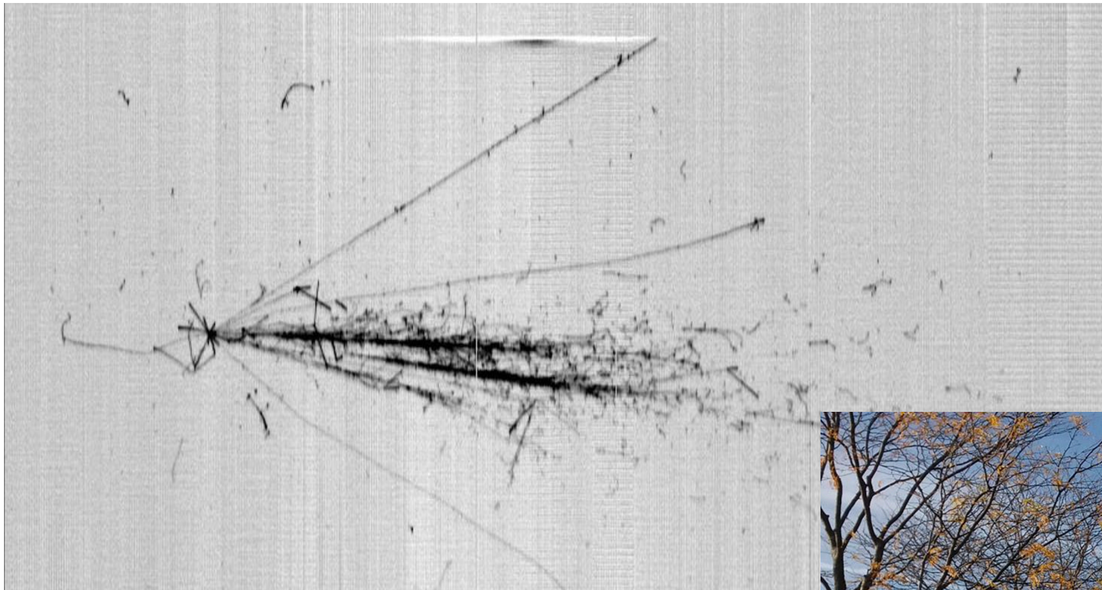
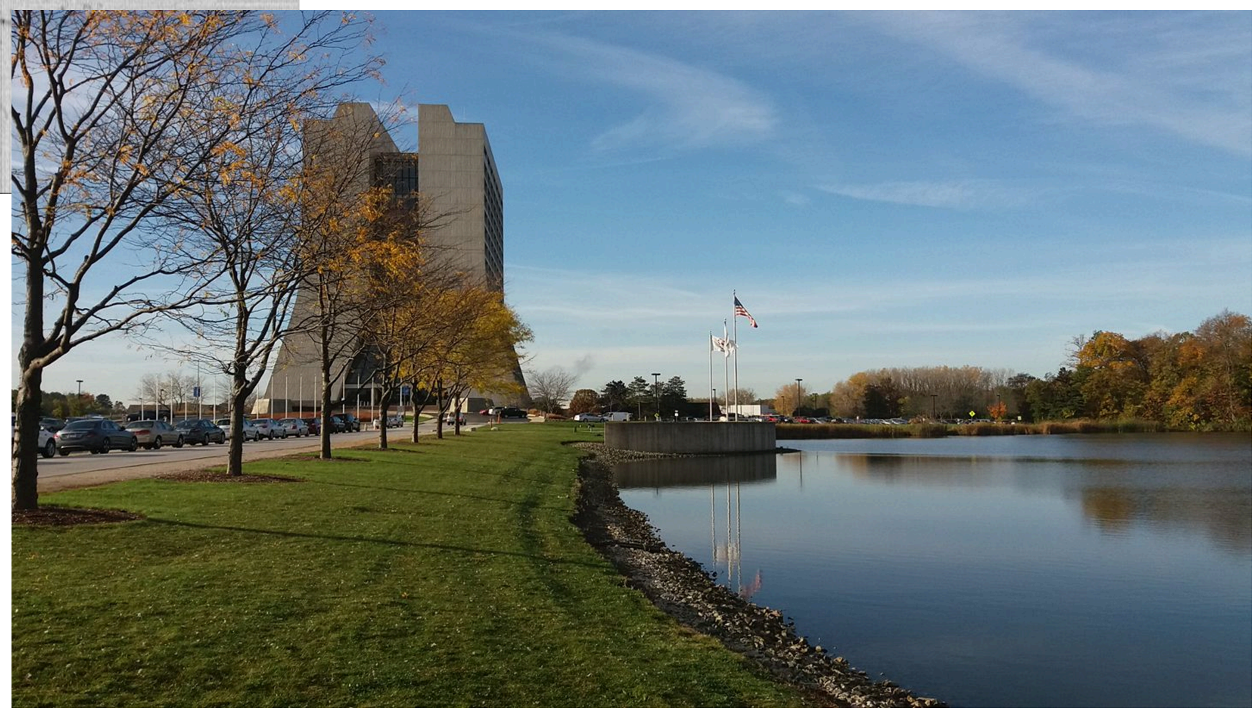
ICARUS and the Fermilab Short Baseline Neutrino Project



