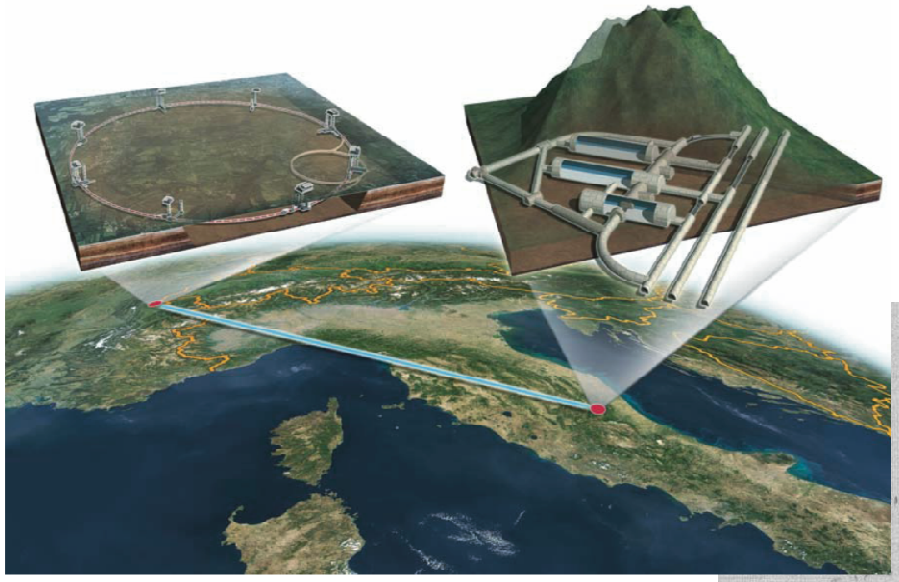
ICARUS T600 and beyond:

LAr-TPC for neutrino physics and proton decay search



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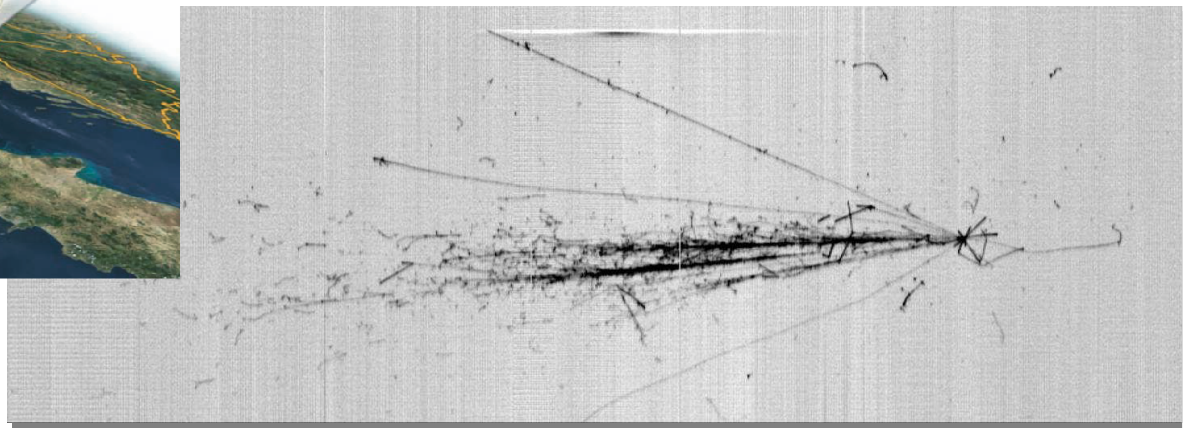
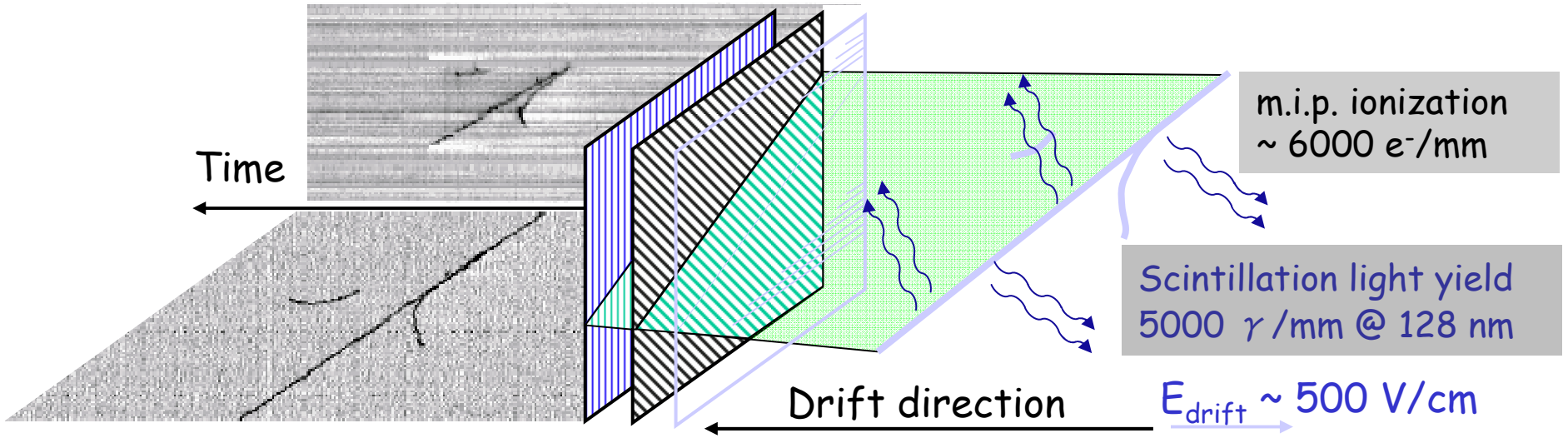


- LAr-TPC imaging technique
- ICARUS-T600@ LNGS
- Beyond ICARUS-T600: a new experiment at CERN-PS

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)

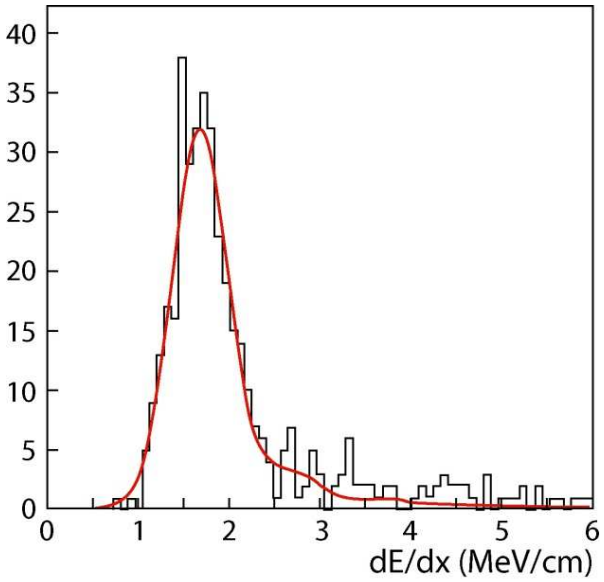


Electrons from ionizing track are drifted in LAr by E_{drift}. They traverse transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by collection plane.

Key feature: LAr purity 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).

LAr – TPC performance

- Tracking device
  - Precise event topology
  - μ momentum measurement via multiple scattering
- Measurement of the local energy deposition dE/dx
  - e / γ separation
  - Particle ID by means of dE/dx vs Range
- Total Energy reconstruction of the events from charge integration
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events



dE/dx distribution along a single muon track

RESOLUTIONS

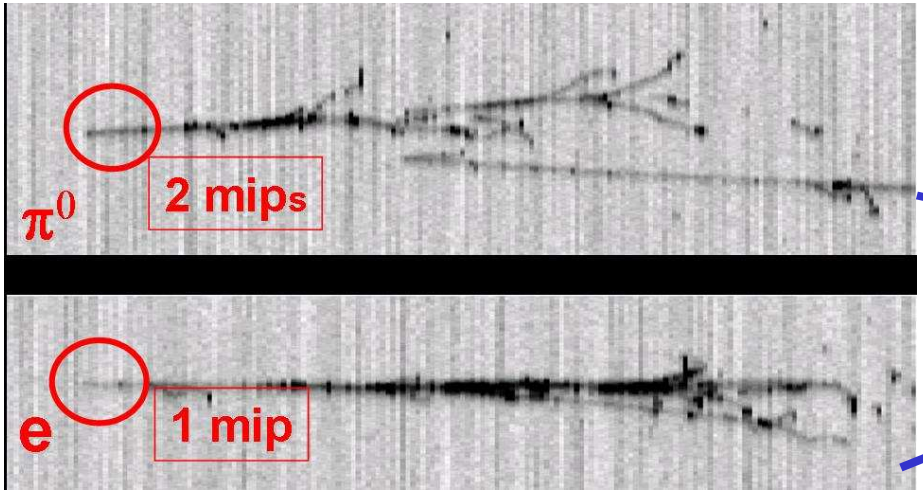
Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$

