Results from the ICARUS experiment and future of the T600 detector

KRZYSZTOF CIESLIK
for the ICARUS Collaboration

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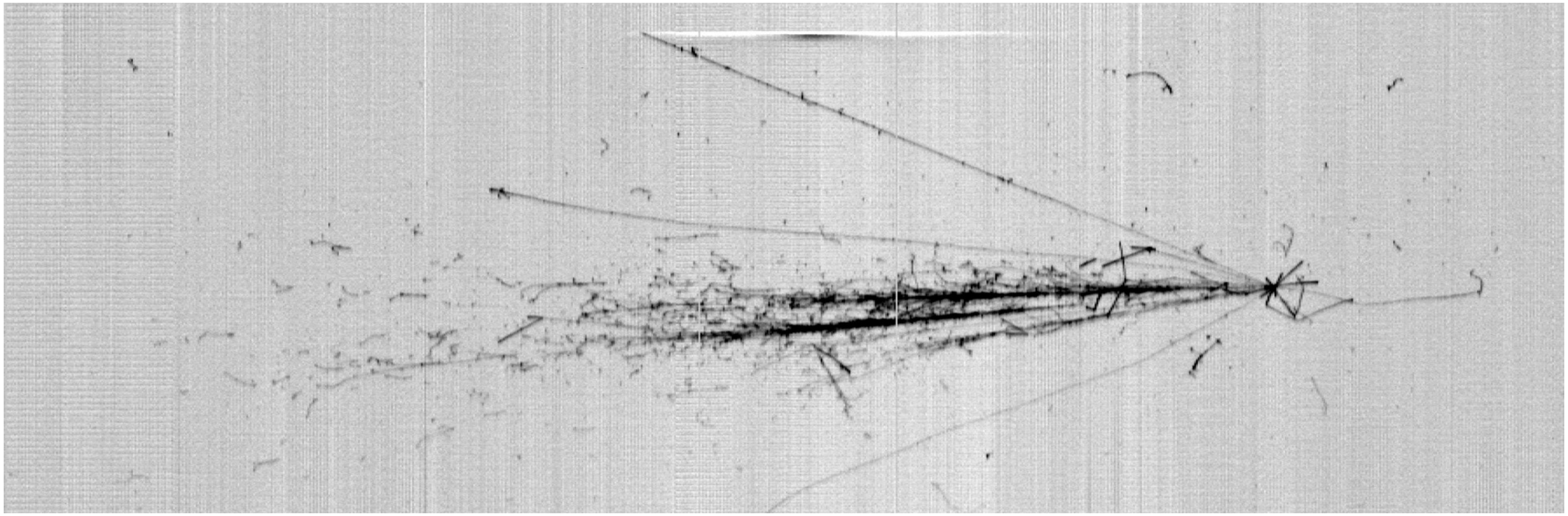

Outline

- The ICARUS experiment
- Main results of the ICARUS experiment
- Future of the T600 detector
- Conclusions

The ICARUS Collaboration

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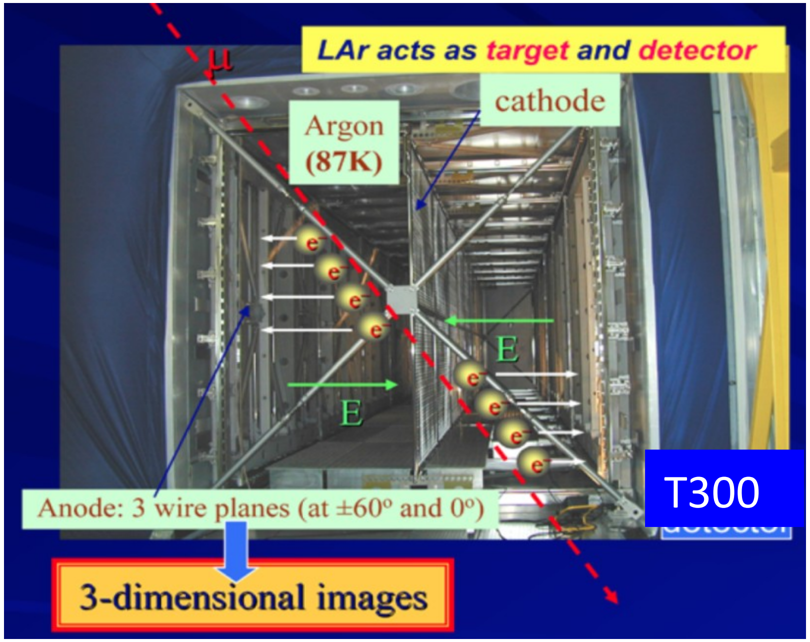
The ICARUS detector (T600)

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.

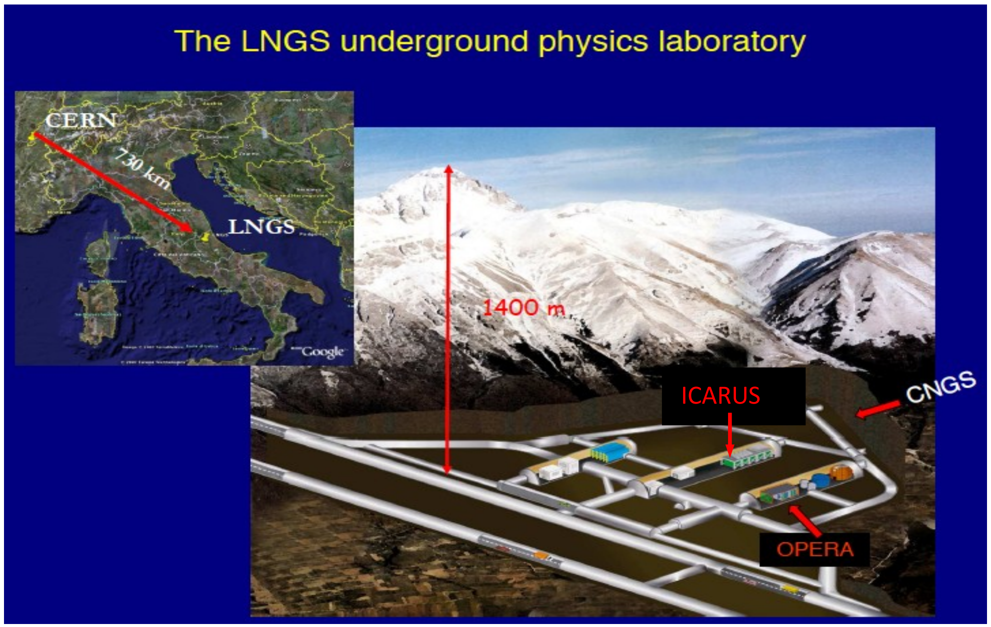


- ionization and scintillation signals are exploited,
- PMTs signal is used for triggering,
- continuous probing of wire signals as a function of time allows 3D reconstruction.
- very pure argon : τ_{ele} > 7 ms

- 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) m^3;
  - 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



