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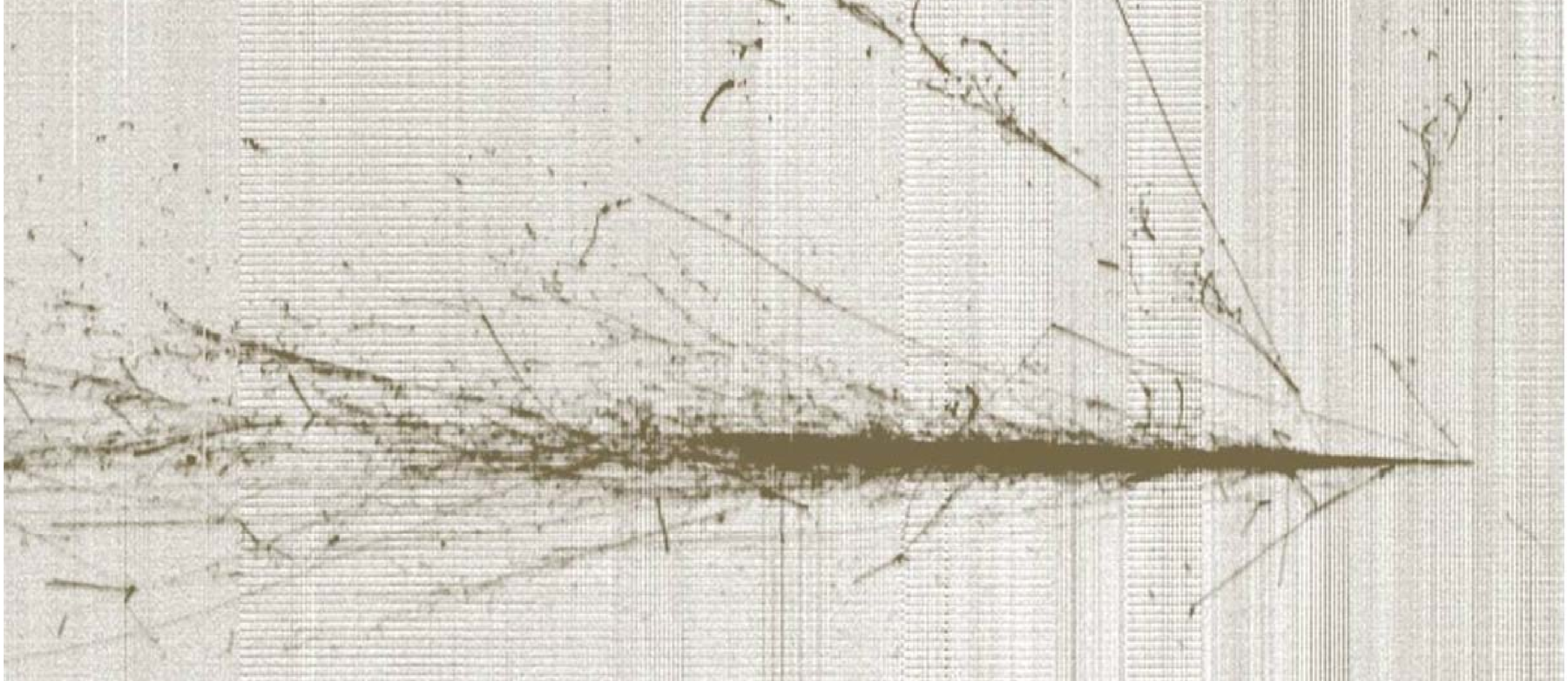
for the ICARUS Collaboration
I.N.F.N. Padova



ICARUS and Status of Liquid Argon Technology

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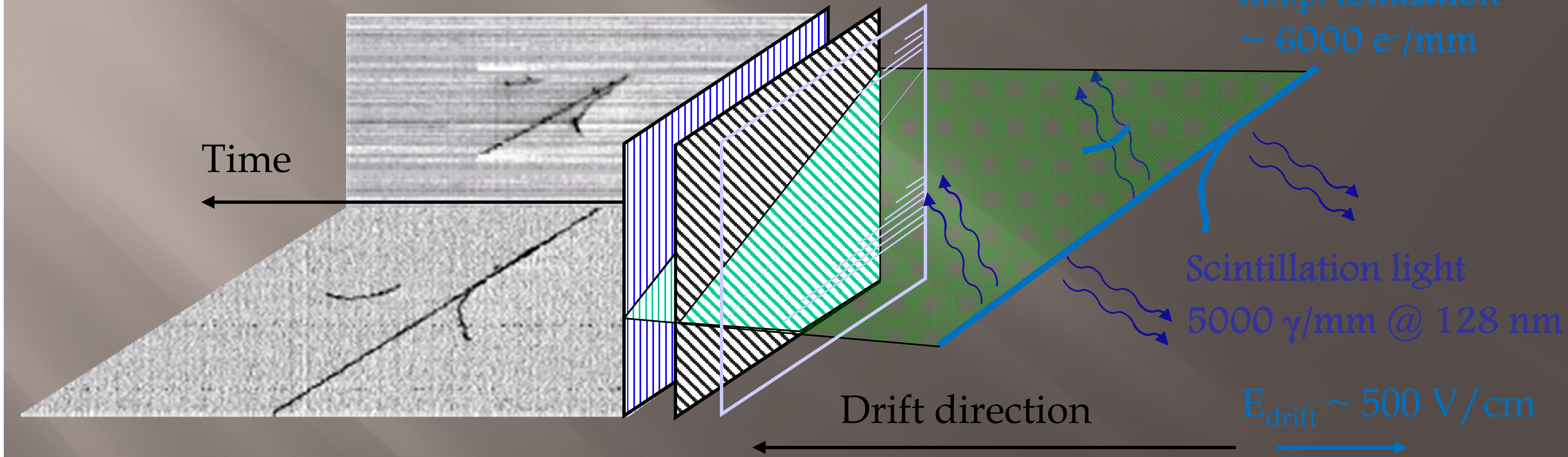
Liquid Argon Time Projection Chamber

A powerful detection technique [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 identification (through dE/dx vs range).



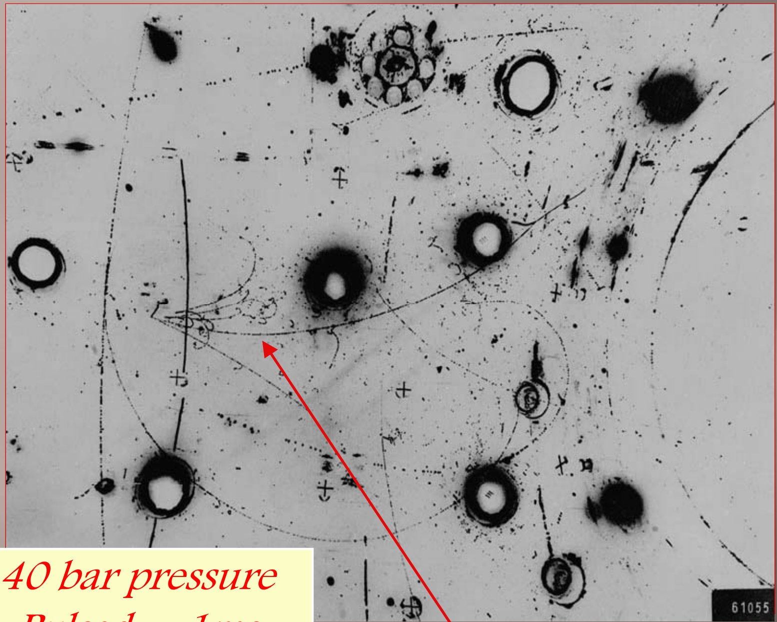
Electrons from ionizing track drifted by E_{drift} to transparent wires arrays recording induction signals; finally electron charge collected by collection wires.

Key feature: LAr purity from electro-negative molecules (O_2, H_2O, CO_2).

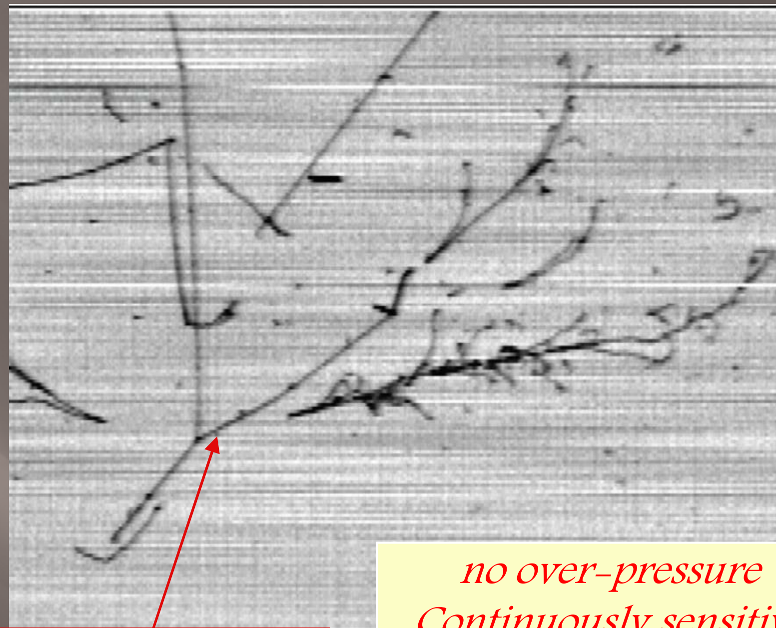
Target: 0.1 ppb O_2 equivalent = 3 ms lifetime (4.5 m drift @ E_{drift} = 500 V/cm).

Thirty years of progress…

Gargamelle bubble chamber



ICARUS electronic chamber



40 bar pressure
Pulsed ≈ 1ms

Bubble diameter ≈ 3 mm
(diffraction limited)

"Bubble" size
3 x 3 x 0.3 mm³

no over-pressure
Continuously sensitive

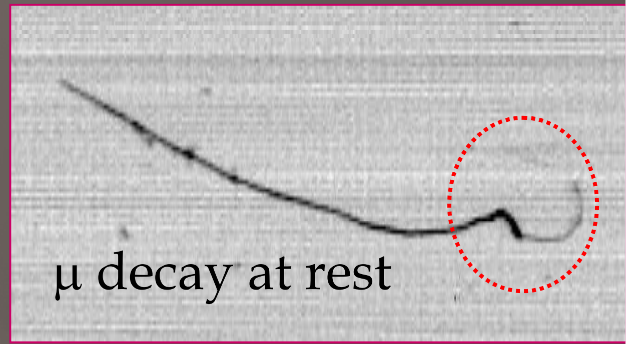
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

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

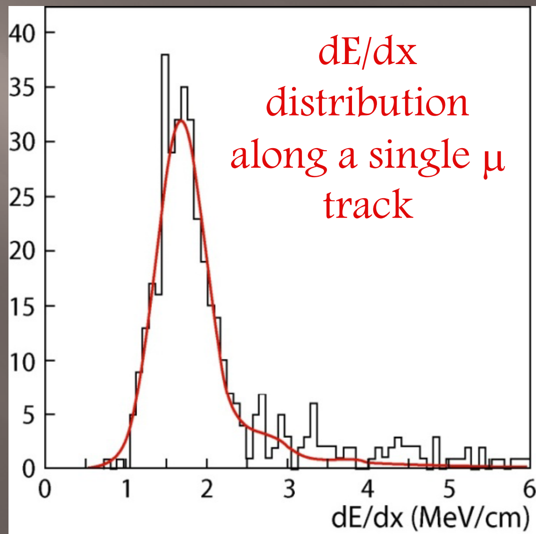
Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

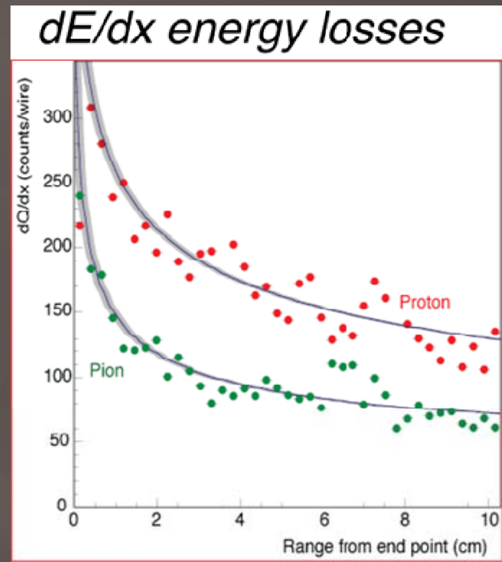
Summary of LAr TPC performance

- Tracking device
  - high resolution imaging ($\sigma_{x,y}$~1mm, σ_z~400μm): precise event topology;
  - μ momentum 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 dE/dx vs range.





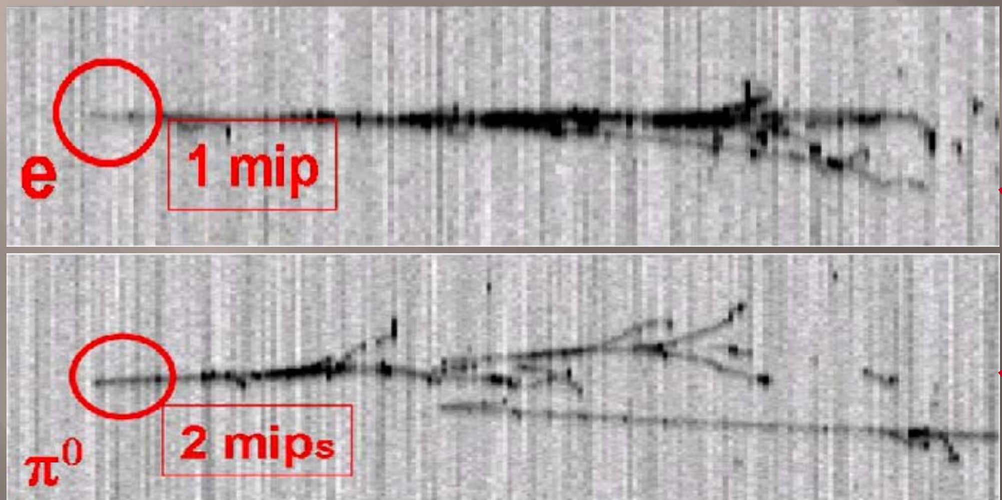
- Total energy reconstruction by charge integration
  - full sampling, homogeneous calorimeter with excellent accuracy for contained events.