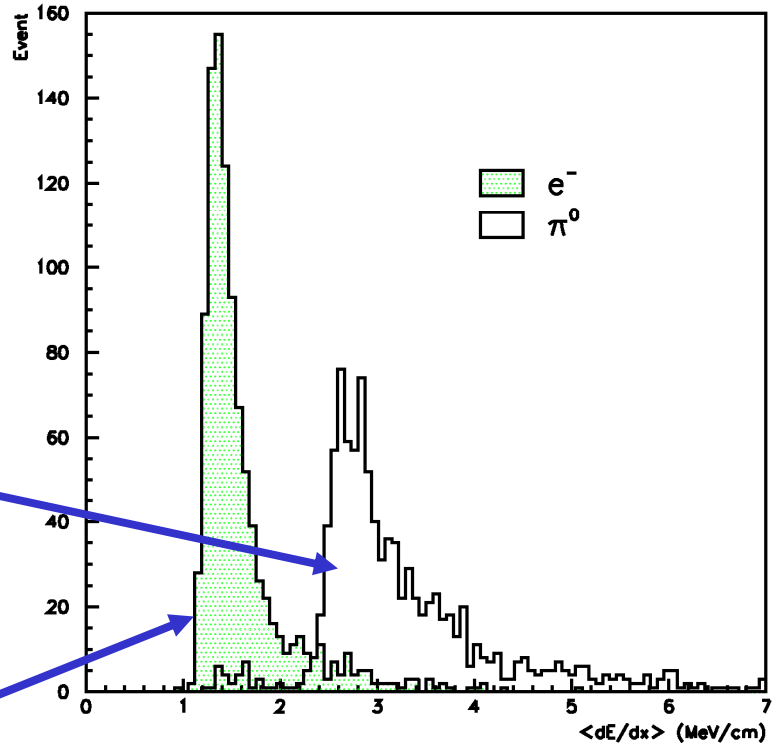
Electromagn. showers: $\sigma(E)/E = 3\% / \sqrt{E(GeV)}$

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

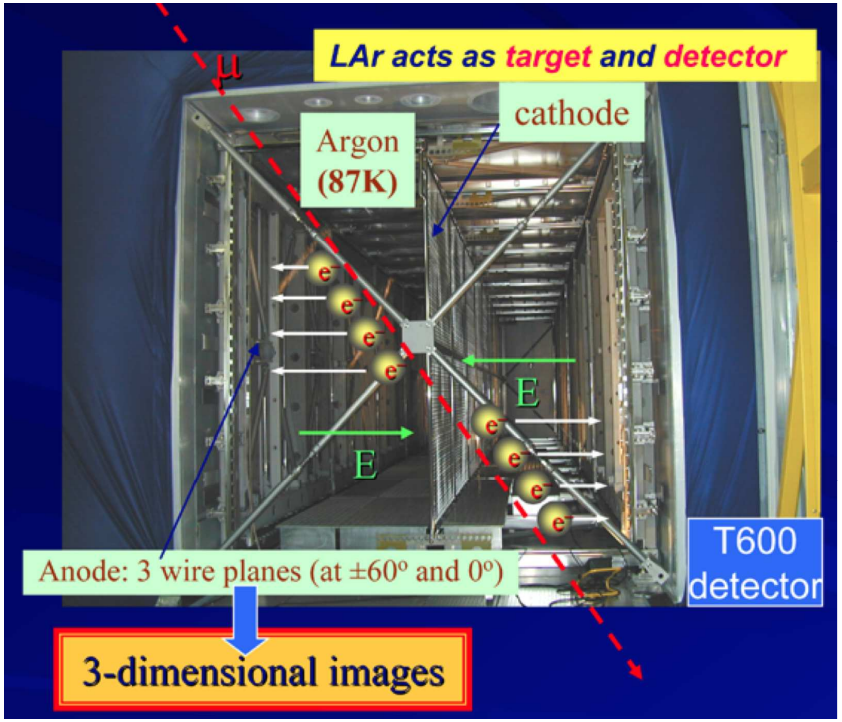
NC rejection in LAr

- NC in LAr suppressed by:
  - topology (γ conversion from vertex)
  - reconstruction of π^0 invariant mass
  - electron/photon separation (dE/dx using 2% X_0 sampling)
- Electron identification eff. = 90%
- Residual misidentification < 0.1%





The ICARUS T600 detector at LNGS

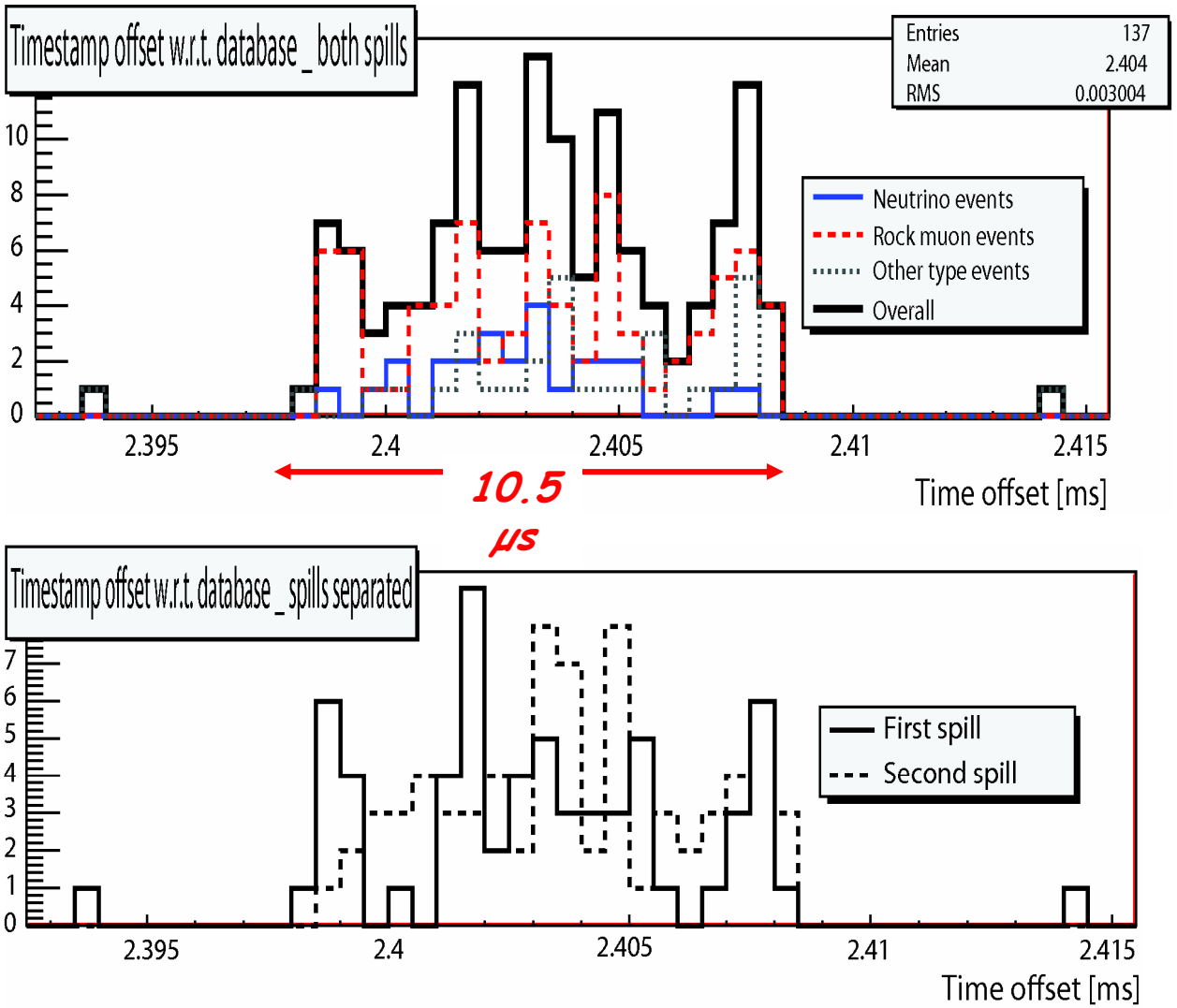


- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Drift length = 1.5 m
  - HV = -75 kV E= 0.5 kV/cm

