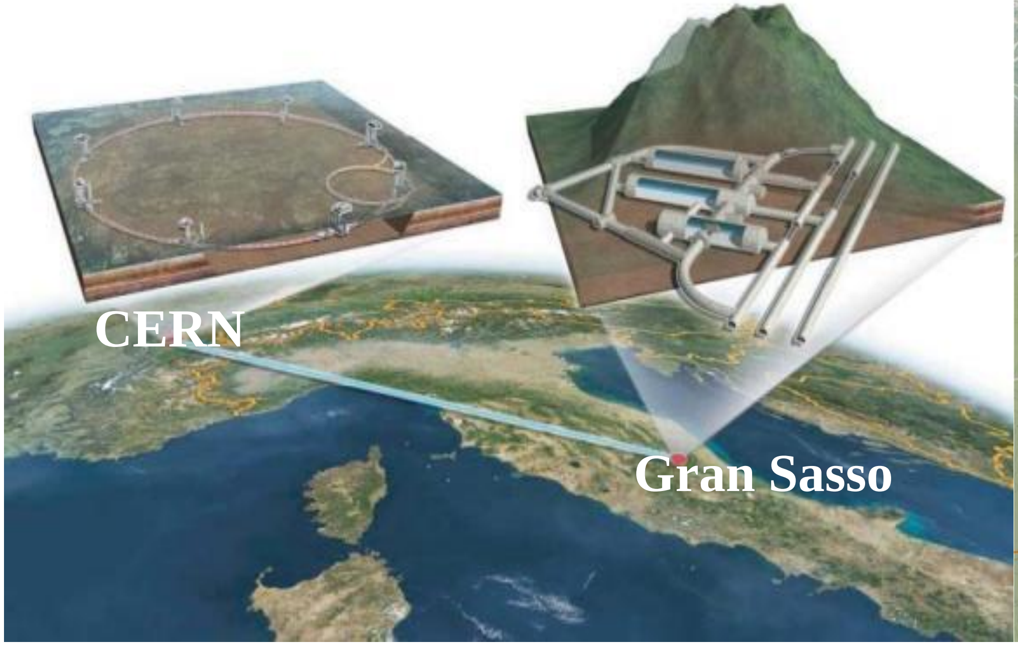
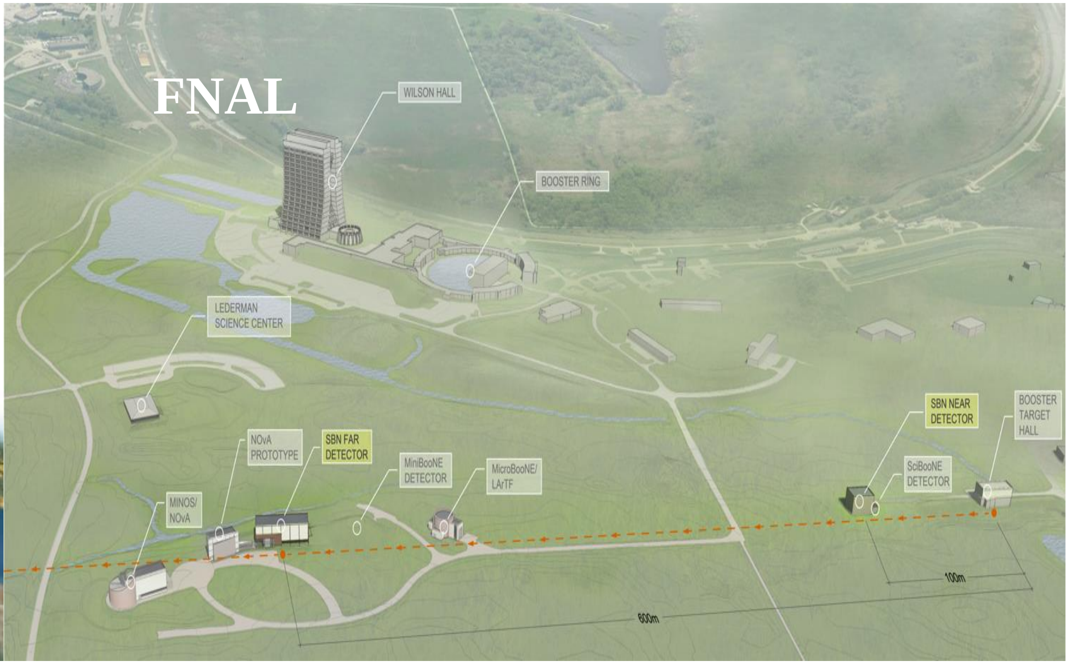
ICARUS experiment - status and perspectives





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(on behalf of the ICARUS Collaboration)

New Trends in High-Energy Physics 2016

The ICARUS Collaboration

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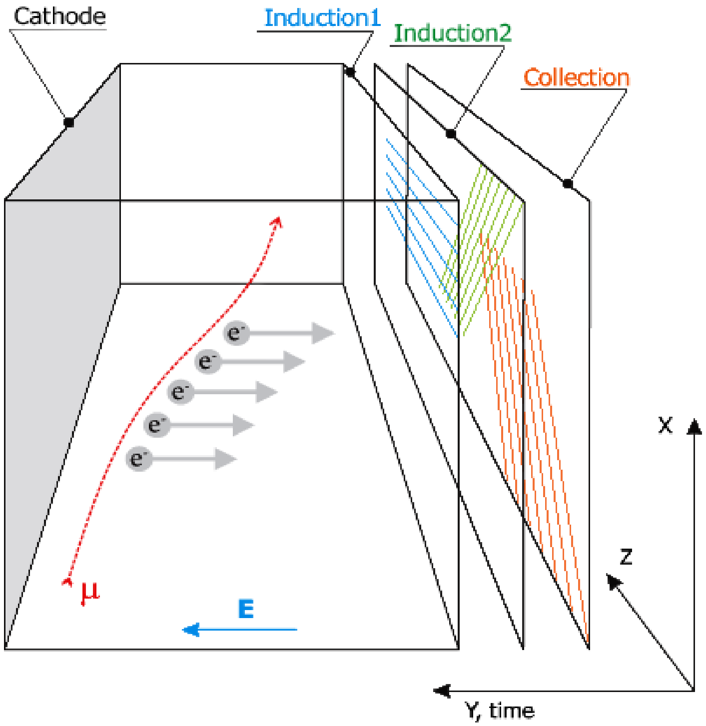
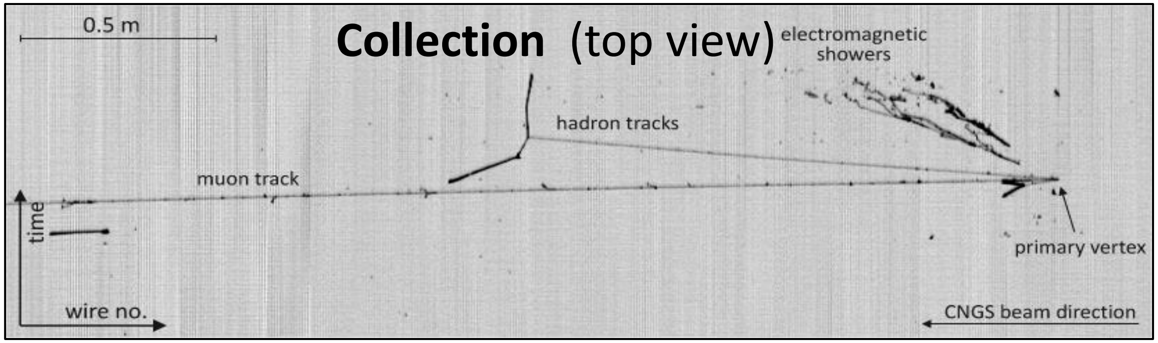
OUTLINE

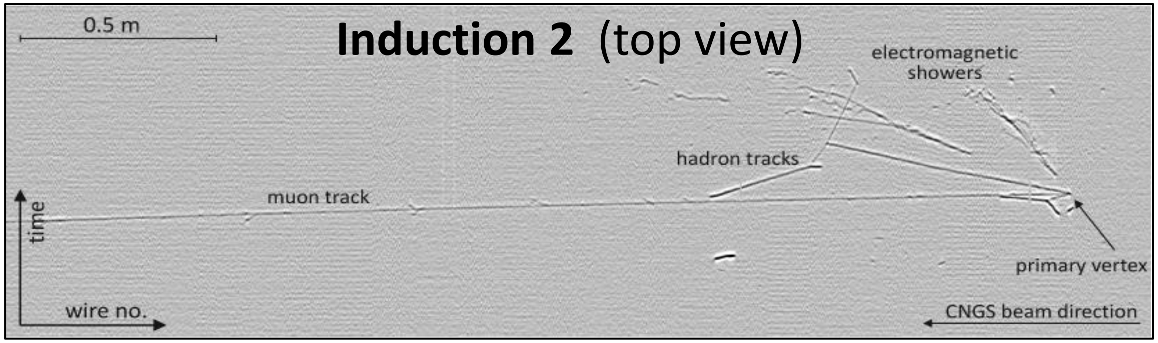
- Liquid Argon TPC detection technique.
- ICARUS T600 detector at Gran Sasso.
- Sterile neutrino searches at Gran Sasso.
- Detector perspective: SBN program at FNAL.
- Present: detector overhauling at CERN (WA104).
- Conclusions

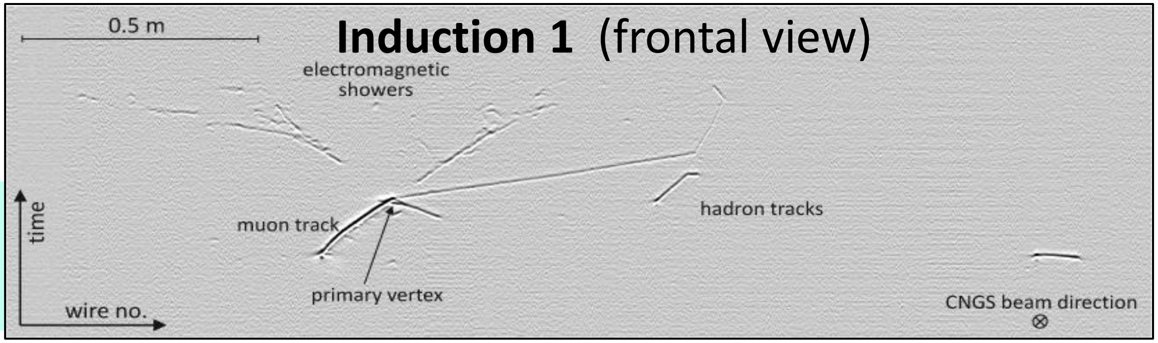
ICARUS LAr-TPC detection technique

- 2D projection for each of 3 wire planes per TPC
- 3D spatial reconstruction from stereoscopic 2D projections
- charge measurement from Collection plane signals
- Absolute drift time from scintillation light collection



