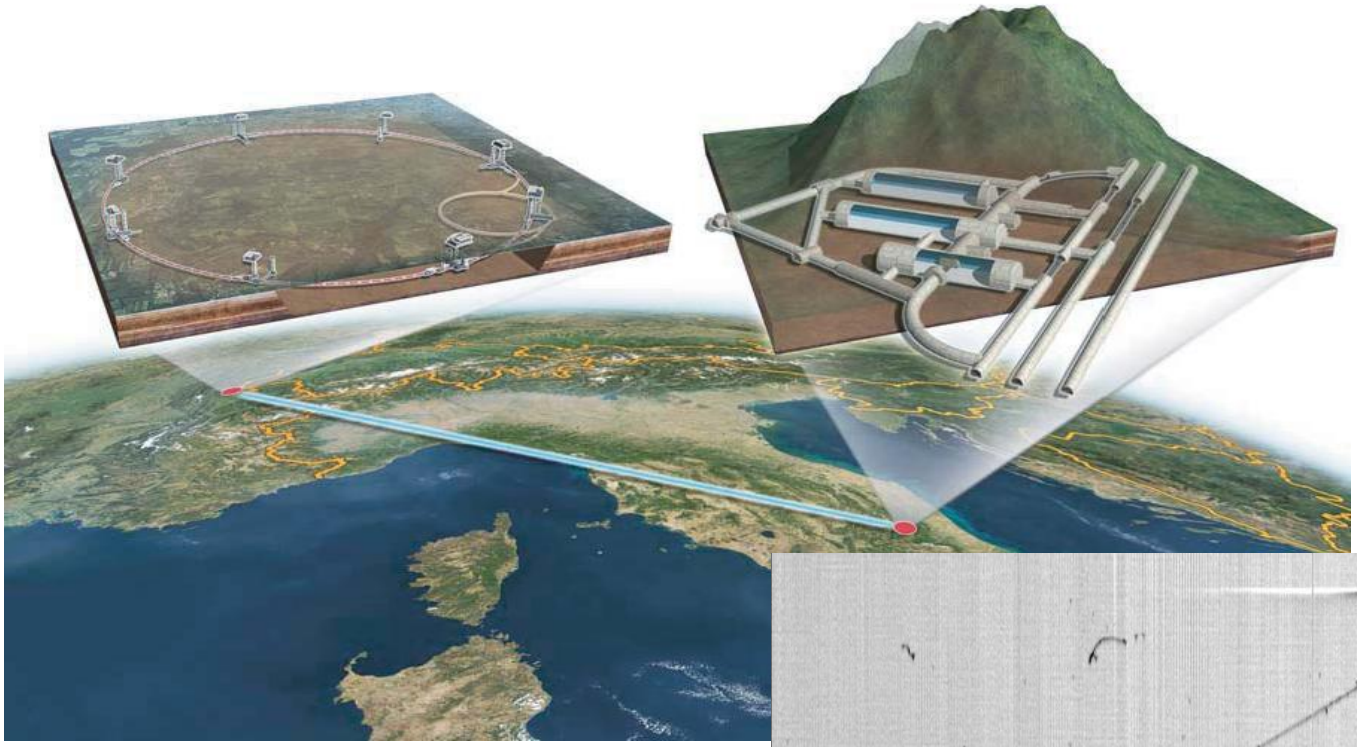
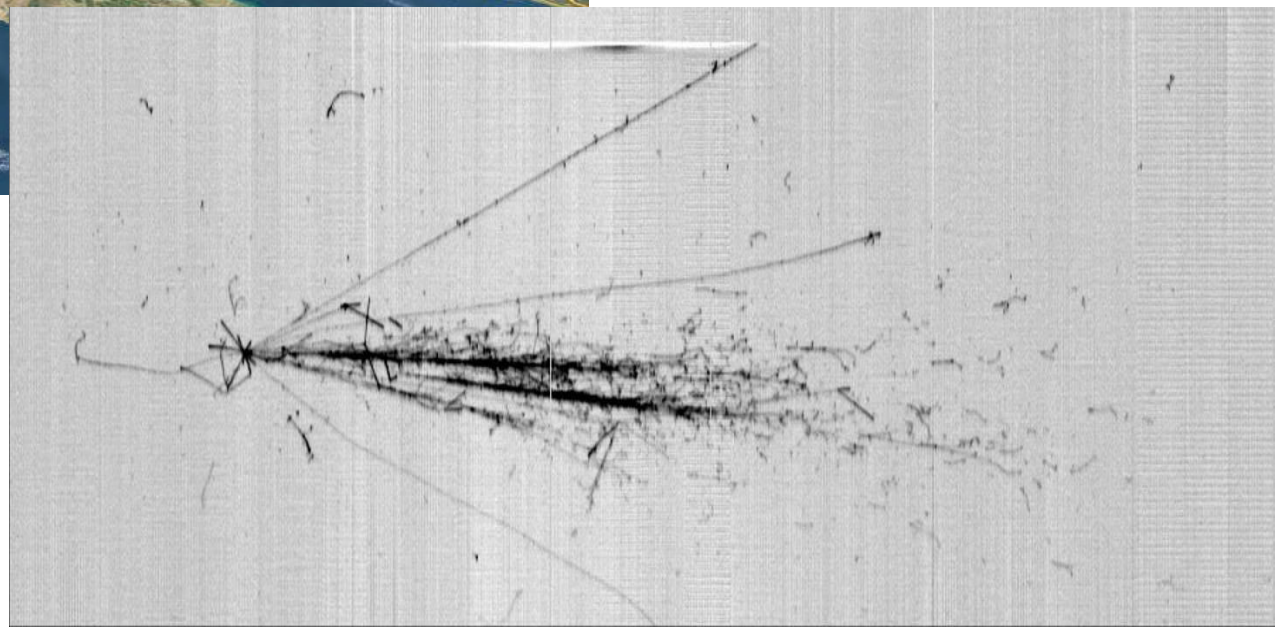
Some recent results from ICARUS

