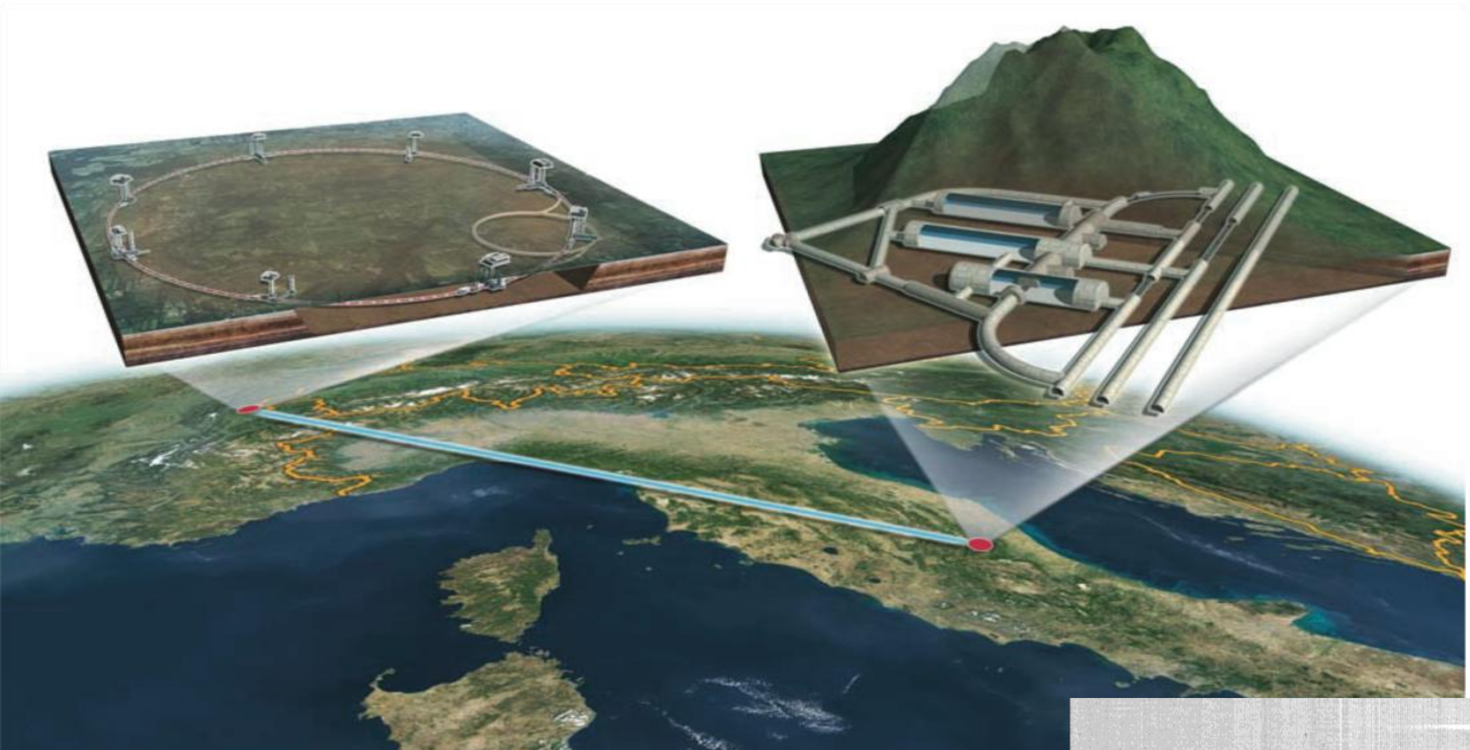
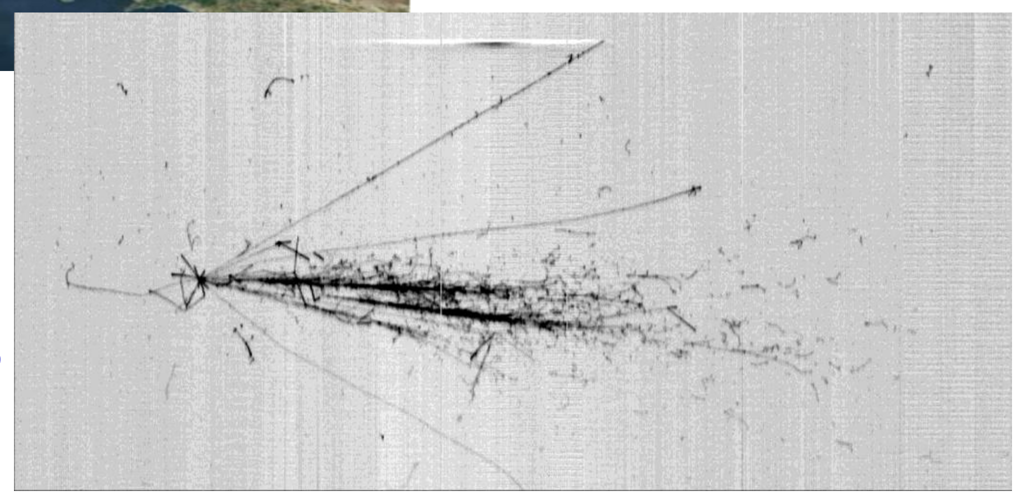
Neutrino experimental search in ICARUS



A. Guglielmi
INFN/Padova

- neutrinos ?!
- ICARUS LAr-TPC
- Sterile neutrino search @ PS



Padova May 2011

@ Physics Frontiers: neutrino oscillations and proton-decay

- Neutrino oscillation have established a coherent picture with number of experimental hints consistent with the mixing of 3 physical neutrinos ν_e, ν_μ and ν_τ with mass eigenstates ν_1, ν_2 and ν_3. In particular the mass differences turn out to be relatively small $\Delta m^2_{31} \approx 2.4 \times 10^{-3}\ eV^2$ and $\Delta m^2_{21} \approx 8 \times 10^{-5}\ eV^2$.

- Are neutrinos a simple carbon copy repetition of quarks?
  important discoveries may be ahead:
  - CP violation in the lepton sector : subleading ν_μ to ν_e oscillations
  - Sterile neutrinos and others "surprises"
  - Majorana or Dirac neutrinos- $\beta\beta$ –decay, ν–masses

  Neutrinos have been origin of impressive number of "Surprises"…

- Similar fundamental question: (barionic) number is forever ?

Neutrino oscillations @ accelerators: toward Θ_{13} , δ_{cp}

- first generation long baseline experiments: K2K over 250 km, NuMI and CNGS L = 730 km with conventional ν beams, 170 KW.
  Present detectors: SK 22.5 kt W-Cherenkov, MINOS 5.4 kt Iron-Scintillator ICARUS 600 t liquid Argon TPC, OPERA emulsion detector (ν_τ appearance)
- Θ_{13} , δ_{cp} measurement in ν_μ - ν_e subleading oscill. requires major improvements:
  - high intensity/purity ν beams, L/E_ν tuned to Δm_{32}^2, well defined spectrum (present beams: intrinsic ν_e contamination mainly from μ and K decay)

    ν Factories: from decay of accelerated muons

    β Beams: from decay of accelerated radioactive ions, just one flavor beam
  - "ultimate" massive detectors, able to measure ν_e-CC (i.e. electrons) rejecting ν-NC (i.e. π^0) adressed also to astroparticle physics/p-decay search: 20 -100 kt LAr-TPC (MODULAr, GLACIER) , 50 kt L-Scint (LENA), 500 kt W-Cerenkov (MEMPHYS, HyperK)...
- 2nd generation experiments at improved Off-Axis conventional beams, 1 MW power and even beyond: T2K SuperK-detector exposed to 0.7 GeV ν_μ beam, 0.7 MW nominal power, L = 295 km

Are neutrinos a simple carbon copy of quarks?

- However the present picture is not so clean…

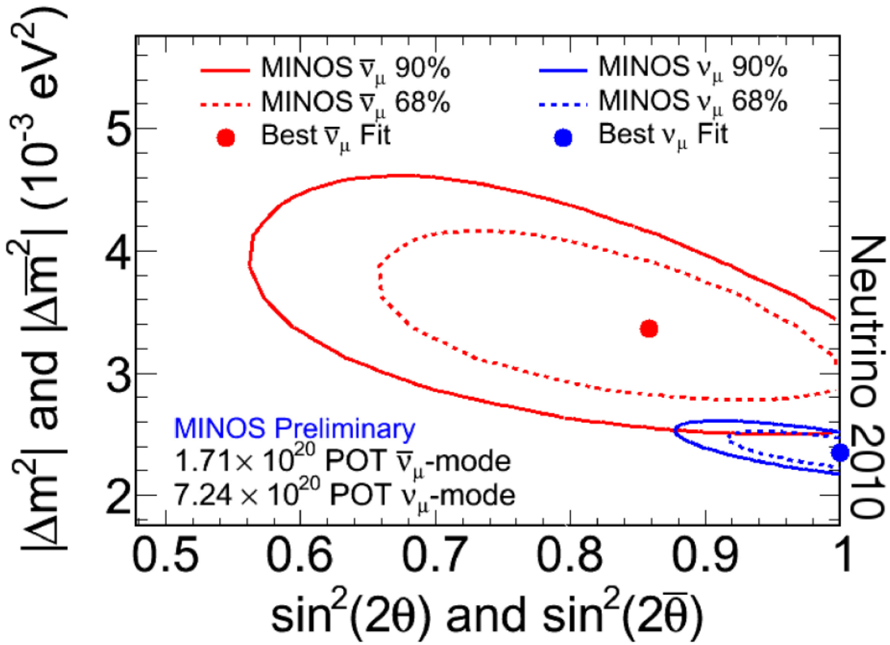
- There are a number of *"anomalies"* which, if confirmed experimentally, could be due to the presence of an additional, large squared mass difference in the framework of additional neutrinos with mixing or of other effects.

- If more than the two oscillation signals were to be eventually confirmed, additional Physics beyond the Standard Model in the neutrino sector will be necessary. If a new mass difference $\Delta m^2_{new} \geq 1$ eV^2 were to be observed, it will also contribute to clarify the Dark Matter problem

CPT violations ?

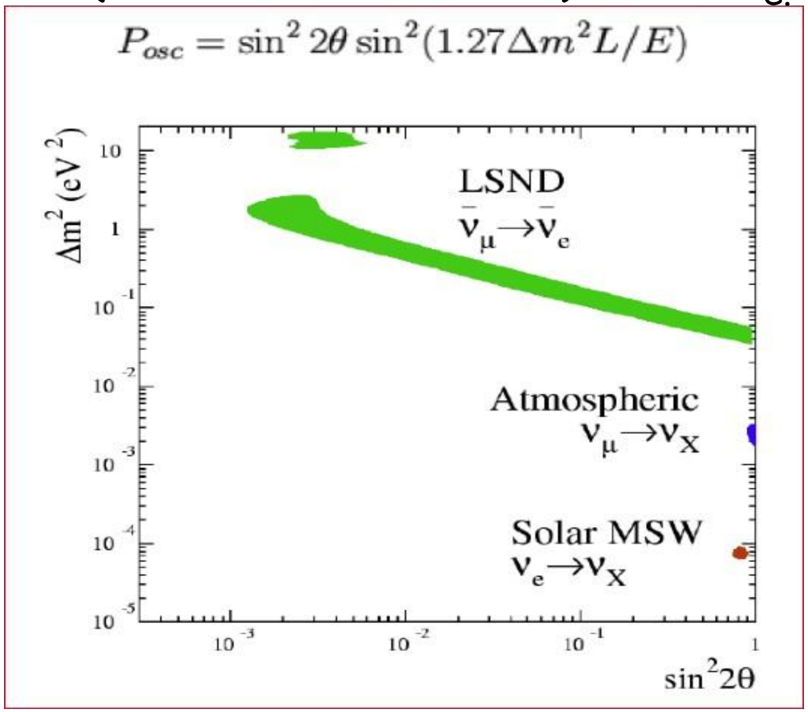
- While reactions and cross sections are different between ν and anti-ν, CPT invariance ensures identity of oscillations.
- The "tension" between the neutrino and antineutrino MiniBooNE + LNSD data seems to indicate a difference of the effective mixing angles in the neutrino and antineutrino channels.
- Such a difference, if confirmed could be due to some unknown mechanism, or perhaps even to CPT violation.

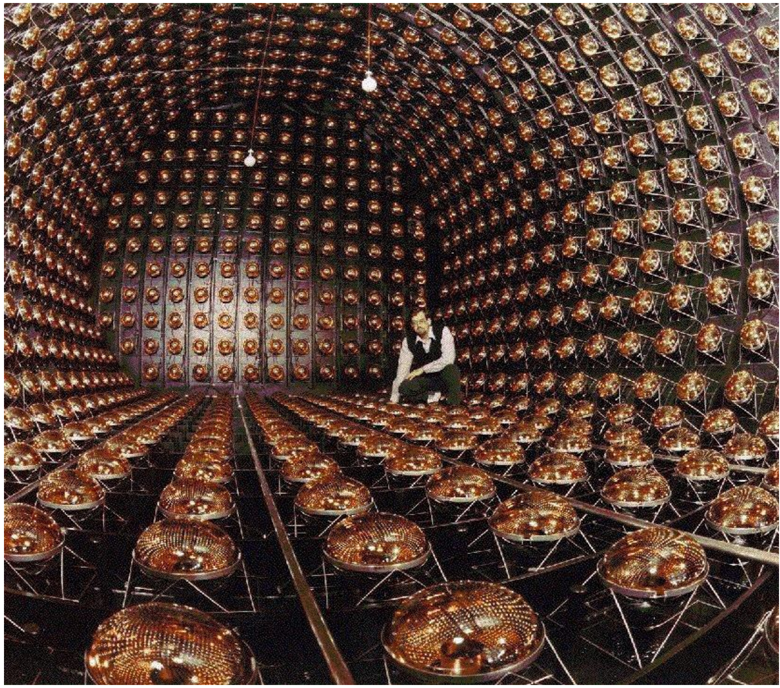
MINOS experiment has recently pointed out a possible difference (2 σ) between the effective mixing ν and anti-ν in the long-baseline channels.



Additional neutrinos: the LSND Experiment (1993-97)

- LSND observed 87.9 ± 22.4 ± 6.0 **(3.8σ)** excess of anti-ν_e events in anti-ν_μ beam from π^+ decay at rest from 800 MeV protons on a Cu/Fe target and an excess of ν_e of 18.1 ± 6.6 ± 3.5 events over backgr. from $\nu_e\, C \rightarrow e^- X$
- Since ν_e is only $4*10^{-4}$ to ν_μ, it results evidence for $\nu_\mu \rightarrow \nu_e$ oscillations in *$0.2 < \Delta m^2 < 2.0\ eV^2$* with probability (0.31±0.12±0.05)% (anti-ν_e) and (0.26±0.10±0.05)% for ν_e.



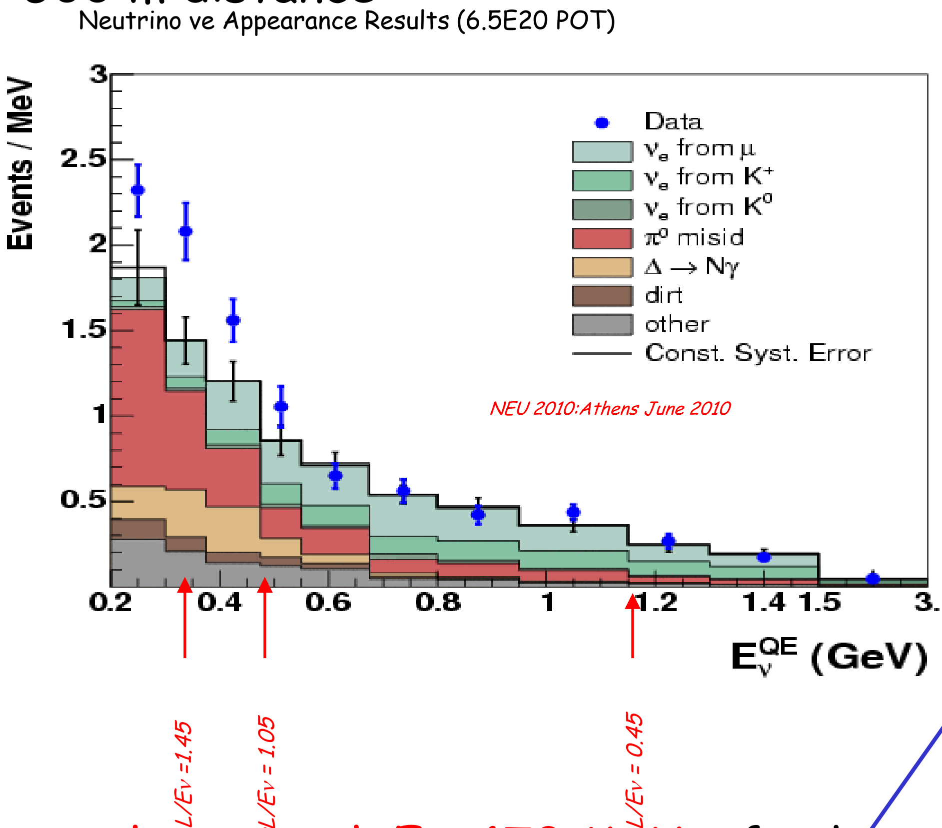


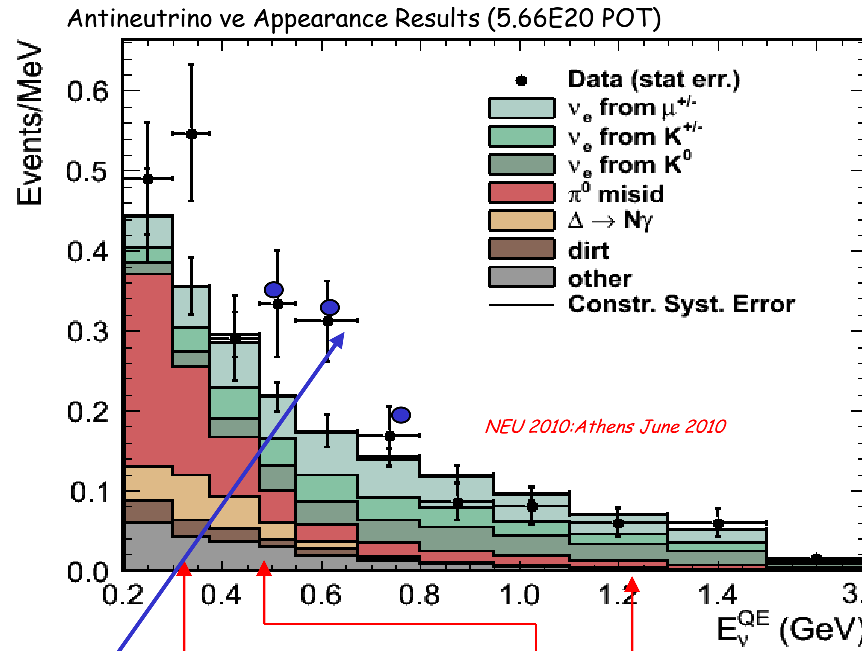
Cylindrical tank at 30 m from the neutrino source, filled with 167 tons of liquid scintillator (both Cerenkov and scintillation light detection)

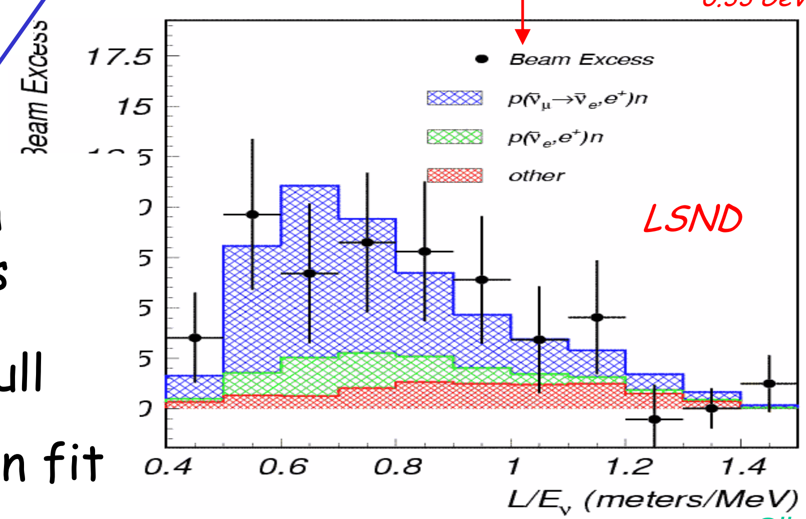
3 oscillation signals, if confirmed, require new physics beyond SM !

MiniBooNE experiment at FNAL (1998-today)

0.8 GeV $\nu\mu$ beam, 445 t oil fiducial mass @ 500 m distance







- Anomalous signal E < 470 MeV, of unknown origin in both Neutrino & Antineutrino runs
- Signal E > 470 MeV on antineutrino only. Null excluded @99.4% wrt 2 neutrino oscillation fit

Fates of secular conservation laws !

Parity	Fallen 1956
Charge Conjugation	Fallen 1956
CP	Fallen 1964
T	Fallen 1999
Lepton Family	Fallen 1998 (μ), 2002 (e)
Lepton Number	Still viable (0 ν β β ?)
Baryon Number	Still viable
CPT	Still viable

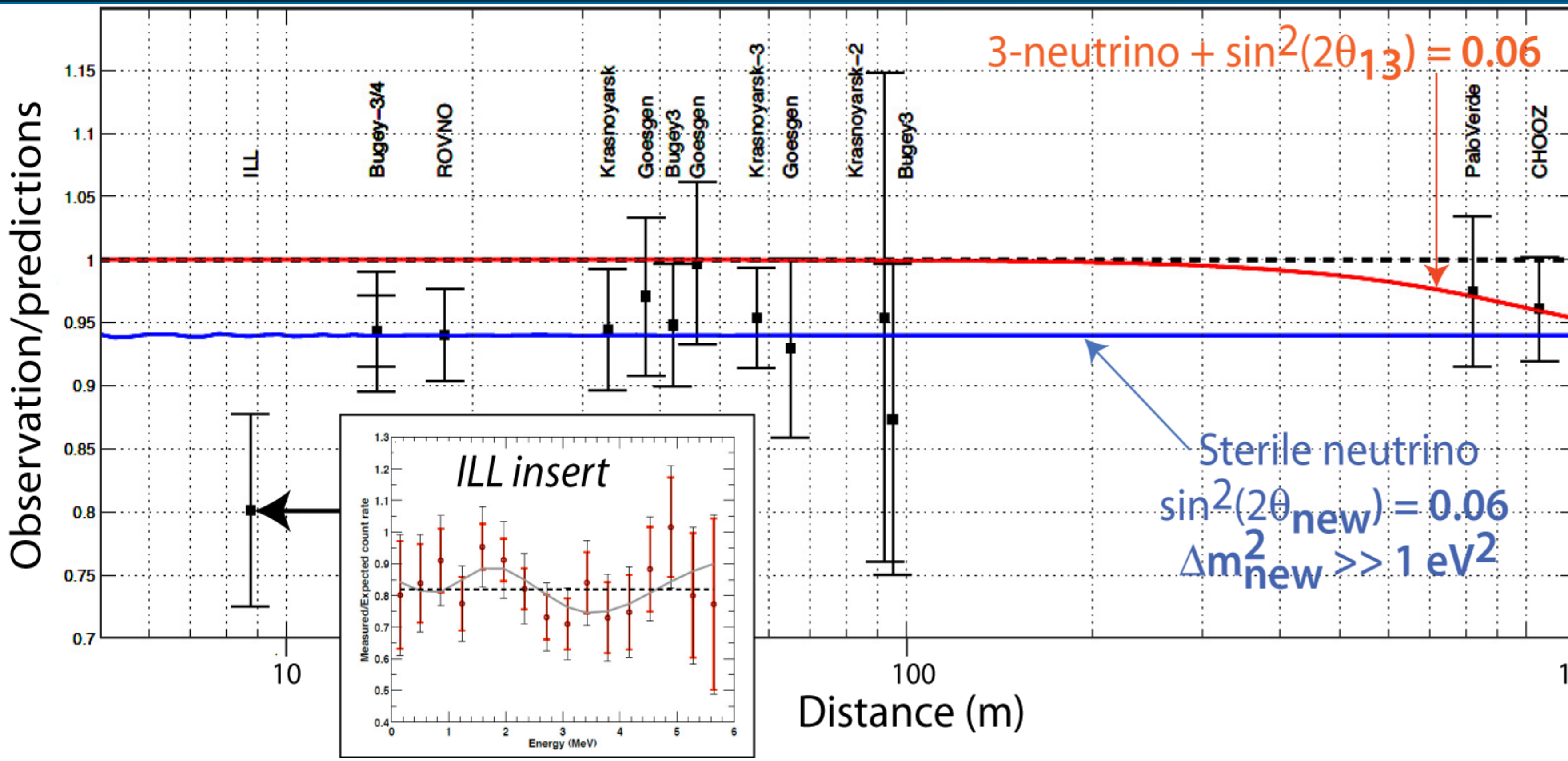
Sterile neutrinos ?

- The possible presence of oscillations into sterile neutrinos has been proposed by B. Pontecorvo, but so far without conclusion.
- Two distinct classes of anomalies have been observed, namely
  - apparent *disappearance signals:* (1) the anti-ν_e events detected from near-by nuclear reactors and (2) from the from Mega-Curie k-capture calibration sources in the Gallium experiments to detect solar ν_e
  - observation for *excess signals* of ν_e electrons from neutrinos from particle accelerators (LNSD/MiniBooNE)
- These experiments may all point out to the possible existence of the fourth non standard neutrino state driving oscillations at a small distances, with typically $\Delta m^2_{new} \geq 1\ eV^2$ and relatively large mixing angle with $\sin^2(2\theta_{new}) \approx 0.1$.
- The existence of a fourth neutrino state may be also hinted — or at least not excluded — by cosmological data

The Gallium experiments

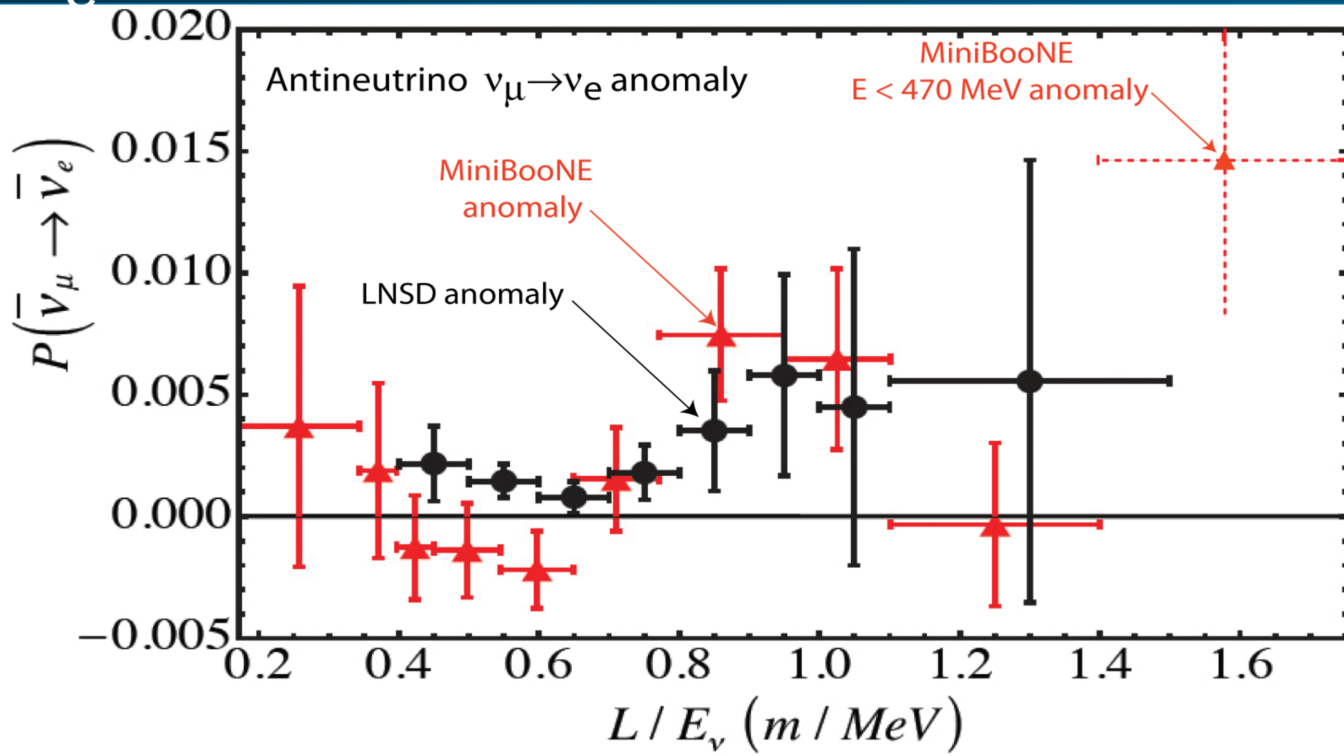
- In the late nineties the SAGE and GALLEX experiments recorded the calibration signal produced by intense artificial k-capture sources of ^{51}Cr and ^{37}Ar near the detector.
- The averaged result of the ratio R between the source detected and predicted neutrino rates are consistent with each other, giving $R = (0.86 \pm 0.05)$ about 2.7σ away from $R = 1$
- The result is somewhat influenced by uncertainties in nuclear models, which however may not be enough to bring R to unity.
- These best fitted values may favour the existence of an undetected sterile neutrino with an evidence of 2.3σ and a broad range of values around $\Delta m^2_{new} \approx 2\ eV^2$ and $\sin^2(2\theta_{new}) \approx 0.3$.

Disappearance signal: the reactor antineutrino anomaly



- From G. Mention et al. arXiv:1101.2755v1 [hep-ex] Experimental results are compared to the prediction without oscillation, taking into account the new spectra, the neutron mean lifetime and the off-equilibrium effects. The averaged ratio is 0.937 ± 0.027. The red line is for $sin^2(2\theta_{13})$ = 0.06. The blue line is for a sterile neutrino with $\Delta m^2_{new} \gg 1\ eV^2$ and $sin^2(2\theta_{new})$ = 0.06.

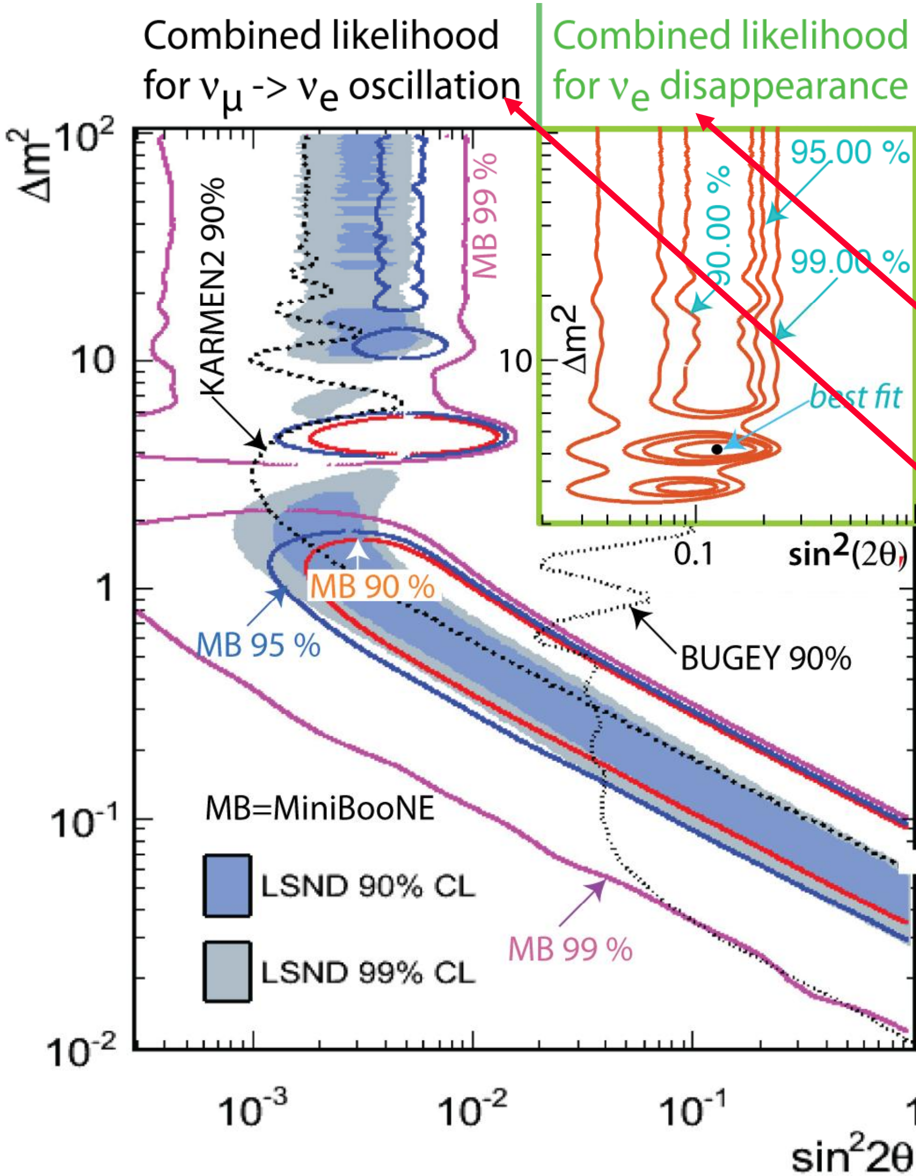
Excess ν_e signal: The LSND/ MiniBooNE anti-neutrinos



G.Mills, ICHEP, July 2010

- The more recent MiniBooNE antineutrino run has shown the direct presence of a LSND like anomaly for neutrino energies > 430 MeV. The result is compelling with respect to the ordinary two-neutrino fit, indicating a 99.4% probability for an anomalous excess in ν_e production.
- The reported effect is broadly compatible with the expectation of LNSD experiment, which, as well known, was originally dominant in the antineutrino channel.

