# Experimental search for a "LSND like anomaly" with ICARUS in the CNGS

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# 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, so is their cosmic evolution.

# "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 cold dark matter or warm 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 $\nu_e$ observation in $\nu_\mu$ accelerator experiments (LNSD anomaly).
  - Neutrino disapperance may have been observed in nuclear reactors and very intense (megacurie) electron conversion neutrino sources with maybe comparable mass differences

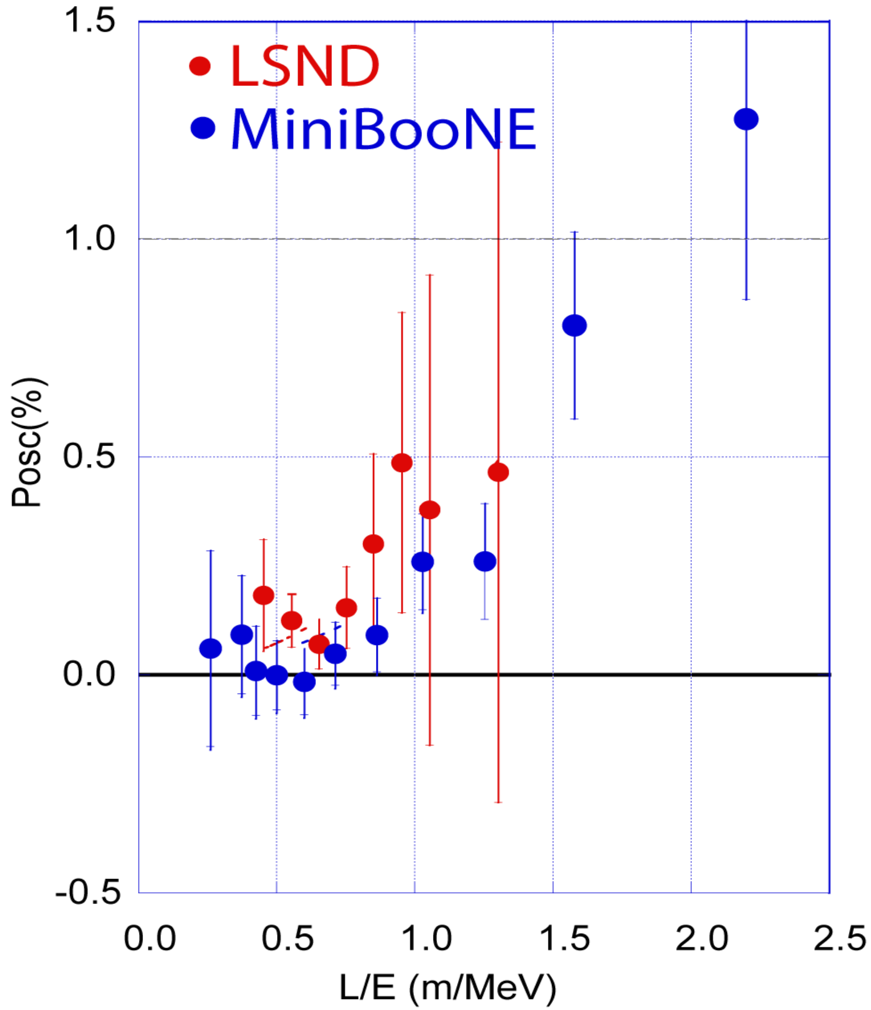
# Over-all evidence is mounting….

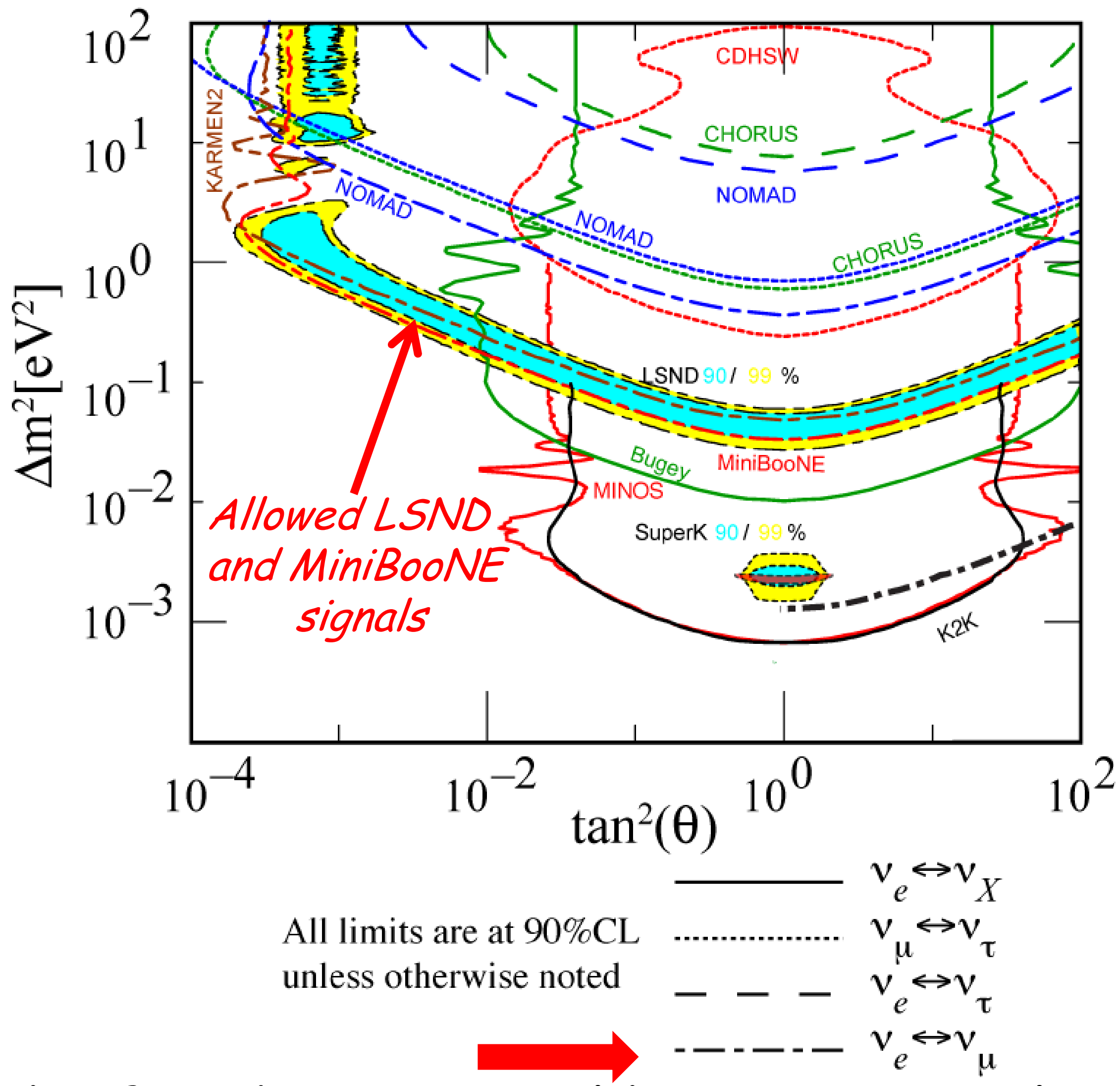
| *Anomaly* | *Source* | *Type* | *Channel* | *Significance* |
|---|---|---|---|---|
| **LSND** | Short baseline | Decay at rest | -νμ –>νe CC | 3.8 σ |
| **MiniBoone** | Short baseline | Neutrino beam | -νμ –>νe CC | 3.0 σ |
| **MiniBoone** | Short baseline | Anti-Neutr. beam | anti-νμ –>νe CC | 1.7 |
| **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 $\nu_\mu$ $\nu_e$ signal from the LNGS $\nu_\mu$ beam at 730 km and $10 \leq E_\nu \leq 30$ GeV

# The ICARUS Collaboration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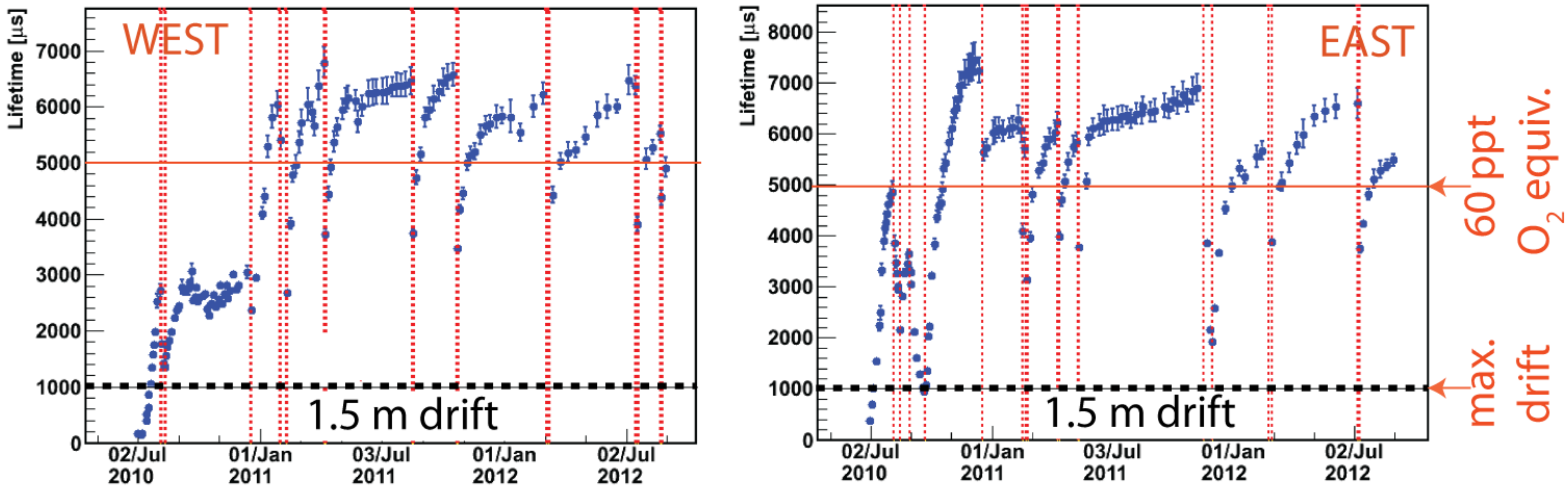
# The ICARUS detector in underground Hall B of LNGS

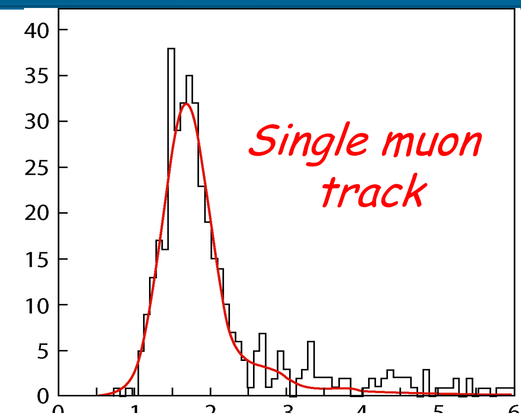
# LAr-TPC purification (< 60 parts per trillion $O_2$ equiv.)