F. Varanini
INFN Padova

on Behalf of the
ICARUS Collaboration



Neutrino Telescopes
XVIII

Venezia
March 21st 2019

Outline

- ICARUS-T600 at LNGS: a very successful run
- Sterile neutrinos and the SBN project
- Making ICARUS better: from underground up to the surface
- Installation and commissioning at FNAL

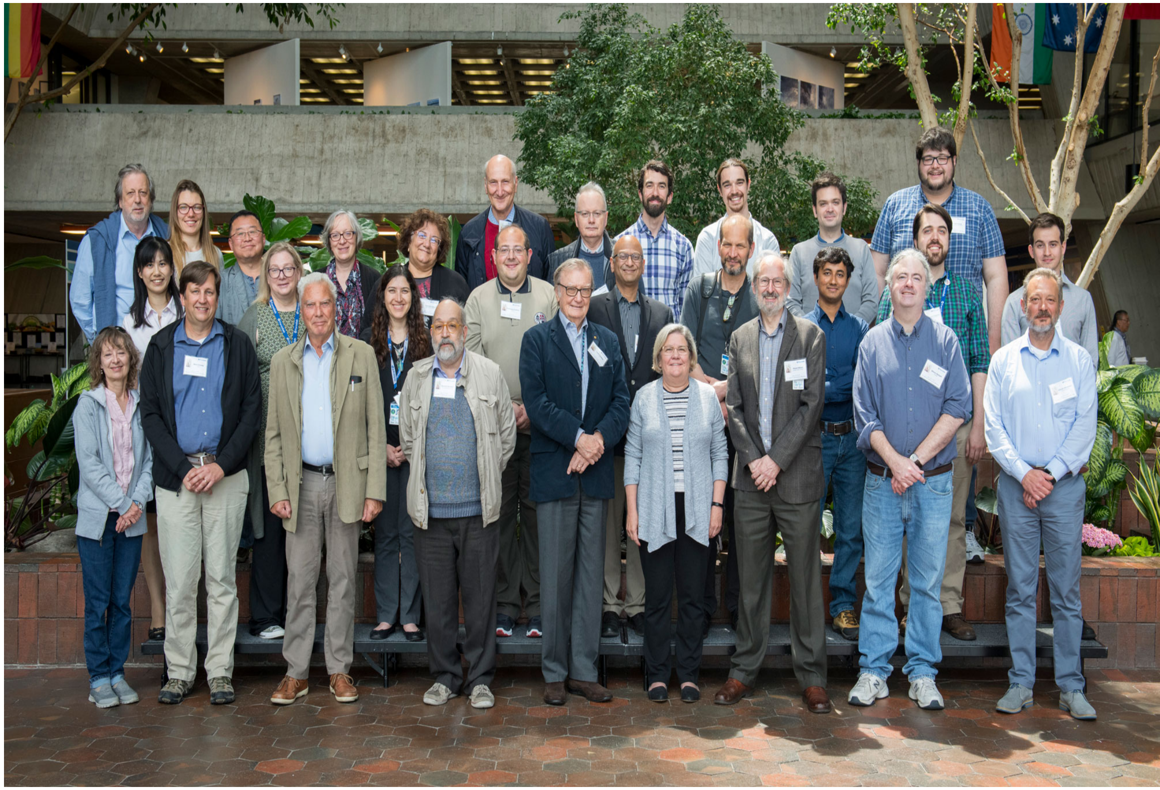
The ICARUS collaboration

Catania (INFN and Univ.)
GSSI
LNGS
INFN Milano Bicocca
INFN Napoli
Padova (INFN and Univ.)
Pavia (INFN and Univ.)

