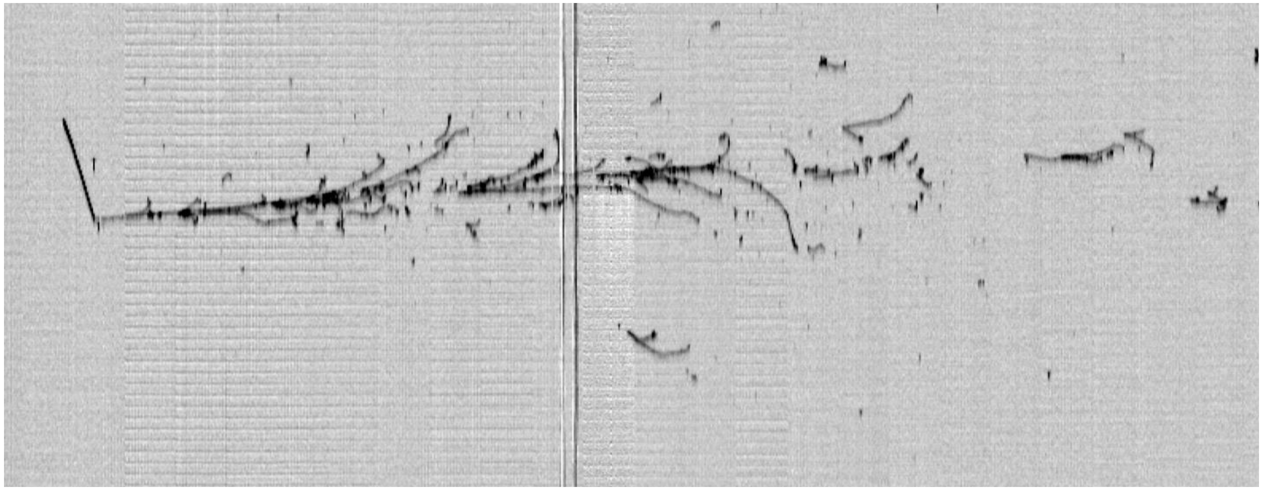
Sterile neutrino searches with ICARUS T600



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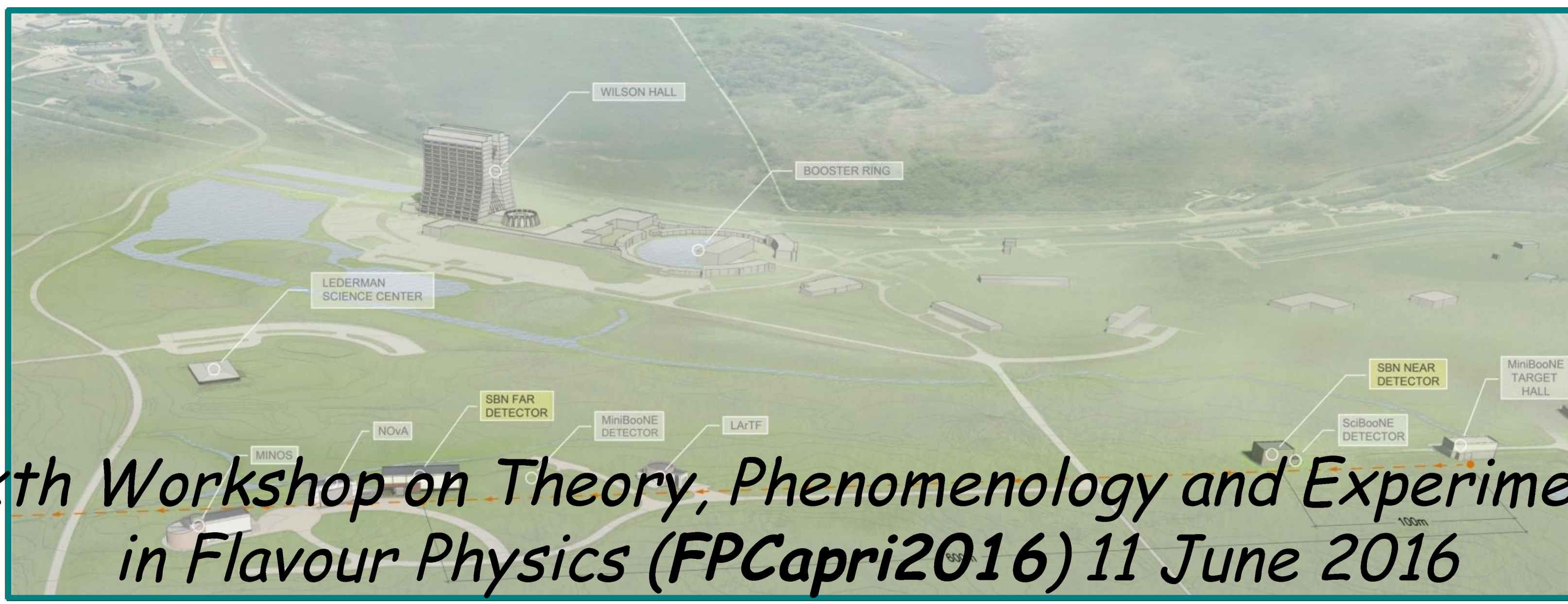
on behalf of the ICARUS Collaboration



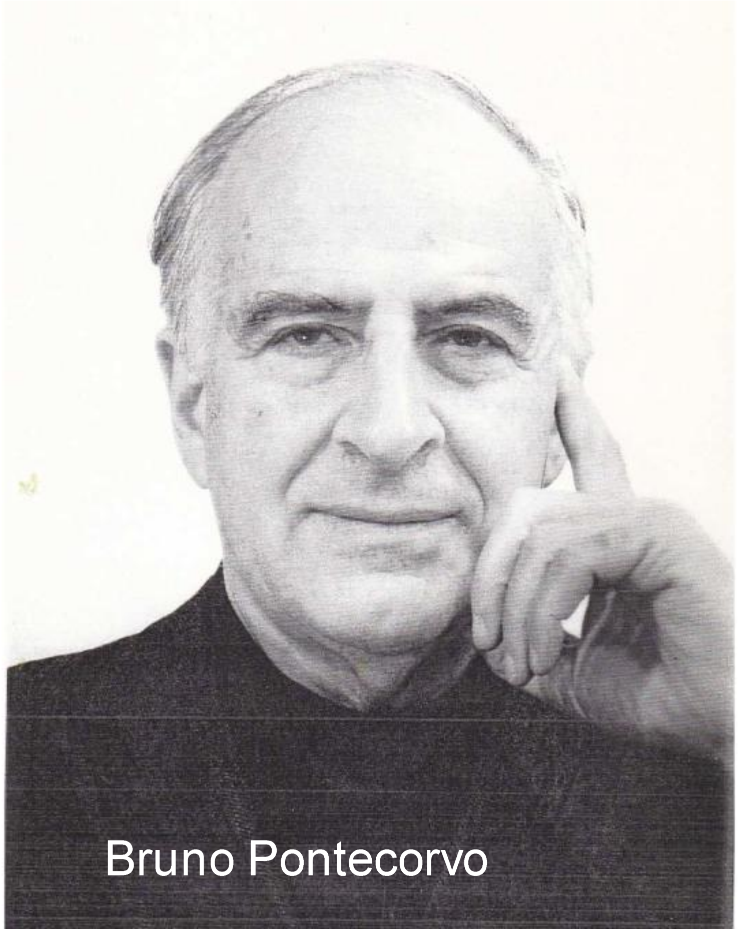
Sixth Workshop on Theory, Phenomenology and Experiments in Flavour Physics (**FPCapri2016**) 11 June 2016

Outline of this talk

- LSND and other anomalies in the standard framework of neutrino oscillations: sterile neutrinos?
- The ICARUS T600 LAr-TPC experiment at LNGS: contribution to sterile neutrino searches.
- A LAr-TPC based SBL experiment to definitively set the LSND anomaly: SBN Collaboration.
- Towards the automatic identification of low energy ν_e CC events in ICARUS: LNGS atmospheric neutrinos analysis.
- Outlook and conclusions.

What are "sterile" neutrinos?

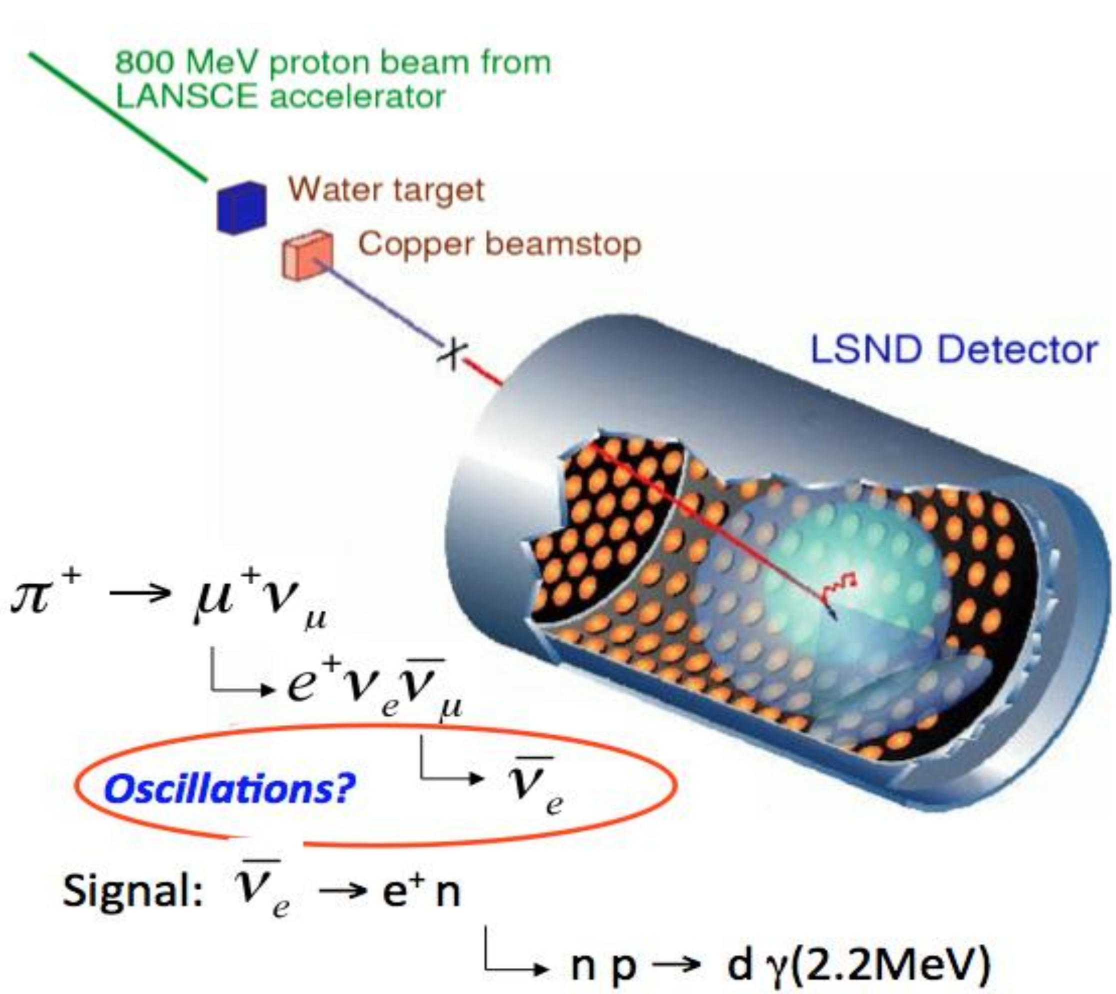
- Sterile neutrinos are a hypothetical type of neutrinos that do not interact via any of the fundamental interactions of the Standard Model except gravity.
- The name was coined in 1957 by Bruno Pontecorvo, who hypothesized their existence in a seminal paper.
- Since per se they would not interact electromagnetically, weakly, or strongly, they are extremely difficult to detect.
- If they are heavy enough, they may also contribute to cold dark matter or warm dark matter.