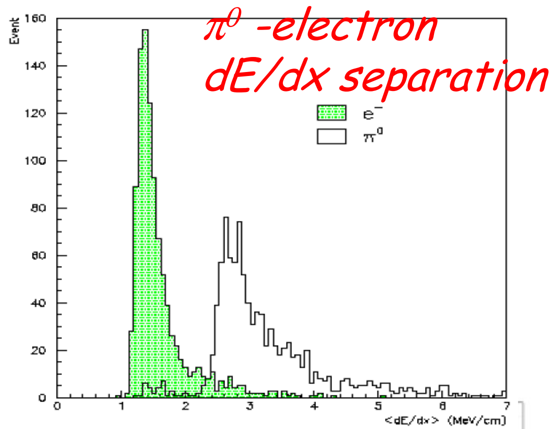


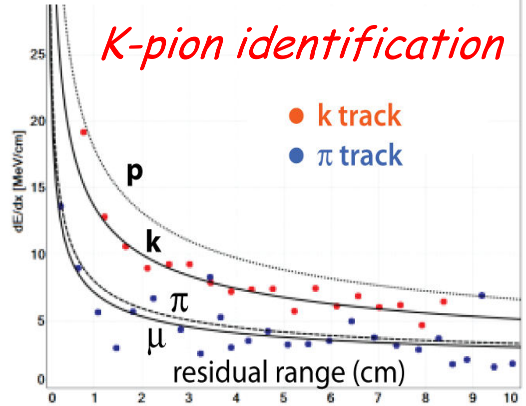

- A main feature of the ICARUS R&D:
  - Highly efficient filters based on Oxysorb/Hydrosorb;
  - Ultra High Vacuum techniques;
  - Continuous purification by recirculation in liquid & gas
- $\tau_{ele}$ > 5 ms (~60 ppt $[O_2]_{eq}$) corresponding to a free electron attenuation of 17% after 1.5 m (longest path length)
- 11 accidental purity stops until now. New pumps ready.

# LAr TPC performance

- Tracking device
  - Precise 3D topology and accurate ionization
  - Momentum via multiple scattering
- Measurement of local energy deposition dE/dx
  - e /γremarkable 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



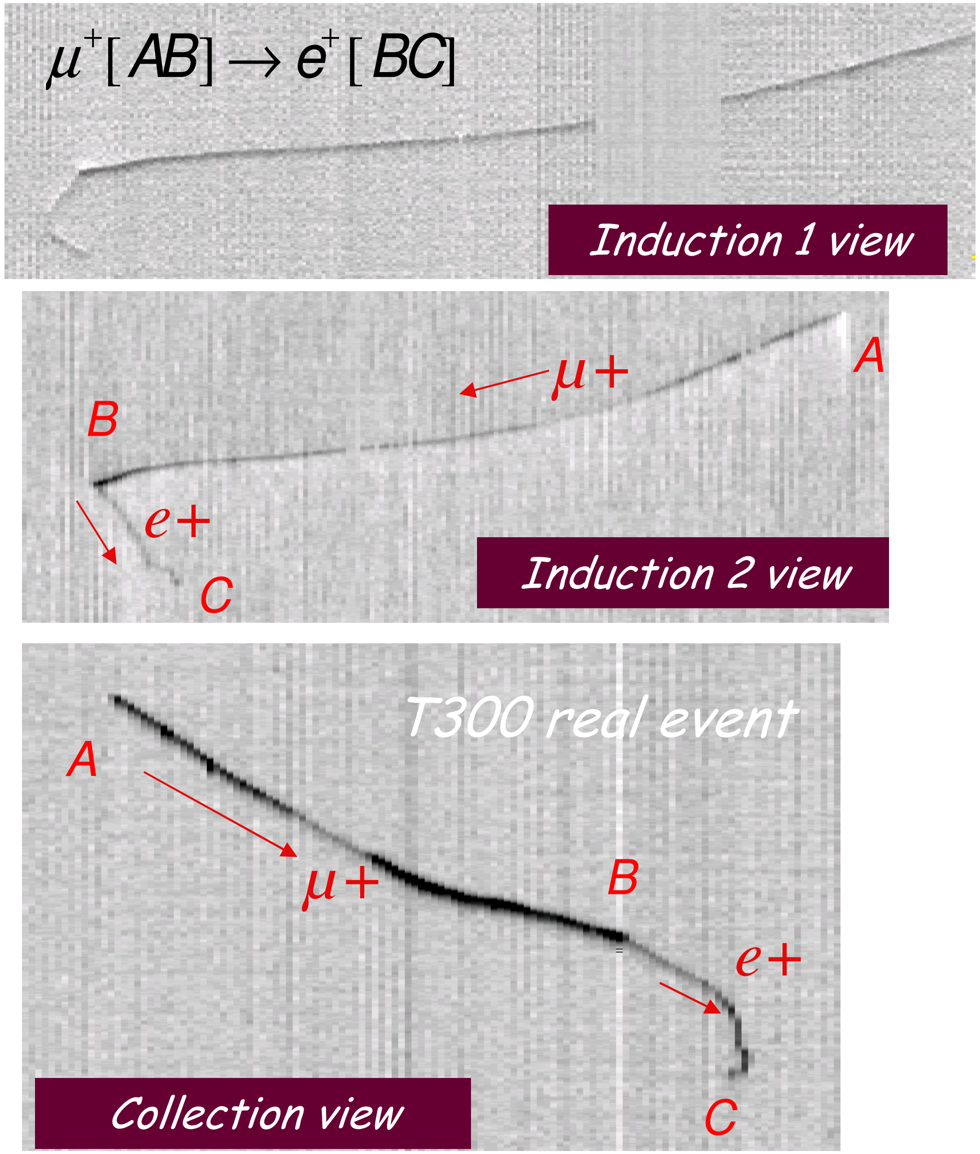

*RESOLUTIONS*

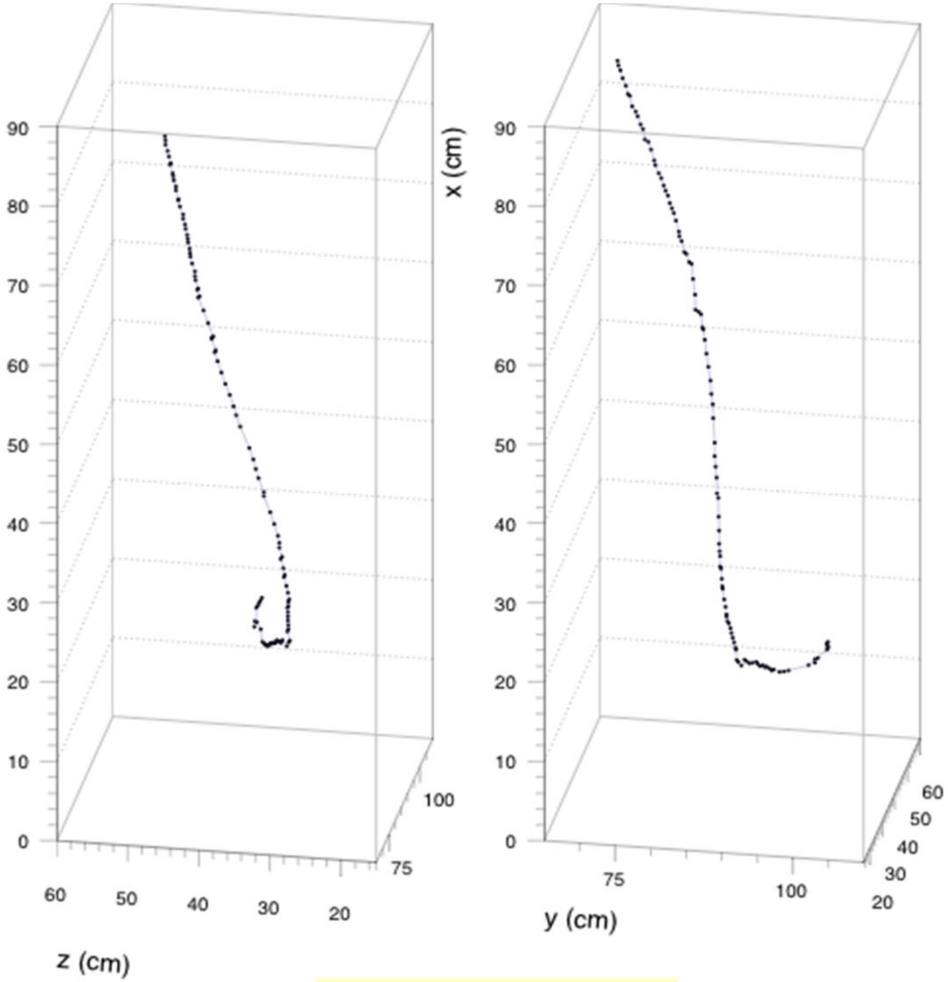
*Low energy electrons:* $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$

