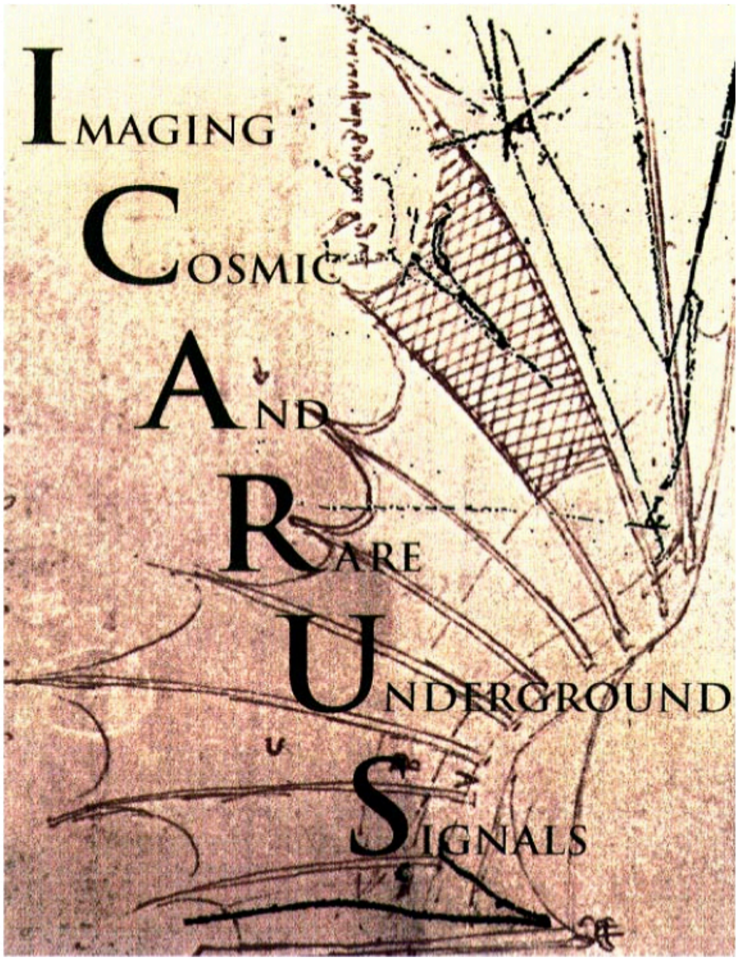
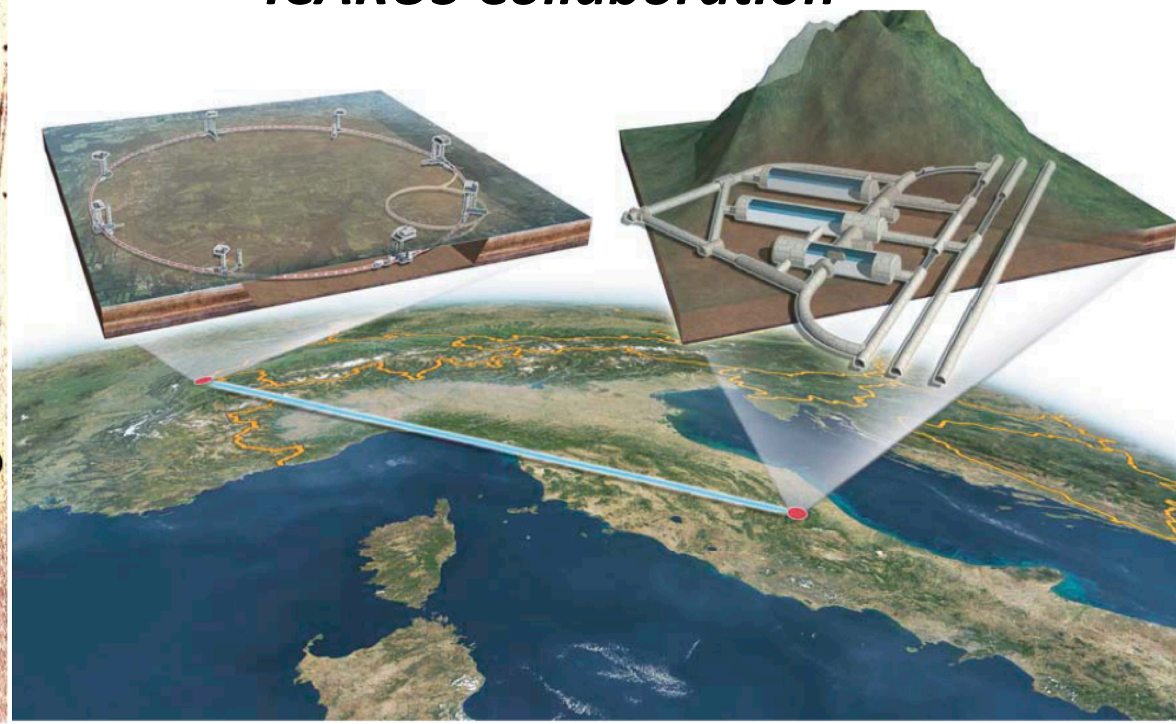
Results from the ICARUS experimental search in the LSND anomaly region



Ettore Segreto
Laboratori Nazionali del Gran Sasso (Italy)
on behalf of the
ICARUS Collaboration



DISCRETE 2012
The Third Symposium on Prospects in the Physics of Discrete Symmetries
3-7 December 2012, Lisbon

The ICARUS Collaboration

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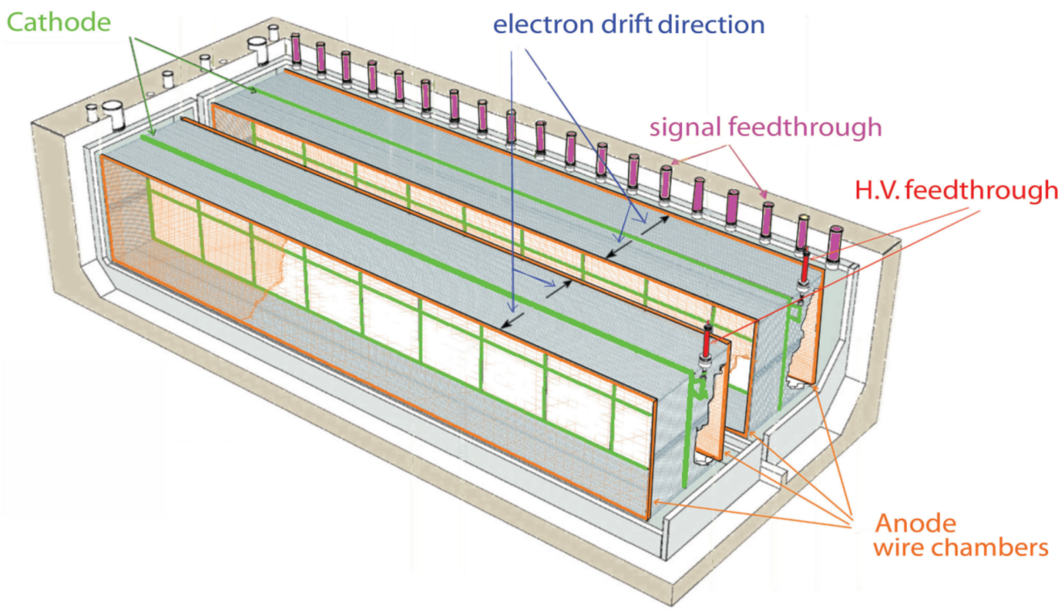
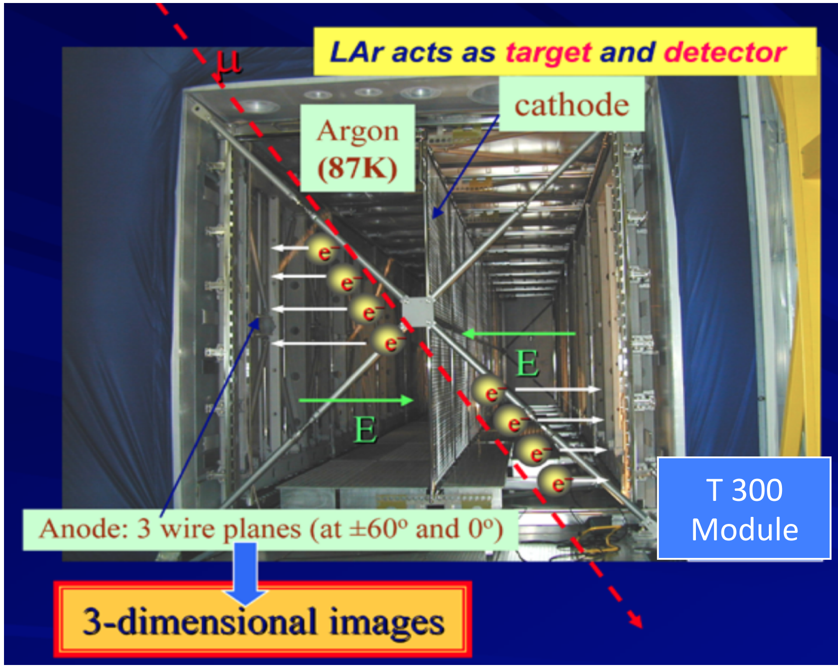
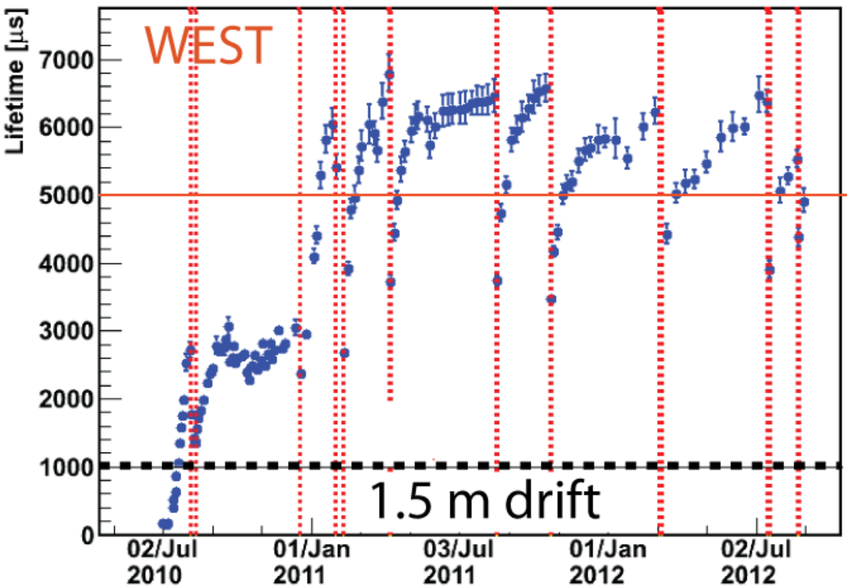
The ICARUS T600 Detector