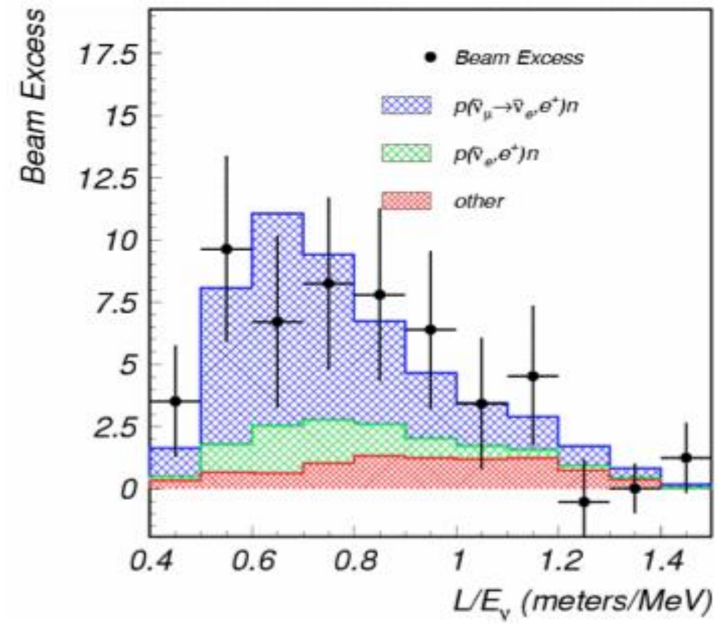

Bruno Pontecorvo

- Sterile neutrinos may mix with ordinary neutrinos via a mass term. Evidence may be building up from several experiments.

Some unexplained $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ events: the LNSD Anomaly

- $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$; L ~ 30 m ; 20 MeV < E < 60 MeV.



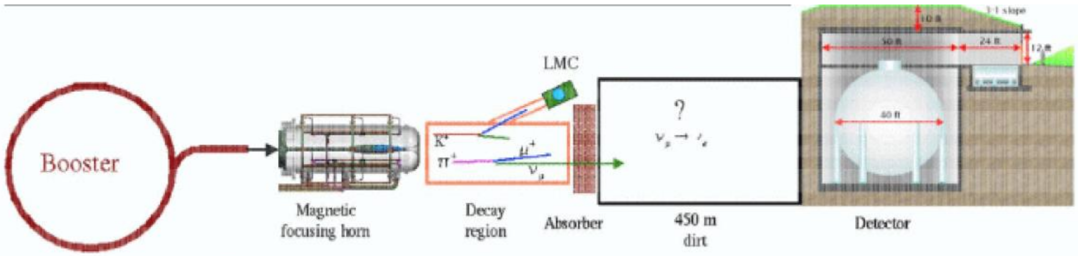


Saw an excess of $\overline{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

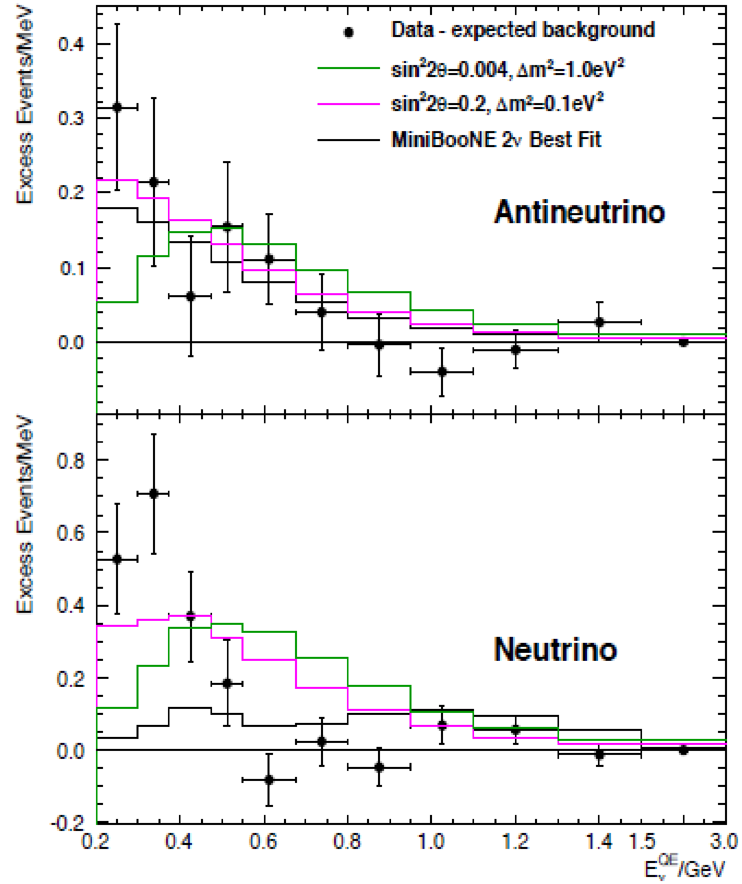
With an oscillation probability of
(0.264 ± 0.067 ± 0.045)% .

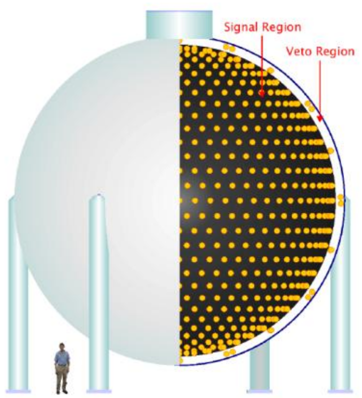
3.8 σ evidence for oscillation.

The MiniBooNE experiment at FNAL



- Booster - 8 GeV proton beam (5 x 10^{20} POT/y)
- Target - 71 cm Be
- Horn - 5 Hz, 170 kA, 143 μs, 2.5 kV, 10^8 pulses/y
- Decay Pipe - 50 m (adjustable to 25 m)
- Neutrino Distance - ~ 0.5 km
- $<E_\nu>$ ~ 1 GeV
- (ν_e / ν_μ) ~ 5×10^{-3}
- Detector - 40' diameter spherical tank
- Mass - 800 (450) tons of mineral oil
- PMTs - 1280 detector + 240 veto, 8" diameter



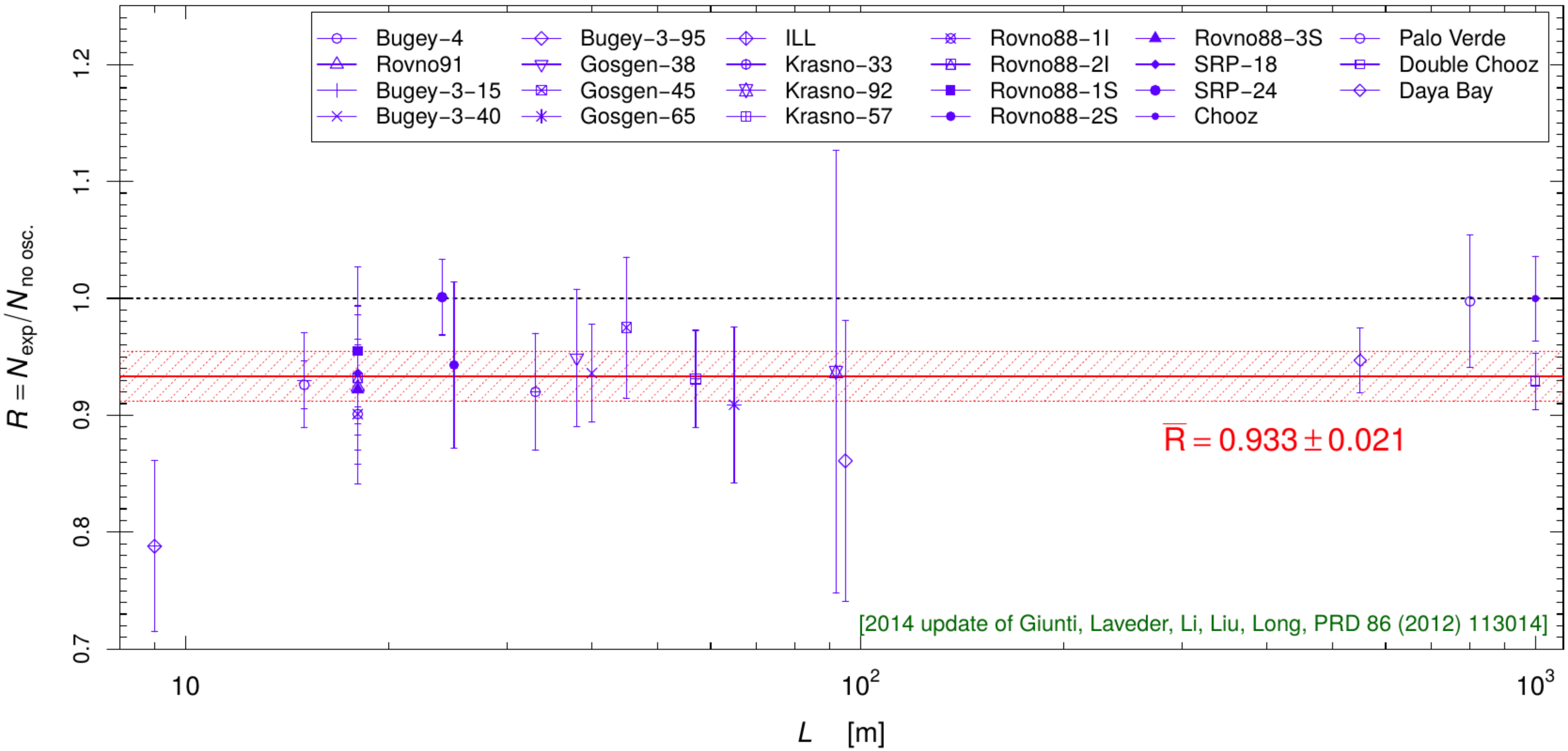


MiniBoone (PRL 110 (2013) 161801) event excess:

- antineutrino 78.4 ± 28.5 events (2.8σ) for 200 < E < 1250 MeV.
- neutrino 162 ± 47.8 events (3.4σ) but the energy distribution is marginally compatible with a two neutrino oscillation formalism.

Reactor driven disappearance anomaly?

New $\overline{\nu}_e$ fluxes: [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



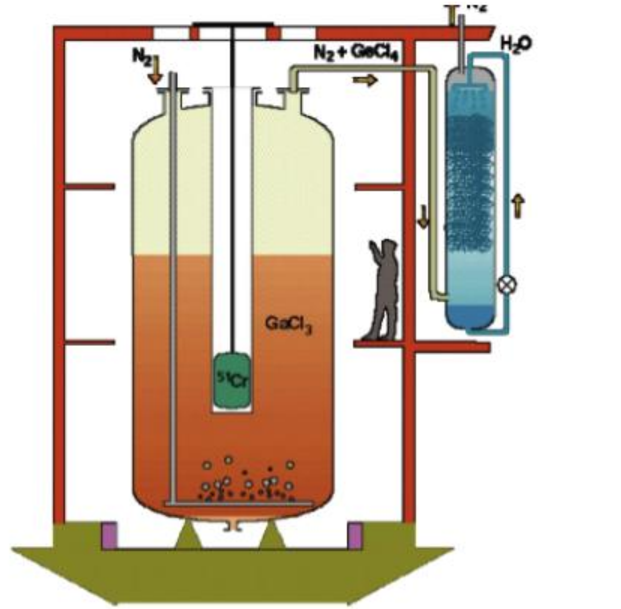
- $\overline{\nu}_e \to \overline{\nu}_e$; L ~ 10 - 100 m ; E ~ 4 MeV.
- R = 0.933 ± 0.021 ; Nominal ~ 3.1σ deficit ; $\Delta m^2 > 0.5\ eV^2$

The Gallium disappearance anomaly

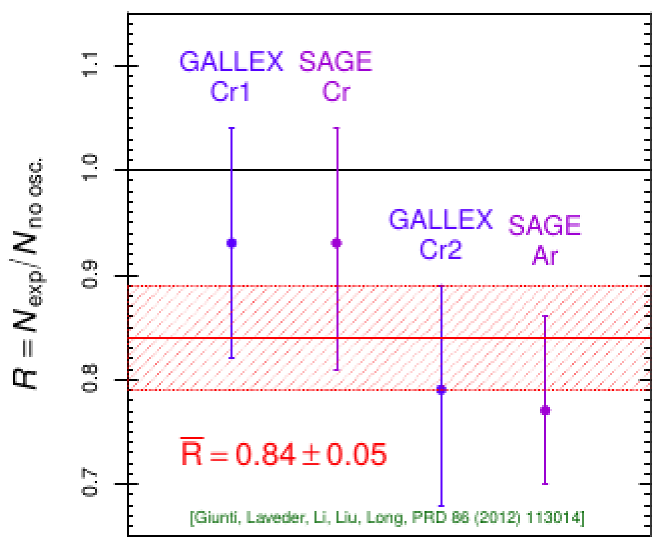
- SAGE and GALLEX experiments recorded the signal produced by intense artificial k-capture sources of 51Cr and 37Ar.

