

# ICARUS T600 results



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Jan Kisiel (Institute of Physics, Univ. Silesia, Katowice, Poland)  
for the ICARUS T600 Collaboration

# The ICARUS T600 Collaboration

M. Antonello, P. Aprili, N. Canci, C. Rubbia, E. Scantamburlo, E. Segreto, C. Vignoli  
*Laboratori Nazionali del Gran Sasso dell'INFN, Assergi (AQ), Italy*

B. Baibussinov, M. BaldoCeolin, S. Centro, D. Dequal, C. Farnese, A. Fava, D. Gibin, A. Guglielmi, G. Meng, F. Pietropaolo, F. Varanini, S. Ventura  
*Dipartimento di Fisica e INFN, Università di Padova, Via Marzolo 8, I-35131, Padova, Italy*

P. Benetti, E. Calligarich, R. Dolfini, A. Gigli Berzolari, A. Menegolli, C. Montanari, A. Rappoldi, G. L. Raselli, M. Rossella  
*Dipartimento di Fisica Nucleare e Teorica e INFN, Università di Pavia, Via Bassi 6, I-27100, Pavia Italy*

F. Carbonara, A. G. Cocco, G. Fiorillo  
*Dipartimento di Scienze Fisiche, INFN e Università Federico II, Napoli, Italy*

A. Cesana, P. Sala, A. Scaramelli, M. Terrani  
*INFN, Sezione di Milano e Politecnico, Via Celoria 2, I-20123*

K. Cieslik , A. Dabrowska, M. Haranczyk , D. Stefan , M. Szarska ,T. Wachala ,A. Zalewska  
*The Henryk Niewodniczanski, Institute of Nuclear Physics, Polish Academy of Science, Krakow, Poland*

D. B. Cline, S. Otwinowski, H.-G. Wang, X. Yang  
*Department of Physics and Astronomy, University of California, Los Angeles, USA*



A. Dermenev, S. Glinenko, M. Kirsanov  
*INR RAS, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia*

A. Ferrari  
*CERN, Ch1211 Geneve 23, Switzerland*

T. Golan , J. Sobczyk ,J. Zmuda  
*Institute of Theoretical Physics, Wroclaw University, Wroclaw, Poland*

J. Holeczek ,J. Kisiel , I. Kochanek, S. Mania  
*Institute of Physics, University of Silesia, 12 Bankowa st., 40-007 Katowice, Poland*

J. Lagoda , T. J. Palczewski ,P. Przewlocki ,J. Stepaniak ,R. Sulej  
*A. Soltan Institute for Nuclear Studies, 05-400 Swierk/Otwock, Warszawa, Poland*

G. Mannocchi, L. Periale, P. Picchi,  
*Laboratori Nazionali di Frascati (INFN), Via Fermi 40, I-00044, Italy*

P. Plonski , K. Zaremba  
*Institute for Radioelectronics, Warsaw Univ. of Technology Pl. Politechniki 1, 00-661 Warsaw, Poland*

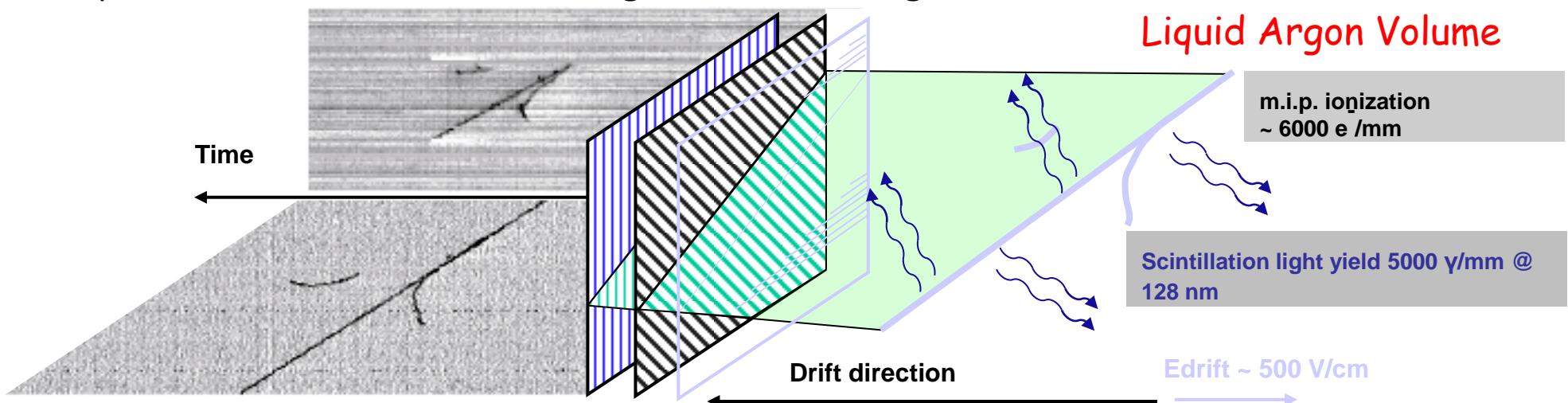
F. Sergiampietri  
*Dipartimento di Fisica, Università di Pisa, Largo Bruno Pontecorvo 3, I-56127, Pisa, Italy*

# A powerful detection technique

The **Liquid Argon Time Projection Chamber** [C. Rubbia: CERN-EP/77-08 (1977)]

A 3D imaging of any ionizing event ("electronic bubble chamber"):

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



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

Key feature: LAr purity from 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).

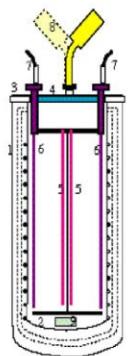
# The path to larger LAr detectors

2

3 ton prototype

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

CERN



CERN

24 cm drift wires chamber

1

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

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

4



10 m<sup>3</sup> 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  
AirLiquide, Brem, Cinel, CAEN

6

LNGS Hall-B

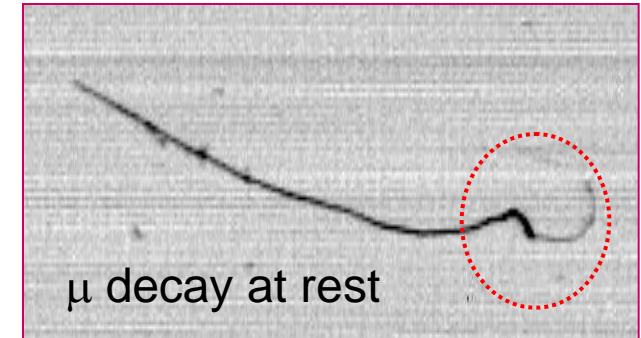
2010 - ... : Data taking with CNGS beam



# LAr-TPC performance

- Tracking device:

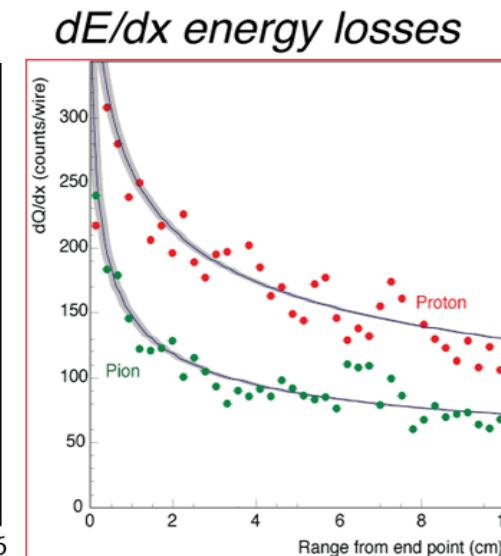
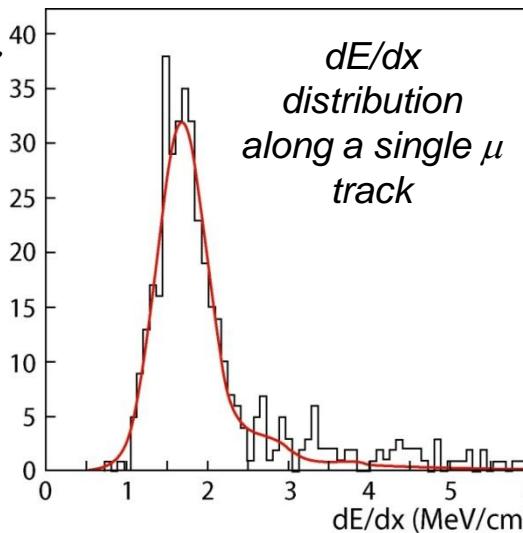
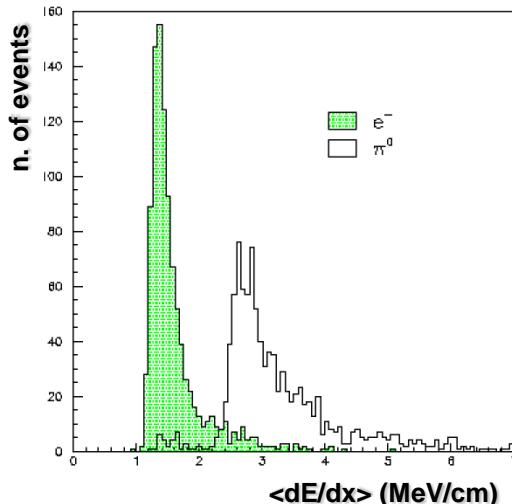
- precise event topology ( $s_{x,y} \sim 1\text{mm}$ ,  $s_z \sim 0.4\text{mm}$ )
- $\mu$  momentum measurement via multiple scattering:  $\Delta p/p \sim 10\text{-}15\%$  depending on track length and  $p$
- Total energy reconstruction by charge integration



- Measurement of local energy deposition  $dE/dx$ :

- $e/\mu$  separation (sampling at  $1/50 X_0$ );
- particle ID by means of  $dE/dx$  vs range

