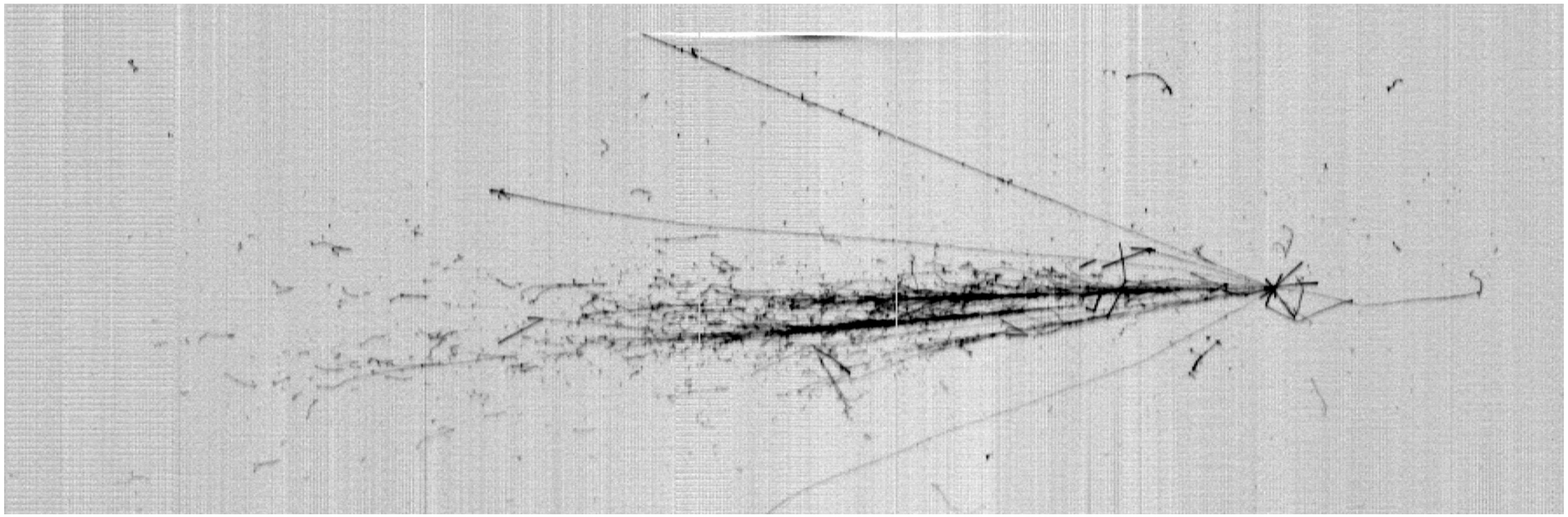
Search for sterile neutrinos including recent results from the ICARUS T600

KRZYSZTOF CIESLIK
for the ICARUS Collaboration

*The Henryk Niewodniczanski Institute of Nuclear Physics,
Polish Academy of Sciences, Krakow*

Matter To The Deepest 2013, 03.09.2013 r.



Outline

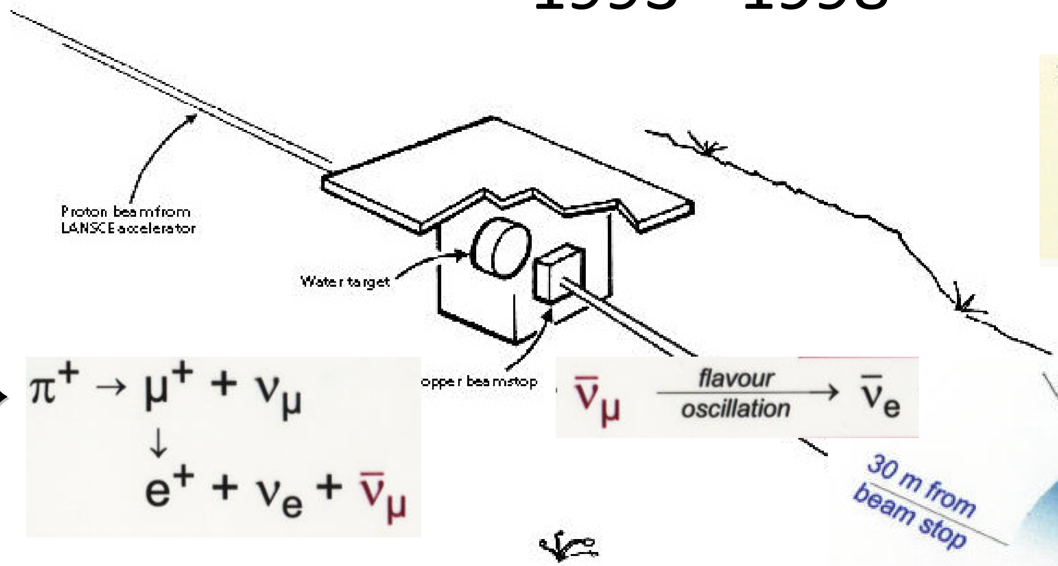
- Sterile neutrinos (LSND/MiniBooNE anomaly)
- The ICARUS experiment
- Search for sterile neutrinos in the CNGS beam
  1. *Experimental search for the „LSND anomaly" with the ICARUS detector in the CNGS beam, Eur. Phys. J. C 73(2013) (arXiv:1209.0122 Sep 2012)*
  2. *New improved results: (arXiv:1307.4699 Jul 2013)*
- Conclusions

Sterile neutrinos

- Sterile neutrinos were hypothesized in 1957 by B.Pontecorvo as particles not interacting via any of fundamental interactions except gravity.
- They are extremely difficult to detect. If they are heavy enough, they may also contribute to the dark matter.
- Sterile neutrinos may mix with standard neutrinos via a mass term. The „LSND anomaly” and results from the MiniBooNE experiment may be considered as the experimental hints for sterile neutrinos.

LSND (Liquid Scintillator Neutrino Detector)

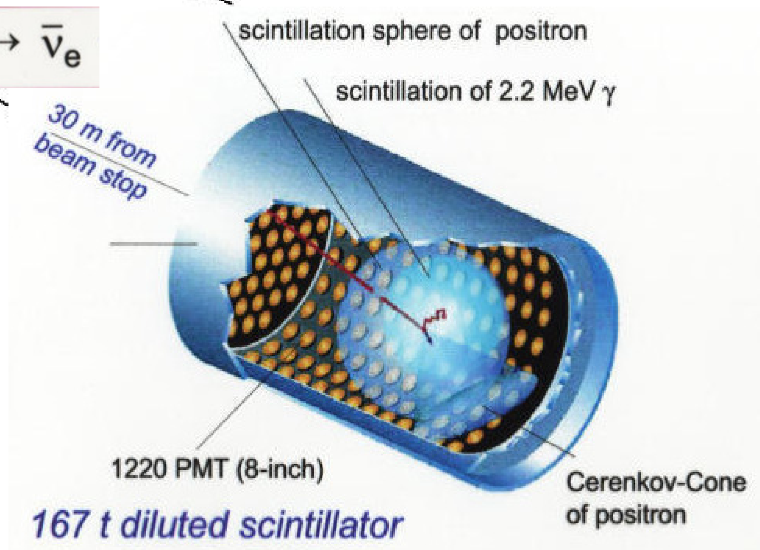
1993 - 1998

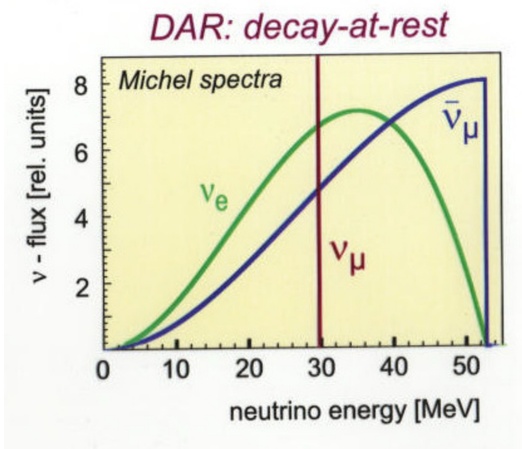


$$p \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\bar{\nu}_\mu \xrightarrow[\text{oscillation}]{\text{flavour}} \bar{\nu}_e$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow \quad \tau = 186\ \mu s$$
$$p(n,\gamma)d \quad (2.2\ \text{MeV})$$