- The averaged result of the ratio R between the source detected and predicted neutrino rates are consistent with each other, giving R = (0.84 ± 0.05), or about 2.9σ from R=1.

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$



30.3 tons of Gallium
in an aqueous solution : $GaCl_3$ + HCl



- $\nu_e \rightarrow \nu_e$; L ~ 1 m ; E ~ 0.7 MeV.
- Nominal ~ 2.9σ deficit ; $\Delta m^2 > 1\ eV^2$

LAr-TPC detectors for neutrino searches

- Cherenkov detectors in water/ice and liquid scintillator detectors have been main technologies so far for neutrino and rare event physics. *Unfortunately these detectors do not permit to identify unambiguously each ionizing track.*

- As an alternative, the LAr-TPC technique, effectively an electronic bubble-chamber, was originally proposed by C. Rubbia in 1977 [CERN-EP/77-08], supported by Italian Institute for Nuclear Research (INFN).

- It acts as an "Electronic bubble chamber": excellent spatial resolution (~mm), homogeneous calorimetry, self-triggering detector.

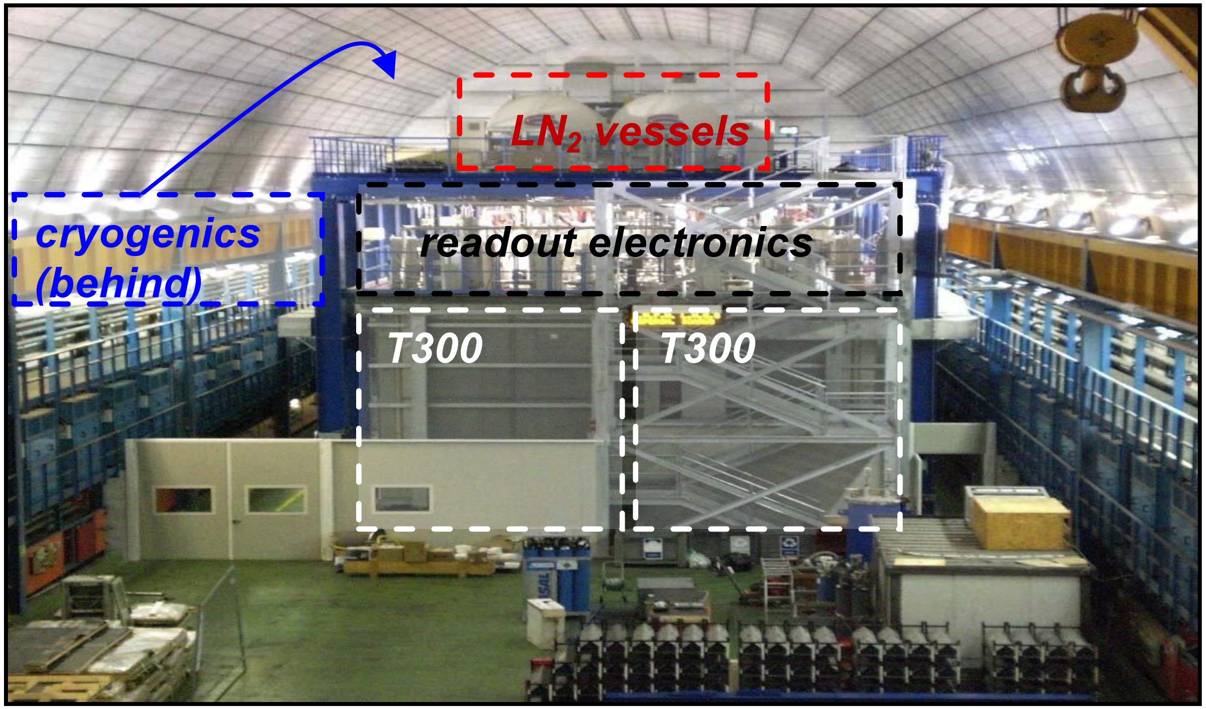
- Thanks to ICARUS collaboration, LAr-TPC has been taken to full maturity with the T600 detector receiving CNGS neutrino beam and cosmic rays.

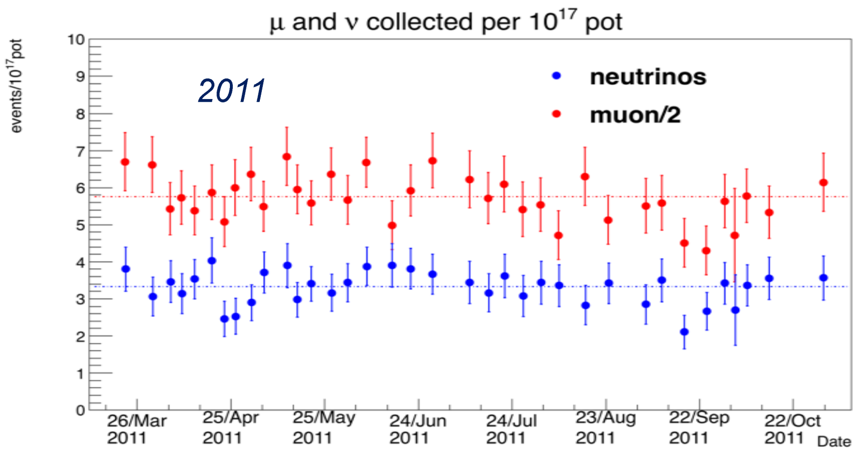
- ICARUS T600 is also a technological milestone towards future larger LAr-TPCs (tens of kton as the DUNE project in USA).

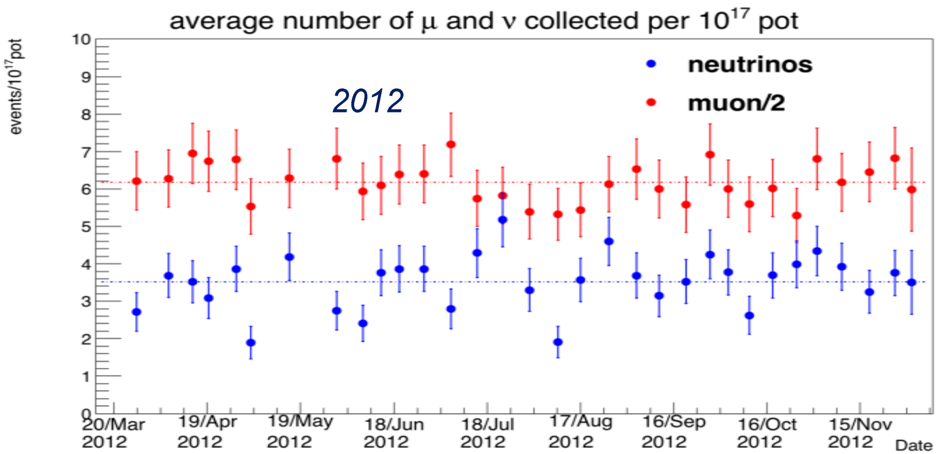
The ICARUS T600 experiment at LNGS

- ICARUS is the first large volume LAr-TPC (760 tons), installed in Hall B of LNGS underground laboratory.

- ICARUS concluded in 2013 a very successful 3 years long run at LNGS, collecting 8.6 × 10^{19} pot event with a detector live time > 93%, recording 2650 CNGS neutrinos (in agreement with expectations) and cosmic rays (0.73 kty).



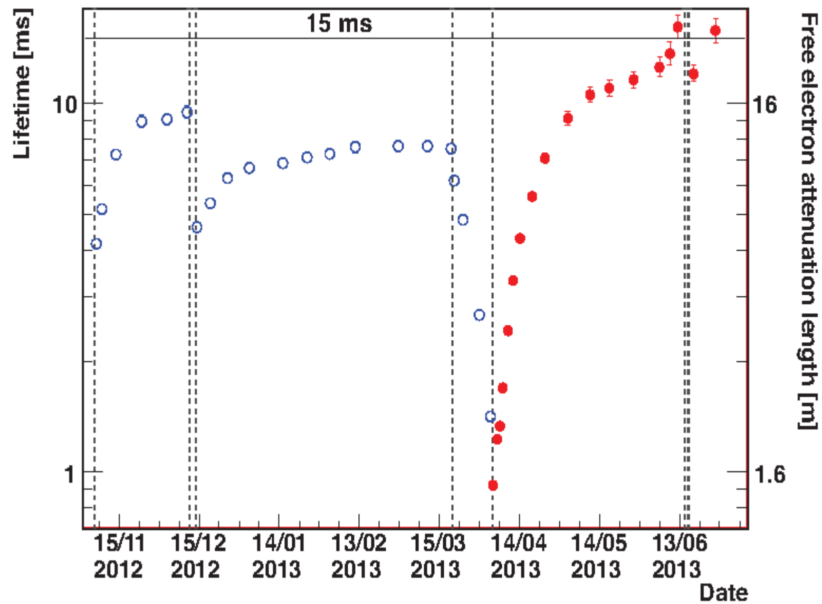


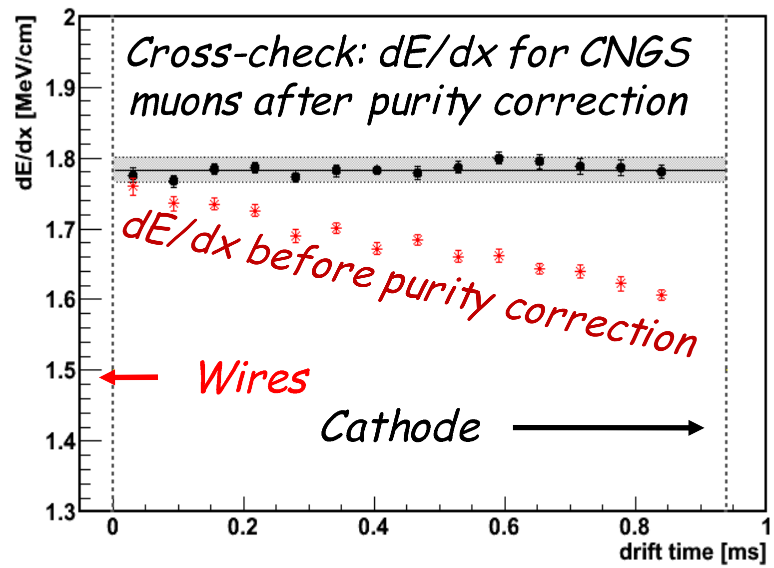


Key features of LAr imaging: very long e⁻ mobility

- Level of electronegative impurities in LAr must be kept exceptionally low to ensure ~m long drift path of ionization e^- with very small attenuation.
- New industrial purification methods developed to continuously filter and re-circulate both in liquid (100 m^3/day) and gas (2.5 m^3/hour) phases.
- Electron lifetime measured during ICARUS run at LNGS with cosmic μ's: τ_{ele} >7 ms (~40 p.p.t. [O_2] eq) →12% max. charge attenuation.
- With the new pump installed at the end of LNGS run: τ_{ele} > 15 ms (~20 p.p.t.).