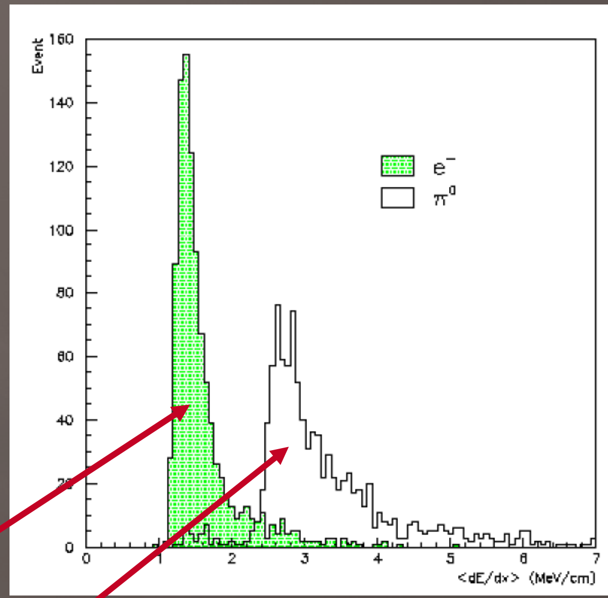
RESOLUTIONS

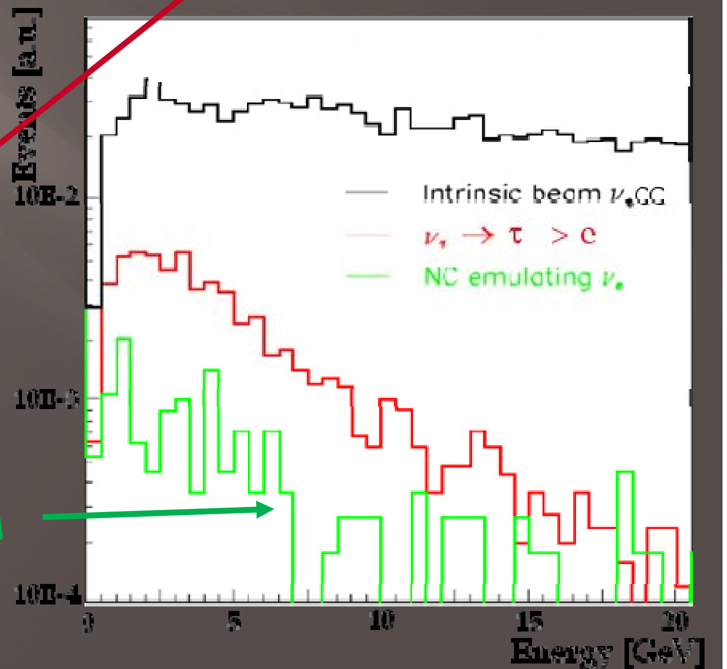
Low energy electrons:	$\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$
Electromagn. showers:	$\sigma(E)/E = 3\% / \sqrt{E(GeV)}$
Hadron shower (pure LAr):	$\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

NC rejection in LAr-TPC

- NC interactions in LAr-TPC recognized by:
  - topology (γ conversion distance from vertex);
  - reconstruction of π^0 invariant mass;
  - e^-/γ separation via dE/dx.
- ν_eCC leading electron identification efficiency: 90 %
- NC residual misidentification < 0.1 %

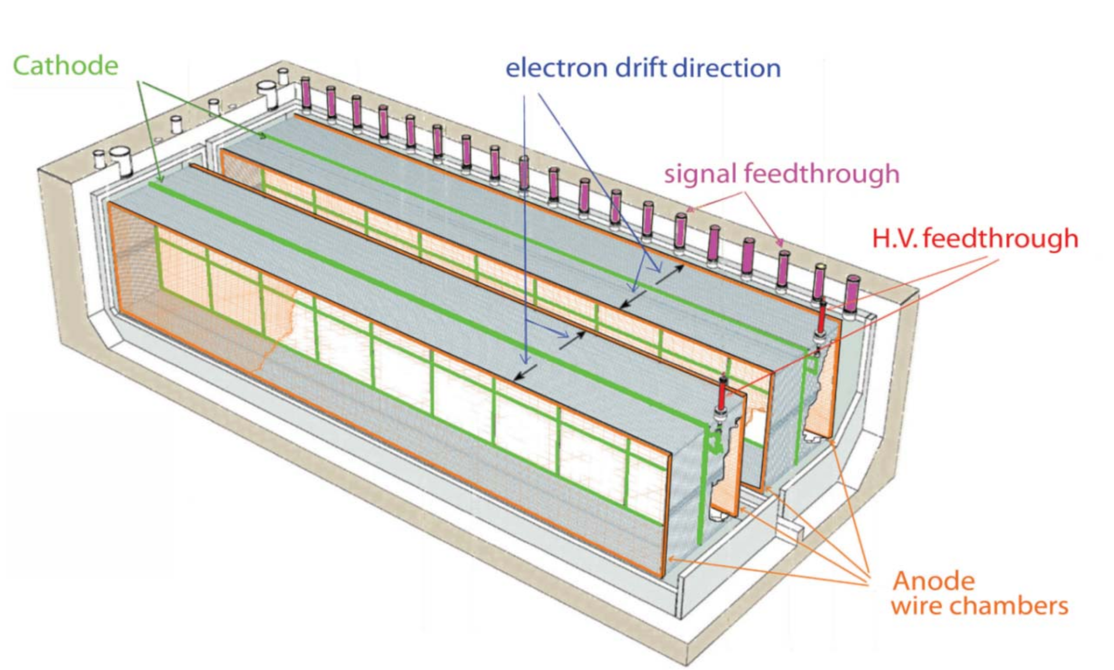






NC background in ν_μ low-energy beam on axis @ LNGS

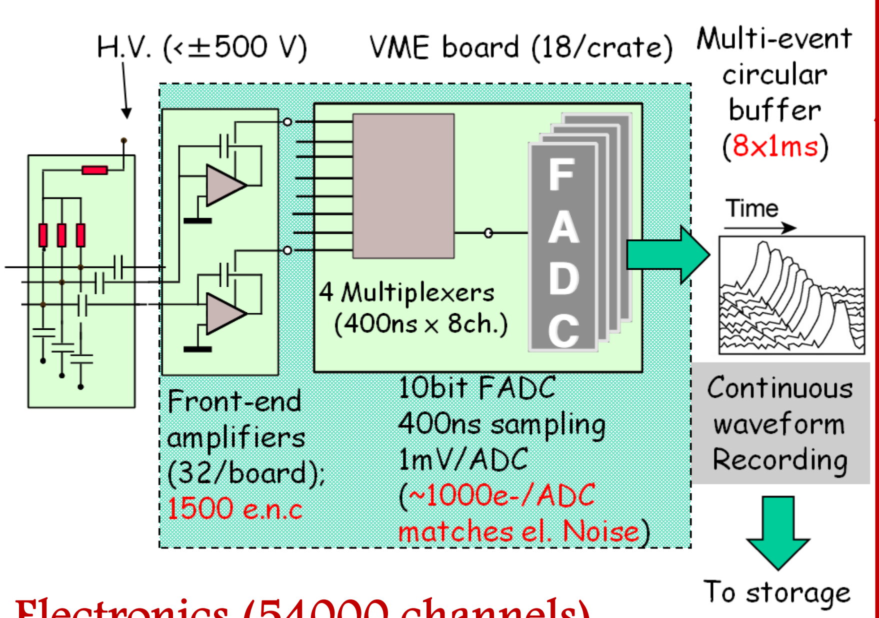
ICARUS T600 LAr-TPC



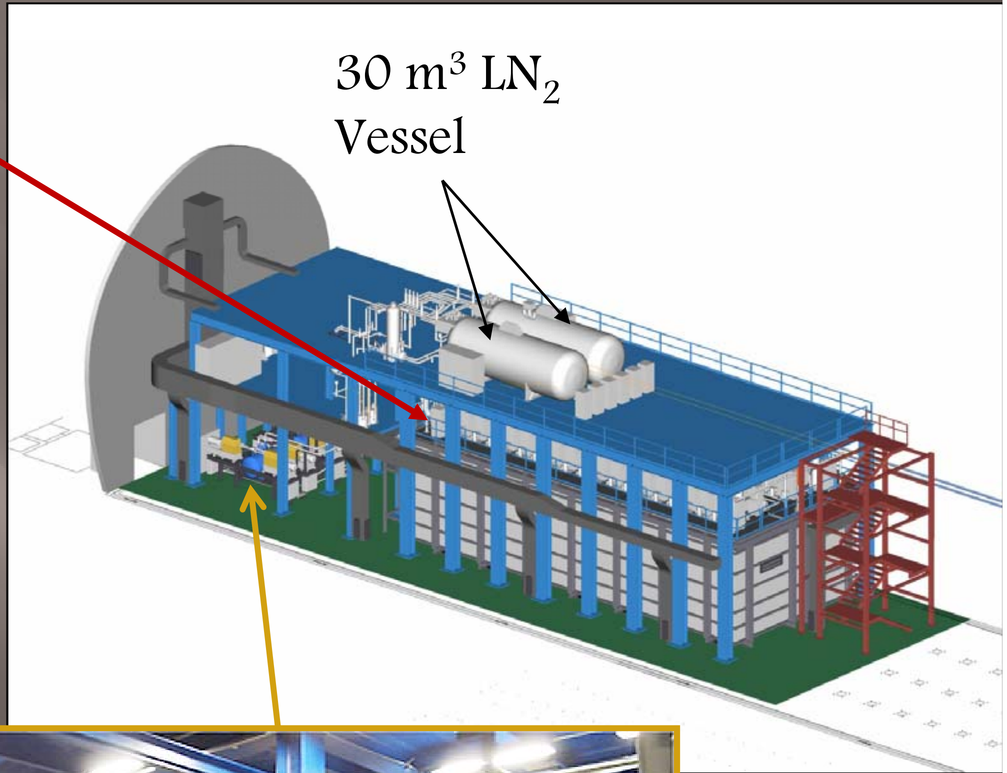
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes/chamber at 0°, ±60°, 3 mm plane spacing
  - ≈ 54000 wires, 3 mm pitch
- PMT for scintillation light:
  - 74 PMTs, 8" Ø
  - VUV sensitive (128nm) with wavelength shifter (TPB)

- Two identical T300 modules, total LAr active mass 476 t:
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each;
  - drift length = 1.5 m;
  - HV = -75 kV _ E_{drift}= 0.5 kV/cm;
  - v_{drift} = 1.55 mm/μs.

Cryo plant & read-out



Electronics (54000 channels)