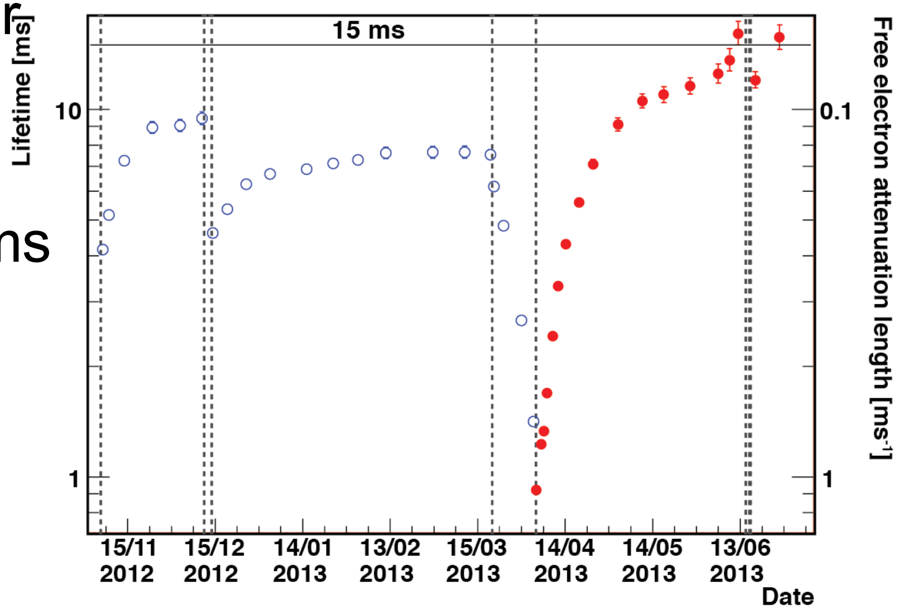
- CNGS data useful for analyzes (01.10.2010 - 03.12.2012)
- Technical run with cosmics (Dec. 2012 – Jun. 2013)
- detector live-time > 93%
- total 8.6 x 10^{19} pot collected

E → 10 - 30 GeV, L ≈ 730 km

$\nu_e/\nu_\mu \sim 0.8\%$, $\nu_\mu/\bar{\nu}_\mu \sim 2.1\%$, $\nu_e/\nu_\mu \sim 0.07\%$

ICARUS T600 LAr purity

- The electron lifetime τ_{ele} is crucial for LAr TPC performance and strongly depends on the LAr purity
- ICARUS has operated with $\tau_{ele} > 7$ ms
- After installation of new pumps on April 4th 2013 $\tau_{ele} > 14$ ms
- ICARUS has demonstrated the effectiveness of the single phase LAr-TPC technique, paving the way to huge detectors with ~5 m drift length



LAr T600 reconstruction performance

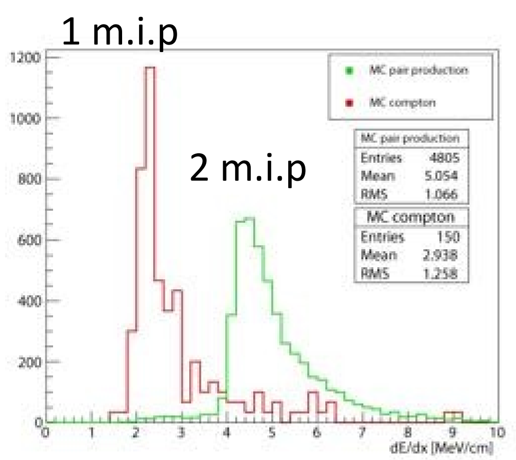
Tracking:

- The 3D tracking is done with high spatial resolution (~ 1 mm^3)
- Muon momentum via multiple scattering ($\Delta p/p$ ~16% in the 0.4-4 GeV/c range).

Total energy reconstruction from charge integration

ENERGY 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) $\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$

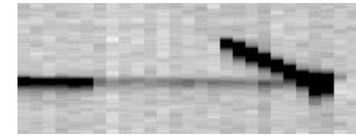


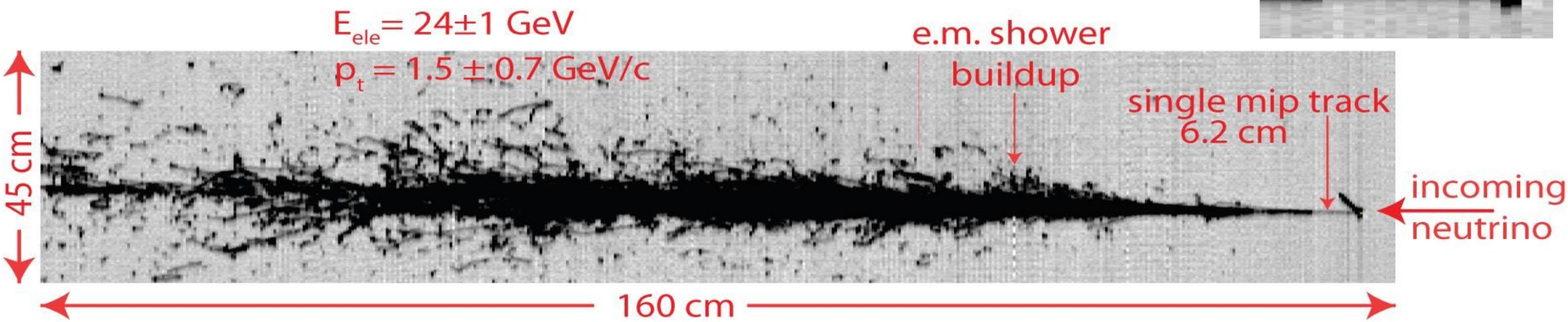
Measurement of local energy deposition dE/dx:

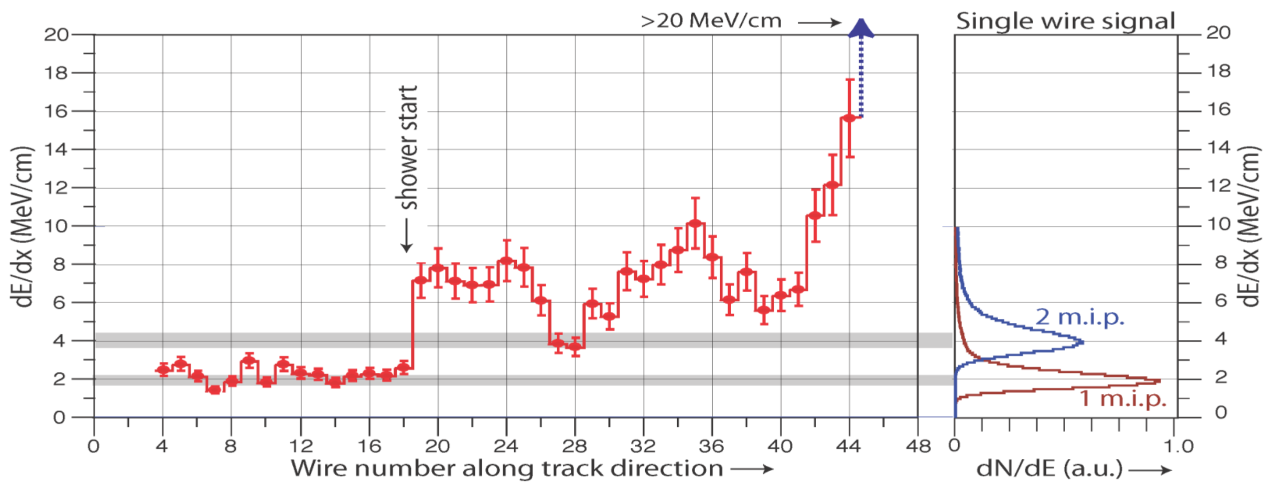
- Very good e/π^0 separation by means of dE/dx in the first part of the cascade
- Particle identification by dE/dx vs range

e/γ separation in ICARUS

• Unique detection properties of Lar-TPC technique allow to identify unambiguously individual e-events with high efficiency.







