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

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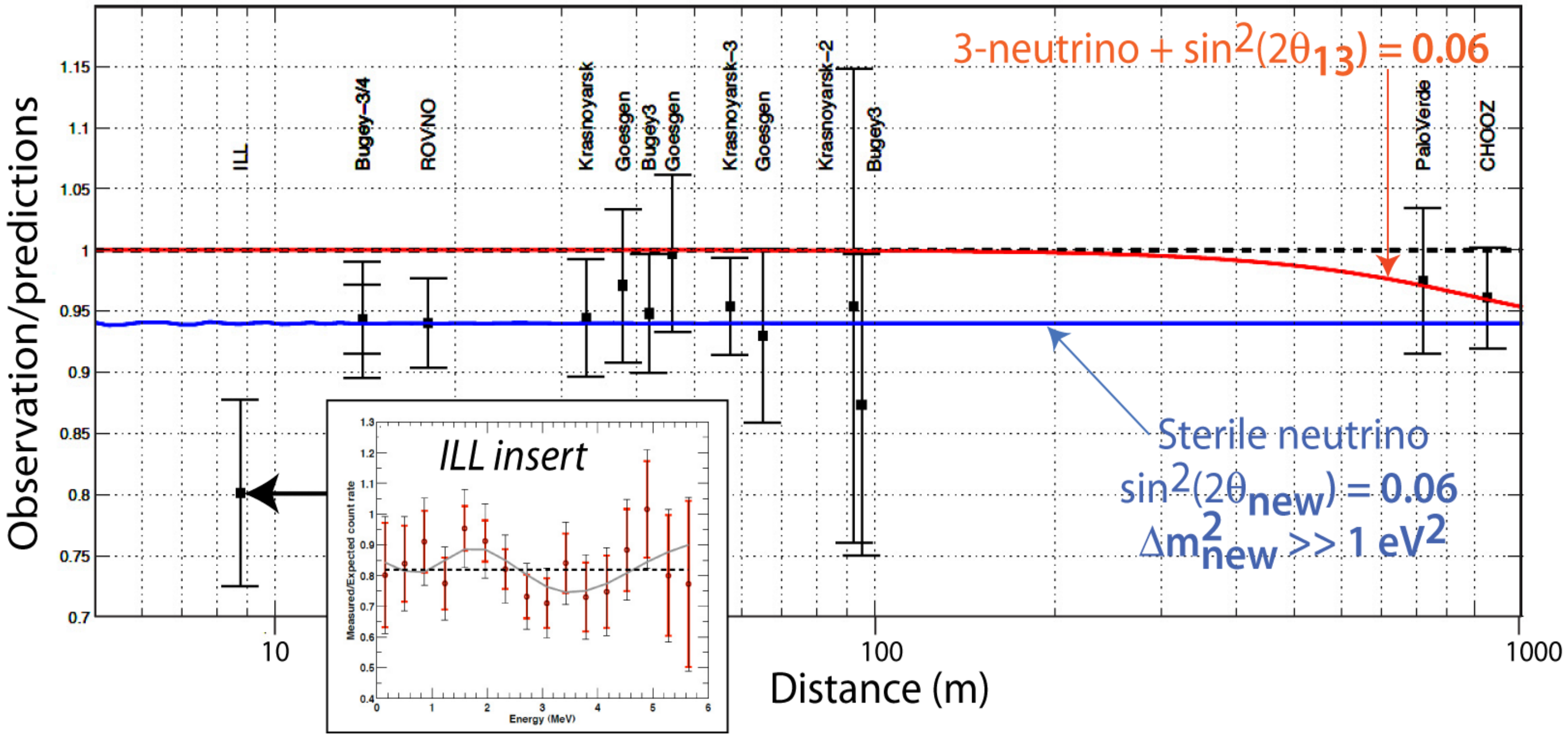
Neutrino oscillation "anomalies": sterile neutrino hints

- Neutrino oscillation experiments are establishing a picture consistent with the mixing of three neutrinos ν_e, ν_μ, ν_τ with mass eigenstates ν_1, ν_2, ν_3 with $\Delta m^2_{31} \approx 2.4 \times 10^{-3}\ eV^2$ and $\Delta m^2_{21} \approx 8 \times 10^{-5}\ eV^2$.
- There are however a number of *"anomalies"* which could be attributed to the presence of additional, larger squared mass differences in the framework of neutrinos with mixing or of other effects.
- Two distinct classes of anomalies have been observed:
  - apparent *disappearance signals:* (1) the anti-ν_e events detected from near-by nuclear reactors and (2) from the Mega-Curie k-capture calibration sources in the solar-ν_e Gallium experiments
  - 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 additional 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.

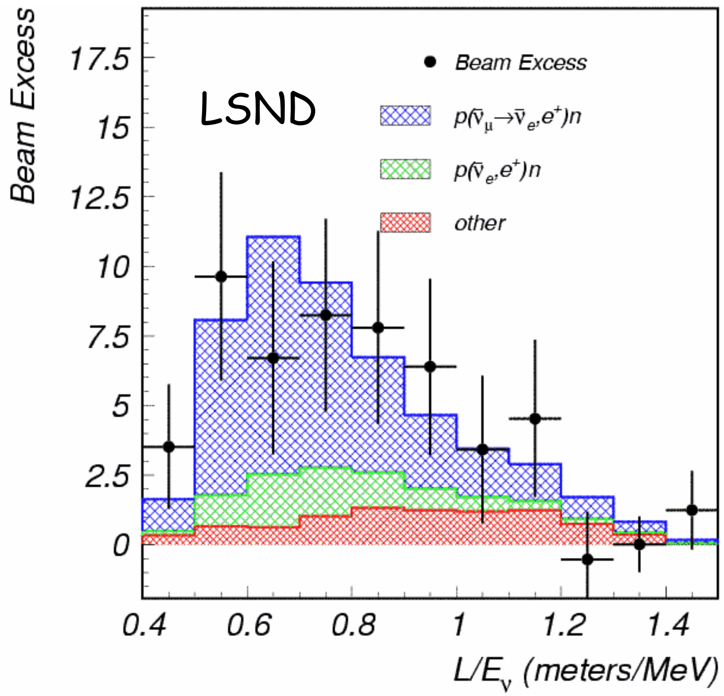
Disappearance signal: the reactor antineutrino anomaly



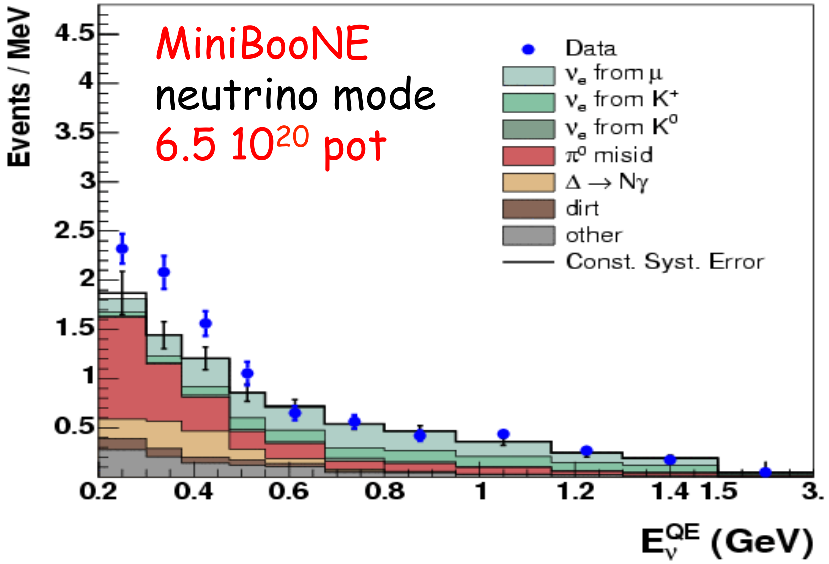
- From G. Mention et al. arXiv:1101.2755v1 [hep-ex] Experimental results are compared to the prediction without oscillation, taking into account the new spectra, the neutron mean lifetime and the off-equilibrium effects. The averaged ratio is 0.937 ± 0.027. The red line is for $sin^2(2\theta_{13})$ =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

The LSND/MiniBooNE like anomalies ($\nu_\mu \rightarrow \nu_e$)

- As well known, the LSND signal with anti-ν oscillations implies an additional mass-squared difference largely in excess of the Standard Model's values.
- The LSND anti-ν_e signal excess (87.9 ± 22.4 ± 6.0) represented a 3.8 σ effect at L/E distances of about 0.5 – 1.0 m/MeV.