A unified approach ?



Allowed regions in the plane for combined results:

the νe disappearance rate (right)

the LSND /MiniBooNE anti-νe anomaly (left).

While the values of Δm^2_{new} may indeed have a common origin, the different values of $\sin^2(2\theta_{new})$ may reflect within the ≥ 4 neutrinos hypothesis and a mass matrix $U_{(4,k)} \approx 0.1$, where k = μ and e.

The need of imaging detectors of high target density

The success of bubble chamber as main tool in H.E. fixed target physics is due to two facts:

- it provides a massive homogeneous target, of substatial density
- it provides complete imaging/reconstruction of events in itself

This technology permitted in the past very substantial advances in Physics based on

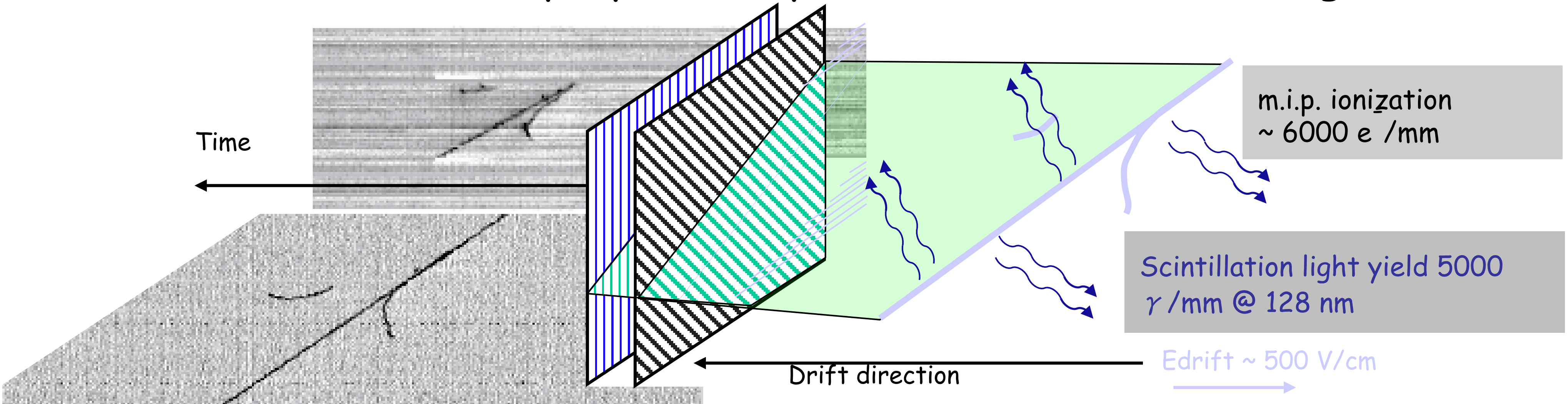
- single event with complete reconstruction (i.e. Ω^- discovery)
- surprise events, i.e. topologies not a priori expected (e.g. Neutral Current)

However this technology is costly/complicated, non expandable to large masses…

Liquid Argon Time Projection Chamber

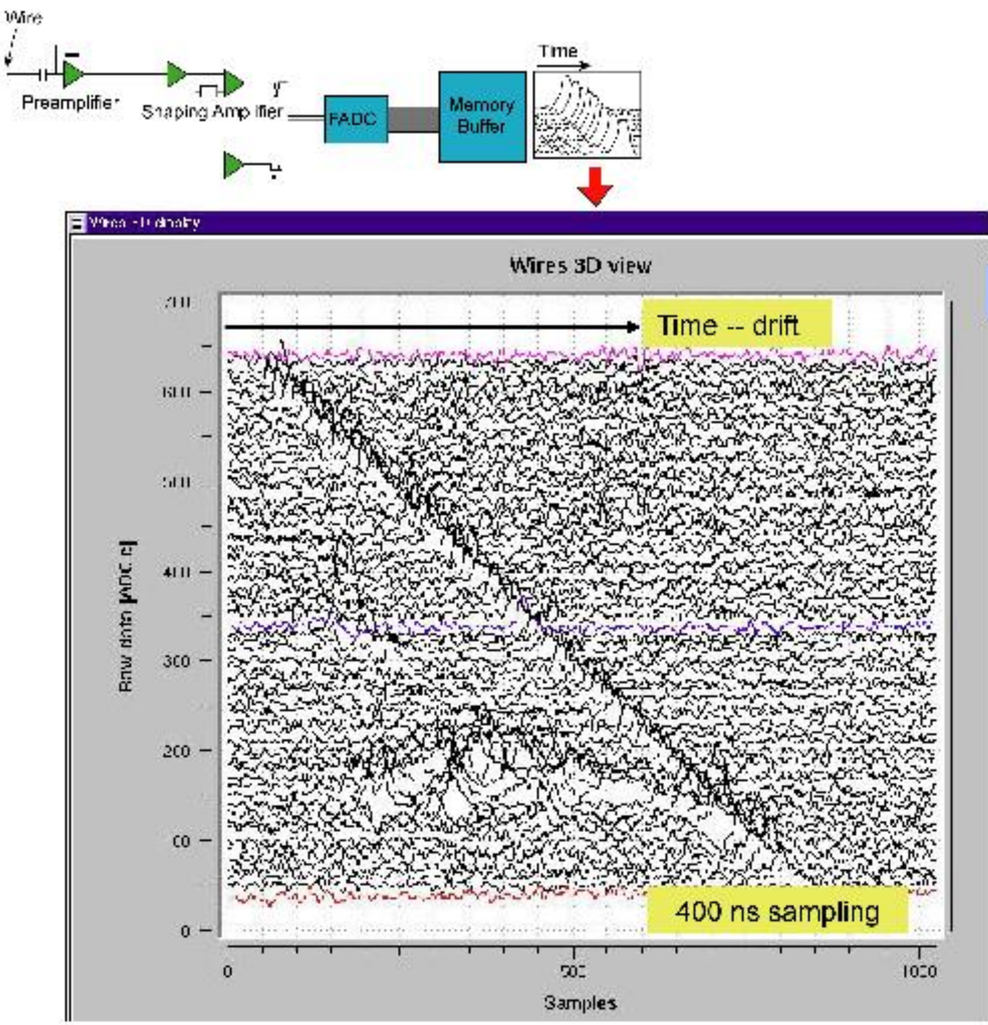
A powerful detection technique invented by C. Rubbia[CERN/-EP/77-08(1977)]: 3D imaging of any ionizing event ("electronic bubble chamber")

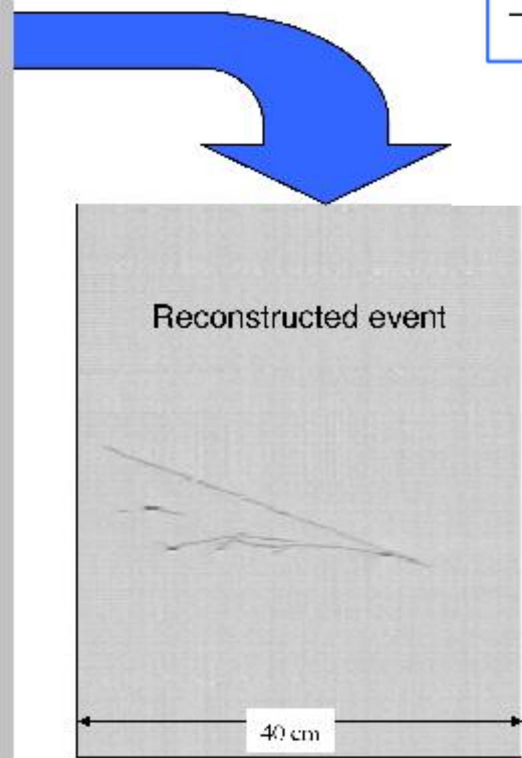
- continuously sensitive, self triggering
- high granularity (~ 1 mm)
- excellent calorimetric properties, particle id. (dE/dx vs range)

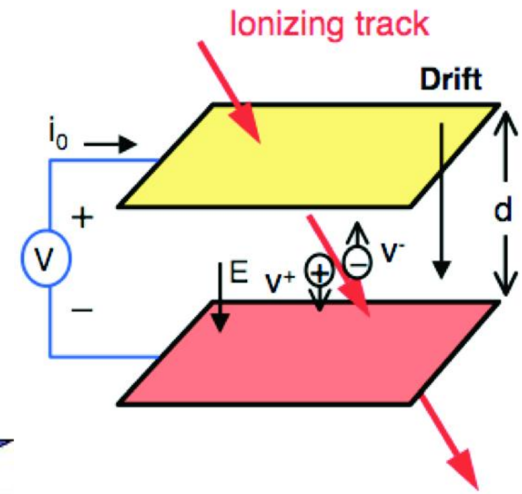


Electrons from ionizing track drifted by Edrift to transparent wires arrays where induction signals are recorded. Finally electron charge is collected by collection wires. Key feature: LAr purity form electro-negative molecules (O2, H2O,C02).

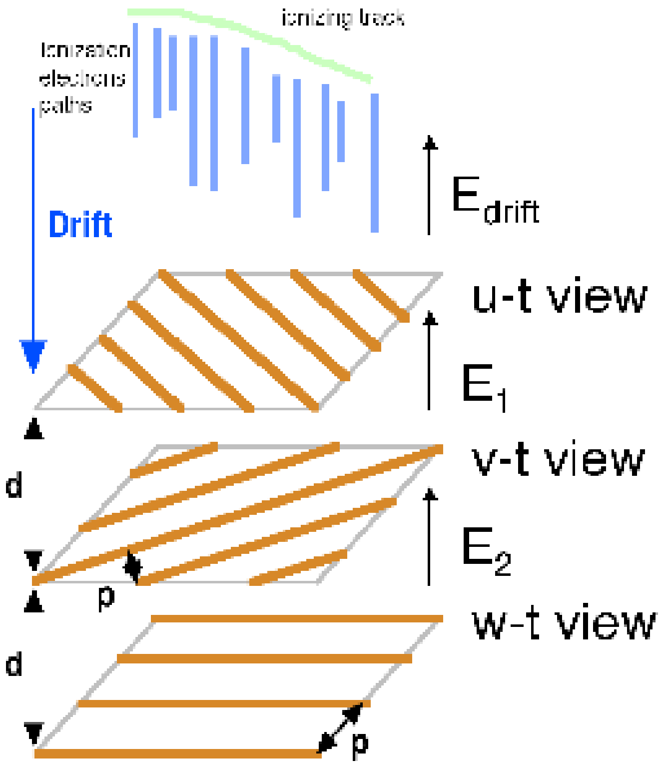
Collecting a track charge

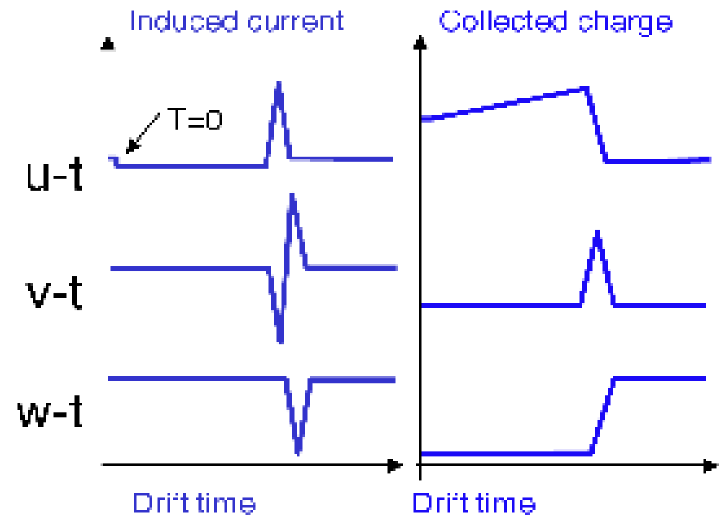






Non destructive readout: the induction signals (3D) !





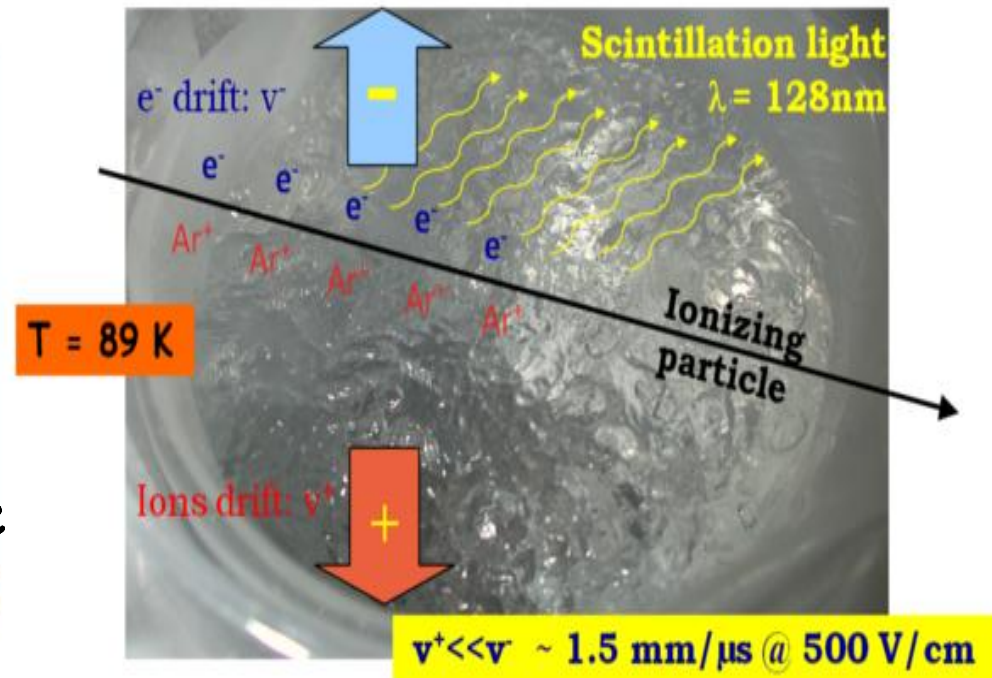
With at least 3 views, a three-dimensional localization of position for each value of t

Drifting electrons are traversing 3 transparent wire arrays oriented in direction of the required view. The ionizing track records in each plane a triangular induction signal. Finally electron charge is collected by the last "Collection plane ". The generated topological view of the event is the one seen by a camera at infinity with the optical axis in direction of wires.

LAr: a noble liquid as target/tracking medium

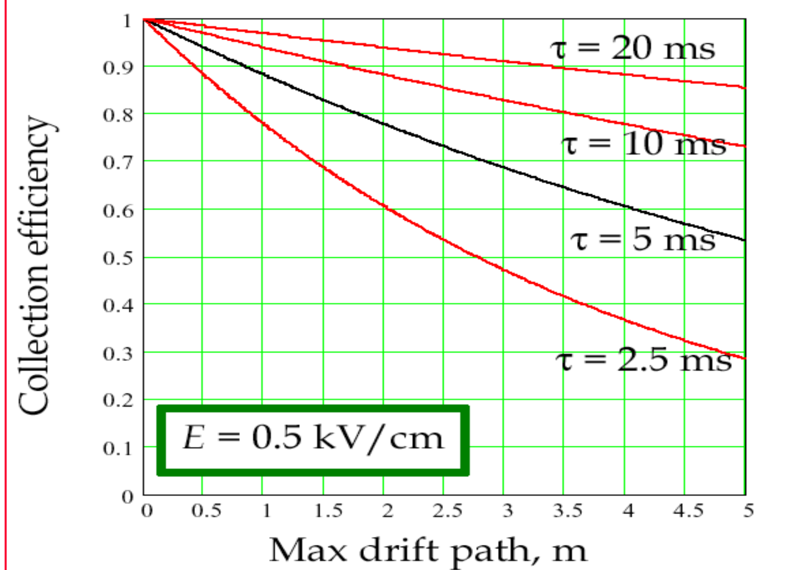
Ideal material, commercially easy to obtain (1 % of air content), for detection of ionizing radiation:

- Dense (1 g/cm3), homogeneous, it acts as target and detector
- High electron mobility, does not attach electrons (long drift path in liquid)
- Inert, not flammable can be made very pure (impurities can be frezed out)
- Ionization: 42000 e^- - ion/MeV
- Scintillation light: 104 g/MeV, UV spectrum λ =128 nm, LAr is transparent, no successive ionizations because low energy
- Cherenkov light (if fast particle)

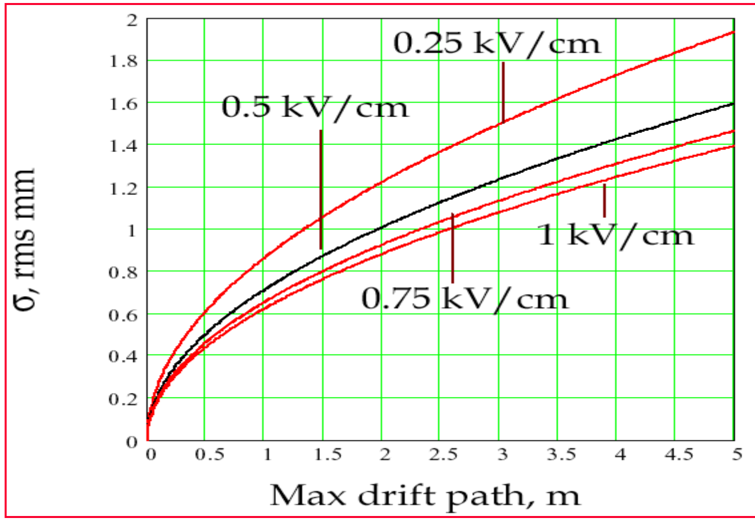


Free electron signal in LAr

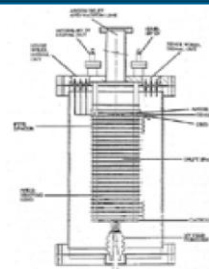
- The strong e—ion recombination due to comparable thermalisation distance (140 nm) and separation is reduced to 30% for E_{drift} = 500 V/cm
- The presence of e- trapping impurities attenuates electron signal as exp $-t/t_{ele}$: it can be expressed in equivalent Oxygen molar densities: τ_{ele} = 300 ms 1 ppb/N(O_2)
- Because of temperature (87 K) most of contaminants freeze out spontasnouly. Main residuals: O_2, H_2O, CO_2 and N_2. Goal: 10 ms lifetime for a 30 ppt (t = trillion!) of O_2 equivalent!
- At 500 V/cm, 5 m drift corresponds to 3.1 ms drift time (v_D = 1.6 m/ms)
- Intrinsic bubble size (diffusion) tiny w.r.t. 3 mm pitch: 1 mm r.m.s. after 5 m of drift!



Drifting charge attenuation versus drift path at different electron lifetimes



The path to larger LAr detectors



CERN

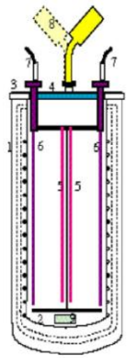
24 cm drift wires chamber

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.

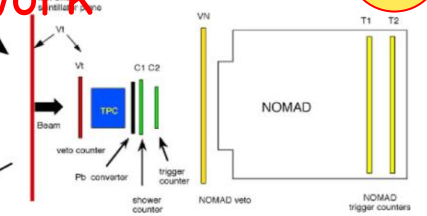
CERN

Laboratory work

CERN

3

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

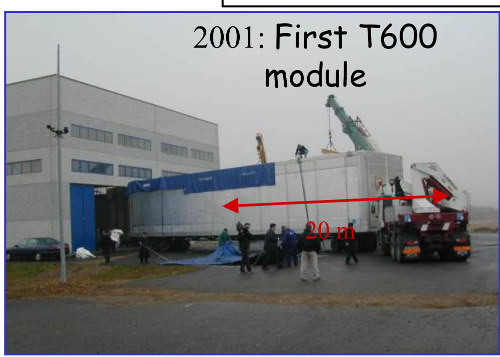
4

Pavia

T600 detector

10 m3 industrial prototype

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



5

Cooperation with industry
AirLiquide, Breme, Cinel, CAEN

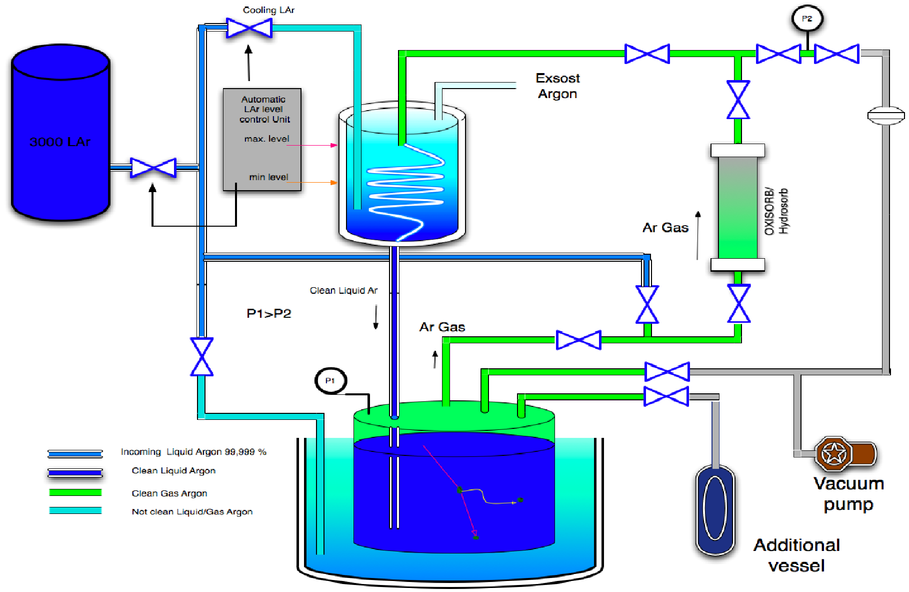
2010 - … : Data taking with CNGS beam

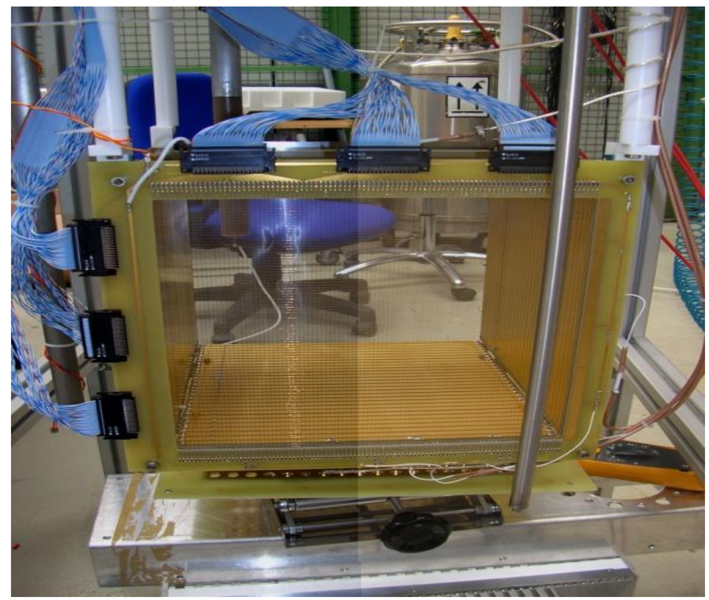
6

LNGS Hall-B

Recent progress in experimental purity achievements

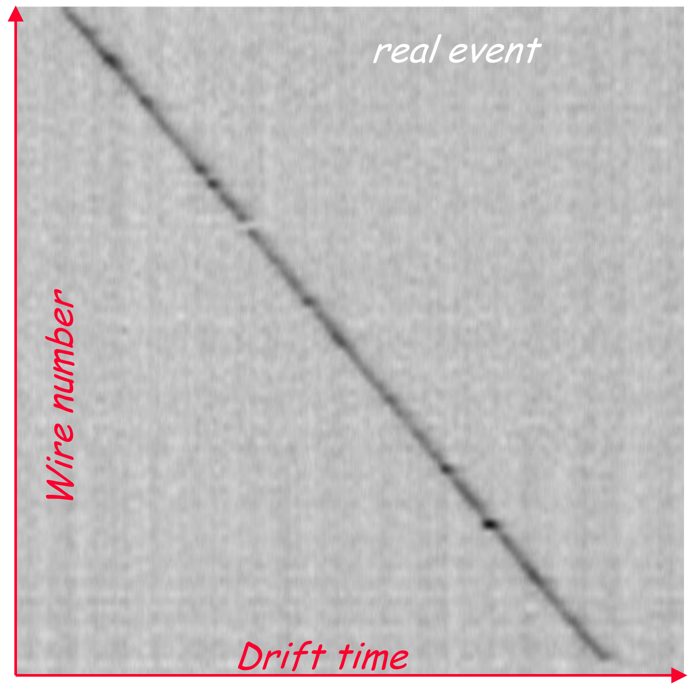
- New industrial purification methods have been developed at an exceptional level, especially remnants of O_2 which have to be initially and continuously purified.
- Extremely high τ_{ele} have been determined with cosmic μ's in a small 50 litres LAr-TPC.
- The short path length used (30 cm) is compensated by the high accuracy in the observation of the specific ionization
- The result here reported is $\tau_{ele} \approx 21$ ms corresponding to 15 ppt, namely $\approx 10^{-11}$ molecular impurities in Ar

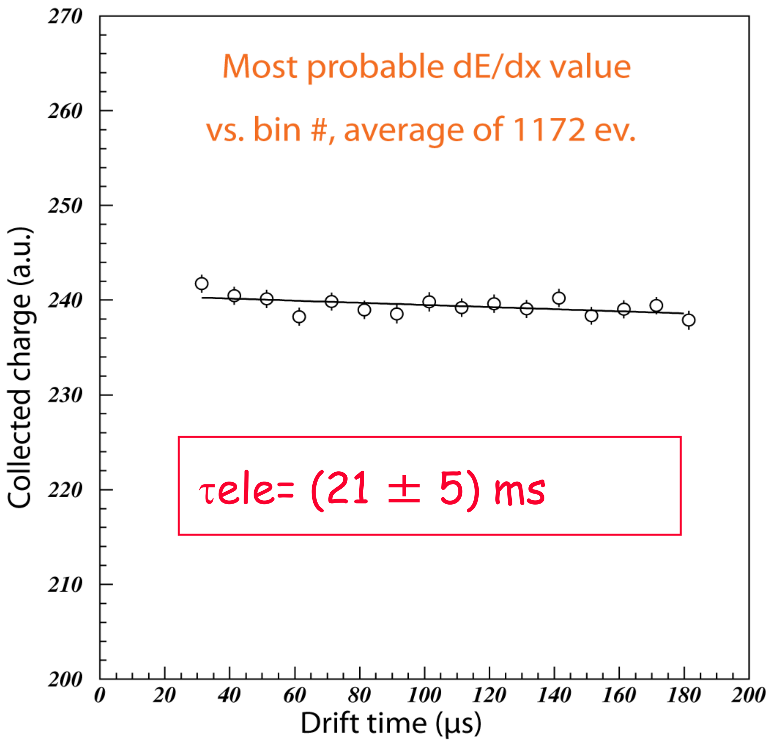


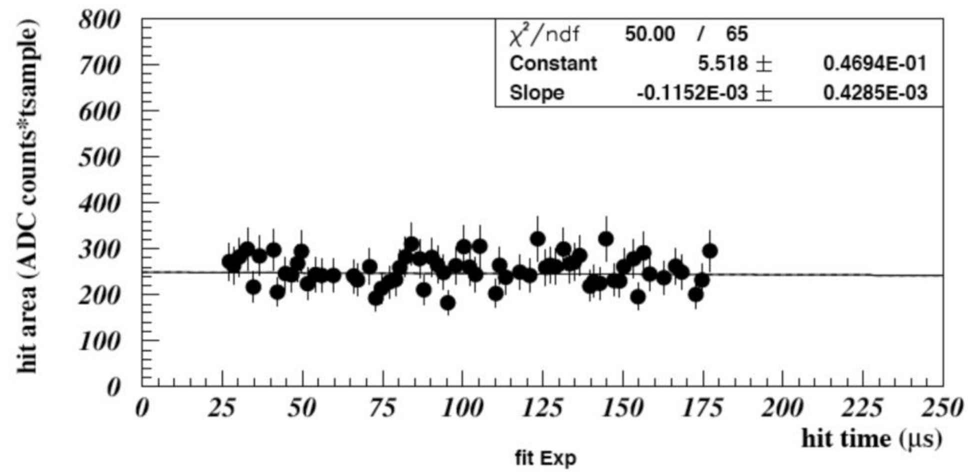


ICARINO-Legnaro

- The measured value to the experimental τ_{ele} corresponds to an attenuation of about 10 % for a longest drift of 5 meters, opening the way to exceptionally long drift distances.

