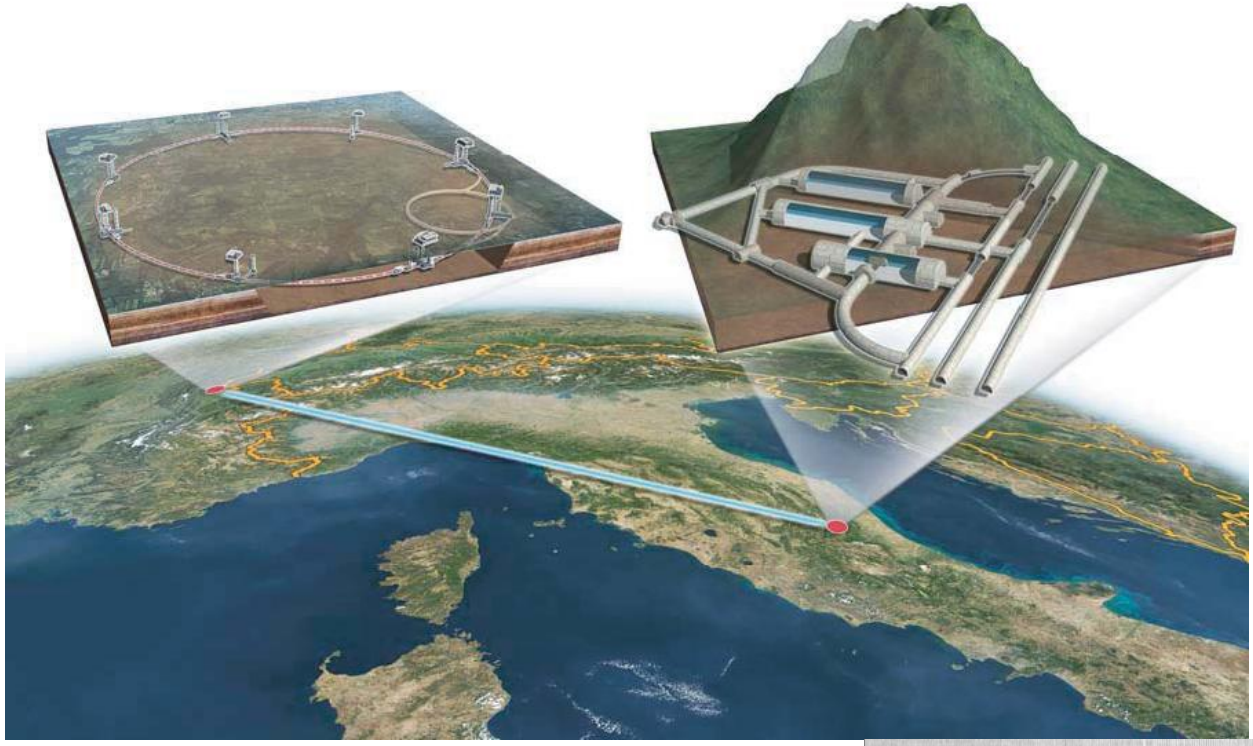
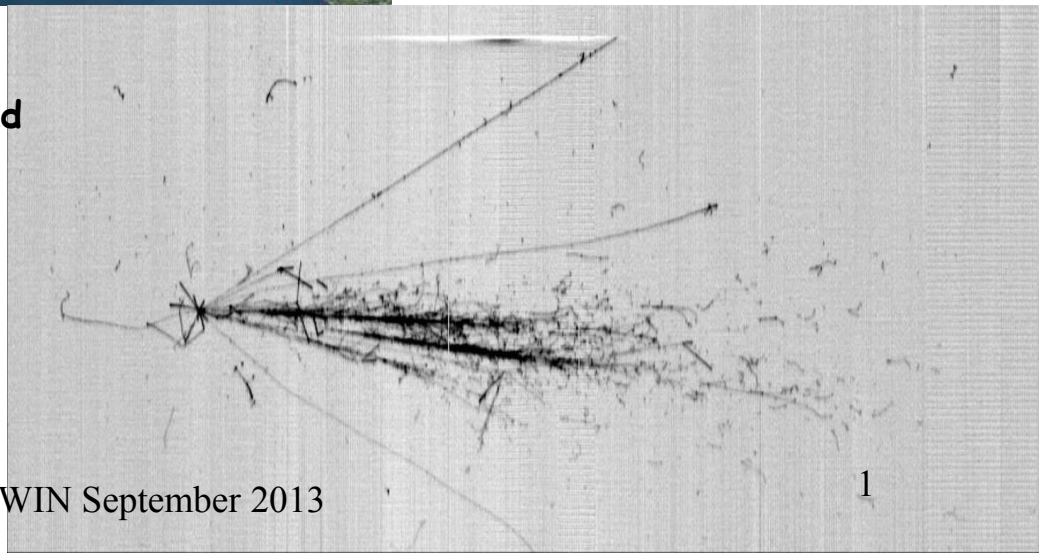
Recent results from the ICARUS experiment



Jan Kisiel
Inst. of Physics, Univ. Silesia, Katowice, Poland
For the ICARUS Collaboration



Introduction

- Three years (May 2010 – June 2013) of continuous underground operation of the ICARUS detector in Hall B of the LNGS lab. resulted in plenty of high quality data, both from LNGS beam and cosmics.
- Such a long period allowed for detailed studies of all technical aspects of the detection technique,… and
- Development of advanced reconstruction algorithms.

June 27th: Detector decommissioning

July 25th: cryostat empty

740 ton (out of 760 tons) recovered

In this talk

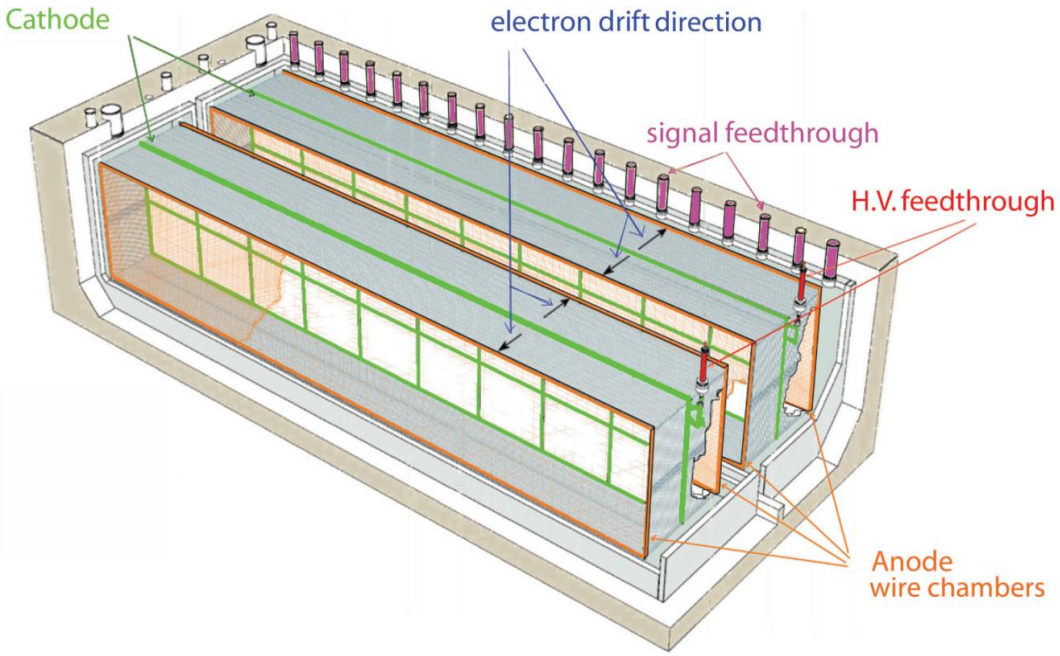
- **ICARUS LAr TPC – detector performance**
- **Results: search for the LSND/MiniBooNE anomaly, i.e. search for the oscillations $\nu_\mu \rightarrow \nu_e$ with LNGS beam**
- **Conclusions**

