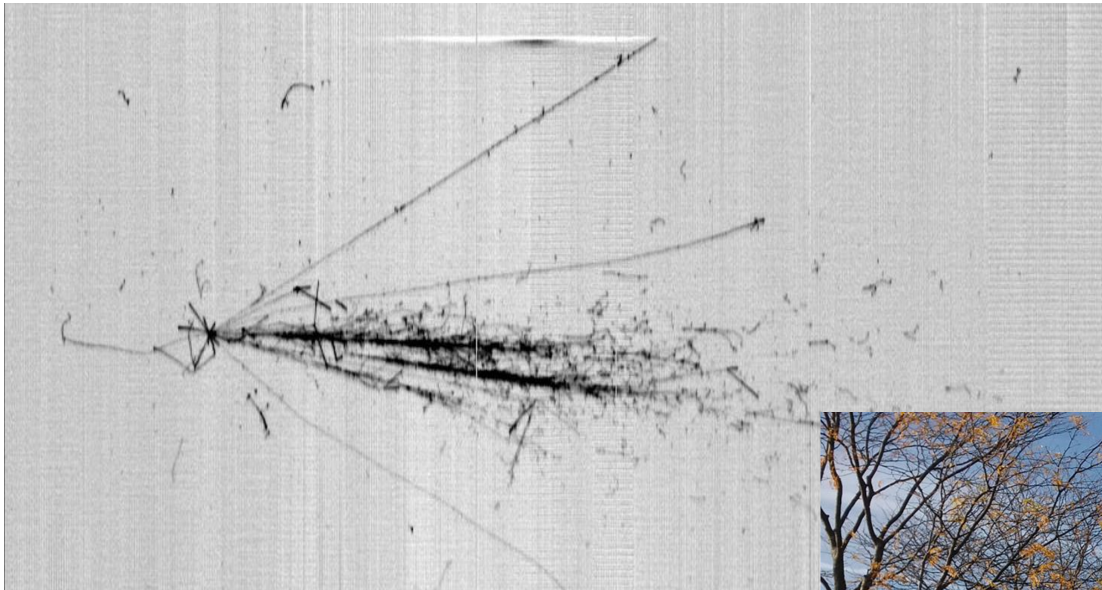
Sterile Neutrino searches with the ICARUS detector

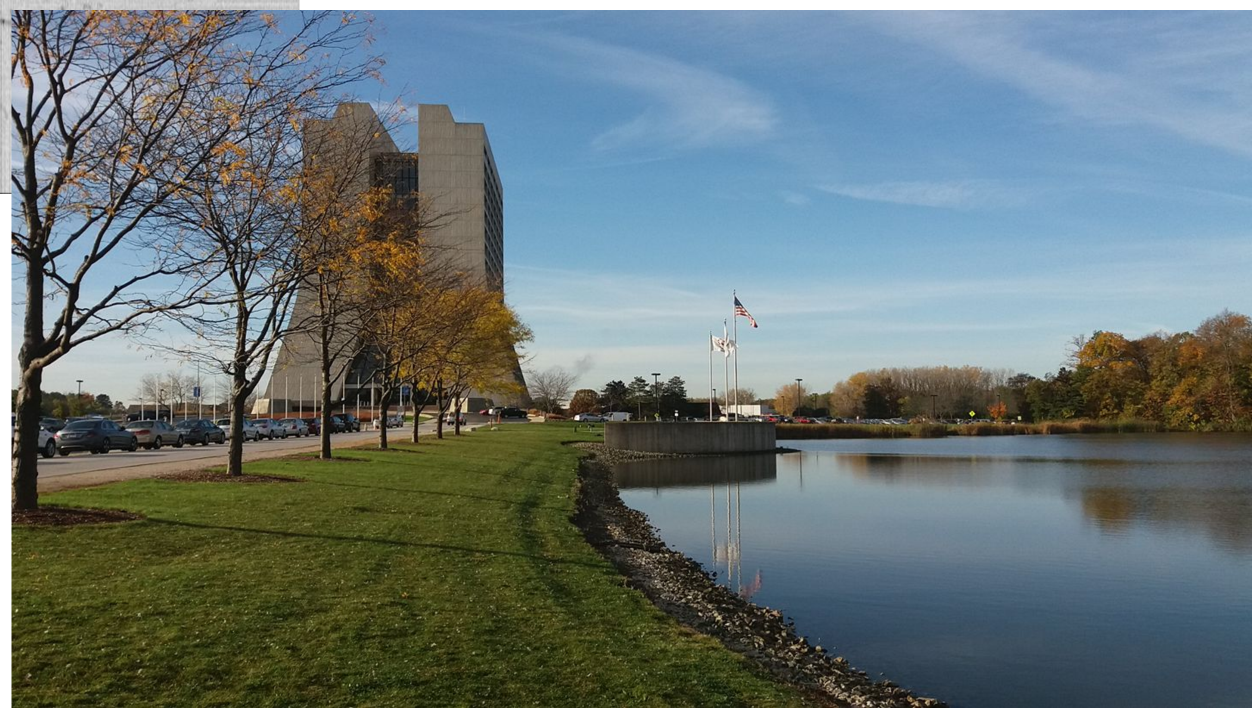


Christian Farnese
INFN Padova

on behalf of the
ICARUS collaboration

The 27th International Workshop on Weak Interactions and Neutrinos

Bari
June 3-8, 2019



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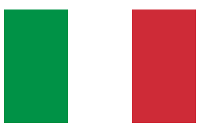

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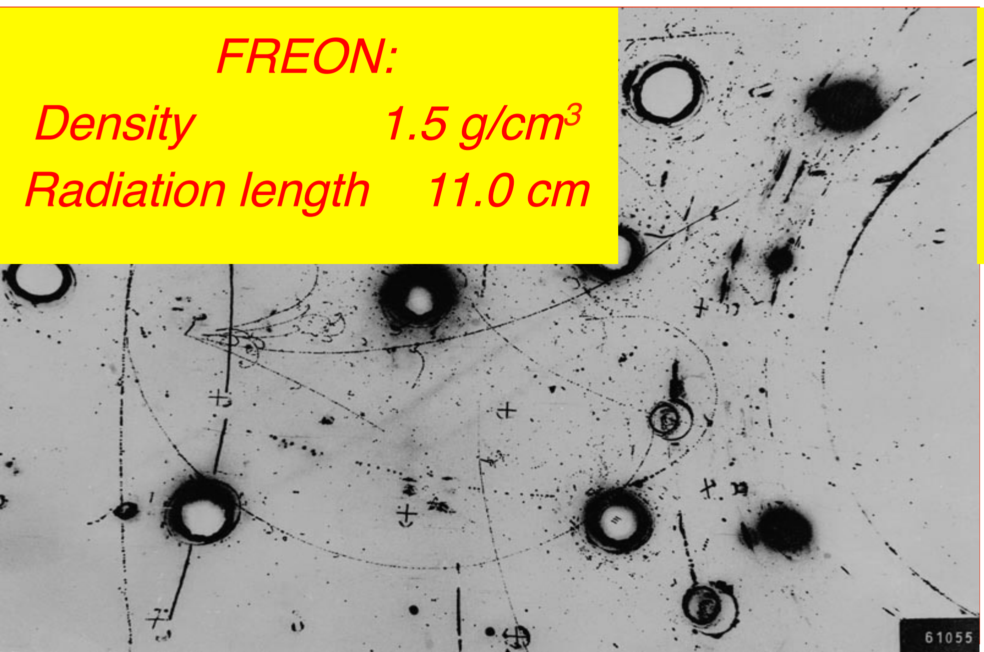
- *ICARUS Spokesman: <u>C. Rubbia, GSSI.</u>*
- *7 INFN groups, 9 USA institutions, 1 Mexico institution.*

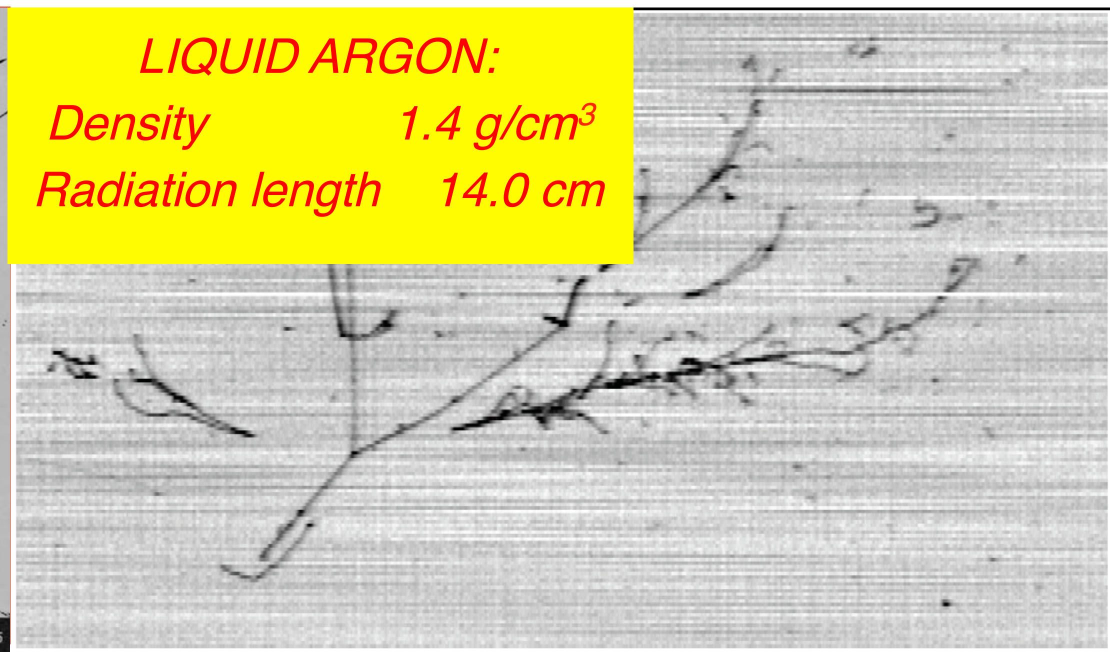
Liquid Argon TPC: an "electronic bubble chamber"

- LAr-TPCs are ideal detectors for neutrino physics and nucleon decay:
  - 3D reconstruction with high (mm^3) spatial granularity
  - Homogeneous, full-sampling calorimetry for contained particles
  - Scintillation light can provide fast signals for timing/triggering
  - Electrons can drift for several meters (if Argon is sufficiently pure)
  - LAr is dense and cheap: very large masses (ktons) are realistic
- First proposed by C. Rubbia in 1977: long R&D at INFN and CERN culminated in first large-scale experiment: ICARUS-T600 at LNGS (2010)
- LAr physical parameters very similar to Freon of "classic" bubble chambers:

FREON:
Density 1.5 g/cm^3
Radiation length 11.0 cm

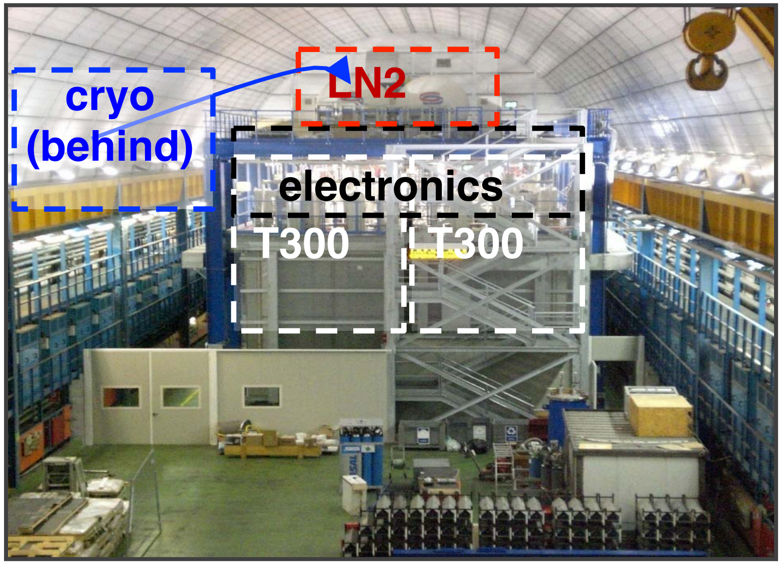


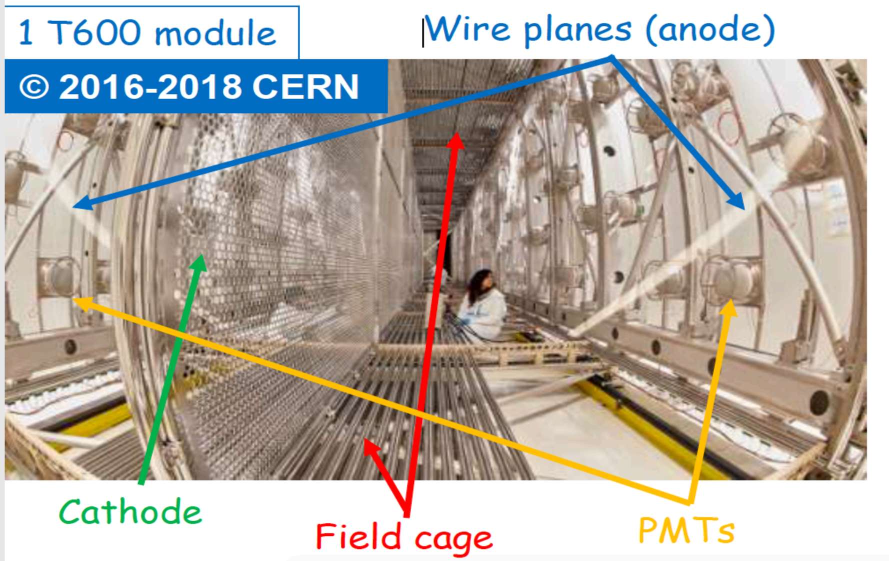
LIQUID ARGON:
Density 1.4 g/cm^3
Radiation length 14.0 cm



ICARUS-T600 at LNGS

- 2 identical modules: each is 19.6x3.6x3.9 m^3, with active mass of 476 t (total 760 t)
- Drift distance 1.5 m and electric field 500 V/cm -> drift time ~ 1 ms
- 3 signal wire planes (2 Induction+Collection) with "non-destructive" wire readout
- Pitch and inter-plane distance both 3 mm; 400 ns sampling time; ~ 54000 total channels
- 74 (20+54) 8" PMTs with TPB wavelength-shifter coating



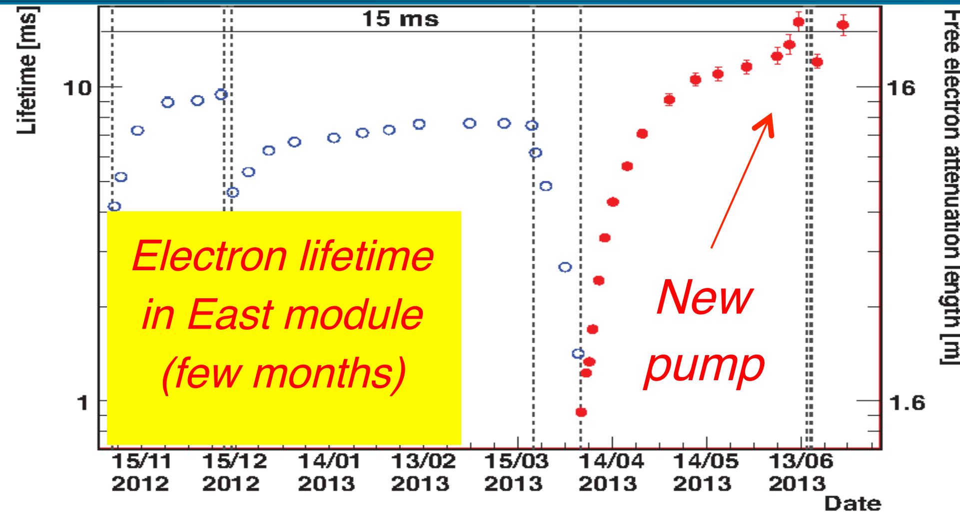


- ICARUS was exposed to CNGS beam and cosmics for 3 years
- Run confirmed expected performance and obtained important physics results
- It proved the maturity of the LAr-TPC technique for large-scale experiments

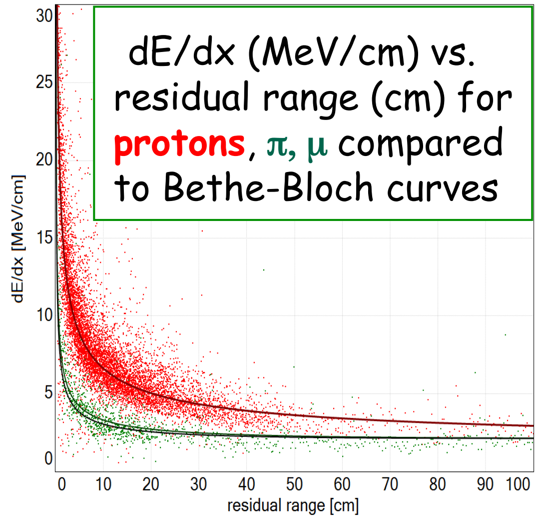
ICARUS paved the way to the next generation long-baseline project: DUNE

ICARUS reconstruction performances

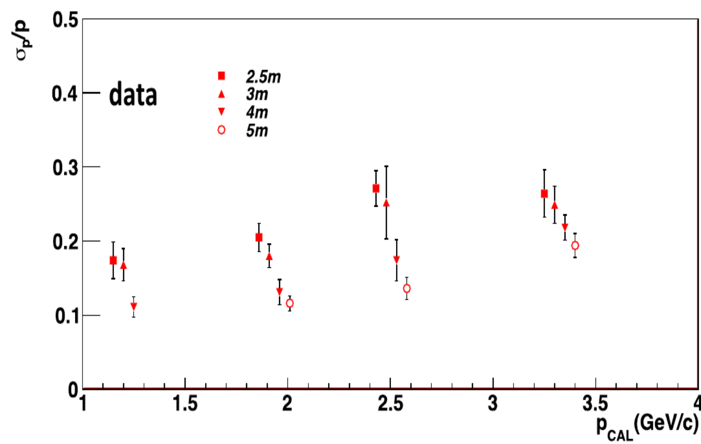
- High electron lifetime: > 7 ms (impurity concentration < 40 ppt) over whole run. Crucial step towards future larger detectors
  2014 JINST 9 P12006



- Excellent spatial/calorimetric reconstruction. Accurate dE/dx measurement with fine sampling ($0.02X_0$). Particle ID from dE/dx vs. range
  AHEP (2013) 260820

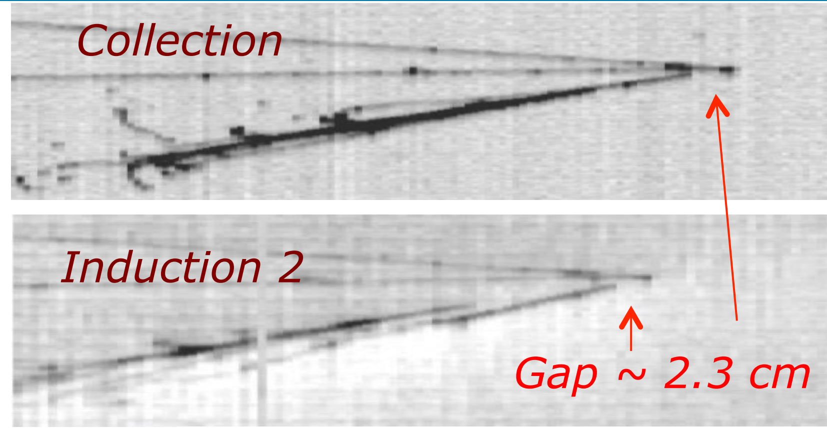


- Momentum of escaping muons measured by multiple Coulomb scattering. Average ~ 15% resolution on stopping muons (0.5÷5 GeV/c)
  JINST 12P04010

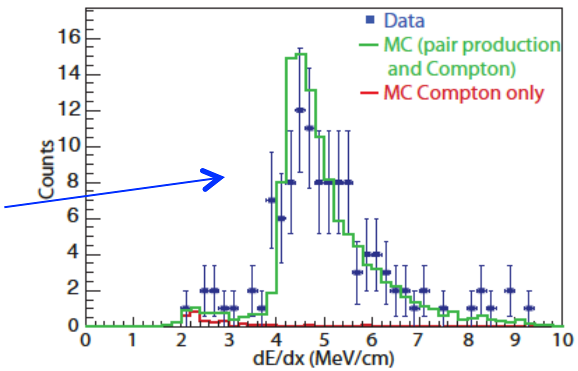


e/γ separation and ν_e identification

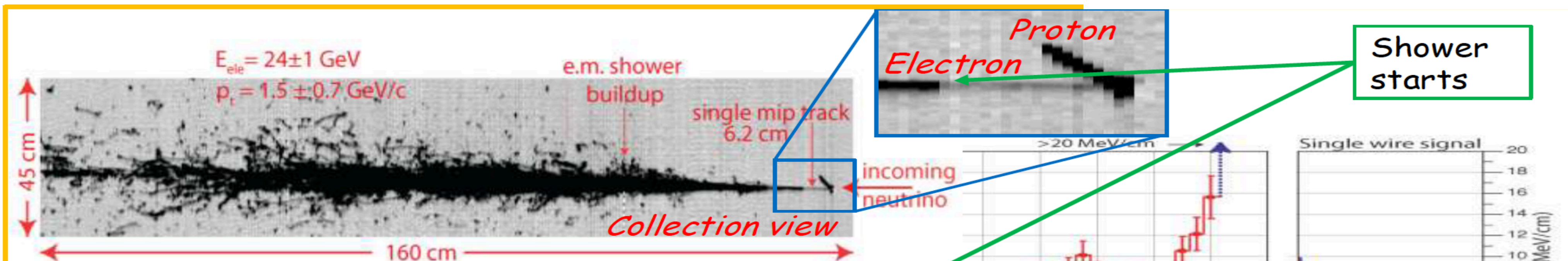
- ν_e CC event (electron-initiated EM showers) separation from NC background with π^0 (γ-initiated showers): crucial for oscillation physics
- LAr-TPC provides 3 handles:
  - Visual identification of γ conversion gap
  - Reconstruction of π^0 invariant mass
  - dE/dx: calorimetric accuracy and fine sampling (2% X_0) allow measuring dE/dx on each wire: single MIP corresponds to an electron.



