ICARUS and Double LAr programme

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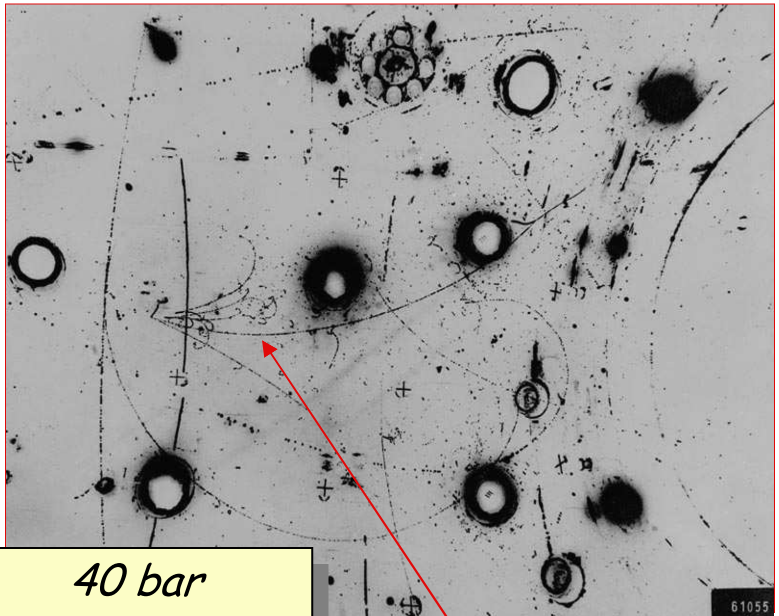
Thirty years of progress …

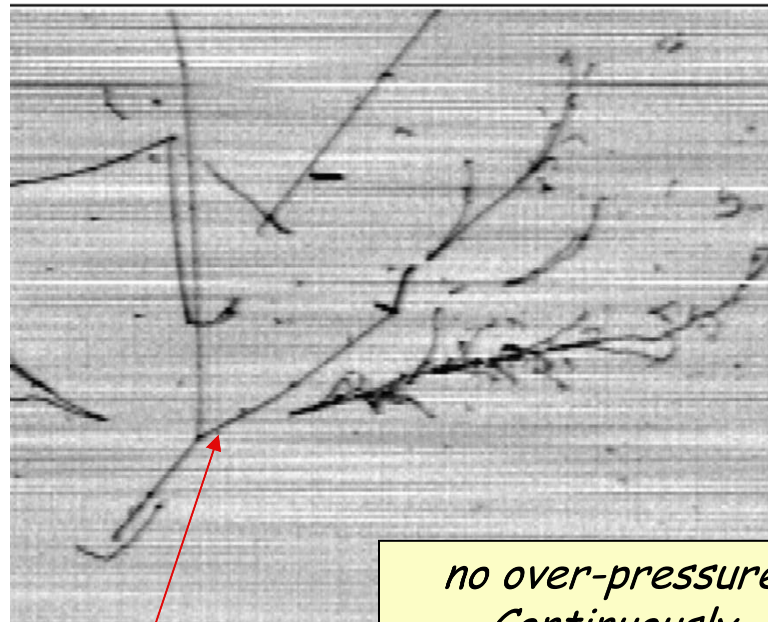
Gargamelle bubble chamber



40 bar pressure
Pulsed ≈ 1ms

Bubble diameter ≈ 3 mm
(diffraction limited)

ICARUS electronic chamber



"Bubble" size
3 x 3 x 0.3 mm3

no over-pressure
Continuously sensitive

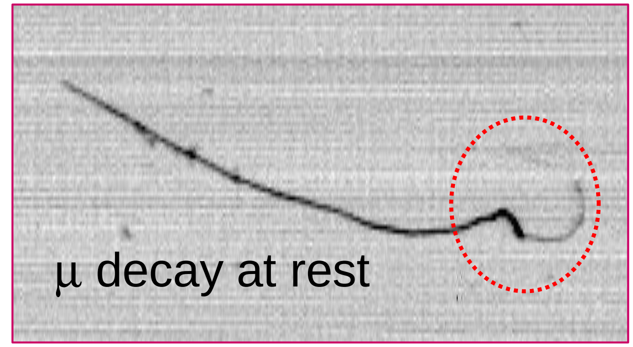
Medium	Heavy freon	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

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

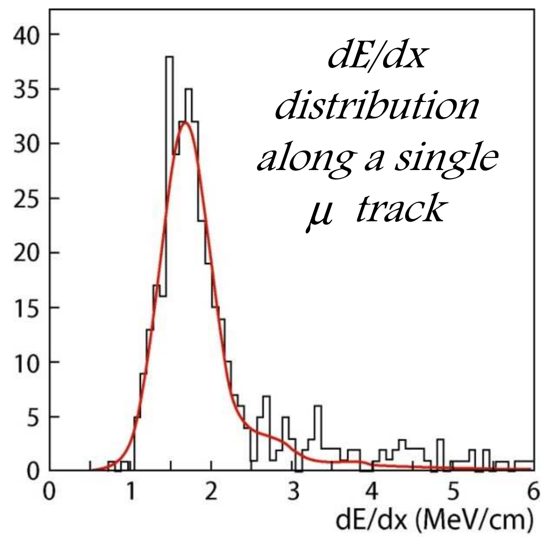
Medium	Liquid Argon	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

LAr-TPC performance

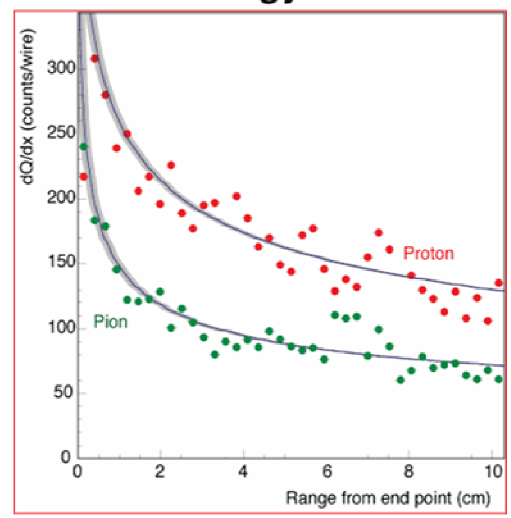
- Tracking device:
  - precise event topology ($\sigma_{x,y} \sim 1mm$, $\sigma_z \sim 0.4mm$)
  - μ momentum measurement via multiple scattering: $\Delta p/p$ ~10-15% depending on track length and p



- Measurement of local energy deposition dE/dx:
  - e/γ separation (2% X_0 sampling);
  - particle ID by means of dE/dx vs range



dE/dx energy losses



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

RESOLUTIONS

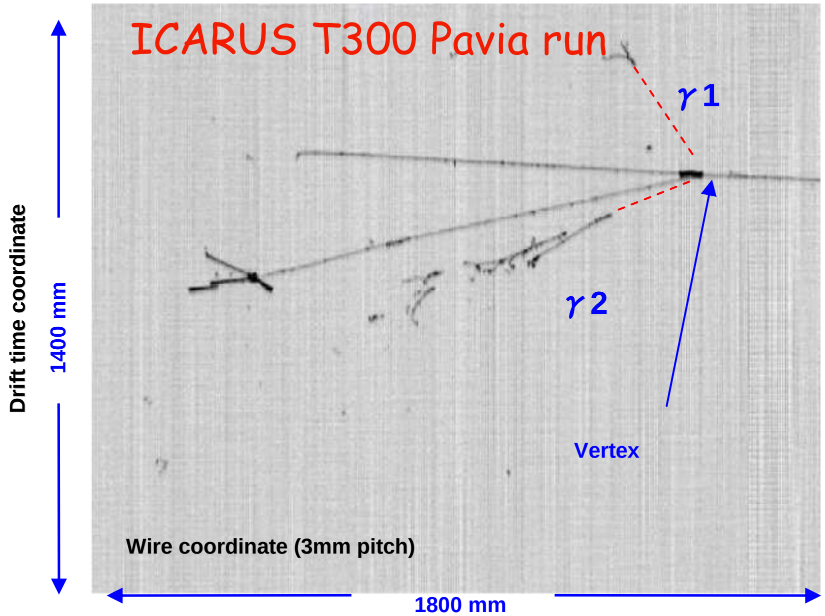
Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$

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

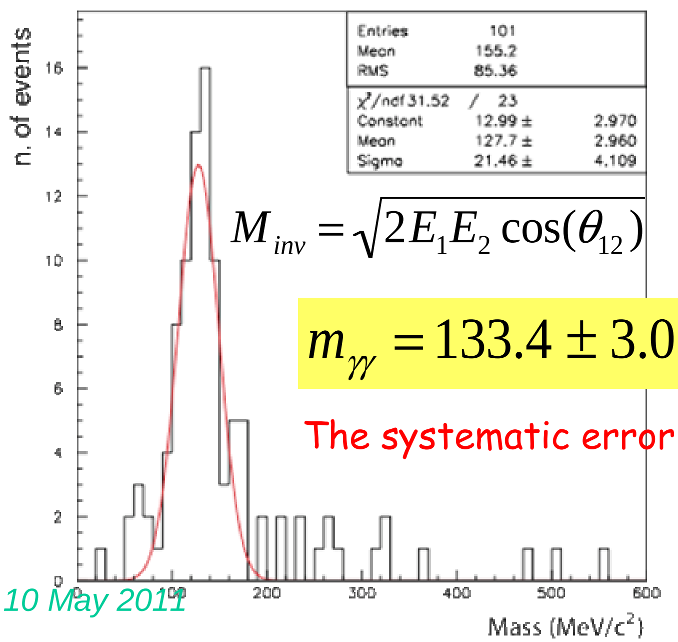
Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

electron - π^0 identification

Reconstruction of π^0-showers



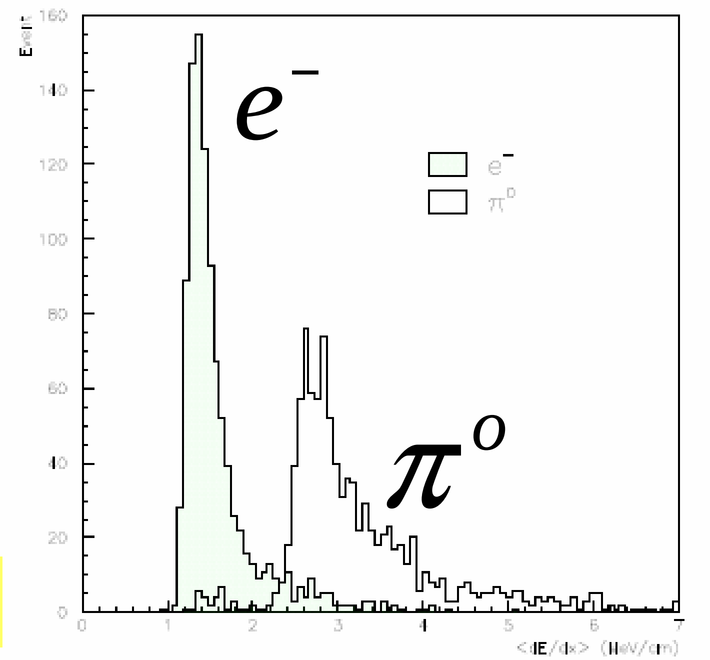
Electron shower events are extremely well identified experimentally, because of the ionization behaviour in the first cells after the vertex.



