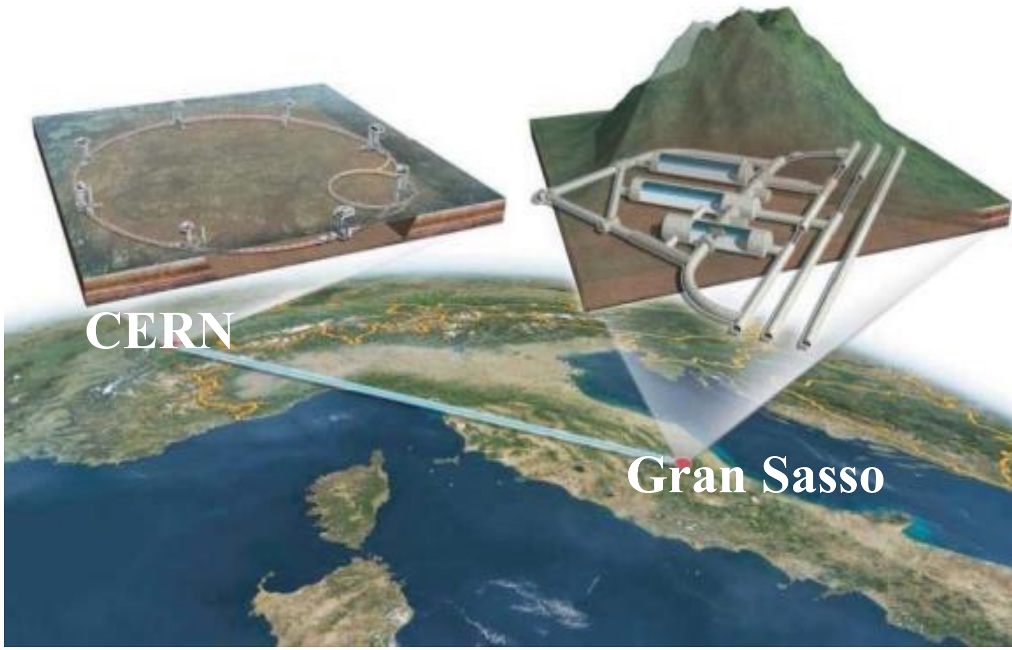
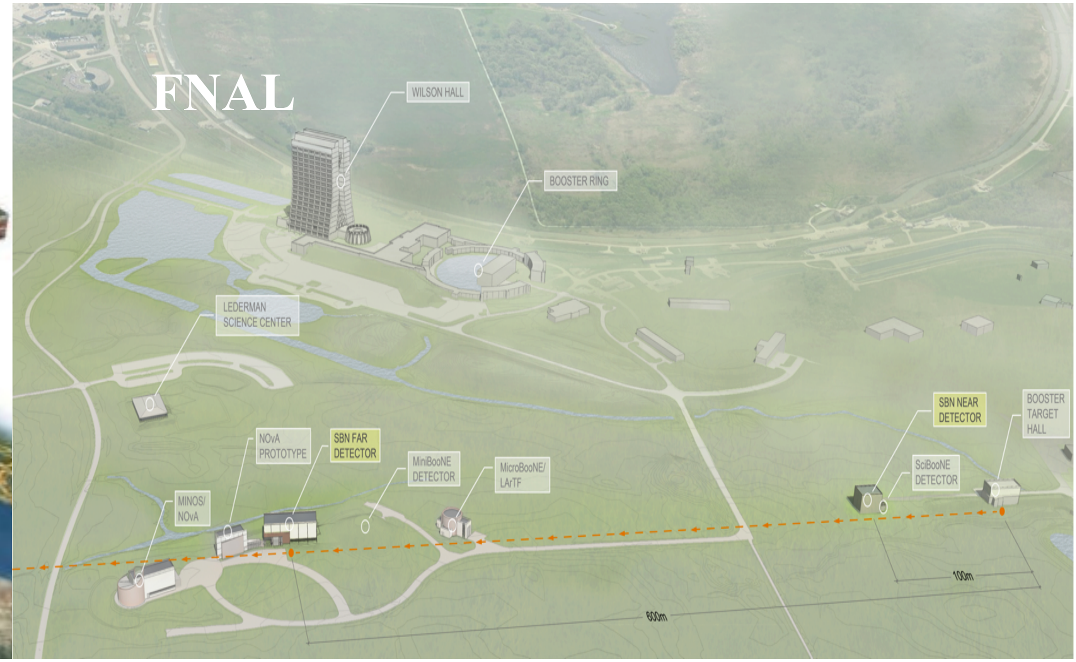
Past, present and future of ICARUS T600





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ICPPA 2016, Moscow

The ICARUS Collaboration

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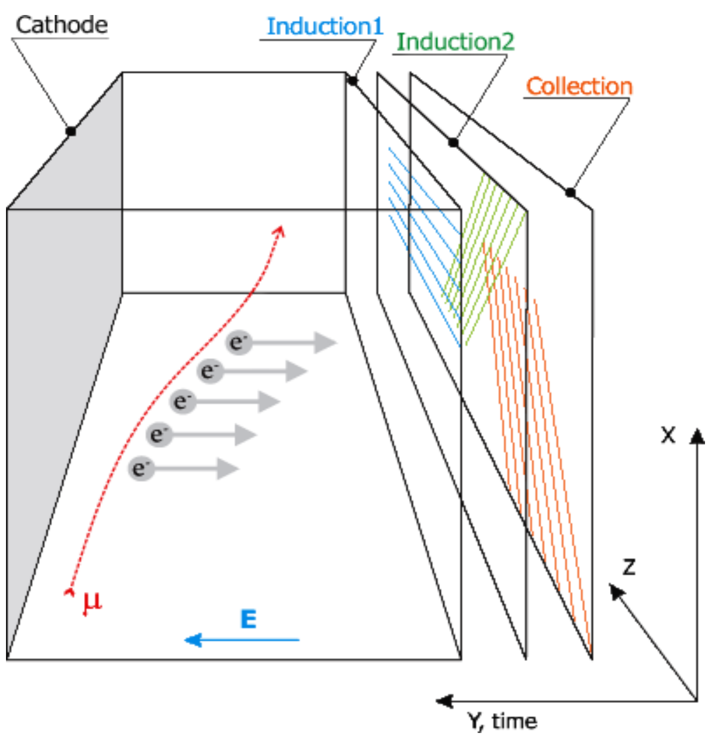
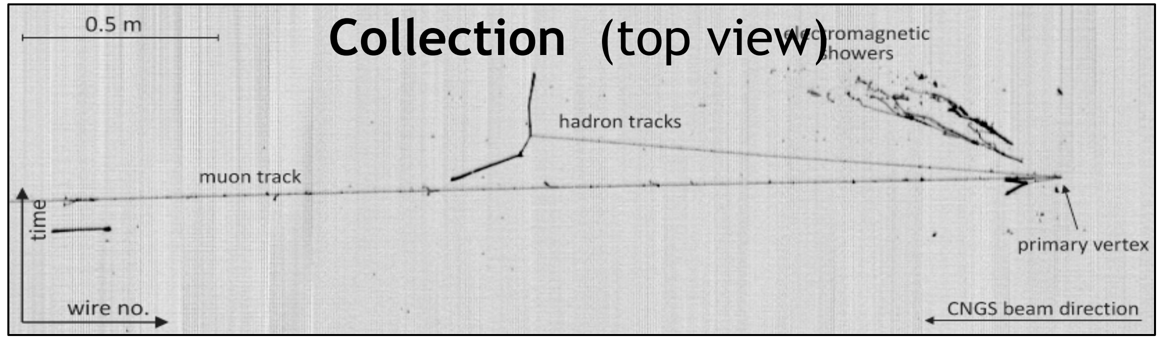
OUTLINE

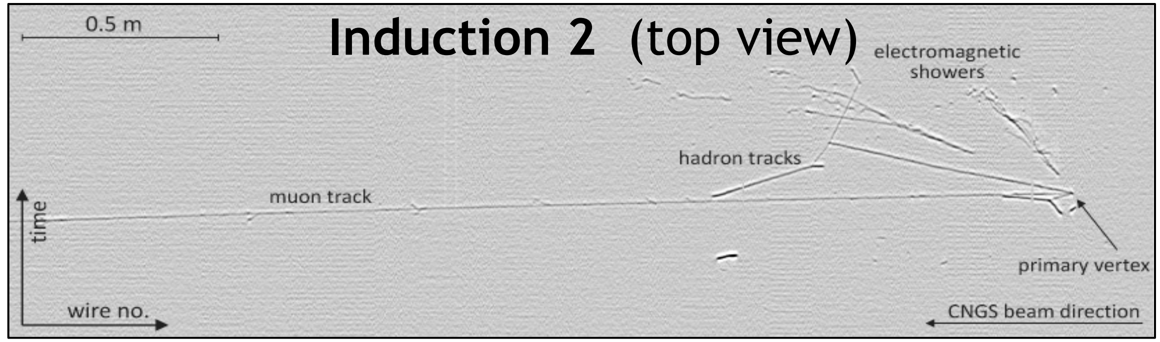
- Liquid Argon TPC detection technique.
- ICARUS T600 detector performance and results.
    - CNGS events analysis
    - atmospheric neutrino candidates selection
    - sterile neutrino anomaly investigation
- Detector perspective: SNB programme at FNAL.
- Present: detector overhauling at CERN (WA104).
- Conclusions