C. FARNESE
INFN Padova

On behalf of the
ICARUS Collaboration





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The ICARUS Collaboration

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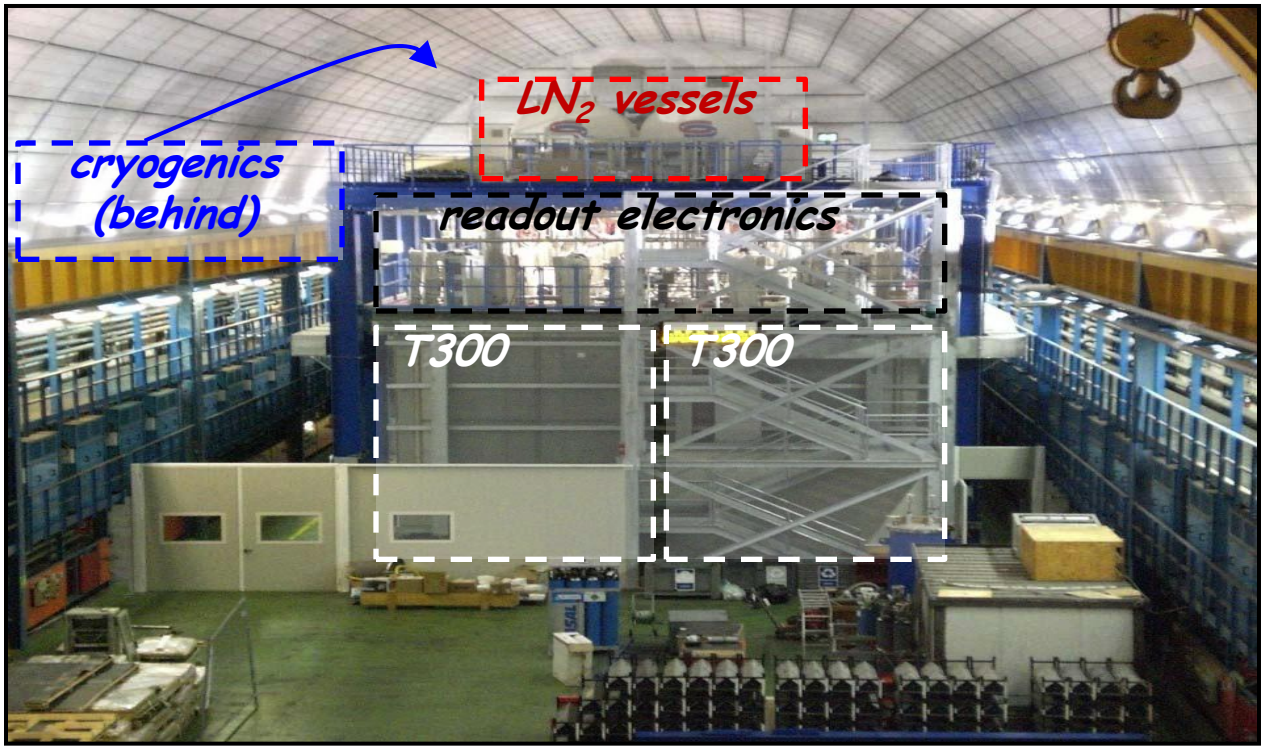
The ICARUS T600 at LNGS Laboratory

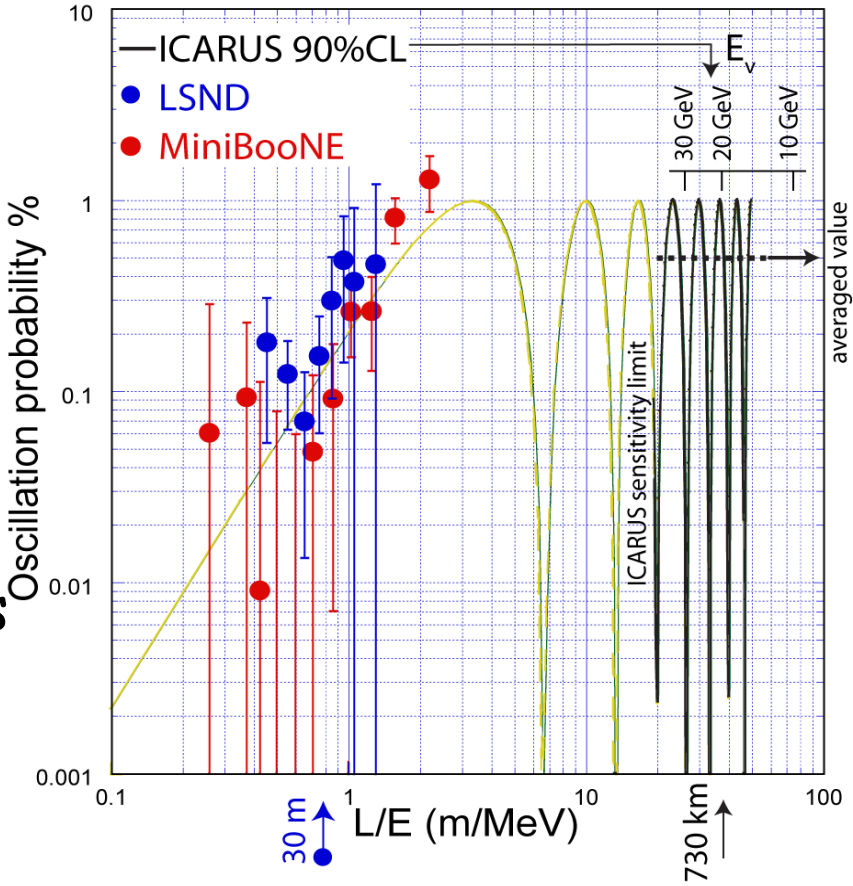
- ICARUS has been successfully exposed to CNGS beam from Oct 1st 2010 to Dec. 3rd 2012
- **8.6 10^{19} protons on target** have been collected with a remarkable **detector live time > 93 %**
- Data taking has been conducted in parallel with cosmic rays to study atmospheric ν and p-decay (0.73 kty)



- Three new results will be briefly described:
  - New, improved search for anomalous MiniBooNe ν–e events in CNGS
  - Determination of muon momentum by multiple scattering
  - New LAr purification methods and improvements of the electron lifetime

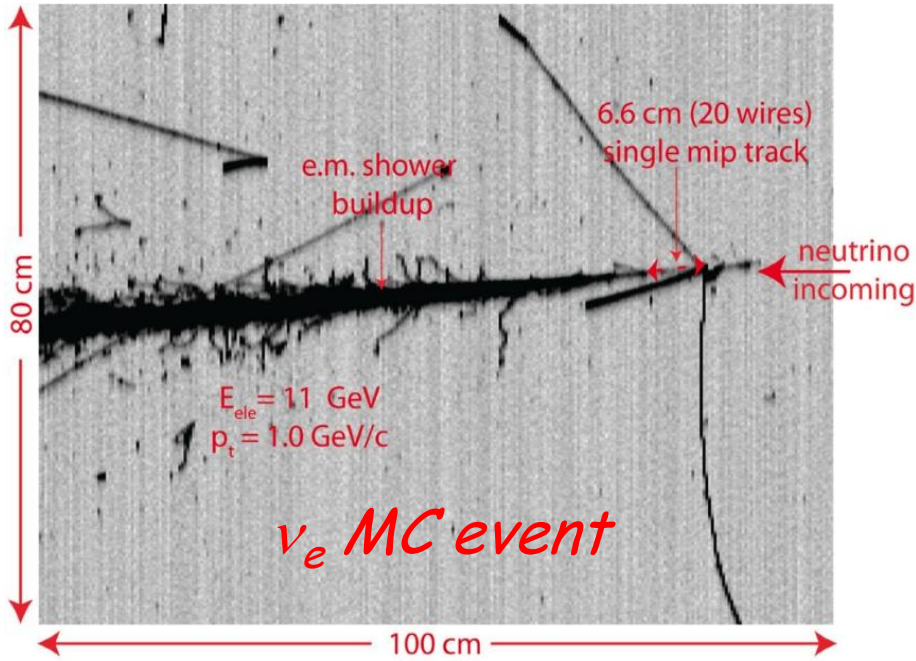
Search for anomalous MiniBooNe ν–e events in CNGS

- *The CNGS facility delivered an almost pure ν_μ beam in 10-30 GeV E_ν range (beam associated ν_e ~1%) at a distance L=732 km from target.*
- There are differences w.r.t. LSND exp.
  - L/E_ν ~1 m/MeV at LSND, but L/E_ν ≈36.5 m/MeV at CNGS
  - LSND-like short distance oscill. signal averages to $\sin^2(1.27\Delta m^2_{new} L/E) \sim 1/2$ and $\langle P\rangle_{\nu\mu\to\nu e} \sim 1/2 \sin^2(2\theta_{new})$
- When compared to other long baseline results (MINOS and T2K) ICARUS operates in a L/E_ν region in which contributions from standard ν oscillations [mostly $\sin(\theta_{13})$] are not yet too relevant.
- Unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.