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



## RESOLUTIONS:

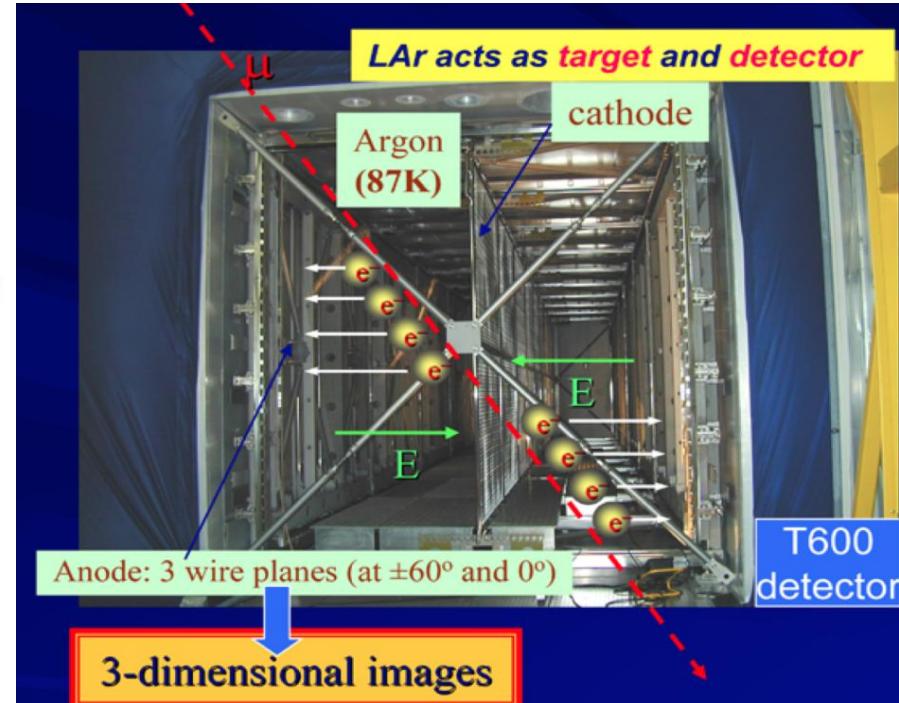
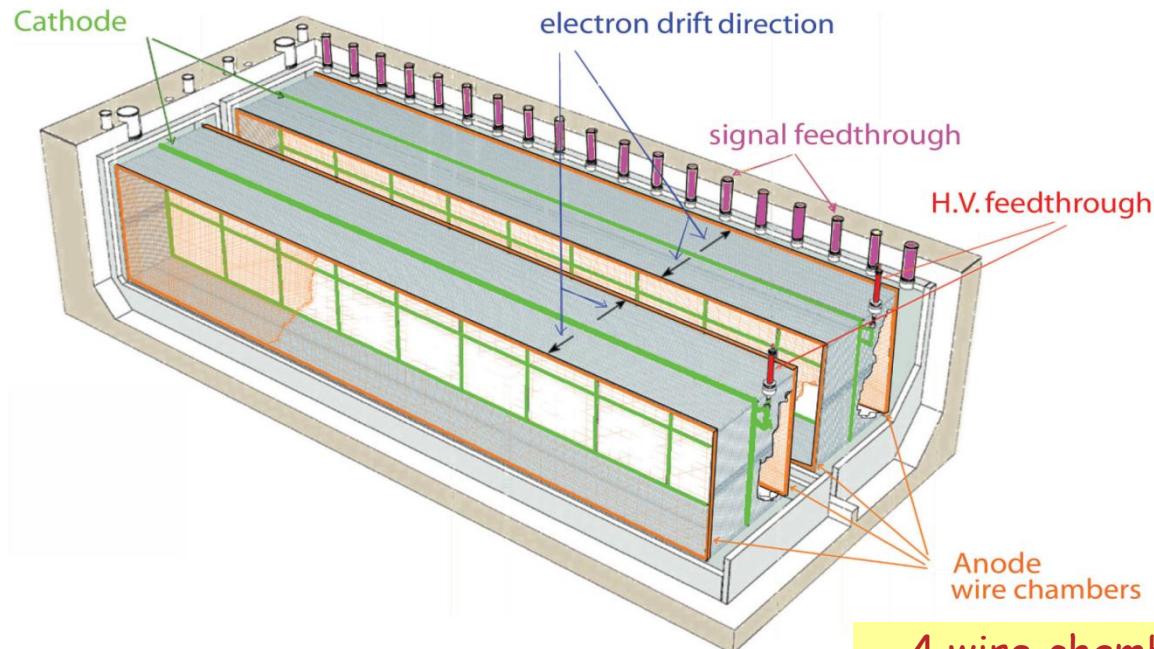
- Low energy electrons
- Electromagnetic showers
- Hadronic showers

$$\sigma(E)/E = 11\% / \sqrt{E(\text{MeV})} + 2\%$$

$$\sigma(E)/E = 3\% / \sqrt{E(\text{GeV})}$$

$$\sigma(E)/E \sim 30\% / \sqrt{E(\text{GeV})}$$

# The ICARUS T600 detector



- Two identical modules

- $3.6 \times 3.9 \times 19.6 \approx 275 \text{ m}^3$  each
- Liquid Ar active mass:  $\approx 476 \text{ t}$
- Drift length = 1.5 m
- HV = -75 kV   E = 0.5 kV/cm
- vdrift = 1.55 mm/ $\mu$ s

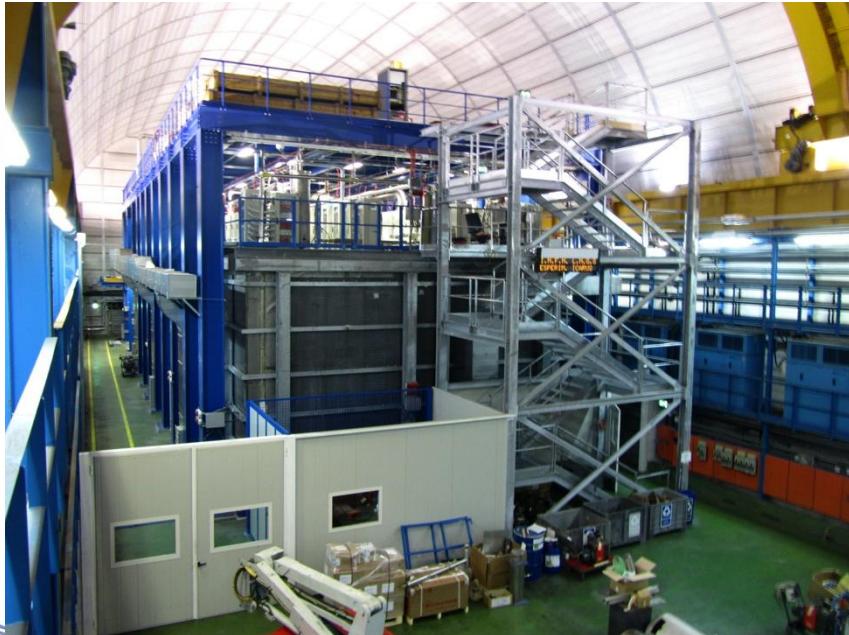
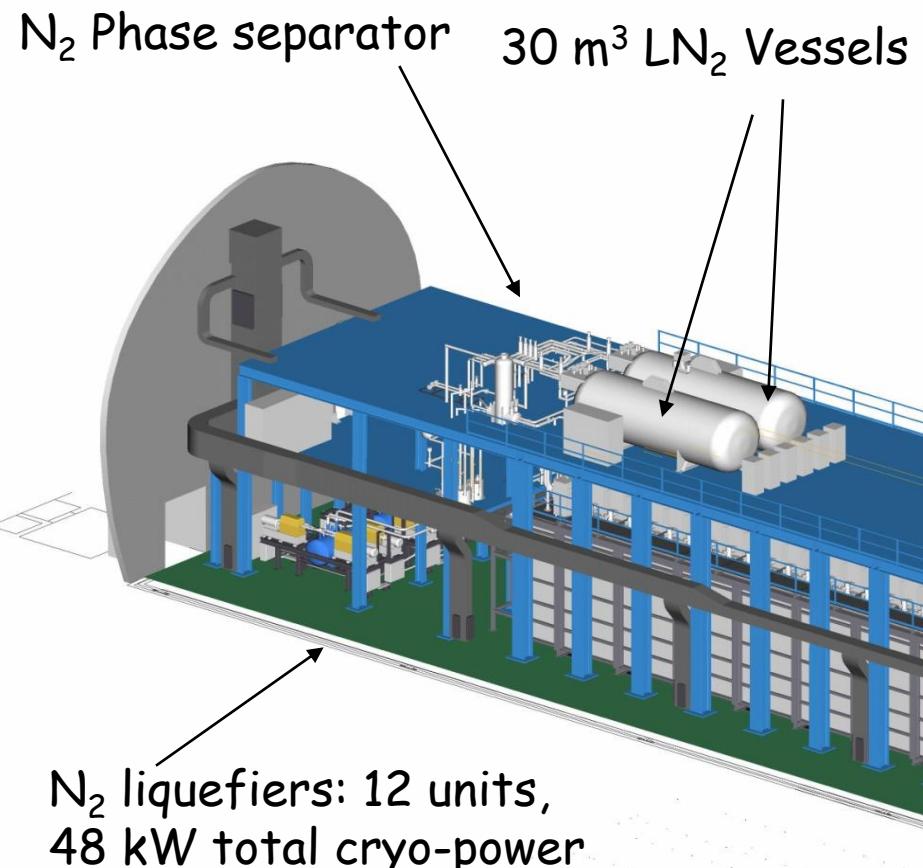
- 4 wire chambers:

- 2 chambers per module
- 3 readout wire planes per chamber, wires at  $0^\circ$ ,  $\pm 60^\circ$
- 53248 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

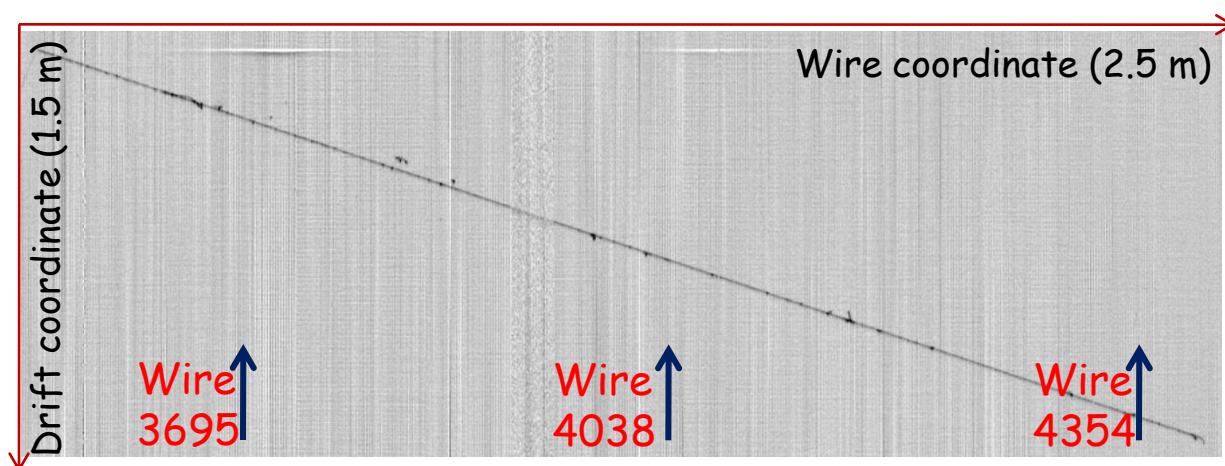
Optimization phase in summer 2010

Data taking in stable condition from 01st Oct. 2010

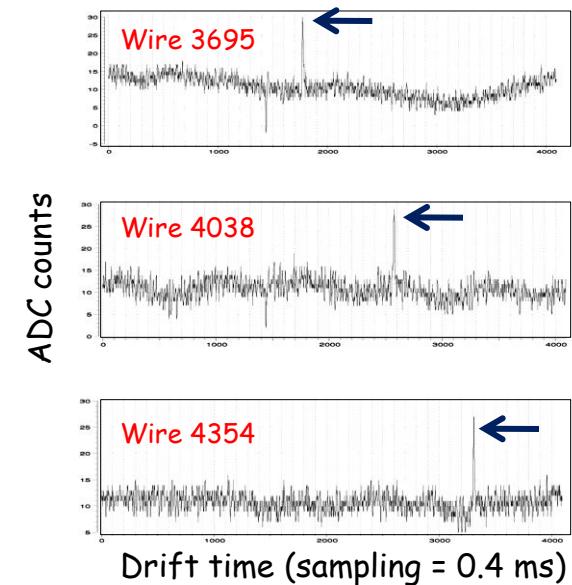
# LAr Purification and measurement in T600

- The presence of electron trapping polar impurities attenuates the electron signal.
- Most of the contaminants freeze out spontaneously (87 K) . Residuals: O<sub>2</sub>, H<sub>2</sub>O, CO<sub>2</sub>.
- Recirculation/purification of both, the **gas phase** and the **liquid phase** (4 m<sup>3</sup>/h, full volume recirculation in 6 days) to reduce the initial impurities concentration (Hydrosorb/Oxysorb™ filters).