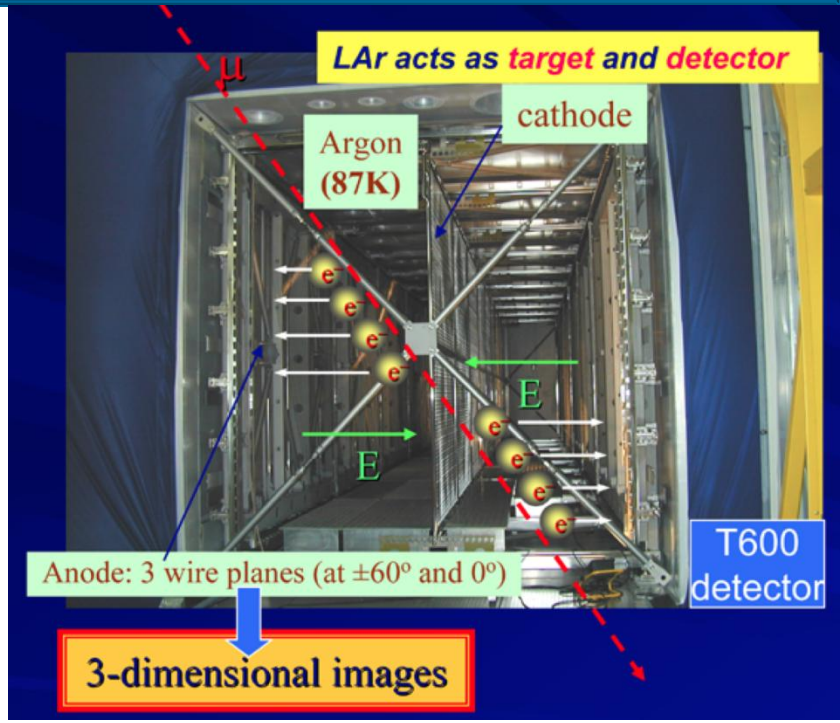
The ICARUS Collaboration

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

a INFN Laboratori Nazionali del Gran Sasso Assergi, Italy
b Dipartimento di Fisica e Astronomia, Università di Padova and INFN, Padova, Italy
c Dipartimento di Fisica Nucleare e Teorica Università di Pavia and INFN, Pavia, Italy
d Politecnico di Milano and INFN, Milano, Italy
e Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Science, Krakow, Poland
f Department of Physics and Astronomy, University of California, Los Angeles, USA
g Dipartimento di Scienze Fisiche Università Federico II di Napoli and INFN, Napoli, Italy
h INR RAS, Moscow, Russia
i CERN, Geneva, Switzerland
j National Centre for Nuclear Research, Otwock/Swierk, Poland
k Institute of Physics, University of Silesia, Katowice, Poland
l INFN Laboratori Nazionali di Frascati, Frascati, Italy
m GSSI, Gran Sasso Science Institute, L'Aquila, Italy
n Institute of Radioelectronics, Warsaw University of Technology, Warsaw, Poland
o INFN Pisa. Pisa, Italy

The ICARUS T600: the first LARGE LAr TPC





- 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 (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV sensitive (128nm) with wave shifter (TPB)

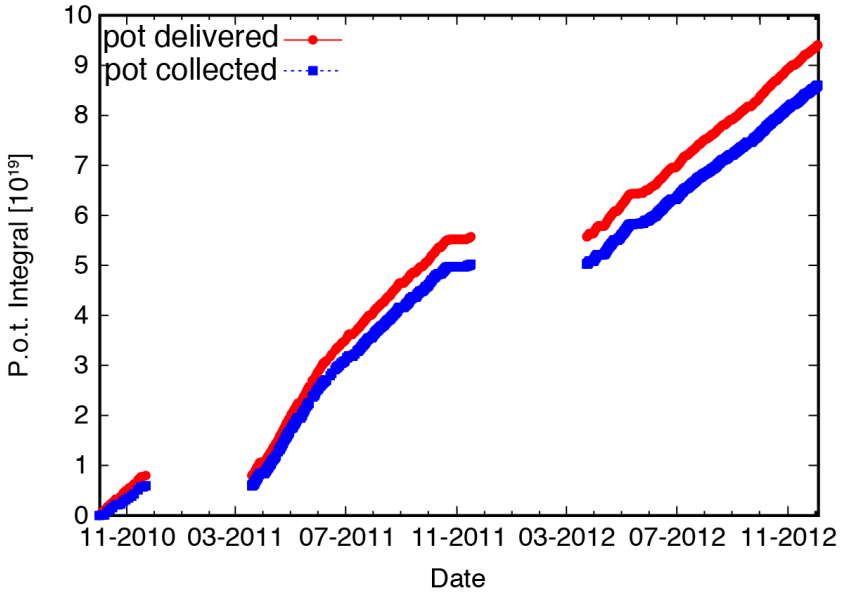
Key feature: LAr purity from electro-negative molecules (O_2, H_2O,CO_2).