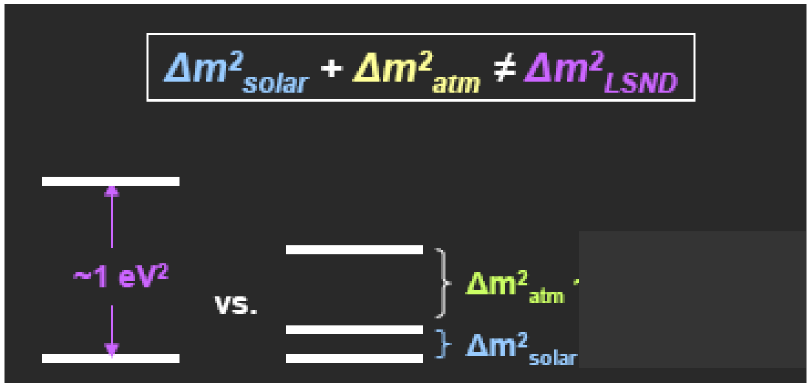
LSND anomaly

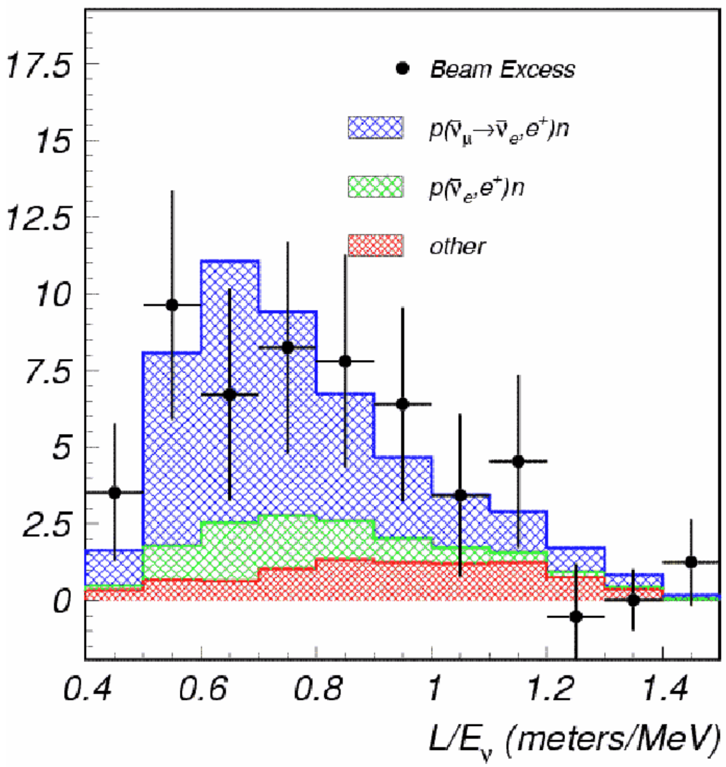
LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam

Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)

Oscillation probability: 0.264 ± 0.067 ± 0.045

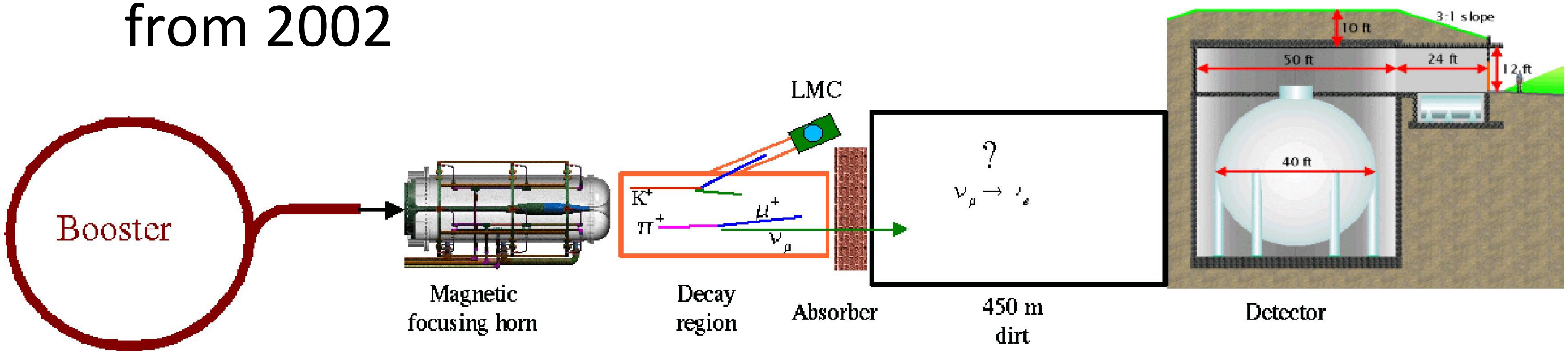
Δm^2 : 0.2 – 10 eV^2





MiniBooNE

from 2002

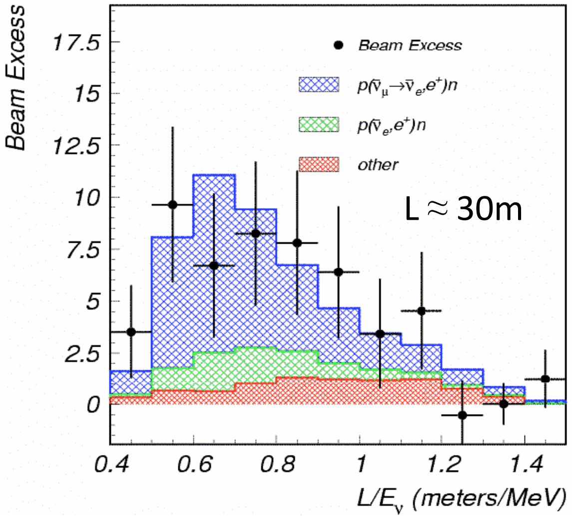


- Test the LSND anomaly
- Keep L/E same, change beam and energy
- 8 GeV proton beam (Be target)

neutrino energy (E):		**baseline (L):**	
MiniBooNE:	~700 MeV	MiniBooNE:	~540 m
LSND:	~30 MeV	LSND:	~30 m

- Mineral Oil Cherenkov Detector
- 800 tons, 12 m diameter sphere
- 1280 eight-inch PMT's
- 240 PMT for VETO
- 611,000 ν events

LSND and MiniBooNE

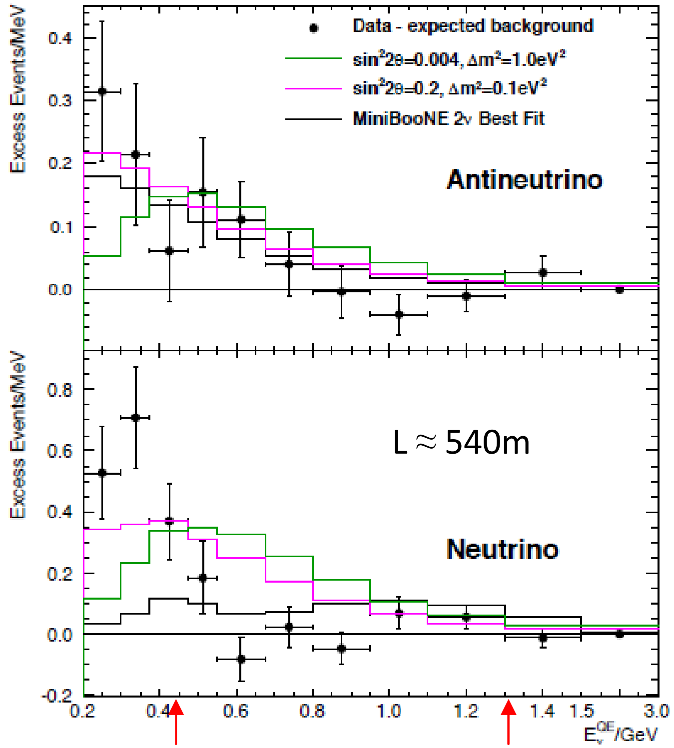


LSND has observed an excess of $\bar{\nu}_e$ events in $\bar{\nu}_\mu$ beam,

87.9 ±22.4 ±6.0 (3.8 σ)

Experiments showing negative evidence:

KARMEN, NOMAD, BUGEY, NUTEV



L/E ≈ 1.2 L/E ≈ 0.4

for 200 < E_{QE} < 1250 MeV

antineutrino: 78.4 ± 28.5 (2.8 σ)

neutrino: 162 ± 47.8 (3.4 σ)

for neutrinos the energy distribution is marginally compatible with a two neutrino oscillation formalism

MiniBoone results do not fully confirm the „LSND anomaly”

Positive hints

Anomaly	*Source*	*Type*	*Channel*	*Significance*
LSND	Short baseline	Decay at rest	-νμ –>νe CC	3.8 σ
MiniBoone	Short baseline	Neutrino beam	-νμ –>νe CC	**3.4 σ**
MiniBoone	Short baseline	Anti-Neutr. beam	anti-νμ –>νe CC	**2.8 σ**
Gallium	Electron capture	Source	ν disapp.	2.7 σ
Reactors	Fission	Beta decay	ν disapp.	3.0 σ

Zhang, Qian, Vogel: ***„Reactor antineutrino with known θ_{13}"*** → **1.4 σ**
(arXiv:1303.0900), Mar 2013

The ICARUS Collaboration

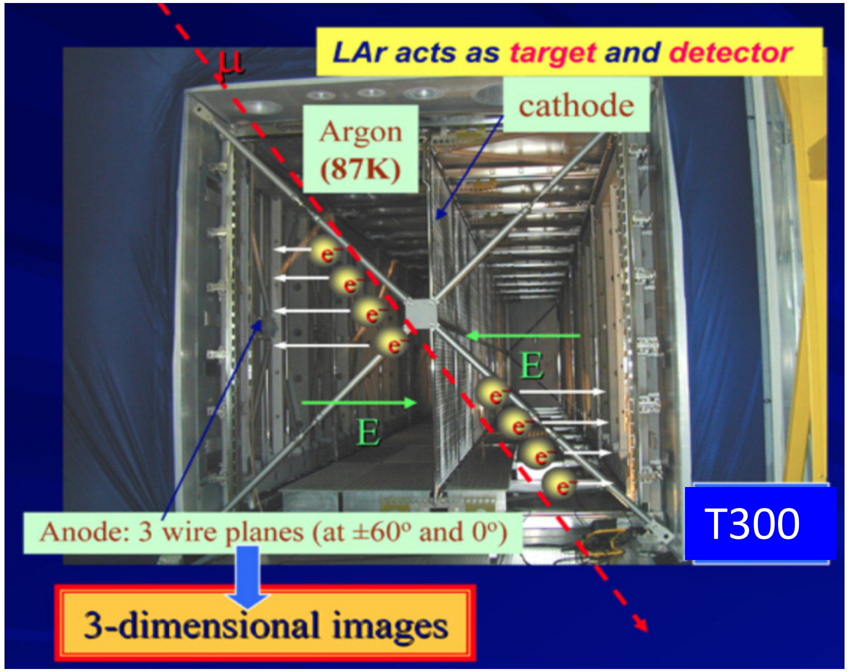
M. Antonello[a], P. Aprili[a], B. Baibussinov[b], M. Baldo Ceolin[b], P. Benetti[c], E. Calligarich[c], N. Canci[a], S. Centro[b], A. Cesana[f], K. Cieslik[g], D. B. Cline[h], A.G. Cocco[d], A. Dabrowska[g], D. Dequal[b], A. Dermenev[i], R. Dolfini[c], C. Farnese[b], A. Fava[b], A. Ferrari[j], G. Fiorillo[d], D. Gibin[b], A. Gigli Berzolari[c], S. Gninenko[i], A. Guglielmi[b], M. Haranczyk[g], J. Holeczek[l], A. Ivashkin[i], J. Kisiel[l], I. Kochanek[l], J. Lagoda[m], S. Mania[l], G. Mannocchi[n], A. Menegolli[c], G. Meng[b], C. Montanari[c], S. Otwinowski[h], L. Periale[n], A. Piazzoli[c], P. Picchi[n], F. Pietropaolo[b], P. Plonski[o], A. Rappoldi[c], G.L. Raselli[c], M. Rossella[c], C. Rubbia[a,j], P. Sala[f], E. Scantamburlo[e], A. Scaramelli[f], E. Segreto[a], F. Sergiampietri[p], D. Stefan[a], J. Stepaniak[m], R. Sulej[m,a], M. Szarska[g], M. Terrani[f], F. Varanini[b], S. Ventura[b], C. Vignoli[a], H. Wang[h], X. Yang[h], A. Zalewska[g], K. Zaremba[o]

a *Laboratori Nazionali del Gran Sasso dell'INFN, Assergi , Italy*
b *Dipartimento di Fisica e INFN, Università di Padova, Italy*
c *Dipartimento di Fisica Nucleare e Teorica e INFN, Università di Pavia, Italy*
d *Dipartimento di Scienze Fisiche, INFN e Università Federico II, Napoli, Italy*
e *Dipartimento di Fisica, University of L'Aquila, Italy*
f *INFN, Sezione di Milano e Politecnico, Milano, Italy*
g *Institute of Nuclear Physics, Polish Academy of Science, Krakow, Poland*
h *Department of Physics and Astronomy, University of California, Los Angeles, USA*
i *INR RAS, prospekt 60-letiya Oktyabrya 7a, Moscow, Russia*
j *CERN, Ch1211 Geneve 23, Geneva, Switzerland*
l *Institute of Physics, University of Silesia, 12 Bankowa st., 40-007 Katowice, Poland*
m *A. Soltan Institute for Nuclear Studies, 05-400 Swierk/Otwock, Warszawa, Poland*
n *Laboratori Nazionali di Frascati (INFN), Frascati, Italy*
o *Institute for Radioelectronics, Warsaw Univ. of Technology, Warsaw, Poland*
p *Dipartimento di Fisica, Università di Pisa, Italy*

The ICARUS detector (T600)

The **Liquid Argon Time Projection Chamber** (*electronic bubble chamber*)
[C. Rubbia: CERN-EP/77-08 (1977)] capable of providing a 3D imaging of any charged particle with:

- high granularity (spatial resolution of the detector ~ 1 mm^3);
- excellent calorimetric properties.

