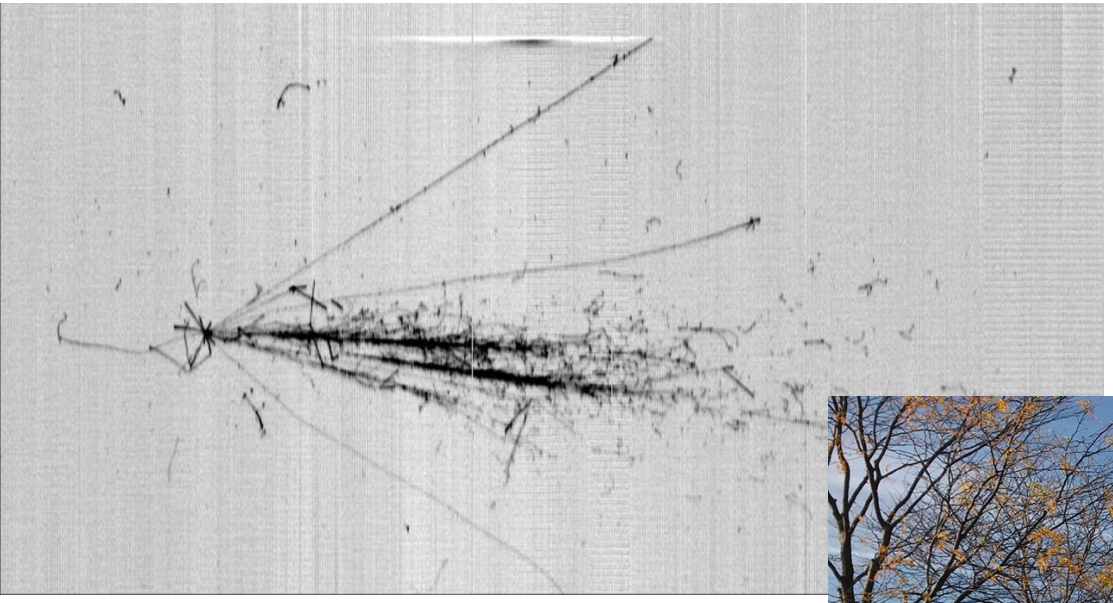
Sterile neutrino searches at FNAL within the Short Baseline Neutrino program



F. Varanini
INFN Padova

on Behalf of the
ICARUS Collaboration

106° Congresso
Nazionale SIF

18 settembre 2020

The present ICARUS Collaboration at SBN

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[a] On Leave of Absence from INFN Padova
[b] On Leave of Absence from INFN Pavia

1. Brookhaven National Lab., USA
2. CERN, Switzerland
3. CINVESTAV, Mexico
4. Colorado State University, USA
5. Fermi National Accelerator Lab., USA
6. INFN Bologna and University, Italy
7. INFN Catania and University, Italy
8. INFN Genova and University, Italy
9. INFN GSSI, L'Aquila, Italy
10. INFN LNGS, Assergi (AQ), Italy
11. INFN LNS, Catania, Italy
12. INFN Milano, Milano, Italy
13. INFN Milano Bic. and University, Italy
14. INFN Napoli, Napoli, Italy
15. INFN Padova and University, Italy
16. INFN Pavia and University, Italy
17. SLAC National Accelerator Lab., USA
18. Southern Methodist University, USA
19. Tufts University, USA
20. University of Houston, USA
21. University of Pittsburgh, USA
22. University of Rochester, USA
23. University of Texas (Arlington), USA

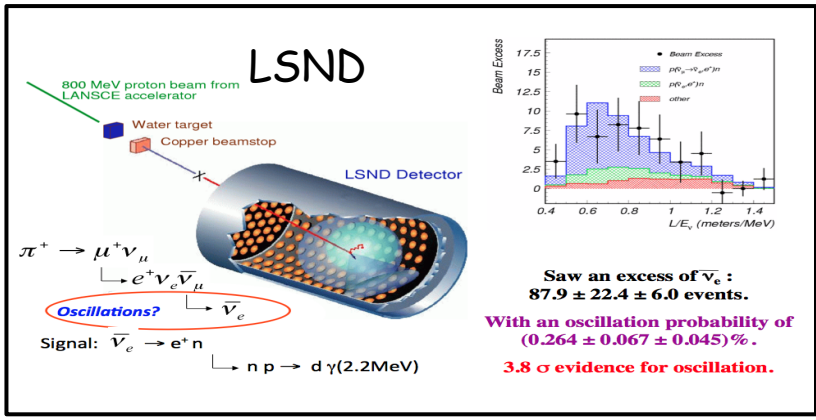
11 INFN groups, 10 USA institutions, 1 Mexican institution, CERN

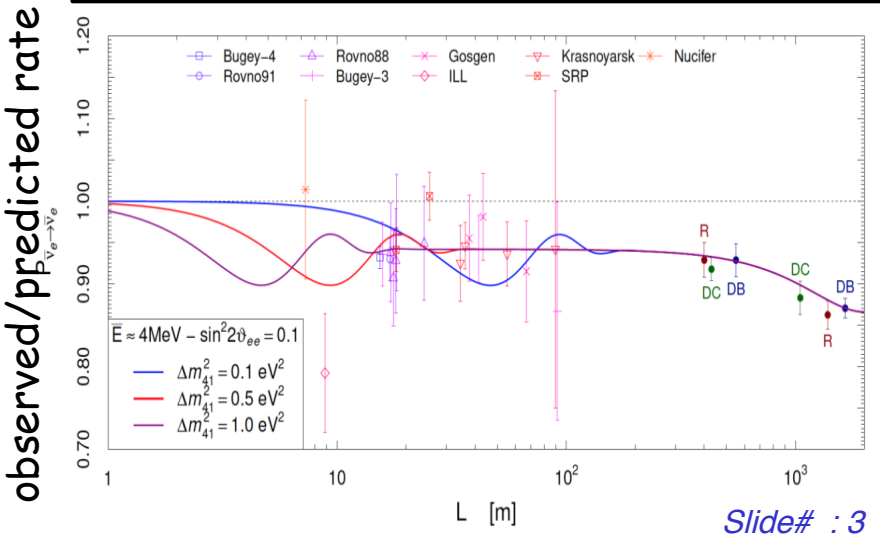
Spokesman: C. Rubbia, GSSI

Anomalies in neutrino experiments

- Most experimental results in neutrino oscillation are consistent with the standard 3-neutrino scenario
- However, some anomalies have been observed for ~20 years, pointing to oscillations with L/E ~ 1 m/MeV, corresponding to a new sterile flavour state with Δm^2 ~ 1-10 eV^2 :
  - anti–νe appearance in anti-νμ beams at LSND experiment, 3.8 σ CL;
  - Excesses observed in MiniBoone accelerator experiment (in both νμ and anti-νμ beams)

    LSND+MB combined significance ~6 σ
  - νe disappearance from Mcurie radioactive sources at SAGE/GALLEX, observed/predicted rate R = 0.84±0.05;
  - anti-νe disappearance at short-baseline reactor experiments: R = 0.934±0.024