Charge attenuation along track allows event-by-event measurement of LAr purity  
(Use of about 50 muon tracks without evident associated  $\delta$ -rays and  $\gamma$ 's, day-by-day)  
(Pulse height for 3 mm m.i.p.  $\sim 15$  ADC # (15000 electrons; noise r.m.s. 1500 electrons)

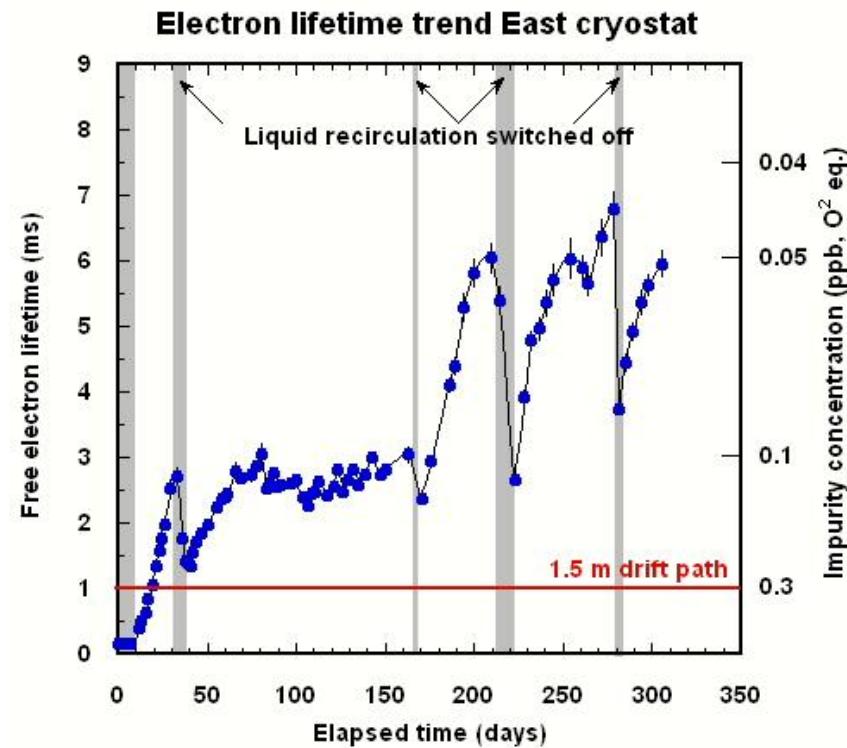
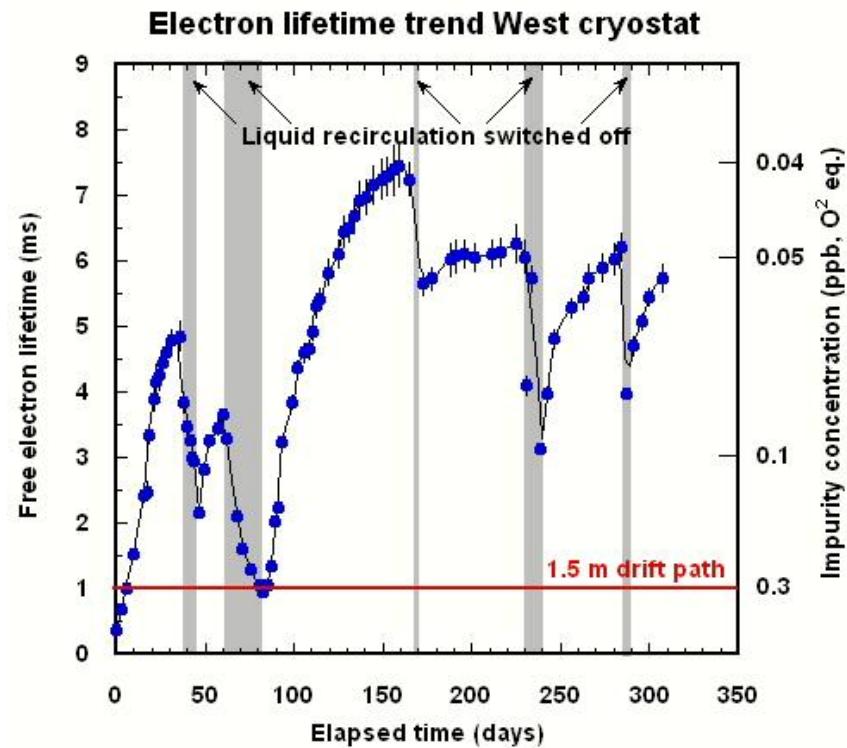


Run 10139 Event 8961 Collection view



Drift time (sampling = 0.4 ms)

# LAr purity time evolution



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

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

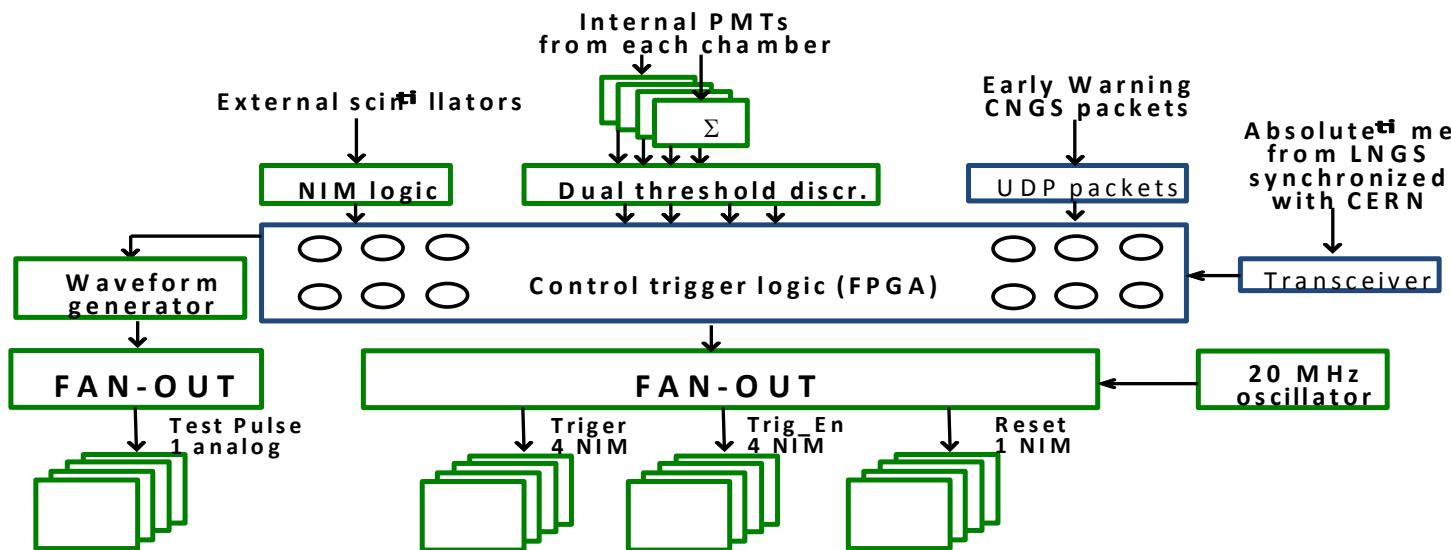
$\tau_R$ : recirculation time for a full detector volume

$k_D$ : internal residual degassing rate assumed to vanish with a time constant  $\tau_D$

$k_L$ : total impurity leak rate and degassing rate

# 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.



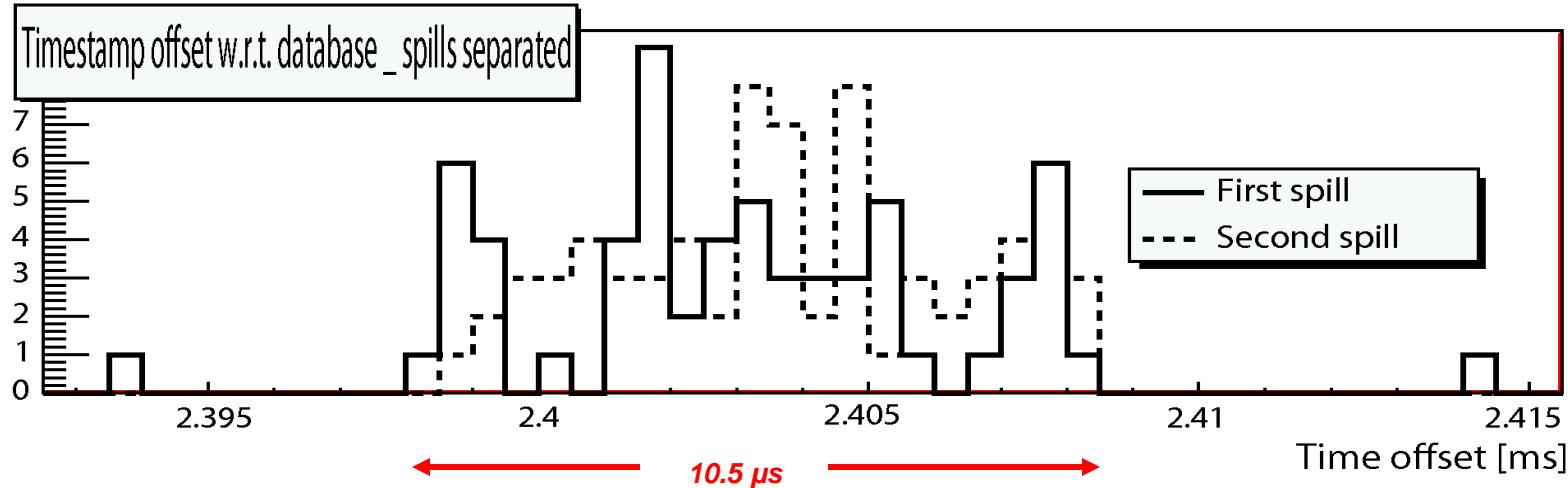
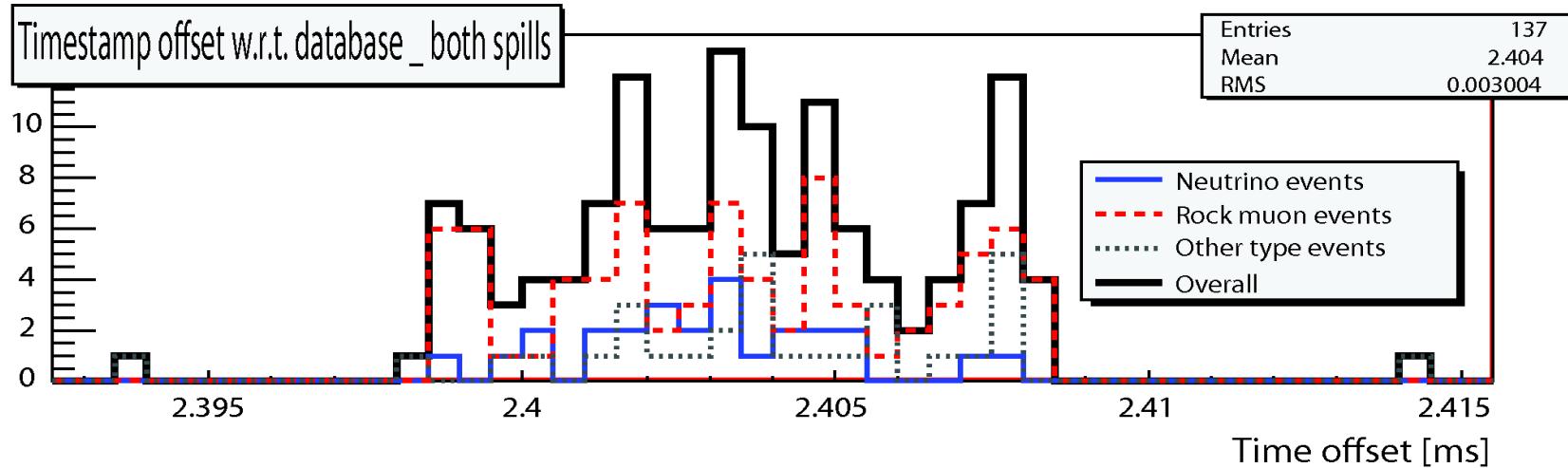
## Different trigger sources:

- 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

# CNGS events timing w.r.t. CERN proton extraction time

Very narrow beam distribution: only  $10 \mu\text{s}$  wide  $\approx$  spill duration ( $10.5 \mu\text{s}$ )

Mean offset value (2.404 ms) in agreement with  $\nu$  t.o.f. (2.437 ms) in view of  $\sim 40 \mu\text{s}$  fiber transit time from ext. LNGS labs to Hall B (8km)



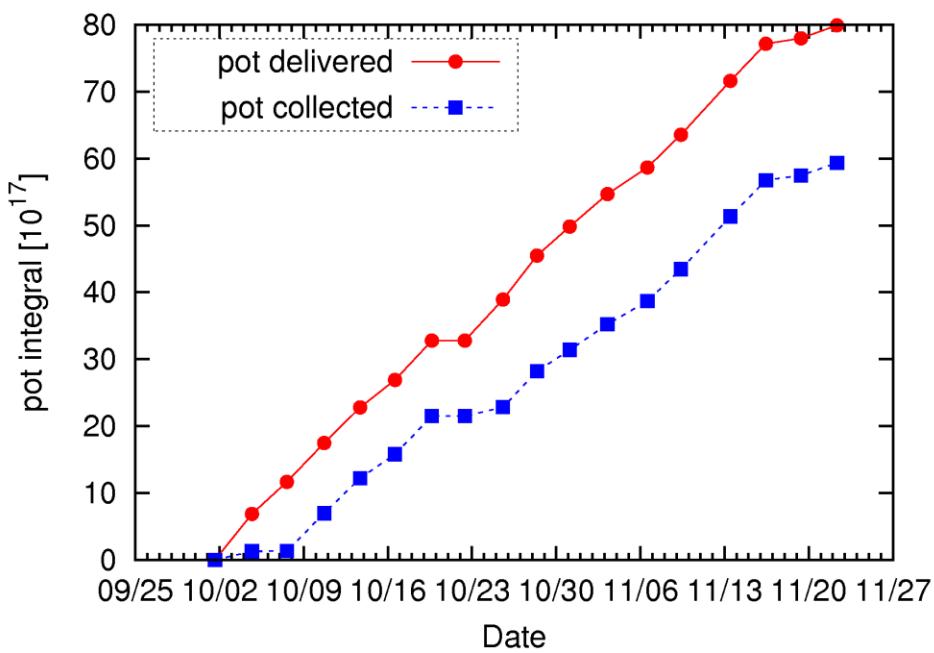
# ICARUS T600 physics potential

- ICARUS T600: major milestone towards realization of large scale LAr detector, but interesting physics in itself:
- CNGS  $\nu$  events collection (beam intensity  $4.5 \cdot 10^{19}$  pot/year,  $E_\nu \sim 17.4$  GeV):
  - 1200  $\nu_\mu$  CC events/year;
  - $\sim 8$   $\nu_e$  CC events/year;
  - observation of  $\nu_\tau$  events in the electron channel, using kinematical criteria;
  - search for sterile  $\nu$  in LSND parameter space (deep inelastic  $\nu_e$  CC events excess).
- "Self triggered" events collection:
  - $\sim 80$  events/y of unbiased atmospheric  $\nu$  CC;
  - zero background proton decay with  $3 \times 10^{32}$  nucleons for "exotic" channels.
  - supernova explosion neutrinos (if any).

# CNGS run during 2010

- ICARUS fully operational for CNGS events recording in Oct. 1<sup>st</sup> - Nov. 22<sup>nd</sup>.
- Trigger: photomultiplier signal for each chamber with low threshold discrimination at 100 phe, within 60  $\mu$ s wide beam gate.

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



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

Analyzed sample corresponds to  $5.3 \times 10^{18}$  pot (corresponds to the 91% of statistics).

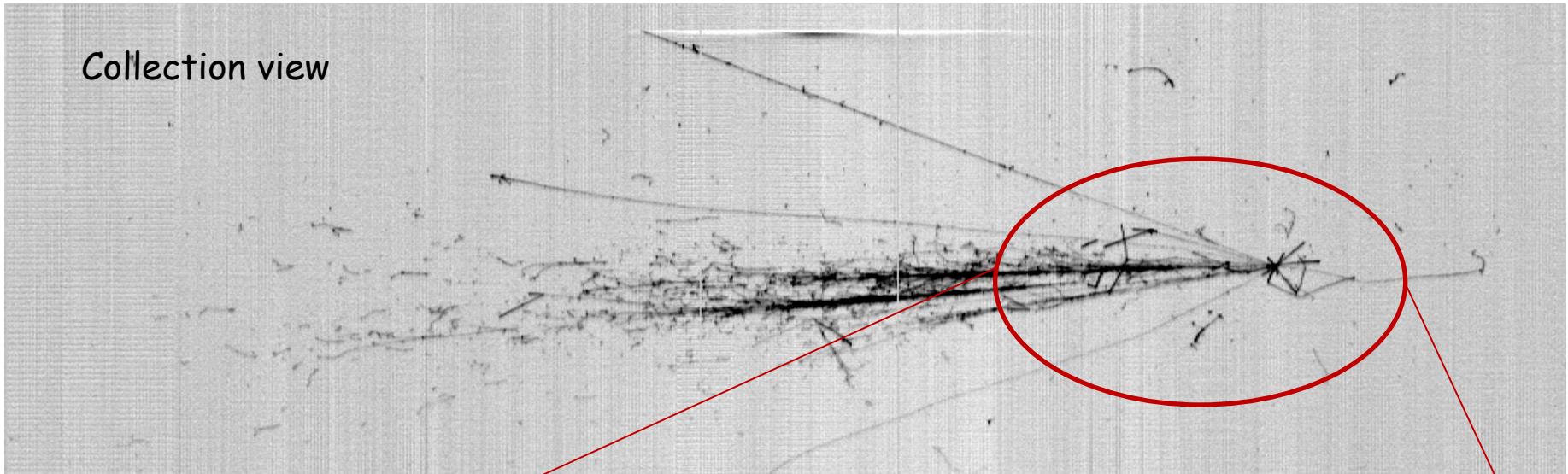
Event type	Collected	Expected
$v_\mu CC$	108	115
$v NC$	36	37
$v XC^*$	6	-
Total	150	152

\* Events at edges, with  $\mu$  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

Drift time coordinate (1.4 m)

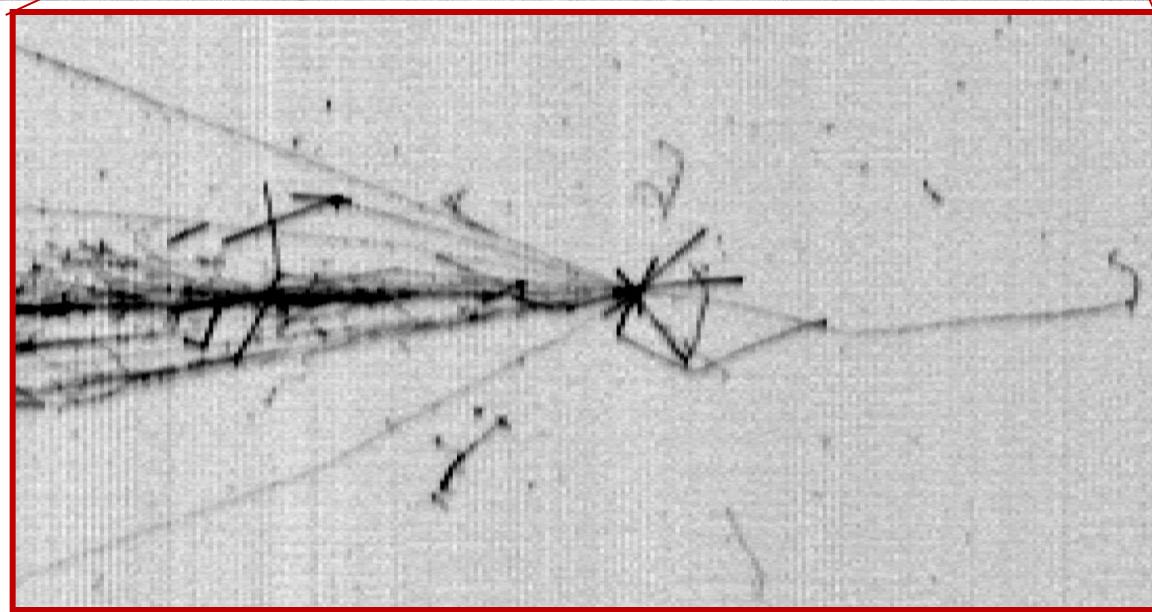


Wire coordinate (8 m)