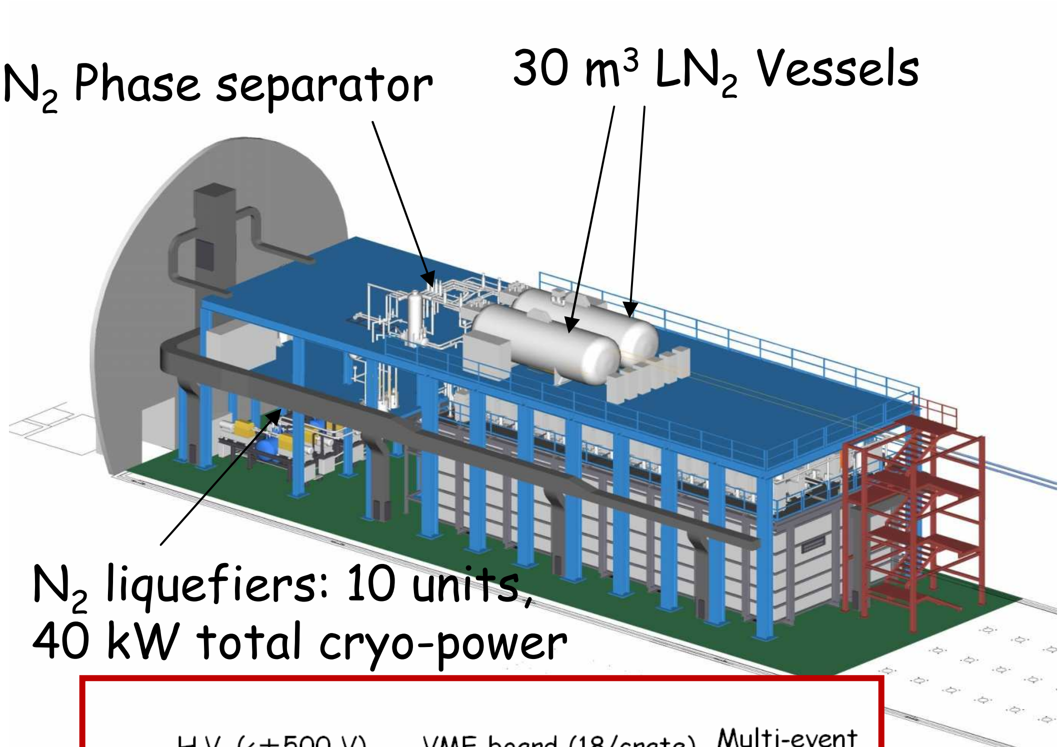
$$M_{inv} = \sqrt{2E_1E_2\cos(\theta_{12})}$$

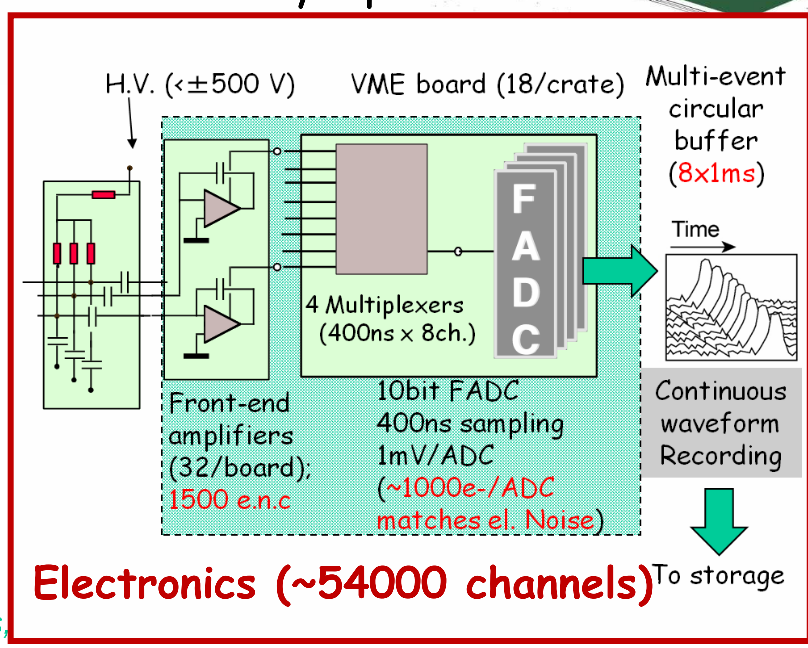
$$m_{\gamma\gamma} = 133.4 \pm 3.0(stat) \pm 4.0(sys)\mathrm{MeV/c^2}$$

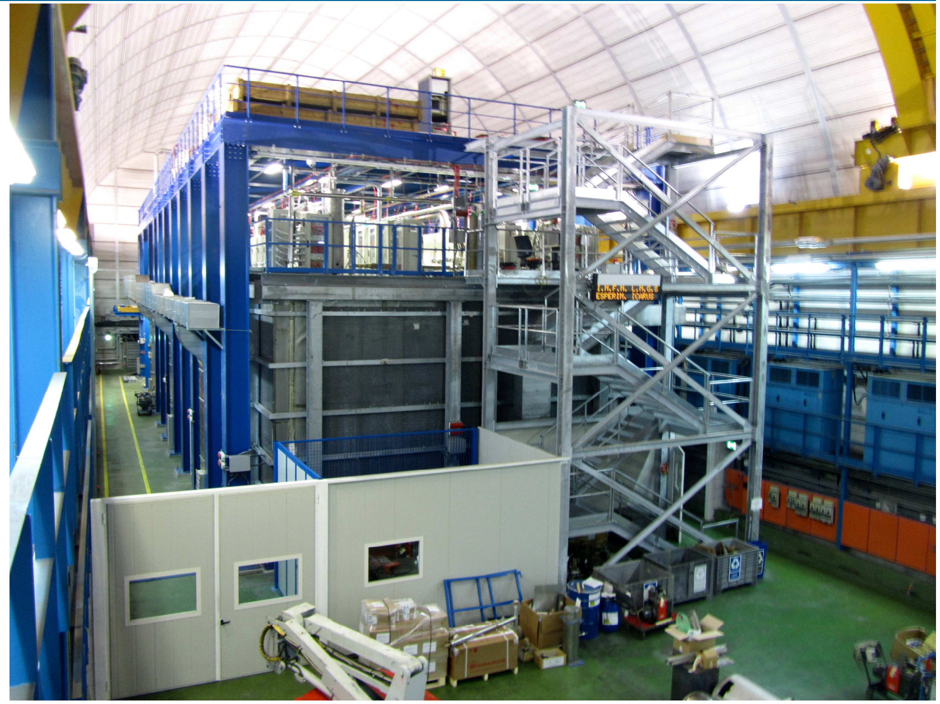
The systematic error mostly due to the calibration



ICARUS T600 in LNGS Hall B



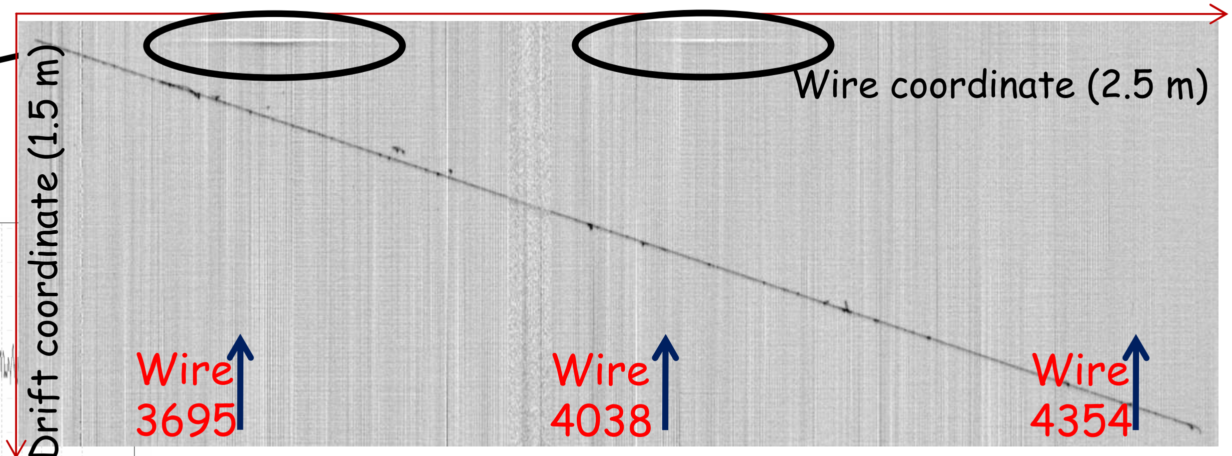




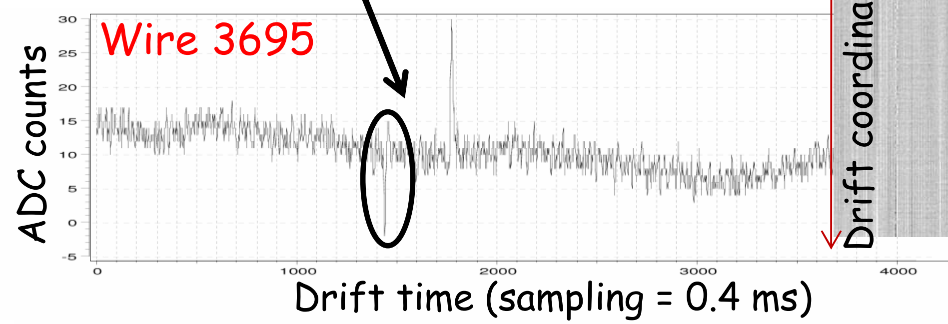
LAr purity measurement with muon crossing tracks

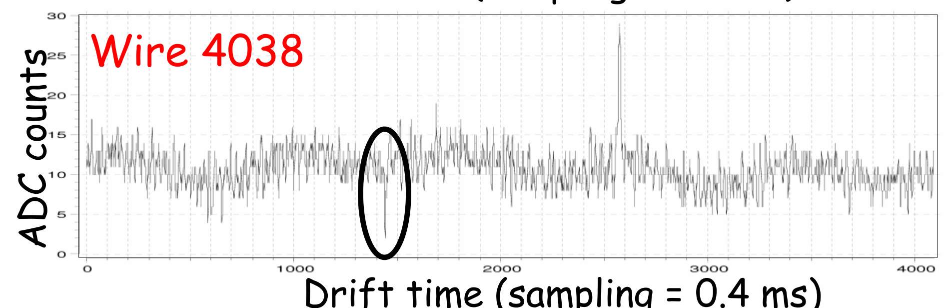
Charge attenuation along track allows event-by-event measurement of LAr purity.