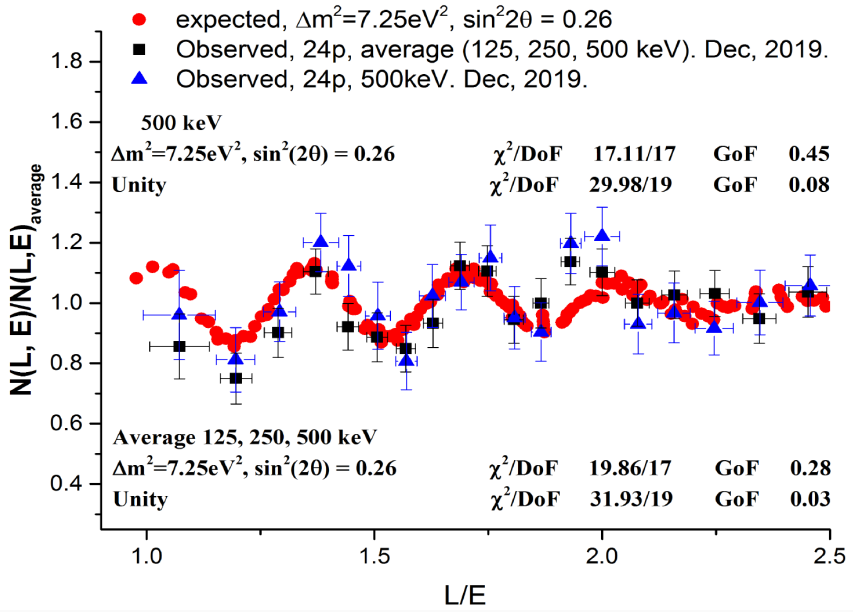
Recent Neutrino-4 results

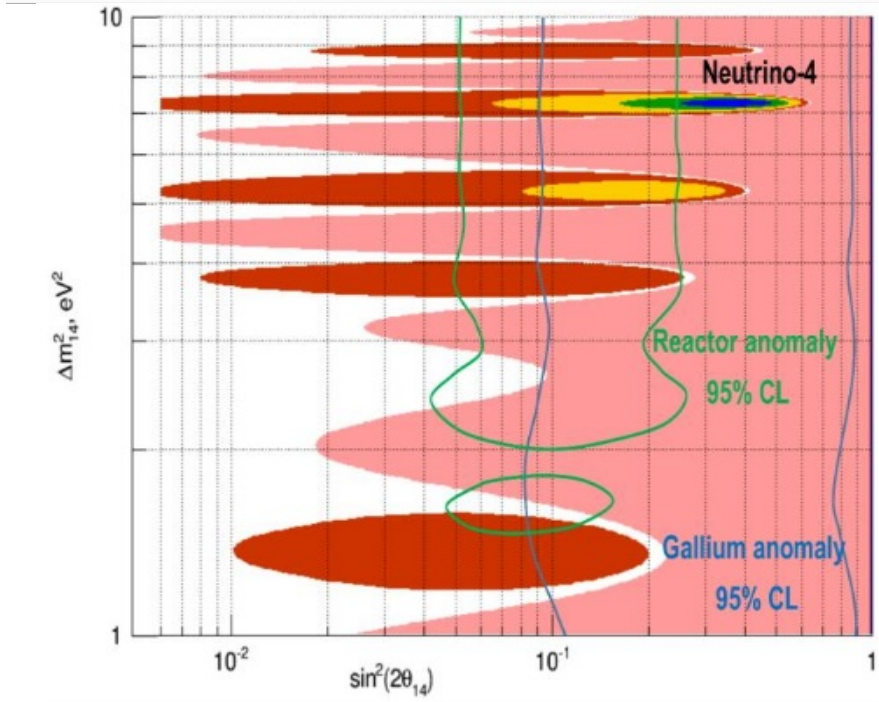
- The Neutrino-4 reactor experiment is characterized by ⟨Eν⟩ ~ 4MeV and a movable detector (liquid scintillator+Gadolinium) with L=6÷12 m
- 3 year data-taking + 1 year background measurement
- It recently observed an antineutrino disappearance signal corresponding to a high $\Delta m^2 \sim 7.25\ eV^2$ and a large mixing angle $\sin^2 2\theta \sim 0.26$ (2.8σ significance)
- This result is very marginally compatible with existing reactor results

arXiv:2005.05031

A verification of the Neutrino-4 signal is needed

The most direct test will involve a search for neutrino disappearance with a similar L/E





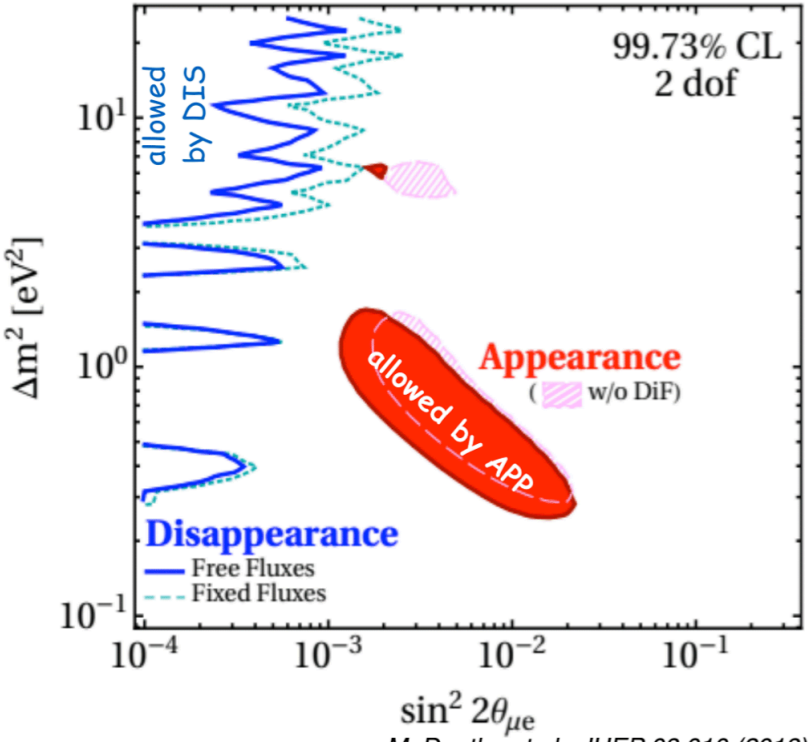
The sterile neutrino puzzle

- Many experimental searches for sterile neutrinos did not find evidence for deviations from the standard 3-flavour oscillations:
  - Accelerator searches via νμ->νe appearance (ICARUS, OPERA)
  - Accelerator searches via νμ disappearance (MINOS, MINOS+, NOvA)
  - Disappearance searches in atmospheric neutrinos (IceCube)
  - Cosmological searches (via the effect of relativistic species on structure formation): Planck allows at most 1 further flavour with m<0.24 eV

The sterile neutrino puzzle is far from solved

In particular, clear tension between νμ disappearance and νe appearance results

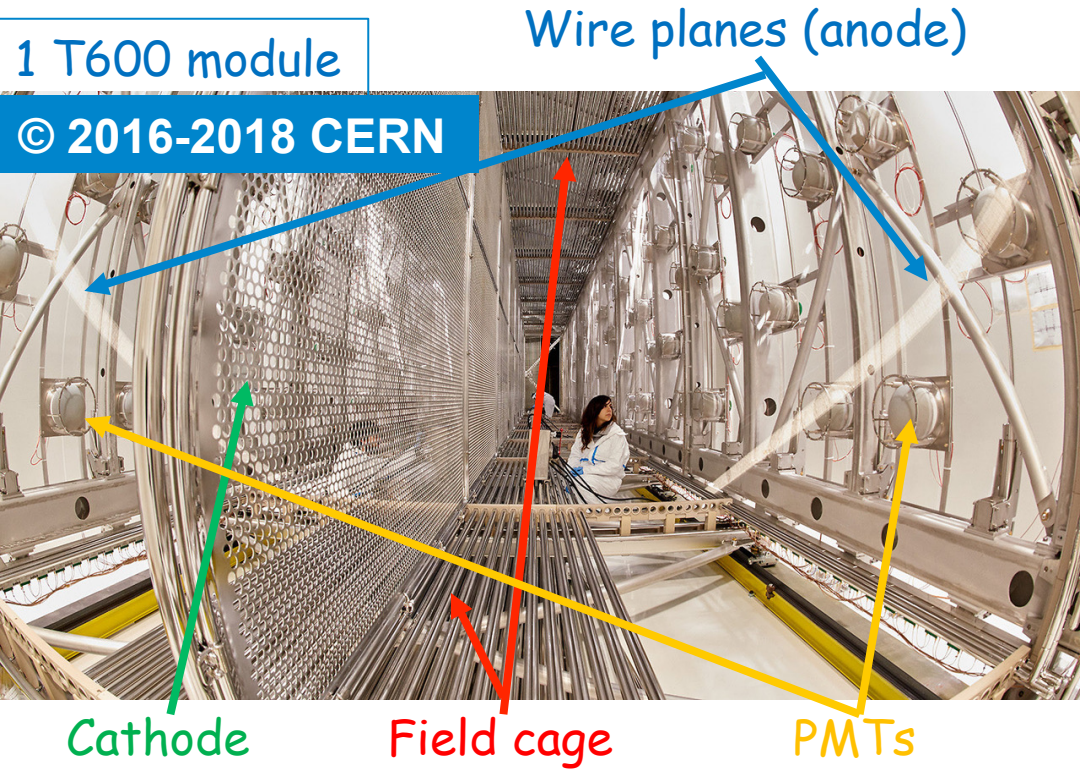
A definitive clarification is needed !



M. Dentler et al., JHEP 08:010 (2018)

ICARUS: the first large-scale Liquid Argon TPC

- Culmination of a long R&D effort by INFN in liquid Argon detectors, starting from the first proposal by C. Rubbia in 1977
- First large-scale liquid argon TPC: total active mass of 476 t (2 identical modules)
- 2 TPCs per module, with a common central cathode: E_D= 0.5 kV/cm, v_D~1.6 mm/μs, 1.5 m drift length;
- Non-destructive readout: 3 wire planes (2 Induction and 1 Collection) per TPC at 0°, ±60° w.r.t. horizontal

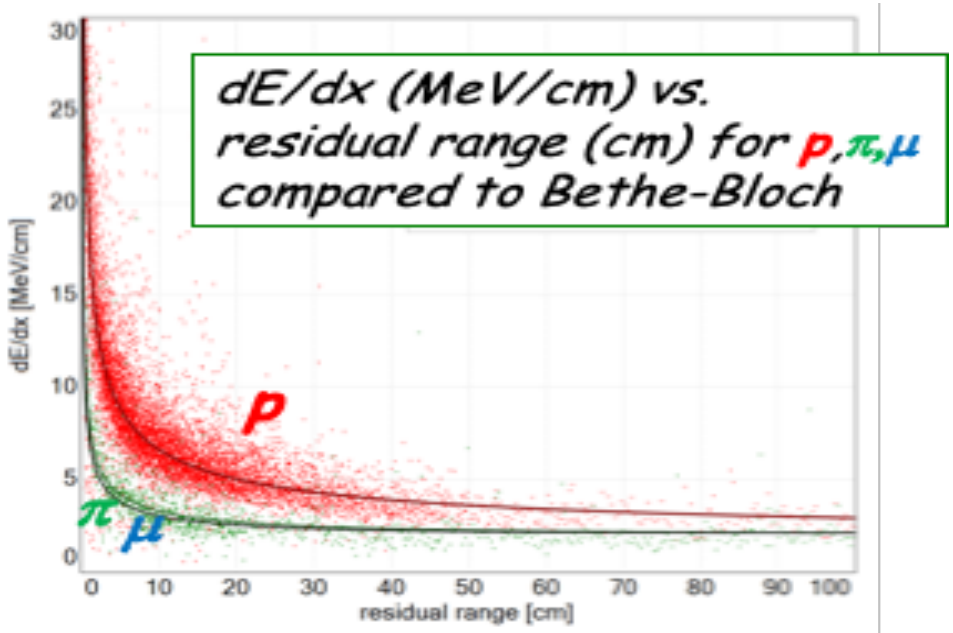


- Ionization charge continuously read (0.4 μs sampling time);
- 8" PMTs, coated with TPB wls, for t_0, timing and triggering.
- Successful data-taking run at LNGS underground lab (2010-13) exposed to CNGS neutrino beam
- Collected an event statistics of 8.6×10^{19} pot and cosmic ray events, with a detector live time >93%