The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.

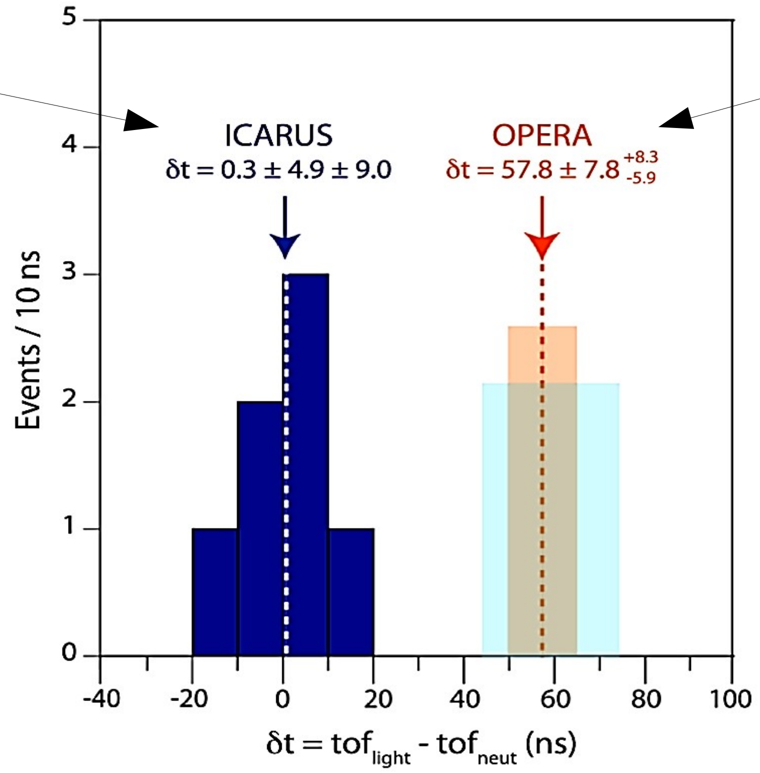
Main results of the ICARUS experiment

- **"Operation and performance of the ICARUS-T600 cryogenic plant at Gran Sasso underground Laboratory",** (2015), sub. to JINST,
- **"Experimental observation of an extremely high electron lifetime with the ICARUS-T600 Lar-TPC",** (2014), JINST 9 P12006,
- **"The trigger system of the ICARUS experiment for the CNGS beam",** (2014), JINST 9 P08003,
- **"Precise 3D track reconstruction algorithm for the ICARUS T600 liquid argon time projection chamber detector",** (2013), Advances in High Energy Physics, AHEP, Volume 2013, Article ID 260820,
- **"Experimental search for the 'LSND anomaly' with the ICARUS LAr-TPC detector in the CNGS beam",** (2013), Eur. Phys. J. C 73:2345,
- **"Search for anomalies in the ve appearance from a vμ beam",** (2013), Eur. Phys. J. C 73:2599,
- **"Measurement of the neutrino velocity with the ICARUS detector at the CNGS beam",** (2012), Physics Letters B 713 17-22,
- **"Precision measurement of the neutrino velocity with the ICARUS detector in the CNGS beam"**, (2012) JHEP 11 (2012) 049
- **"A search for the analogue to Cherenkov radiation by high energy neutrinos at superluminal speeds in ICARUS"**, (2012), Physics Letters B 711 (2012) 270-275,
- **"Underground operation of the ICARUS T600 LAr-TPC: first results",** (2011), JINST 6 P07011.

Superluminal speeds of neutrinos

Mar 2012

Sep 2011



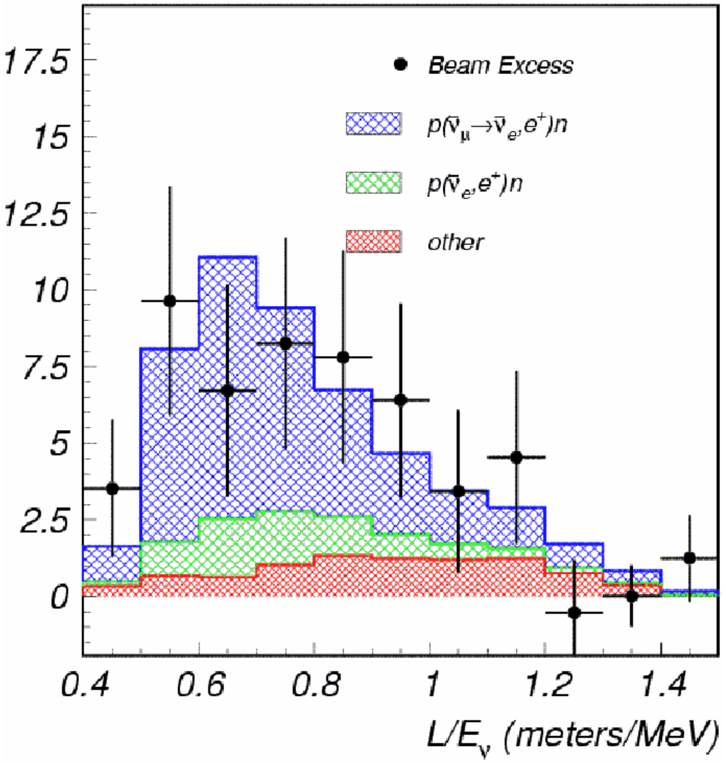
The main measurement error for OPERA experiment concerned the optical fiber connector which was not functioning correctly when the measurements were taken.

Sterile neutrinos

- Sterile neutrinos were hypothesized in 1957 by B.Pontecorvo as particles not interacting via 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.
- There are also disappearance anomalies in the anti-ν_e signal from the reactor experiments, and from the Mega-Curie sources in the solar neutrino experiments.

LSND (Liquid Scintillator Neutrino Detector) anomaly

Based on the data 1993 - 1998

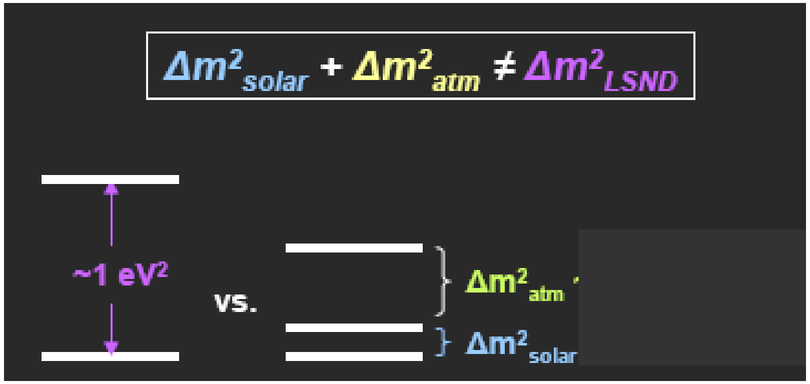


LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam

Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)

