A proposed search for Sterile Neutrinos with the ICARUS detector at the CERN-PS

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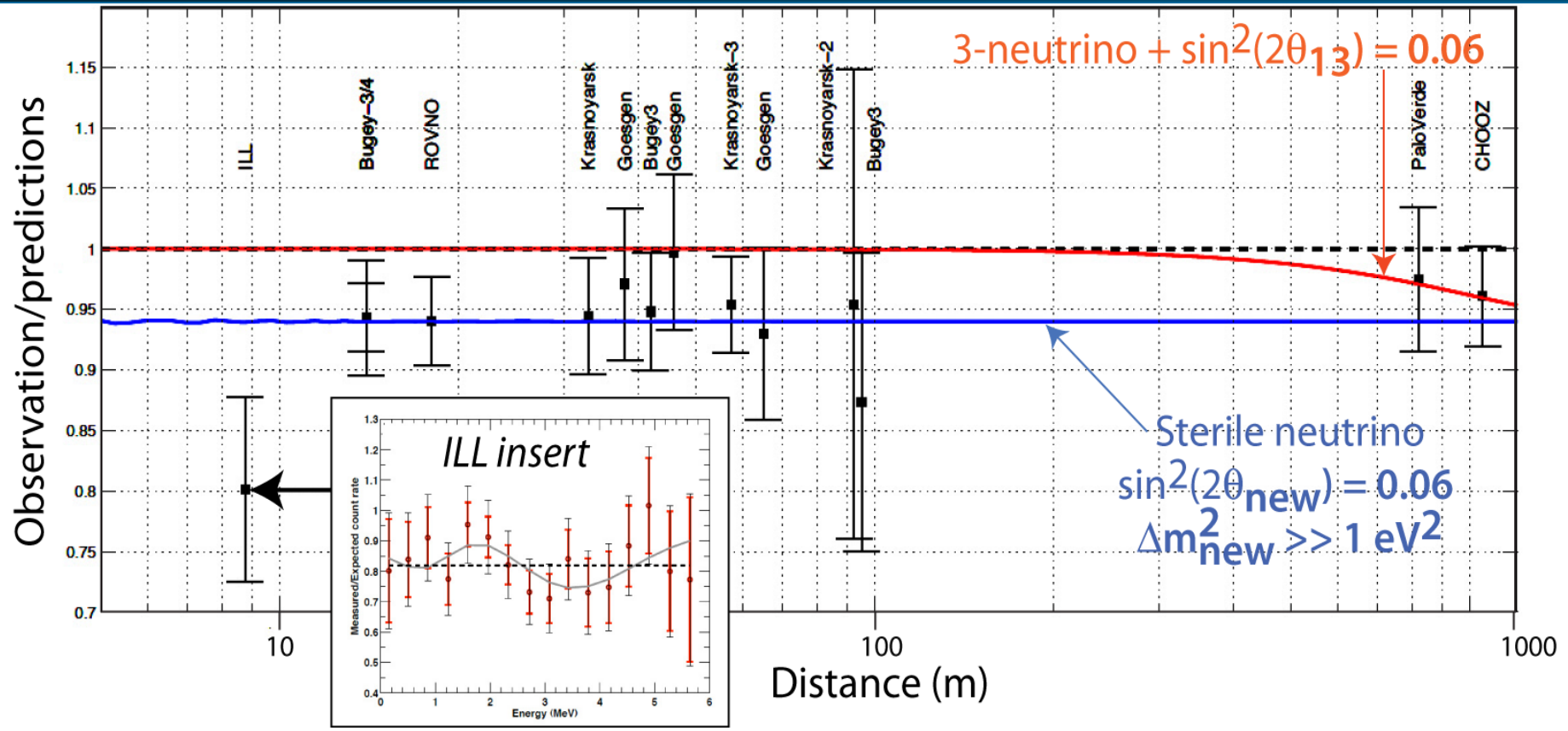
Neutrinos

- Neutrino oscillations have established a picture and a large number of experiments consistent with the mixing of three physical neutrino 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 $\Delta m^2_{21} \approx 8 \times 10^{-5}\ eV^2$.
- There are however 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.

Sterile neutrinos

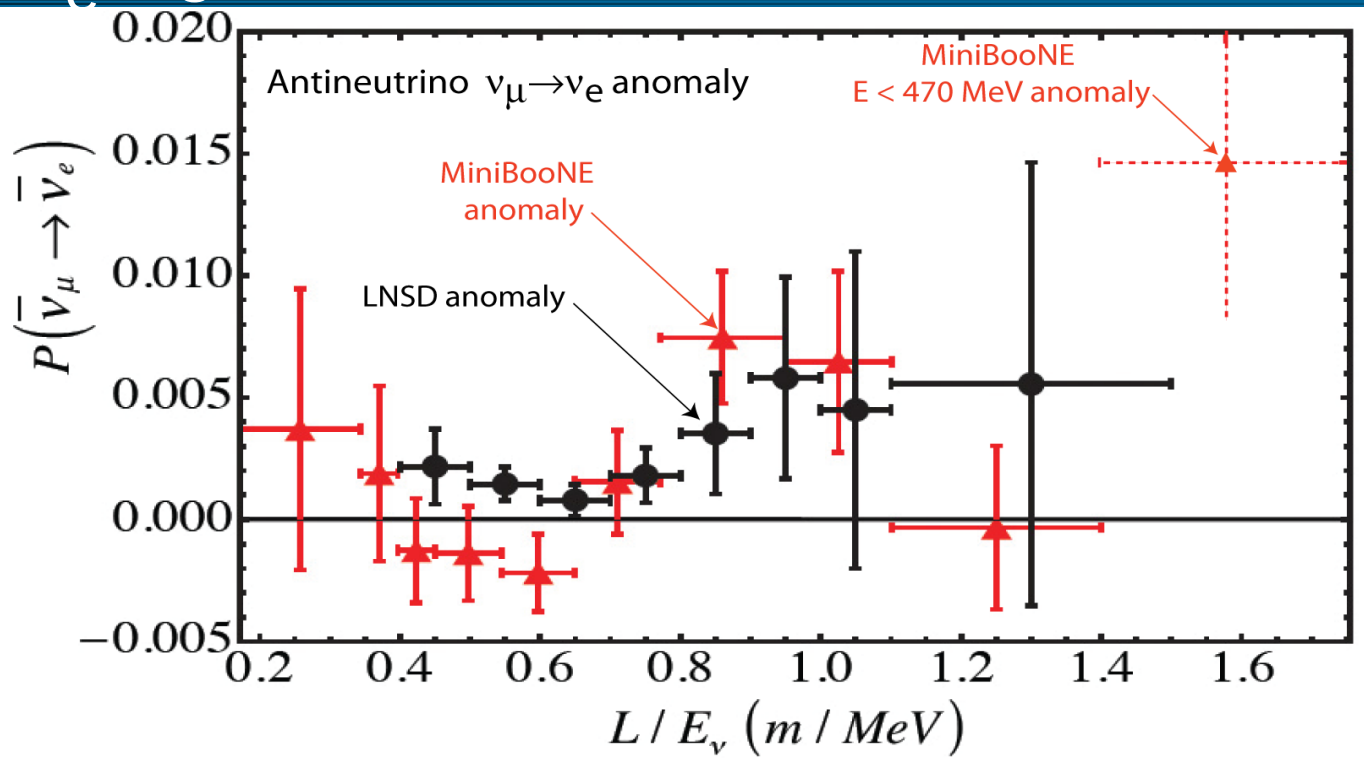
- The possible presence of oscillations into sterile neutrinos has been proposed by B. Pontecorvo, but so far without conclusion.
- Two distinct classes of anomalies have been observed, namely
  - apparent *disappearance signals:* (1) the anti-ν_e events detected from near-by nuclear reactors and (2) 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

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 $sin^2(2\theta_{new}) = 0.06$.

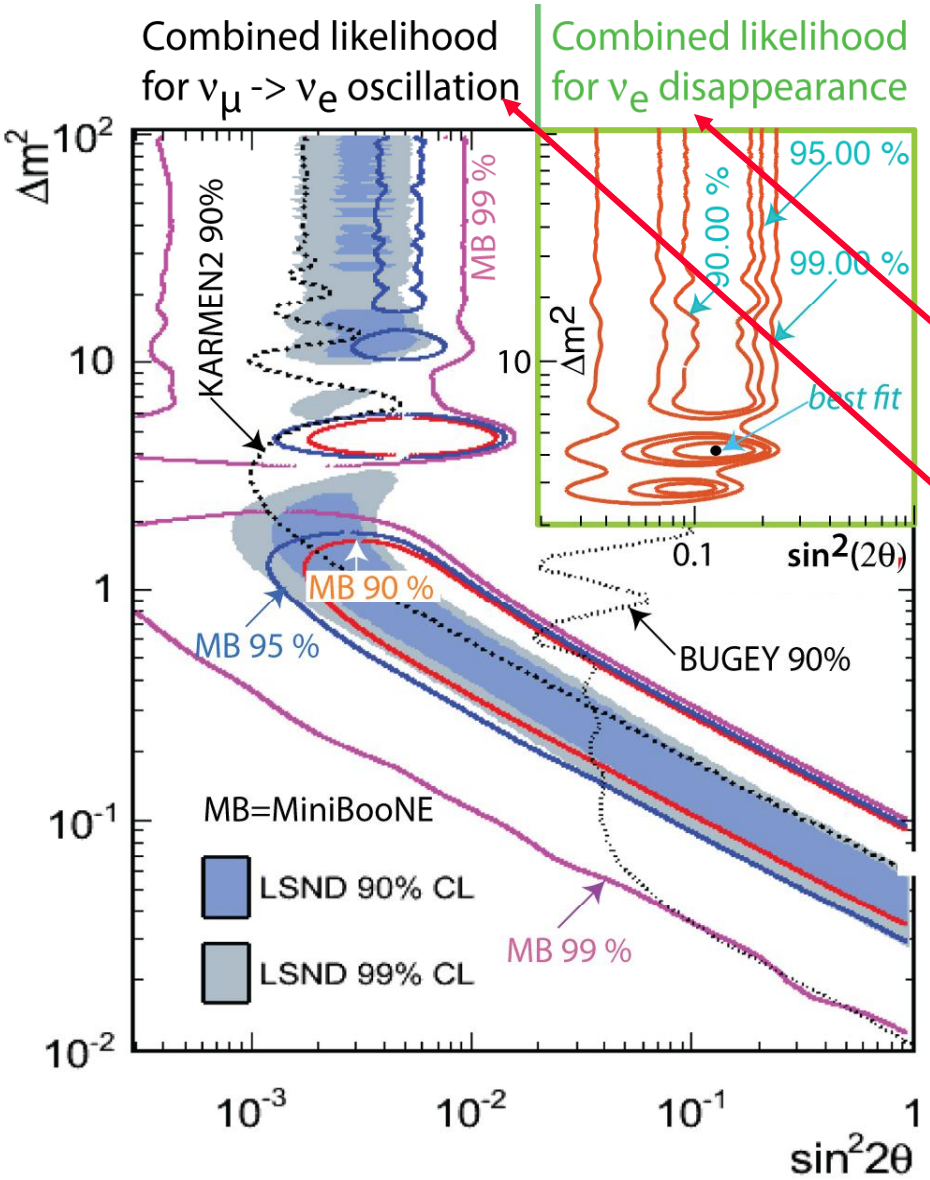
Excess ν_e signal: The LSND/ MiniBooNE anti-neutrinos



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.

A definitive experiment: LAr TPC at the 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 $\nu\mu$, ≈10^4 νe)
  - Both initial νe and $\nu\mu$ components cleanly identified.