Total LAr active mass: ≈ 476 t

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

ICARUS T600 Trigger System

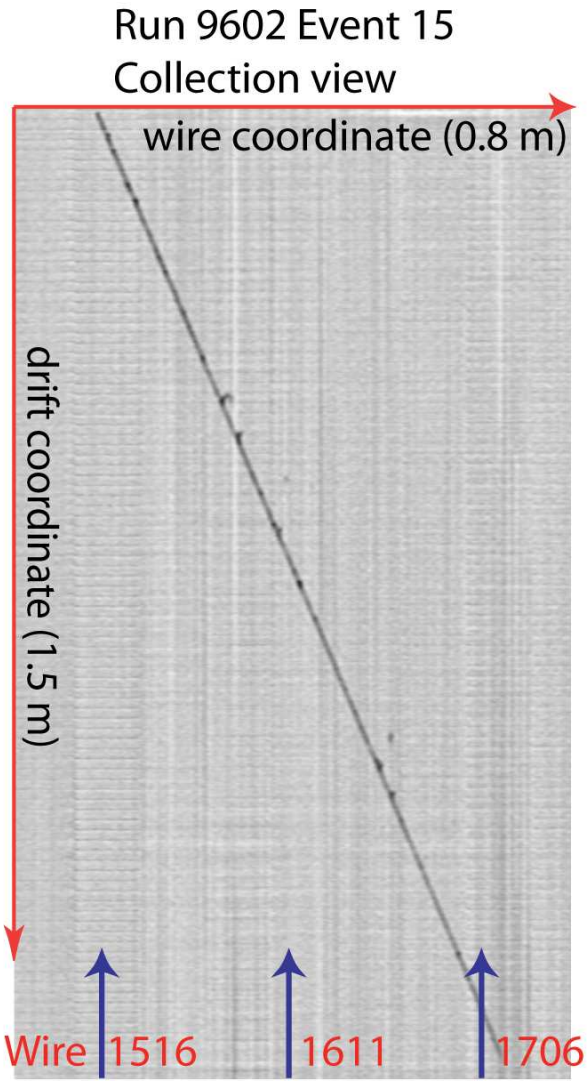


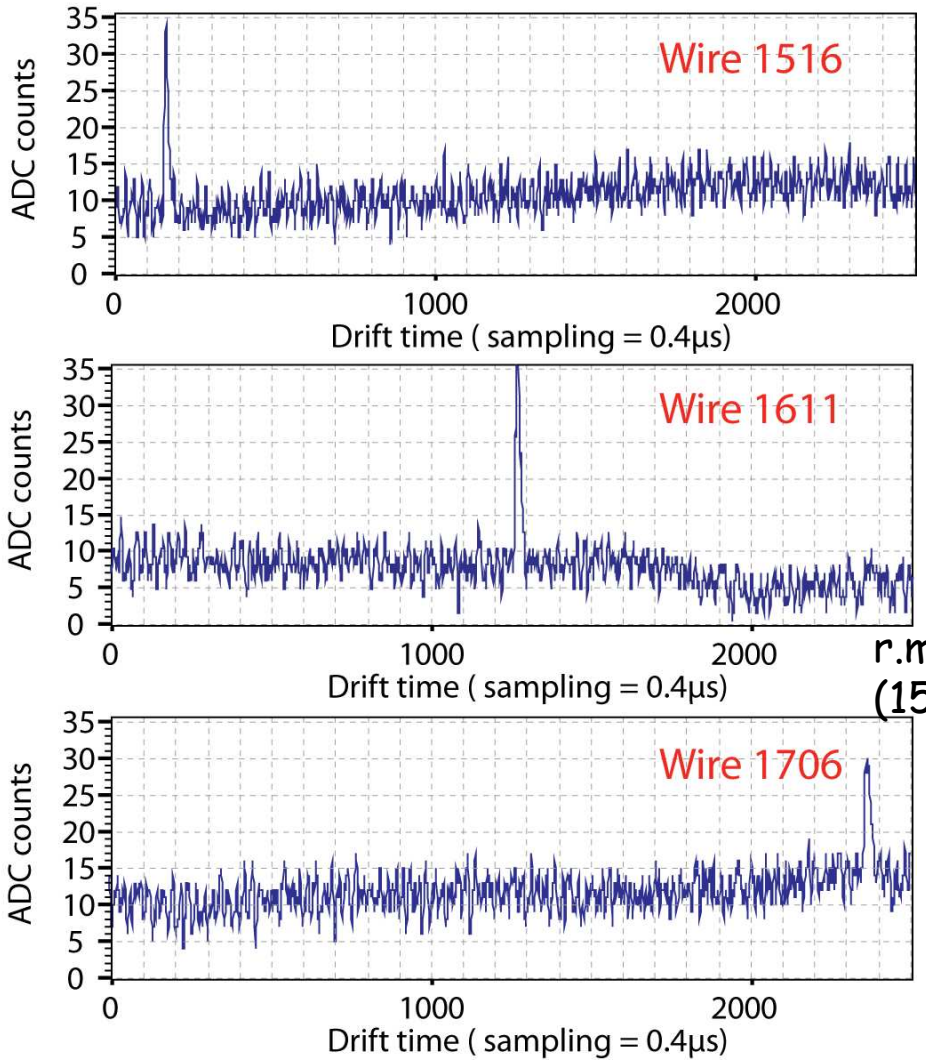
- Trigger based on prompt scintillation light in LAr, collected by internal PMT's.
- Trigger rates are dominated by c-ray muons ~40 mHz
- CNGS trigger: PMT signals inside 60 μs gate based on the proton extraction early warning signals from CERN.

Width of the distribution: 10.5 *μs* = spill duration

Time offset compatible with the neutrino travel time

ICARUS-T600: Example of muon crossing track





Typical pulse height for a 3 mm m.i.p. ~12 ADC # (12000 electrons).

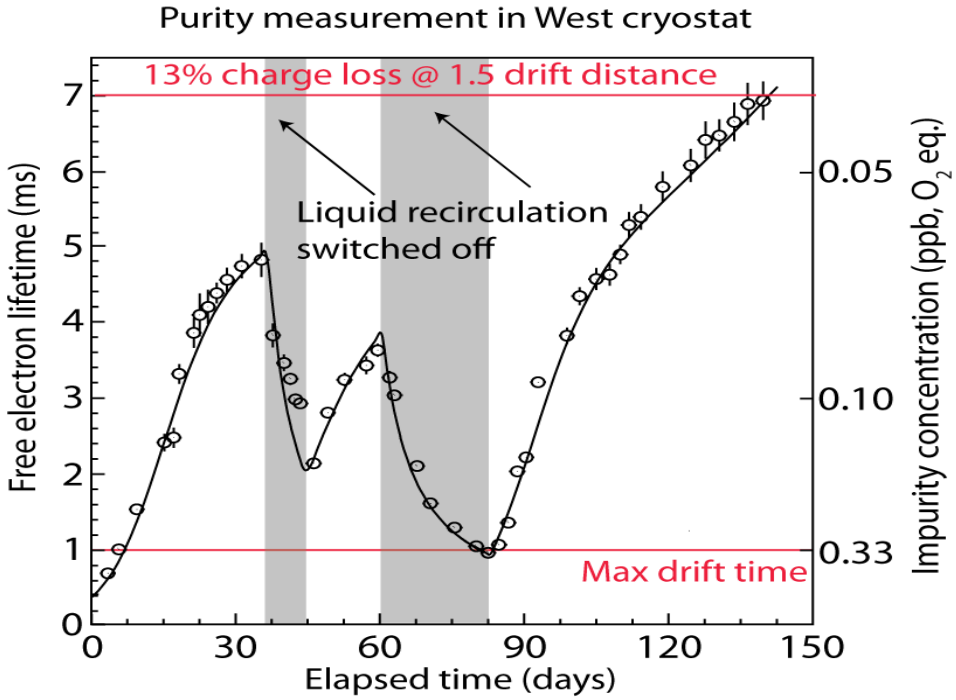
r.m.s noise ~1.5 ADC# (1500 electrons eq.)

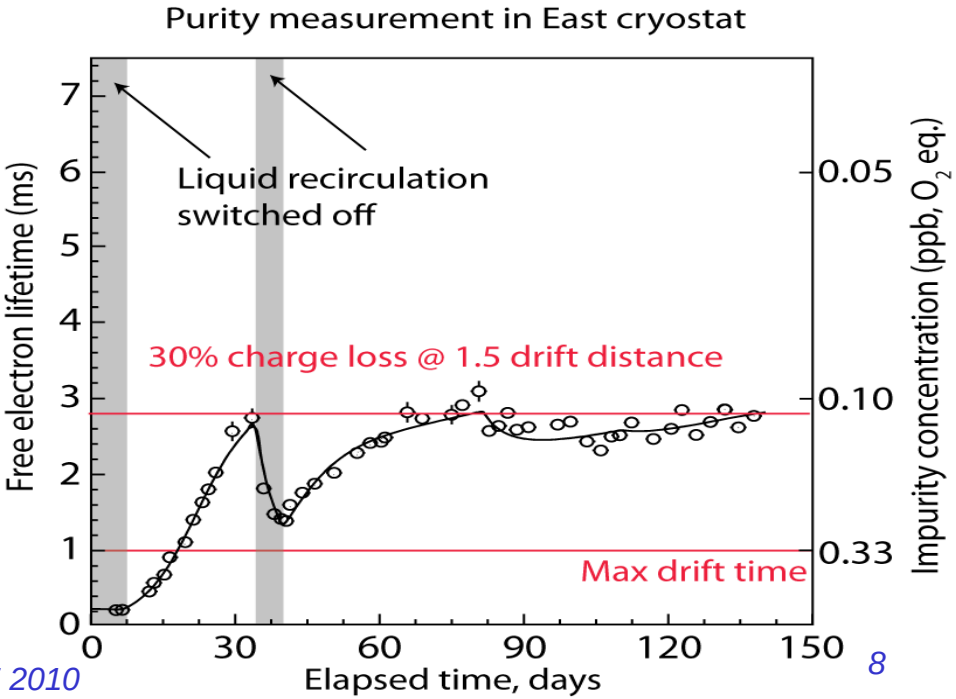
Charge attenuation along the track allows event-by-event measurement of LAr purity