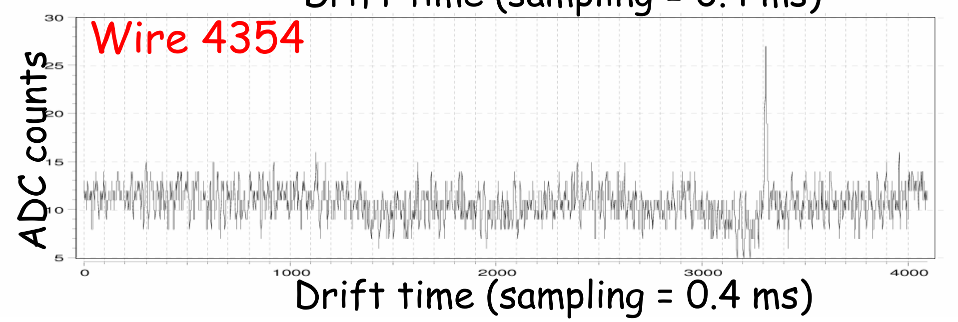
T = 0 estimated by induction of PMT signal on Collection view.



Run 10139 Event 8961 Collection view



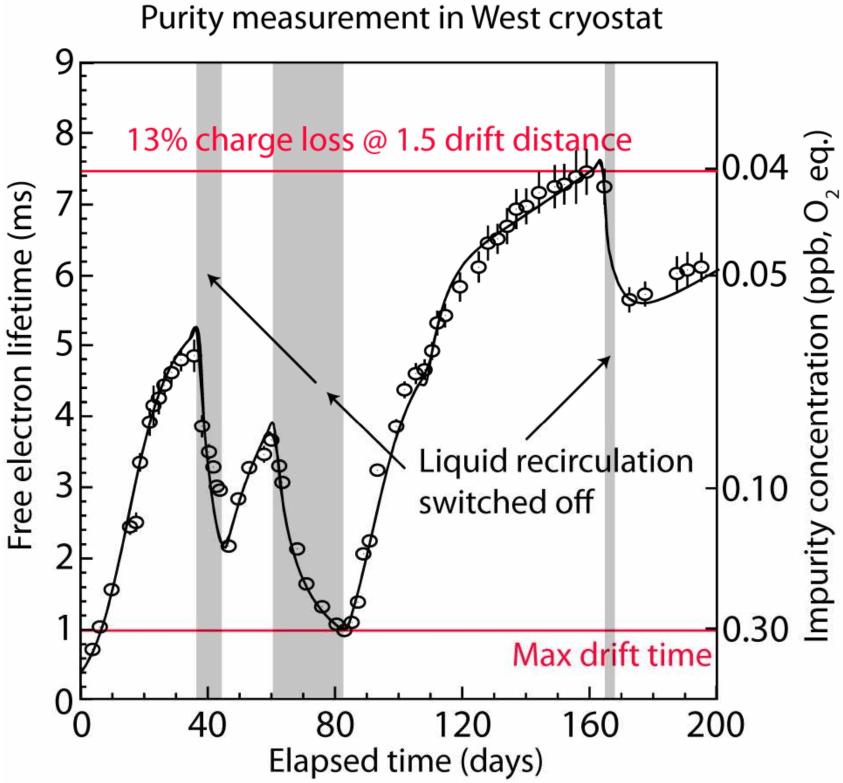


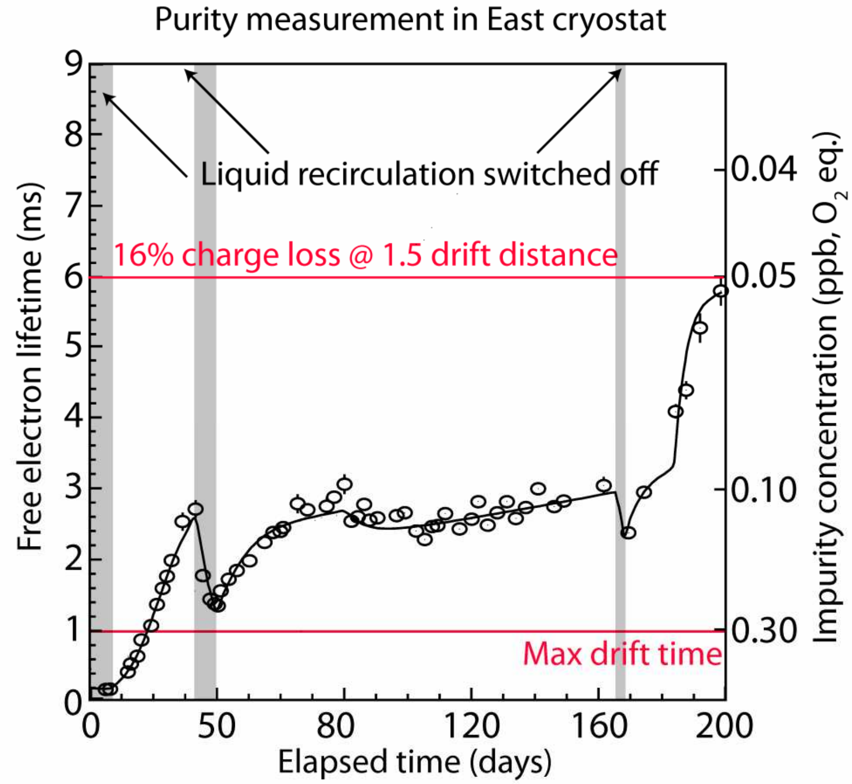


Pulse height for 3 mm m.i.p.
~ 15 ADC # (15000 electrons)

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.

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

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

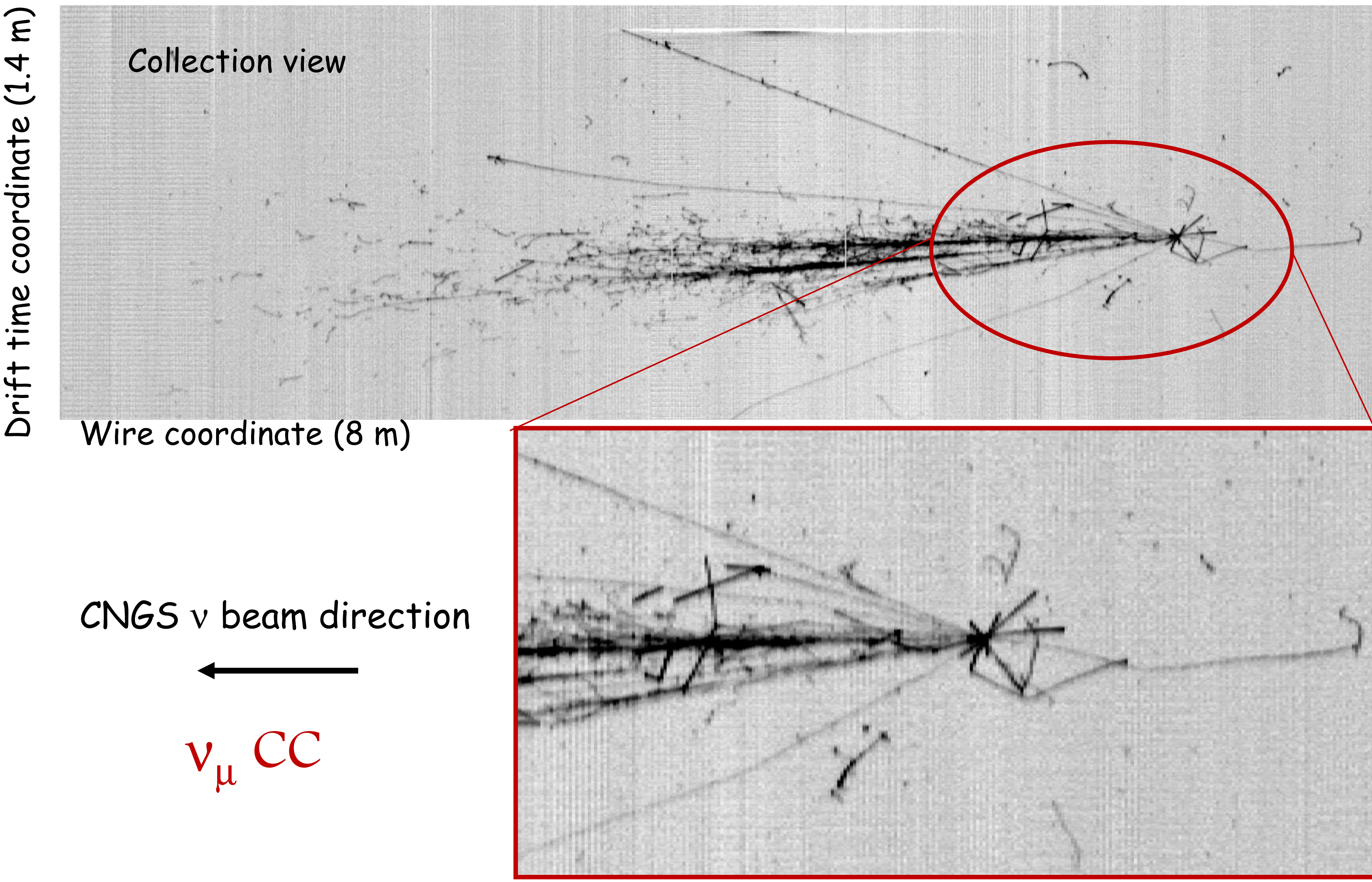
τ_R: recirculation time for a full detector volume
k_I and τ_I : related to the total degassing internal rate
k : related to the external leaks