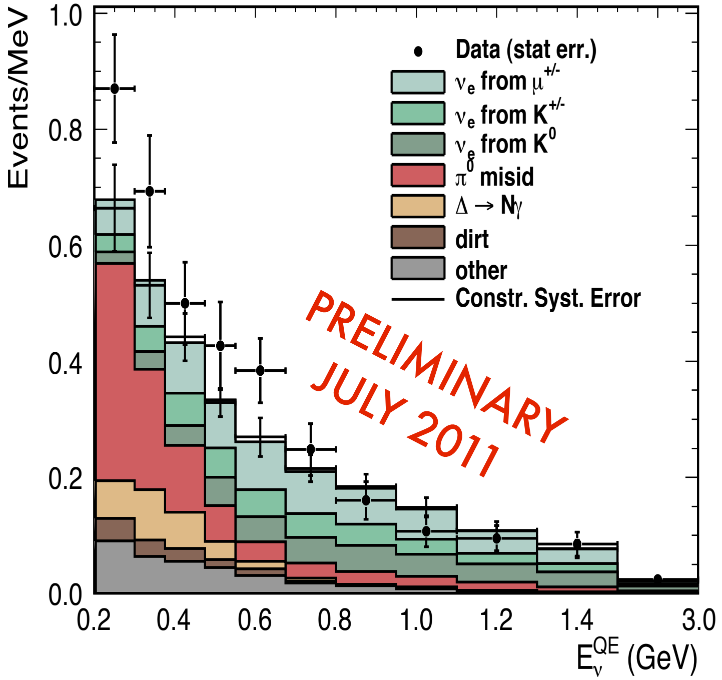


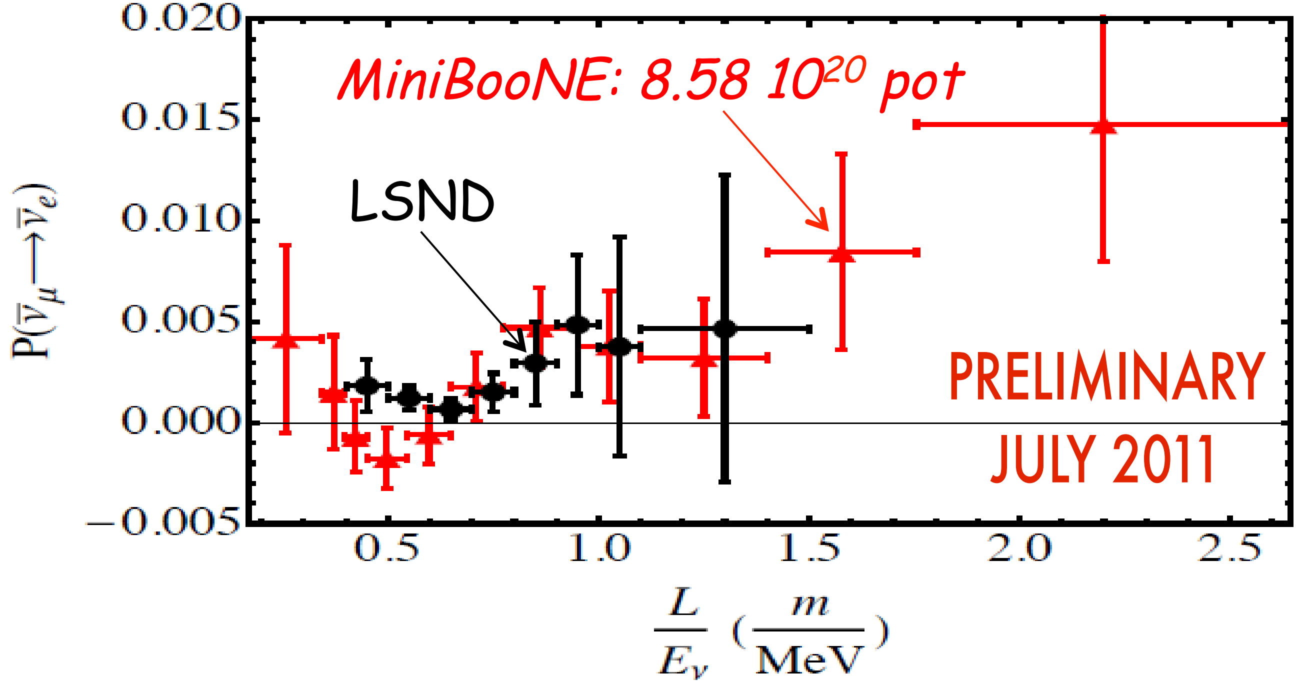
- The MiniBooNE experiment is taking data at the FNAL Booster to verify the observation of the LSND anti-ν_e anomaly in both ν_μ and anti-ν_μ beams.
- While the LSND like anomaly seems to be absent in the MiniBoone neutrino data, a new ν_e excess "anomaly" appears at lower energy.



The MiniBooNE anti-neutrinos recent results

E.D. Zimmerman, Panic 2011

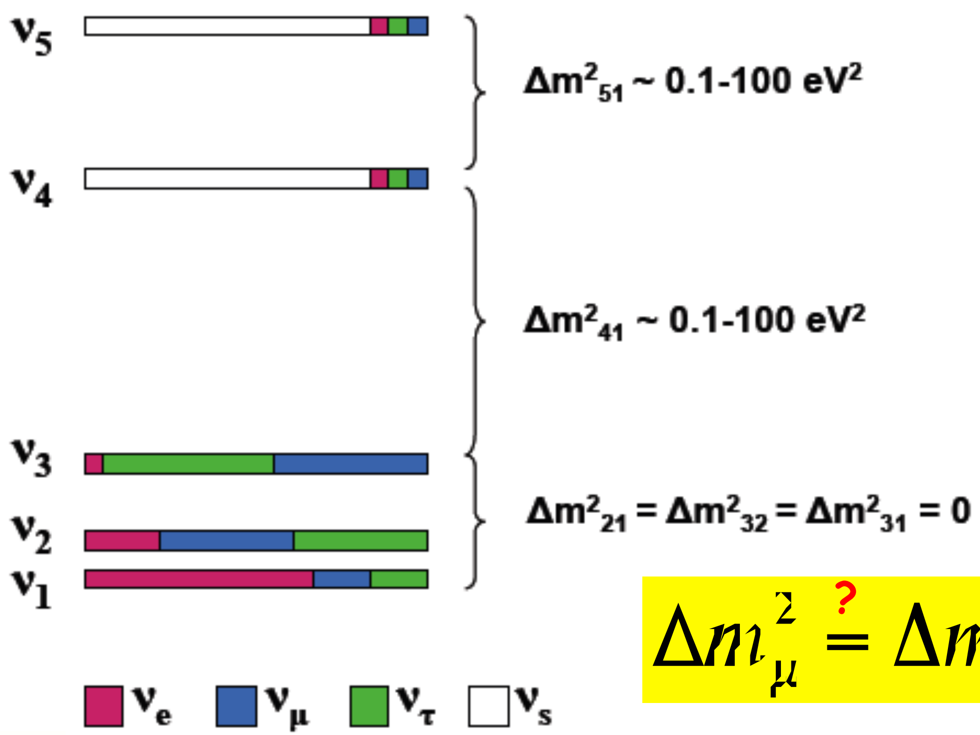




- The MiniBooNE anti-neutrino run with increased statistics and improved systematics (from SciBooNE "near detector") still show the presence of the "LSND like" anomaly for neutrino energies > 430 MeV. In addition it confirms the MiniBooNE low energy excess, now in better agreement with the ν case.
- These results, even if not conclusive, indicate the possible existence of new physics beyond the standard neutrino framework. They confirm the need of a new experiment based on near/far identical detectors to cancel systematics due to beam spectra, cross sections and detector response.

Can the anomalies indicate a more complicated picture?

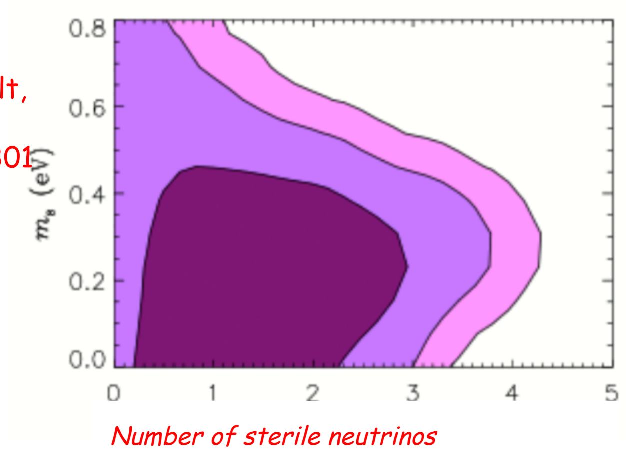
- Sterile neutrino models
- 3+2 next minimal extension to 3+1 models
- 2 independent Δm^2
- 4 mixing parameters
- 1 Dirac CP phase allowing difference between neutrinos and antineutrinos



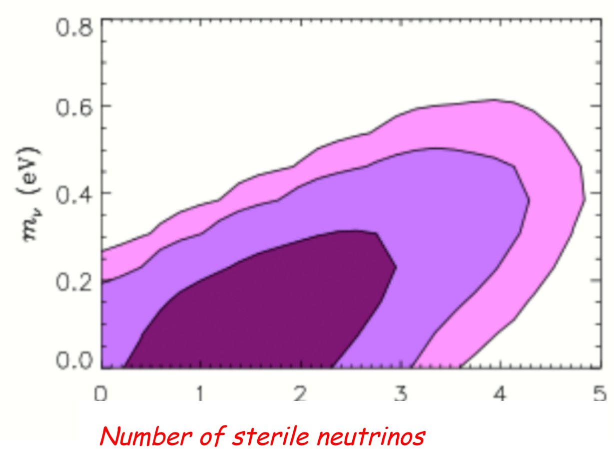
$$\Delta m^2_{\mu} \stackrel{?}{=} \Delta m^2_{\bar{\mu}}$$

From cosmology

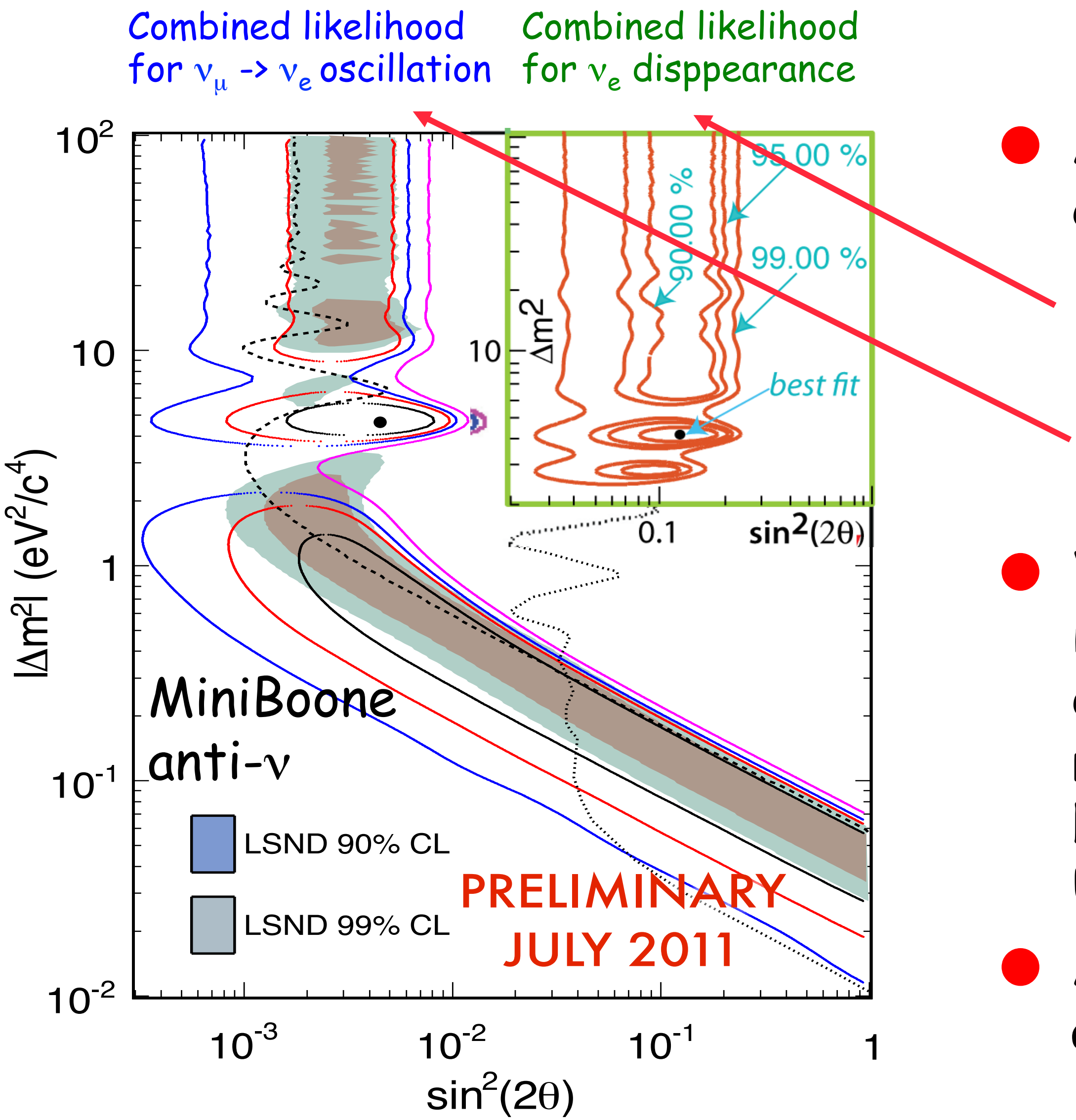
CMB + LSS + ΛCDM
Ns= 1.6 ± 0.9
Hamann, Hannestad, Raffelt, Tamborra,
Wong, PRL 105 (2010) 181301



BBN:
Ns= 0.64 ± 0.4
Izotov, Thuan,
ApJL 710 (2010) L67



A unified approach ?