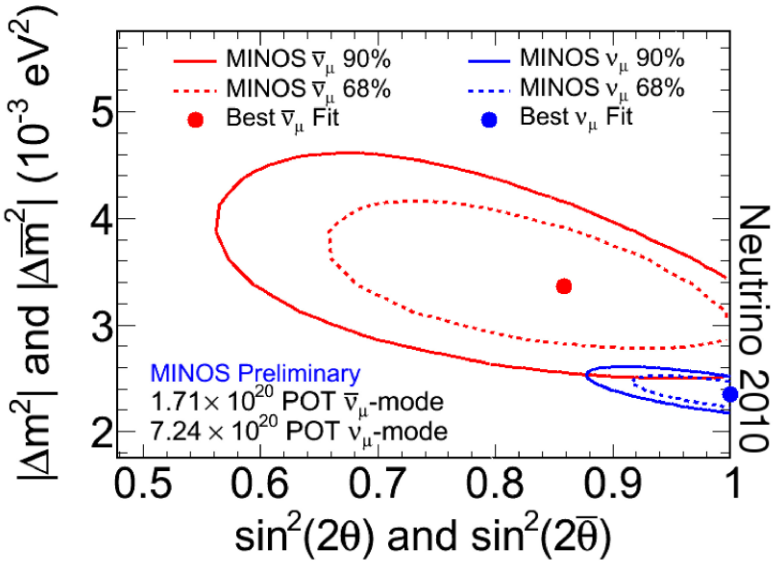
Basic features of the proposed experiment

- 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 ν–μ 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.

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.



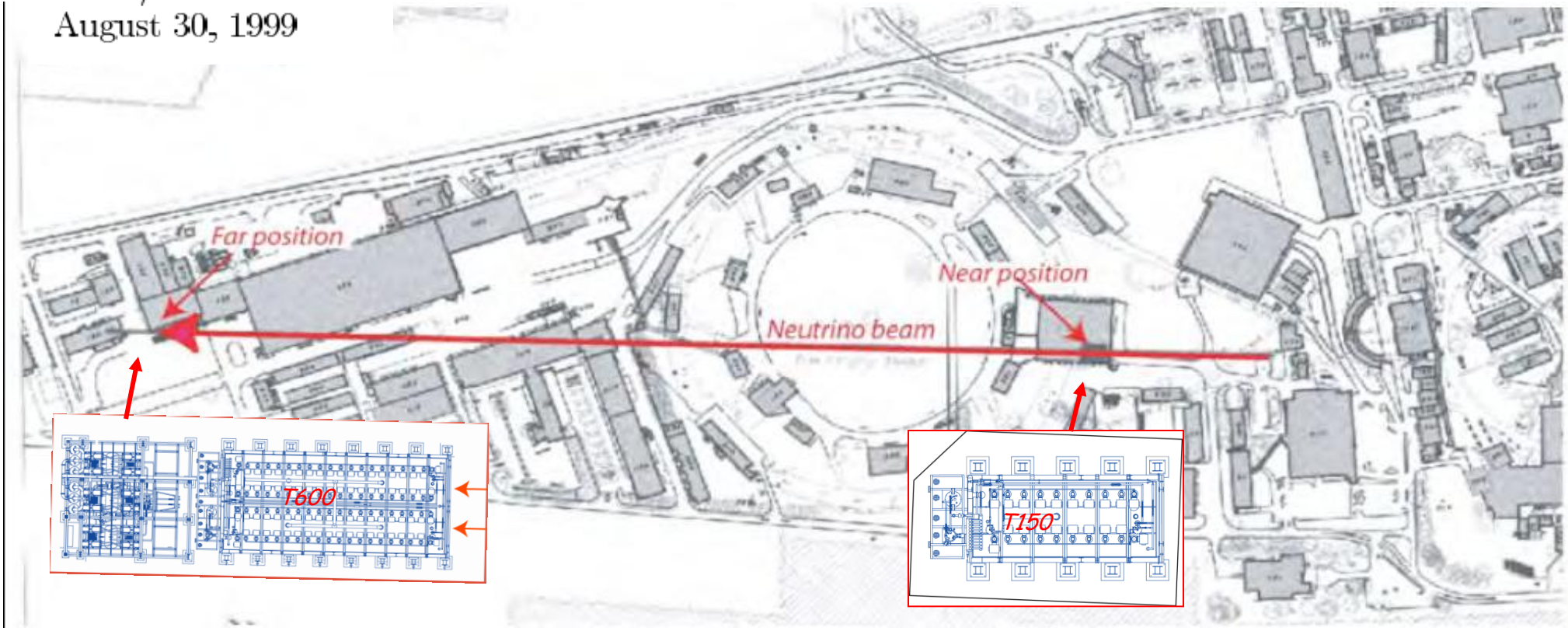
Fates of secular conservation laws !

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

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

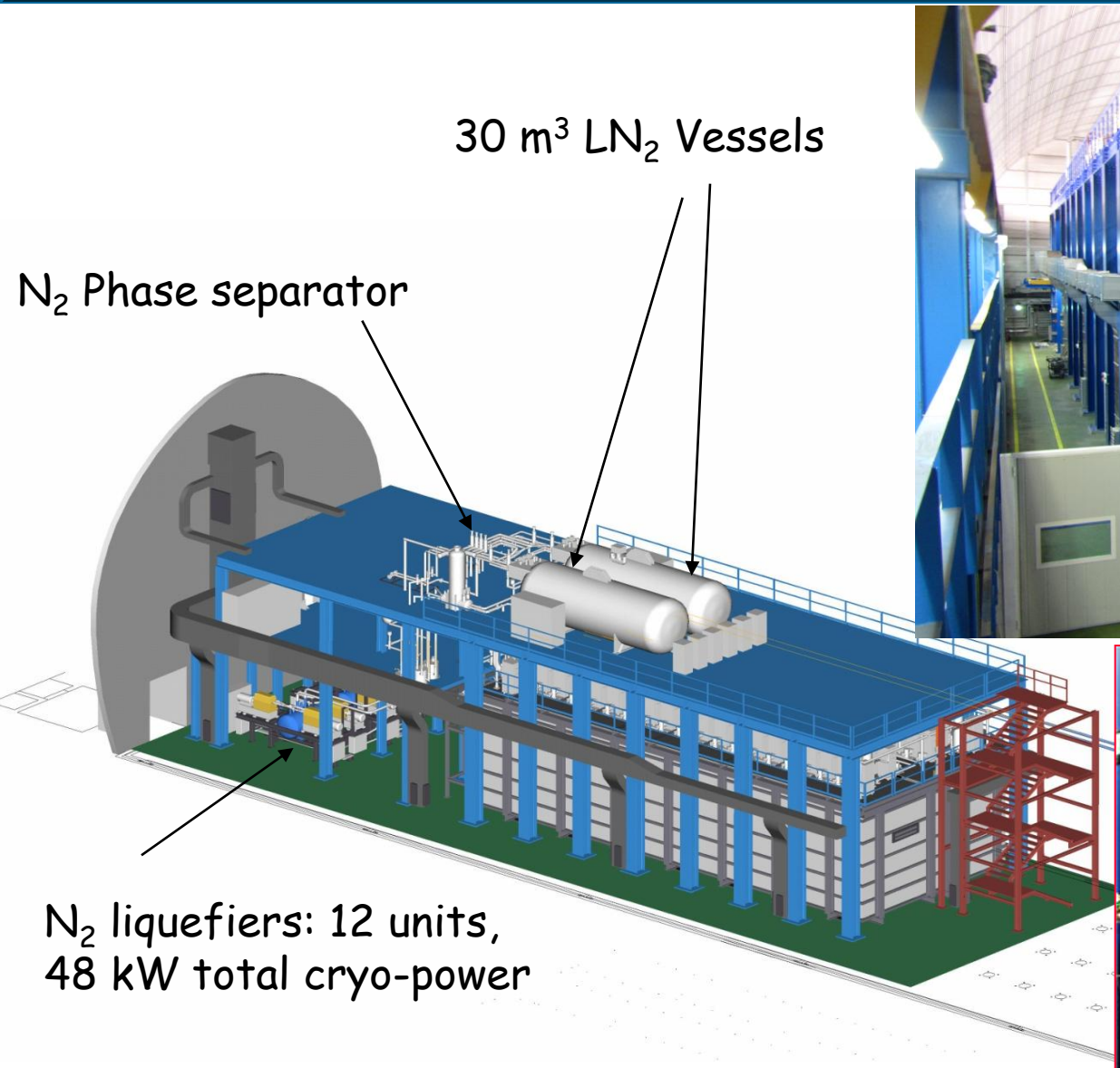


Two positions are foreseen for the detection of the neutrinos
The far (ICARUS-T600) location at 850 m from the target: L/E ~ 1 km/GeV;
The additional detector and new location at a distance of 127 m from the target: L/E 0.15 km/GeV

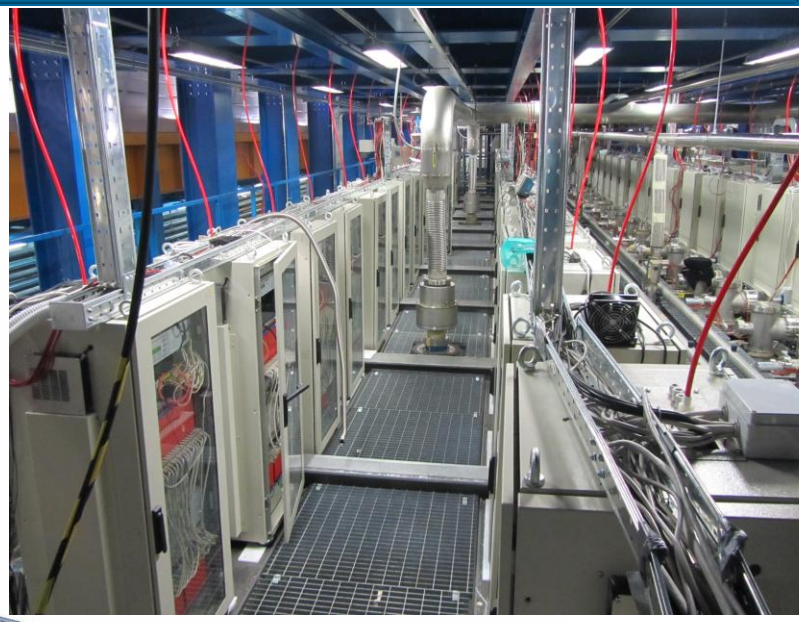
The configuration at the CERN-PS

- 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.

ICARUS T600 in LNGS Hall B



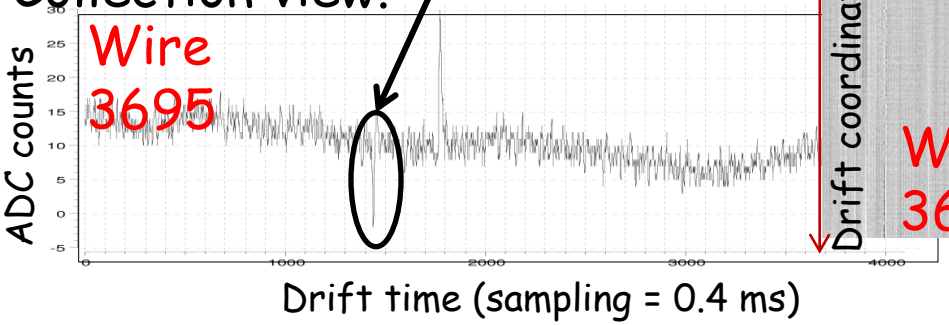
T600 cryostats layout

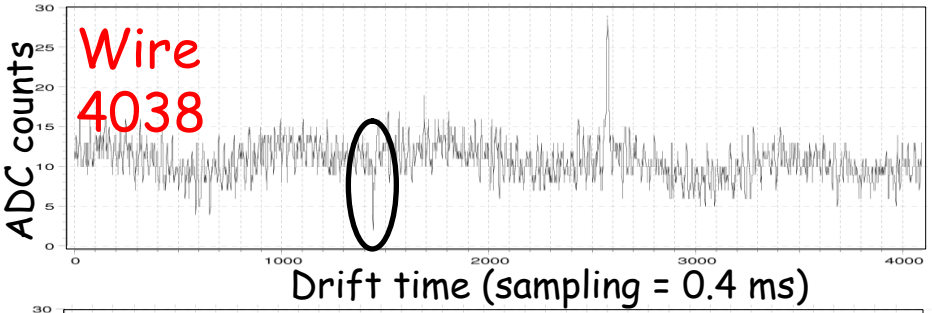


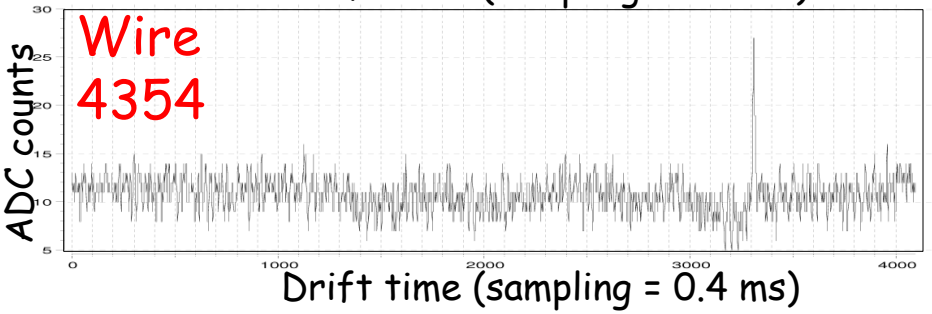
LAr purity measurement with muon crossing tracks

