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

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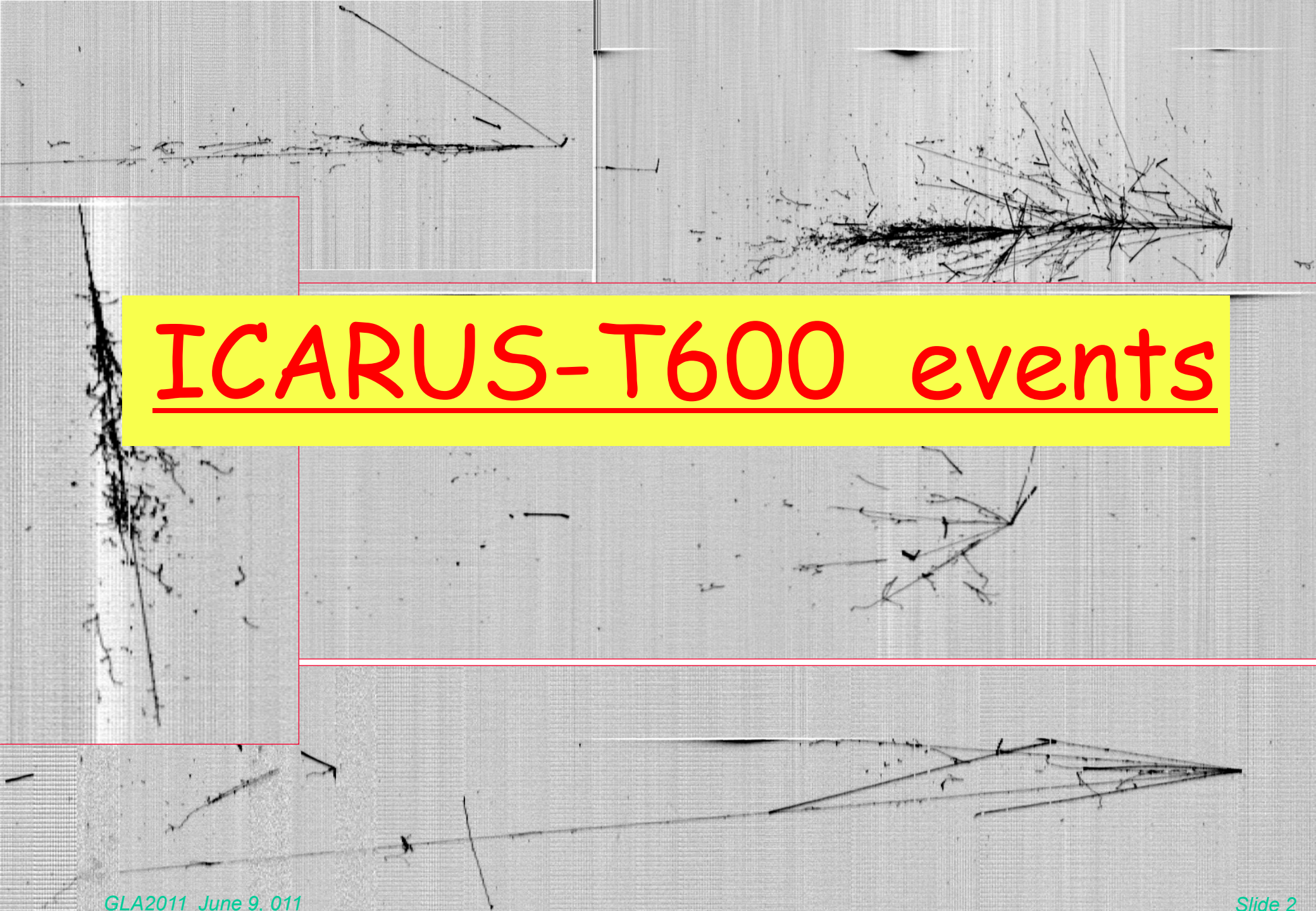
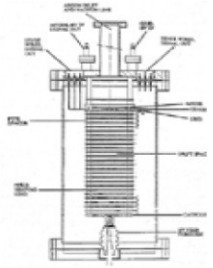


ICARUS-T600 events

The path of ICARUS to larger LAr detectors



CERN

24 cm drift wires chamber

1

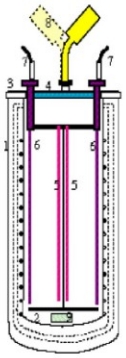
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

2

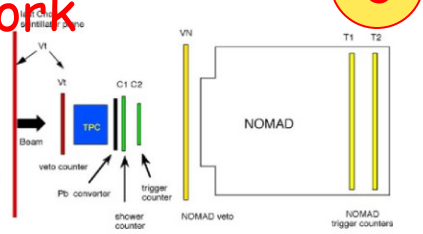
3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

CERN



Laboratory work



3

CERN

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

2010 - … : Data taking with CNGS beam

4

Pavia

T600 detector

10 m^3 industrial prototype

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

Cooperation with industry
AirLiquide, Breme, Cinel, CAEN

5

6

LNGS Hall-B

LAr-TPC requirements for LARGE detectors

- Cryogenic temperature
  - T = 88 K at 1 bar
  - high standards of technical reliability, stability and safety, UHV techniques

Cryogenic plant ✓

- High purity required for long-drift time
  - 0.1 ppb of O_2 equivalent for 3 ms drift

Argon purification ✓

- No signal amplification in liquid
  - 1 m.i.p. over 3 mm yields 20000 electrons equivalent noise charge 1200 electrons

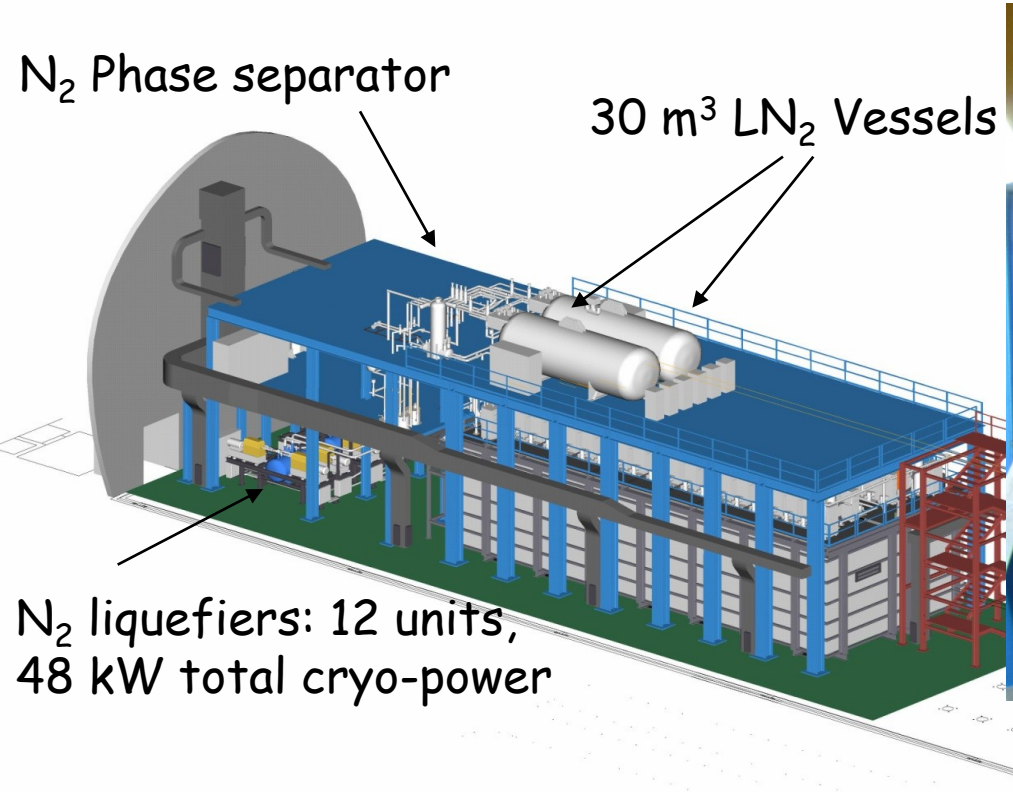
Low noise warm electronics ✓

- Self triggering
  - Prompt scintillation VUV light (128 nm) abundantly produced by ionizing events

PMT's with wave-shifter ✓

ICARUS-T600 fulfillments:
0.77 kton LAr-TPC @ LNGS

ICARUS-T600 @LNGS: 0.77 kton LAr-TPC

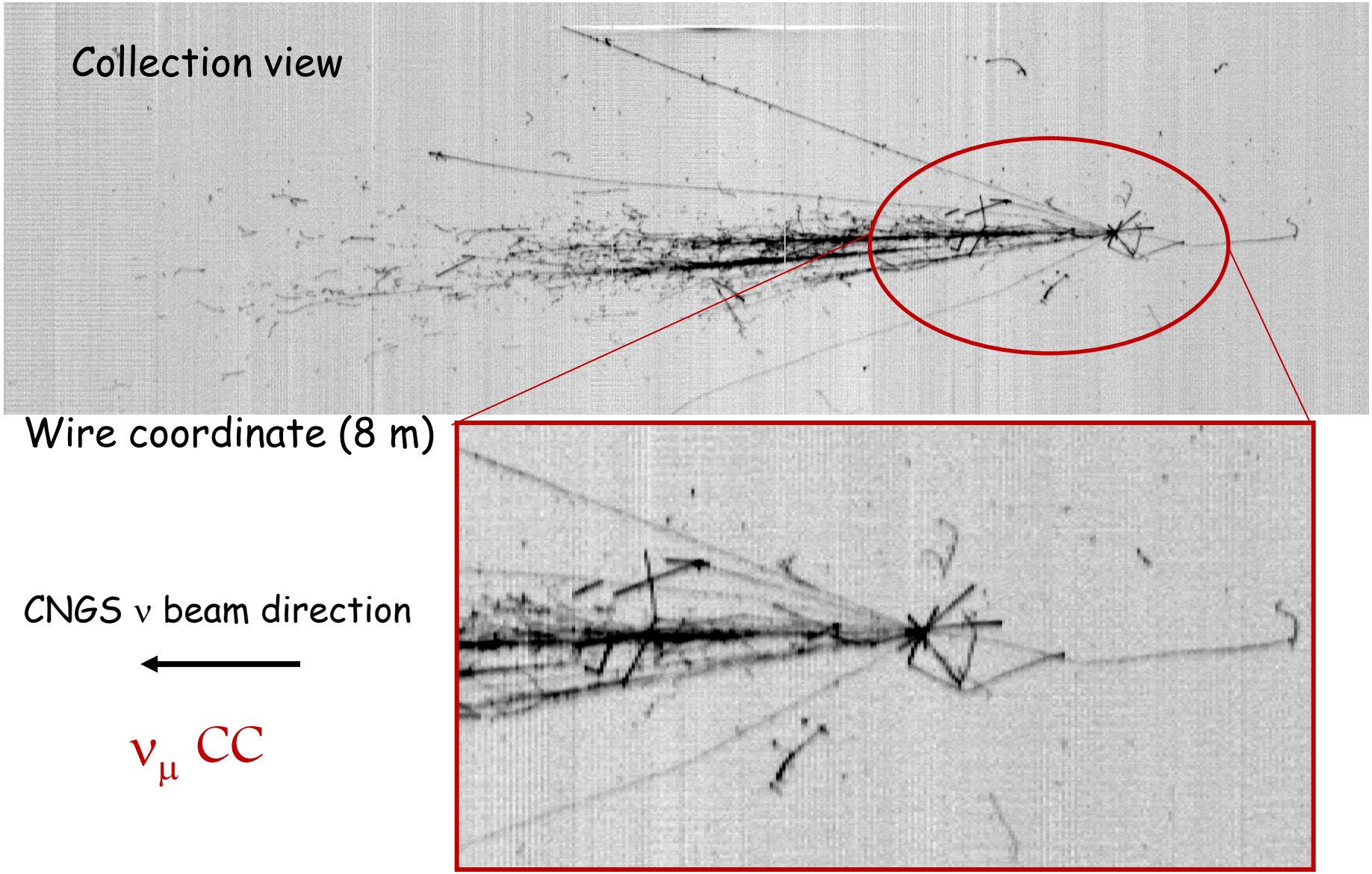


Detector activated on 27 May 2010

Optimization phase in summer 2010

Data taking in stable condition since 01 Oct.