*Electromagn. showers:* $\sigma(E)/E = 3\% / \sqrt{E(GeV)}$

*Hadron shower (pure LAr):* $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

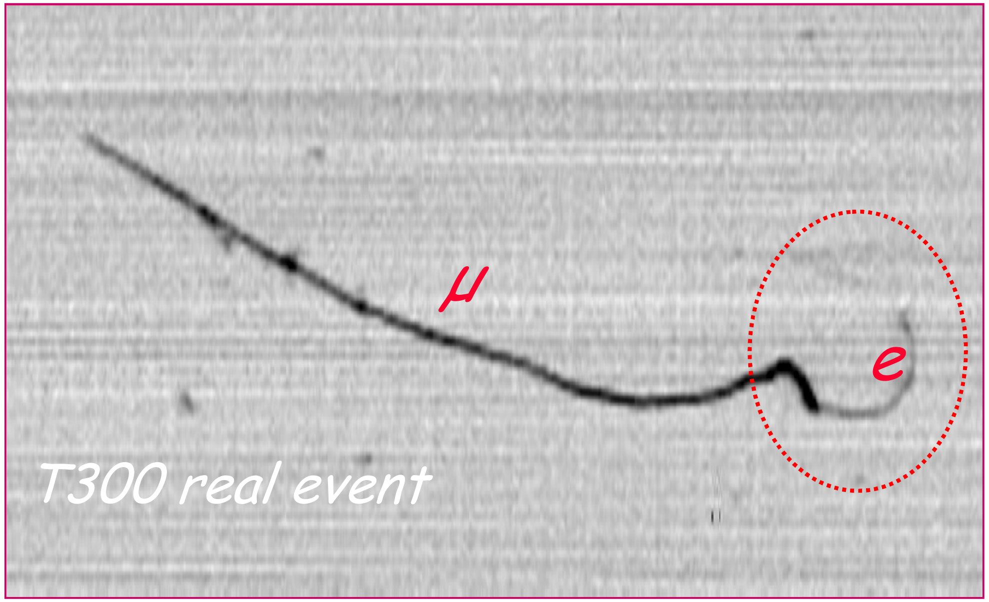
# 3D reconstruction from three views 0°, ± 60° (stopping μ)

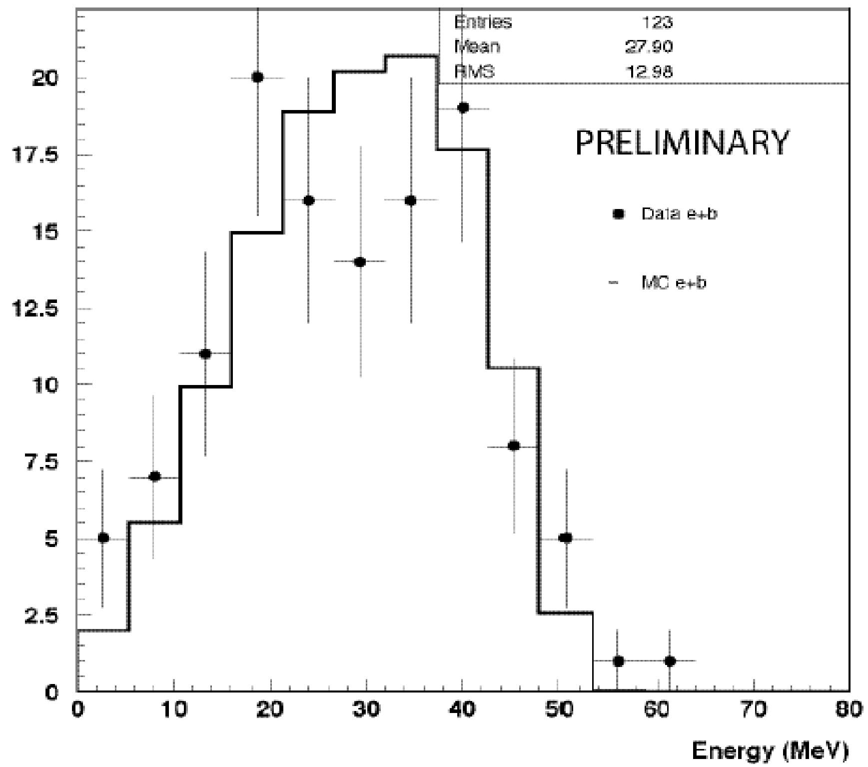



Te=36.2 MeV
Range=15.4 cm

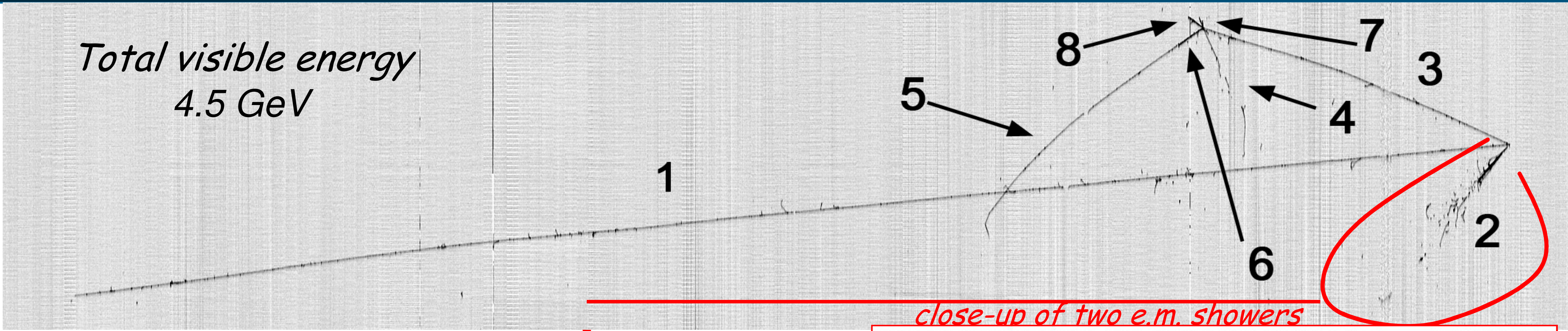
## Michel electrons (μ - e decays)




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

# Run 9927 Event 572



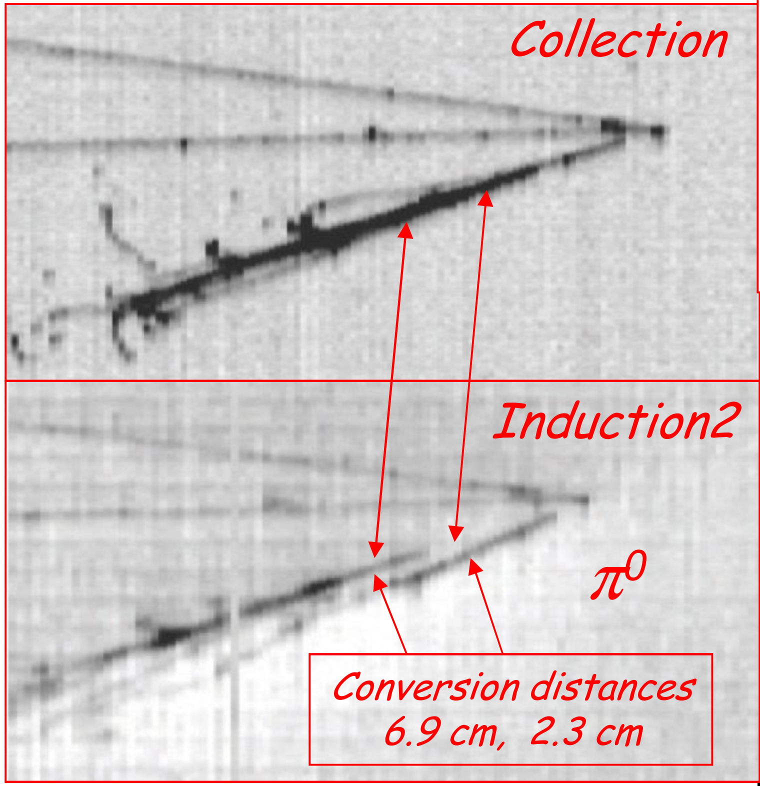

*Primary vertex (A):*

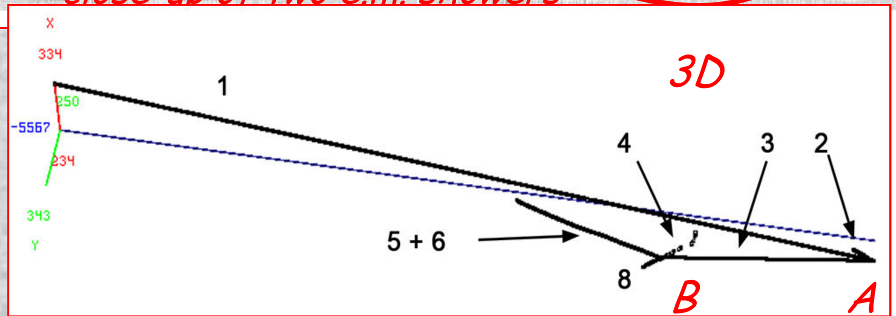
*very long (1), e.m. cascades (2), pion (3)*