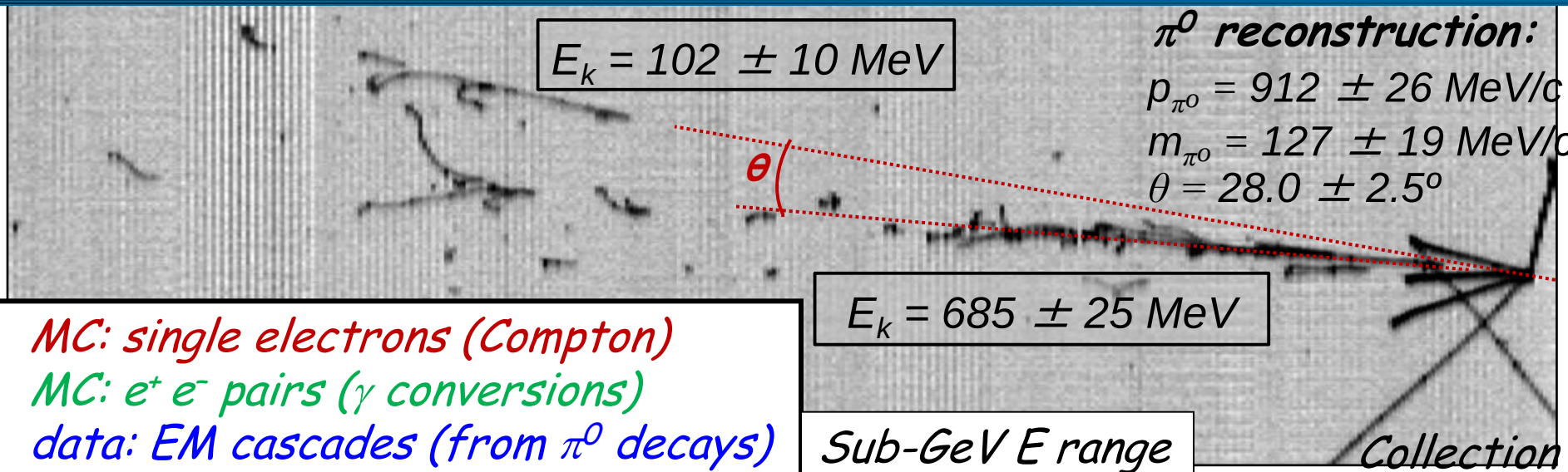
Search for ν–e events in CNGS beam

- ν_e CC event candidates are visually selected with vertex inside fiducial volume (for shower id.) : > 5 cm from TPC walls and 50 cm downstream
- Energy selection: <30 GeV
  - 50% reduction on intrinsic beam ν_e
  - only 15% signal events rejected
- ν_μ CC events identified by L > 2.5 m long track without hadronic interactions



- The "Electron signature" requires:
  - A charged track from primary vertex, m.i.p. on 8 wires, subsequently building up into a shower; very dense sampling: every 0.02 X_0;
  - Isolation (150 mrad) from other ionizing tracks near the vertex in at least one of the TPC views.
- Electron efficiency has been studied with events from a MC (FLUKA) reproducing in every detail the signals from wire planes:
  $\eta = 0.74 \pm 0.05$ ($\eta' = 0.65 \pm 0.06$ for intrinsic ν_e beam due to its harder spectrum).

e/γ separation and π^0 reconstruction in ICARUS



π^0 reconstruction:

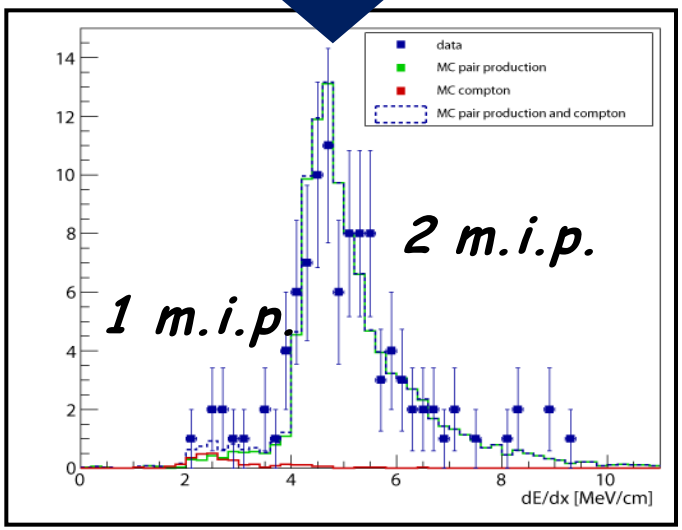
p_{π^0} = 912 ± 26 MeV/c

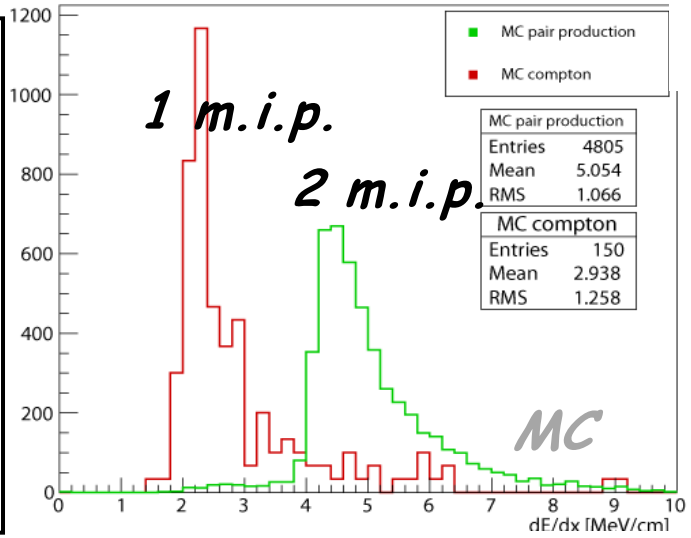
m_{π^0} = 127 ± 19 MeV/c²

θ = 28.0 ± 2.5°

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

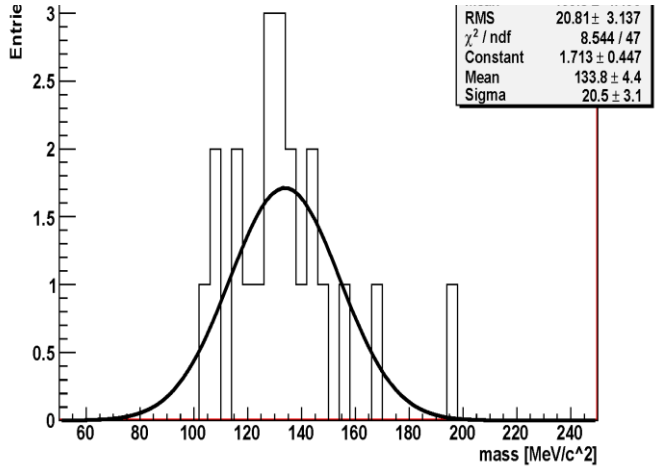
Sub-GeV E range





$M_{\gamma\gamma}$:

133.8±4.4(stat)±4(syst) MeV/c²



Unique feature of LAr to distinguish e from γ and reconstruct π^0

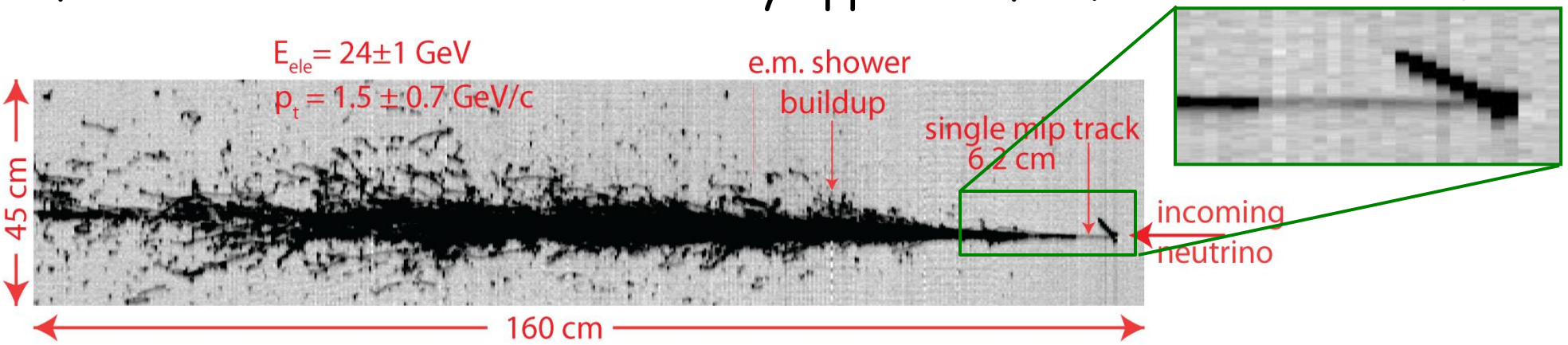
➔ Estimated bkg. from π^0 in NC and ν_μ CC: negligible

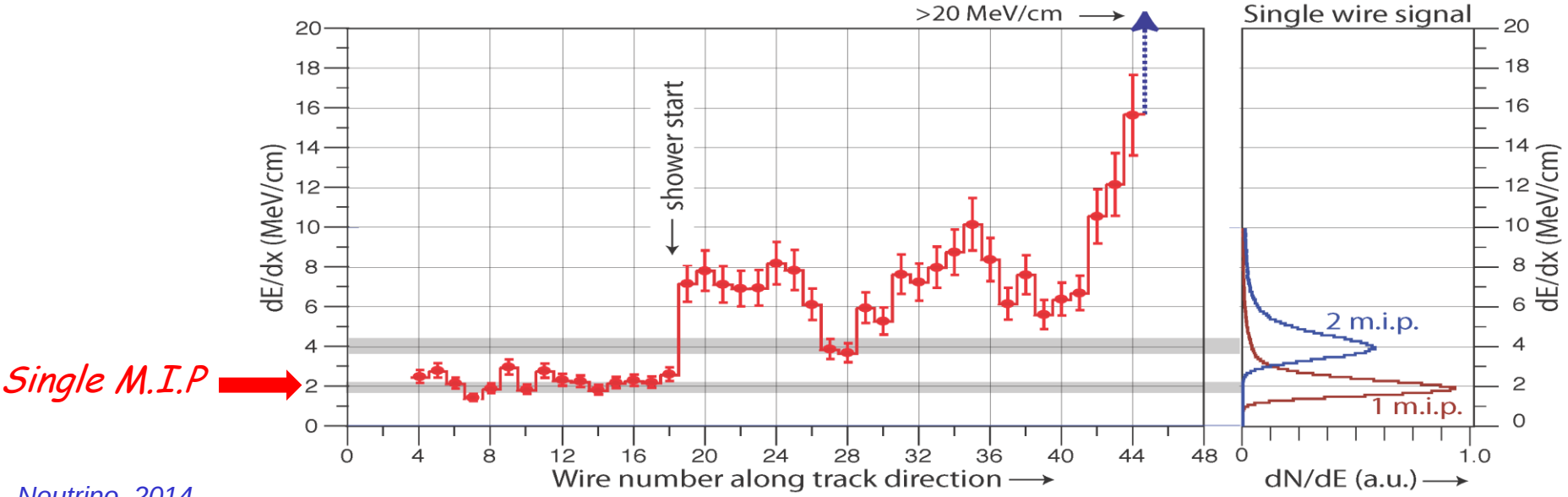
ICARUS results: upgrade of the data sample

- New statistics w.r.t. the previously published result in Eur. Phys. J. C73:2599 2013 and based on 1995 ν interactions (6.0 10^{19} pot).
- An additional sample of 455 ν interactions, corresponding to 1.2 10^{19} pot: the analysis presented here refers to 2450 ν events and 7.23 10^{19} pot out of the fully collected statistics of 8.6 10^{19} pot.
- Expected number of ν_e events:
  - 7.0 $\pm$ 0.9 due to the intrinsic ν_e beam contamination
  - 2.9 $\pm$ 0.7 due to θ_{13} oscillations, $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$
  - 1.6 $\pm$ 0.1 from $\nu_\mu \rightarrow \nu_\tau$ oscillations with subsequent *e* production
- Total number of expected events: 11.5 $\pm$ 1.2
- The expected number of electron events, taking into account the detection efficiency: 7.9 $\pm$ 1.0 (syst.only)
- ***2 additional electron neutrino events identified: now 6 ν_e events***
- In all the 6 electron neutrino identified events the single electron shower is opposite to hadronic component in the transverse plane.

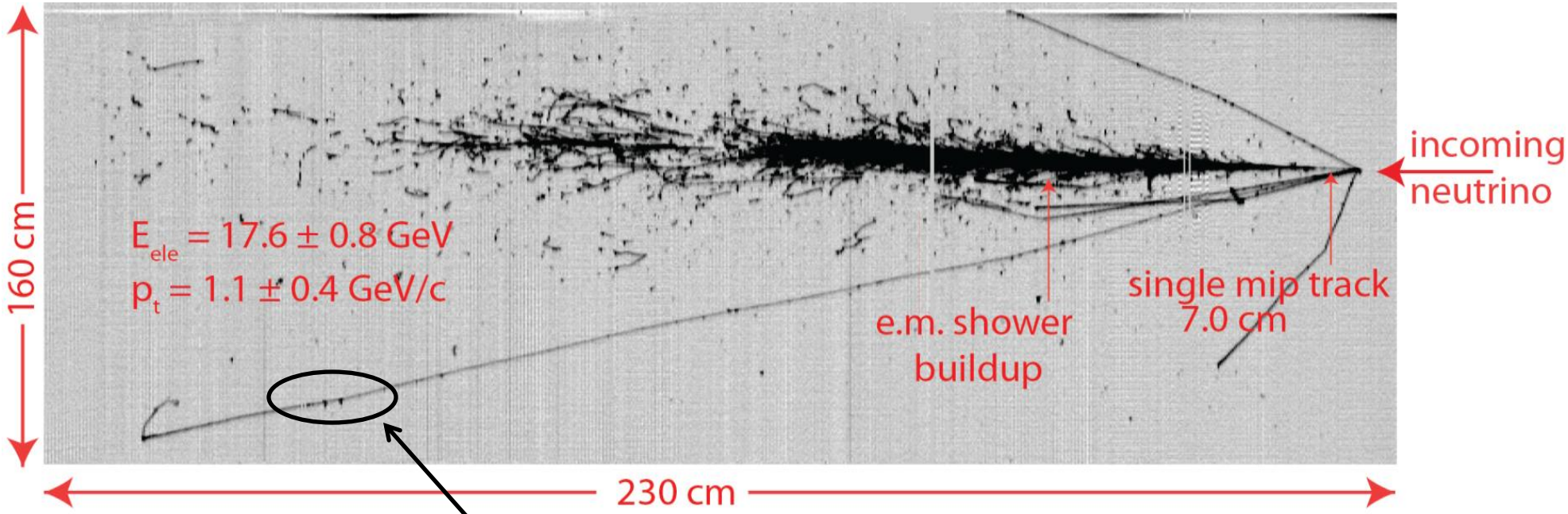
The new ICARUS result with 2450 ν interactions