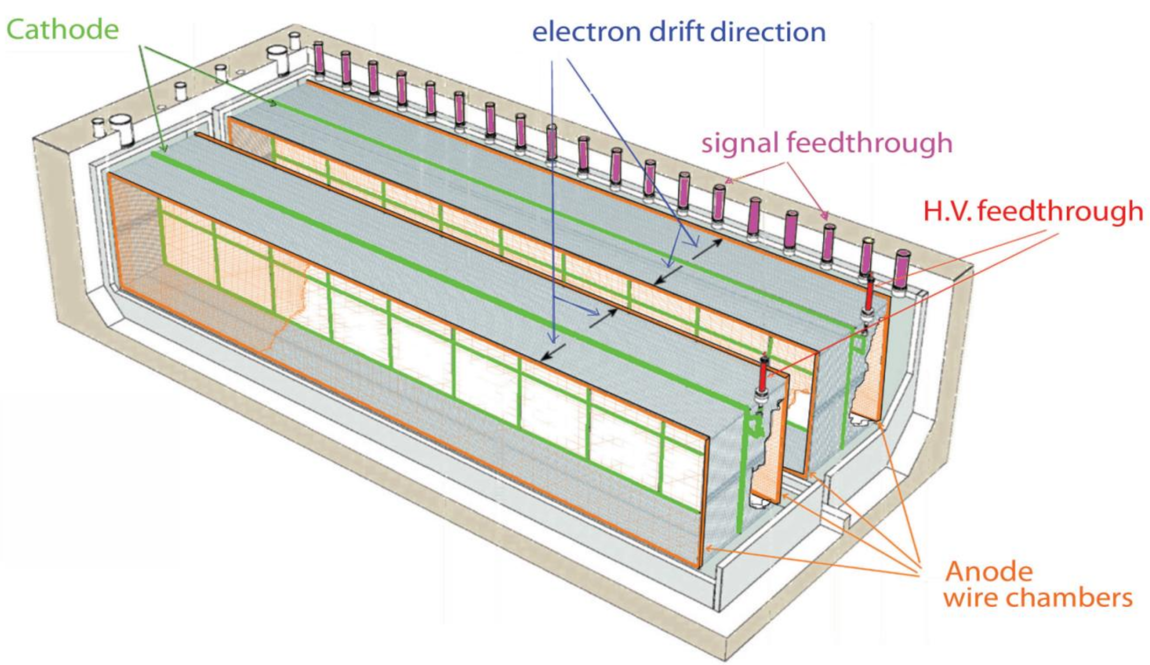


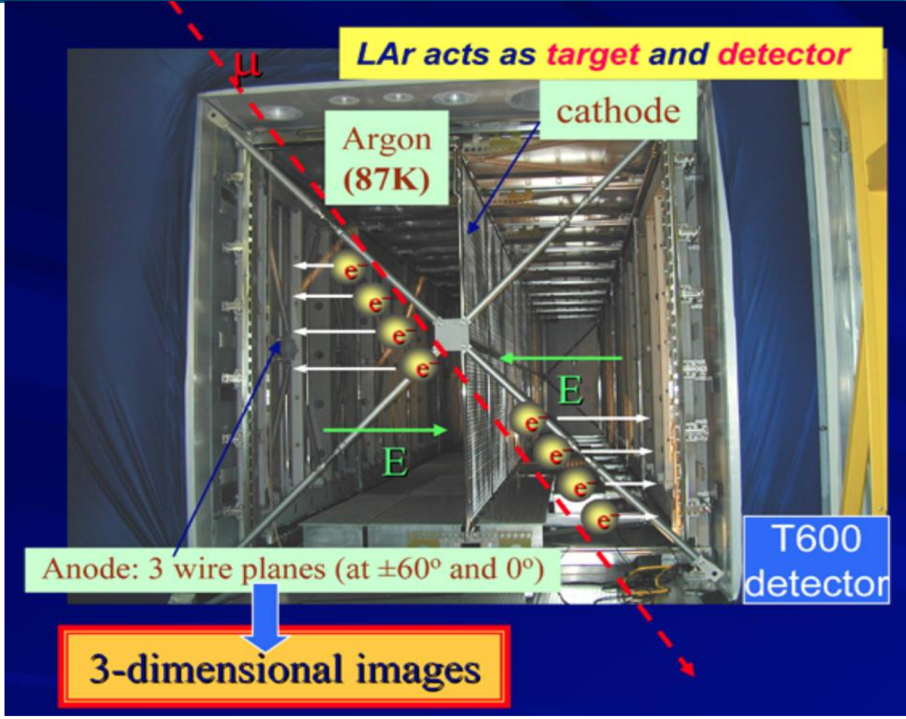




CNGS ν_μ charge current interaction, one of TPC's shown

The ICARUS T600 detector





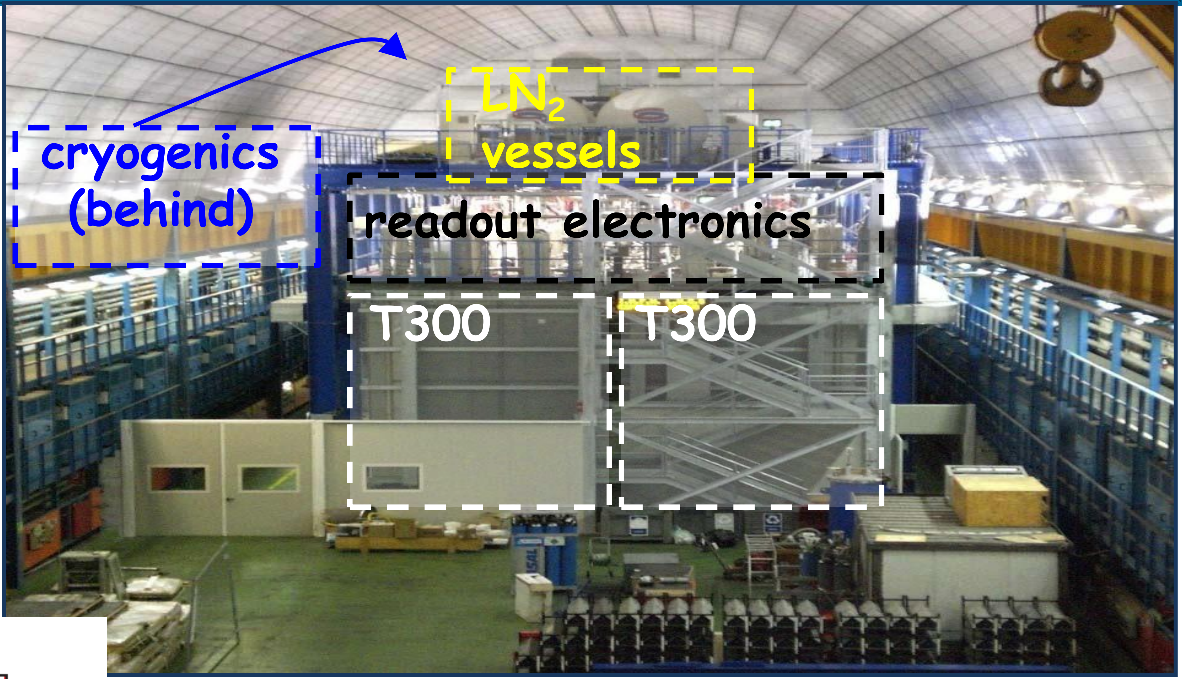
- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV sensitive (128nm) with wave shifter (TPB)

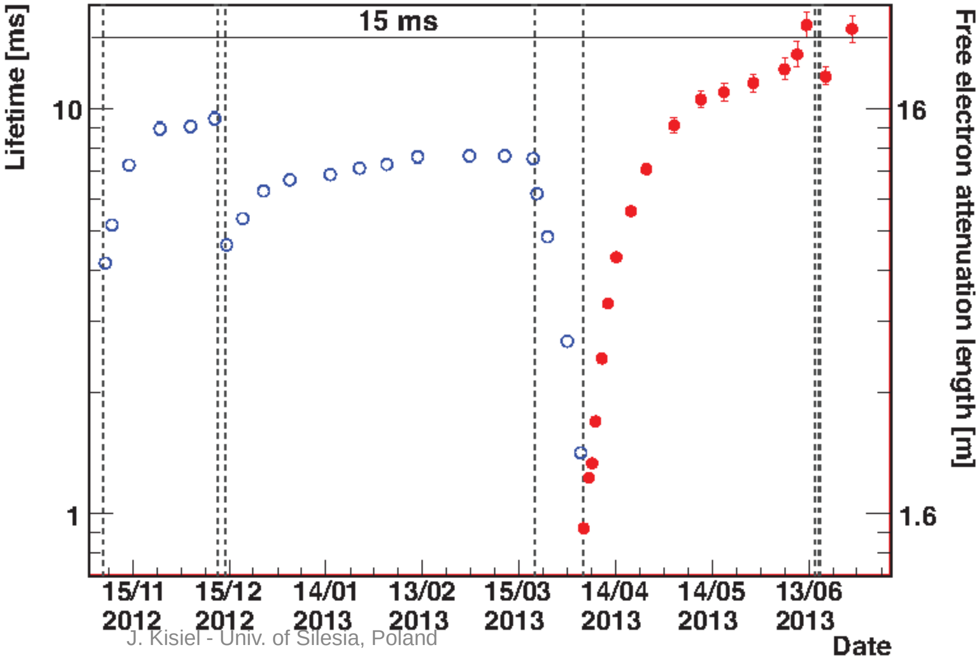
ICARUS T600 at LNGS

Four identical LAr-TPCs, successfully exposed to CNGS beam from Oct. 1st 2010 to Dec. 3rd 2012.

A total of **8.6×10^{19} protons on target** has been collected, with a remarkable **detector live time>93%**

In parallel cosmics have been studied with exposure of 0.73 kton year.





Key feature: LAr purity from electro-negative molecules (O2, H2O, C02).