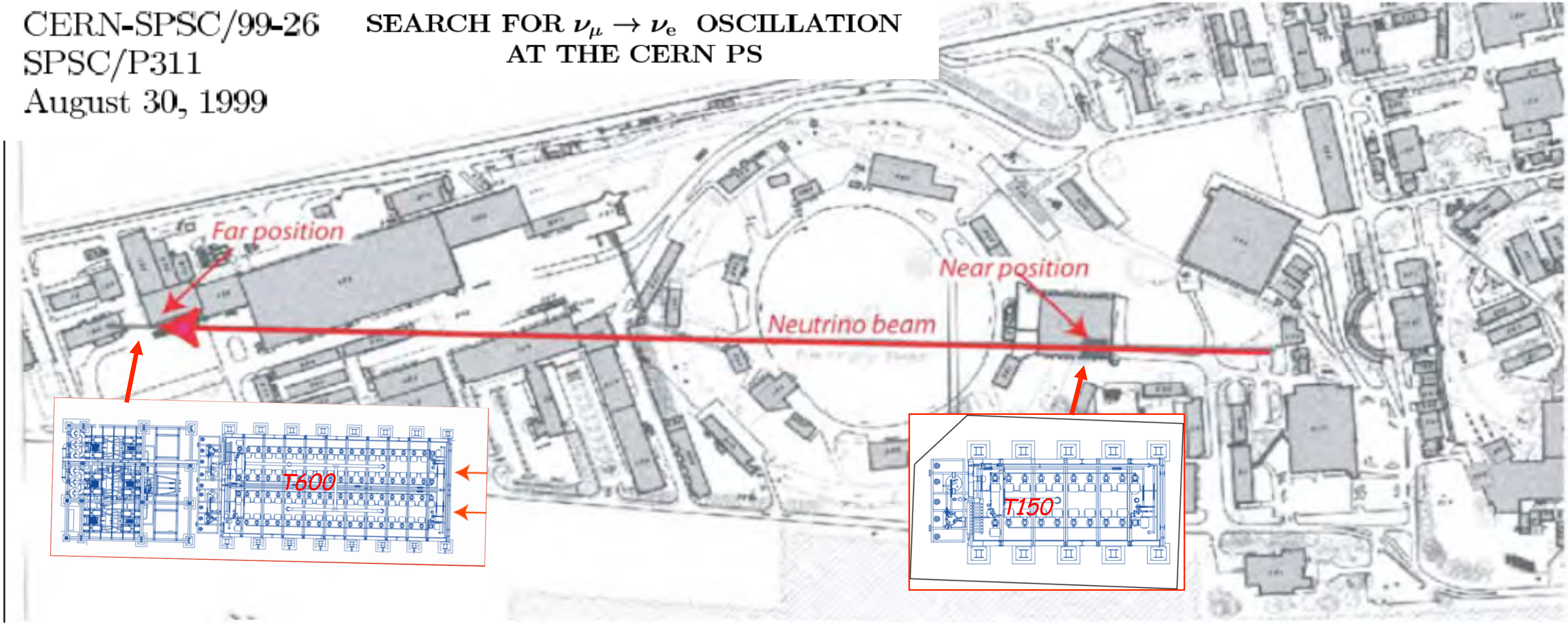


- Allowed regions in the plane for combined results:
  - the ν_e disappearance rate (right) (reactors and Gallium sources)
  - the LSND and MiniBooNE (anti)-ν_e anomalies (left).
- While the values of Δm^2_{new} may indeed have a common origin, the different values of $\sin^2(2\theta_{new})$ may reflect within the ≥ 4 neutrinos hypothesis and a mass matrix $U_{(4,k)} \approx 0.1$, where k = μ and e.
- Attempts to reconcile "amomalies" also studied (see f.i. Giunti talk)

The LAr TPC at the CERN-PS

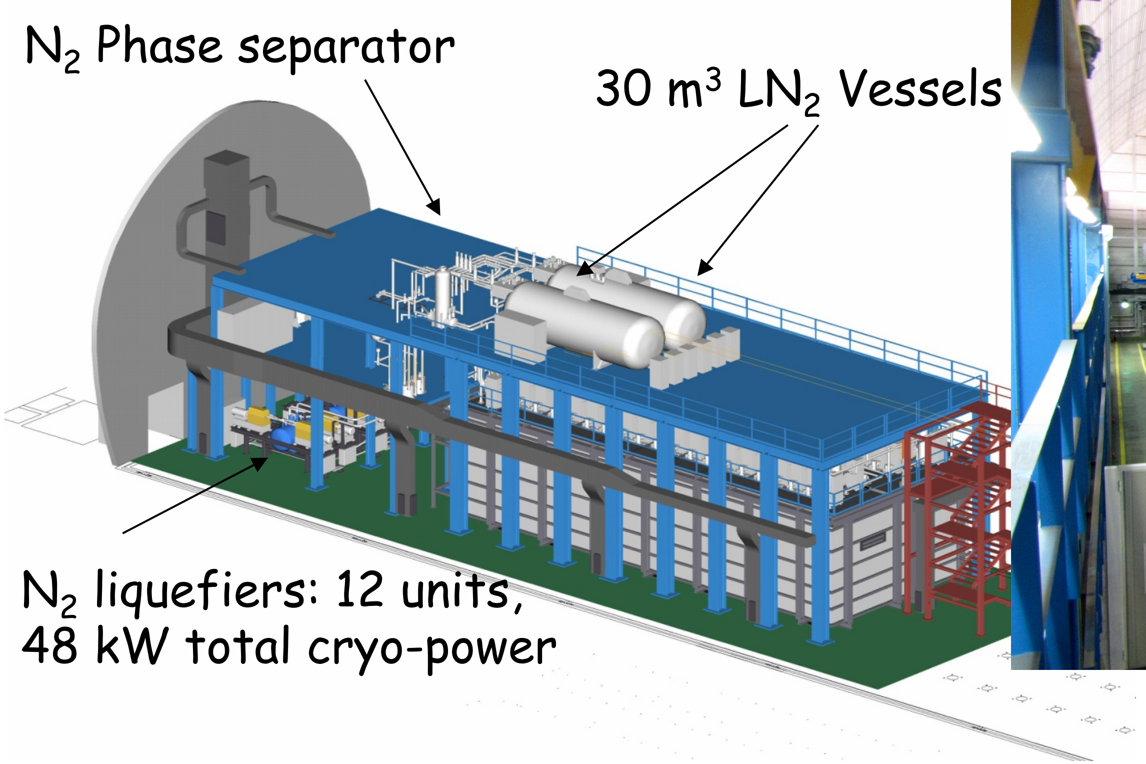
- The direct, unambiguous measurement of an oscillation pattern requires necessarily the (simultaneous) observation at different distances. In this way, the values of Δm^2 and of $sin^2(2\theta)$ can be separately identified.
- The present proposal at CERN-PS introduces important new features, *which should allow a definitive clarification of the above described "anomalies"*:
  - "Imaging" detector capable to identify unambiguously all 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 percent level ($>10^6$ ν_μ, $\approx 10^4$ ν_e)
  - Both initial ν_e and ν_μ components cleanly identified.

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



- Two positions are foreseen for the detector locations, 127 m and 850 m from target (L/E ~ 0.15 and 1 km/GeV)
- "Far" detector: ICARUS T600, now fully operational in Hall B at LNGS collecting neutrino data from CNGS beam.
- "Near" detector: to be constructed anew, as much as possible identical to the T600 but with a mass of 150 t, cloning a T300 half-module with the length reduced by a factor 2.

ICARUS-T600 @LNGS: 0.74 kton LAr-TPC



Detector activated on 27 May 2010

Optimization phase in summer 2010

Data taking in stable condition since 01 Oct.

See ICARUS talk (D. Stefan)