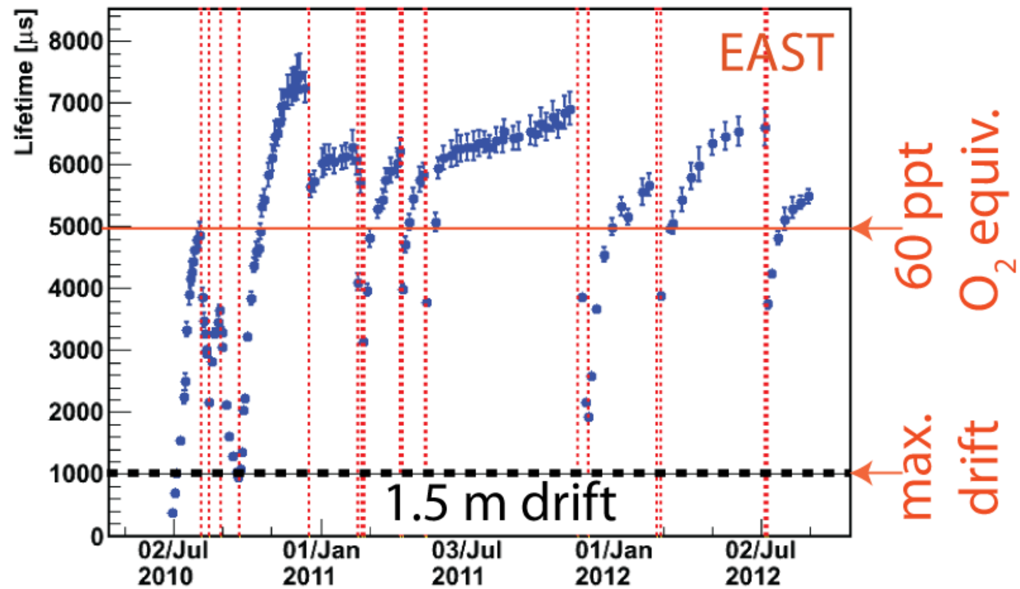




- Two "T300" identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E = 0.5 kV/cm
  - v_{drift} = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0°, ±60°
  - ≈ 53000 wires, 3 mm pitch, 3 mm plane spacing
- PMT for scintillation light:
  - (20+54) PMTs, 8" Ø
  - VUV sensitive (128nm) with wave shifter (TPB)

LAr-TPC purification (<60 part per trillion O_2 equiv.)





- A main feature of the ICARUS R&D:
  - ✓ Highly efficient filters based on ***Oxysorb/Hydrosorb***;
  - ✓ *Ultra High Vacuum techniques*;
  - ✓ *Continuous purification by recirculation in liquid & gas*.
- τ_{ctrons} > 5 ms (***~60 ppt [O2]$_{eq}$***) corresponding to a free electron attenuation of 17% after 1.5 m (longest path length);
- 11 accidental purity stops until now. New pumps ready.

ICARUS T600 physics program

- ICARUS T600
  - ✓ major milestone towards *multi-kton high performance LAr detectors*: unique ***imaging*** capability, high ***spatial/calorimetric*** resolutions, ***e/π_0 separation*** power
  - ✓ Interesting physics potentialities in itself

- the detector is collecting CNGS events. For 10^{20} pot:
  - ✓ 2800 CC + 900 NC events expected
  - ✓ Muons from upstream GS rock ≈ 12000 ev (≈ 8200 on TPC front face)
  - ✓ Intrinsic beam ν_e CC ≈ 26 ev
  - ✓ $\nu_\mu \rightarrow \nu_\tau$ detecting τ decay with kinematical criteria (~2 event $\tau \rightarrow e$)
  - ✓ $\nu_\mu \rightarrow \nu_e$ (θ_{13}) from e-like CC events excess at E < 20 GeV (~5 events CC)
  - ✓ *Search for sterile neutrinos in LSND parameter space, studying e-like CC events at E > 10 GeV*

- ICARUS is also simultaneously collecting "self triggered" events:
  - ✓ ≈ 100 ev/year of *atmospheric ν CC interactions*.
  - ✓ *Proton decay* with 3×10^{32} nucleons , zero bckg. in some of the channels

- ICARUS contributed to the *superluminal neutrino problem raised by OPERA*:
  - ✓ Search for the ***analogue to Cherenkov radiation*** by high energy CNGS neutrinos at superluminal speeds: *Physics Letters B **711** (3-4): 270–275*
  - ✓ ***Precision Measurement of the neutrino time-of-flight*** with the 2011 *(Physics Letters B 713 (1): 17–22*) and 2012 *(arXiv:1208.2629)* CNGS ν_μ bunched beams

Precision measurement of the neutrino velocity

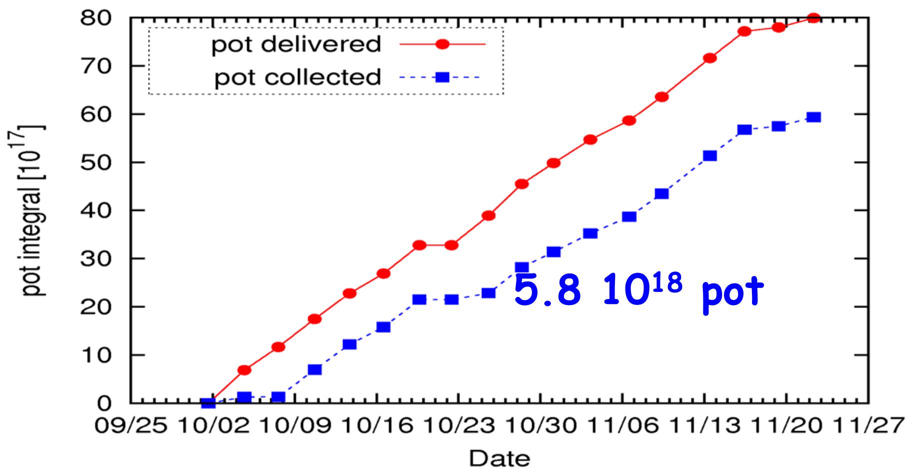
- In May 2012 the CERN-CNGS neutrino beam has been operated (1.8×10^{17} pot)., with the proton beam made of bunches, few ns wide and separated by 100 ns. This beam structure allows a very accurate time of flight measurement of neutrinos from CERN to LNGS;
- Four different time distribution systems:
  - ✓ Existing LNGS PPmS (1kHz) signal synchronized with a PolaRx2 GPS receiver is sent underground through an ~8 km optical fiber (already used in 2011 measurement);
  - ✓ *HPTF – Borexino setup*: ICARUS trigger signal sent through an ~ 9 km optical fiber to a new independent clock synchronization system (Rb clock + PolaRx4 GPS receiver);
  - ✓ *White Rabbit*: open source protocol for reliable, fast and deterministic transmission of control information. Set up at CERN and LNGS by CERN staff => *Two different inter-calibrated GPS receivers (PolarRx2 and PolarRx4) - Provides 2kHz signal recorded by ICARUS PMT-DAQ - Time stamping exploited for the ICARUS trigger signal*
- ICARUS PMT readout equipped with independent DAQ system based on 8 bit, 1GHz Acqiris AC240 digitizers
- New geodetic high precision measurement of CERN-ICARUS baseline (σ ~ 4cm) from Politecnico di Milano
- ICARUS observed 25 beam events: 17 rock μ's (1 stopping); 6 ν_μCC; 2 ν NC
- Reference point for neutrino timing: upstream wall position of ICARUS active volume. Topological corrections (visual scanning): vertex position; γ propagation from vertex to "identified" closest PMT
- Actual result (arXiV:1208.2629):