First CNGS neutrino interaction in ICARUS T600

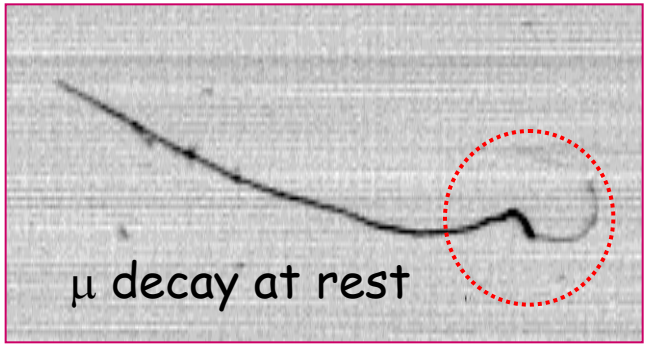


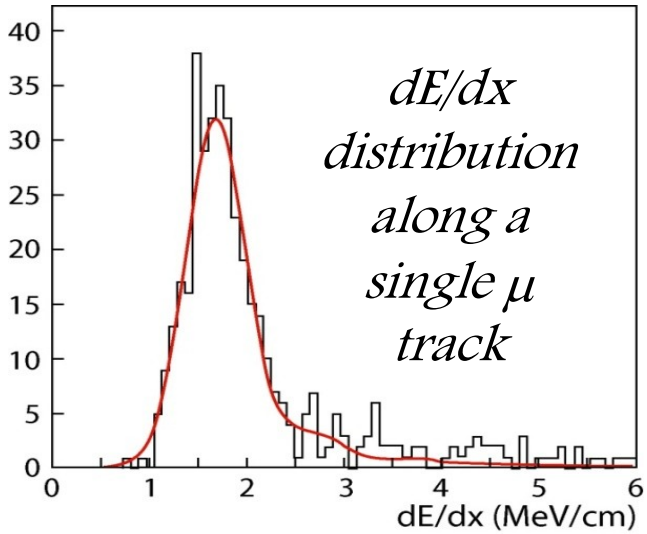
ICARUS-T600 LAr-TPC performance - 1

- Tracking device:
  - precise event topology ($\sigma_{x,y} \sim 1$mm, $\sigma_z \sim 0.4$mm)
  - μ momentum measurement via multiple scattering: $\Delta p/p \sim 10$-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 retaining 90 % ν_e CC

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





RESOLUTIONS

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

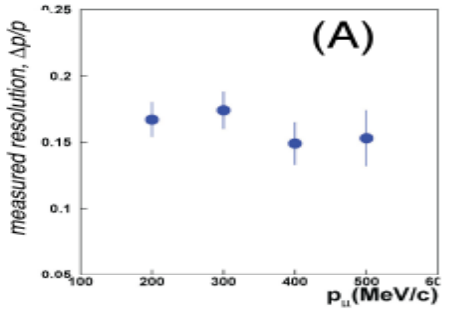
Electromagnetic showers: $\sigma(E)/E = 3\%/\sqrt{E(\text{GeV})}$

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

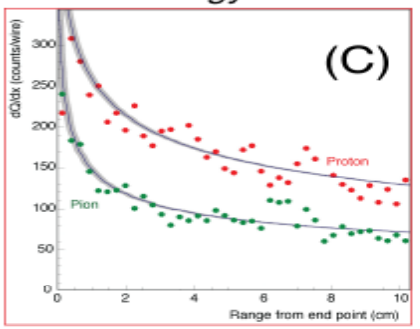
ICARUS-T600 LAr-TPC performance -2

(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.

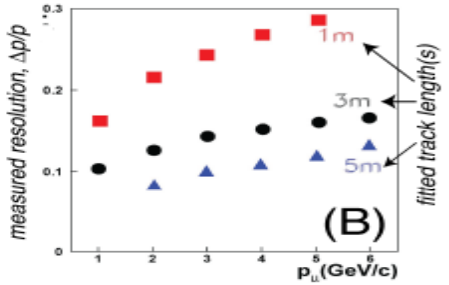
stopping muons



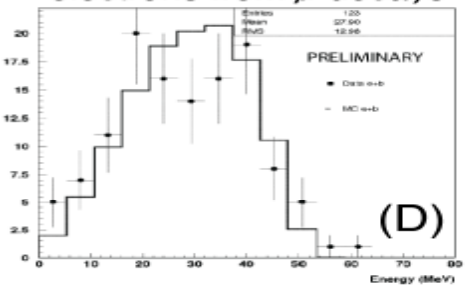
dE/dx energy losses



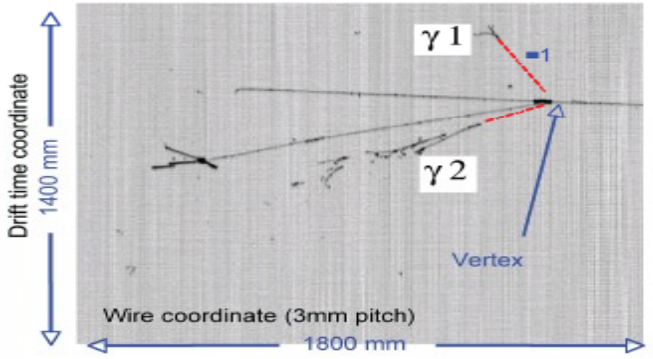
traversing muons
Kalman filter on segmented track

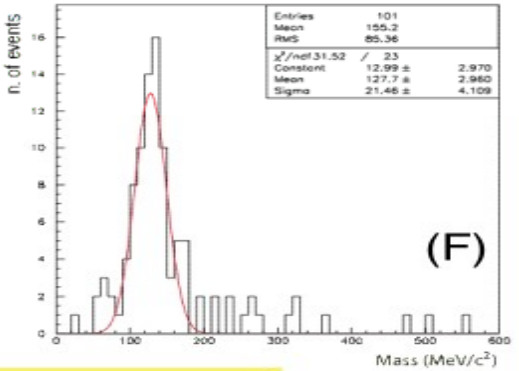


electrons from μ decays



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





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

Addressing new interesting neutrino physics with LAr-|TPC

- ICARUS T600 @LNGS is a **major milestone** towards realization of a large scale LAr detector: a unique imaging capability, spatial/ calorimetric resolutions and e/π^0 separation $\rightarrow$ **events "seen in a new Bubble chamber like" way**. CERN will provide 2 years full intensity neutrino beam for long baseline oscillation searches before the foreseen 2013 accelerator stop.
- Meanwhile a number of *"neutrino anomalies"* are emerging suggesting the presence of an additional, large squared mass difference in the framework of additional neutrinos with mixing or of other effects. These sterile neutrino hints can be addressed with a new high precision short baseline neutrino oscillation programme relying on LAr-TPC detection technique.
- ICARUS-T600 can be transported to CERN for a dedicated exp. on sterile neutrinos exposed at refurbished PS neutrino beam starting data taking in 2014.

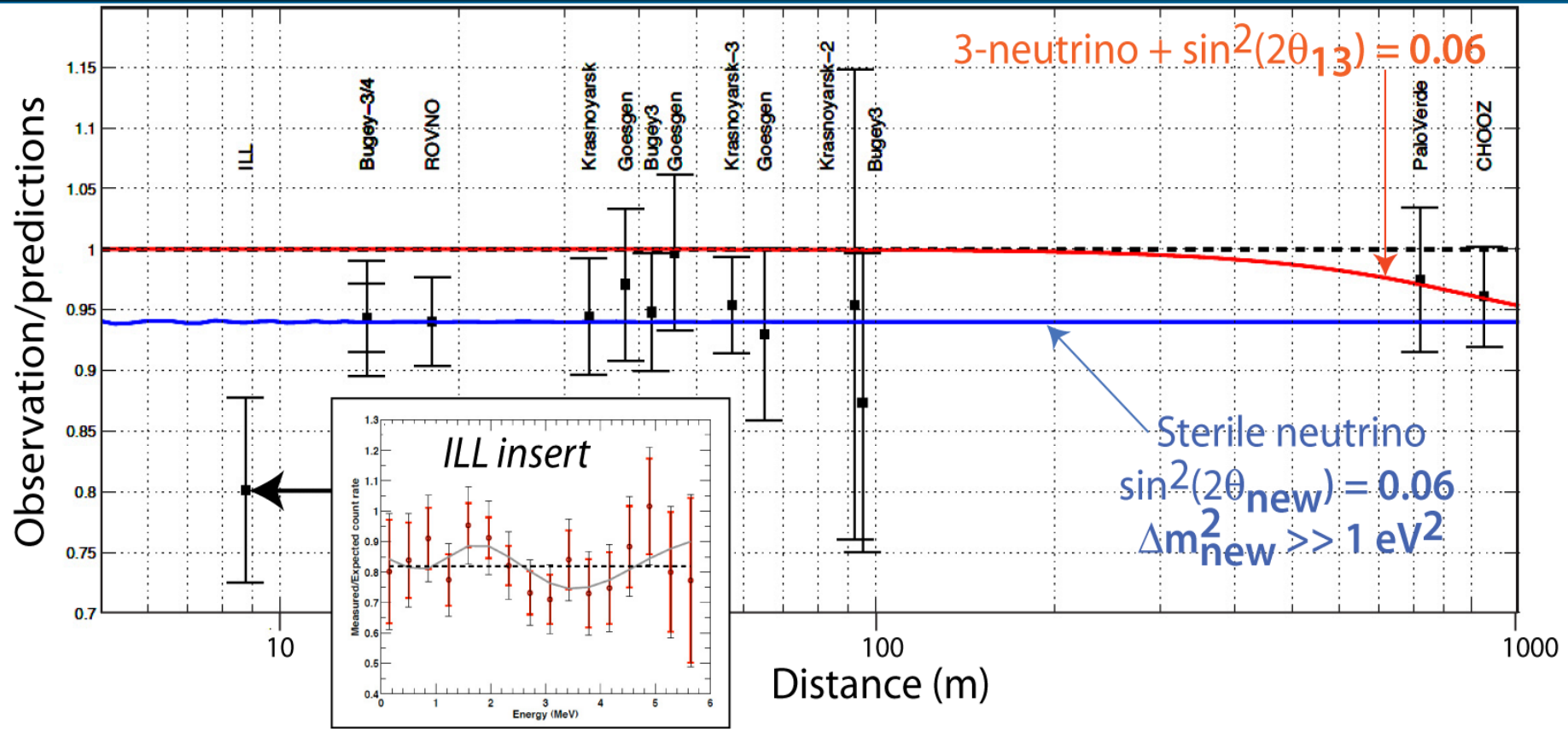
Neutrino oscillation "anomalies": sterile neutrino hints