- Event with a clear electron signature found in the sample of 2450 ν interactions (7.23 10^{19} pot).
- 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.





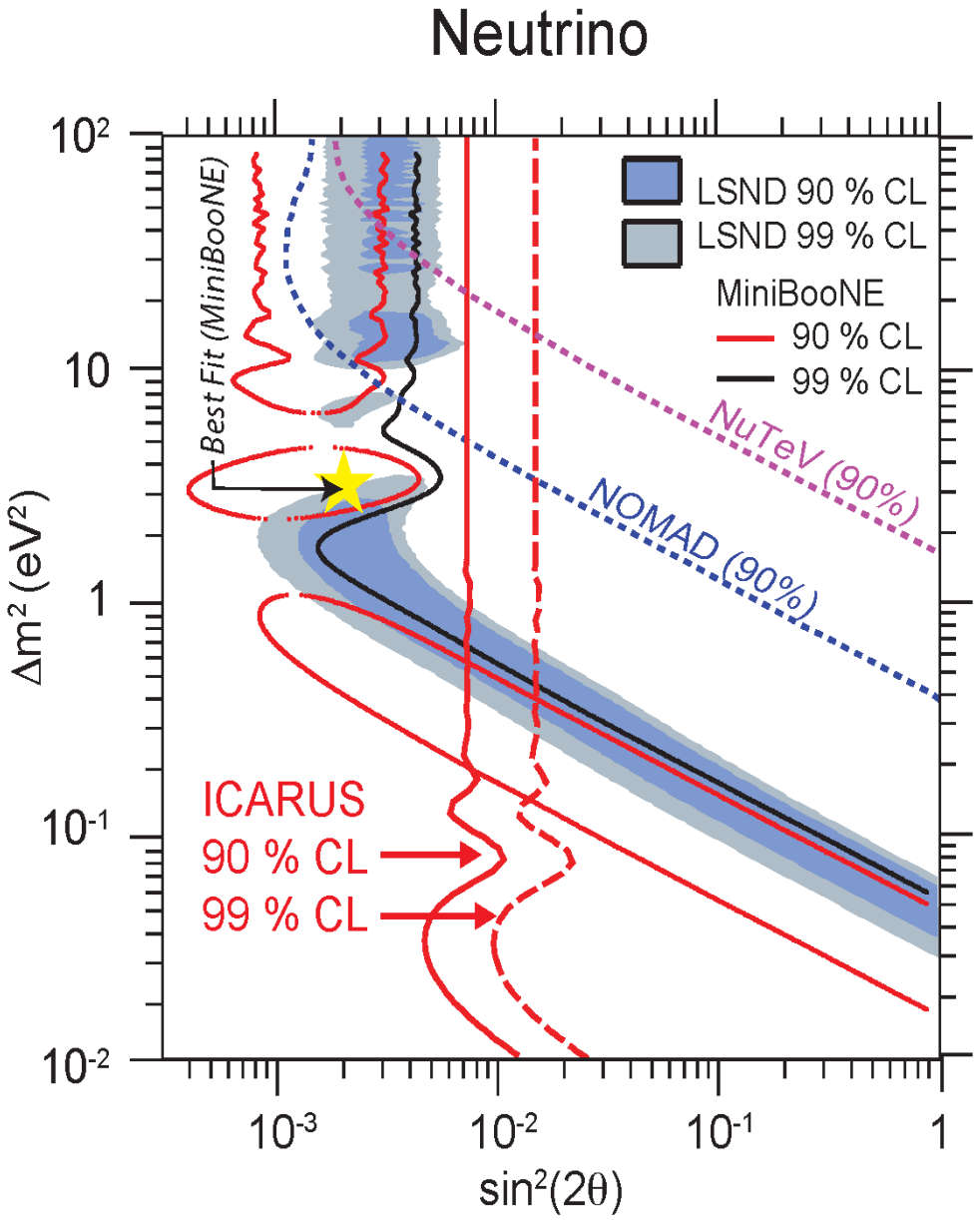
Event with a clearly identified electron signature