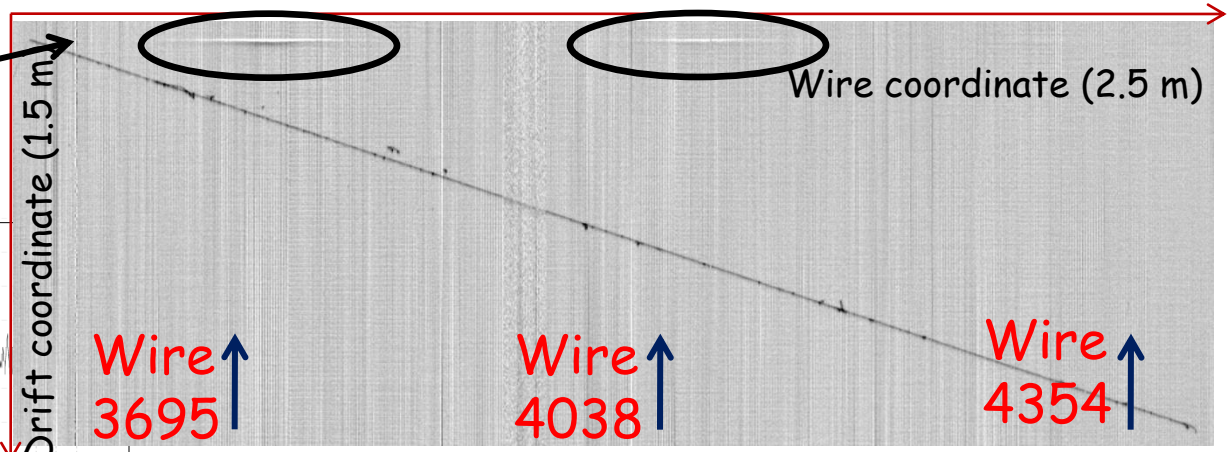
Charge attenuation along track allows event-by-event measurement of LAr purity.

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







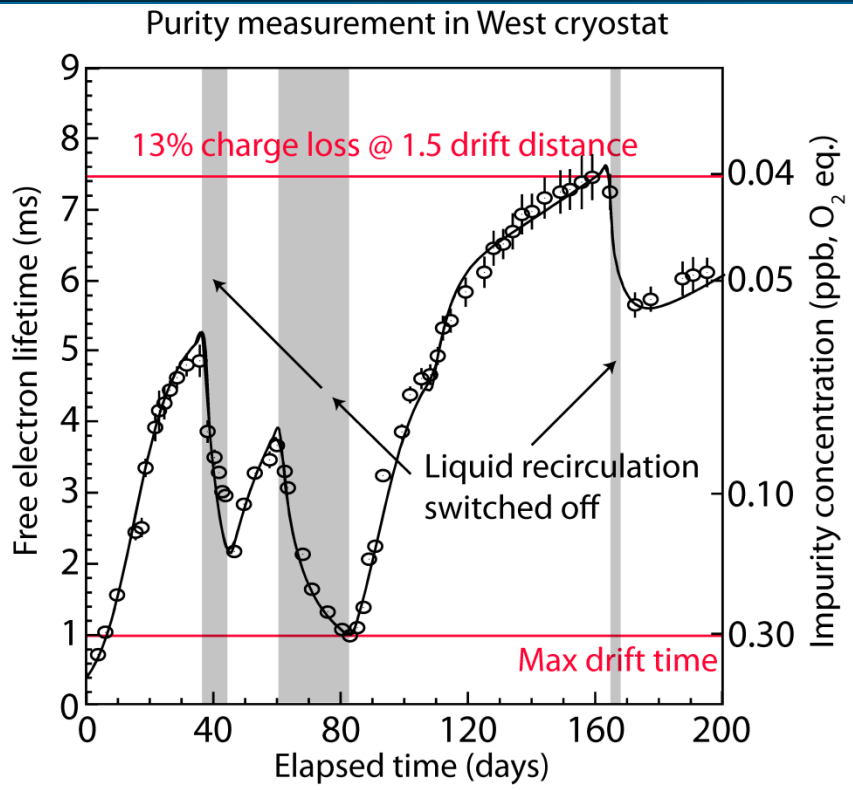


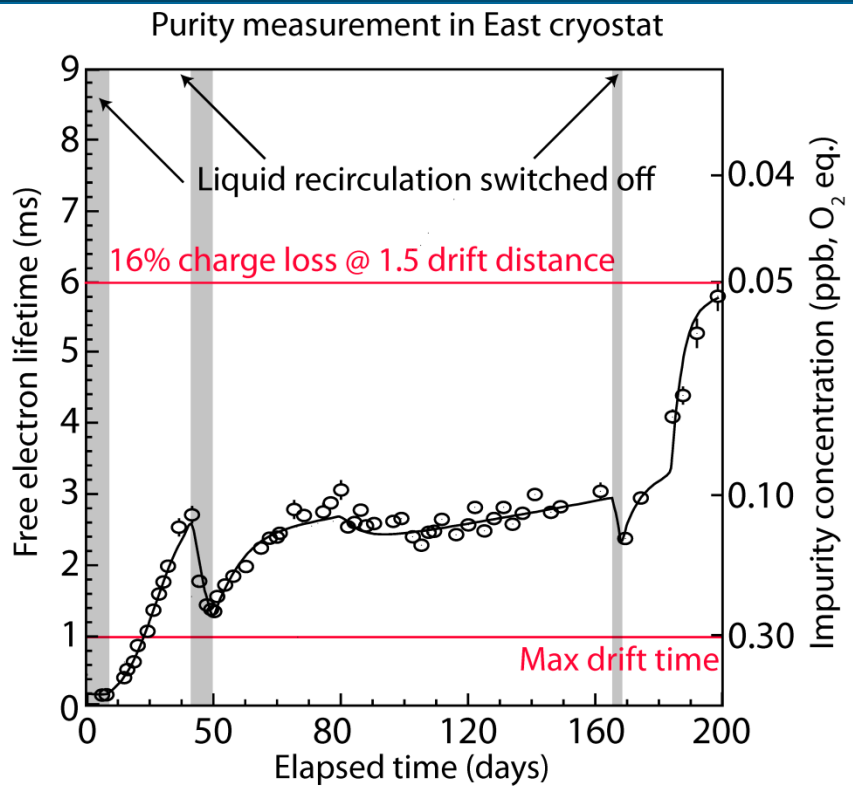
Run 10139 Event 8961 Collection view

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.

$$dN/dt = -N/t_R + k + k_I \exp(-t/t_I)$$

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 m³/h corresponding to ≈ 6 day cycle time*

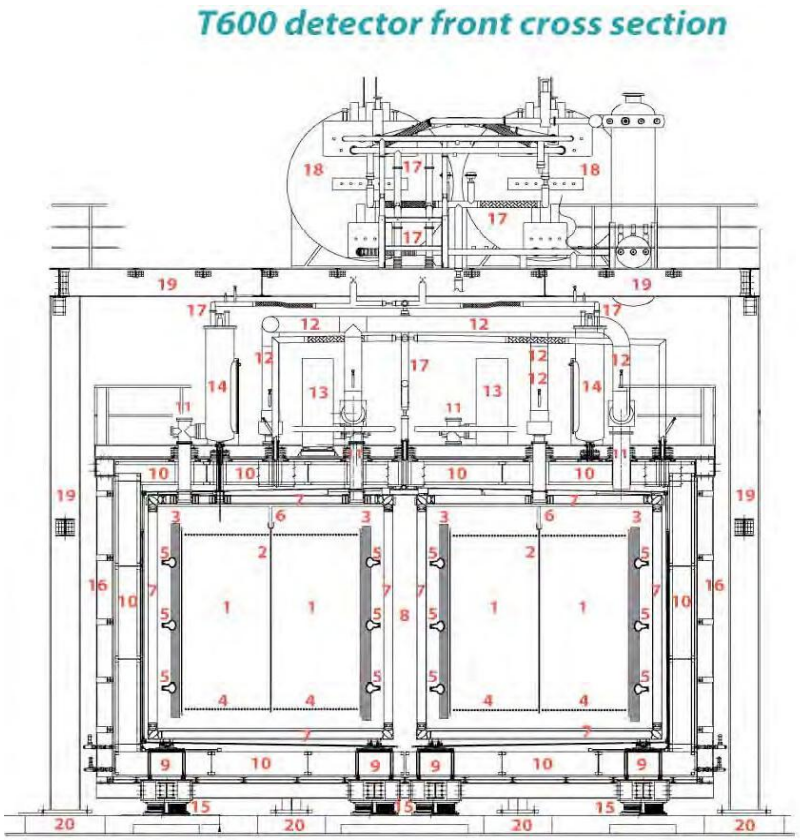
T600 transport from LNGS to CERN and T150 construction

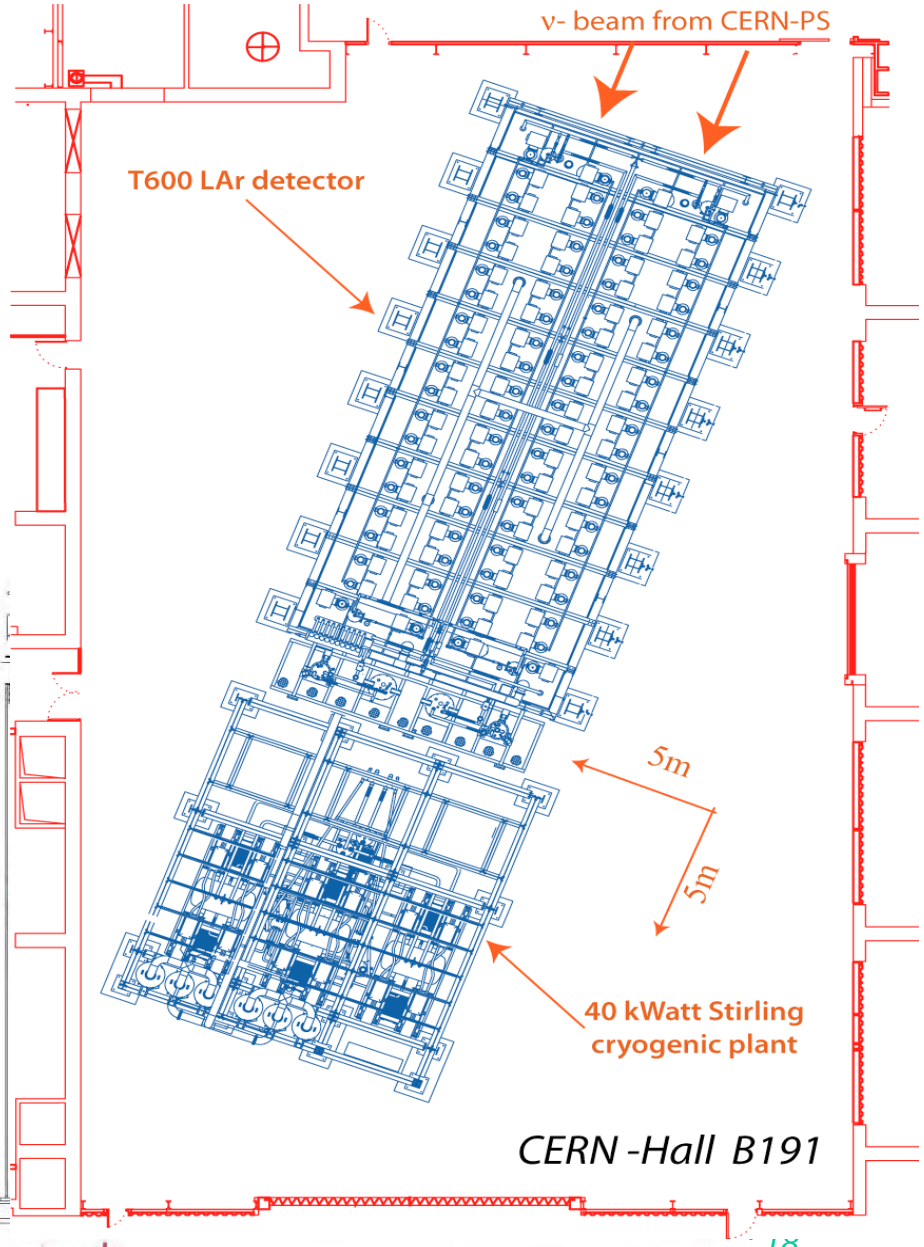
- According to the present programme CERN will provide 2 years full intensity beam to ICARUS before 2013 stop when T600 can be transported to CERN, ensuring the new experiment operation again in 2014.
- The 2 sub-modules can be extracted from thermal insulation, dismounted, transported and reconstructed in Hall B-191 in 12-14 mounths –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.