CINVESTAV

Brookhaven (BNL)
Colorado State
FNAL
Houston
Pittsburgh
Rochester
SLAC
Southern Methodist Univ.
Texas (Arlington)

~90 scientists

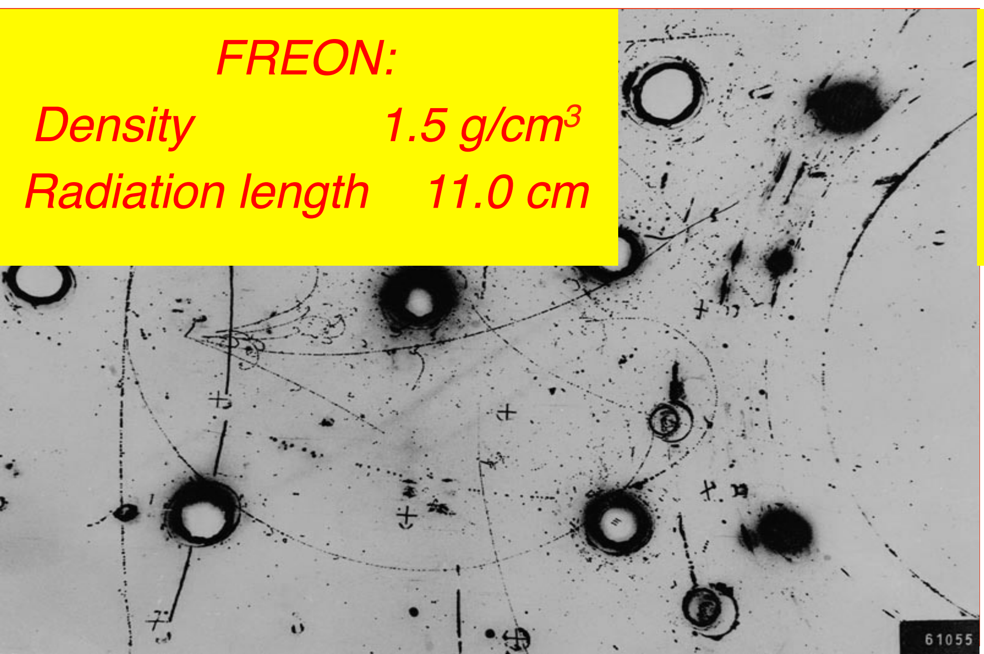


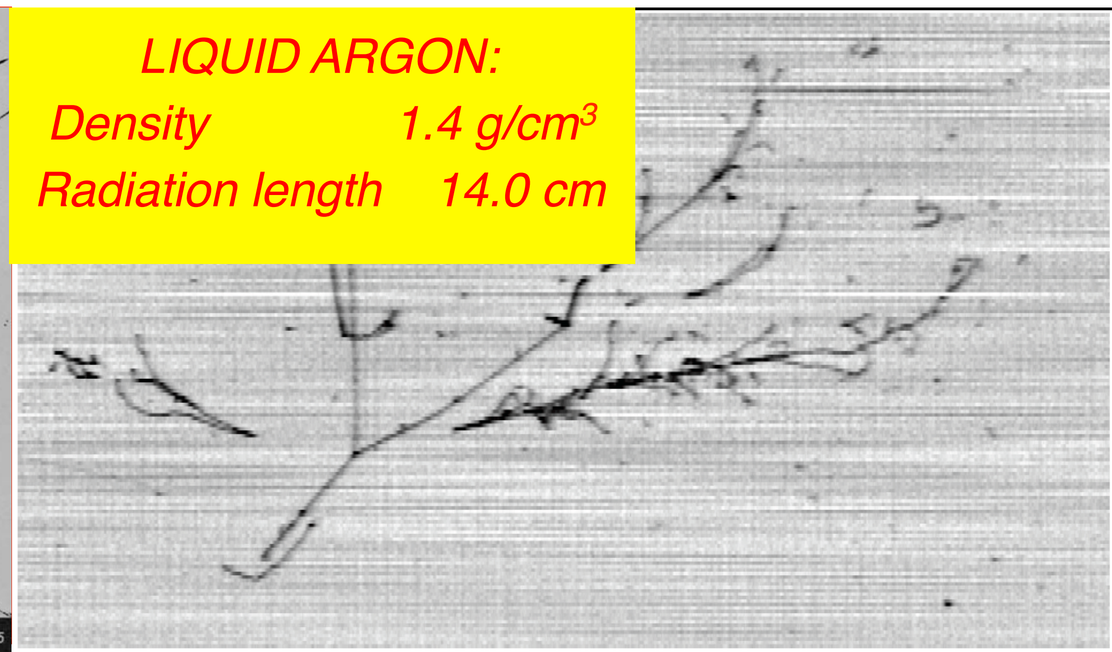
Spokesman: C. Rubbia (GSSI)