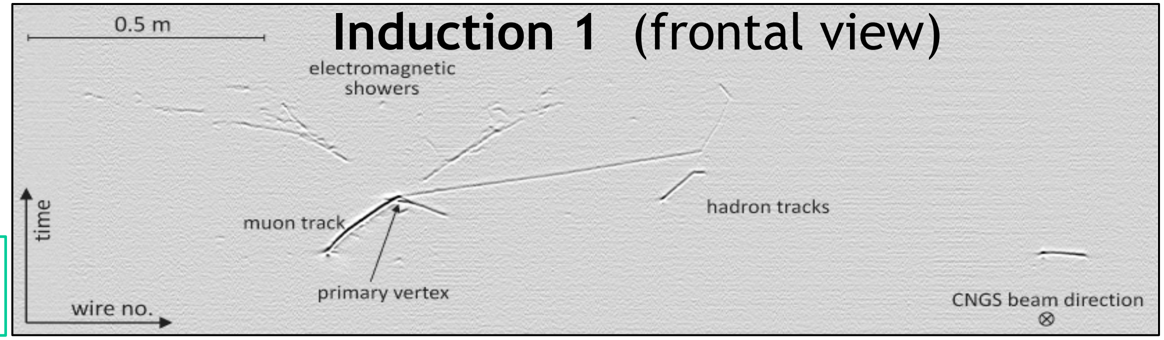
LAr-TPC detection technique

- 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









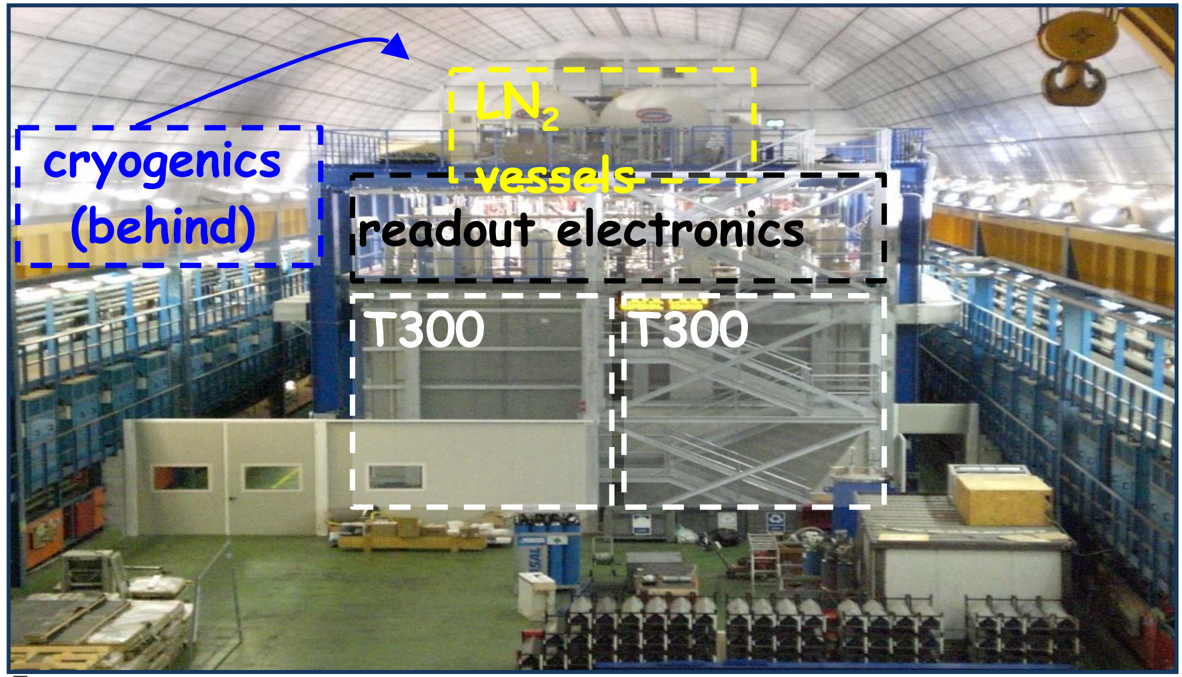
CNGS ν_μ charge current interaction, one of TPC's shown

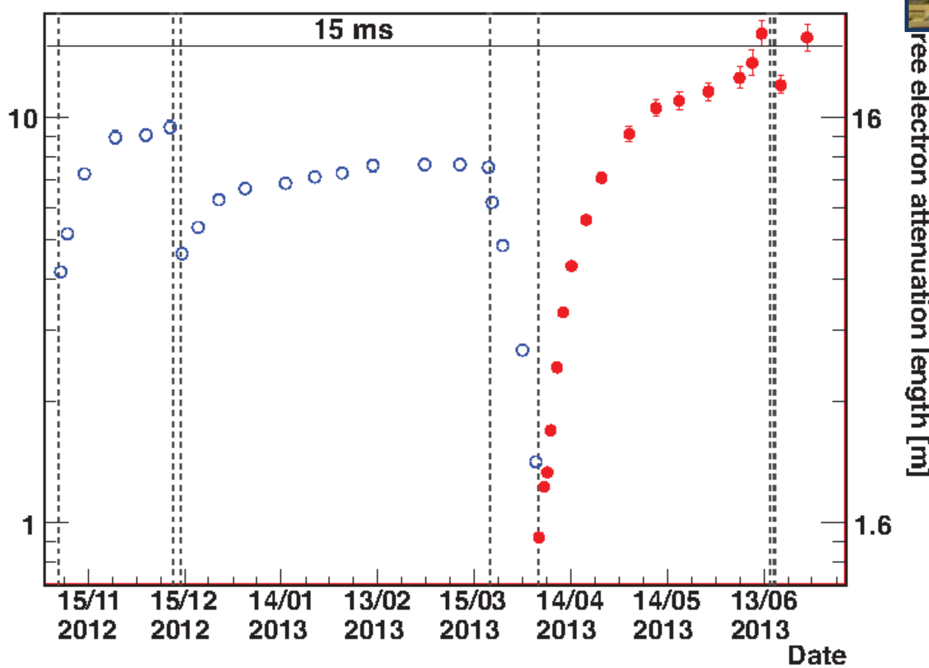
ICARUS T600 at LNGS

Four identical LAr-TPCs, successfully exposed to CNGS beam from Oct. 1st 2010 to Dec. 3rd 2012. In 2013 operation without CNGS beam.

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**.



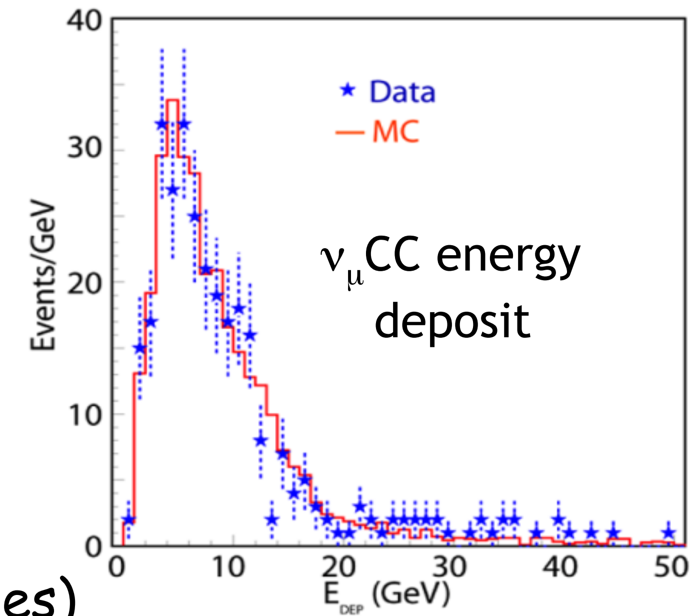


Key feature: LAr purity from electro-negative molecules (O_2, H_2O, CO_2) to prolongate elektron lifetime.