The present ICARUS Collaboration: to be extended

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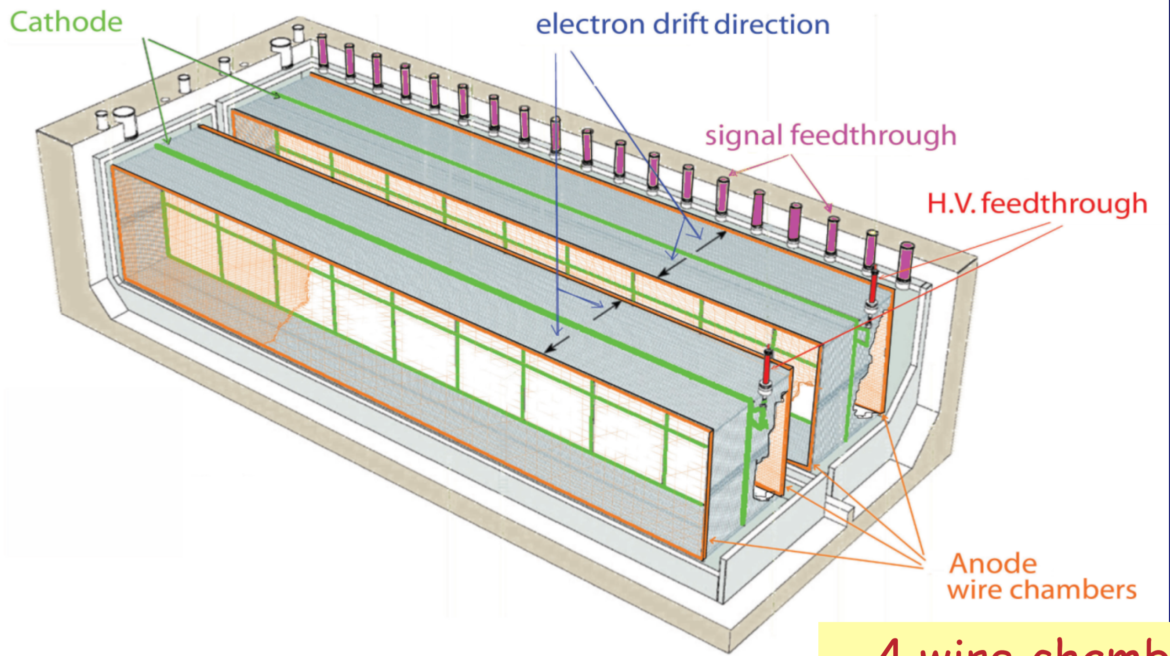
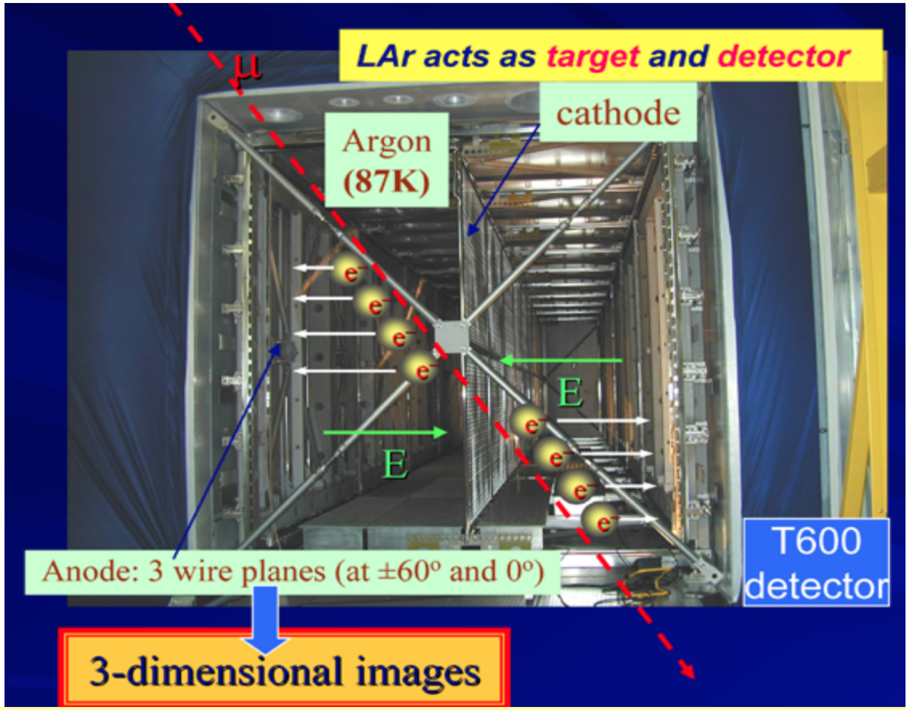
The ICARUS T600 detector

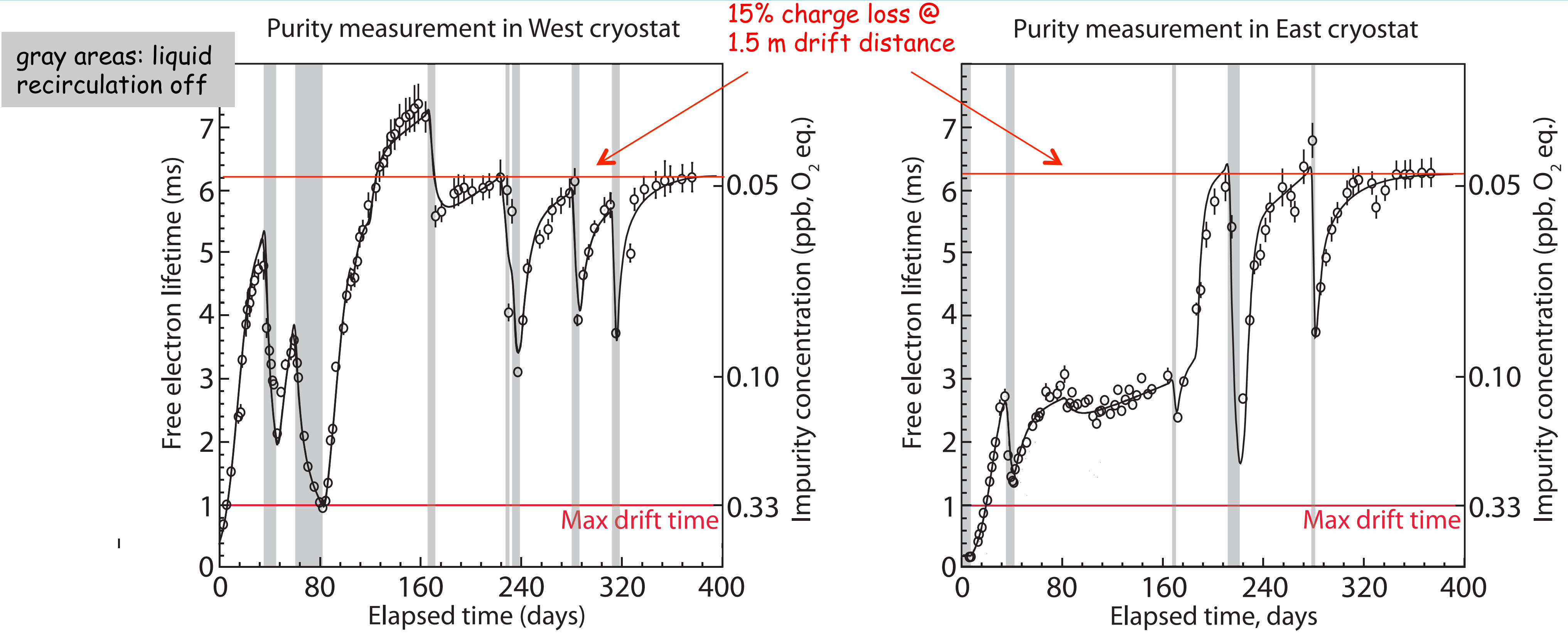




- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E = 0.5 kV/cm
  - vdrift = 1.55 mm/μs

- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes / chamber, wires @ 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- PMT for scintillation light:
  - (20+54) PMTs, 8" Ø
  - VUV sensitive (128nm) with wave shifter (TPB)

LAr purity time evolution



Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

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

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

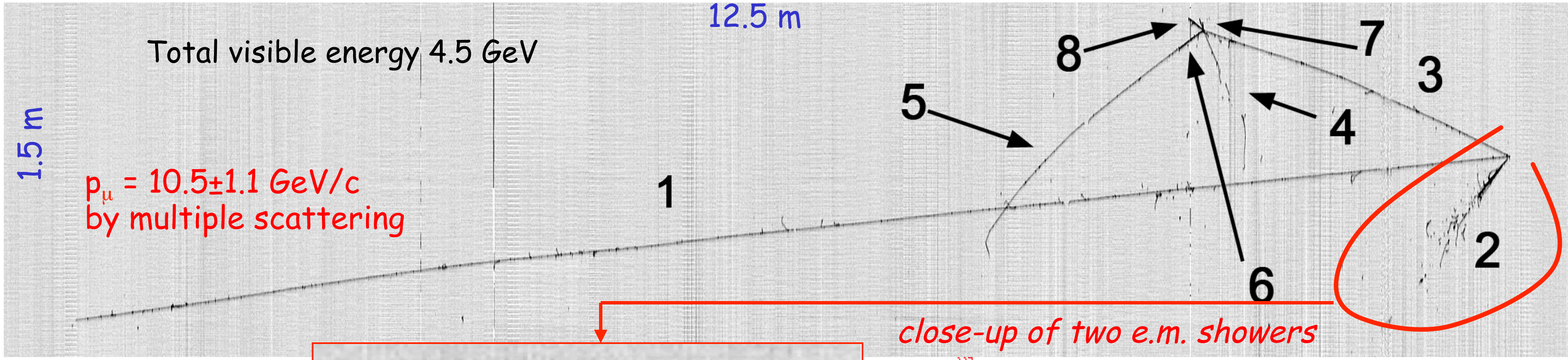
τ_R: recirculation time for a full detector volume

k_I and τ_I : related to the total degassing internal rate

k : related to the external leaks

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

LAr-TPC: powerful technique. Run 9927 Event 572

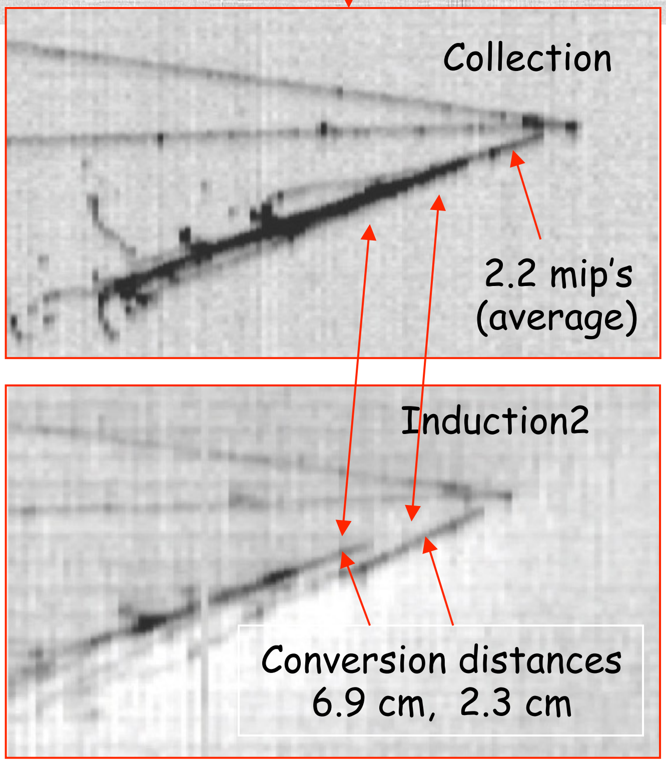


Primary vertex:

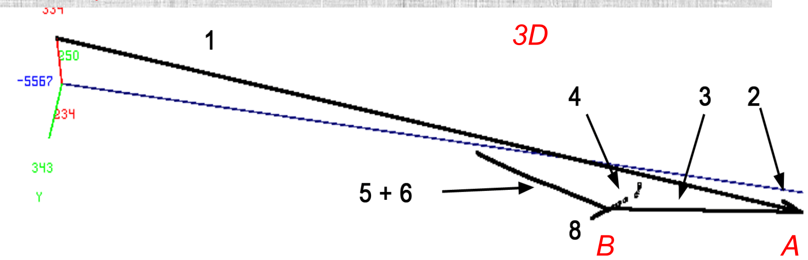
very long μ (1), e.m. Cascade (2), pion (3).