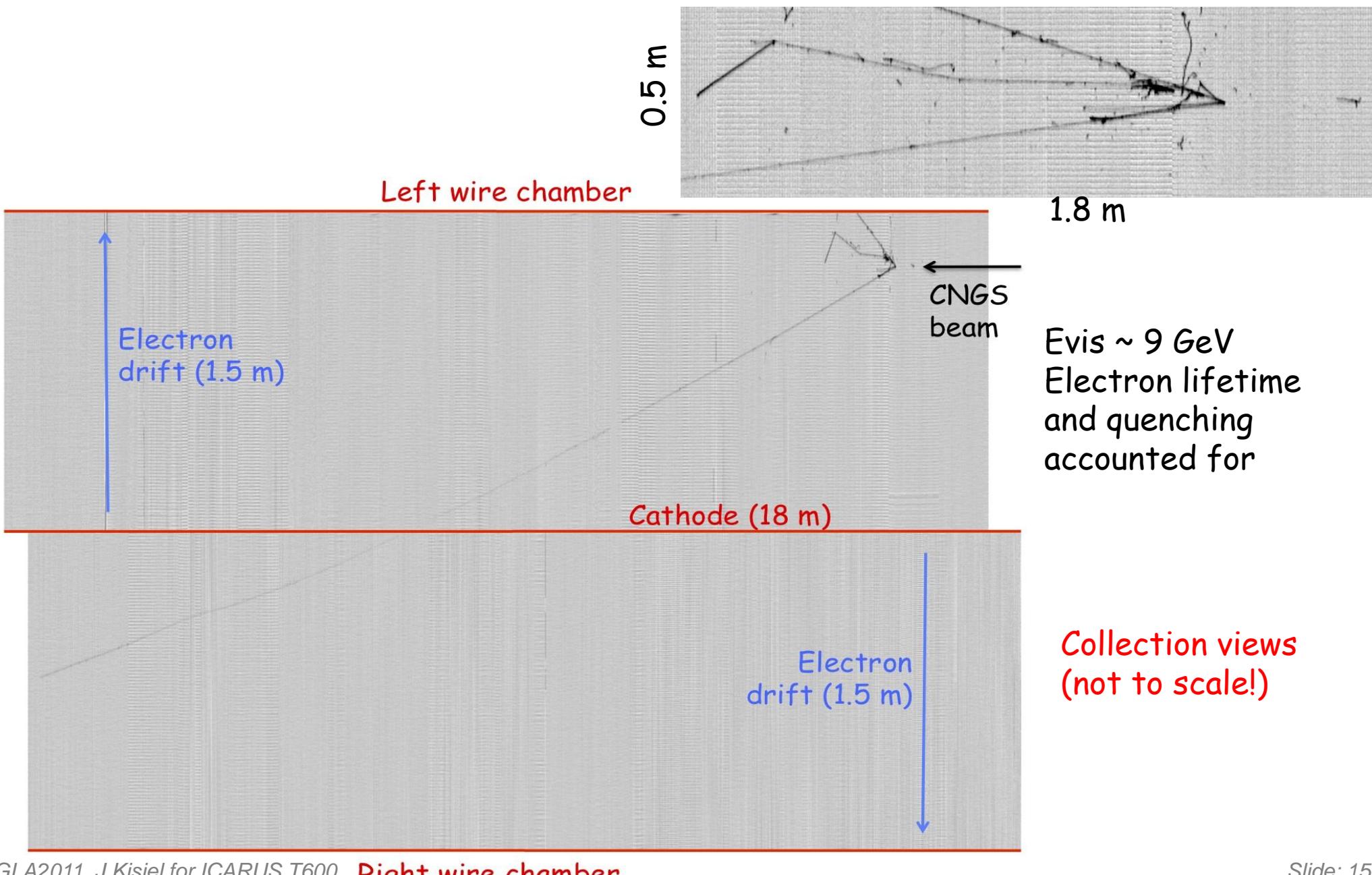
CNGS  $\nu$  beam direction



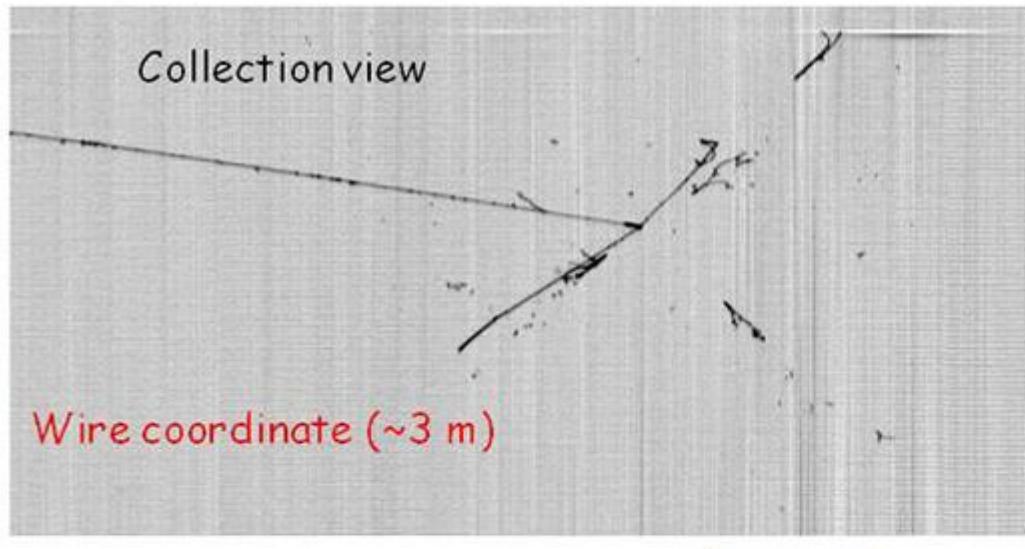
$\nu_\mu$  CC



# Low energy CNGS neutrino interaction

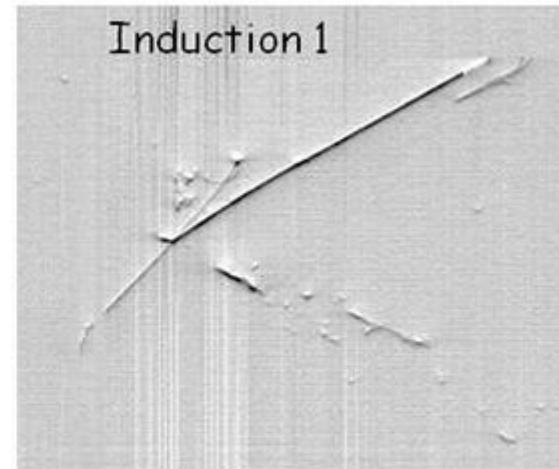


# CNGS CC neutrino interaction with $\pi^0$ production

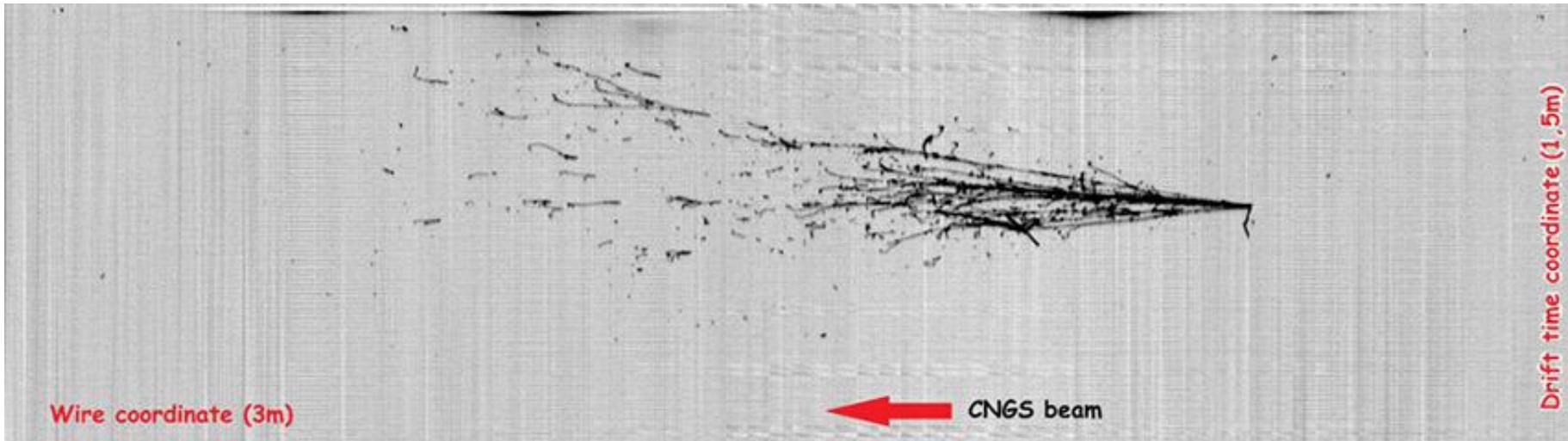


Wire coordinate (~3 m)