τele >7 ms (~40 p.p.t. [O2] eq),

τele > 15 ms (~20 p.p.t.).

ICARUS LAr-TPC performance

Energy reconstruction from charge integration

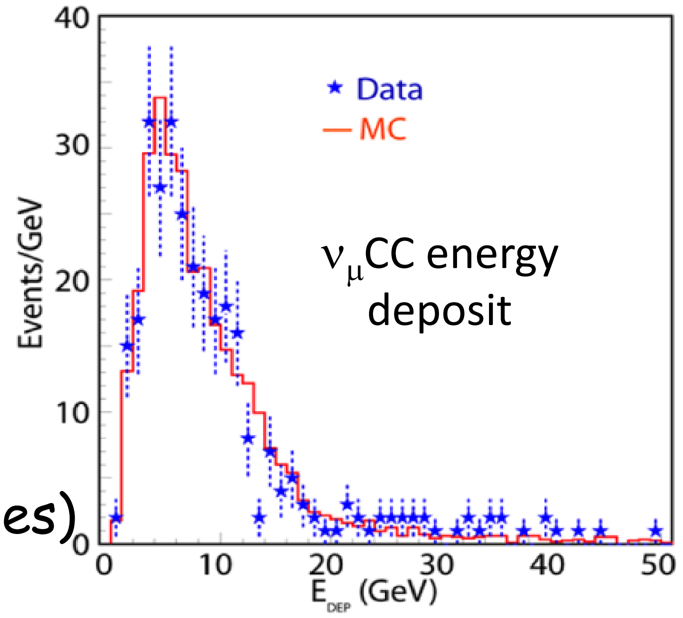
- Full sampling, homogeneous calorimeter with excellent accuracy for contained events

Tracking device

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

Measurement of local energy deposition dE/dx

- e/γ remarkable separation ($0.02\ X_0 = 14$cm samples)
- Particle identification by dE/dx vs range



ν_μCC energy deposit

Low energy electrons:

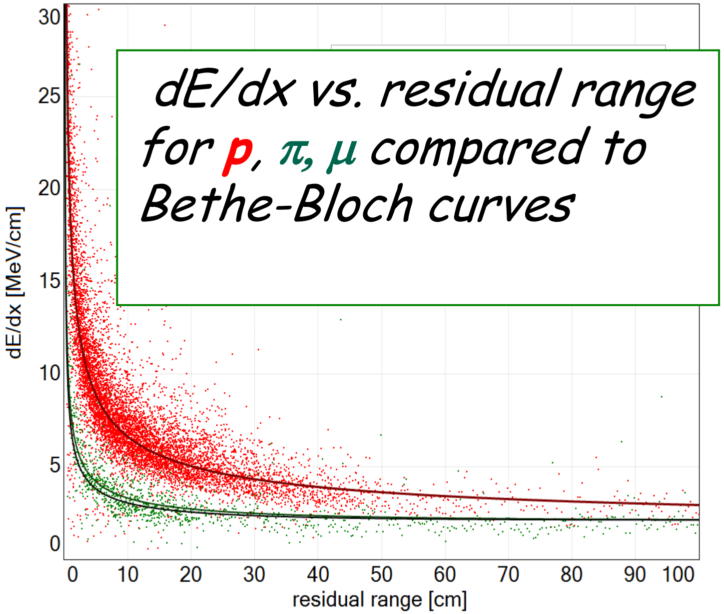
$\sigma(E)/E = 11\%/\sqrt{E(\mathrm{MeV})} + 2\%$

Electromagn. showers:

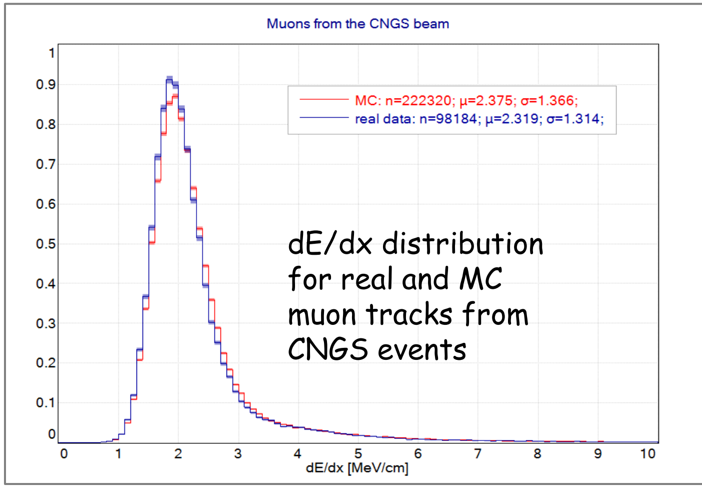
$\sigma(E)/E = 3\%/\sqrt{E(\mathrm{GeV})}$

Hadron showers:

$\sigma(E)/E \approx 30\%/\sqrt{E(\mathrm{GeV})}$

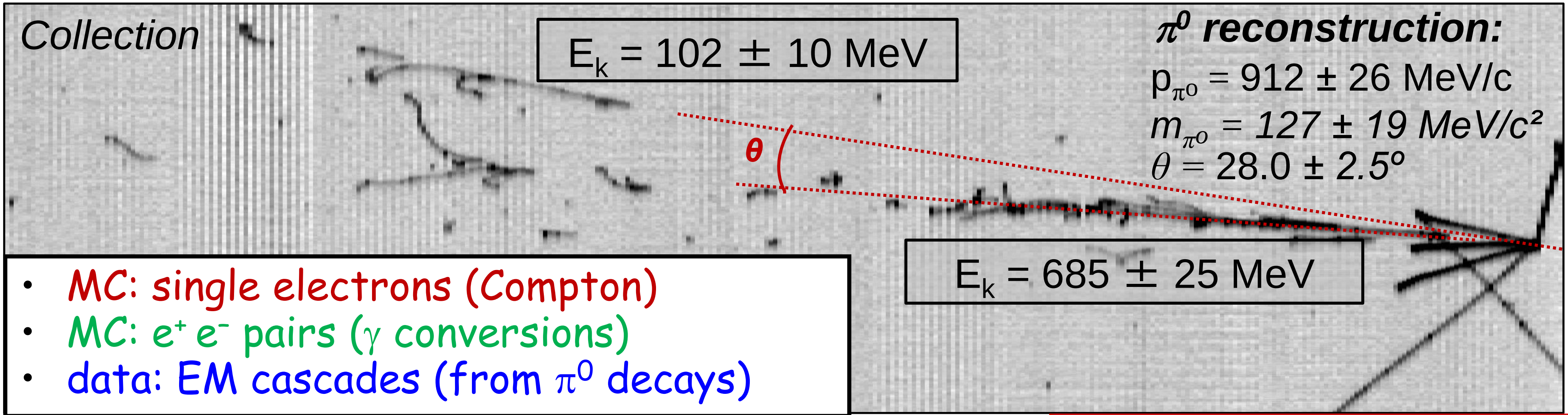


*dE/dx vs. residual range for **p**, π, μ compared to Bethe-Bloch curves*



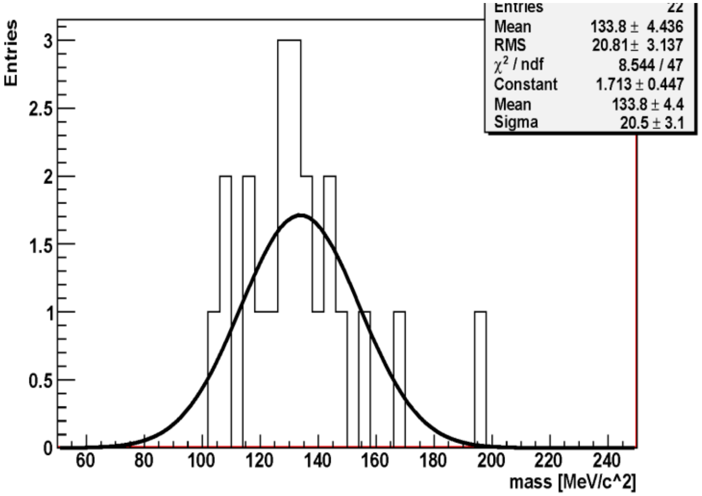
dE/dx distribution for real and MC muon tracks from CNGS events

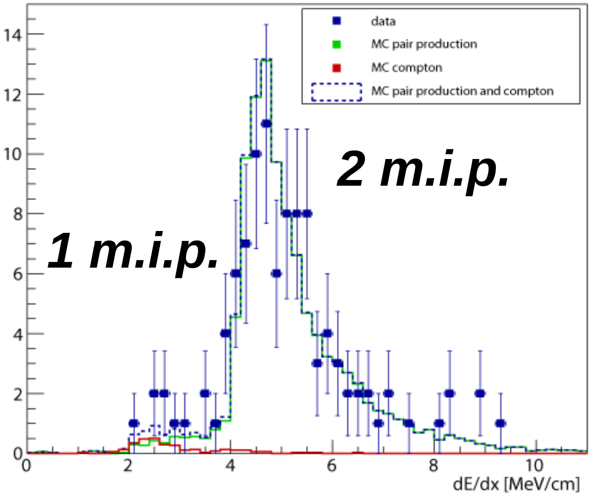
ICARUS: e/γ separation and π^0 reconstruction

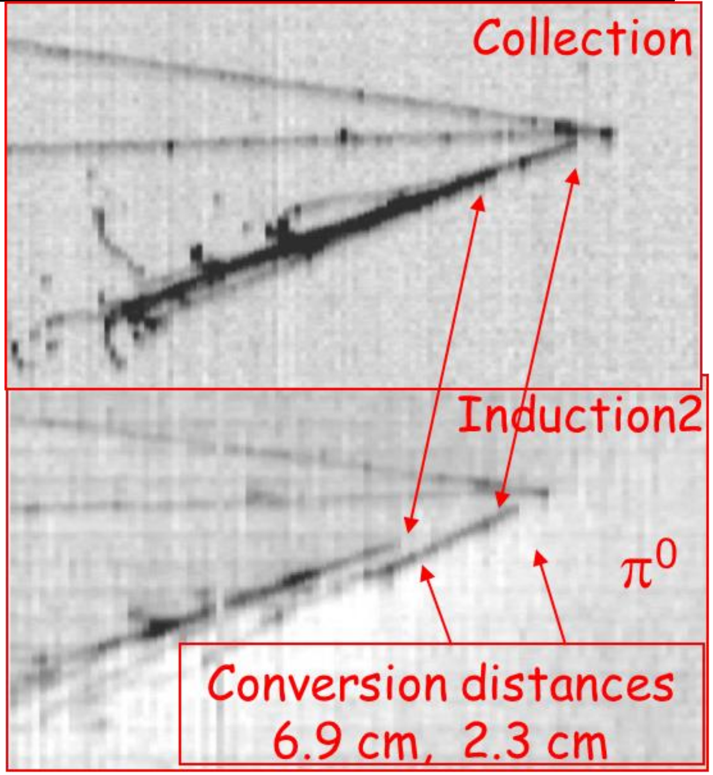


- MC: single electrons (Compton)
- MC: $e^+ e^-$ pairs (γ conversions)
- data: EM cascades (from π^0 decays)