Liquid Argon Purity in ICARUS T600

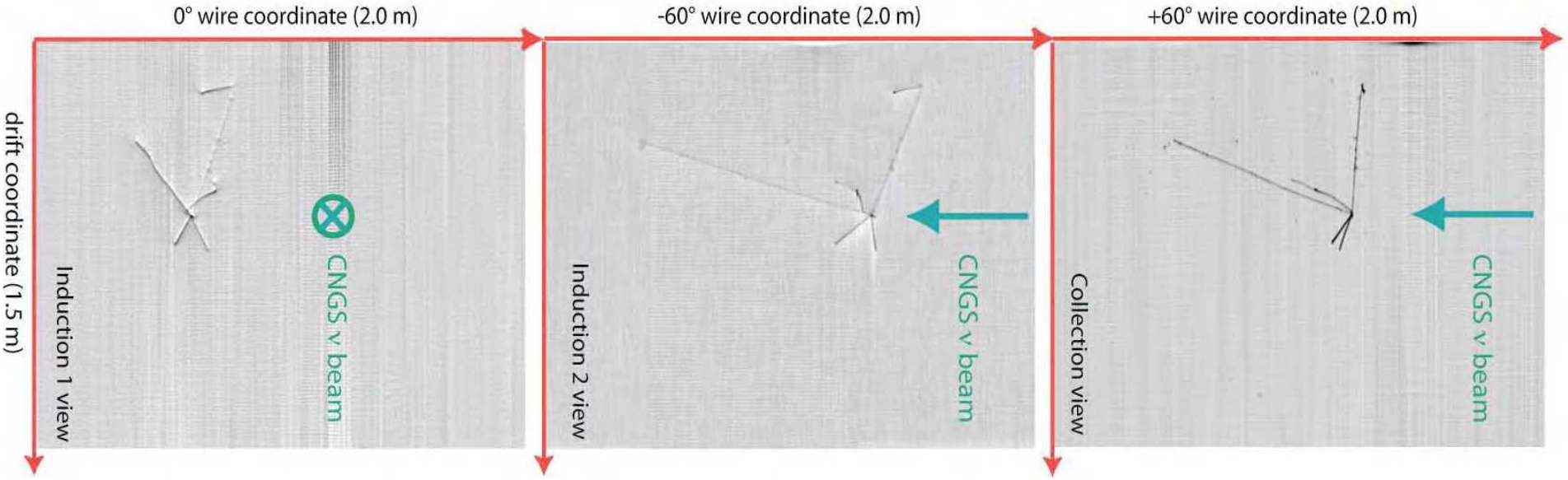
Measurement of LAr purity based on charge attenuation vs drift time for single muon crossing tracks:

- West module: 7ms still increasing
- East module: 2.8 ms (to be investigated)
- Free electron charge attenuations for 1.5 m less then 13% in West cryostat and ~ 30% in East cryostat

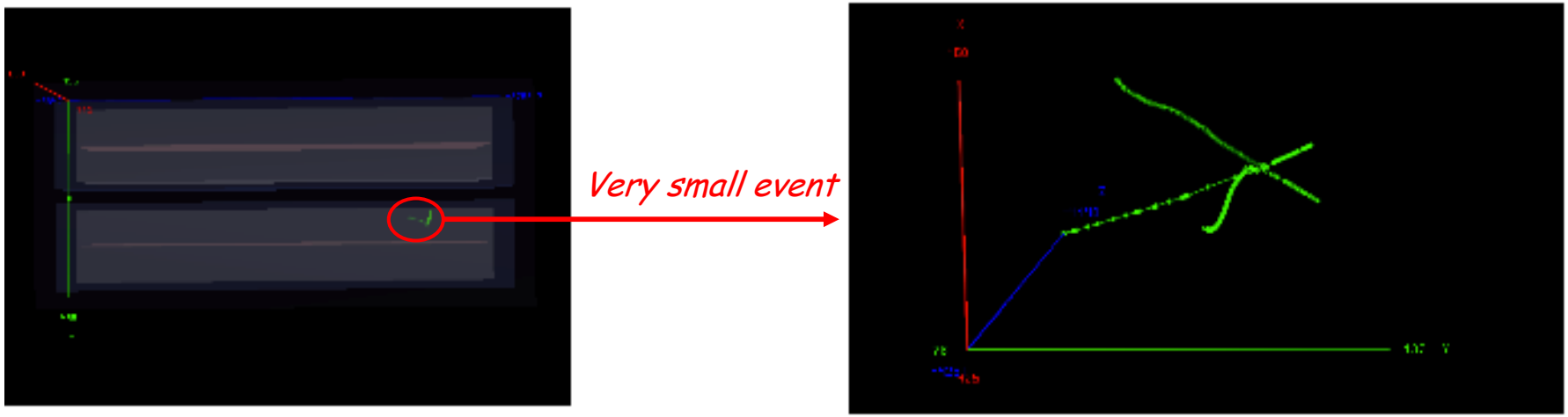


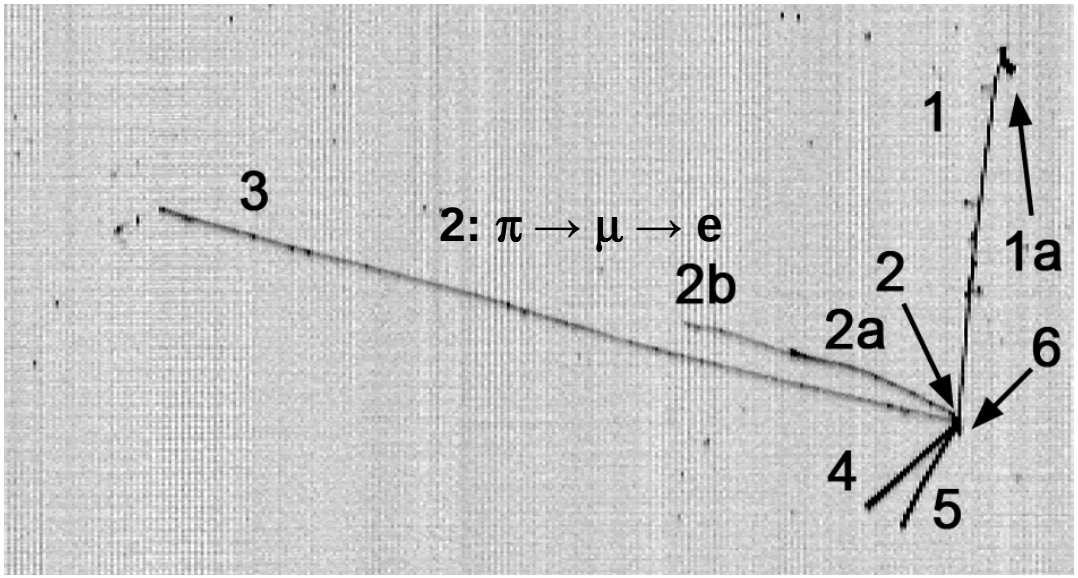


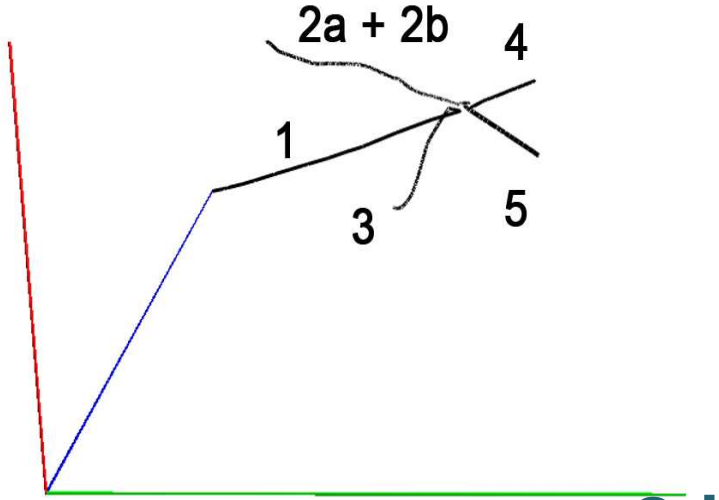
Very low energy CNGS neutrino interaction



Total visible energy: 887 MeV (including quenching and electron lifetime corrections)