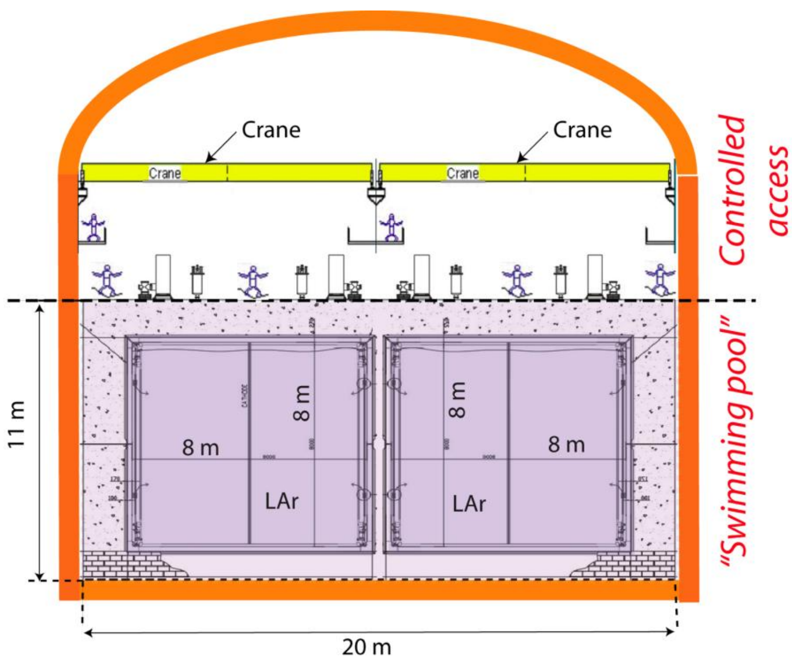


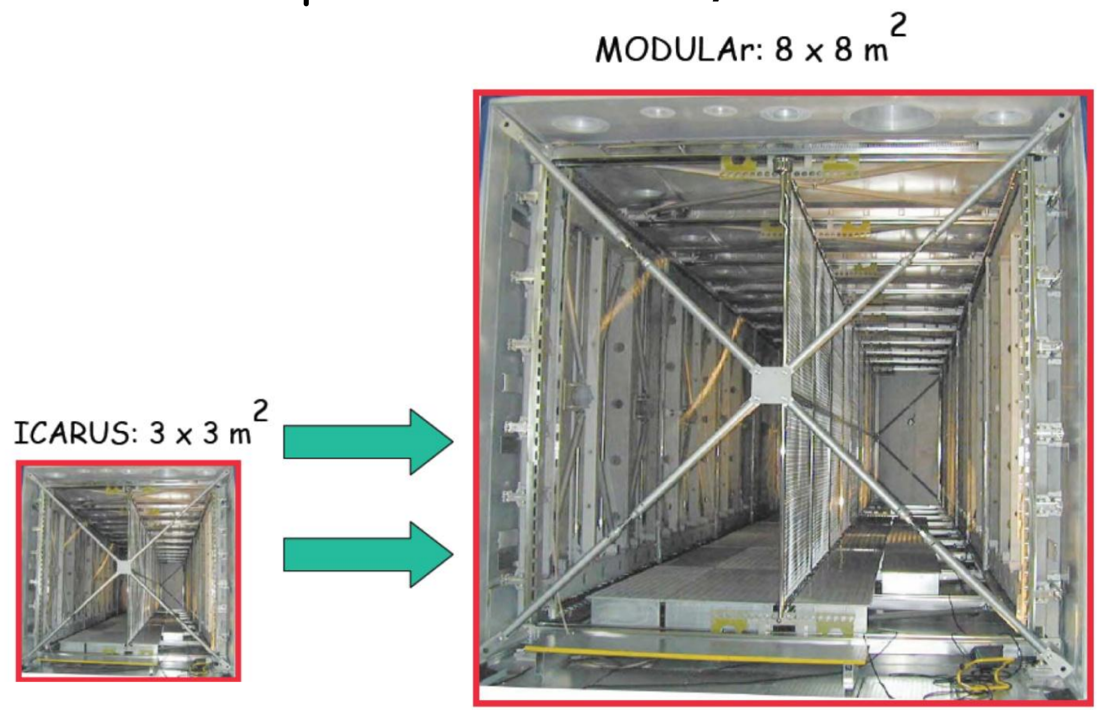




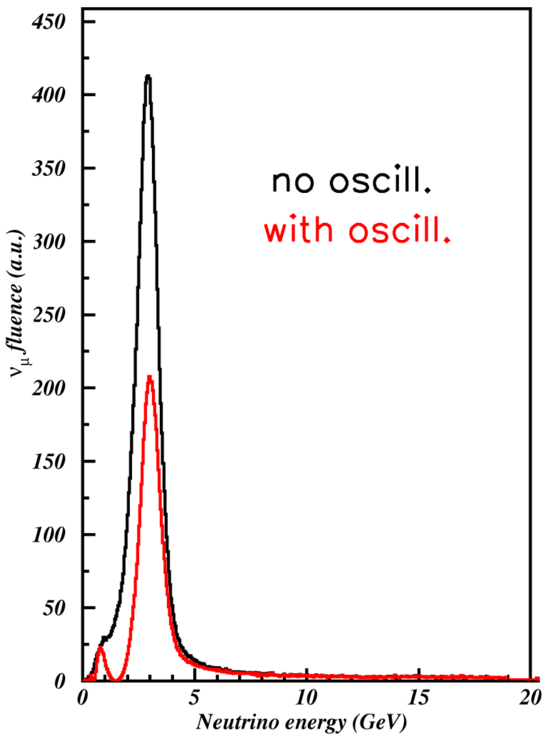
Toward 20 kton LAr-TPC: MODULAr project

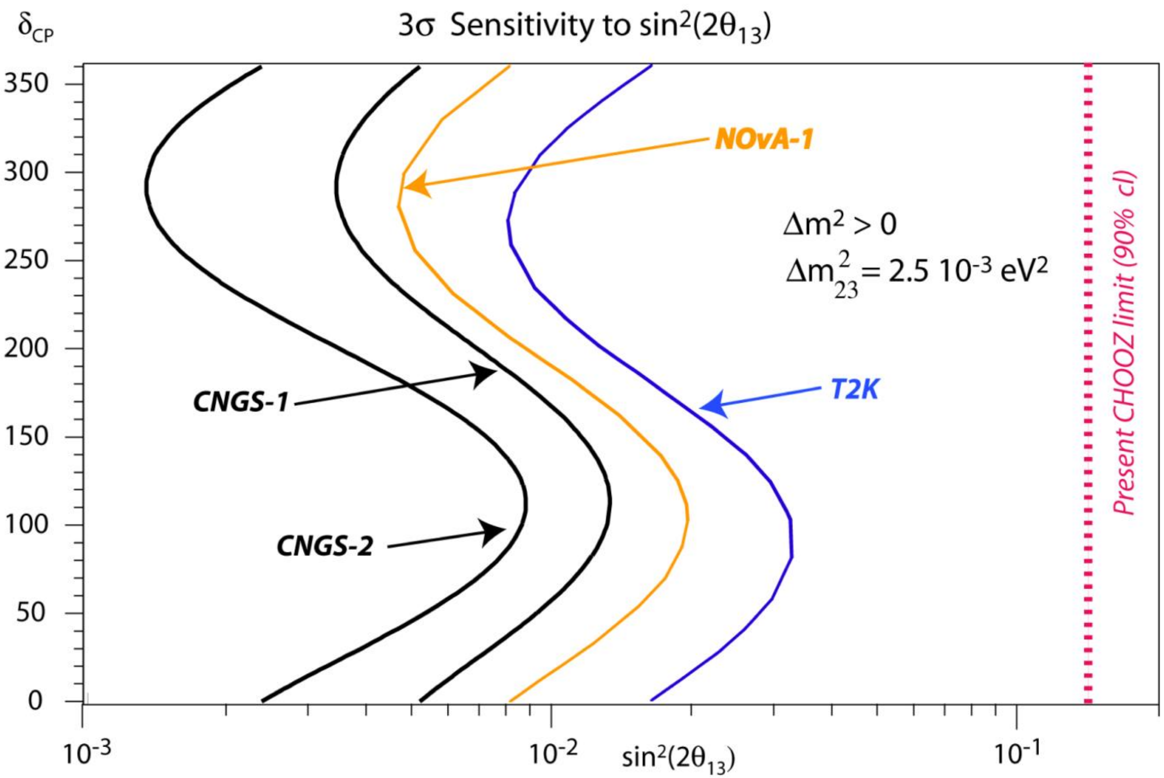
- The achieved milestones open the way to development of new line of modular elements, which may be progressively extrapolated to the largest conceivable LAr-TPC sensitive masses.
- Based on the T600 experience, the ICARUS collaboration has now proposed a next generation LAr-TPC in tens of kt scale: the MODULAr project. (*Astroparticle Physics 29 (2008) 174*)
- New 20 kt detector, *using the present CNGS beam off axis with 5 kton* units will maintain the majority of components developed with industry for T600.





MODULAr Sensitivity to θ_{13} and δ_{cp}





Event rates in MODULAr

20 kt, 5 y, 1.2 10^{20} pot/y, $\sin^2(2\theta_{13})$=0.1
5% beam systematics. $\Delta E/E$ = 15%

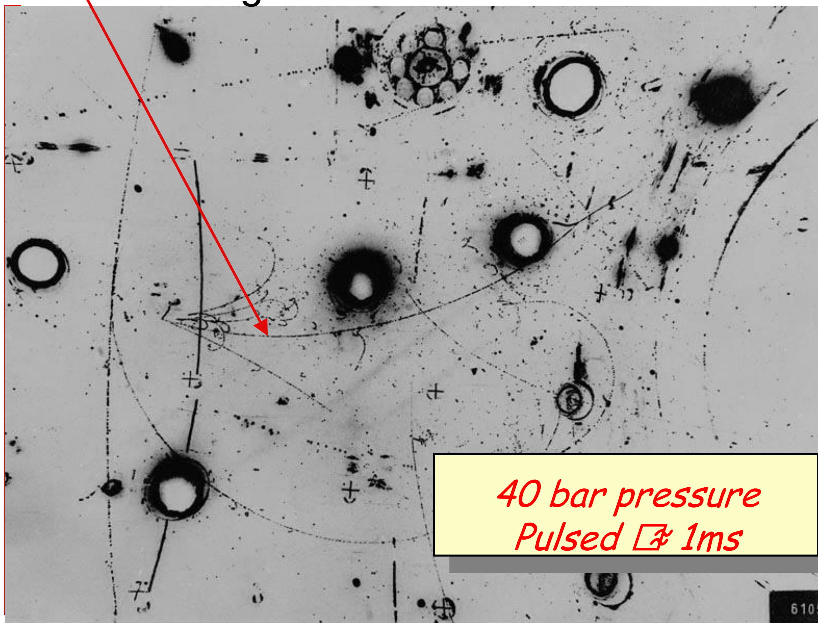
ν_μ CC	e bkg	Signal	S/√(bkg)
5700	28	250	47

Thirty years of progress........

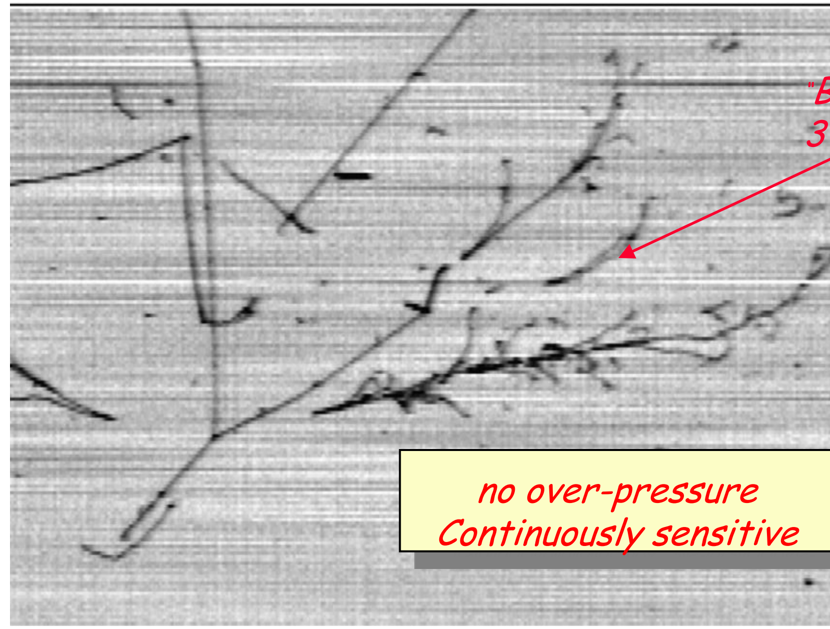
LAr is a cheap liquid (≈1CHF/litre), vastly produced by industry

Bubble diameter ≈ 3 mm (diffraction limited)

Gargamelle bubble chamber



ICARUS electronic chamber

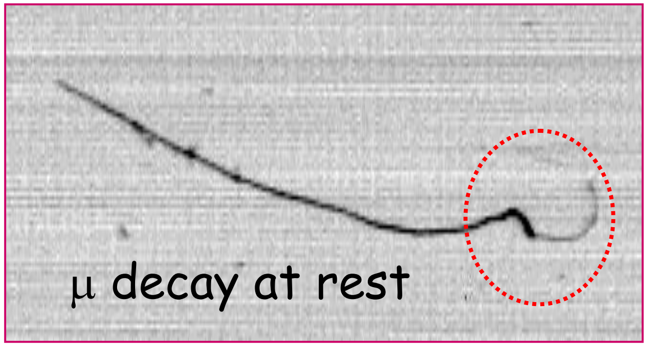


Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm^3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

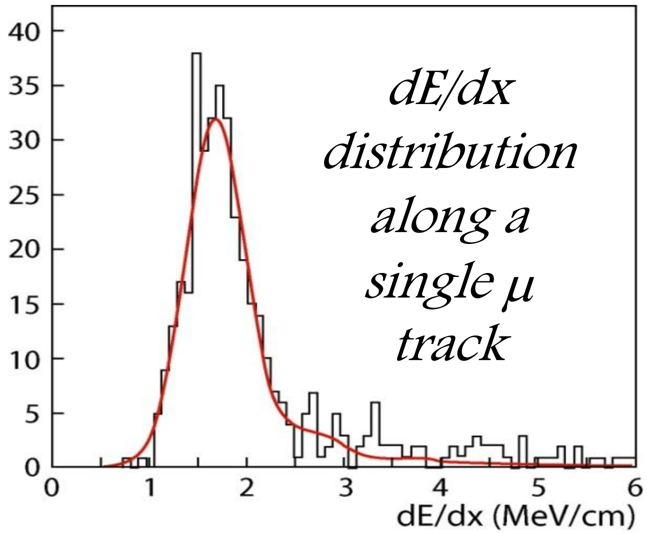
Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm^3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

LAr-TPC performance -1

- Tracking device:
  - precise event topology ($\sigma_{x,y}$ ~ 1mm, σ_z ~ 0.4mm)
  - μ momentum measurement via multiple scattering: $\Delta p/p$ ~10-15% depending on track length and p



- Measurement of local energy deposition dE/dx:
  - e/γ separation (2% X_0 sampling);
  - particle ID by means of dE/dx vs range
  - e/π^0 discrimination at 10^{-3} by γ conversion from vertex, π^0 mass and dE/dx measurements (90 % electron identification efficiency)



- Total energy reconstruction by charge integration:
  - full sampling, homogeneous calorimeter with excellent accuracy for contained events

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): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

LAr-TPC performance -2

(A) momentum resolution of stopping muons;

(B) momentum resolution of traversing μ with the Kalman filter method: p is extracted from measurement of deflection angle ϕ and from χ^2 of the fit.

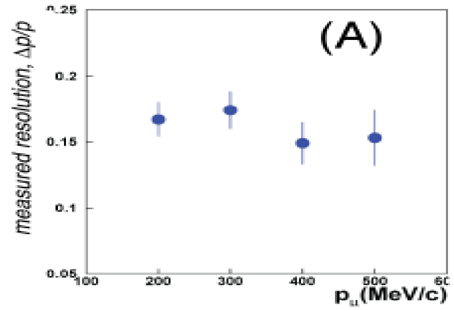
(C) dE/dx energy loss for slow π (green) and protons (red);

(D) Michel electron decay spectrum from $\mu \rightarrow e$ decays;

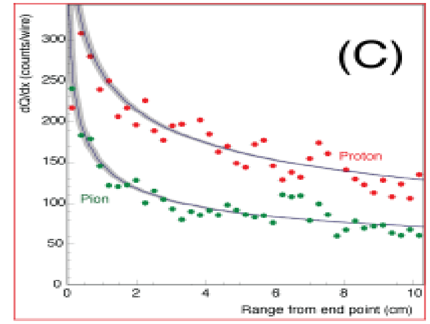
(E) $\pi^0 \rightarrow 2\gamma$ reconstruction and mass determination;

(F) mass spectrum of 230 interactions with $\gamma\gamma$ candidates.

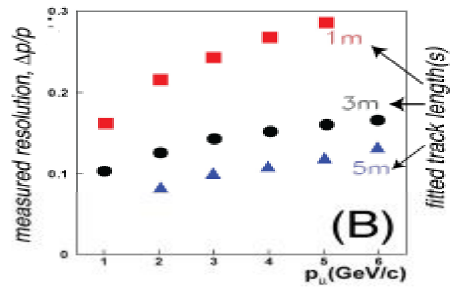
stopping muons



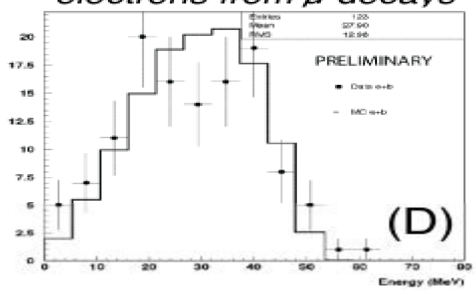
dE/dx energy losses



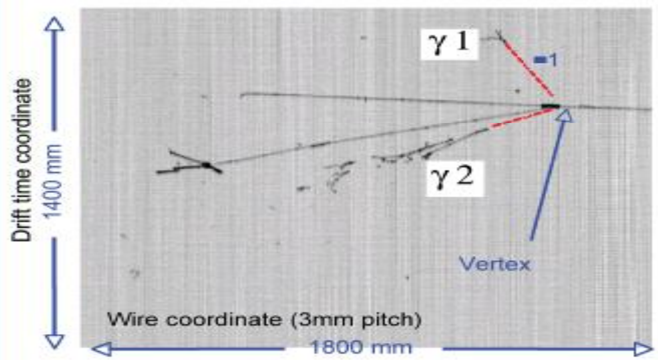
traversing muons
Kalman filter on segmented track

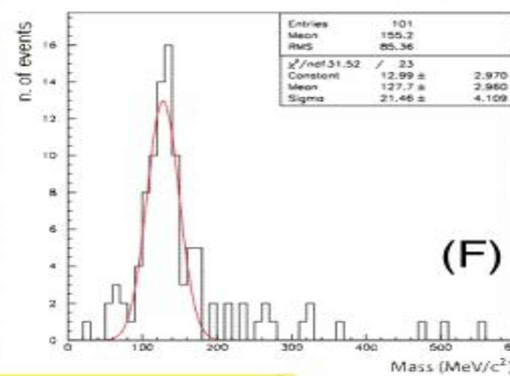


electrons from μ decays



$\pi^0 \rightarrow 2\gamma$ *event reconstruction and mass determination* (E)



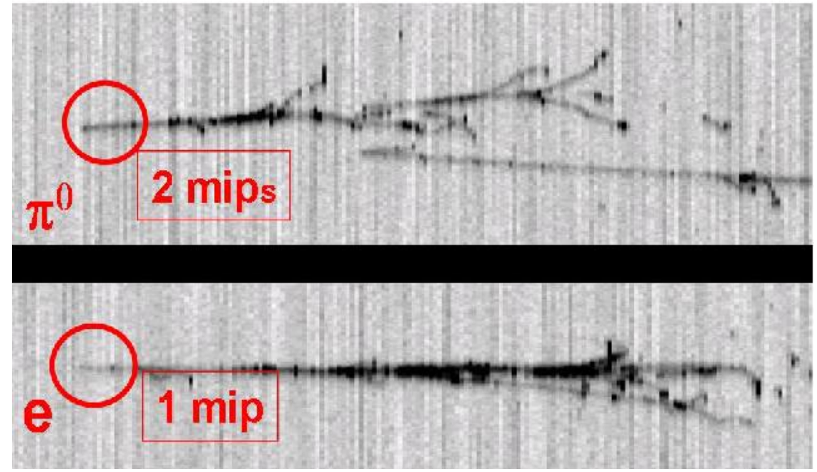


$$m_{\gamma\gamma} = 133.4 \pm 3.0(stat) \pm 4.0(sys)\mathrm{MeV/c^2}$$

LAr- TPC performance-3: Electron $-\pi^0$ separation

NC π^0 background suppressed in LAr at 10^{-3} level by:

- Topology (γ conversion from vertex)
- Reconstructed π^0 mass
- Electron/photon separation (dE/dx)



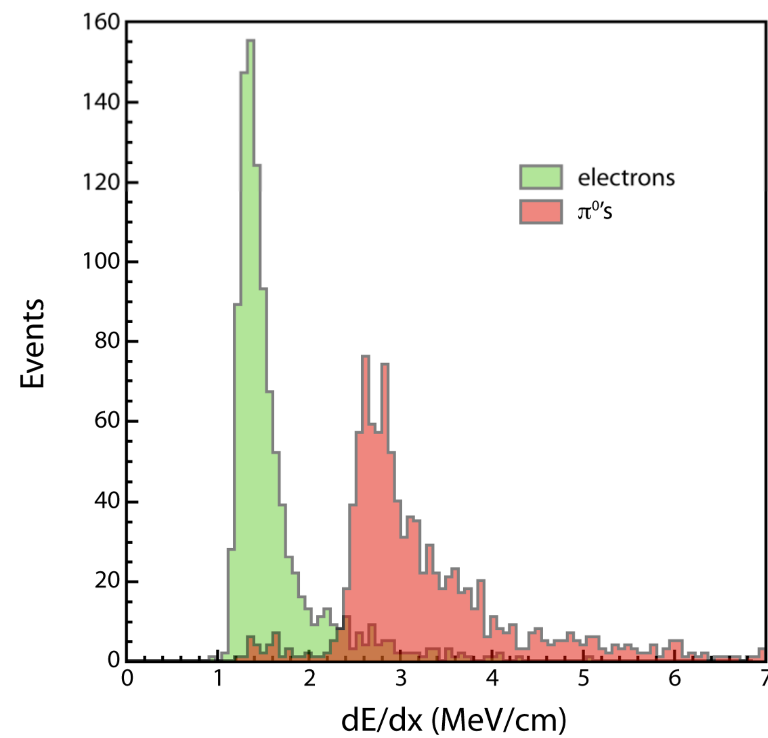
Electron identification efficiency: 90 %

Residual misidentification < 0.1 %

ν_μ to ν_e oscillations:

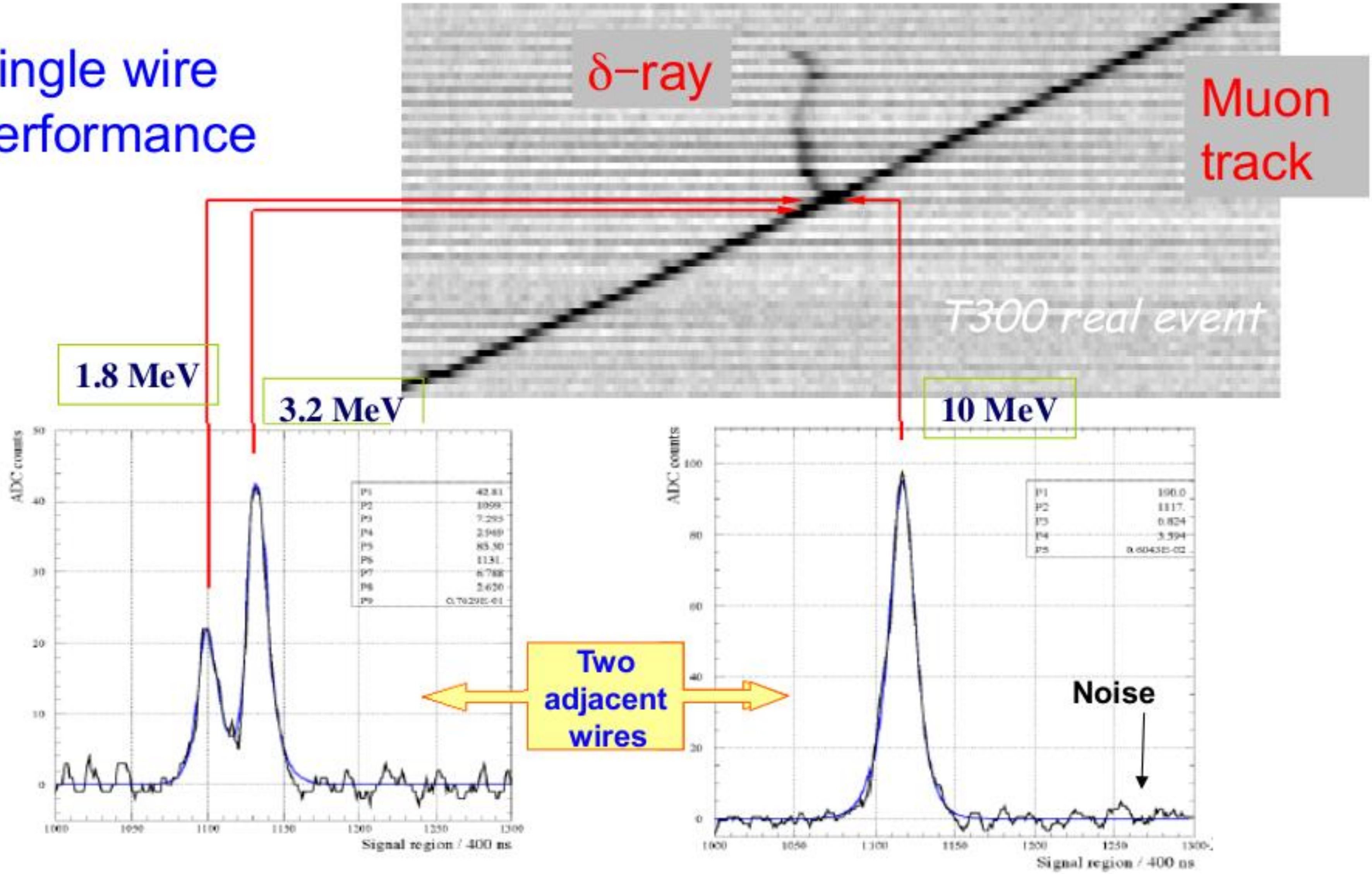
much higher discovery potential of LAr w.r.t. L-Scint./W-Cherenkov:

5 kton LAr detector = 20 kton of L-Scint

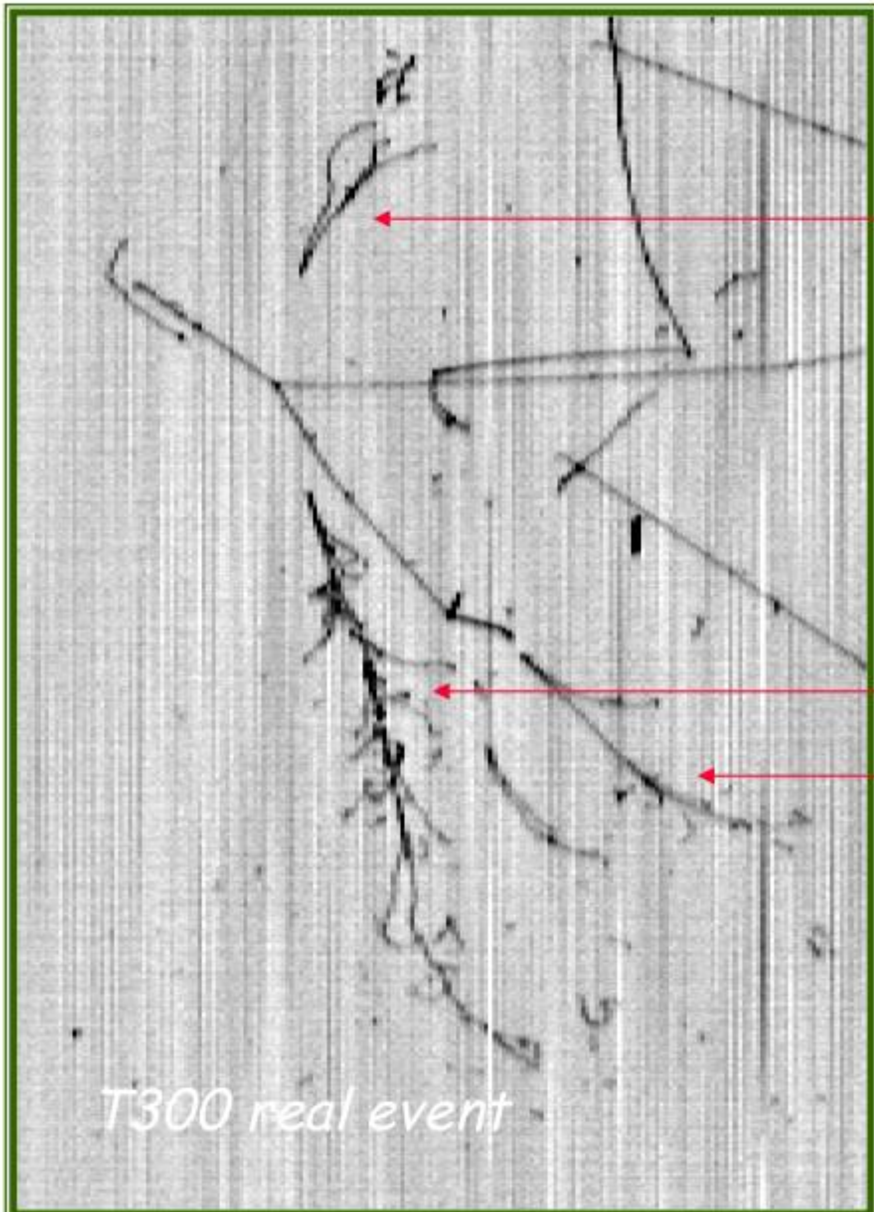


Low energy detail

Single wire performance



3D π^0 identification and reconstruction



$$M_{inv} = \sqrt{2E_1E_2\cos(\theta_{12})}$$

158 MeV

752 MeV

140 MeV

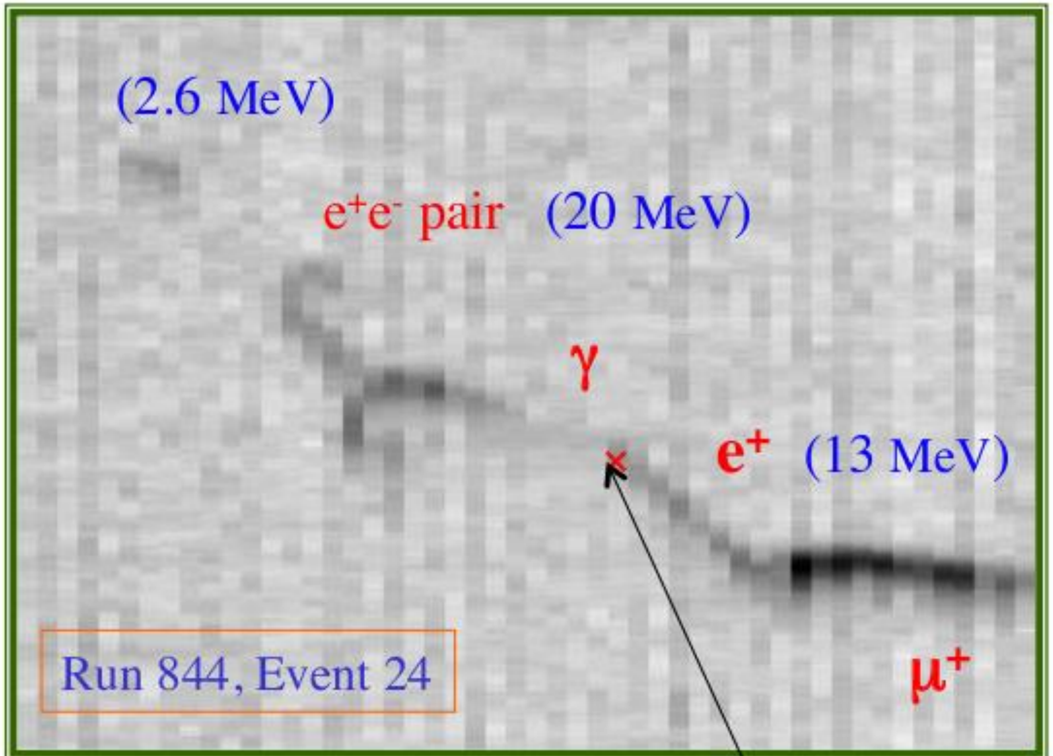
θ = 141°

M_{inv} = 650 MeV

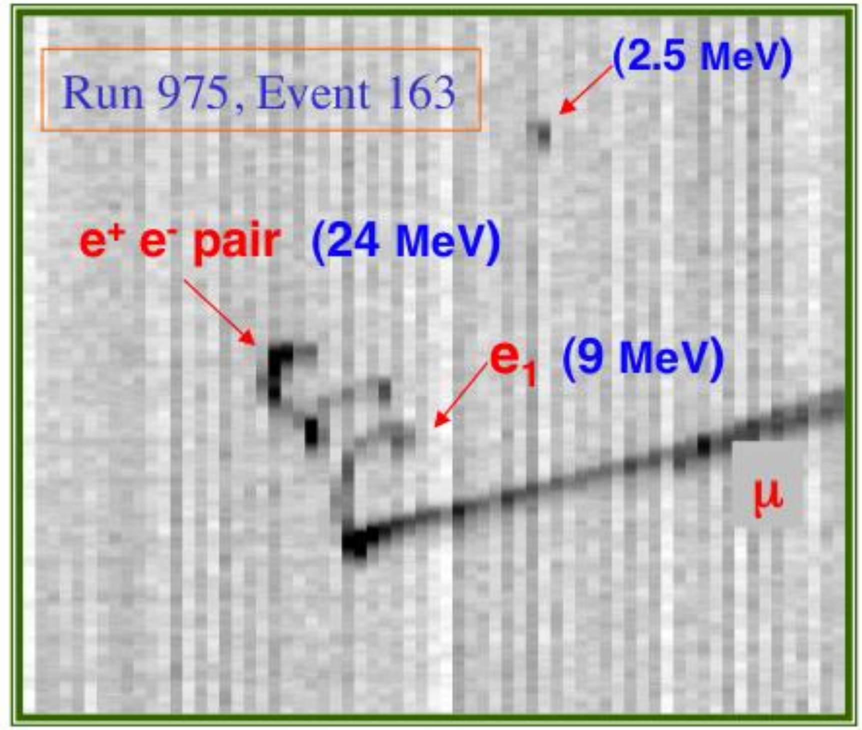
θ = 25°

M_{inv} =140 MeV

3D Bremsstralung + Pair-production

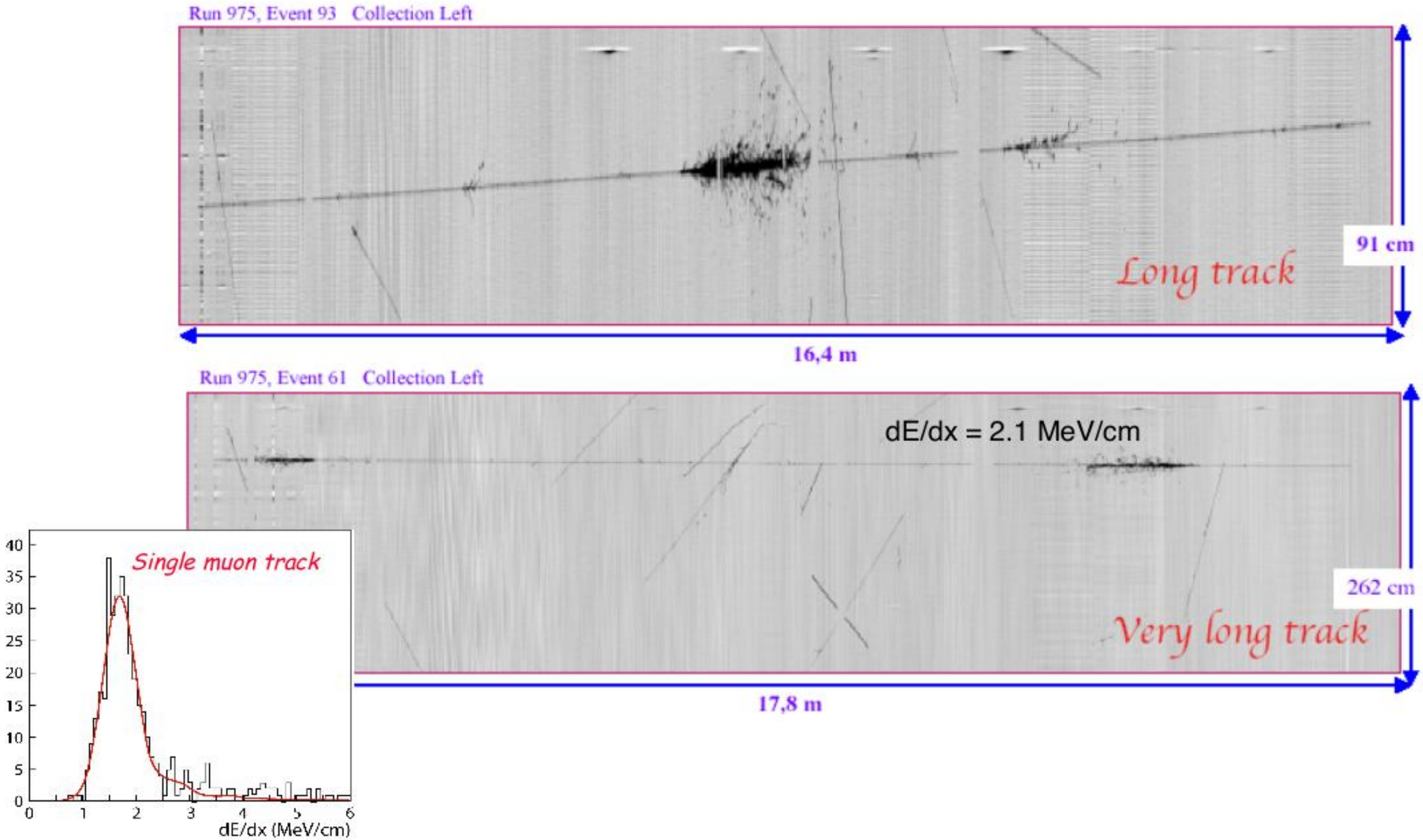


Annihilation point

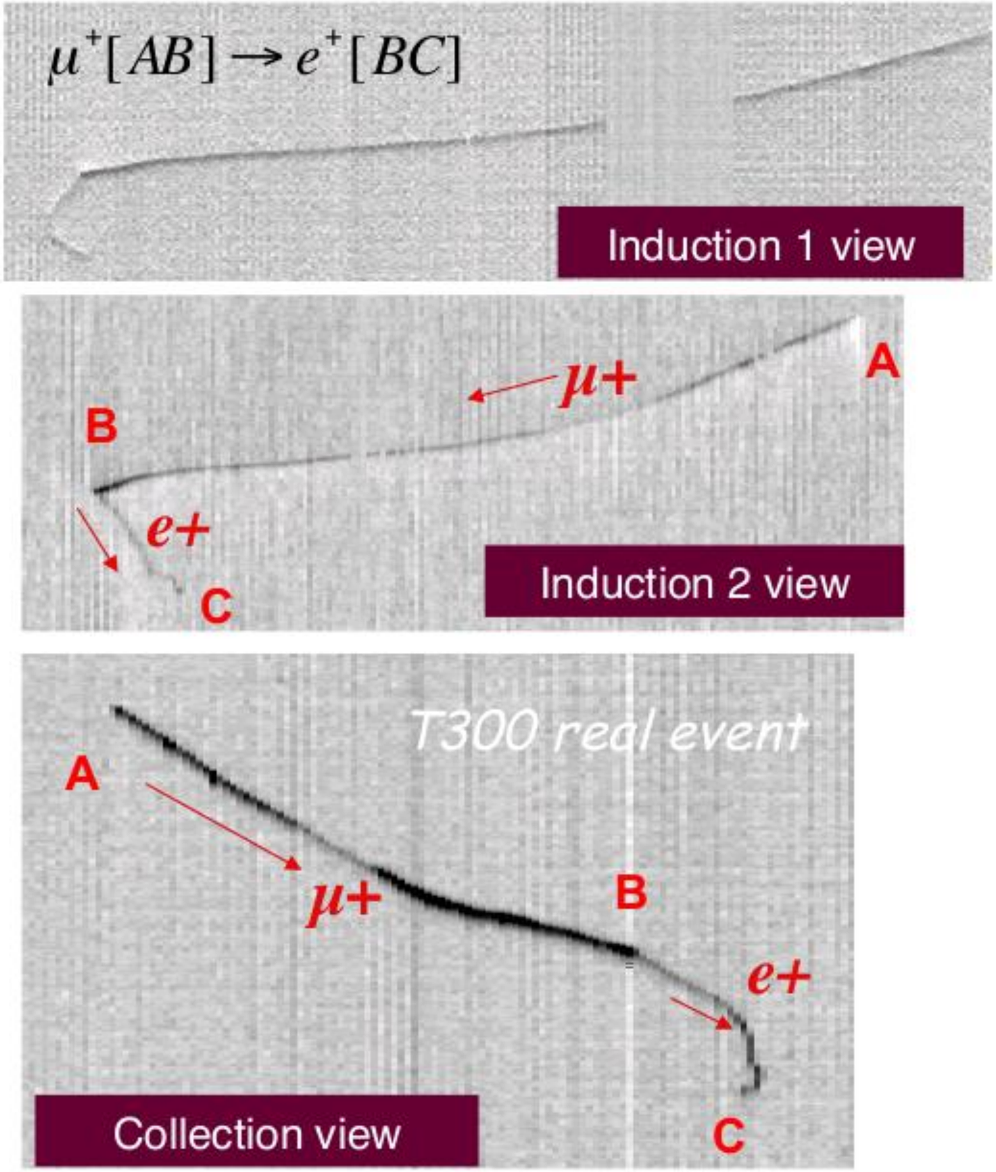


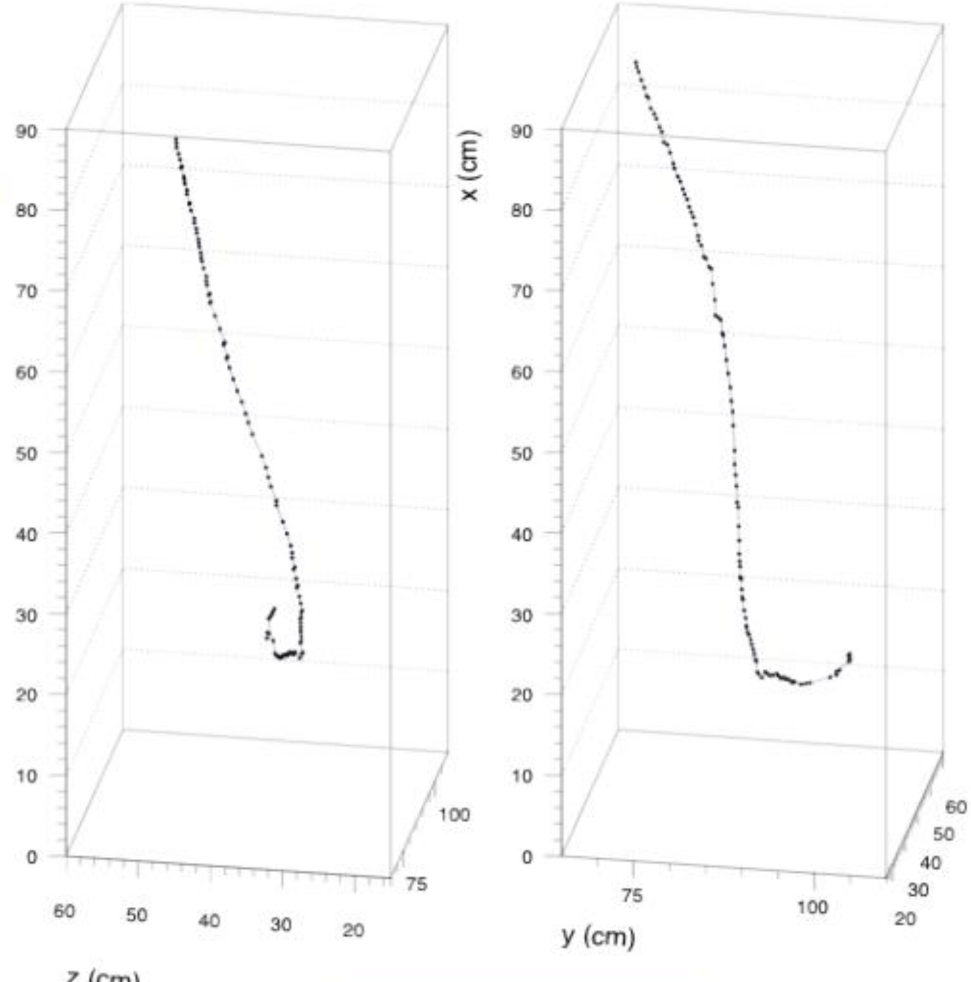
≈20% of positron from μ decays expected to annihilate before stopping

A long muon track



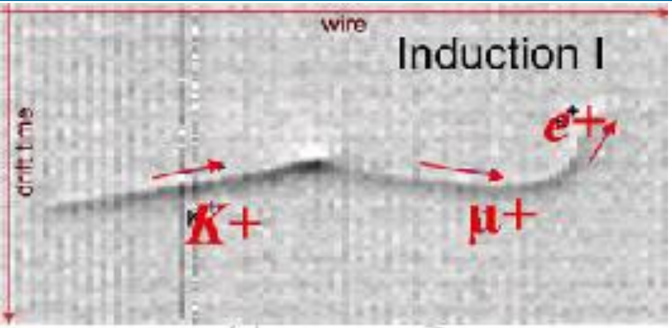
3D reconstruction: stopping μ

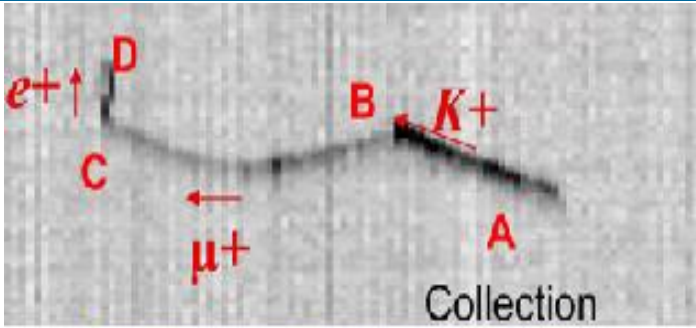




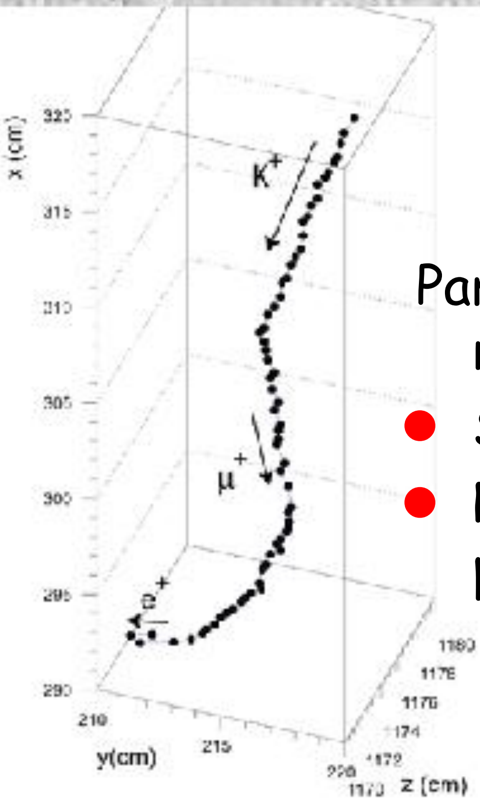
T_e=36.2 MeV
Range=15.4 cm

Particle ID: K^+ μ^+ e^+, π/P



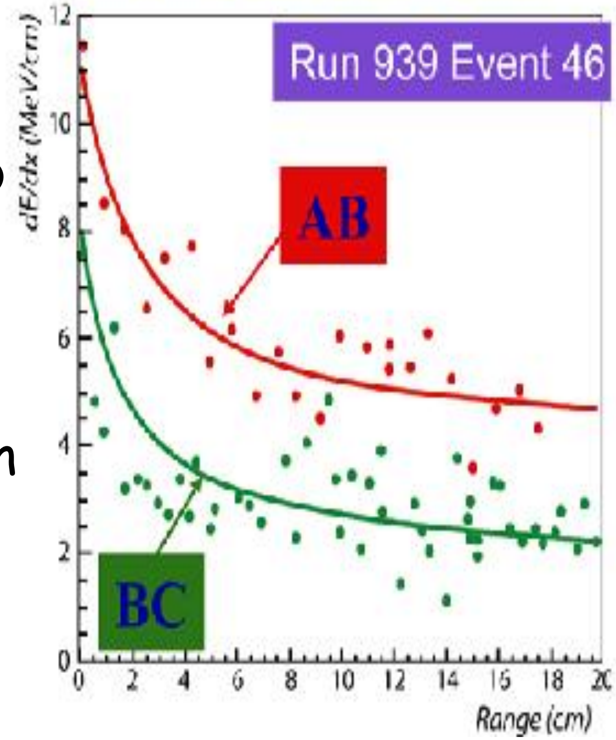


$$K^+[AB] \to \mu^+[BC] \to e^+[CD]$$

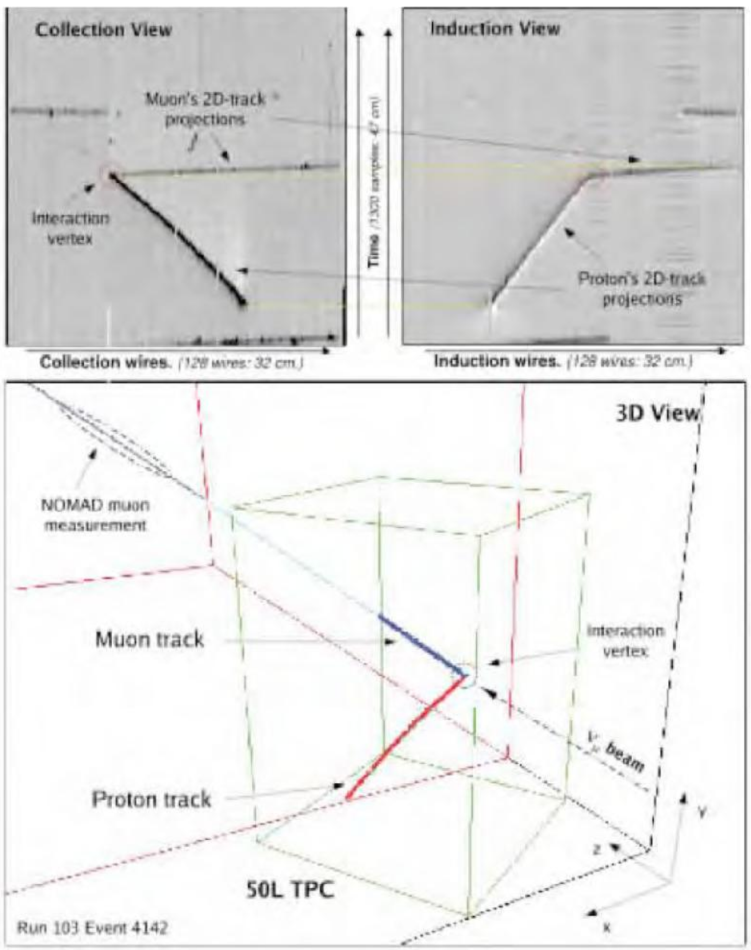


Particle identification by precise 3D reconstruction, dE/dx, range

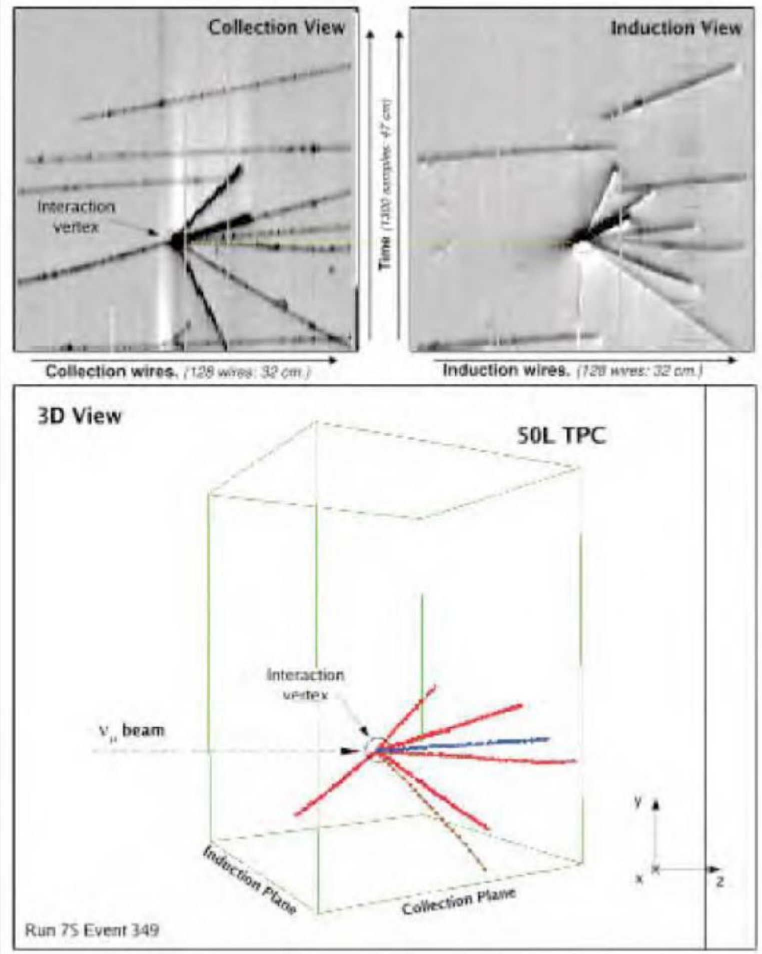
- Stopping power
- Recognition of secondary particle production after decay/interaction



- Quasi-elastic events reconstructed @ CERN WANF:
  - quasi-elastic event with a muon and a proton recoil track (A)
  - a multi-prong neutrino event reconstructed in 3D (B)



(A)

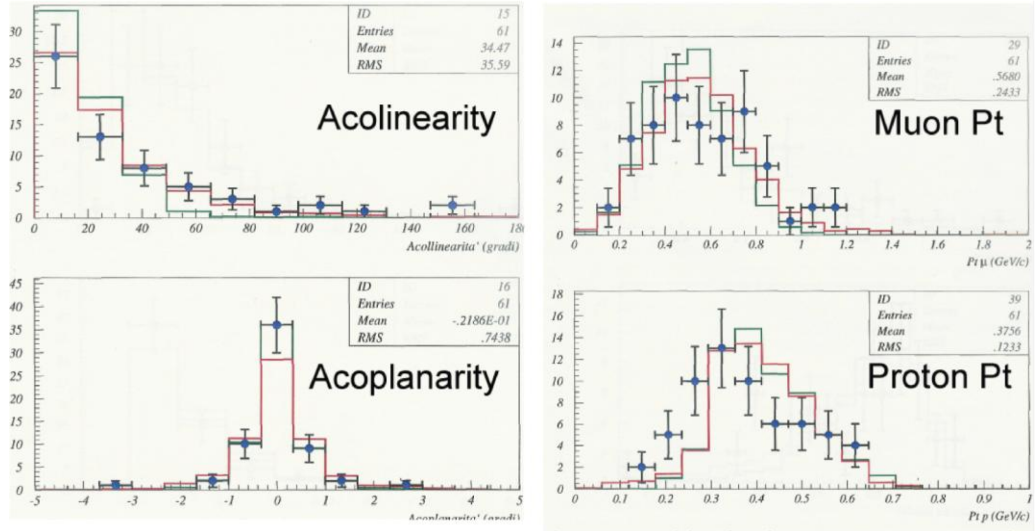


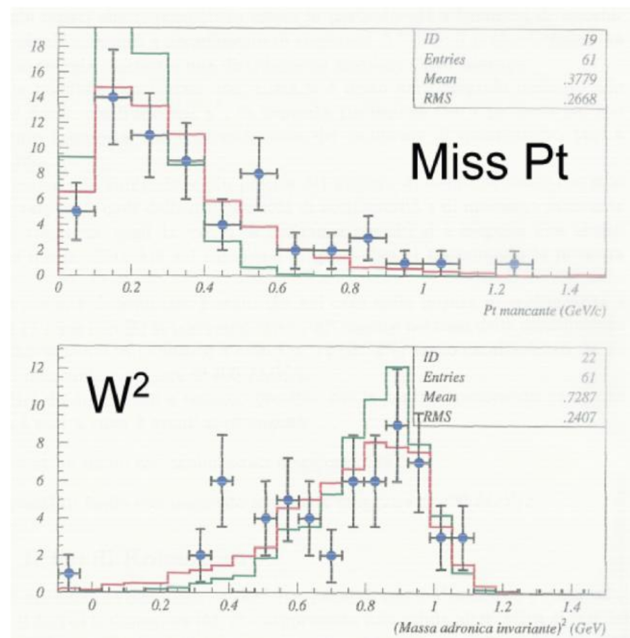
(B)

200 quasi elastic final states with one proton $T_P>50$ MeV

- Quasi-elastic neutrino events in LAr have been reconstructed in the 50 litre ICARUS LAr-TPC exposed to the CERN-WANF beam in coincidence with the NOMAD experiment.

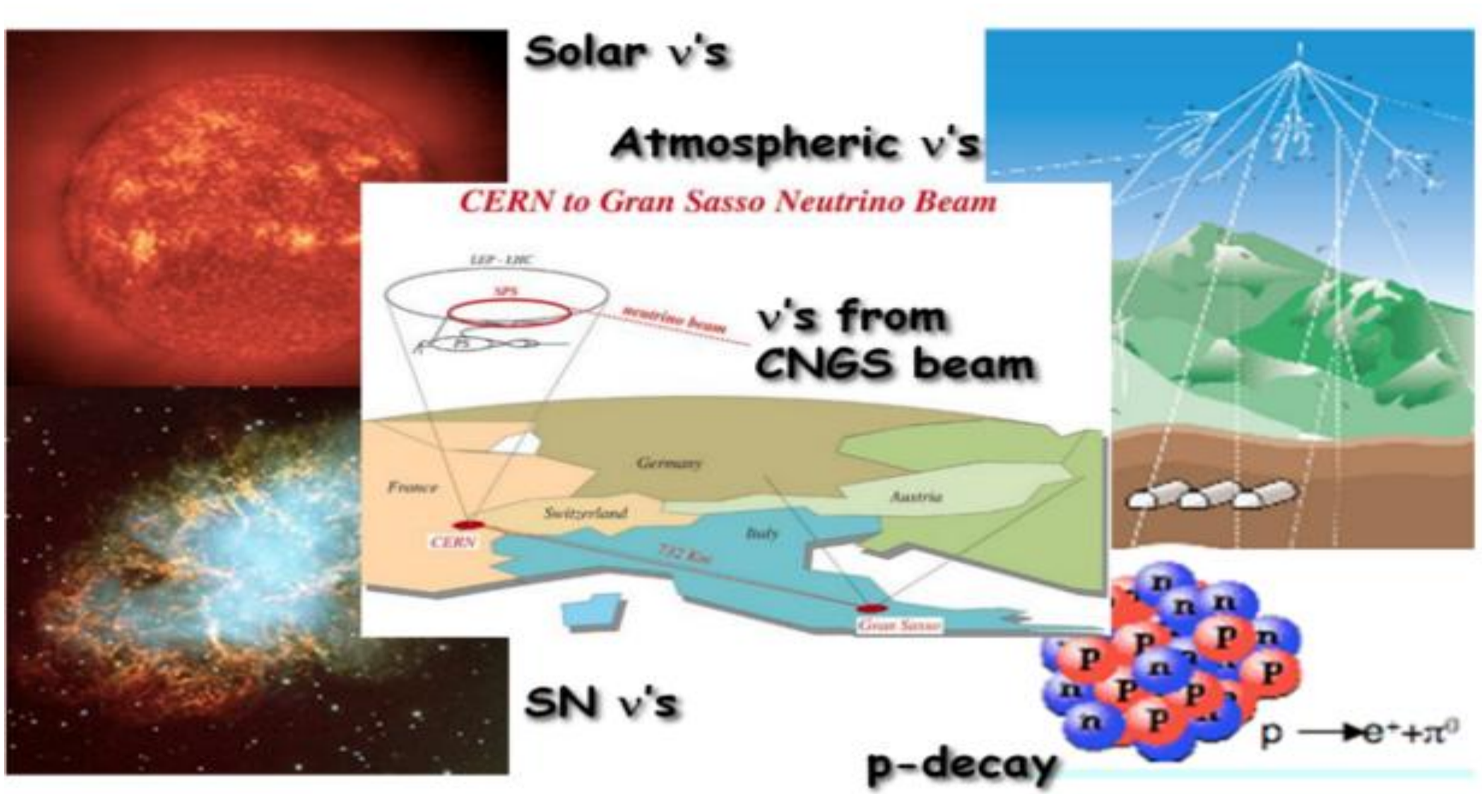
- Simulations, accounting for Nuclear Fermi motion and re-interactions in nuclei, are found in good agreement with a 200 pure lepton-proton final state events with 1 proton TP > 50 MeV (range > 2 cm) and any number protons TP< 50 MeV.



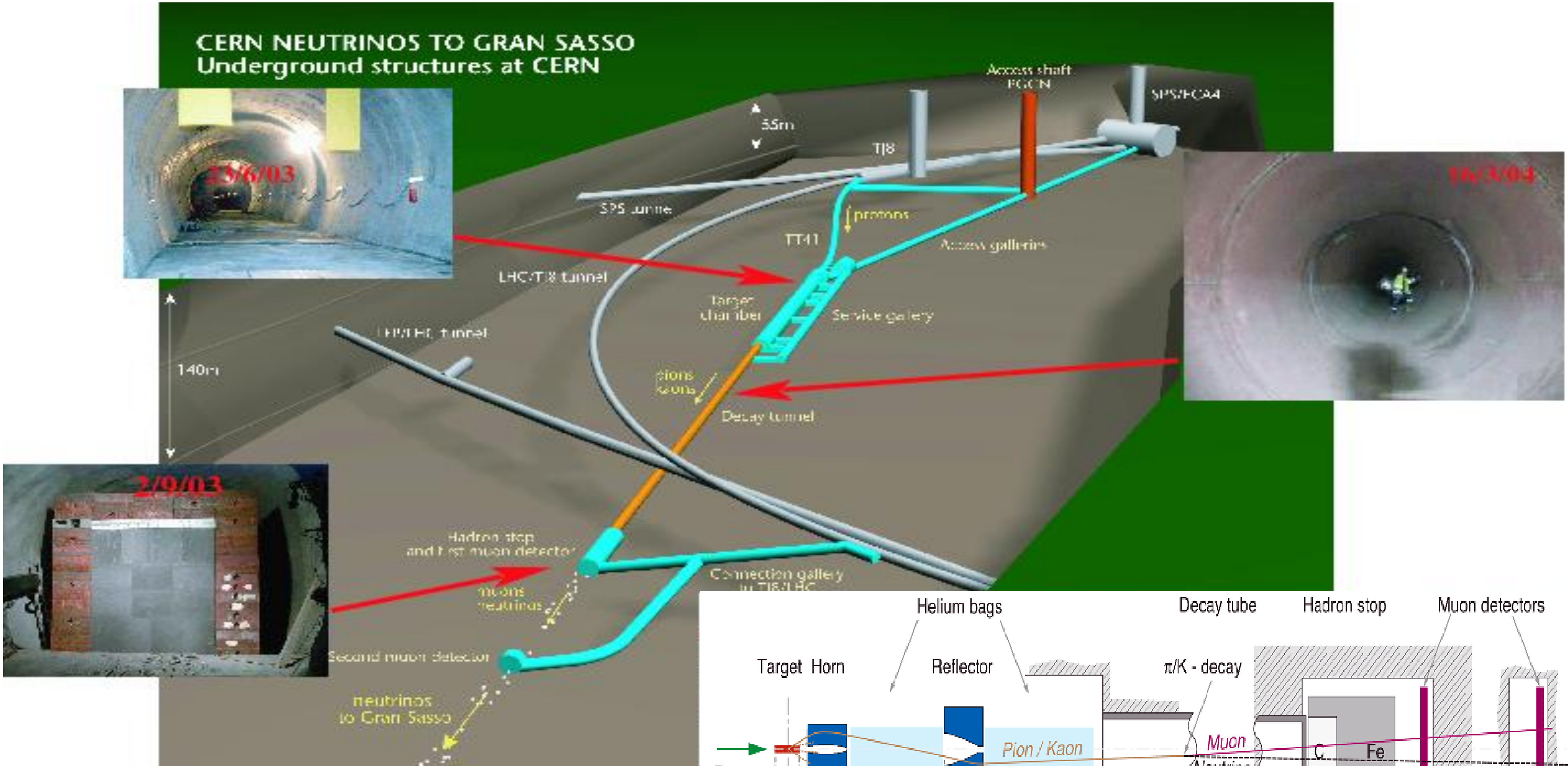


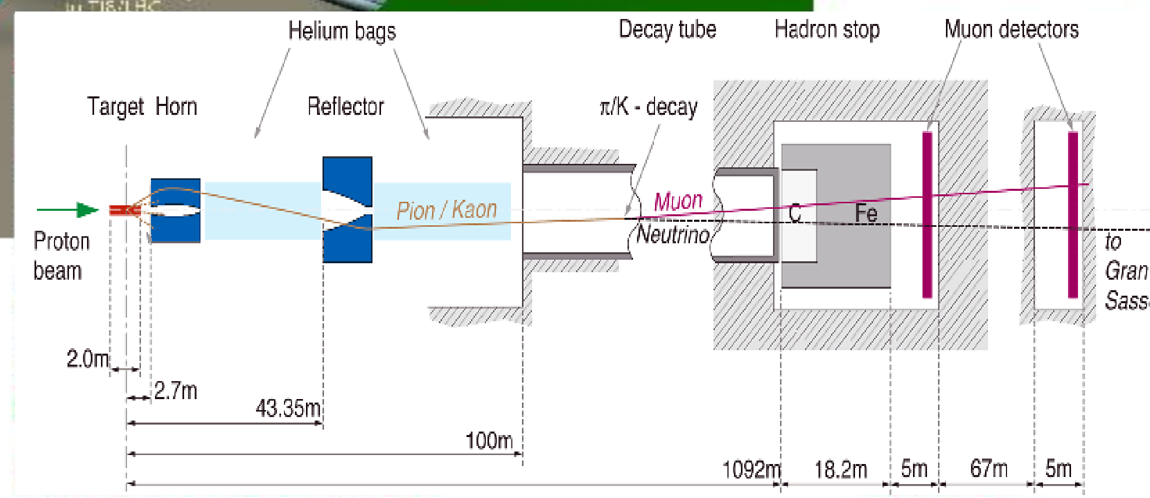
ICARUS T600: a marvelous detector exploring new physics

- A major milestones in the practical realization of a large scale LAr detector: now operational in Hall B of LNGS
- ICARUS-T600 at LNGS will collect simultaneously "bubble chamber like" neutrino events of different nature, investigating also the barion matter stability



Present CNGS neutrino facility for ν_μ to ν_τ appearance



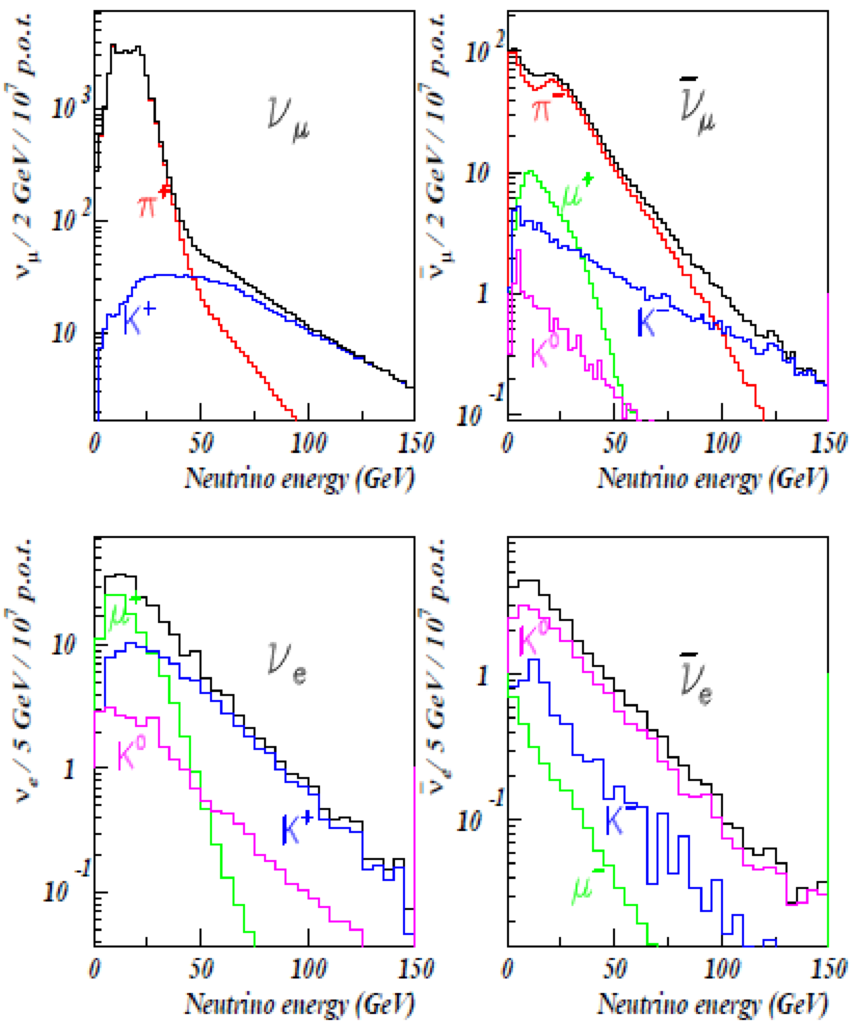


- 2 fast 400 GeV/c p estractions
  2 x 2 10^{13} protons every 6 s
- 0.5 MW on target, 4.5 10^{19} pot/y

CNGS target


INFN
CNGS target
and target
revolver
Graphite
13 rods , spaced
4 or 5 mm diameter
total length 2m
C length ≈ 130 cm
FOR LOW FOCUS:
1 m
without spaces
11

Expected neutrino flux @ Gran Sasso



	Flux ($\nu/\text{cm}^2/10^{19}$pot)	$< E_\nu >$ $[GeV]$	ν_i/ν_μ (%)	ν_i/ν_μ-CC (%)
ν_μ	$7.4 \cdot 10^6$	17.9		
$\overline{\nu}_\mu$	$2.9 \cdot 10^5$	21.8	3.9	2.40
ν_e	$4.7 \cdot 10^4$	24.5	0.65	0.89
$\overline{\nu}_e$	$6.0 \cdot 10^3$	24.4	0.08	0.06

CC event rate - FLUKA calculation -

600 $\nu_\mu CC/kt/10^{19}$ pot

5.5 $\nu_e CC/kt/10^{19}$ pot

ancillary experiment at CERN-SPS to measure hadron production: SPY: Secondary Particle Yield

ICARUS T600 @ LNGS: 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**.