Liquid Argon TPC: an "electronic bubble chamber"

- LAr-TPC 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 (>kton) are realistic

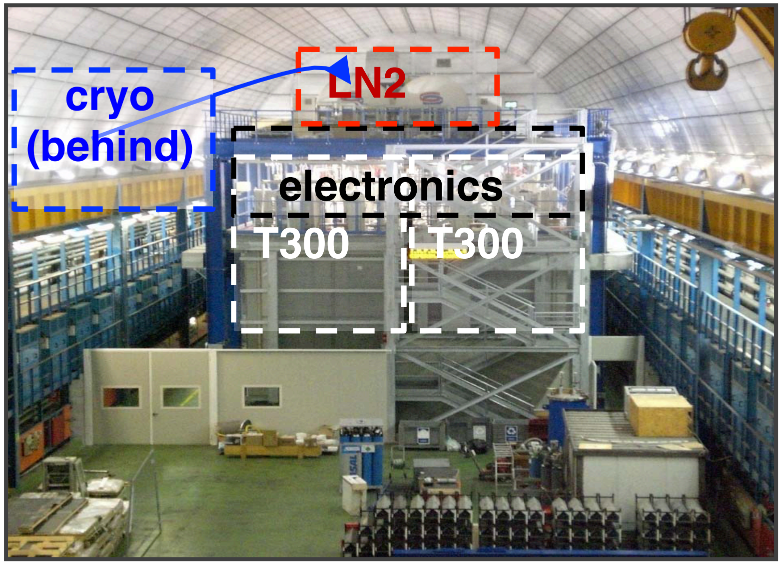
- First proposed by C. Rubbia in 1977: long R&D at INFN and CERN culminated in first large-scale experiment: ICARUS-T600 at LNGS (2010)
- LAr physical parameters very similar to Freon of "classic" bubble chambers:

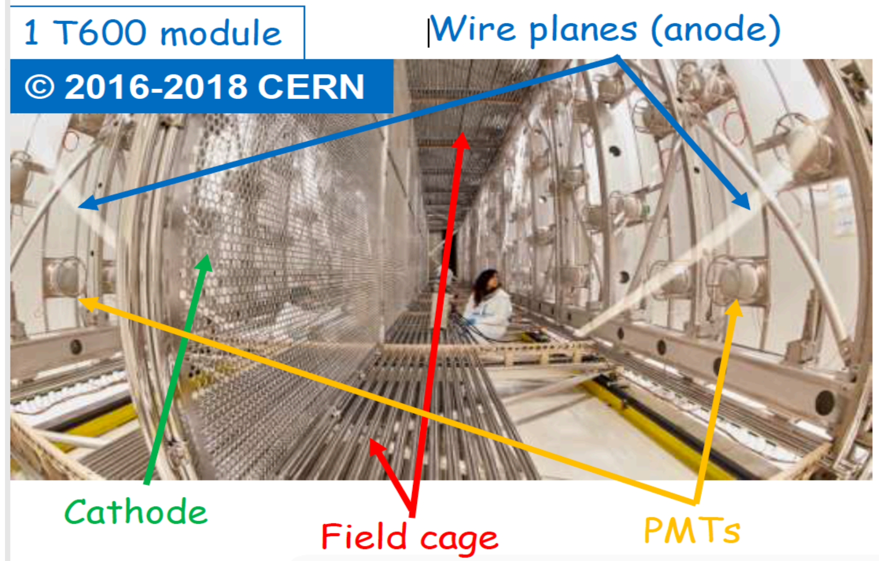




ICARUS-T600 at LNGS

- 2 identical modules: each is 19.6x3.6x3.9 m^3; active mass 476 t (total 760 t)
- Drift distance 1.5 m. 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
- PMTs (20+54) with TPB wavelength-shifting coating