$$\delta(v/c) = (v_\nu - c)/c = 0.4 \pm 2.8\ stat \pm 9.8\ syst\ 10^{-7}$$

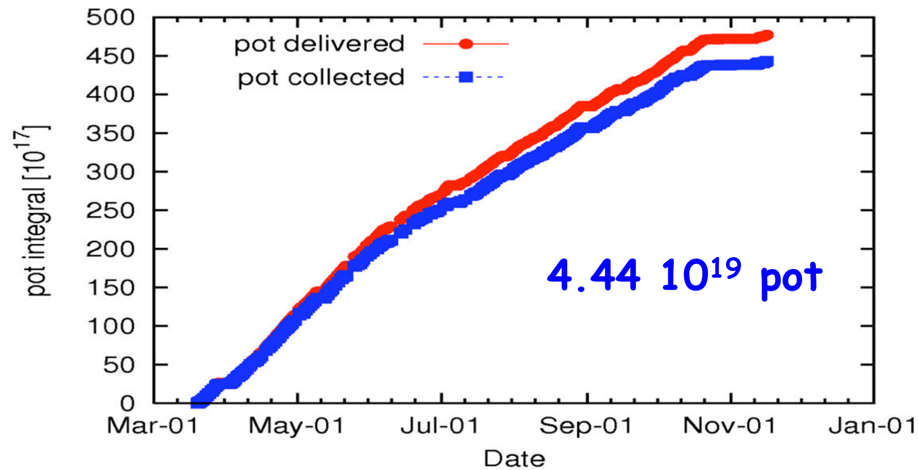
ICARUS (CNGS2) data collection

ICARUS T600 operational since Oct. 1st 2010

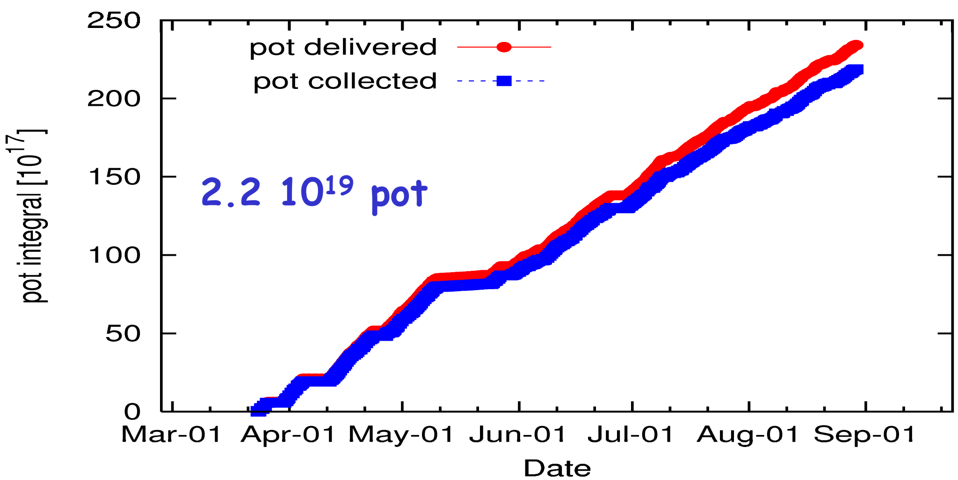
2010: Oct. 1st ÷ Nov. 22nd



2011: Mar. 19th ÷ Nov. 14th



2012: March 23rd ÷ now



- Detector live-time > ***93% in 2011 and 2012***;
- End data taking: December 2012;
- Analyzed to date: 3.3 10^{19} pot (1091 contained events) ≈ *1/3 of "ultimate" sample*;

The new frontier

- The discovery of a *Higgs boson* at CERN/LHC has crowned the successful Standard Model (SM) and will call for a verification of the Higgs couplings to the gauge bosons and to the fermions.

- *Neutrino masses and oscillations* represent today a main experimental evidence of physics beyond the Standard Model.

- Being the only elementary fermions whose basic properties are still largely unknown, neutrinos must naturally be one of the main priorities to complete our knowledge of the SM.

- Albeit still unknown precisely, *the incredible smallness of the neutrino rest masses*, compared to those of other elementary fermions points to some specific scenario, awaiting to be elucidated.

- *The astrophysical importance of neutrinos is immense*

“Sterile” neutrinos ?

- Sterile neutrinos are a hypothetical type of neutrino that *does not interact via any of the fundamental interactions* of the Standard Model except gravity.

- Since per se they may not interact directly, they are extremely difficult to detect. If they are heavy enough, they may also contribute to dark matter.

- Sterile neutrinos may mix with ordinary neutrinos via a mass term. Evidence may be building up by ***“anomalies”*** observed by several neutrino experiments:
  - ✓ sterile neutrino(s) with $\Delta m^2 \approx 10^{-2}$ — 1 eV^2 from ν_e observation in ν_μ *accelerator experiments* (LNSD anomaly).
  - ✓ Neutrino disappearance may have been observed in *nuclear reactors* and very intense (megacurie) *electron conversion neutrino sources* with maybe comparable mass differences

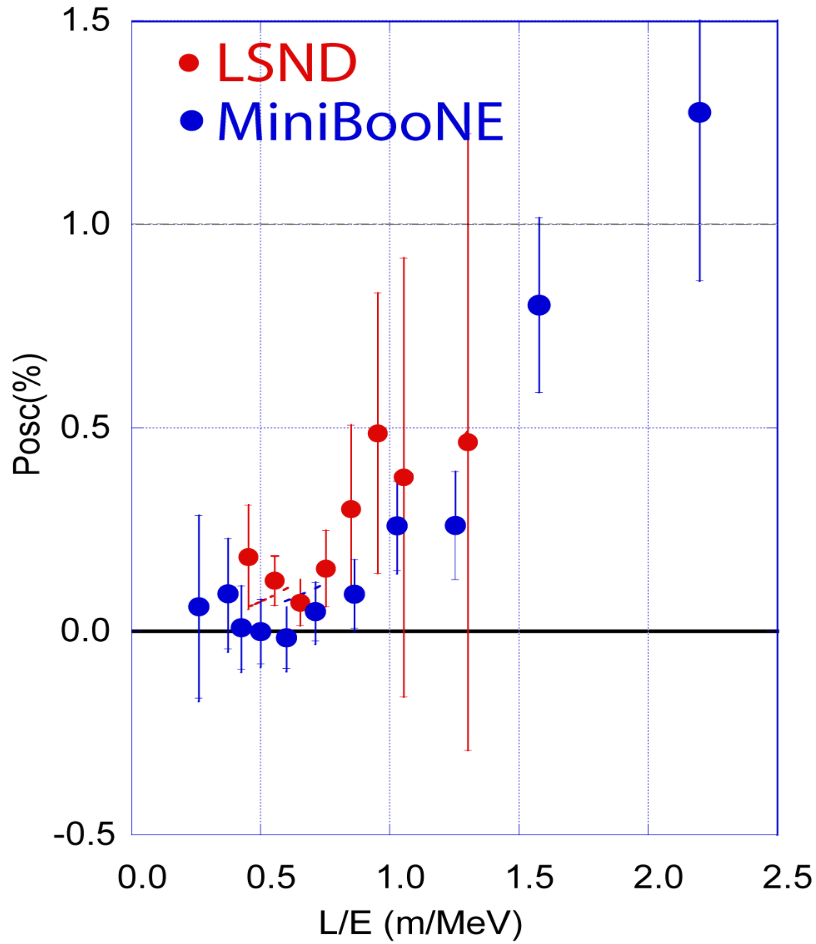
Over-all evidence is mounting...

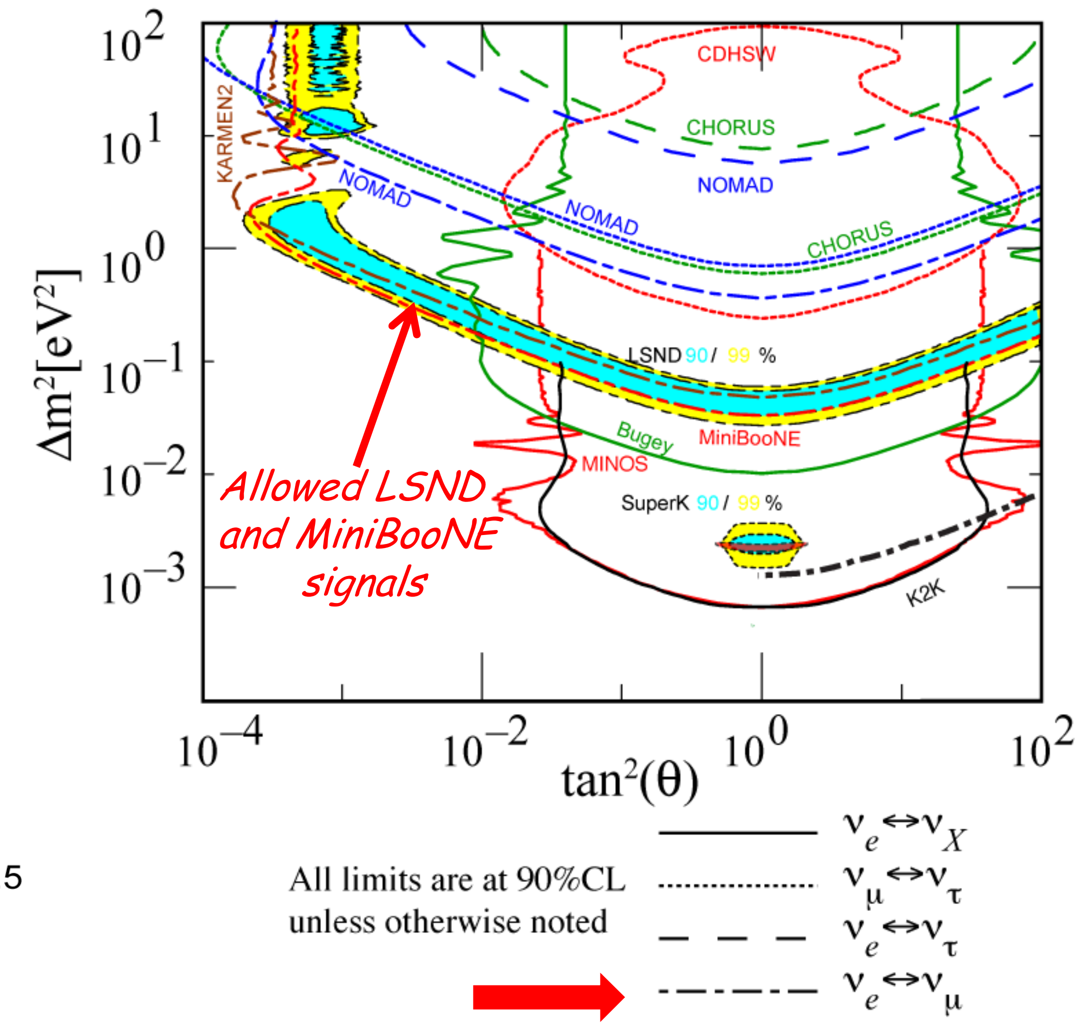
Anomaly	*Source*	*Type*	*Channel*	*Significance*
LSND	Short baseline	Decay at rest	-νμ –>νe CC	3.8 σ
MiniBoone	Short baseline	Neutrino beam	-νμ –>νe CC	3.0 σ
MiniBoone	Short baseline	Anti-Neutr. beam	anti-νμ –>νe CC	1.7
Gallium	Electron capture	Source	ν disapp.	2.7 σ
Reactors	Fission	Beta decay	ν disapp.	3.0 σ
Cosmology	Big bang WMAP	No of neutrino		≈ 2 σ

Combined evidence
≈ 3.8 s

Combined evidence for some possible anomaly :
(3.8 + 3.8 + 2.7 + 3.0 + 2.0) S.D !