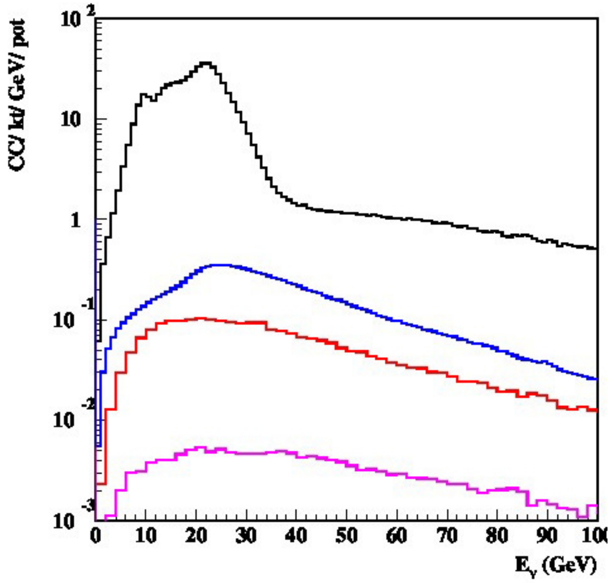


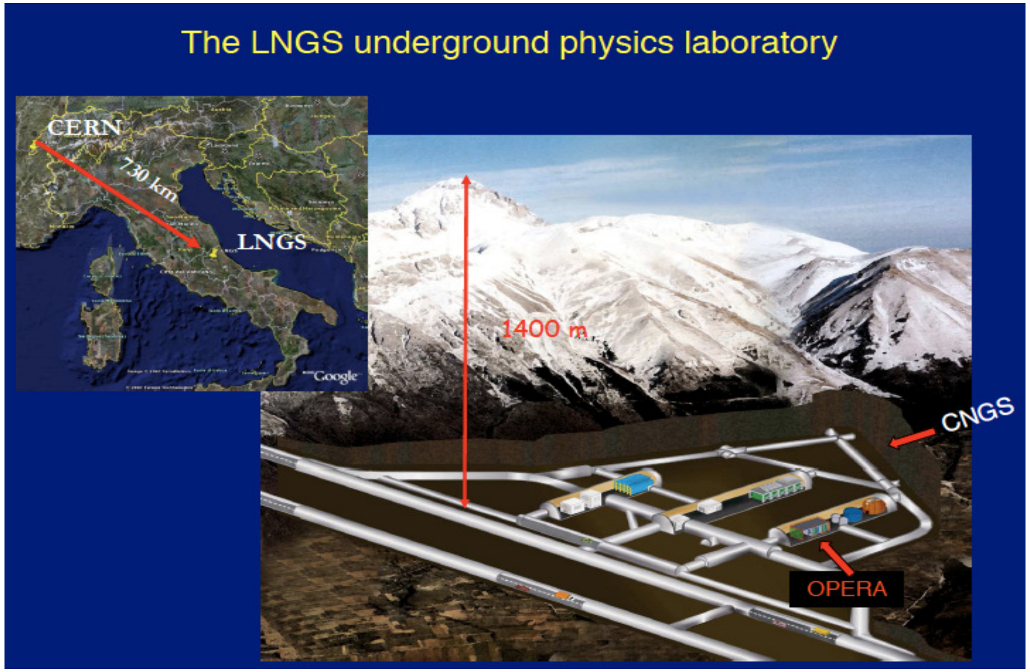
- ionization and scintillation signals are exploited,
- PMTs signal is used for triggering,
- continuous probing of wire signals as a function of time allows 3D reconstruction.
- very pure argon : $\tau_{ele} > 5$ ms

- Total LAr mass 600 t, active mass 476 t
- Two identical T300 modules
  (2 TPC chambers for each module).
- TPC characteristics:
  - (17.9 x 3.1 x 1.5 for each TPC) m3;
  - drift length = 1.5 m;
  - E_{drift} = 0.5 kV/cm; v_{drift} = 1.6 mm/μs.
- 3 readout wire planes/chamber at 0°, +-60°,
  3 mm plane and wire spacing:
  - ~ 53000 wires;
  - two induction planes and one collection
- PMTs for scintillation light (128 nm):
  - (20+54) PMTs.

CNGS – CERN Neutrinos to Gran Sasso

Conventional beam based on protons from the SPS accelerator at CERN



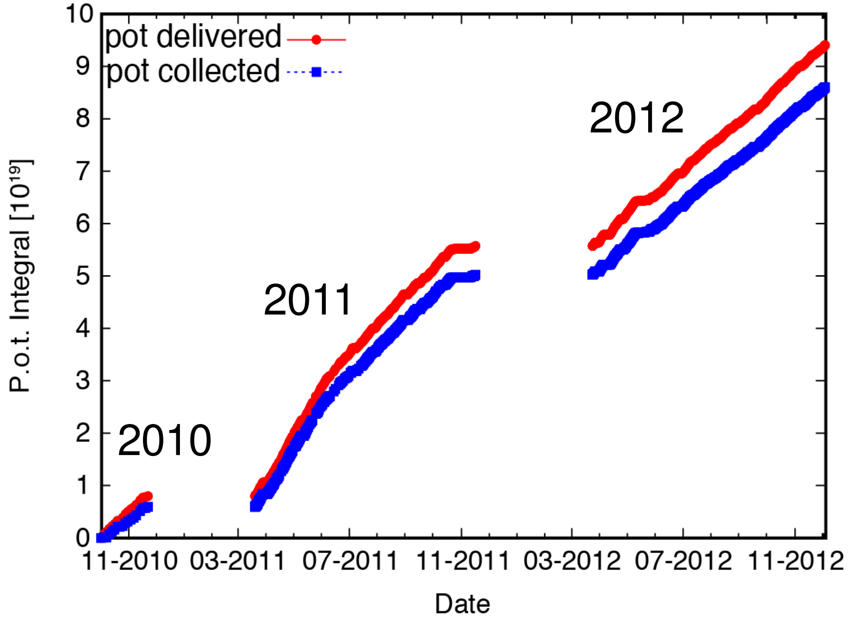


E → 10 - 30 GeV, L ≈ 730 km

ν_e/ν_μ ~ 0.8%, $\bar{\nu}_\mu/\nu_\mu$ ~ 2.1%, $\bar{\nu}_e/\nu_\mu$ ~ 0.07%

CNGS data taking

- CNGS data useful for analysis (01.10.2010 – 03.12.2012)
- Technical run with cosmics (Dec. 2012 – Jun. 2013)
- Trigger based on PMT signals, in coincidence with proton extraction
- detector live-time > 93%
- total 8.6 x 10^{19} pot collected



LAr T600 reconstruction performance

Tracking:

- The tracking is done with high sampling (~ 3mm)
- Muon momentum via multiple scattering

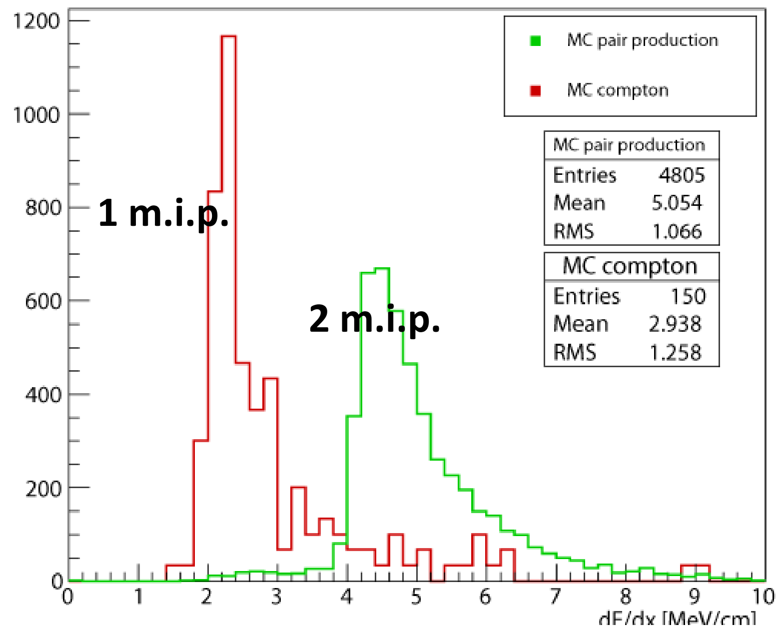
Total energy reconstruction from charge integration

ENERGY RESOLUTIONS:

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

Measurement of local energy deposition dE/dx:

- Very good e/π^0 separation by means of dE/dx in the first part of the cascade
- Particle identification by dE/dx vs range

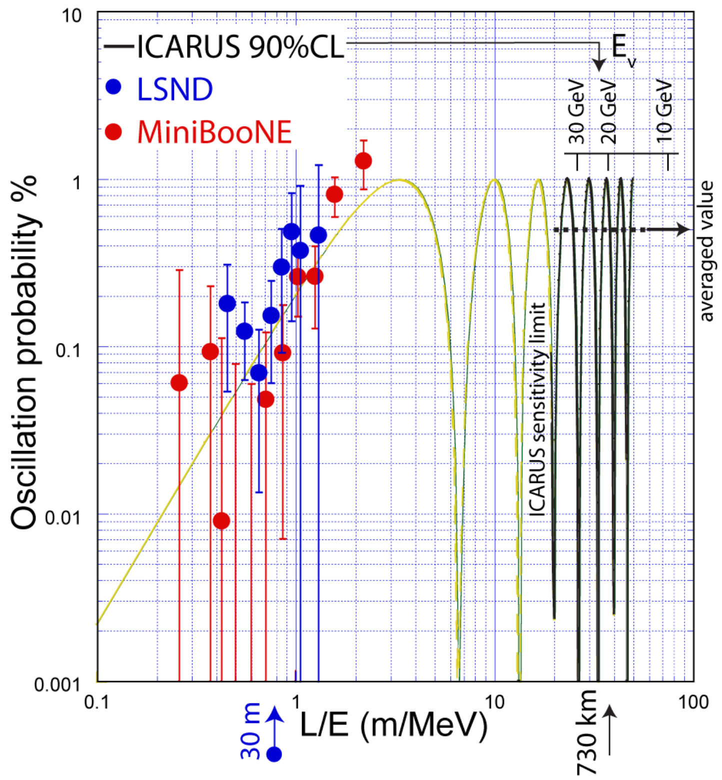


A search for the LSND effect in the ICARUS T600

- Search for $\nu_\mu \rightarrow \nu_e$ appearance in CNGS beam neutrinos
  - L = 730 km, E = 10 – 30 GeV