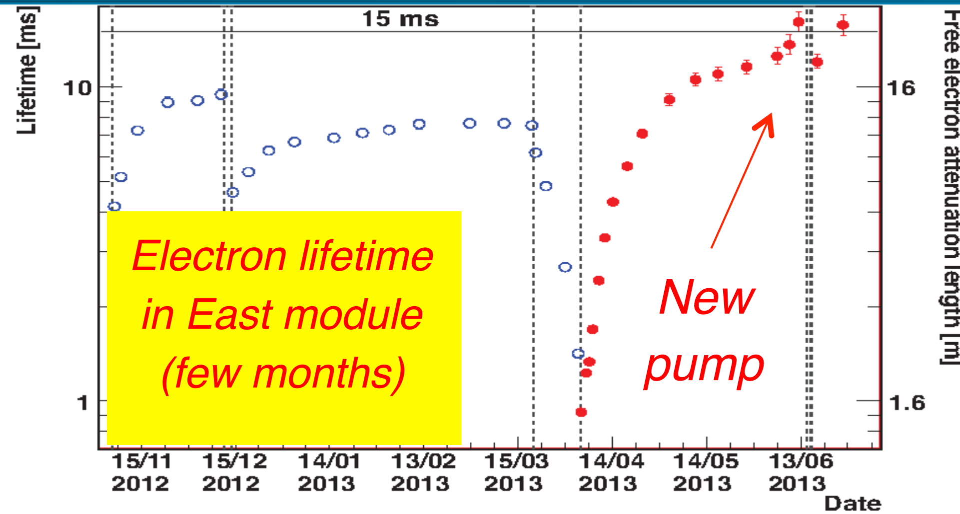


- ICARUS was exposed to CNGS beam and cosmics for 3 years
- Run confirmed expected performance and obtained important physics results
- It proved the maturity of the LAr-TPC technique for large-scale experiments

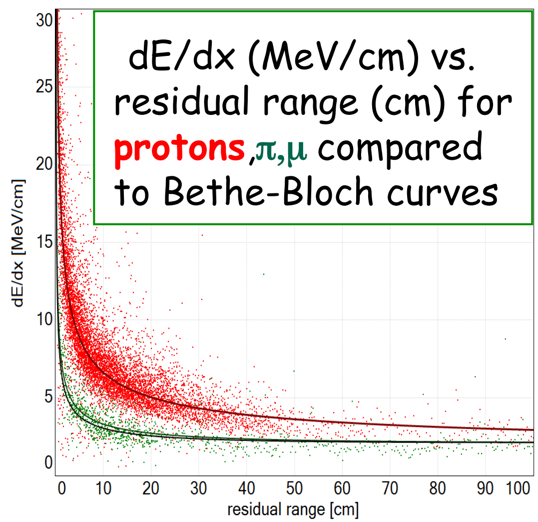
ICARUS paved the way to the next generation long-baseline project: DUNE

ICARUS reconstruction performances

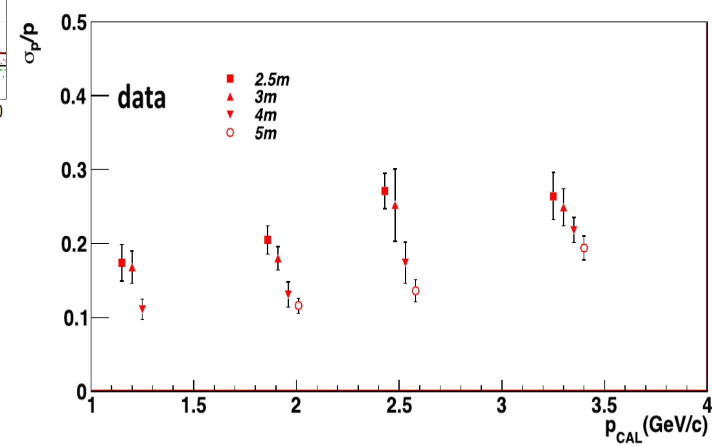
- High electron lifetime: >7 ms (impurity concentration <40 ppt) over whole run. Crucial step towards future larger detectors
  2014 JINST 9 P12006