*Secondary vertex (B):*

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

*μ decay is observed*



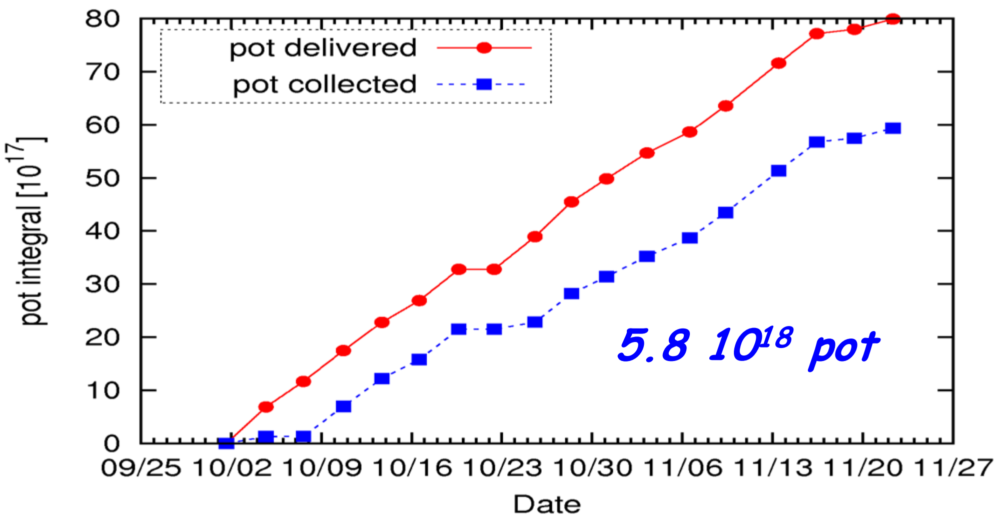




| Track | $E_{dep}$[MeV] | cosx | cosy | cosz |
|---|---|---|---|---|
| 1 (μ) | 2701.97 | 0.069 | -0.040 | -0.997 |
| 2 | 520.82 | 0.054 | -0.420 | -0.906 |
| 3 (p) | 514.04 | -0.001 | 0.137 | -0.991 |
| Sec. vtx. | 797 | | | |
| 4 | 76.99 | 0.009 | -0.649 | 0.761 |
| 5 (μ) | 313.9 | | | |
| 6 (K) | 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 |

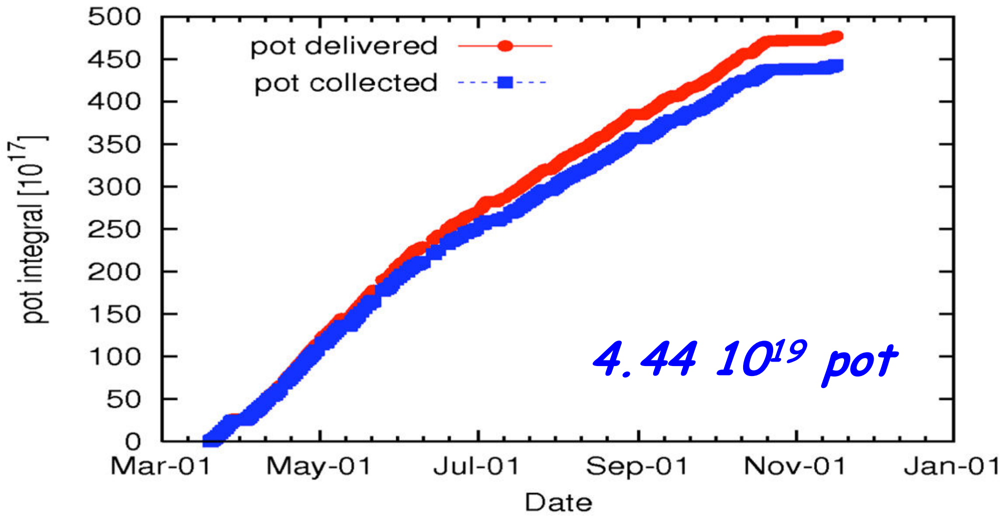
# ICARUS (CNGS2) data collection

- ICARUS T600 operational since Oct. 1$^{st}$ 2010

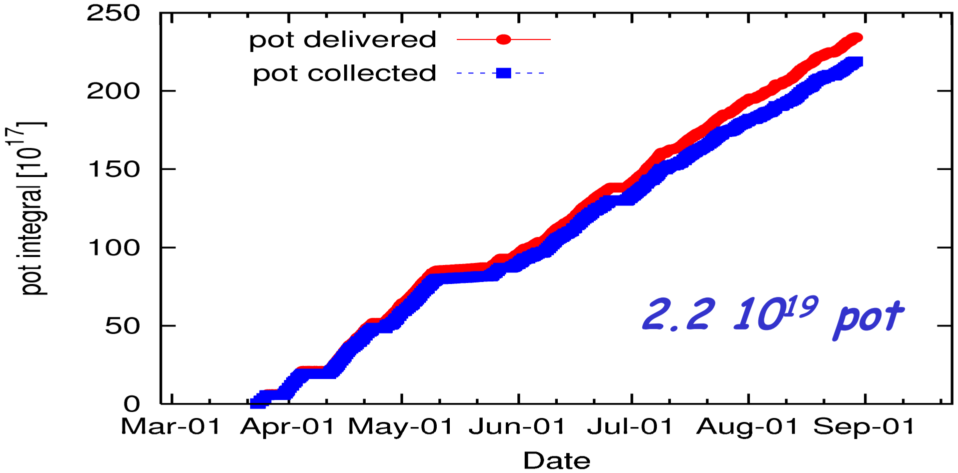
*2010: Oct. 1$^{st}$ ÷ Nov. 22$^{nd}$*




*2011: Mar. 19$^{th}$ ÷ Nov. 14$^{th}$*




*2012: March 23$^{rd}$ ÷ now*




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

# Signal selection

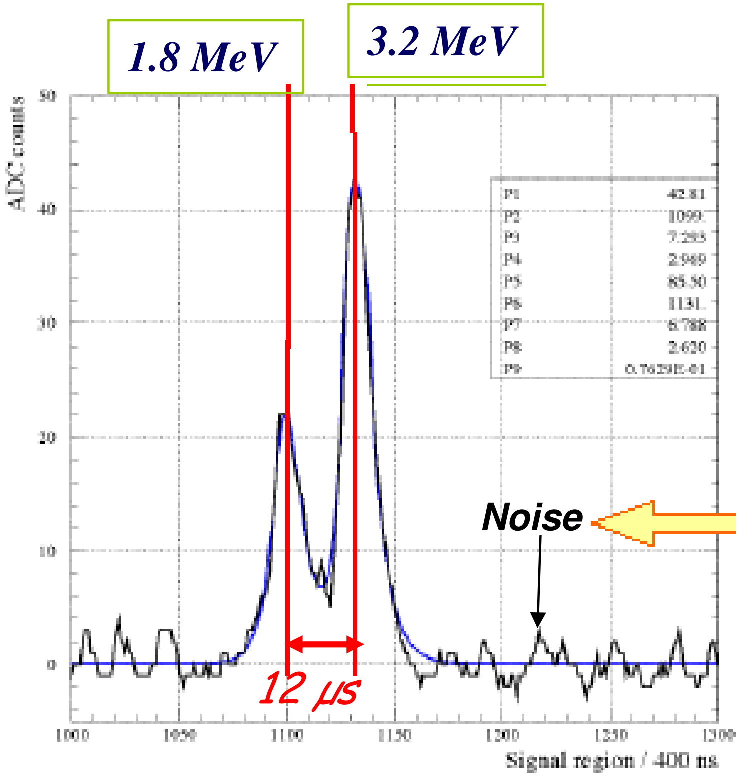
- CNGS facility delivers an almost pure $\nu_\mu$ beam peaked in the range $10 \leq E_\nu \leq 30$ GeV (beam associated $\nu_e$ about 1/2%). The signature of the $\nu_\mu$ $\nu_e$ signal is observed visually.
- Present sample: 1091 neutrino events from 2010 and 2011.
- There are differences with respect to LNSD experiment:
  - $L/E_\nu \sim 1$ 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 $\langle P \rangle_{\nu\mu\rightarrow\nu\varepsilon} \sim \frac{1}{2}\sin^2(2\theta_{new})$
- Expected conventional $\nu_\mu$ $\nu_e$ the same energy range and fiducial volumes :
  - 3 events due to the intrinsic $\nu_e$ beam contamination
  - 1.3 events due to $\theta_{13}$ oscillations:
  - 0.7 events of $\nu_\mu$ $\nu_\tau$ oscillations with electron production.
- The total is therefore of 5 expected events.