dE/dx of sub-Gev photons:



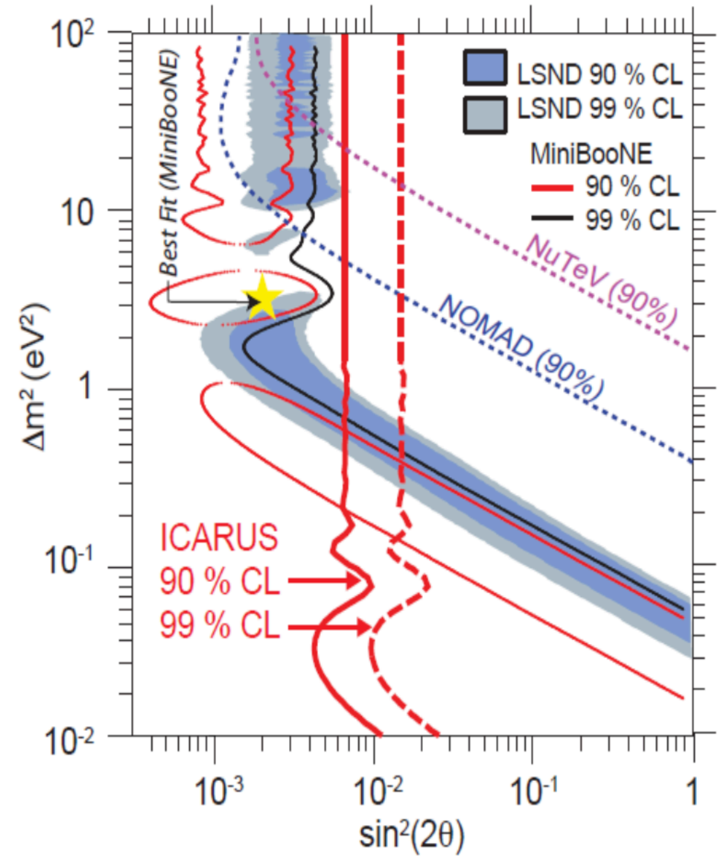
High-energy CNGS ν_e CC interaction:



Evolution in Collection view from single m.i.p. to e.m. shower evident from dE/dx (MeV/cm) on individual wires.

ICARUS search for sterile neutrinos

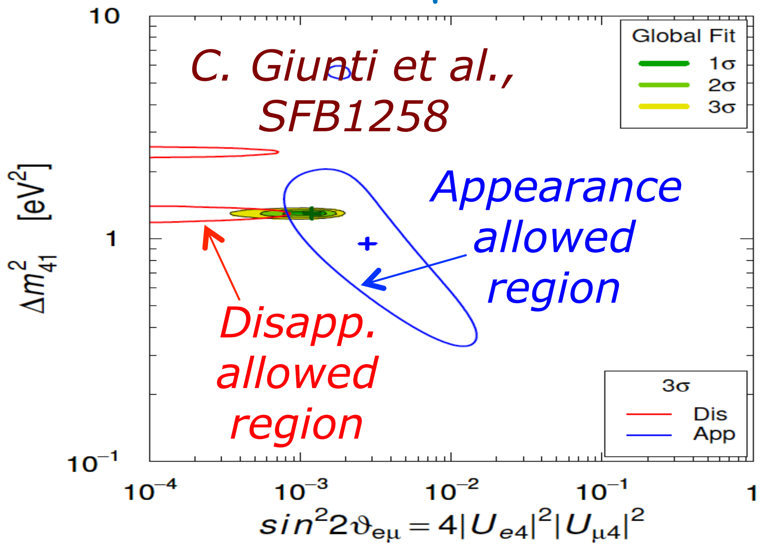
- ICARUS searched for sterile ν oscillations through ν_e appearance in the CNGS beam
- L/E ~ 36 km/GeV, far from LSND value ~ 1 km/GeV -> "sterile-like" oscillation was averaged out, canceling energy dependence
- 7.9 10^{19} pots analyzed (~2650 ν interactions)
- Expected ~ 8.5±1.1 ν_e background events in absence of anomaly, mostly from intrinsic ν_e beam contamination
- Estimated ν_e identification efficiency ~74% with negligible background from misidentification
- 7 events observed → no evidence of oscillation
- Most of LSND allowed region is excluded – except for small area around $\sin^2 2\theta$ ~ 0.005, $\Delta m^2 < 1$ eV^2
- Similar result by OPERA with same CNGS beam and different detection technique



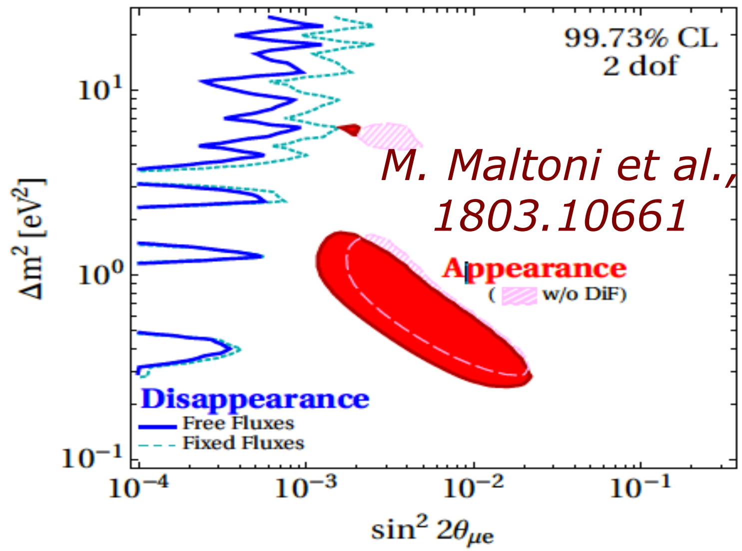
Eur. Phys. J. C (2013) 73:2599

Perspectives for sterile neutrino physics

- The sterile neutrino scenario is far from understood and needs a definitive clarification
- Some "anomalies" from accelerators (LSND), reactor, neutrino sources, point out to flavour transitions in the $\Delta m^2 \sim 1\ eV^2$ range
- However, no evidence of oscillations in ν_μ disappearance data (MINOS, IceCube)
- Tension between ν_e appearance and ν_μ disappearance results. Measuring both channels with the same experiment will help disentangle



Combined analyses



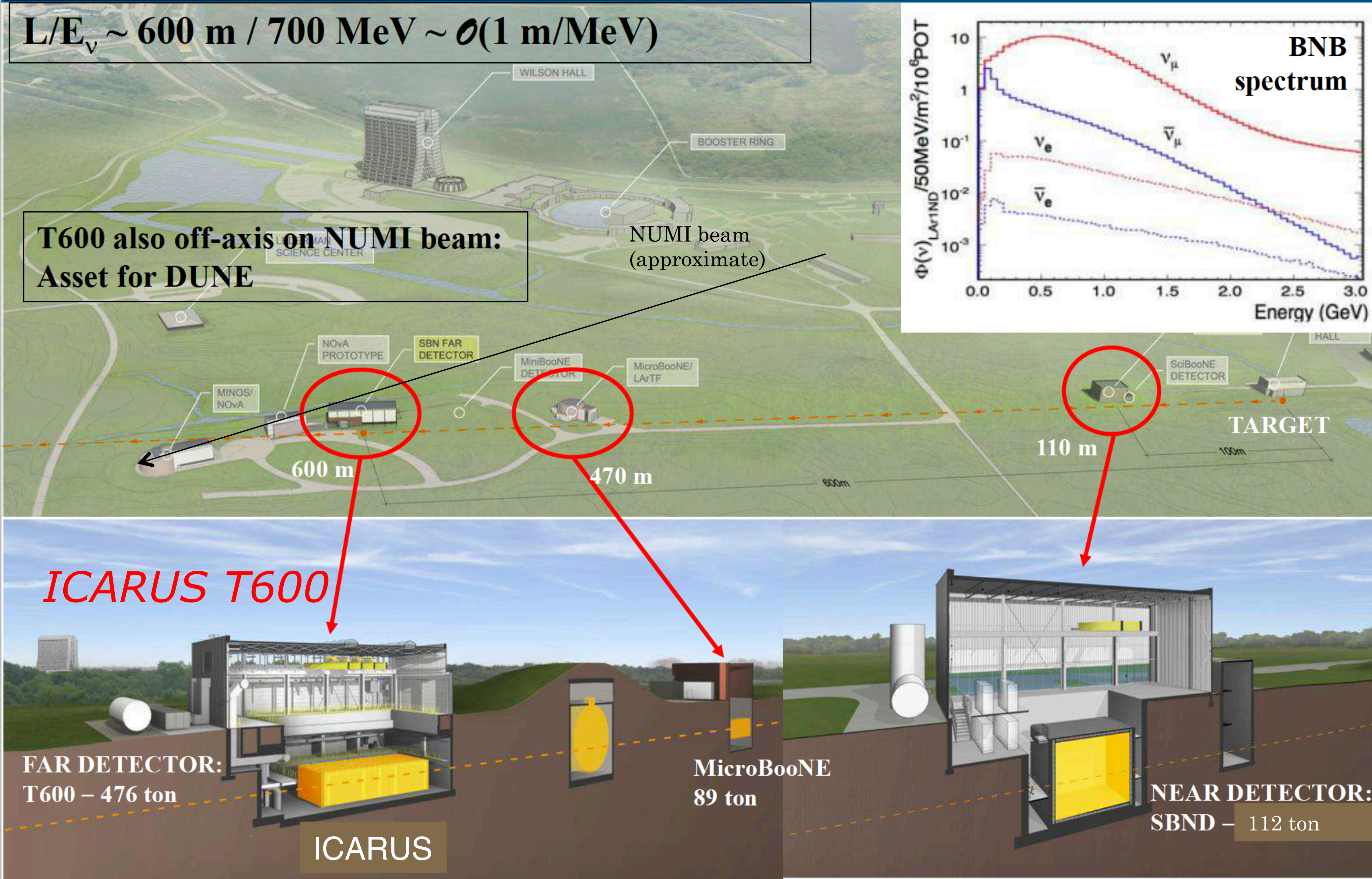
- A comparison between far/near detector is crucial for any accelerator experiment, with a better control of backgrounds and systematics

SBN satisfies these requirements: it could have a crucial role in solving the sterile neutrino puzzle!