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

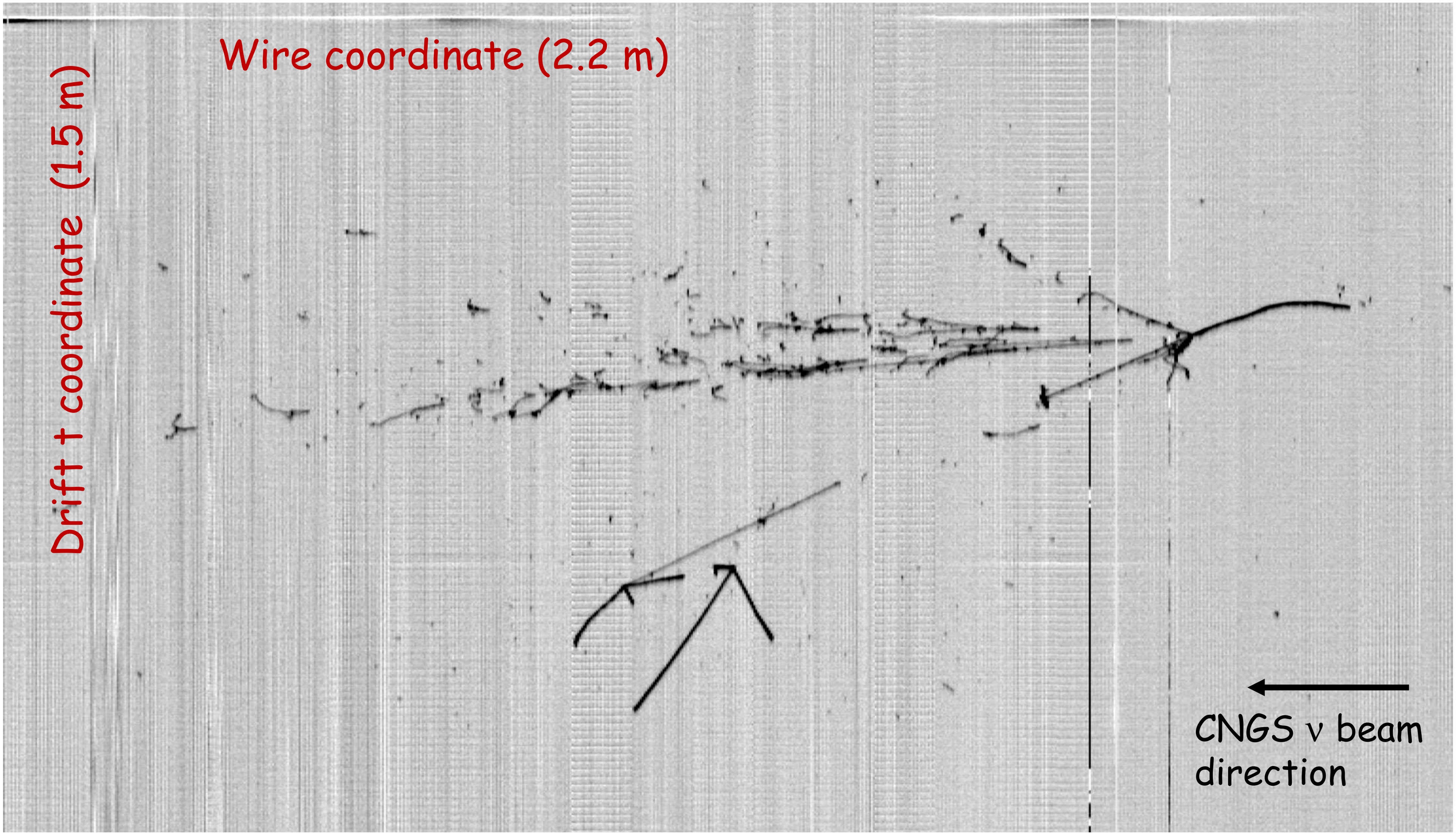
ICARUS T600 physics potential

- 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 collection (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 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 events/y of unbiased atmospheric ν CC;
  - zero background proton decay with 3 x 10^{32} nucleons for "exotic" channels.

CNGS “first’’ neutrino interactions in ICARUS T600

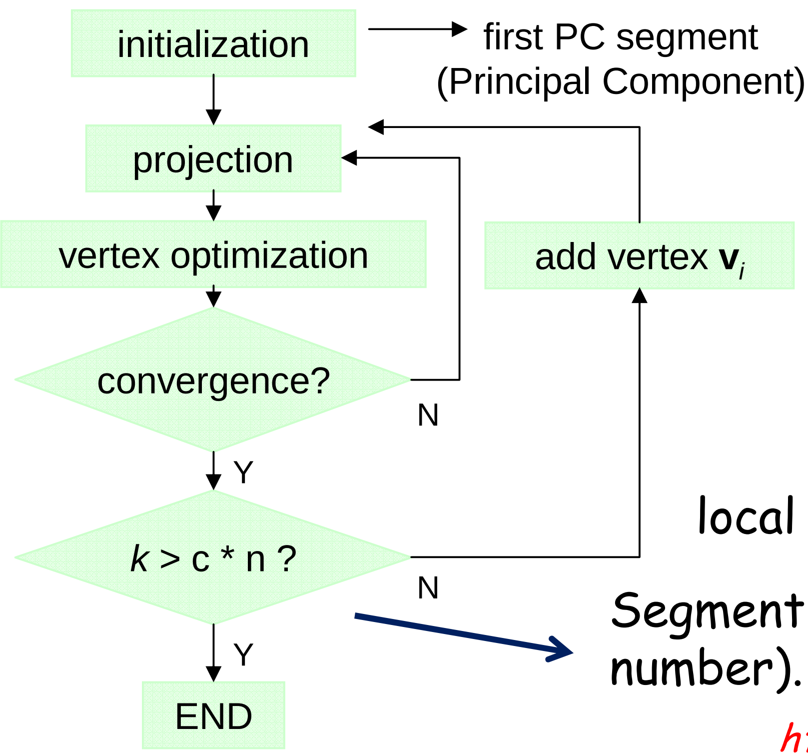


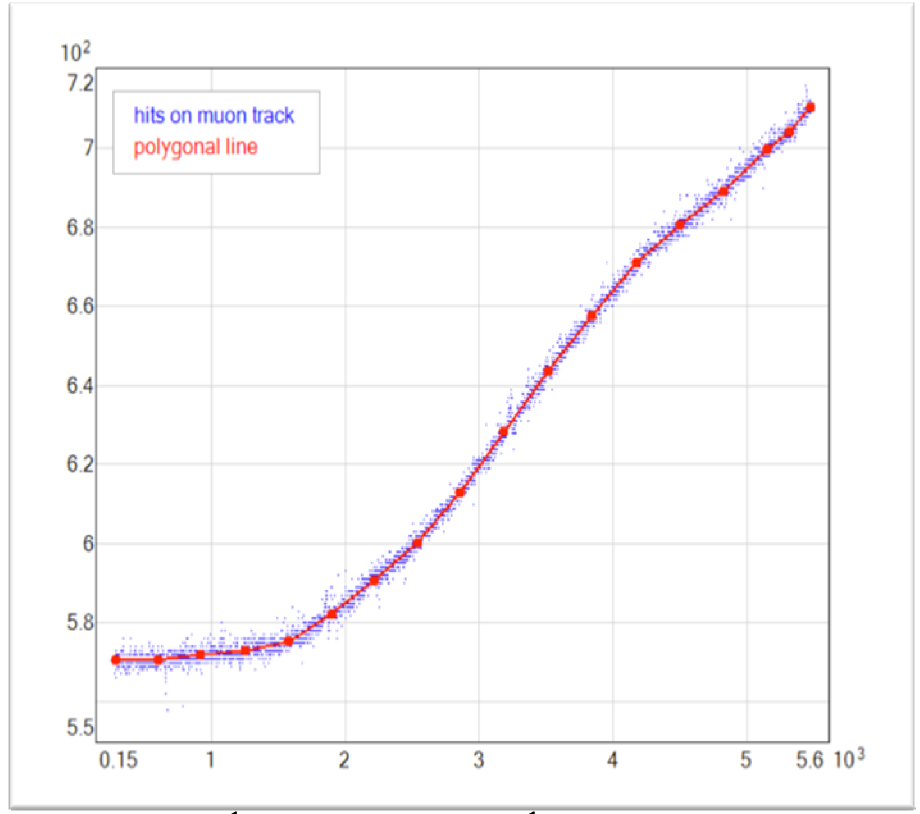
CNGS NC interaction



3D reconstruction

- 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

Segment number *k* exceeds given ratio *c * n (n* track hits number). Longer tracks usually are more straight.

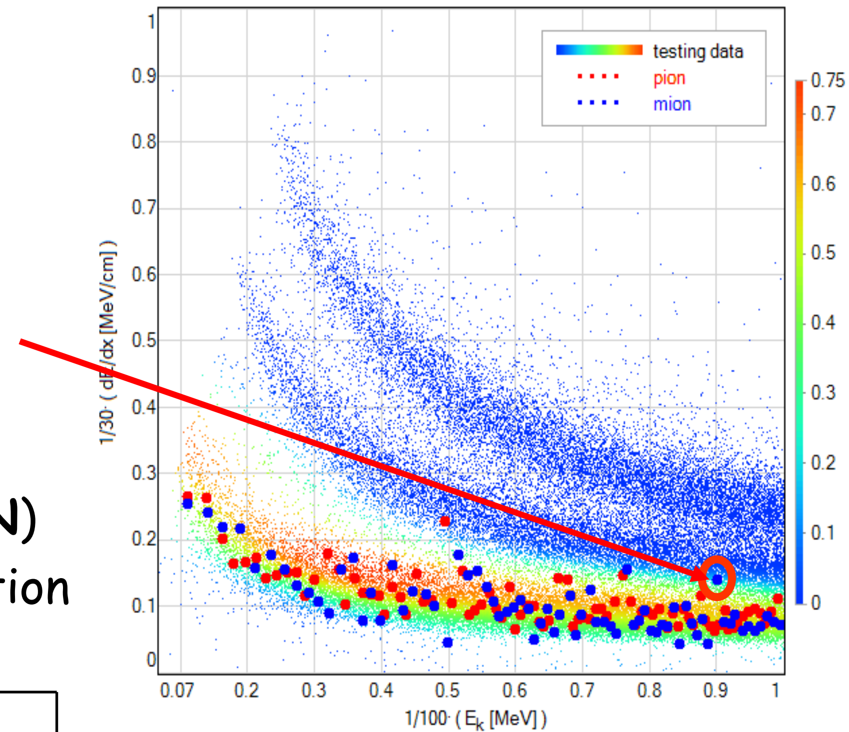
http://www.iro.umontreal.ca/~kegl/research/pcurves/

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

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

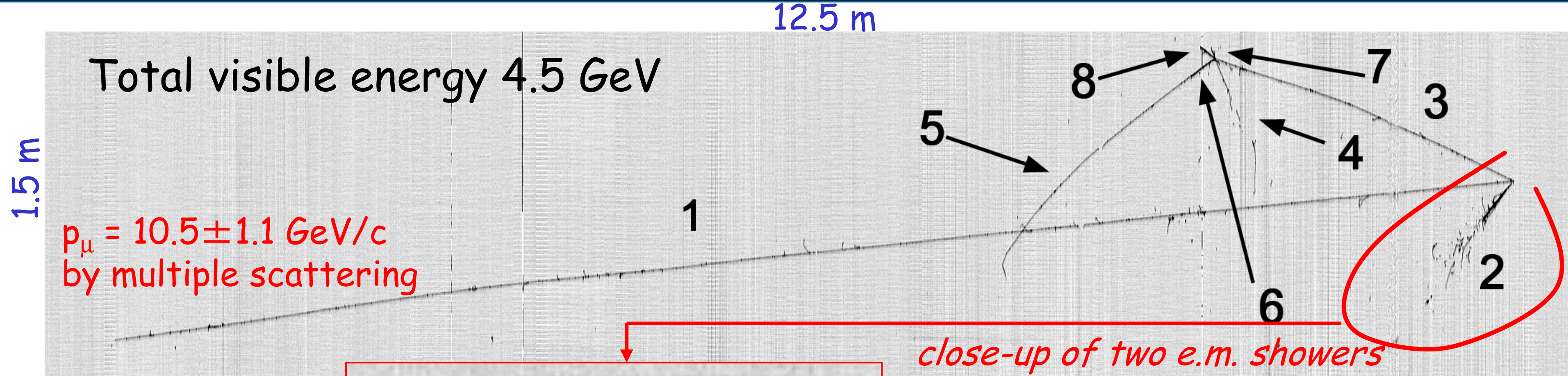
  NN = S($\mathbf{nn}_i$)/M
- Identify track as particle corresponding to max(**NN**)
- Energy reconstructed including quenching in simulation