Secondary vertex:

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



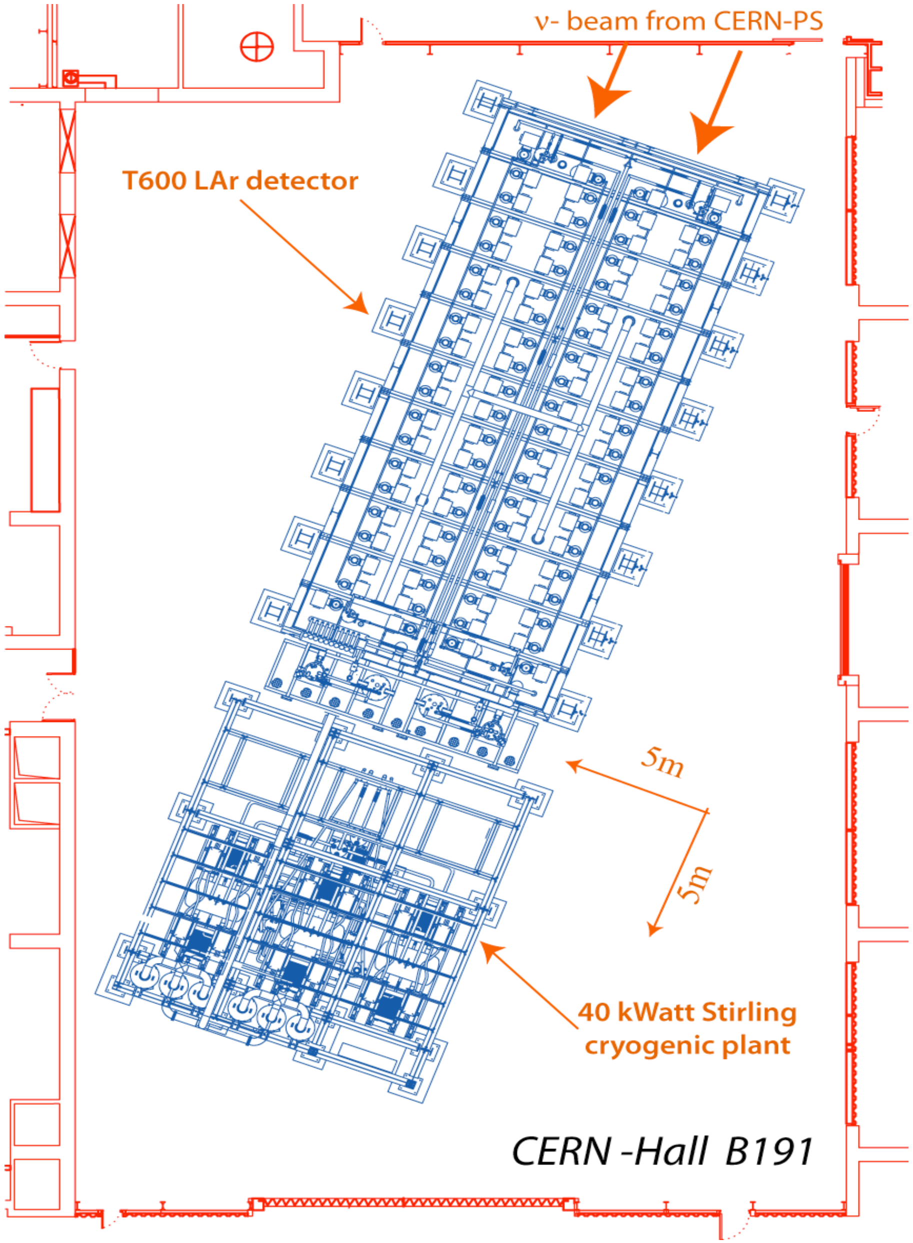
$M^*_{\gamma\gamma}$ = 125±15 MeV/c²



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.			
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

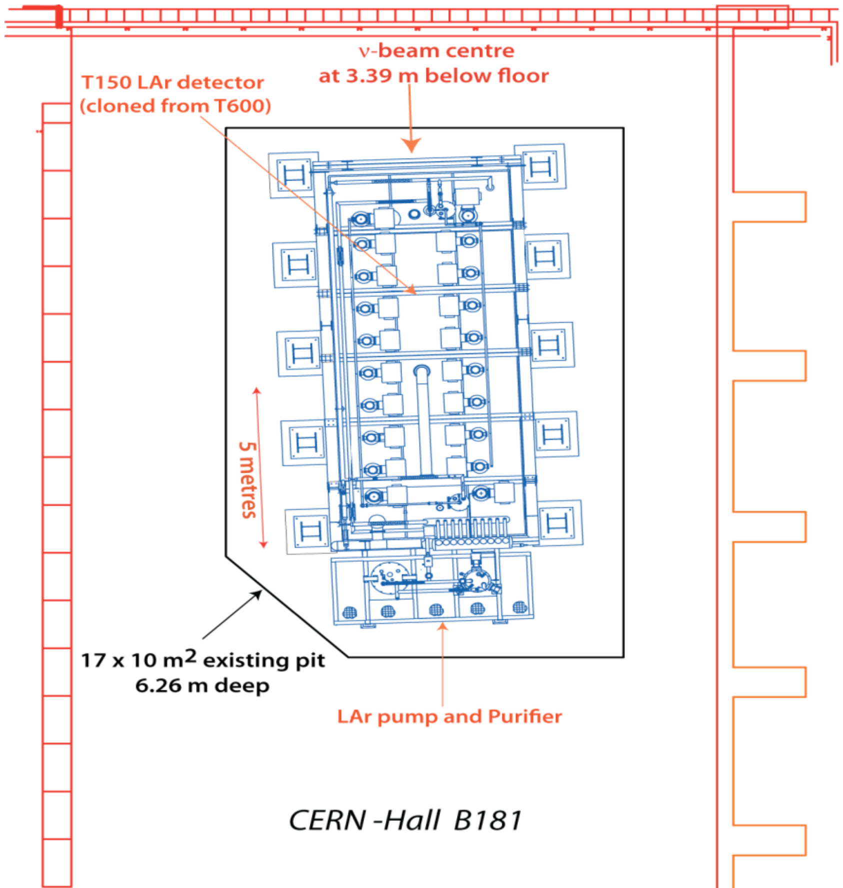
The ICARUS T600 as "Far" detector in Hall B191

- 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 at LNGS, dismounted, transported and reconstructed in Hall B-191 in about 12-14 months.
- A large number of additional components can be disassembled and transported: electronics for DAQ, ancillary systems located in 3 levels of the supporting structure surrounding T600 and LN_2 liquefaction system.



The additional T150 detector (to be constructed)

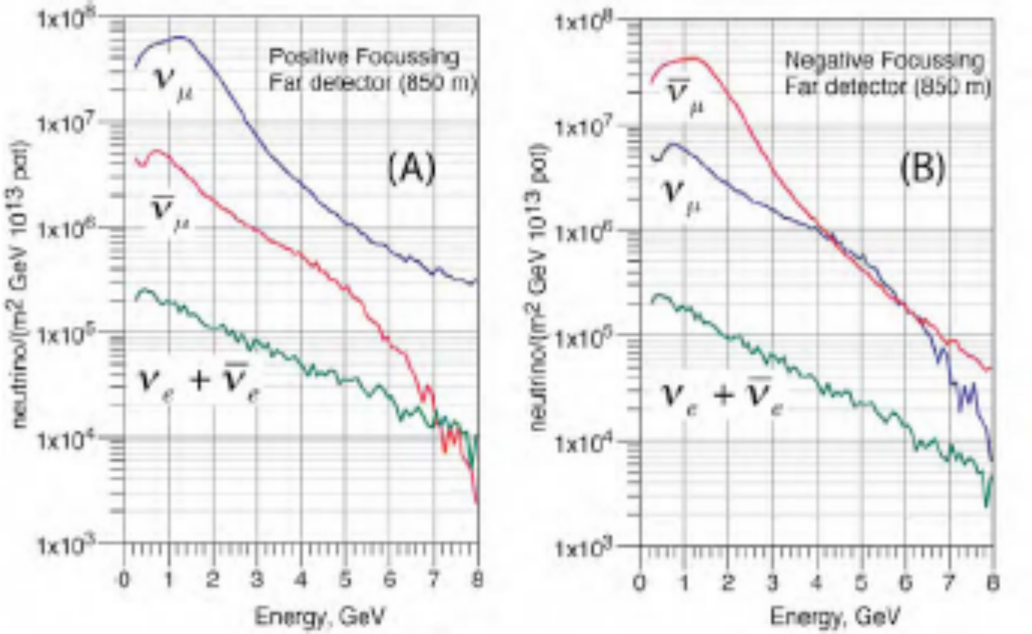
- A clone of a T600 semi-module, with length reduced by a factor 2 (about 12 m) keeping untouched the inner detector layout (TPC structure) with a mass of 150 t.
- Near detector dimensions (including 1 m passive insulation): 13 x 6 m^2 with 6 m height. It fits perfectly the existing basement pit of Hall 181, previously used for neutrino exps.
- The same wire chambers mechanics and existing wiring infrastructures can be used for the construction of T150 Near Detector in ~ 2 year timescale.