- Differences w.r.t. the LSND experiment:
  - L/E ≈ 1 m/MeV at LSND
    L/E ≈ 36.5 m/MeV at CNGS
  - LSND-like short distance oscillation signal averages to: $\sin^2(1.27\Delta m^2 L/E) \approx ½$
    $\langle P \rangle_{\nu_\mu \rightarrow \nu_e} \approx ½ \sin^2(2\theta)$

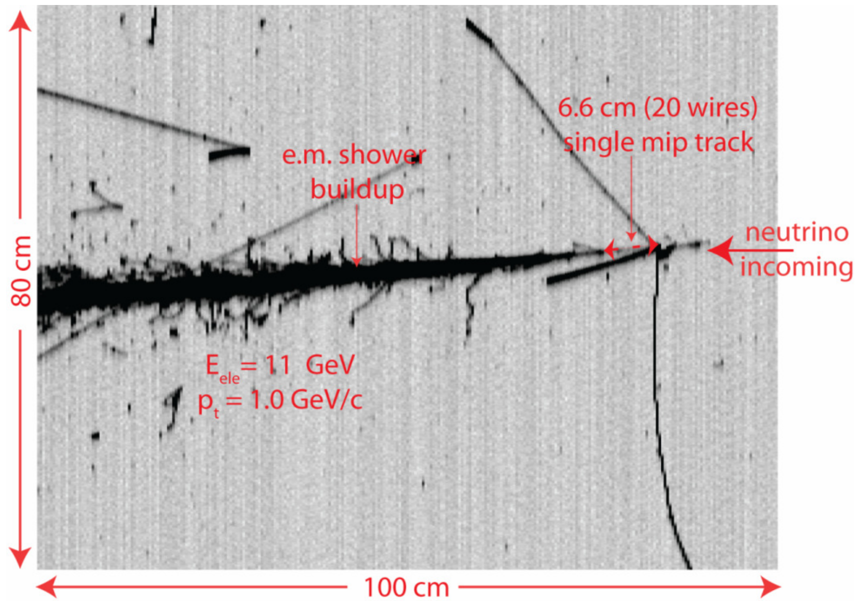
- ICARUS operates in a L/E region in which contributions from standard neutrino oscillations are not yet too relevant



Selection of ν_e events

- the signature of ν_e is observed visually
- primary vertex min. 5 cm from wall and min. 50 cm from downstream wall to allow shower identification
- visible energy < 30 GeV (~50% reduction on the ν_e from the beam and only 15% signal events rejected)
- ν_μCC events identified by track without hadronic interaction with lenght > 250 cm from the primary vertex (a muon candidate)
- A charged track from primary vertex, m.i.p. on 8 wires (dE/dx < 3.1 MeV/cm) , developing into EM-shower
- Clear separation (150 mrad) from other tracks at the vertex in at least one of two transverse views
- Selection efficiency validated on MC sample of the ν_e events (3 independent scanners):

$\eta = 0.74 \pm 0.05$

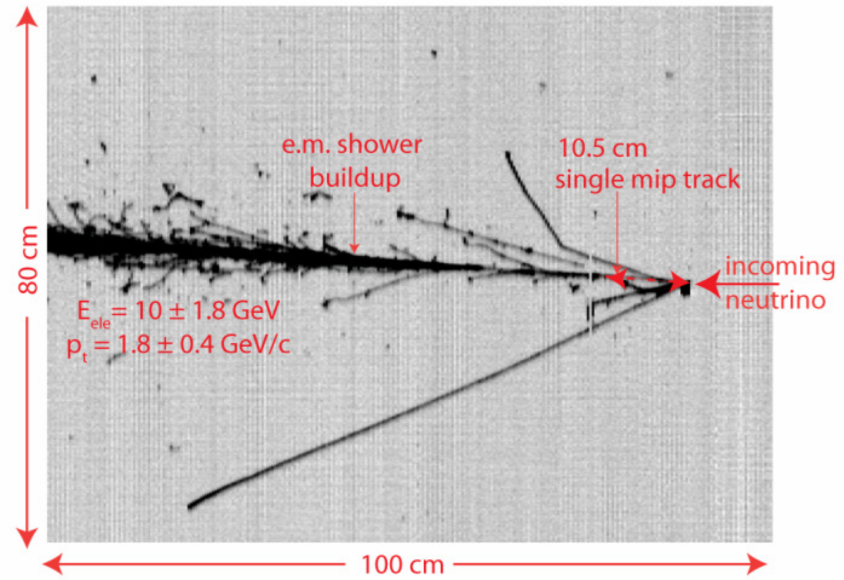


MC event (only the vertex region is shown)
E_ν= 11 GeV, p_t= 1.0 GeV/c

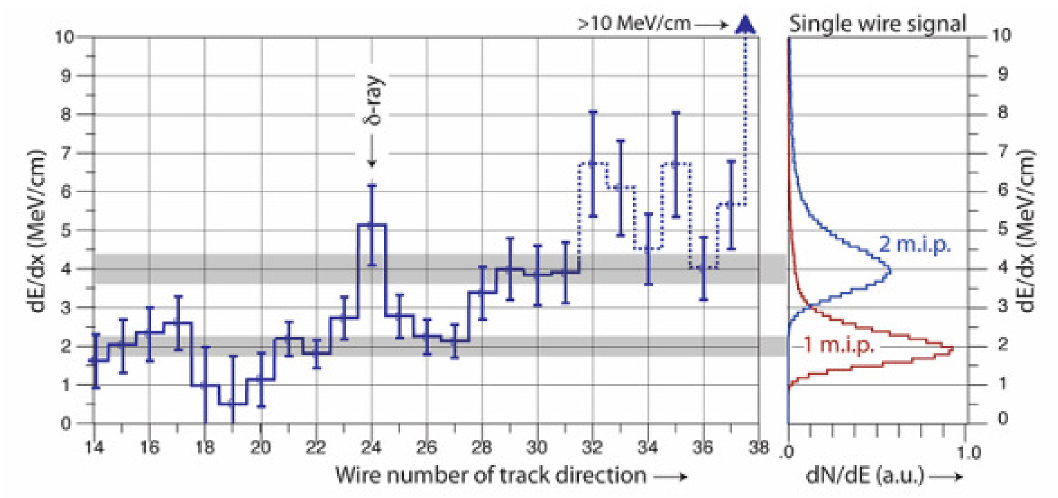
Event rates

- Presented results (arXiv:1307.4699 Jul 2013) refer to 1995 neutrino interactions ($6.0 \cdot 10^{19}$ pot)
- The expected number of ν_e events due to conventional sources:
  - 5.7 ± 0.8 events due to ν_e beam contamination,
  - 2.3 ± 0.5 events due to the oscillations $\nu_\mu \rightarrow \nu_e$
  - 1.3 ± 0.1 events due to the oscillations $\nu_\mu \rightarrow \nu_\tau$ with $\tau \rightarrow e$
- Taking into account the selection efficiency, the expected number of the ν_e events is then: 6.4 ± 0.9 (syst. only)
- 4 ν_e events observed in the data