τ_e >7 ms (~40 p.p.t. [O2] eq),

τ_e > 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 = 14cm samples)
- Particle identification by dE/dx vs range

Energy resolution:

Low energy electrons:

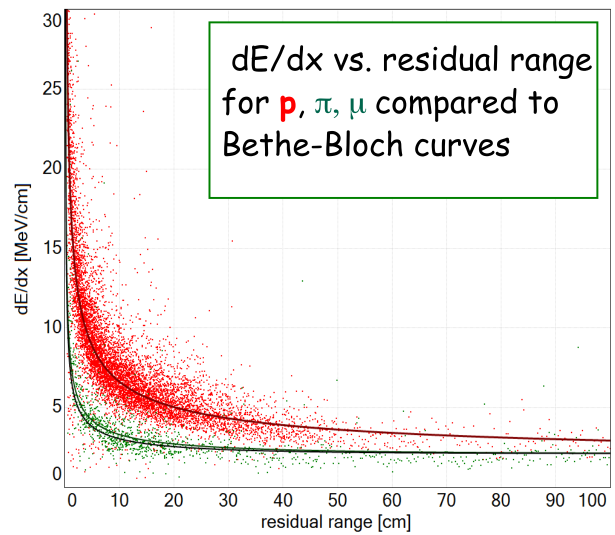
$\sigma(E)/E = 11\%/\sqrt{E(MeV)}+2\%$

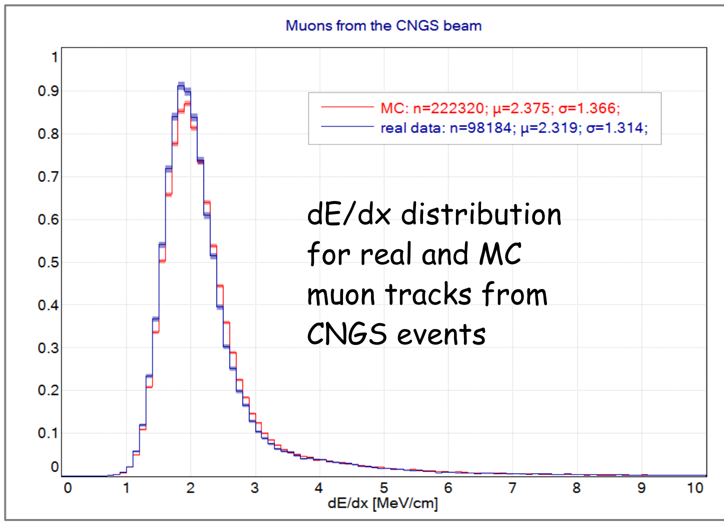
E-M showers:

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

Hadronic showers:

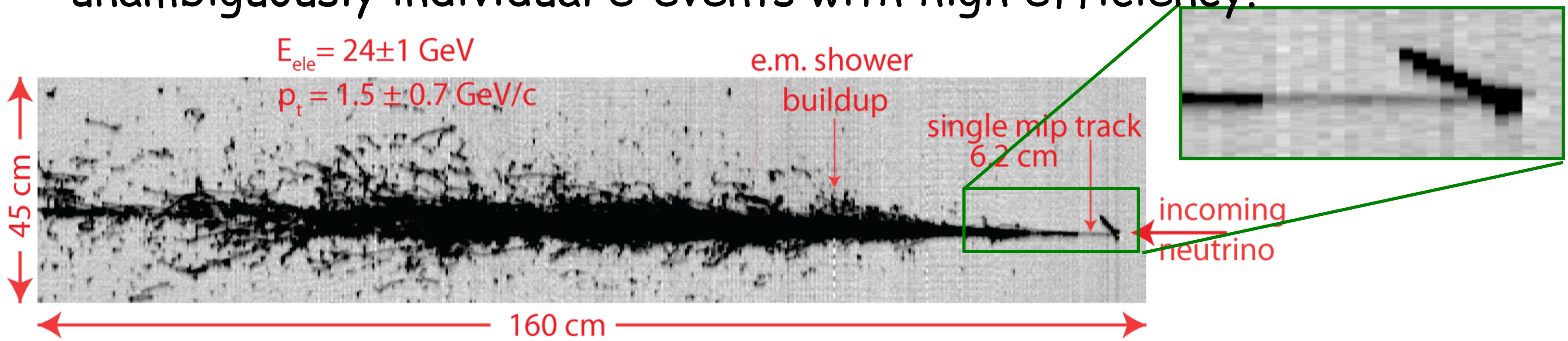
$\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$



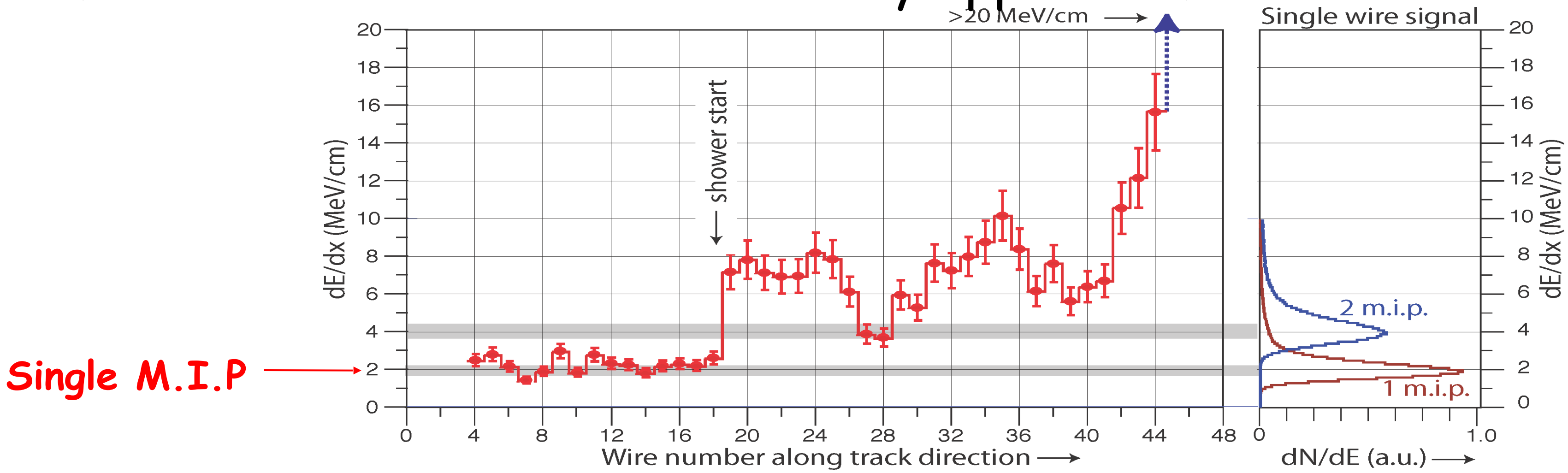


ν_e CC identification in CNGS beam

- 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.

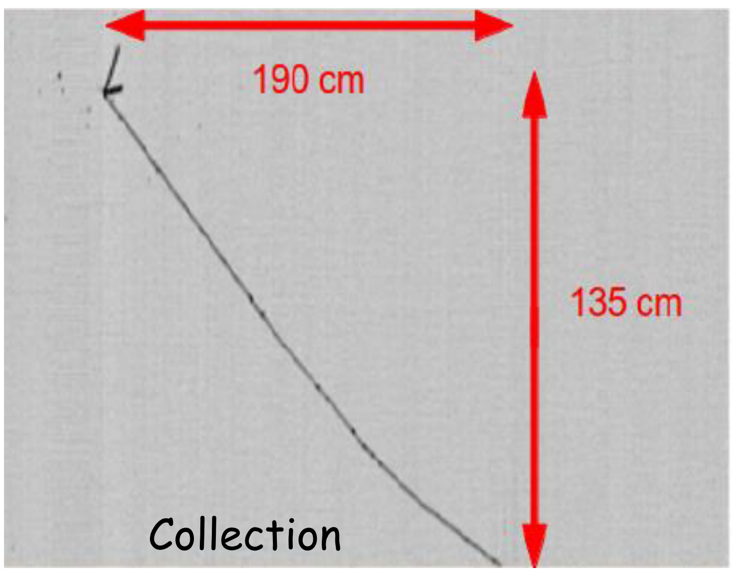


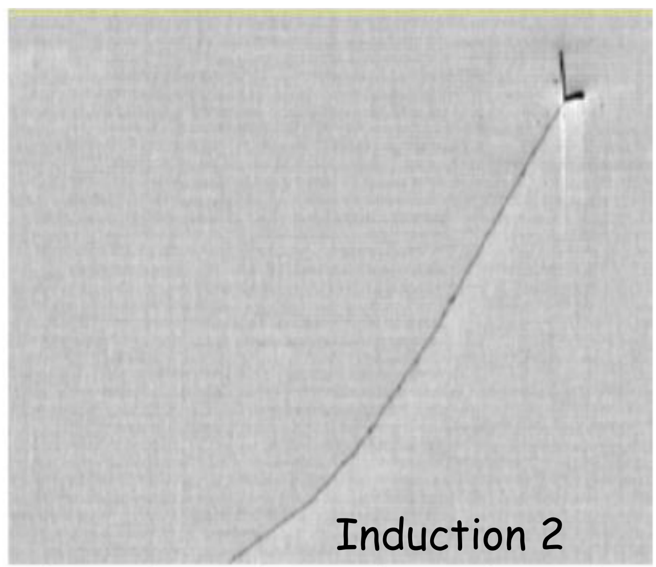
Atmospheric neutrinos

- Data collected in LNGS are being filtered by an automatic algorithm looking for interaction vertex and multi-prong event topology to select candidates for atmospheric neutrino interactions. The second filter looks particularly for E-M cascades in a search for electron like events.