Oscillation probability: 0.264 ± 0.067 ± 0.045

Δm^2 : 0.2 – 10 eV^2



Search for the LSND/MiniBooNE effect in the ICARUS T600

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

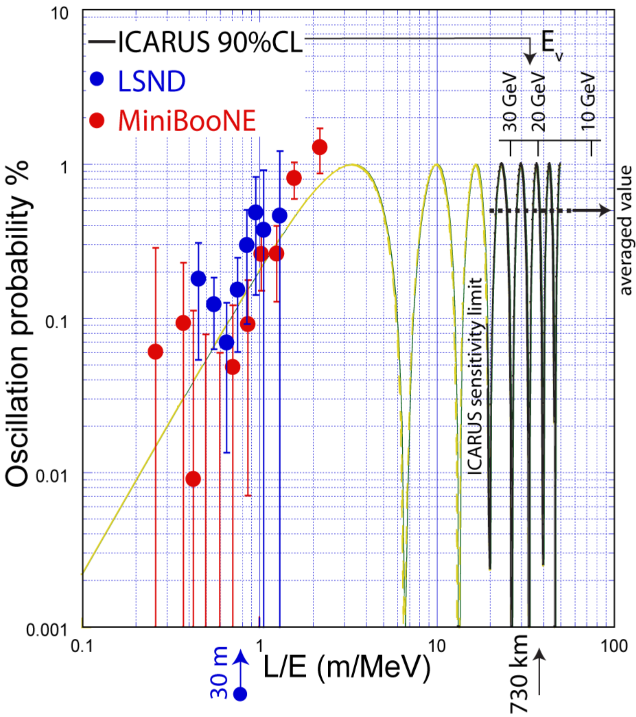
- Differences w.r.t. the LSND experiment:
  - L/E ≈ 1 m/MeV at LSND

    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



Search for sterile neutrinos - results

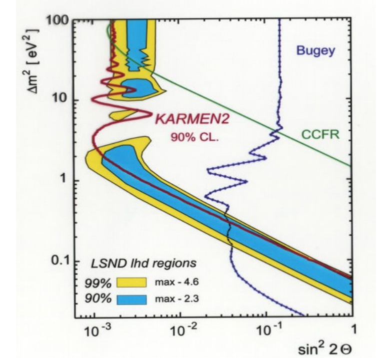
- New analysis w.r.t. the previously published result in Eur. Phys. J. C73:2599 (2013) and based on 1995 ν interactions (6.0 $\times 10^{19}$ pot).
- An additional sample of 455 ν interactions, corresponding to 1.2 $\times 10^{19}$ pot., has been added and the result based on 2450ν events and 7.2$\times 10^{19}$ pot (fully collected statistics - 8.6 $\times 10^{19}$ pot) is presented below.

The expected number of ν_e events due to conventional sources:

- 4.8 ± 0.6 events due to ν_e beam contamination,
- 2.0 ± 0.5 events due to the oscillations $\nu_\mu \rightarrow \nu_e$
- 1.1 ± 0.1 events due to the oscillations $\nu_\mu \rightarrow \nu_\tau$ with $\tau \rightarrow e$

- Total number of expected ν_e events: 7.9 ± 1.0 (syst. only)
- 6 ν_e events observed in the data

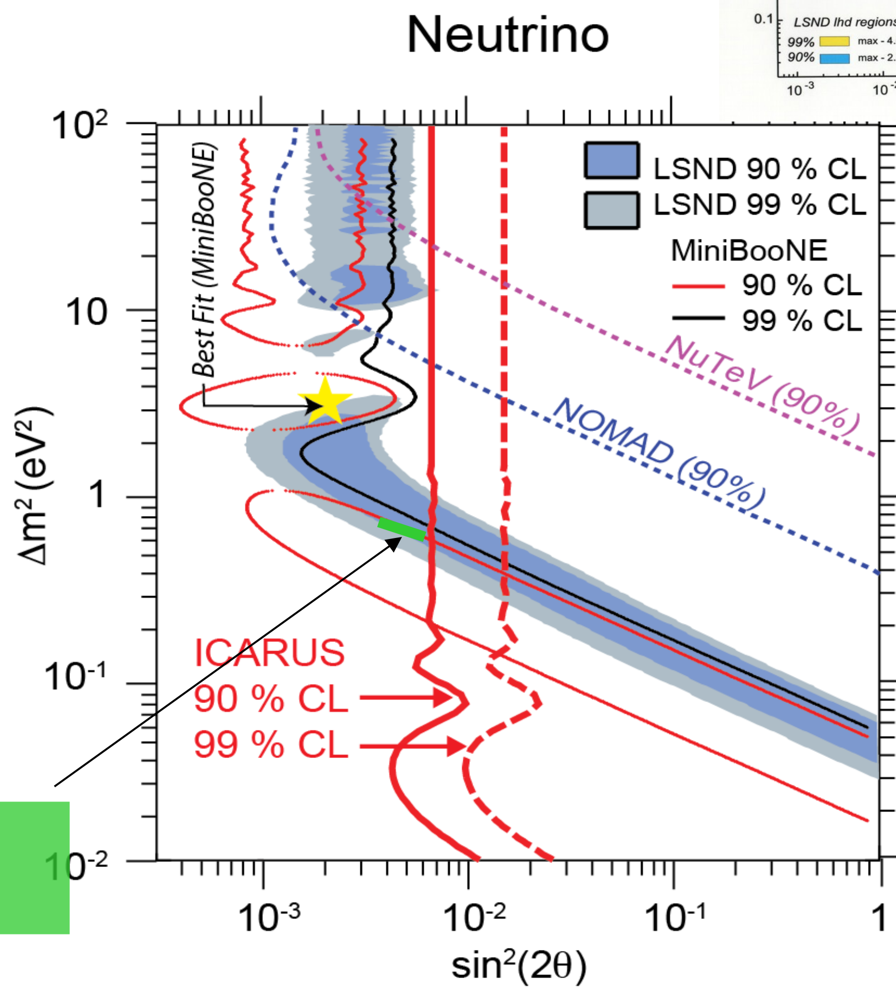
ICARUS results on the LSND/MiniBooNE anomaly



- 6 ν_e events have been observed in agreement with the expectations 7.9 ± 1.0 due to the conventional sources

- Limits on number of events due to LSND/MiniBooNE anomaly:
  5.2 (90% CL) and 10.3 (99% CL)

- the corresponding limits on oscillation probability are:
  - $P(\nu_\mu \rightarrow \nu_e) \leq 3.9 \cdot 10^{-3}$ (90% CL)
  - $P(\nu_\mu \rightarrow \nu_e) \leq 7.6 \cdot 10^{-3}$ (99% CL)



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

ICARUS result strongly limits the window of possible parameters for LSND/MiniBooNE anomaly indicating a narrow region:
$\Delta m^2 \approx 0.5$ eV^2, $\sin^2(2\theta) \approx 0.005$

Future of the ICARUS T600 detector

Part of the international Short Baseline Neutrino Oscillation Program at FNAL's BNB (and NuMI off-axis beam) with three detectors (near: Lar1-ND, mid: MicroBooNE, far: ICARUS at shallow depths) which will measure both ν_μ disappearance nad ν_e appearance. The LSND 99% CL reagion will be covered at the ~ 5σ level in 3 years data taking.