The SBN project

$L/E_\nu \sim 600\ m\ /\ 700\ MeV \sim \mathcal{O}(1\ m/MeV)$

T600 also off-axis on NUMI beam: Asset for DUNE



SBN Sterile neutrino search at FNAL Booster ν beamline

- The experiment will exploit 3 LAr-TPCs exposed to the FNAL Booster Neutrino Beam, with only ~ 0.5% ν_e contamination, at different distances from target:

  SBND, MicroBooNE and ICARUS at 110, 470, and 600 meters respectively

- The experiment is expected to clarify the sterile anomaly by precisely/independently measuring both ν_e appearance and ν_μ disappearance

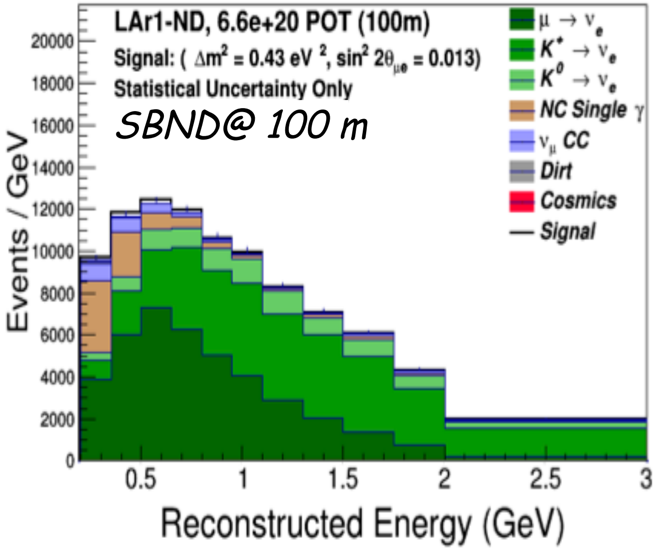
- Using the same detector technology for all the 3 detectors will greatly reduce the systematic errors: SBND (near detector) will provide the "initial" beam composition and spectrum

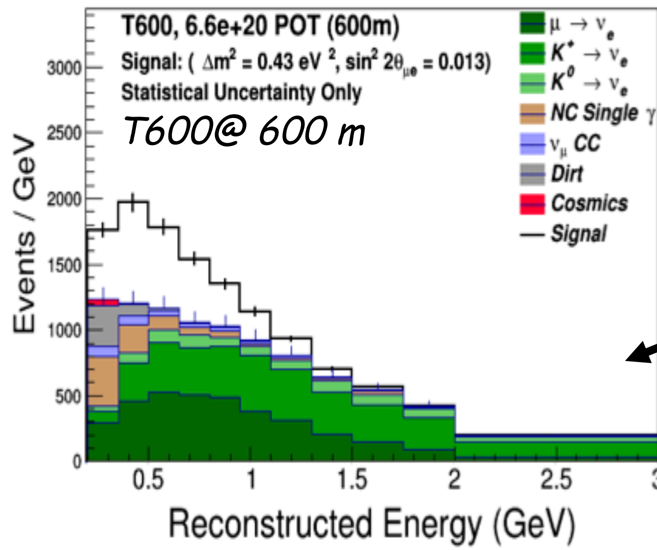
- The great ν_e identification capability of LAr-TPC will help reduce the NC background

- During SBN operations, ICARUS will also collect ~ 2 GeV neutrinos from NuMI (Neutrino Main Injector) Off-Axis beam. This will be an asset for the future long-baseline project:
  - ν interaction cross-section measurements and identification/reconstruction studies
  - In particular, a large ν_e component with ~ 3 GeV energy (in the DUNE range)

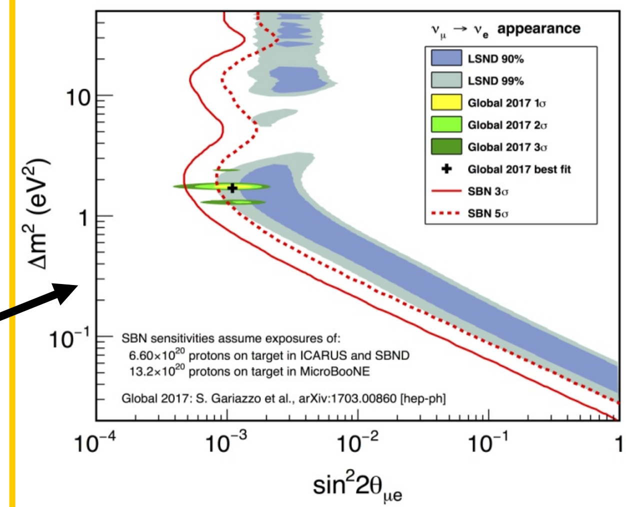
SBN spectra and sensitivities for 3 years (6.6 10^{20} pot)

ν_e spectra (oscillation signal + backgrounds),
Example for $\sin^2 2\theta = 0.013$ $\Delta m^2 = 0.43$ eV^2





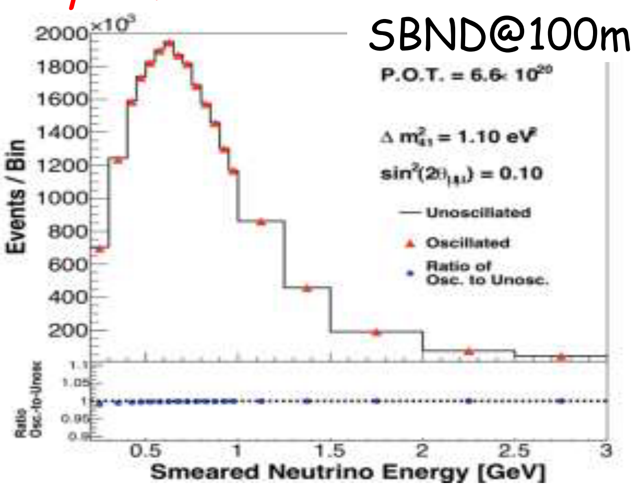
ν_e appearance: LSND 99% CL region covered at 5 σ level

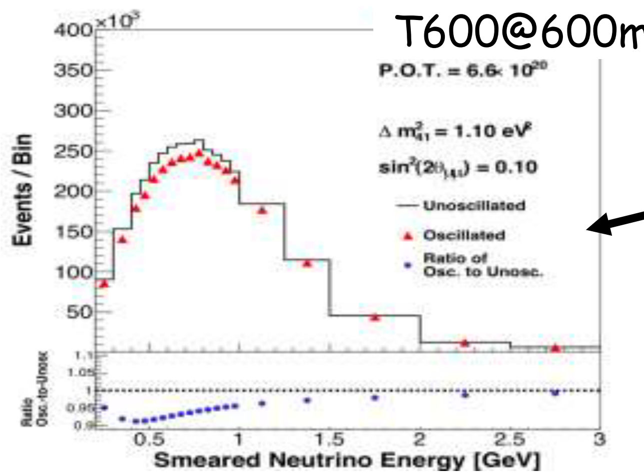


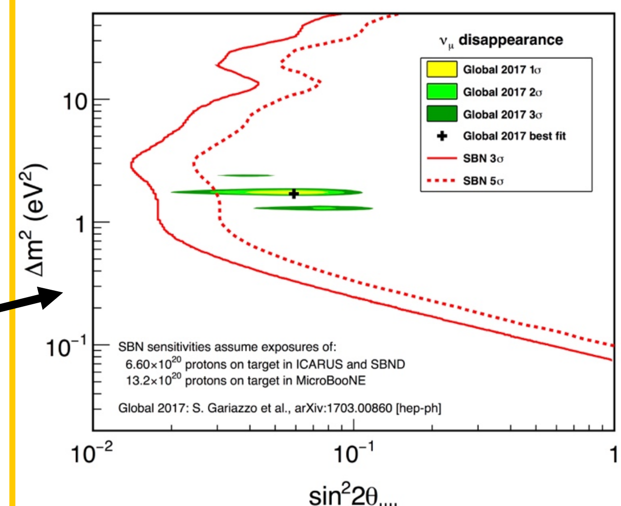
In absence of oscillations, spectra should be ~identical

3-5 σ ν_μ disapp. SBN sensitiv.

ν_μ spectra (oscillation modulation) for 3 years (6.6 10^{20} pot)
Example for $\sin^2 2\theta = 0.01$ $\Delta m^2 = 1.10$ eV^2



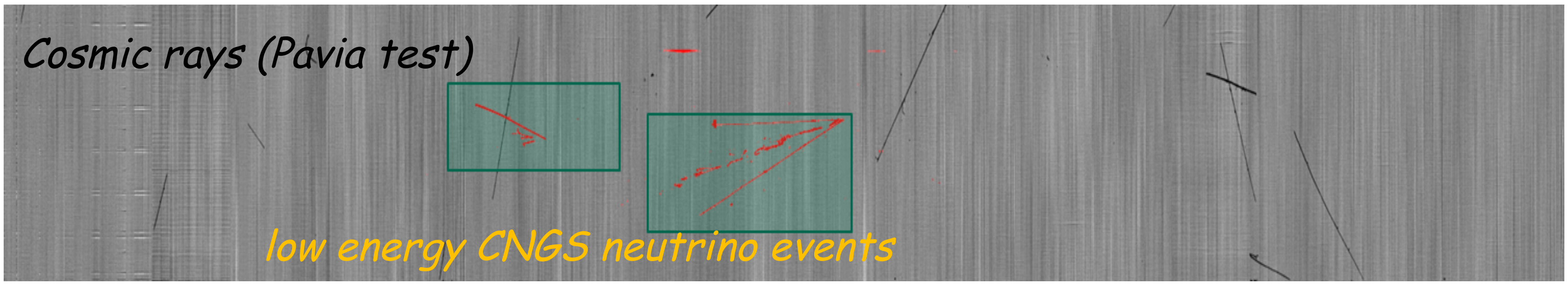




A new experimental challenge: a LAr-TPC on surface

ICARUS at FNAL is facing a more challenging experimental condition than at LNGS, requiring the recognition of $O(10^6)$ ν interactions amongst 11 KHz of cosmic rays.