One of four candidate signal events observed in the data

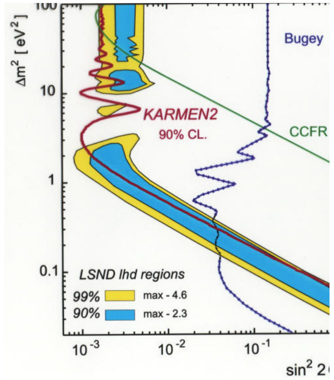


$E_{tot} = 11.5 \pm 1.8$ GeV,
$p_t = 1.8 \pm 0.4$ GeV/c



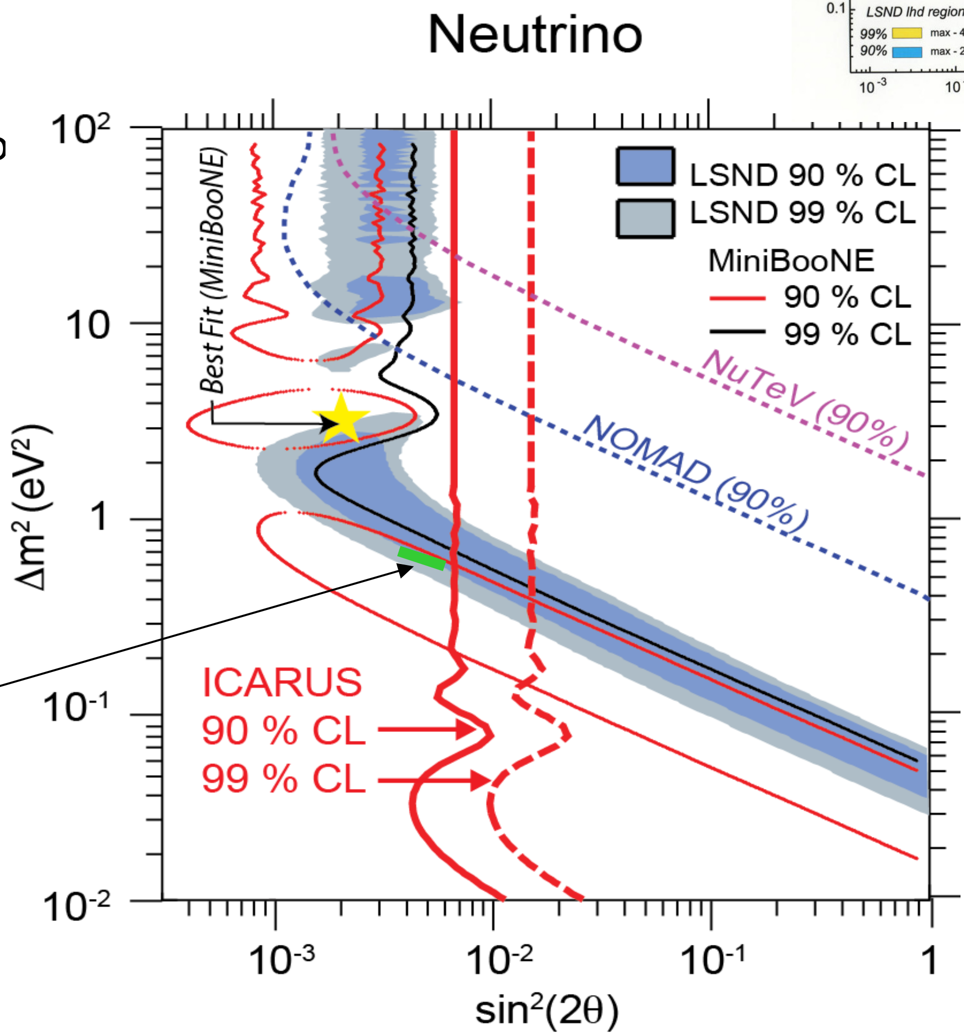
In all events: single electron shower clearly separated from hadronic component in the transverse plane

ICARUS results on the LSND anomaly



- 4 ν_e events observed considering 6.4 ± 0.9 expected background
- Limits on number of events due to LSND anomaly:
  - 3.68 (90% CL)
  - 8.34 (99% CL)
- the corresponding limits on oscillation probability are:
  - $P(\nu_\mu \rightarrow \nu_e) \leq 3.4 \cdot 10^{-3}$ (90% CL)
  - $P(\nu_\mu \rightarrow \nu_e) \leq 7.6 \cdot 10^{-3}$ (99% CL)

$P(\nu_\mu \rightarrow \nu_e) \approx 1/2 \sin^2(2\theta)$



„LSND anomaly" surviving area 90% CL based on all experimental results

ICARUS result strongly limits the window of possible parameters for LSND anomaly indicating a narrow region: $0.4 < \Delta m^2 < 0.7$ and $0.002 < P(\nu_\mu \rightarrow \nu_e) < 0.003$

Conclusions

- The ICARUS result strongly limits the window of possible parameters for LSND anomaly indicating a narrow region around:

  $(\Delta m^2, \sin^2 2\theta) = (0.5\ eV^2, 0.005)$

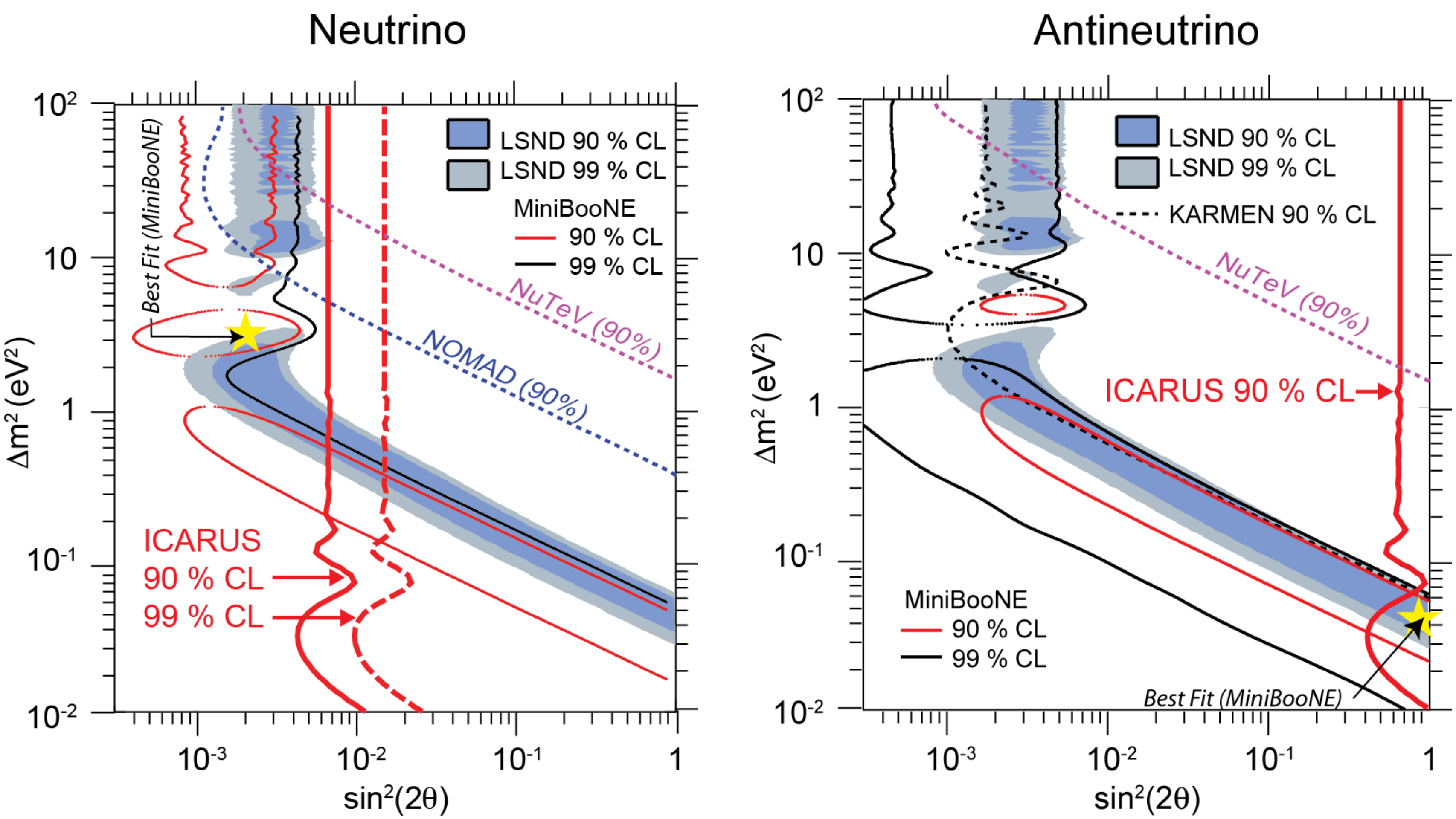
  - where there is an overall agreement (90 % CL) between:
    - the present ICARUS limit
    - the limits of KARMEN
    - the positive signals of LSND and MiniBooNE

- The OPERA experiment also performing on the CNGS beam has confirmed our finding with a bit greater limit: $\sin^2(2\theta) < 7.2\times10^{-3}$

- Definitive answer to the sterile ν search would be given by the experiment at CERN with ICARUS T600 and a new 150 t detectors at 1.6 km and 460 m baselines exposed to a new 2GeV neutrino beam.