- 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 and rates

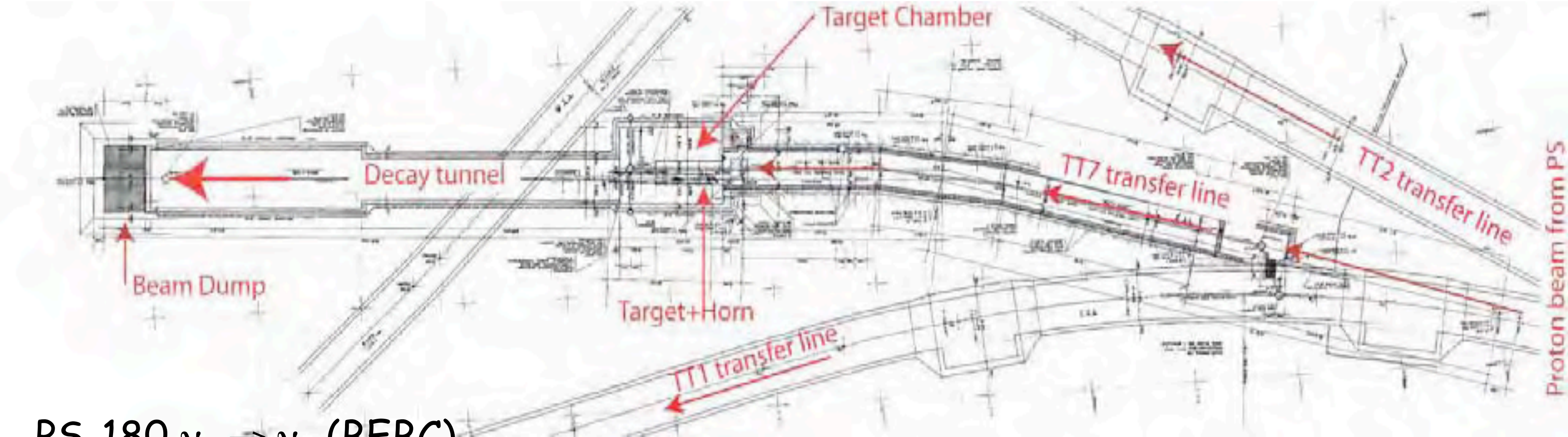
- Starting point: PS-180 experiment and I216/P311 proposal
- 19.2 GeV protons -1.25 10^{20} pot/y (30 kW average power)
- 2 year PS neutrino beam exposure for both neutrino (A) and antineutrino (B) mode, positive/ negative meson focusing
- Anti-ν_μ CC rate ~ 1/3.5 w.r.t. the neutrino case, due to $\pi^-/\pi^+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

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)

Preliminary studies at CERN are confirming that the civil infrastructure are available (after consolidation / safety upgrade) to be equipped with the new beam line. The required proton intensity is possibly at reach based on a more efficient use of the PS beam (R. Steerenberg et al.).

More info @ http://info-psnf.web.cern.ch/info-psnf/

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
  - If an oscillatory disappearance maybe present in the ν_μ signal, it should also be detectable.
  - Accurate comparison between neutrino and antineutrino related oscillatory anomalies, maybe due to CPT violation.
- In absence of these "anomalies", the ν_e signals in 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.

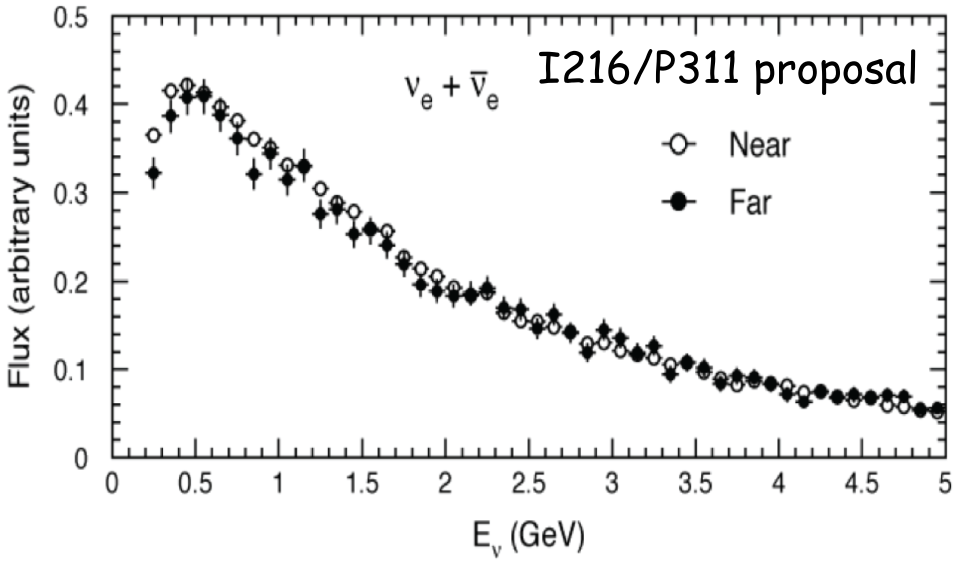
The CERN-PS ν_e and anti-ν_e spectral shape

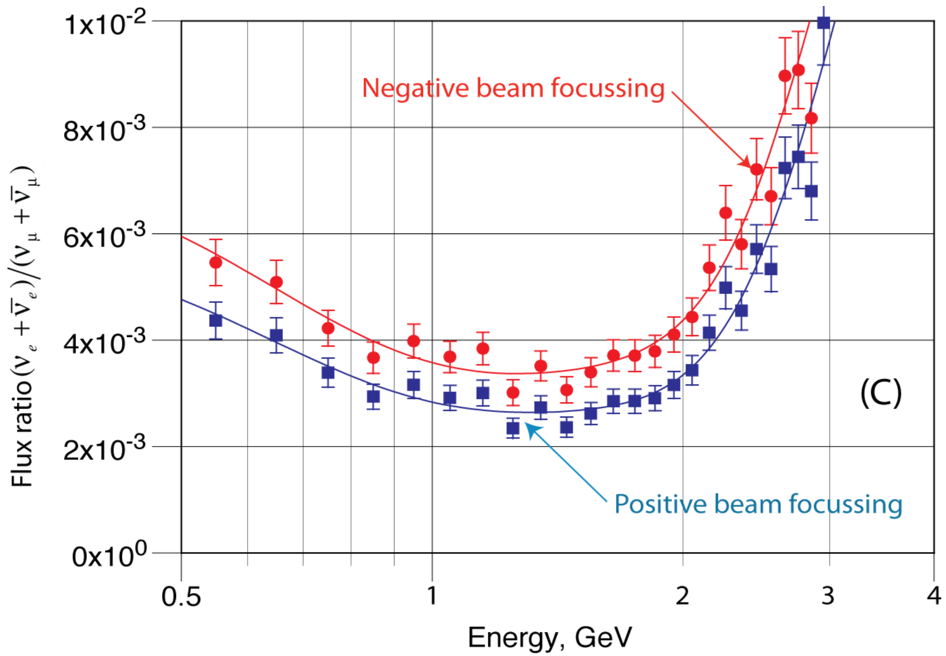
- The ν_e spectra are expected very closely identical in the "Near" and "Far" positions.

- 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.

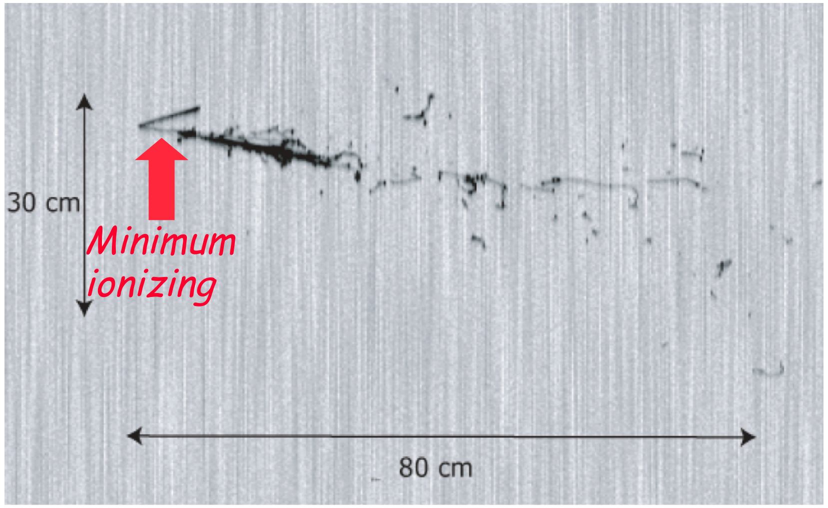
- The (anti-ν_e + ν_e) in anti-ν_μ beam ~ 1.5 of the corresponding in ν_μ focusing

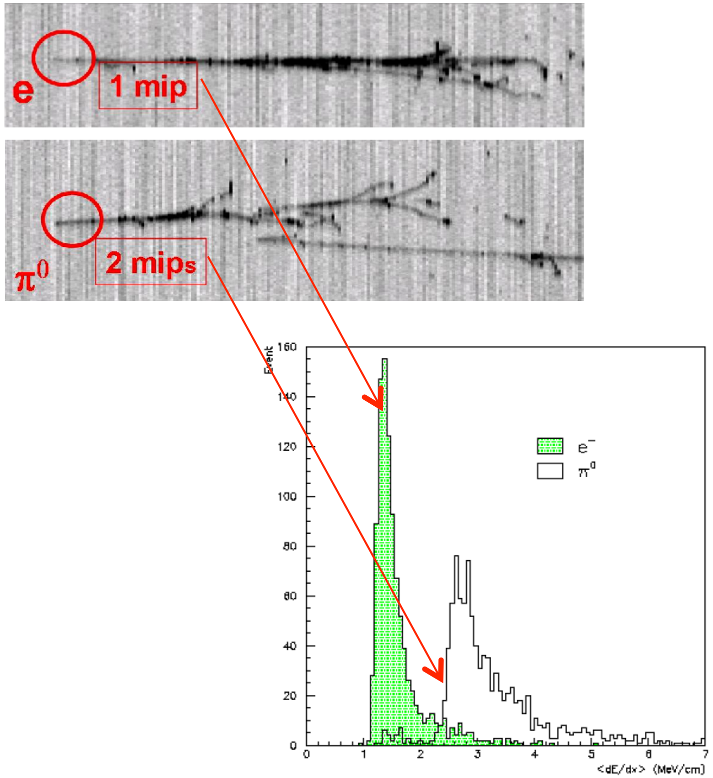




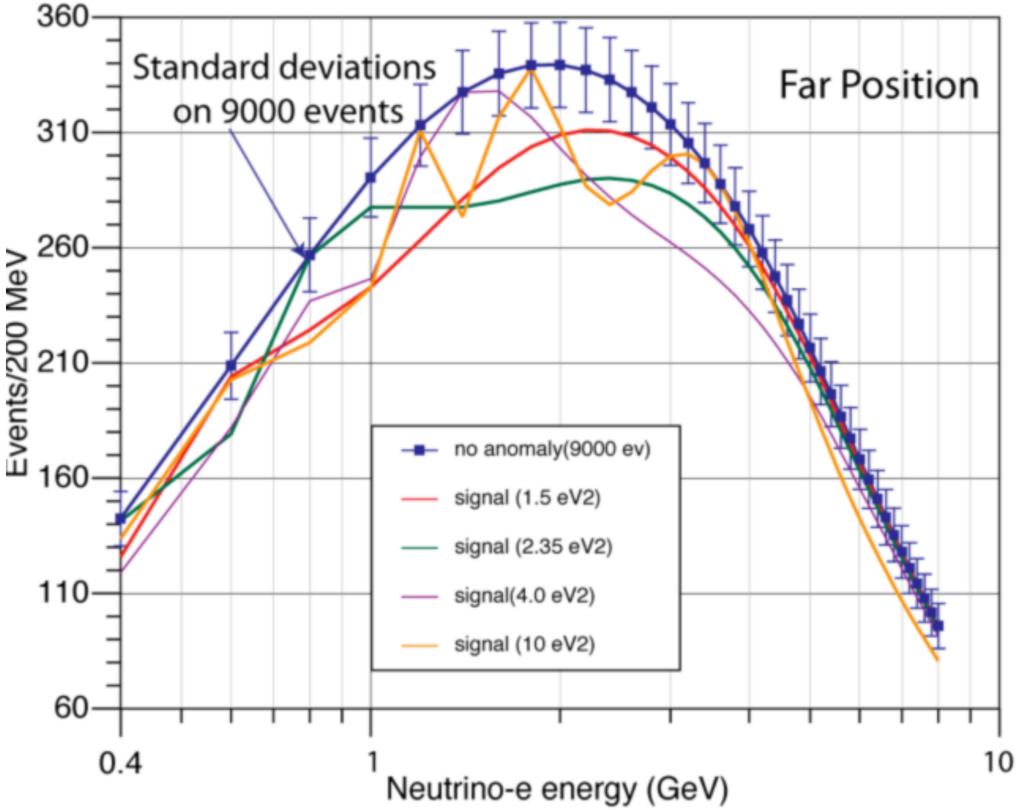
ν_e CC interaction at ~ 1.5 GeV and electron – π^0 separation