- A 3 m concrete overburden will remove contribution from charged hadrons/γ's.
- ~11 μ tracks will hit the T600 in 1 ms TPC drift window: associated γ's represent a serious background source for νe search since e's produced via Compton scatt./ pair prod. can mimic a genuine νe CC.



- To face new experimental conditions, T600 underwent an intensive overhauling at CERN in the Neutrino Platform framework from 2015 to 2017, before shipping to US.
- Several technology developments were introduced *while maintaining the already achieved performance at LNGS run:*
  - new cold vessels, with a purely passive insulation;
  - renovated LAr cryogenics/purification equipment;
  - improvement of the cathode planarity
  - upgrade of the PMT system: higher granularity and ns time resolution
  - new faster, higher-performance read-out electronics;

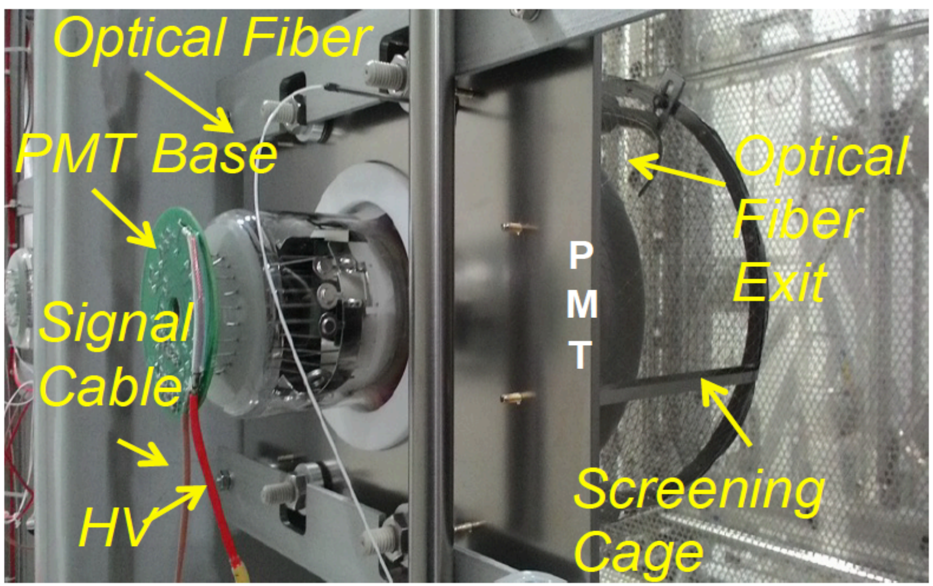
Upgrade of the light collection system

In shallow depth operation, the light collection system will allow to:

- Precisely identify the time of occurrence (t_0) of any ionizing event in the TPC
- Determine the event rough topology for selection purposes
- Generate a trigger signal for read-out

ICARUS@SBN exploits 90 PMTs per TPC (5% coverage, 15 phe/MeV) that provides:

- Sensitivity to low energy events (~ 100 MeV)
- Good spatial resolution (≲ 50 cm)
- ≈ ns timing resolution
- Possible cosmics identification by PMT space/time pattern



Timing/gain equalization will be performed with laser pulses

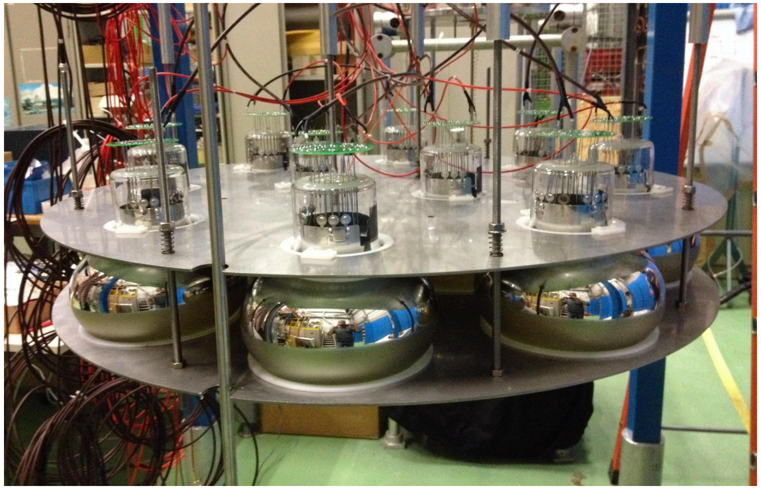
λ = 405 nm

FWHM < 100 ps

peak power ~ 400 mW

PMT tests at CERN

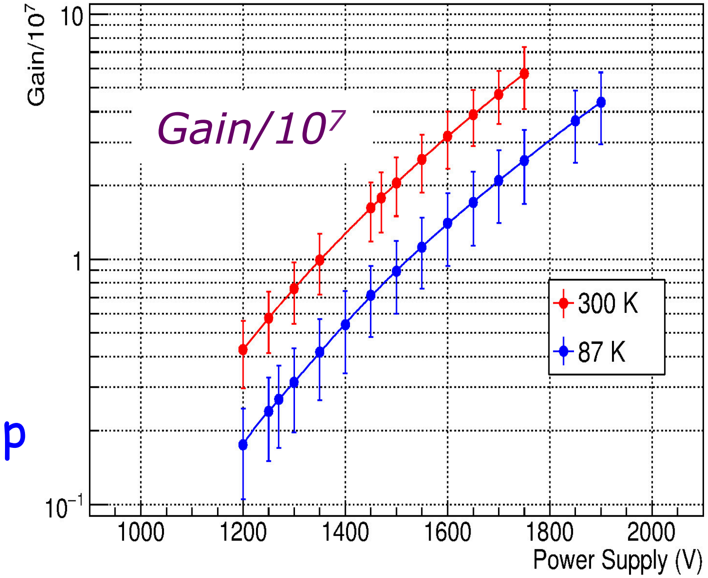
- All PMTs tested at room temperature in a dedicated dark room at CERN
- A subset of 60 PMTs tested immersed in LAr to compare the PMT performance in cryogenic environment to room temperature
- All PMTs illuminated with laser light pulses

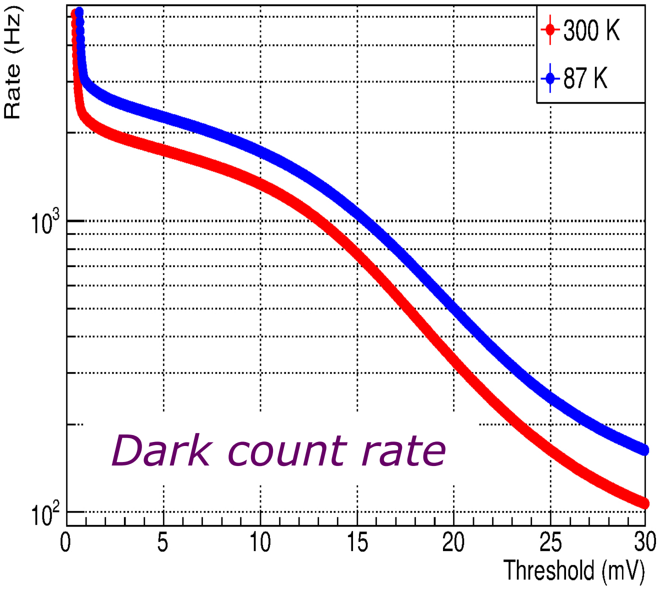


PMTs were characterized individually at 300K and 87K:

- Gain
- Dark count rate
- Peak/valley ratio
- Uniformity of photocathode response

The gain reduction in LAr w.r.t. room temperature (up to a factor 10) will be compensated by a ~ 100 V increase in power supply voltage



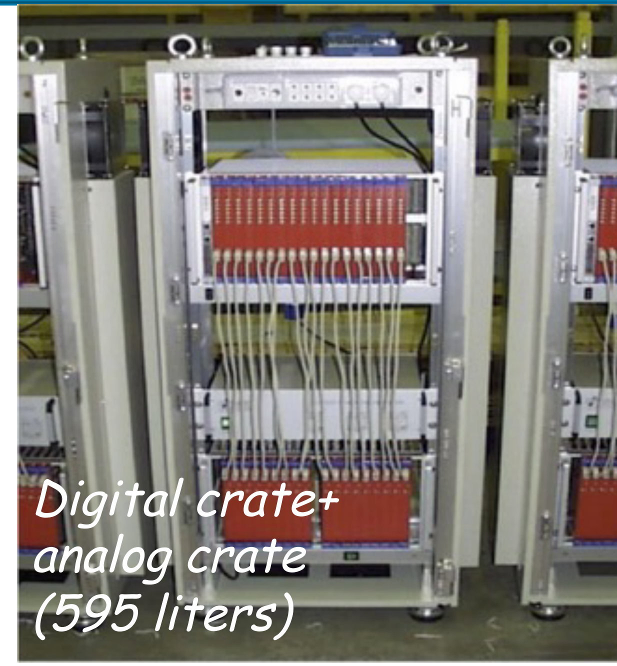


JINST 13 (2018) P10030

Upgrade of the TPC read-out electronics

ICARUS electronics at LNGS was based on:

- "warm" low-noise front-end amplifier
- Multiplexed 10-bit ADC
- Digital VME module for local storage, data compression, trigger information

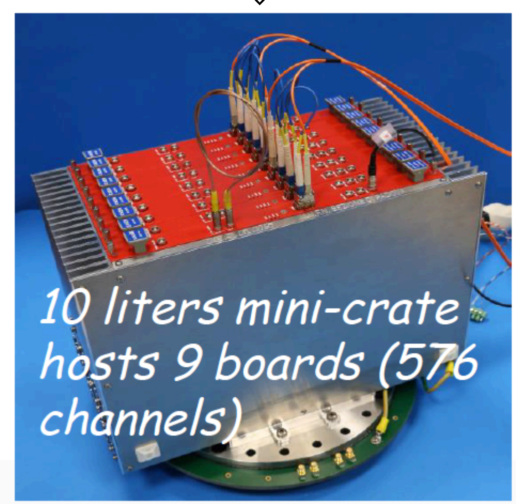


Performances proved adequate for track reconstruction and muon momentum measurement (Multiple Coulomb Scattering)

$(S/N)_{m.i.p.}$ ~ 7 in Collection, resolution σ_y ~ 0.7 mm along drift

However, in view of the SBN program, some components were modernized and improved:

- Serial 12-bit ADC, fully synchronous in the whole detector -> ~20% improvement in muon momentum resolution via MCS
- Serial bus architecture increases transmission rate to Gbit/s
- More compact layout: both analog+digital electronics hosted on a single flange