# Event simulation with Montecarlo

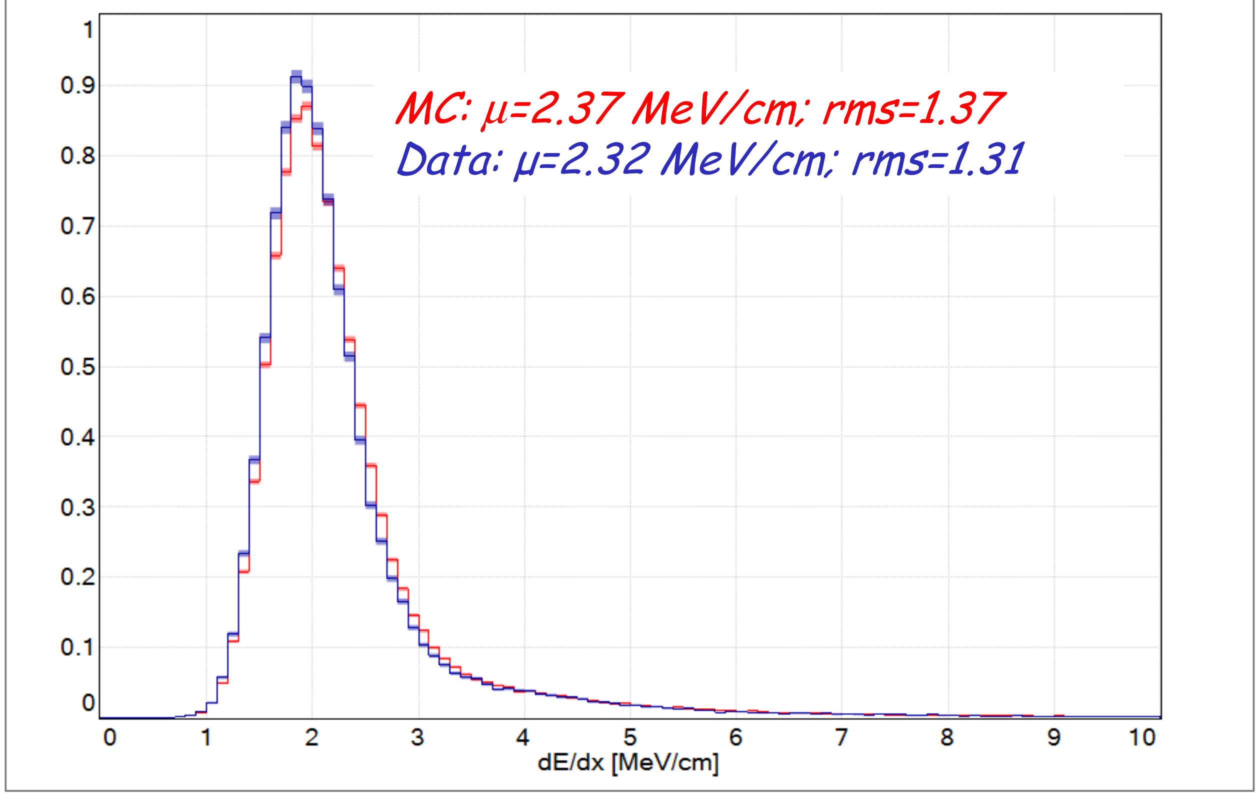
- The detection of events has been widely simulated by a very sophisticated Montecarlo emulation, reproducing in every detail the actual signals from the wire planes. The agreement between MC and observed events has been excellent.
- An "electron signature" has been defined by presence of a single minimum 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 an electron tracks to $\eta = 0.74 \pm 0.05$. In a good approximation | is independent of the shape of the energy spectrum.
- The number of expected events with visible $\nu_\mu$ $\nu_e$ is then 3.7.

# Real data and MC simulated tracks

## Single wire performance

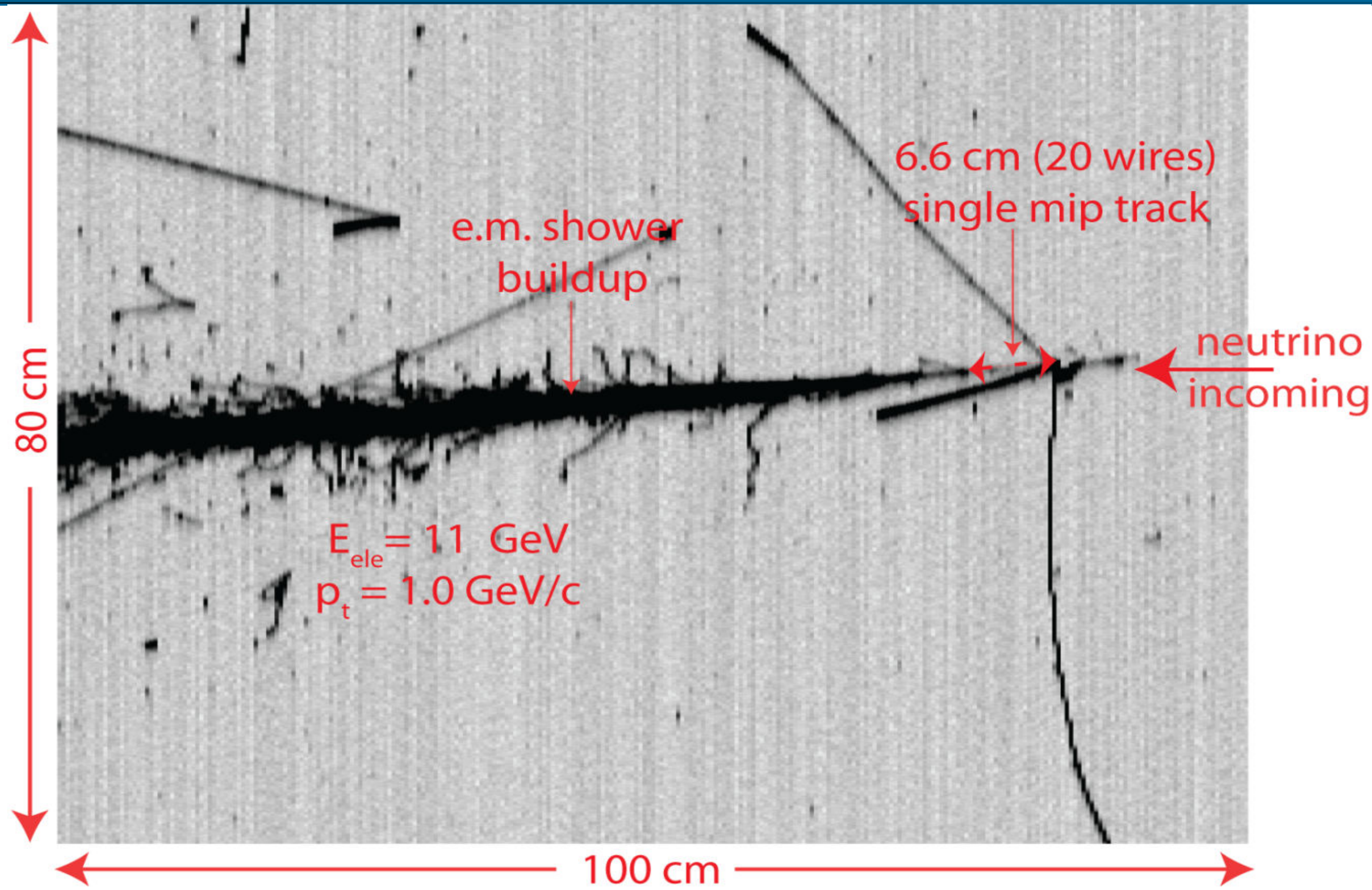



## Comparison MC and actual data




- 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

# Visual identification of a ν–e event (MC)




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

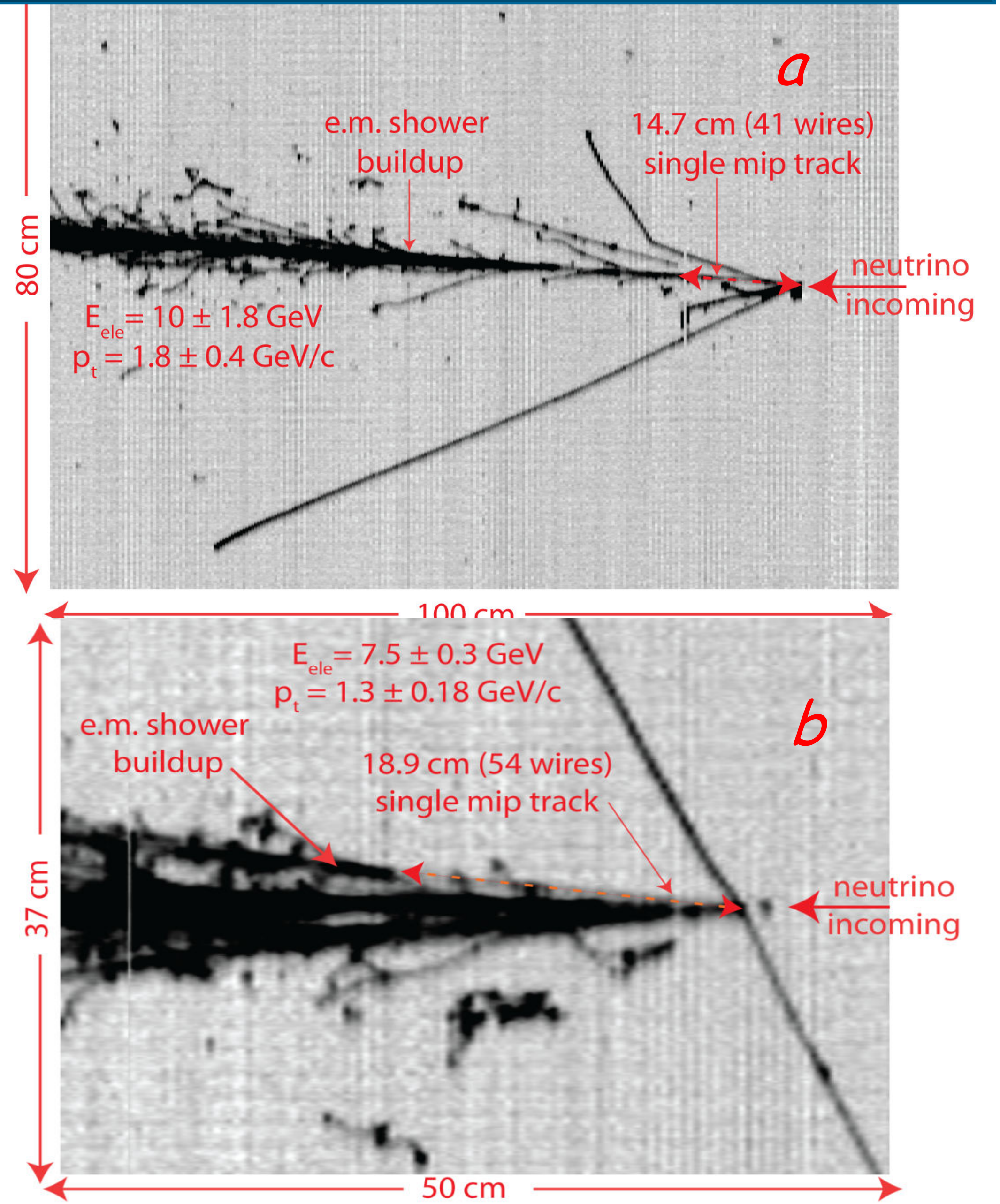
# Events in the data

- Two CC events have been observed in data sample, with a clearly identified electron signature:

(a) total energy = 11.5 ± 1.8 GeV, Pt = 1.8 ± 0.4 GeV/c

(b) Total visible energy = 17 GeV. Pt = 1.3 ±0.18 GeV/c

- In both events the single electron shower in the transverse plane is clearly opposite to the remaining of the event

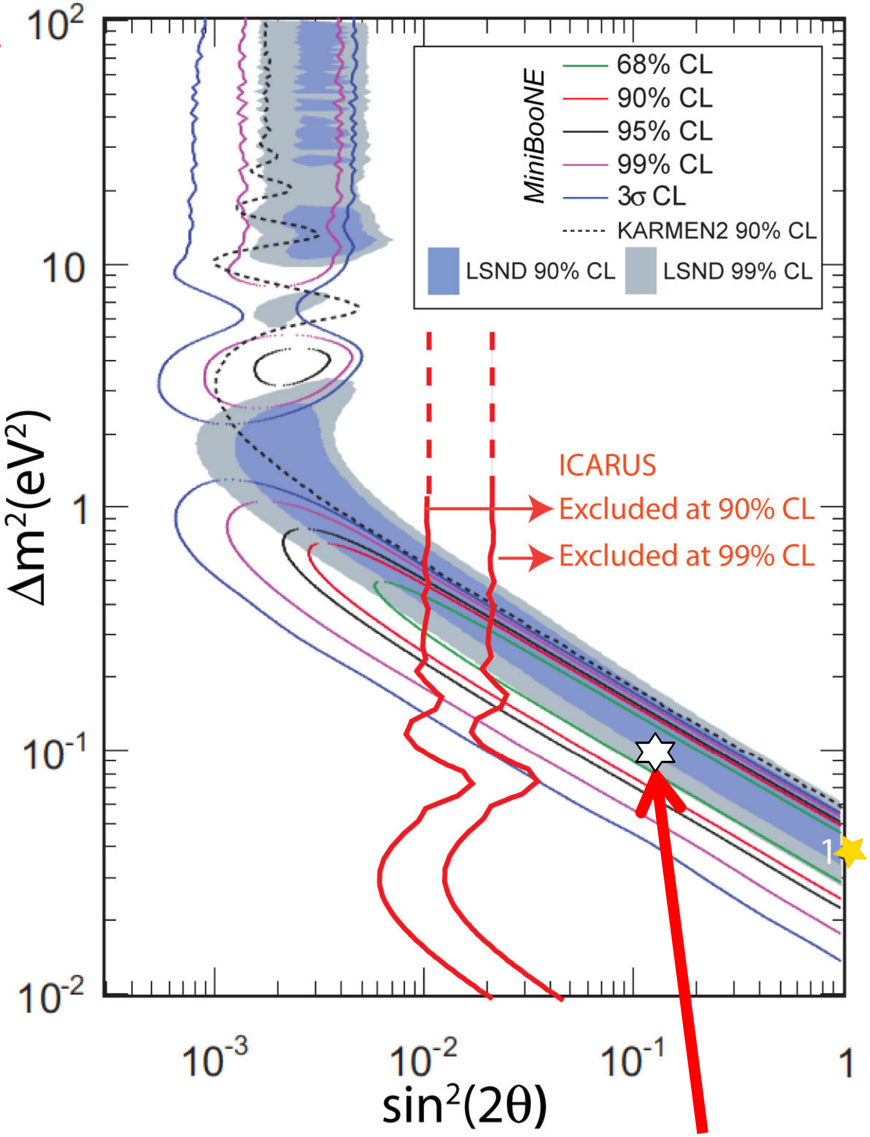


# Results

- 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 $\nu_\mu$ - CC events, the limits to the oscillation probability are:

  $P_{\nu\mu \to \nu e} \leq 5.4 \times 10^{-3}$ (90% CL)

  $P_{\nu\mu \to \nu e} \leq 1.1 \times 10^{-2}$ (99% CL)
- The exclusion area is shown for the plot $\Delta m^2$ –$\sin^2(2\theta)$. At small $\Delta m^2$ ICARUS strongly enhances the probability with respect to the short baseline experiments.



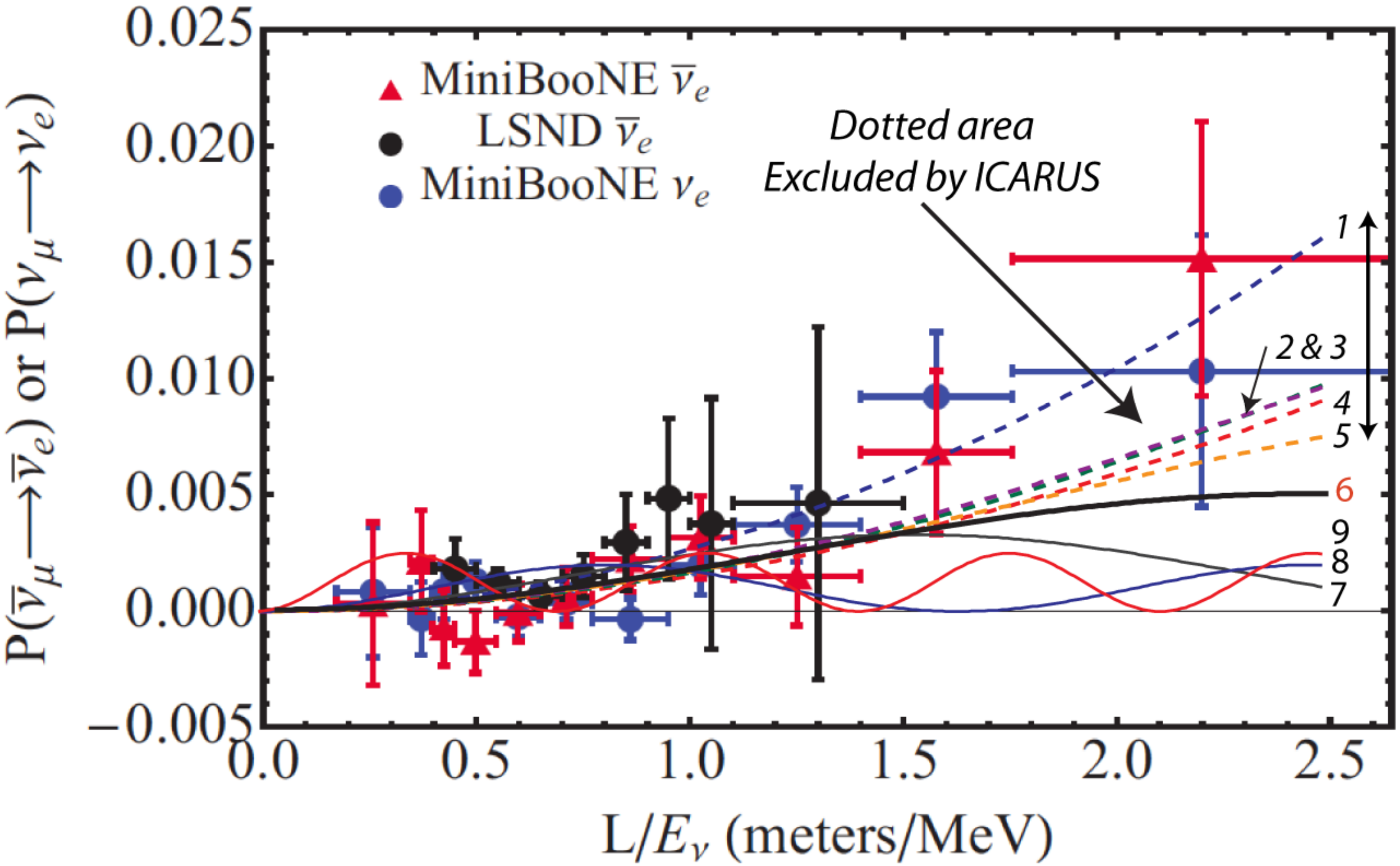

*With ($\Delta m^2$ –$\sin^2(2\theta)$) = (0.11 eV², 0.10) as many as 30 events should have been seen*

# Comparing with MiniBooNE

- The present result strongly limits the window of options from the MiniBooNE experiment.
- Using a likelihood-ratio technique, CP conservation and the same oscillation probability for neutrinos and antineutrinos, a best MiniBooNE 3+1 oscillation fit for $200 < E_\nu < 3000$ MeV has been given with $(\Delta m^2 - \sin^2(2\theta)) = (0.037\ eV^2, 1.00)$. This is clearly excluded by the ICARUS result.
- A 3+2 joint oscillation fit as a function of $E\nu$ in both neutrino and antineutrino modes has also been reported with $\Delta m^2_{41} = 0.082\ eV^2$, $\Delta m^2_{51} = 0.476\ eV^2$. This MiniBooNE value is clearly incompatible with the present ICARUS result.
- The oscillation probabilities from LSND are at $\lesssim 1$ m/MeV. MiniBooNE has extended the data to additional values in the region $L/E_\nu > 1$ and to a significant signal peak at small $E_n$. This may require a further clarification.