The ICARUS T600 as "Far" detector in Hall B191

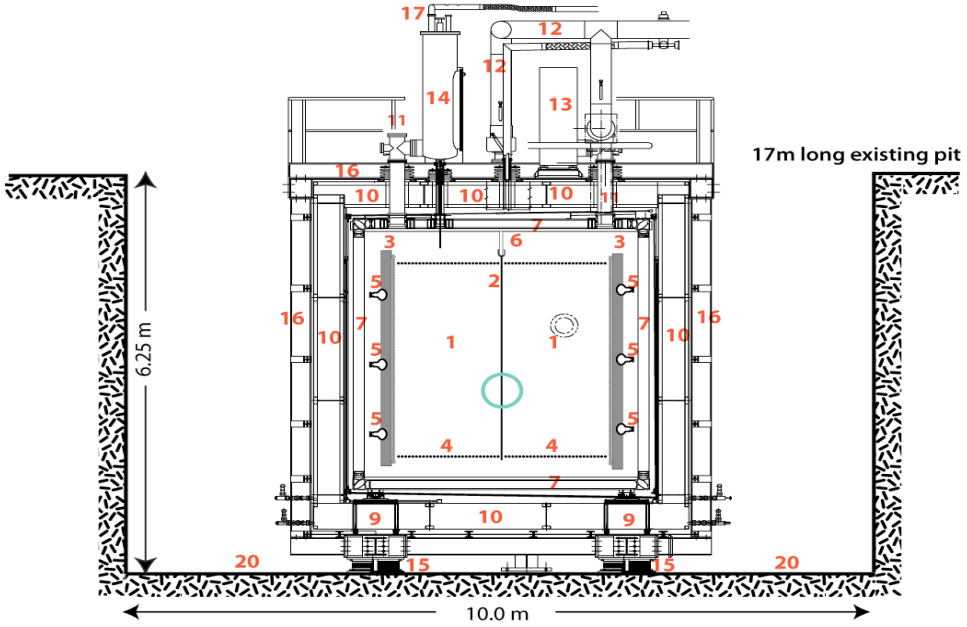
- The T600 detector could be moved and operated at CERN in the old BEBC experimental hall (Hall 191) without major modifications

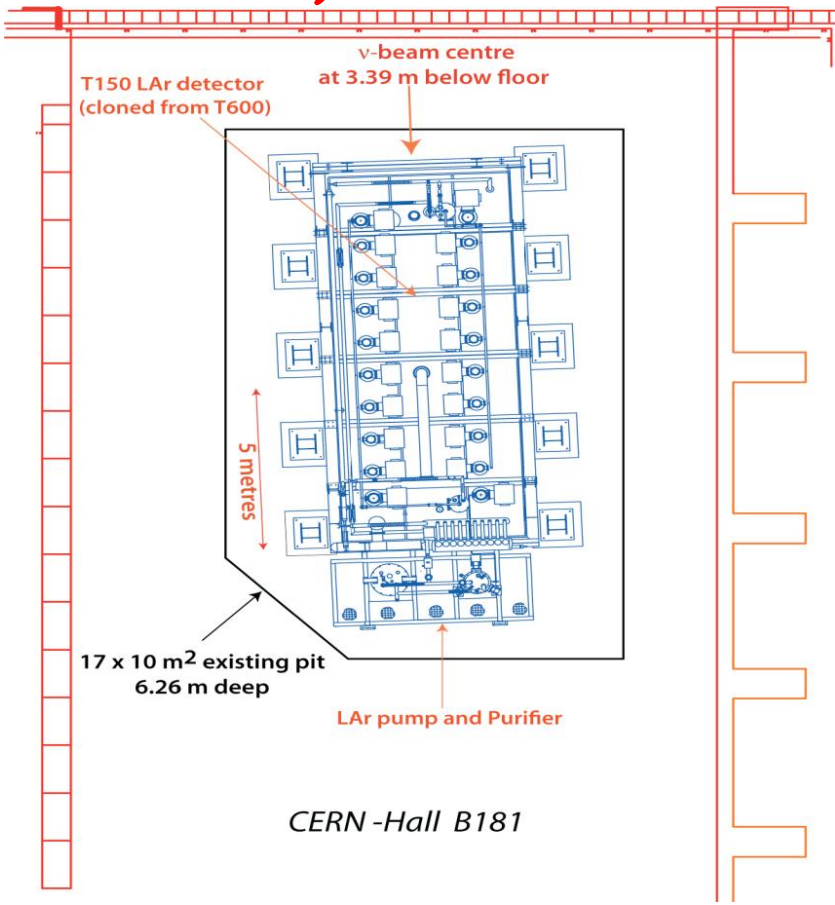




The additional T150 detector (to be constructed)

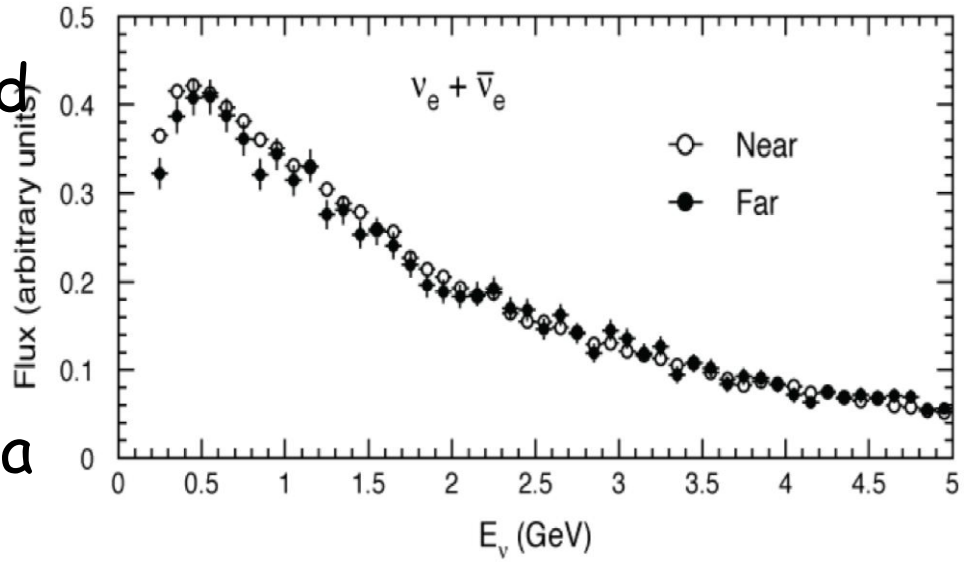
- Maximum of similarity with Far: a clone of a single semi-module, length reduced by a factor 2 (about 12 m) keeping untouched the inner detector layout (TPC structure) with a mass of 150 t.
- Near detector dimensions (1 m passive insulation): 13 x 6 m^2 with 6 m height. It fits perfectly the existing basement pit of Hall 181, previously used for neutrino exps.

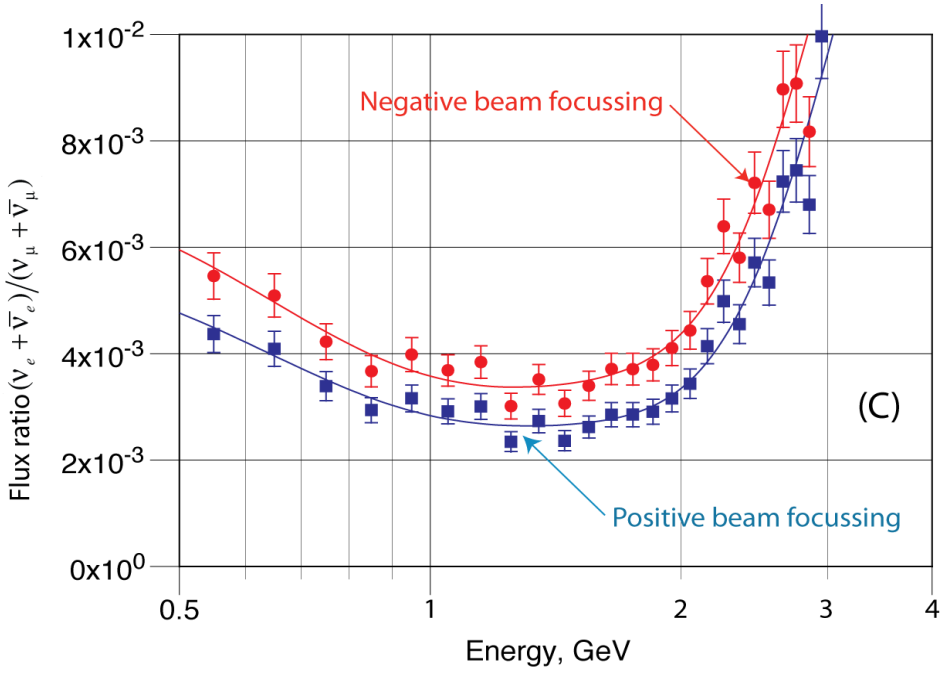




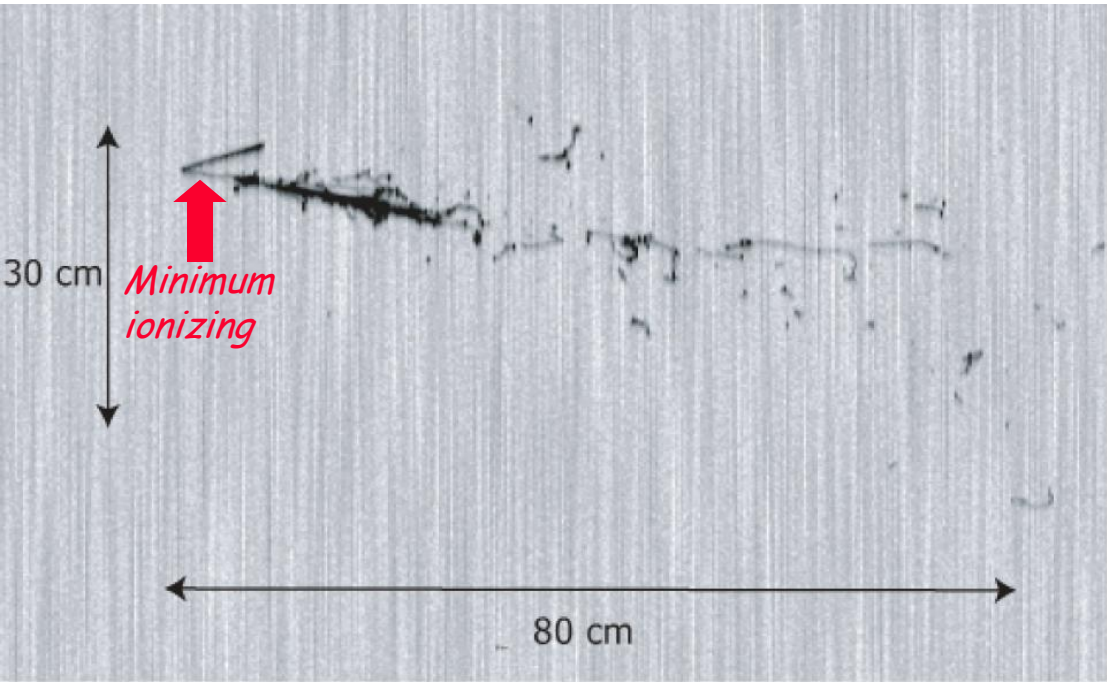
The CERN-PS neutrino and antineutrino e-beams