- Candidate events undergo additional visual scanning (~5% of total data sample)

- 6 μ-like, and 4 e-like events within a sample of 24 observed atm. ν candidates have been identified so far in 49% of collected statistics (17±2 multi-prong νCC events are expected)



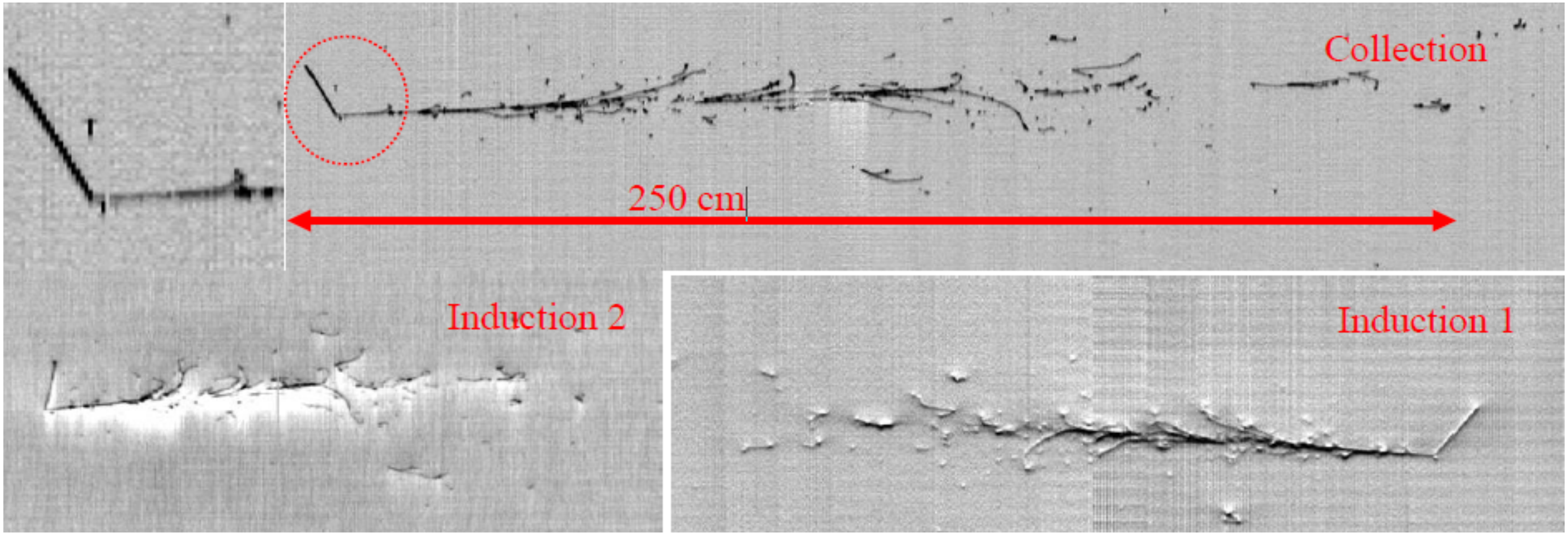


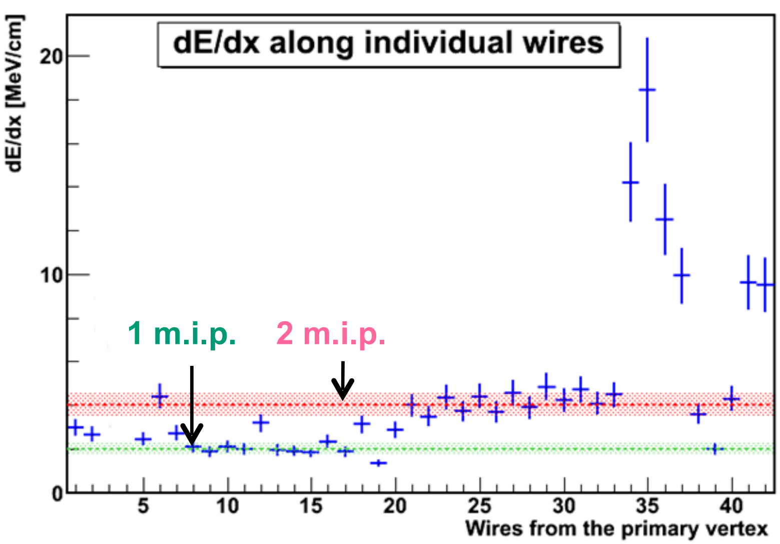
ν_μ CC atm. candidate:

E_{dep} ~ 630 MeV

- 2.3 m muon track and 2 charged particle tracks leaving the neutrino interaction vertex

The first observed „LAr TPC" **atmospheric** ν_e CC event



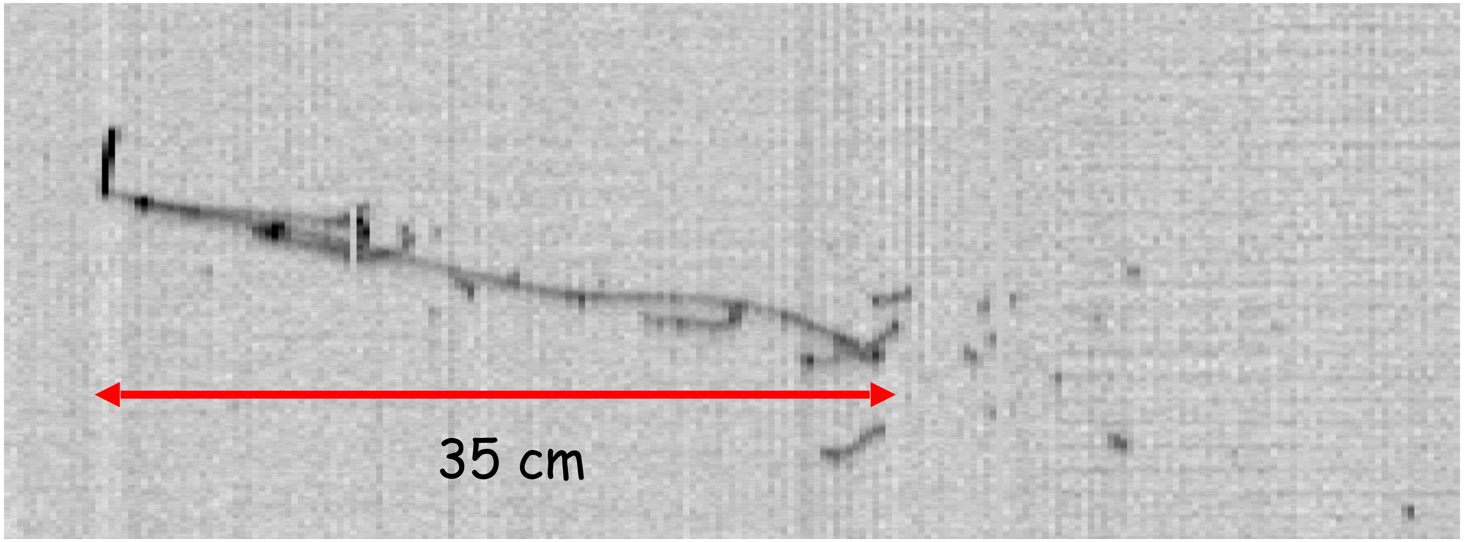


Deposited energy: ~ 2.1 GeV:

- 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 atmospheric ν_e CC candidate: **lower 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.

Example of ICARUS analysis: LSND-like anomaly

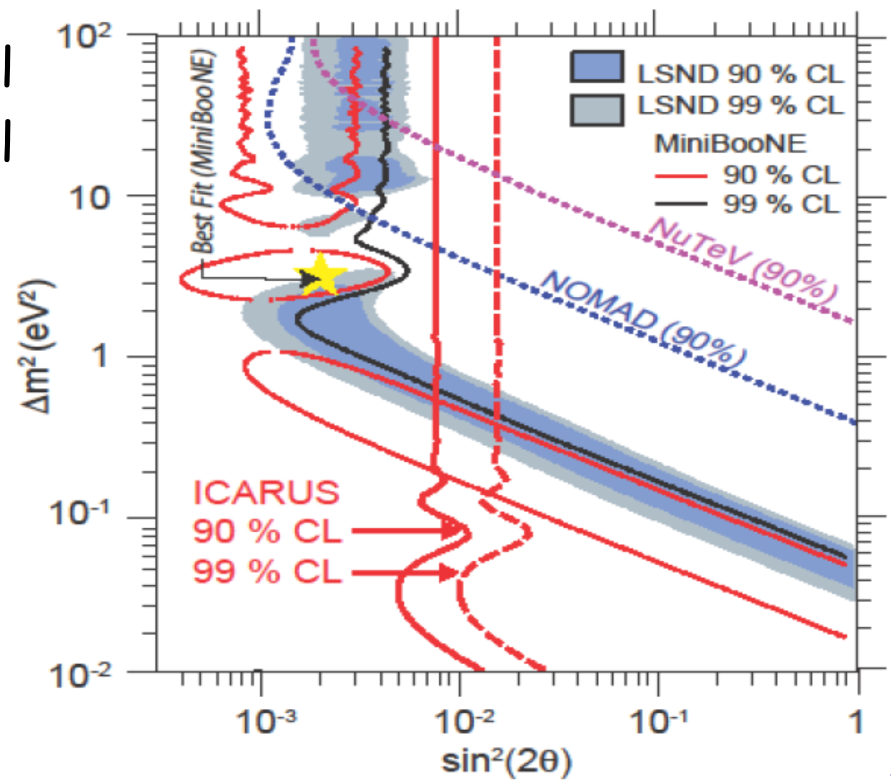
- ICARUS searched for ν_e excess related to LSND-like anomaly on the CNGS beam (~1% intrinsic ν_e contamination, L/E_ν ~ 36 km/GeV).
- **No excess** was observed in 7.93×10^{19} pot sample: **7ν_e** was observed, **8.5 ± 1.1** events was expected in absence of the LSND signal.
- The estimated limit on the oscillation probability is: **$P(\nu_\mu \rightarrow \nu_e) \leq 3.86\ (7.76) \times 10^{-3}$ at 90 (99) % C.L.**