- 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 Mega-Curie k-capture ^{51}Cr and ^{37}Ar calibration sources in Gallium SAGE/GALLEX solar ν_e experiments, i.e. detected/predicted ν rate ratio $R = (0.86 \pm 0.05)$, 2.7σ away from $R = 1$
  - observation for *excess signals* of ν_e electrons from neutrinos from particle accelerators (LNSD/MiniBooNE)

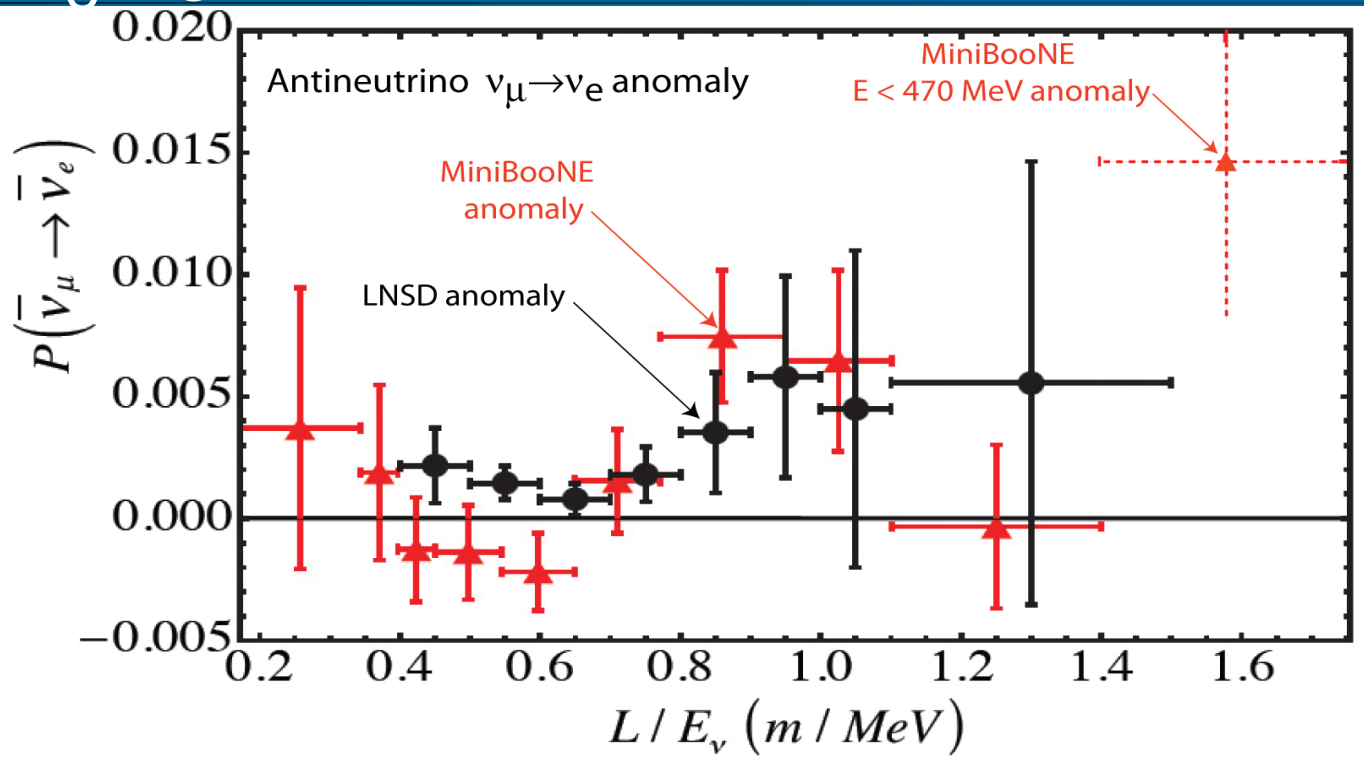
- These experiments may all point out to possible existence of a fourth non standard neutrino state driving oscillations at small distances with $\Delta m^2_{new} \geq 1\ eV^2$ and relatively large mixing angle $\sin^2(2\theta_{new}) \approx 0.1$.
- The existence of a fourth neutrino state may be also 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 compared to predictions without oscillation taking into account new spectrum calculation, 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 $\Delta m^2_{new} \gg 1$ eV² and $sin^2(2\theta_{new}) = 0.06$.

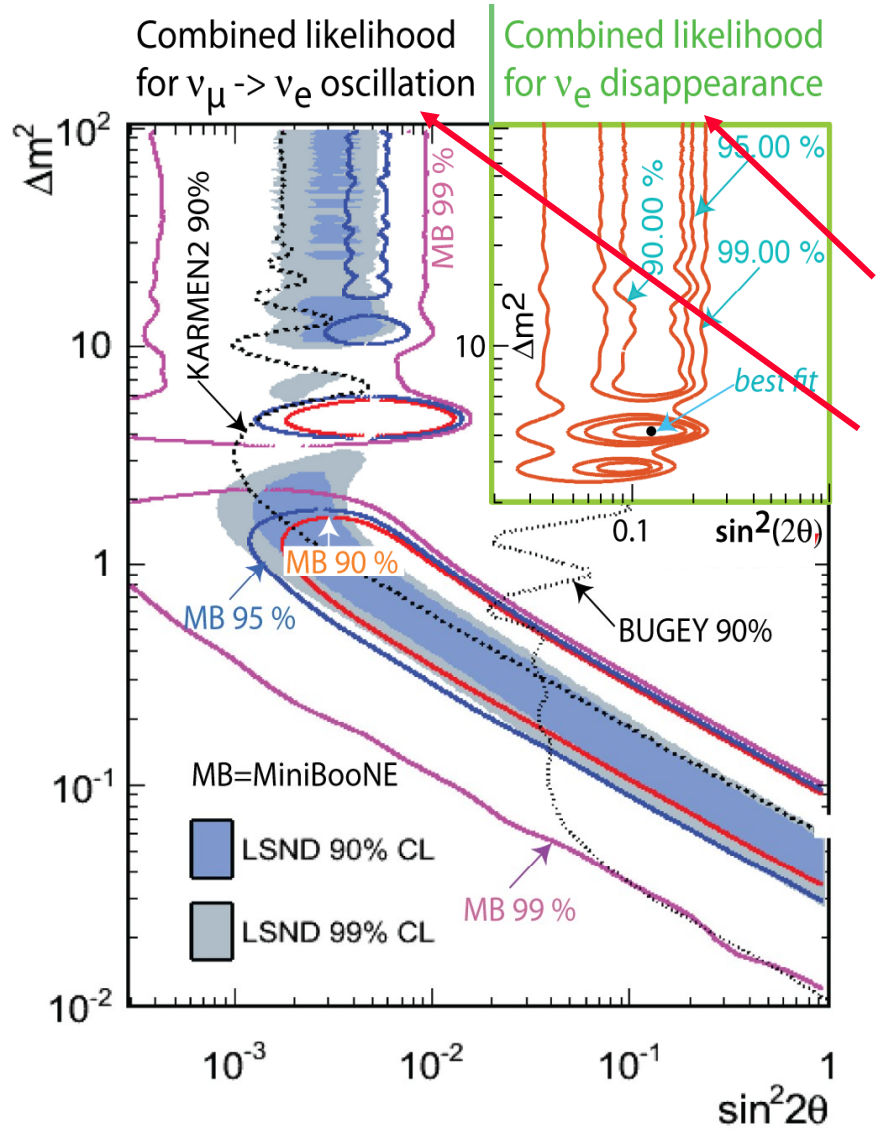
Excess ν_e signal: The LSND/ MiniBooNE anti-neutrinos



G.Mills, ICHEP, July 2010

- The 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 LNSD expectations which, as well known, was originally dominant in the antineutrino channel.

A unified approach ?



Allowed regions in the parameter plane for combined results:

νe disappearance rate (right)

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, e.

In addition: tension between νe and antiνe data: CPT violation hints (MINOS) ?

The LAr TPC at the CERN-PS

- The direct, unambiguous measurement of an oscillation pattern requires necessarily the (simultaneous) observation at different distances. It's only in this way that the values of Δm^2 and $\sin^2(2\theta)$ can be separately identified.

- The present proposal at 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 ν_μ, ≈10^4 ν_e);
  - Both initial ν_e and ν_μ components cleanly identified.

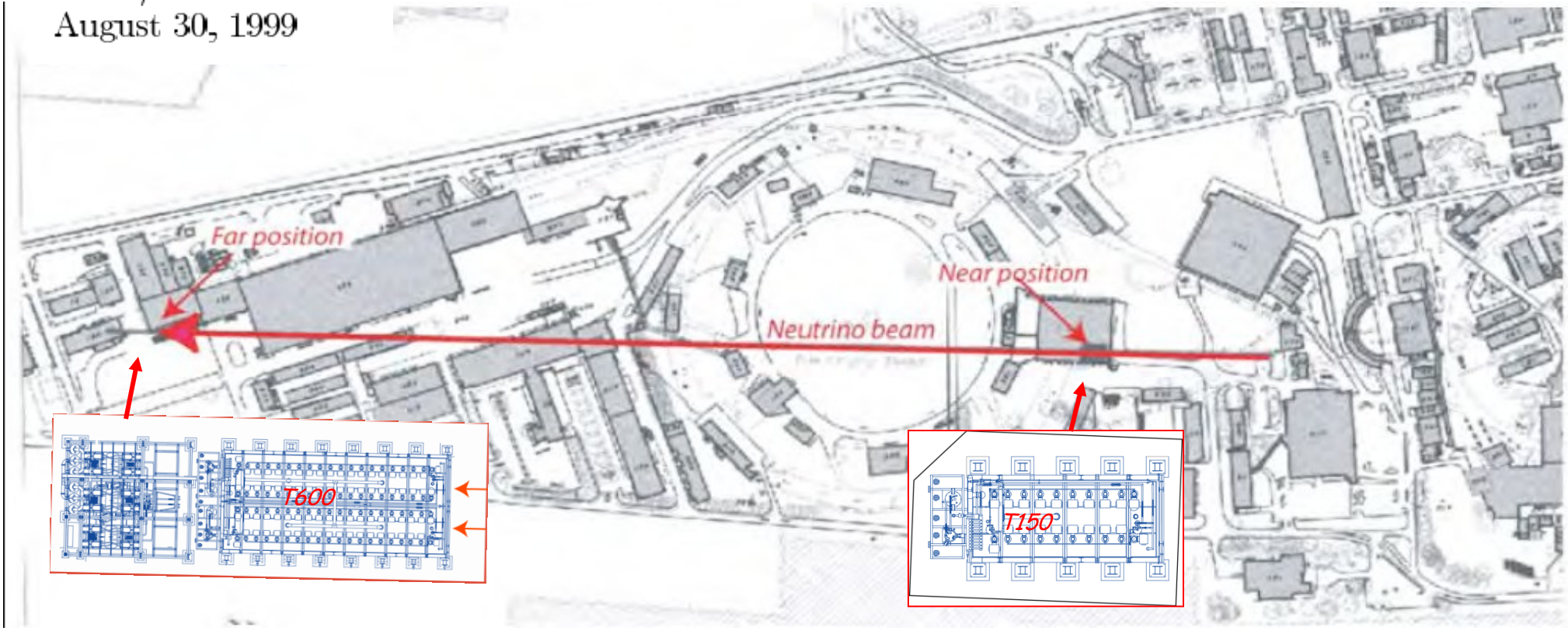
Basic features of the proposed experiment

- 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 may be 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.