# The low energy excess ?

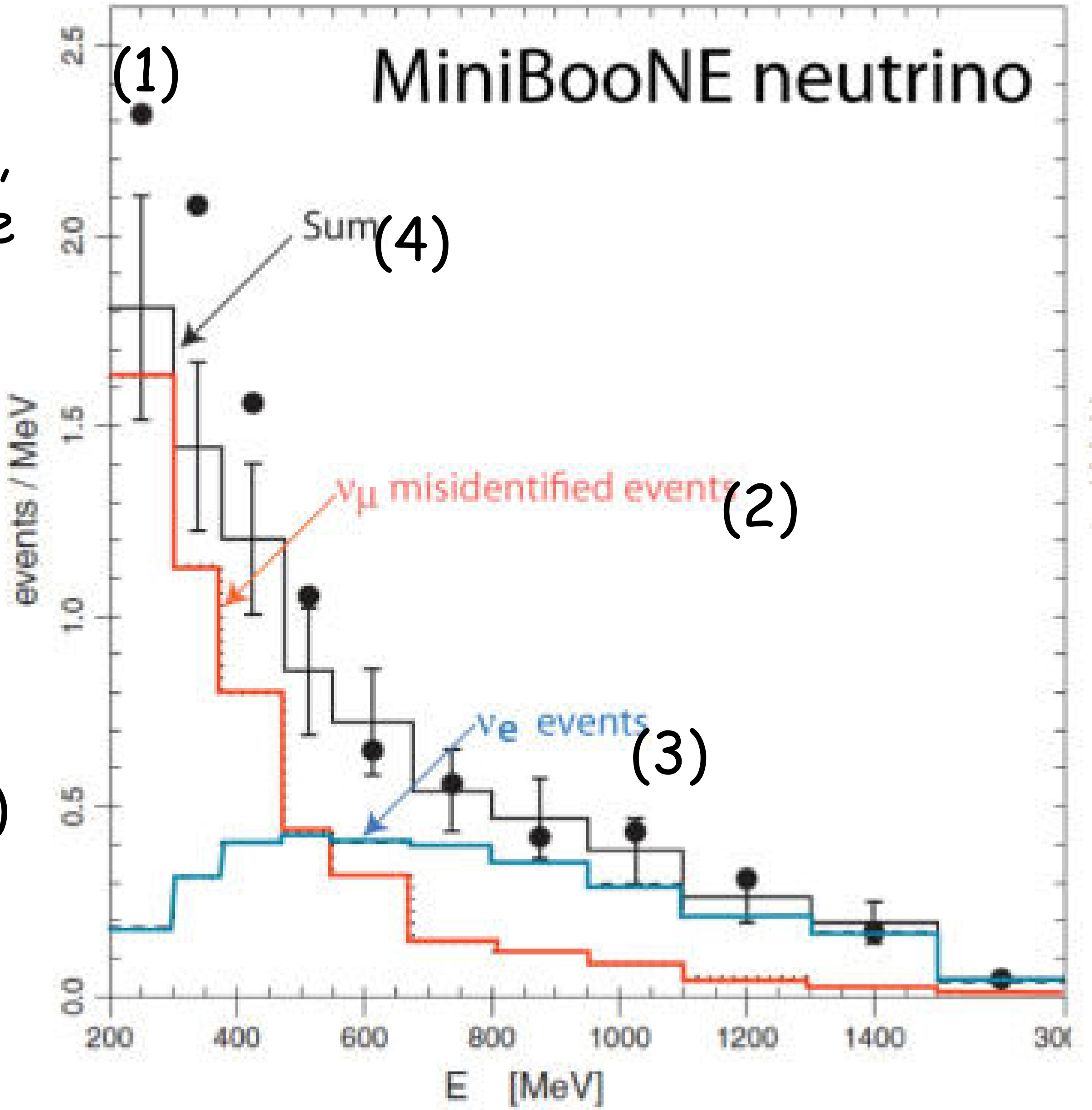
- The ICARUS result excludes a substantial fraction of the MiniBooNE curves corresponding to lines from 1 to 5.
- The origin of the $L/E_\nu > 1$ excess observed by MiniBooNE may need further clarification.




| # | $\sin^2(2\theta)$ | $\Delta m^2(eV^2)$ |
|---|---|---|
| 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 |

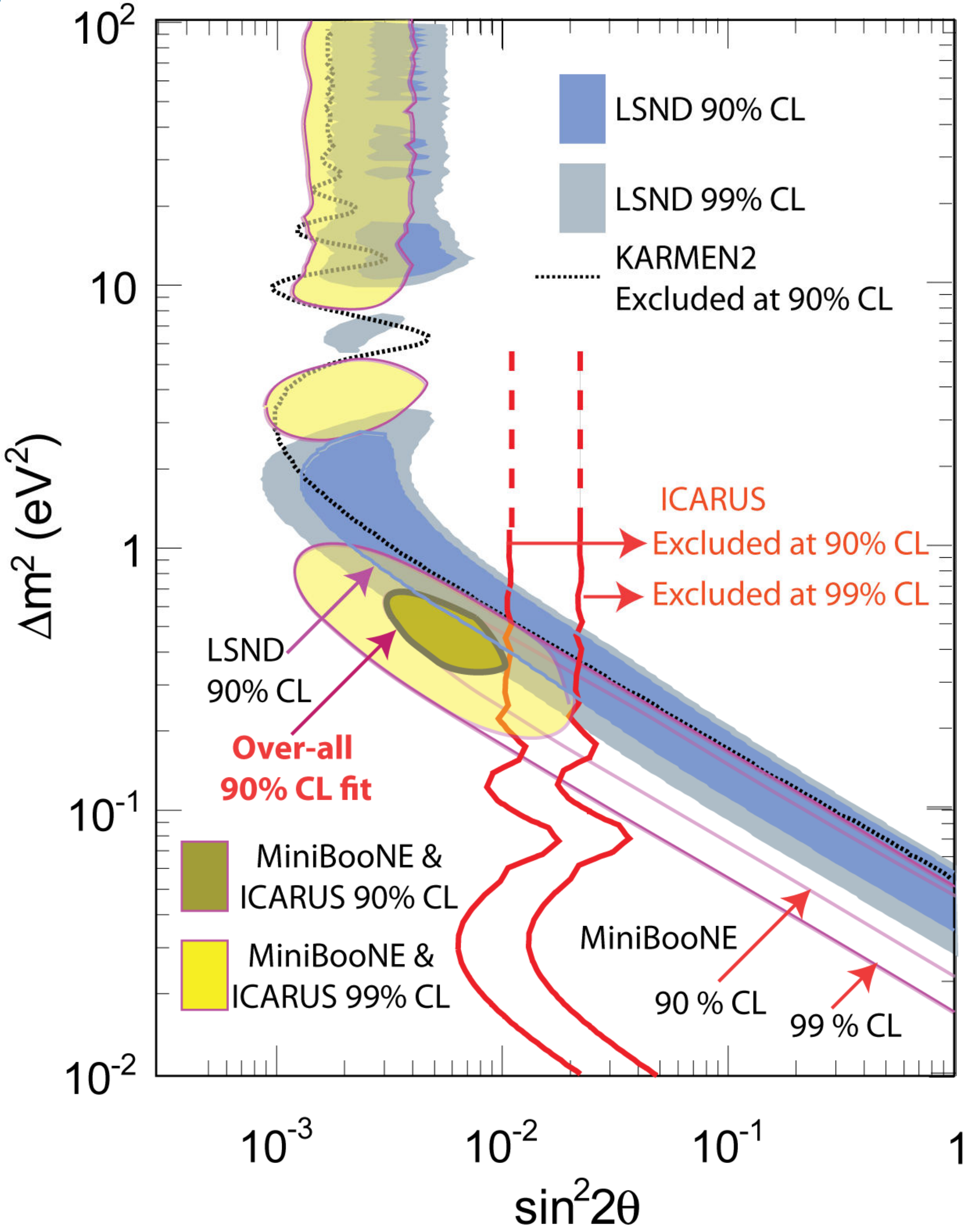
# The MiniBooNE low energy effect

- The energy dependent neutrino experimental spectrum (1), unlike LSND, is characterized by a large peak of events with E < 450 MeV (1).
- In the peak region the dominant signal is due to νμ misidentified background (2).
- Expectations from LNSD (2) + the νμ background(3) below E < 450 MeV do not add (4) to the observed signal (1)