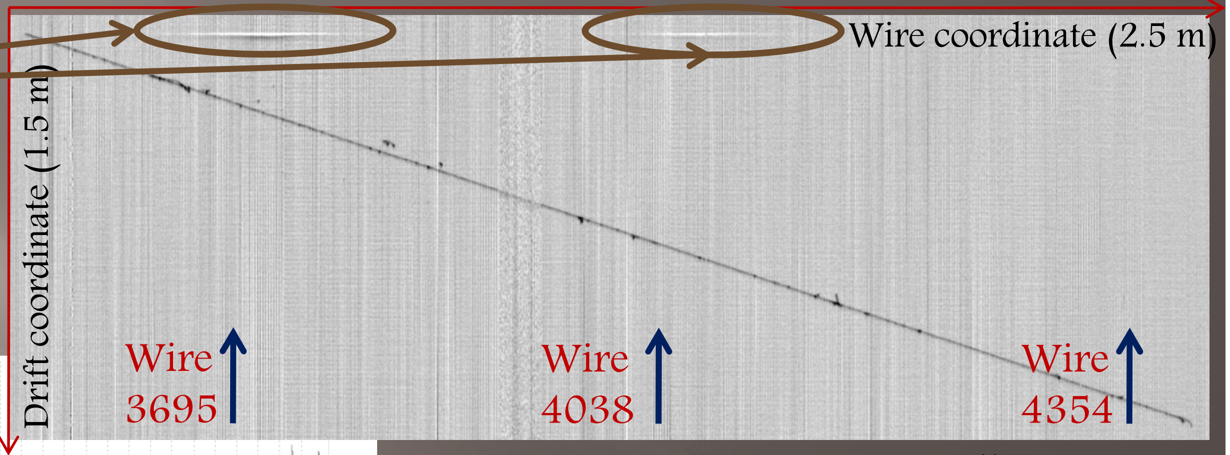


10 liquefiers units,
40 kW global cryo-power

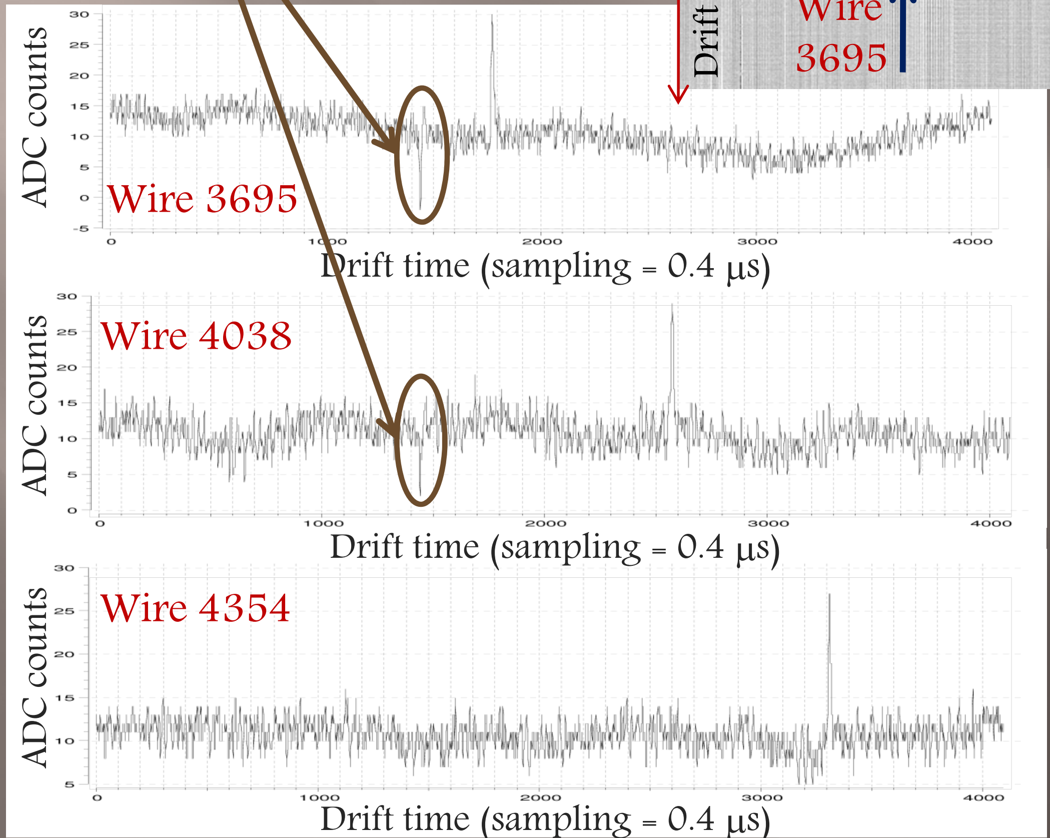
LAr purity measurement

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

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

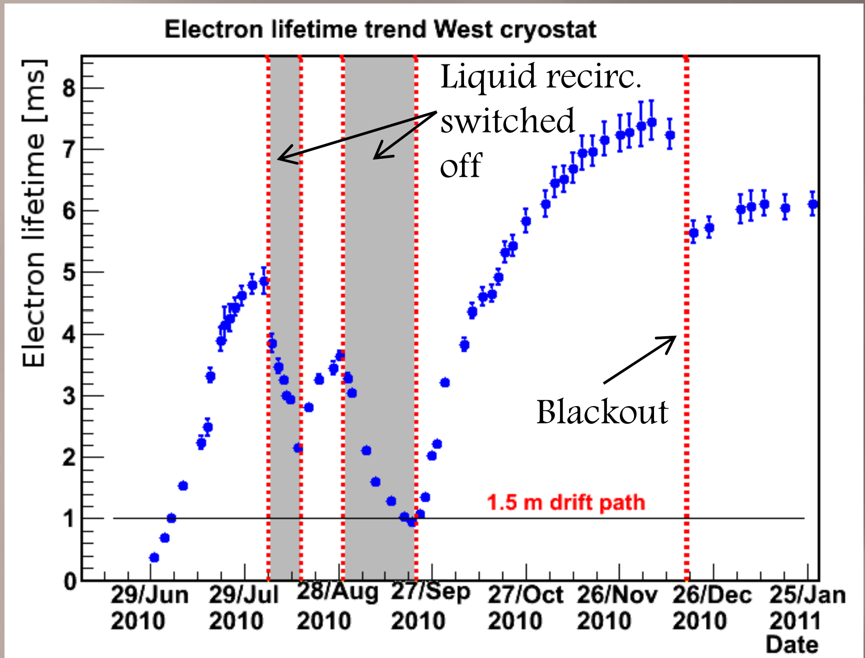


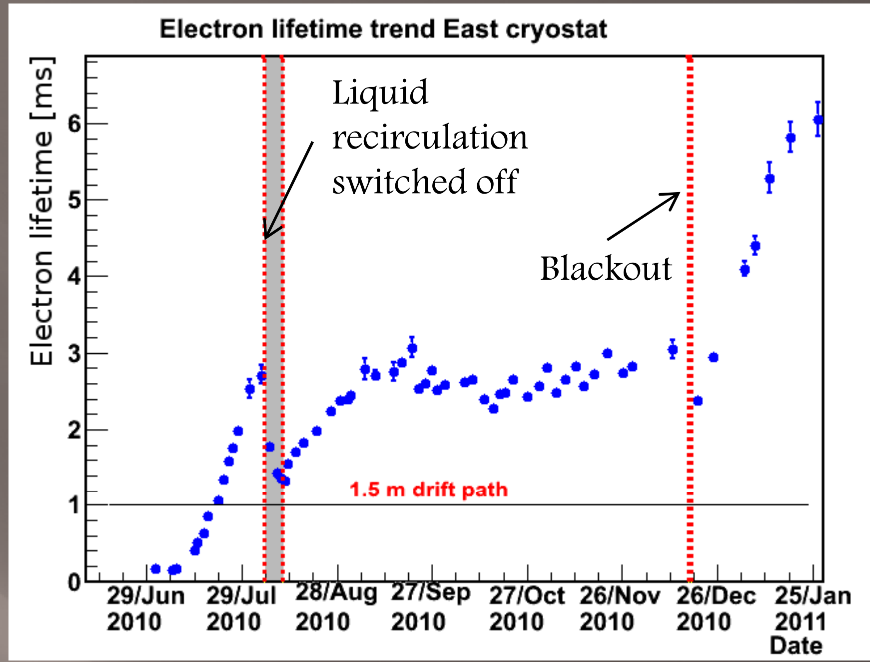
Run 10139 Event 8961 Collection view



Pulse height for 3 mm m.i.p.
~ 24 ADC # (24000 electrons)

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





At present 6 ms electron lifetime both in West and East cryostats, well above the 1ms maximum drift time

$\Rightarrow$ charge attenuation < 16 % at 1.5 m drift distance.

$$\tau_{ele}\,[ms] = 0.3/N\,[ppb]$$

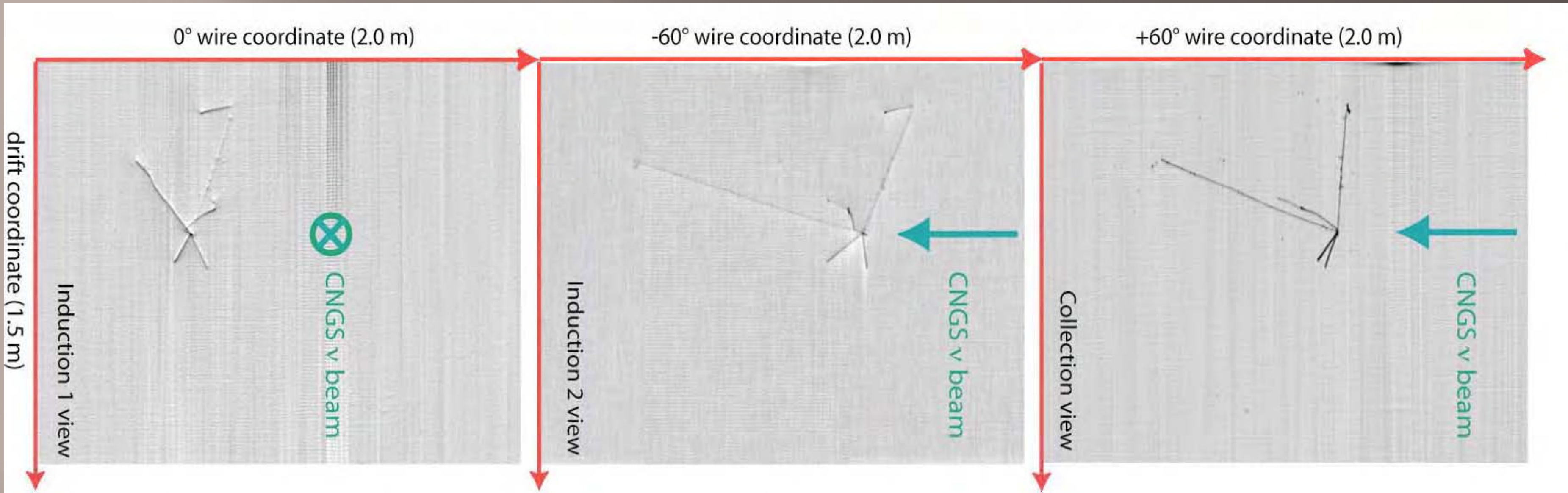
Impurity concentration, expressed in O_2 equivalent ppb units

6 ms electron lifetime $\rightarrow$ 0.05 ppb O_2 equivalent impurity concentration

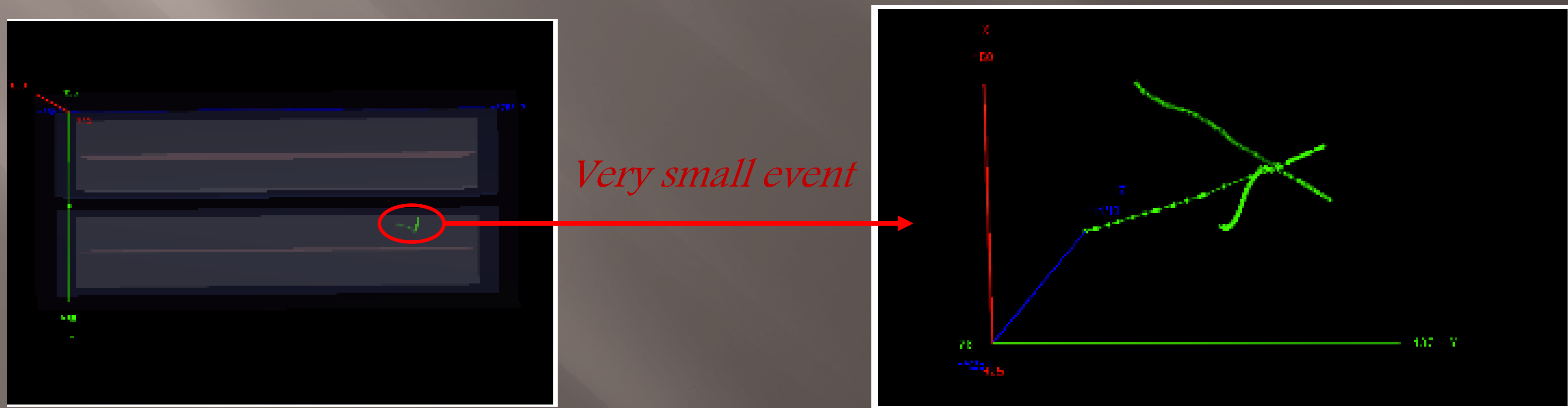
ICARUS T600 physics potential

- ICARUS T600: major milestone towards realization of large scale LAr detector. Successfully operated on surface, now operational underground (LNGS - Hall B). Exposed to CNGS (CERN to Gran Sasso) ν_μ beam, $E_\nu \sim 17.4$ GeV.
- Interesting physics in itself: unique imaging capability, spatial/calorimetric resolutions and e/π^0 separation $\rightarrow$ events "seen" in a new way.
- "Bubble chamber like" CNGS ν events collection (beam intensity 4.5 10^{19} pot/year):
  - 1200 ν_μ CC event/year ;
  - 8 ν_e CC event/year;
  - search for ν_τ events in the electron channel, using kinematical criteria;
  - search for sterile ν in LSND parameter space (deep inelastic ν_e CC events excess).
- "Self triggered" events collection:
  - ~ 80 ev/y of unbiased atmospheric ν CC;
  - solar ν_e rates > 8 MeV;
  - zero background proton decay with 3 x 10^{32} nucleons for "exotic" channels.

Atmospheric ν interaction

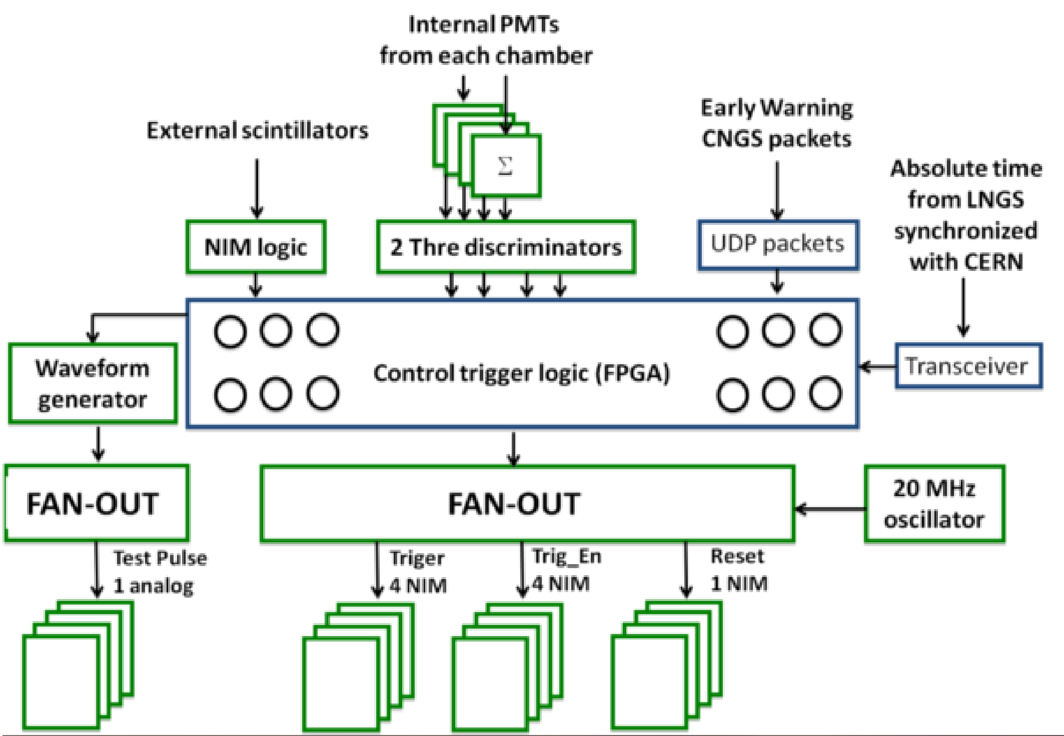


- Total visible energy: 887 MeV (including quenching and e⁻ lifetime corrections).
- Out-of-time from CNGS spill AND angle w.r.t. beam direction: 35°.