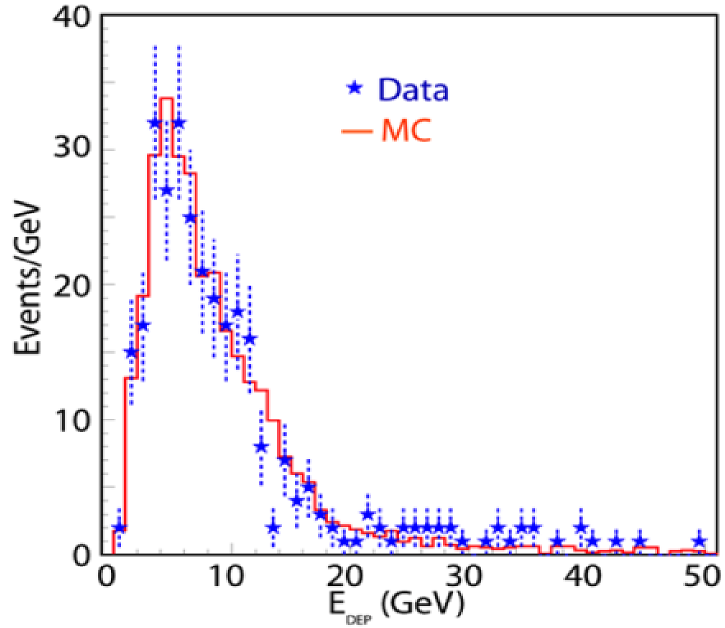
ICARUS demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors (DUNE project requires ~5 m drift).



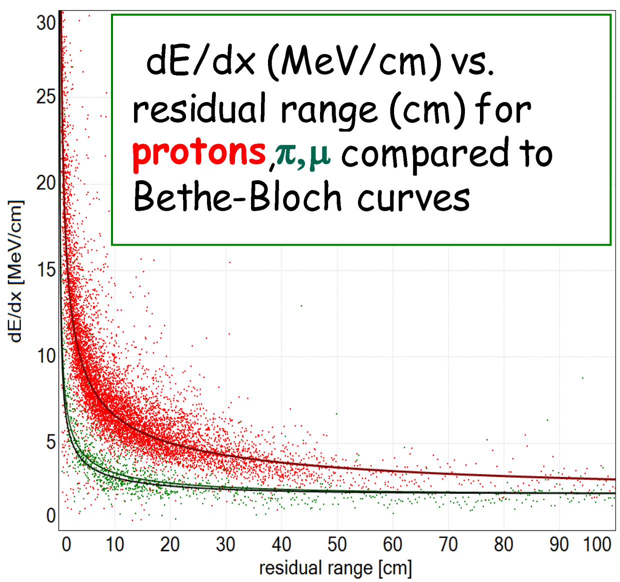


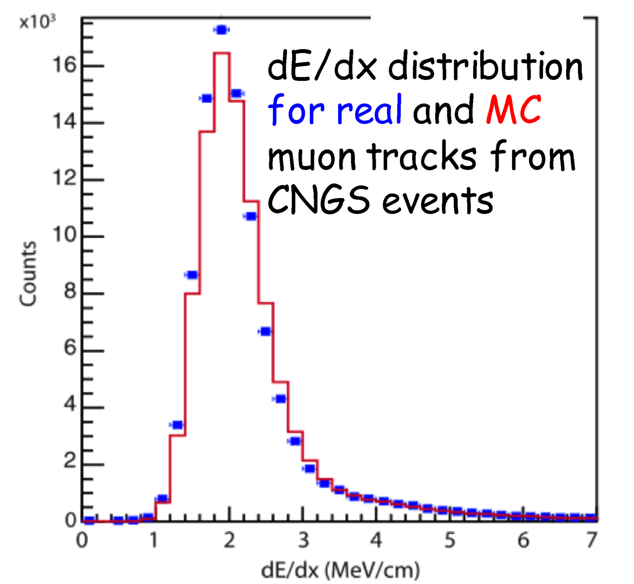
ICARUS LAr-TPC performance

- *Tracking device:* precise ~mm^3 resolution, 3D event topology, accurate ionization measurement;
- *Global calorimeter:* total energy reconstruction by charge integration - excellent accuracy for contained events; momentum of non contained μ determined via Multiple Coulomb Scattering $\Delta p/p$ ~15% in 0.4-4 GeV/c range;
- *Measurement of local energy deposition dE/dx:* e/γ remarkable separation (0.02 X_0 sampling, X_0 = 14 cm particle identification by dE/dx vs range);



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

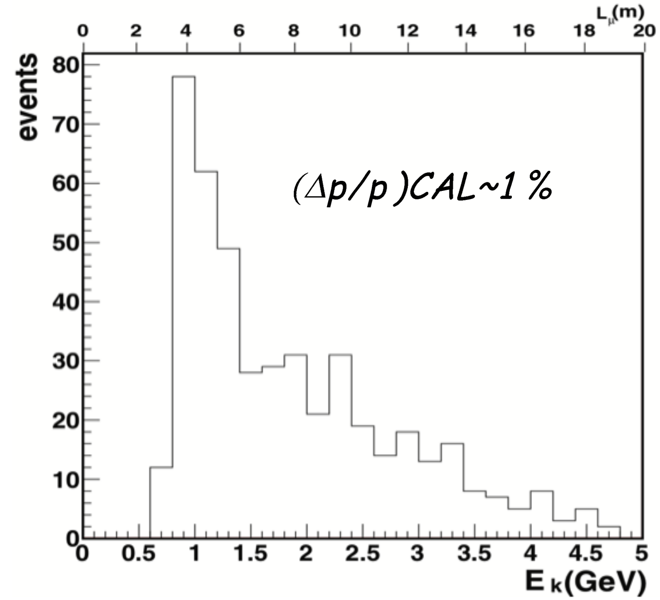


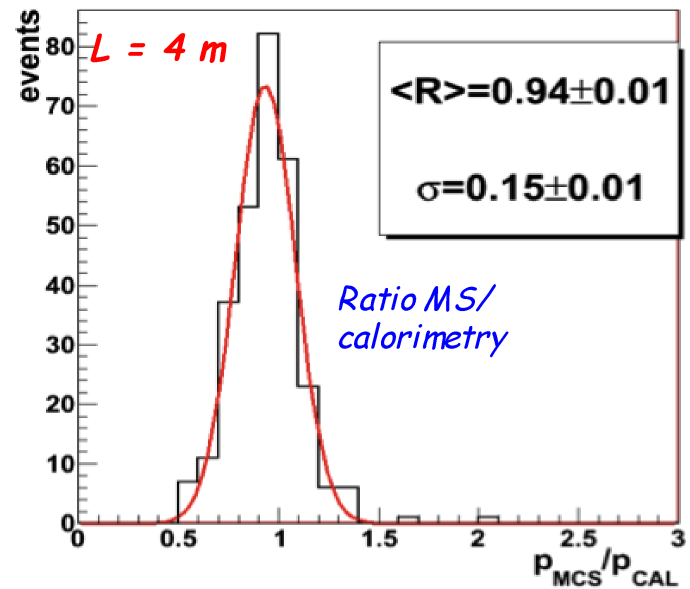


Measurement of muon momentum via multiple scattering

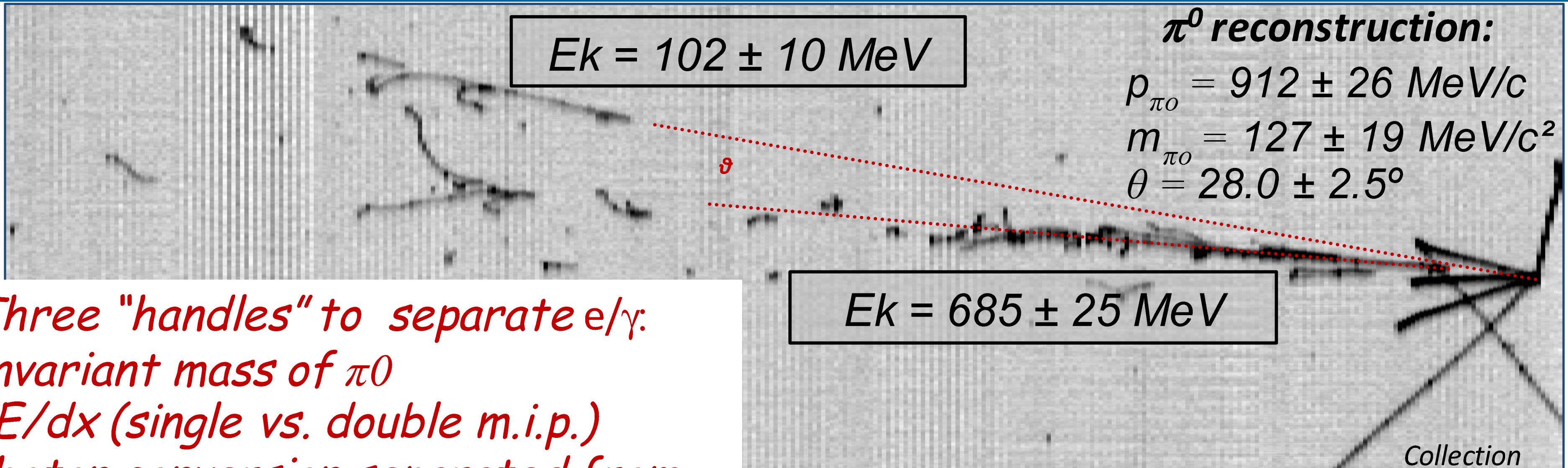
- Multiple Coulomb Scattering (MCS) is the only way to measure momentum of non-contained muons.
- Algorithm validated on ~400 *stopping muons*: produced in ν_μCC interactions of CNGS neutrinos upstream of T600, and stopping/decaying inside the detector.
- Good agreement between MCS and calorimetric measurements.
- Average resolution of ~15% on the stopping muon sample.
- Resolution depends both on momentum and effective muon track length used for measurement.