Neutrino related anomalies

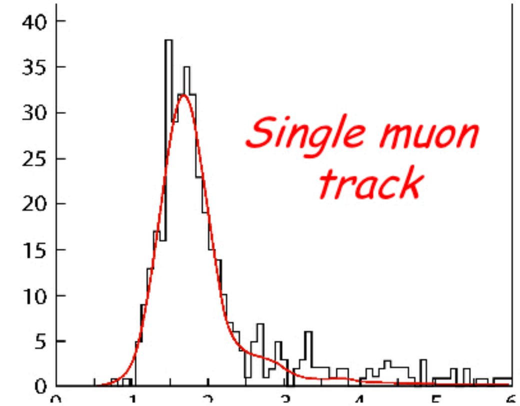


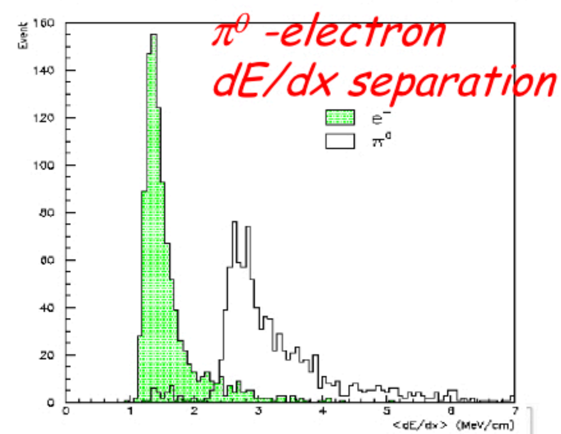


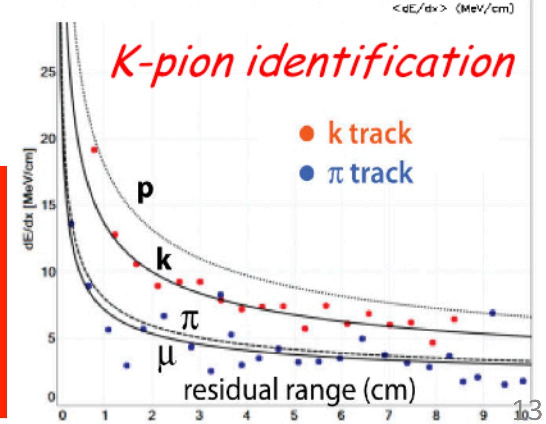
The present experiment looks for the a LSND like ν_μ-> ν_e signal from the LNGS ν_μ beam at 730 km and $10 \leq E_\nu \leq 30$ GeV

LAr TPC performance

- Tracking device
  - ✓ Precise *3D topology* and accurate ionization measurement
  - ✓ 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
- Total energy reconstruction of the events from charge integration
  - ✓ Full sampling, homogeneous calorimeter with excellent accuracy for contained events

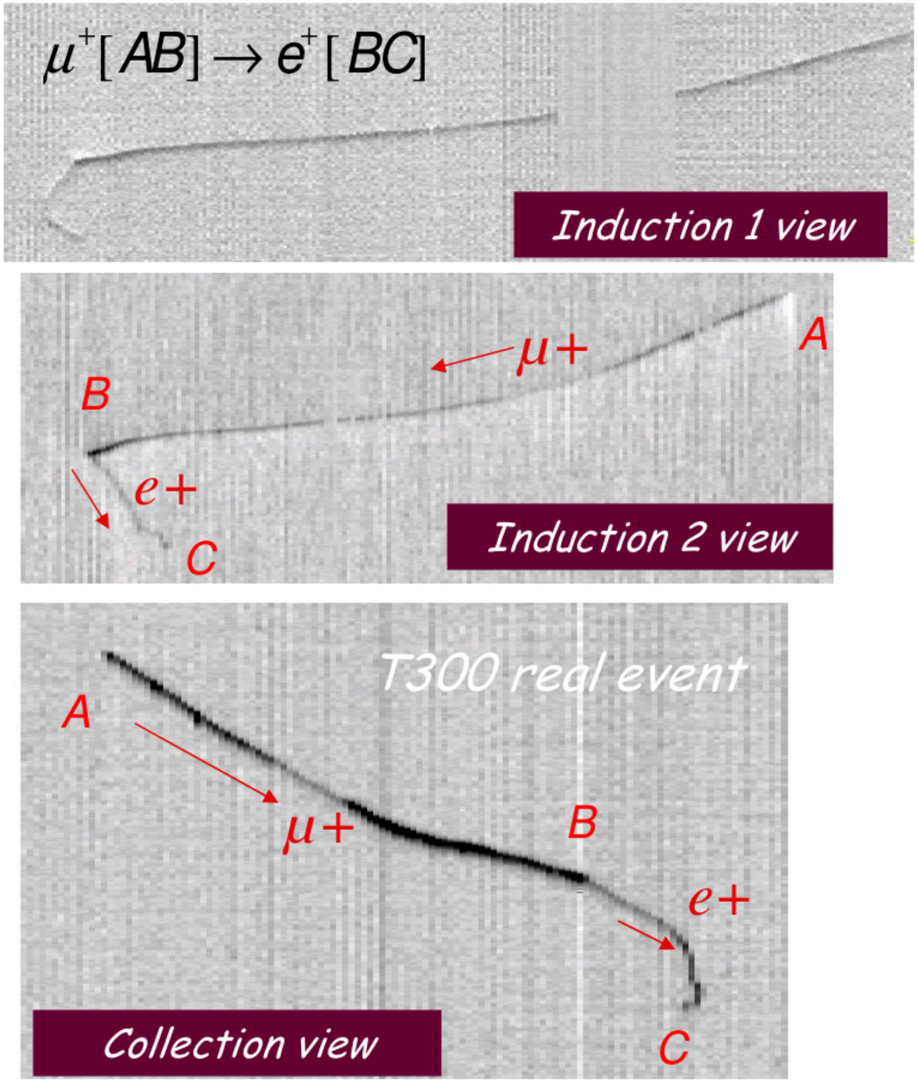


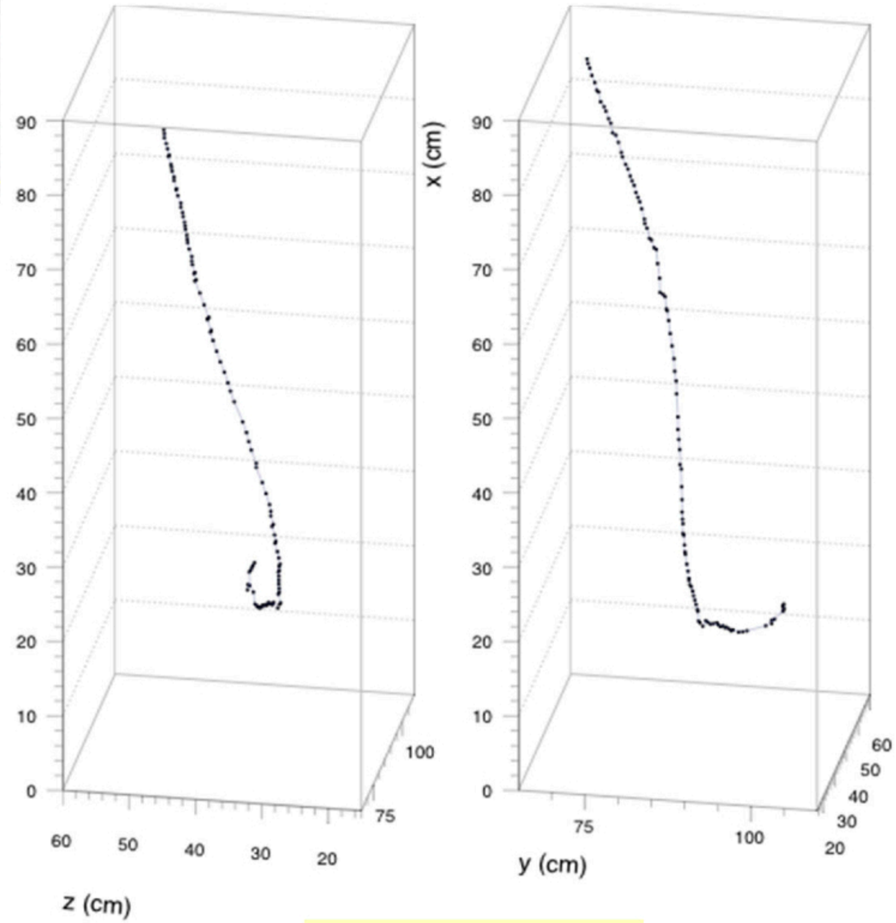




RESOLUTIONS
Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$
Electromagn. showers: $\sigma(E)/E = 3\% / \sqrt{E(GeV)}$
Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

3D reconstruction from three views 0°, ± 60° (stopping μ)