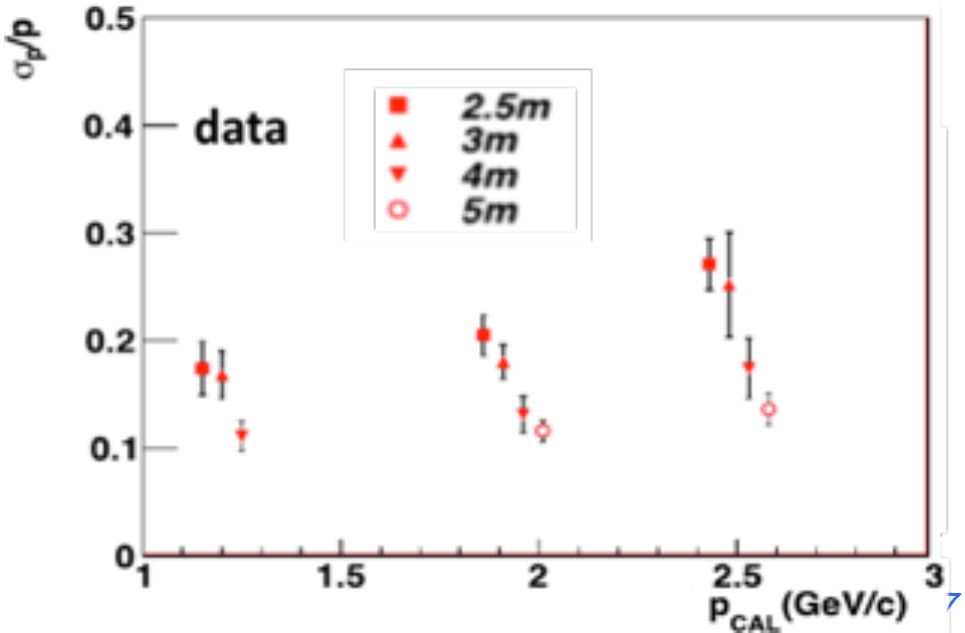
JINST 6 P07011 (2011)

ICARUS reconstruction performance

- ICARUS data confirmed expected performances, which make LAr-TPC an ideal detector for neutrino physics
  - 3D tracking with mm-scale resolution
  - Homogeneous calorimetry for contained events
  - Very accurate dE/dx measurement (X_0~14 cm) and particle identification via dE/dx vs. range
  - Measurement of non-contained muon momentum via multiple Coulomb scattering

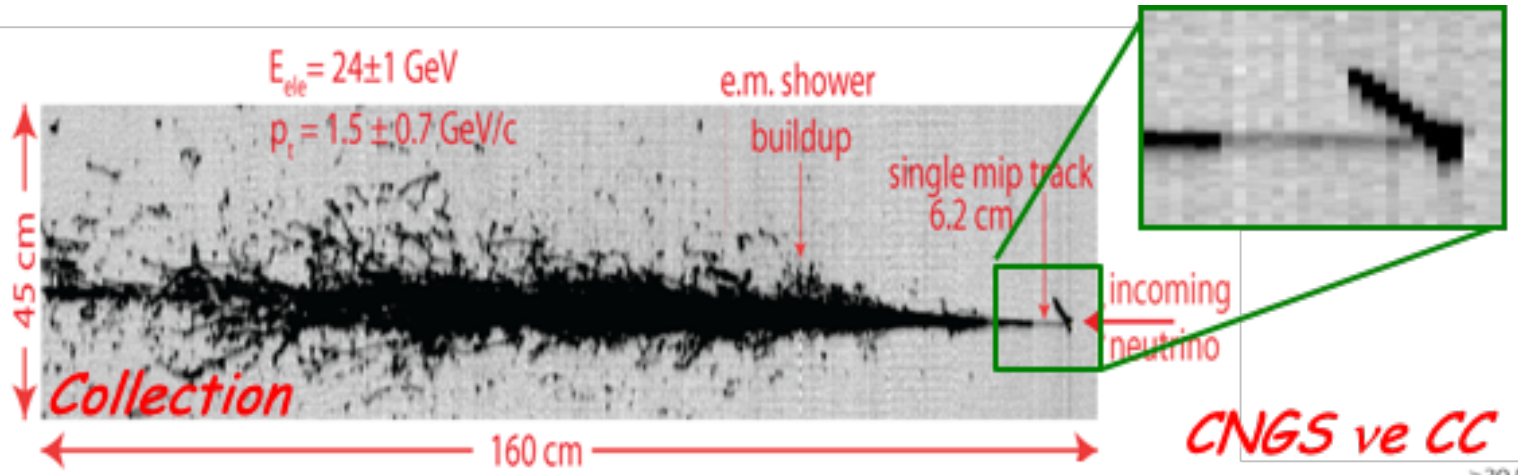


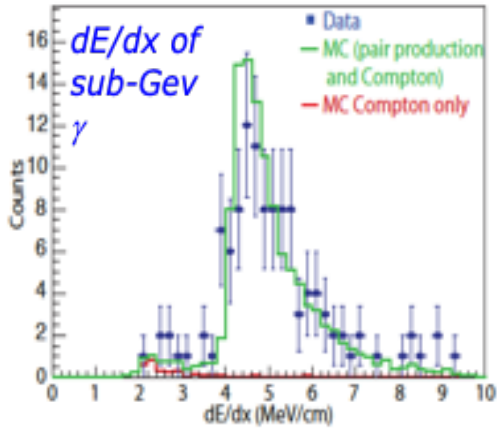
MCS muon momentum
JINST 12 P10010 (2017)



e/γ separation in ICARUS

- Separation of ν_eCC signal from background of neutral current with π_0 is crucial
- The LAr-TPC technology provides:
  - Identification of γ conversion by gap from the primary neutrino vertex
  - Reconstruction of π_0 invariant mass
  - dE/dx: fine sampling and calorimetric accuracy allow to distinguish single vs. double MIP at shower onset

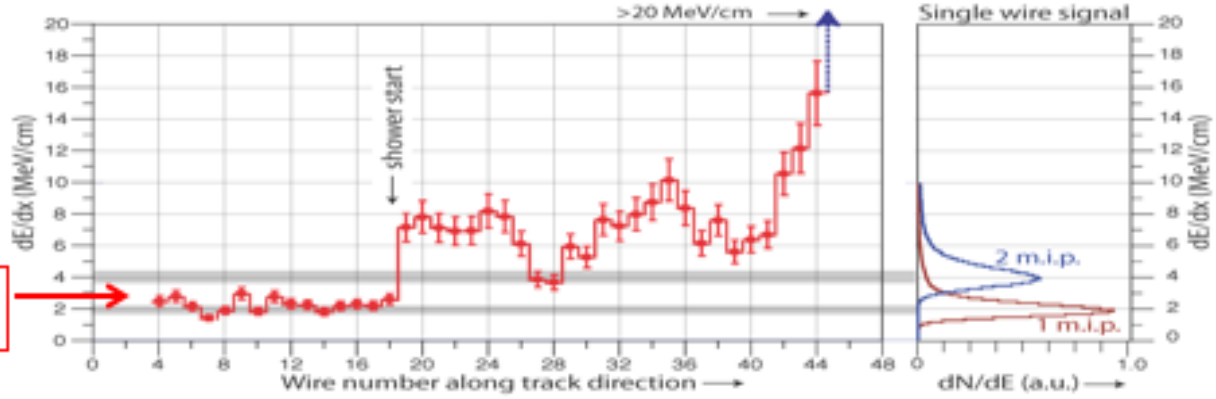




CNGS ν_e CC

Evolution in Collection view from single mip to EM shower is evident from dE/dx on individual wires.

Single mip

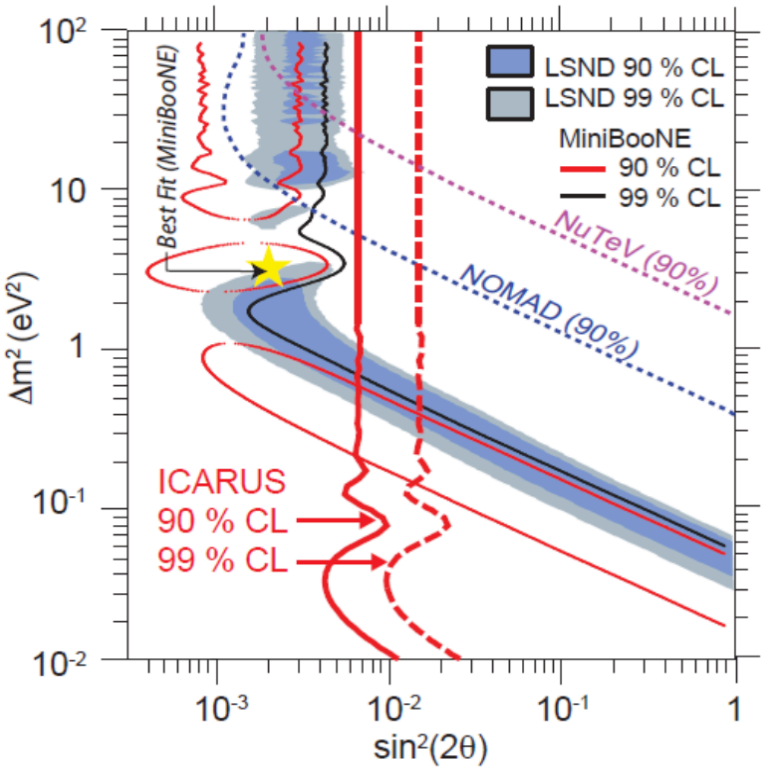


ICARUS search for sterile neutrinos

- ICARUS searched for sterile ν oscillations through νe appearance in the CNGS beam
- L/E~36 m/MeV, far from the LSND value -> "sterile-like" oscillation was averaged out, canceling energy dependence
- 7.9 10^{19} pots analyzed (~2650 ν interactions)