- The T600 was moved to CERN in Dec 2014 and is being upgraded within the WA104 experiment,
- The detector will be ready for the transportation to FNAL before the end of 2016
- The muon tagging system will be designed and constructed,
- Fully automatic tools for event reconstruction have to be developed,
- Start of the data taking with the beam is planned in Apr 2018

The ICARUS/WA104 Collaboration

CERN, Geneve, Switzerland
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Pavia University and INFN, Pavia, Italy
Padova University and INFN, Padova, Italy
Gran Sasso Science Institute, L'Aquila, Italy
INFN LNF, Frascati (Roma), Italy
INFN LNGS, Assergi (AQ), Italy
INFN Milano Bicocca, Milano, Italy
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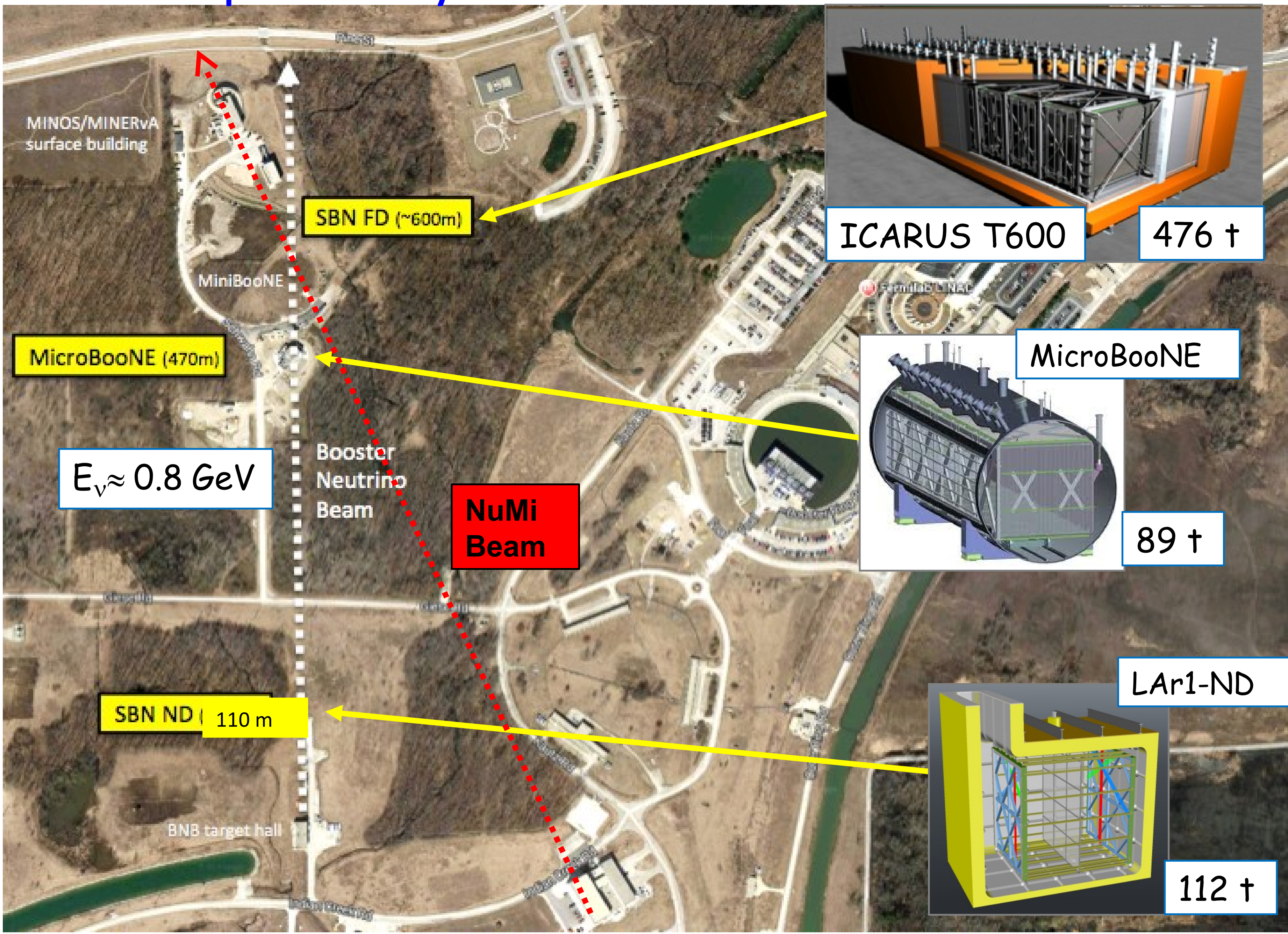
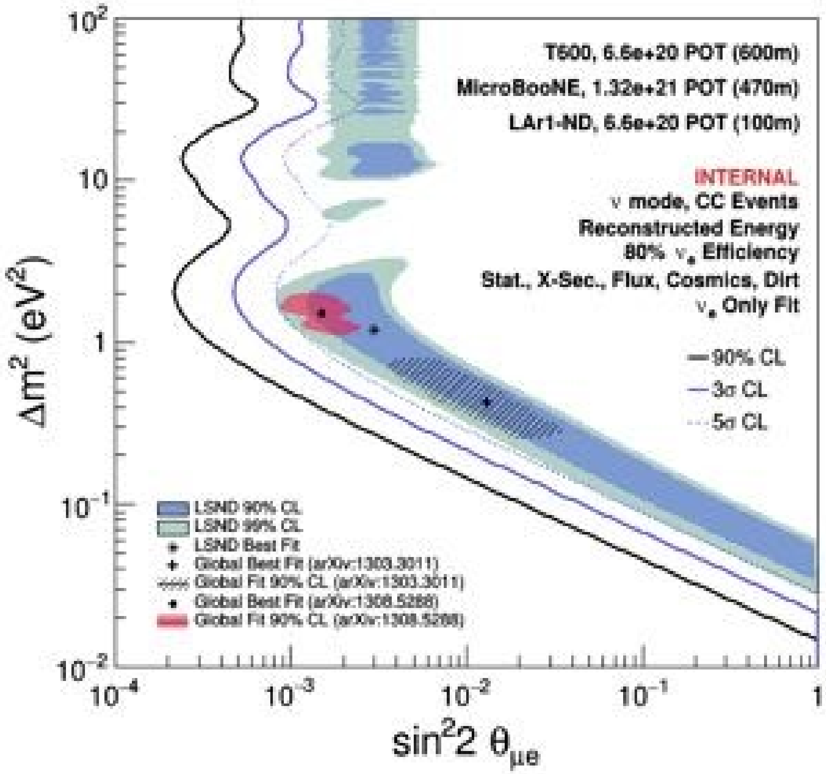
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
Institute of Nuclear Physics, Polish Academy of Science, Kraków, Poland
Institute for Radioelectronics, Warsaw University of Technology, Poland
Institute of Physics, University of Silesia, Katowice, Poland
Institute of Theoretical Physics, Wroclaw University, Wroclaw, Poland
National Centre for Nuclear Research, Warsaw, Poland
Argonne National Laboratory, USA
Colorado State University, USA
Los Alamos National Laboratory, USA
FermiLab, USA
University of Pittsburgh, USA
SLAC National Accelerator Laboratory, USA

Proposed layout of SBN detectors at FNAL



Physics program for the SBN



- The search for sterile neutrinos and exploration of the LSND/MiniBooNE anomalies using ν_μ disappearance and ν_e appearance (ν_e appearance calculated sensitivity: ~5σ for the LSND allowed (99% C.L.) region for 6.6 x10^{20} pot,

- Precision measurements in the few hundred MeV to few GeV energy range – the world's best measurement of ν_μ-Ar and ν_e-Ar scattering,

- MicroBooNE and ICARUS will also record large samples of events from the off-axis flux of the NuMI Baseline neutrino beam (Long Baseline Neutrino Oscillation Program).