- including ICARUS results a very small region of sterile mixing parameters is still available at:

  $\Delta m^2 \sim 0.5\ eV^2$, $\sin^2 2\theta \sim 0.005$

  where all experimental results can be be accommodated at 90% CL.

There is a need for a definitive experiment on sterile neutrinos to clarify observed neutrino anomalies. => SBN at Fermilab.



The SBN Collaborations – Institutions (July 2016)

ICARUS

- Argonne National Lab, USA
- Brookhaven National Lab, USA
- CERN, Switzerland
- Colorado State University, USA
- Fermi National Lab, USA
- INFN and University, Catania, Italy
- INFN GSSI, L'Aquila, Italy
- INFN LNGS, Assergi (AQ), Italy
- INFN Sez. di Milano Bicocca, Milano, Italy
- INFN Sez. di Napoli, Napoli, Italy
- INFN and University, Padova, Italy
- INFN and University, Pavia, Italy
- H. Niewodniczanski Inst. of Nucl. Phys., Polish Acad. of Science, Krakow, Poland
- Institute for Nuclear Research (INR), Institute of Physics, University of Silesia, Katowice, Poland
- Inst. for Radio-Electronics, University of Technology, Warsaw, Poland
- Los Alamos National Lab, USA
- Nat. Centre for Nucl. Research, Warsaw, Poland
- University of Pittsburgh, USA
- Russian Academy of Science, Moscow, Russia
- SLAC, USA
- Texas University at Arlington, USA

MicroBooNE

- University of Bern, Switzerland
- 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

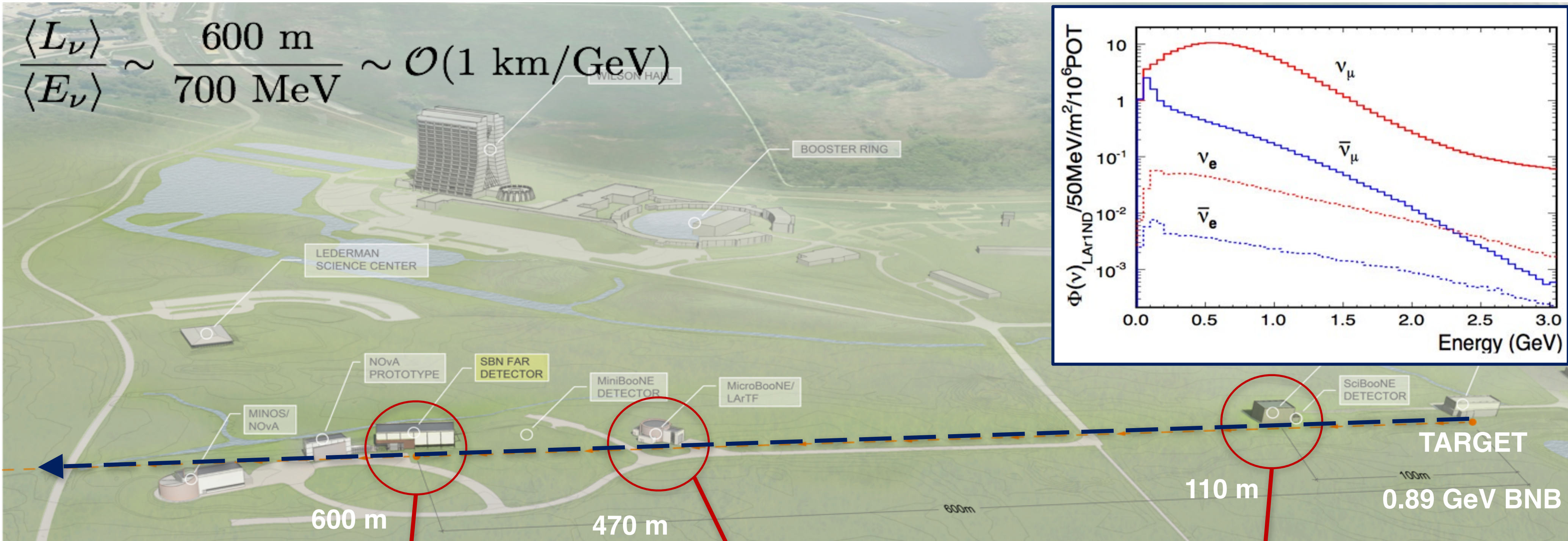
SBND

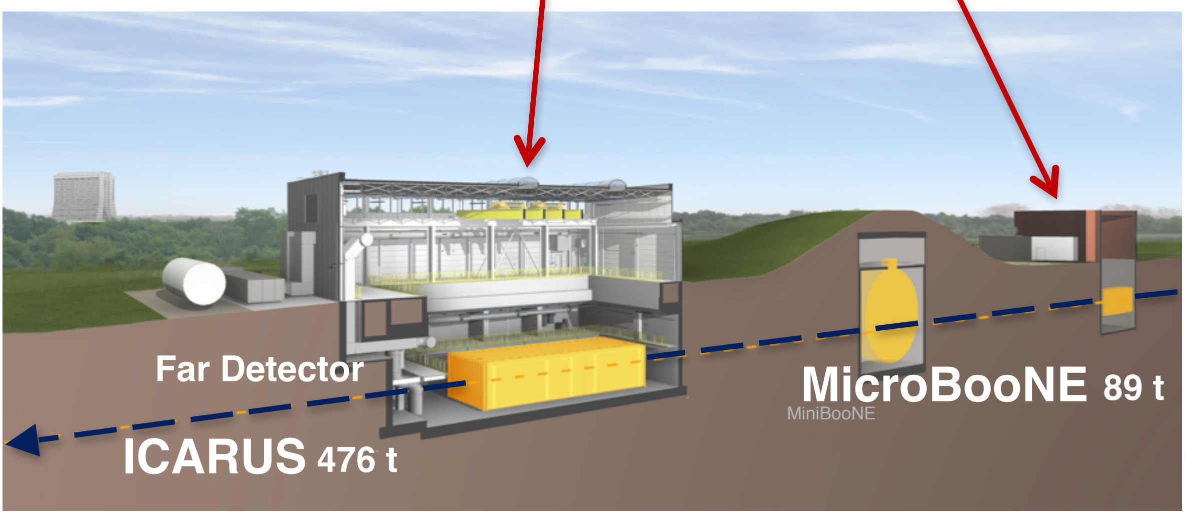
- Argonne National Lab, USA
- University of Bern, Switzerland
- Brookhaven National Lab, USA
- University of Cambridge, UK
- Univ. of Campinas – UNICAMP, Brazil
- CERN, Switzerland
- University of Chicago, USA
- Columbia University, USA
- Federal Univ. of ABC – UFABC, Brazil
- Federal Univ. of Alfenas – 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