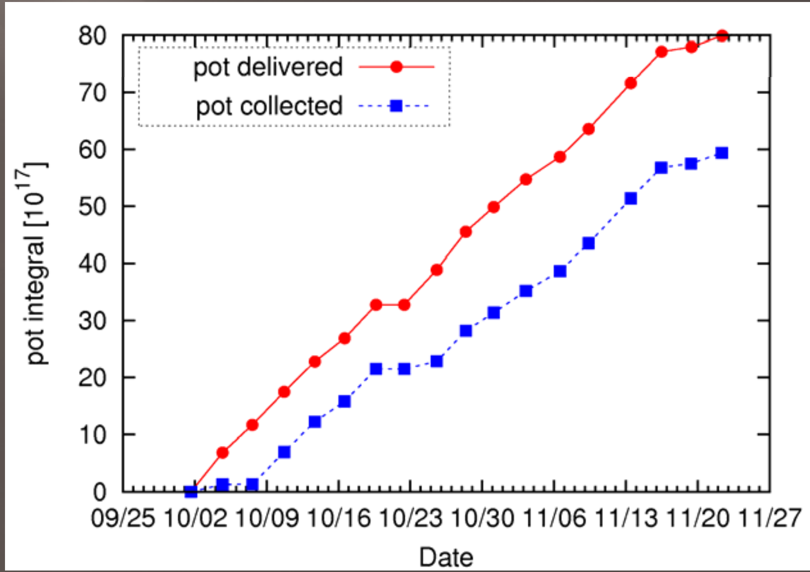


CNGS run during 2010

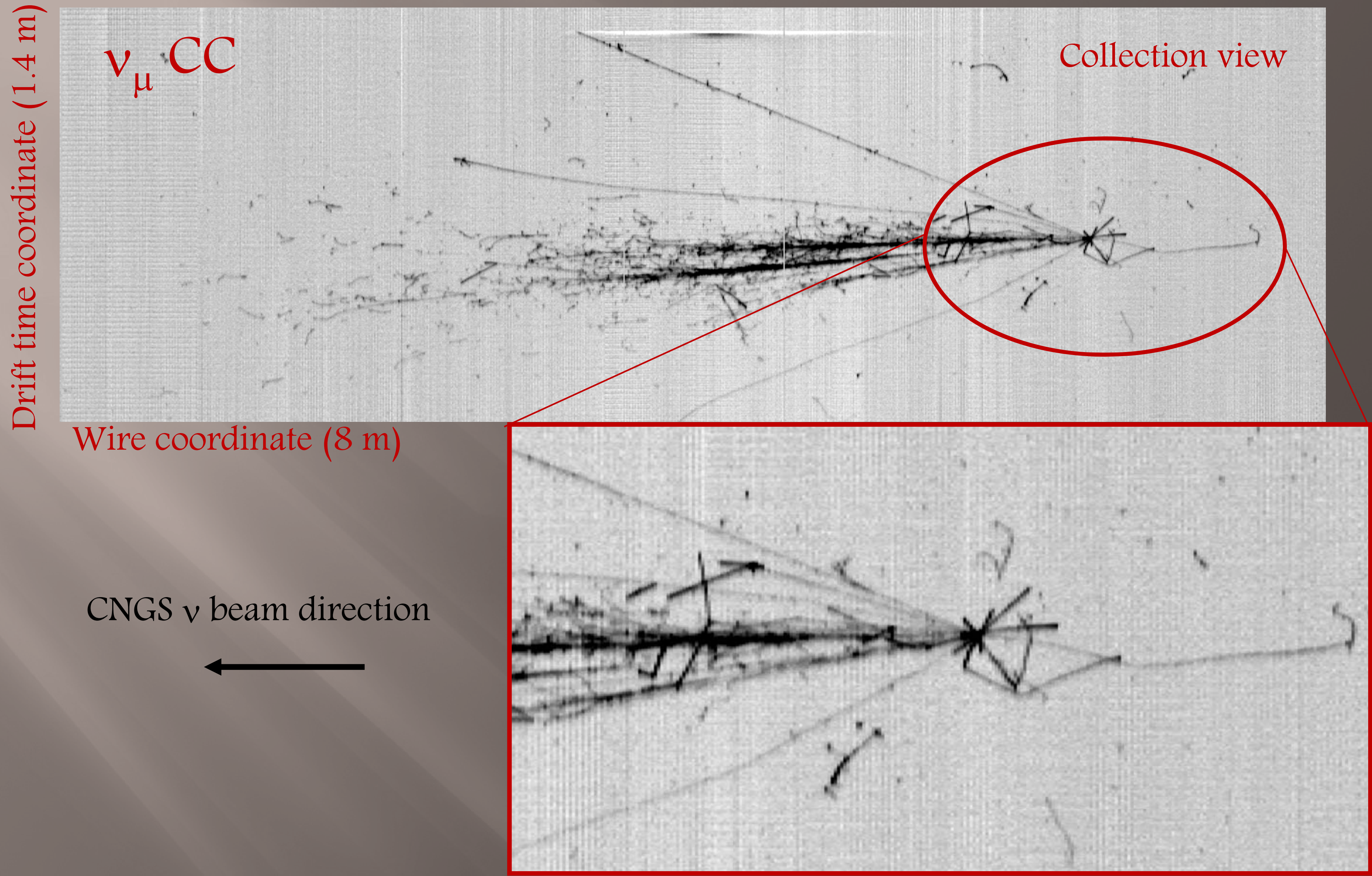
- ICARUS fully operational for CNGS events recording in Oct. 1^{st} – Nov. 22^{nd}.
- At every CNGS cycle 2 spills lasting 10.5 μs each, 50 ms apart; ppp = $2.1\ 10^{13}$.
- CNGS "Early Warning" signal sent 80 ms before the proton spill extraction, containing information on the time foreseen for the next extraction.
- Trigger: photomultiplier signal for each chamber with 100 phe threshold discrimination, within 60 μs wide beam gate.



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



CNGS “first” ν interaction in ICARUS T600



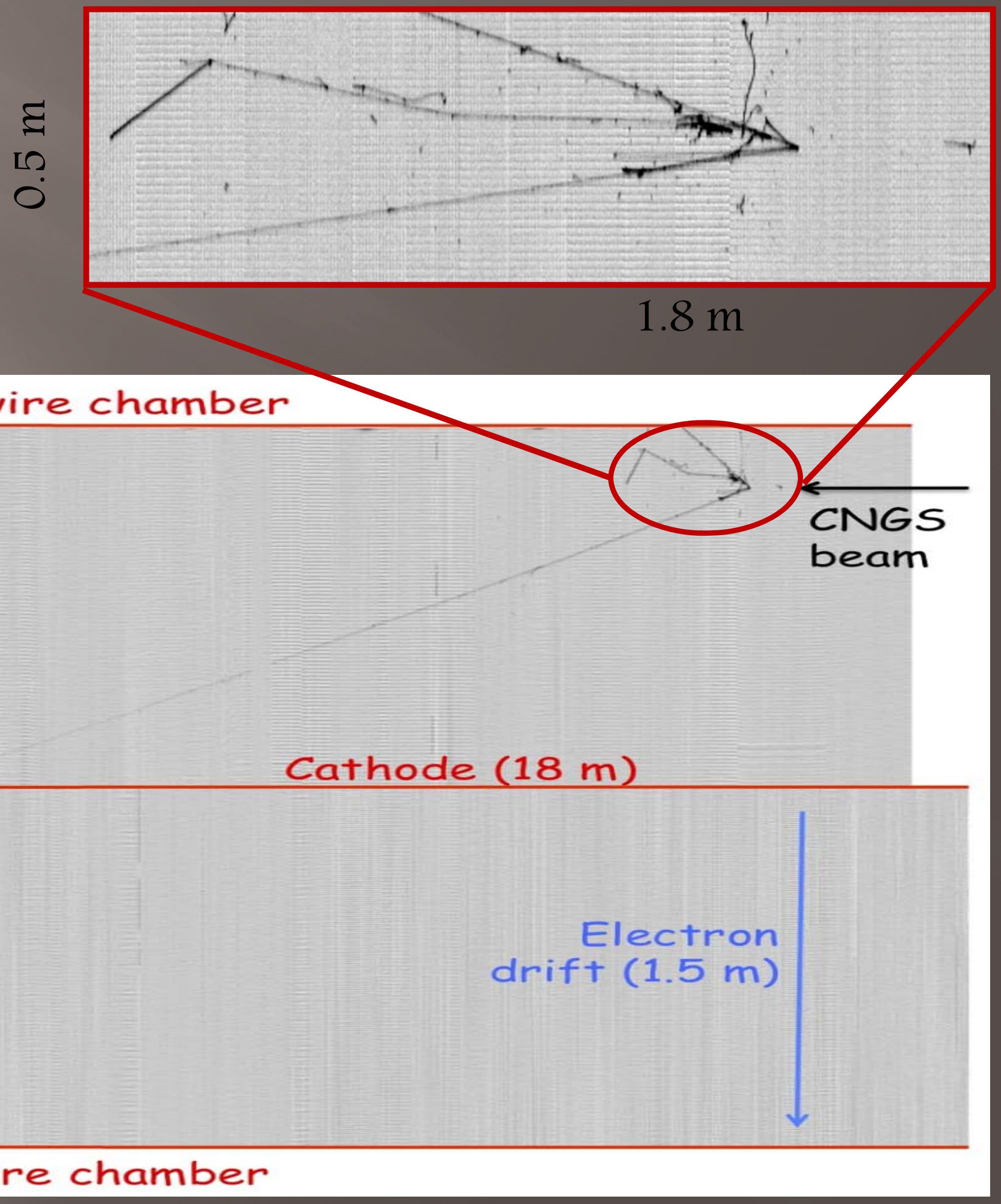
CNGS ν beam direction

←

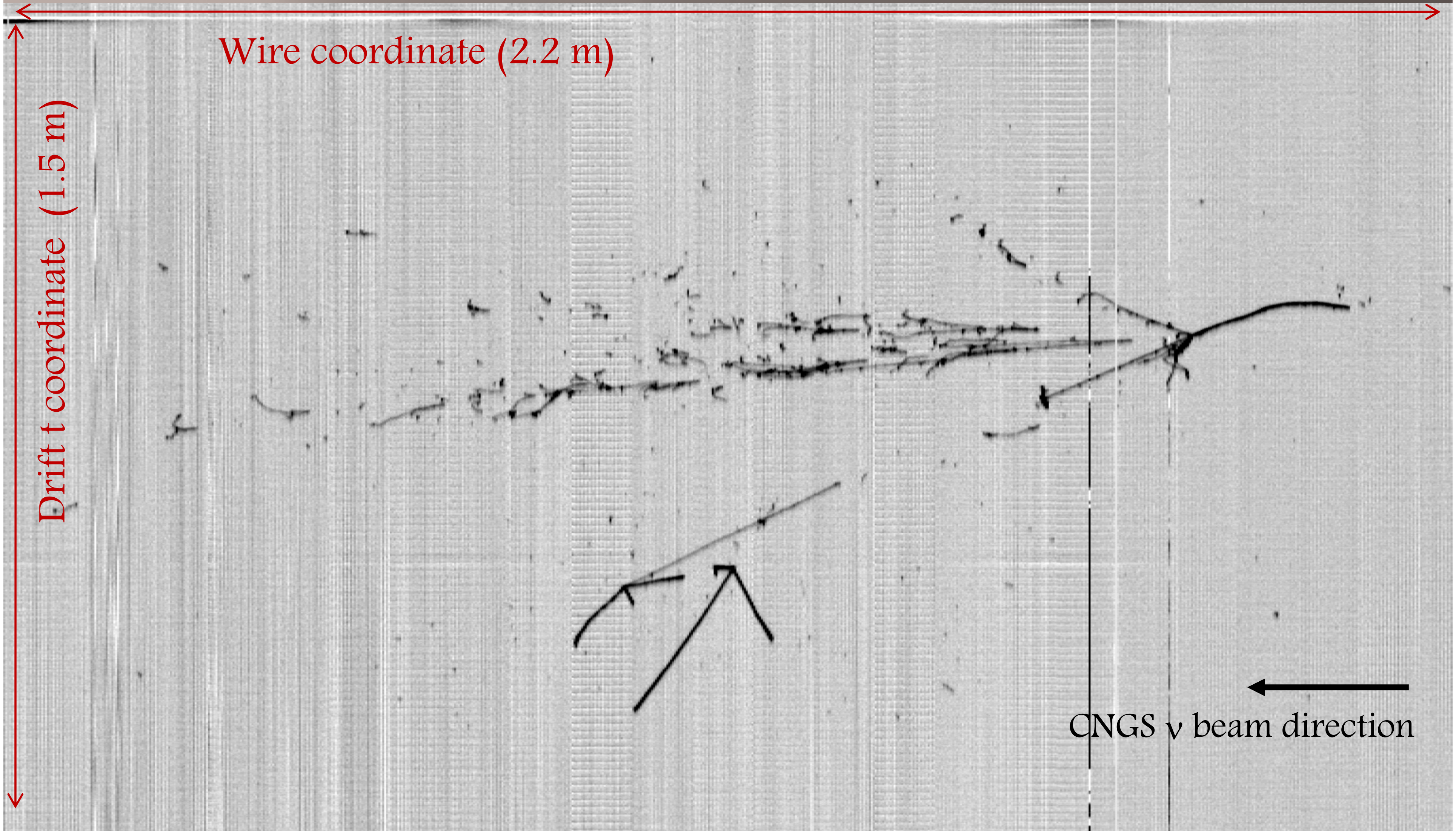
Low energy CNGS ν_μ CC interaction

E_{vis} ~ 9 GeV

Electron lifetime and quenching accounted for.



CNGS NC interaction



Preliminary results of first CNGS 2010 run

- Analyzed sample: 1332 CNGS triggers, i.e. $4.2 \cdot 10^{18}$ pot = 72 % out of whole sample. Classified by visual scanning into fiducial volume 434 t.
- Number of collected interactions compared with number of interactions predicted per pot ($2.6/0.86\ 10^{-17}$ ν CC/NC), in the whole energy range, corrected by fiducial volume and DAQ dead-time.

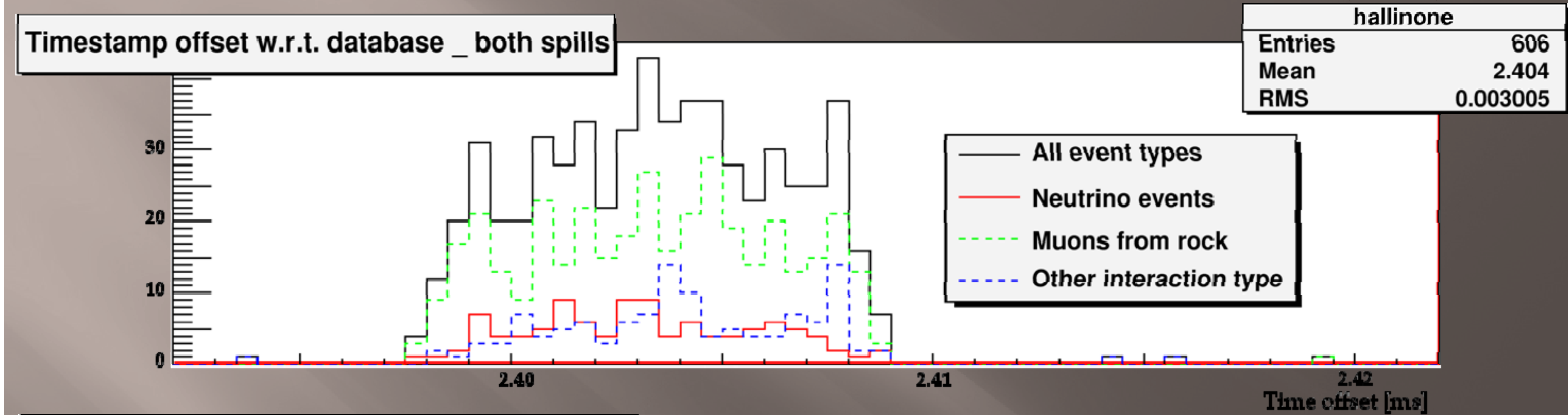
Event type	Collected	Predicted
ν_μ CC	85	89
ν NC	26	28
ν XC *	6	
Total	117	117

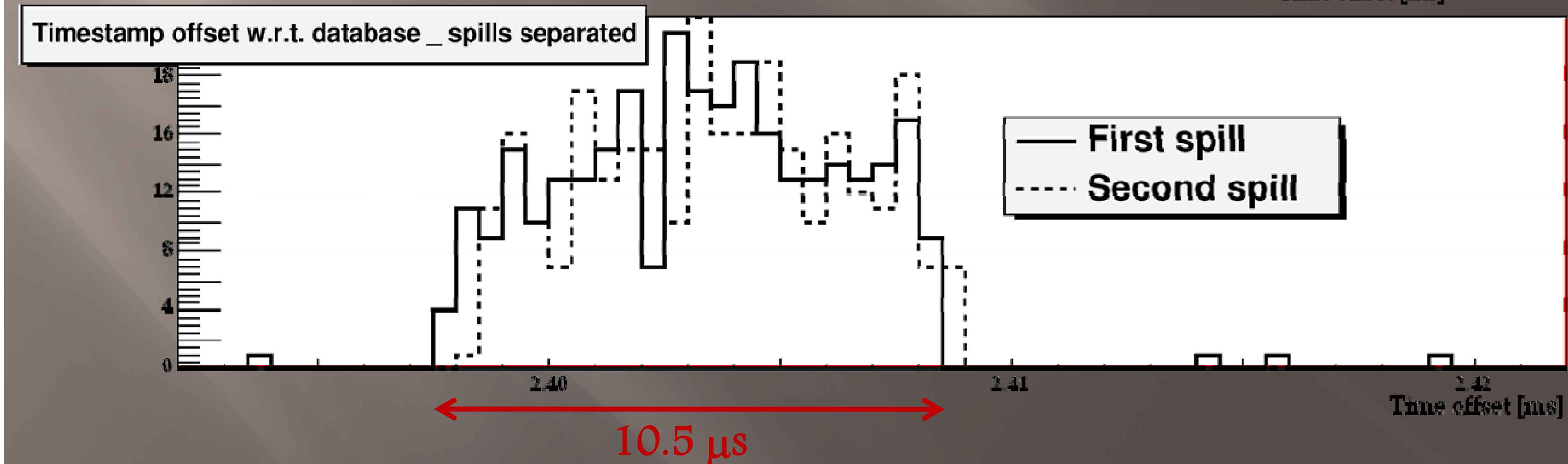
* Events at edges, with μ track too short to be visually recognized: further analysis needed.