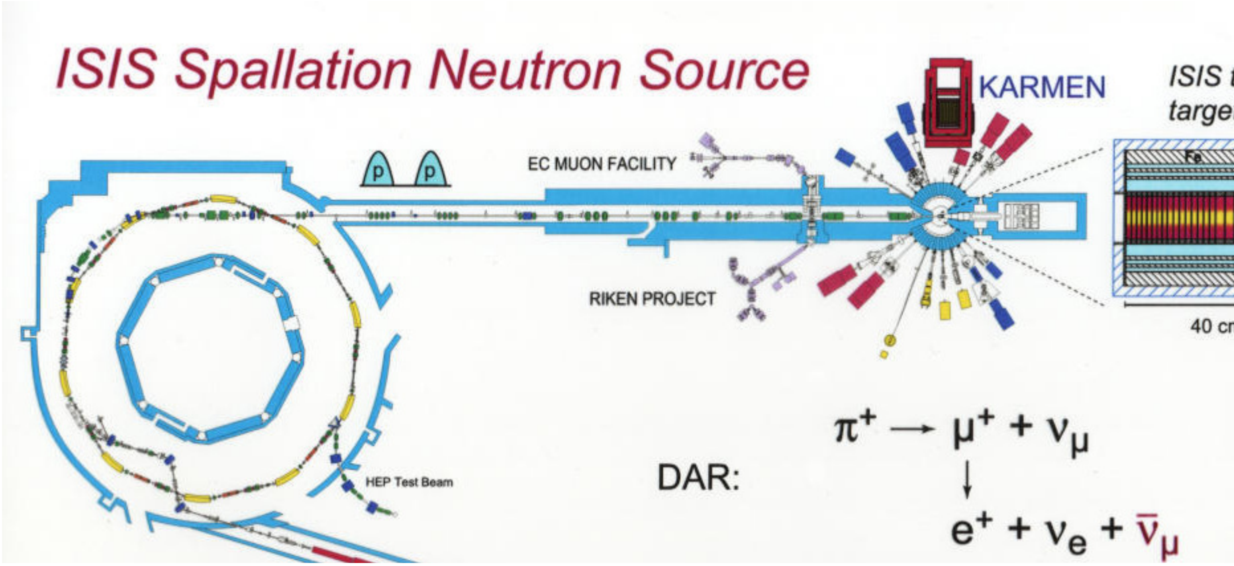
BACK-UP

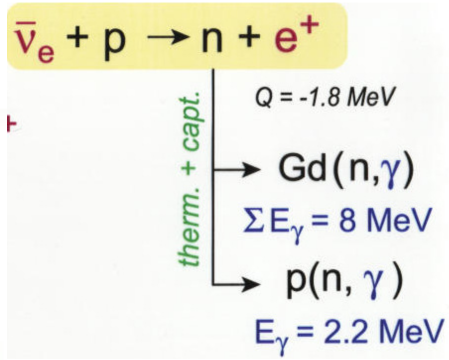
ICARUS results on the LSND-like anomaly



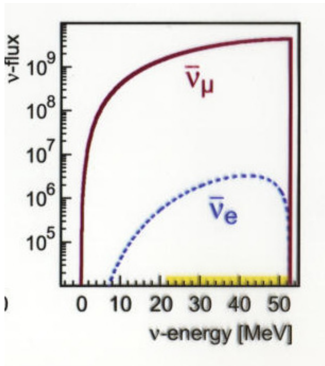
KARMEN

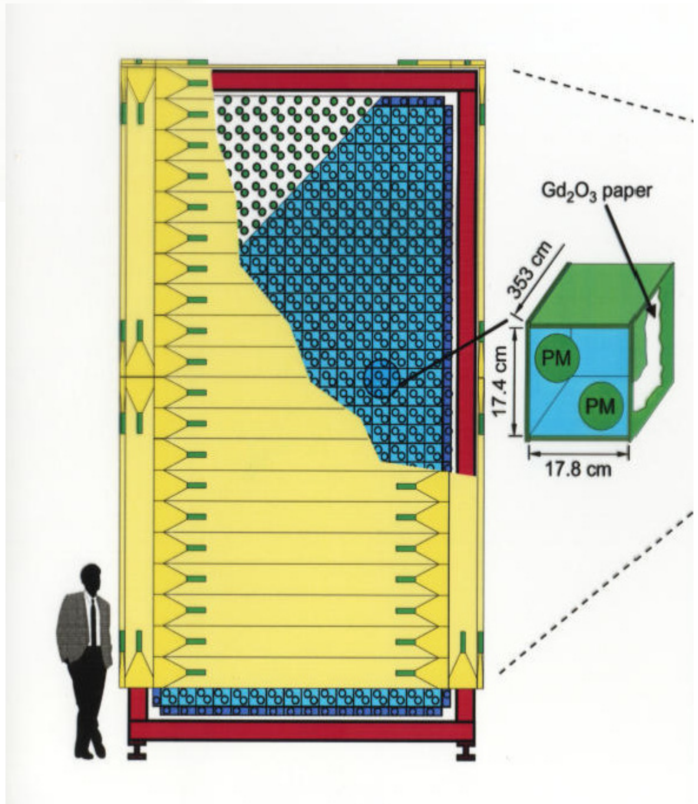
1997 - 2001





- 50 t scintillator (5.6 x 3.2 x 3.5) m³
- L ≈ 18 m
- E < 50 MeV
- L/E = 0.4 - 1

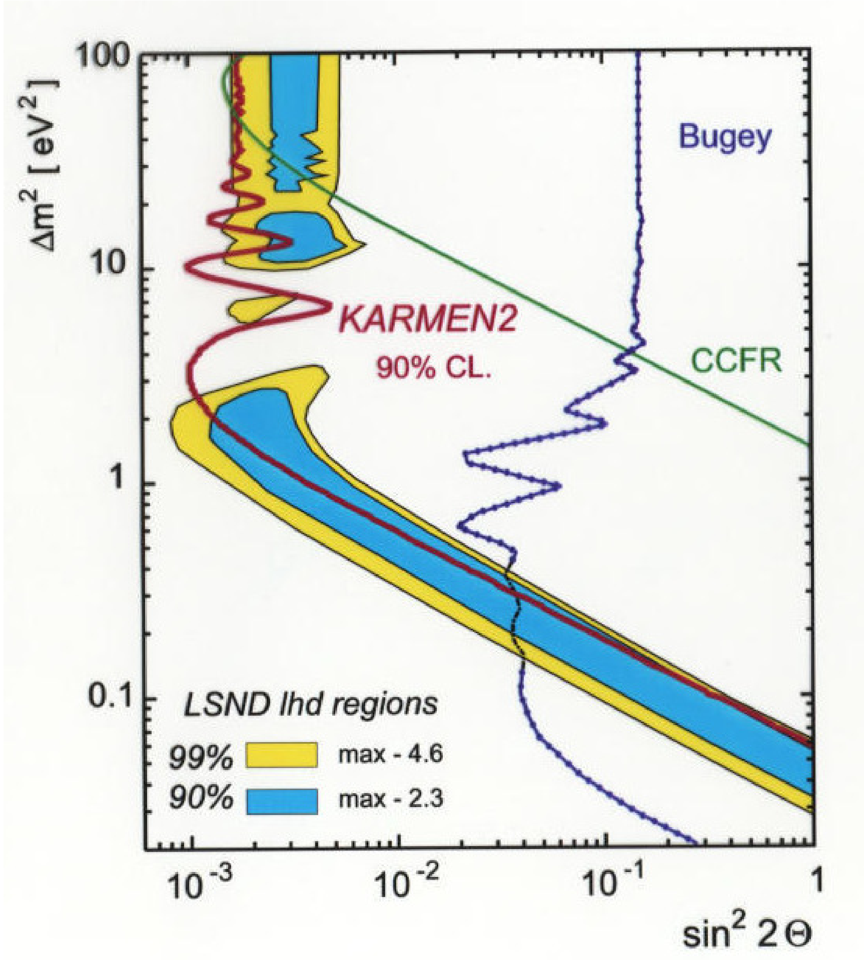




KARMEN – no oscillation excess

- candidate events : 15
- background : 15.8 ± 0.5
  - cosmic : 3.9 ± 0.2
  - ν_e from CC : 9.9 ± 0.4
  - $-\nu_e$ contamination : 2.0 ± 0.2