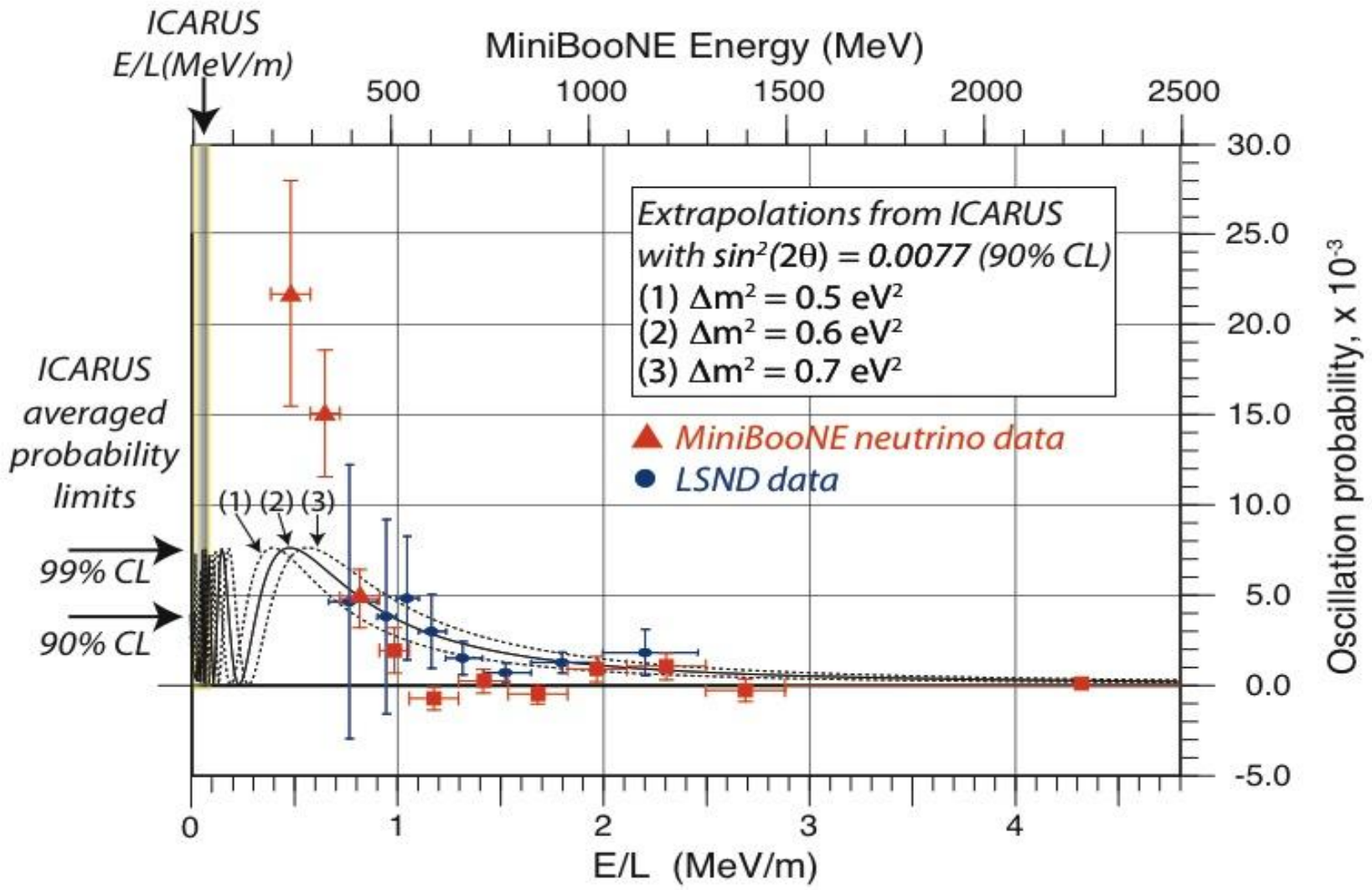
Pion inelastic scattering with hadronic activity

ICARUS result on the search of the LSND-anomaly

- 6 ν_e events have been observed in agreement with the expectations 7.9 ± 1.0 due to the conventional sources (the probability to observe ≤6 ν_e events is ~33%).
- Weighting for the efficiency, ICARUS limits on the number of events due to LSND anomaly are: 5.2 (90 % C.L.) and 10.3 (99 % C.L.).
- These provide the limits on the oscillation probability:
  - $P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3}$ (90 % C.L.)
  - $P(\nu_\mu \rightarrow \nu_e) \leq 7.60 \times 10^{-3}$ (99 % C.L.)

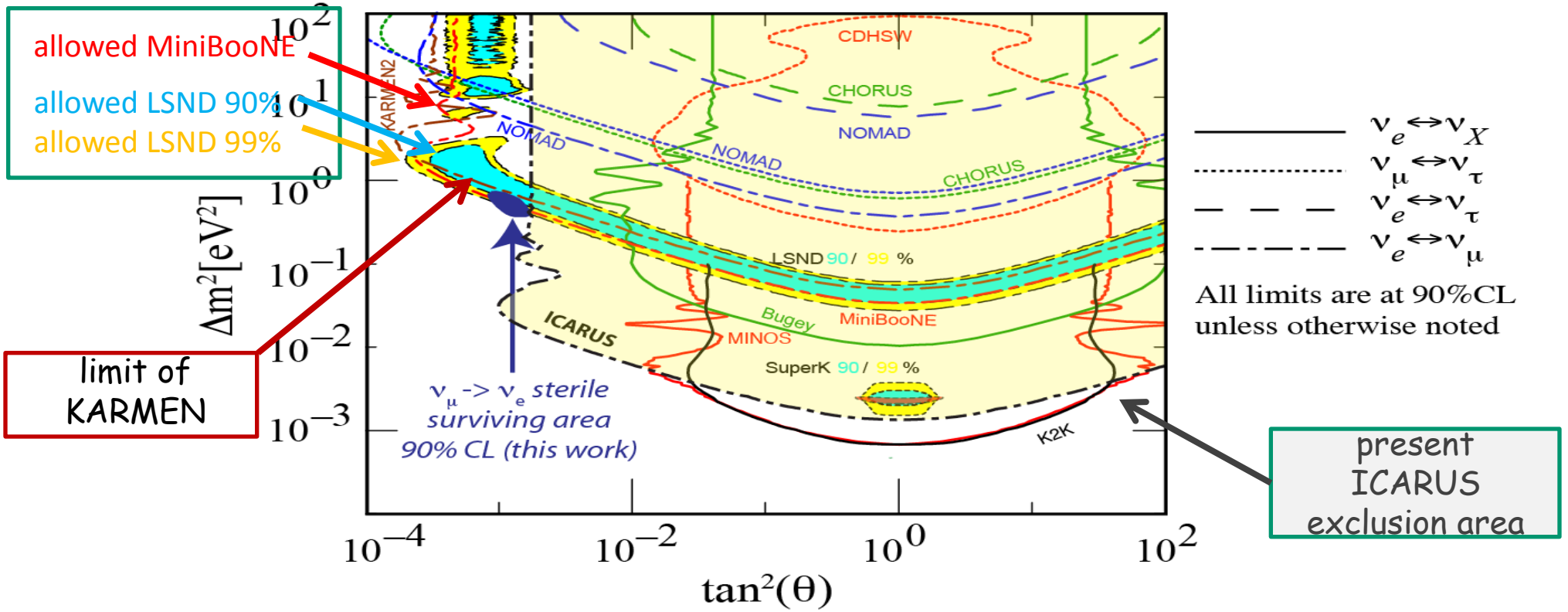


Exclusion of the low energy MiniBooNE experiment



- ICARUS has excluded the low energy sterile neutrino peak reported by MiniBooNE both in the neutrino and antineutrino channels. This result has also been confirmed by OPERA.

LSND-like exclusion from the ICARUS experiment

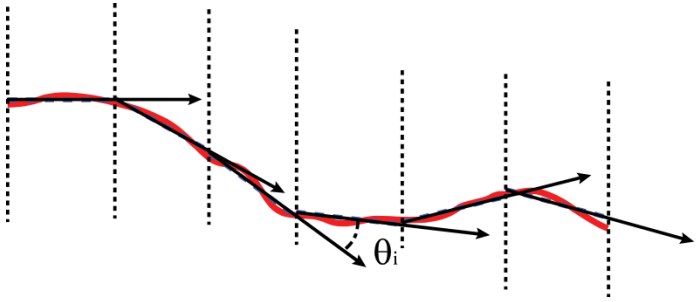


ICARUS result strongly limits the window of parameters for *the* LSND anomaly to a very narrow region *($\Delta m^2 \approx 0.5$ eV^2 and $\sin^2 2\theta \approx 0.005$)* for which there is an overall agreement (90% CL) *of*