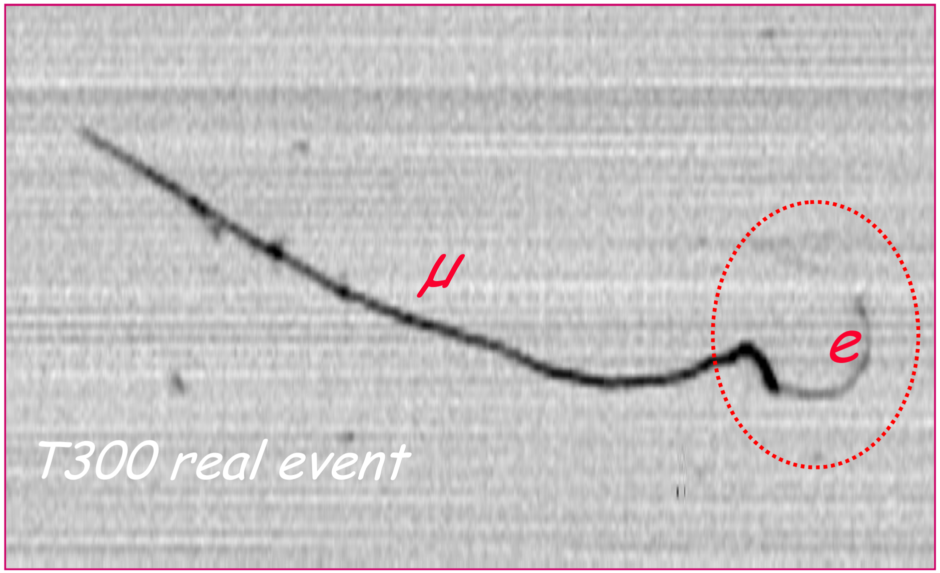


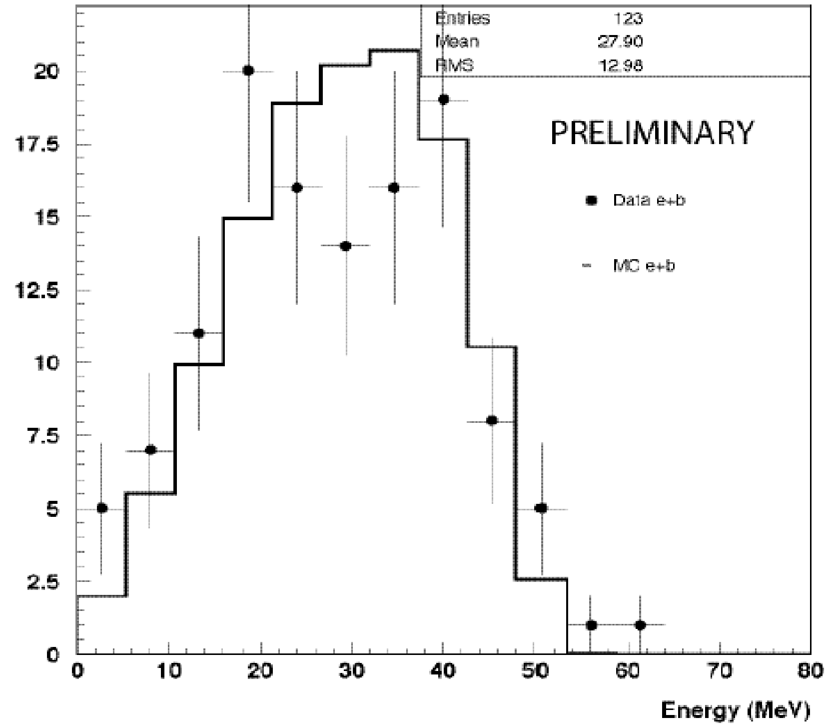


Te=36.2 MeV
Range=15.4 cm

Calorimetric reconstruction

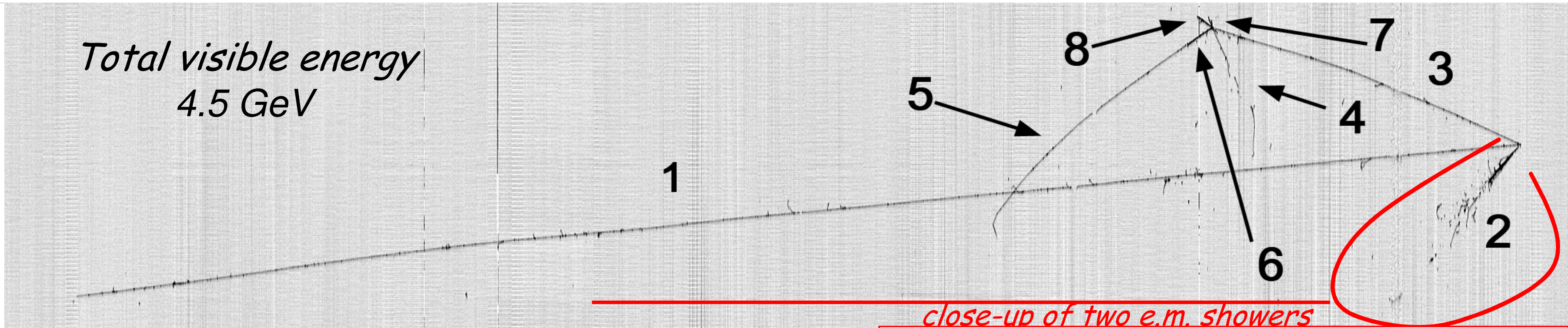
- ***Electrons from μ decay (Michel electrons)***





Energy resolution = $\frac{\sigma}{E} = \frac{(13 \pm 2)\%}{\sqrt{E(MeV)}} \oplus (1.8 \pm 0.3)\%$

Run 9927 Event 572



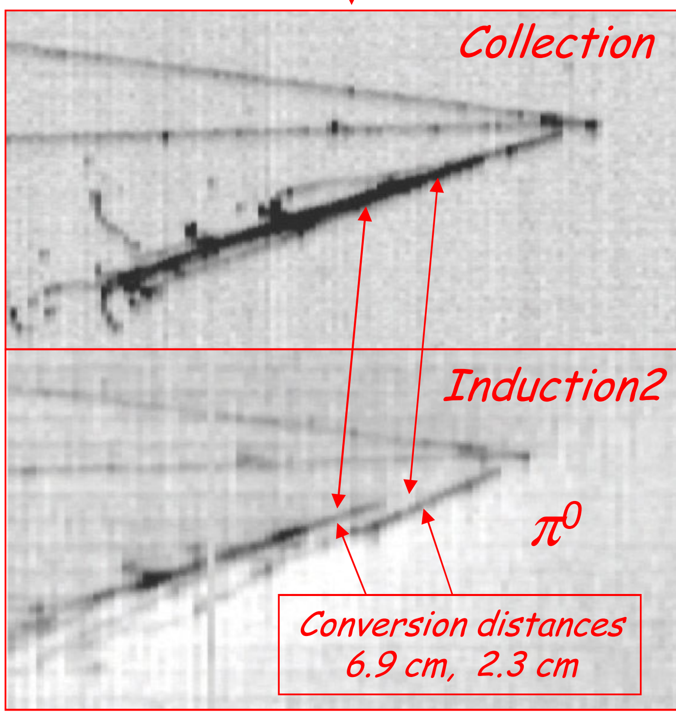
Primary vertex (A):

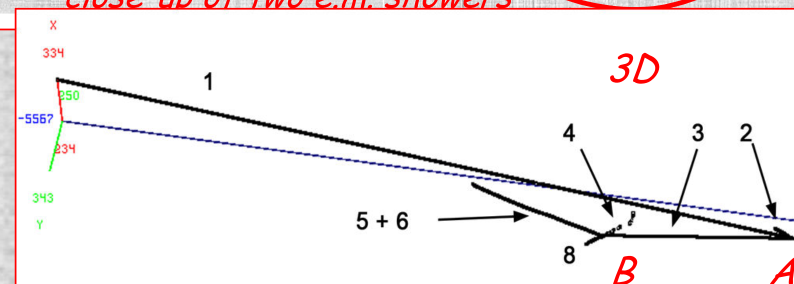
very long (1), e.m. cascades (2), pion (3)

Secondary vertex (B):

*The longest track (5) is a μ coming from stopping **k** (6).*

μ decay is observed





Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	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

Signal selection

- CNGS facility delivers an almost pure ν_μ beam peaked in the range *$10 \le E_\nu \le 30$ GeV* (beam associated ν_e about 1/2%). ***The signature of the ν_μ-> ν_e signal is observed visually***.

- Present sample: 1091 neutrino events from 2010 and 2011. There are differences with respect to LNSD experiment:
  - ✓ L/E_ν ~ 1 m/MeV at LNSD, but $L/E_\nu \approx 36.5$ m/MeV at CNGS
  - ✓ A LNSD-like short distance oscillation signal averages to ***$\sin^2(1.27\Delta m^2_{new} L/E) \sim 1/2$ and $\langle P \rangle_{\nu\mu \to \nu e} \sim 1/2 \sin^2(2\vartheta_{new})$***

- Expected conventional ν_μ -> ν_e in the same energy range and fiducial volumes :
  - ✓ 3 events due to the *intrinsic ν_e beam contamination*
  - ✓ 1.3 events due to *ϑ_{13} oscillations*:
  - ✓ 0.7 events of *ν_μ-> ν_τ oscillations with electron production*.

- The total is therefore of ***5 expected events***.