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



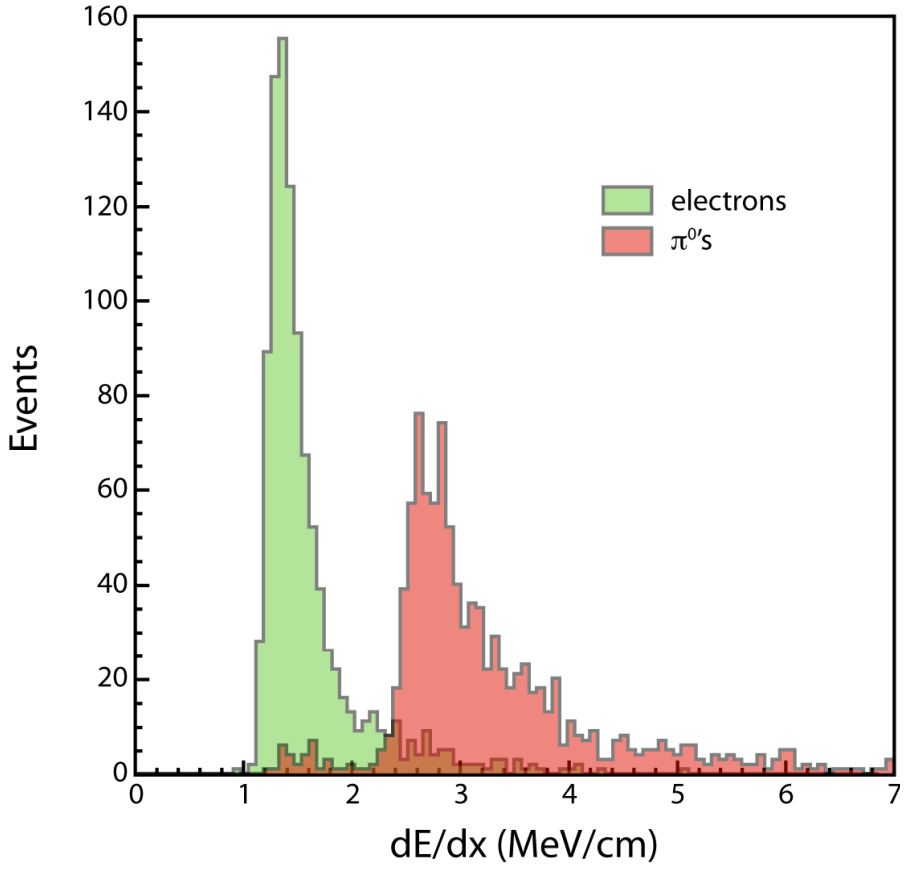


Quasi elastic νe events



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

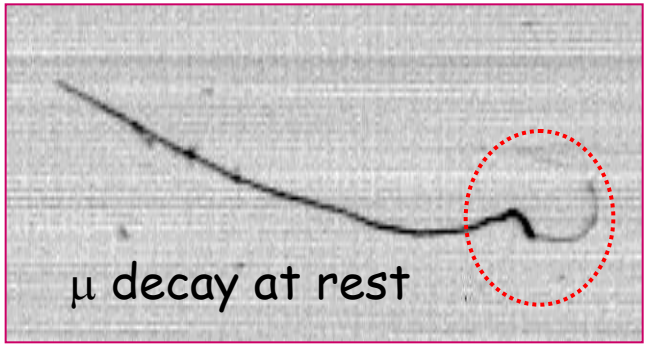
In spite of the much smaller ν_e yield (0.5% of ν_μ) the extremely high sensitivity for the electron signature ensures an excellent detection efficiency



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

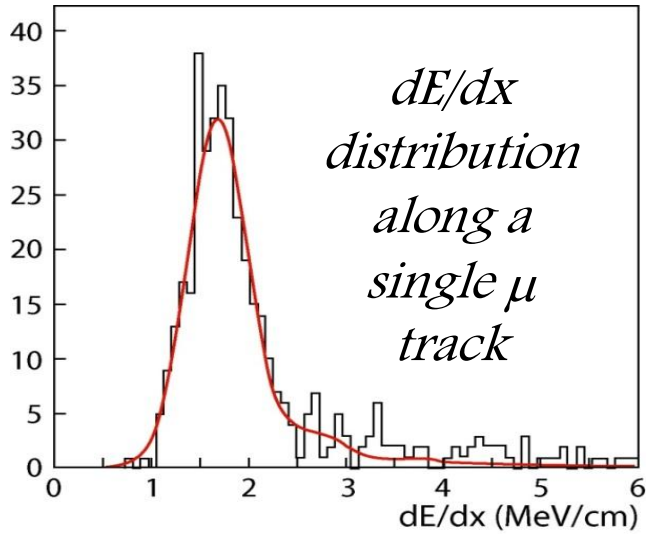
LAr-TPC performance -1

- 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 with 90 % electron identification efficiency

  … NC/CC rejection at 10^{-3} level keeping 90 % nue CC



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

RESOLUTIONS

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

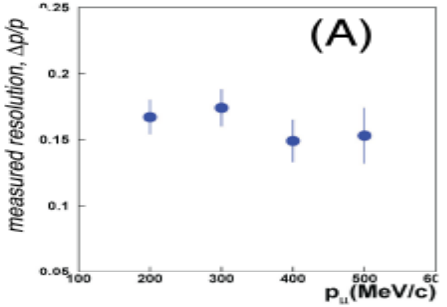
Electromagnetic showers: $\sigma(E)/E = 3\% / \sqrt{E(GeV)}$

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

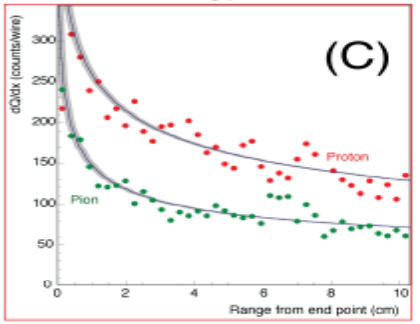
LAr-TPC performance -2

(A) momentum resolution of stopping muons;
(B) momentum resolution of traversing muons with the Kalman filter method;
(C) dE/dx energy loss for slow pions (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.

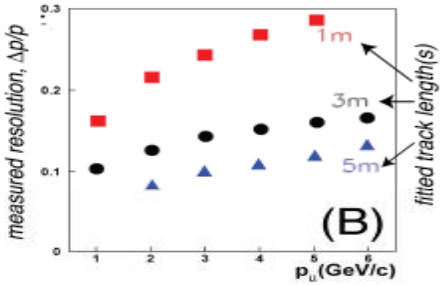
stopping muons



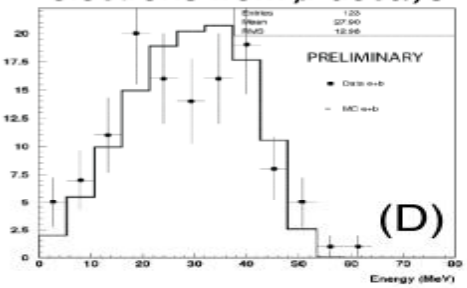
dE/dx energy losses



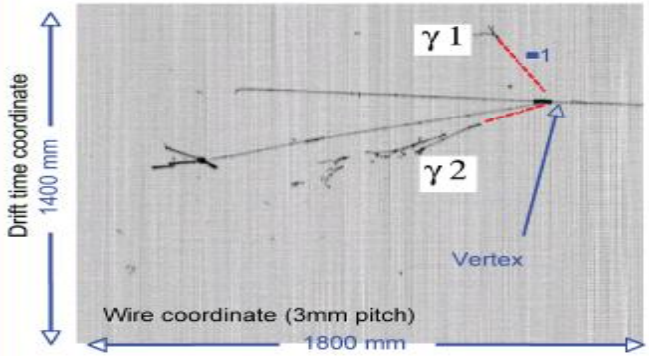
traversing muons
Kalman filter on segmented track

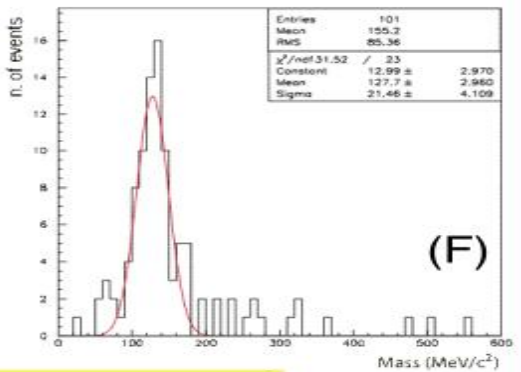


electrons from μ decays



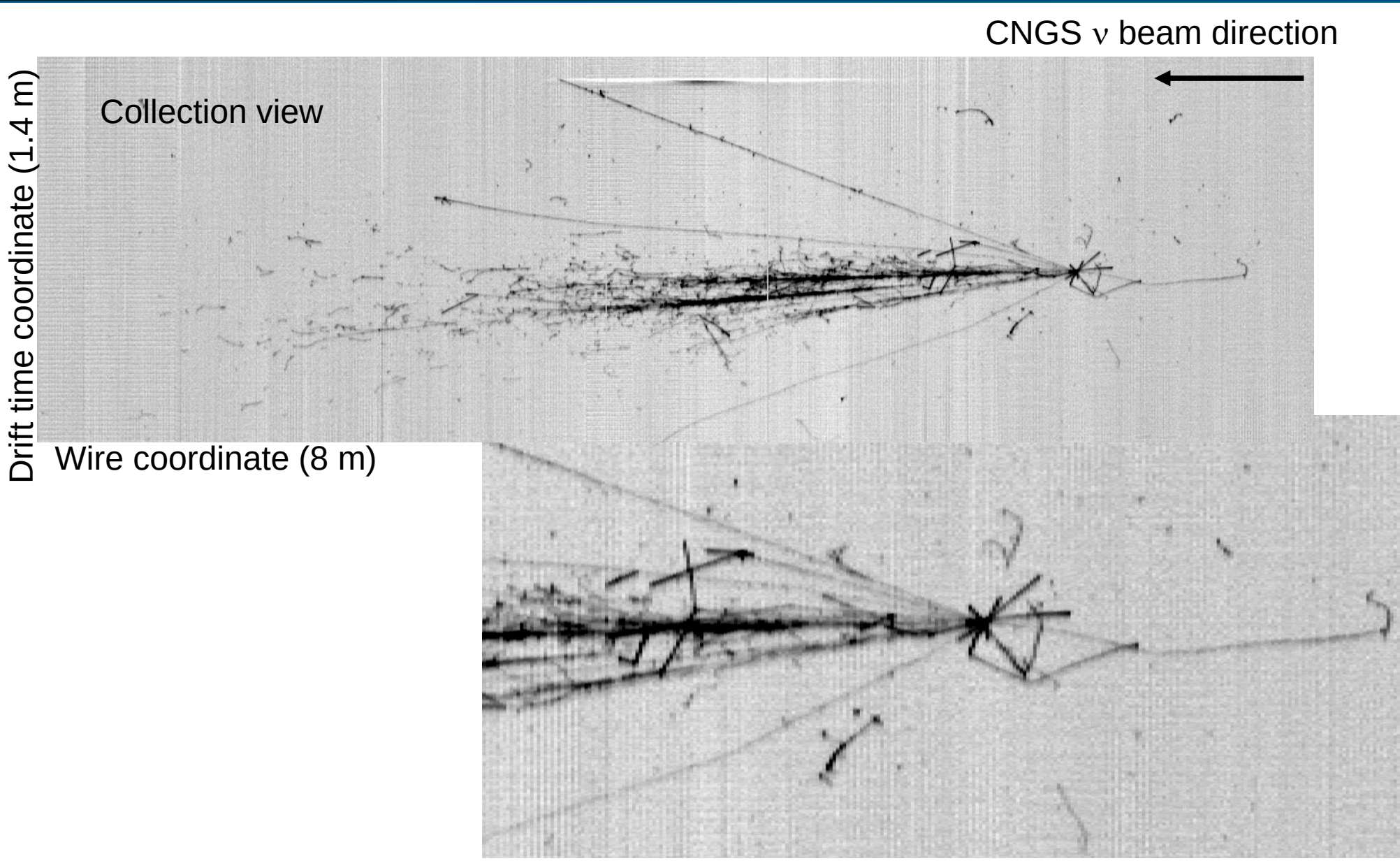
$\pi^0 \rightarrow 2\gamma$ event reconstruction and mass determination (E)