On overall statistics of 117 ν in agreement with expectations.

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

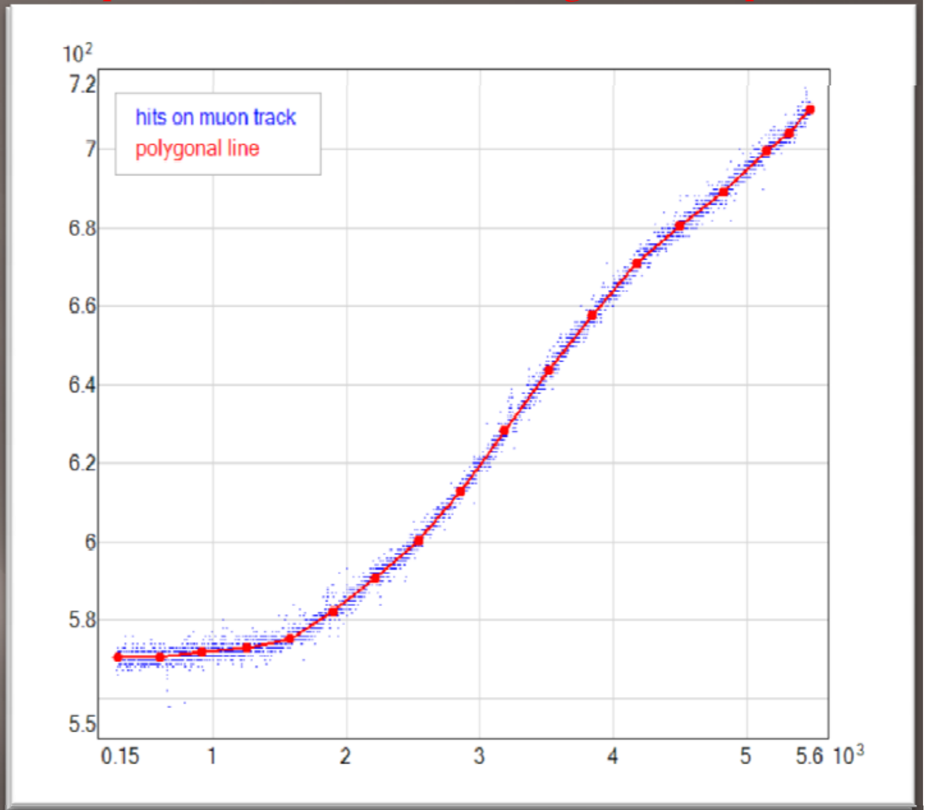
- Narrow distribution ~ spill duration (10.5 μs)
- Minimum offset value (2.40 ms) in agreement with 2.44 ms ν t.o.f. from CERN to LNGS, in view of 40 μs fiber transit time from ext. LNGS labs to Hall B (8km).



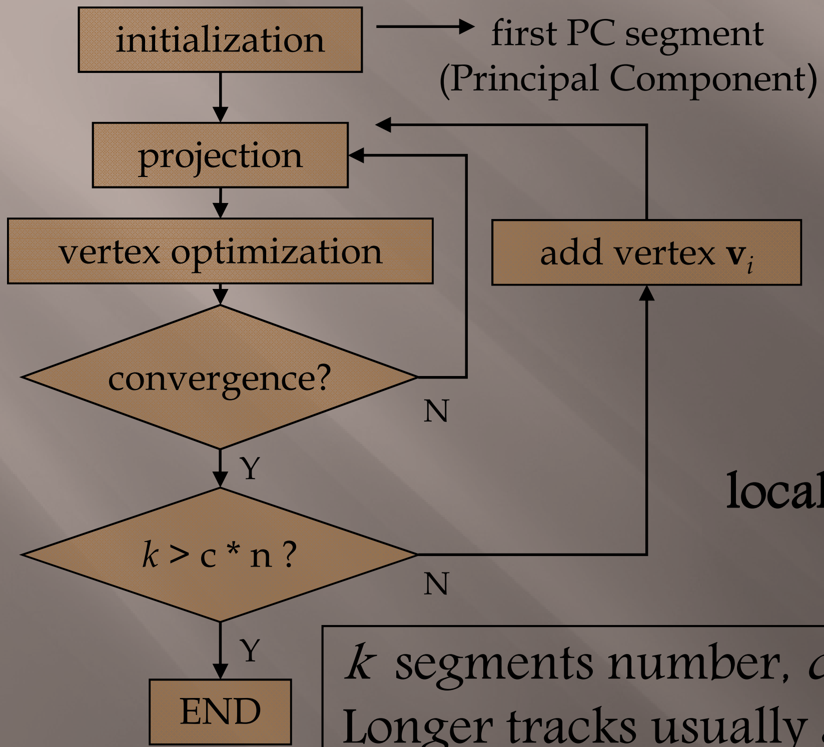


3D reconstruction

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



- Complement of 2D reconstruction based on Polygonal Line Algorithm (PLA).
- 3D reconstruction: linking hit projections between views according to
  - drift sampling;
  - sequence of hits.



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

local squared distance to hits

local angle penalty term

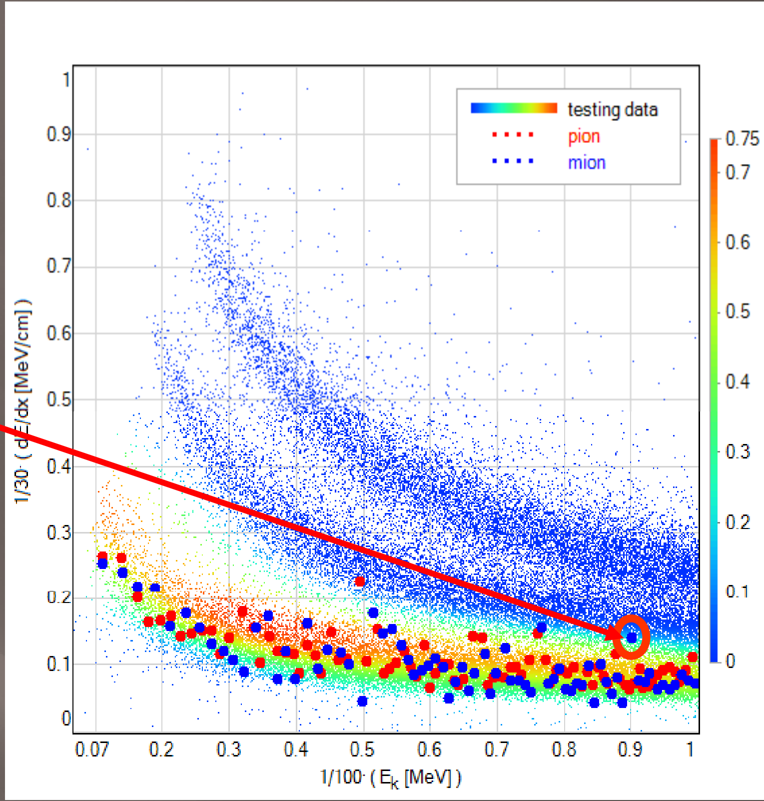
k segments number, c threshold parameter, n track hits number.
Longer tracks usually are more straight.

Neural network particle identification

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

  p_i: [E_k, dE/dx] → nn_i : [P(p), P(K), P(π), P(μ)]
- Average M output vectors for the points

  NN = S(**nn**$_i$)/M
- Identify track as particle corresponding to max(**NN**)
- Energy reconstr. 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

LAr-TPC: powerful technique. Run 9927 Event 572

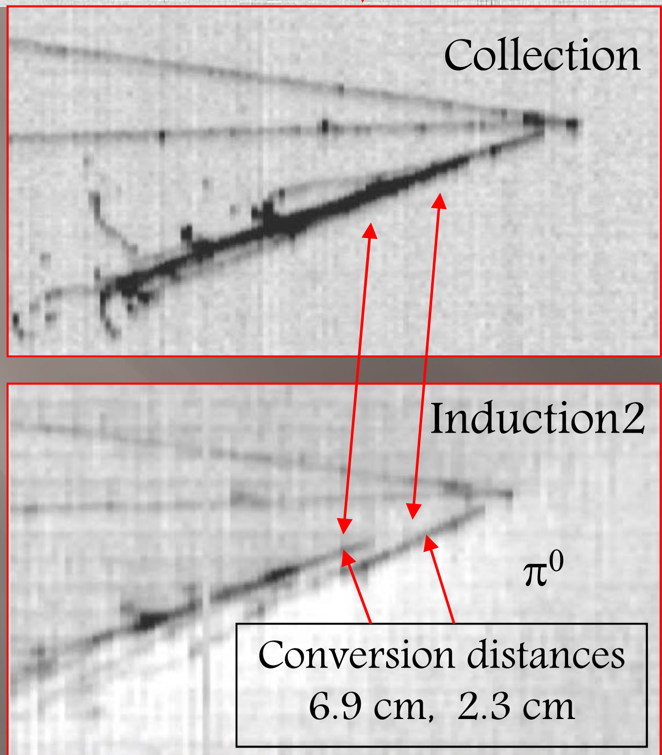
Primary vertex (A)

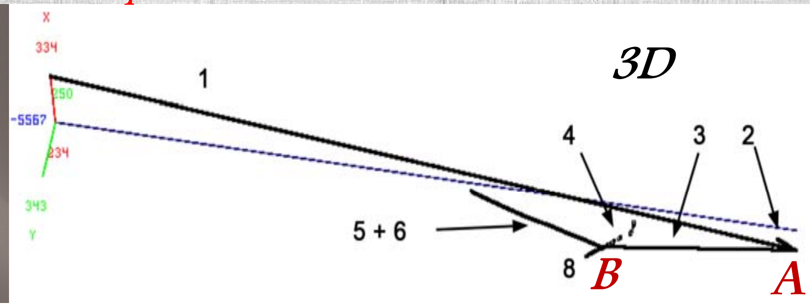
very long μ(1), e.m. cascade(2), pion (3).

Secondary vertex (B)

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

– μ decay is observed.





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 (π)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

2011-2012 CNGS run: physics perspectives

- 2011-2012 run with dedicated SPS periods @ high intensity: **expected >10^{20} pot**.
- For 1.1 10^{20} pot → 3000 beam related ν_μCC events expected in ICARUS T600.

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

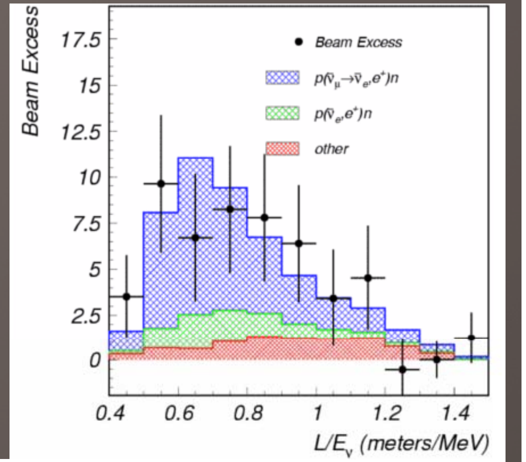
Background

- 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_τCC events expected .
- $P(\tau \rightarrow e\nu\nu)$ = 18% ⇒ 3 electron deep inelastic events with visible energy <20 GeV.

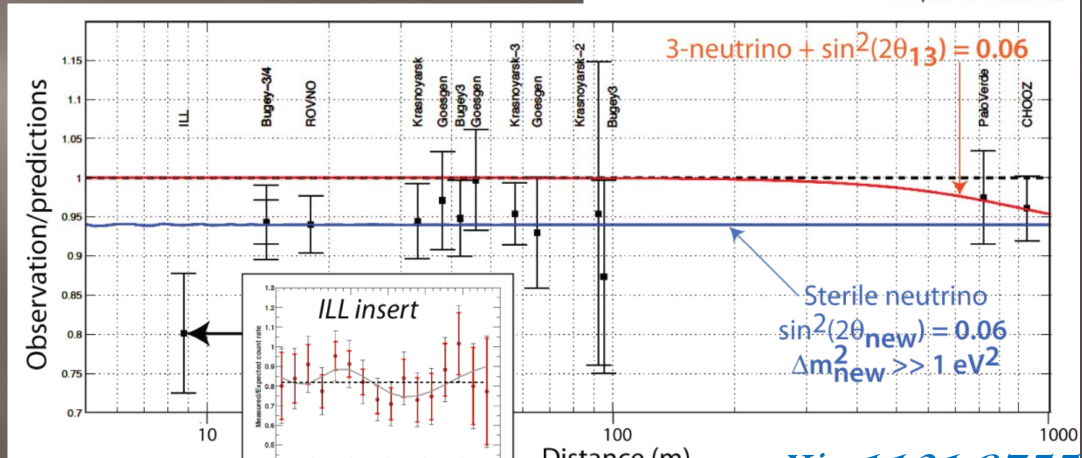
Signal

- $\tau \rightarrow e\nu\nu$ events characterized by momentum unbalance (because of 2ν emission) and relatively low electron energy.
  Selection criteria suggest a sufficiently clean separation with kinematic cuts and efficiency ~ 50%, allowing to detect 1-2 ν_τ CNGS events in ICARUS in next 2 years.