- Expected ~8.5±1.1 νe background events in absence of anomaly, mostly from νe beam contamination (taking into account ~74% efficiency estimated on MC)
- 7 events observed - no evidence of oscillation

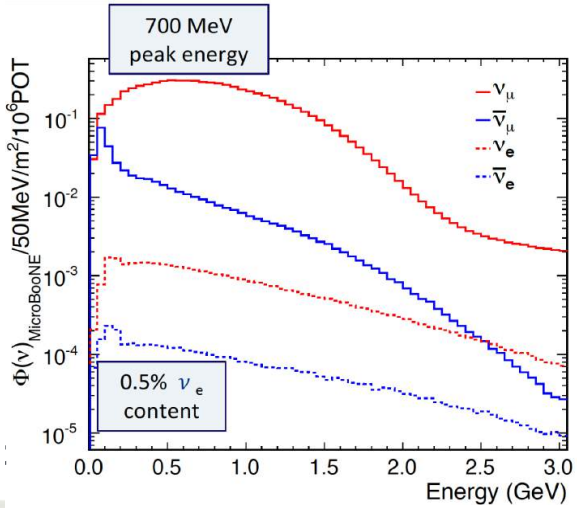
- Most of LSND allowed region excluded – except for small area around $\sin^2\theta$~0.005, Δm^2~0.1 eV^2
- Similar result by OPERA with same CNGS beam and different detection technique

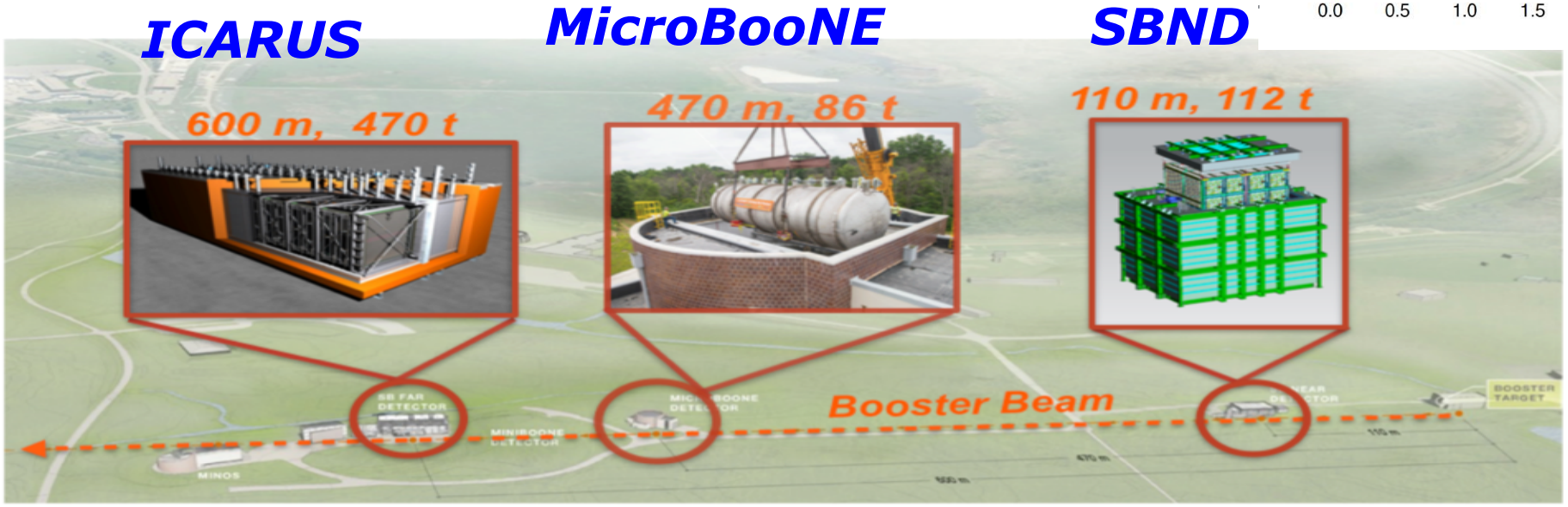


Eur. Phys. J. C (2013) 73:2599

The Short Baseline Neutrino (SBN) program

- It will search for a definitive clarification of the sterile neutrino anomalies, searching for both νe appearance and νμ disappearance at the same time
- It will use 3 very similar LAr-TPC detectors at different distances along the Fermilab Booster beam (peak energy ~700 MeV, νe contamination ~0.5%)

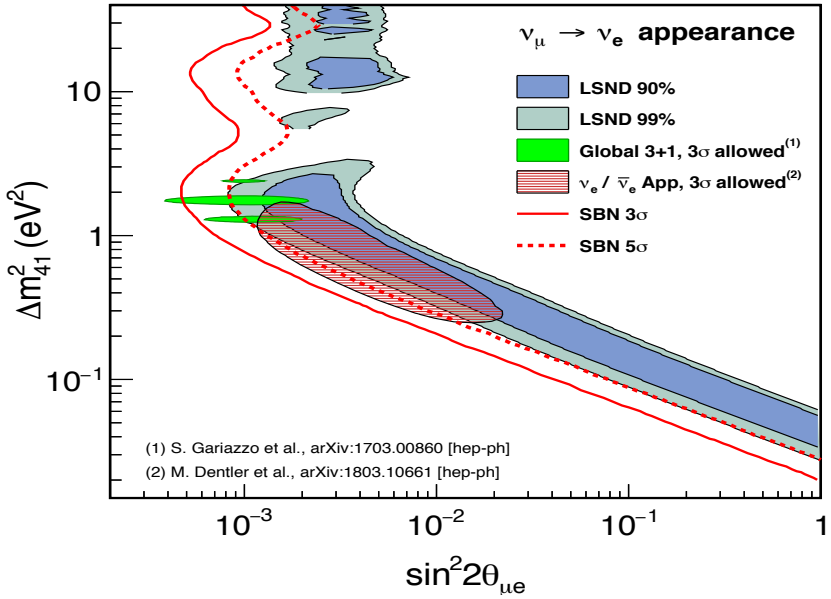


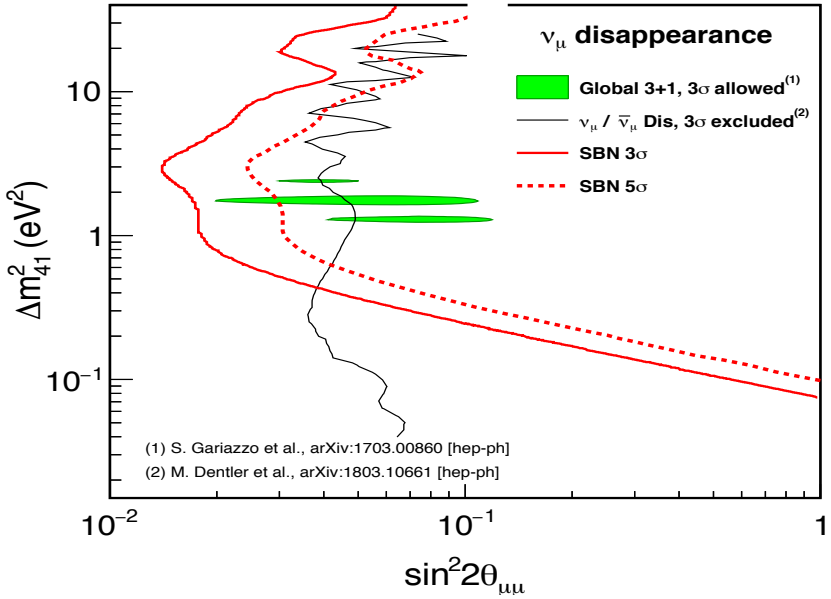


- ICARUS will also be exposed to off-axis NuMI beam, with a large νe component, allowing cross-section measurements and identification/ reconstruction studies of great impact for DUNE experiment

SBN sensitivity

- The comparison between near and far detector will allow to reduce beam and cross-section systematics to few percent
- The LAr-TPC technology will allow efficient νe identification and NC background reduction
- Oscillation probability will be negligible at near detector -> any difference will imply new physics





Sensitivities from SBN proposal (arXiv:1503.01520) compared with more recent global fits (arXiv:1903.04068)