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

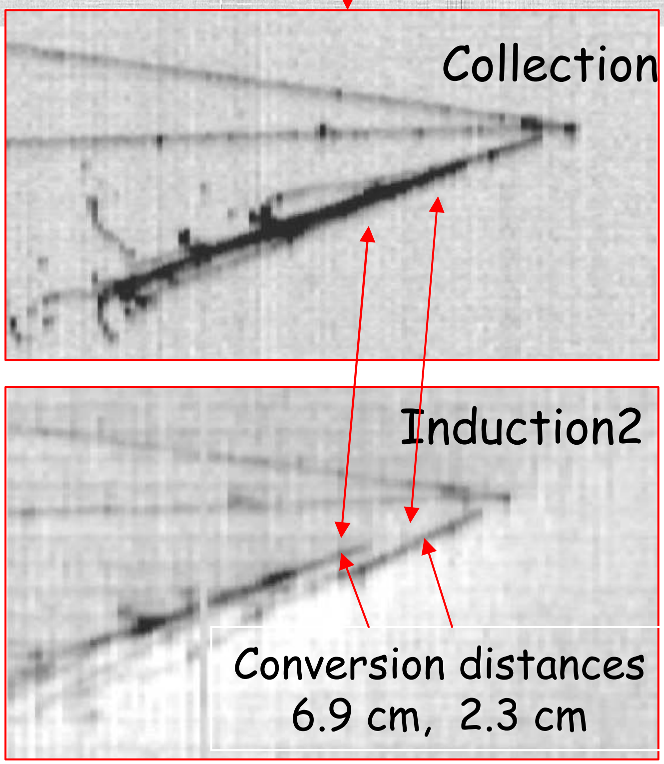


Primary vertex (A)

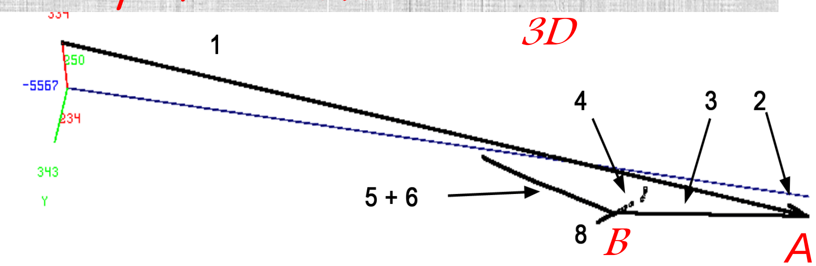
very long μ (1), e.m. cascade(2), pion (3).

Secondary vertex (B)

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



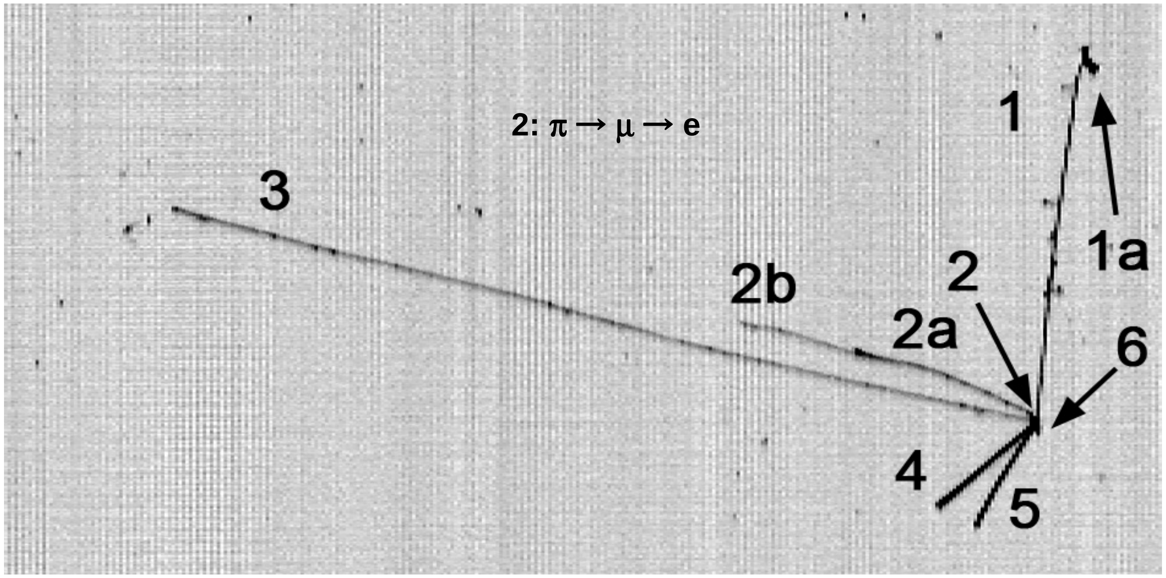
$M^{*}_{\gamma\gamma}$ = 125±15 MeV/c^2

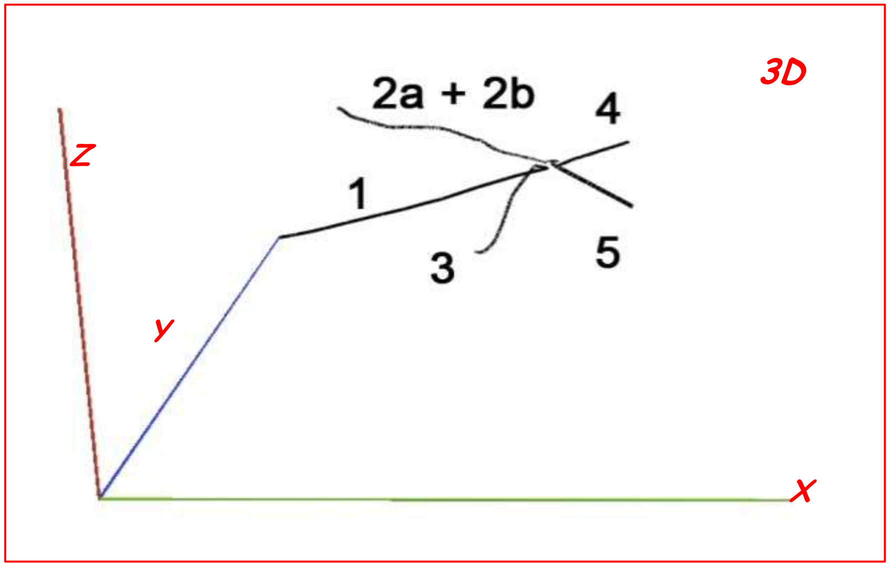


Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2 (π^0)	520.82	0.054	-0.420	-0.906
3 (π)	514.04	-0.001	0.137	-0.991
Sec.vtx	797.			
.	76.99	0.009	-0.649	0.761
4	313.9			
5 (μ)	86.98	0.000	-0.239	-0.971
6 (K)	35.87	0.414	0.793	-0.446
7	283.28	-0.613	0.150	-0.776

8

Run 9392 Event 106





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

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

Preliminary results of first CNGS 2010 run

- Analyzed sample: 1494 CNGS triggers, i.e. $4.54 \cdot 10^{18}$ pot = 78 % out of whole sample. Classified by visual scanning into fiducial volume of 434 t.
- Number of collected interactions compared with number of interactions predicted ((2.6 ν CC + 0.86 ν NC) 10^{-17}/pot), in the whole energy range up to 100 GeV, corrected by fiducial volume and DAQ dead-time.

Event type	Collected	Expected
ν_μ CC	94	98
ν NC	32	31
ν XC *	6	-
Total	132	129

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

On overall statistics in agreement with expectations.

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_μ CC events expected in ICARUS-T600.

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

Background

- At the effective neutrino energy of 20 GeV and $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$, $P(\nu_\mu \rightarrow \nu_\tau) = 1.4\%$
- 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

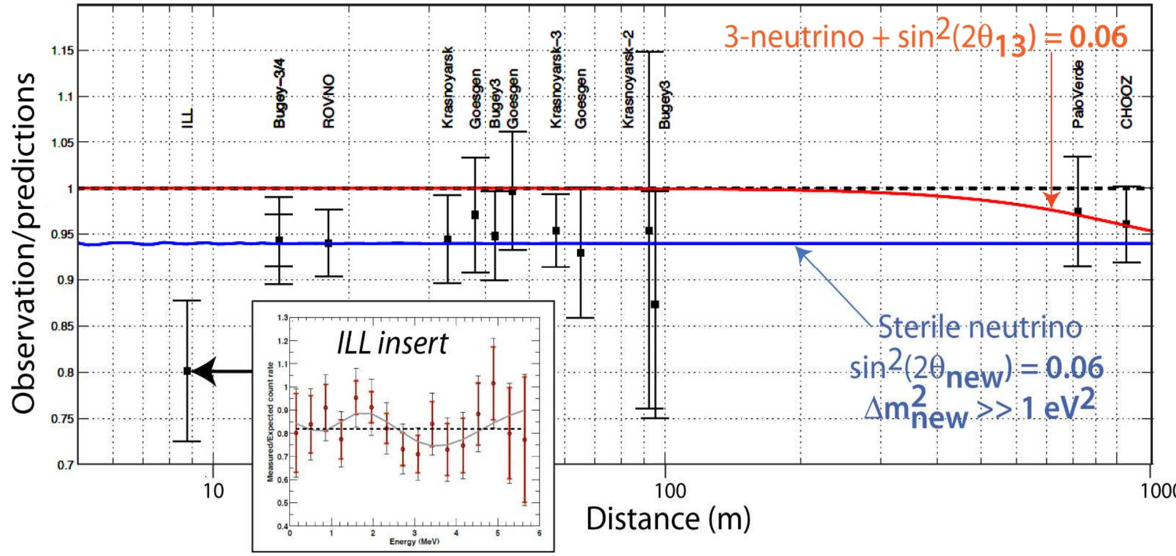
- $\tau \rightarrow e\nu\nu$ events characterized by momentum unbalance (because of 2ν emission) and relatively low electron momentum.
  Selection criteria suggest a sufficiently clean separation with kinematic cuts and efficiency ~ 50%, allowing to detect 1-2 ν_τ CNGS events expected in ICARUS T600 in next 2 years.