Conclusions

- ICARUS T600 detector has successfully completed the CNGS experiment conclusively demonstrating that LAr-TPC is a leading technology for future short/long baseline accelerator neutrino projects,

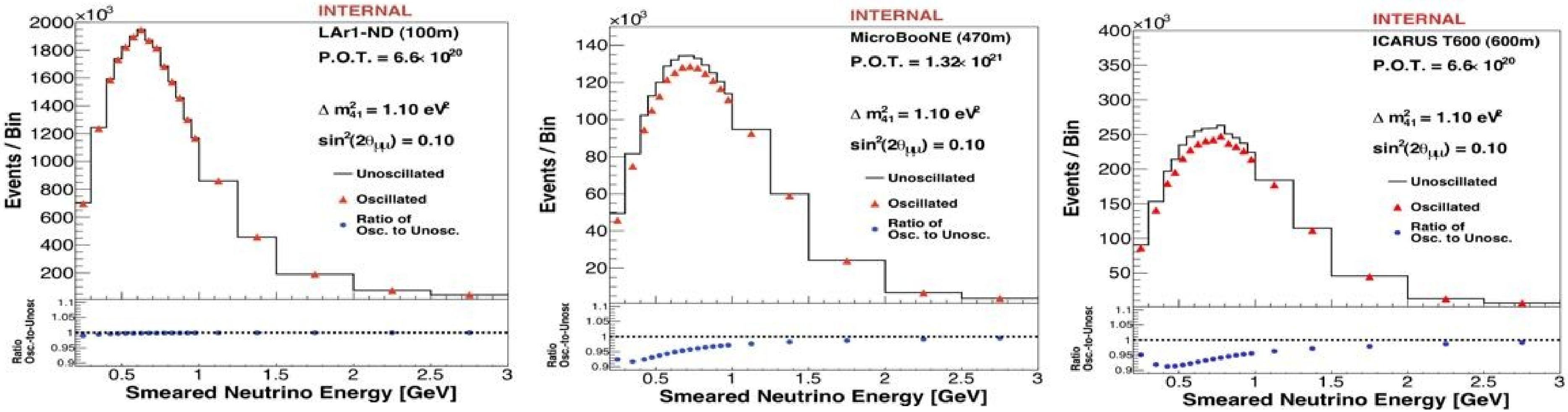
- Presently the ICARUS T600 detector is being overhauled at CERN,

- The detector will run again in 2018, this time as the far detector of the Short Baseline Neutrino Oscillation experiment at FNAL,

- The main aim of the SBN experiment is the definitive clarification of the LSND signal in terms of neutrino oscllations.

BACK-UP

The search for sterile neutrinos

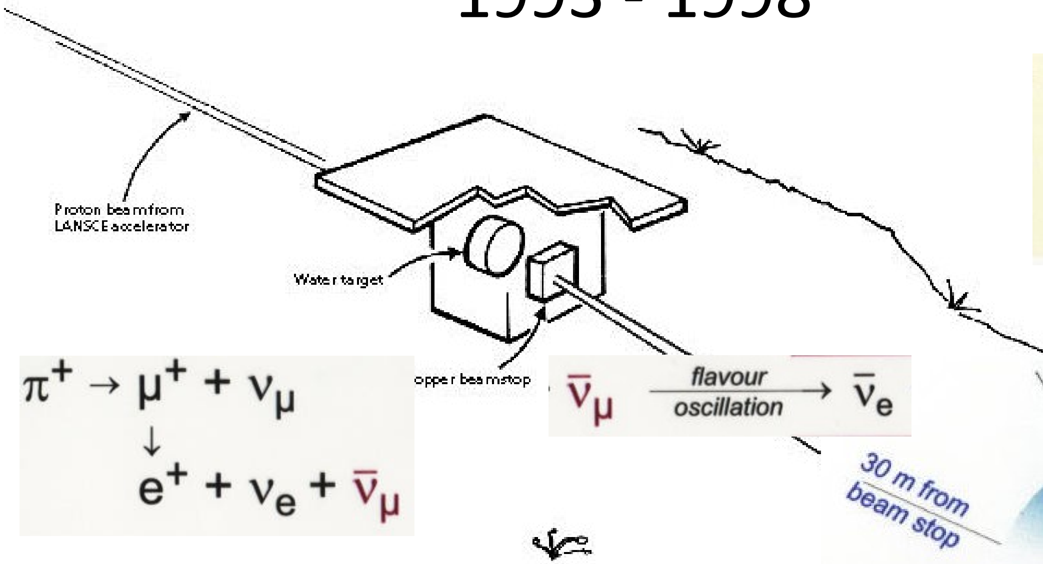


- The experiment will likely clarify both LSND/MiniBooNE and Gallex/reactor anomalies by precisely and independently measuring both ν_e appearance and ν_μ disappearance
- Disappearance analysis can profit from high rates and correlations between the three LAr-TPC detectors

LSND (Liquid Scintillator Neutrino Detector)

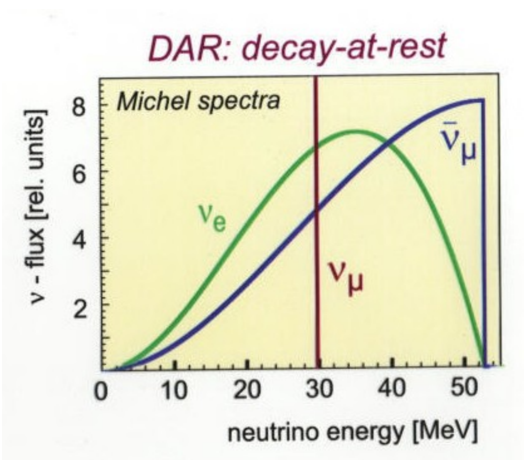
1993 - 1998

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



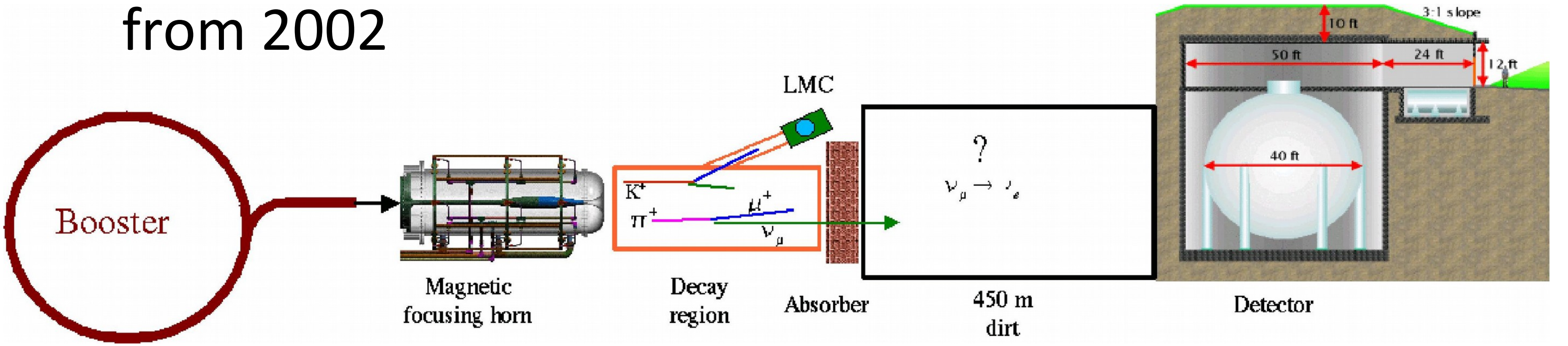
$$p \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$