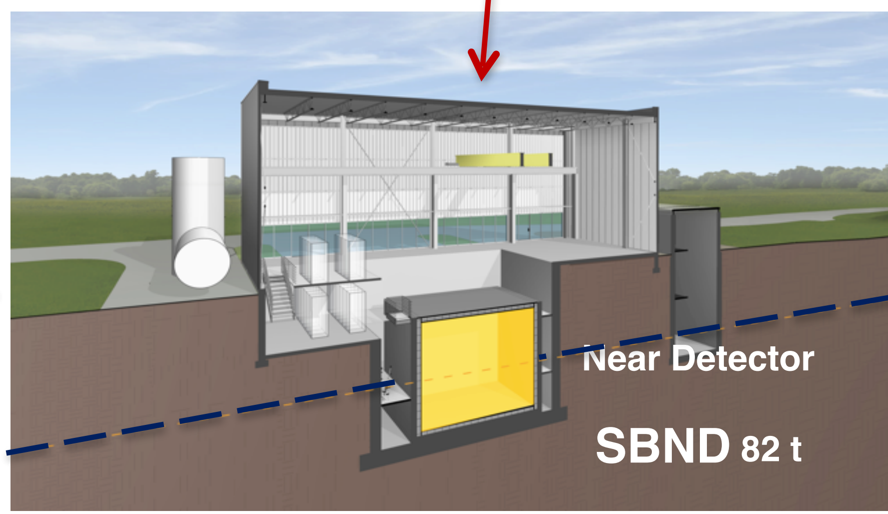
27 US + 26 non-US Institutions

Short Baseline Neutrino Program at Fermilab

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







SBN Sterile neutrino search at FNAL Booster ν Beamline

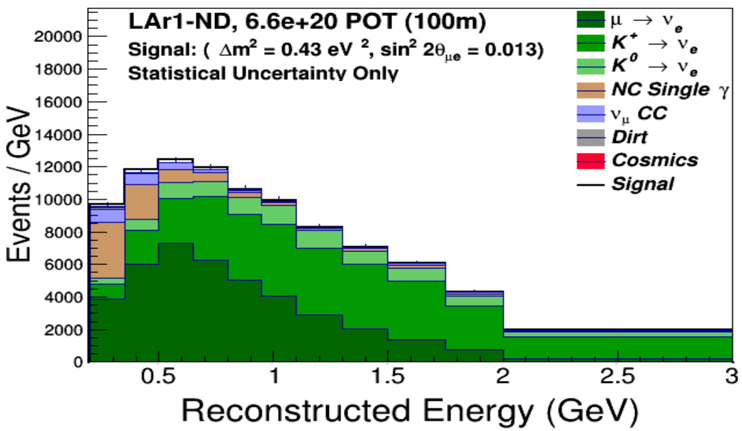
- The experiment will exploit 3 LAr-TPCs exposed to ~ 0.8 GeV FNAL **Booster Neutrino Beam (BNB)** : SBND (82 t active mass), MicroBooNE (89 t) and ICARUS (476 t).

- The SBN programme is expected to definitely clarify LSND/MiniBooNE, by independently measuring both ν_e appearance and ν_μ disappearance channels

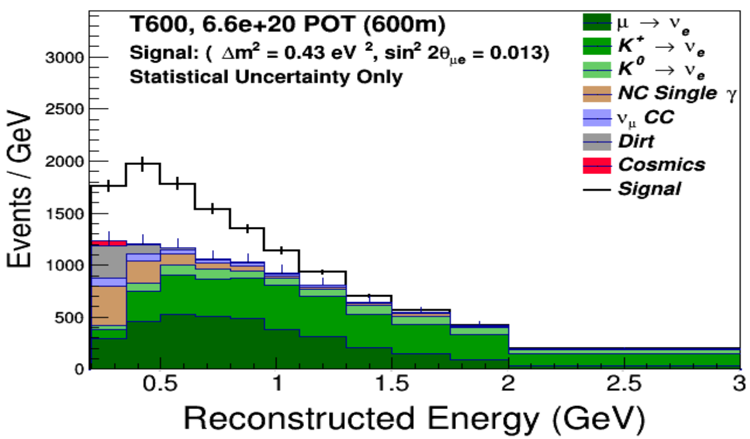
- Additionally ICARUS will be exposed to ~2GeV neutrinos from **NUMI** off-axis beam. It can help to measure cross sections in LAr, and study CC/NC channels to improve neutrino identification algorithms. An asset for DUNE-LBNF project.

the SBN $\nu_\mu \rightarrow \nu_e$ appearance study

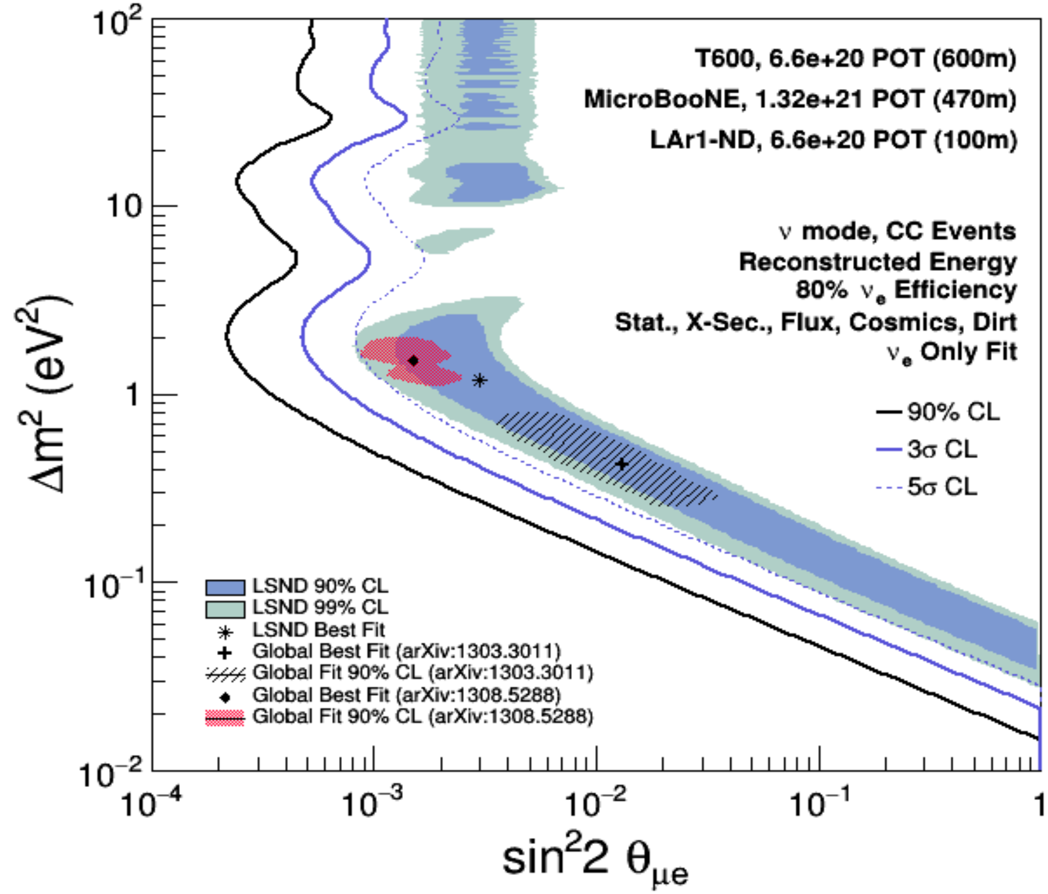
SBND @ 100 m



ICARUS-T600 @ 600 m



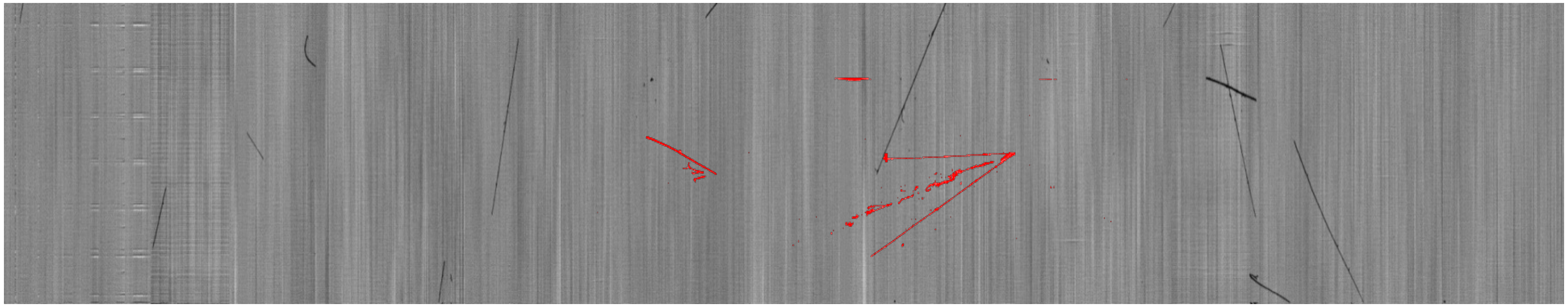
Example for
$\sin^2(2\theta)=0.013$
$\Delta m^2=0.43\ eV^2$



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

Facing a new situation: the LAr-TPC on 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.

Automatic tools to select, identify and reconstruct ν events among the millions of events triggered by cosmics are mandatory.

T600 overhauling at CERN (WA104)

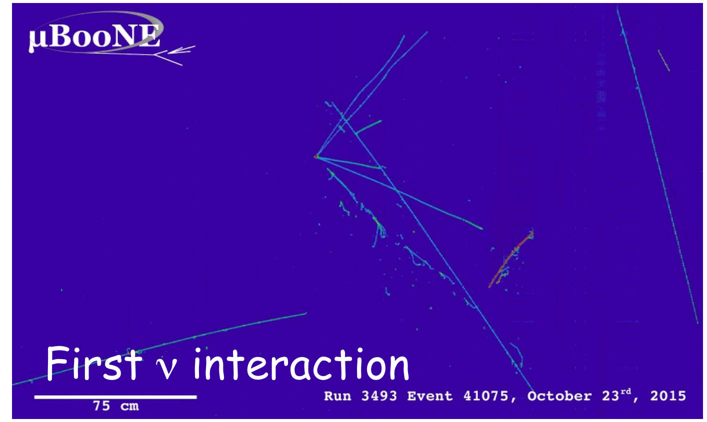
- T600 detector has been moved to CERN for overhauling in the framework of CERN Neutrino Platform for LAr-TPC development for short/long baseline neutrino experiments (WA104 project).
- The activities are progressing, introducing technology developments :

  - Improvement of the cathode planarity;
  - New cold vessels with a purely passive insulation
  - Renovated cryogenics/LAr purification equipment;
  - Upgrade of the light collection system: 160 8" PMTs behind the wire planes (~5% photo-cathode coverage) to localise precisely the collected events in ~ 1.5 ms window;

New faster, higher performance read-out electronics.