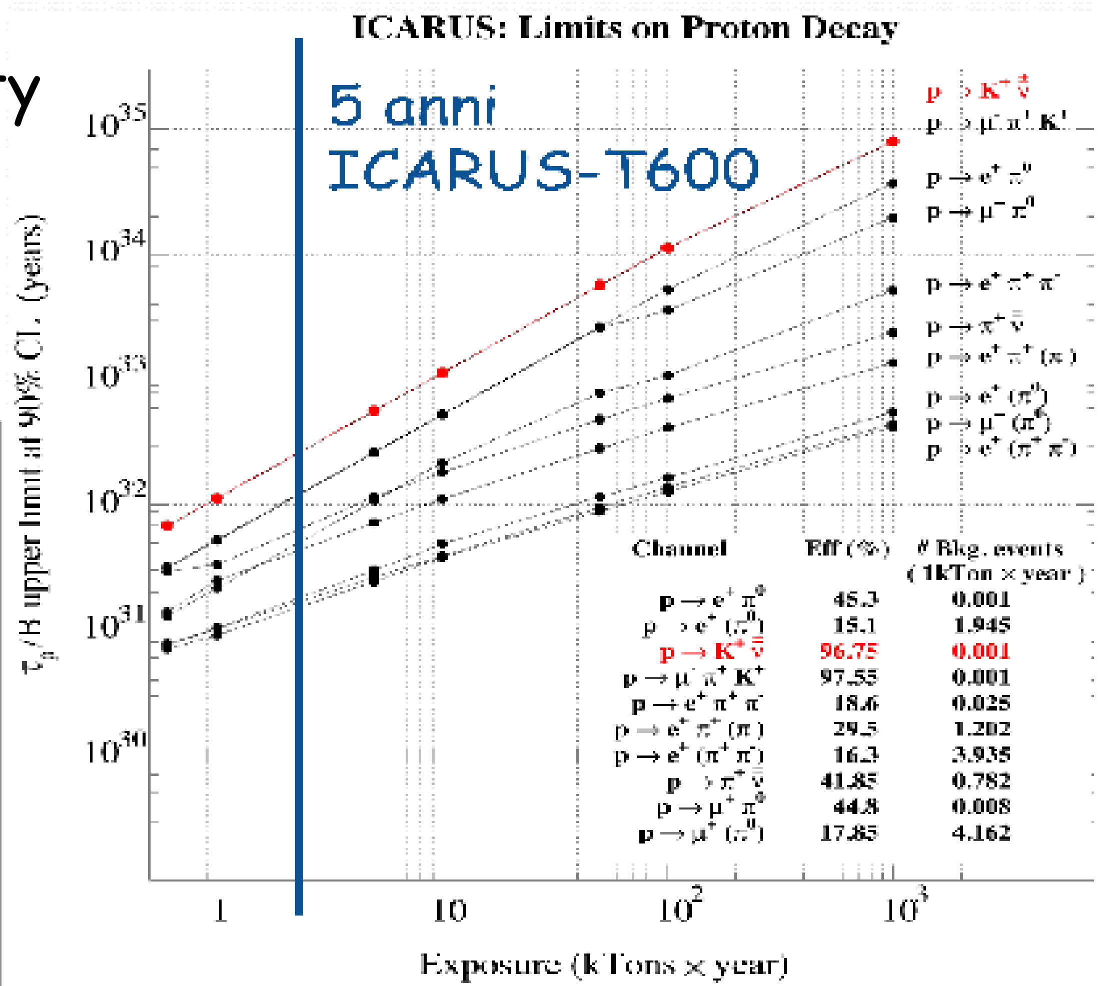
- CNGS ν events (beam intensity 4.5 10^{19} pot/year, E_ν ~ 17.4 GeV):
  - 1200 ν_μ CC event/year;
  - ~ 8 ν_e CC event/year;
  - observation of ν_τ in electron channel, with kinematical criteria;
  - search for sterile ν in LSND parameter space (deep inelastic ν_e CC events excess).

- "Self triggered" events collection:
  - ~ 80 events/y of unbiased atmospheric ν CC;
  - zero bkg proton decay, 3 x 10^{32} nucleons for "exotic" channels.

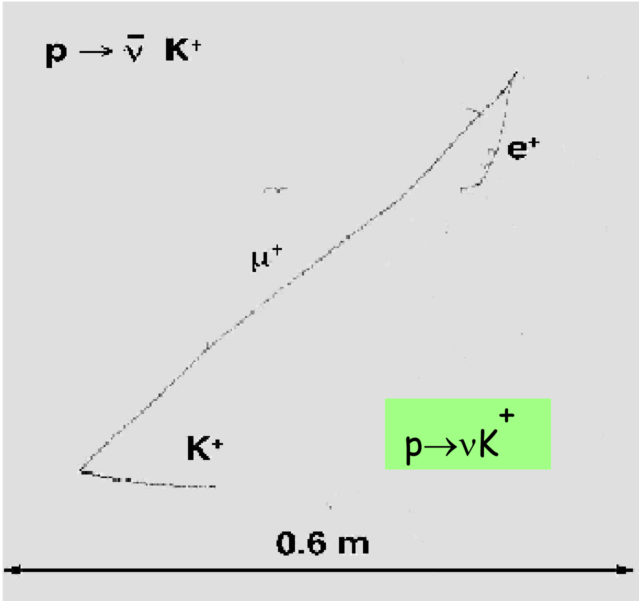
Nucleon decay search

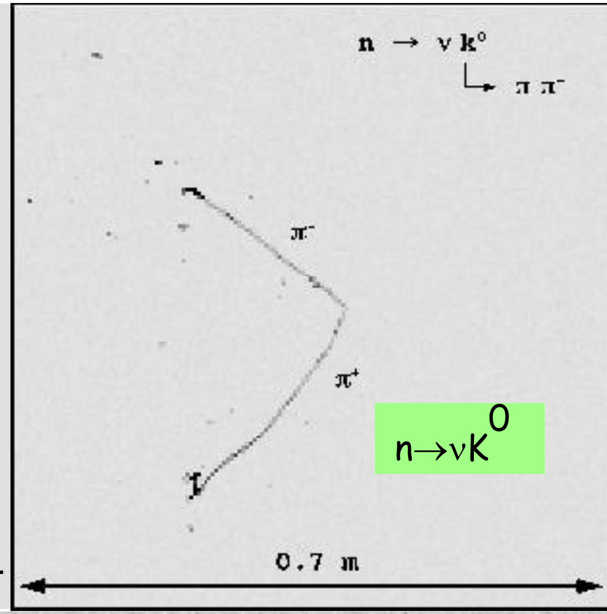
- 3 10^{32} nucleons
- Several bkg-free channels: the experimental sensitivity increases linearly with the exposition time

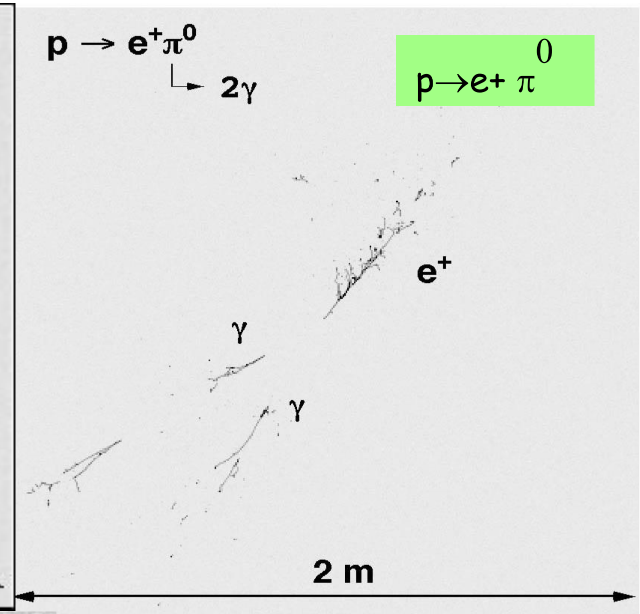
Decay channel	PDG limit [10^{31} anni]	T600 yrs to reach PDG limit
$n \to e^- K^+$	3,2	0,5
$p \to \pi^+ \bar{\nu}$	2,5	1,1
$n \to \mu^+ \pi^-$	10,0	3,3
$p \to \mu^- \pi^+ K^+$	24,5	4,5
$n \to \pi^0 \bar{\nu}$	11,2	5,1
$n \to e^+ \pi^-$	15,8	5,3

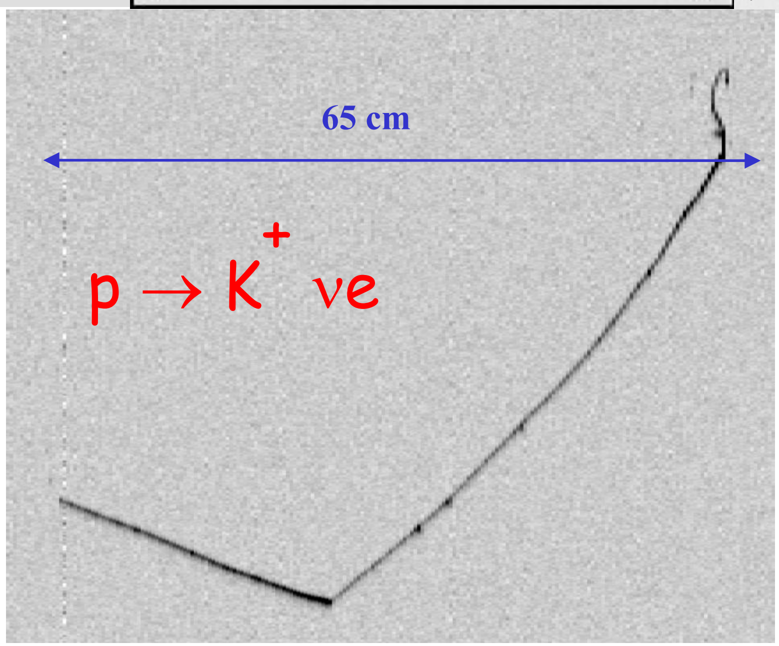


Nucleon decay : single event capability

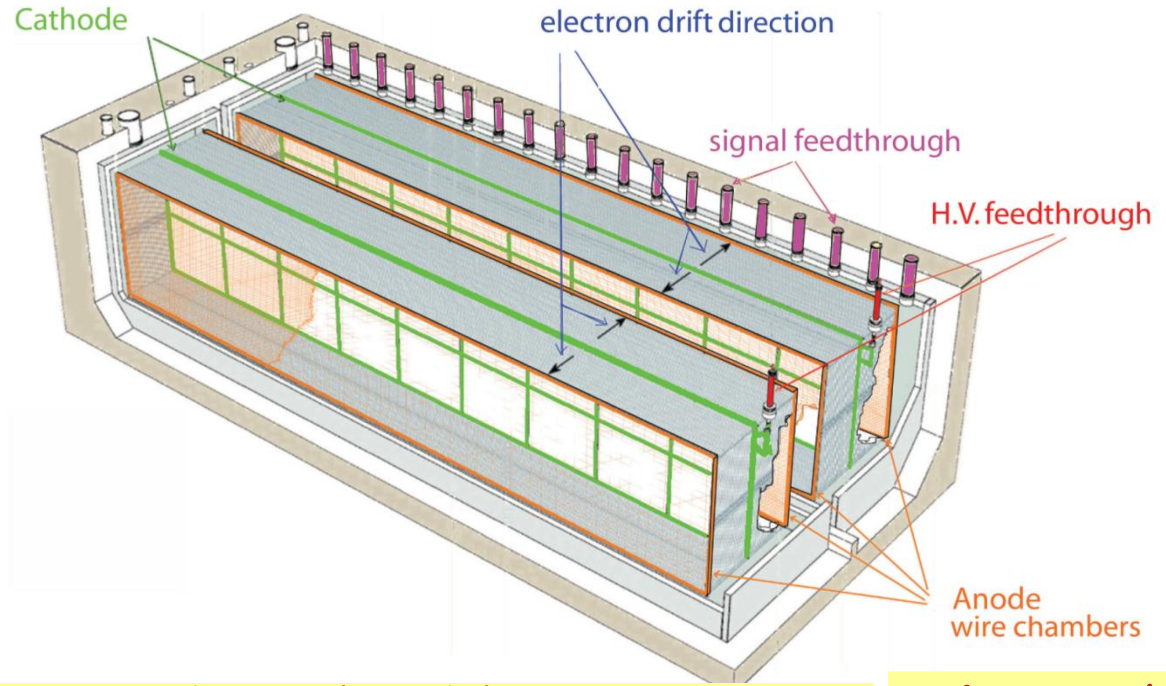


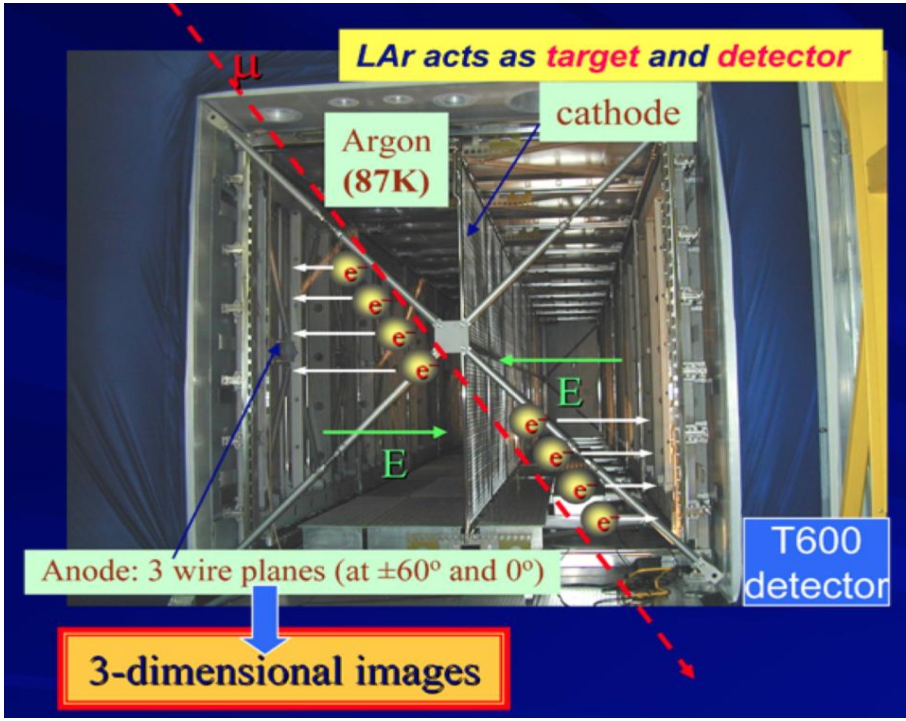






ICARUS T600: the first large scale LAr detector

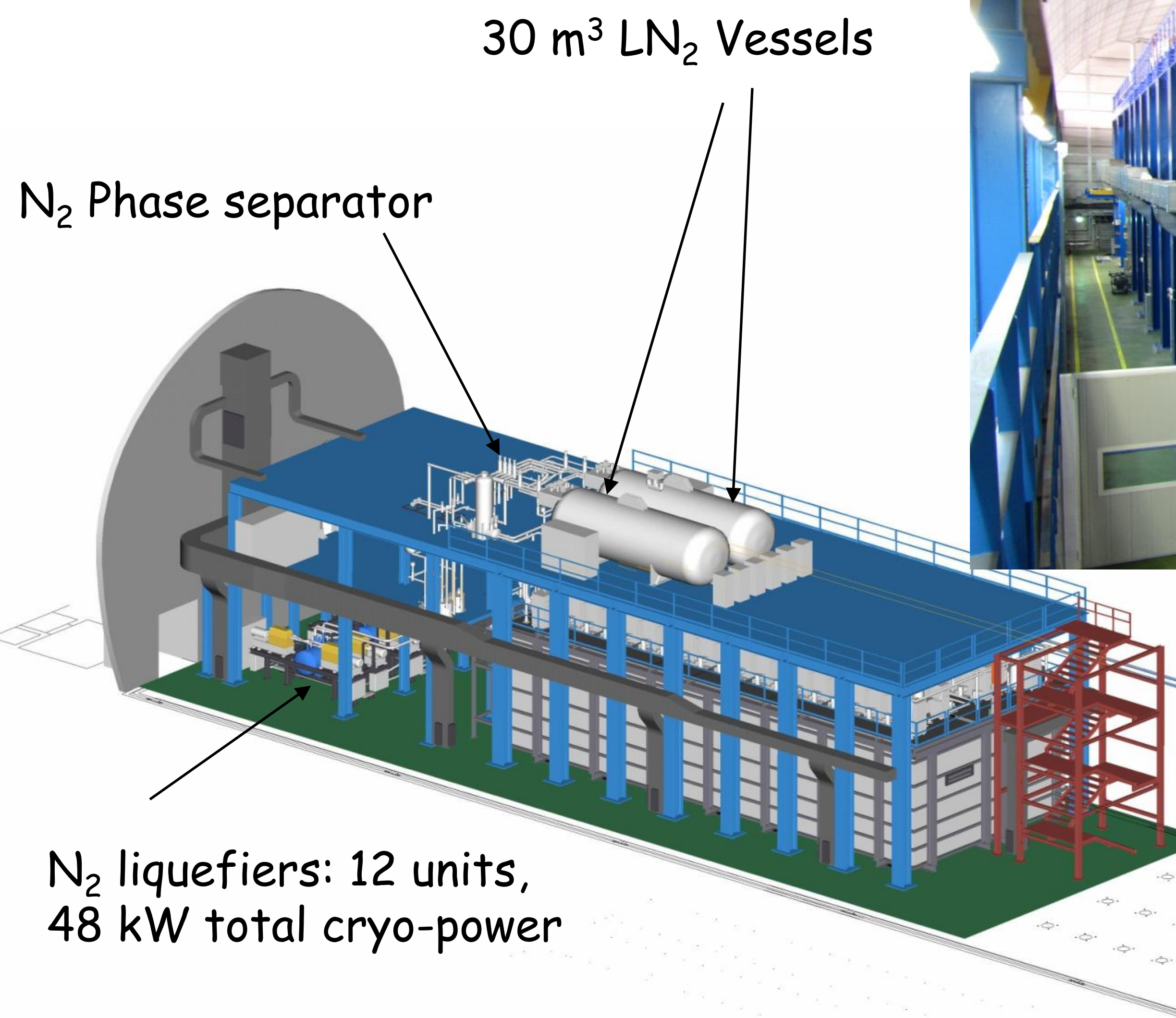




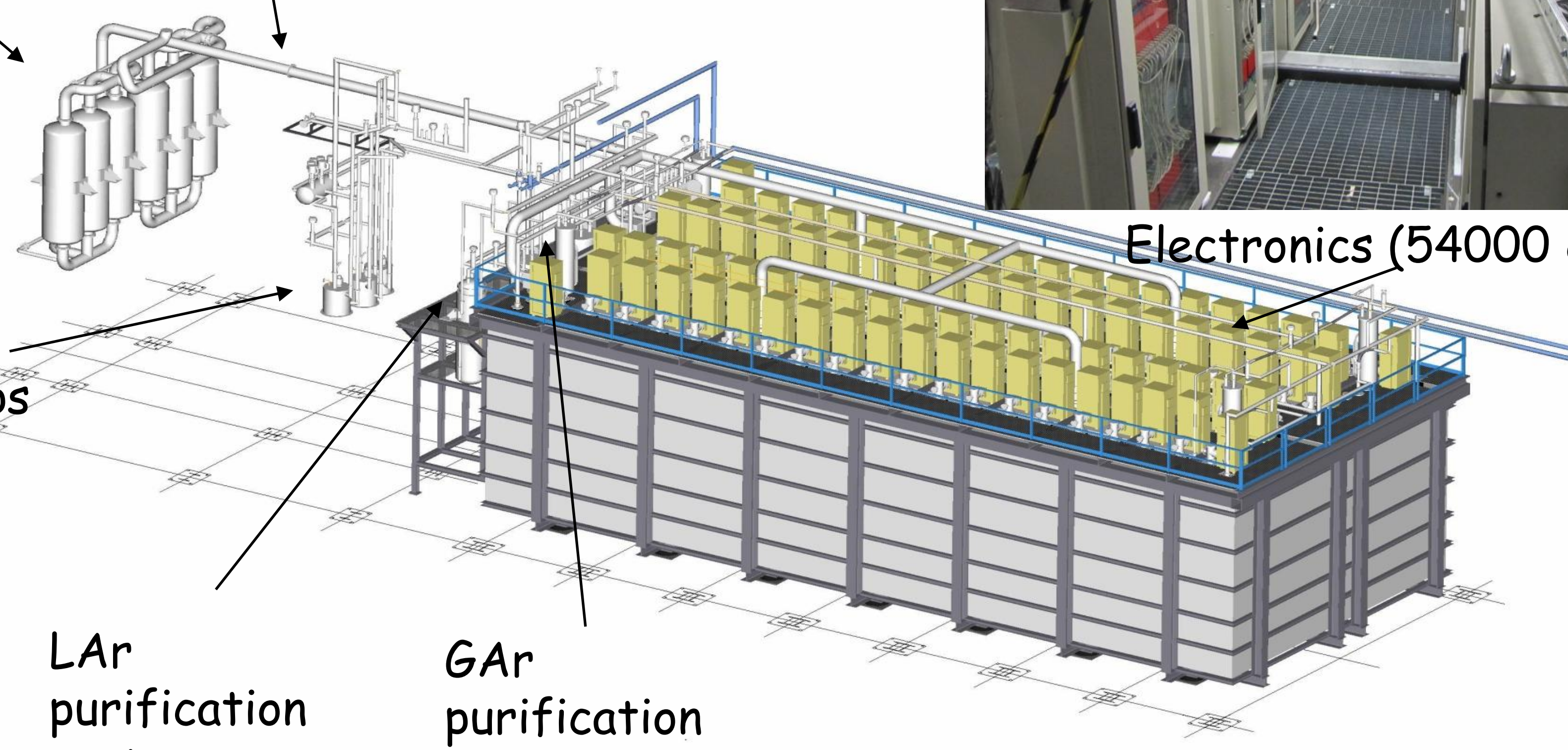
- Two identical modules
  - 3.6 × 3.9 × 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E = 0.5 kV/cm
  - vdrift = 1.55 mm/μs

- 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
- (20 + 54) PMTs, 8" Ø for scintillation light:
  - VUV sensitive (128nm) with wave shifter (TPB)

ICARUS T600 in LNGS Hall B

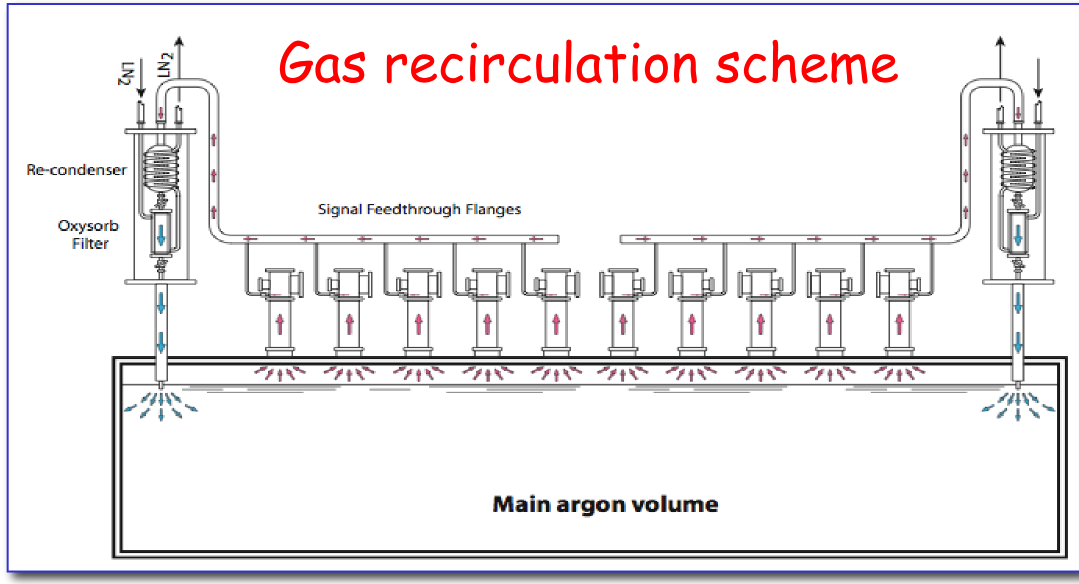


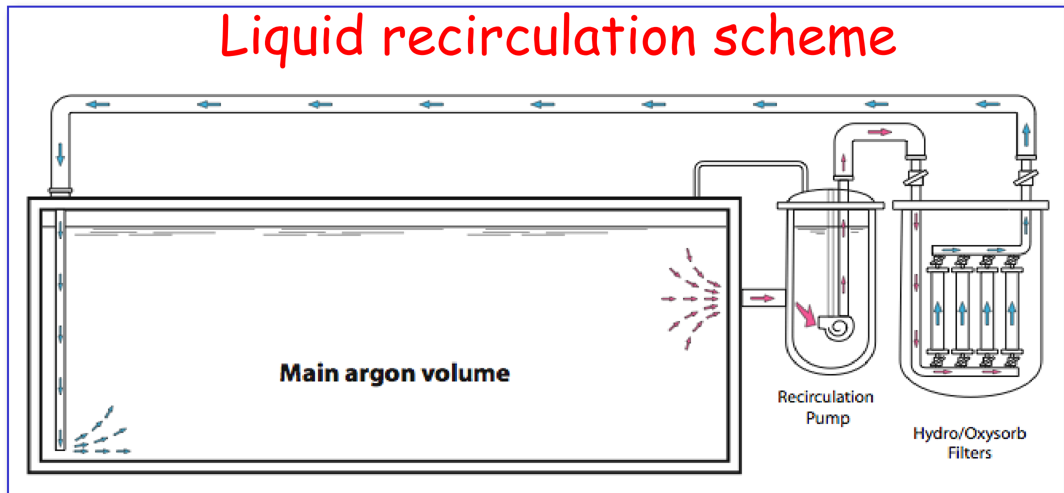
T600 cryostats layout



LAr Purification in T600

- Recirculation/purification (100 Nm³/h) of the gas phase (~40 Nm³) to block 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 m³/h) of the bulk liquid volume (~550 m³) to efficiently reduce initial impurities (can be switched on/off).

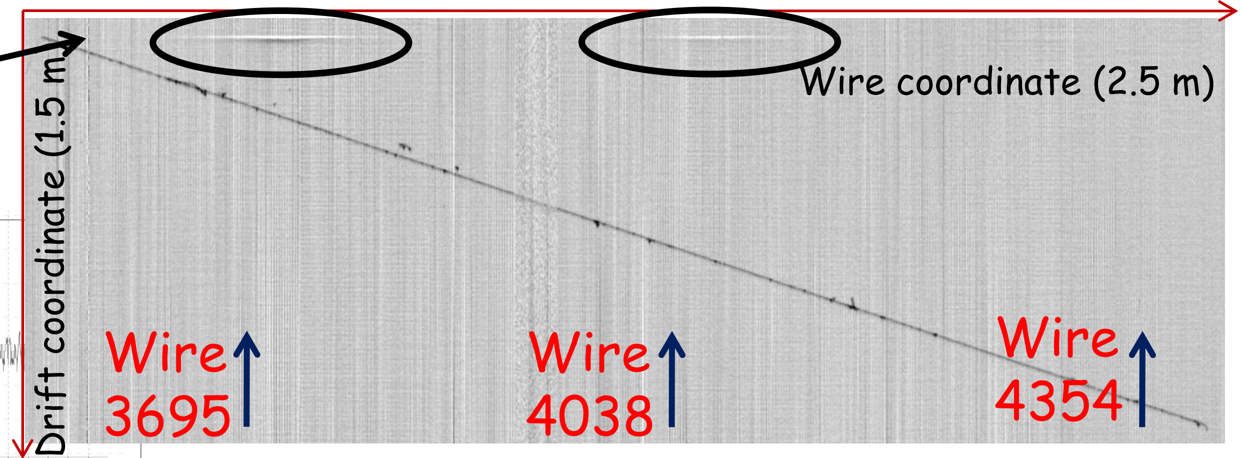




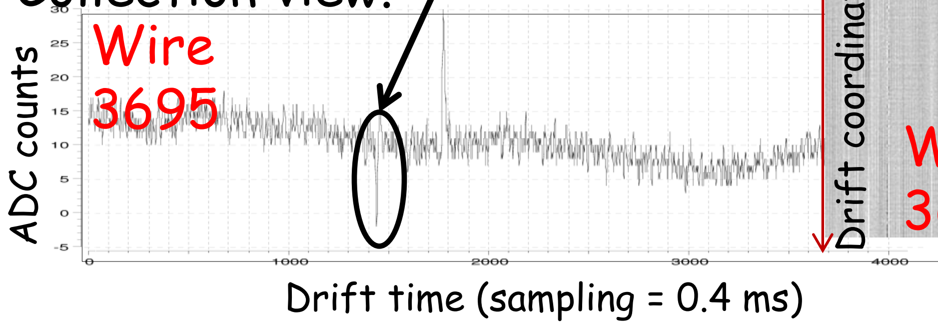
LAr purity measurement with muon crossing tracks

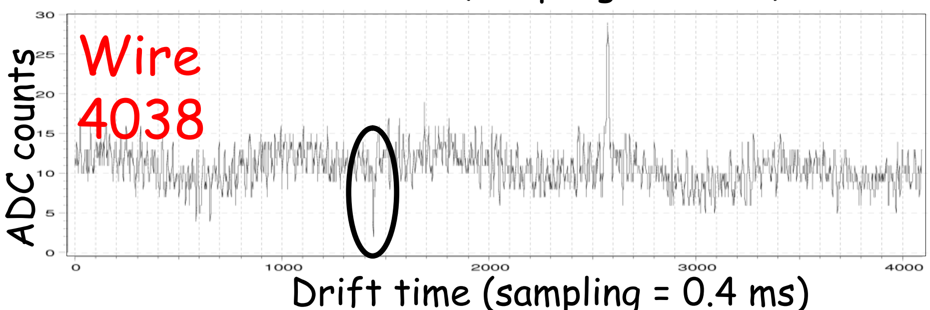
Charge attenuation along track allows event-by-event measurement of LAr purity.

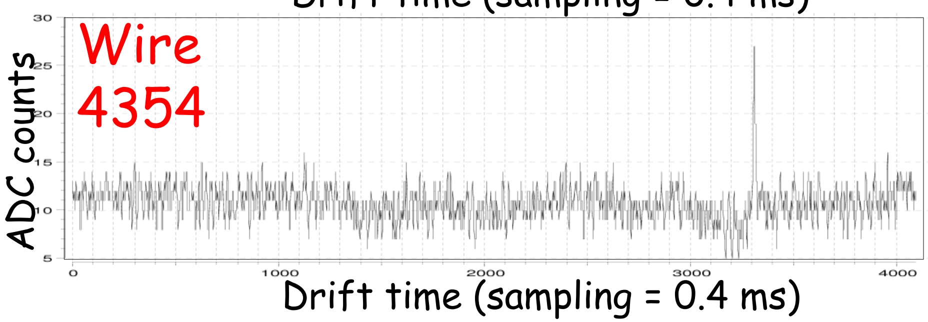
T = 0 estimated by induction of PMT signal on Collection view.