Mγγ: 133.8±4.4(stat)±4(syst) MeV/c²



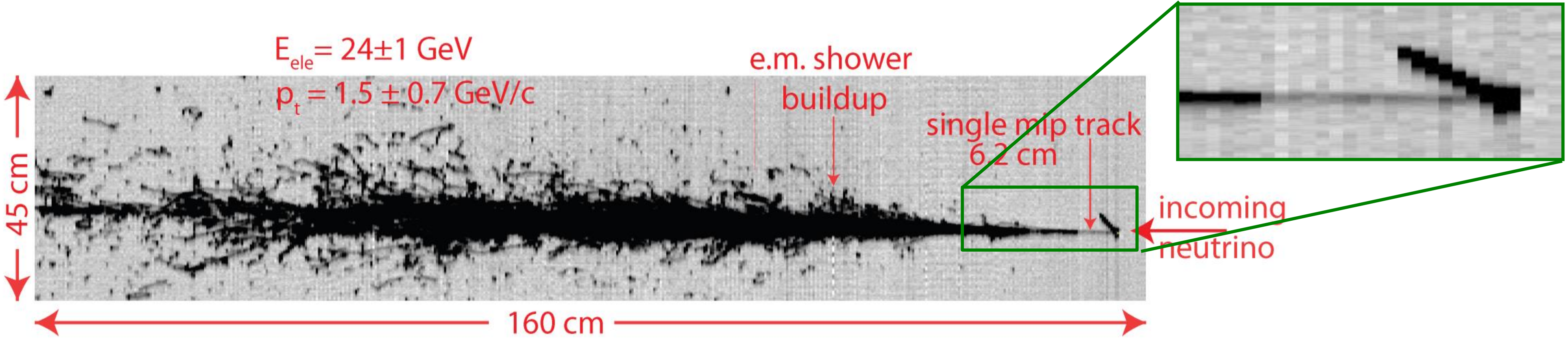




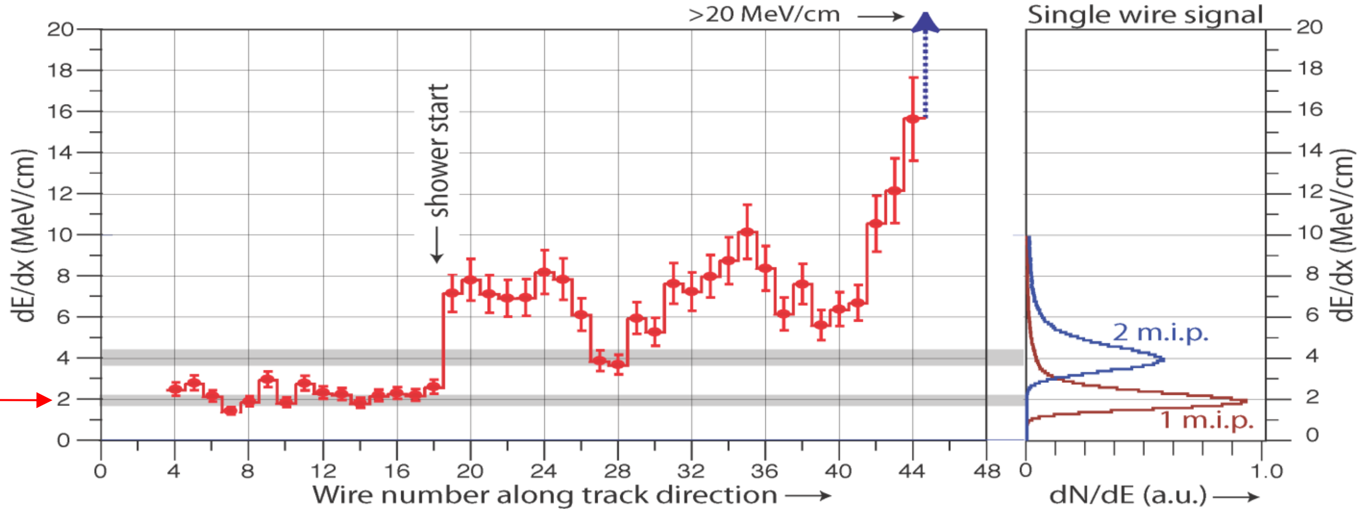
LAr TPC: very good e/γ separation: excellent rejection of NC background to ν_e events

ν_e CC identification in CNGS beam

- The unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.



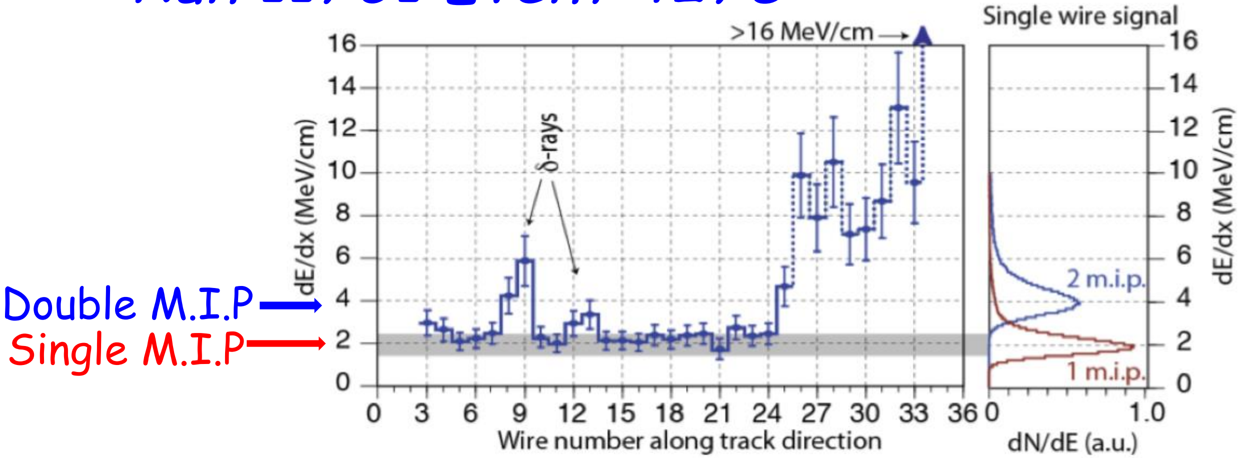
- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.

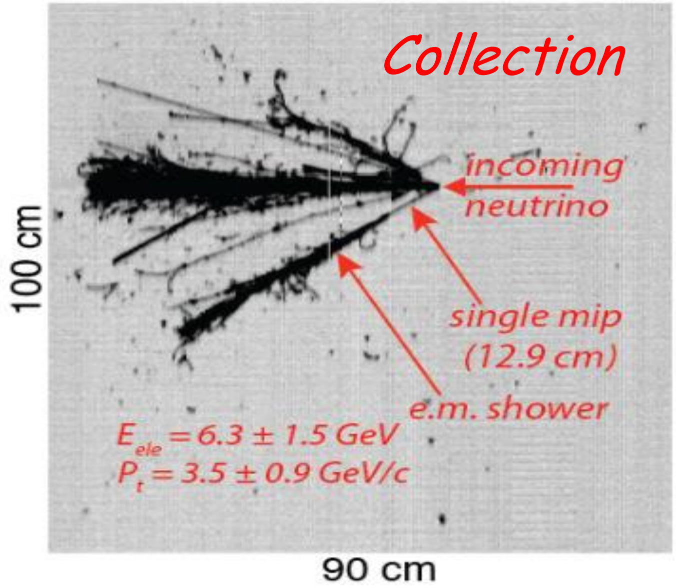


Single M.I.P

Another example of CNGS ν_e CC interaction

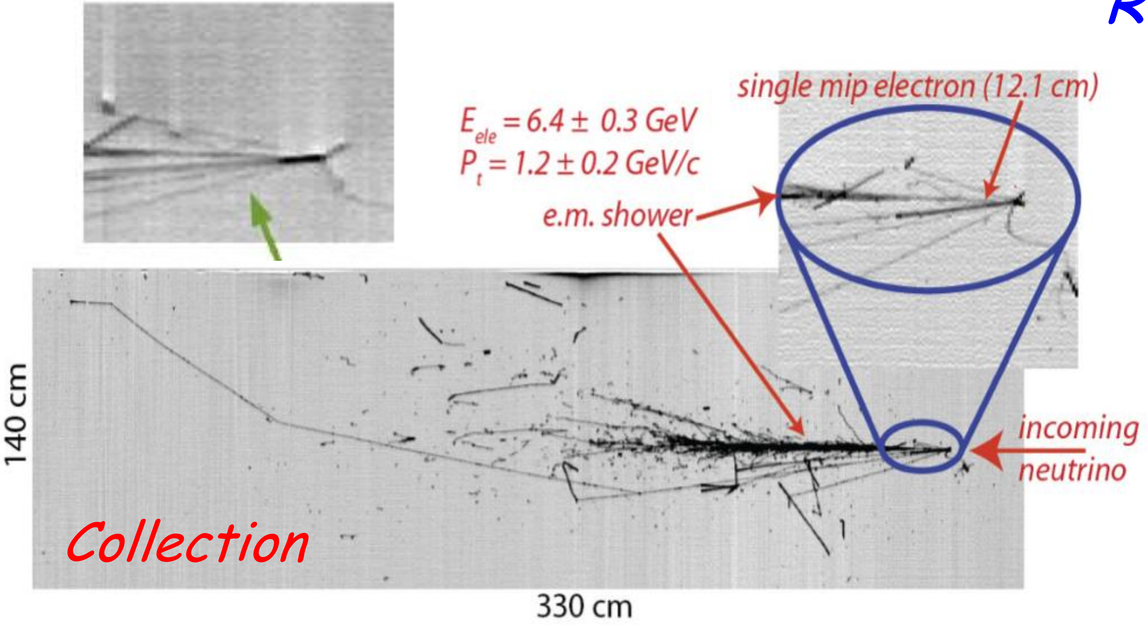
Run 11731 Event 4278:



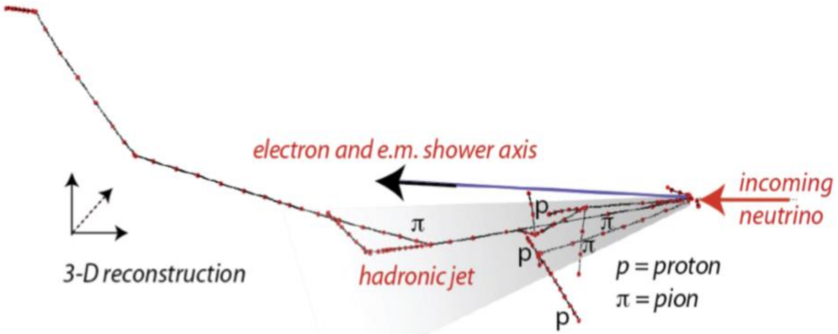


Zoomed Induction 2

Run 11319 Event 2862:



Scheme of 3D reconstruction



Observed neutrino anomalies

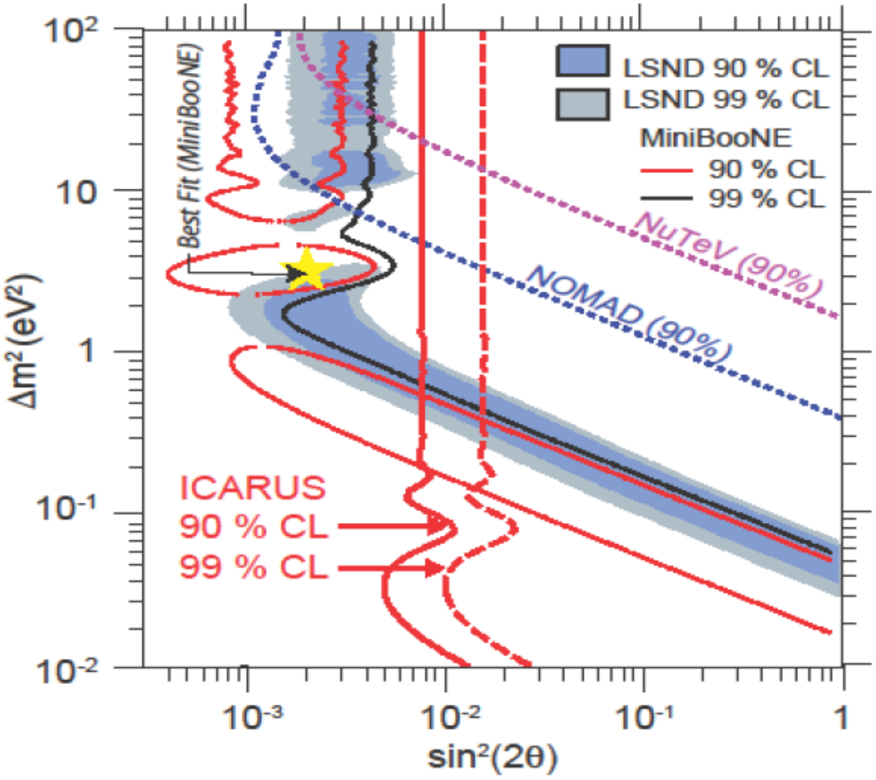
- Three independent, short baseline neutrino exps., reported results not fitted in well established mixing of three flavors with small mass differences ($\Delta m^2_{atm} \sim 2.5 \times 10^{-3}$ eV^2, $\Delta m^2_{sol} \sim 7.4 \times 10^{-5}$ eV^2), and therefore could hint at additional 4th, sterile neutrino driving oscillation with $\Delta m^2_{new} \sim 1$ eV^2 and $\sin^2(2\theta_{new}) \sim 0.005$.
  - Disappearance in anti-ν_e events detected from near-by nuclear reactors (R = 0.938 ± 0.023 ratio between observed and predicted event rates);
  - Disappearance in ν_e events from Mega-Curie k-capture calibration sources in solar neutrino experiments (R = 0.86 ± 0.05);
  - Excess of ν_e/anti-ν_e events in ν_μ/anti-ν_μ beams, with 3.4 σ (MiniBooNE) and 3.8 σ (LSND) evidence for oscillations.

- Contradictory, from data from Cosmic Microwave Background exps. and observation of Lyman-α forest the sum of 3 massless and 1 sterile neutrino appear to be < 0.26 eV at 95% CL.

Search for LSND-like anomaly by ICARUS at LNGS

- ICARUS searched for ν_e excess related to LSND-like anomaly on the CNGS ν beam (~1% intrinsic ν_e contamination, L/E_ν ~ 36 km/GeV).
- No excess was observed in 7.93×10^{19} pot sample : number of observed 7 ν_e compared to 8.5 ± 1.1 events expected in absence of LSND signal provided the limit on the oscillation probability $P(\nu_\mu \rightarrow \nu_e) \leq 3.86\ (7.76) \times 10^{-3}$ at 90 (99) % C.L.
- Sample of collected 2650 CNGS neutrino events allow to study also „disappearance oscillations".

- ICARUS and OPERA results indicates a very narrow region
  $\Delta m^2 \sim 0.5\ \mathrm{eV}^2$, $\sin^2 2\theta \sim 0.005$
  where all experimental results can be be accommodated at 90% CL.



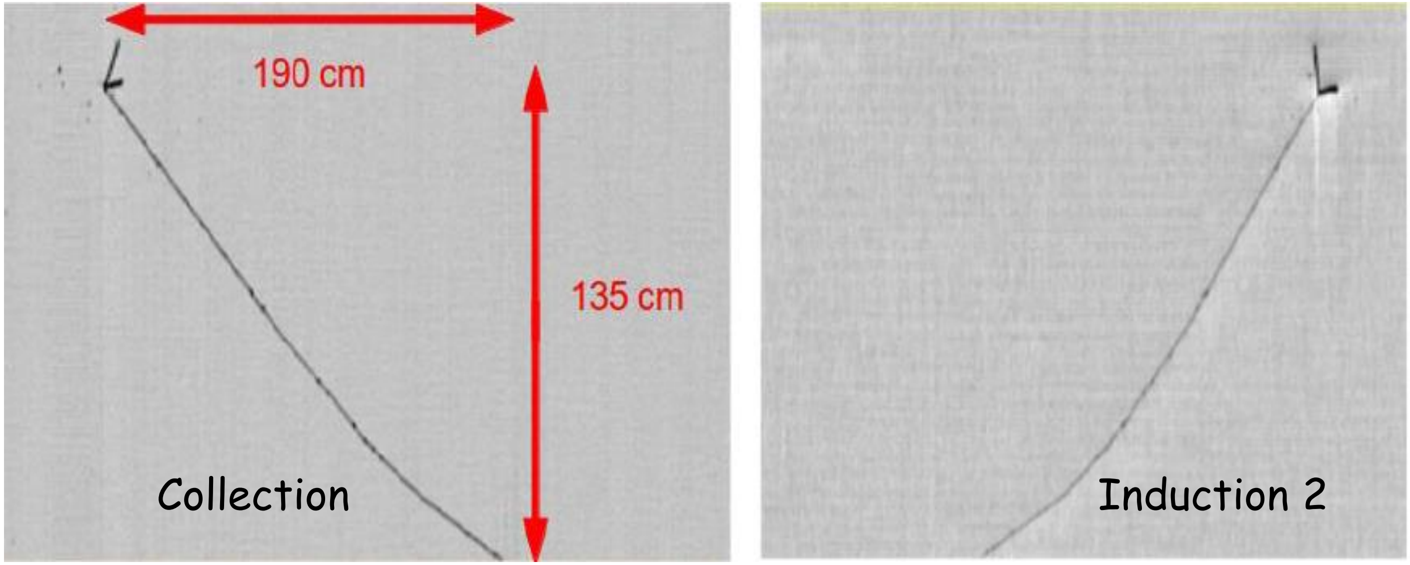
There is a need for a definitive experiment on sterile neutrinos to clarify all the reported neutrino anomalies .

Towards automatic neutrino search: atmospheric ν

- LNGS data are being filtered by an automatic algorithm looking for interaction vertex and multi-prong (at least 2 charged primary) event topology to select candidates for atmospheric neutrino interactions.

- By the development of selection filter algorithms a drastic to 0.5% reduction of events undergoing visual scanning has been achieved.

- 3 μ-like, 2 e-like within a total sample of 12 observed atm. ν candidates have been identified so far in 25% of collected statistics (10 ± 2 multi-prong events are expected).