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



MiniBooNE

from 2002



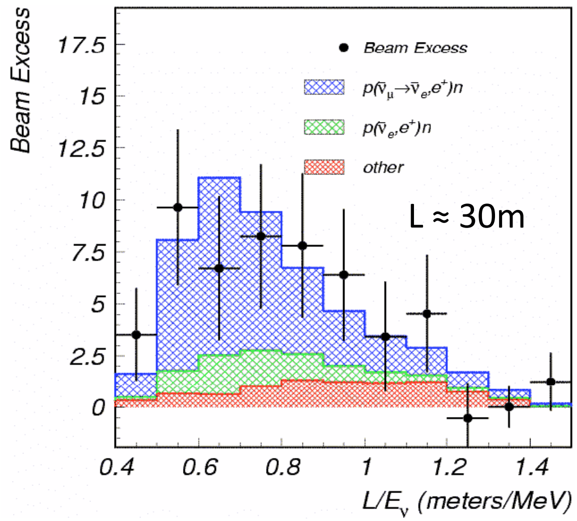
- Test the LSND anomaly
- Keep L/E same, change beam and energy
- 8 GeV proton beam (Be target)

neutrino energy (E): MiniBooNE: ~700 MeV; LSND: ~30 MeV

baseline (L): MiniBooNE: ~540 m; 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

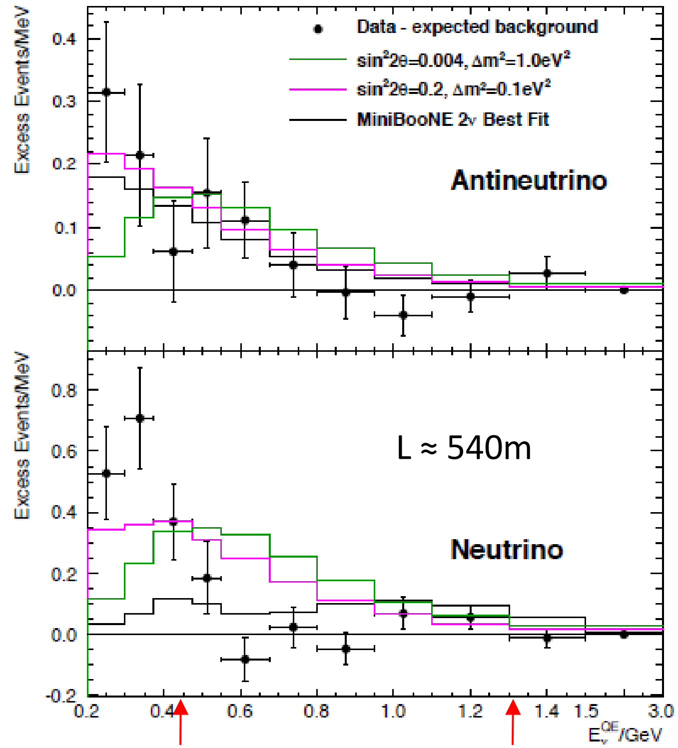


LSND has observed an excess of ν_e events in ν_μ beam,

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"

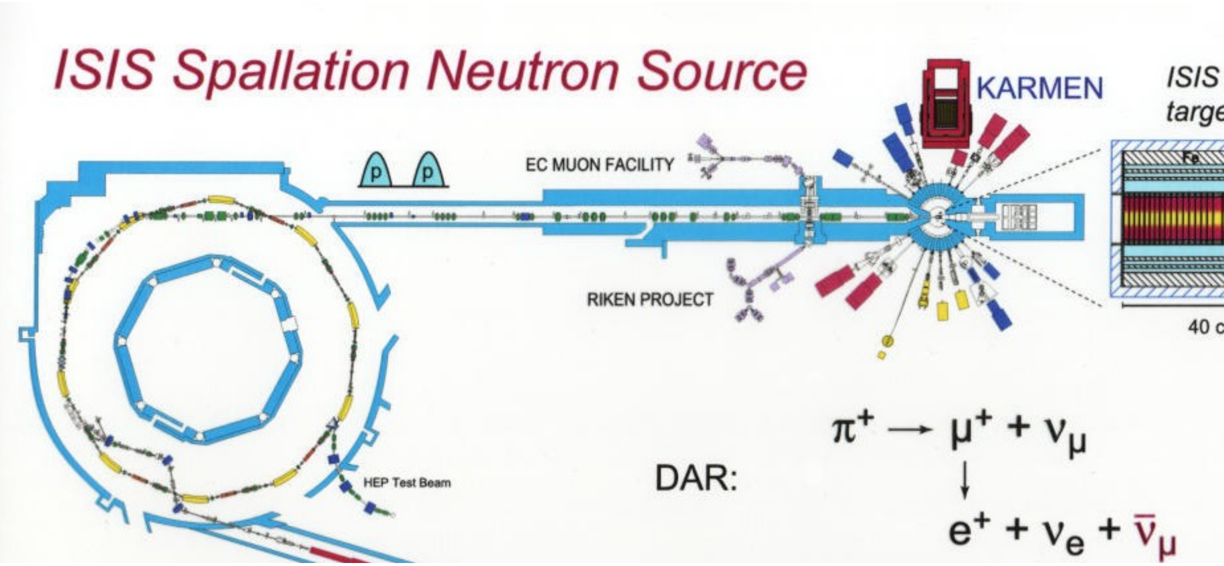
Positive hints

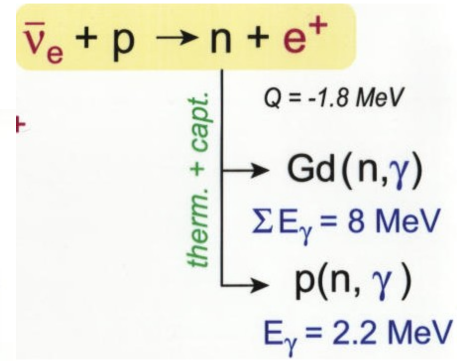
Anomaly	*Source*	*Type*	*Channel*	*Significance*
LSND	Short baseline	Decay at rest	-νμ –>νe CC	3.8 σ
MiniBoone	Short baseline	Neutrino beam	-νμ –>νe CC	**3.4 σ**
MiniBoone	Short baseline	Anti-Neutr. beam	anti-νμ –>νe CC	**2.8 σ**
Gallium	Electron capture	Source	ν disapp.	2.7 σ
Reactors	Fission	Beta decay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