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 target: L/E ~ 1 km/GeV;
The additional detector/new location at 127 m from 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 distances*, at "Far/Near" locations, respectively at 850 m & 127 m away from the source.

- "Far" detector : ICARUS T600, the largest liquid Argon TPC ever built and now perfectly operational in underground Hall B LNGS in a neutrino beam from CERN-SPS, collecting data as CNGS2 experiment.

- "Near" detector: to be constructed anew, 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.

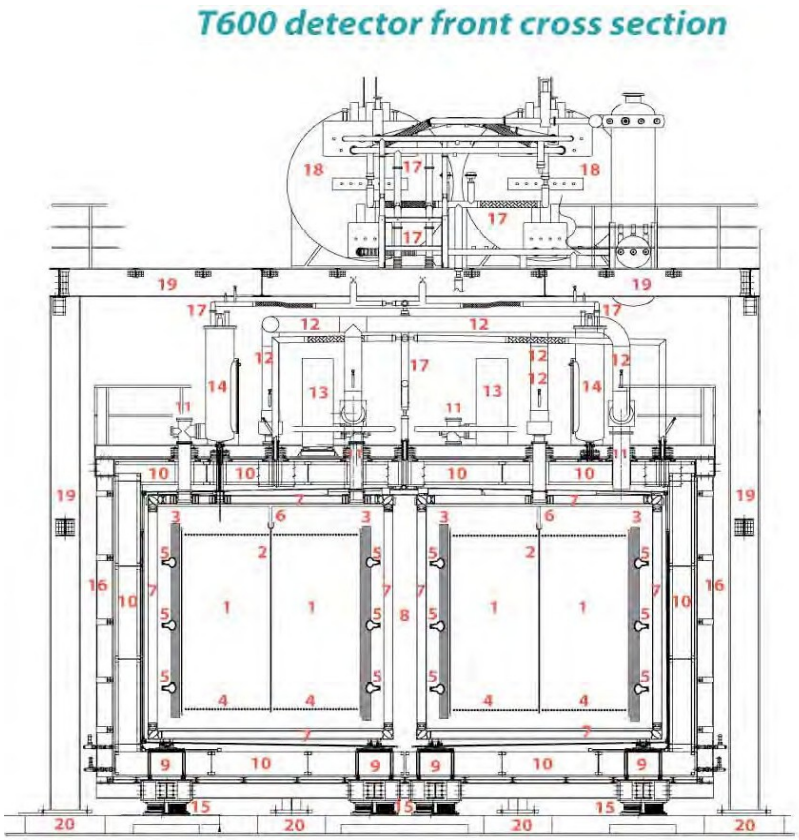
T600 transport from LNGS to CERN and T150 construction

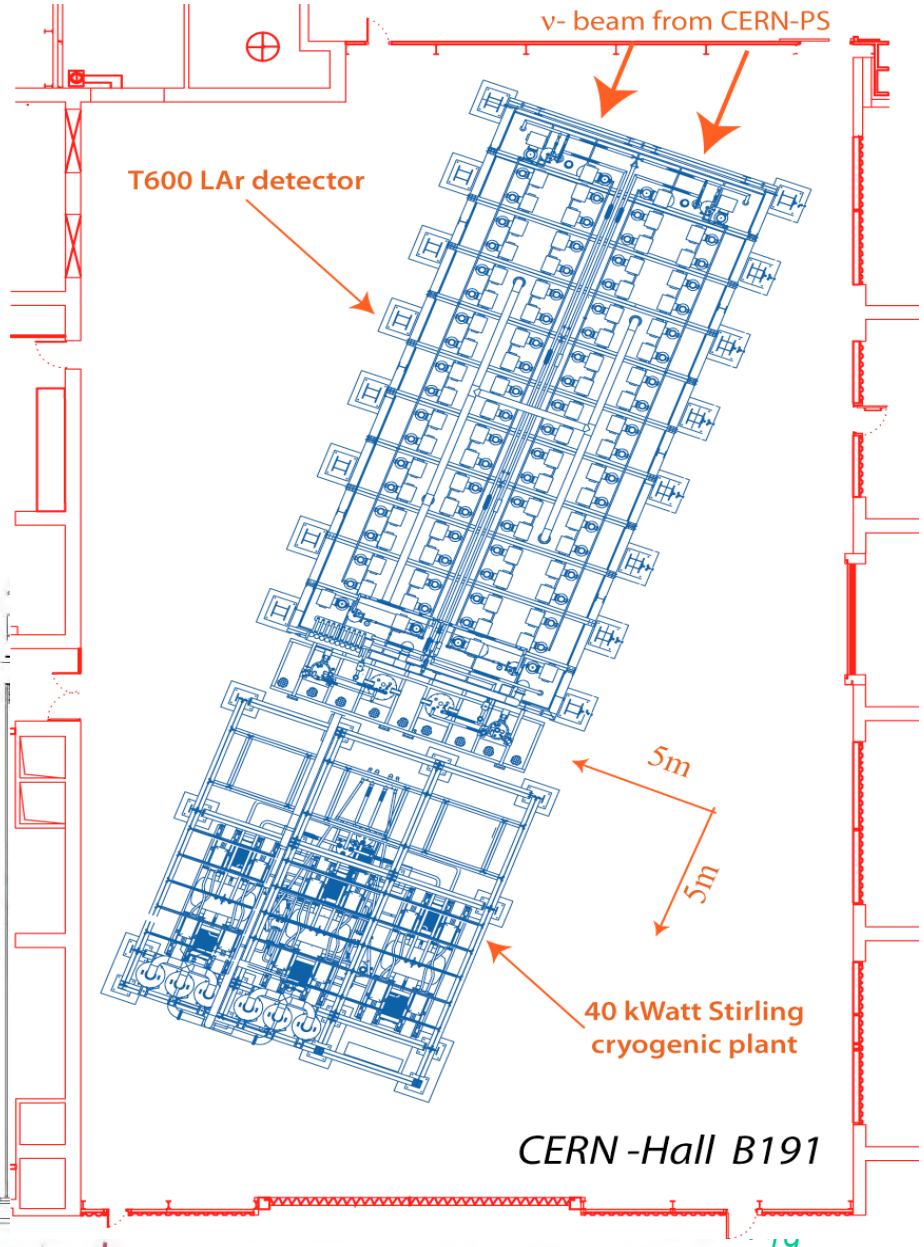
- T600 can be transported to CERN in 2013, after the CNGS programme completion , ensuring the new experiment operation again in 2014

- The 2 sub-modules can be extracted from thermal insulation, dismounted,transported and reconstructed in Hall B-191 in 12-14 mounths;
- A large number of components can be disassembled/transported: electronics for DAQ, ancillary systems located in 3 levels of the supporting structure surrounding T600 and LN_2 liquefaction system.
- Same wire chambers mechanics / existing wiring infrastructures can be used for the T150 Near Detecor construction in 2/3 year timescale.
- Cryogenics, PMTs, front-end electr.s, DAQ and ancillary equipments, can be replicated according to the downscaled detector mass: one GAr/ 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

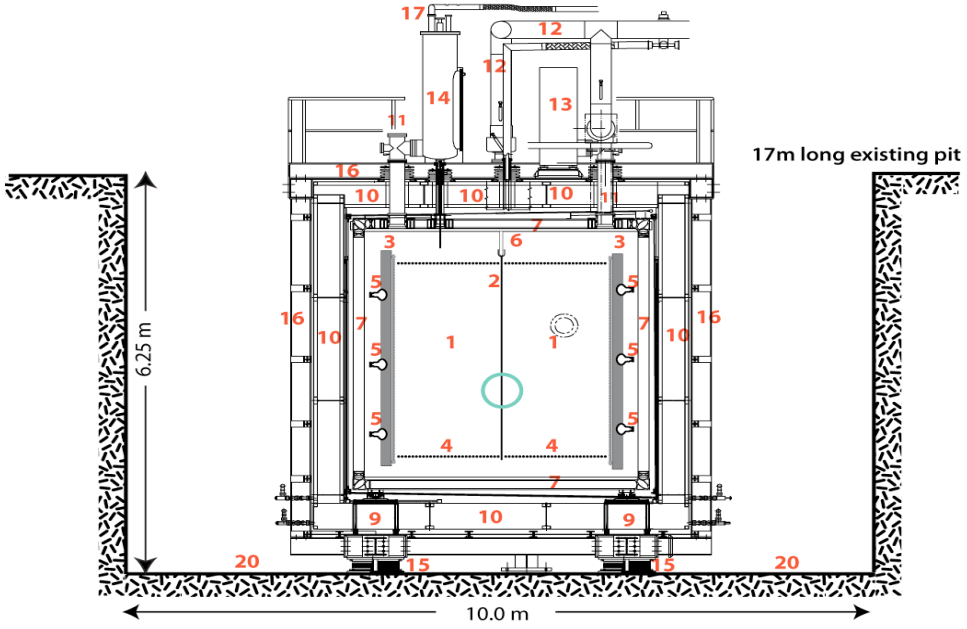
- The T600 detector could be moved and operated at CERN in the old BEBC experimental hall (Hall 191) without major modifications.