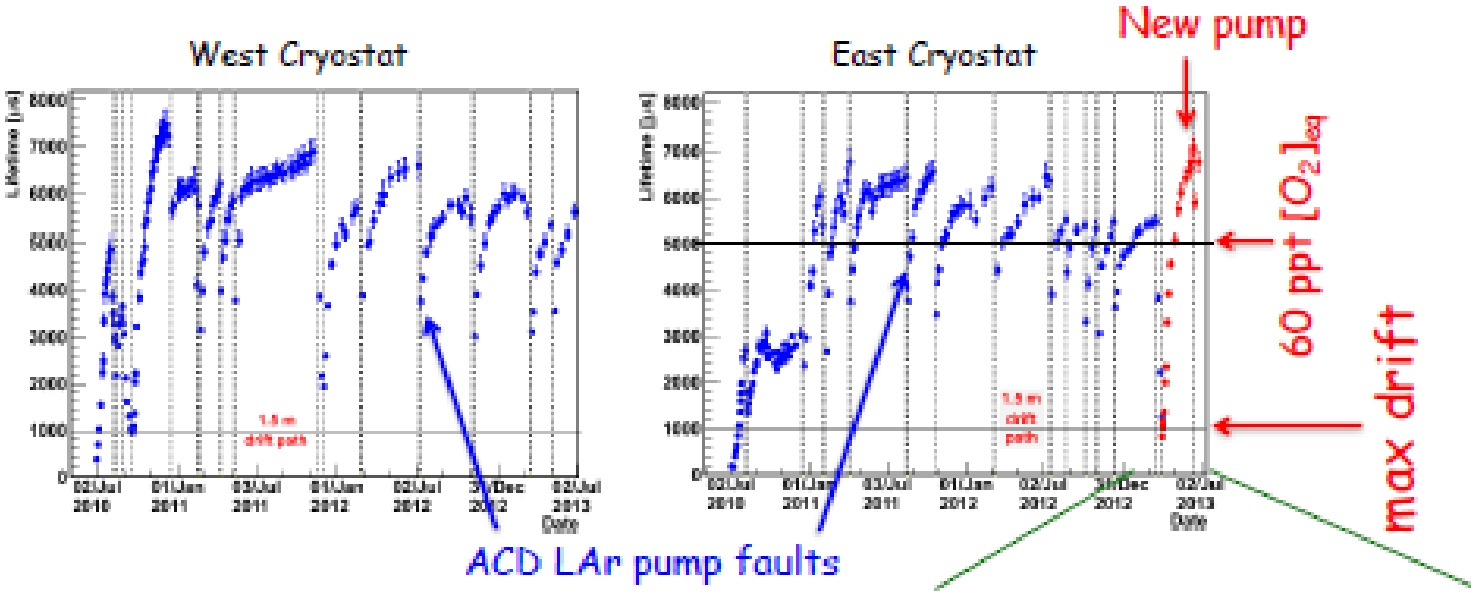
The ICARUS detector in underground Hall B of LNGS

CNGS RUN (Oct 1st 2010 – Dec 3rd 2012)

- Detector live-time > 93%
- November 2011 and May 2012: timing measurement with bunched beam.
- PMT's signal in coincidence with beam extraction → trigger

Collected 8.6 x 10^{19} protons on target (pot)





LAr continuously filtered, max. charge attenuation at 1.5m: 17%

ICARUS LAr-TPC performance

Total energy reconstr. from charge integration

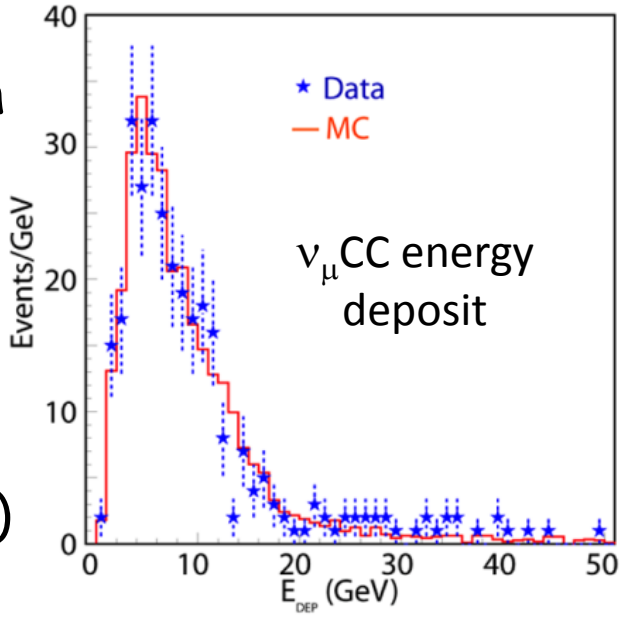
- Full sampling, homogeneous calorimeter with excellent accuracy for contained events

Tracking device

- Precise 3D topology and accurate ionization
- Muon momentum via multiple scattering

Measurement of local energy deposition dE/dx

- e/γ remarkable separation (0.02 X_0 samples)
- Particle identification by dE/dx vs range



Low energy electrons:

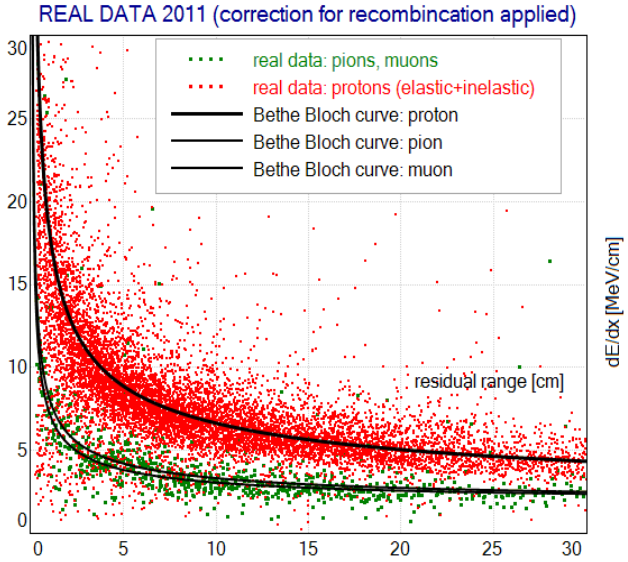
σ(E)/E = 11%/√ E(MeV)+2%

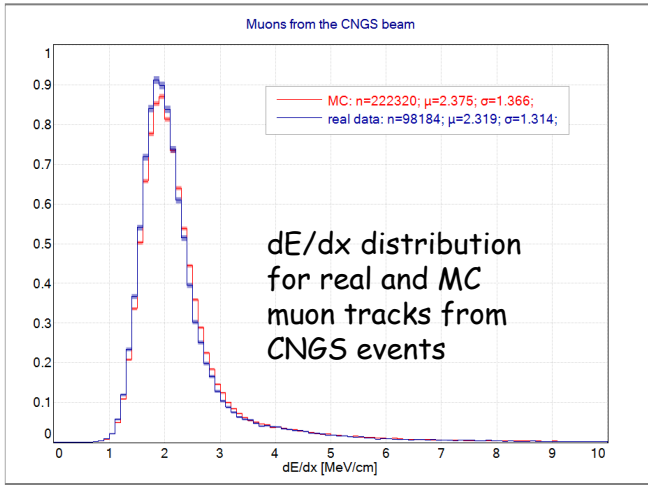
Electromagn. showers:

σ(E)/E = 3%/√ E(GeV)

Hadron showers:

σ(E)/E ≈ 30%/√ E(GeV)