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

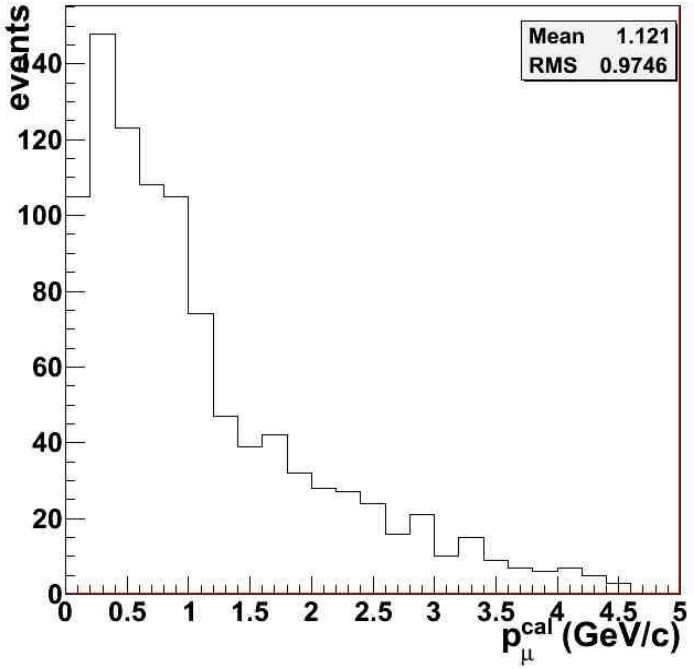
Measurement of muon momentum via multiple scattering

- In absence of a magnetic field, the initial muon momentum can be determined through the reconstruction of multiple Coulomb Scattering (MS) in LAr



The RMS of θ deflection depends on p , on the spatial resolution σ and on the segmentation L_{seg}

$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$



The method has been tested in T600 on ~1000 stopping muon sample from CNGS ν interactions in the upstream rock, comparing the initial momemtum measured by p^{MS} with the corresponding calorimetric determination p^{CAL}.

Muon momentum reconstructed by calorimetric measurement for the stopping muon sample with Δp/p ~ 1%

This energy range (0.5-4 GeV) is appropriate to proposed short / long baseline experiment at FNAL

Determination of muon momentum by multiple scattering

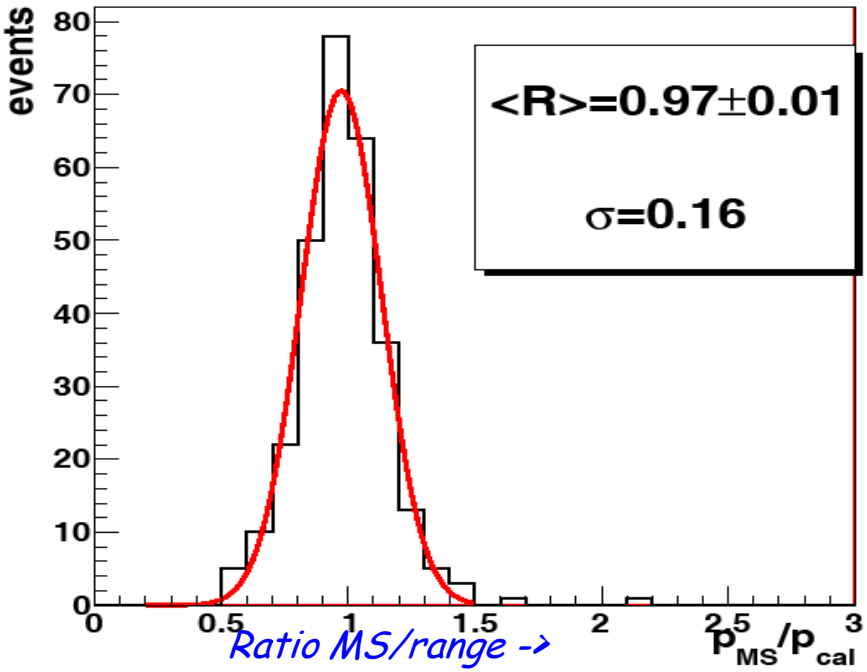
- Stopping muons have been visually selected amongst all the neutrino events recorded in coincidence with the CNGS beam spill.
  - μ-identification : $L\mu \geq 2.5$ m (~ three hadronic interaction lengths) and the absence of nuclear interactions along the track.
  - No other activity in the event
- Automatic 3D track reconstruction (visually validated); only collection view has been used for multiple scattering analysis.
- Identification/removal of δ rays, outliers before proceeding to p fit:
  - multiple hits on the same wire
  - charge of the hit (noise, large δ rays)
- Momentum extracted from measurement of deflection angle θ and from χ^2 of the fit:

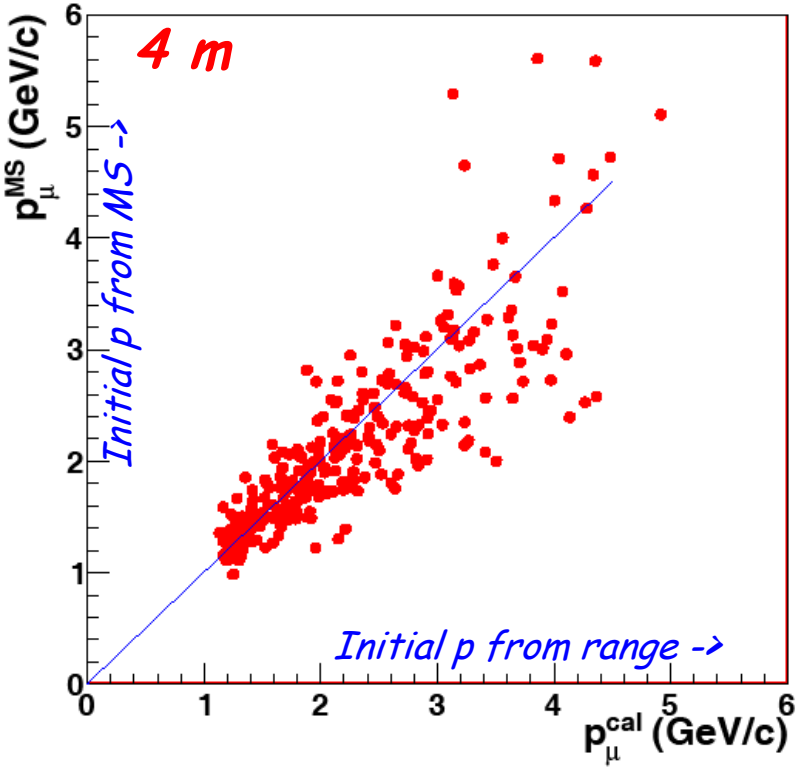
$$\begin{cases} \theta_{MS} \propto \sqrt{L_{seg}}/p & \leftarrow \text{MS angle} \\ \theta_{det} \propto L_{seg}^{-3/2} & \leftarrow \text{detector resolution} \end{cases}$$

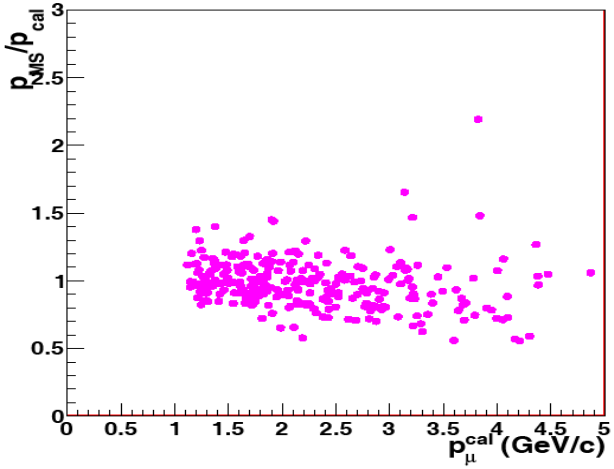
- The actual momentum is iteratively generated starting from an initial trial trajectory of p_{trial} = 10 GeV/c