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

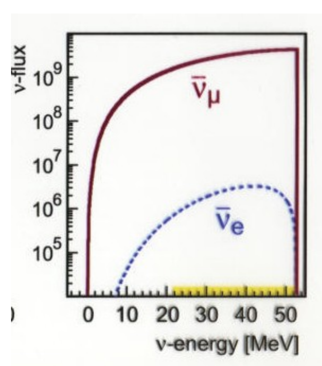
KARMEN

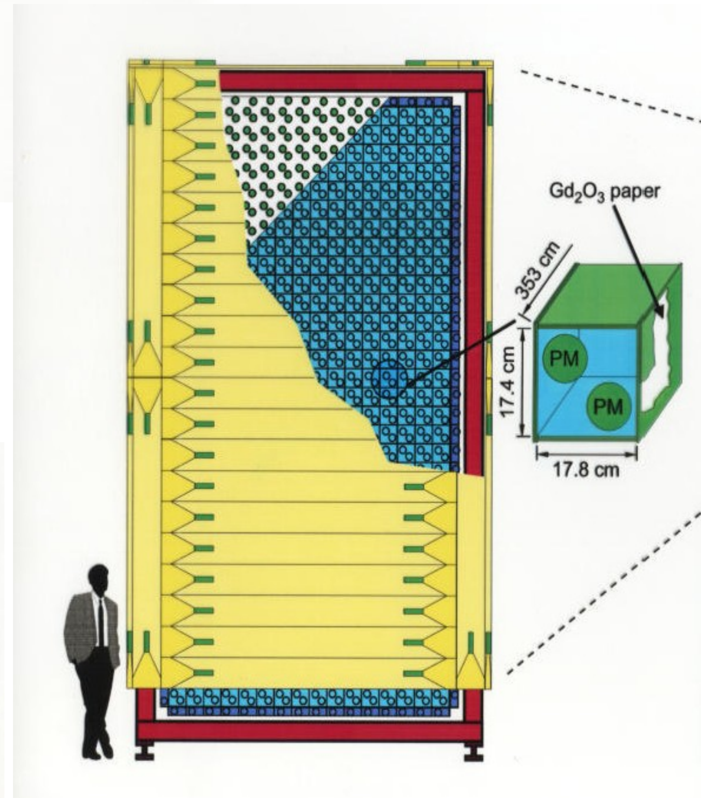
1997 - 2001





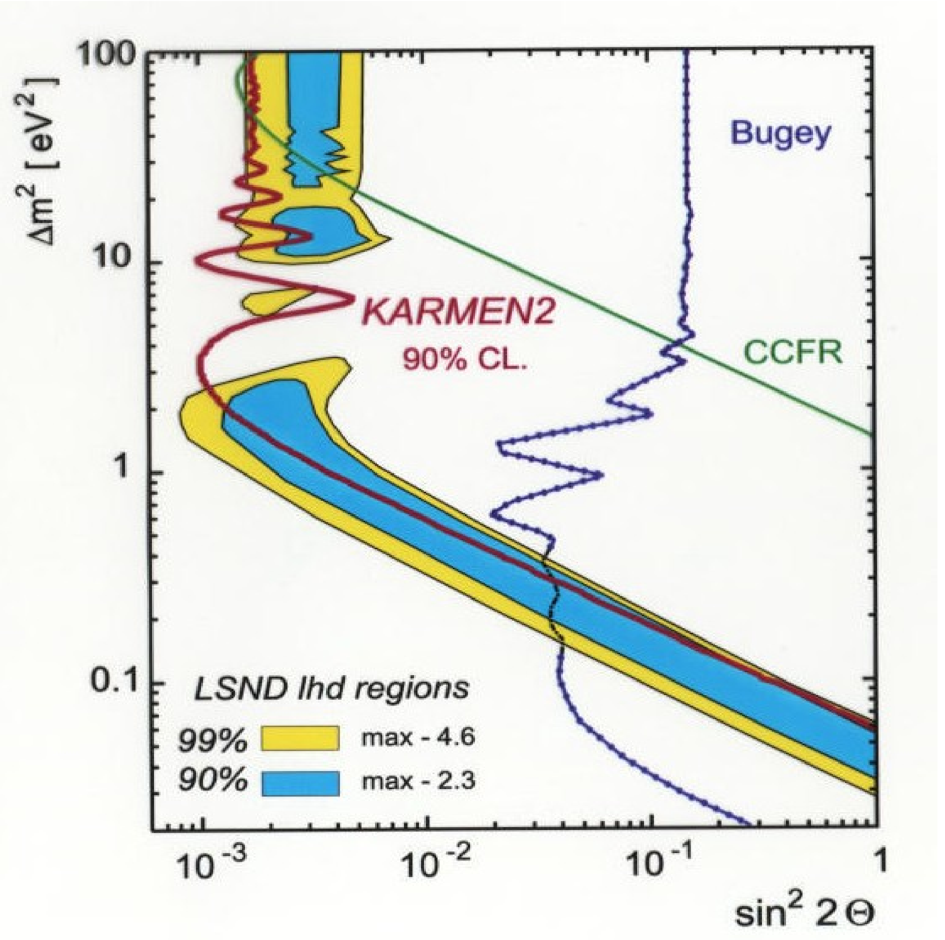
- 50 t scintillator (5.6 x 3.2 x 3.5) m³
- L ≈ 18 m
- E < 50 MeV
- L/E = 0.4 - 1





KARMEN – no oscillation excess

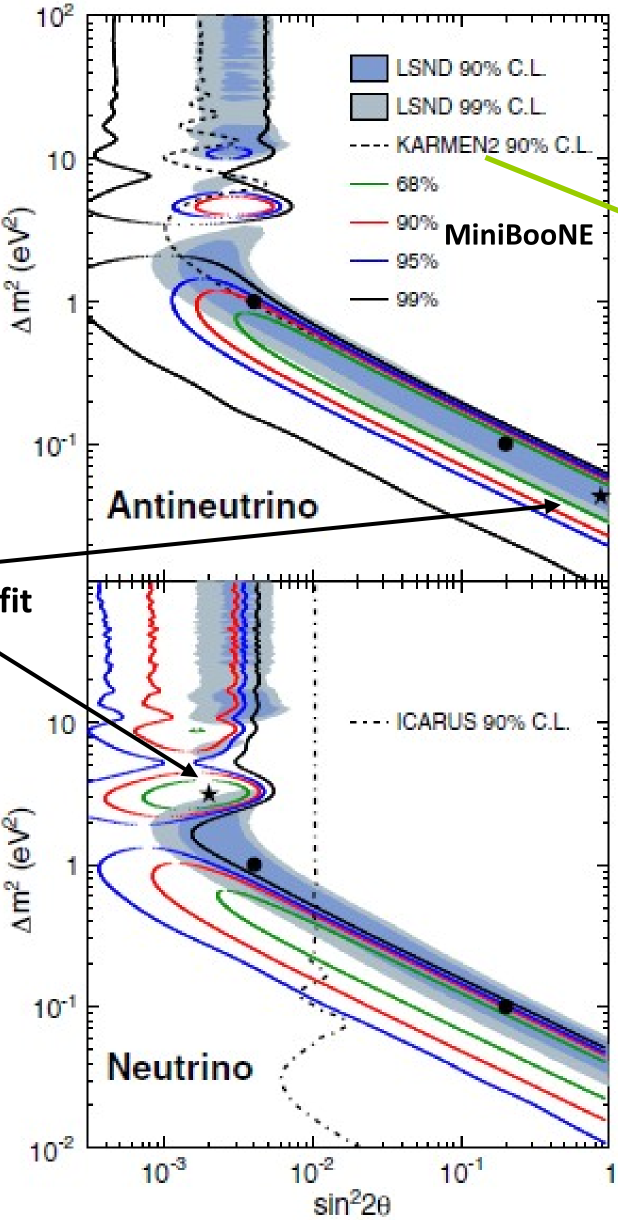
- candidate events : 15
- background : 15.8 ± 0.5
  - cosmic : 3.9 ± 0.2
  - ν_e from CC : 9.9 ± 0.4
  - $-\nu_e$ contamination : 2.0 ± 0.2



- oscillation limit:
  - for $\Delta m^2 > 1$ eV^2 : $\sin^2\theta < 0.0017$
  - $0.2 < \Delta m^2 < 1$ eV^2 :

    $10^{-3} < \sin^2\theta < 3\cdot 10^{-2}$

LSND anomaly area

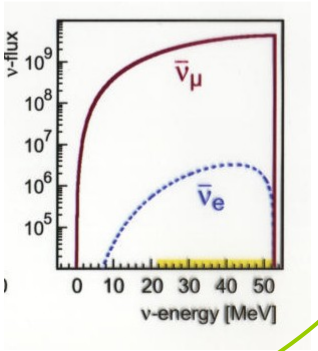


KARMEN – negative evidence

1997 - 2001

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

- 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)