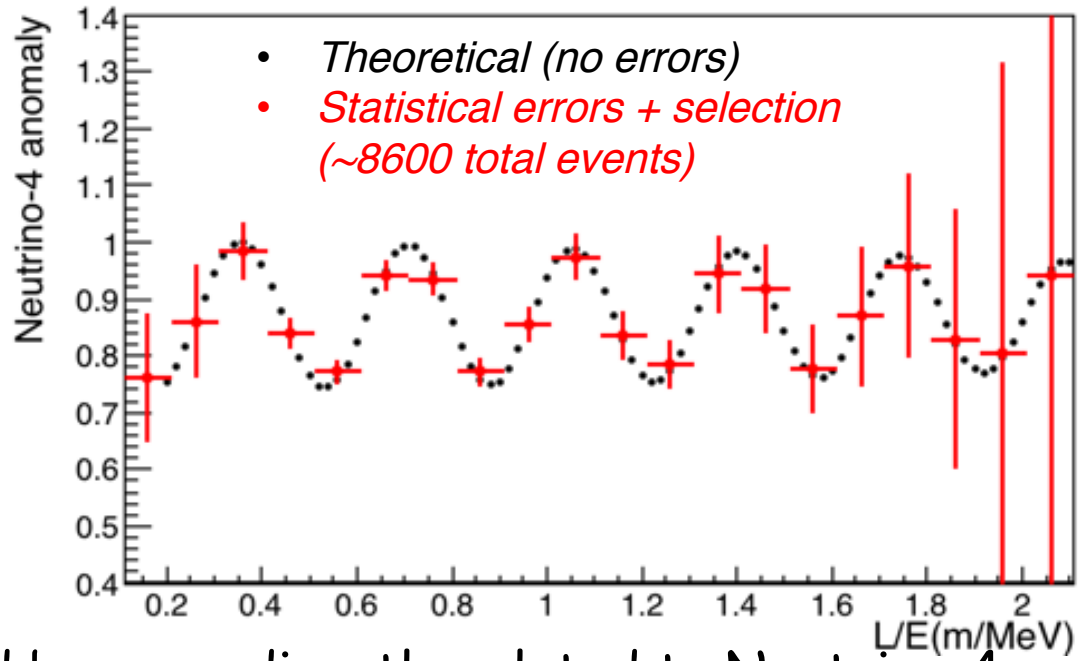
SBN will be able to cover most of the parameter region allowed by past anomalies with 5σ significance in 3 years (6.6 10^{20} pot)

Verification of Neutrino-4 result with ICARUS

- ICARUS has a L/E ~ 1÷3 m/MeV: very similar to Neutrino-4
- A search for $\nu\mu$ disappearance in the Booster beam can be sensitive to the Neutrino-4 oscillation parameters and verify their claim
- This can be performed with ICARUS alone in a short time frame
- Even in 3 months, the oscillation pattern as a function of L/E is clearly visible

$\nu\mu$ survival probability as a function of L/E:

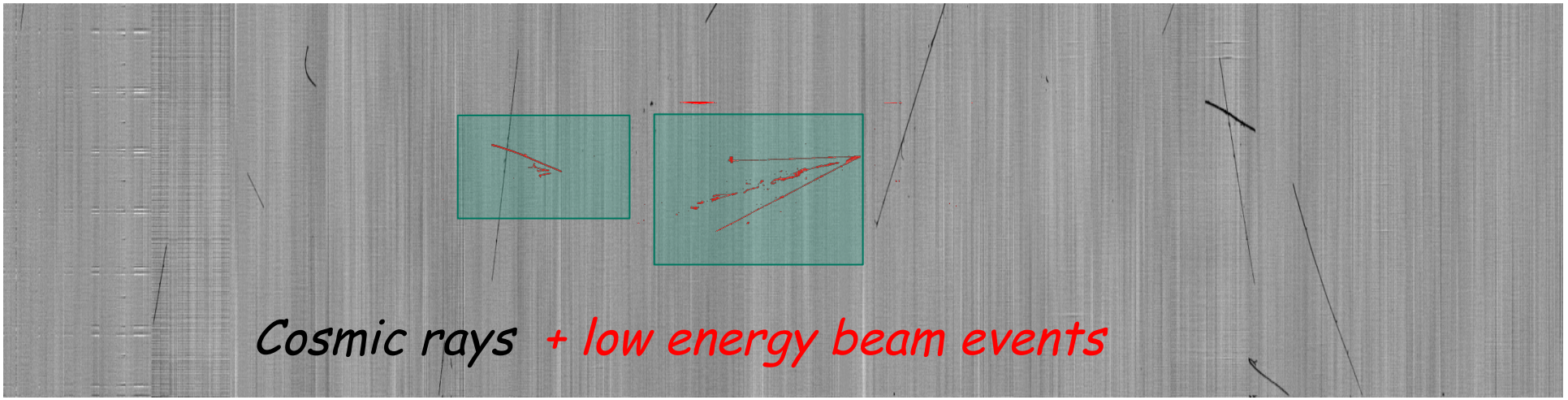
- *3 months data-taking*
- *Trigger efficiency (as modeled in SBN) is included*
- *Selection on μ identification: Lμ > 50 cm*



- A νe disappearance search would be more directly related to Neutrino-4 and sensitive to the same mixing angle
- While the BNB νe statistics is too low, such a search can be performed with the NuMI beam (~7300 expected events)

A new experimental challenge: a LAr-TPC on surface

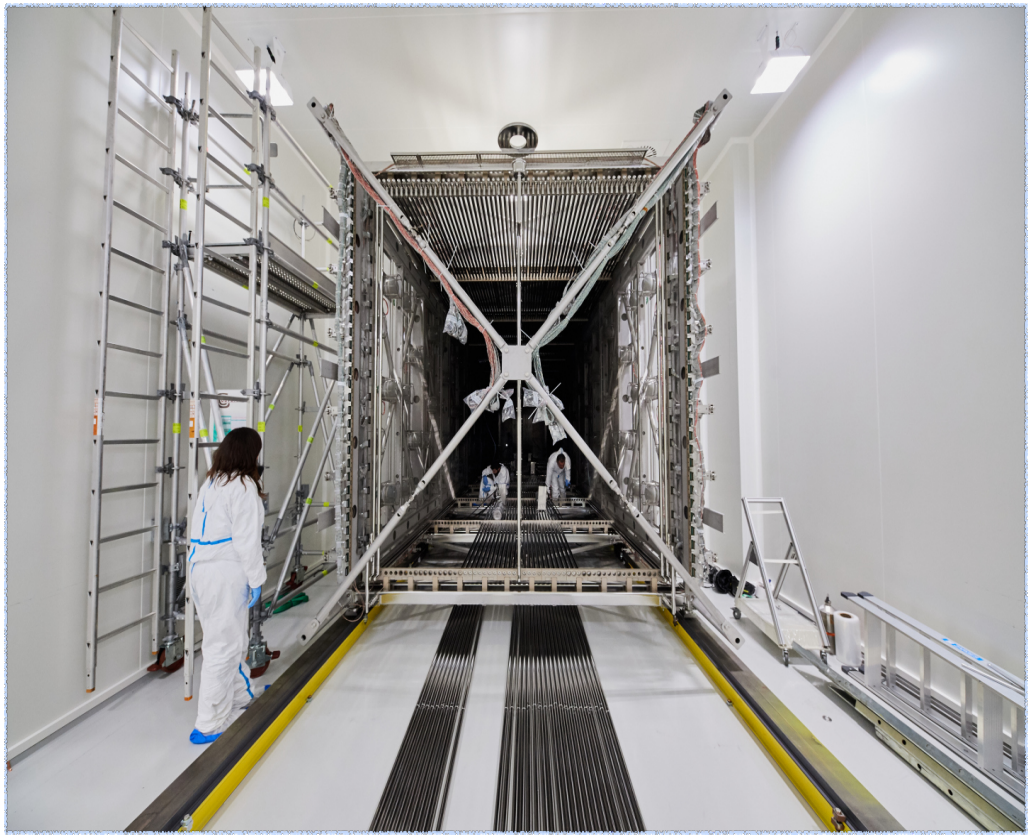
- ICARUS surface operation will be extremely challenging because of cosmic rays
- A 3 meter concrete overburden will filter out most γ's and charged hadrons
- ~11 cosmic muon tracks will hit each ICARUS module in the ~1 ms drift window: the associated γs can produce electrons (via Compton/pair production) that represent a critical background to νe searches



- Rejection of this background requires precise timing of each ionizing event overlapped with the genuine beam neutrino interaction
- This will be possible with much faster signals than the TPC ones:
  - Scintillation light (detected by a much improved PMT system)
  - An external Cosmic Ray Tagger (CRT) detecting incoming particles

Improving ICARUS: the overhauling at CERN

- To face the new experimental conditions at FNAL (shallow depth, higher beam rate) T600 underwent intensive overhauling at CERN, before shipping to US.
- Overhauling took place in the CERN Neutrino Platform framework (WA104) from 2015 to 2017.
- The goal was to introduce technology developments *while maintaining the already achieved performance:*
  - new cold vessels, with a purely passive insulation;
  - Renovated LAr cryogenics/ purification equipment;
  - Improvement of the cathode planarity
  - new faster, higher-performance read-out electronics;
  - Upgrade of the PMT system: higher granularity and ~ns time resolution

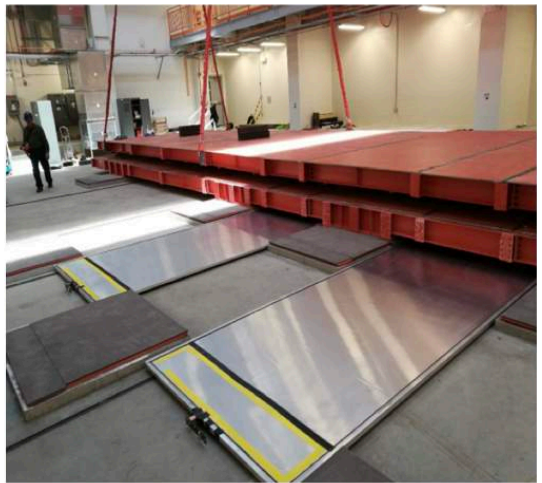


The Cosmic Ray Tagging system (CRT)

- Three subsytems (Bottom, Sides, Top) surrounding the cryostat with two layers of plastic scintillators ~1000 m^2;
- Tags incident cosmic or beam-induced muons with high efficiency (95%) giving spatial and timing coordinates of the track entry point
- Reconstructed CRT hits are matched to activity in the LAr volume
- Few ns time resolution allows measuring direction of incoming/outgoing particle propagation via time of flight;
- Commissioning of the two walls with cosmics is ongoing