Run 10139 Event 8961 Collection view



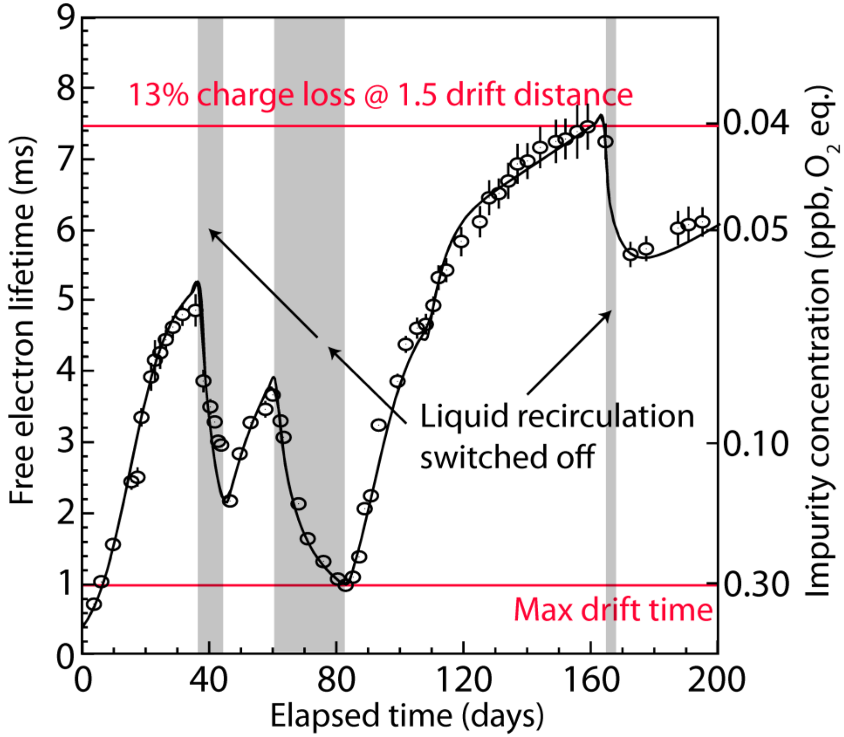


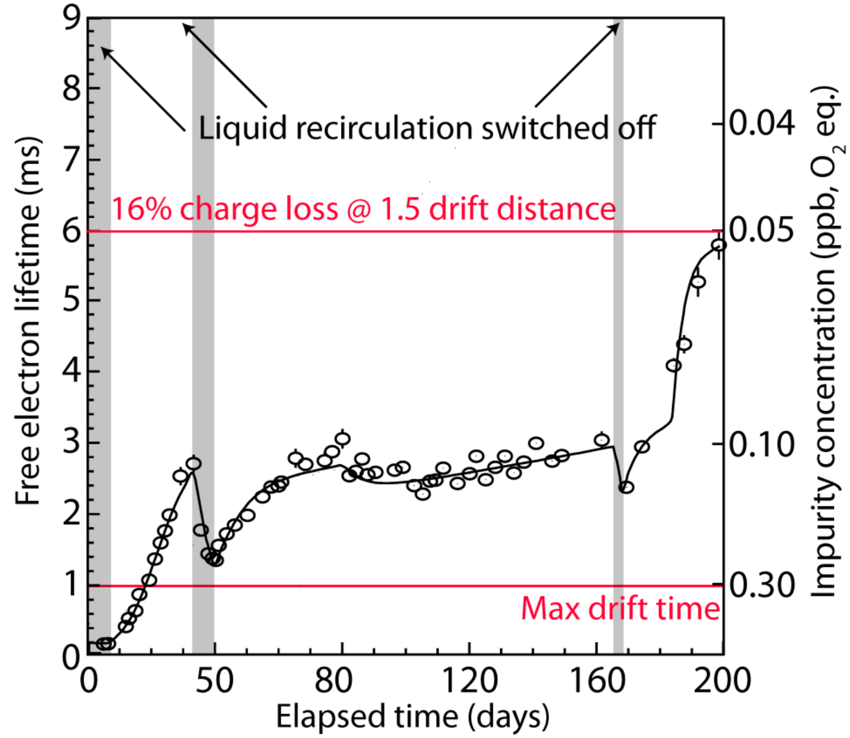


Pulse height for 3 mm m.i.p.
~ 15 ADC # (15000 electrons)

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.

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

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

τ_R: recirculation time for a full detector volume

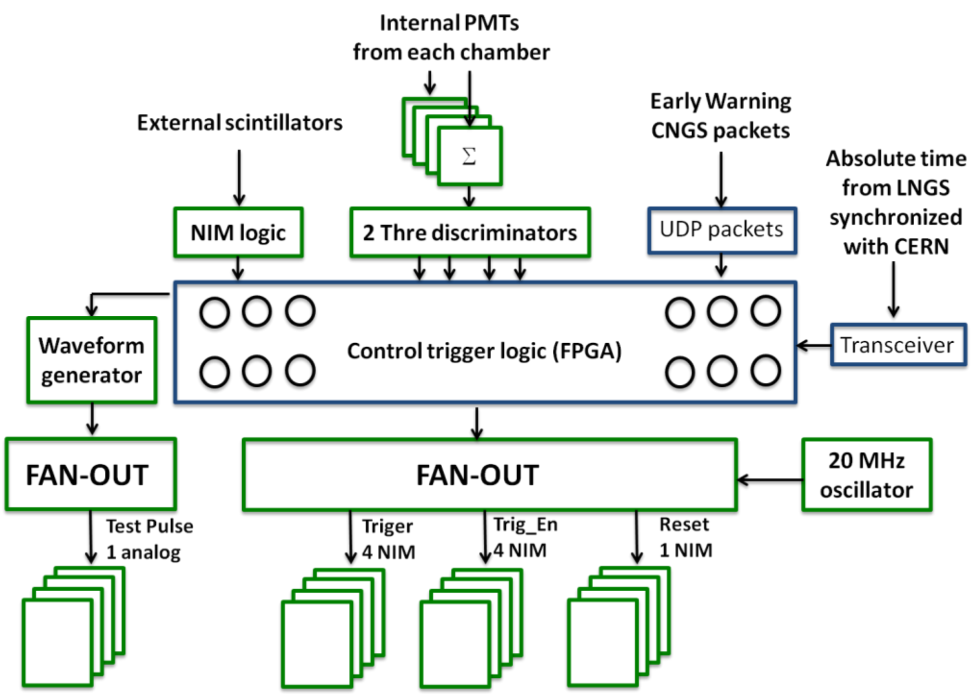
k_I and τ_I : related to the total degassing internal rate

k : related to the external leaks

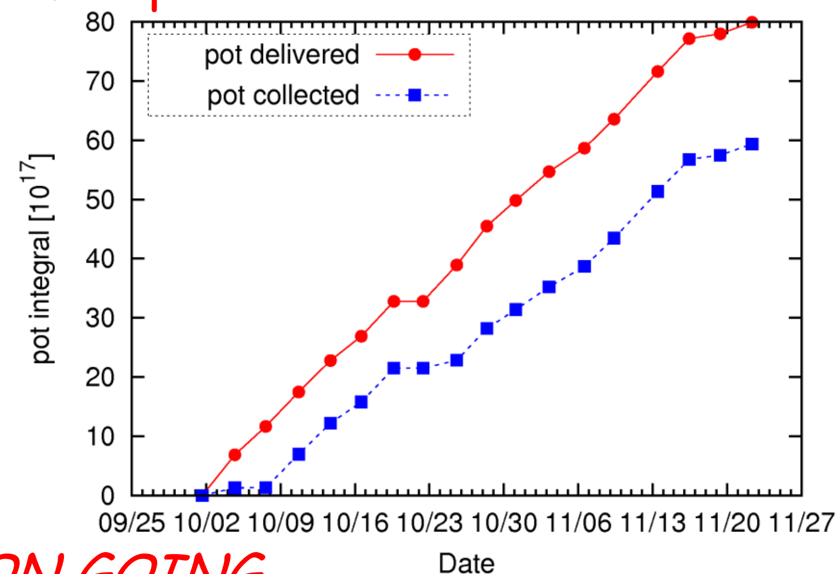
τ_R: 2 m^3/h corresponding to ≈ 6 day cycle time

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.



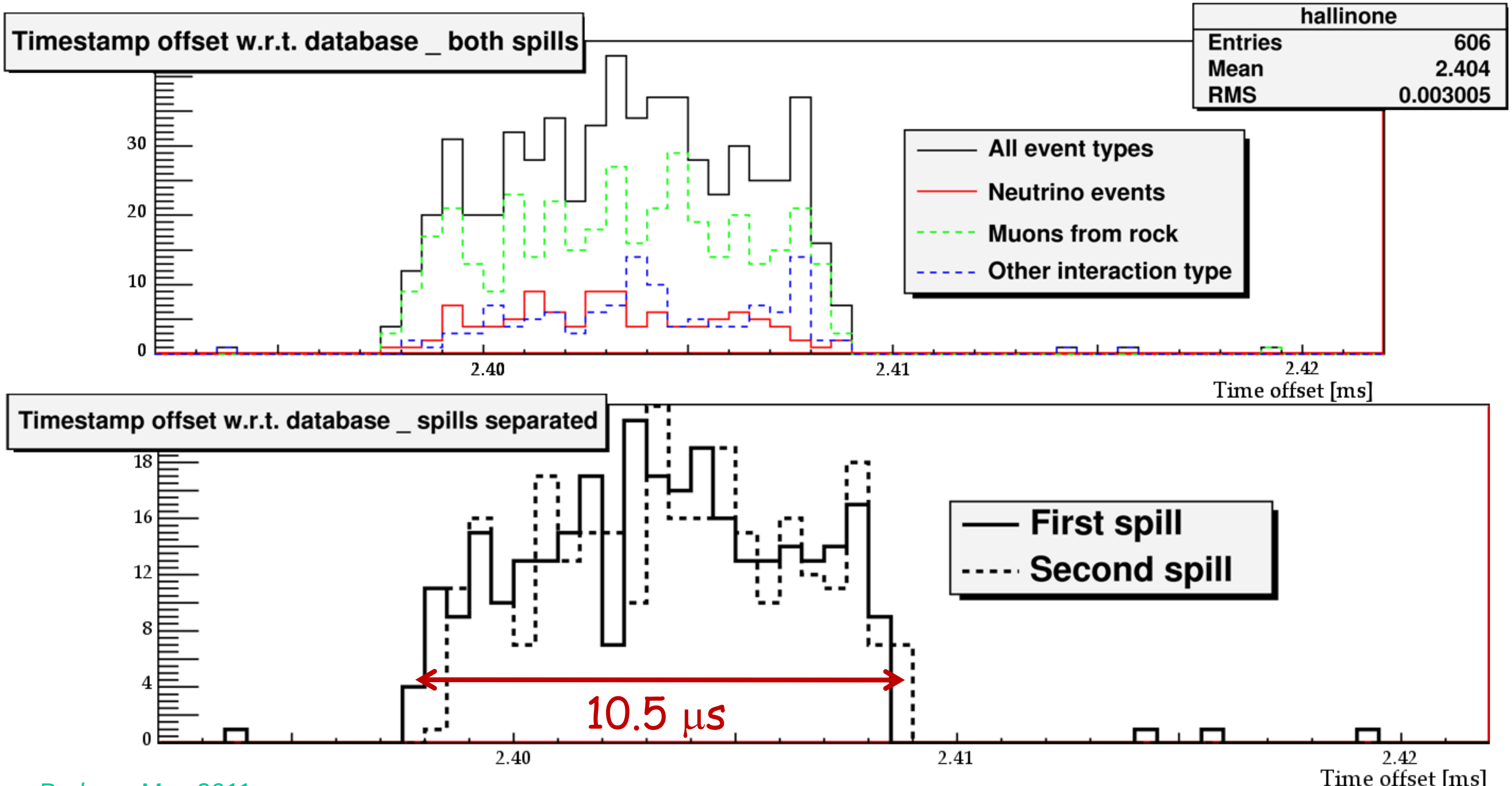
Oct. 1st ÷ Nov. 22nd: $8 \cdot 10^{18}$ ($5.8 \cdot 10^{18}$) pot delivered (collected). Detector lifetime up to 90% since Nov. 1st.



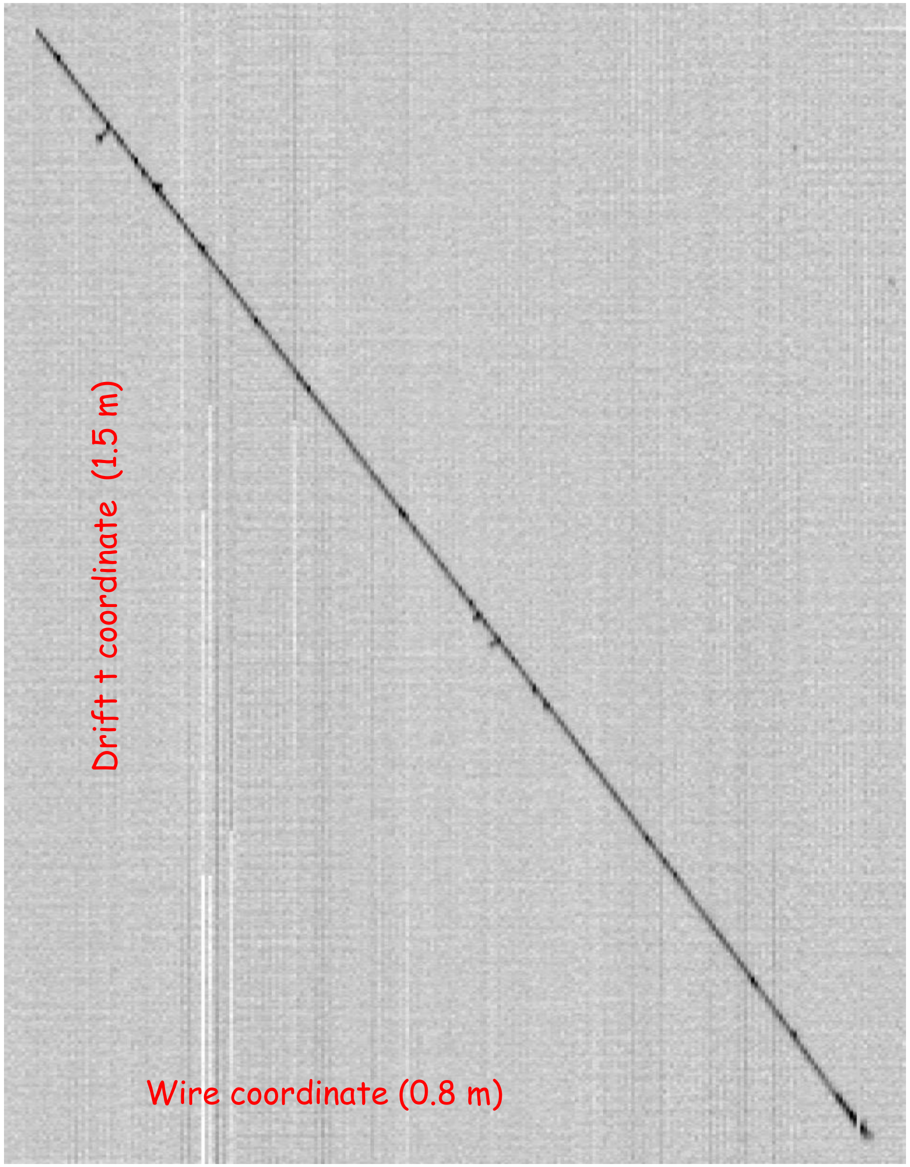
ANALYSIS : ON GOING

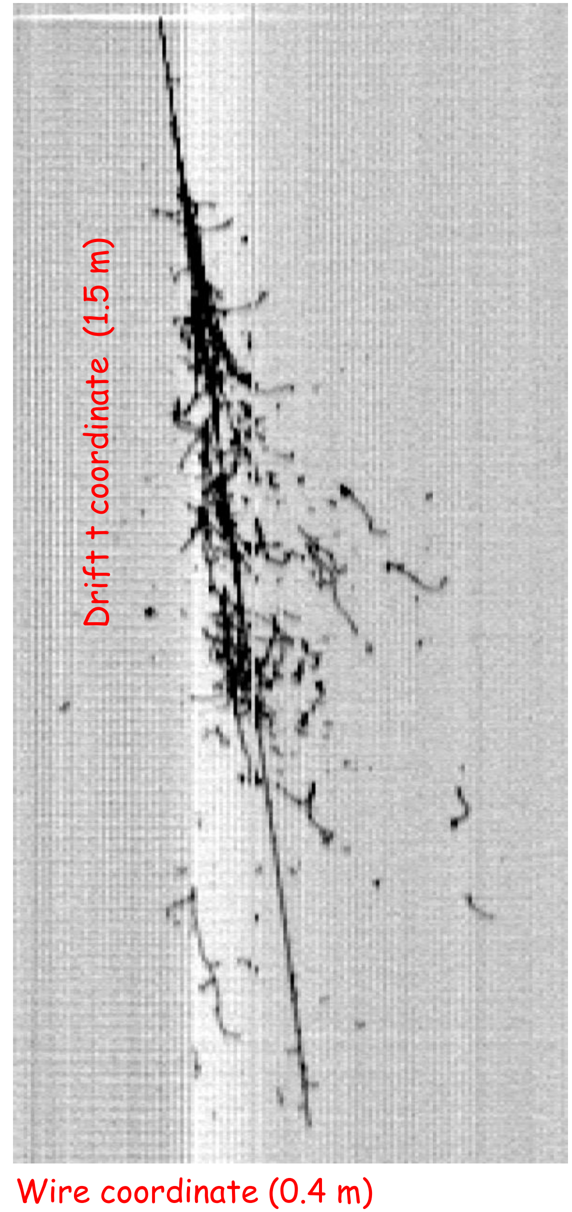
CNGS events timing w.r.t. p extraction time

- Narrow distribution ~ spill duration (10.5 μs)
- Minimum 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 to Hall B (8km).

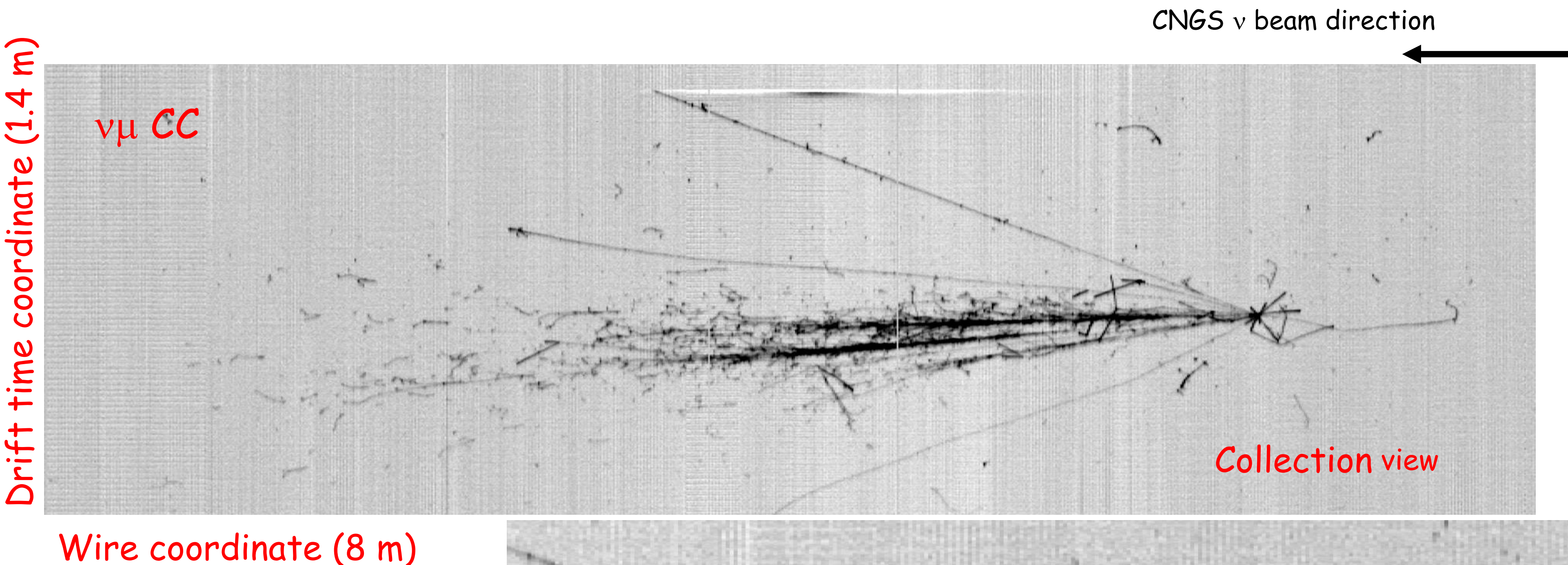


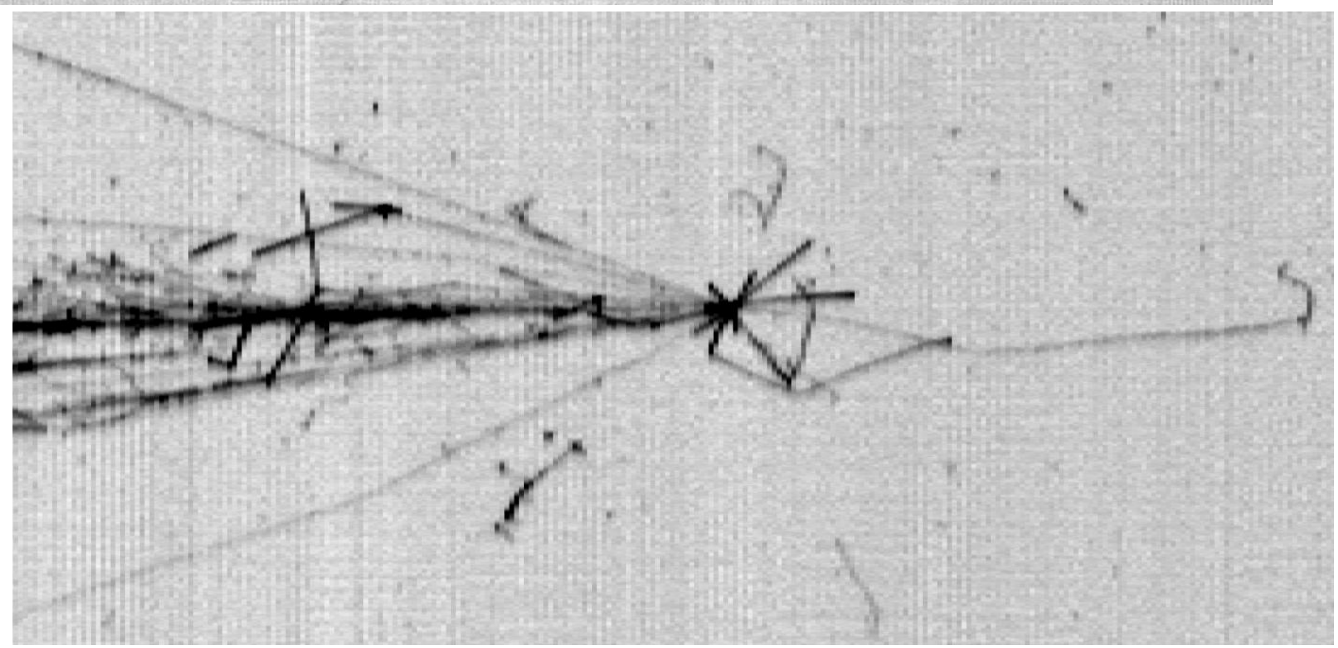
Cosmic μ interactions in ICARUS T600





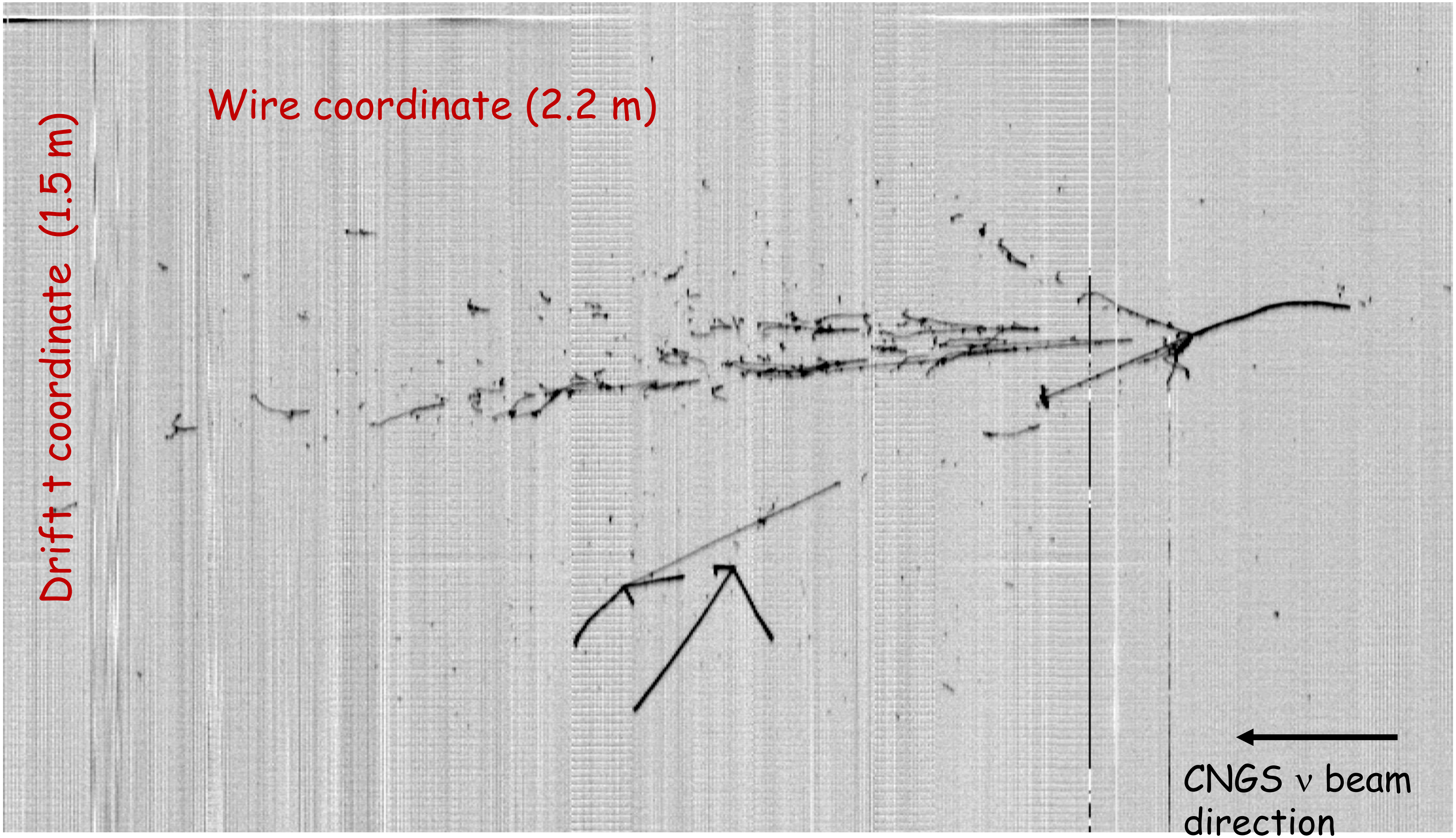
CNGS “first” neutrino interaction in ICARUS T600



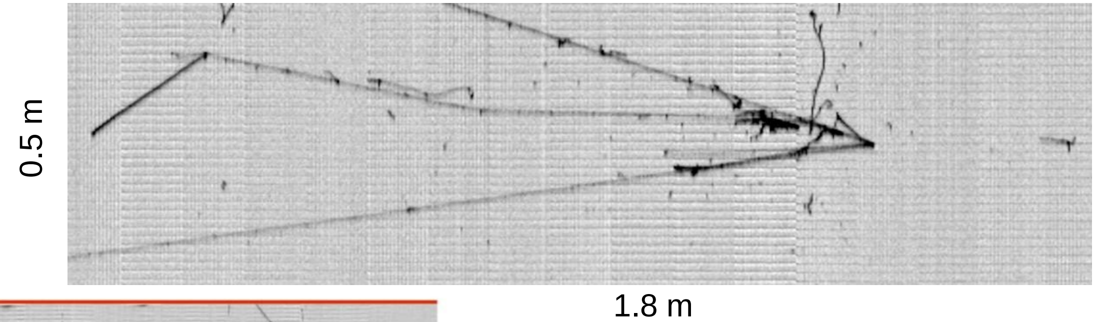


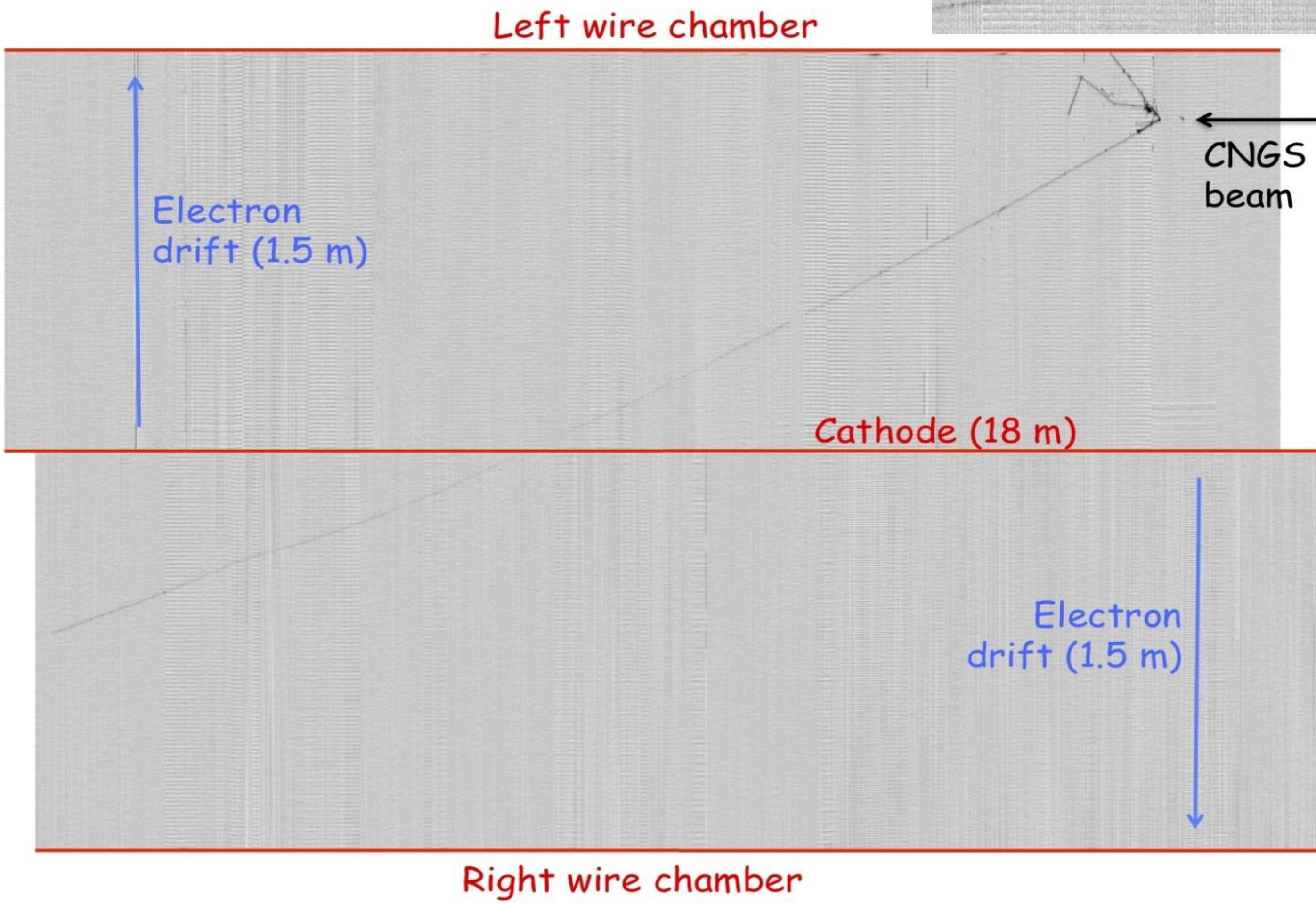
Selected events are reconstructed, analyzed: tuning of reconstruction/ analysis programs