Some deviations for p > 3.5 GeV/c induced by non-perfect planarity of TPC cathode





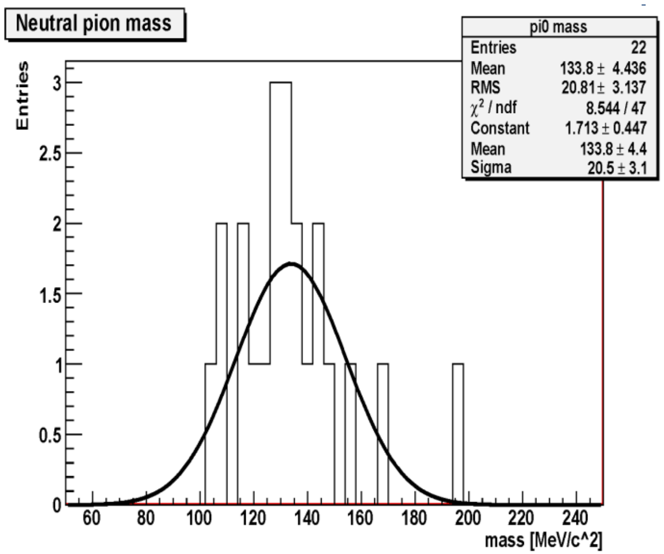
e/γ separation and π^0 reconstruction

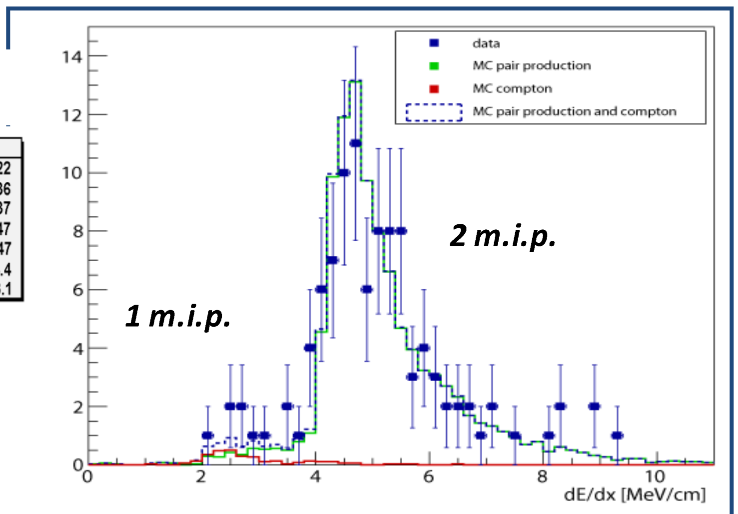


Three "handles" to separate e/γ:

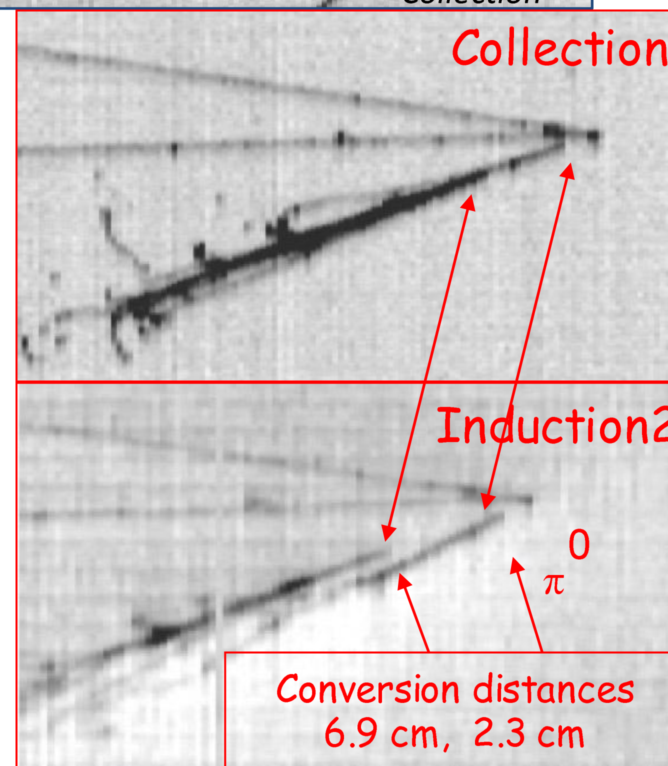
- *invariant mass of $\pi 0$*
- *dE/dx (single vs. double m.i.p.)*
- *photon conversion separated from primary vertex*

$M_{\gamma\gamma}$:133.8±4.4±4 MeV/c^2





Unique feature of LAr
Crucial for νe physics

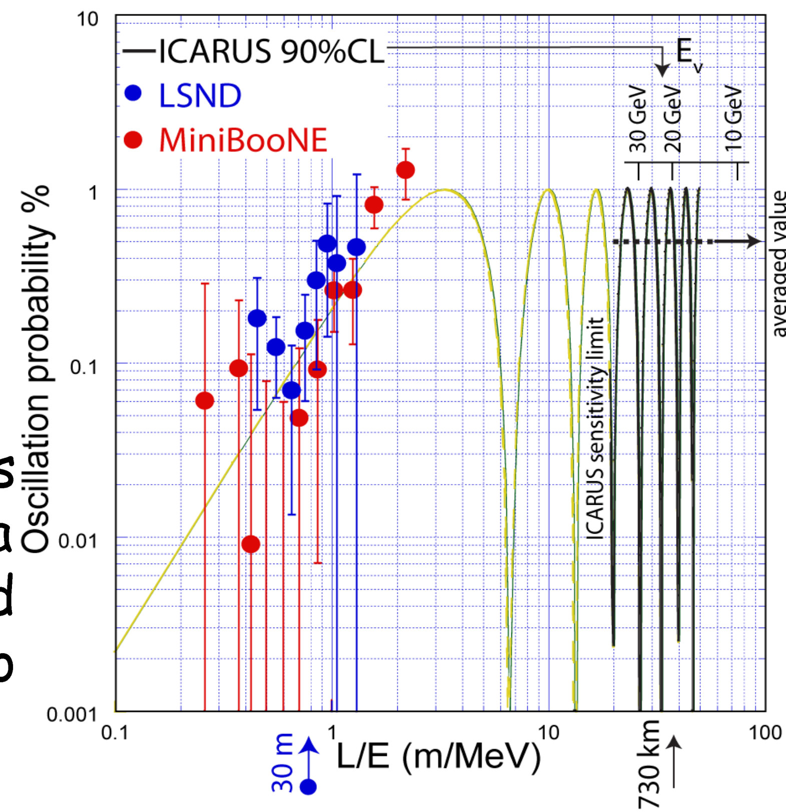


Search for anomalous LSND ν_e events in CNGS

- 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.

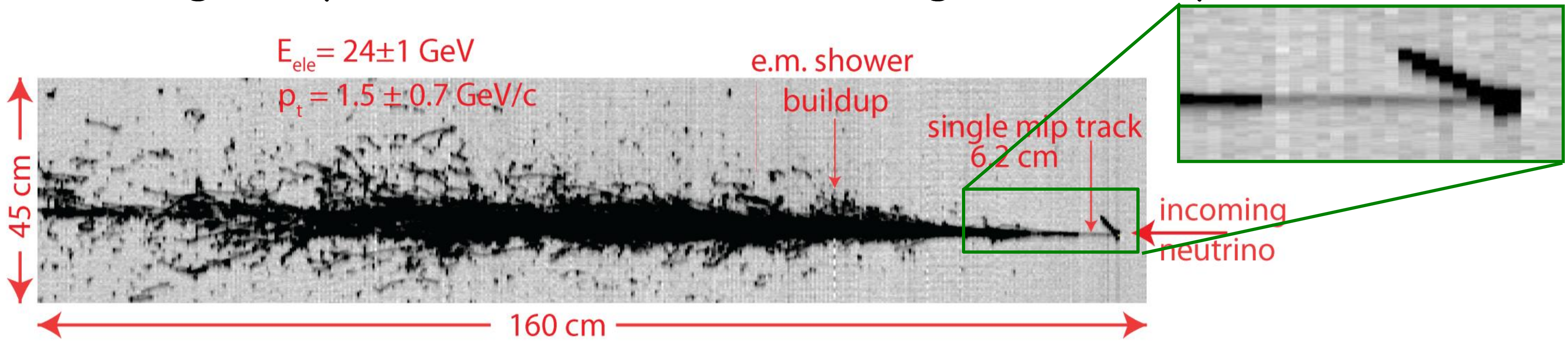
- There are differences w.r.t. LSND experiment:
  - L/E_ν ~ 1 m/MeV at LSND, but
  - L/E_ν ~ 36.5 m/MeV at CNGS
  - LSND-like short distance oscillation signal averages to $\sin^2(1.27\Delta m^2_{new}\, L/E) \sim 1/2$ and $\langle P \rangle_{\nu\mu \to \nu e} \sim 1/2 \sin^2(2\theta_{new})$.

- 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 $\sin(\theta_{13})$)] not yet too relevant.



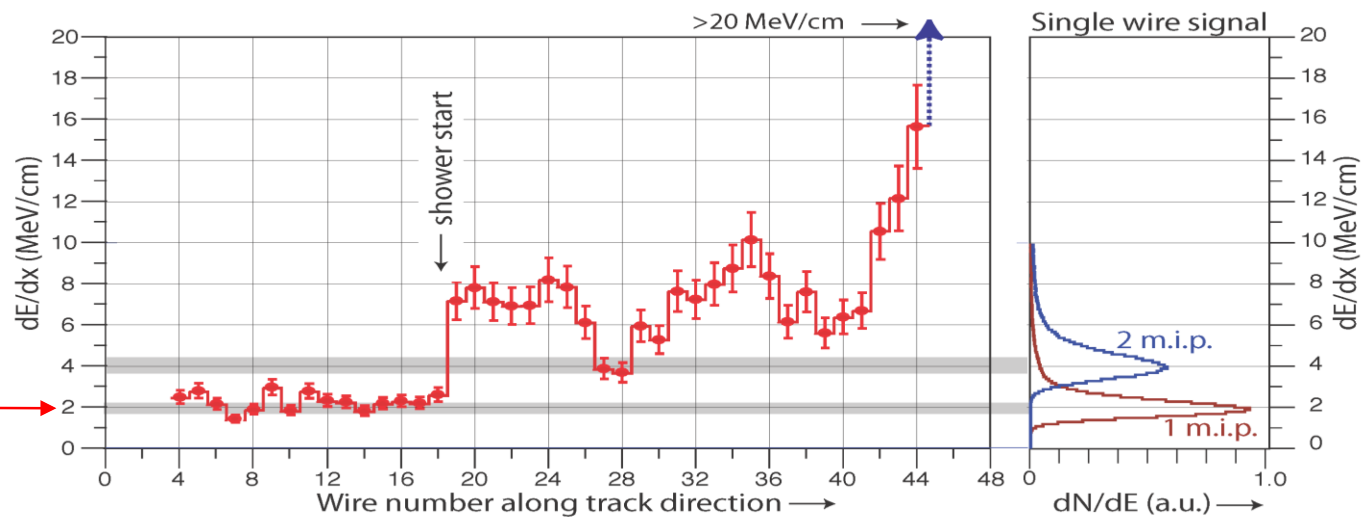
ν_e identification in ICARUS LAr-TPC

- The 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.

Single M.I.P



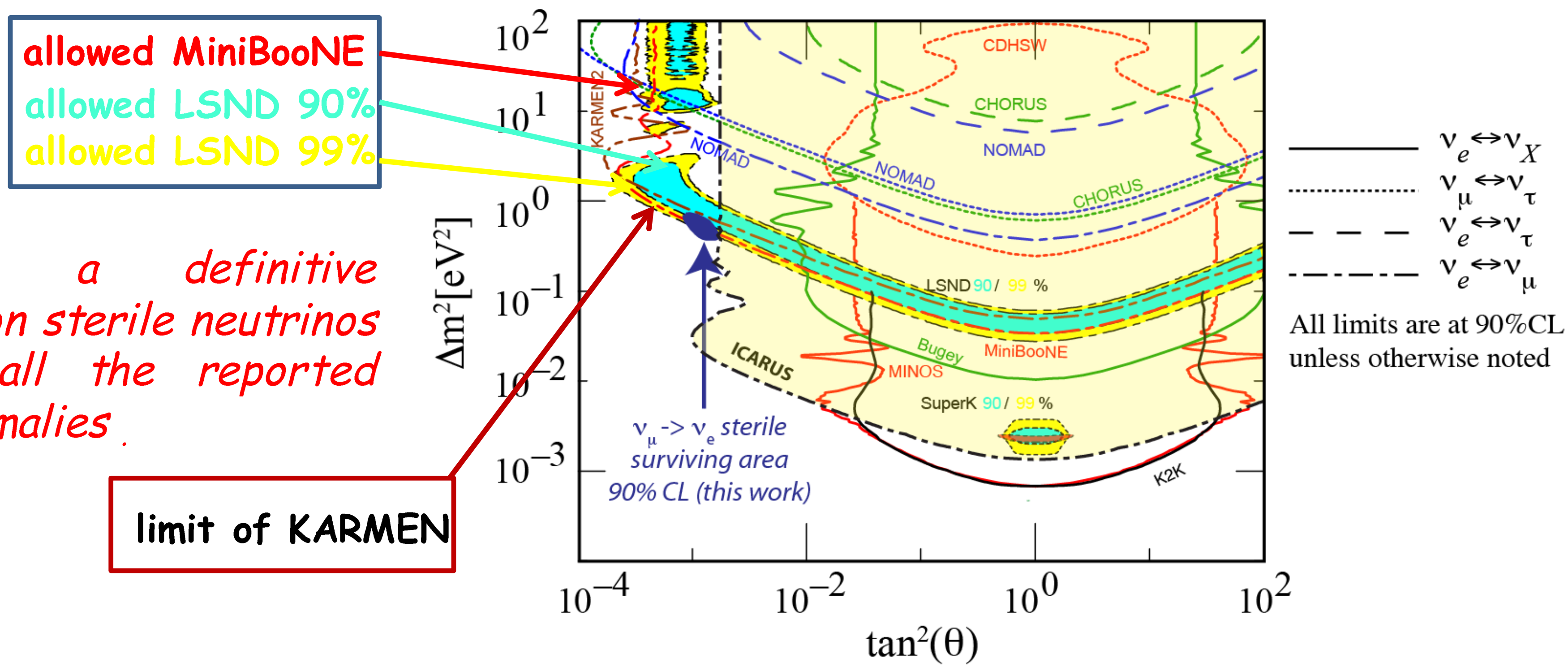
Search for LSND-like anomaly by ICARUS at LNGS

- ICARUS searched for νe excess related to LSND-like anomaly on the CNGS ν beam (~1% intrinsic ν_e contamination, L/Eν ~36.5 m/MeV). No excess was observed: number of ν_e events as expected in absence of LSND signal.