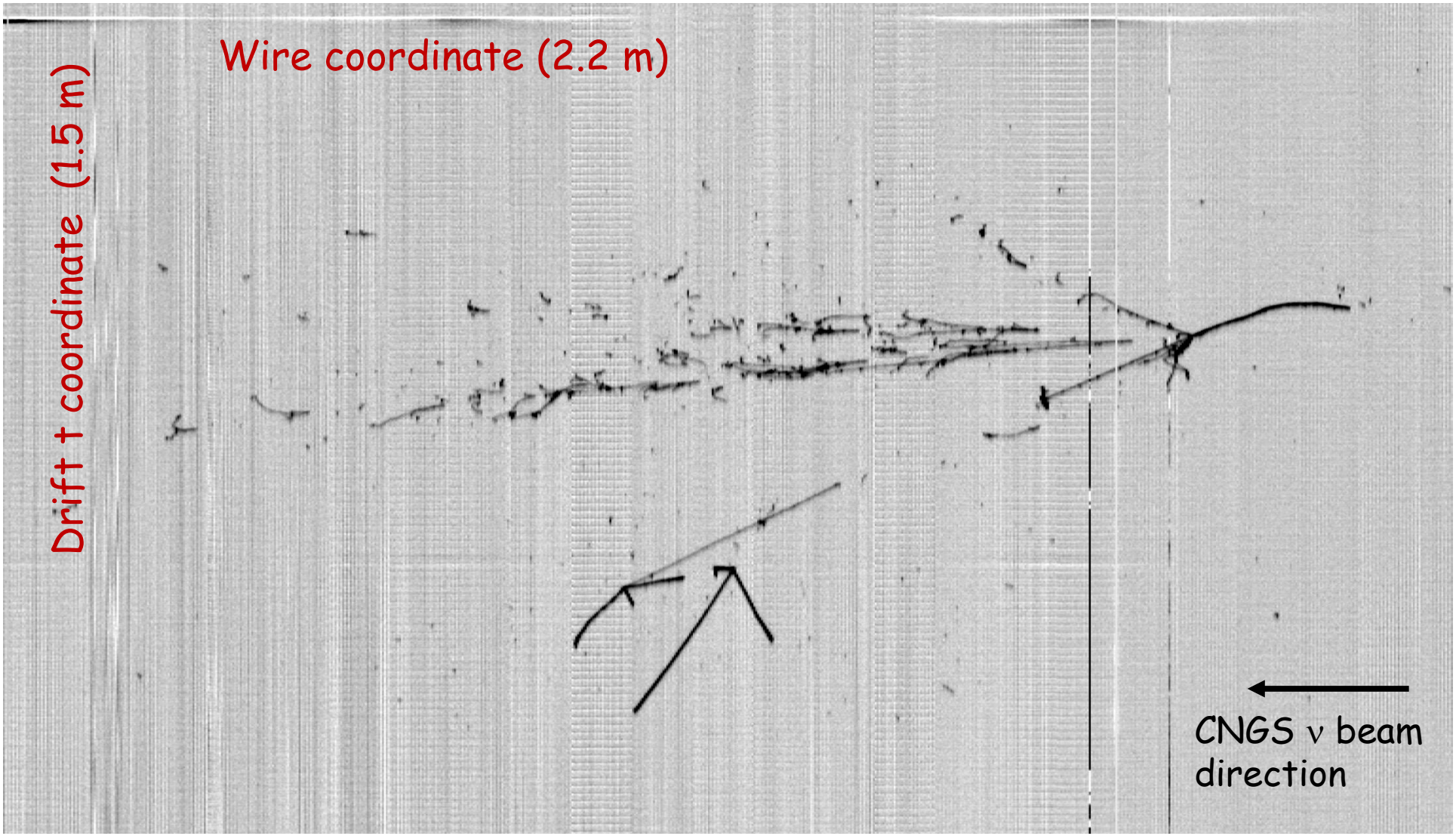


$m_{\gamma\gamma} = 133.4 \pm 3.0(stat) \pm 4.0(sys) \mathrm{MeV/c^2}$

CNGS neutrino interaction in ICARUS T600

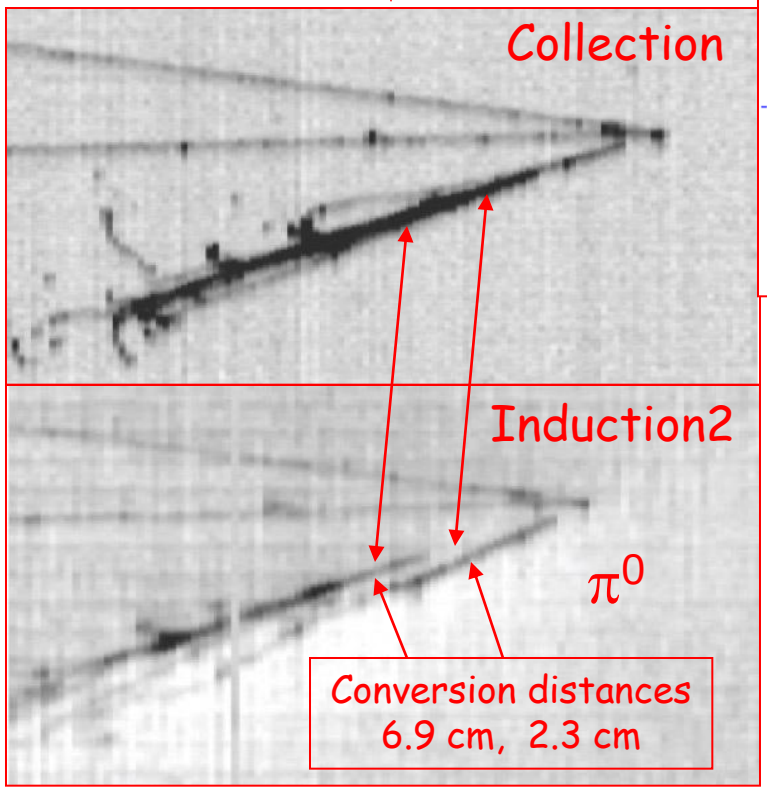


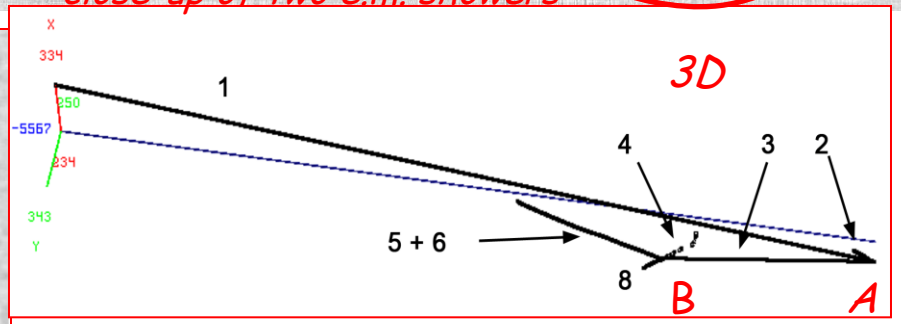
CNGS NC interaction



Run 9927 Event 572

close-up of two e.m. showers





Primary vertex (A):

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

Secondary vertex (B):

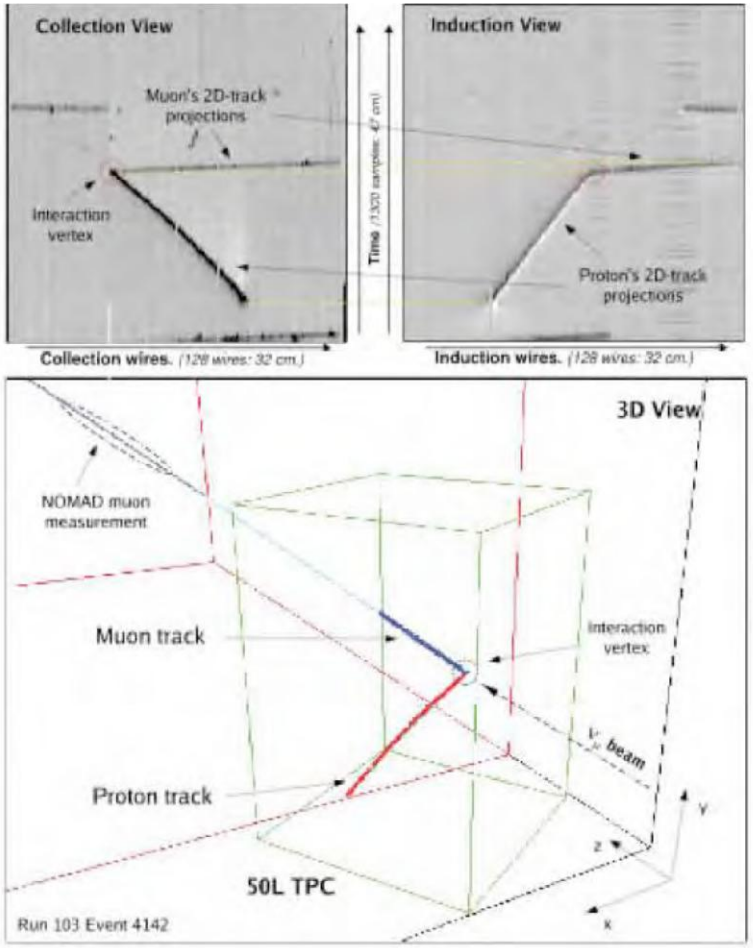
The longest track (5) is a μ coming from stopping **k** (6).

μ decay is observed

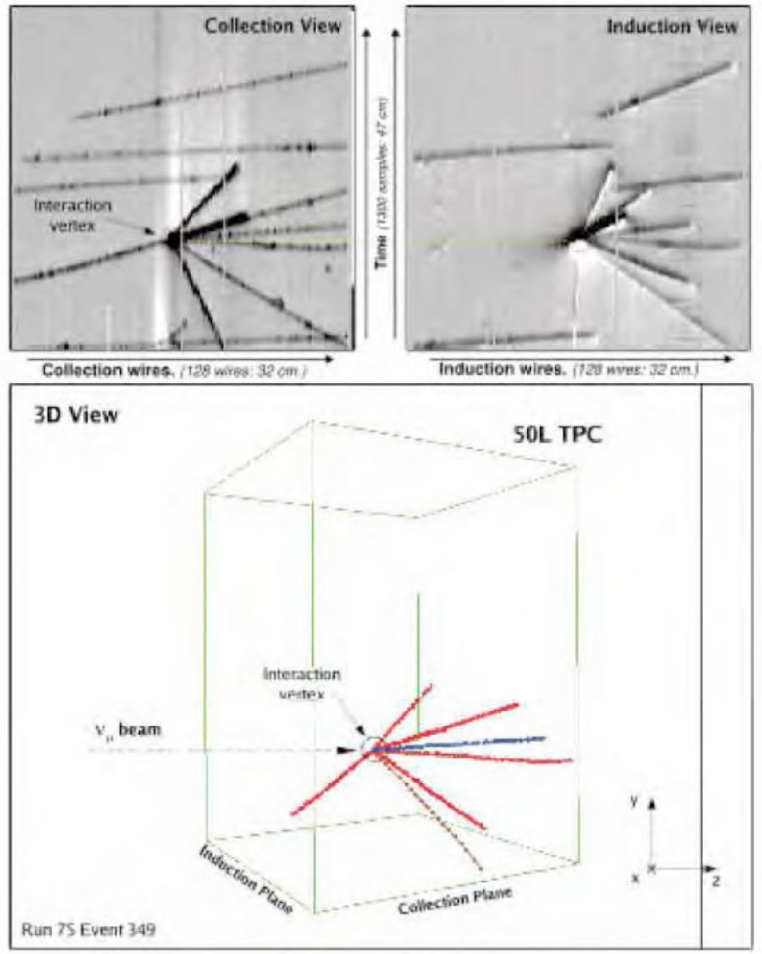
Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

neutrino events recorded in the LAr-TPC

- 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)