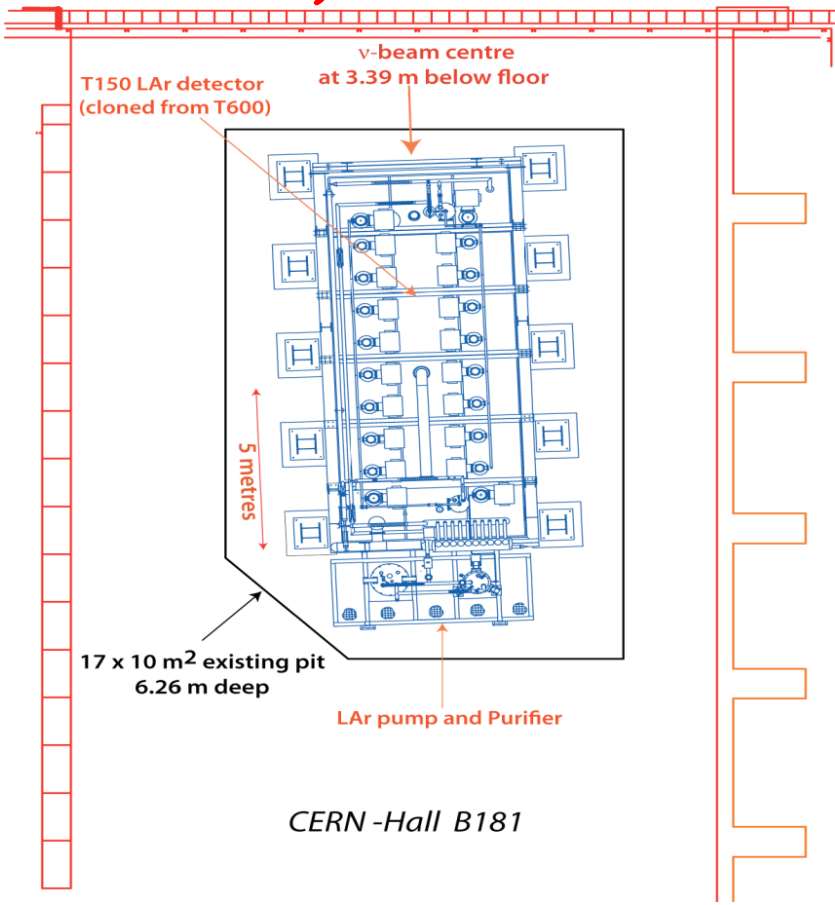




The additional T150 detector (to be constructed)

- 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.

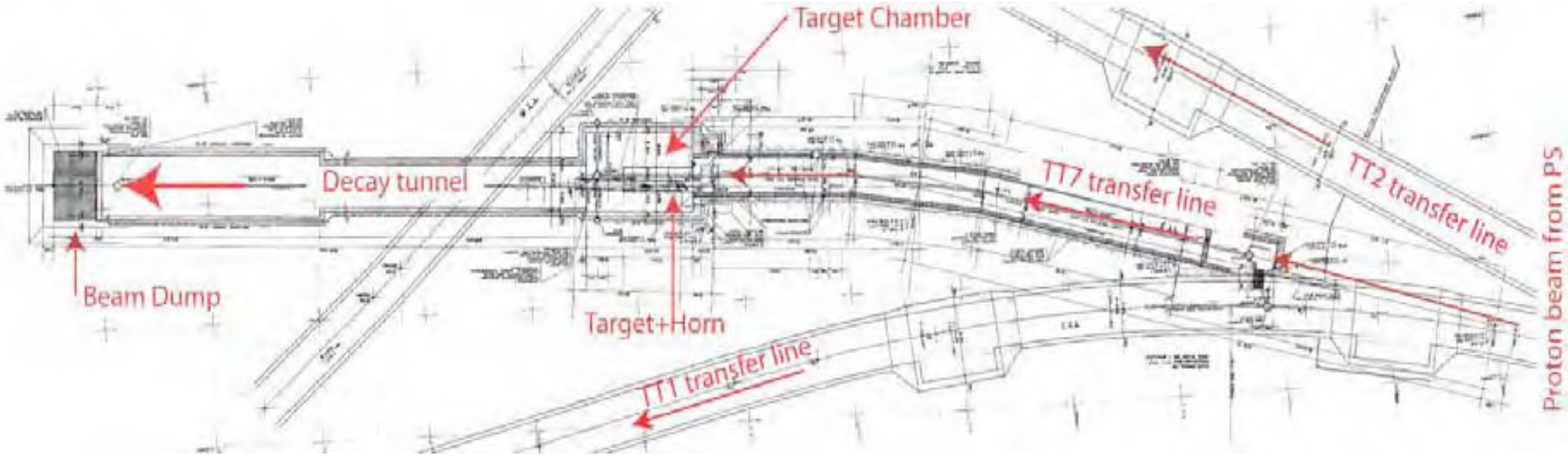




Refurbishing the old line used by BEBC

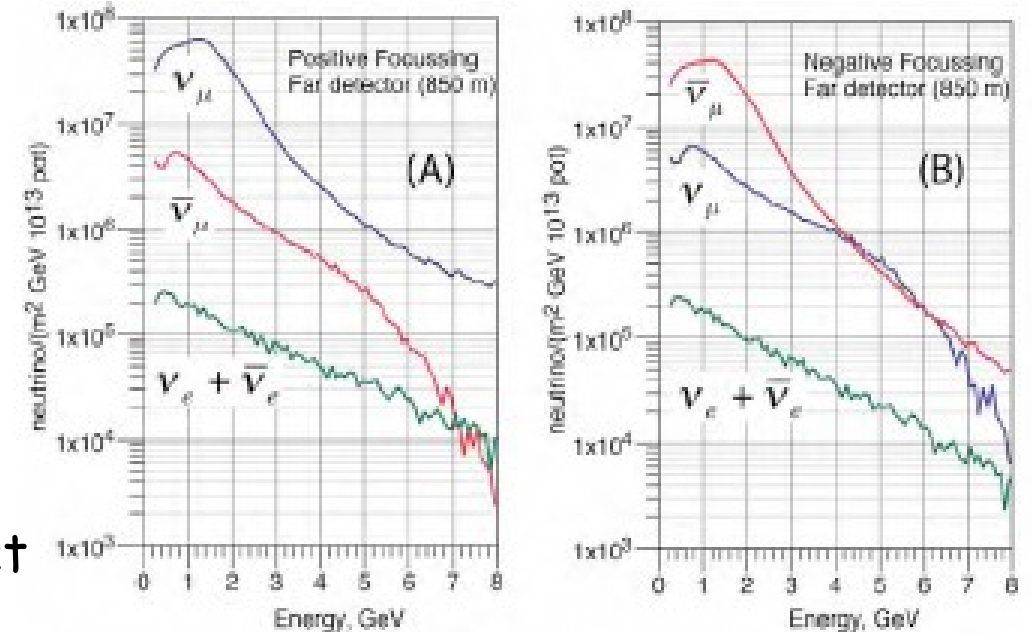
- The PS proton beam at 19.2 GeV/c is extracted via TT2, TT1 and TT7
- The magnetic horn is designed to focus particles of momentum≈3GeV/c
- The decay tunnel is about 50 m long, followed by an iron beam stopper

PS-180 $\nu\mu \rightarrow \nu e$ (BEBC)



Expected CERN PS neutrino beam spectra and rates

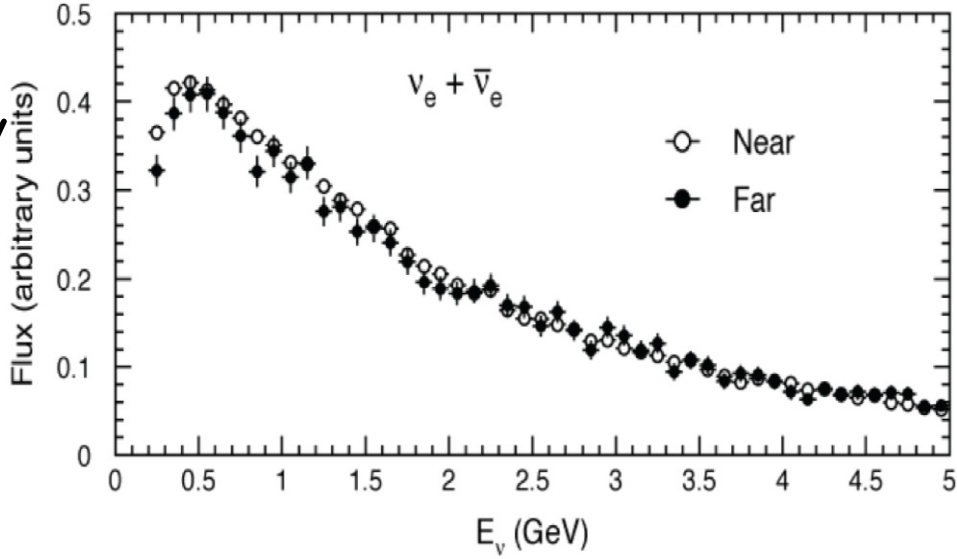
- Starting point: PS-180 experiment and I216/P311 proposal;
- 19.2 GeV protons -1.25 10^{20} pot/y (30 kW average power only!);
- 2 year PS neutrino beam exposure for both neutrino (A) and antineutrino (B) mode, positive/ negative meson focusing;
- Anti-ν_μ CC rate ~ 1/3.5 w.r.t. the neutrino case, due to $\pi^-/\pi^+ < 1$ production & smaller anti-ν/ν xsect

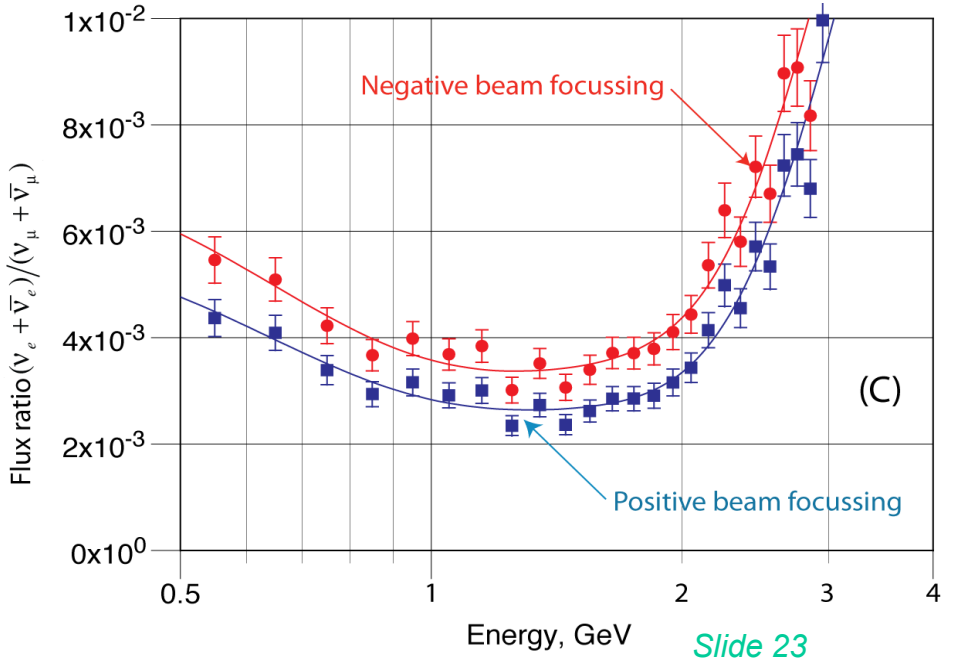


2 year PS neutrino beam	Neutrino focus		Anti-neutrino focus	
	Far	Near	Far	Near
Fiducial mass	500t	150t	500t	150t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions	1.2×10^6	18×10^6	2.0×10^5	2.3×10^6
QE ν_μ interactions	4.5×10^5	66×10^5	87000	1.0×10^6
Events/burst	0.17	2.5	0.03	0.3
Intrinsic ν_e from beam	9000	120000	2000	29000