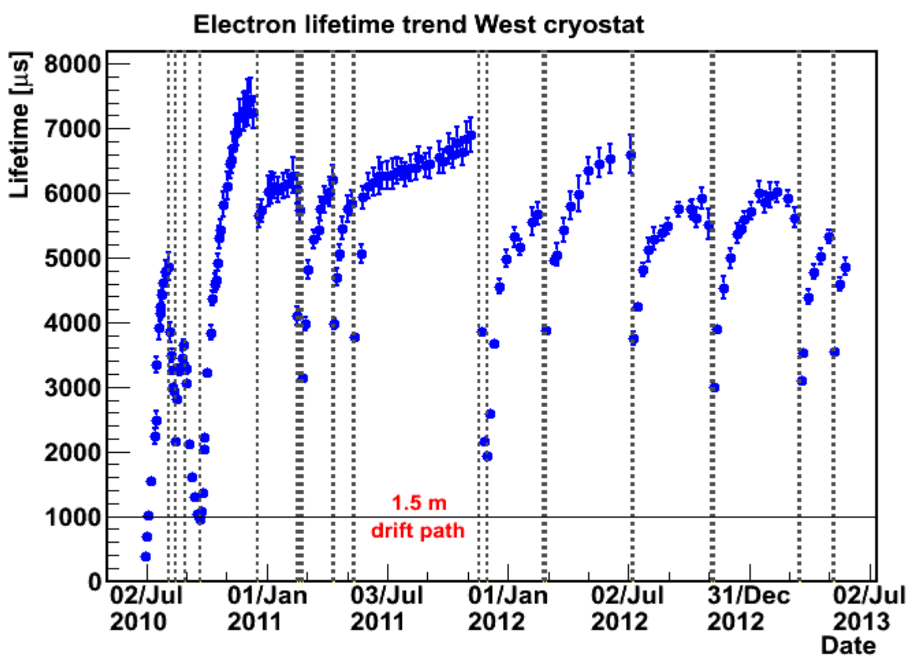
- oscillation limit:
  - for $\Delta m^2 > 1\ eV^2$: $\sin^2\theta < 0.0017$
  - $0.2 < \Delta m^2 < 1\ eV^2$: $10^{-3} < \sin^2\theta < 3 \cdot 10^{-2}$

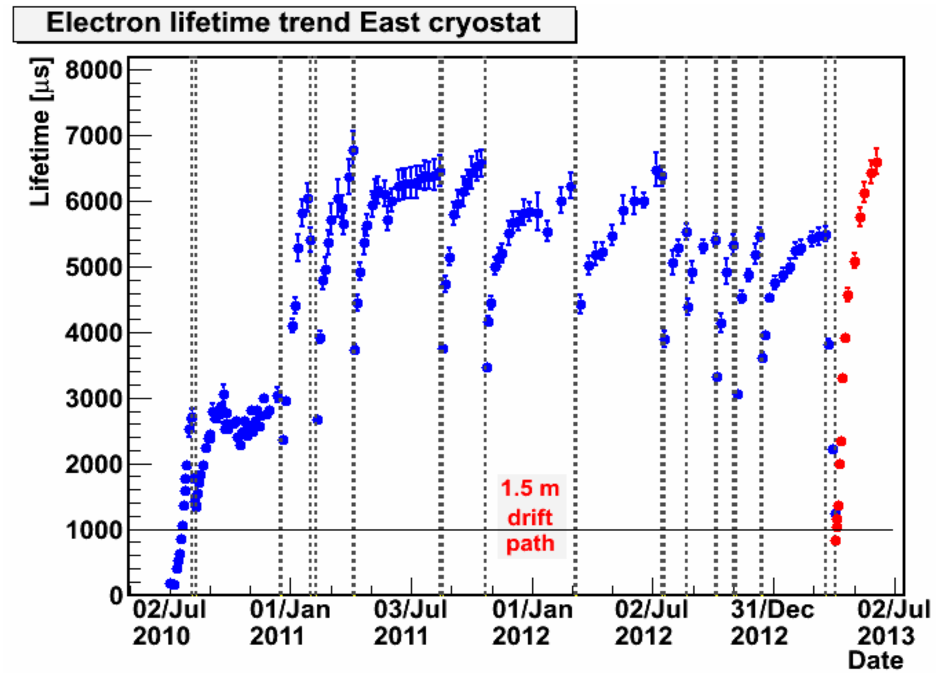


LAr purification

Key feature: LAr purity from electro-negative molecules (O_2, H_2O,$C0_2$).

LAr continuously filtered, electron ionization life-time is measured

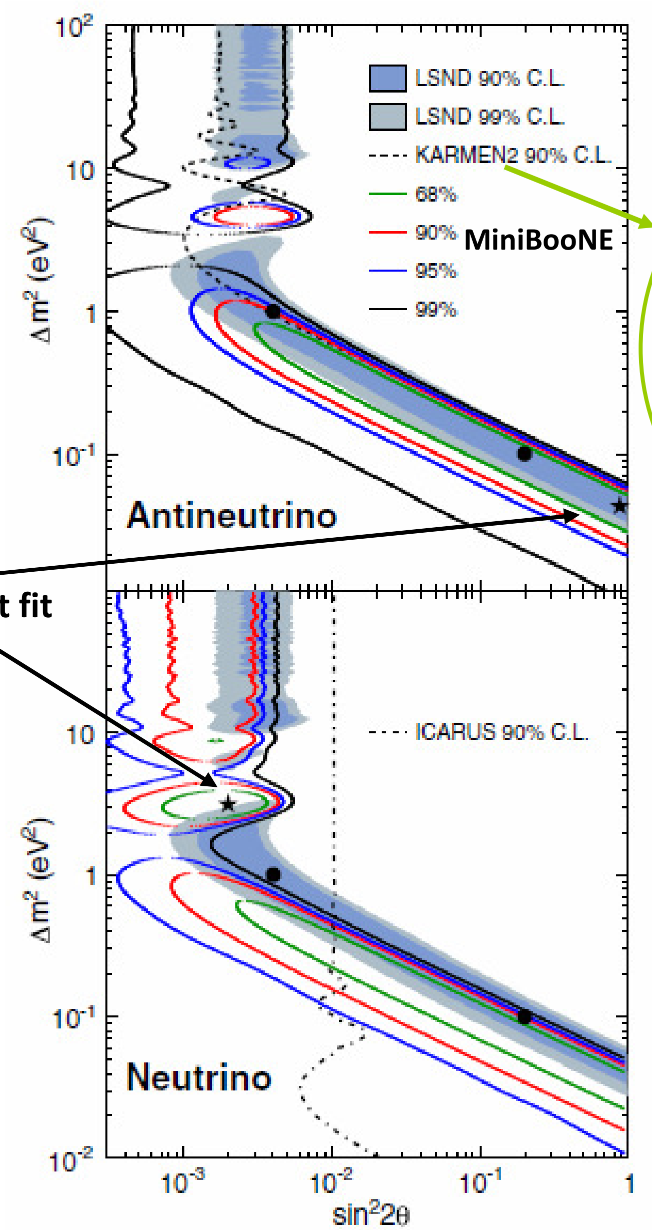




corresponding to a maximum charge attenuation of 17% at 1.5m

Would allow operation at larger drift distances

LSND anomaly area



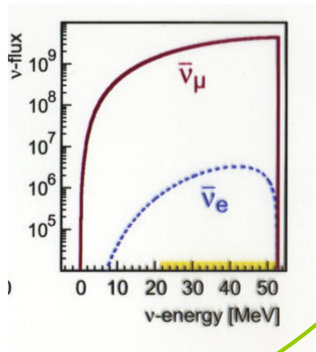
Best fit

KARMEN – negative evidence

1997 - 2001

$\bar{\nu}_\mu \xrightarrow[\text{oscillation}]{\text{flavour}} \bar{\nu}_e + p \rightarrow e^+ + n$

- 50 t scintillator (5.6 x 3.2 x 3.5) m**3**
- L ≈ 18 m E < 50 MeV
- background : 15.8 ± 0.5
- candidate events : 15



Other exp. with the negative evidence:

NOMAD, BUGEY, NUTEV

MiniBooNE : PRL 110, 161801 (19 April 2013)