Sterile neutrinos? What a puzzle!



- Experimental anomalies
  - 3.8 σ $\bar{\nu}_e$ excess signal from $\bar{\nu}_\mu$ beam observed by LSND / confirmed by MiniBooNE $\Rightarrow$ possible $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations ($0.2<\Delta m^2<2.0$ eV^2, $\sin^2 2\theta > 10^{-3}$) beyond the 3ν flavour oscillation as observed in solar/atmospheric ν;
  - recent re-evaluation of $\bar{\nu}_e$ reactor spectra (~ 3% flux increase): $\bar{\nu}_e$ deficit @ reactor experiments + SAGE/GALLEX ν_e deficit from MegaCurie radioactive source $\Rightarrow$ hint of fast disappearance rate ($\Delta m^2>1.5$ eV^2, $0.02<\sin^2 2\theta<0.23$ at 99.7 C.L.).



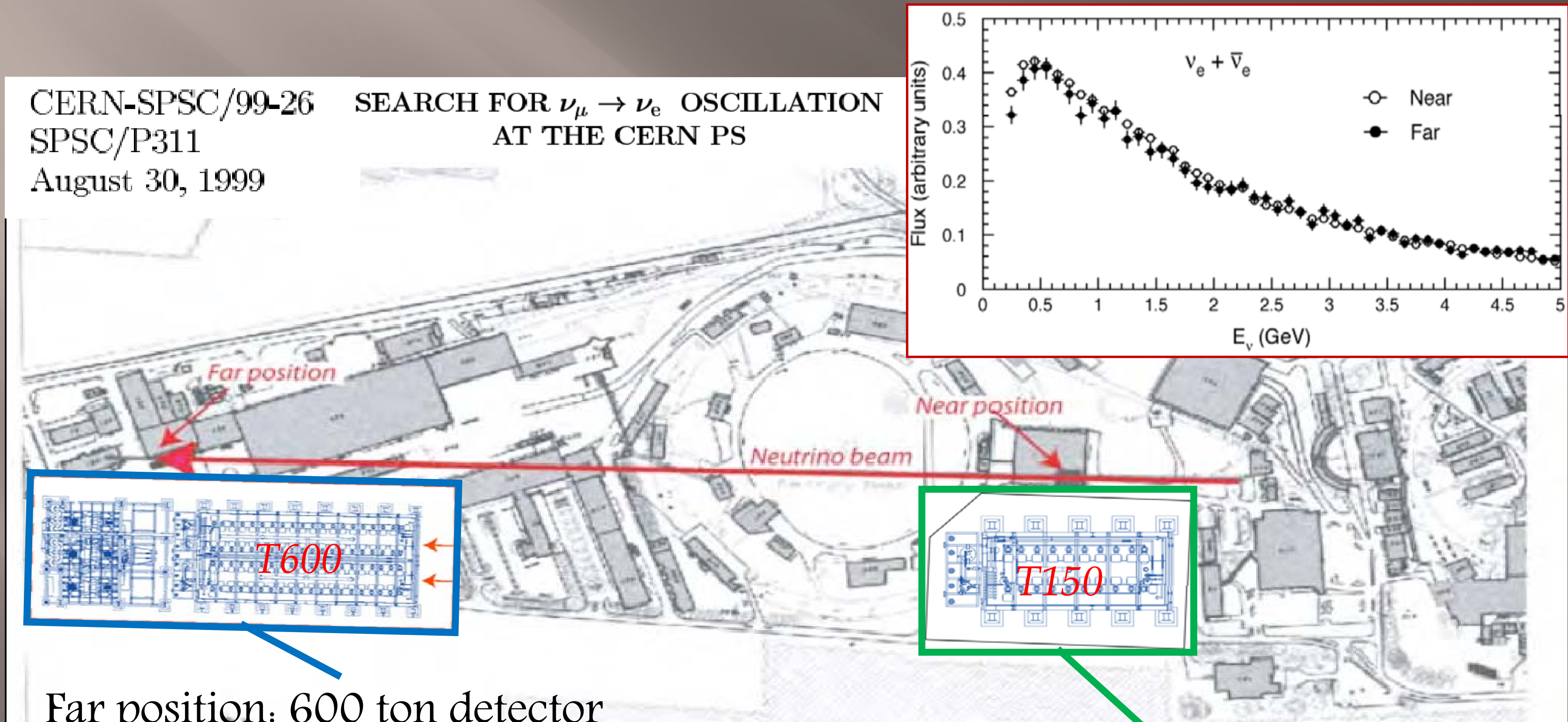
arXiv:1101.2755

- Cosmological data (WMAP) not excluding 4th neutrino state.
- "Tension" between neutrino and antineutrino data in short baseline ν_e appearance channel (MiniBooNE + LSND) and in long baseline ν_μ disappearance channel (MINOS) $\Rightarrow$ different effective mixing angles in ν and $\bar{\nu}$ channels?

ν knowledge still incomplete: definitive experiment needed.
LAr-TPC experiment at a CERN-PS refurbished ν beam can be the solution

A dual LAr-TPC detector @ CERN-PS

- Two strictly identical LAr-TPC to search for both $\nu_\mu \rightarrow \nu_e$ LSND signal (appearance) and $\nu_e \rightarrow \nu_x$ reactor anomaly (disappearance) in Near and Far positions.
- Cross sections and experimental biases canceling out in the comparison because of ν_e identical spectra and same LAr-TPC technique of the two detectors.



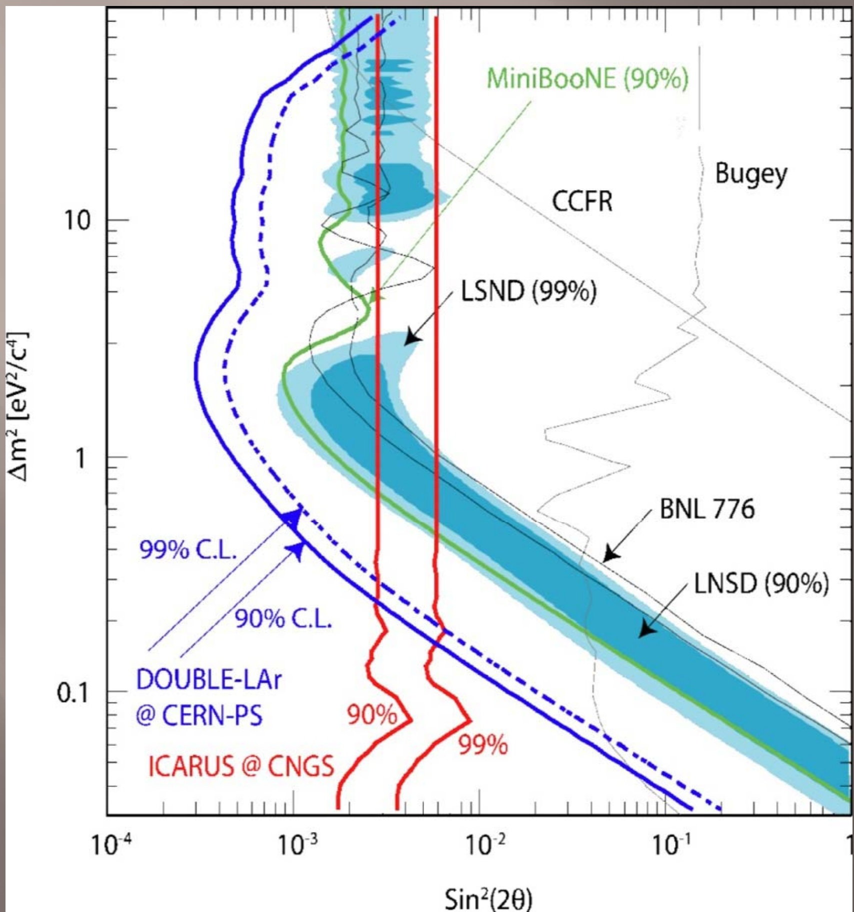
Far position: 600 ton detector (ICARUS T600) at 850 m from target: L/E ~ 0.7 km/GeV

Near position: 150 ton detector (new) at 127 m from target: L/E ~ 0.1 km/GeV

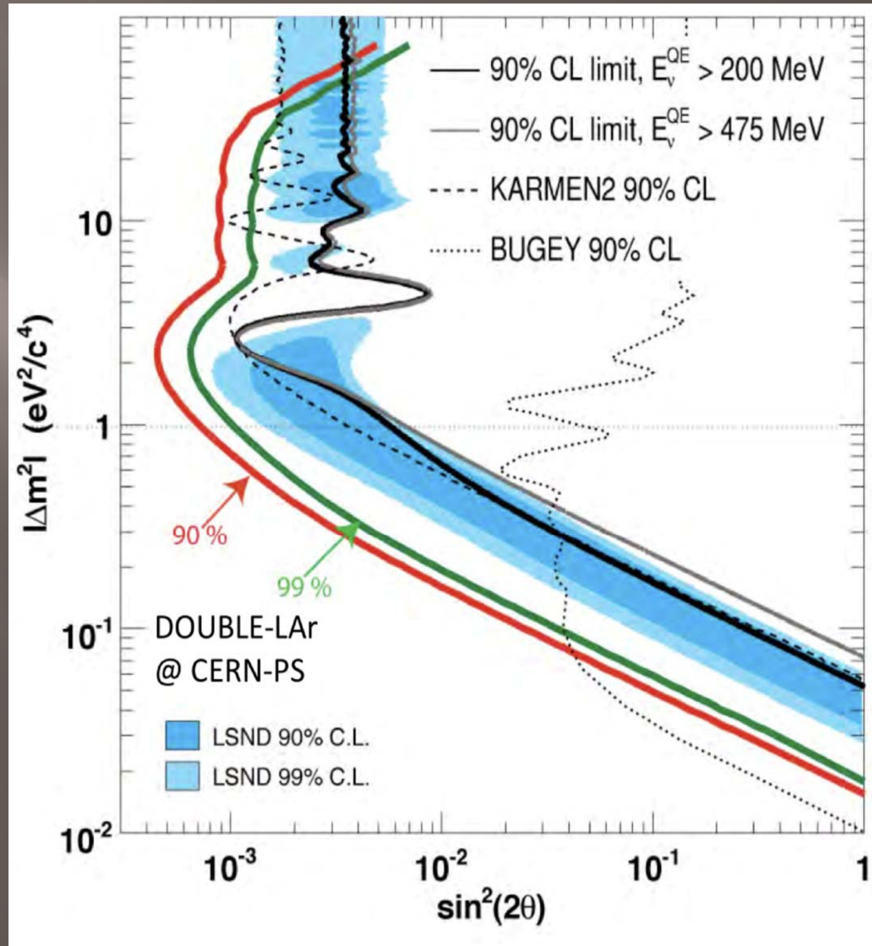
Sensitivity in ν_e appearance channel

- Possibility to determine both Δm^2 and $\sin^2 2\vartheta$.
- LSND region fully explored in 2/4 y data taking with 1.25 10^{20} pot/year ν/ $\bar{\nu}$ beam.

Neutrino beam



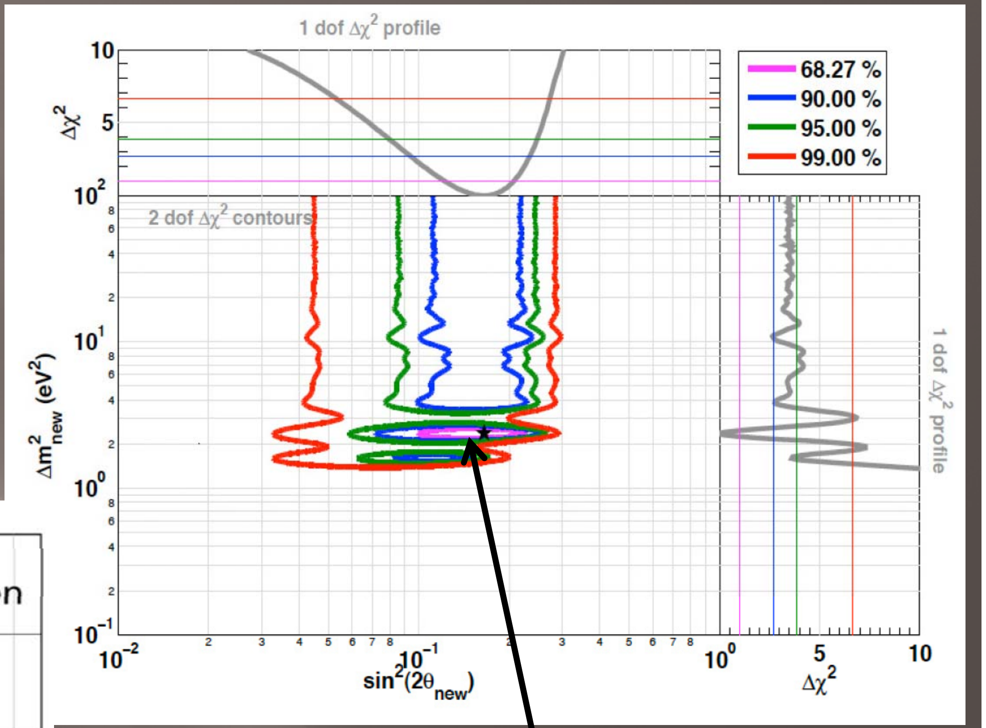
Antineutrino beam

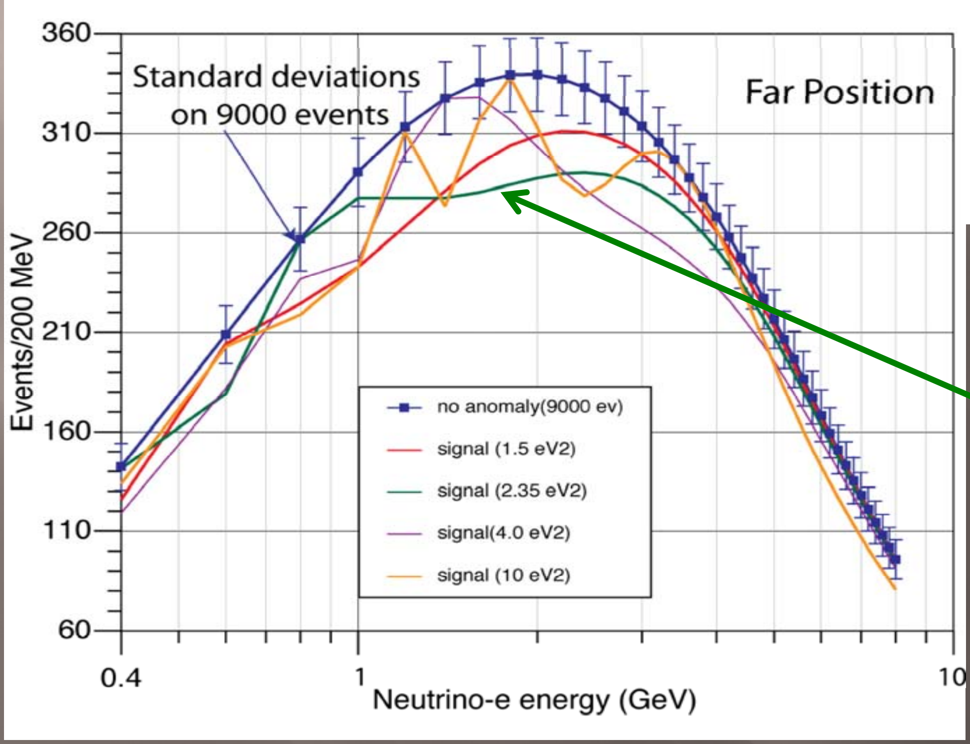


arXiv:0909.0355

ν_e disappearance channel

Possibility to detect "reactor anomaly" for several Δm^2 values in 2 years data taking with 1.25 10^{20} pot/year ν beam, using the ν_e beam contamination .