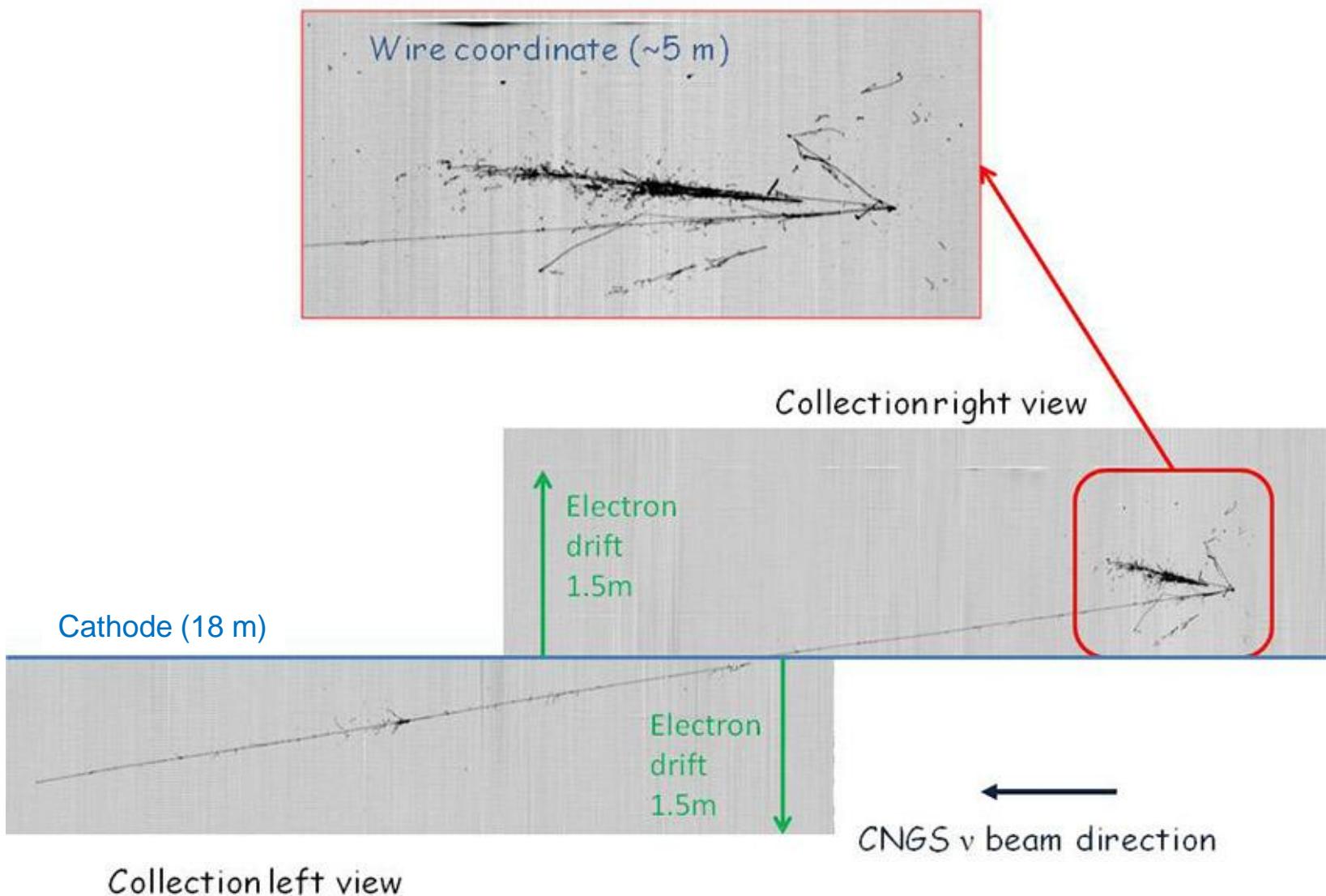
CNGS  $\nu$  beam direction



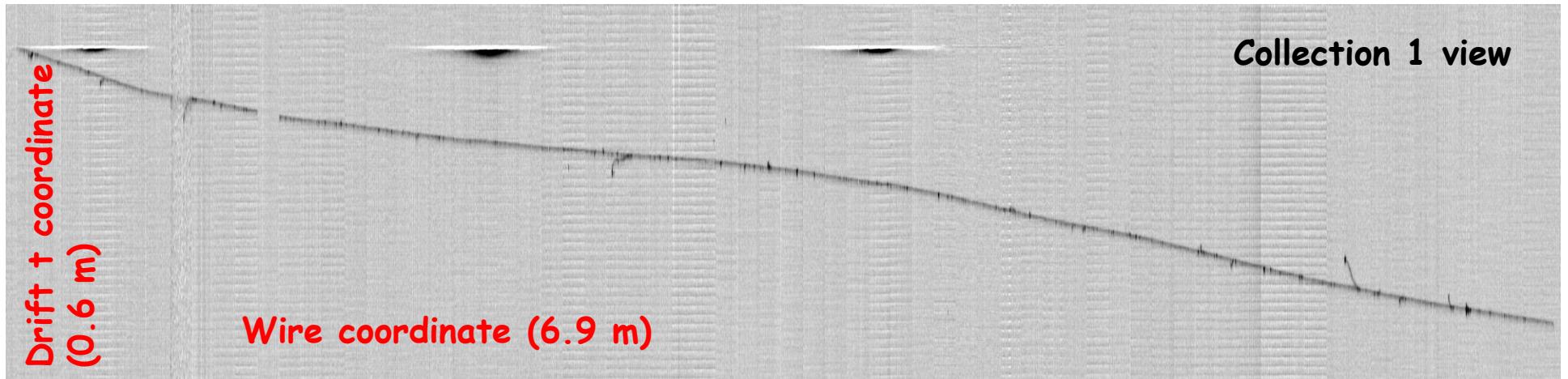
# CNGS NC interaction



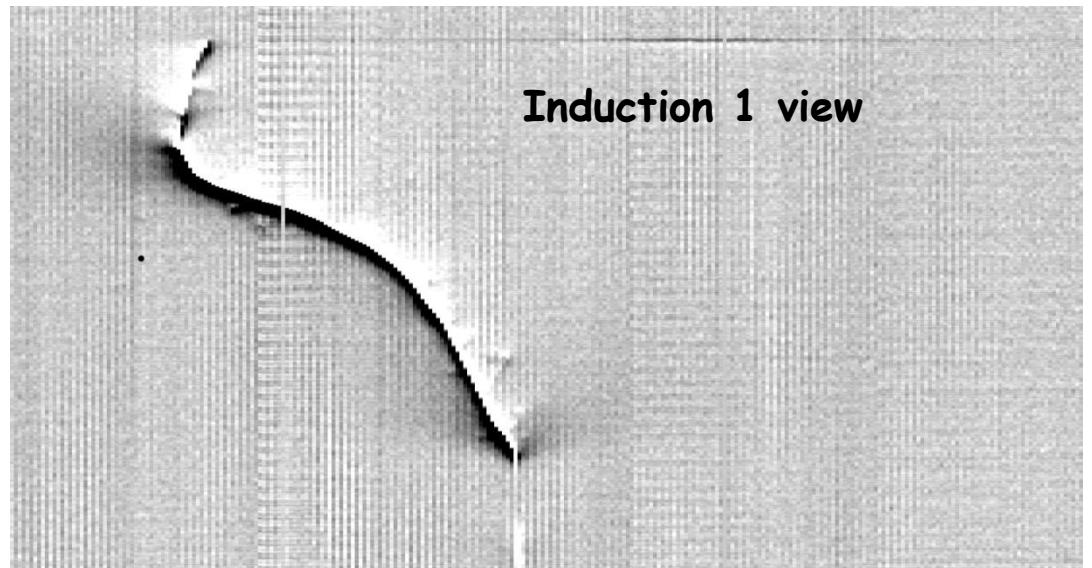
# CNGS CC interaction with both TPC signals



# CNGS ν interaction in the rock



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

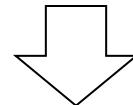


# Analysis: 3D reconstruction and particle identification

- 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:  $d\mathbf{x}$
  - 3D hits and charge deposition :  $dE/dx$

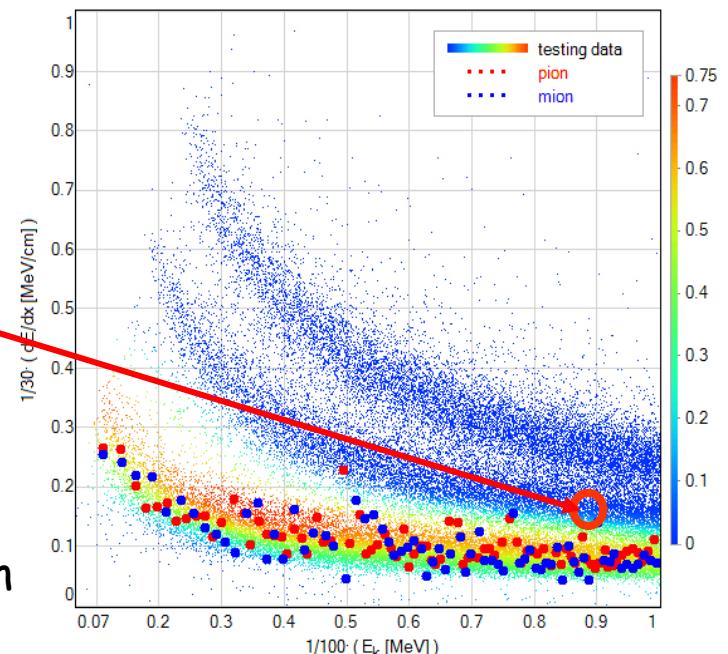
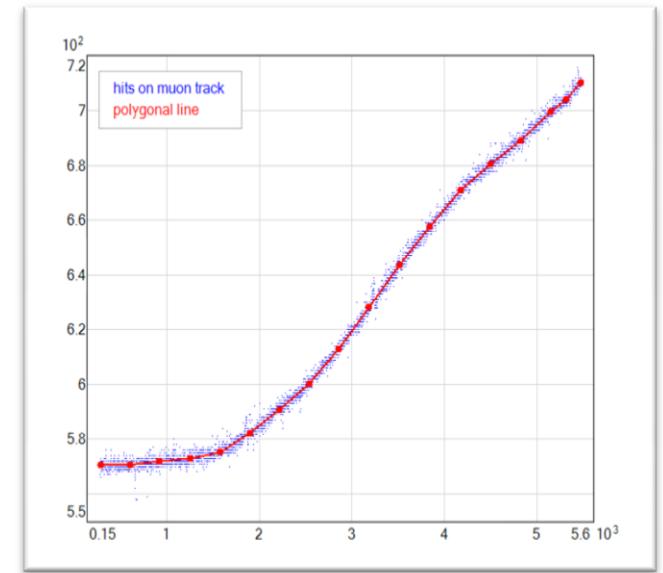
- Classify single  $i^{\text{th}}$  point on the track
$$p_i: [E_k, dE/dx] \rightarrow nn_i: [P(p), P(K), P(\pi), P(\mu)]$$