Beam-associated stopping long muons (both range and MS)

Stopping μ track length: > 5 m Used length: 4m







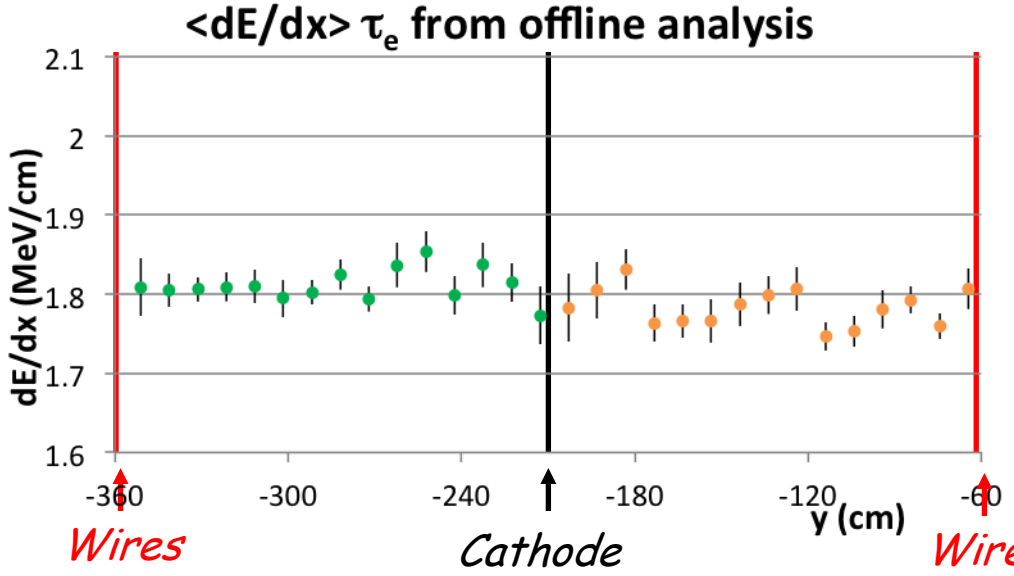
Multiple scattering is measured on the first 4 m for stopping tracks L > 5 m: p_{MS} is compared with the momentum from the observed range.

Resolution ~16%!

Some bias still appears for larger momenta

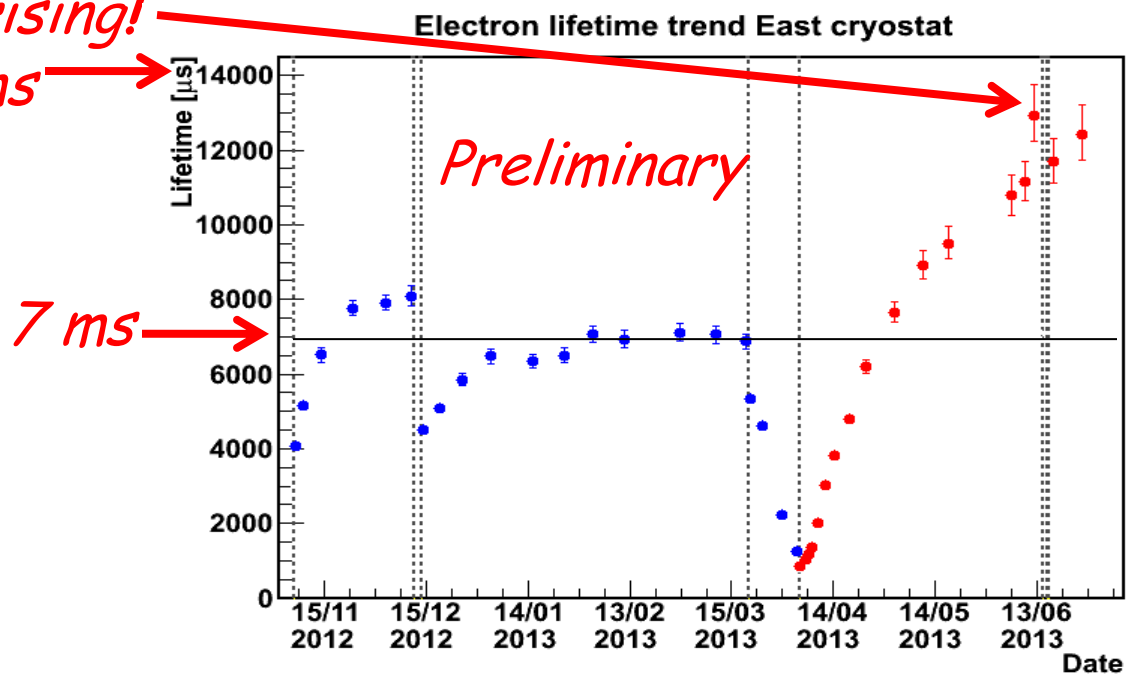
ICARUS T600 LAr purity

- The electron lifetime τ_{ele} is a crucial parameter since LAr TPC performance strongly depends on the LAr purity.
- A detailed offline analysis with a robust algorithm and large μ statistics has been performed to measure very small signal attenuation along the drift:
  - Accurate identification/removal of δ and e.m. activity associated to μ;
  - A 10% truncated mean is applied to signals of single tracks to remove under/over fluctuations;
  - $1/\tau_{ele}$ is used as estimation of the signal attenuation.
- Cross check with muons from CNGS ν interacting in the upstream rock: <dE/dx> is correctly reconstructed constant along the drift coordinate



ICARUS T600 LAr purity offline analysis: new results

- ICARUS has operated with τ_{ele} > 7 ms (~40 p.p. trillion $[O_2]_{eq}$) corresponding to a 12% maximum charge attenuation at longest drift distance!
- New pump has been installed on East cryostat since April 4th, 2013: *τ_{ele} exceeding 12 ms and still rising!*
- A remarkable purity has been achieved on ~1 kt scale detector, to be compared with ≈ 1ms longest electron drift time, approaching the LAr lifetime of τ_{ele} ≈ 21 ms previously observed with a ~100 litres prototype



ICARUS has demonstrated the effectiveness of the single phase LAr-TPC technique, paving the way to huge detectors/~5 m drift as required for LBNE project

Conclusions

- ICARUS T600 detector has successfully completed the CNGS-2 experiment conclusively demonstrating that LAr-TPC is *a leading technology for future short/long baseline accelerator driven neutrino physics.*
- The accurate analysis of the CNGS events and the identification of 6 νe events provide no evidence of oscillation into sterile neutrinos in ICARUS L/E interval.
- This result allows to exclude that the "low energy MiniBooNE anomaly" is due to neutrino oscillations.
- The global fit of all SBL data + ICARUS limits the window of parameters for a possible LSND anomaly to a very narrow region around 0.5 eV^2.
- Muon p measurement by Multiple Scattering is achieved with ≈ 16% resolution in the momentum range of interest for future LAr TPCs.
- A remarkable LAr purity, exceeding 12 ms, has been measured opening the way for future large TPC detectors.


Thank you !