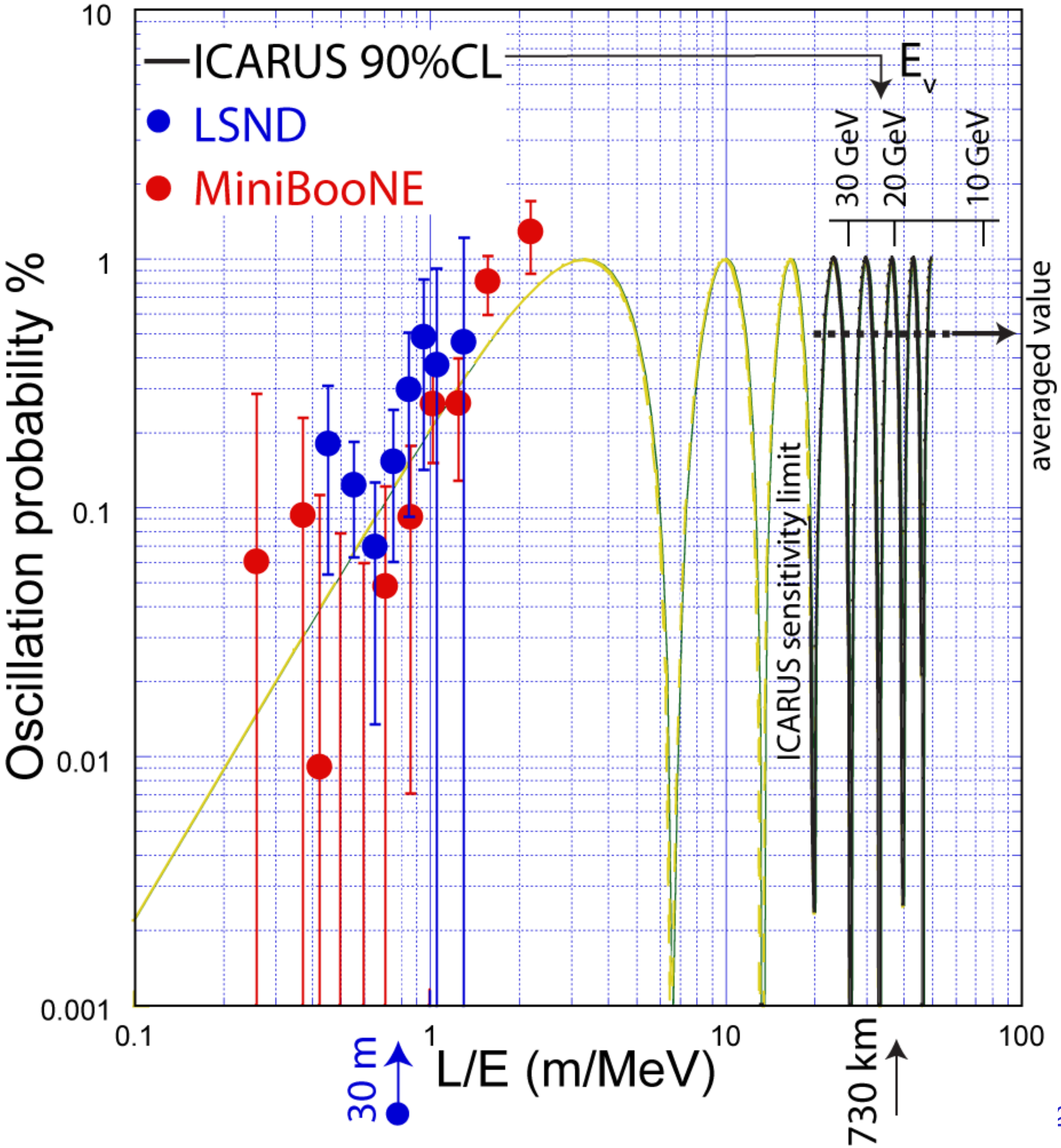
# Conclusions

- 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



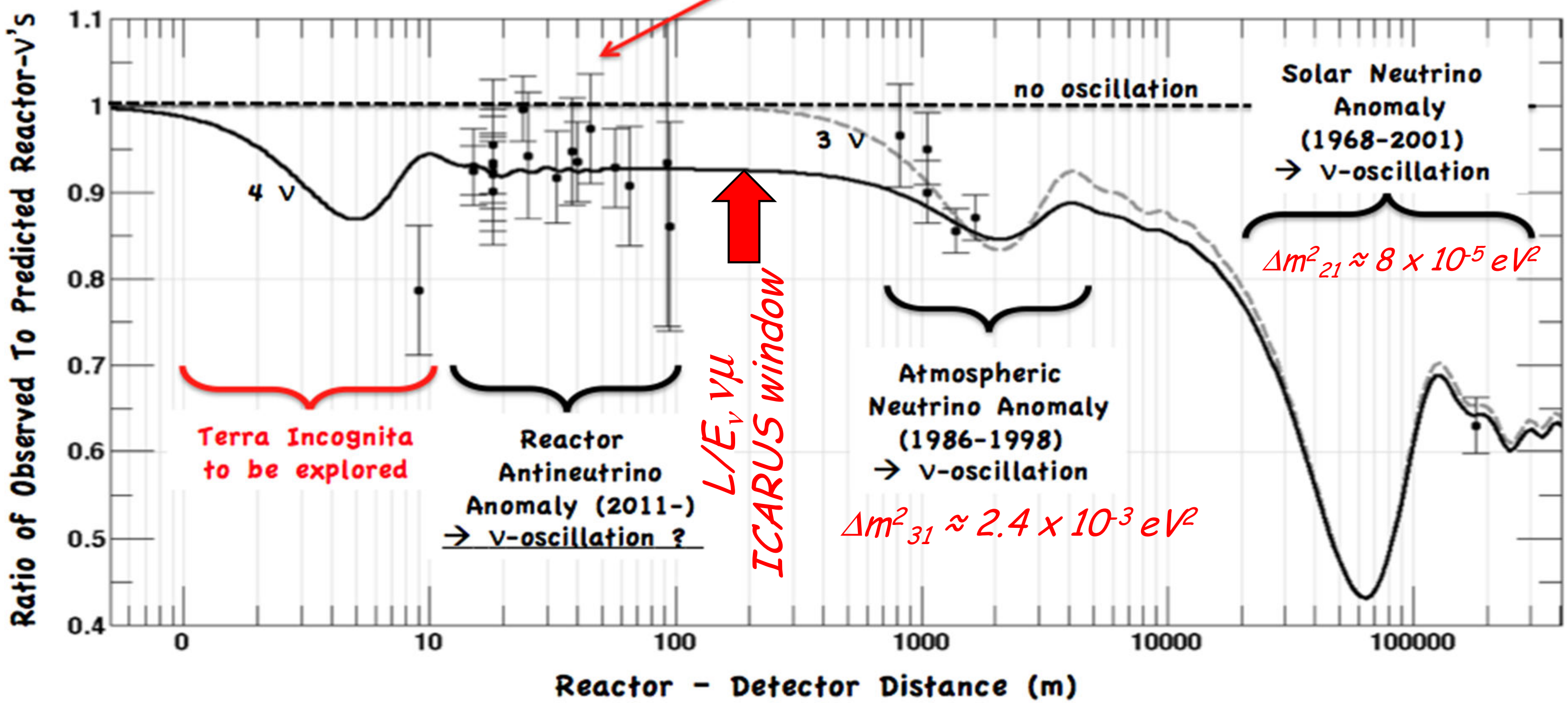
# Specific characteristics of ICARUS

- When compared to the other long baseline results (MINOS and T2K) ICARUS operates in a $L/E_{\nu}$ region in which the size of the contributions from neutrino oscillations are not yet too relevant.
- Unique detection properties of Lar-TPC permit to identify unambiguously individual electron events with high efficiency



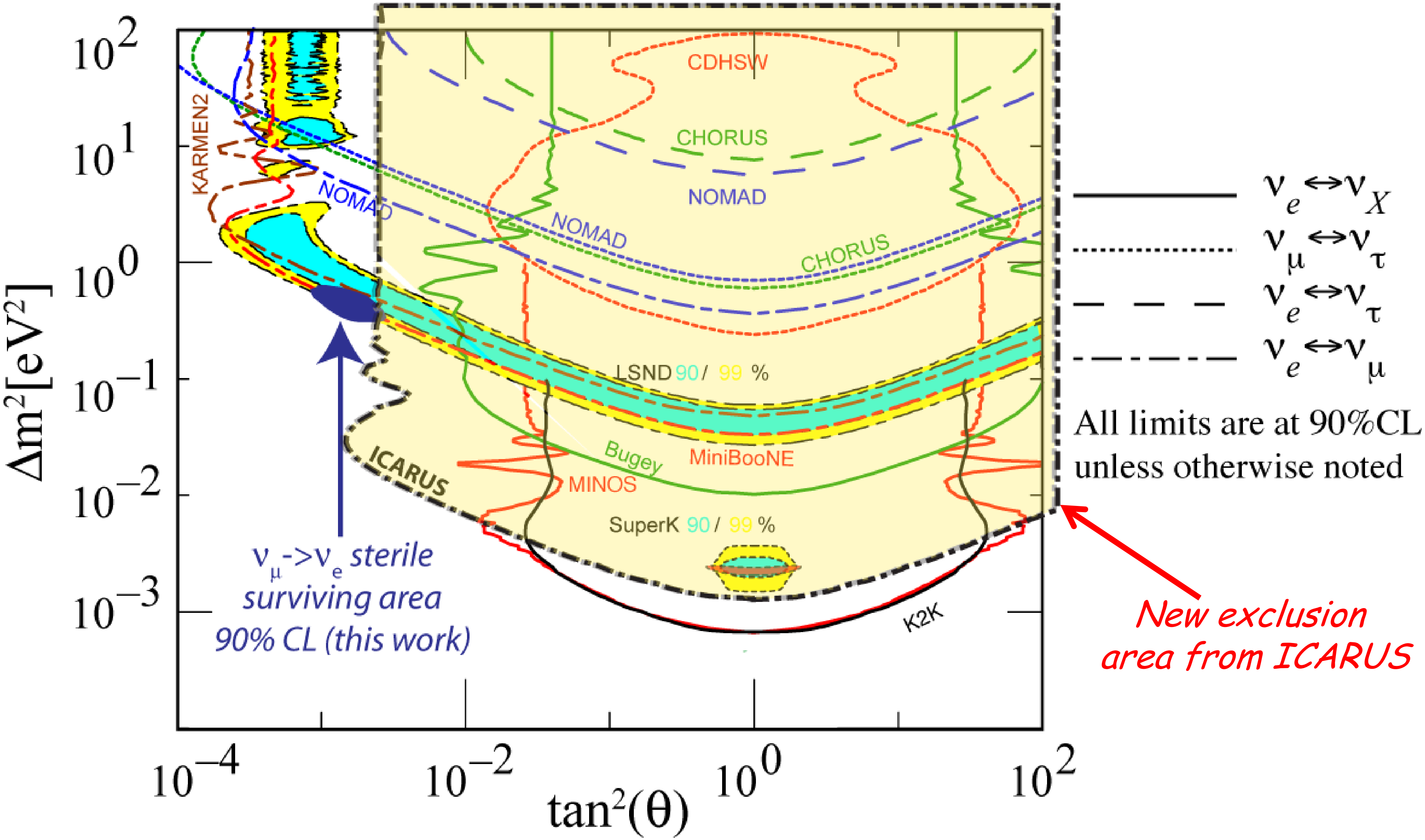
# Comparing ICARUS and reactor disappearance anomaly ?

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)




- ICARUS may offer in the future also the possibility of comparing the observed/predicted ratio $R_\mu$ of neutrino events to the one expected from the CERN accelerator neutrino beam.
- The ν production flux may then be compared with predictions and checked with the observed muon flux at nearby distances.

# 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 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".

# Thank you !