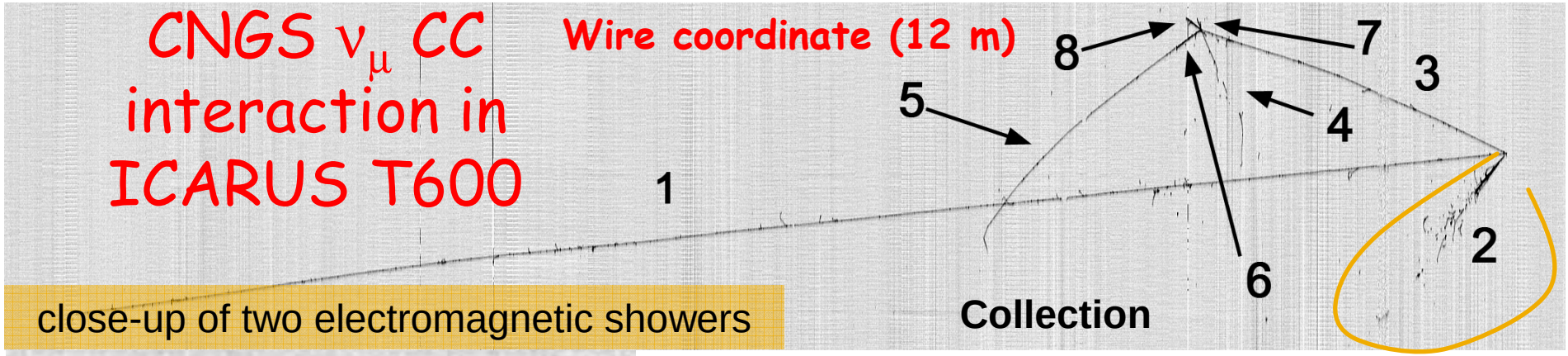
3d

Track	E_k [MeV]	range [cm]
1 (prob. π, decays in flight)	136	56
2 **(π)**	26	3
2a **(μ)**	79	18
2b **(e)**	24	10
3 **(μ)**	232	99
4 **(p)**	168	19
5 **(p)**	152	16
6 (?) (merged with vtx)		3

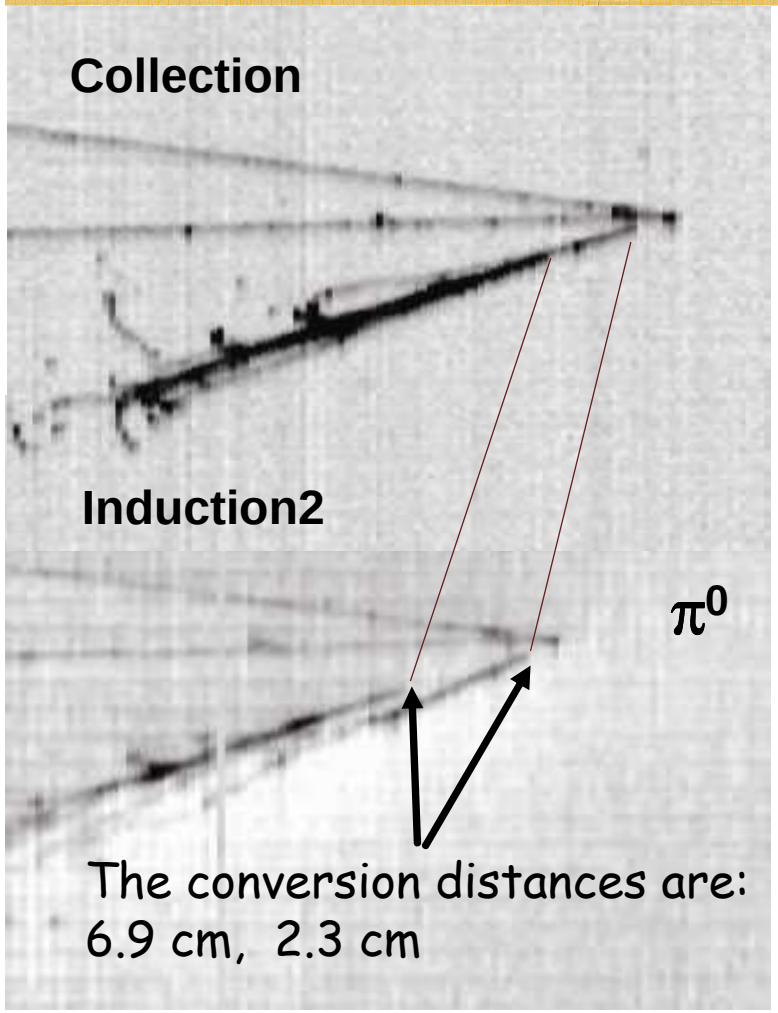
Total deposited energy=887 MeV

Total reconstructed momentum = 929 MeV/c in a direction at about 30 degrees from the CNGS beam direction

CNGS ν_μ CC interaction in ICARUS T600



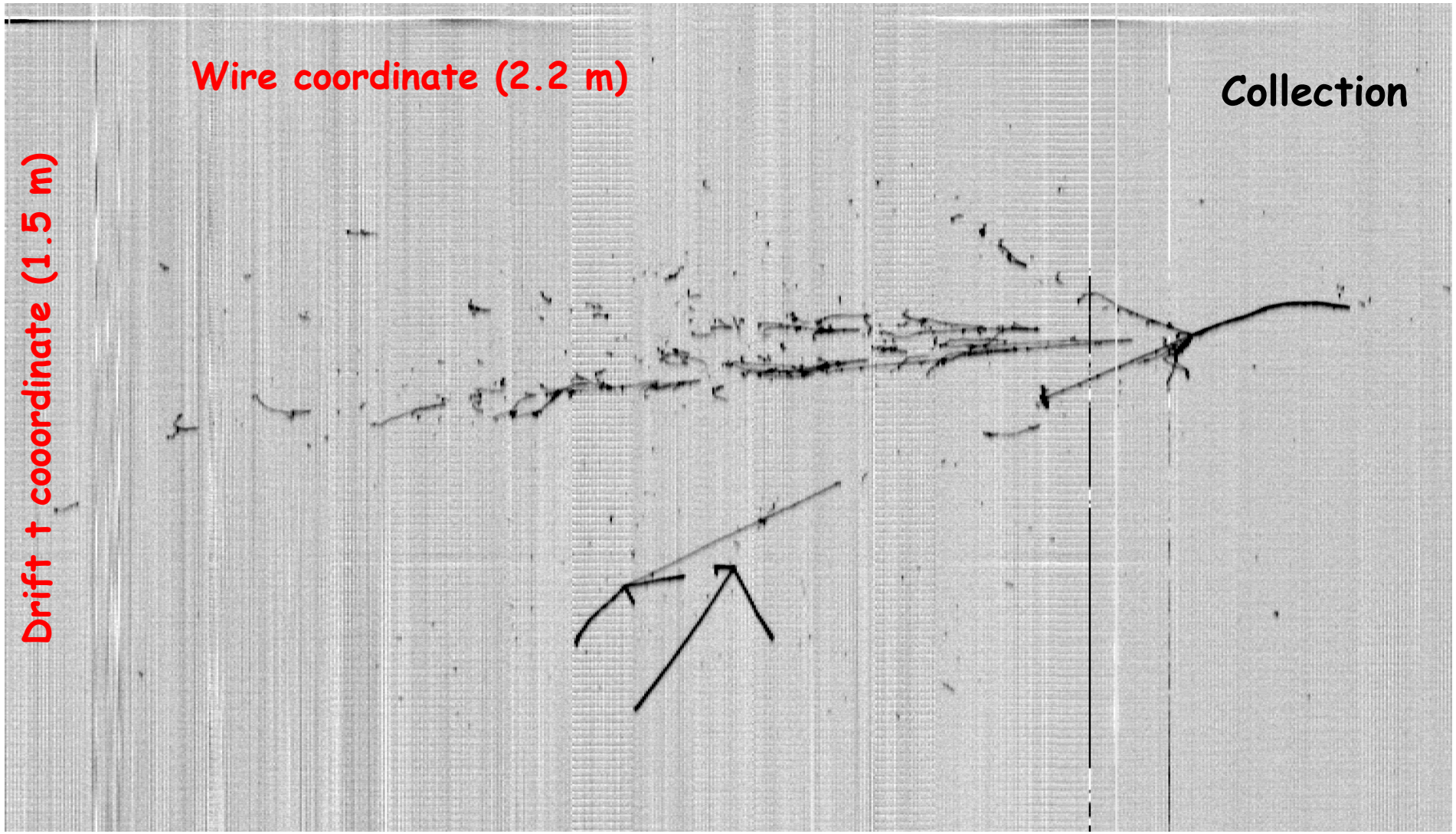
close-up of two electromagnetic showers



Deposited energy and track directions:

Track	E_{dep} [MeV]	cosx	cosy	cosz
1 (μ)	2702	0.069	-0.040	-0.997
2	521	0.054	-0.420	-0.906
3 (π)	514	-0.001	0.137	-0.991
Sec. vtx.	797			
4	77	0.009	-0.649	0.761
5 (μ)	314			
6 (K)	87	0.000	-0.239	-0.971
7	36	0.414	0.793	-0.446
8	283	-0.613	0.150	-0.776
	4.5 GeV			