Neutrino experimental anomalies

- anti-νe deficit at reactor experiments from recent spectra re-evaluation, the neutron lifetime and the off-equilibrium effects: average ratio is 0.937 ± 0.027

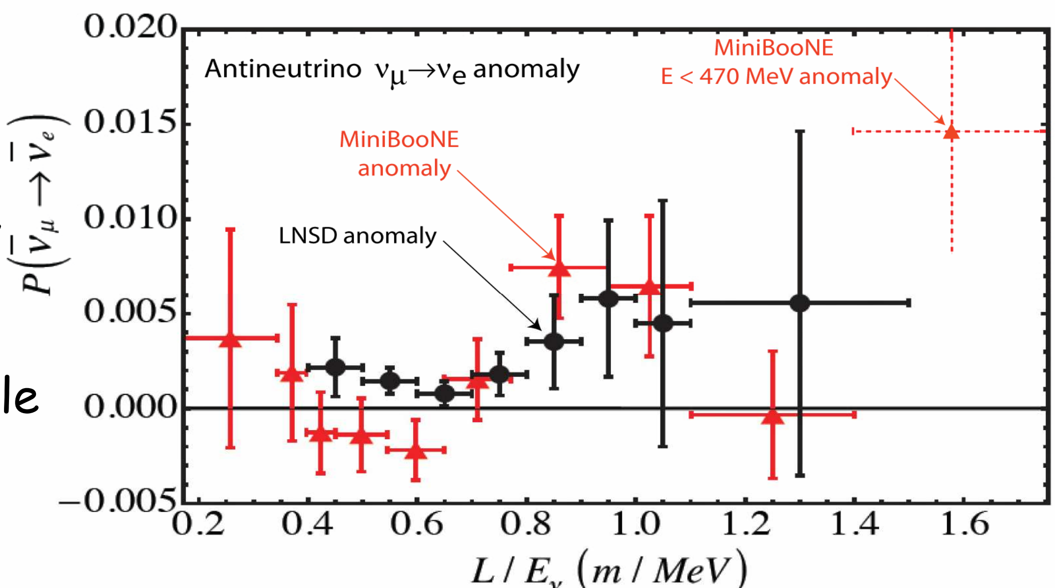
→ hint of fast disappearance rate

the blue line is for a sterile neutrino with $\Delta m^2_{new} \gg 1\ eV^2$ and $sin^2(2\theta_{new}) = 0.06$.



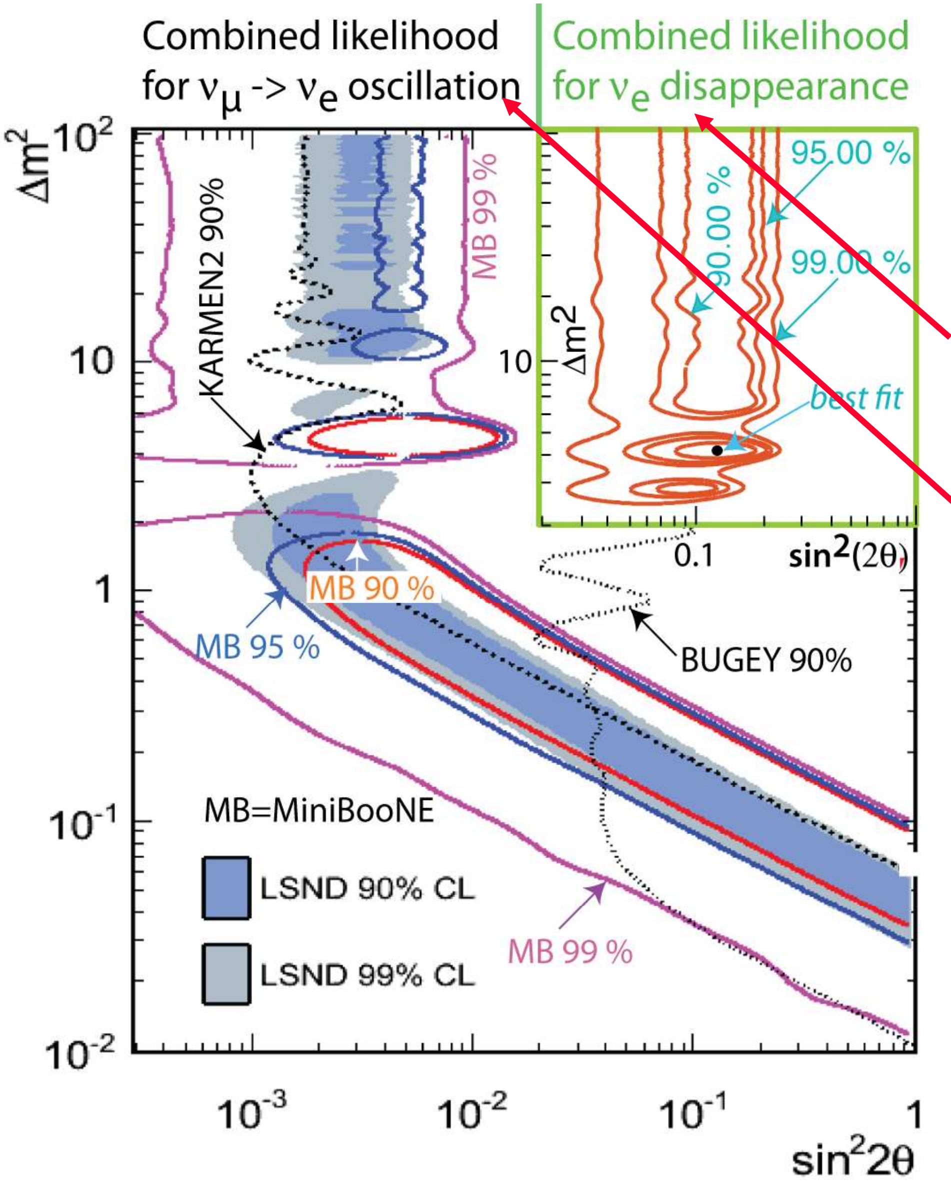
Mention et al. arXiv:1101.2755

- 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.



G.Mills, ICHEP, July 2010

A unified approach ?



Allowed regions in the plane for combined results:

the νe disappearance rate (right)

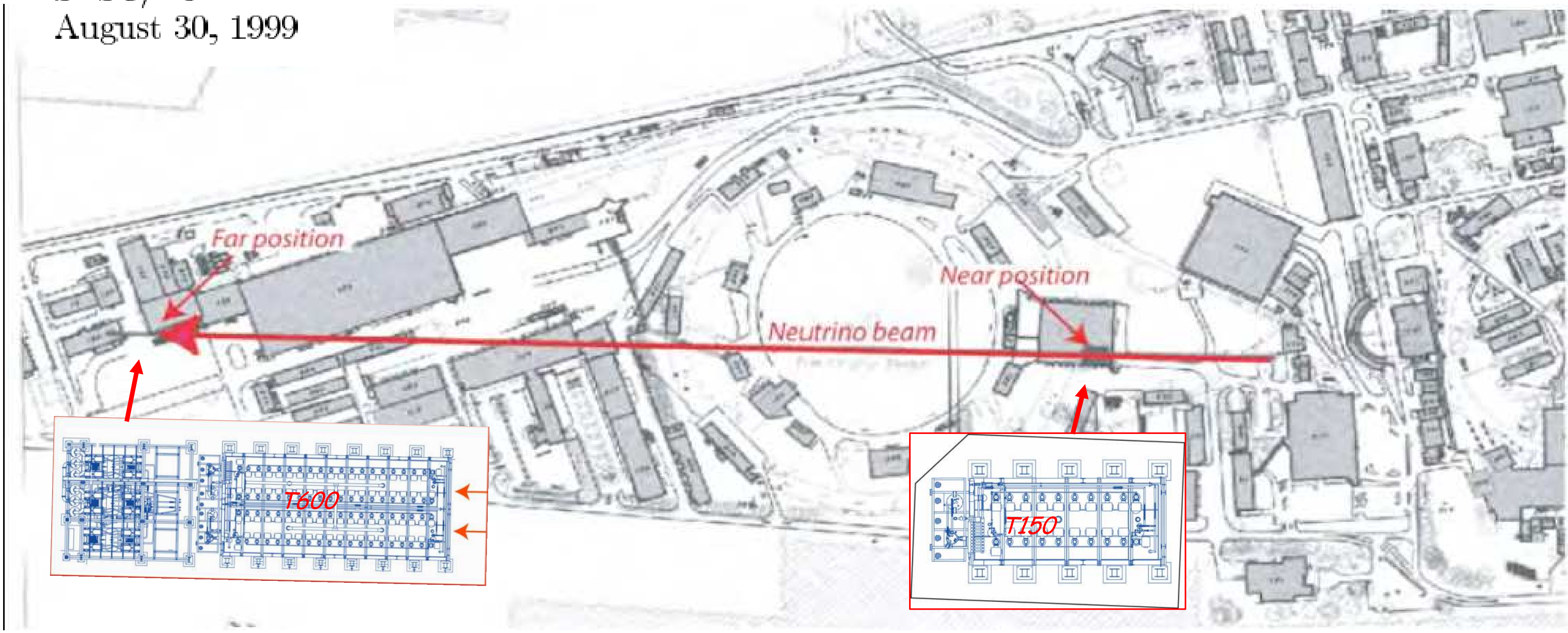
the LSND /MiniBooNE anti-νe anomaly (left).

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 $\geq$ 4 neutrinos hypothesis and a mass matrix $U_{(4,k)} \approx 0.1$, where k = μ and e.

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

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

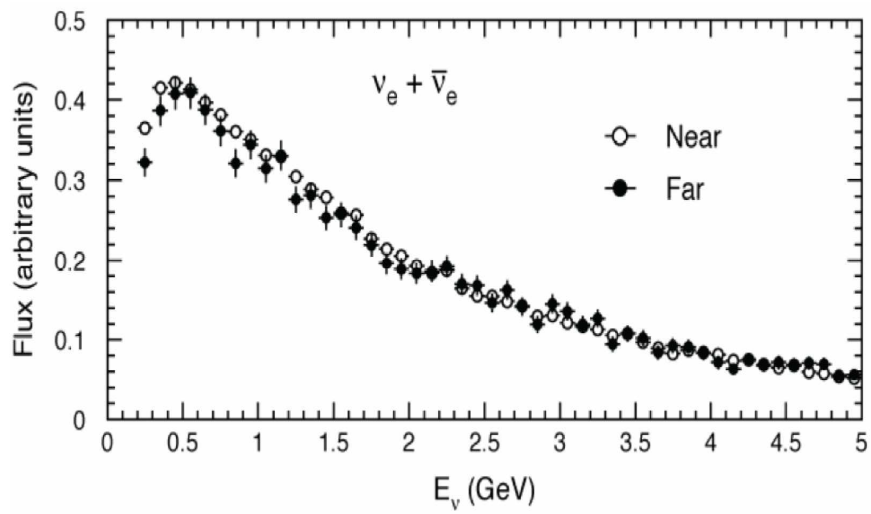
SEARCH FOR $\nu_\mu \rightarrow \nu_e$ OSCILLATION AT THE CERN PS