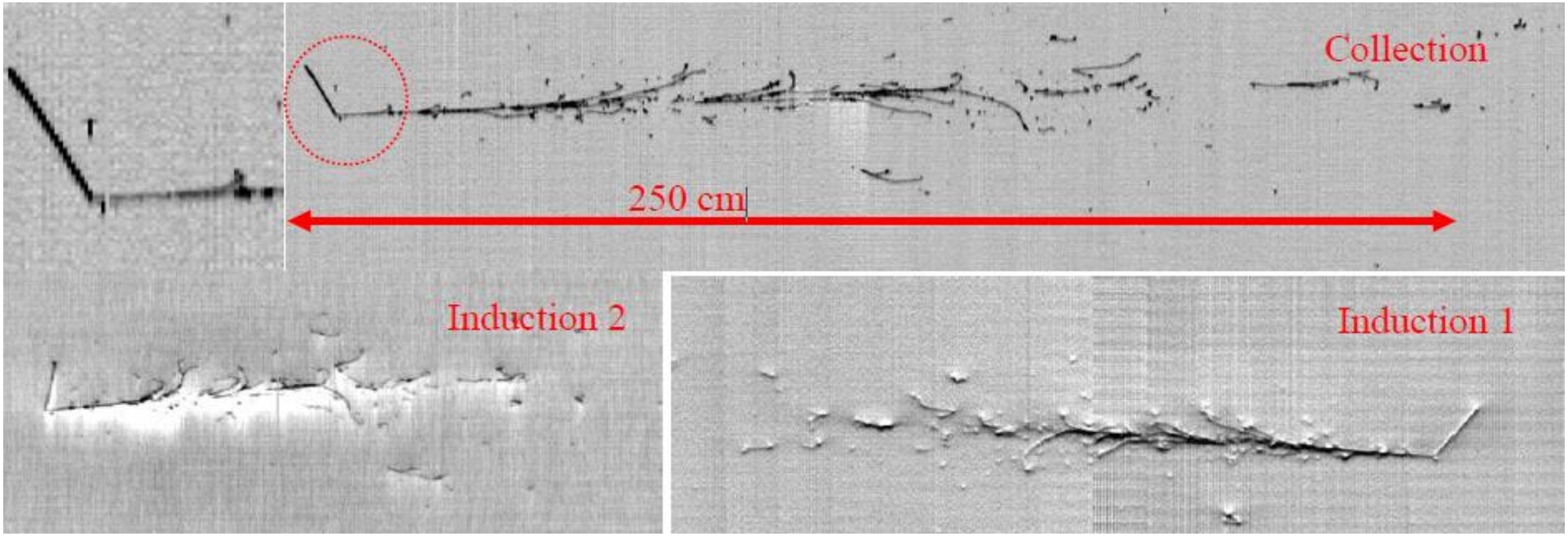


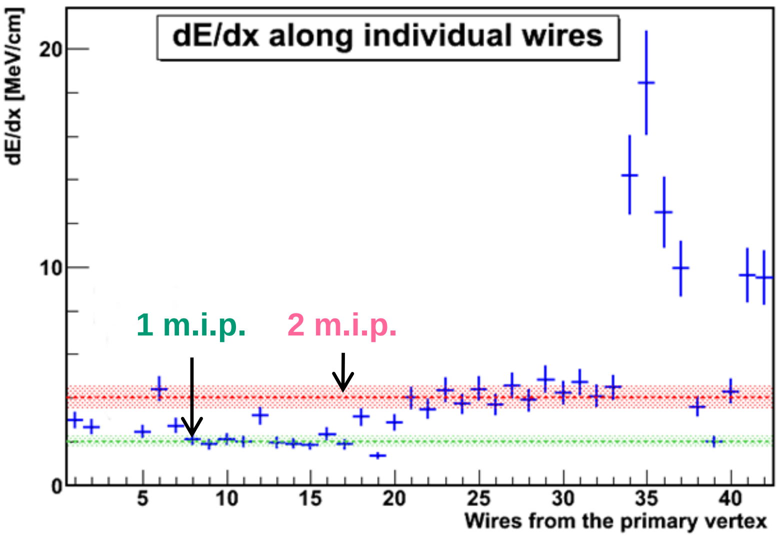
ν_μ CC atm. candidate:

E_{dep} ~ 630 MeV

- 2.3 m μ track and 2 charged tracks

The first observed „LAr TPC" atmospheric ν_e CC event



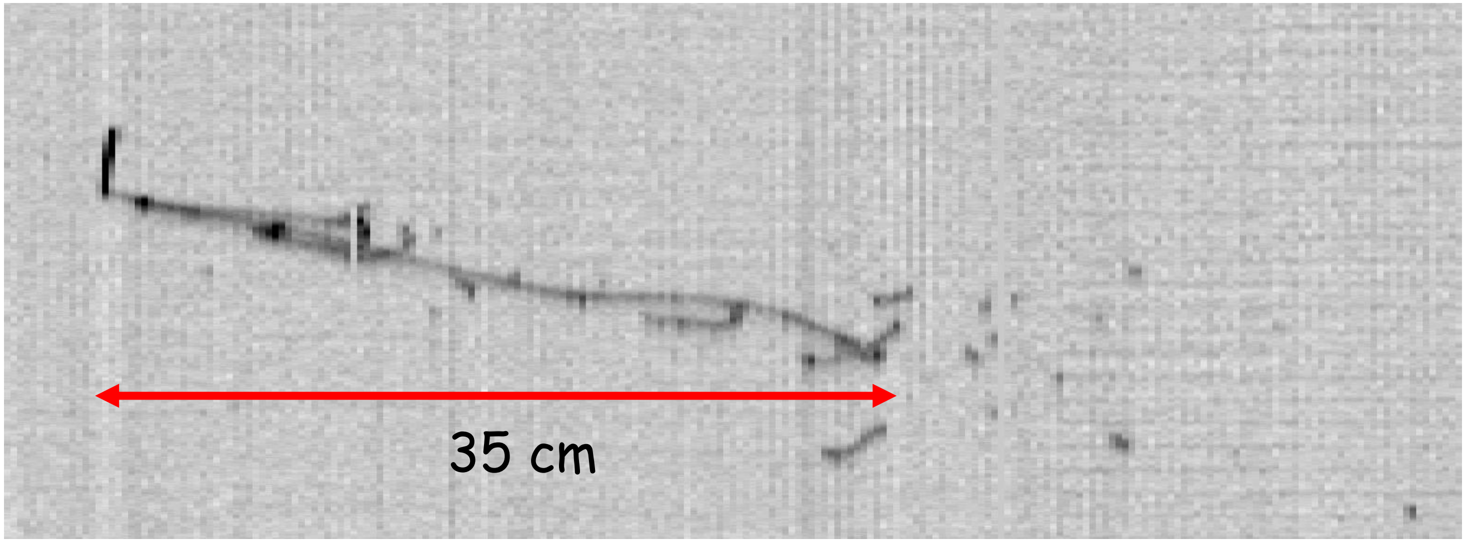


Deposited energy: ~ 2.1 GeV:

- E.m. shower (~ 2 GeV): clear single m.i.p from vertex;
- Identified short proton track (~ 0.1 GeV).

Automatic search for ν_e CC with E_{dep} of the order of several GeV is feasible.

The second atmospheric ν_e CC event: **very low energy**



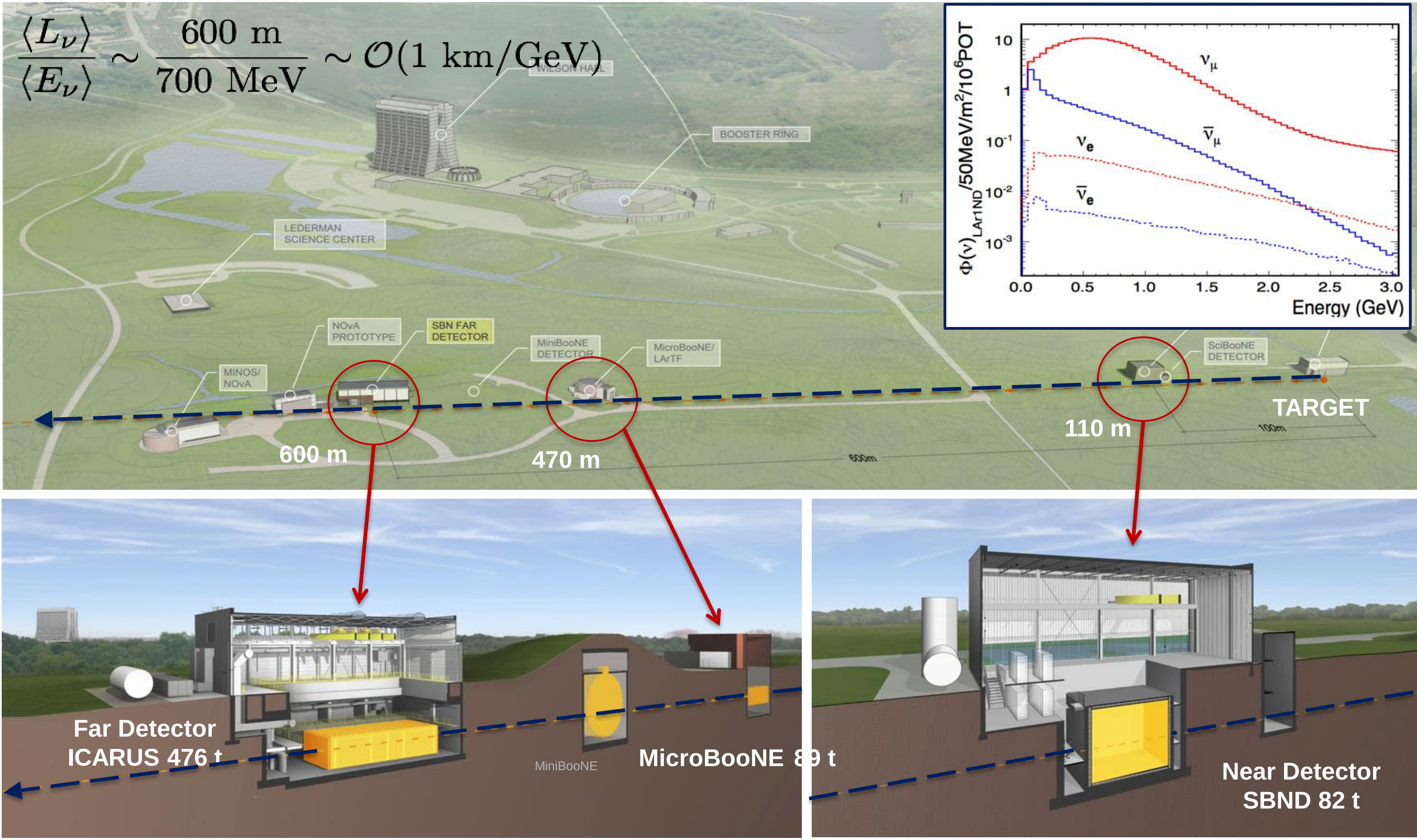
Downward-going, quasi-elastic event, deposited energy: ~ **240 MeV**

- dE/dx measured on the first wires (2.1 MeV/cm) corresponds to a m.i.p. particle
- One short proton track.

ICARUS LAr TPC: unambiguous identification and measurement capability of ν_e interactions down to sub GeV energy range.