Event simulation with Montecarlo

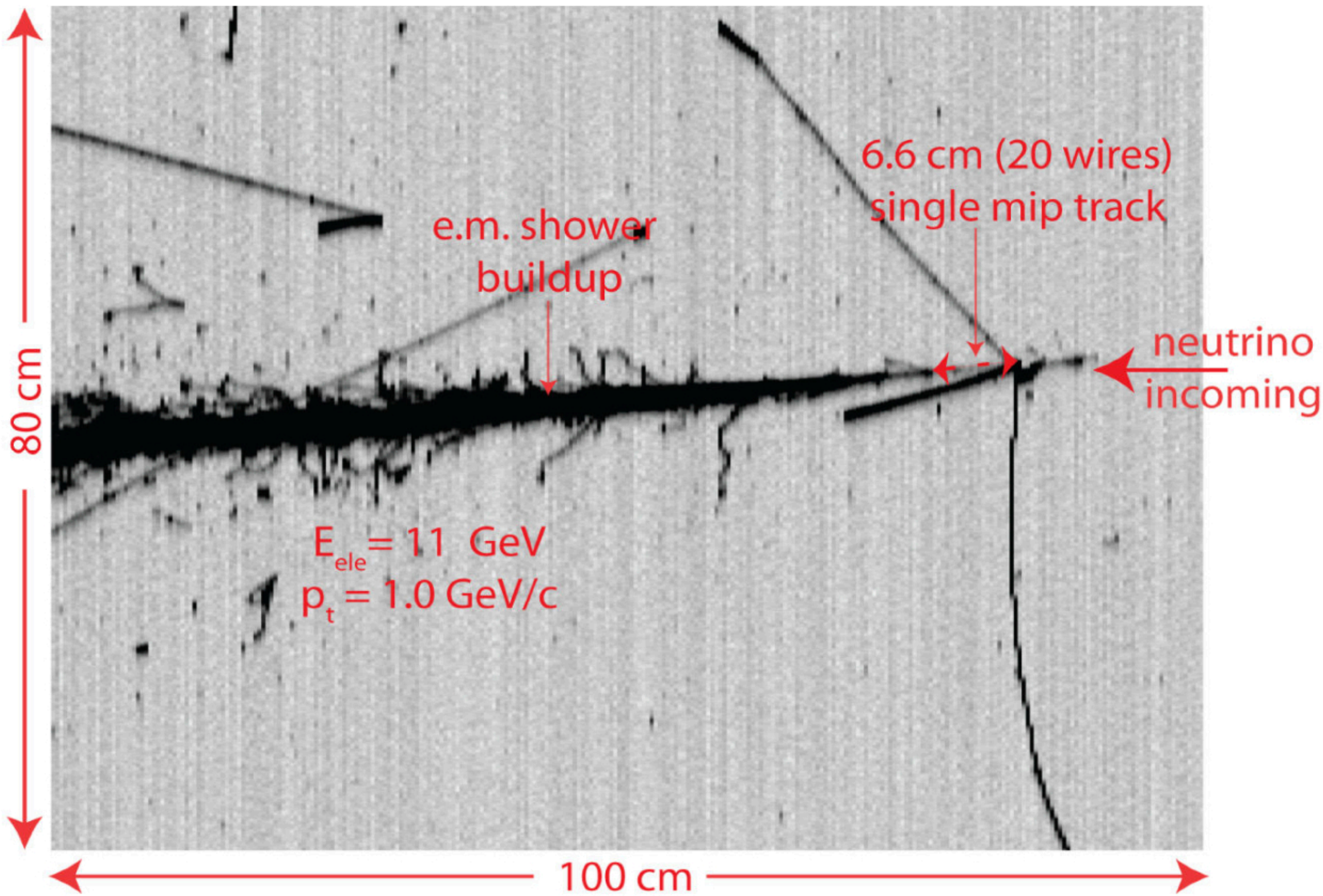
- The detection of events has been *widely simulated by a very sophisticated Montecarlo emulation*, reproducing in every detail the actual signals from the wire planes. *The agreement between MC and observed events has been excellent.*

- An ***"electron signature"*** has been defined by presence of a *single minimum ionizing relativistic electron track*:
  - ✓ of sufficient length from the vertex, subsequently building up into a shower; very dense sampling: ***every 0.02*** X_0 !!!
  - ✓ *clearly separated from other ionizing tracks near the vertex in at least one of the two transverse views*.

- Visibility cuts reduce the probability of identification of an electron tracks to $\eta = 0.74 \pm 0.05$. In a good approximation η is independent of the shape of the energy spectrum.

- The number of expected events with visible $\nu_\mu \to \nu_e$ ***is then 3.7***.

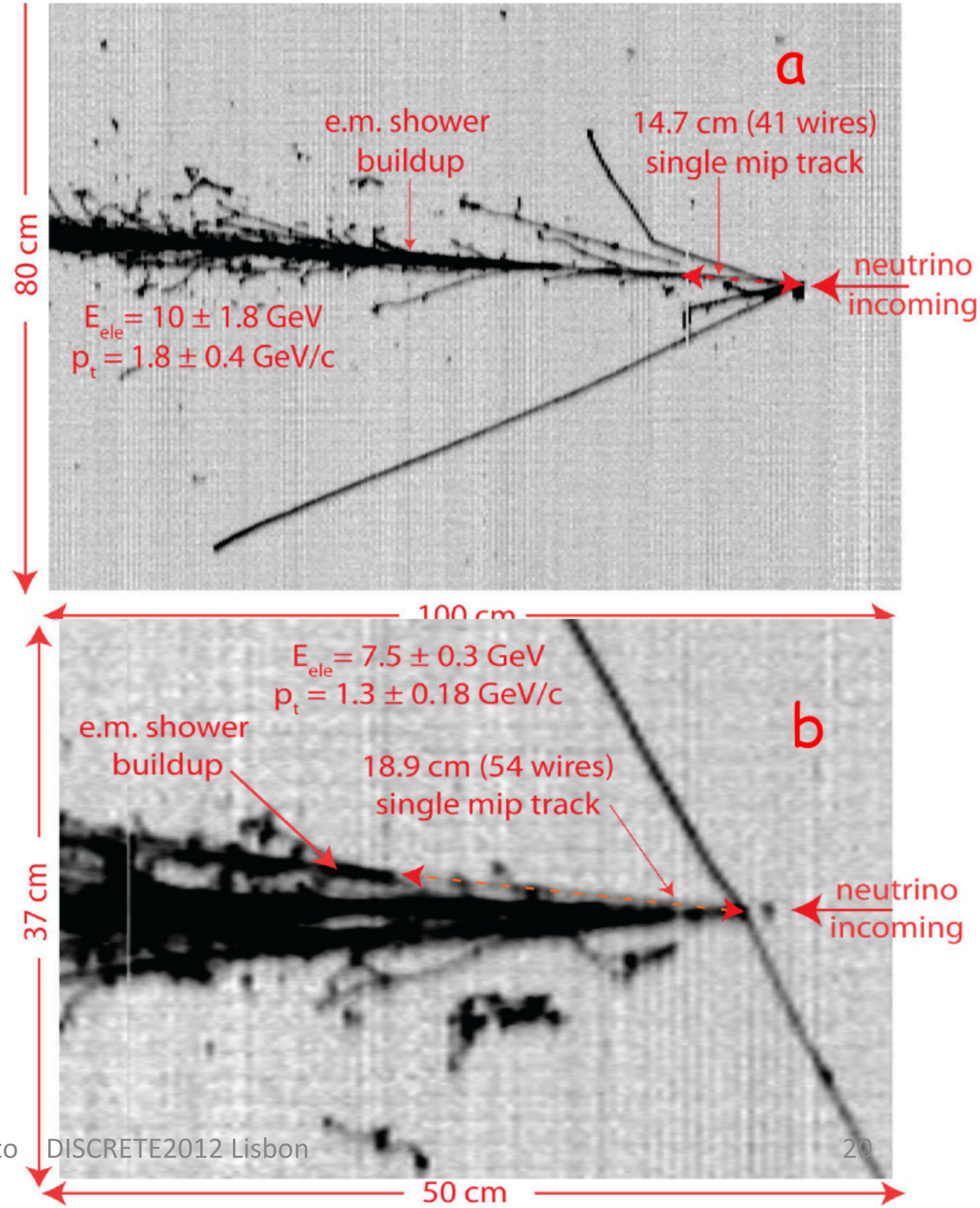
Visual identification of a ν–e event (MC)



Typical Montecarlo generated event from the ICARUS simulation program with E_{ele}= 11 GeV and p_t= 1.0 GeV/c. Only the vertex region is shown.

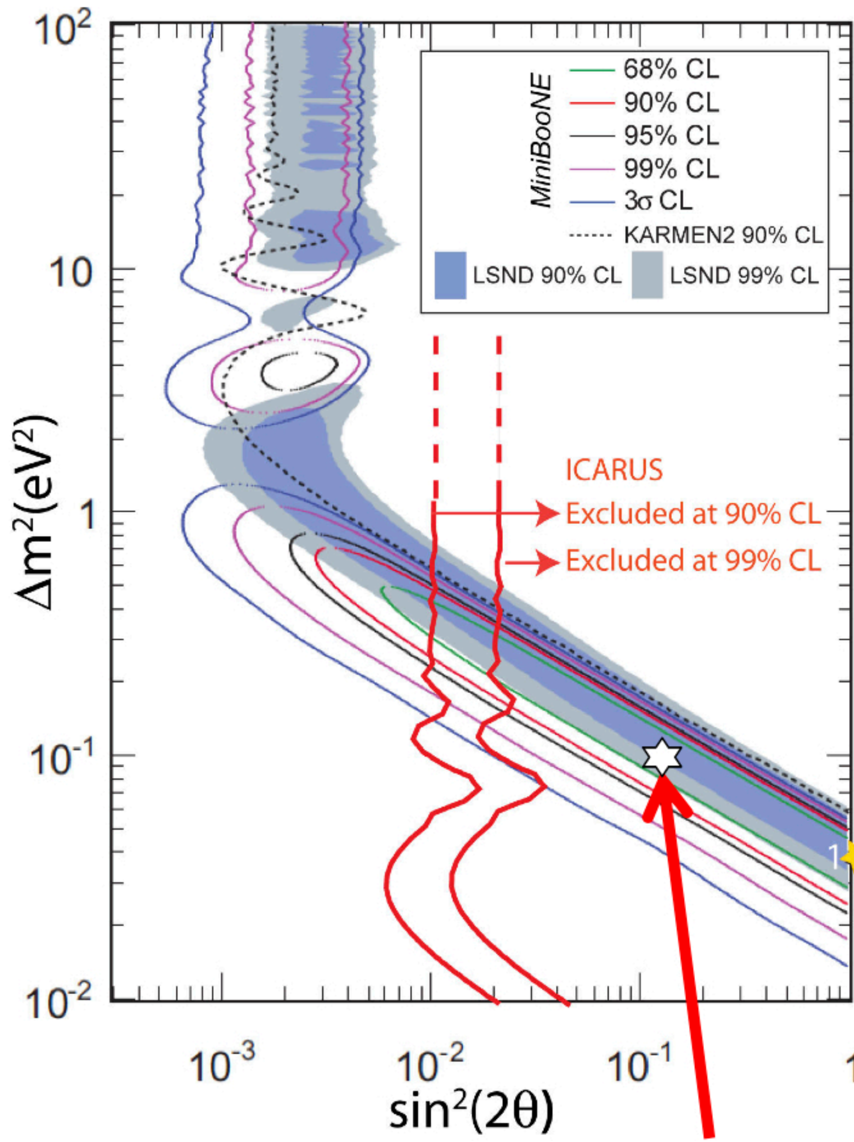
Events in the data

- ***Two CC events have been observed in data sample***, with a clearly identified electron signature:
  a) *total energy = 11.5 ± 1.8 GeV, P_t = 1.8 ± 0.4 GeV/c*
  b) *Total visible energy = 17 GeV. P_t = 1.3 ±0.18 GeV/c*
- *In both events the single electron shower in the transverse plane is clearly opposite to the remaining part of the event*