- Analysis on 7.23×10^{19} pot event sample provided the limit on the oscillation probability $P(\nu_\mu \rightarrow \nu_e) \leq 3.85\ (7.60) \times 10^{-3}$ at 90 (99) % C.L.

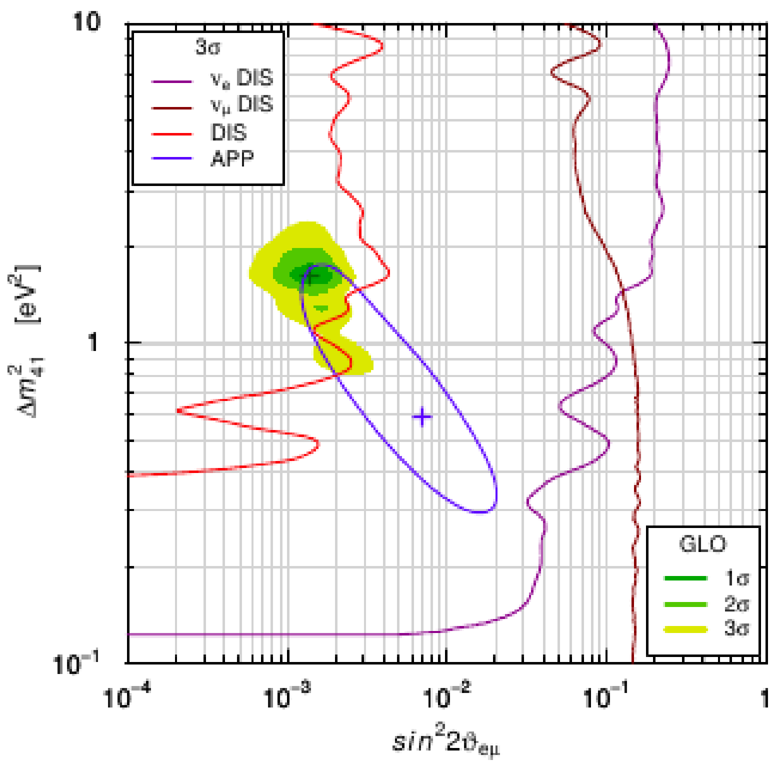
- ICARUS result indicates a very narrow region (Δm^2~0.5 eV^2, $\sin^2 2\theta$~0.005) where all experimental results can be accommodated at 90% CL.

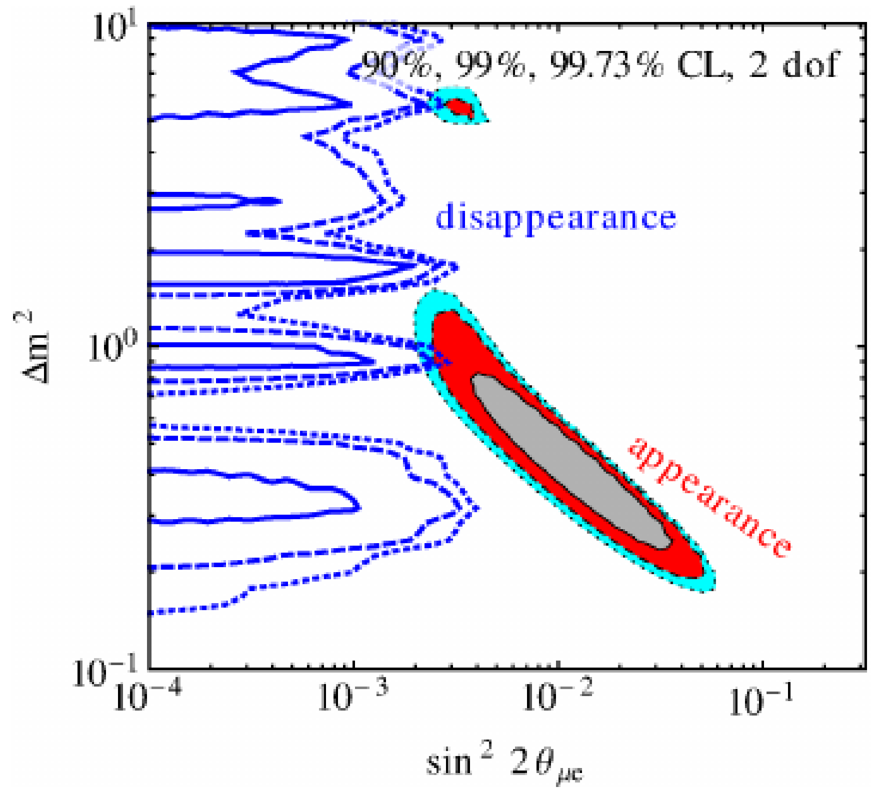
Need for a definitive experiment on sterile neutrinos to clarify all the reported neutrino anomalies .



Global analysis of SBL data

Global analysis of SBL neutrino oscillation data in 3+1 mixing scheme:





ArXiv:1308.5288 by C. Giunti et al.:

- No MiniBooNE < 475 MeV
- 0.8 < Δm^2_{41} < 2 ev^2 (3σ) → No oscillation disfavoured at 6.3σ

JHEP 1305 (2013) 050 by Kopp et al.:

There is no globally allowed region in this paper!

SBN Sterile neutrino search at FNAL Booster ν beamline

- Joint ICARUS/SBND/MicroBooNE CDR received *Stage 1 Approval from FNAL PAC Jan 2015*. Three LAr-TPC's at different distances from target (Booster Neutrino Beam ~ 1 GeV ν_μ): SBND (82 t), MicroBooNE (89 t) and ICARUS T600 (476 t) at 100, 470 and 600 m.

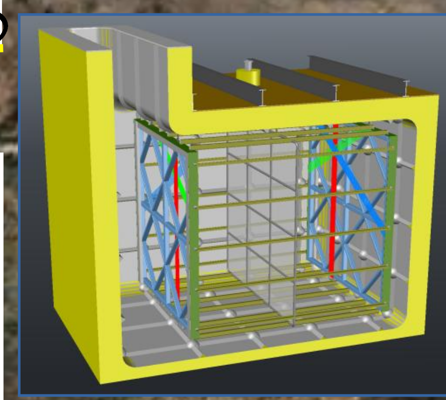
- The experiment will likely clarify LSND/MiniBooNE, Gallex, reactor anomalies by precisely/independently measuring both ν_e appearance and ν_μ disappearance, mutually related through

$$\sin^2(2\vartheta_{\mu e}) \leq \frac{1}{4}\sin^2(2\vartheta_{\mu x})\sin^2(2\vartheta_{ex})$$

- In absence of "anomalies", three detector signals should be a close copy of each other for all experimental signatures.

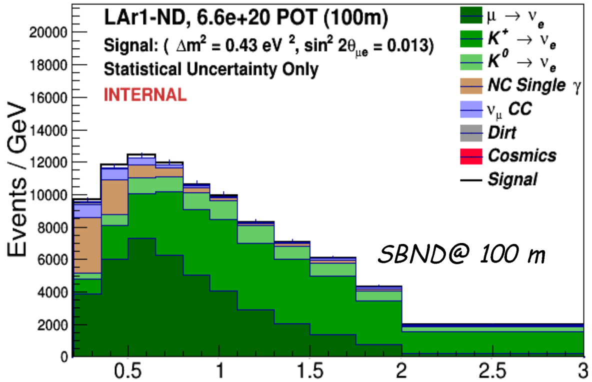
- During its SBN operations, ICARUS will collect also ~ 2 GeV ν_e CC events with NUMI Off-Axis beam, an asset for the DUNE project at FNAL:
  - accurate determination of cross sections in LAr ;
  - experimental study of all individual CC/NC channels to realize algorithms improving the identification of ν interactions.

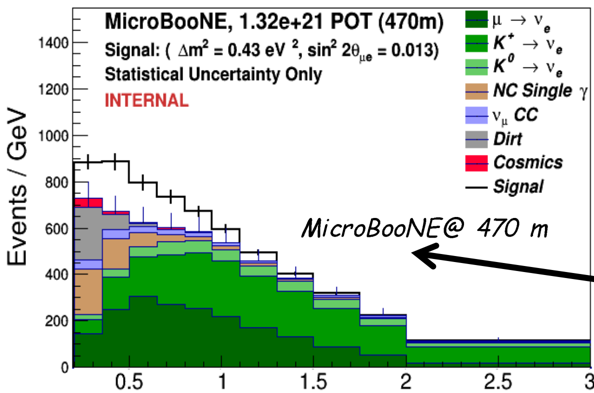
SBN@BNB

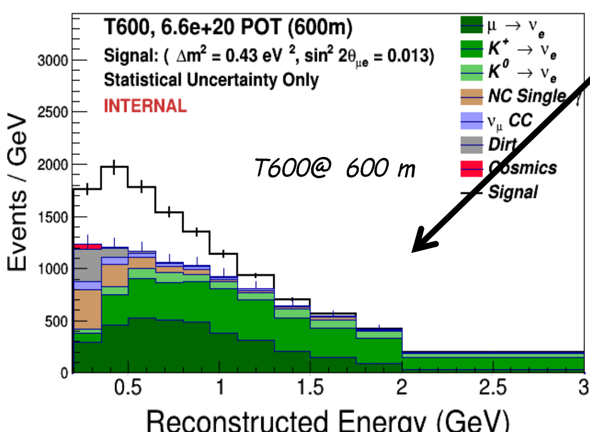


ICARUS T600 moved to CERN in 2014, to be upgraded (WA104 project). The detector will be transferred to FNAL at the beginning of 2017 for installation, commissioning and start of data taking with BNB beam.