- Average M output vectors for the points
$$\text{NN} = S(nn_i)/M$$

- Identify track as particle corresponding to  $\text{max}(\text{NN})$ 

**Very high identification efficiency for  $p, K, \pi + \mu$**

- Energy reconstructed including quenching in simulation



# LAr-TPC: powerful technique. Run 9927 Event 572

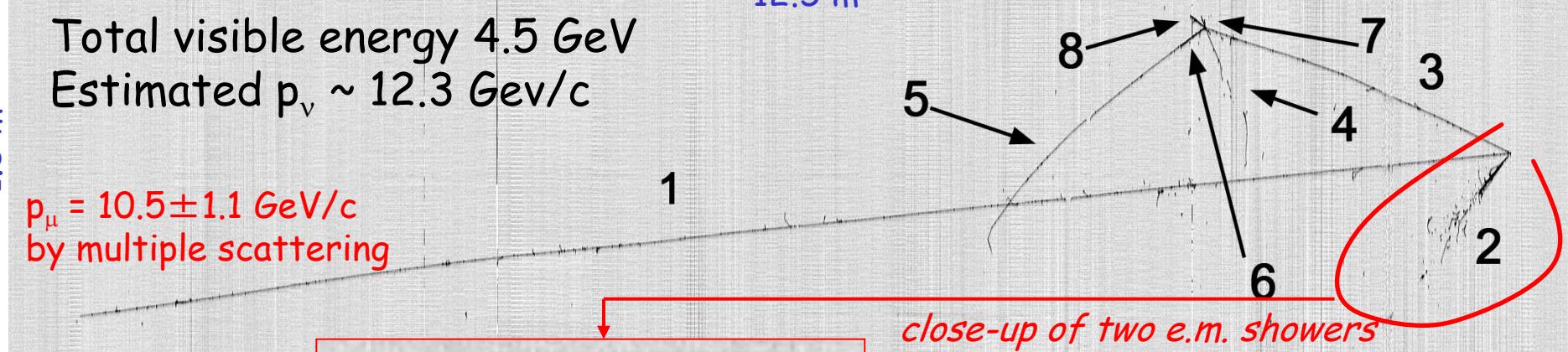
1.5 m

Total visible energy 4.5 GeV

Estimated  $p_v \sim 12.3 \text{ GeV}/c$

$p_\mu = 10.5 \pm 1.1 \text{ GeV}/c$   
by multiple scattering

12.5 m

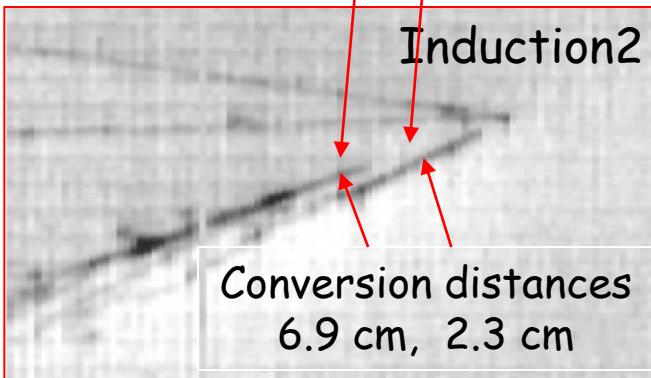
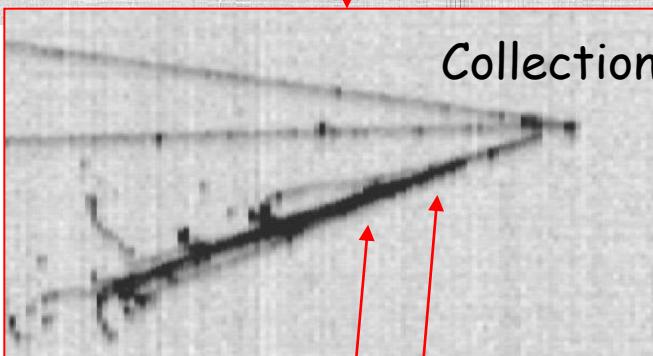


Primary vertex  
(A)

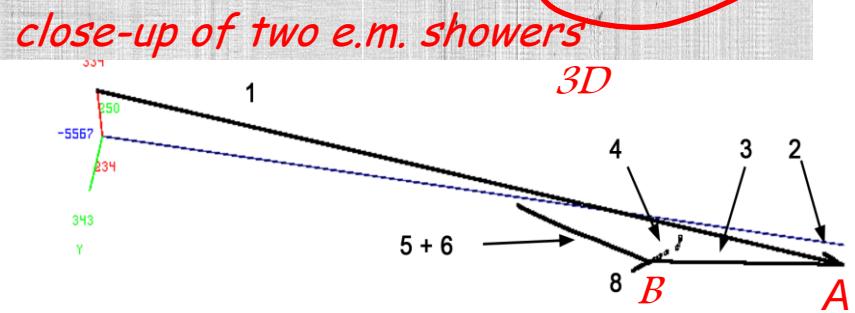
very long  $\mu$  (1),  
e.m. cascade(2),  
pion (3).

Secondary  
vertex (B)

The longest  
track (5) is a  $\mu$   
coming from  
stopping K (6).  
-  $\mu$  decay is  
observed.

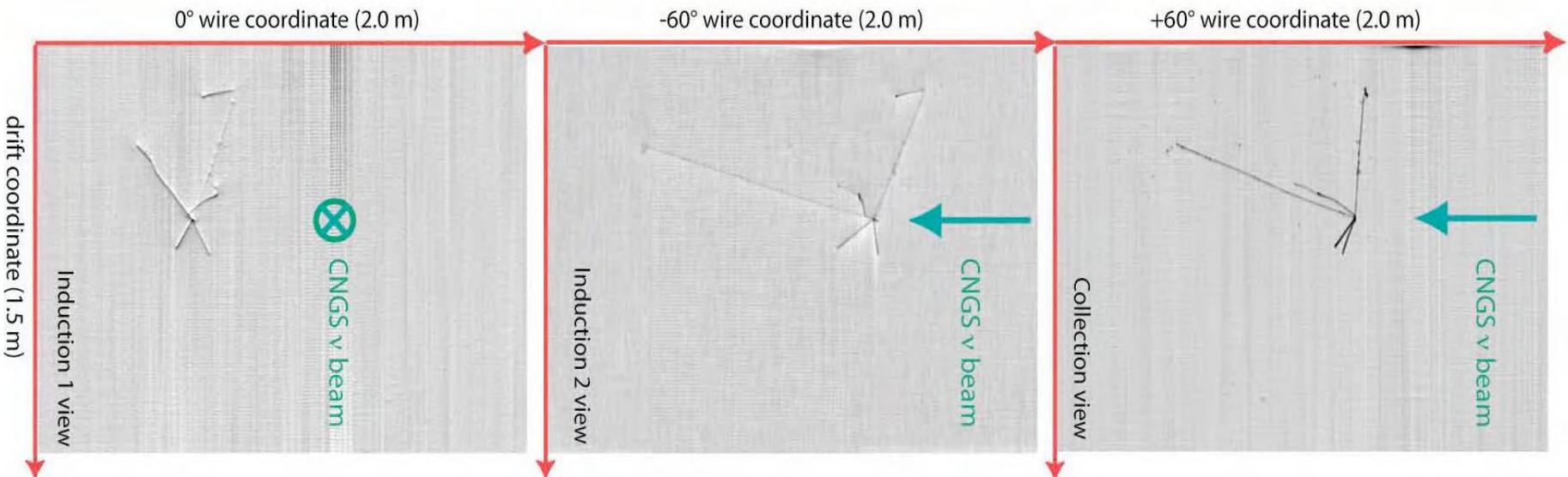


$$M_{\gamma\gamma}^* = 125 \pm 15 \text{ MeV}/c^2$$



Track	$E_{\text{dep}}[\text{MeV}]$	$\cos x$	$\cos y$	$\cos z$
1 ( $\mu$ )	2701.97	0.069	-0.040	-0.997
2 ( $\pi^0$ )	520.82	0.054	-0.420	-0.906
3 ( $\pi$ )	514.04	-0.001	0.137	-0.991
Sec. vtx.	797.			
4	76.99	0.009	-0.649	0.761
5 ( $\mu$ )	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

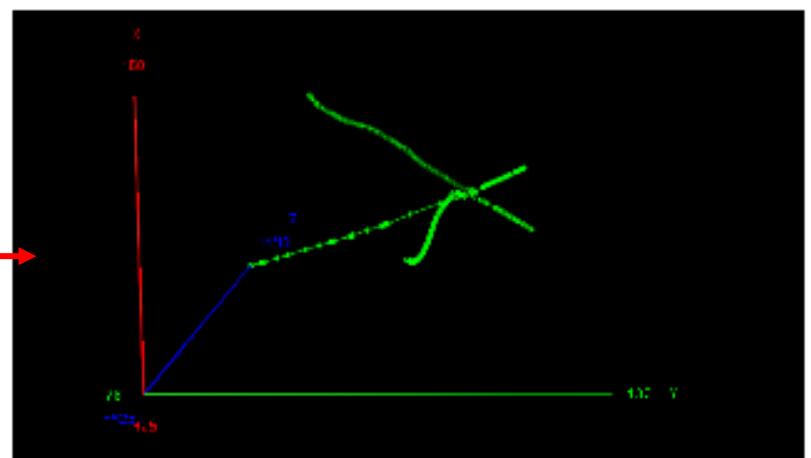
# Atmospheric $\nu$ candidate



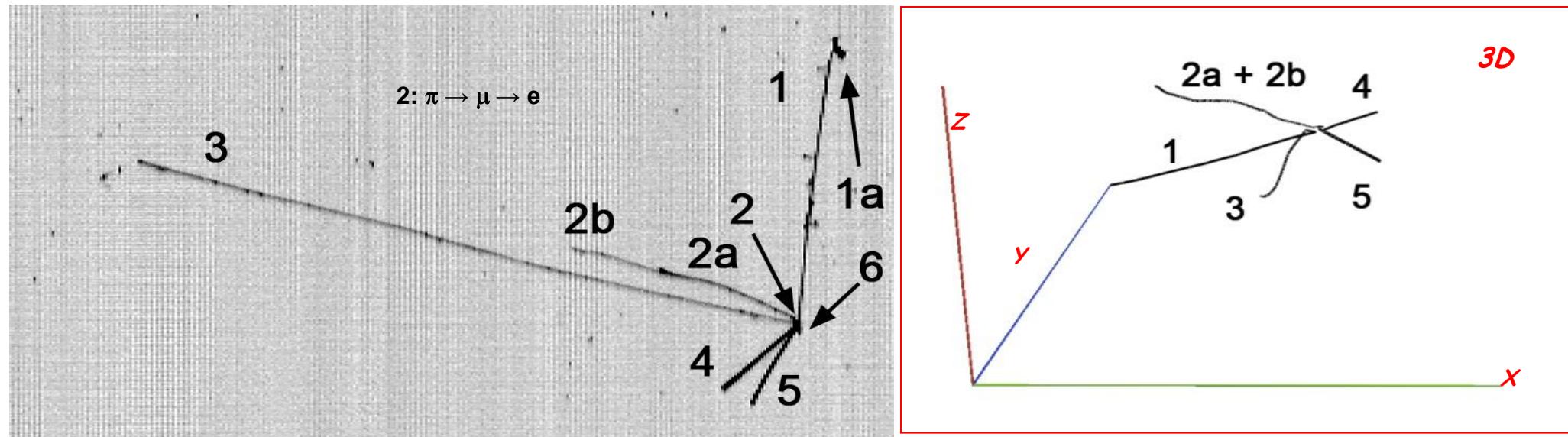
- Total visible energy: 887 MeV (including quenching and  $e^-$  lifetime corrections).
- Out-of-time from CNGS spill AND angle w.r.t. beam direction:  $35^\circ$  .