Side CRT partially installed

Bottom CRT installed



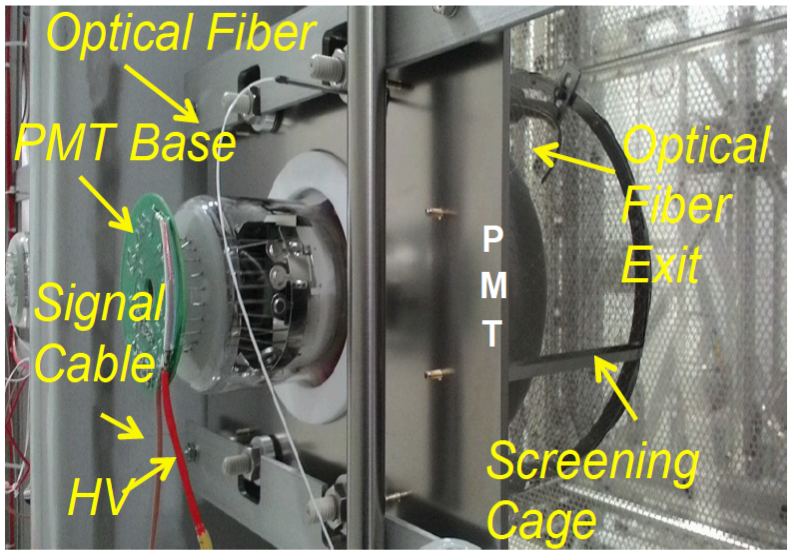
Top CRT modules ready

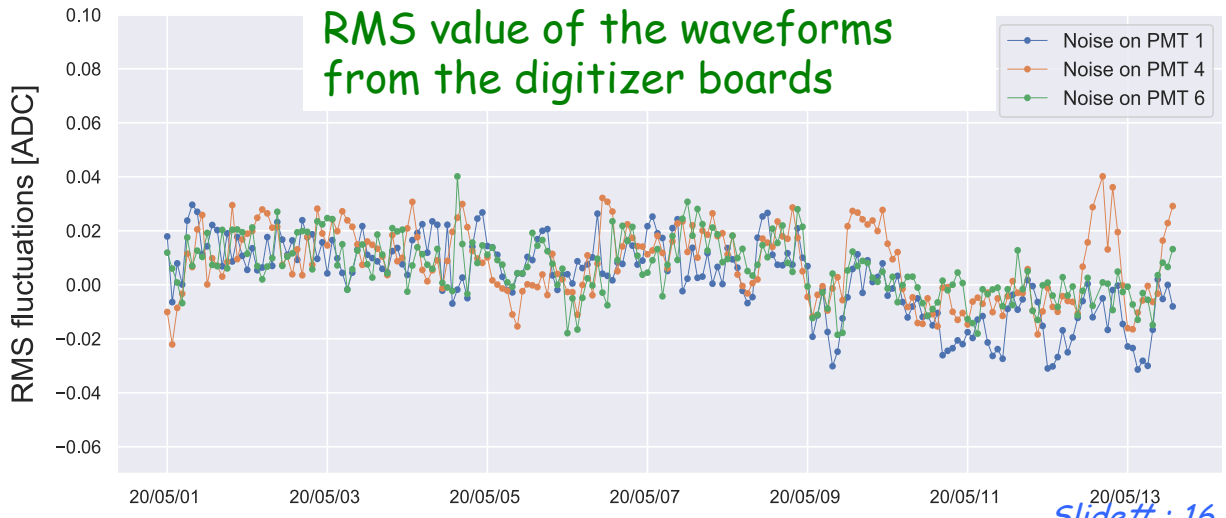
Upgrade of the light collection system

The ICARUS@SBN PMT system includes 360 PMTs (5% coverage, 15 phe/MeV). It will allow to:

- Precisely identify the time of occurrence (t_0) of any ionizing event in the TPC with ns timing resolution
- Determine the event rough topology for selection purposes
- Generate a trigger signal for read-out with sensitivity down to ~100 MeV
- Localize events with <50 cm spatial resolution

Commissioning is in progress: activation and calibration at LAr temperature

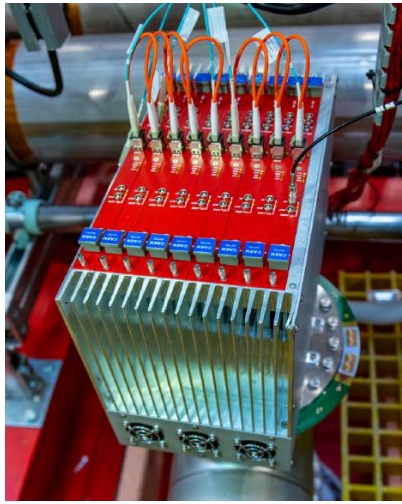




Upgrade of the TPC read-out electronics

New TPC readout electronics extensively tested on a 50 liter TPC@CERN:

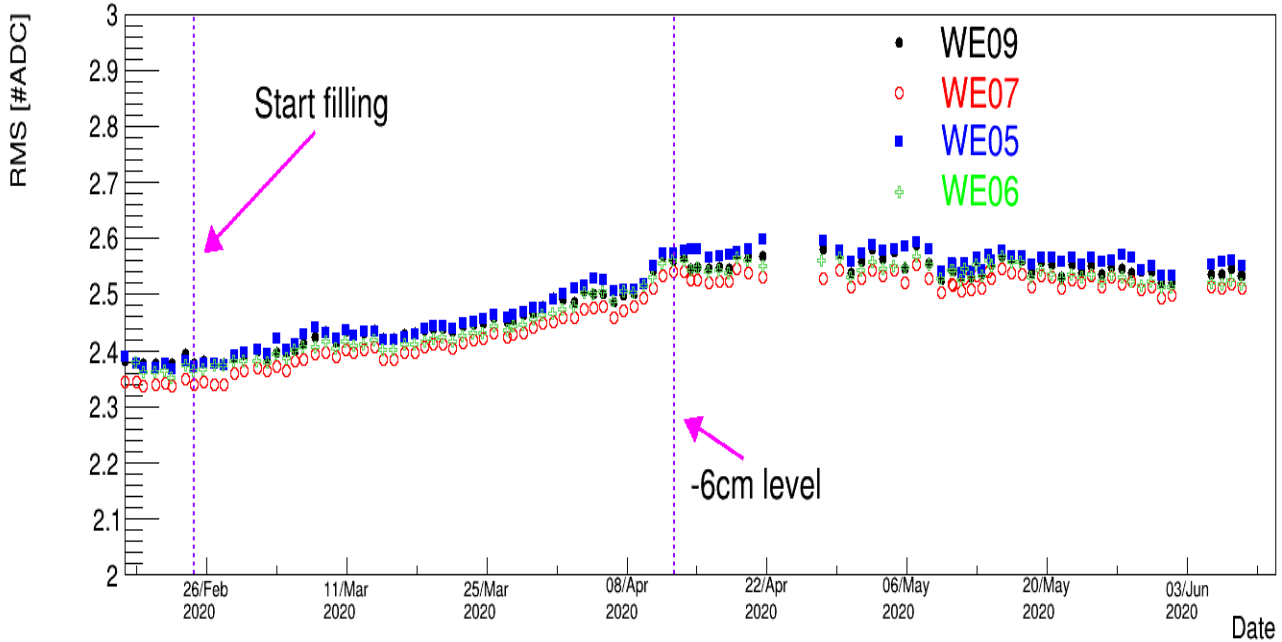
- Front-end based on analog low noise/charge sensitive pre-amplifier
- More compact layout: both analog+digital electronics in a single flange
- Lower noise ~1200 e- equivalent (~20% S/N improvement w.r.t LNGS)
- Shorter shaping time ~1.5 μs matching e- transit time between wire planes, providing a better hit separation in vertex region



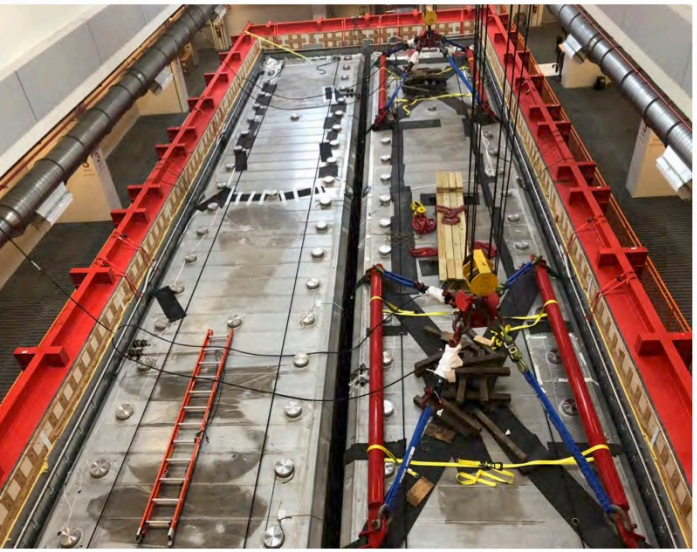
10 liters mini-crate hosts 9 boards (576 channels)

All TPC electronics have been installed. 10 mini-crates have been continuously recorded to monitor noise conditions during filling:

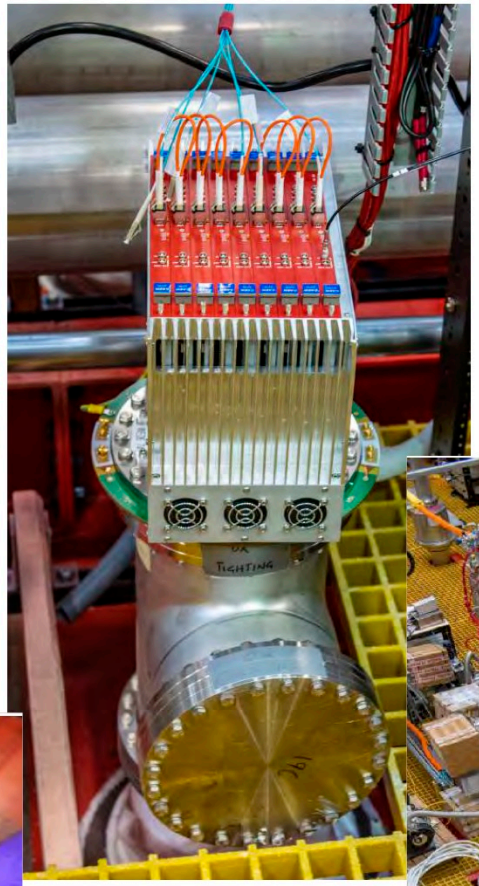
- A steady increase of the noise level (after the removal of the observed coherent noise component) has been observed during the Liquid Argon filling, in agreement with the expected variation of the wire capacitance due to increase of the level of the Liquid Argon inside the detector



ICARUS installation at FNAL



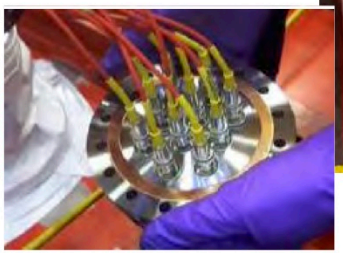
Placement of ICARUS inside the warm vessel (August 2018)

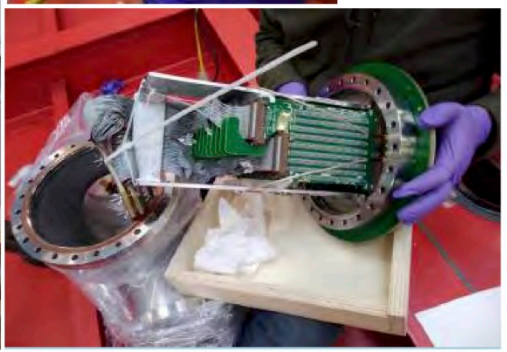


All TPC readout electronics installed (May 2019) and tested

All cryogenics equipment installed, welded and tested (May 2019)

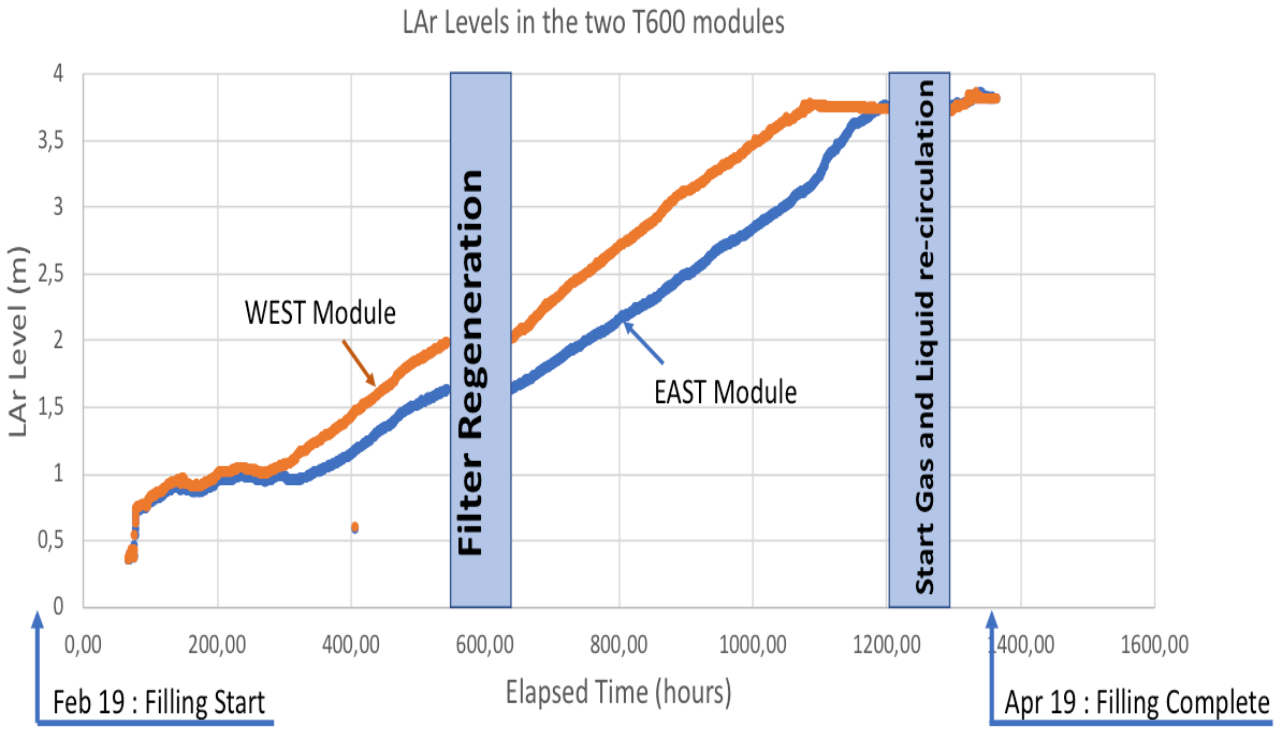
Feedthrough TPC/PMT/laser flanges installation (December 2018)

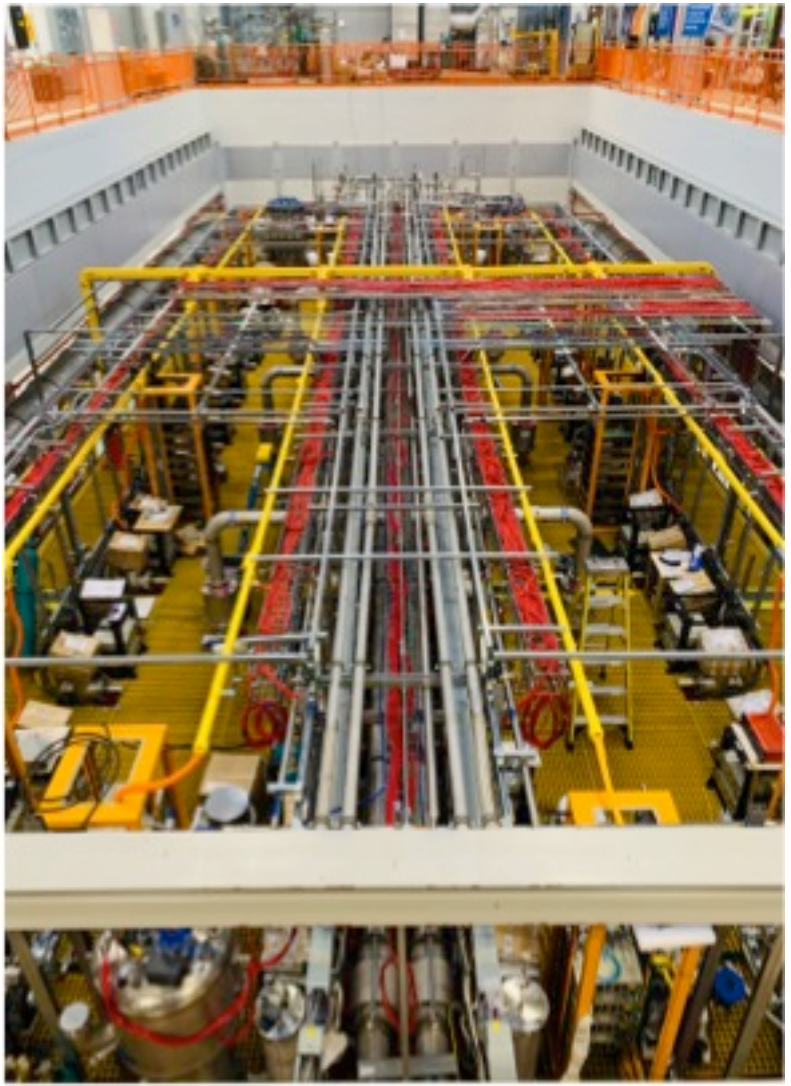




ICARUS filling and cryogenics commissioning

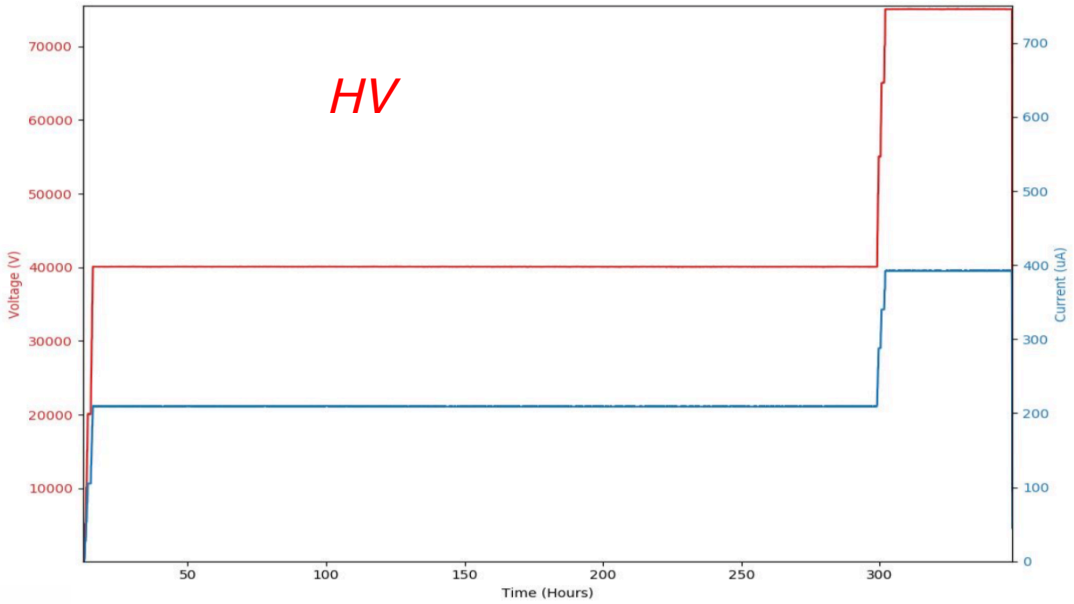
- Filling with Liquid Argon (two months) completed on April 19, 2020
- Increase of TPC wire noise due to capacitive effect agrees with expectations
- Both liquid and gas recirculation are online and in steady state conditions (1.85 m^3/hr West, 2.25 m^3/hr East)
- Pressure and temperature across both modules are stable