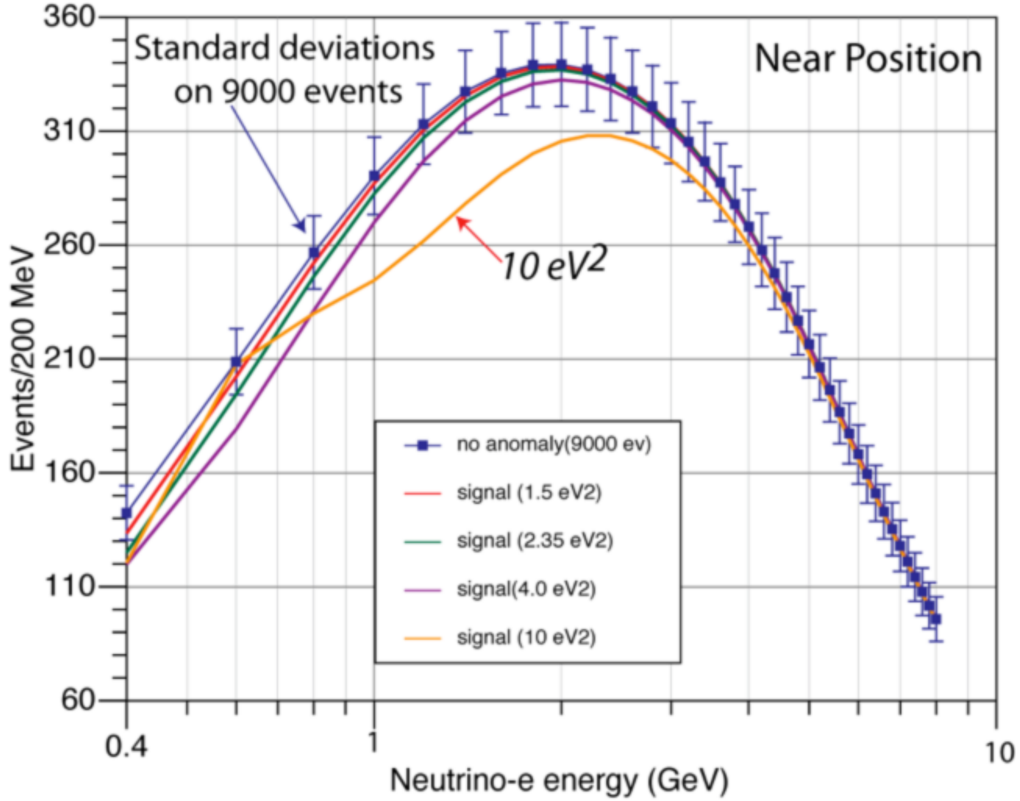
- Electron id. and energy reconstruction of ν_e events in LAr-TPC are ensured with ~5 X_0 (X_0=14cm) longitudinal and ~2 X_0 side cut of the sensitive volume, corresponding to a fiducial volume of ~ 80% of the active one. The expected ν_e energy resolution is around 14 %.
- π^0 from NC are rejected by photon vertex identification, $\gamma\gamma$ invariant mass reconstruction and dE/dx measurement: the expected π^0 mis-interpretation probability is 0.1 %, with νe detection efficiency of 90 % in the fiducial volume.
- All reaction channels with electron production can be analyzed without the need to restrict the search to the quasi-elastic channel, which accounts for slightly less then one half of the events.





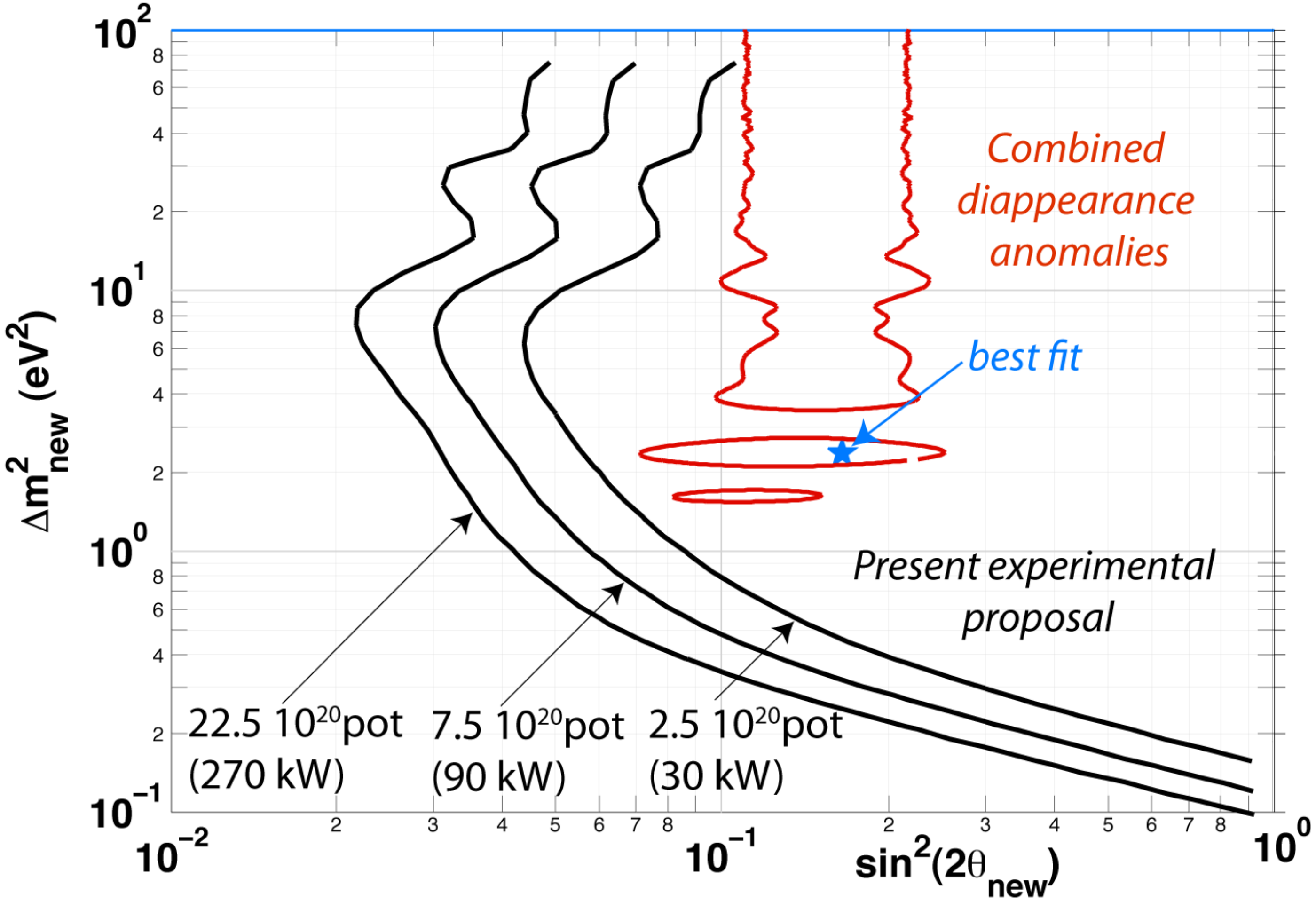
Sensitivity to ν_e disappearance signals





- The energy distributions of the electron neutrino events is shown 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.
- The LAr-TPC energy resolution should be adequate to resolve the oscillation pattern in a wide range of Δm^2 values (full simulation underway).

Sensitivity to ν_e disappearance anomalies



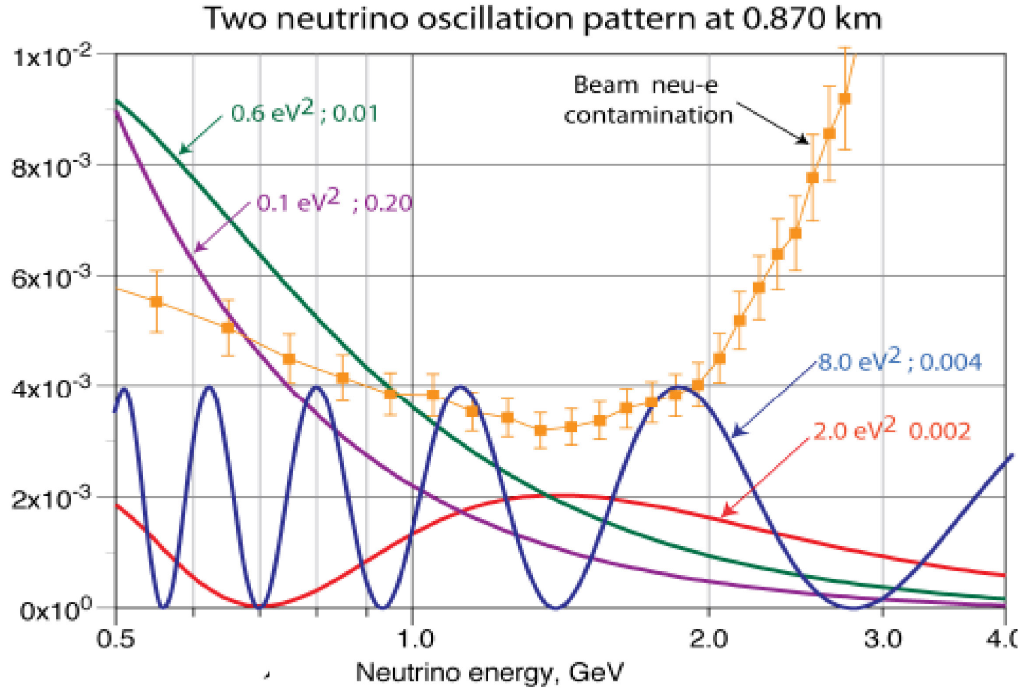
- Sensitivities (90% CL) in the $\sin^2(2\theta_{new})$ vs. Δm^2_{new} for an integrated intensity of 2.5 10^{20} pot (30 kW average CERN/PS beam intensity), a fully dedicated (90 kW) neutrino beam and a 270 kW curve. They are compared (red) with the "anomalies" of the reactor + Gallex and Sage experiments. A 1% overall and 3% bin-to-bin systematic uncertainty is included (for 100MeV bins).