The CERN-PS ν_e and anti-ν_e spectral shape

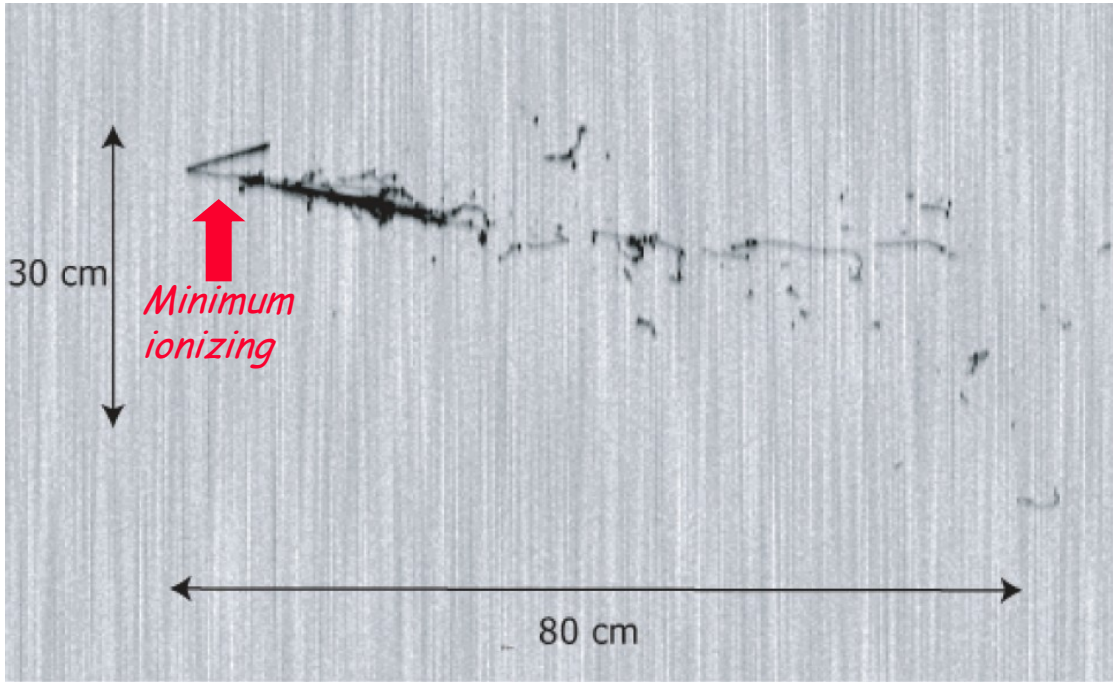
- The ν_e spectra are expected very closely identical in the "Near" and "Far" positions. This specific property of the electron neutrino is due to the fact that they are produced essentially by the K-decays with a much wider angular distribution;
- The effect is enhanced by the fact that both detectors have been designed with identical experimental configurations;
- The (anti-ν_e + ν_e) in anti-ν_μ beam ~ 1.5 of the corresponding in ν_μ focusing.





ν_e CC interaction at ~ 1.5 GeV

- At these energies, electron identification and energy reconstruction of ν_e events is ensured with 5 X_0 (X_0=14cm) longitudinal cut and ~2 X_0 side cut of the sensitive volume corresponding to a fiducial volume of ~ 80 % of the active one.

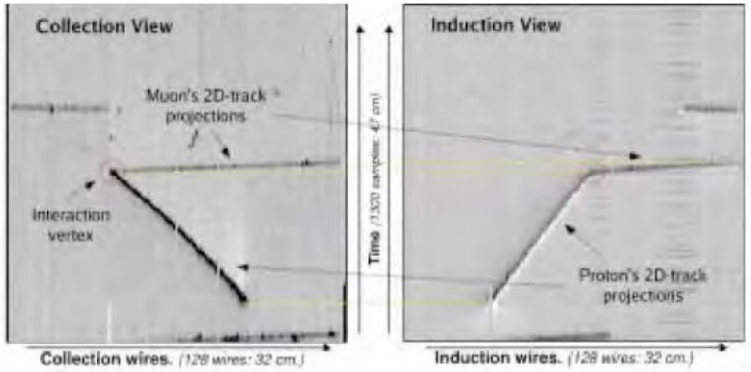


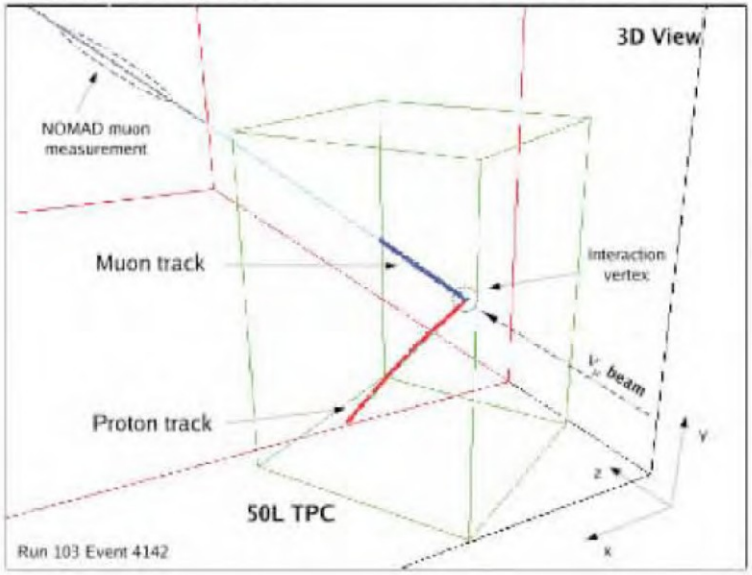
π^0 from NC are rejected by photon vertex identification, invariant mass reconstruction and dE/dx measurement: the expected π^0 mis-interpretation probability is 0.1 %, with ν_e detection efficiency of 90 % within the fid. volume.

With these fiducial cuts, the expected ν_e energy resolution is around 14 %

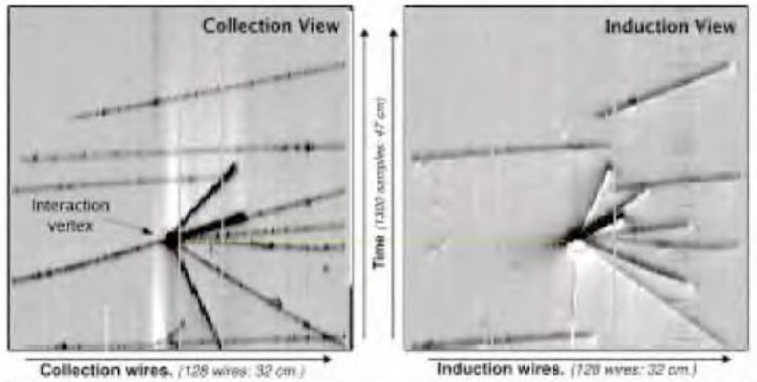
Neutrino events in the 50 l LAr-TPC @ CERN WANF

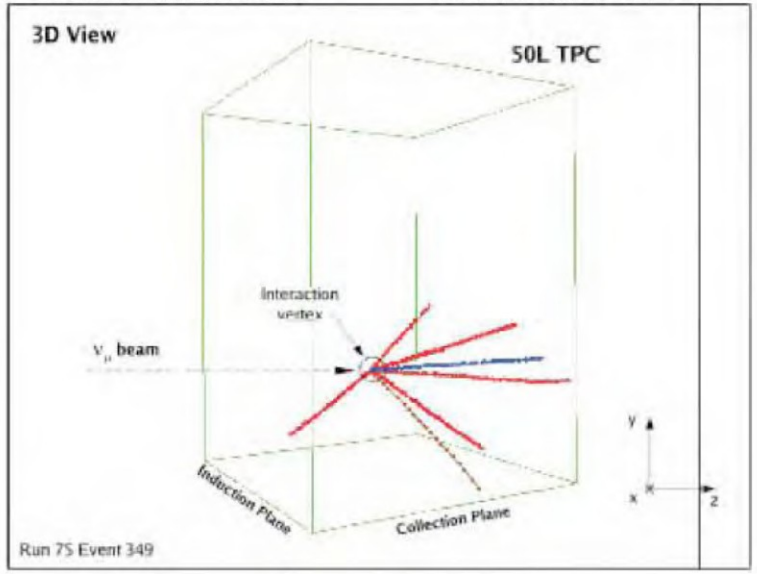
- Example of 3D reconstruction in the vertex region of:
  - quasi-elastic event with a muon and a proton recoil track (A)
  - a multi-prong neutrino event (B)





(A)

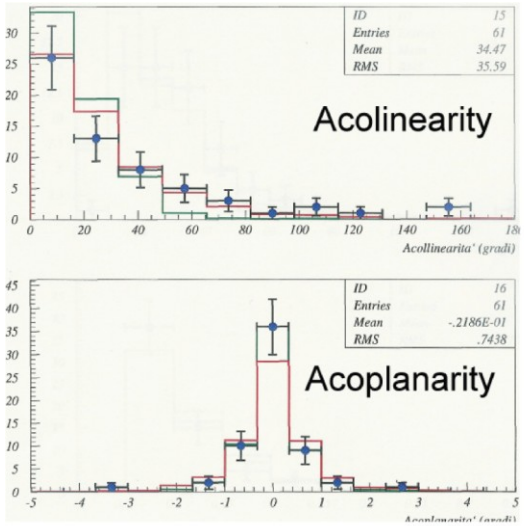


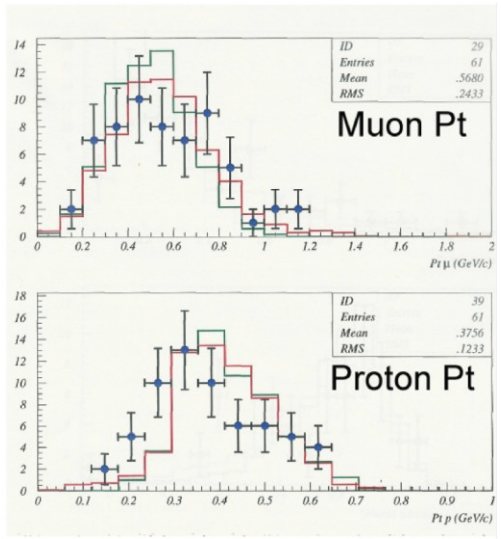


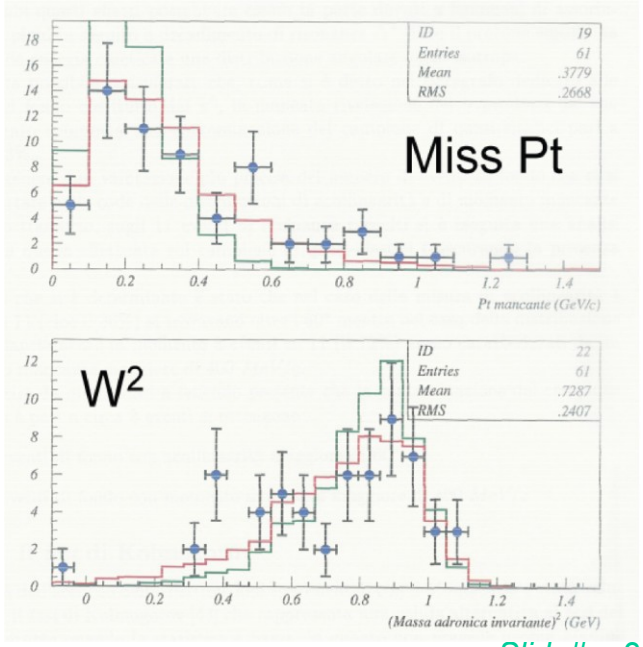
(B)