Results

- The ICARUS experiment is presently **compatible with the absence of a LSND anomaly**. The limits due to the LSND anomaly are respectively 3.41 (90% CL) and 7.13 events (99% CL)
- Given the sample of 627 ν_μ - CC events, the limits to the oscillation probability are:
  $P_{\nu\mu \rightarrow \nu e} \leq 5.4 \times 10^{-3}$ (90% CL)
  $P_{\nu\mu \rightarrow \nu e} \leq 1.1 \times 10^{-2}$ (99% CL)
- The exclusion area is shown for the plot $\Delta m^2 - \sin^2(2\theta)$. *At small Δm^2 ICARUS strongly enhances the sensitivity with respect to the short baseline experiments*.

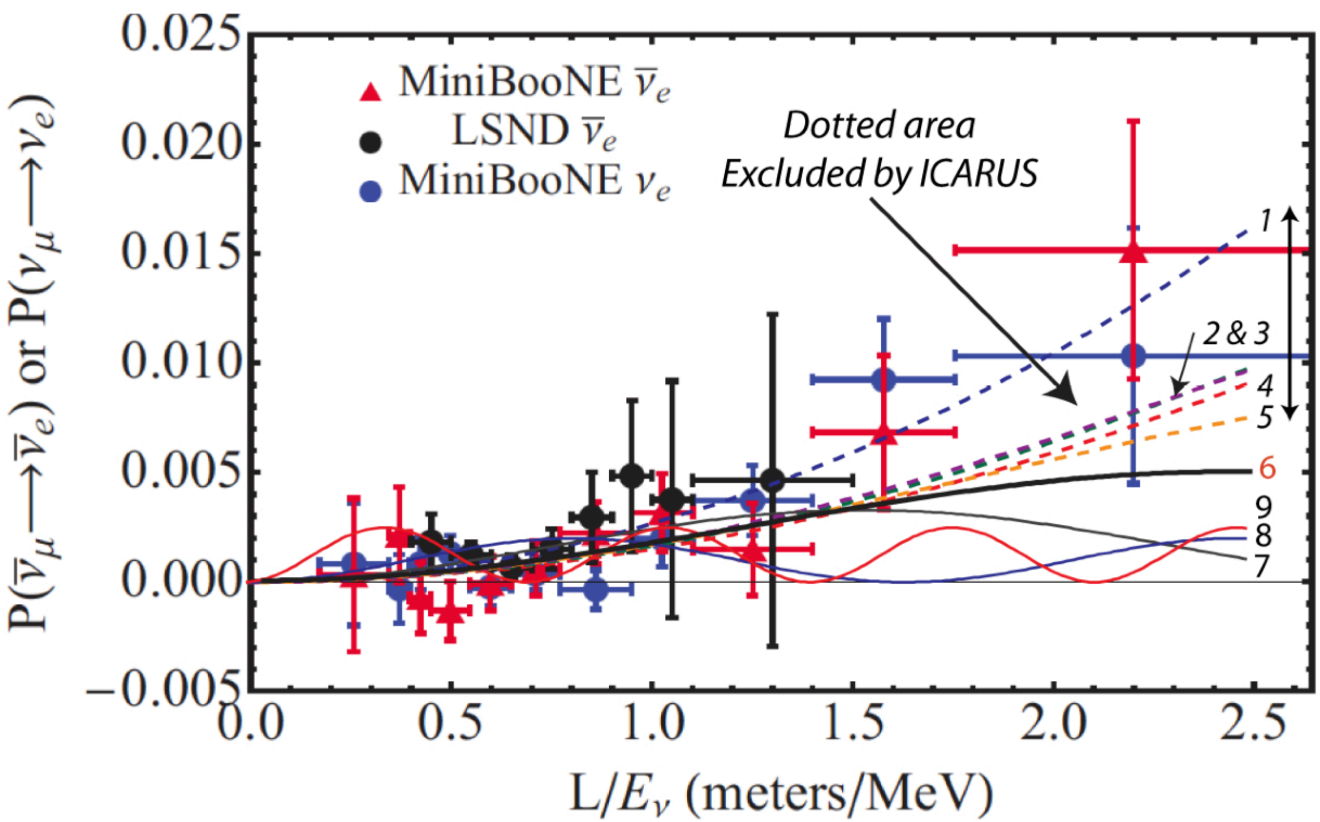


With $(\Delta m^2 - \sin^2(2\theta)) = (0.11\ eV^2, 0.10)$ as many as 30 events should have been seen

The low energy excess ?

- The ICARUS result excludes a substantial fraction of the MiniBooNE curves corresponding to lines from 1 to 5.

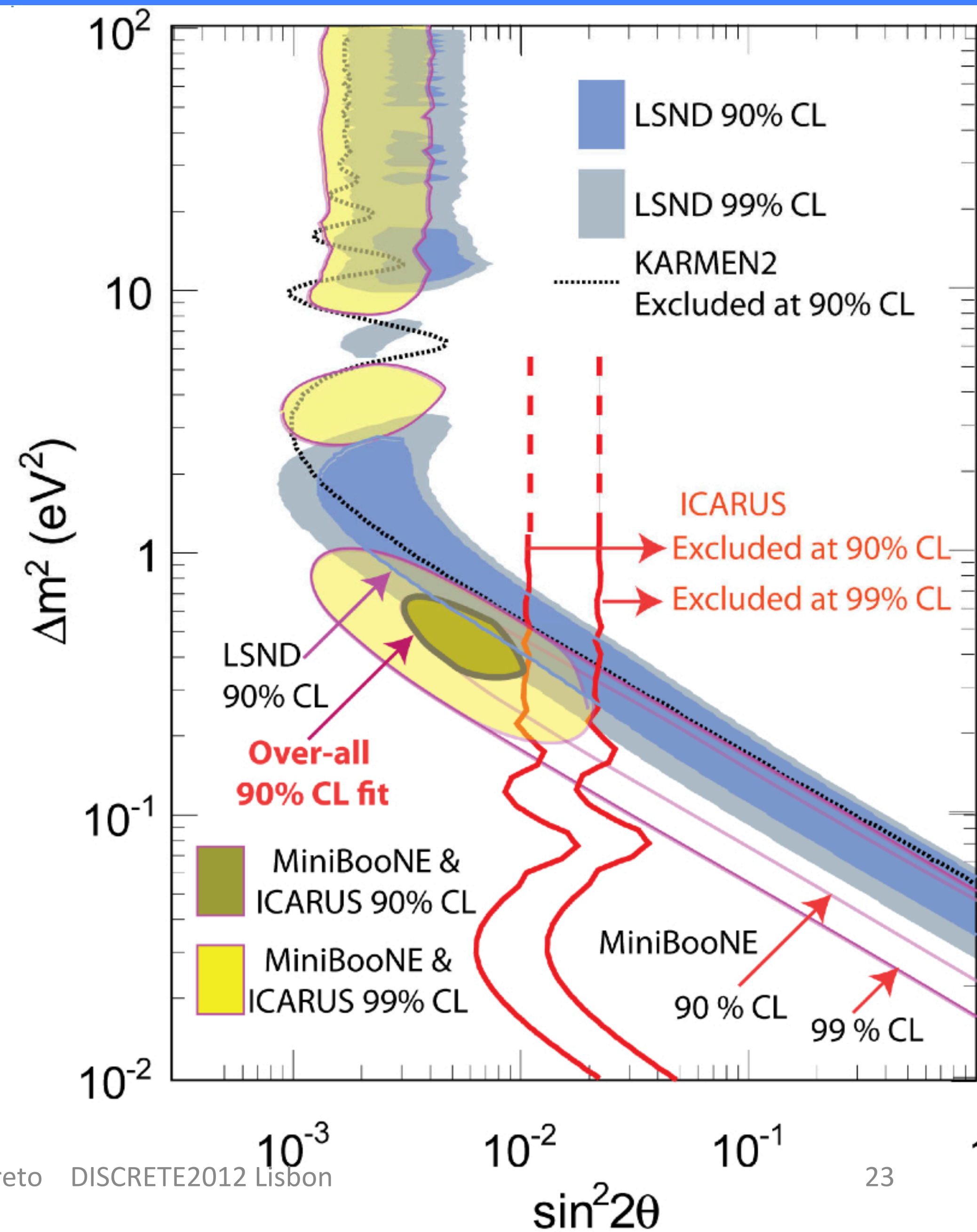
- The origin of the L/E_ν> 1 (low energy) excess observed by MiniBooNE may need further clarification.