ICARUS: published physics results

- **Search for superluminal neutrinos (not in this talk):**

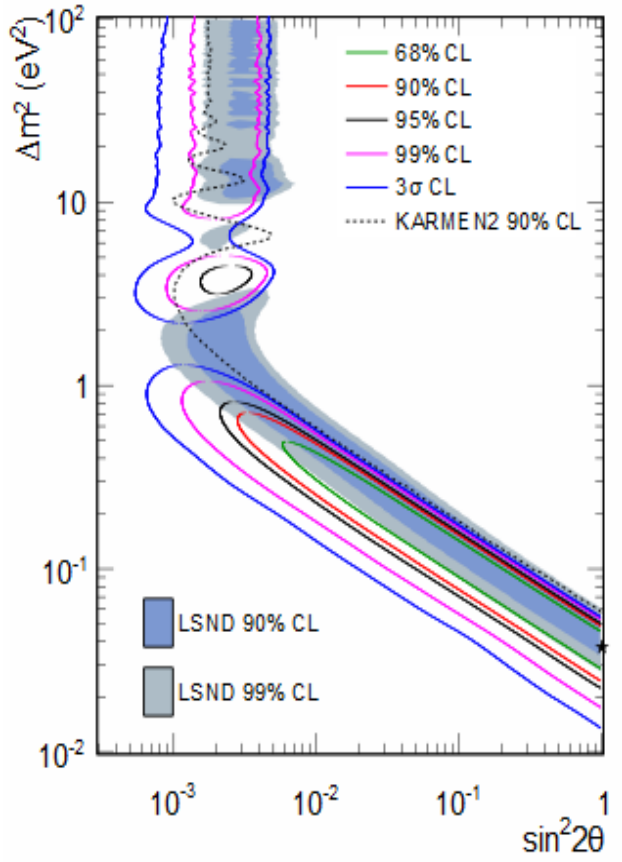
1. Cherenkov-like emission of e^+e^- pair: PL B711 (2012) 270
2. Mesurement of neutrino tof: PL B713 (2012) 17
3. Precison measurement of ν tof: JHEP 11 (2012) 049

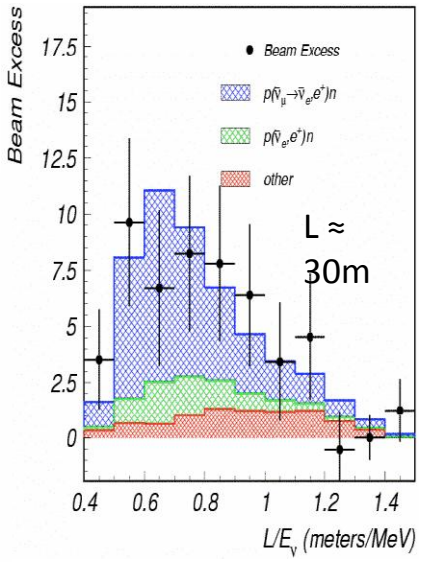
- **Search for „LSND" anomaly (this talk):**

1. Limited statistics result: Eur. Phys. J. C73 (2013) 2345
2. Improved statistics result: arXiv:1307.4699

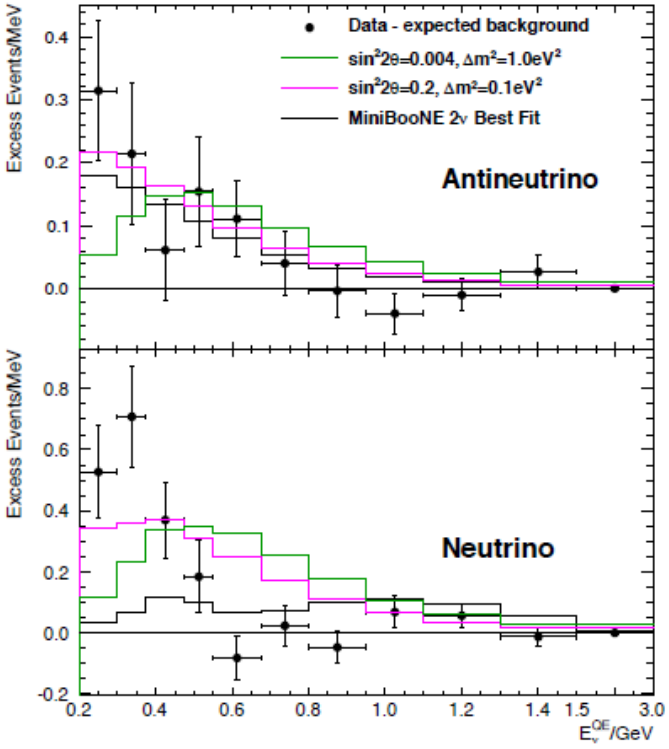
LSND anomaly

- The **LSND** has observed an access of anti-ν_e nuetrino events in anti-ν_μ beam: **87.9 ± 22.4 ± 6.0 (3.8σ)**





- LSND anomalous production signal has been later partly confirmed by **MiniBoone** experiment.



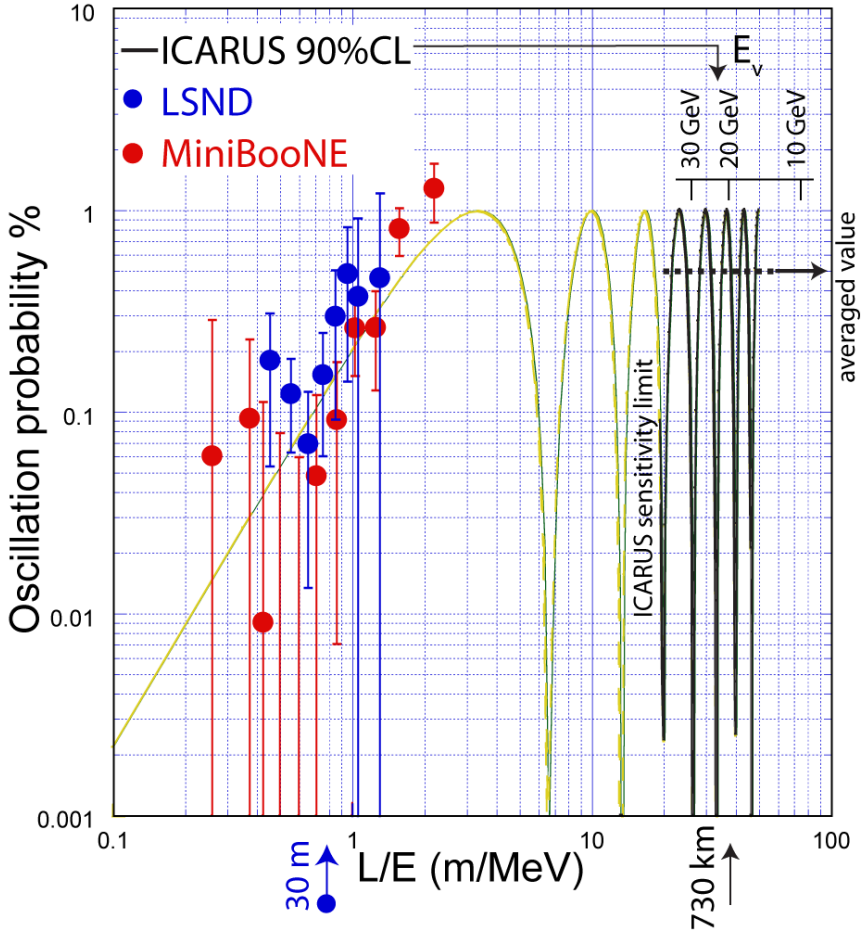
MiniBooNE (PRL 110 (2013) 161801)
Event excess for 200 < EQE < 1250 MeV
antineutrino: 78.4 ± 28.5 (2.8 σ)
neutrino: 162 ± 47.8 (3.4 σ), but the energy distribution of the excess is marginally compatible with a simple two neutrino oscillation

