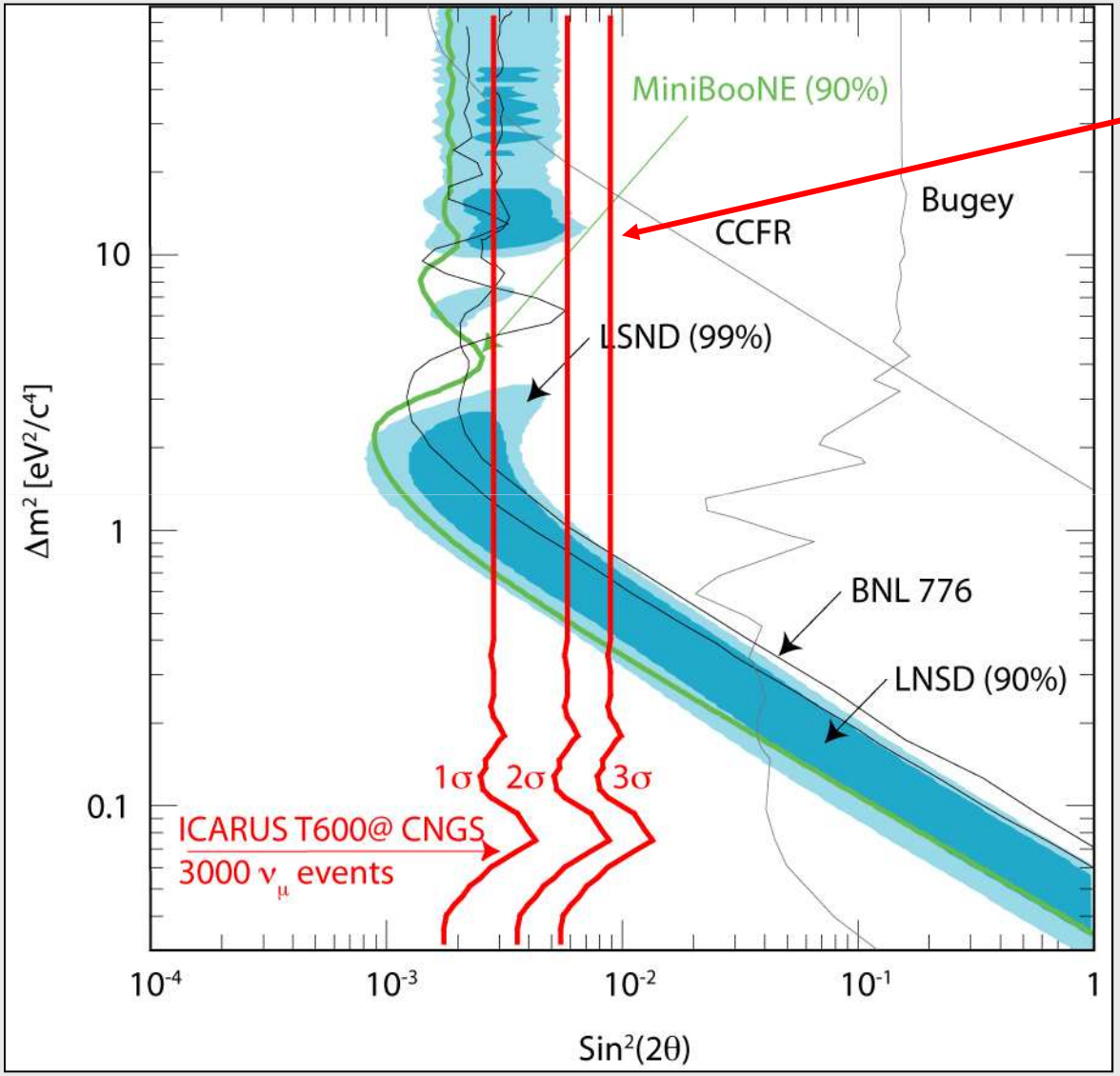
  - $\tau \rightarrow e\nu\nu$ events are characterized by momentum unbalance (2ν emission) and relatively low electron momentum.

  - Selection criteria suggest a sufficiently clean separation with kinematic cuts and 50% efficiency, opening the possibility to identify 1-2 ν_τ CNGS events in the next 2 years, <u>only in this gold channel</u>.

- search for sterile ν in LSND parameter space (deep inelastic ν_e CC events excess).

- *Self triggered* events collection:
  - $\approx$ 80 events/year of unbiased atmospheric ν CC;
  - zero background proton decay with 3×10^{32} nucleons for *exotic* channels.

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.

Conclusions

- ICARUS T600 @ LNGS is taking data with the CNGS beam in stable conditions since October 2010.
- The successful assembly and operation of ICARUS T600 is the experimental proof that this technique is suitable for large scale experiments.
- The unique imaging capability of ICARUS and its spatial and calorimetric resolutions allow to reconstruct and identify events in a new way w.r.t. previous and current experiments.
- The 2011-2012 run with CNGS ν_μ beam will allow to possibly detect few ν_τ appearance events. Interesting perspective also for atmospheric neutrinos, sterile neutrinos and proton decay.
- *The ICARUS experiment at the Gran Sasso Laboratory is so far a major milestone towards the realization of much more massive LAr detectors .*


Thank you!