CNGS ν_μ NC interaction in ICARUS T600



Physics potentials of ICARUS T600

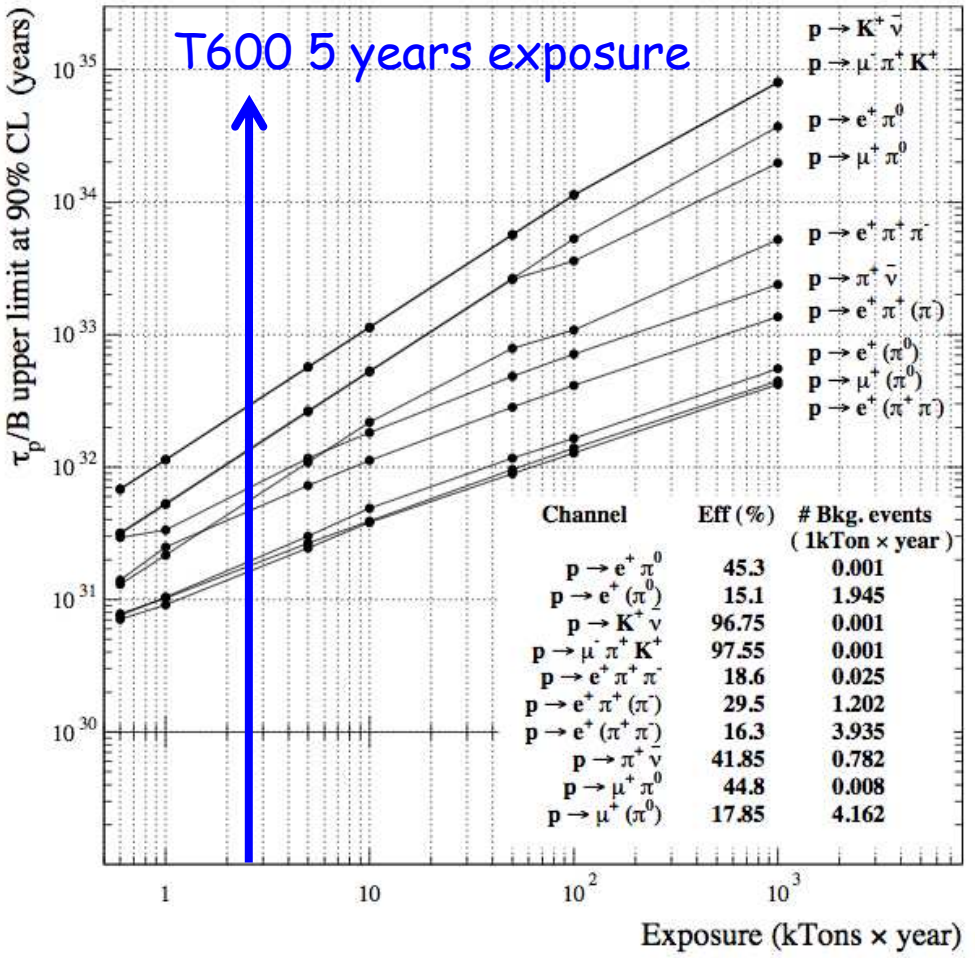
- T600 is a major milestone towards the realization of a much more massive multikton LAr detector, but it offers also some interesting physics in itself. The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, and e/π^0 separation allow "to see" events in a new way, w.r.t. previous/current experiments.
- The detector is collecting "bubble chamber like" CNGS events:
  - a beam related rate ≈ 1200 ev/year within fiducial volume ≈ 480 t for a total of ≈ 2800 CC events for 10^{20} pot.
  - Search for $\nu_\mu \Rightarrow \nu_\tau$ using kinematical criteria.
  - Search for sterile neutrinos in LSND parameter space, with deep inelastic ν_e CC events excess.
- The T600 is also collecting simultaneously "self triggered" events:
  - ≈ 80 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.

Nucleon decay search

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

Channel	90%CL-5y	(pdg 90%CL)
$p \rightarrow \nu\ \pi^+$	$1.1\ 10^{32}$	$(2.5\ 10^{31})$
$p \rightarrow \mu^-\ \pi^+ K^+$	$2.7\ 10^{32}$	$(2.5\ 10^{32})$

ICARUS SENSITIVITY on proton decay



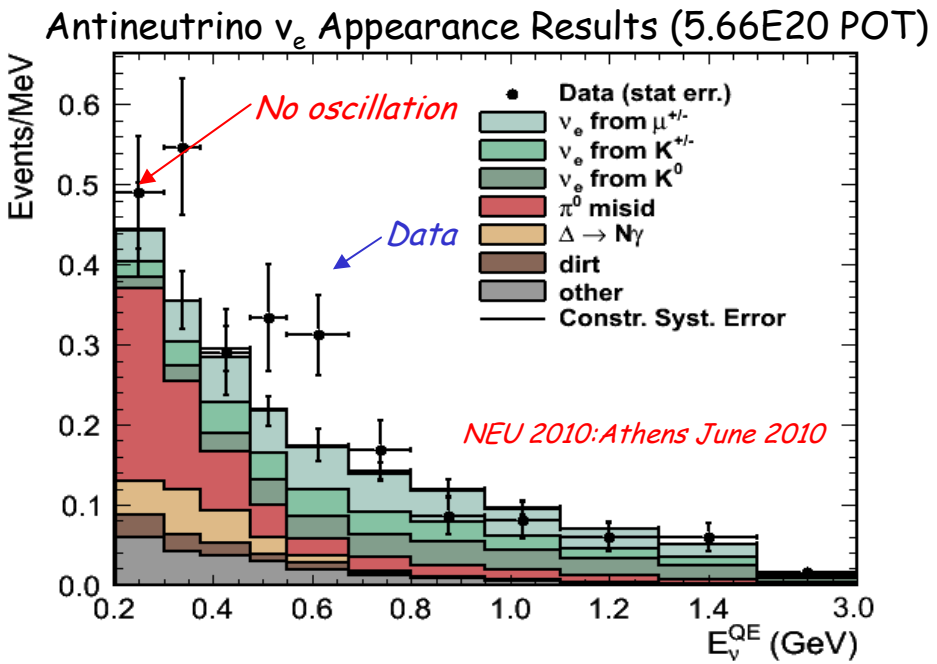
Channel	Eff (%)	# Bkg. events (1kTon × year)
$p \rightarrow e^+ \pi^0$	45.3	0.001
$p \rightarrow e^+ (\pi^0)$	15.1	1.945
$p \rightarrow K^+ \nu$	96.75	0.001
$p \rightarrow \mu^- \pi^+ K^+$	97.55	0.001
$p \rightarrow e^+ \pi^+ \pi^-$	18.6	0.025
$p \rightarrow e^+ \pi^+ (\pi^-)$	29.5	1.202
$p \rightarrow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

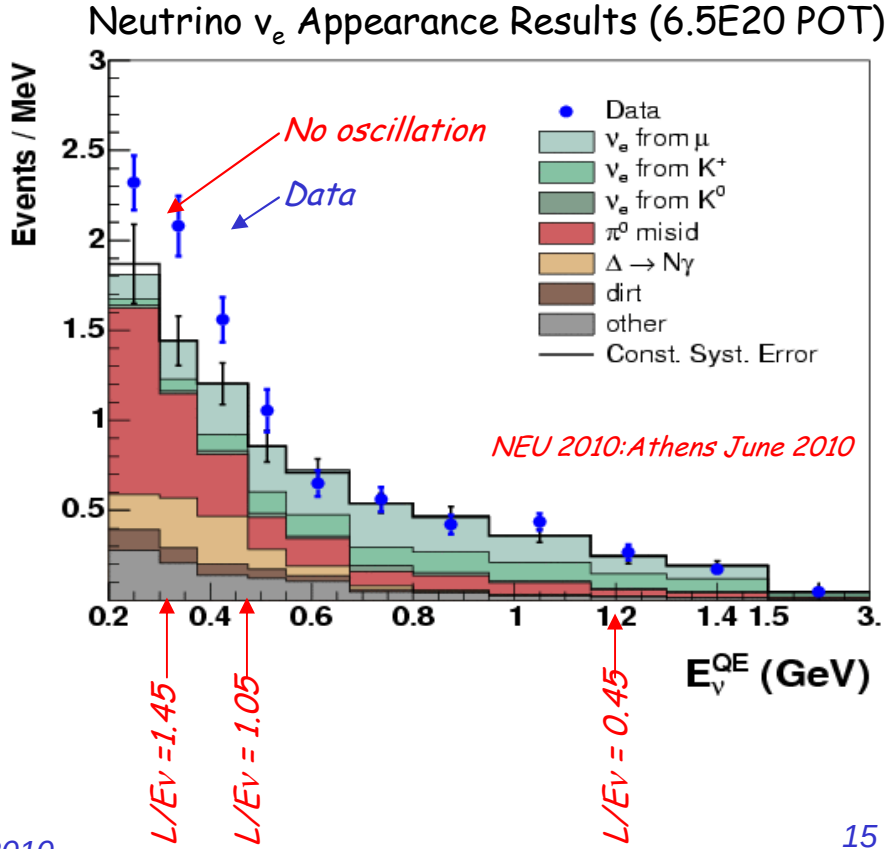
$n \rightarrow e^- K^+$	$3.2\ 10^{32}$	$(3.2\ 10^{31})$
$n \rightarrow \mu^+ \pi^-$	$1.5\ 10^{32}$	$(1.0\ 10^{32})$
$n \rightarrow \nu\ \pi^0$	$1.1\ 10^{32}$	$(1.1\ 10^{32})$

LNSD and MiniBooNE: sterile ν's?