Reactor signal best fit:
$\Delta m^2 = 2.35$ eV^2,
$\sin^2 2\theta = 0.165$

Promising: sensitivity under evaluation.

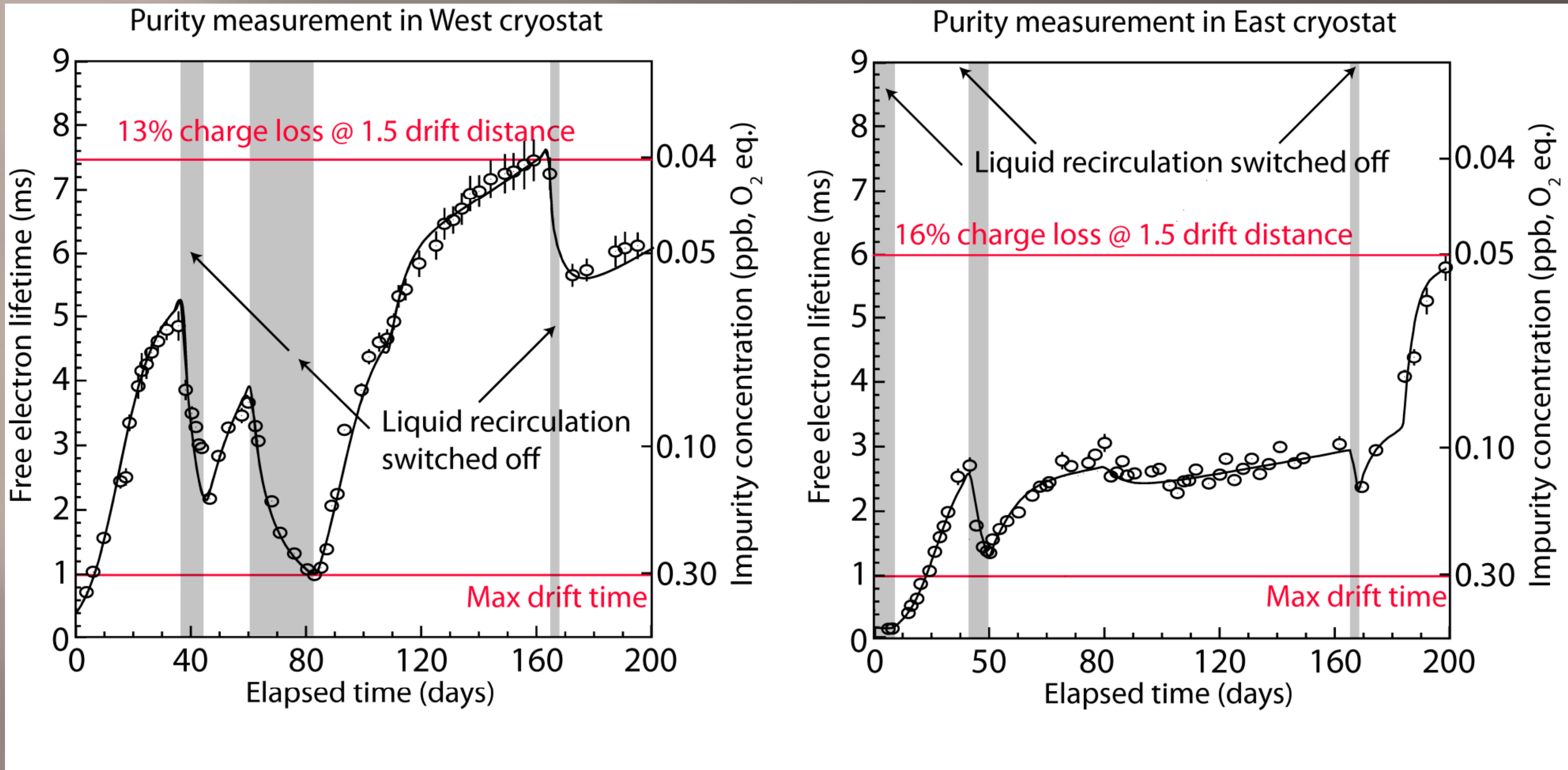
Conclusions

- ICARUS T600 @ LNGS has started data taking during 2010 after a long R&D and installation phase.
- 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 technique is mature.
- ICARUS T600 is ready for the 2011-2012 run with CNGS ν_μ beam: possibility to detect few ν_τ appearance events. Interesting physics perspectives also concerning the detection of solar and atmospheric neutrinos, nucleon decay search…
- **The ICARUS experiment at the Gran Sasso Laboratory is so far the major milestone towards the realization of a much more massive LAr detector.**
- LAr-TPC can be employed to solve the "sterile neutrino puzzle":
  a novel search with a refurbished ν beam at the CERN-PS is proposed after the ICARUS T600 exploitation @ LNGS.


Thank you

Backup

LAr purity measurement



Simple model: uniform distribution of the impurities, internal degassing, decreasing in time because of external leak balanced by liquid recirculation (t_{ele}[ms] = 0.3 / N[ppb])

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

τ_R: recirculation time of the full detector volume

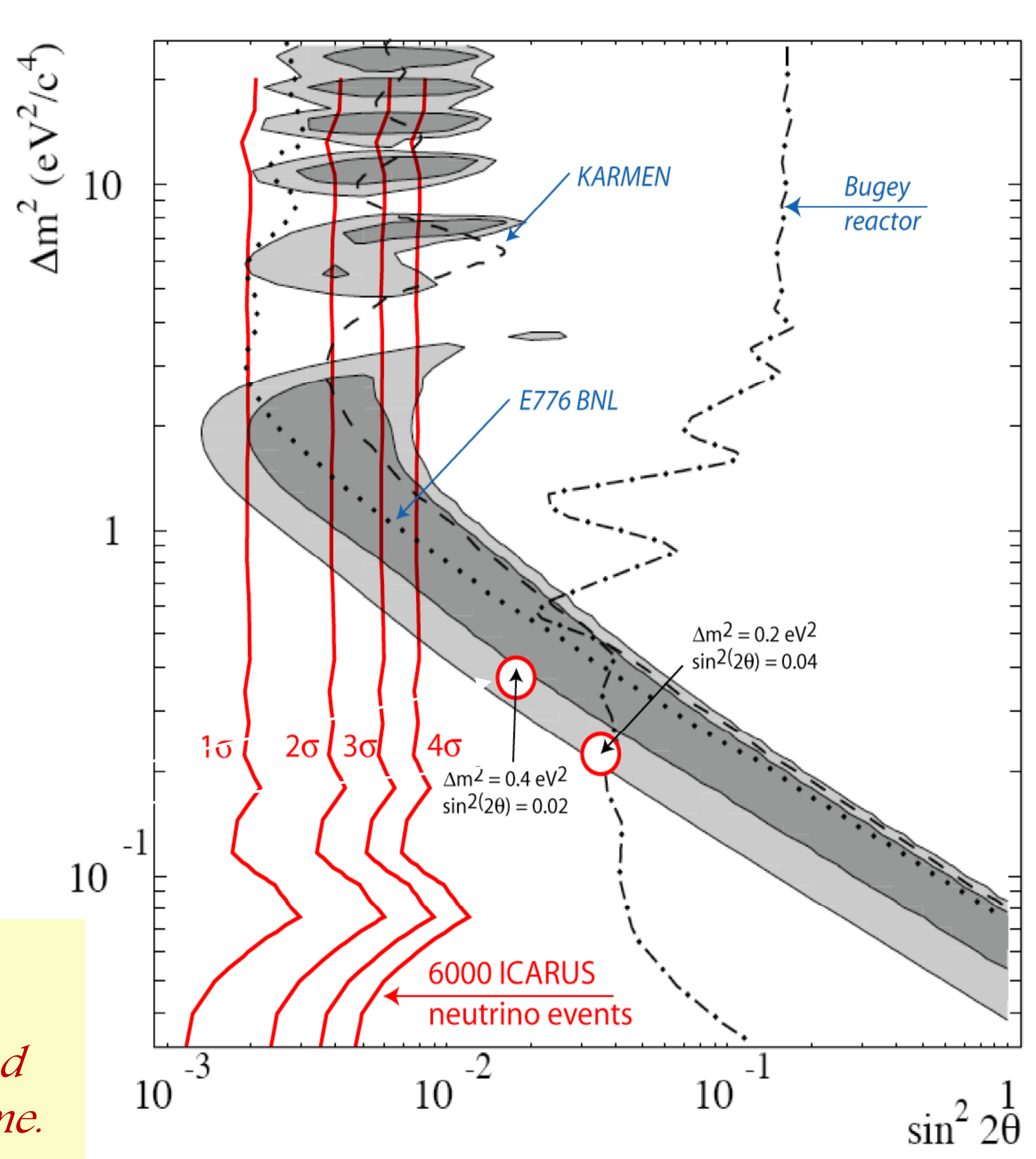
k_I and τ_I: related to the total degassing internal rate

k: related to the external leaks

	WEST	EAST
INITIAL IMPURITY	0.791 ± 0.016	1.776 ± 0.037
EXTERNAL LEAK RATE [ppt/day]	0. ± 0.39	2.3 ± 0.3
INITIAL INTERNAL DEGASSING [ppt/day]	0.37 ± 0.015	0.76 ± 0.018
DEGASSING REDUCTION TIME [days]	178 ± 20	297 ± 20
RECIRCULATION TIME 1 [days]	5.69 ± 0.06	5.42 ± 0.06
RECIRCULATION TIME 2 [days]	6.50 ± 0.11	5.99 ± 0.11
RECIRCULATION TIME 3 [days]	5.92 ± 0.06	6.21 ± 0.12
RECIRCULATION TIME 4 [days]	4.34 ± 0.06	4.54 ± 0.11
RECIRCULATION TIME 5 [days]	4.98 ± 0.08	2.60 ± 0.06

Sterile (LSND) neutrino search

- Sensitivity region, in terms of standard deviations σ, for 6000 raw CNGS neutrino events. The potential signal is above the background generated by the intrinsic ν_e beam contamination, in the deep inelastic interval 10-30 GeV.
- The Δm^2 distribution extends widely beyond the LNSD and MiniBoone regions.
- Two indicated points are reference values of MiniBoone.

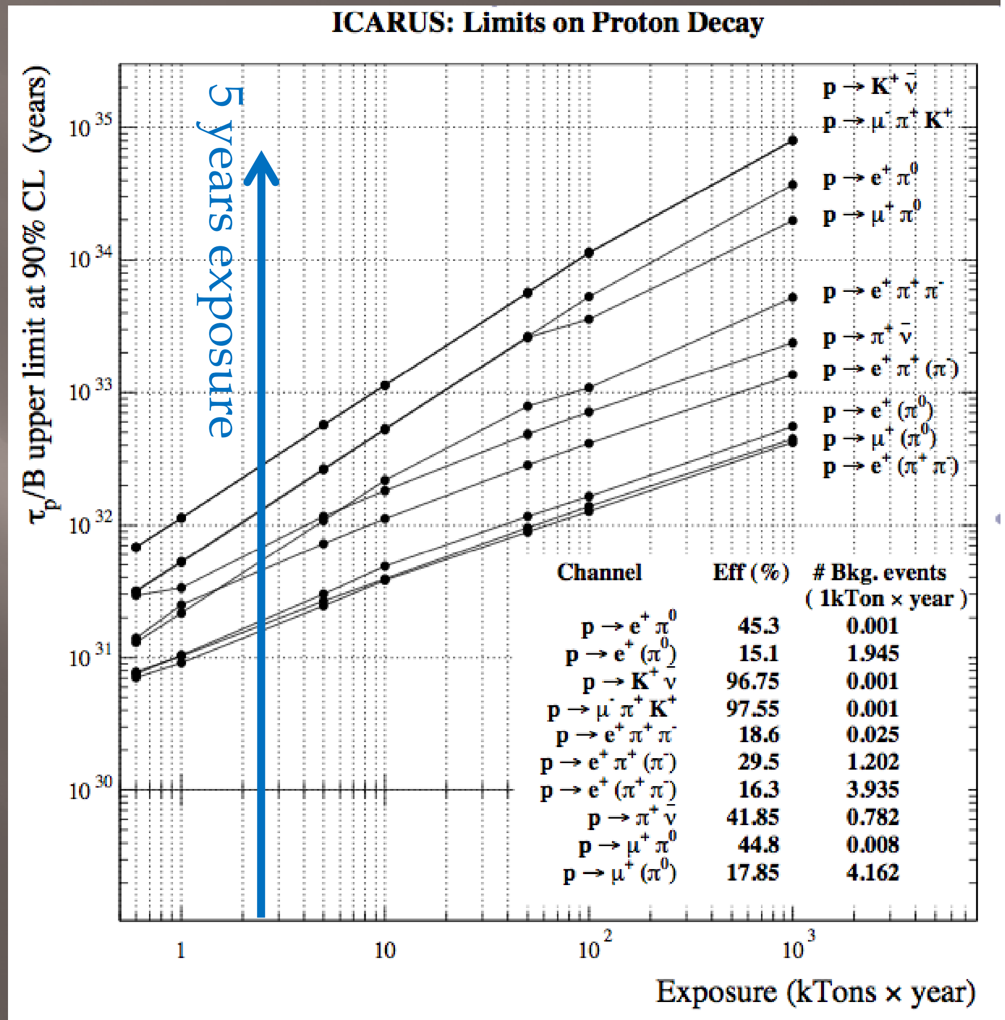


T600 at the CNGS offers an unique possibility of searching for sterile neutrinos, largely complementary and comparable to the Fermilab programme.