Very small event



# Run 9392 Event 106

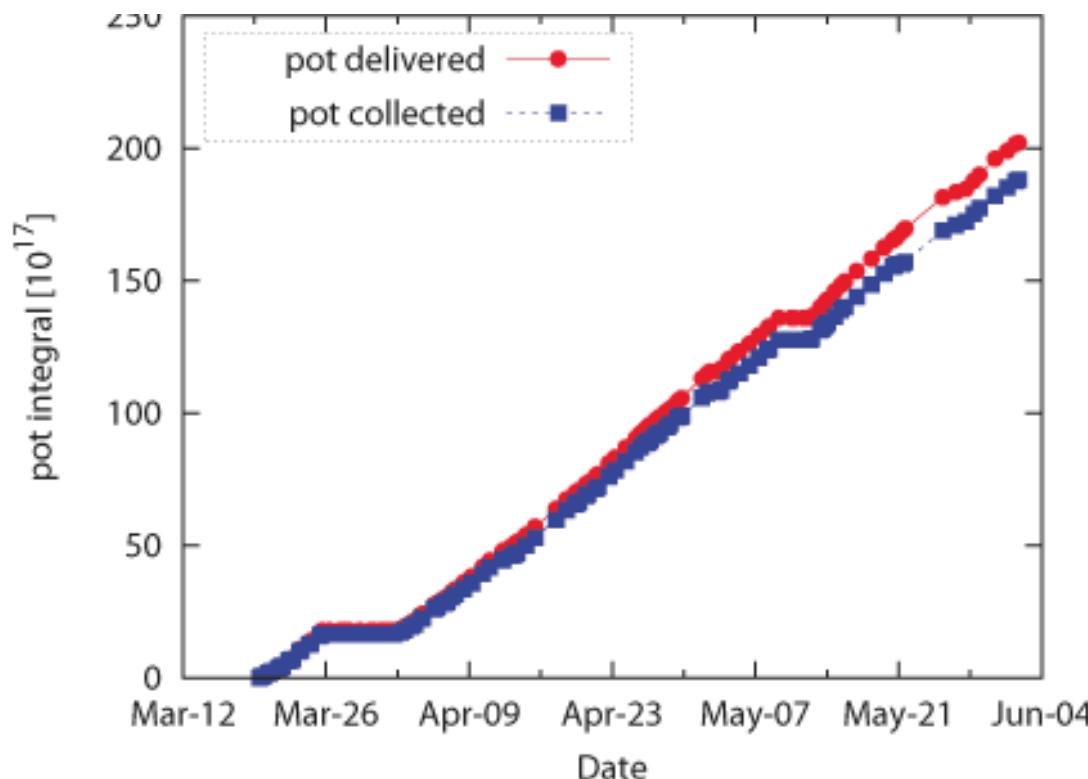


Track	$E_k$ [MeV]	Range [cm]
1 (prob. $\pi$ , decays in flight)	136.1	55.77
2 ( $\pi$ )	26	3.3
2a ( $\mu$ )	79.1	17.8
2b ( $e$ )	24.1	10.4
3 ( $\mu$ )	231.6	99.1
4 (p)	168	19.2
5 (p)	152	16.3
6 (?) (merged with vtx)		2.9

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

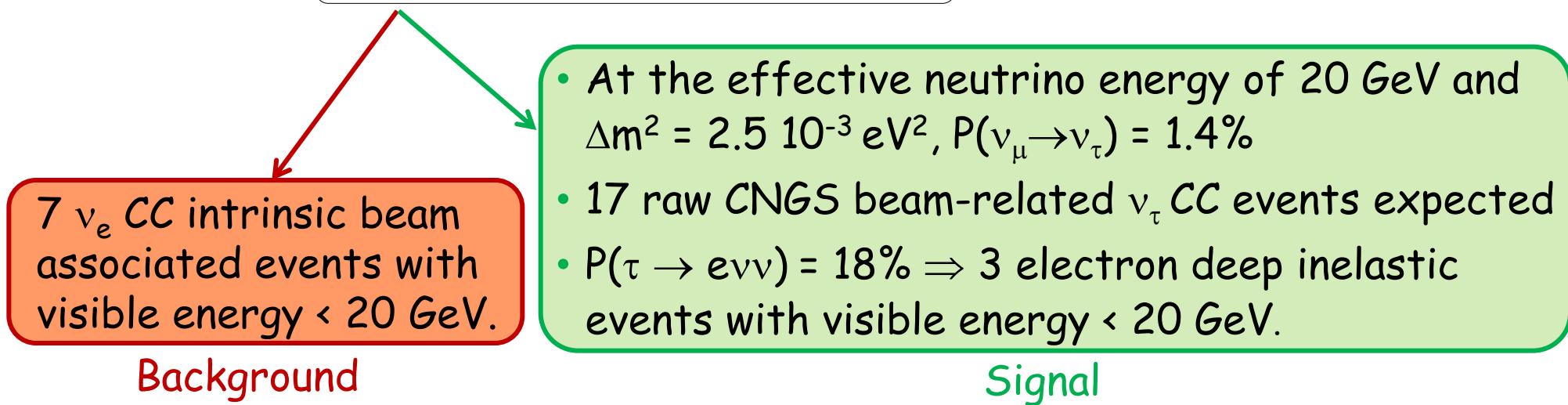
# 2011 CNGS run

- ICARUS fully operational / data taking for CNGS events from 19<sup>th</sup> March.
- The detector lifetime above 90% with the new trigger/DAQ feature improvements.
- $2.16 \times 10^{19}$  ( $1.99 \times 10^{19}$ ) pot delivered (collected).



# 2011-2012 CNGS run: physics perspectives

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



- $\tau \rightarrow e\nu\nu$  events characterized by momentum unbalance (2 $\nu$  emission) and relatively low electron momentum. Selection criteria suggest a sufficiently clean separation with kinematic cuts opening the possibility to identify 1-2  $\nu_\tau$  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  $\tau$  search.

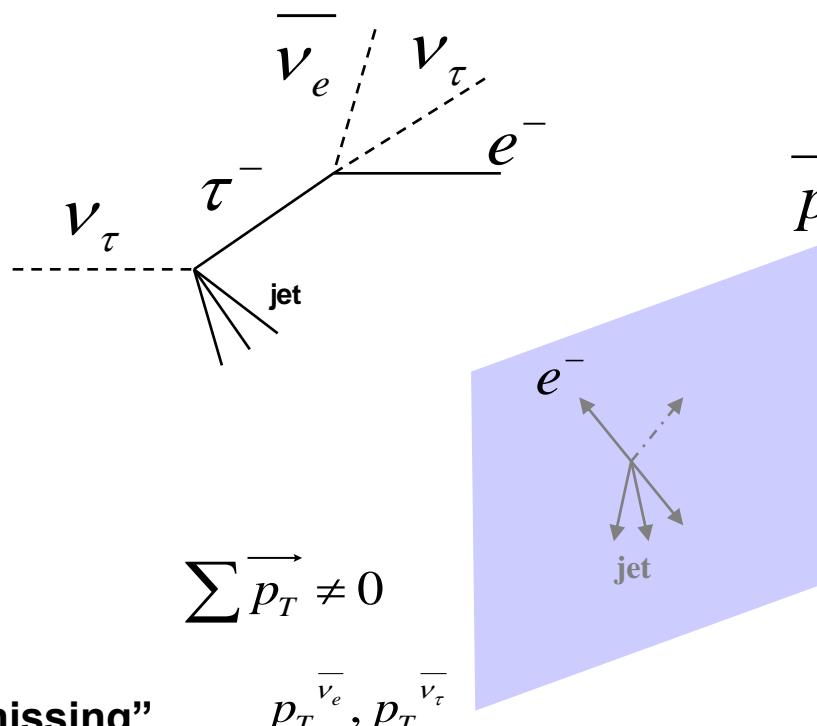
# CNGS: $\nu_T$ signal vs background

## SIGNAL

$$\nu_\tau + N \rightarrow \tau^- + X$$



$$e^- \bar{\nu}_e \nu_\tau \quad (BR \sim 17\%)$$

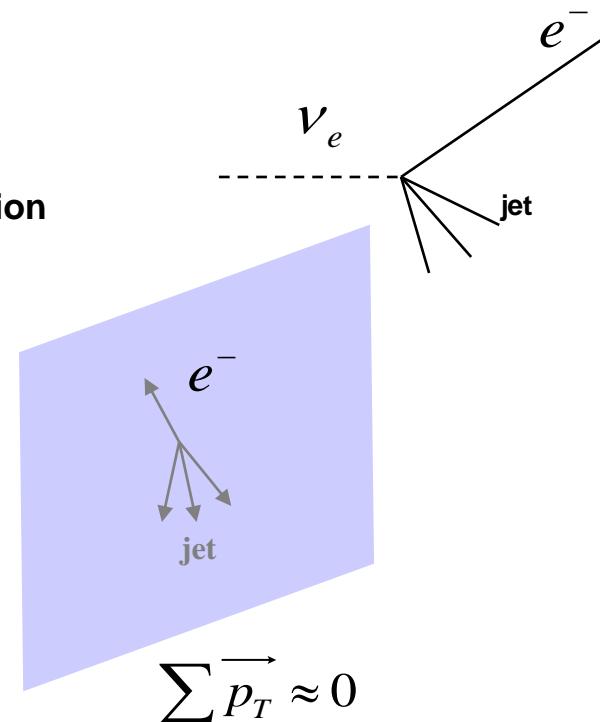


## BACKGROUND

$$\nu_e + N \rightarrow e^- + X$$

$$(\nu_e \quad CC)$$

Flux contamination



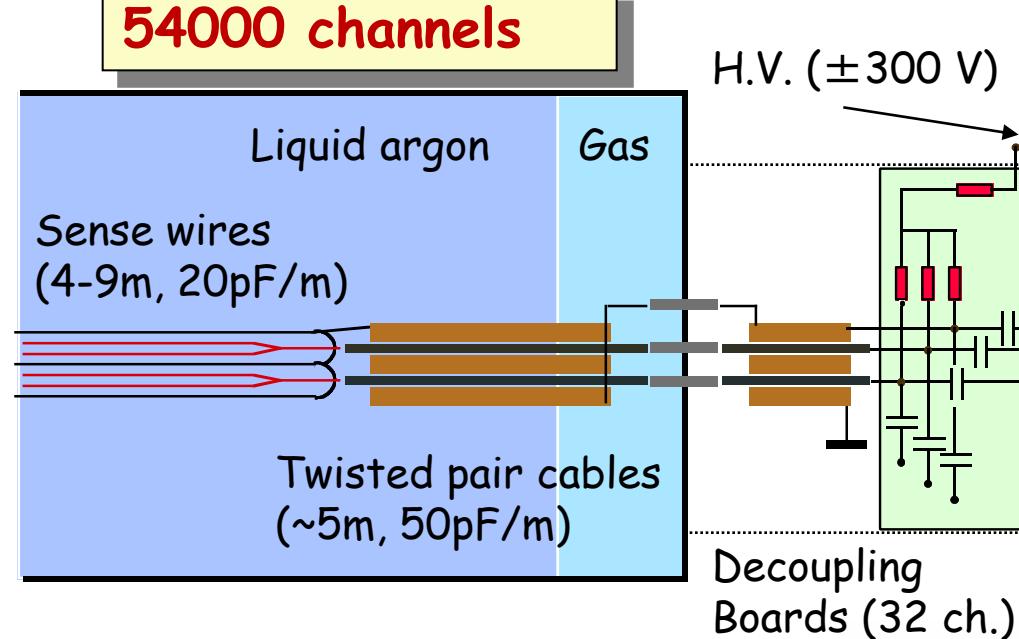
# Conclusions

- 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 an 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 high resolution will be addressed already with the T600 detector:
  - Underground physics (proton decay, atmospheric  $\nu$ , 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 will be exposed to CNGS beam in 2011-2012.

Thank you !

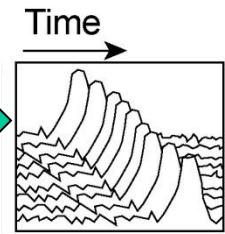
# Front-end Electronics and DAQ

**54000 channels**

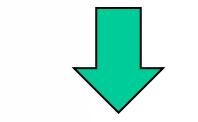


(18 board + 1 CPU)/VME crate

Multi-event circular buffer (8x1ms)



Continuous waveform Recording



To storage