CNGS NC interaction



Low energy CNGS ν_μ CC interaction

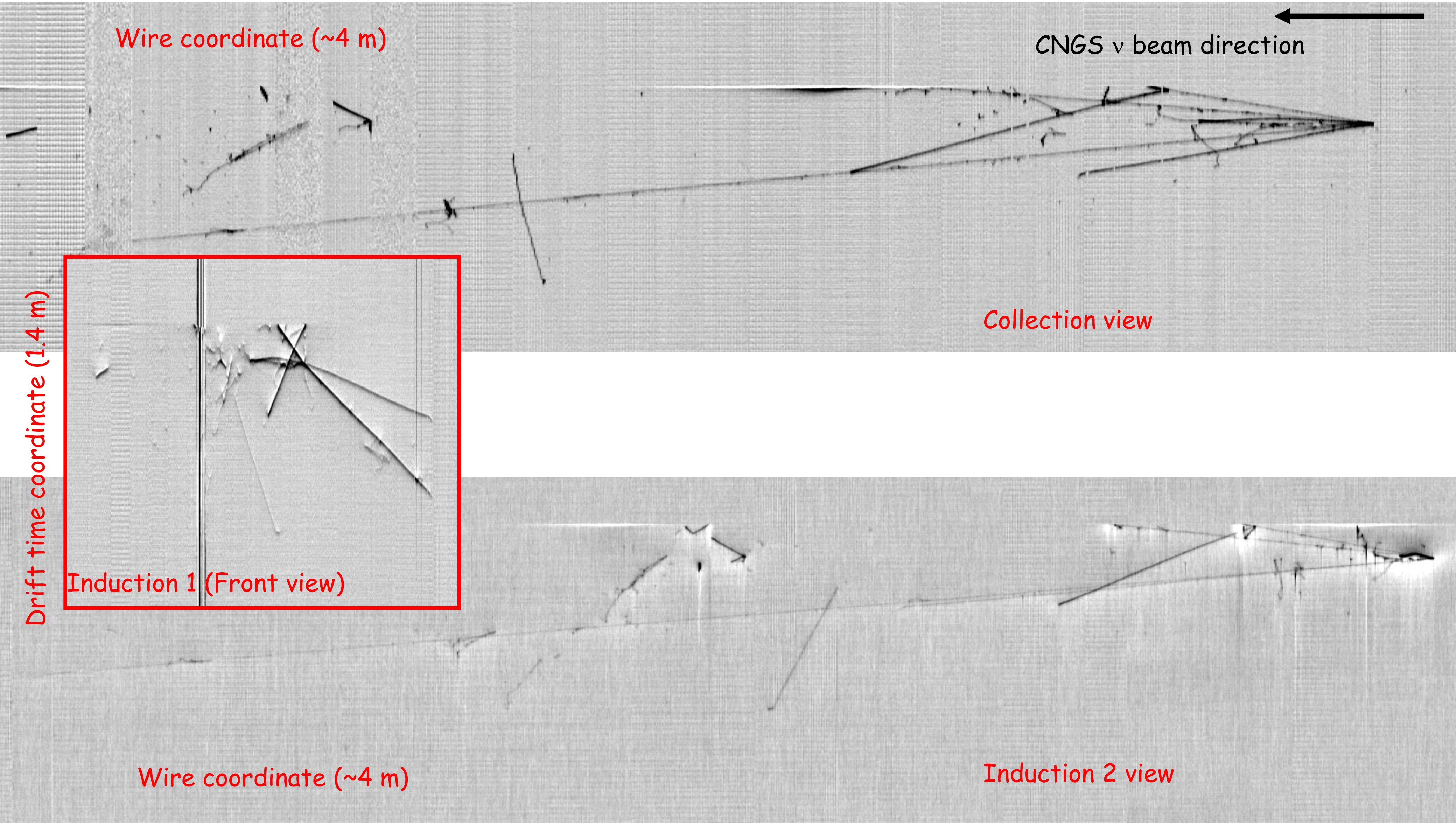




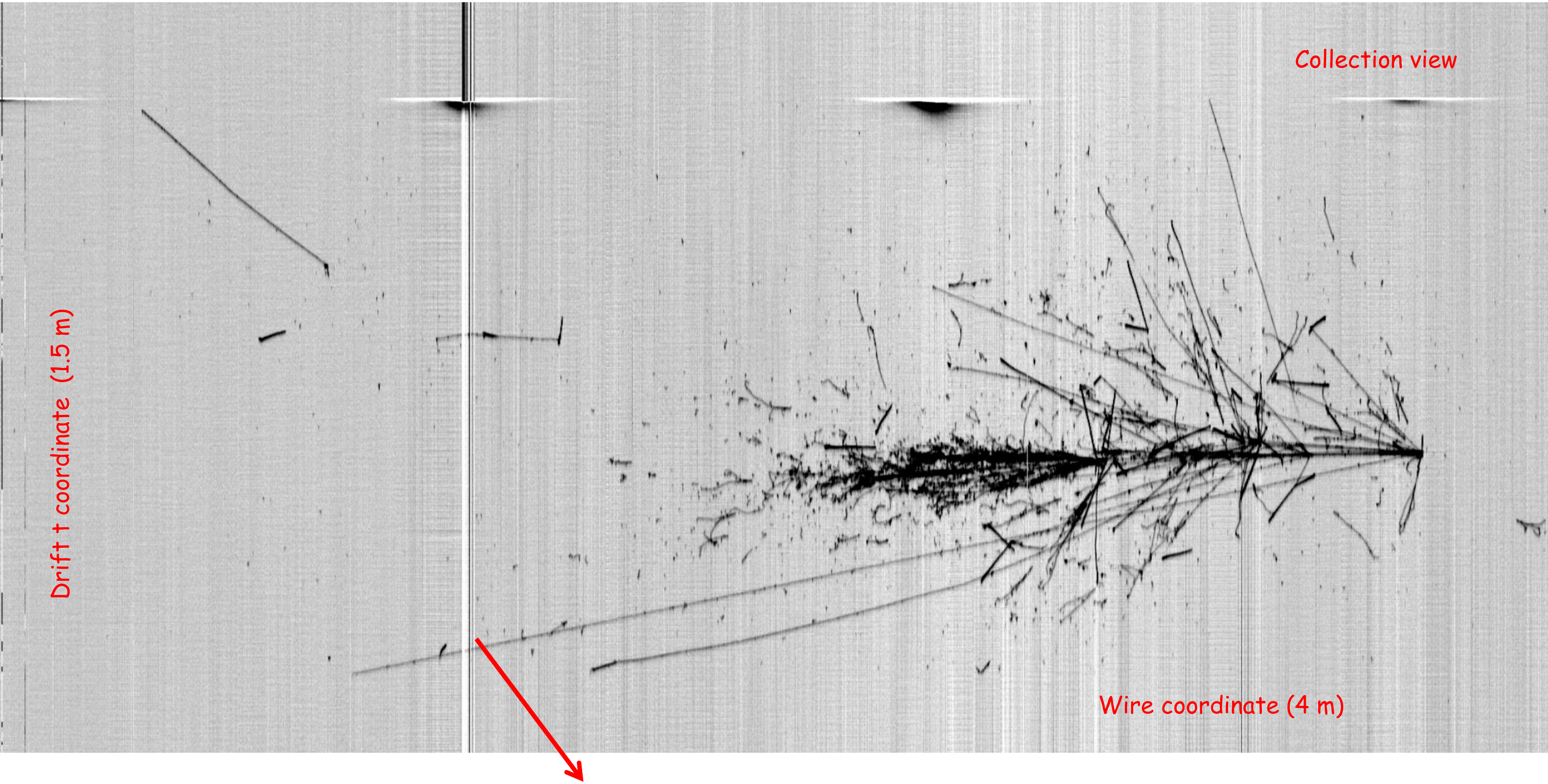
Evis ~ 9 GeV
Electron lifetime and quenching accounted for

Collection views
(not to scale!)

CNGS neutrino ν_μ CC interaction

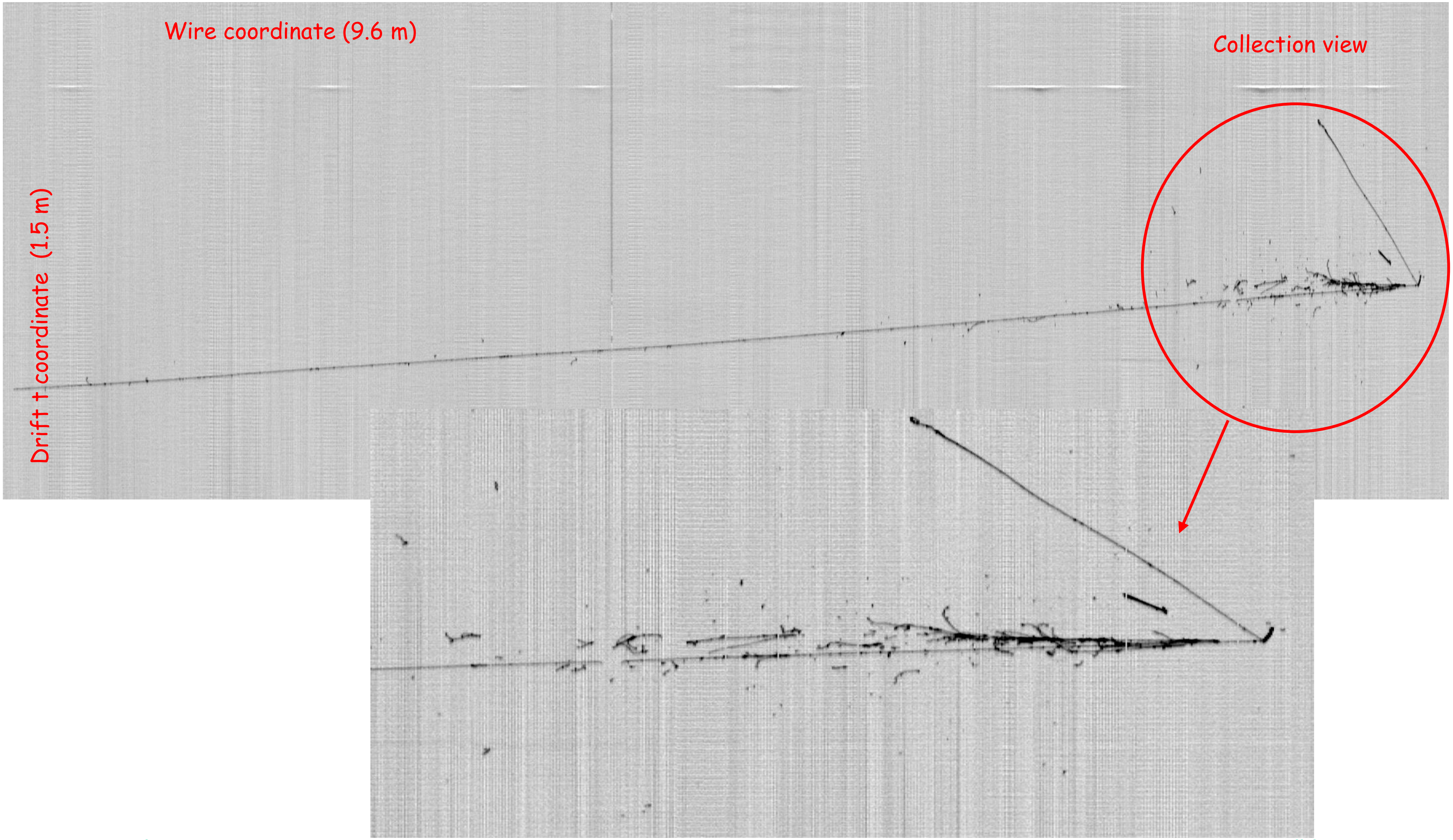


CNGS ν_μ CC interaction in ICARUS T600

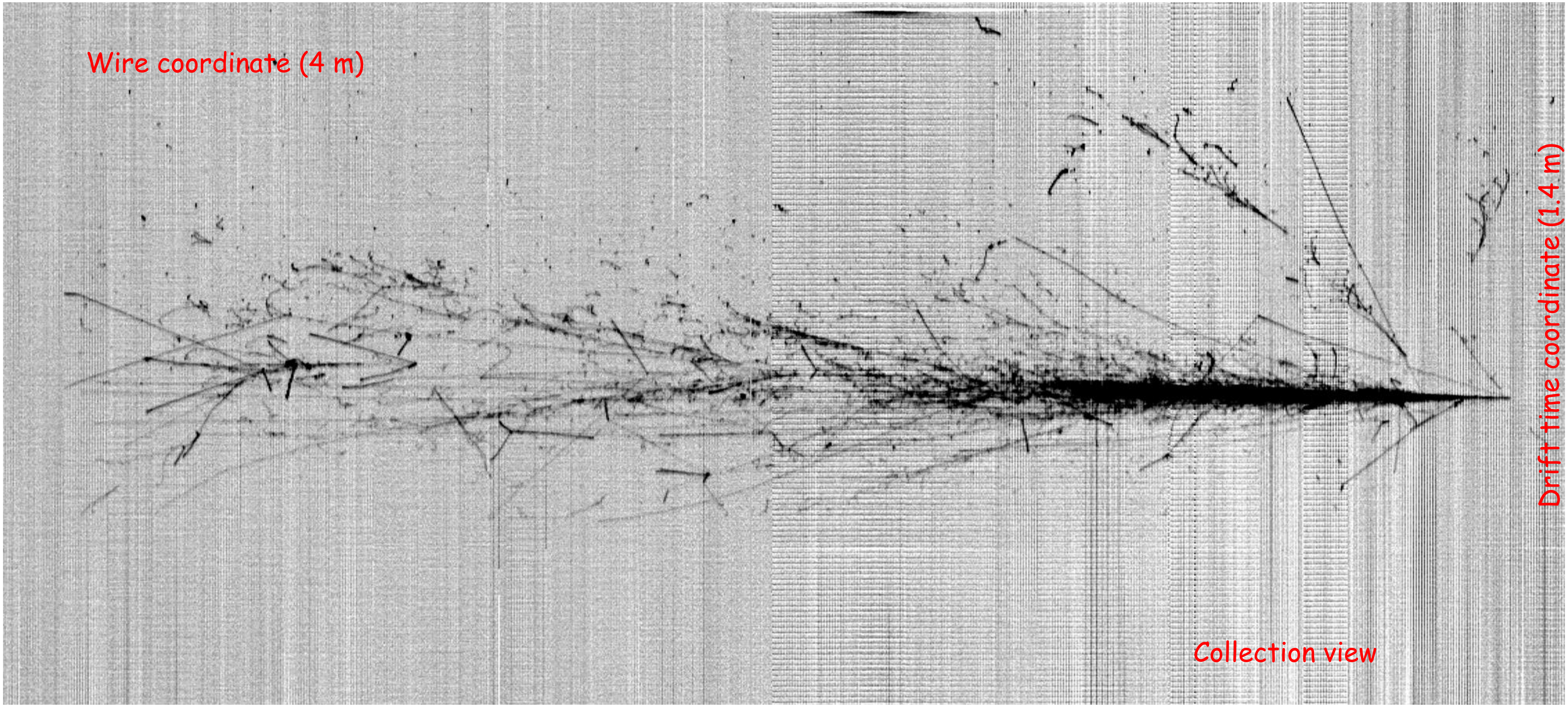


μ continuing in adjacent TPC chamber

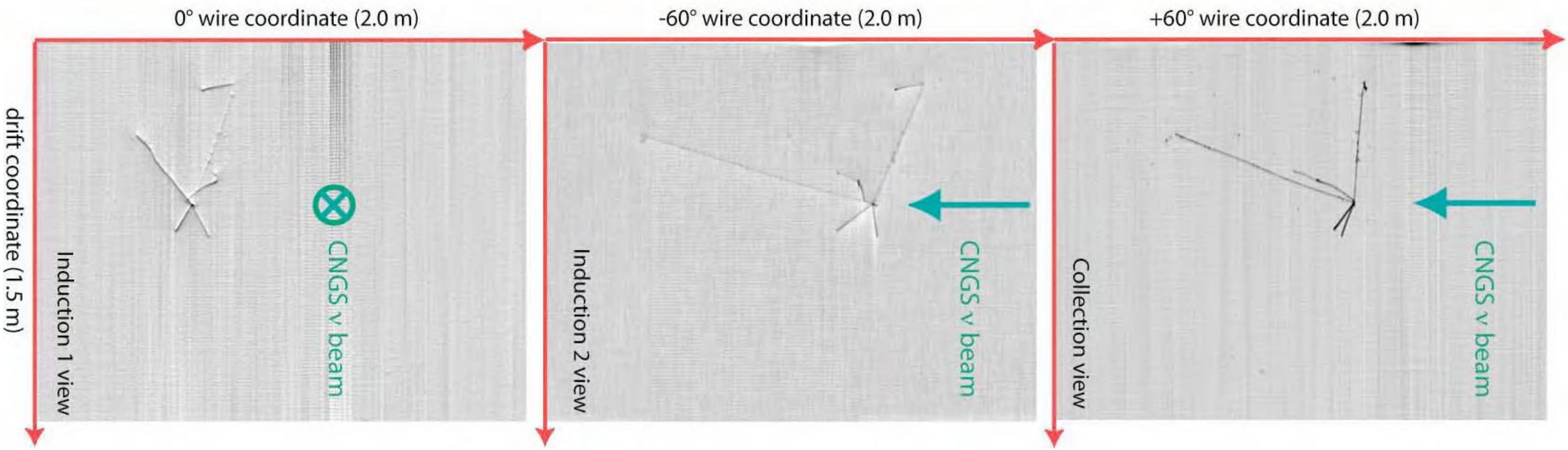
CNGS ν_μ CC interaction in ICARUS T600



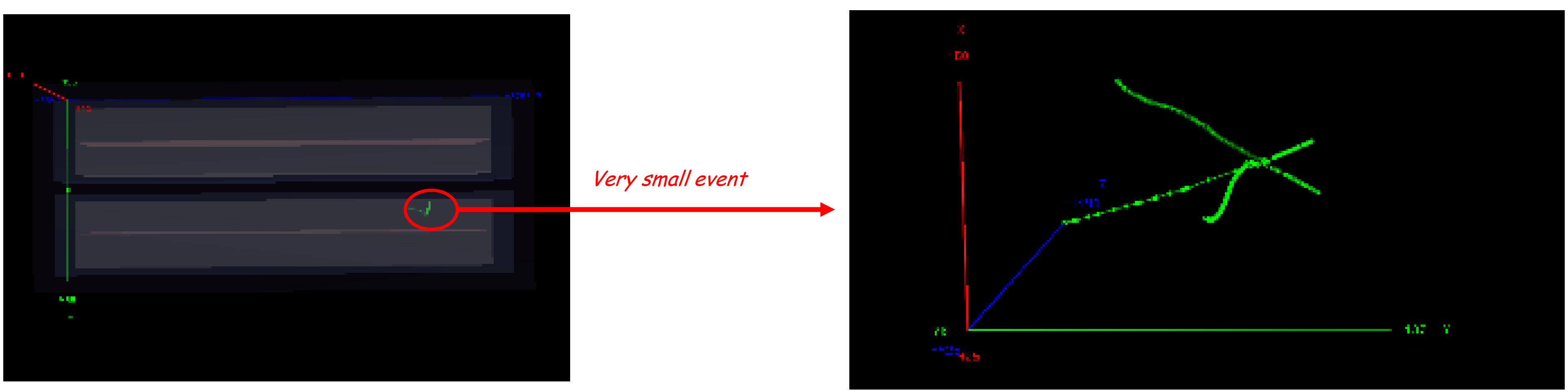
CNGS NC interaction



Atmospheric neutrino interaction



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

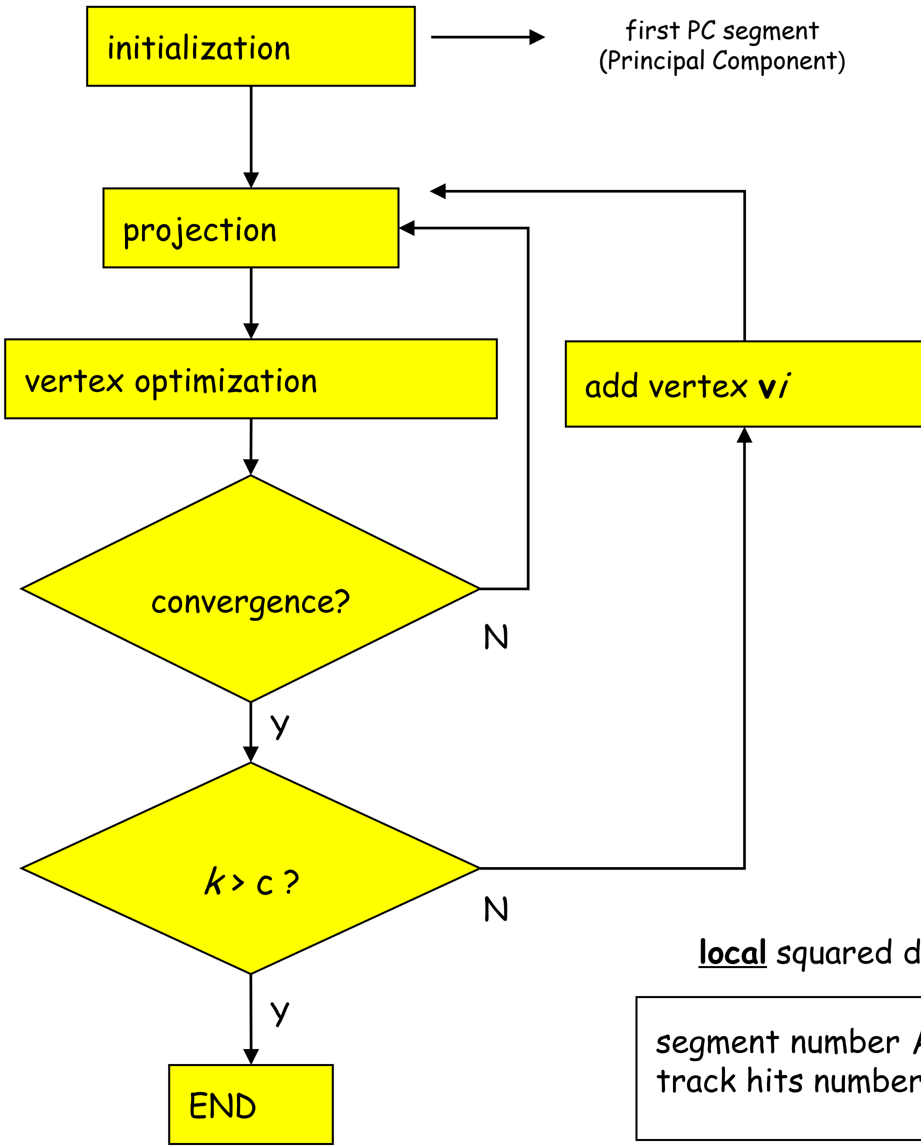


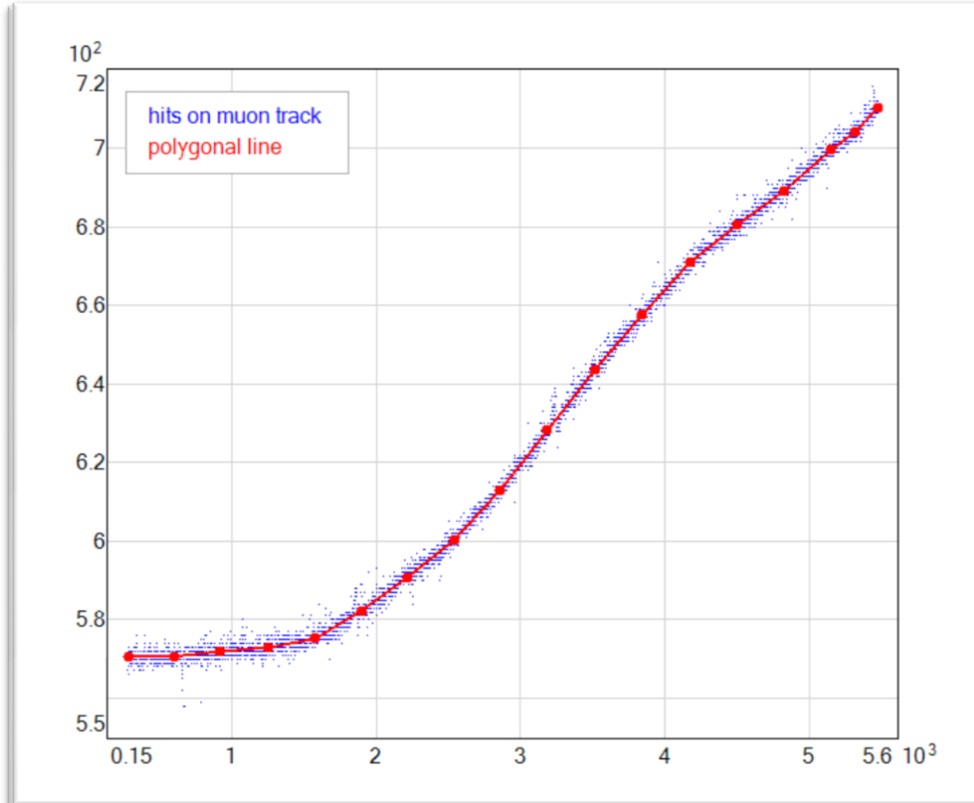
Outline of the 3D reconstruction

- Complement of 2D reconstruction
  - It is based on Polygonal Line Algorithm (PLA) [1]
  - Procedure of sorting hits along 2D tracks independly in each view
- As a result of the PLA application
  - PLA-fit through hits of a track
  - both hits and hit projections to the fit are sorted along the track
- 3D reconstr.: Linking hit projections between views according to
  - drift sampling
  - sequence of hits

[1] http://www.iro.umontreal.ca/~kegl/research/pcurves/

Polygonal Line Algorithm





$$G(\mathbf{v}_i) = \frac{1}{n}\Delta_n(\mathbf{v}_i) + \lambda \frac{1}{k+1} P(\mathbf{v}_i)$$

local squared distance to hits

local angle penalty term

segment number *k* exceeds given ratio *c = k/n*
track hits number: longer tracks usually are more straight

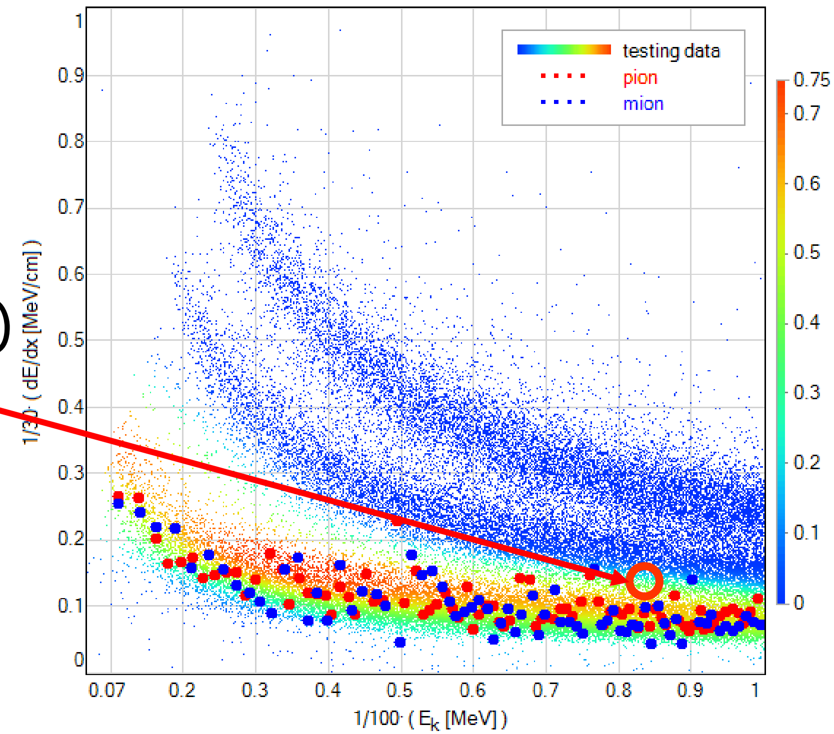
http://www.iro.umontreal.ca/~kegl/research/pcurves/

Neural Network particle identification

- P.id based on:
  - ↗ distance between nearby 3D hits: dx
  - ↗ 3D hits and charge deposition : dE/dx
- classify single i^{th} point on the track

  $\mathbf{p}_i$: $[E_k, dE/dx]$ → $\mathbf{nn}_i$: [P(p), P(K), P(p), P(m)
- Average M output vectors for the points

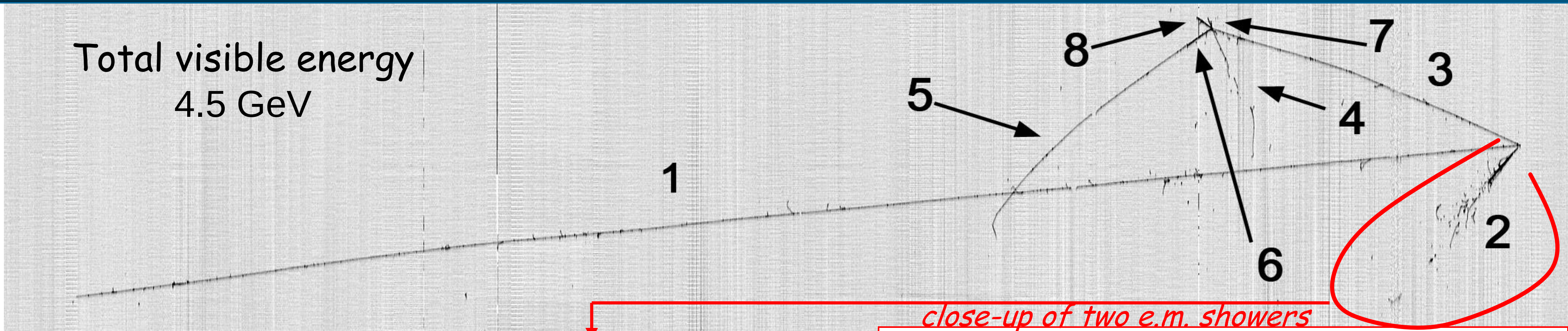
  $\mathbf{NN} = S(\mathbf{nn}_i)/M$
- Identify track as particle corresponding to max(**NN**)
- Energy reconstruction with simulation for quenching



pid / MC	p	K	π	μ	efficiency [%]	purity [%]
p	**481**	4	0	0	99.2	98.0
K	10	**380**	0	0	97.4	99.0
π	0	0	**196**	40	83.1	98.5
μ	0	0	3	**216**	98.6	84.4

Very high identification efficiency for p, k, pion+muon

Run 9927 Event 572



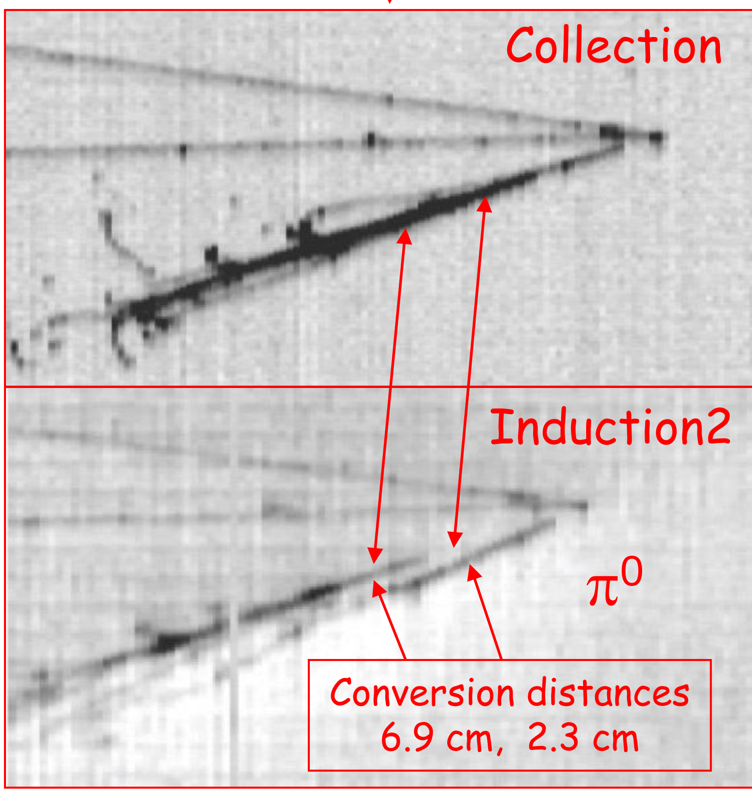
Primary vertex (A):

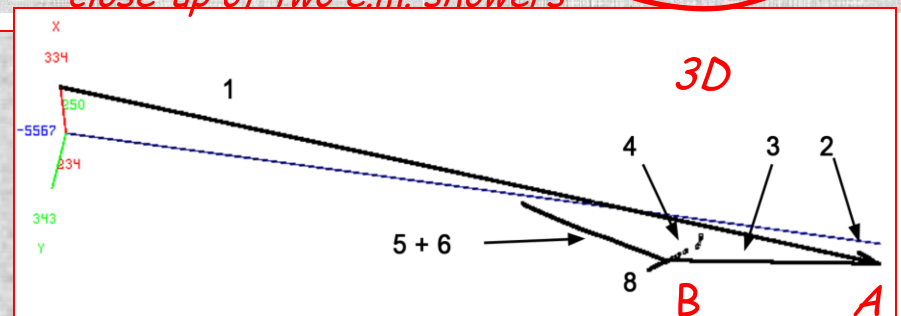
very long μ (1), e.m. cascades (2), pion (3)

Secondary vertex (B):

The longest track (5) is a μ coming from stopping **k** (6).

μ decay is observed





Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	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

2011-2012 CNGS run: physics perspectives

- 2011-2012 run: expected 10^{20} pot.
- For 1.1 10^{20} pot: 3000 beam related ν_μ CC events expected

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

Background

- At the effective neutrino energy of 20 GeV and Δm^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 (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.

After 2012: LAr -TPC experiment at CERN-PS

- The direct, unambiguous measurement of an oscillation pattern requires necessarily the (simultaneous) observation at several different distances. It is only in this way that the values of Δm^2 and of $\sin^2(2\theta)$ can be separately identified.
- The present proposal at the CERN-PS introduces important new features, *which should allow a definitive clarification of the above described "anomalies"*:
  - "Imaging" detector capable to identify unambiguously <u>all</u> reaction channels with a *"Gargamelle class" LAr-TPC*
  - L/E oscillation paths lengths to ensure appropriate matching to the Δm^2 window for the expected anomalies.
  - Interchangeable ν and anti-ν focussed beams
  - Very high rates due to large masses, in order to record relevant effects at the % level (>10^6 νμ, ≈10^4 νe)
  - Both initial νe and νμ components cleanly identified.