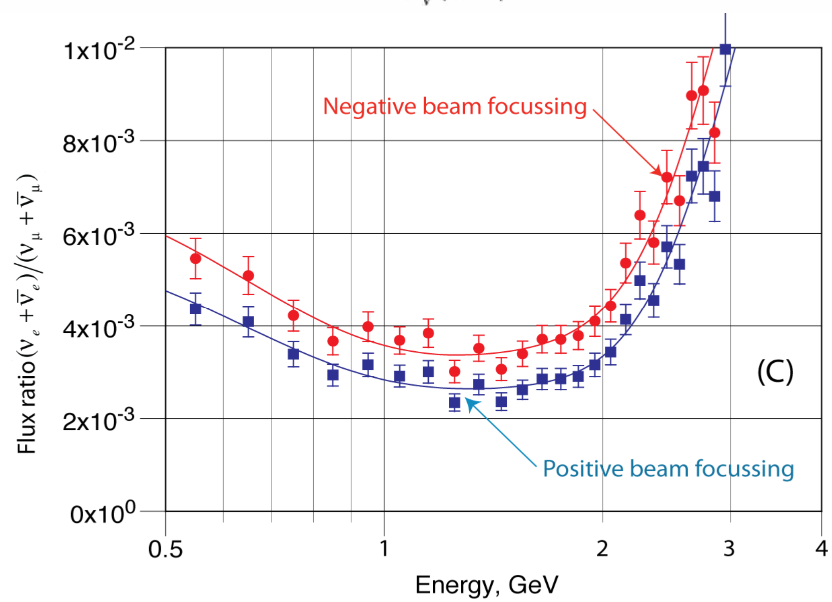


Two positions are foreseen for the detection of the neutrinos
The far (ICARUS-T600) location at 850 m from the target: L/E ~ 1 km/GeV;
The additional detector and new location at a distance of 127 m from the target: L/E 0.15 km/GeV

The configuration at the CERN-PS

- The present proposal at the CERN-PS is based on the search for spectral differences of electron like specific signatures *in two identical detectors but at two different neutrino distances*, at the "Far" and the "Near" locations, respectively at 850 m and 127 m away from the source.
- The "Far" detector is the ICARUS T600, now perfectly operational in the underground Hall B of the LNGS in a neutrino beam from the CERN-SPS, collecting data as CNGS2 experiment. The T600 detector is the largest liquid Argon TPC ever built, with a size of about 600 t of imaging mass.
- The "Near" detector has to be constructed anew and it is as far as possible identical to the T600 but with a mass of 150 t, namely a clone of a single T300 half-module with the length reduced by a factor 2.





The ratio of the electron/muon beam fluxes for neutrino and antineutrino focussing at the CERN-PS

T600 transport from LNGS to CERN and T150 construction

- According to the present programme CERN will provide 2 years full intensity beam to ICARUS before 2013 stop when T600 can be transported to CERN, ensuring the new experiment operation again in 2014.
- The 2 sub-modules can be extracted from thermal insulation, dismounted, transported and reconstructed in Hall B-191 in 12-14 months –new insulator
- A large number of additional components can be disassembled/transported: electronics for DAQ, ancillary systems located in three levels of the supporting structure surrounding the T600 and LN_2 liquefaction system.
- The same wire chambers mechanics and wiring infrastructures can be used for the construction of the T150 Near Detector. Cryogenics, PMTs, front-end electronics, DAQ and ancillary equipments, can be replicated according to the downscaled detector mass: one Gar and LAr recirculation system, two LN2 recondenser units, 14200 electronic channels with 25 electronic racks and 30 PMT's of 8" diameter.

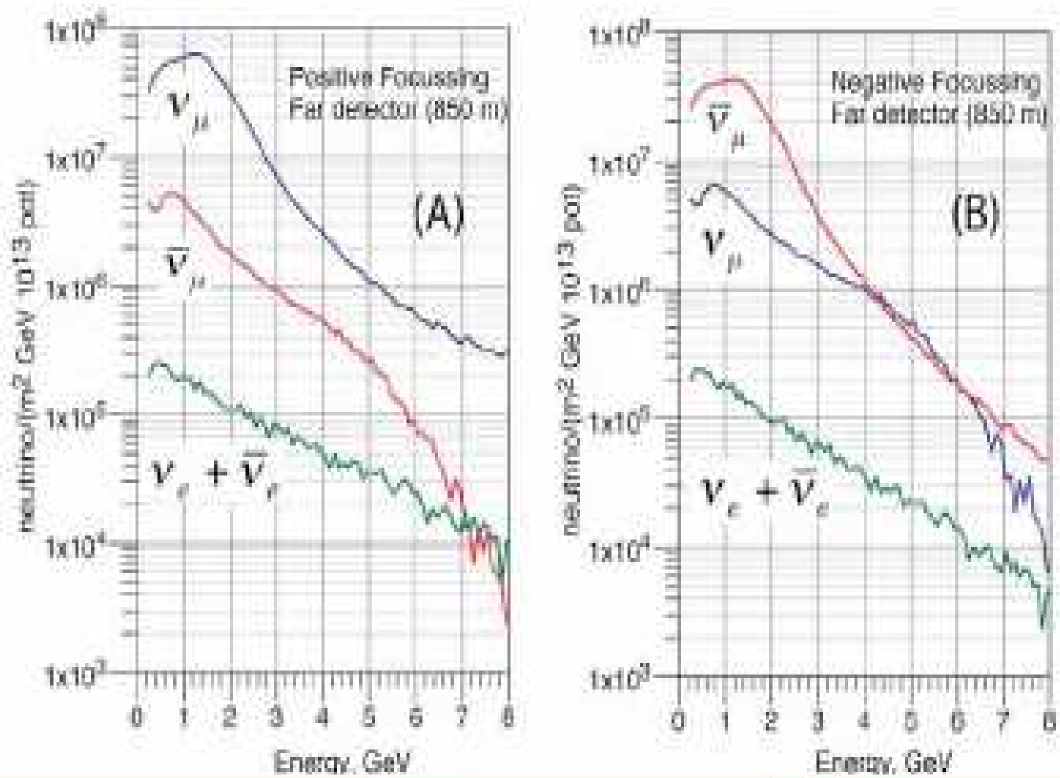
- Some improvement/simplification may be studied and implemented.

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:

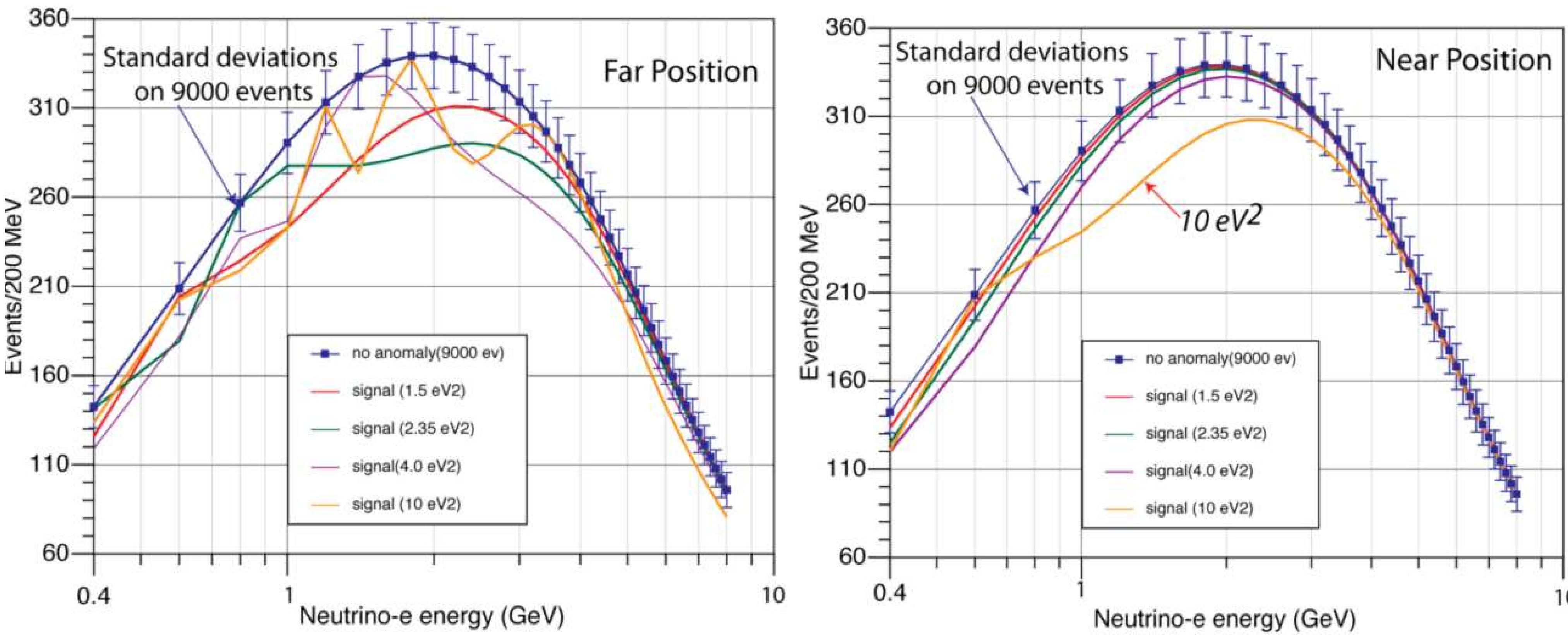
- 2.5 10^{20} pot - basic old "I216" option corresponding to only 30 kW beam power

- 7.5 10^{20} pot – upgraded PS option (90 kW)