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



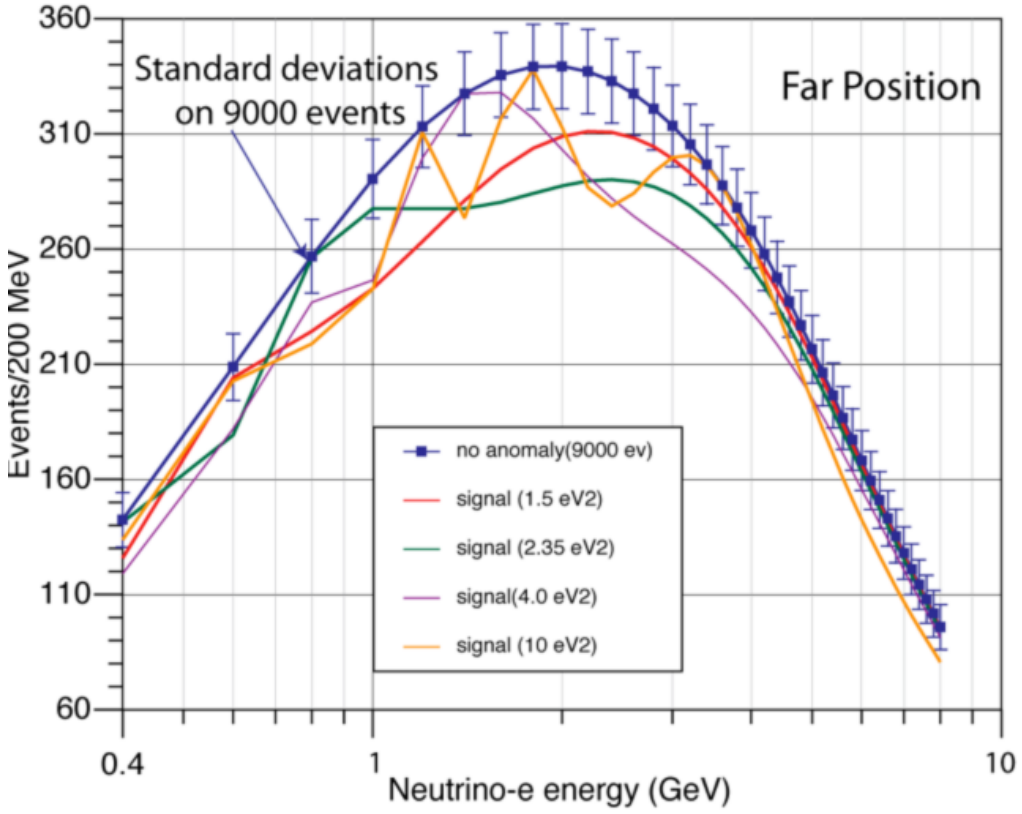


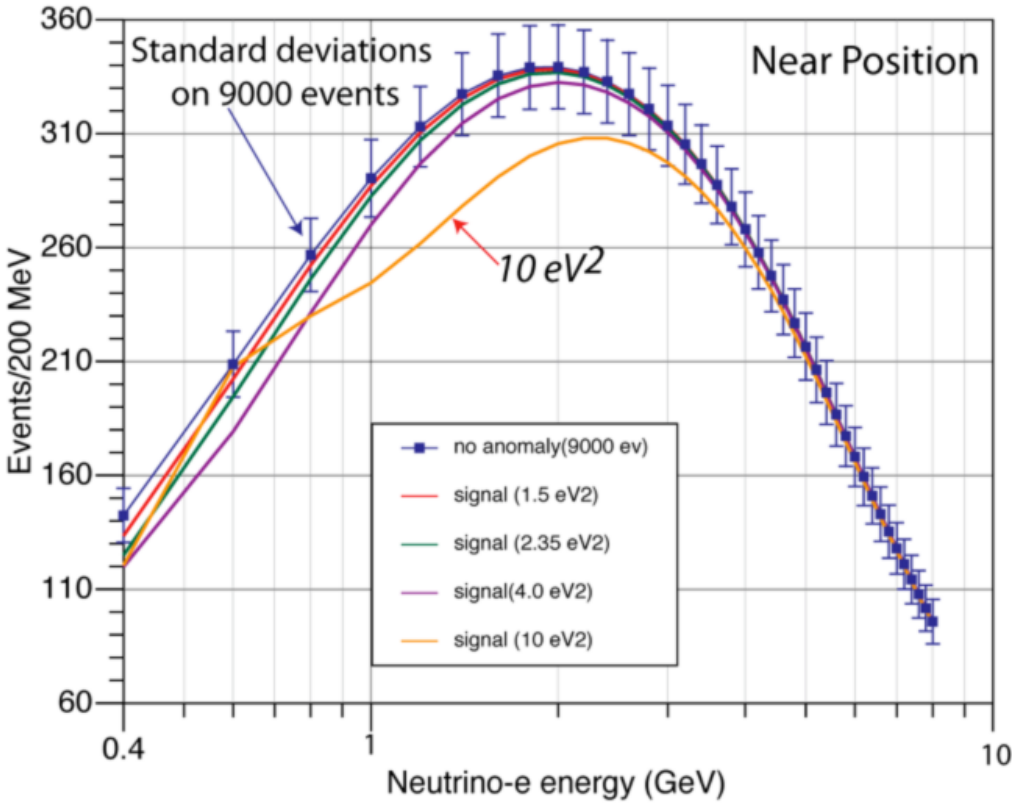


Signal selection and background rejection

- Energy resolution and detector granularity are largely adequate for the lower energy range (1 ÷ 3 GeV) relevant for the present proposal;
- A key issue of the experiment is the detection capability of genuine ν_e events and the very high level of rejection of associated background events, in primis from π^0 decay;
- LAr-TPC detector: very well suited for this purpose, because of its excellent imaging /calorimetric capabilities, which allow very efficient e-π^0 separation, together with unambiguous electron identification;
- In the LAr-TPC all reaction channels with electron production can be analyzed without the need to restrict the search to quasi-elastic channel, which accounts for about slightly less than one half of events;
- Moreover, events due to neutral currents are also very well identified and can be rejected to a negligible level.

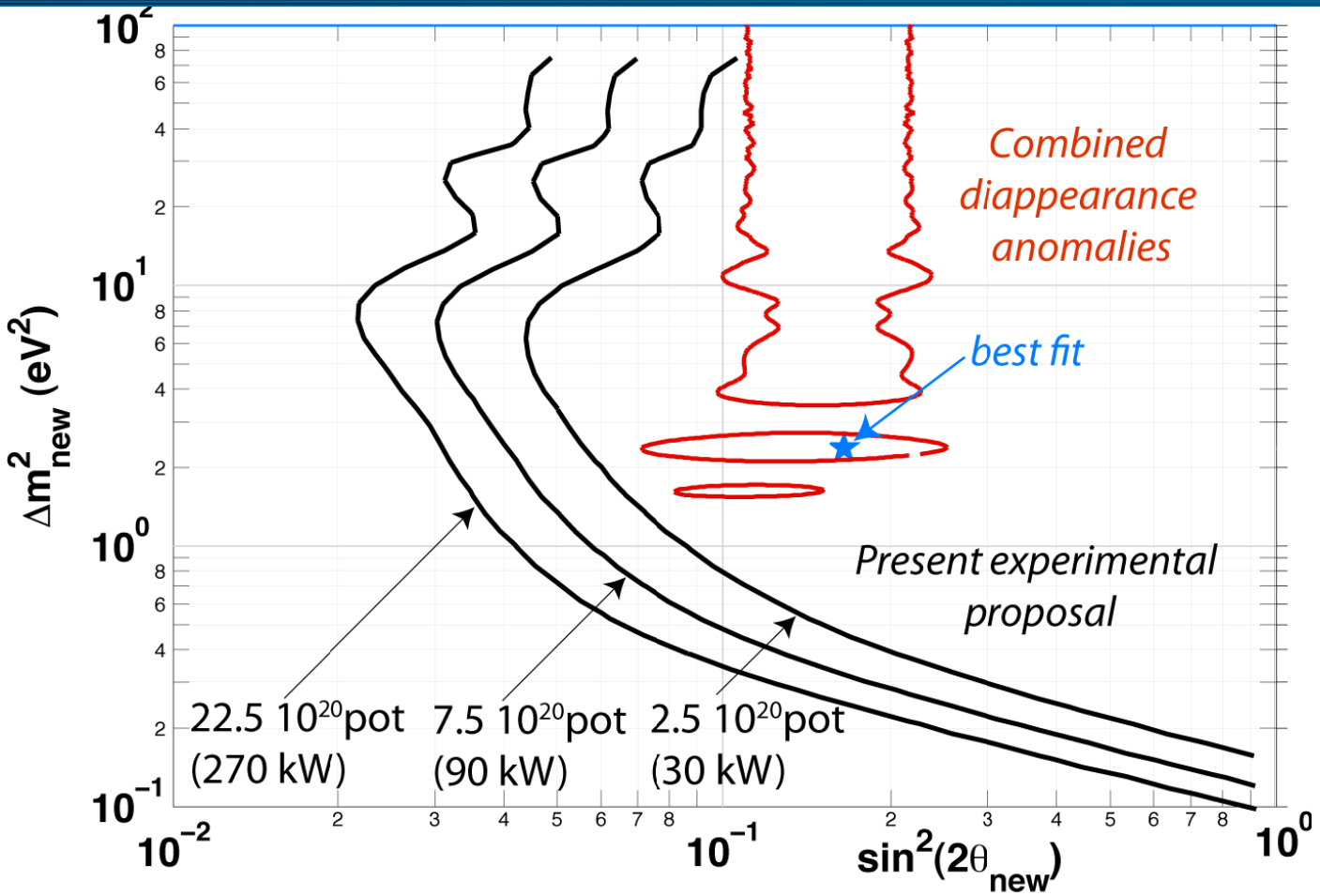
Sensitivity to νe (and νμ) disappearance signals





The energy distributions of electron neutrino events is shown for the "Far" and "Near" position respectively and a number of possible values in the region of $\Delta m^2 > 1 eV^2$ 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 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) 30 kWatt beam intensity (previous CERN/PS experiments), (b) the newly planned 90 kWatt neutrino beam and (c) 270 kWatt curve. They are compared (in red) with the "anomalies" of the reactor + Gallex/Sage exp. A 1% overall + 3% bin-to-bin systematic uncertainty is included (100 MeV bins).