ICARUS search for LSND anomaly

LSND: L/E=1 m/MeV

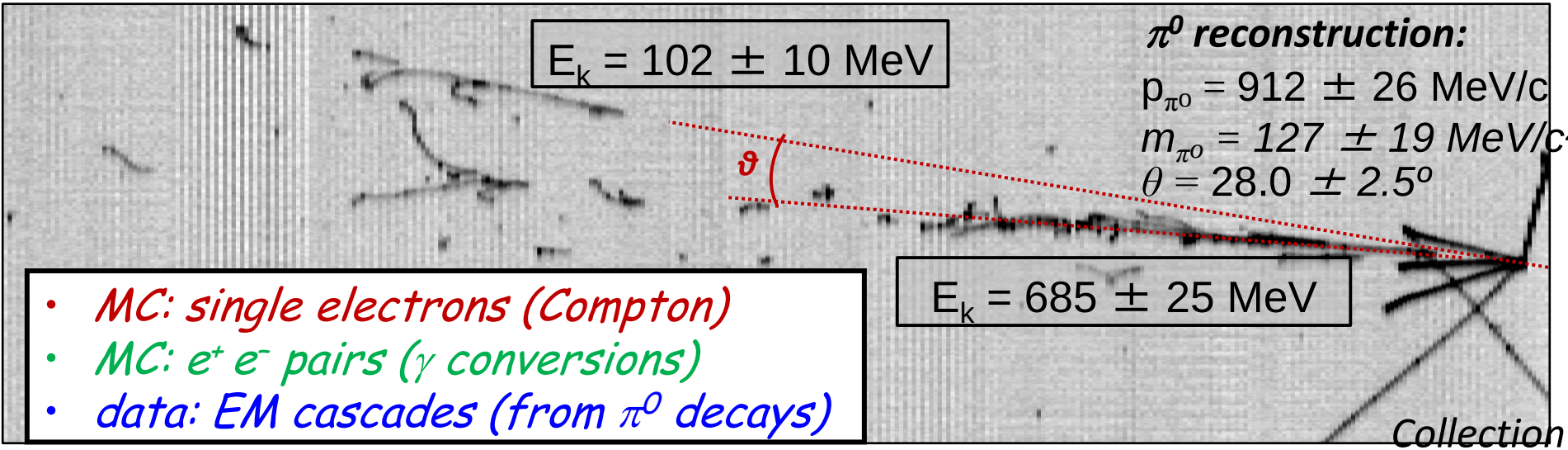
ICARUS: L=730km, $E_\nu \in [10,30]$ GeV, almost pure ν_μ beam ($\nu_e \approx 1\%$)
L/E ≈ 36.5 m/MeV, i.e. fast oscillations as a function of E_ν averaging to
$\sin^2(1.27\Delta m^2 L/E) \approx \frac{1}{2}$
$\langle P \rangle_{\nu_\mu \to \nu_e} \approx \frac{1}{2} \sin^2(2\theta_{new})$

A sterile neutrino signal would appear for ICARUS as an access of ν_e events.



ν_e CC event recognition becomes crucial, and possible due to unique Liquid Argon feature and our reconstruction algorithms.

ICARUS: e/γ separation and π^0 reconstruction



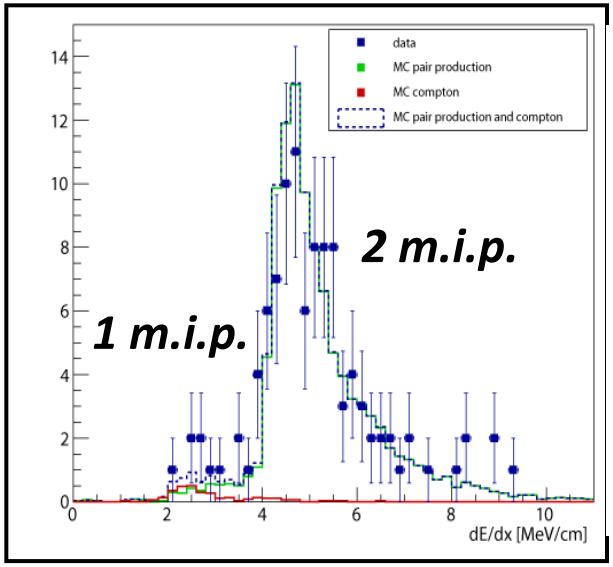
π^0 reconstruction:

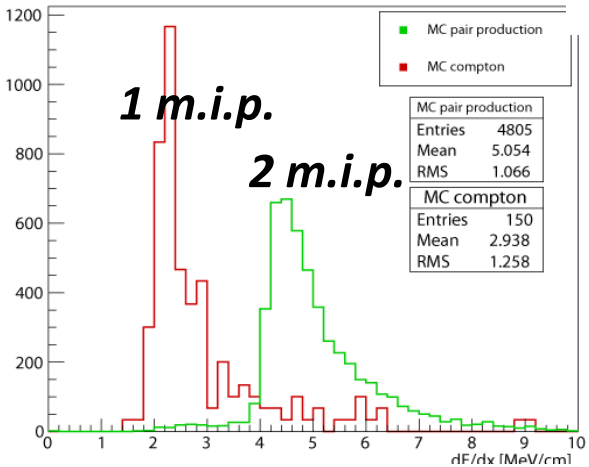
p_{π^0} = 912 ± 26 MeV/c

m_{π^0} = 127 ± 19 MeV/c^2

θ = 28.0 ± 2.5°

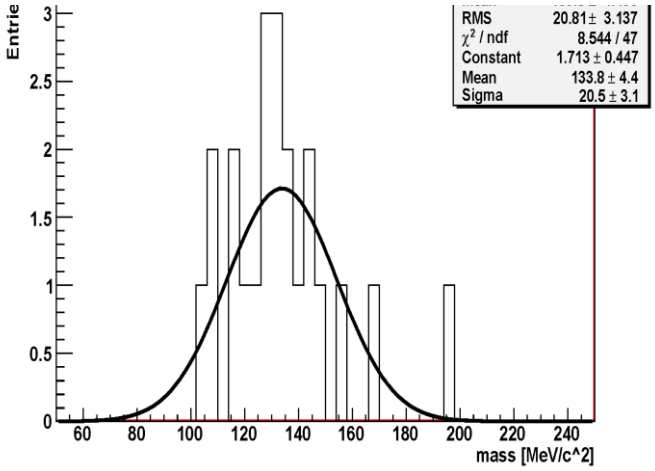
- *MC: single electrons (Compton)*
- *MC: e^+ e^- pairs (γ conversions)*
- *data: EM cascades (from π^0 decays)*





Mγγ:

133.8±4.4(stat)±4(syst) MeV/c^2



LAr TPC: very good e/γ separation

ICARUS: ν_e signal selection

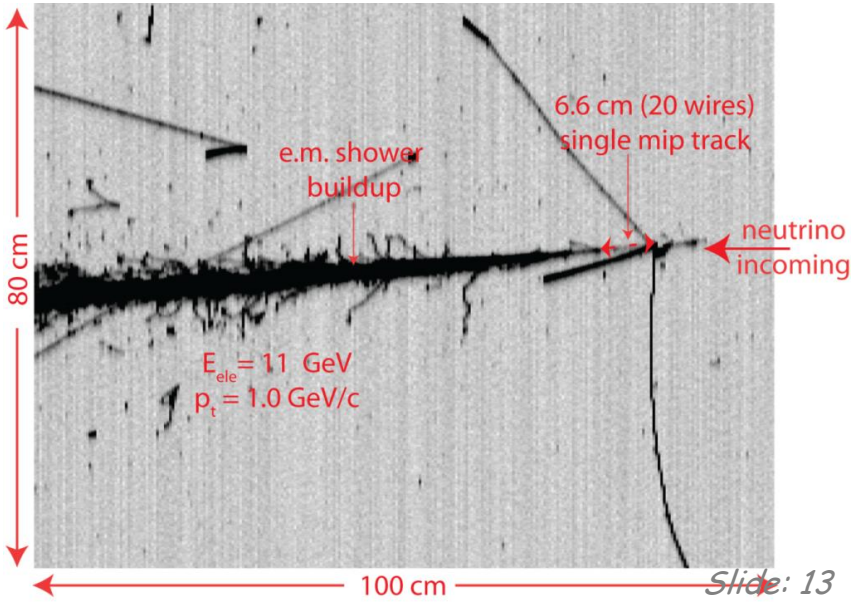
- Visual selection of ν_e event candidates in the following fiducial volume for shower id: > 5 cm from walls and 50 cm downstream.
- Energy cut: < 30 GeV (≈50% reduction on ν_e beam, but only 15% reduction of signal events.

Selections for ν_e during visual scan:

Single m.i.p. from vertex, al least 8 wires long (dE/dx ≤ 3.1 MeV/cm, excluding δ-rays), later developing into EM shower.

Minimum spatial separation (150 mrad) from other tracks coming from vertex, at least in one of 2 transverse views.

- visibility cuts: (3 independent scanners), leading to **0.74 ± 0.05 efficiency**;
- no ν_e-like events selected among NC simulated sample of 800 events.
- ν_μ CC events identified by L > 2.5 m primary track without hadronic interaction



Data sample and event rates

First result based on the analysis of 1091 ν events (3.3×10^{19} pot, 2010-2011 data, half the total statistic) published in Eur. Phys. J. C73 (2013).

Analysis presented here refers to 1995 ν events (6.0×10^{19} pot)

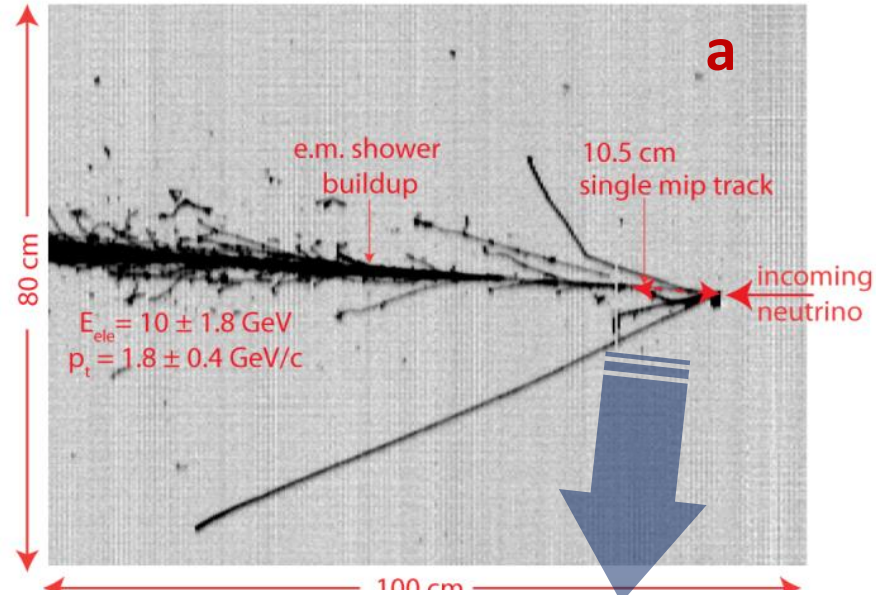
Expected number of ν_e events:

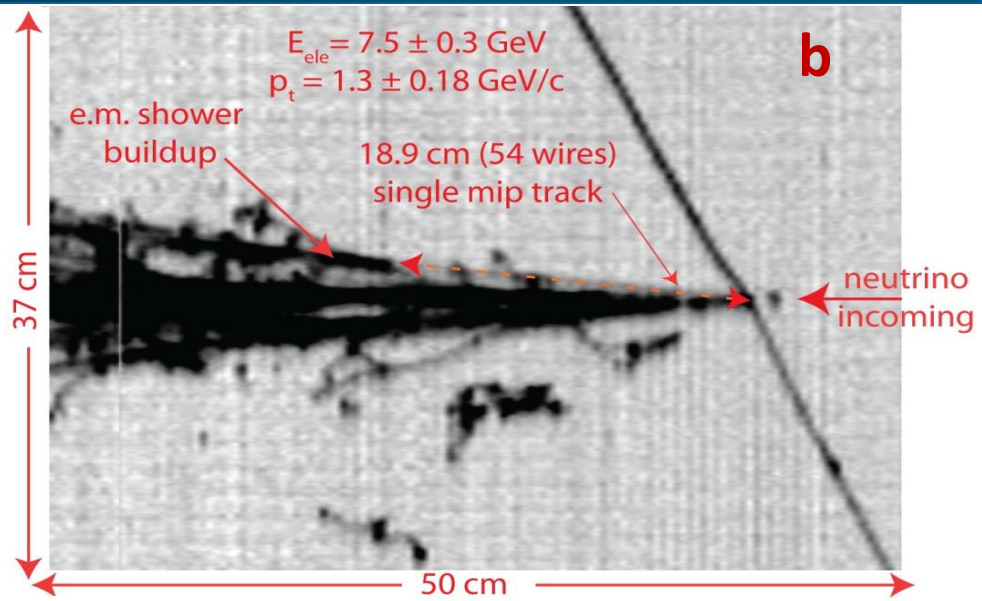
- 5.7 ± 0.8, due to the intrinsic ν_e beam contamination,
- 2.3 ± 0.5, due to θ_{13} oscillations, $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$,
- 1.3 ± 0.1, from $\nu_\mu \rightarrow \nu_\tau$ oscillations with subsequent electron production, (3ν mixing).