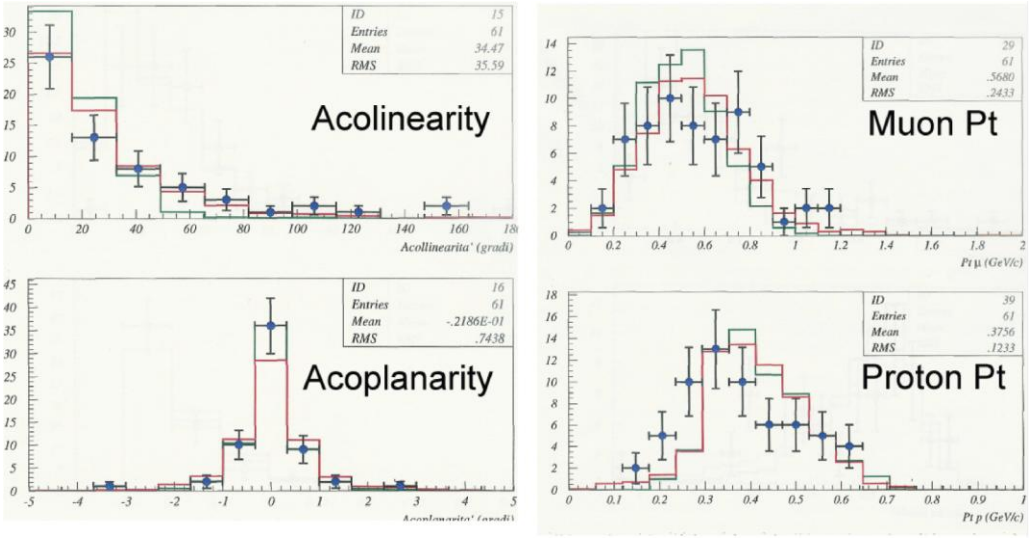


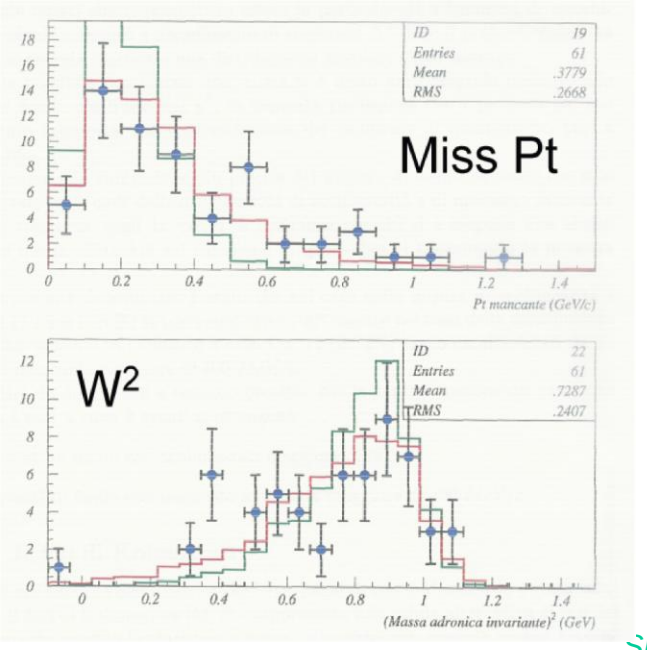
(B)

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.

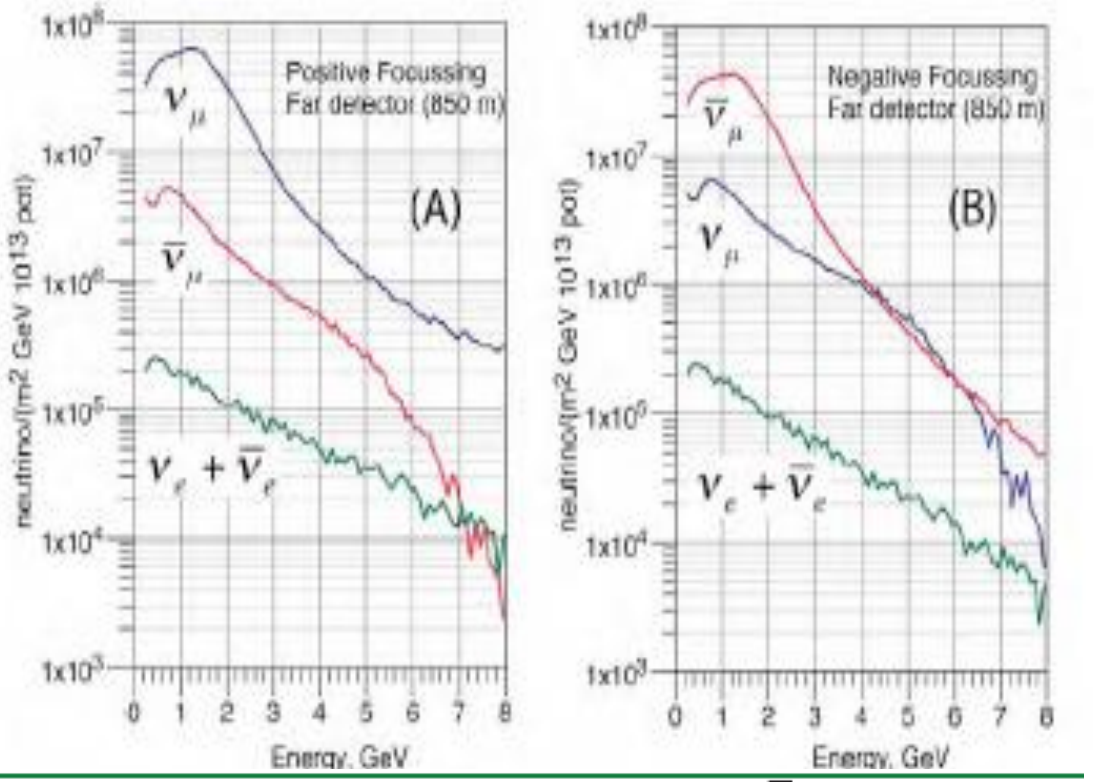




Expected CERN PS neutrino beam spectra

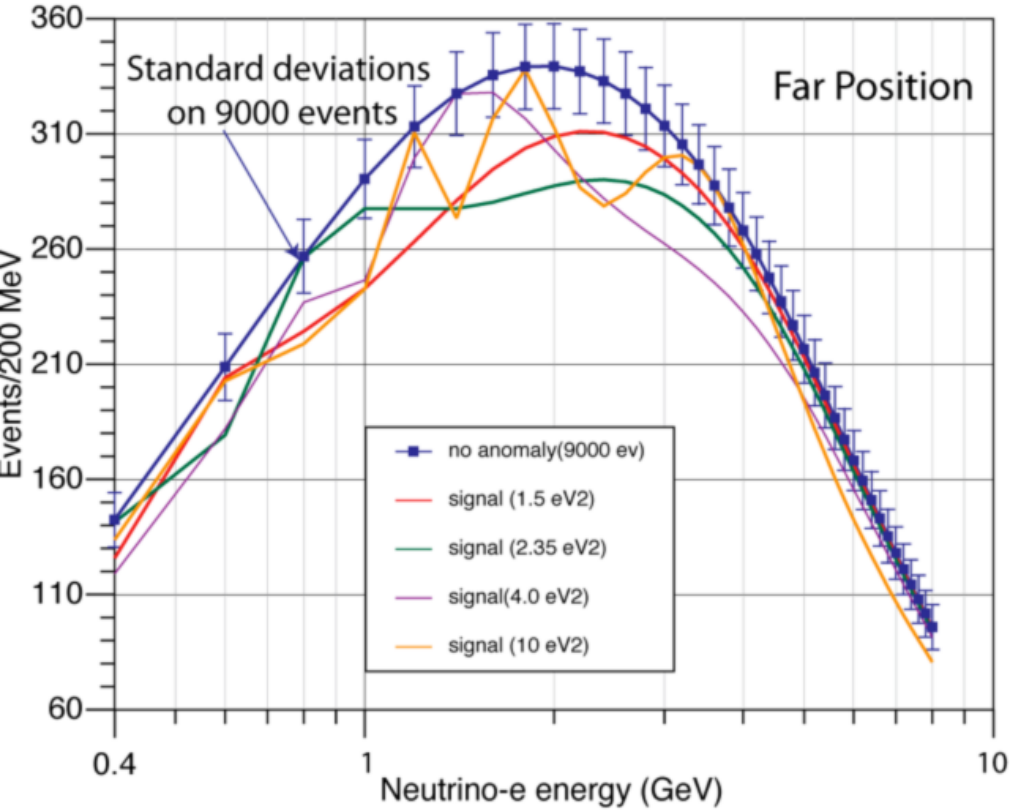
2 year PS neutrino beam T600 + T150 exposure for both neutrino (A) /antineutrino (B) mode with positive/negative meson focusing for different pot intensity:

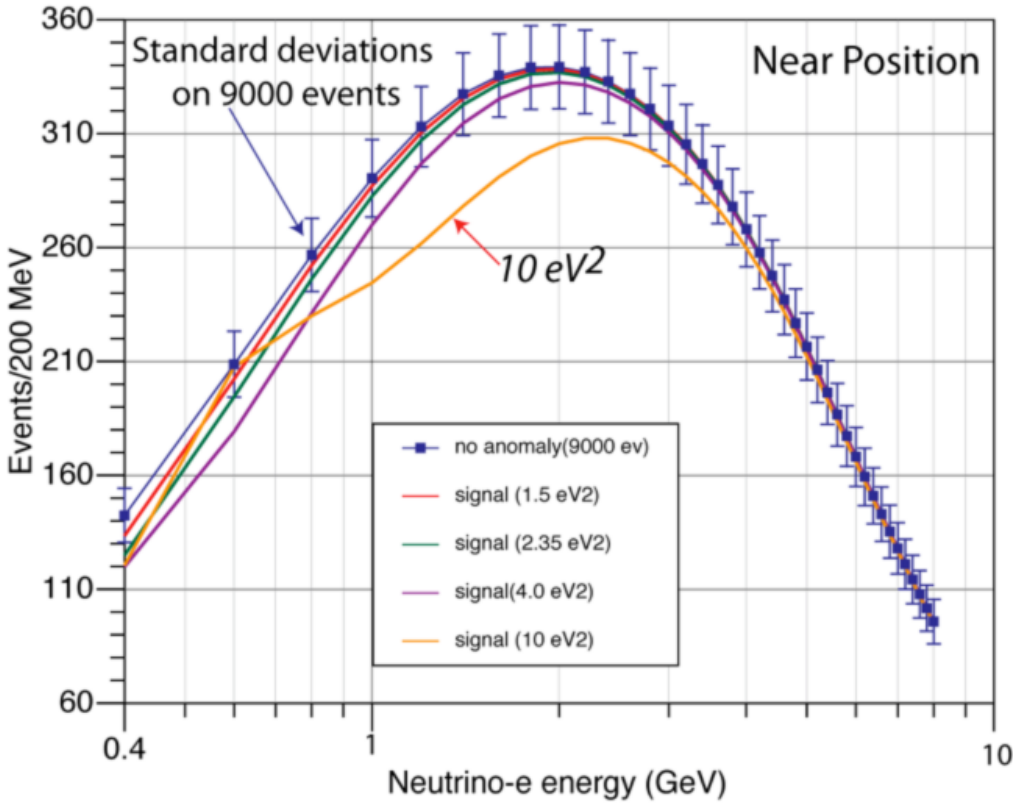
- 2.5 10^{20} pot - basic old "I216" option corresponding to only 30 kW beam power
- 7.5 10^{20} pot – upgraded PS option (90 kW)