The Three LArTPC SBN Program

$$\frac{\langle L_\nu\rangle}{\langle E_\nu\rangle} \sim \frac{600\ \text{m}}{700\ \text{MeV}} \sim \mathcal{O}(1\ \text{km/GeV})$$



The SBN Collaborations – Institutions (July 2016)

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Colorado State University, USA
Fermi National Lab, USA
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SLAC, USA
Texas University at Arlington, USA

MicroBooNE

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Brookhaven National Lab, USA
University of Cambridge, UK
University of Chicago, USA
University of Cincinnati, USA
Columbia University, USA
Fermi National Lab, USA
Illinois Institute of Technology, USA
Kansas State University, USA
Lancaster University, UK
Los Alamos National Lab, USA
University of Manchester, UK
MIT, USA
University of Michigan, USA
New Mexico State University, USA
Oregon State University, USA
Otterbein University, USA
University of Oxford, UK
University of Pittsburgh, USA
Pacific Northwest Nat. Laboratory, USA
Princeton University, USA
Saint Mary's University of Minnesota, USA
SLAC, USA
Syracuse University, USA
University of Texas at Arlington, USA
Tubitak Space Tech. Research Inst., Turkey
Virginia Tech, USA
Yale University, USA

SBND

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Brookhaven National Lab, USA
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Univ. of Campinas – UNICAMP, Brazil
CERN, Switzerland
University of Chicago, USA
Columbia University, USA
Federal Univ. of ABC – UFABC, Brazil
Federal Univ. of Alfenas – UFAL, Brazil
Fermi National Laboratory, USA
Illinois Institute of Technology, USA
Indiana University, USA
Kansas State University, USA
Lancaster University, UK
University of Liverpool, UK
Los Alamos National Lab, USA
University of Manchester, UK
University of Michigan, USA
MIT, USA
University of Oxford, UK
Pacific Northwest National Lab, USA
University of Pennsylvania, USA
University of Puerto Rico
University of Sheffield, UK
Syracuse University, USA
University of Texas, Arlington, USA
University College London, UK
Virginia Tech, USA
Yale University, USA

27 US + 26 non-US Institutions

SBN Sterile neutrino search at FNAL Booster ν Beamline

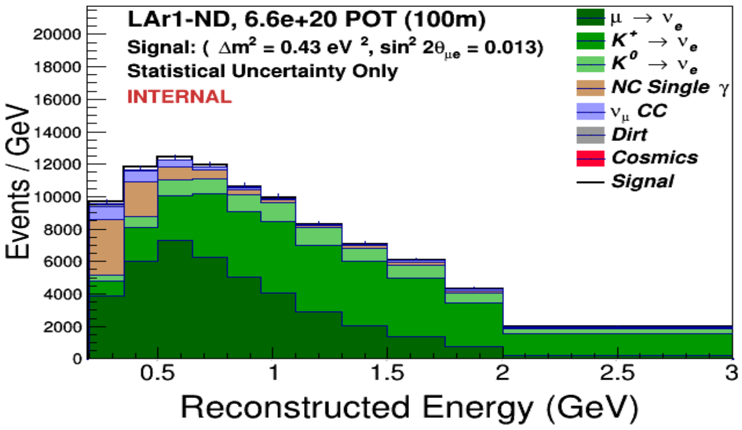
- The experiment will exploit 3 LAr-TPCs exposed to ~ 0.8 GeV FNAL Booster Neutrino Beam (BNB) at different distances from target: SBND (82 t active mass), MicroBooNE (89 t) and ICARUS (476 t) at 110, 470, and 600 m;
- The SBN program is expected to definitely clarify LSND/MiniBooNE, reactor and solar exp. calibration radioactive sources anomalies by precisely/independently measuring both ν_e appearance and ν_μ disappearance, mutually related through

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

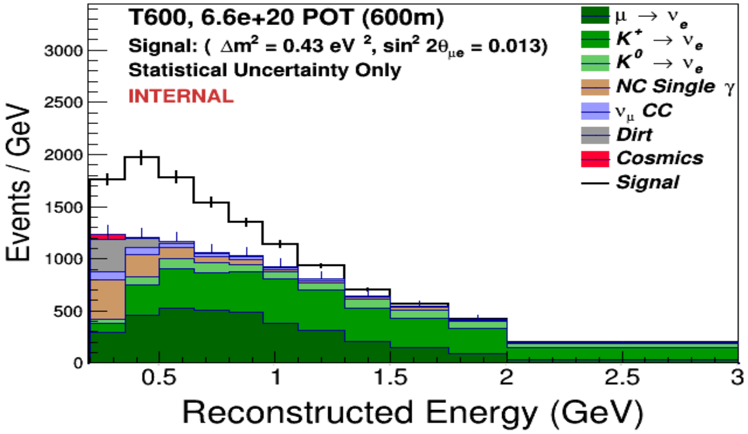
- In absence of "anomalies" the 3 detector signals should be a close copy of each other for all experimental signatures. A disappearance signal from <1% intrinsic beam ν_e (if confirmed by reactors) may reduce the superimposed LSND ν_e signal: the two effects can be disentangled by changing horn/decay tunnel length to modify the ν spectrum.
- ICARUS will also collect ~2GeV neutrinos from NUMI off-axis beam to measure cross sections in LAr, and study all CC/NC channels to improve neutrino identification algorithms (asset for DUNE-LBNF project).