LSND observed an excess of anti-ν_e events in anti-ν_μ beam, 87.9 ± 22.4 ± 6.0 **(3.8σ)** and an excess of ν_e of 18.1 ± 6.6 ± 3.5 events over background from ν_e C → e^-X: *oscillation with 0.2 < Δm^2 < 2.0 eV² incompatible with the 3 neutrino oscillation scheme*

MinibooNE found anomalous signal < 470 MeV, of unknown origin in both neutrino and antineutrino runs and signal >470 MeV only on antineutrino run.





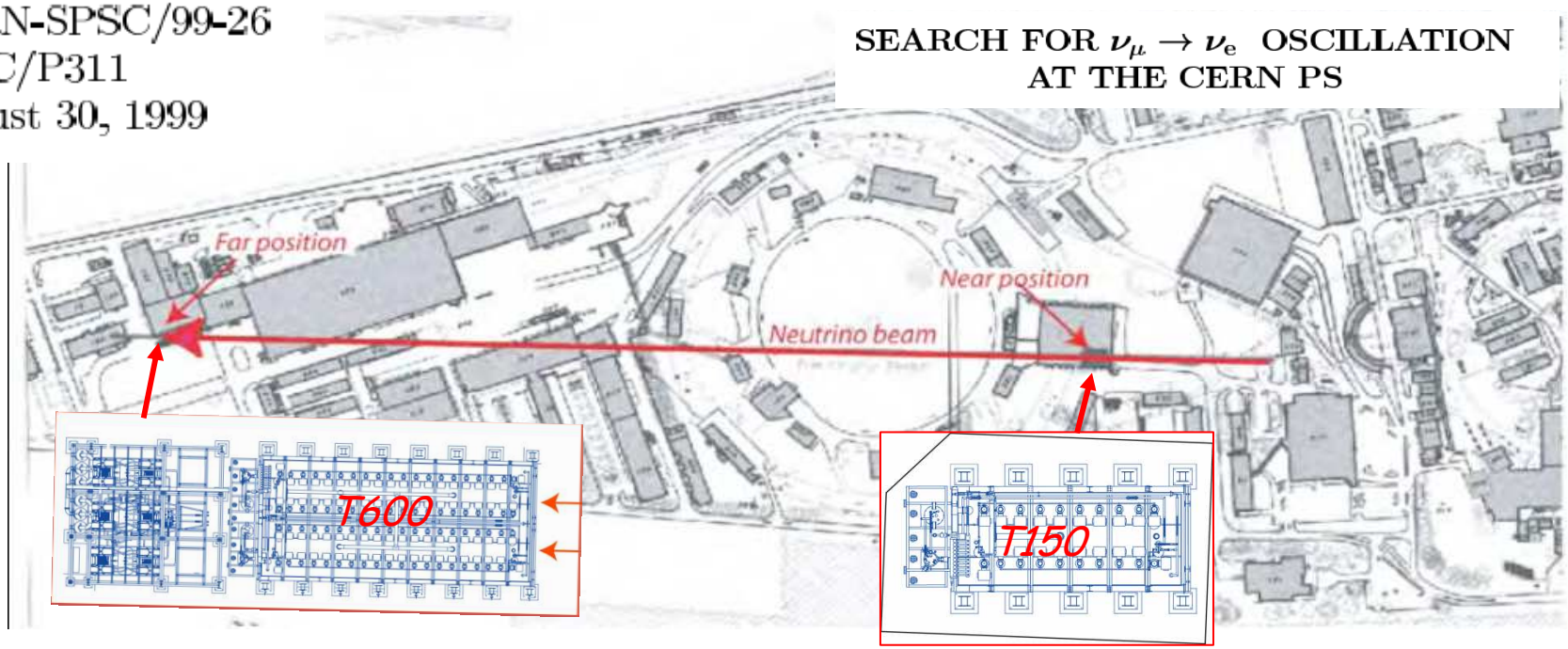
ICARUS T600 after CNGS2: a new esperiment at CERN PS

- The LAr-TPC is the viable device to solve the anomalies found by LSND/Miniboone puzzle thanks to
  - detection capability of genuine ν_e events
  - energy resolution and detector granularity largely adequate for low energy range (E<3GeV)
  - high level of rejection of associated background events (π^0).
- A novel experimental search based on two strictly identical LAr-TPC detector in the Near and Far position observing the ν_e signals both for anti- ν_μ and ν_μ beams is proposed at CERN – PS
- The neutrino beam, produced by 19.2 GeV protons of integrated intensity of 1.25 10^{20} pot/yr, will be centred at ~1.3 GeV
- Anti-neutrino beam by inverting the current of the horn (designed to focus particle of momentum ~3 GeV)

Two detectors at the PS neutrino beam

CERN-SPSC/99-26
SPSC/P311
August 30, 1999

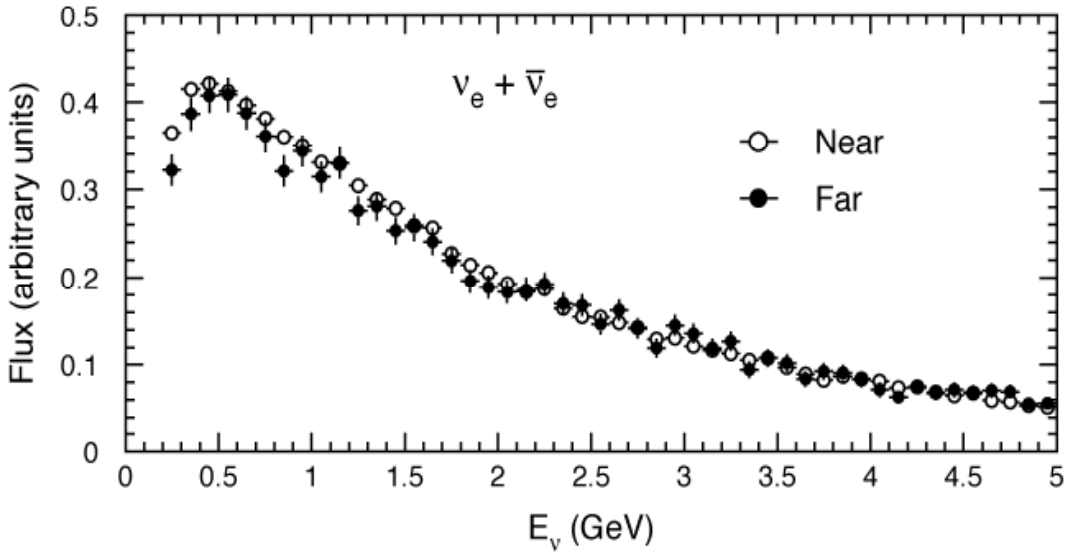
SEARCH FOR $\nu_\mu \rightarrow \nu_e$ OSCILLATION
AT THE CERN PS



- Two positions are foreseen for the detection of the neutrinos: far detector (~600 ton) at 850 m from target (L/E ~ 1) and near detector (~150 ton) at 127 m from the target: (L/E 0.15)
- ICARUS T600 used as "far" detector!!
- To ensure the maximum similarity between Near and Far detectors, the Near one will be a clone of a module of T600 with length reduced by a factor 2, keeping untouched the inner detector layout.