	ν focus		ν̄ 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

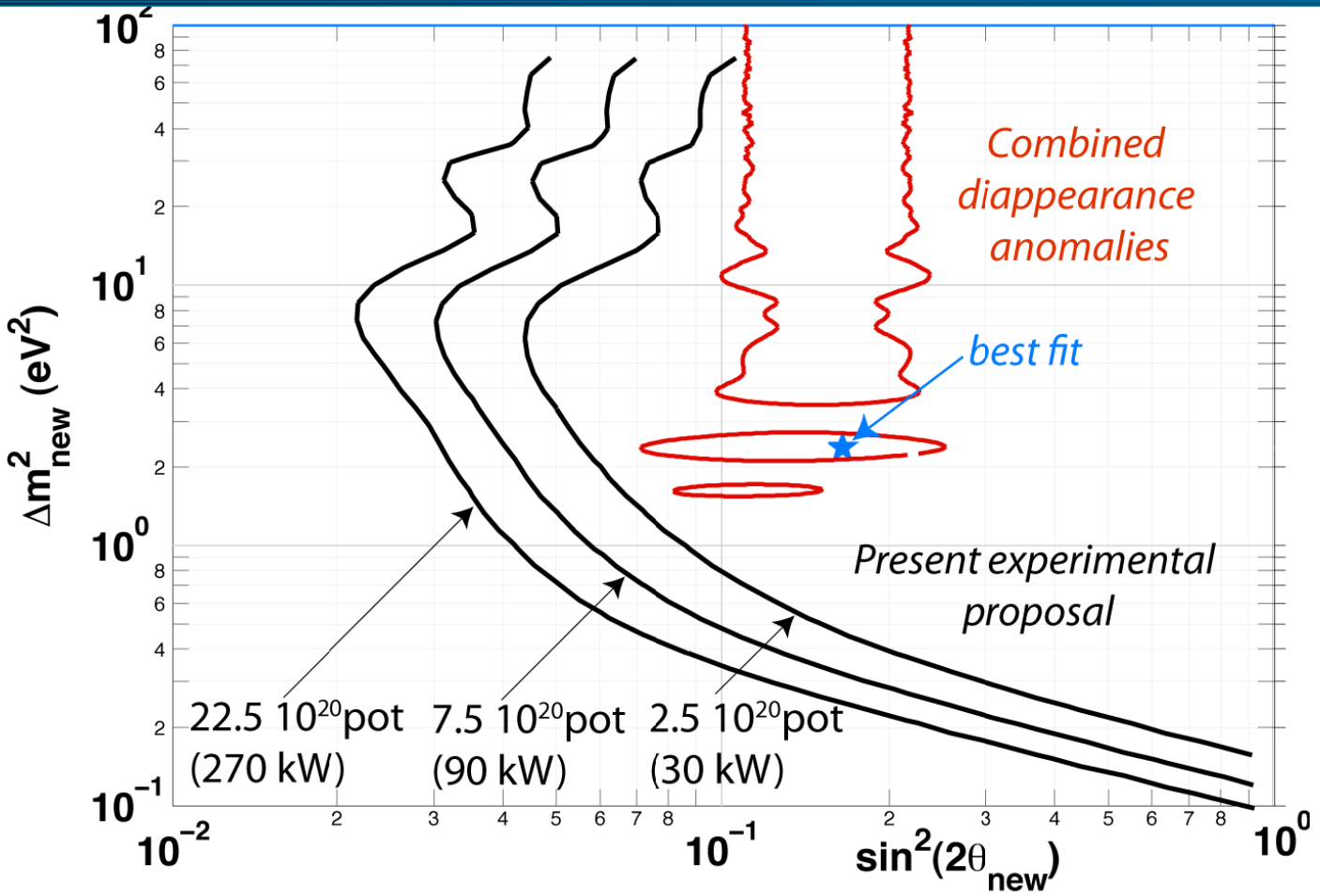
Sensitivity to νe (and νμ) disappearance signals





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).

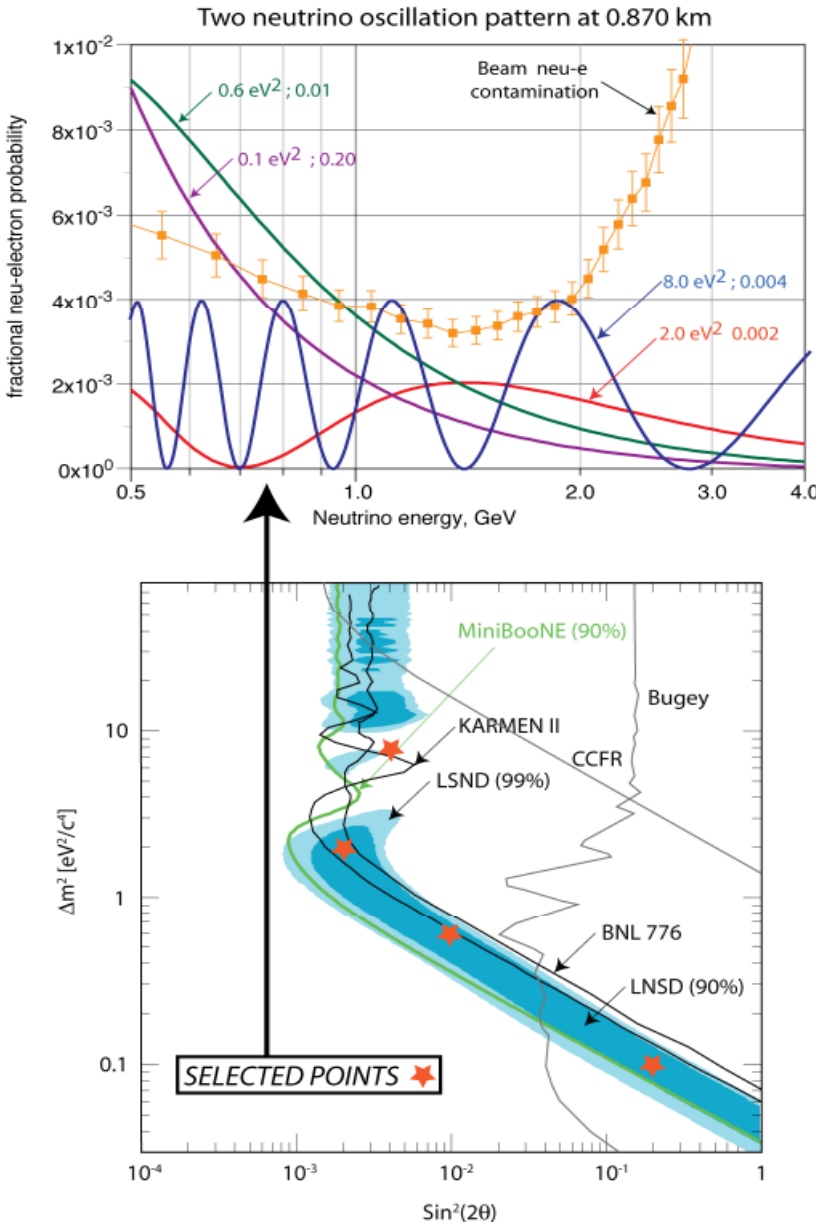
Expected signal for LSND/MiniBooNE anomalies

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

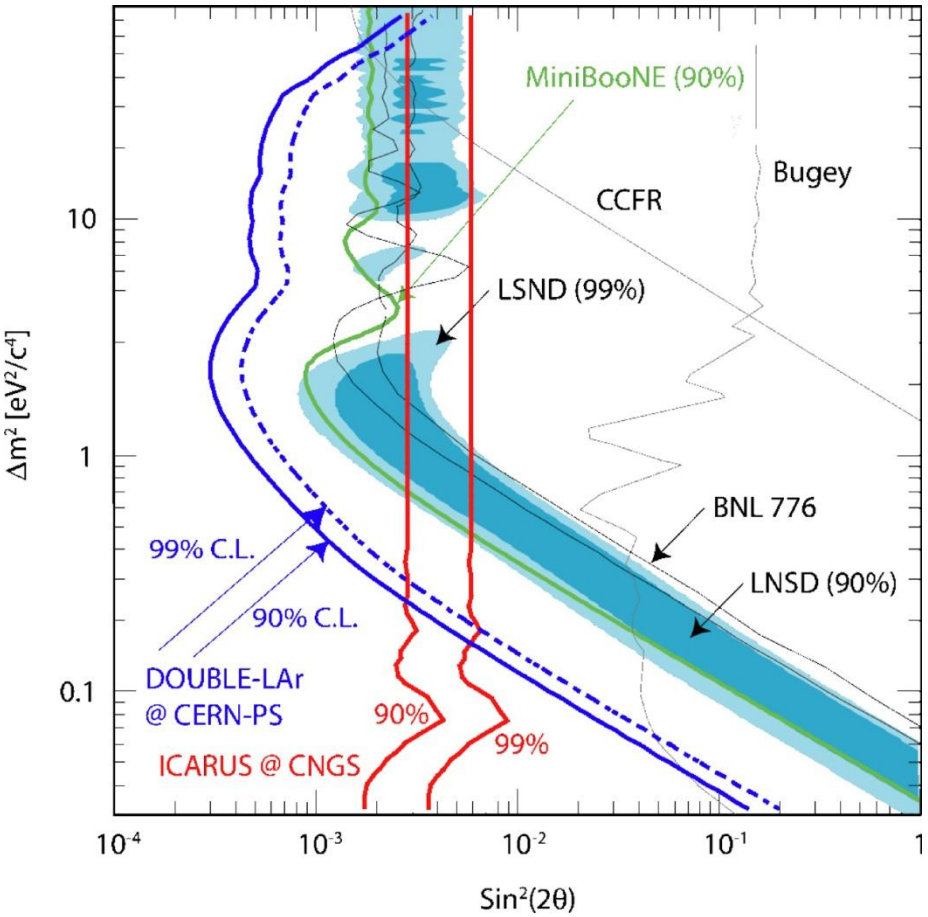
	ν focus		$\bar{\nu}$ focus	
	FAR	NEAR	FAR	NEAR
Fiducial mass	500 t	150 t	500 t	150 t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions (or $\bar{\nu}_\mu$ for $\bar{\nu}$ focus)	3.600E+6	5.400E+7	6.000E+5	6.900E+6
QE ν_μ (or $\bar{\nu}_\mu$) interactions	1.350E+6	1.980E+7	2.610E+5	3.000E+6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

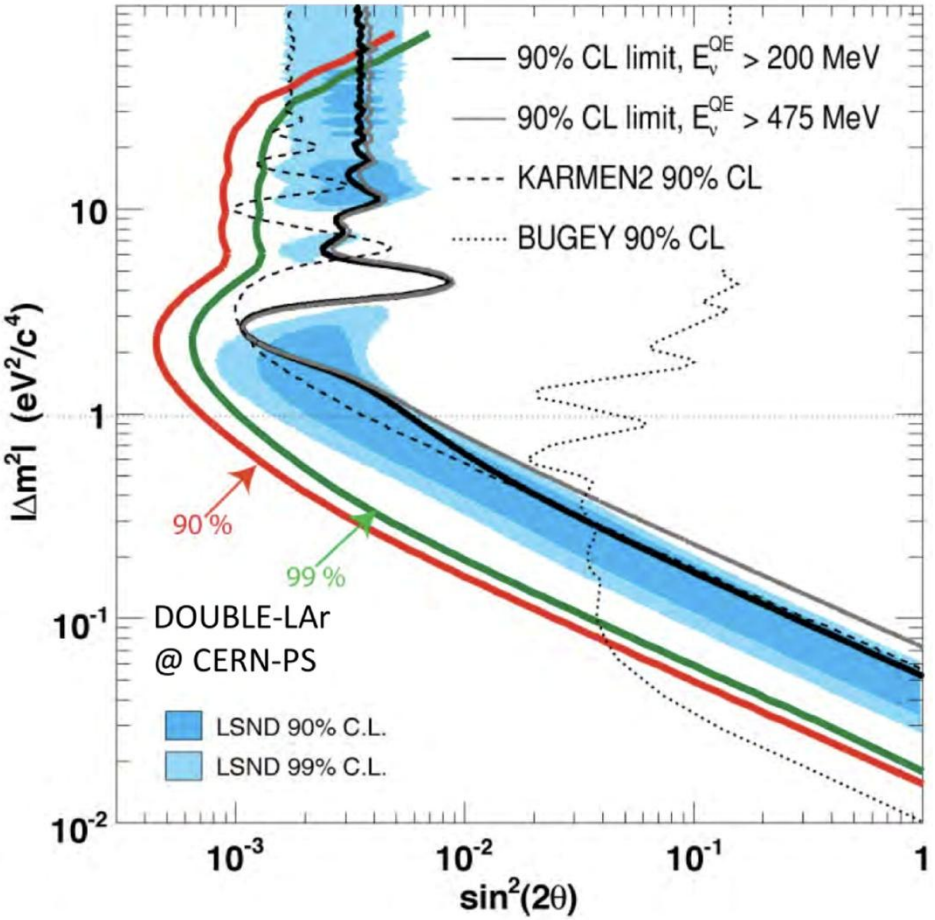
Determination Δm^2 and $\sin^2 2\theta$ values in $\nu\mu \rightarrow \nu e$ anomaly

- 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.

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 !