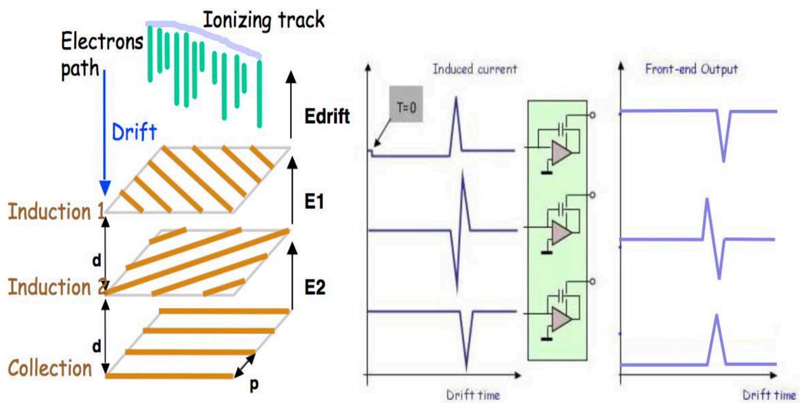
New electronics extensively tested on a 50-liter TPC@CERN

JINST 13 (2018) P12007

Front-end electronics for ICARUS@SBN

The analog front-end shaping was also modified:

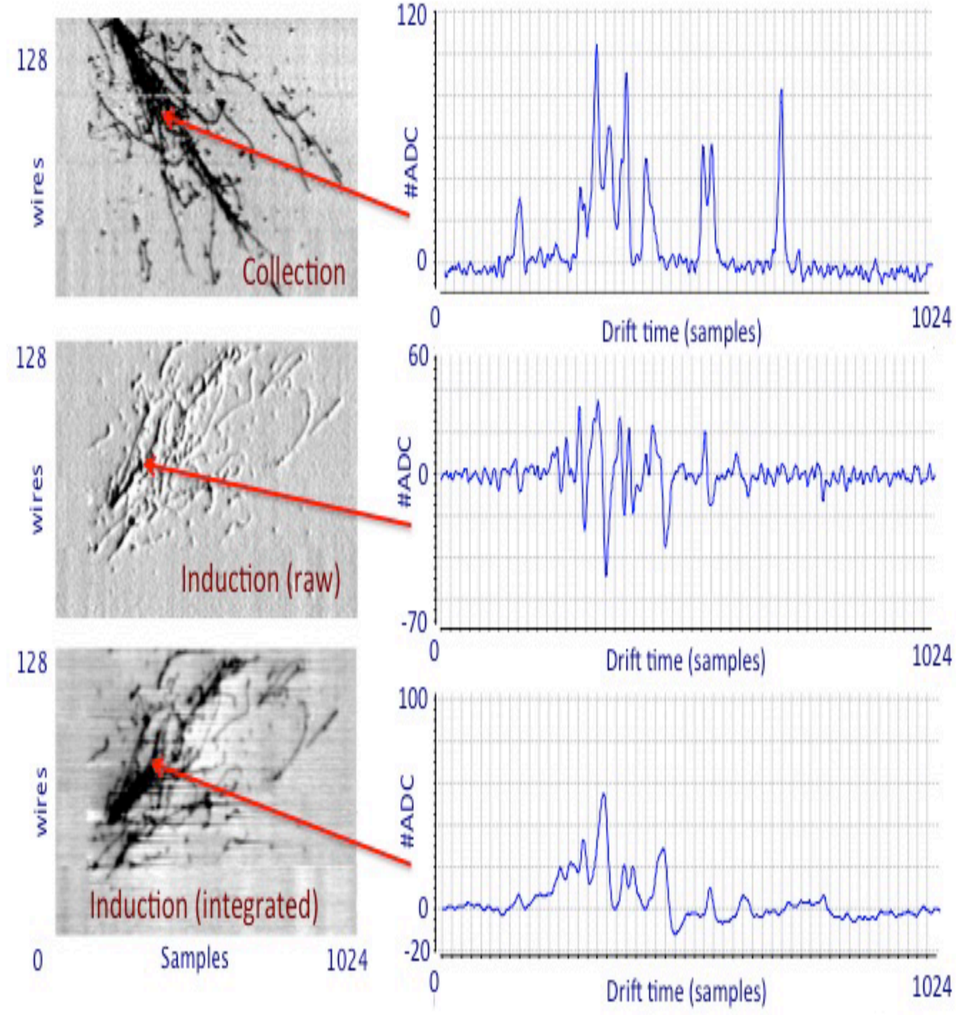
- Lower noise ~ 1200 e- equivalent (~20% S/N improvement w.r.t. LNGS electronics)
- Shorter shaping time (~ 1.5 μs for all planes) matching electron transit time between planes
- Drastic reduction of undershoot after large signals: better description of crowded vertex region



In particular, Induction 2 signal keeps bipolar shape (unlike in old front-end):

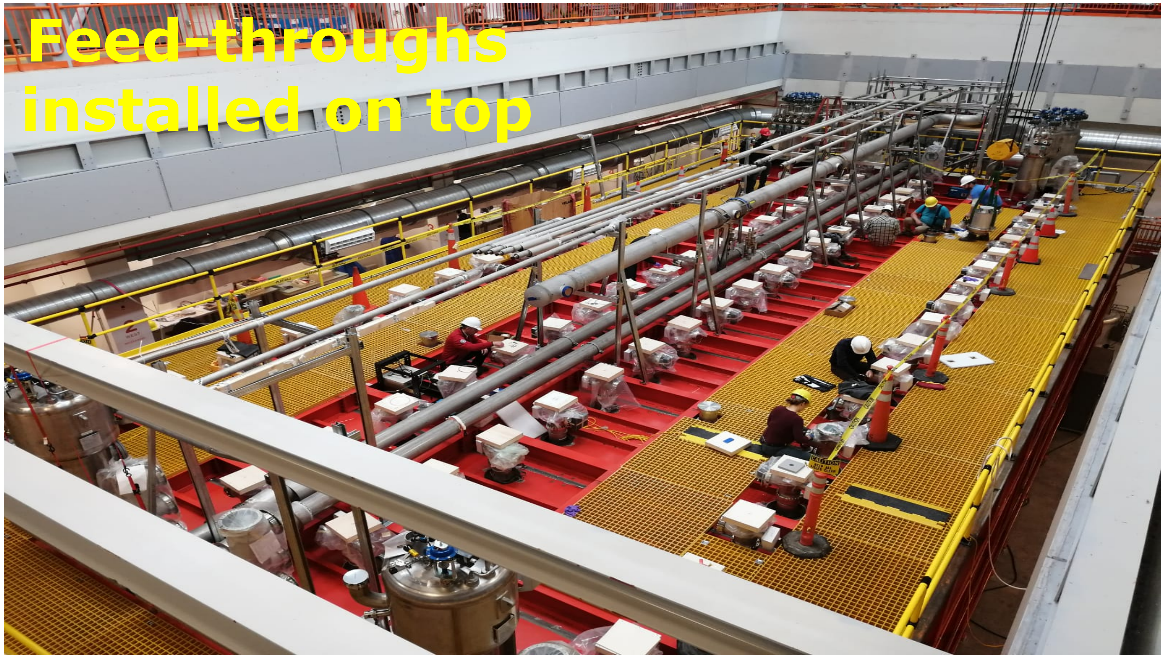
- Possible off-line integration with suitable LF filtering
- Allows calorimetric measurement in this plane too (with ~2 worse resolution than Collection)
- May improve νe identification efficiency by ~20%

Tests on 50-liter TPC at CERN:



ICARUS installation at FNAL - status

- T600 installed inside warm vessel in August 2018
- Installation of TPC/PMT feedthrough flanges and connectivity tests, completed by February 2019
- Leak tightness tests completed
- Top cold shields and top CRT support installed



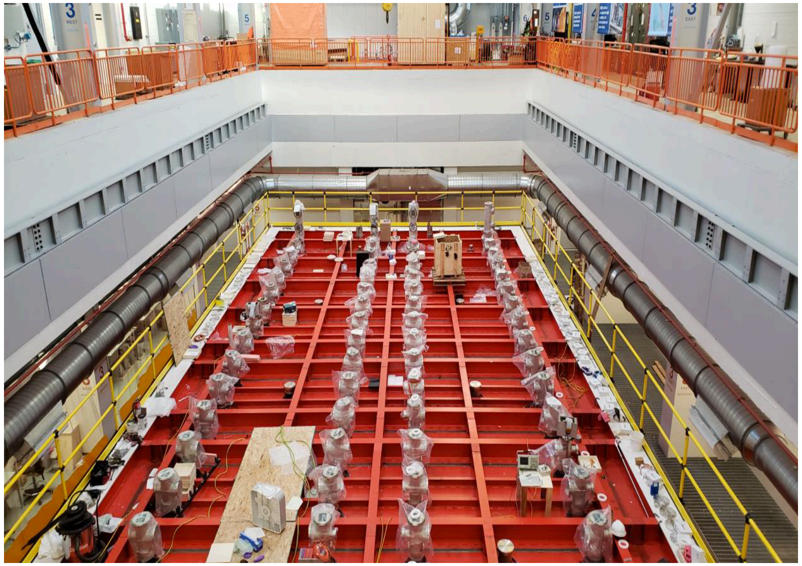
- PMT electronics and trigger being tested at cryogenic temperatures at CERN
- Installation of proximity cryogenics started in February
- Side CRT installation also ongoing
- Director's Review in December 2018 recognized the great progress of SBN