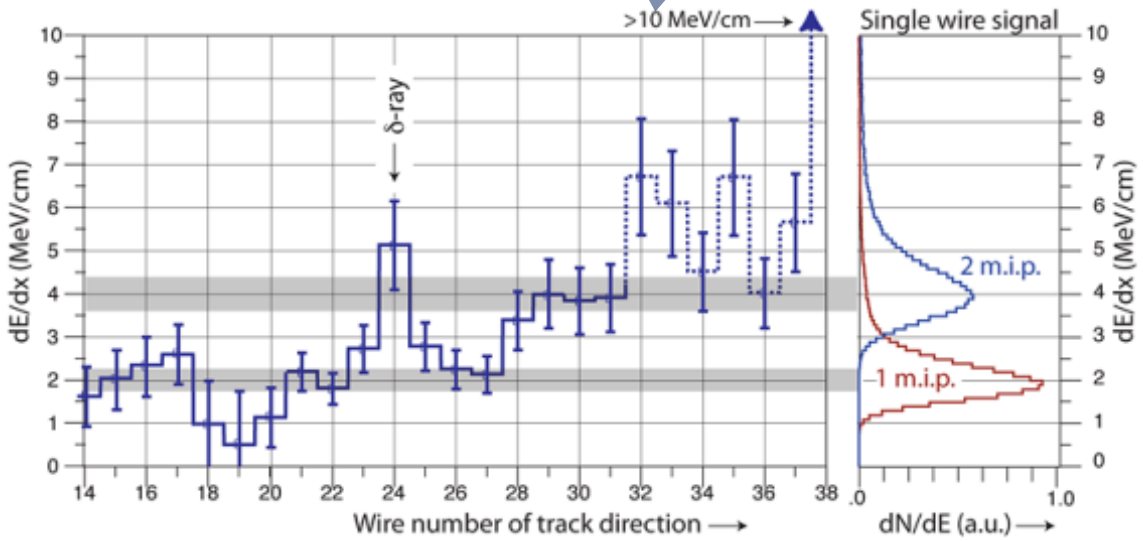
Total: 9.3 ± 0.9 expected events.

Expected events, weighting for efficiency: 6.4 ± 0.9 events.

Example: 2 (out of 4) ν_e CC events observed in 1995 events







(a) vis E_{tot} = 11.5 ± 1.8 GeV,
p_t = 1.8 ± 0.4 GeV/c

(b) vis E_{tot} = 17 GeV,
p_t = 1.3 ±0.18 GeV/c

In all events: single electron shower in the transverse plane clearly opposite to hadronic component

Search for an LSND-like effect with ICARUS at LNGS

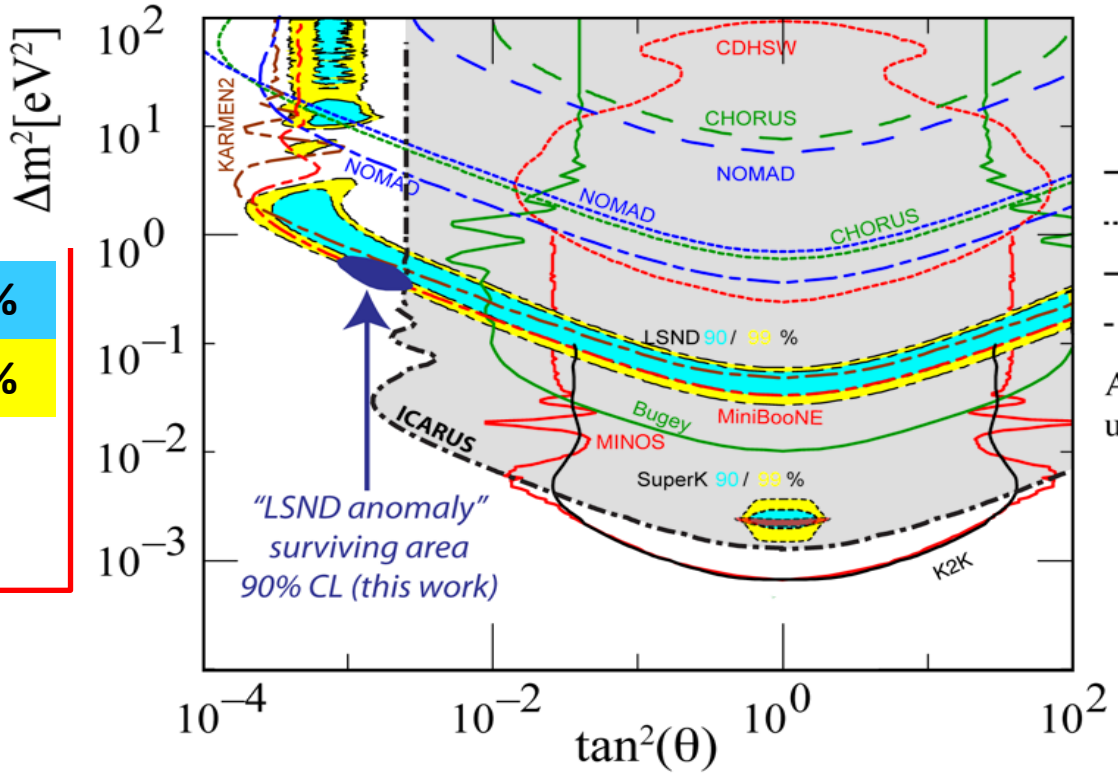
The first result (Eur. Phys. J. C73 (2013) 2345)

Allowed LSND 90%

Allowed LSND 90%

MiniBoone limit

KARMEN limit



ICARUS excluded region

ICARUS results strongly limit the allowed parameters values for LSND anomaly indicating a narrow region **(Δm^2, $\sin^2 2\theta$) = (0.5 eV^2, 0.005)** where there is overall agreement (90% CL) among:

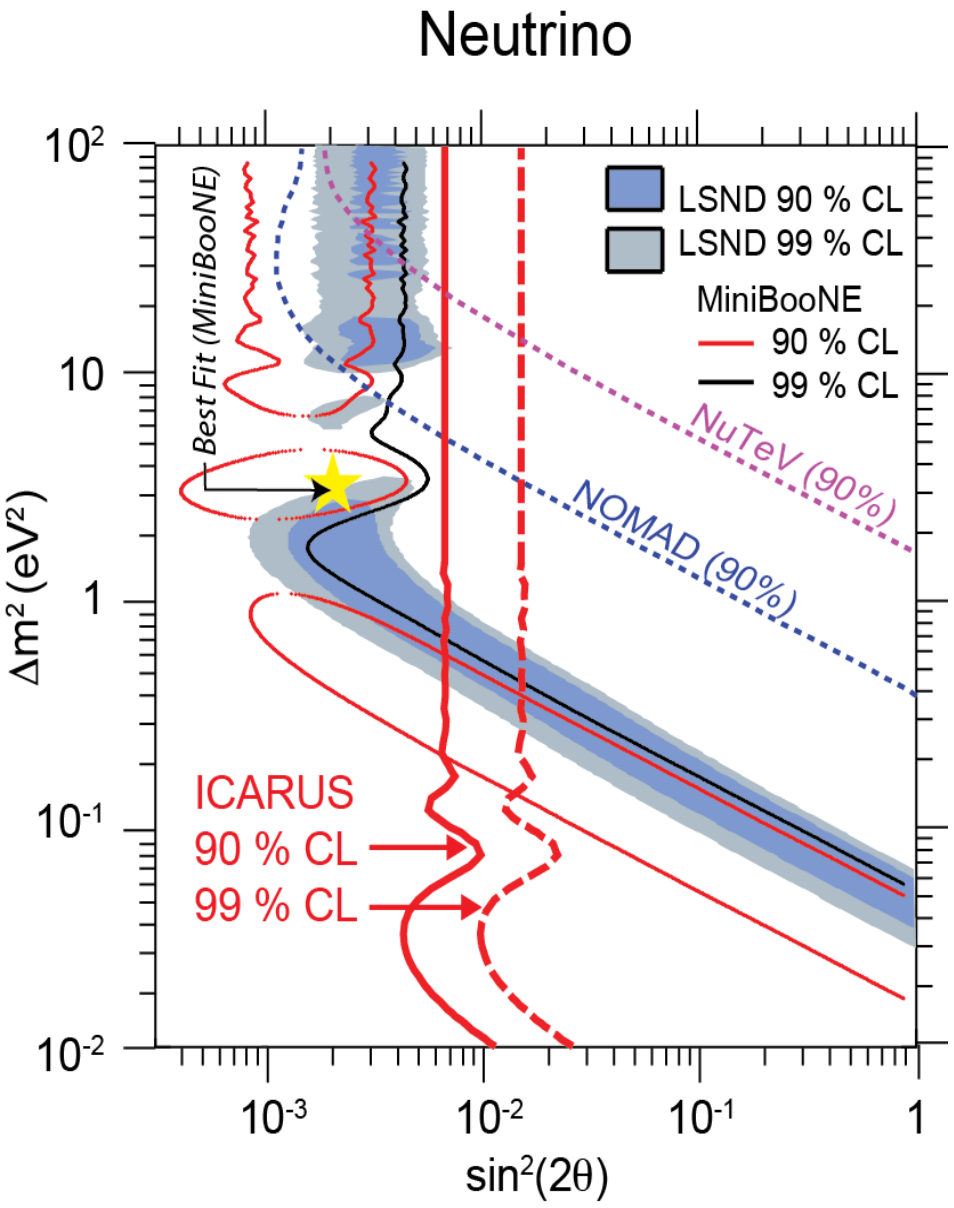
- **the present ICARUS limit**
- **the limits of KARMEN**
- **the positive signals of LSND and MiniBooNE Collaborations**

ICARUS results on the LSND-anomaly search (double statistics)

Within the present observation, our results is consistent with the absence of the LSND anomaly.

Weighting for efficiency, our limits on the number of events due to LSND anomaly are:
3.68 (90% CL) and
8.34 (99% CL).

which give the limits on oscillation probabilities:
$P(\nu_\mu \rightarrow \nu_e) \leq 3.4 \times 10^{-3}$ **(90% CL);**
$P(\nu_\mu \rightarrow \nu_e) \leq 7.6 \times 10^{-3}$ **(99% CL).**

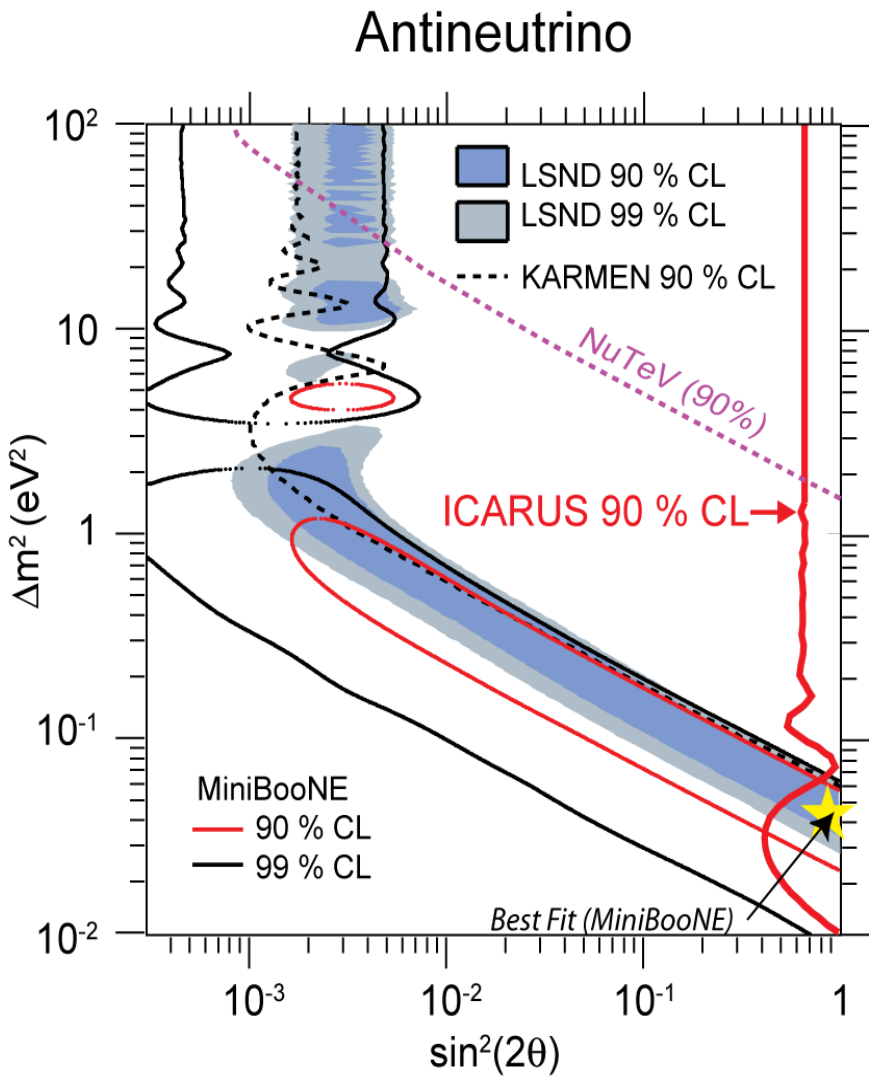


ICARUS: antineutrino result

A small ~2% anti-neutrino event contamination is present in the CNGS beam → search for $\bar{\nu}_e$ appearance could be possible.

Anti-ν_μ CC event rate is (1.2 ± 0.25) % of ν_μ CC for E_ν < 30 GeV (from simulations).

In the limiting case in which the whole effect is due to $\bar{\nu}_\mu$, the absence of an anomalous signal gives a limit of 4.2 events (90% CL.)
Corresponding to
$\langle P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \rangle \leq 0.32$
Or
$\sin^2(2\theta_{new}) \leq 0.64$.



In case of MiniBoone best fit, ~12 events expected (5.4 signal +6.4 bgd)

Conclusions

- ICARUS is the first large TPC operated underground.
- ICARUS has been acquiring data without interruption for more than 3 years with both, CNGS beam and cosmics.
- Efficient reconstruction algorithms for the tracks allow to resolve most of the events collected, down to their single components. Consequence of this is for example the accurate analysis of ν_e events, which allows for an investigation of sterile neutrino oscillations and a check on previous results (LSND anomaly).
- No evidence of oscillation into sterile neutrinos is found in our measured L/E interval.


Thank you