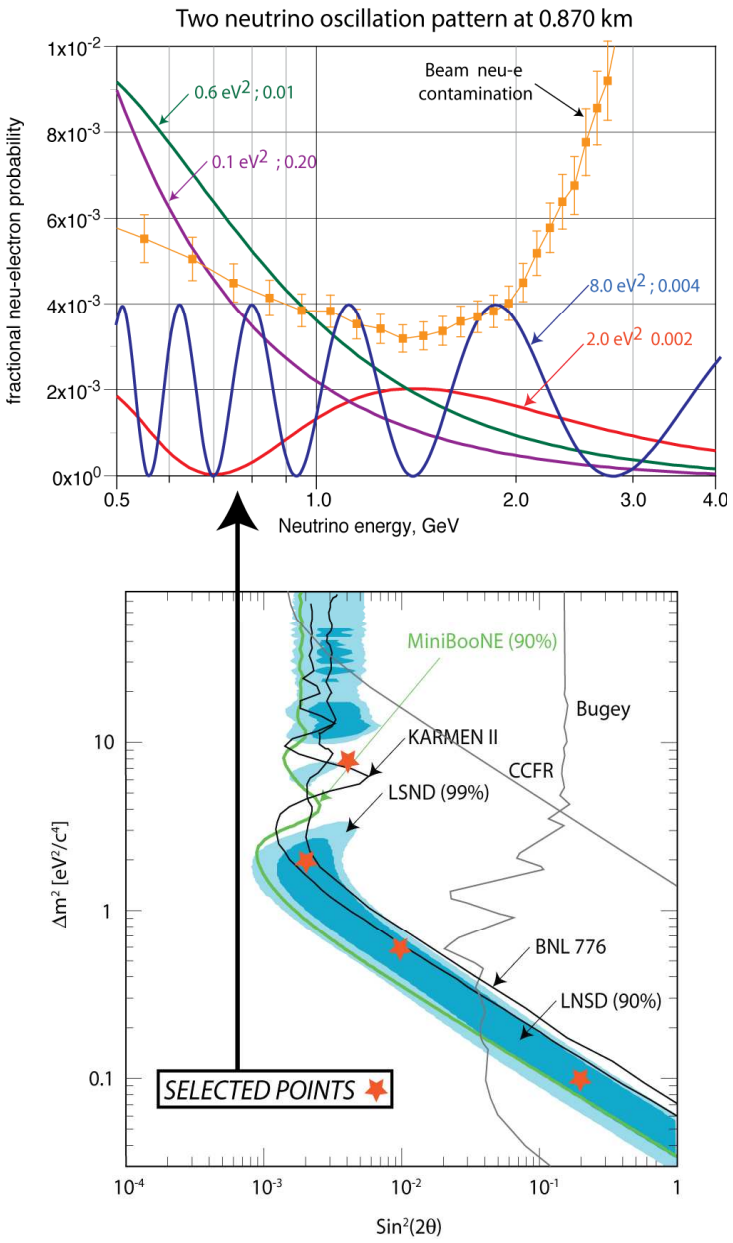
- *In absence of oscillations*, apart some beam related small spatial corrections, the two spectra are a precise copy of each other, independently of the specific experimental event signatures and without any Monte Carlo comparison.

- Therefore an exact, observed proportionality between the two ν_e spectra implies directly the absence of neutrino oscillations over the measured interval of L/E.



(arXiv:0909.0355)

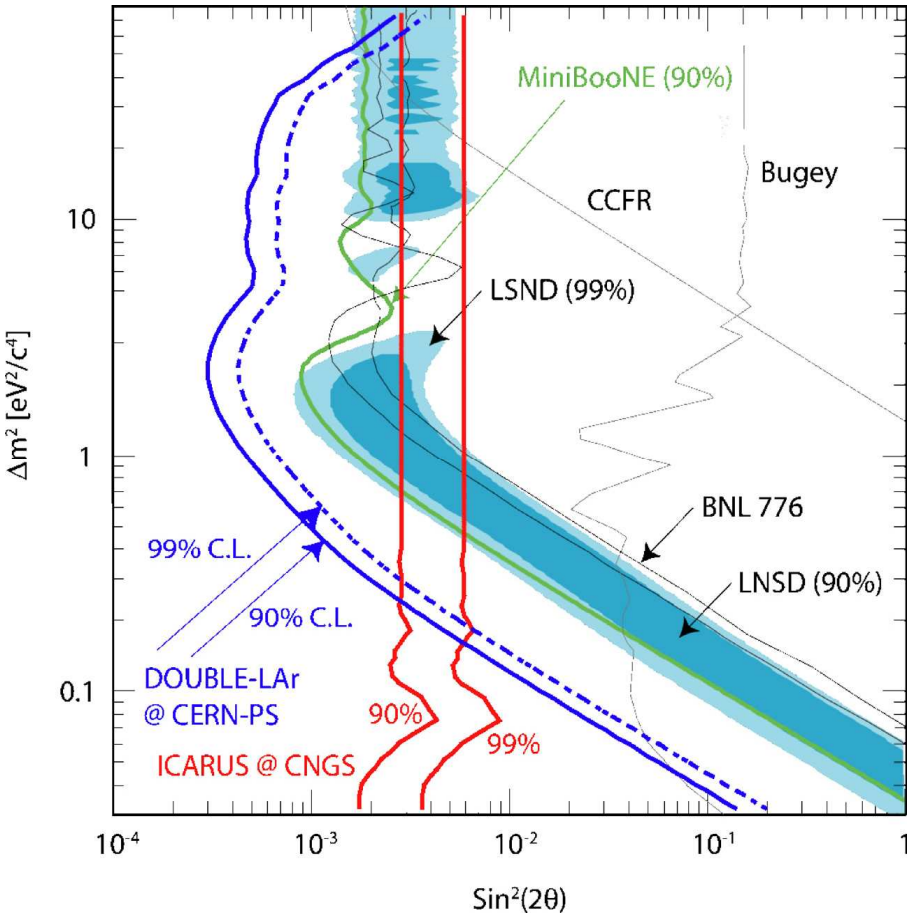
Expected results



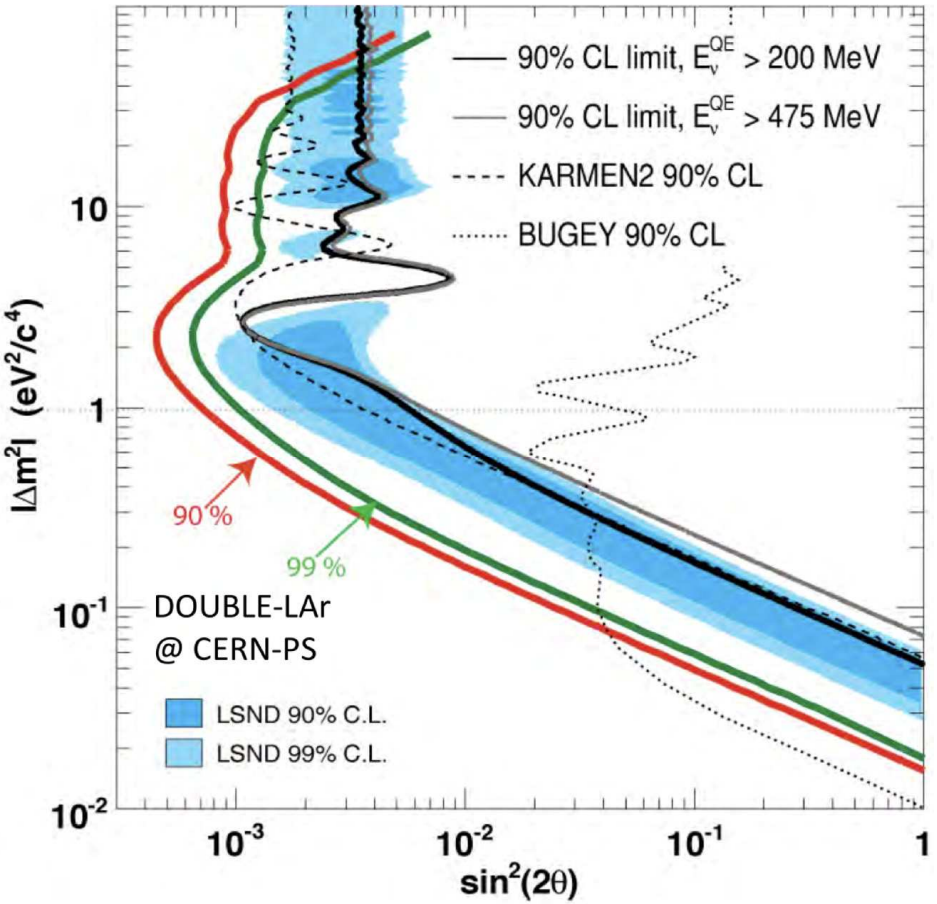
- The present proposal, unlike LNSD and MiniBooNE, can determine both mass difference/mixing angle.
- Very different and distinguishable patterns are possible depending in the (Δm^2 – $\sin^2 2\theta$) plane.
- The intrinsic ν_e background due to the beam contamination is also shown.
- The magnitude of the LNSD expected oscillatory behaviour, for the moment completely unknown, is well above background, also considering the very high statistical impact and resolution of experimental measurement.

Comparing sensitivities *(arXiv:0909.0355)*

Neutrino beam



Antineutrino beam



Expected sensitivity for the proposed experiment exposed at CERN-PS neutrino beam (left) for 2.5 10^{20} pot and twice as much for anti-neutrino (right) . The LSND allowed region is fully explored both for neutrinos. The expectations from one year of ICARUS at LNGS are also shown.

Conclusions

- The ICARUS T600 is presently taking data at LNGS with CNGS beam. Neutrino interactions have been observed and collected for 6 months.
- The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, and e/π^0 separation allow to reconstruct and identify events in a new way, w.r.t. previous/current experiments.
- The successful assembly and operation of this LAr-TPC is the experimental proof that this technology is mature.
- ***The ICARUS experiment*** at the Gran Sasso Laboratory is so far ***the major milestone*** towards the realization of a much more massive LAr detector.
- The provided high imaging granularity and resolution allow to address a wide physics programme
    - Underground physics (cosmic neutrinos, nucleon decay …)
    - Long baseline, high precision neutrino physics
- LAr-TPC can be employed to solve LSND/MiniBooNe anomalies : a novel search with a refurbished ν beam at the CERN-PS is proposed after the ICARUS T600 exploitation at LNGS