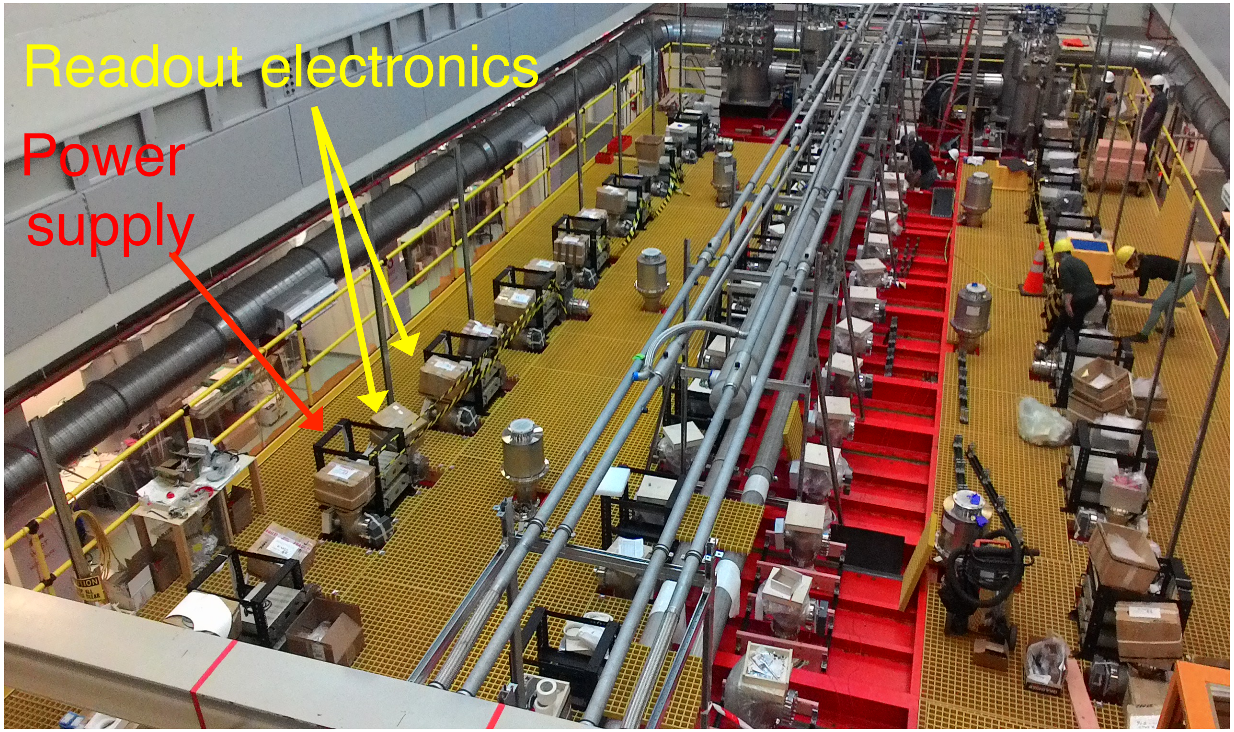
ICARUS installation @FNAL

Placement of ICARUS (August 2018)

Chimneys installation (October 2018)

Feedthrough installation (December 2018)

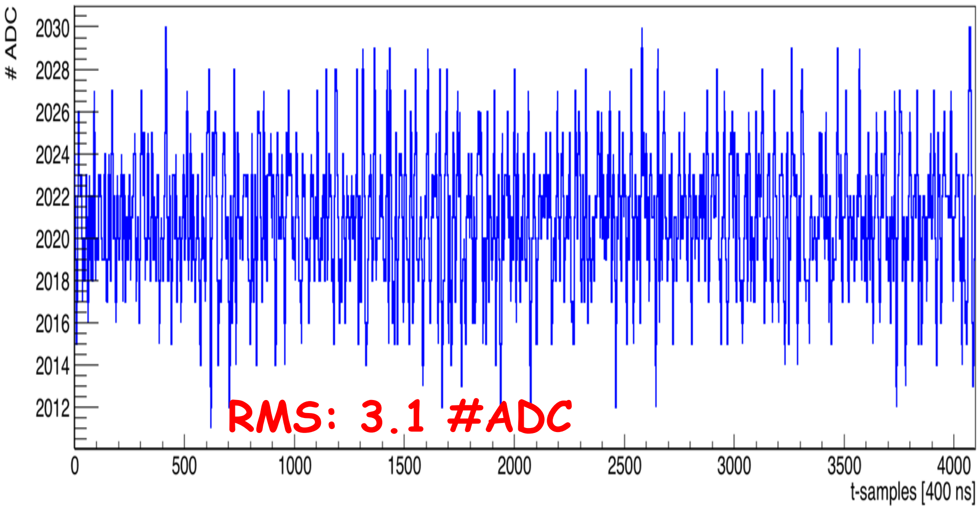


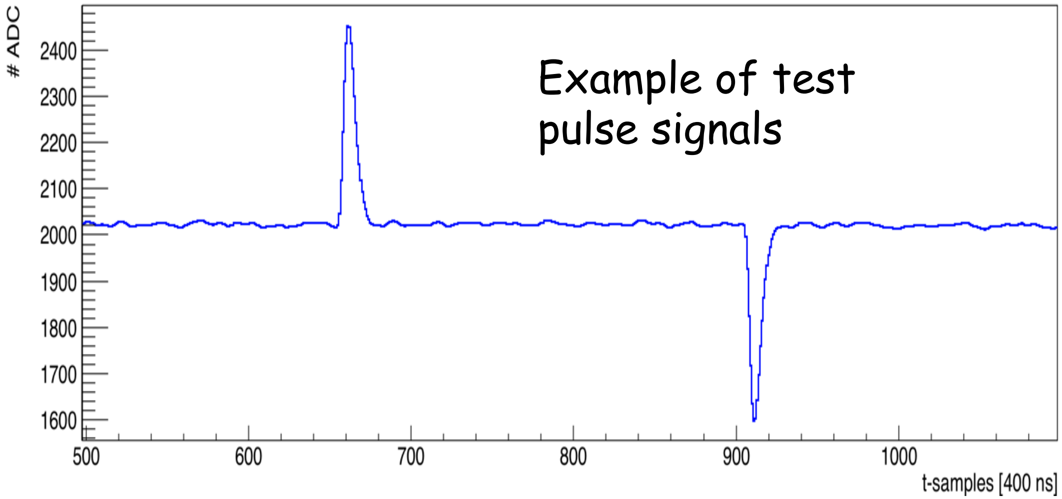


Installing the readout electronics (May 2019)

Recent tests on the readout electronics

- All the feedthrough flanges and the mini-crates with the TPC wire read-out electronics (576 channels + optical links) has been installed
- A test of the full readout chain, from wires to DAQ, has been performed in April/May for all the mini-crates
    - Allowed to check readout and set baseline for future noise monitoring
    - Noise measured on random triggers and test pulses
    - Noise RMS ~1700 e-, not too far from ~1200 e- measured in CERN 50-liter setup: grounding conditions were still far from optimal





The successful readout test confirms the good performance of the full TPC electronics!

The Cosmic Ray Tagging system (CRT)

- Surrounds the cryostat with two layers of plastic scintillators: 1100 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

TOP:

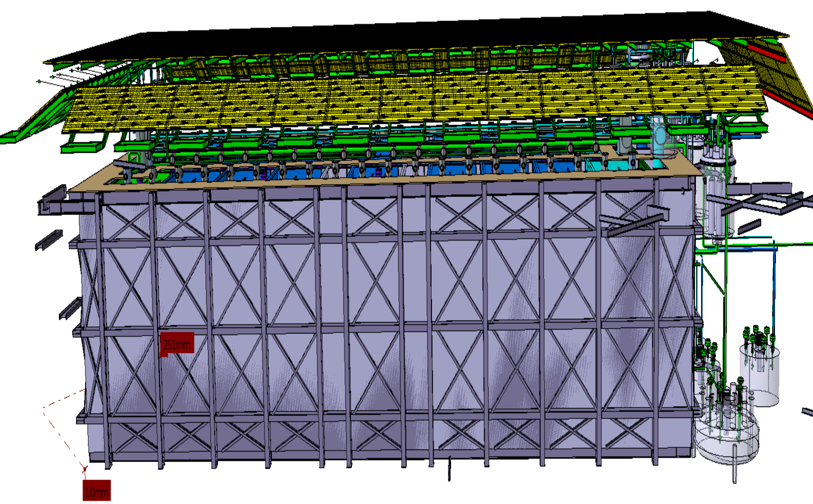
~ 400 m^2: roof+angled parts
Will catch~80% cosmic ms
2 strip layers (X+Y)
SiPM readout

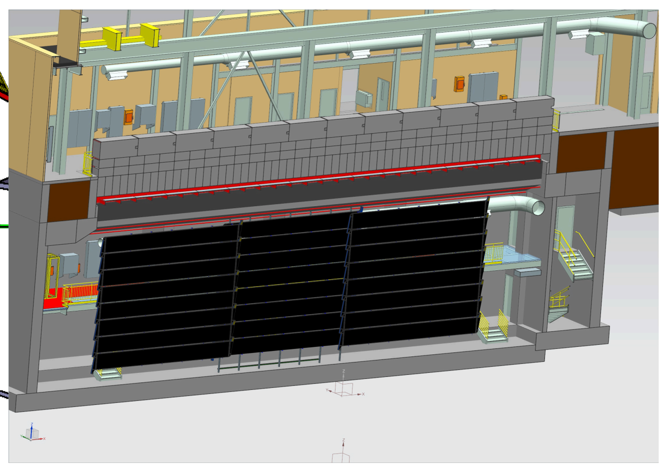
SIDES:

~ 500 m^2 on four sides
Old MINOS veto modules
parallel strips
SiPM readout

BOTTOM:

~ 200 m^2, already installed
D-Chooz veto modules
2 parallel layers
PMT readout

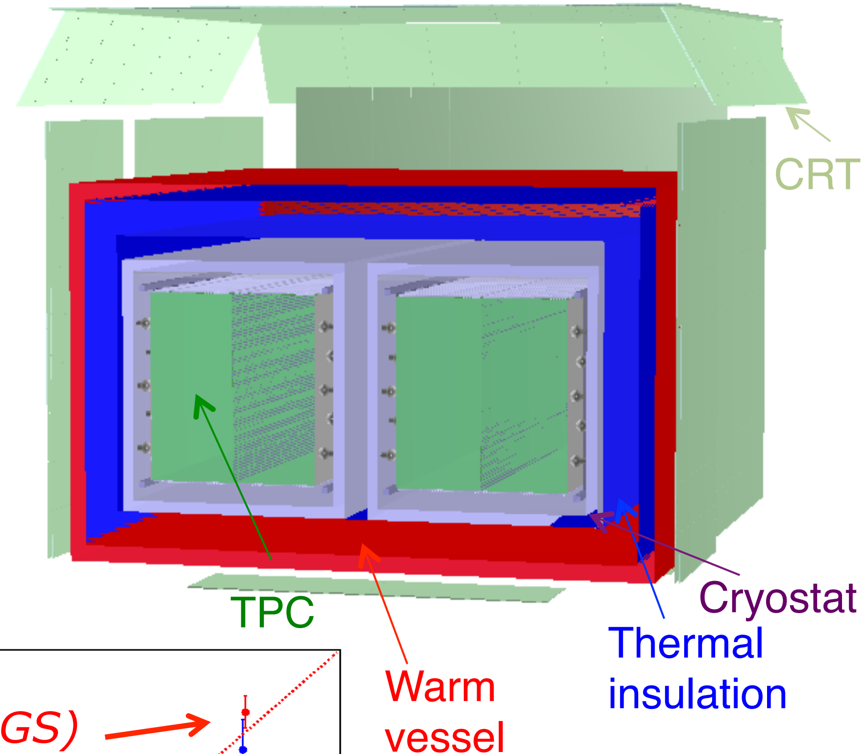


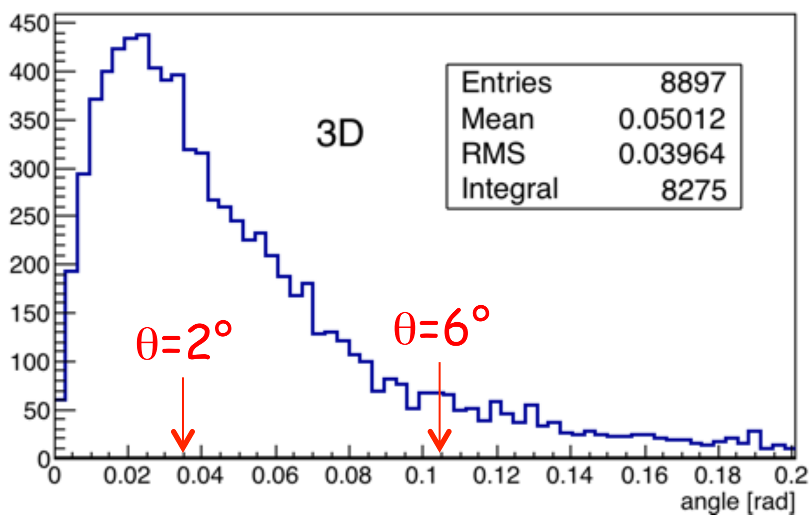


Reconstruction and analysis in SBN

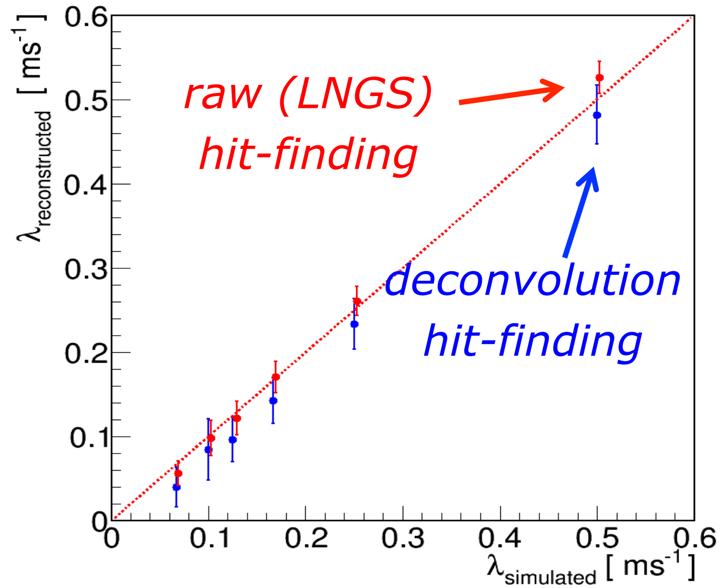
- A detailed understanding of detector-related systematics and their correlation across near/far detectors will be crucial to SBN physics
- Common reconstruction tools and oscillation analysis are therefore fundamental
- ICARUS joined the LArSoft framework: mutual sharing of algorithms and tools and cross-check between different reconstruction approaches
- Full simulation performed with realistic geometry and signals from all sub-detectors (TPC,PMT,CRT)

Scheme of detector geometry





angle between sim/reco direction for EM showers



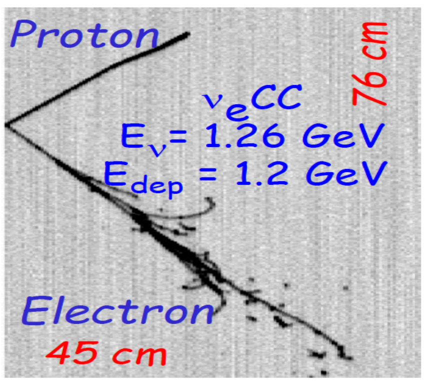
electron lifetime (reco vs. sim)

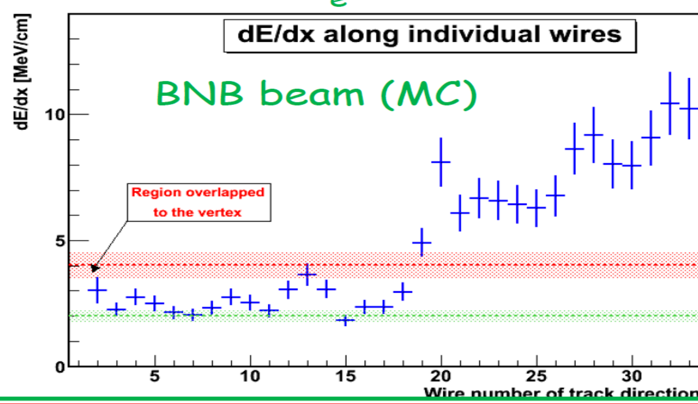
Atmospheric neutrinos in LAr-TPC and SBN

- ICARUS at LNGS was also exposed to atmospheric neutrinos (exposure ~0.74 kt year) first observation of atmospherics with a LAr-TPC
- 14 events found (8 ν_e CC + 6 ν_μ CC) vs. 18 expected (taking into account: triggering, filtering and scanning efficiencies)
- Very good benchmark for the forthcoming SBN experiment: similar energy/features. Useful to develop filtering and reconstruction tools

MC SBN ν_eCC interactions

ν_e

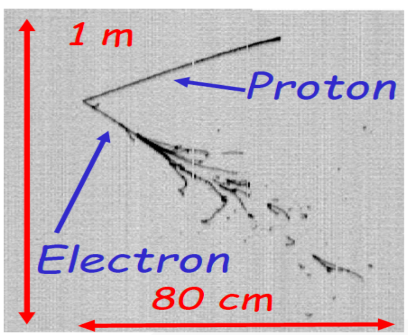


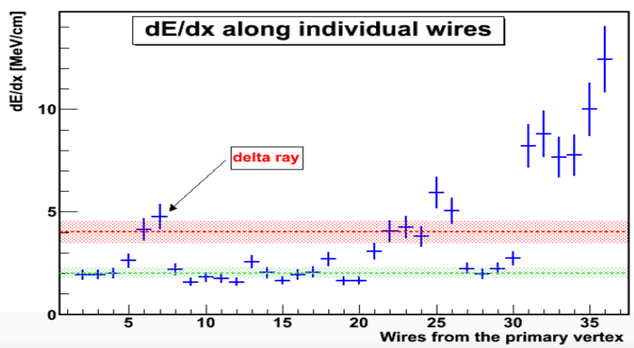


- very alike to typical atmospheric ν_eCC events @ LNGS (below)
- Similar results hold for ν_μCC interactions

LNGS ν_e ATMOSPHERIC EVENT

ν_e

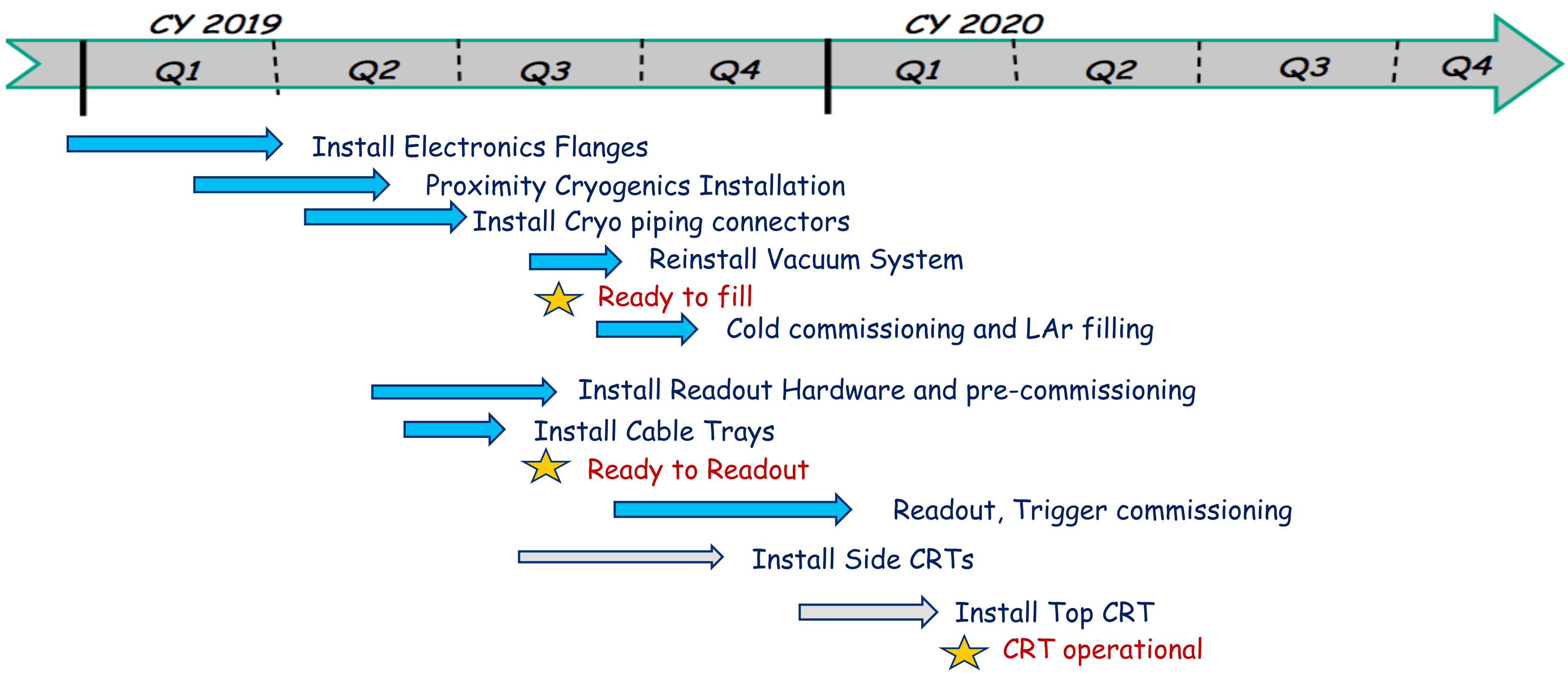




- Quasi-elastic ν_eCC E_{Dep}= 0.9 GeV.
- Proton identified by dE/dx.
- Electron identified by single m.i.p. before showering

ICARUS at FNAL – plans and commissioning

- TPC/trigger electronics installation to be completed and tested by spring 2019
- PMT electronics installation also to be completed during the spring
- ICARUS expected to be ready to fill by August
- After cryogenics commissioning, cool down and filling, ICARUS T600 should be operational in the last quarter of 2019
- Commissioning of CRT, DAQ, trigger and slow controls will follow
- Data-taking for physics is expected by the end of this year



Conclusions

- The ICARUS-T600 successful 3-year run at LNGS proved that LAr-TPC technology is mature and ready for large-scale neutrino physics experiments
- ICARUS searched for LSND-like anomaly via ν_e appearance in the CNGS beam. The negative result constrained significantly the allowed parameter region
- 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, ICARUS is being installed as the SBN far detector at FNAL. Data taking expected in 2019, near detector in 2021
- ICARUS will see first neutrinos by the end of this year !

Thank you