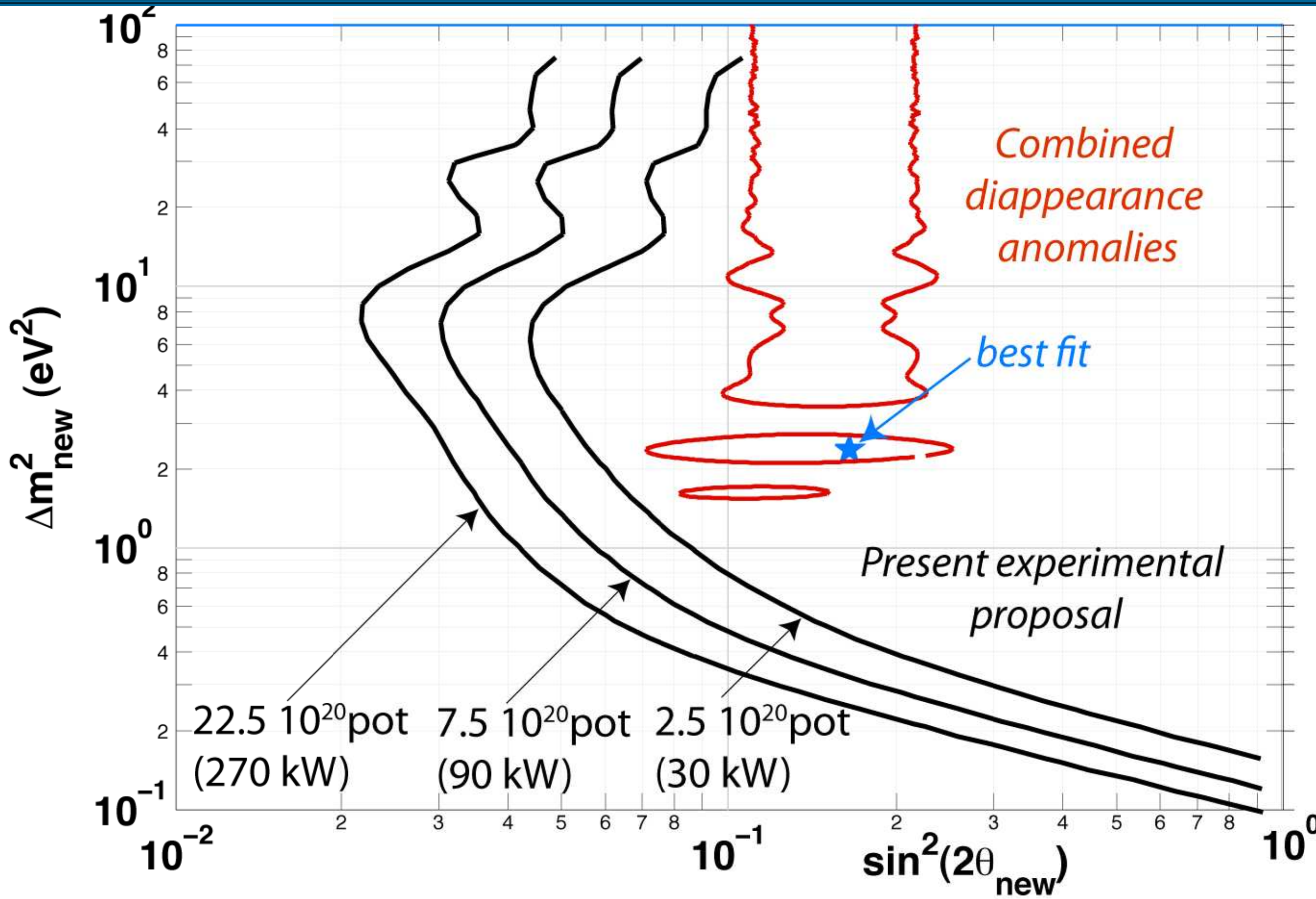
	ν focus		$\bar{\nu}$ focus	
	FAR	NEAR	FAR	NEAR
Fiducial mass	500 t	150 t	500 t	150 t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions (or $\bar{\nu}_\mu$ for $\bar{\nu}$ focus)	3.600E+6	5.400E+7	6.000E+5	6.900E+6
QE ν_μ (or $\bar{\nu}_\mu$) interactions	1.350E+6	1.980E+7	2.610E+5	3.000E+6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

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).

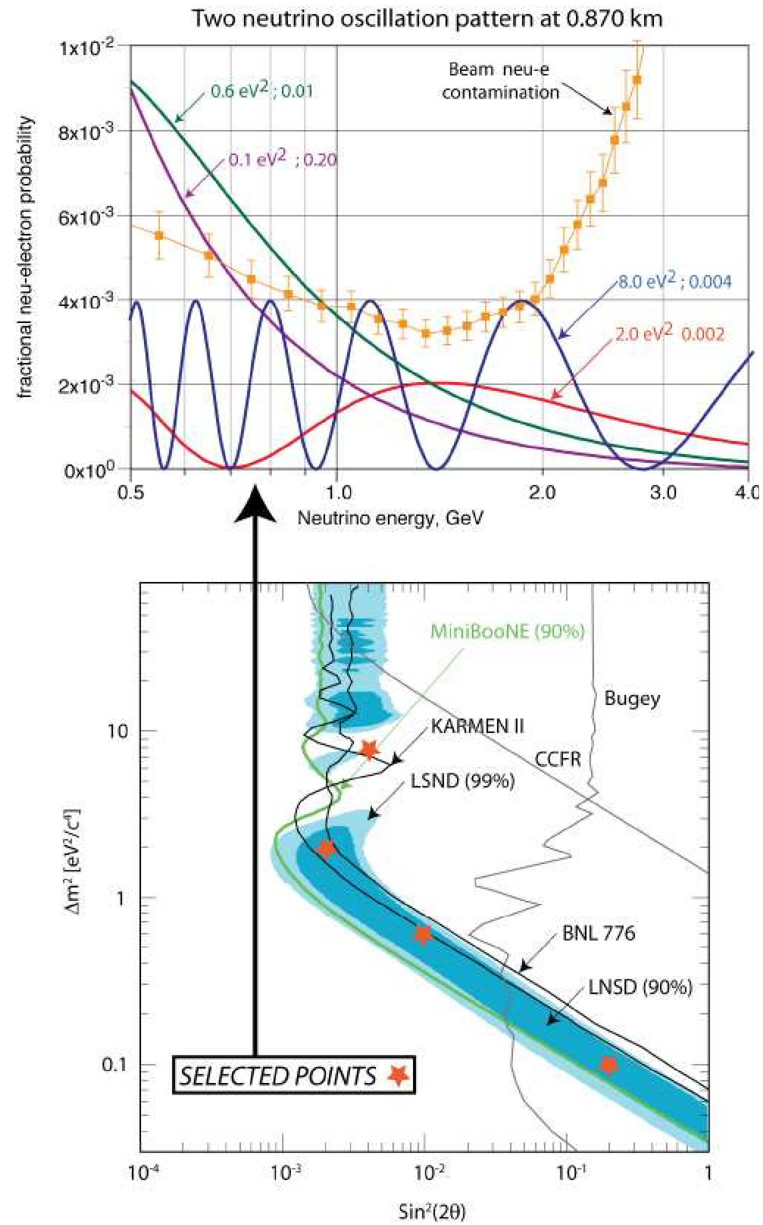
Expected signal for LSND/MiniBooNE anomalies

- 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.

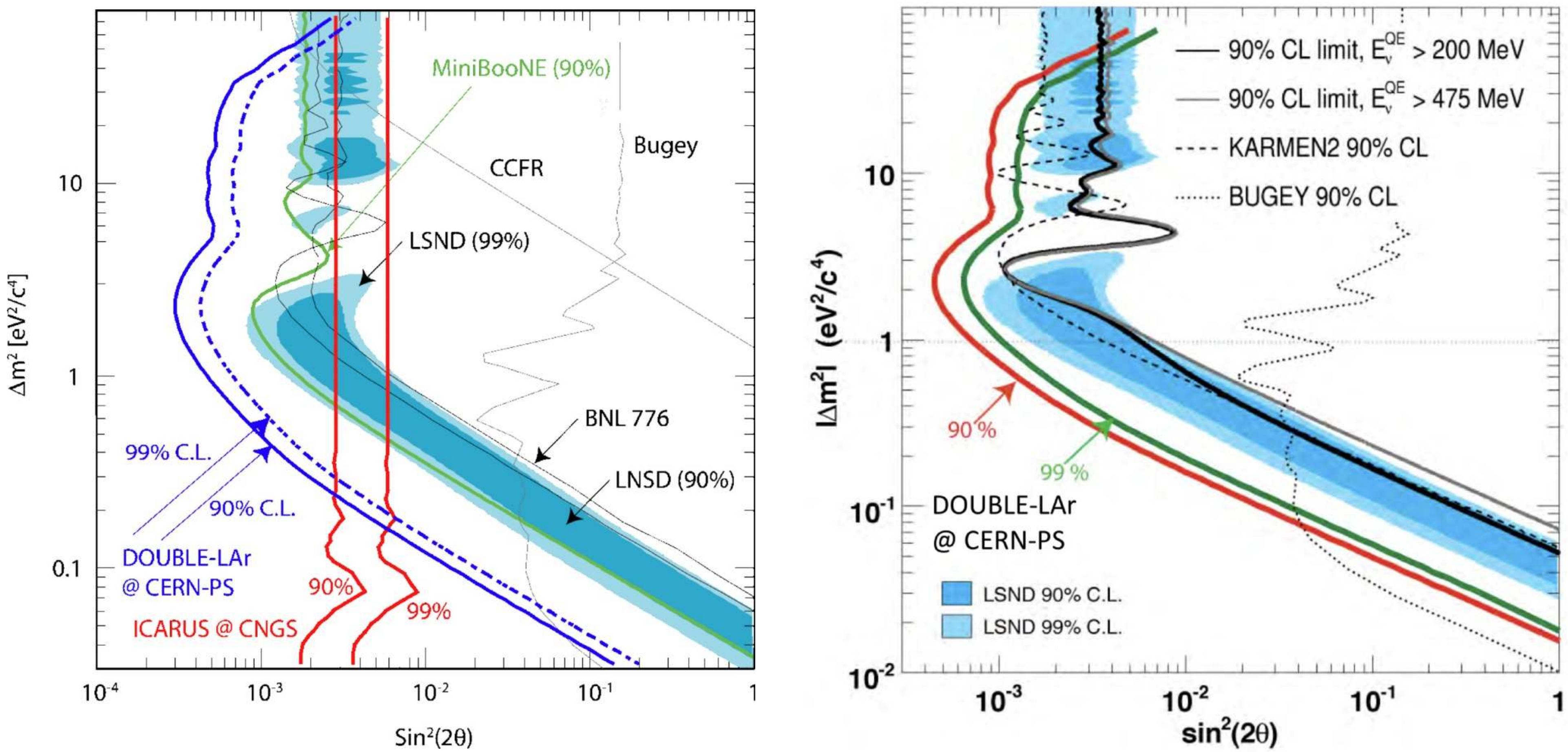
	ν focus		$\bar{\nu}$ focus	
	FAR	NEAR	FAR	NEAR
Fiducial mass	500 t	150 t	500 t	150 t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions (or $\bar{\nu}_\mu$ for $\bar{\nu}$ focus)	3.600E+6	5.400E+7	6.000E+5	6.900E+6
QE ν_μ (or $\bar{\nu}_\mu$) interactions	1.350E+6	1.980E+7	2.610E+5	3.000E+6
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 $\nu\mu \to \nu e$ 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 at LNGS are also shown.

Status of advancement of the Proposal

- A Memorandum has been sent to the CERN-SPS-C dated on March 9th describing a possible continuation of the ICARUS programme at the CERN-PS, with the following three major new steps:
  - the construction, or better the reconstruction of a CERN-PS horn focussed neutrino beam;
  - the enlargement and the reformulation of the collaboration to a wider international team; and
  - the formulation and approval of a formal proposal to the SPS-C, ensuring the availability of appropriate human and financial resources.
- The response of the SPS-C has been positive on all three issues, namely
  - *The SPS-C recognises the physics motivation and the opportunity offered by the ICARUS technology and availability.*
  - *The Committee will review the project once a detailed proposal is available.*
  - In addition *CERN is prepared, within its available resources, to study the re-building of the neutrino beam*.
- Therefore requirements are now fulfilled in order to move ahead towards the detailed proposal.

The present ICARUS Collaboration: to be extended

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Thank you !