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

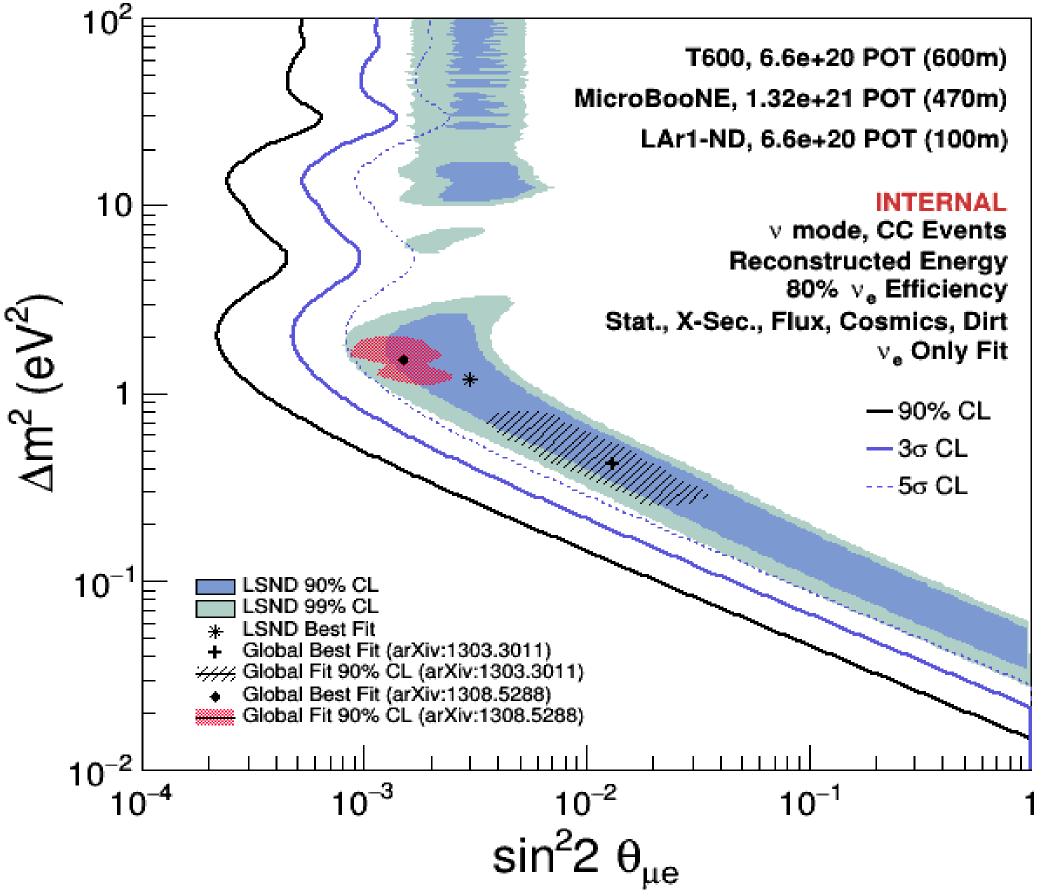
SBND @ 100 m



ICARUS-T600 @ 600 m

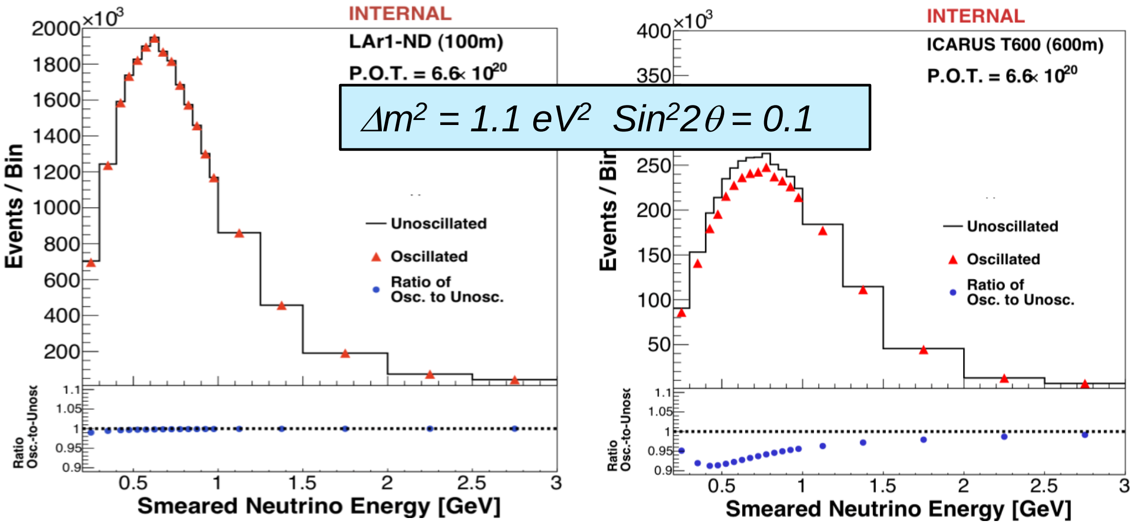


Example for
$\sin^2(2\theta)=0.013$
$\Delta m^2=0.43$ eV^2

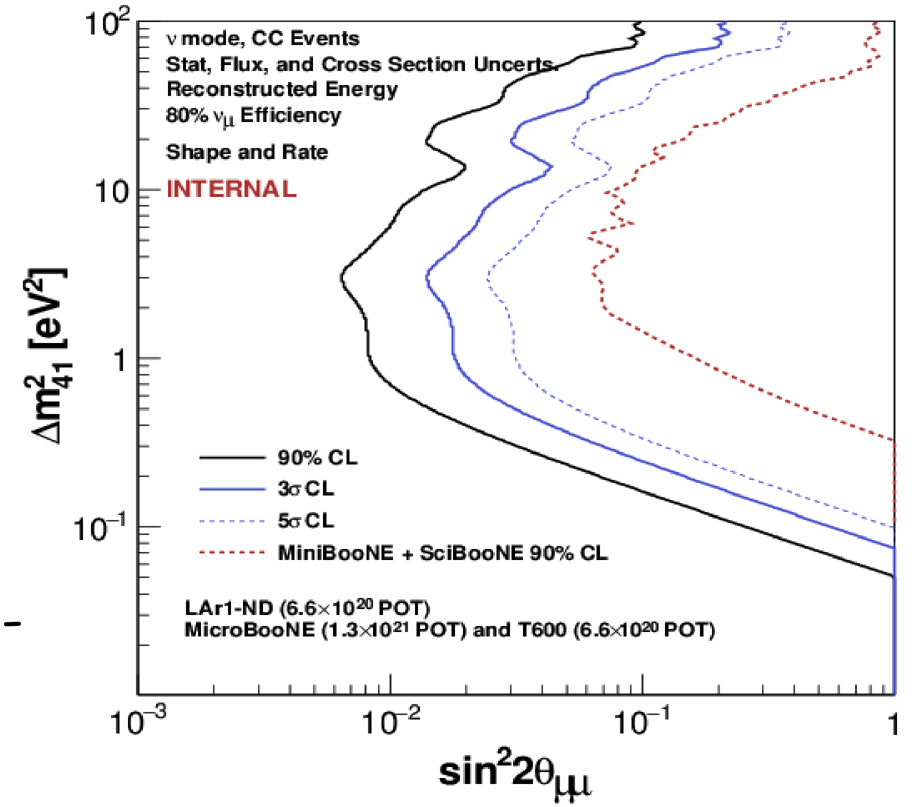


The LSND 99%CL region is covered at ~5σ level in 3 years of data taking (6.6 × 10^{20} pot) with positive focusing of BNB

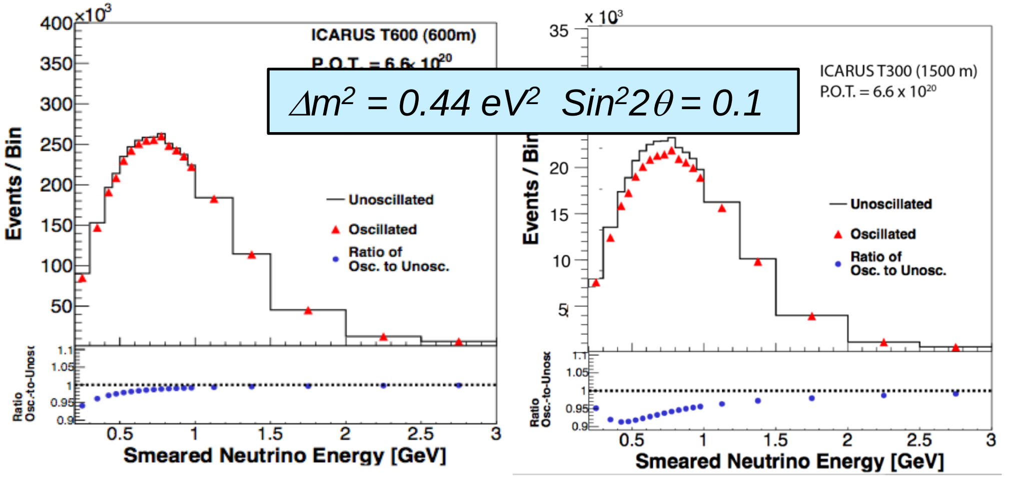
SBN ν_μ disappearance sensitivity



$\Delta m^2 = 1.1\ eV^2\ \ Sin^2 2\theta = 0.1$



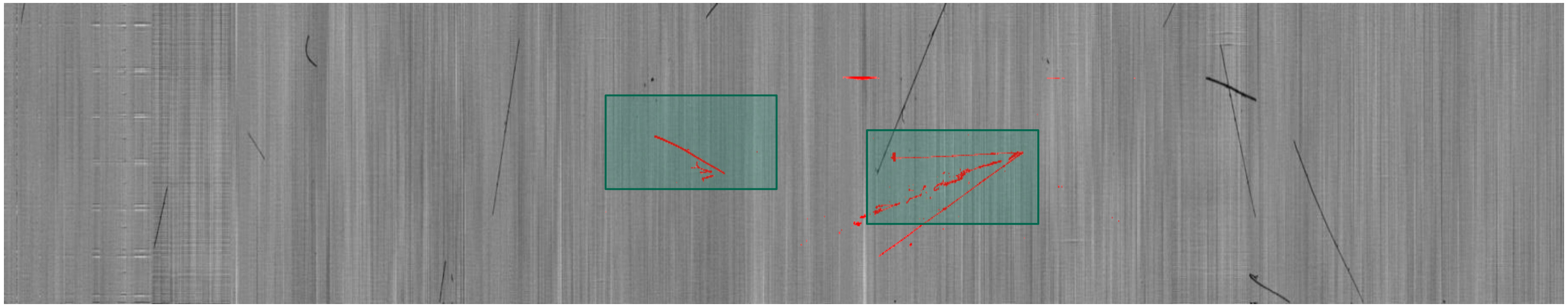
- High event rate/correlation beetwen 3 LAr-TPCs allows extending sensitivity by one order of magnitude beyond present limits
- However, ν_μ disappearance will be limited to 0.2-0.4 GeV lowest ν energy bins for $\Delta m^2 < 0.5\ eV^2$
- To amplify the effect a ICARUS T300 module may be moved, at a later stage, to 1.5 km distance from target.



$\Delta m^2 = 0.44\ eV^2\ \ Sin^2 2\theta = 0.1$

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

- At shallow depth ~12 uncorrelated cosmic rays, depositing > 100 MeV, will occur in T600 fiducial volume, during 1 ms drift window readout: reconstructing track positions along the drift requires to associate to each element of TPC image the proper timing w.r.t. trigger.
- 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.



Cosmic μs
+ low energy CNGS ν event

- A large 4π Cosmic Rays Tagger of plastic scintillators surronding the LAr volume, combined with timing information from internal scintillation light detectors, will unambiguously identify all cosmics entering the detector.

Development of automatic tools to select, identify and reconstruct ν events among the millions events triggered by cosmics (to be compared with ~ 3000 ν events collected at CNGS run) is mandatory.

The ICARUS/WA104 Collaboration

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Brookhaven National Laboratory (BNL), USA
CERN, Geneva, Switzerland
Colorado State University, USA
Fermi National Laboratory (FNAL), USA
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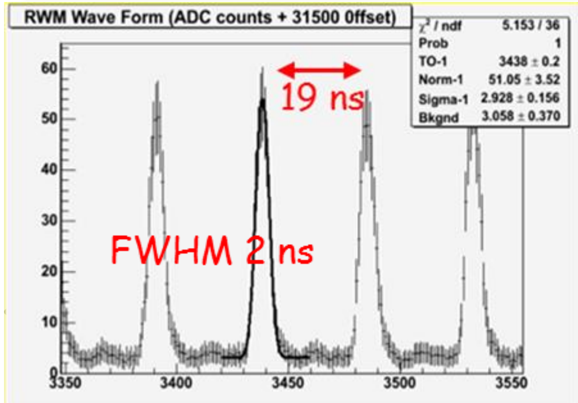
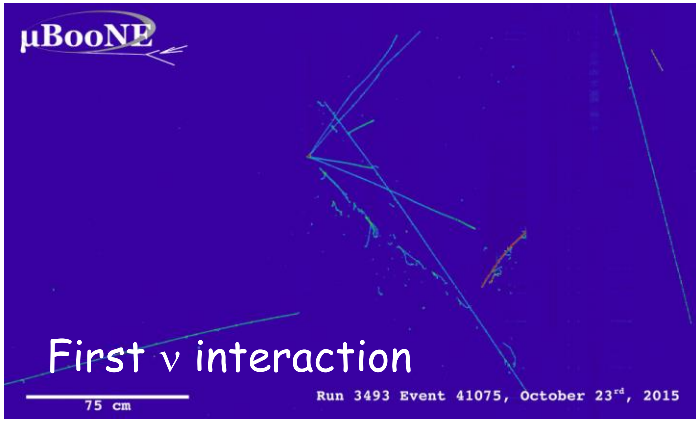
T600 overhauling at CERN (WA104)

- T600 detector has been moved to CERN for overhauling in the framework of CERN Neutrino Platform for LAr-TPC development for short/long baseline neutrino experiments (WA104 project).
- The activities are progressing, introducing technology developments while maintaining the already achieved performance:
  - New cold vessels, with a purely passive insulation;
  - Improvement of the cathode planarity;
  - Renovated cryogenics/LAr purification equipment;
  - Upgrade of the light collection system: 360 8" PMTs behind the wire planes (~5% photo-cathode coverage) to localize precisely the collected events in ~ 1.5 ms window; a fast response - high time resolution, ~1 ns precision, is required for the rejection of cosmics by exploiting 2n/19ns bunched beam;
  - New faster, higher performance read-out electronics



SBN Program Timeline

- **MicroBooNE:**
  - Currently running - addressing the MiniBooNE anomaly. Will continue as intermediate detector in SBN.



First ν interaction

- **ICARUS:**
  - Overhauling of T600 is almost completed and ready for transport by end 2016;
  - Civil construction of far sites and buildings are progressing at FNAL;
  - Installation and commissioning at FNAL in 2017, than start ν data taking.

August 2016

- **SBND:**
  - Begin of TPC assembly at FNAL in 2017, install into cryostat in 2018;
  - Civil construction of near sites and buildings is also progressing;
  - Begin commissioning in 2018.

Conclusions

- ICARUS is the largest, so far, LAr TPC. During 3 years of continuous and safe underground operation at LNGS, ICARUS collected high quality data resulting in new constrains on sterile neutrino searches. It also demonstrated capabilities of this detection technique.
- However, 50 years after their introduction by B. Pontecorvo, sterile neutrinos are still an open question in particle physics.
- After 20 years the LSND anomaly, suggesting sterile neutrino existence at ~eV scale is still surviving direct experimental tests.
- The SBN program at FNAL with three LAr-TPC detectors (SBND, MicroBooNE and ICARUS-T600) exposed to booster neutrino beam should sort out definitively the „sterile neutrino puzzle".
- Overhauling of the ICARUS T600 detector, towards SBN program, within the CERN/INFN ICARUS/WA104 project is progressing at CERN.

Thank you!

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