Nucleon decay: single event capability

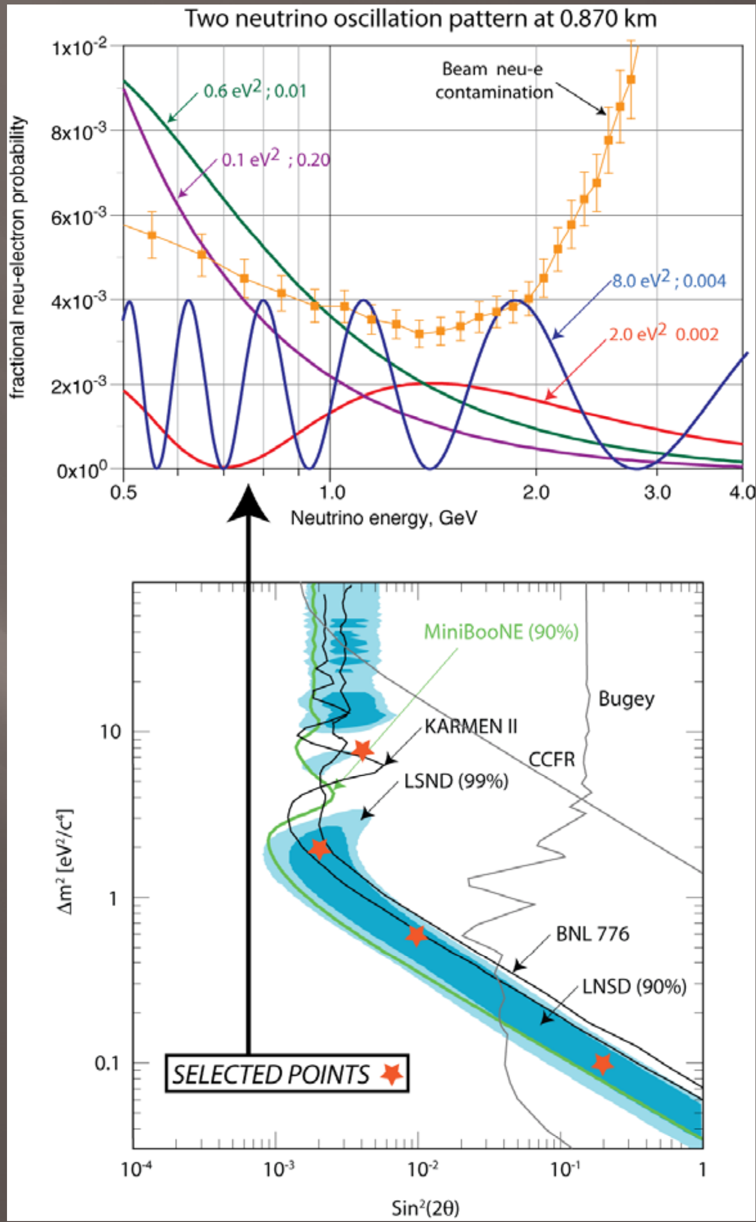
- LAr-TPC provides a much more powerful bkg rejection w.r.t. other techniques: a large variety of exclusive decay modes measurements bkg free.
- ICARUS-T600 (*3 10^{32} nucleons*) well suited for channels not accessible to Č detectors due to complicated event topologies, or because the emitted particles are below 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)
$p \rightarrow n\ p^{+}$	$1.1\ 10^{32}$	$(2.5\ 10^{31})$
$p \rightarrow m^{-}\ p^{+} K^{+}$	$2.7\ 10^{32}$	$(2.5\ 10^{32})$
$n \rightarrow e^{-}\ K^{+}$	$3.2\ 10^{32}$	$(3.2\ 10^{31})$
$n \rightarrow \mu^{+}\ \pi^{-}$	$1.5\ 10^{32}$	$(1.0\ 10^{32})$
$n \rightarrow \nu\ \pi^{0}$	$1.1\ 10^{32}$	$(1.1\ 10^{32})$



Determination of both Δm^2 and $\sin^2 2\theta$ values

- 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 ($\Delta m^2 - \sin^2 2\theta$) 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 in all circumstances well above the backgrounds, also considering the very high statistical impact and the high resolution of the experimental measurement.



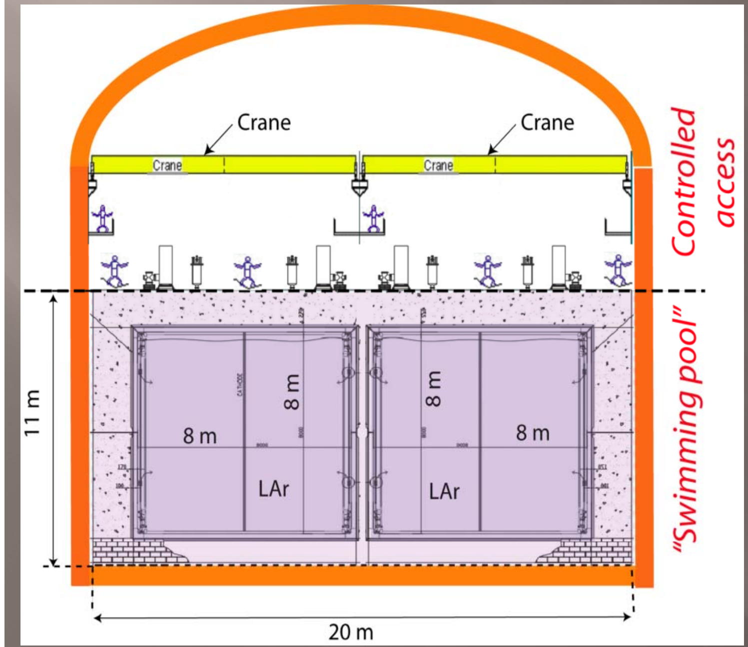
	Neutrino focus		Anti-neutrino focus	
	Far	Near	Far	Near
Fiducial mass	500t	150t	500t	150t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions	1.2×10^6	18×10^6	2.0×10^5	2.3×10^6
QE ν_μ interactions	4.5×10^5	66×10^5	87000	1.0×10^6
Events/burst	0.17	2.5	0.03	0.3
Intrinsic ν_e from beam	9000	120000	2000	29000
Intrinsic ν_e from beam (E_ν < 3 GeV)	3900	54000	880	13000
ν_e oscillations: $\Delta m^2 = 0.064\ eV^2$; $\sin^2 2\theta = 0.96$	2980	1250	465	140
ν_e oscillations: $\Delta m^2 = 0.4\ eV^2$; $\sin^2 2\theta = 0.02$	2083	2340	330	115
ν_e oscillations: $\Delta m^2 = 2.\ eV^2$; $\sin^2 2\theta = 0.002$	1194	1050	230	58
ν_e oscillations: $\Delta m^2 = 4.2.\ eV^2$; $\sin^2 2\theta = 0.0066$	3350	25050	490	3220

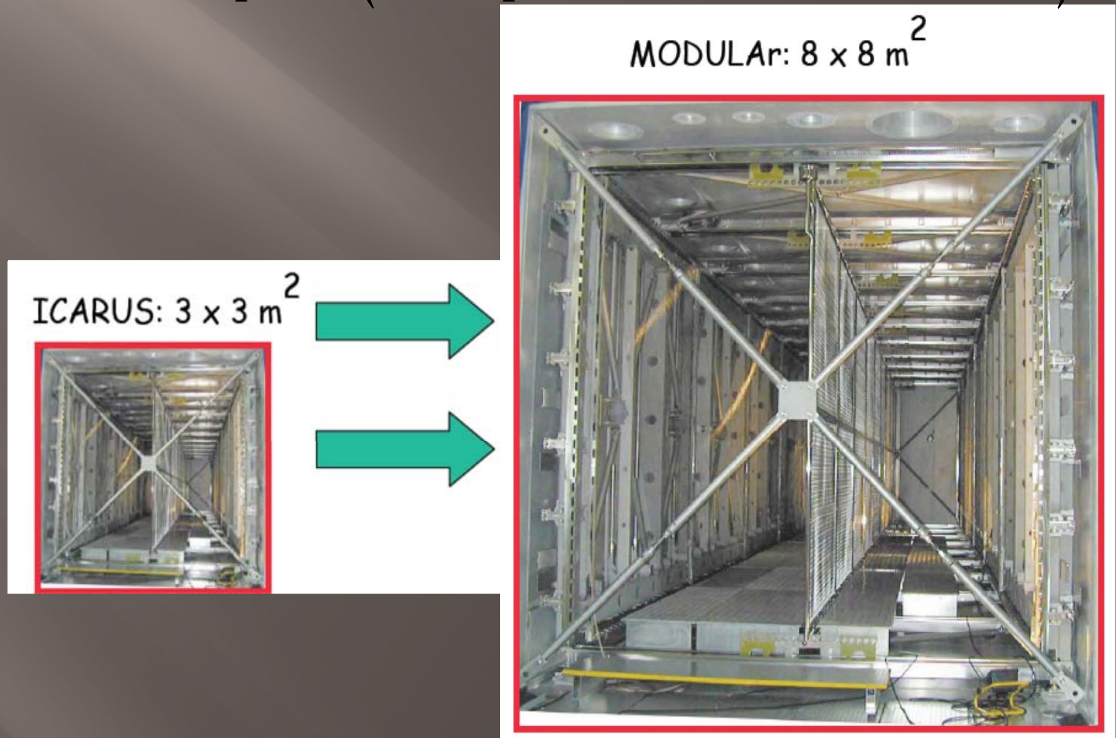
Beyond ICARUS-T600

- The operation of the T600 demonstrates the large number of important milestones which have been achieved in the last several years, opening the way to the development of new line of modular elements, which may be progressively extrapolated to the largest conceivable LAr-TPC sensitive masses.
- Based on the T600 experience, the ICARUS collaboration has now proposed a next generation LAr-TPC in tens of kt scale: the MODULAr project. *Astroparticle Physics 29 (2008) 174*
- The new detector, *using the present CNGS beam off axis with several 5 kton* units will maintain the majority of components developed with industry for the T600.
- This detector might be easily upgraded in the far future to a larger scale, depending on the potential physics goals.

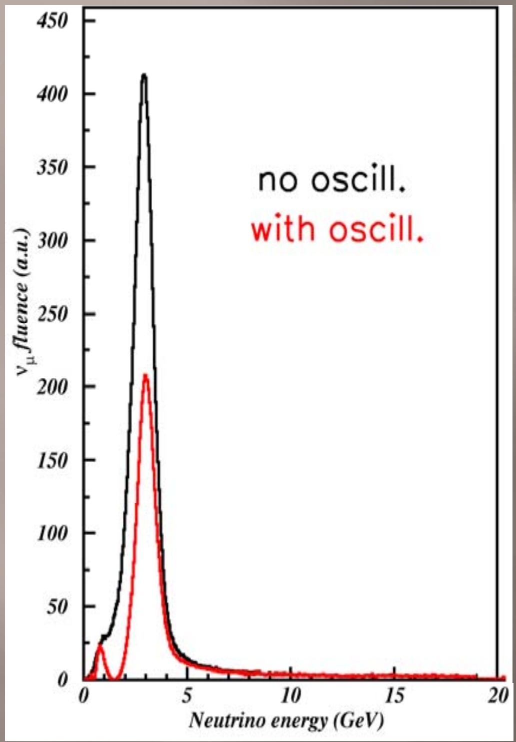
The MODULAr detecor

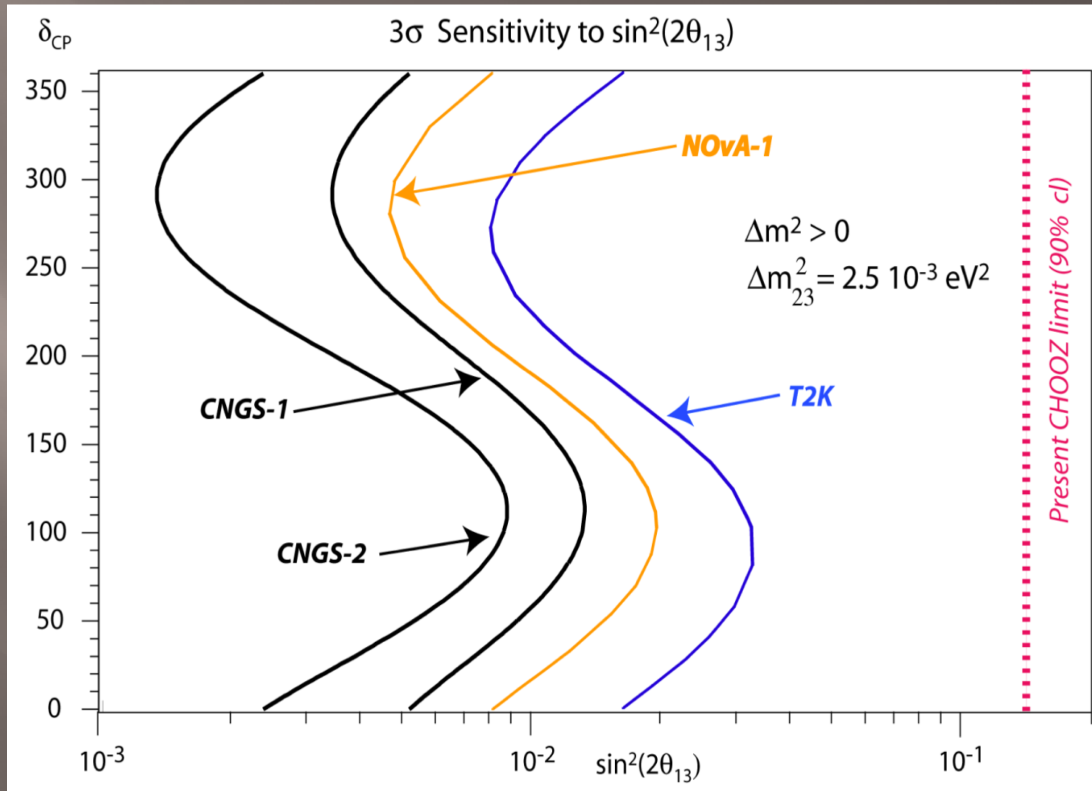
- MODULAr will be initially composed by four identical modules located in a new shallow-depth cavern, 10 km off axis from existing CERN/CNGS beam.
- Each module is a scaled-up version of the T600 (x 2.66^3):
  - 8 x 8 m^2 cross section and about 60 m length;
  - LAr active mass: 5370 ton;
  - 4 m electron drift (2.66 ms), E_{drift} = 0.5 kV/cm, H.V. = -200 kV;
  - 3-D imaging similar to T600 but 6 mm pitch (three planes, ~50000 channels).





MODULAr sensitivity in 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