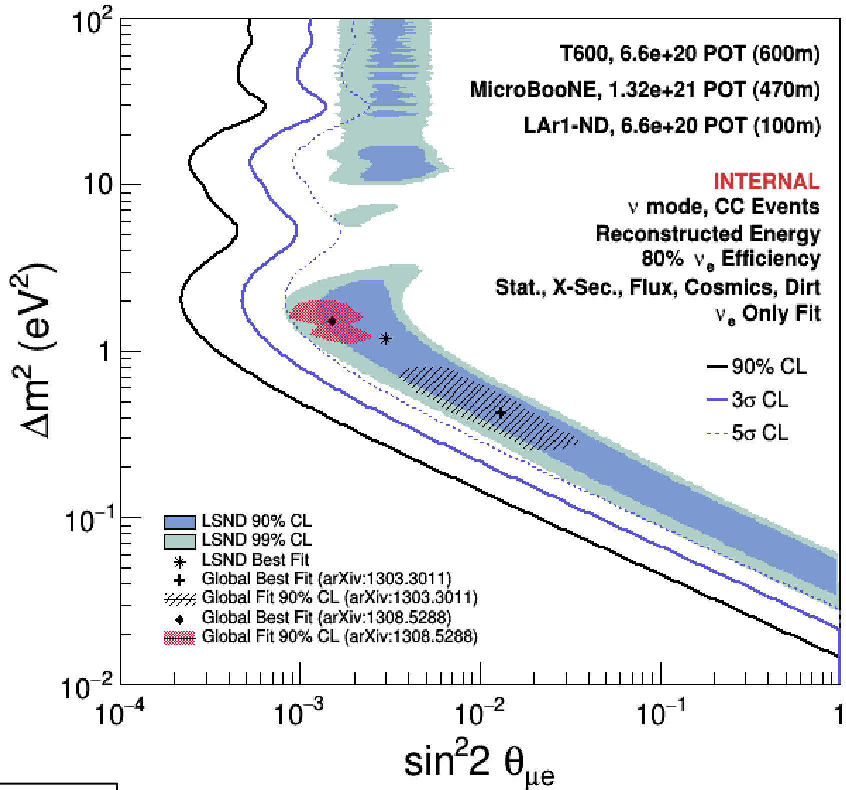
$\nu_\mu \rightarrow \nu_e$ appearance sensitivity







- Expected exposure sensitivity of $\nu_\mu \rightarrow \nu_e$ oscillations for 3 years - 6.6 10^{20} pot BNB positive focusing (6 years for MicroBooNE).

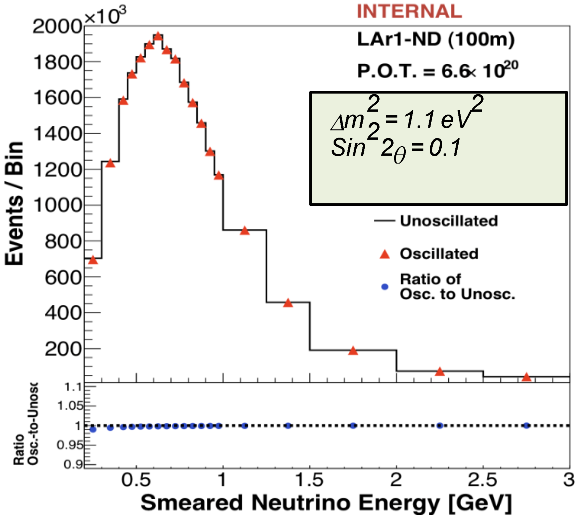


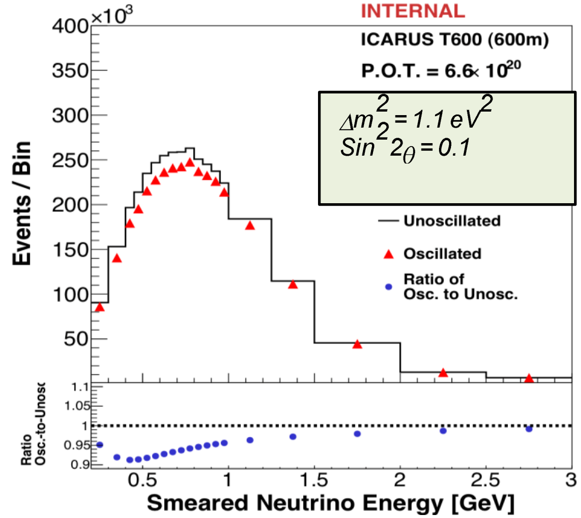
Example for
$(\sin^2(2\theta)=0.013$
$\Delta m^2=0.43\ eV^2)$

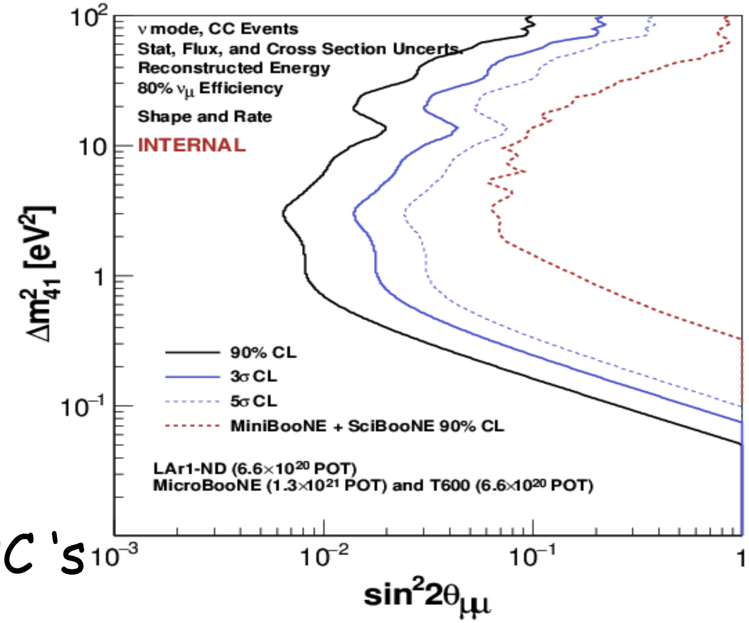
In absence of oscillations, the spectra should be copies of each other

The LSND 99%CL region is covered at ~5σ level

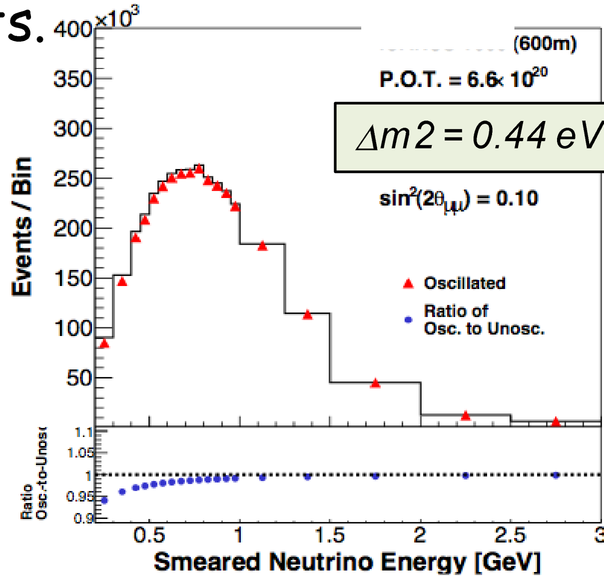
ν_μ disappearance sensitivity

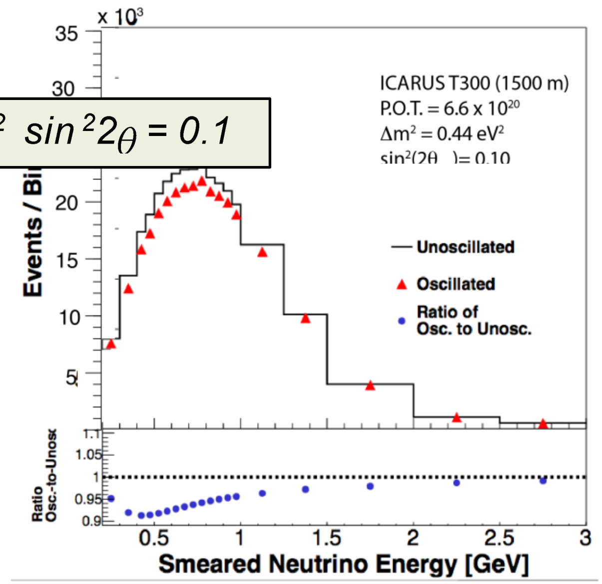






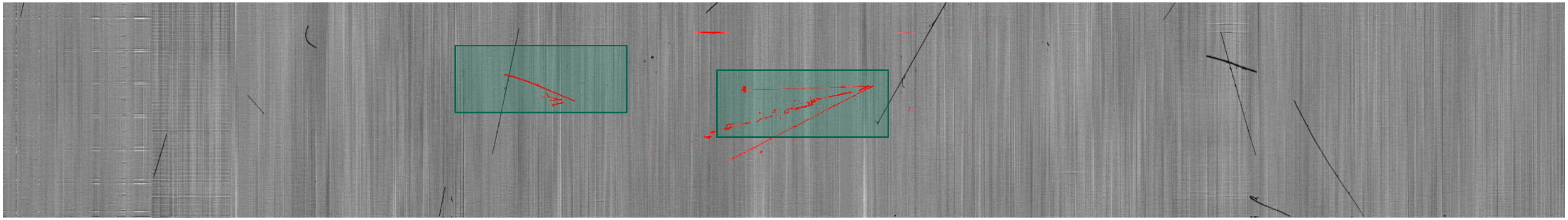
- High event rates/ correlations between 3 LAr-TPC 's will allow extending sensitivity by one order of magnitude beyond present limits.
- However for $\Delta m^2 < 0.5\ eV^2$ ν_μ disappearance at 600 m will be limited at lowest ν energy bins 0.2-0.4 GeV.
- *In order to amplify the effect we may move at a later stage one ICARUS T300 module to 1500 m distance.*



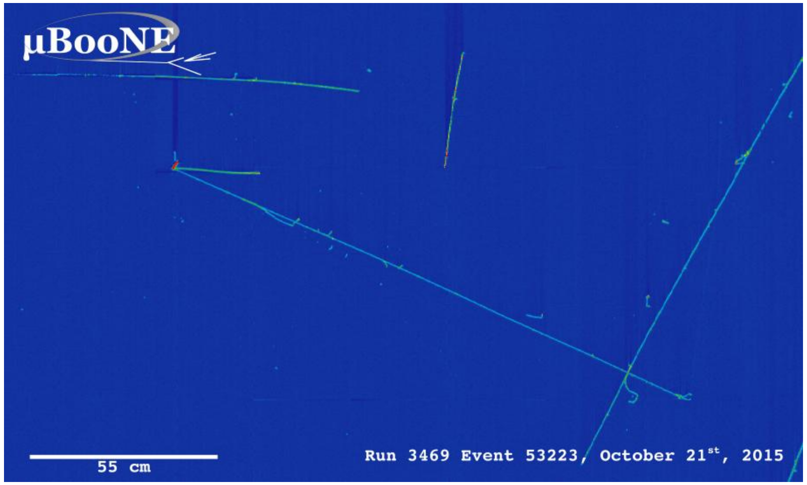


Facing a new situation: the LAr-TPC near the surface

- At shallow depth ~12 uncorrelated cosmic rays will occur in T600 during 1 ms drift window readout at each triggering event.
- This represents a new problem compared to underground operation at LNGS: the reconstruction of the true position of each track requires associating to each element of TPC image the occurrence time with respect to trigger time.



Cosmic rays + low energy CNGS beam event



μBooNE νμ CC event + cosmics

- Moreover, γ's associated with cosmic μ's represent a serious background for the ν_e appearance search since *electrons* generated in LAr via Compton scattering/ pair production can mimic a ν_e CC genuine signal.

Mitigation of cosmogenic background

- A 4π Cosmic Rays Tagger (total surface ~ 1200 m^2) of plastic scintillators around the LAr active volume will unambiguously identify all cosmic ray particles entering the detector providing timing/position to be combined with the TPC reconstructed image.