SBN Programme Timeline

- **MicroBooNE:**
  - Currently running - addressing the MiniBooNE anomaly.



- **ICARUS:**
  - Overhauling of T600 is almost completed at CERN;
  - Civil construction of far sites and buildings are progressing at FNAL;
  - Installation and commissioning at FNAL in 2017, then start ν data taking.

- **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

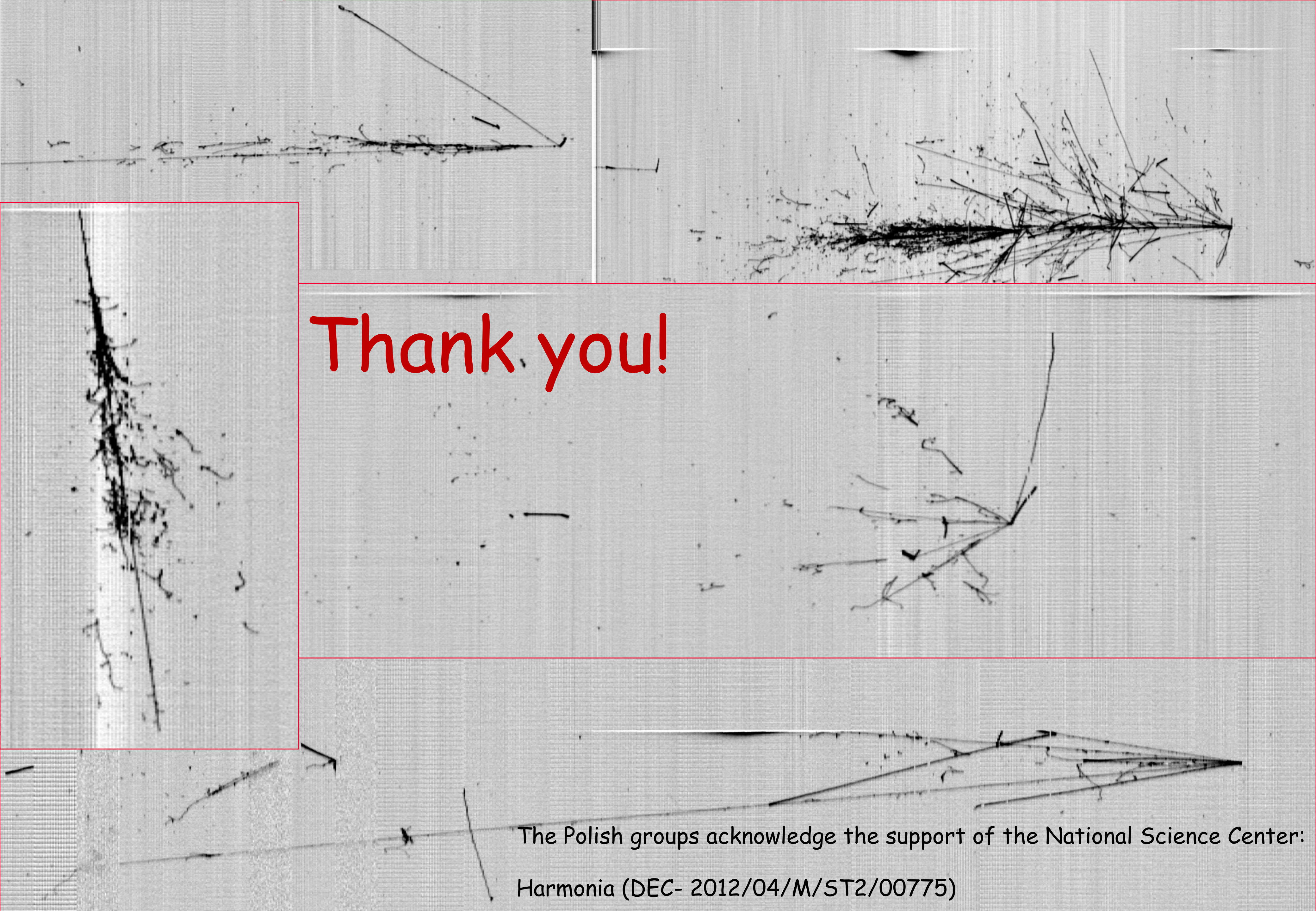
- ICARUS is the largest, so far, LAr TPC. During 3 years of continuous and safe underground operation at LNGS, ICARUS collected high quality data resulting in new constrains on sterile neutrino searches. It also demonstrated capabilities of this detection technique.

- 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.

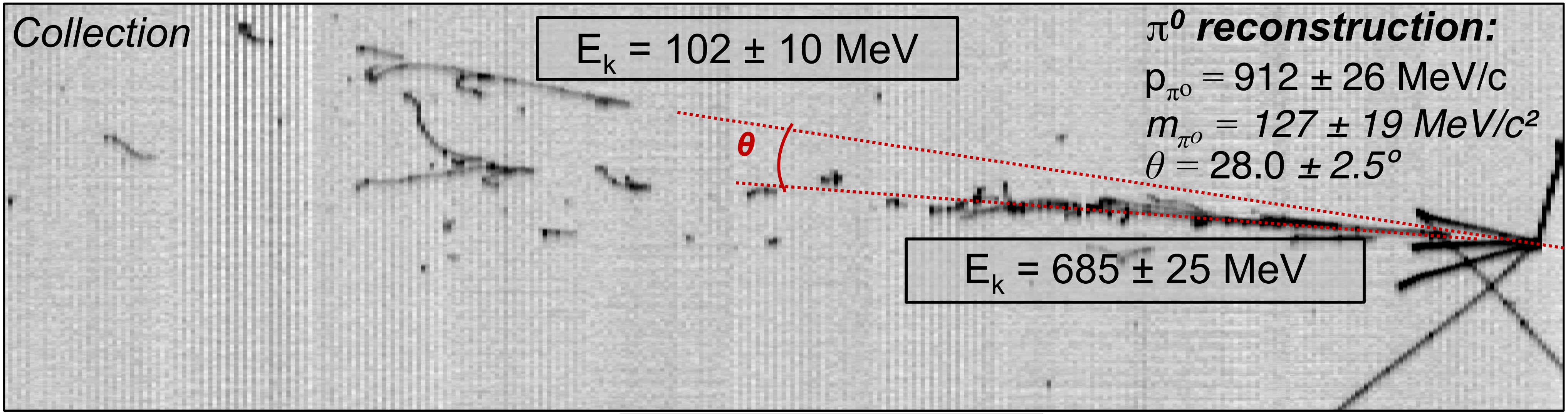


Thank you!

The Polish groups acknowledge the support of the National Science Center:

Harmonia (DEC- 2012/04/M/ST2/00775)

ICARUS: e/γ separation and π^0 reconstruction



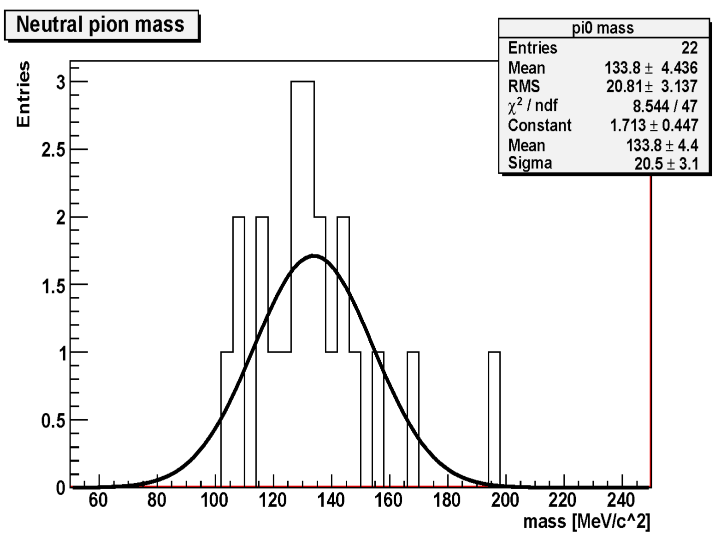
π^0 reconstruction:

$p_{\pi^0} = 912 \pm 26$ MeV/c

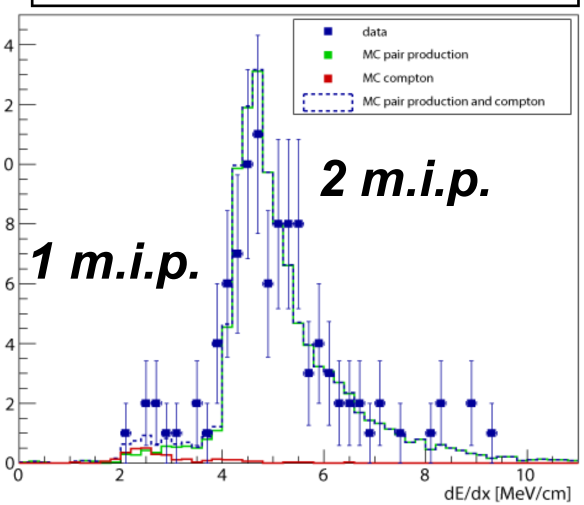
$m_{\pi^0} = 127 \pm 19$ MeV/c²

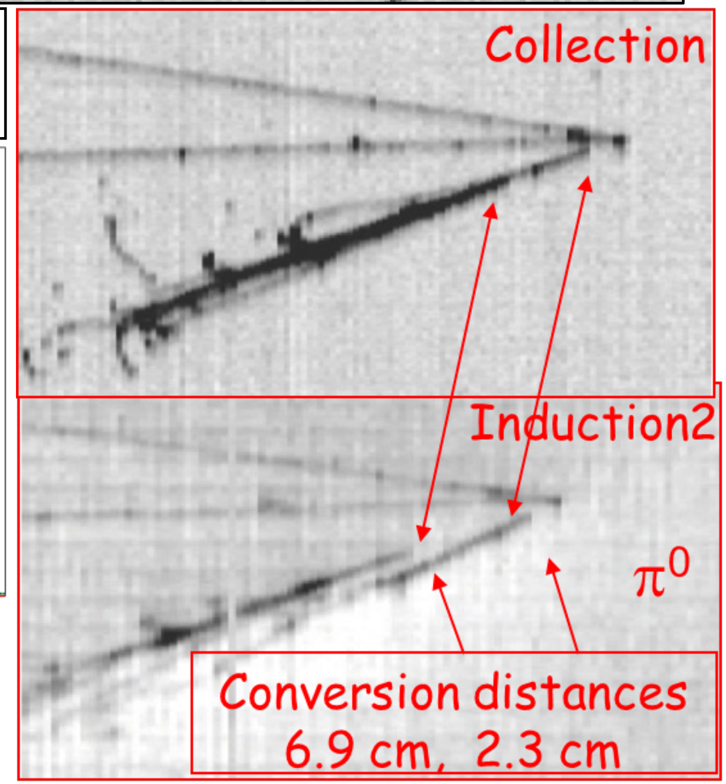
$\theta = 28.0 \pm 2.5^o$

$M_{\gamma\gamma}$: 133.8±4.4(stat)±4(syst) MeV/c²



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

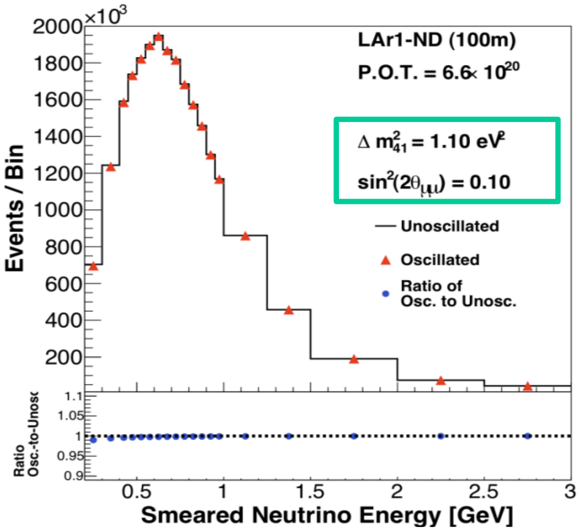


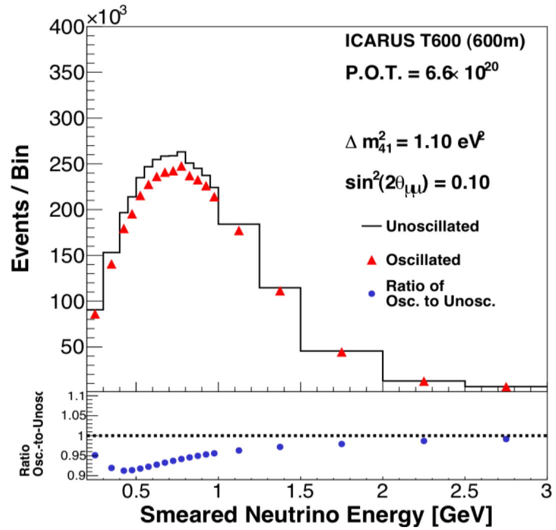


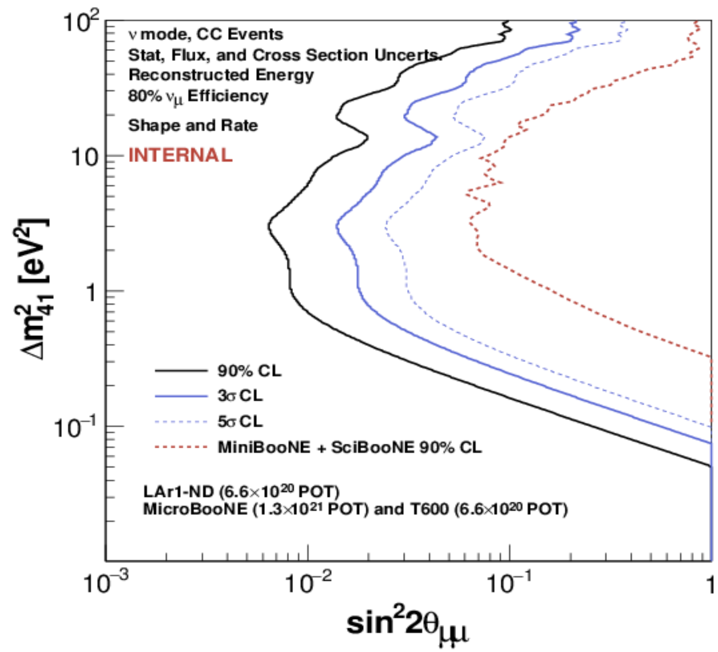
LAr TPC: very good e/γ separation -important for rejection of NC background to ν_e events

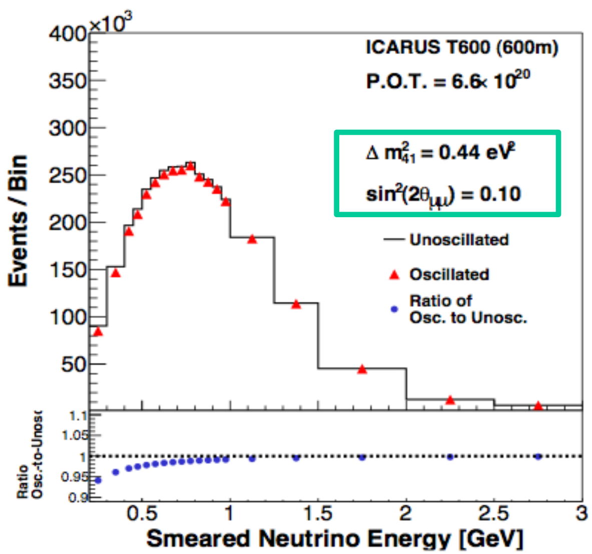
SBN ν_μ disappearance sensitivity

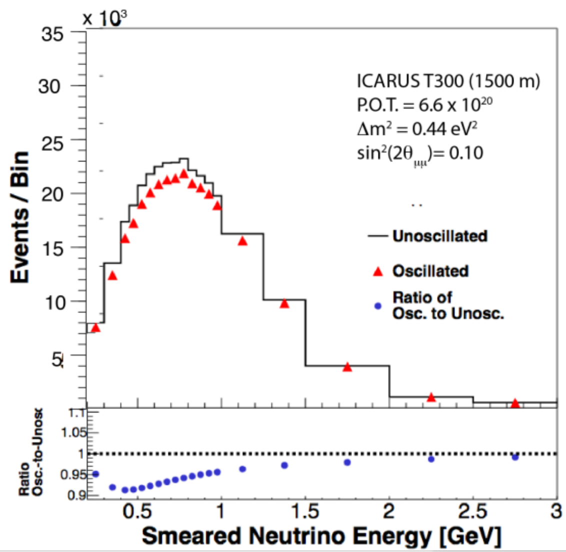
- High event rate and the correlation between all 3 LAr-TPCs allows extending sensitivity by **one order of magnitude beyond present limits**











- However, the ν_μ disappearance will be limited at the lowest ν energy bins 0.2-0.4 GeV, assuming $\Delta m^2 < 0.5\ eV^2$

- To amplify the effect, one T300 module of ICARUS may be moved, at a later stage, to 1.5 km distance from the target.

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;