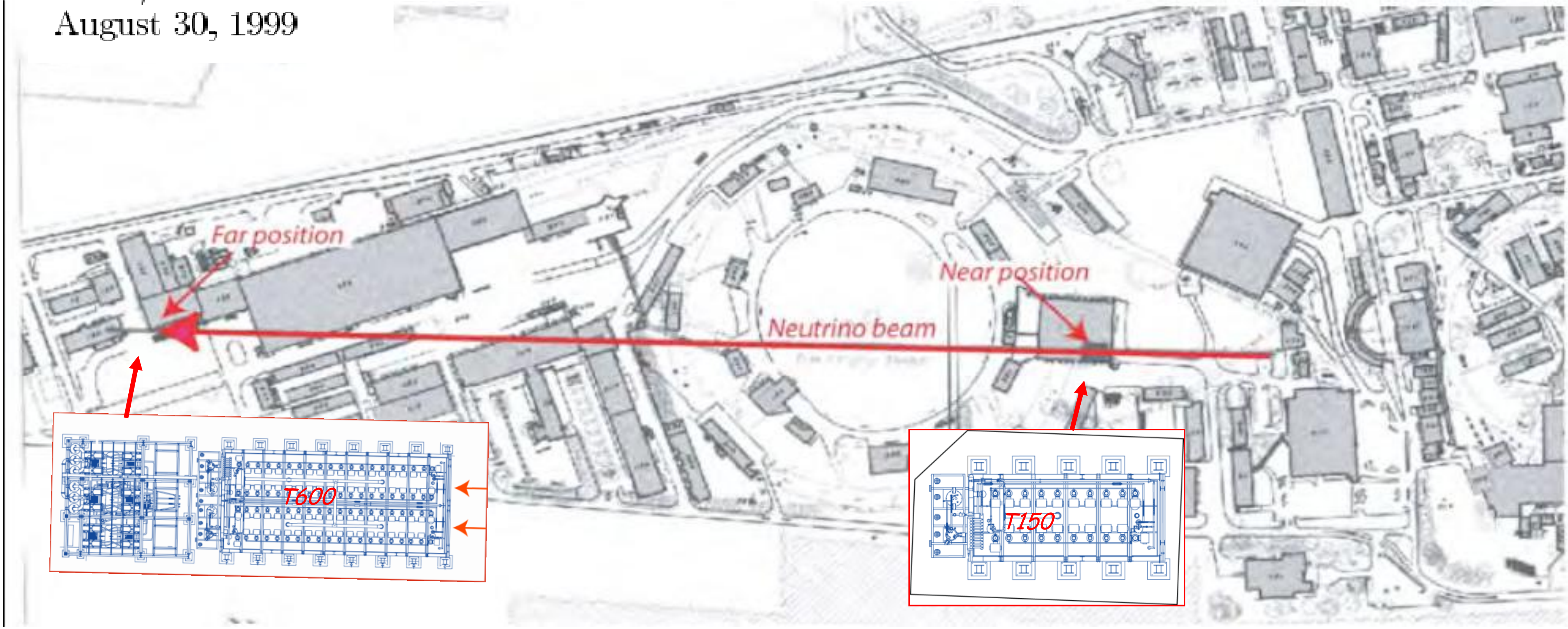
Basic features of the proposed experiment

- Our proposed experiment, collecting a large amount of data both with neutrino and antineutrino focussing, may be able to give a likely definitive answer to the 4 following queries:
  - the LSND/+MiniBooNe both antineutrino and neutrino $\nu\mu \rightarrow \nu e$ oscillation anomalies;
  - The Gallex + Reactor oscillatory disappearance of the initial ν–e signal, both for neutrino and antineutrinos
  - an oscillatory disappearance maybe present in the $\nu-\mu$ signal, so far unknown.
  - Accurate comparison between neutrino and antineutrino related oscillatory anomalies, maybe due to CPT violation.
- In absence of these "anomalies", the signals of the detectors at different distances should be a precise copy of each other for all experimental signatures and without any need of Monte Carlo comparisons.

Two LAr-TPC detectors at the CERN-PS neutrino beam

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

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

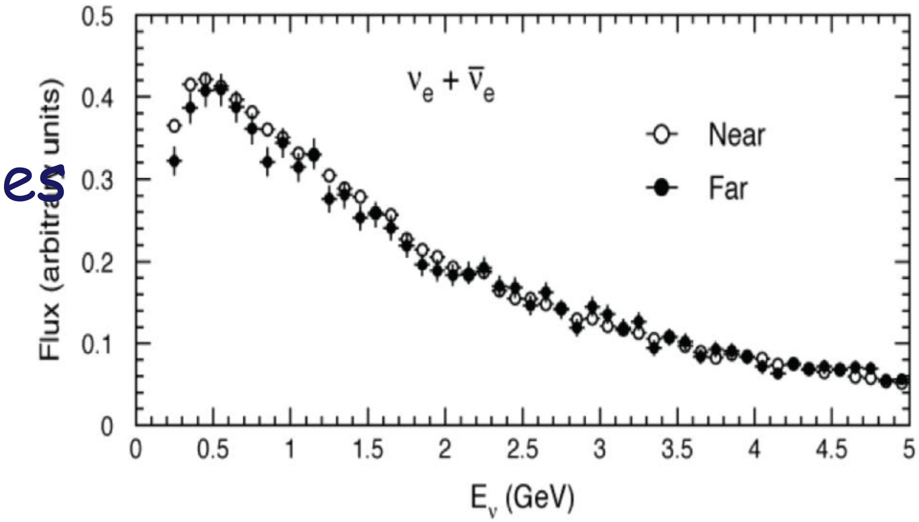


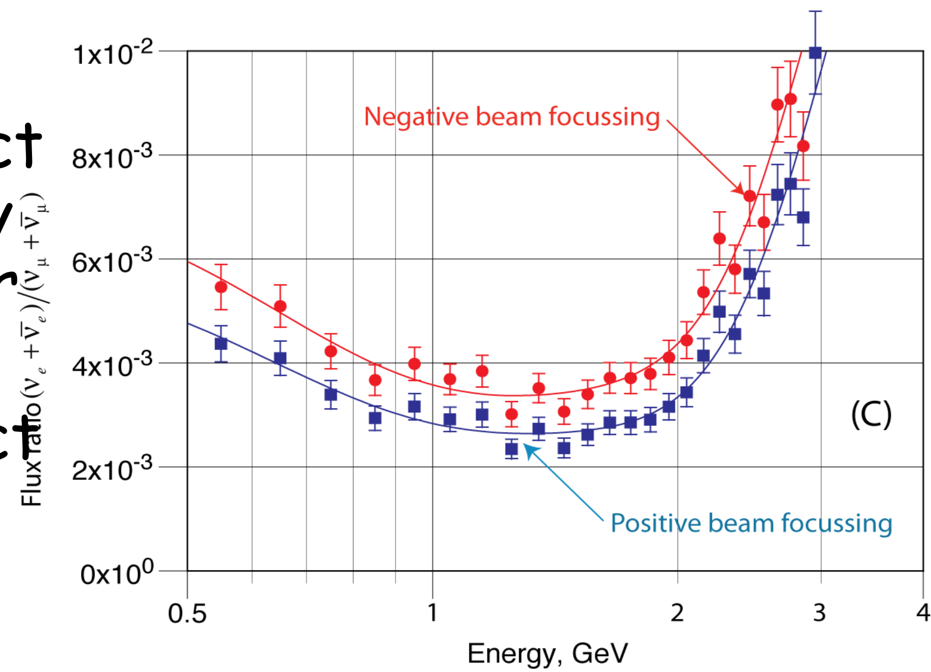
Two positions are foreseen for the detection of the neutrinos
The far (ICARUS-T600) location at 850 m from the target: L/E ~ 1 km/GeV;
The additional detector and new location at a distance of 127 m from the target: L/E 0.15 km/GeV

The CERN-PS neutrino and antineutrino e-beams

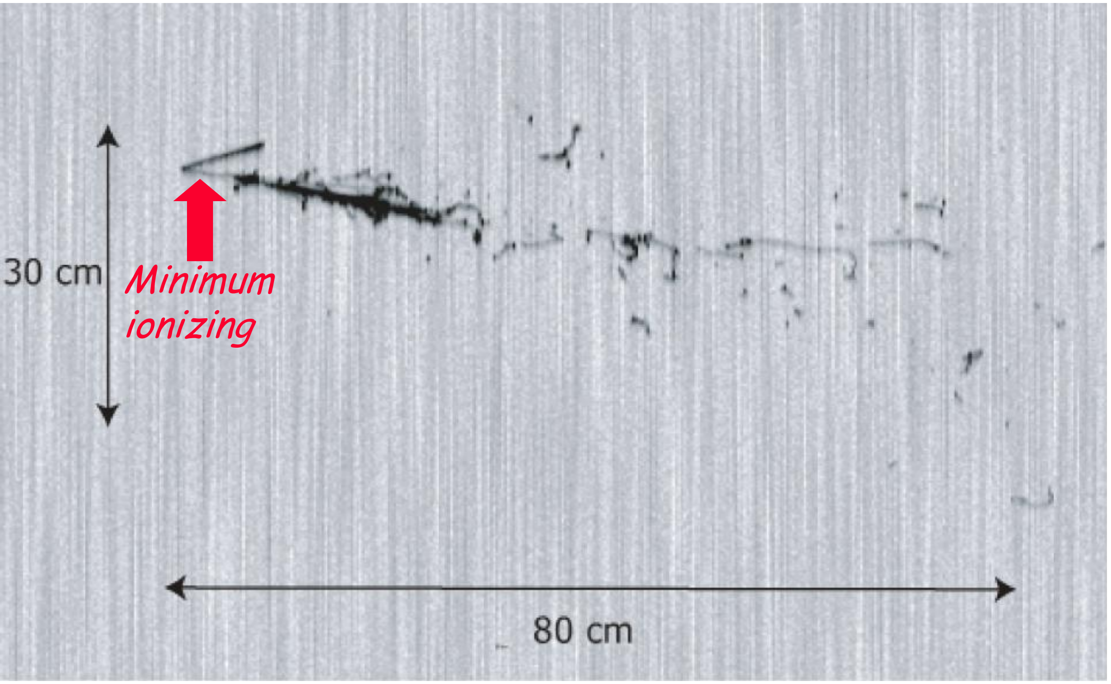
Present proposal at the CERN-PS is based on the search for spectral differences of e-like specific signatures in two identical detectors but at the "Far" and the "Near" locations

- The ν_e spectra are expected very closely identical in the "Near" and "Far" positions.
- This specific property of the electron neutrino is due to the fact that they are produced essentially by the K-decays with a much wider angular distribution.
- The effect is enhanced by the fact that both detectors have been designed with identical experimental configurations



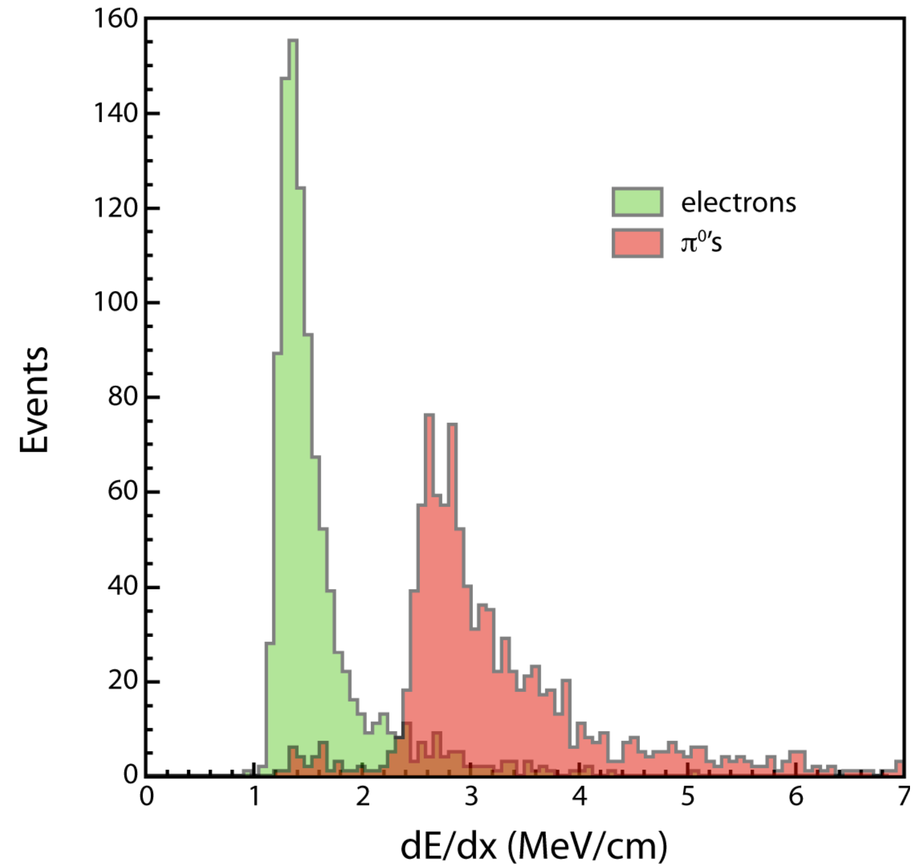


Quasi elastic νe events



Collection view of a 1.5 GeV QE ν_e event. Note the presence of a singly ionizing electron immediately after the event

In spite of the much smaller ν_e yield (0.5% of ν_μ) the extremely high sensitivity for the electron signature ensures an excellent detection efficiency

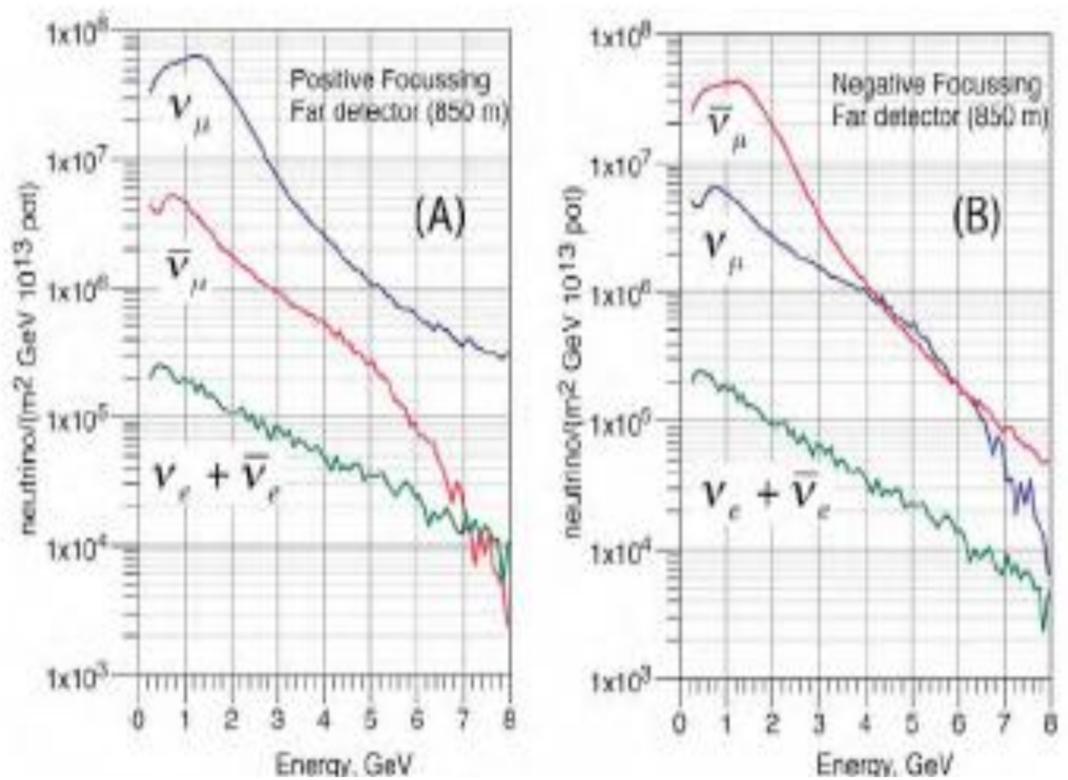


Electron-π^0 separation obtained in the LAr-TPC using ionization measurements along tracks in the vertex region

Expected CERN PS neutrino beam spectra

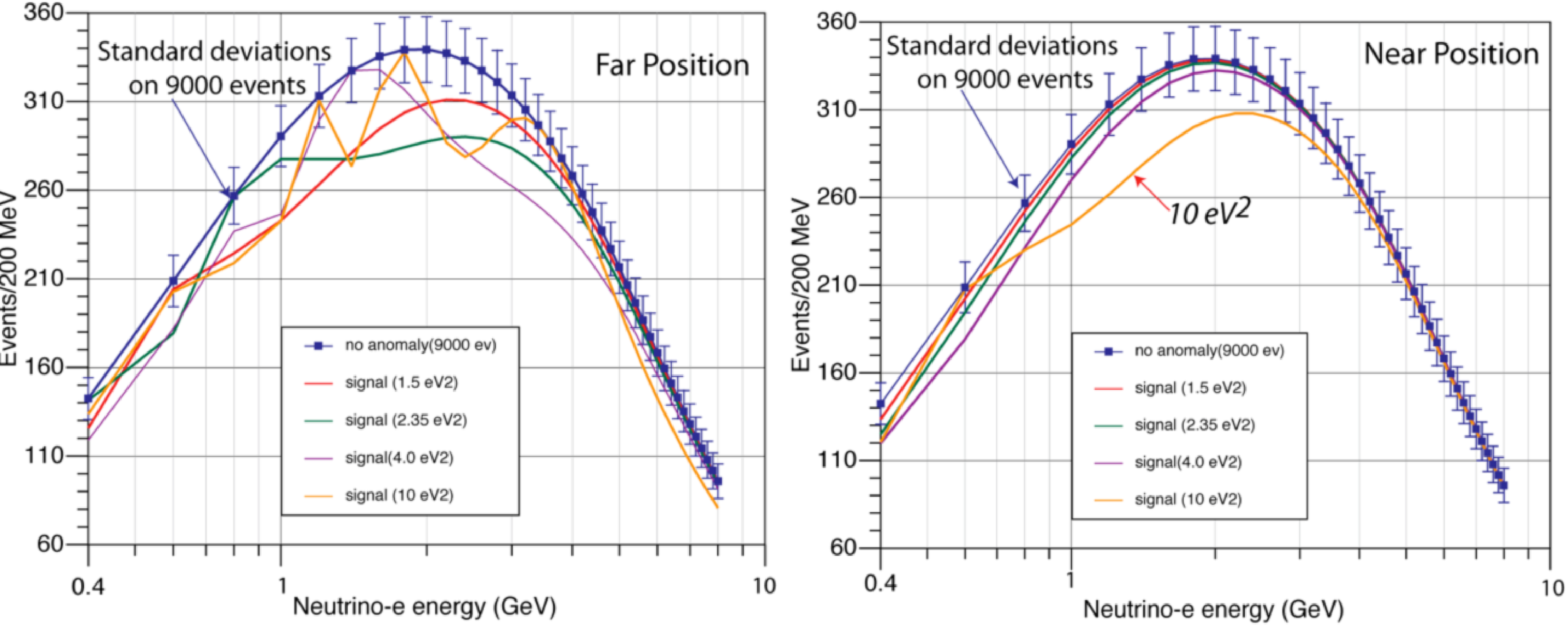
2 year PS neutrino beam T600 + T150 exposure for both neutrino (A) /antineutrino (B) mode with positive/negative meson focusing for different pot intensity:

- 2.5 10^{20} pot - basic old "I216" option corresponding to only 30 kW beam power
- 7.5 10^{20} pot – upgraded PS option (90 kW)



	ν focus		$\bar{\nu}$ focus	
	FAR	NEAR	FAR	NEAR
Fiducial mass	500 t	150 t	500 t	150 t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions (or ν_μ for ν focus)	3.600E+6	5.400E+7	6.000E+5	6.900E+6
QE ν_μ (or $\bar{\nu}_\mu$) interactions	1.350E+6	1.980E+7	2.610E+5	3.000E+6
Events/Burst	0.510	7.500	0.090	0.900
Intrinsic $\nu_e + \bar{\nu}_e$ from beam	27000	360000	6000	87000

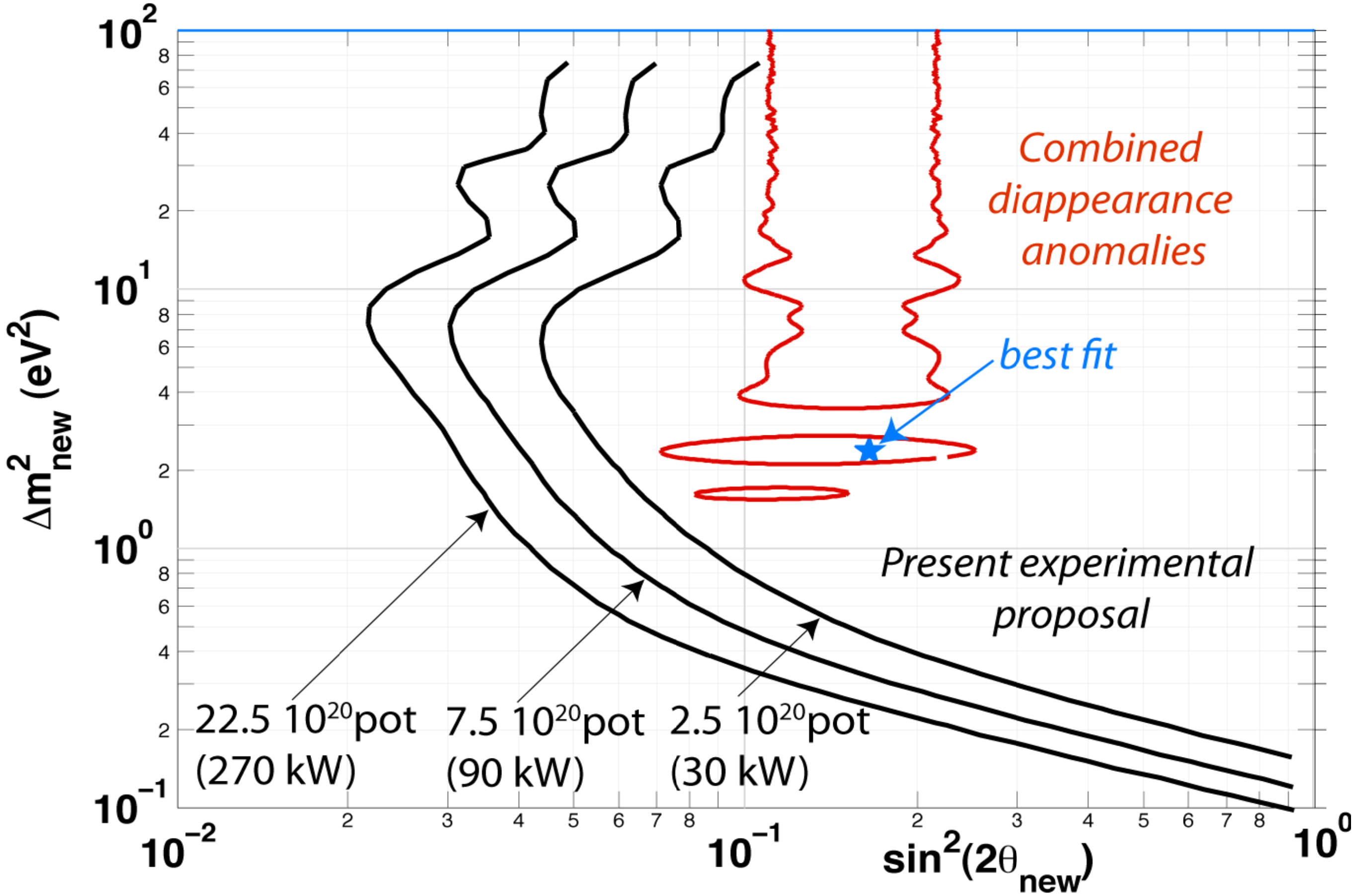
Sensitivity to νe (and νμ) disappearance signals



The energy distributions of the electron neutrino events is shown in (a) and (b)respectively for the "Far" and "Near" and a number of possible values in the region of $\Delta m^2 > 1eV^2$ and $sin^2(2\theta) \approx 0.16$ for 9000 neutrino events.

If confirmed without any doubt such a large mass difference will have an important role in the explanation of the existence of the Dark Mass in the Universe.

Sensitivity to disappearance anomalies



- Sensitivities (90% CL) in the $\sin^2(2\theta_{new})$ vs. Δm^2_{new} for an integrated intensity of (a) at the 30 kWatt beam intensity of the previous CERN/PS experiments, (b) the newly planned 90 kWatt neutrino beam and (c) a 270 kWatt curve. They are compared (in red) with the "anomalies" of the reactor + Gallex and Sage experiments. A 1% overall and 3% bin-to-bin systematic uncertainty is included (for 100 MeV bins).

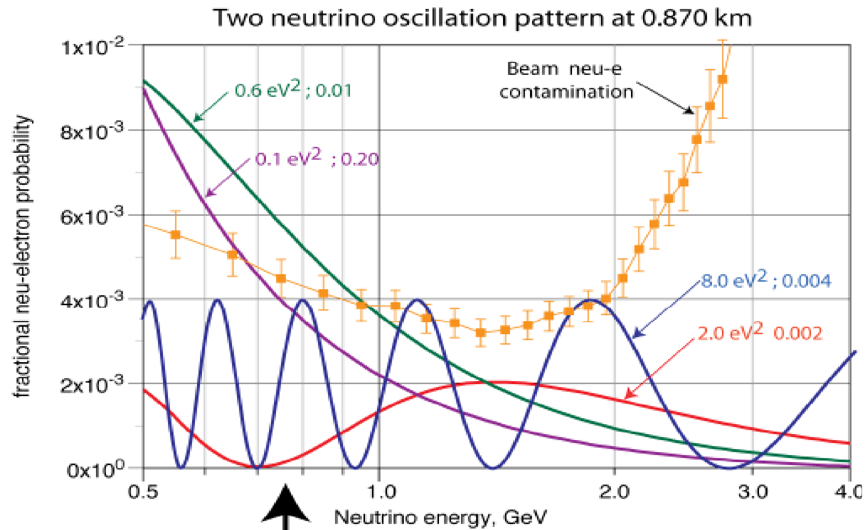
Expected signal for LSND/MiniBooNE anomalies

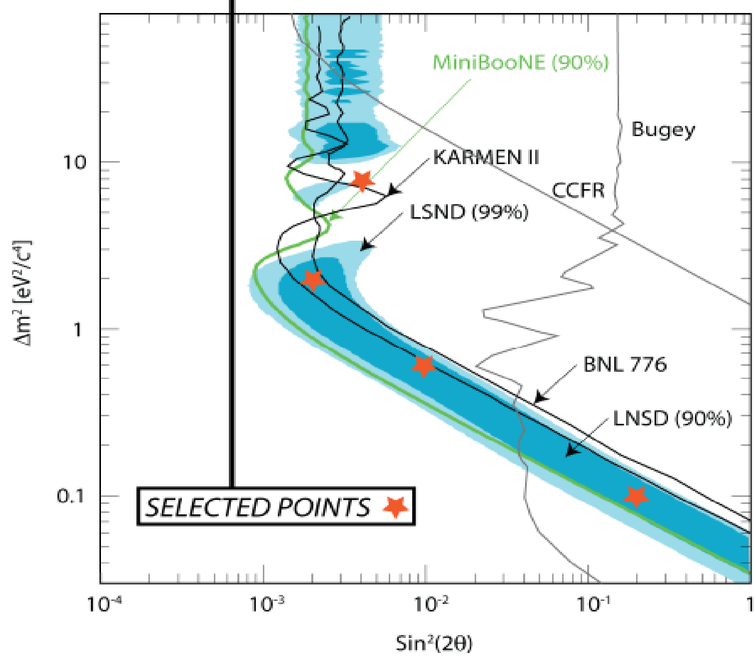
- Event rates for the near and far detectors given for 7.5 10^{20} pot for E_ν < 8 GeV (90 kW beam power). The oscillated signals are clustered below 3 GeV of visible energy.

	ν focus		$\bar{\nu}$ focus	
	FAR	NEAR	FAR	NEAR
Fiducial mass	500 t	150 t	500 t	150 t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions (or $\bar{\nu}_\mu$ for $\bar{\nu}$ focus)	3.600E+6	5.400E+7	6.000E+5	6.900E+6
QE ν_μ (or $\bar{\nu}_\mu$) interactions	1.350E+6	1.980E+7	2.610E+5	3.000E+6
Events/Burst	0.510	7.500	0.090	0.900
Intrinsic $\nu_e + \bar{\nu}_e$ from beam	27000	360000	6000	87000
Intrinsic $\nu_e + \bar{\nu}_e$ ($E_\nu < 3$ GeV)	11700	162000	2640	39000
ν_e oscillations:				
$\Delta m^2 = 2.\ eV^2$; $\sin^2 2\theta = 0.002$	3582	3150	690	174
$\Delta m^2 = 0.4\ eV^2$; $\sin^2 2\theta = 0.02$	6249	7020	990	345
$\Delta m^2 = 0.064\ eV^2$; $\sin^2 2\theta = 0.96$	10050	3750	1395	420
$\Delta m^2 = 4.42 eV^2$; $\sin^2 2\theta = 0.0066$	8940	75150	1470	9660

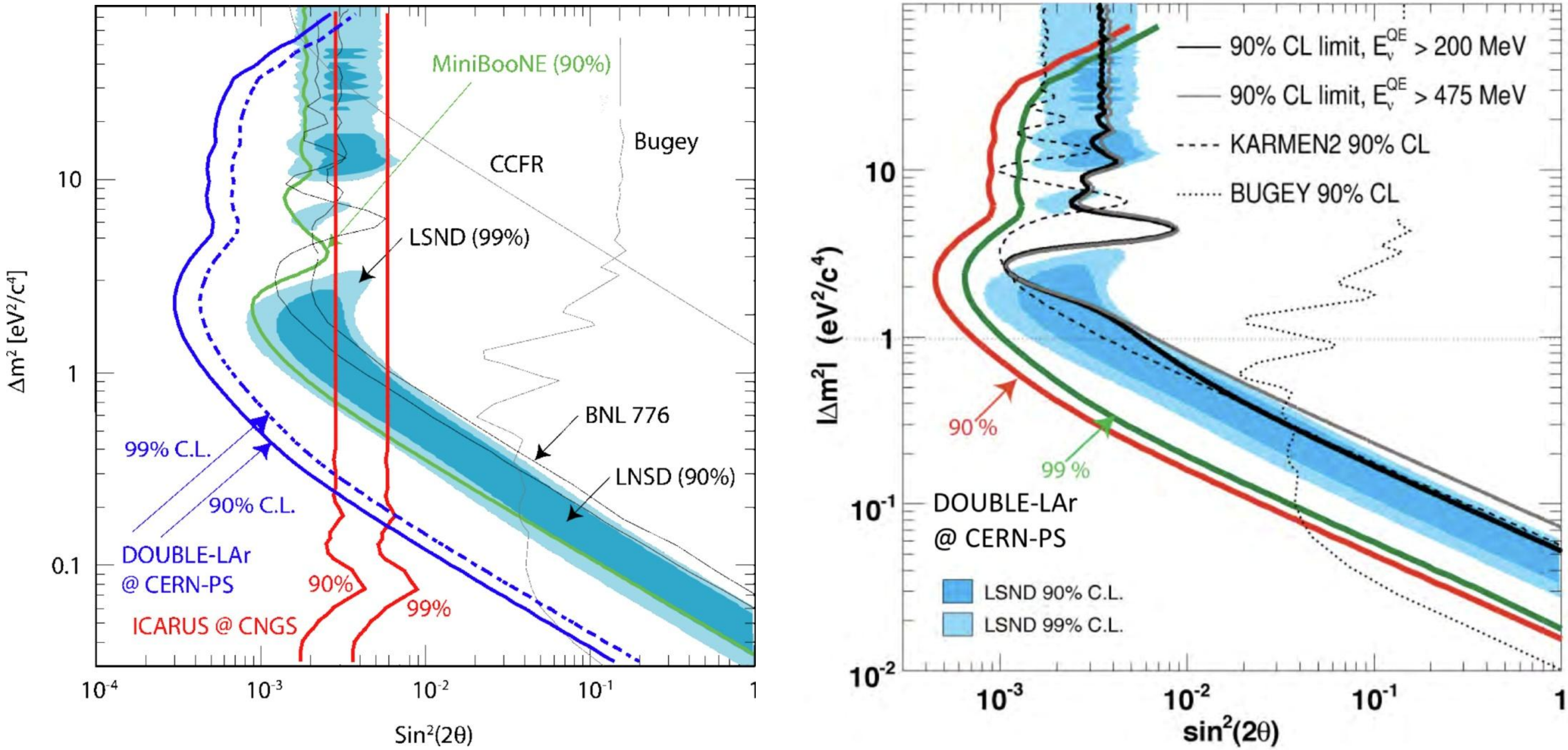
Determination Δm^2 and $\sin^2 2\theta$ values in $\nu\mu \rightarrow \nu e$ anomaly

- It appears that the present proposal, unlike LNSD and MiniBooNE, can determine both the mass difference and the value of the mixing angle.
- Very different and clearly distinguishable patterns are possible depending on the values 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 behavior, for the moment completely unknown, is in all circumstances well above the backgrounds, also considering the very high statistical impact and the high resolution of the experimental measurement.





Comparing LSND sensitivities *(arXiv:0909.0355)*



Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (left) for 2.5 10^{20} pot (30 kW basic option) and twice as much for anti-neutrino (right) . The LSND allowed region is fully explored both for neutrinos. The expectations from one year of at LNGS are also shown.

Thank you !