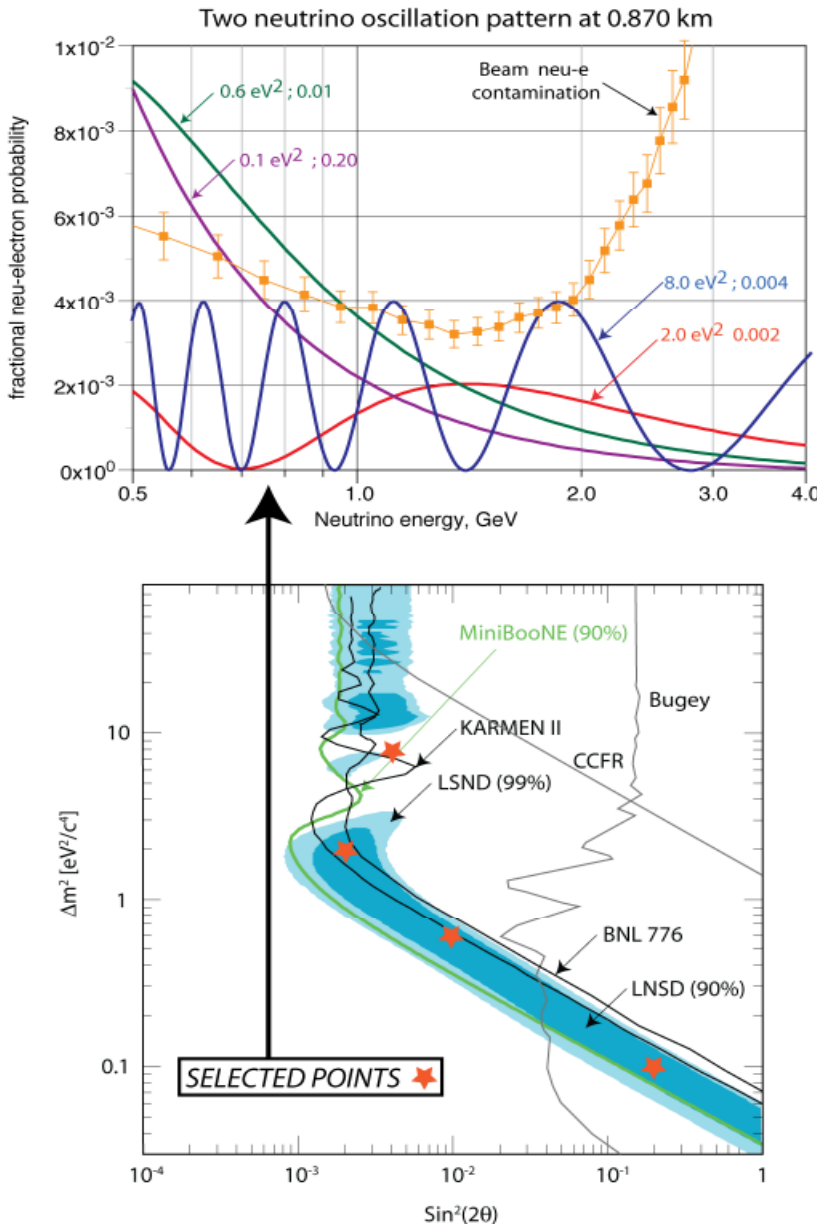
Expected signal for LSND/MiniBooNE anomalies

- Event rates for the near and far detectors given for 2.5 10^{20} pot (30 kW beam power, 2 years) for E_ν < 8 GeV. The oscillated signals are clustered below 3 GeV of visible energy.

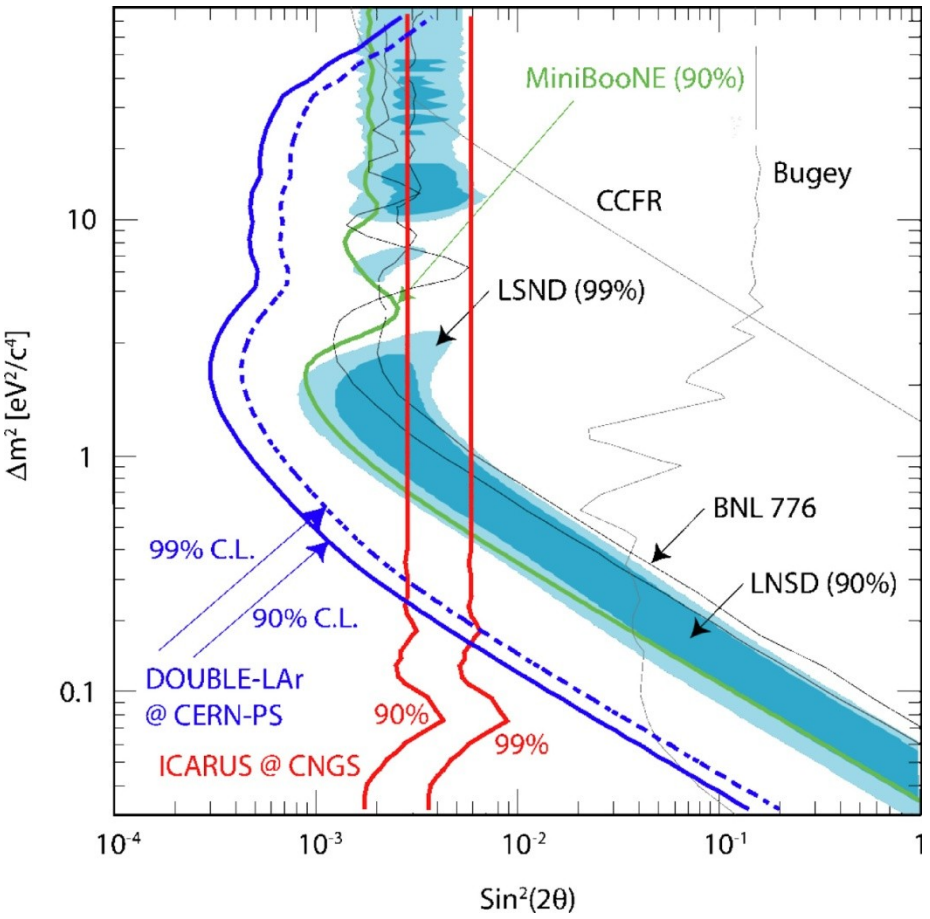
	ν focus		$\bar{\nu}$ focus	
	FAR	NEAR	FAR	NEAR
Fiducial mass	500 t	150 t	500 t	150 t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions (or $\bar{\nu}_\mu$ for $\bar{\nu}$ focus)	1.2 x 10^6	18 x 10^6	2.0 x 10^5	2.3 x 10^6
QE ν_μ (or $\bar{\nu}_\mu$) interactions	4.5 x 10^5	66 x 10^5	87000	
Events/Burst	0.17	2.5	0.03	0.3
Intrinsic ν_e + $\bar{\nu}_e$ from beam	9000	120000	2000	29000
Intrinsic ν_e + $\bar{\nu}_e$ ($E_\nu < 3$ GeV)	3900	54000	880	13000
ν_e oscillations:				
$\Delta m^2 = 2.\ eV^2;\ sin^2 2\theta = 0.002$	1194	1050	230	58
$\Delta m^2 = 0.4\ eV^2;\ sin^2 2\theta = 0.02$	2083	2340	330	115
$\Delta m^2 = 0.064\ eV^2;\ sin^2 2\theta = 0.96$	3350	1250	465	140
$\Delta m^2 = 4.42\ eV^2;\ sin^2 2\theta = 0.0066$	2980	25050	490	3220

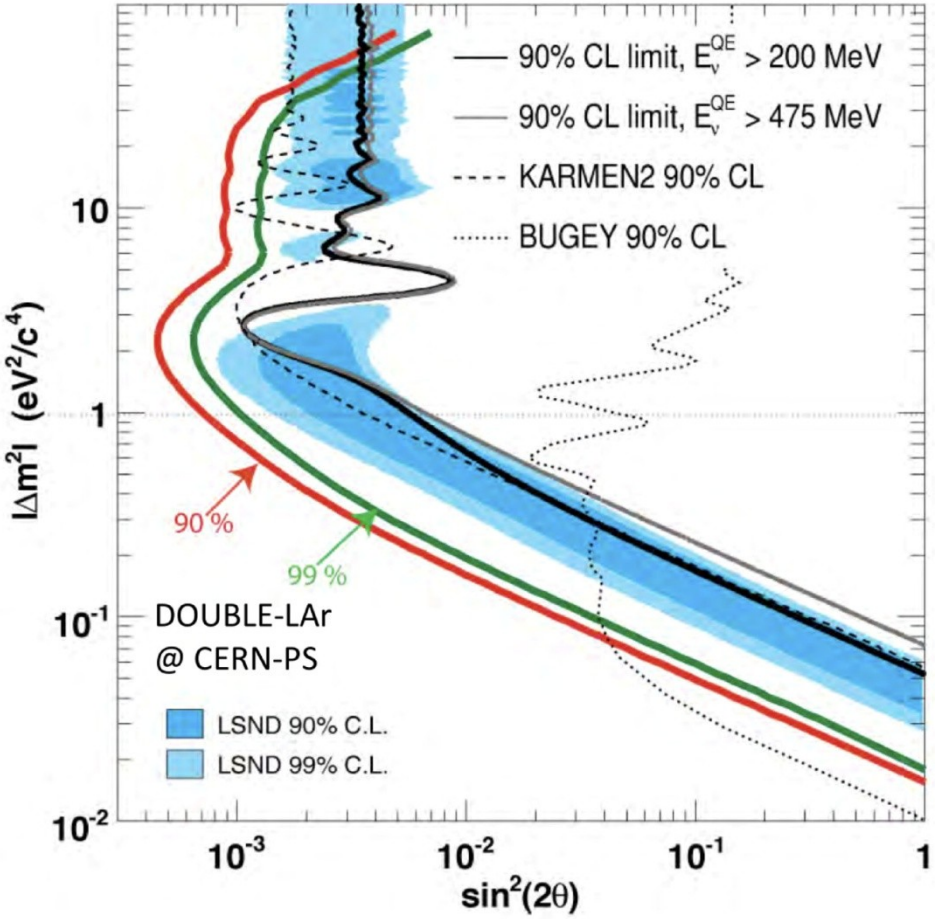
Determination Δm^2 and $\sin^2 2\theta$ values in $\nu\mu \rightarrow \nu e$ anomaly

- The presently proposed experiment, unlike LNSD and MiniBooNE, can determine both mass difference and 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 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

- Memorandum sent to CERN-SPS-C on March 9th describing the possible continuation of ICARUS programme @ CERN-PS, with 3 major new steps:
  - the reconstruction of a CERN-PS horn focussed neutrino beam;
  - the enlargement/reformulation of the collaboration to a wider international team; and
  - the formulation /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*.
- Yesterday's CERN Research Board: PSNF "neutrino beam facility" included in mid-term CERN –plan, a group to define the PS refurbishing has been formed.

Therefore requirements are now fulfilled:
move ahead towards a detailed proposal!

On going activities

- Optimization of the target/focusing optics will be investigated in collaboration with the CERN-PS neutrino facility team

- In parallel detailed study of experiment performance is proceeding:
  - Full detector simulation including true detector response
  - ICARUS event reconstruction machinery
  - Full oscillation analysis.

- Additional studies to possibly disentangle "ν_e appearance" from "disappearance anomalies" are also under way, exploiting the high statistics (anti-) ν_μ CC and NC spectral shapes.

- In addition: interest to complement the LAr TPC's with a down-stream muon spectrometer has been recently expressed to introduce charge measurement and extend momentum measurement in ν_μ interactions (see L. Stanco talk at "Beyond3nu" workshop, LNGS May 4-5, 2011). Possible complementary for the ν_μ disappearance oscillation search.

The present ICARUS Collaboration: to be extended

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Thank you !