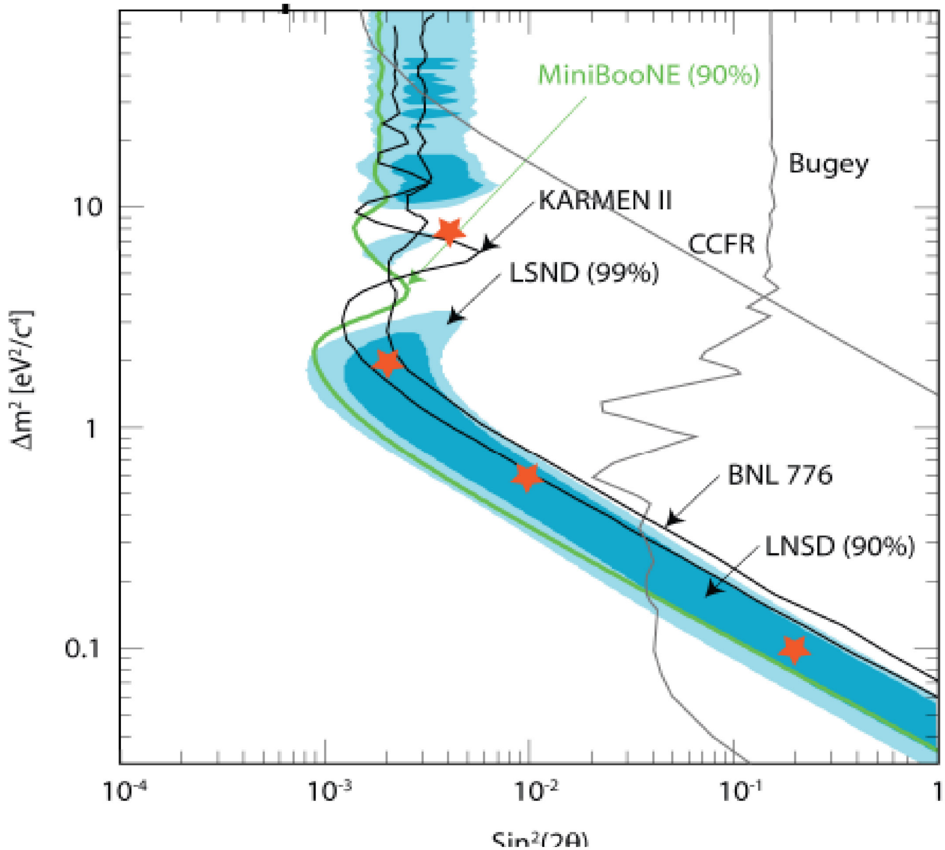
Expected signal for LSND/MiniBooNE anomalies

- Event rates for the near and far detectors given for 2.5 10^{20} pot (30 kW beam power) 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

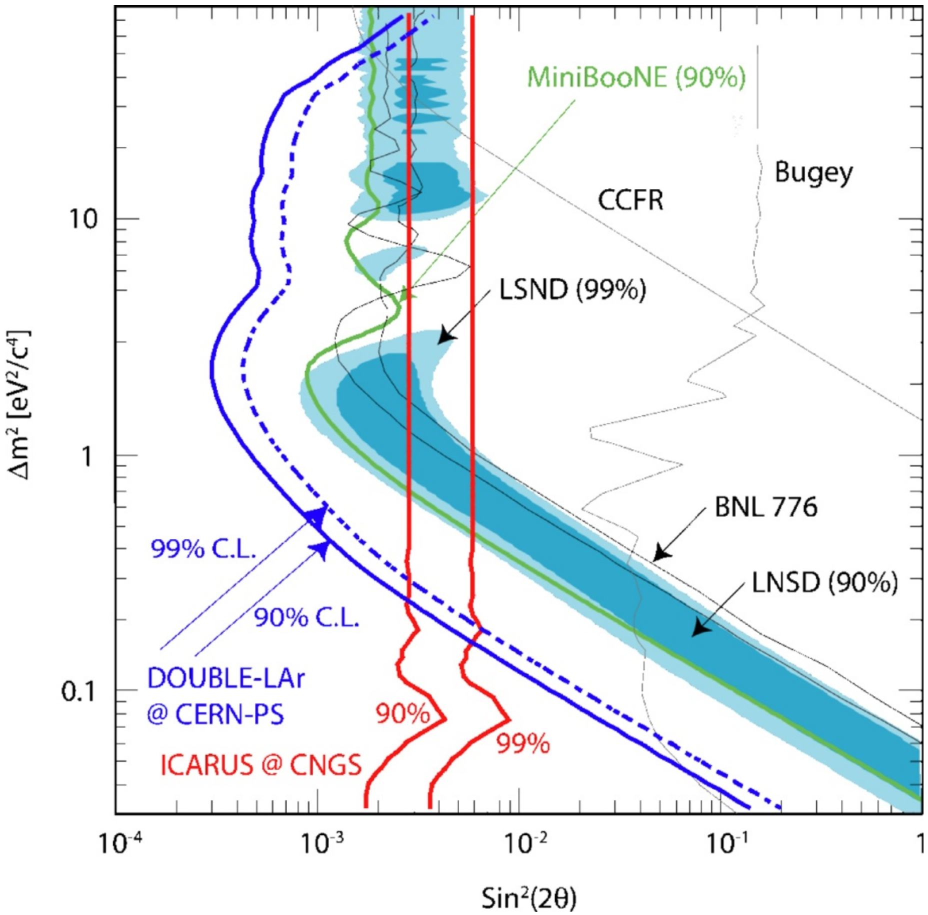
LSND direct determination of mass and mixing angle

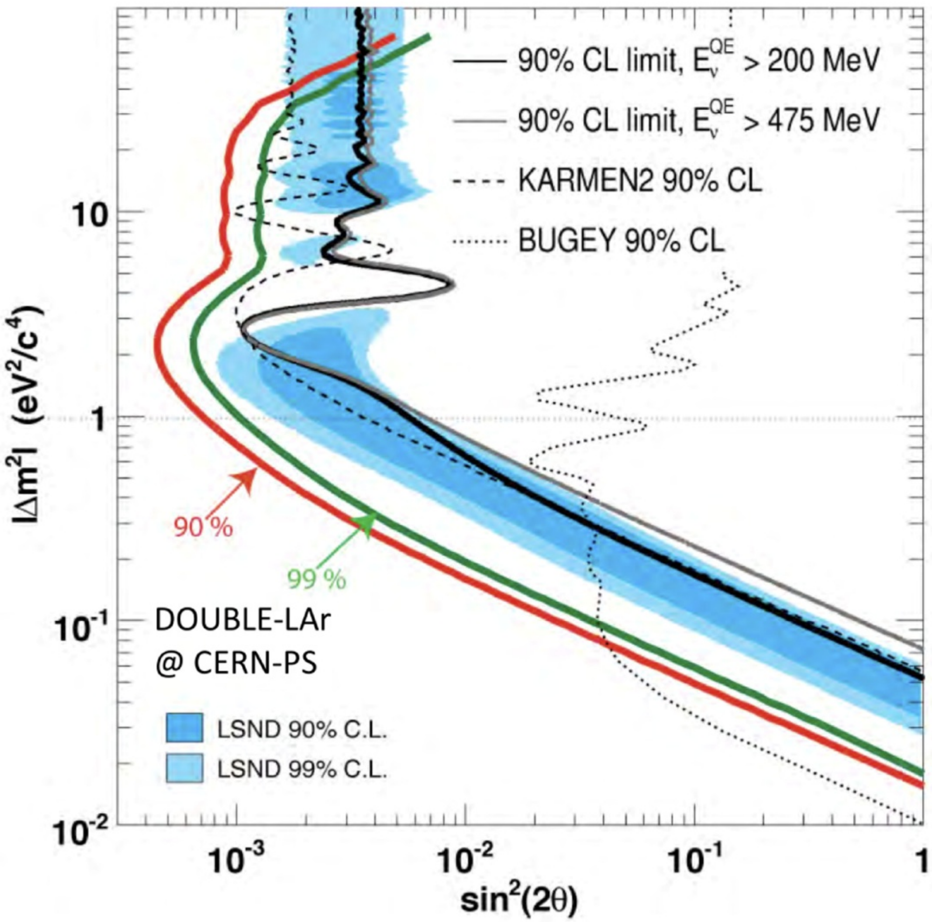




- The present proposed experiment could determine both the mass difference and the value of the mixing angle.
- Very different and clearly distinguishable patterns are possible, depending on the values in the (Δm^2 – $\sin^2 2\theta$) plane.
- The intrinsic ν_e background is also shown.

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 and anti-neutrinos. The T600 expectations for one year nominal exposure to CNGS at LNGS are also shown.

Status of advancement of the Proposal SPSC-M-773

- *The CERN SPS-C and Research Board have recognised the physics motivation and opportunity offered by the ICARUS LAr-TPC technology and availability.*
- On going activities towards the detailed formulation and approval of a formal proposal include:
  - study of the refurbishing of a CERN-PS neutrino beam facility (PSNF) in cooperation with the CERN accelerator teams;
  - the enlargement/reformulation of the present collaboration to a wider international team;
  - detailed study of experiment performance including full detector simulation, ICARUS event reconstruction machinery, full oscillation analysis.
  - additional studies to disentangle "ν_e appearance" from "disappearance anomalies", exploiting the high statistics (anti-)ν_μ CC/NC spectral shapes.
- In addition, interest has been expressed to complement each LAr-TPC detector with down-stream muon spectrometers to introduce charge discrimination and extend momentum measurement in ν_μ interactions (see L. Stanco talk at "Beyond3nu" workshop, LNGS May 4-5, 2011).


Thank you
for your
attention