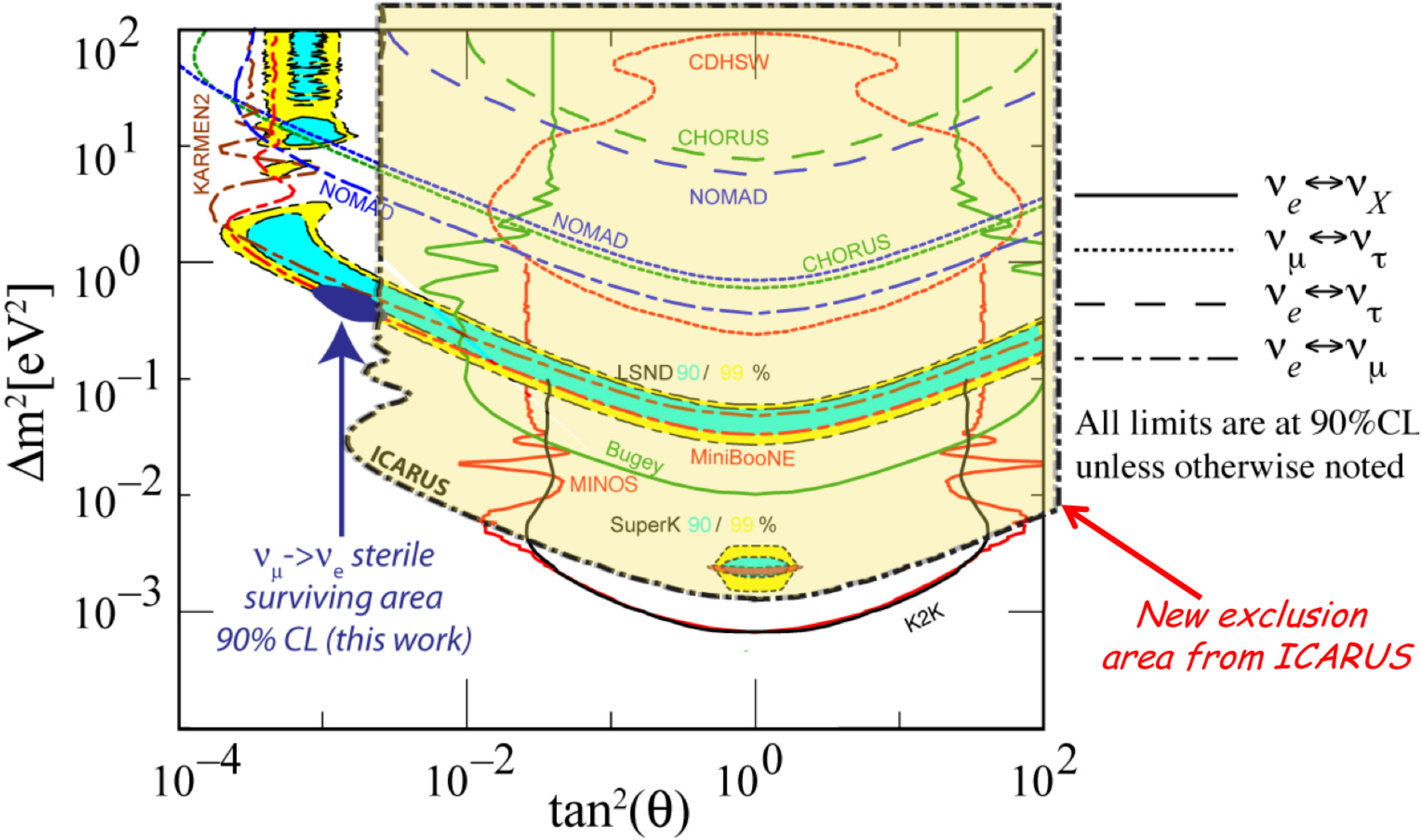
#	$\sin^2(2\theta)$	$\Delta m^2(eV^2)$
1	1	0.04
2	0.3	0.07
3	0.1	0.11
4	3.0E-2	0.21
5	1.0E-2	0.37
6	5.0E-3	0.50
7	3.3E-3	0.8
8	2.0E-3	1.5
9	2.5E-3	3.5

Conclusions

- The present result strongly limits the window of opened options for the LSND anomaly, reducing the remaining effect to a narrow region centered around ($\Delta m^2 - \sin^2(2\theta)$) = (0.5 eV^2 and 0.05) where there is an over-all agreement (90 % CL) between
  - ✓ the present ICARUS limit,
  - ✓ the limits of KARMEN and
  - ✓ the positive signals of LSND and MiniBooNE collaborations



LSND-like exclusion due to the present experiment



A next step on sterile oscillations with the LAr -TPC

- In order to clarify the previously indicated and surviving LSND/ MiniBooNE ($\Delta m^2 - \sin^2(2\theta)$) region, the ICARUS LAr detector will be moved next to CERN, at a much shorter distances (300 m and 1.8 km) and lower neutrino energies.

- This will increase the events rate, reduce the over-all multiplicity of the events, enlarge the angular range and therefore improve substantially the visual electron selection efficiency.

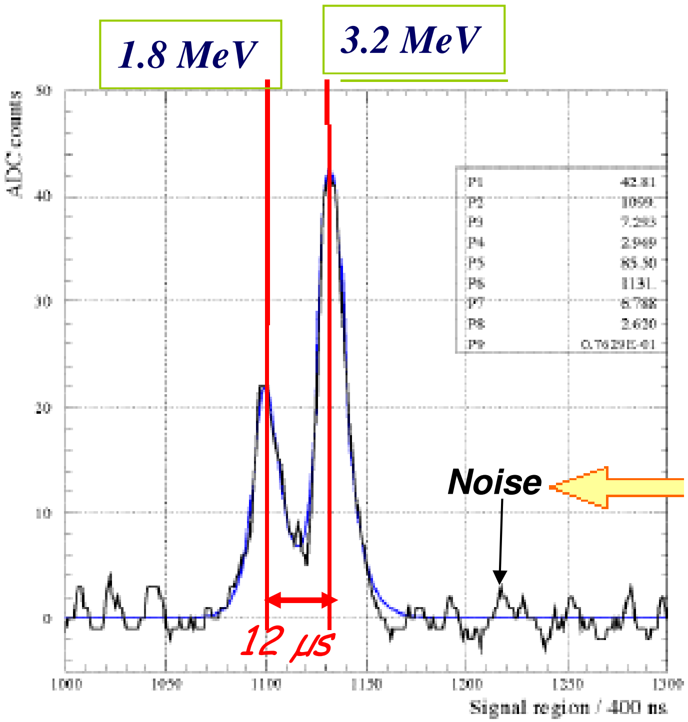
- In absence of oscillations, apart some beam related small spatial corrections, the two spectra at different distances should be a precise copy of each other, independently of the specific experimental event signatures and without any Montecarlo comparisons.

- This will presumably permit a definitive clarification of the "LNSD anomaly".

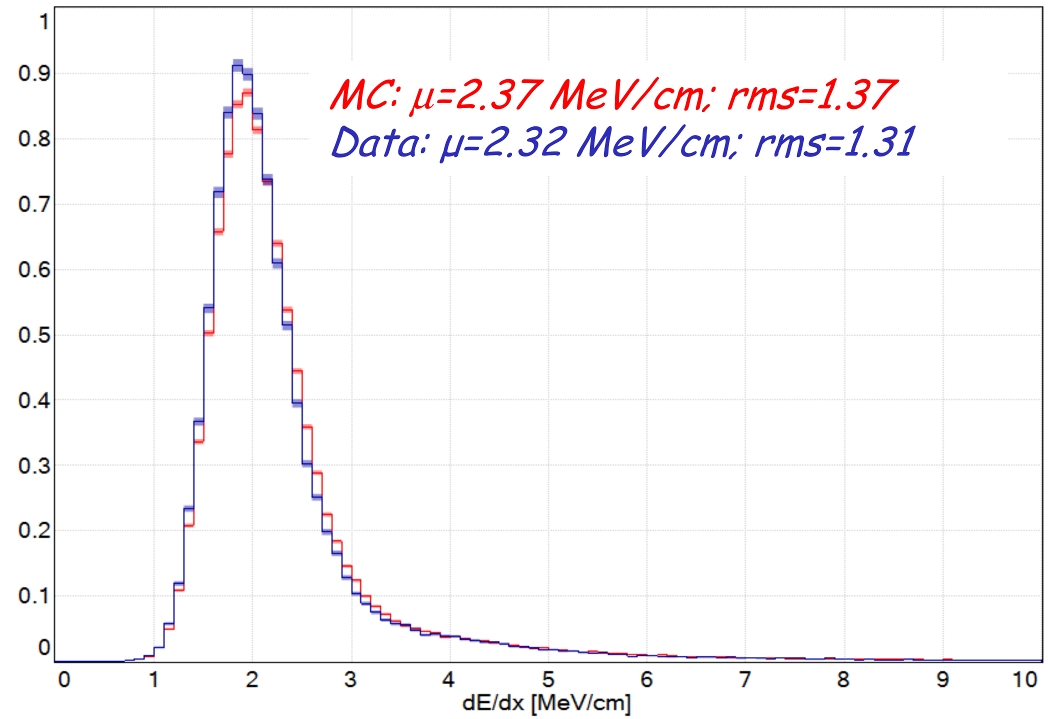
BACK UP

Real data and MC simulated tracks

Single wire performance



Comparison MC and actual data



- *dE/dx of individual 3 mm track segments reconstructed in 3D*, after removing δ rays and e.m. cascades
- ***Excellent agreement*** between real and simulated data *with the theoretical Landau distribution*

The MiniBooNE low energy effect

- The energy dependent neutrino experimental spectrum (1) is characterized by a large peak of events with E < 450 MeV (1).

- In the peak region the dominant signal is due *to ν_μ misidentified background* (2)

- Expectations from LNSD (2) + the ν_μ background(3) below E < 450 MeV do not add (4) to the observed signal (1)