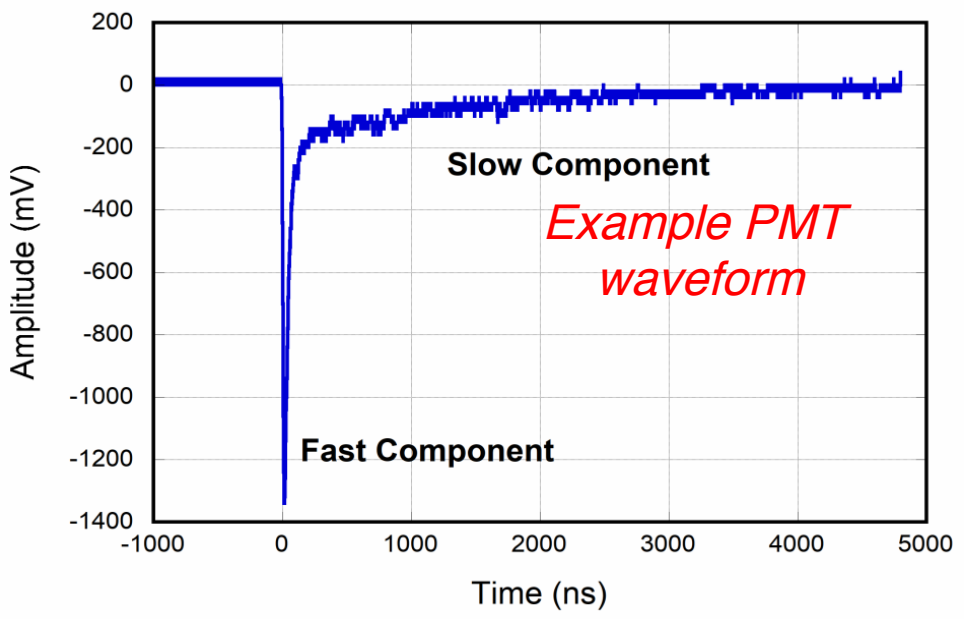




ICARUS detector commissioning

- After filling, commissioning work is going on despite limitations due to Covid19
- HV system brought up to nominal 75 kV voltage: system is stable
- TPC wire bias is under test at nominal values



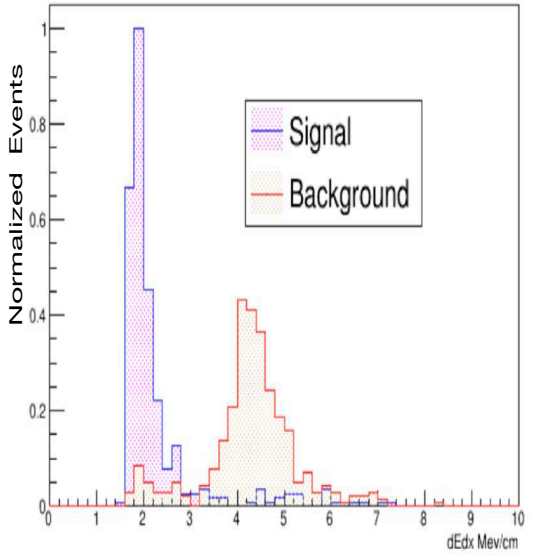


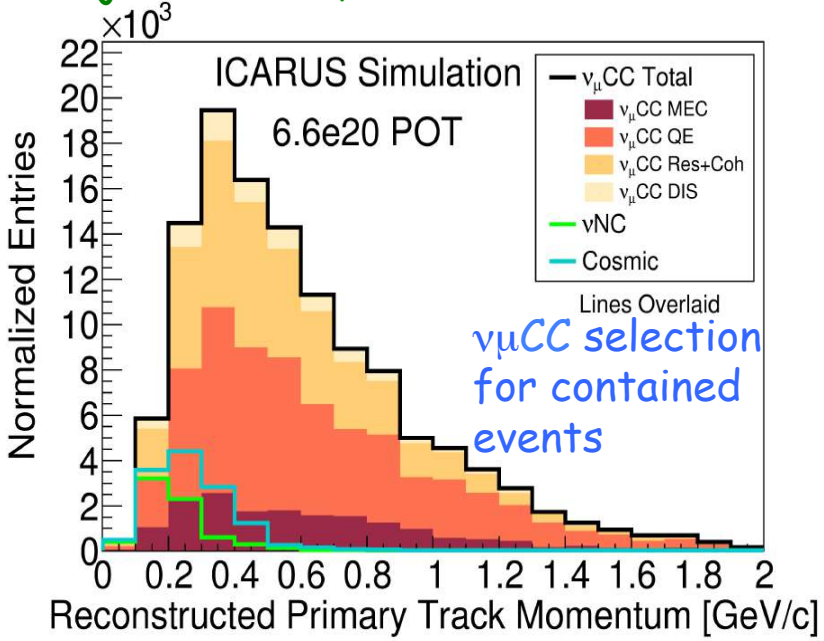
- All PMTs characterized in vacuum, then activated in LAr
- PMT calibration with laser is being performed
- Gain and noise are being measured
- Ar^{39} background was observed
- CRT wall installation is taking place

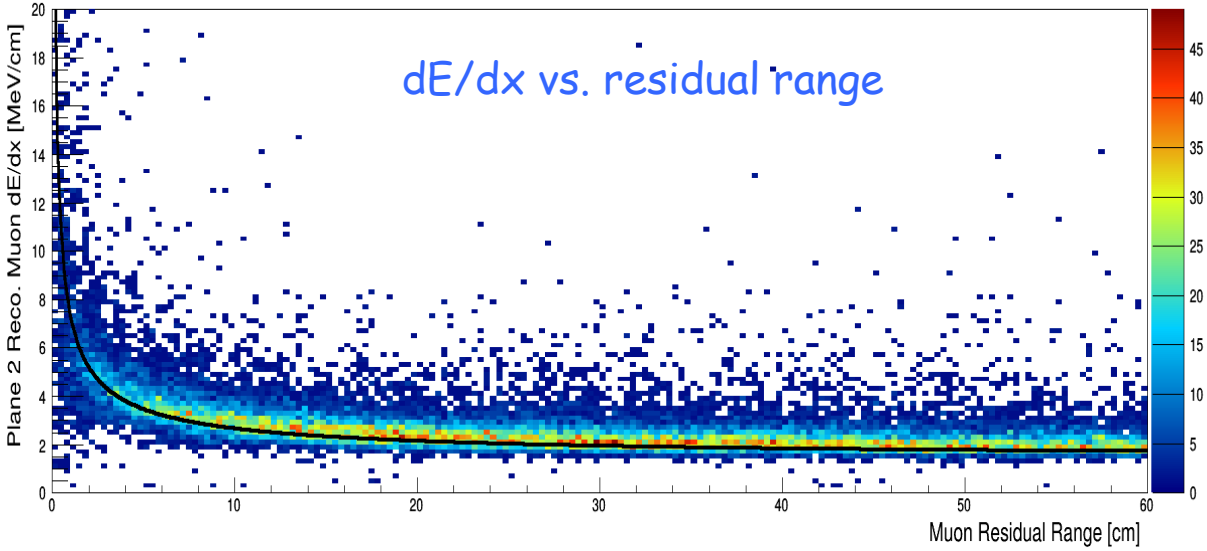
Reconstruction and analysis in SBN

- A detailed understanding of detector-related systematics and their correlation across near/far detectors will be crucial to SBN physics: common reconstruction tools and oscillation analysis are therefore fundamental
- Starting from LNGS experience, neutrino event selection and reconstruction is being developed: the combined signals from TPC, PMTs and CRT will help rejecting background from cosmics
- Promising results with the present stage of the reconstruction tuned for νe search: the dE/dx at the beginning of the shower provide a ~90% electron identification efficiency and ~90% rejection of γ in NC event for well reconstructed ν vertex

e/γ id based on the dE/dx at the beginning of the shower







Summary

- The ICARUS-T600 successful 3-year run at LNGS proved that LAr-TPC technology is mature and ready for large-scale neutrino physics experiments
- The SBN project at FNAL is expected to clarify the sterile neutrino puzzle, by looking at both appearance and disappearance channels with three LAr-TPCs
- After an extensive refurbishing, the ICARUS installation at FNAL in the SBN far site has been completed
- Filling of ICARUS with LAr is completed. The commissioning of all subdetectors (TPC, PMT, CRT) is ongoing
- ICARUS will see first neutrinos soon and the data taking for physics is expected by beginning of the next year !


Thank you!