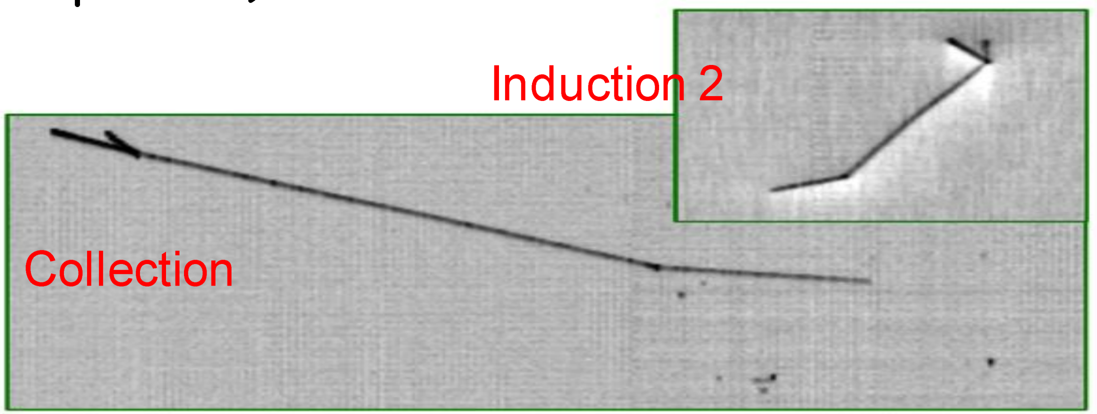
- Further rejection capabilities will come from precise timing information from internal scintillation light detectors.

- Additional background mitigation strategies, exploiting the topological capability of the LAr-TPC, will be also applied to identify photons inside LAr active volume associated with cosmic muons.

- This requires the development of automatic tools to efficiently select, identify and reconstruct the neutrino interactions among the millions events triggered by cosmics (to be compared with the ~ 3000 ν events collected by ICARUS during CNGS run at LNGS!).

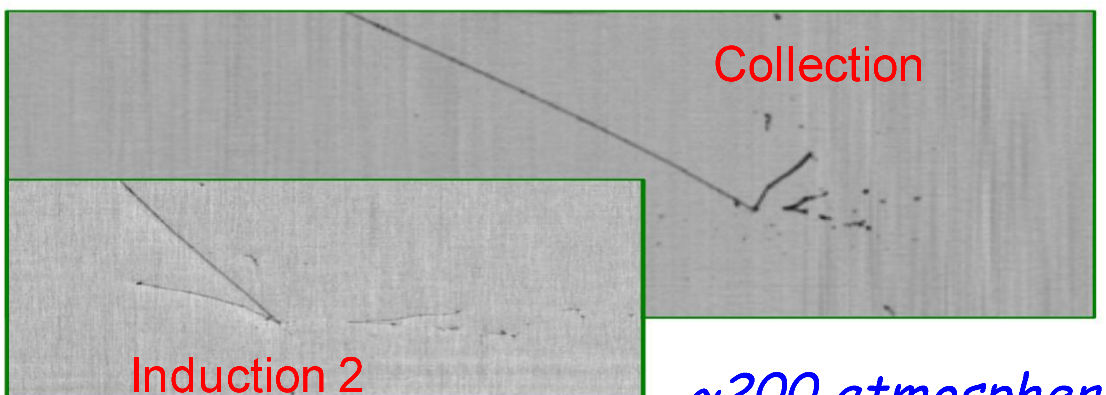
Towards automatic neutrino search: LNGS atmospheric ν

- LNGS data are being filtered through an automatic algorithm looking for interaction vertex and multi-prong event topology, to strongly reduce the scanning time.
- 3 muon-like, 1 electron-like and 7 NC-like atmospheric ν candidates have been identified so far in 25% data sample (4.6±1.2 μ-CC, 3.3±1.1 e-CC and 1.5±0.5 NC expected).



NC atm. candidate: E_{DEP} ~ 200 MeV

- 2 charged particles emerge from interaction vertex.
- π track: 63 cm (interacting and generating 2 protons).

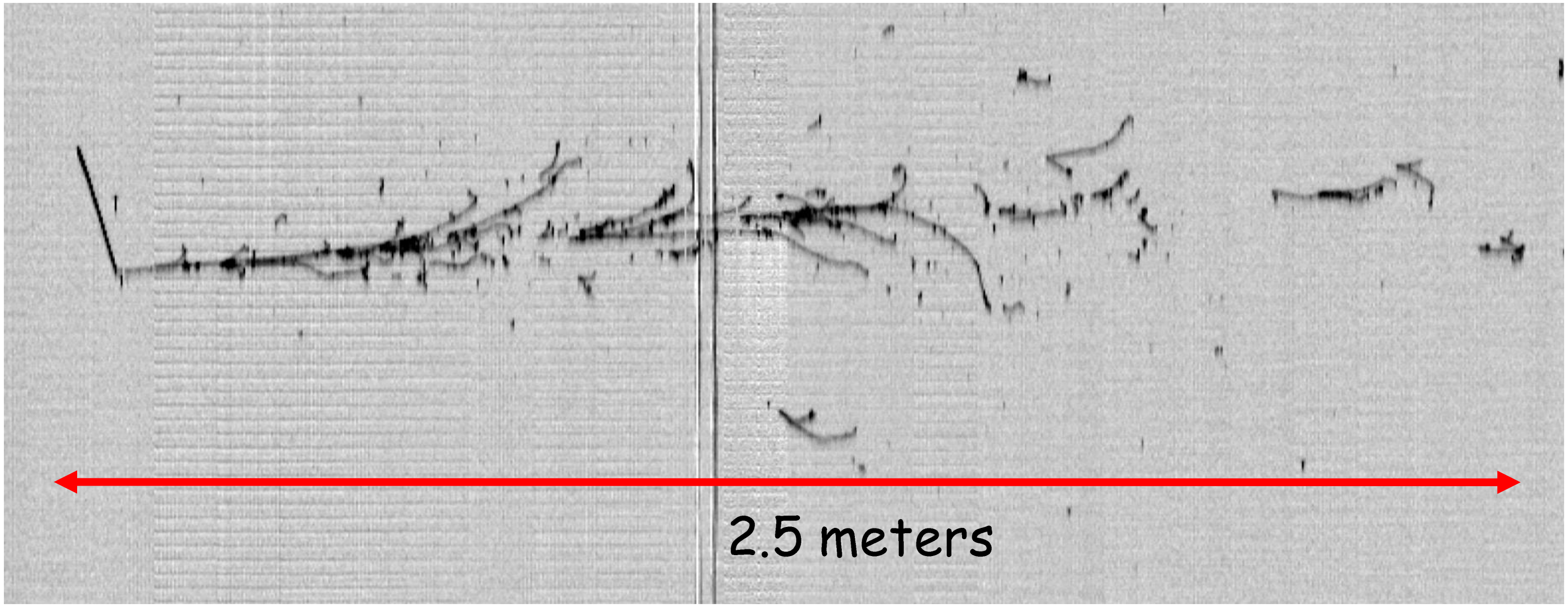


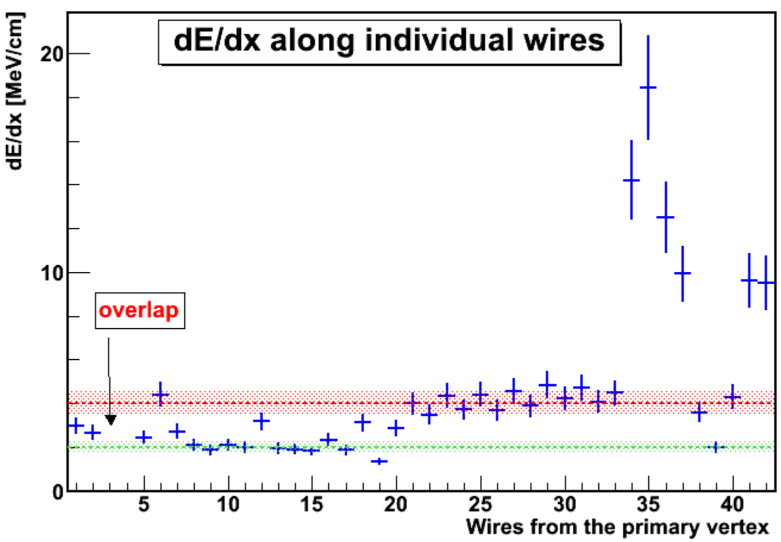
νμ CC atm. candidate: E_{DEP}~ 350 MeV

- μ and p/π tracks are visible.
- μ track candidate: 124 cm.

~200 atmospheric ν expected for 0.73 kt y exposure

The first atmospheric ν_e CC event inside LNGS sample

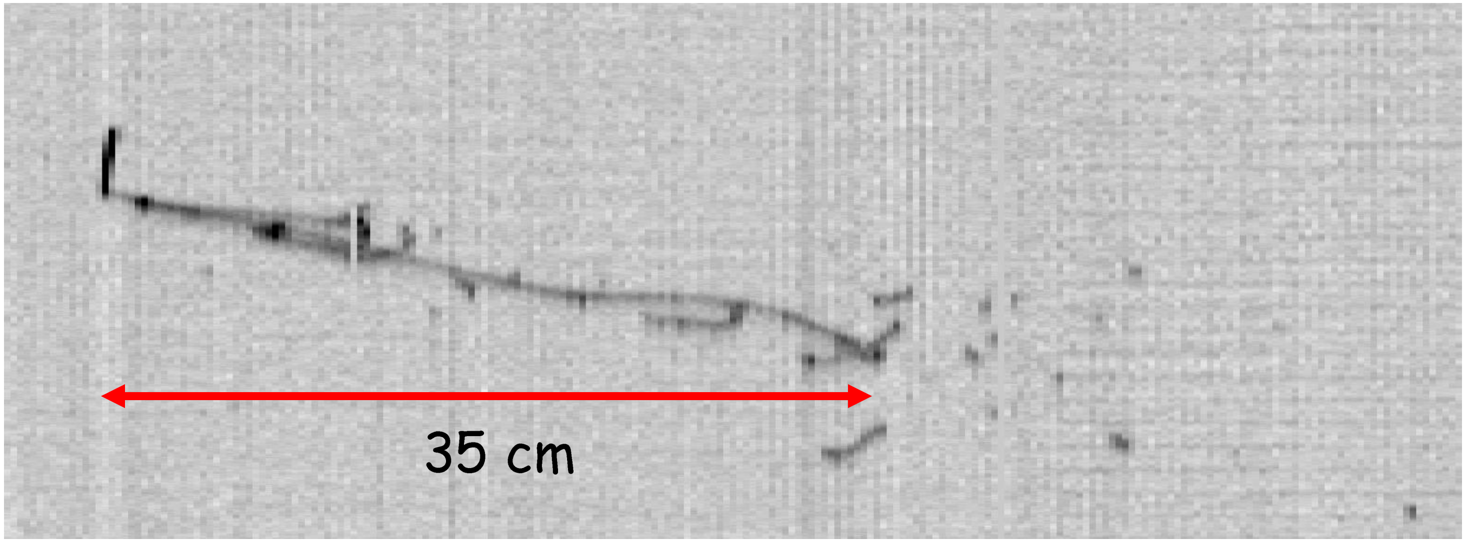




Deposited energy: 2115 MeV:

- E.m. shower (2 GeV): clear single m.i.p from vertex;
- One proton (115 MeV).
- Automatic search for ν_e CC with E_{DEP} ~ GeV is feasible!

The second atmospheric ν_e CC event: low energy



Downward-going, quasi elastic event: deposited energy: 230 MeV!

- New algorithm looking for clusterized energy deposition rather than a vertex.
- dE/dx measured on the first wires (2.1 Mev/cm) corresponds to a m.i.p. particle
- One short proton.
- It demonstrates the identification and measurement capability of the detector even for low energy neutrino interactions!

Outlook and conclusions

- After more than 50 years from their introduction by B. Pontecorvo, sterile neutrinos are still a fundamental topic for particle physics.
- After the LSND anomaly, a number of SBL experiment tried to clarify this matter.
- The ICARUS T600 experiment at LNGS provided new constraints on sterile neutrinos searches with CNGS neutrinos, showing the success of the LAr-TPC technology at the neutrino physics level.
- A global fit of all SBL data + ICARUS limits the window of parameters for a possible LSND anomaly to a very narrow region around 1 eV^2: if sterile neutrinos do exist, we know where they must be!
- A SBL experiment with three LAr-TPC detectors is under preparation at FNAL to definitively set the LSND anomaly within the joint SBN Collaboration.


Thank you!