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

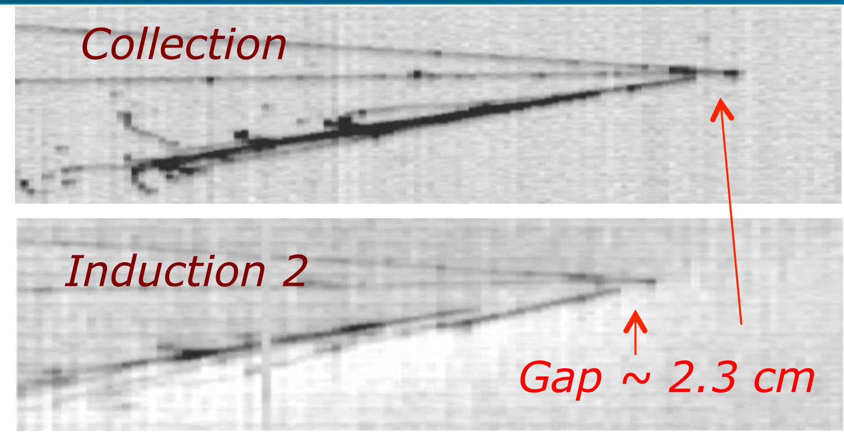


- Momentum of escaping muons measured by multiple Coulomb scattering. Average ~15% resolution on stopping muons (0.5-5 GeV/c)
  JINST 12P04010

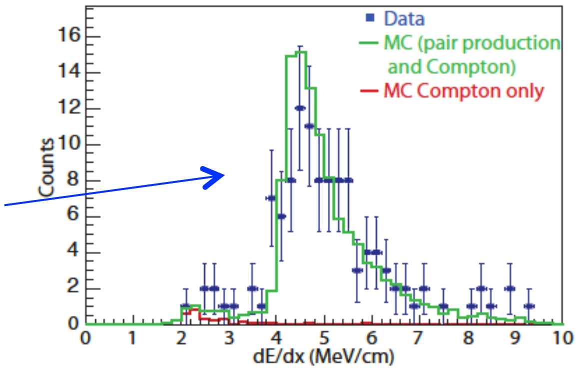


e/γ separation and ν_e identification

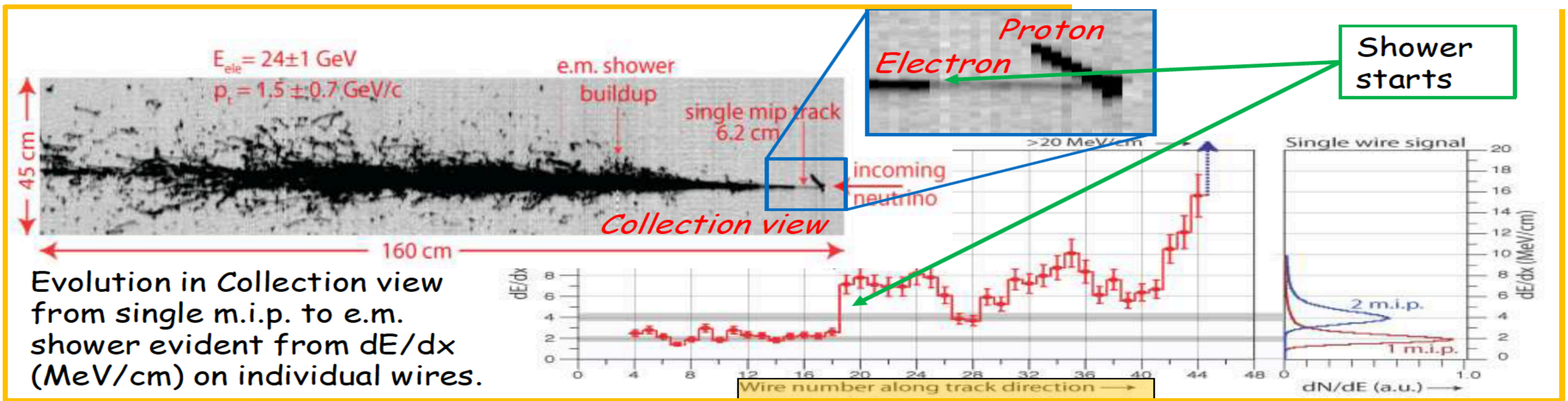
- νeCC event (electron-initiated EM showers) separation from νNC background with π^0 (γ-initiated showers): crucial for oscillation physics
- LAr-TPC provides 3 handles:
  - Visual identification of γ conversion gap
  - Reconstruction of π^0 invariant mass
  - dE/dx: calorimetric accuracy and fine sampling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



dE/dx of sub-Gev photons:



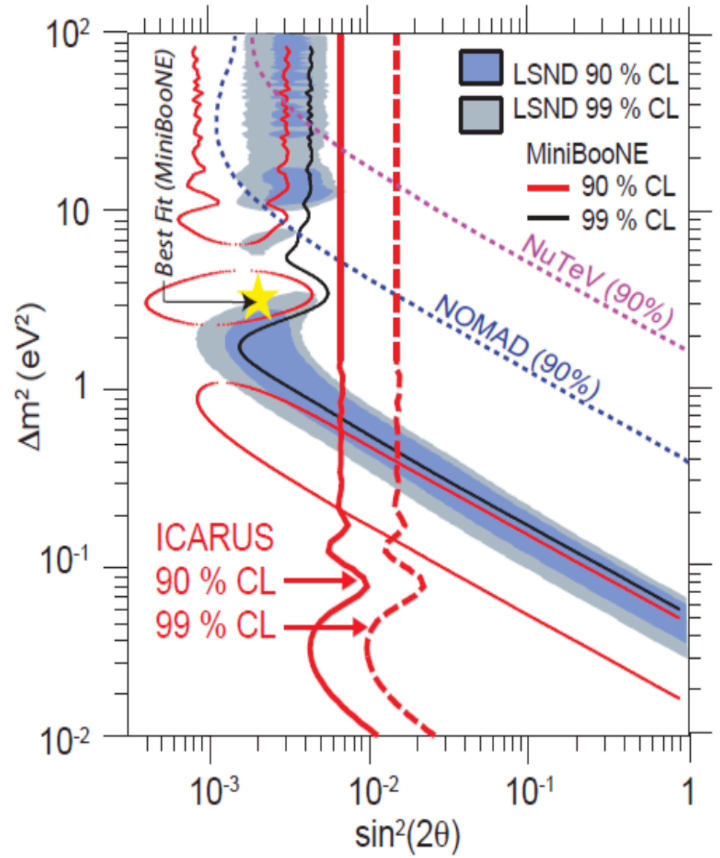
High-energy CNGS νeCC interaction:



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

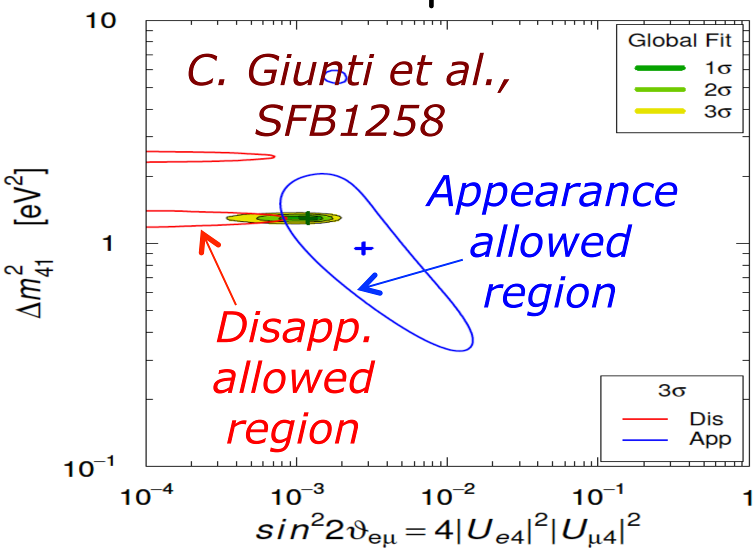
- ICARUS searched for sterile ν oscillations through νe appearance in the CNGS beam
- L/E~36 m/MeV, far from LSND value ~1 m/MeV -> "sterile-like" oscillation was averaged out, canceling energy dependence
- 7.9 10^{19} pots analyzed (~2650 ν interactions)
- Expected ~8.5±1.1 νe background events in absence of anomaly, mostly from intrinsic νe beam contamination
- Estimated νe 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 $\sin^2\theta$~0.005, Δm^2<1 eV^2
- Similar result by OPERA with same CNGS beam and different detection technique

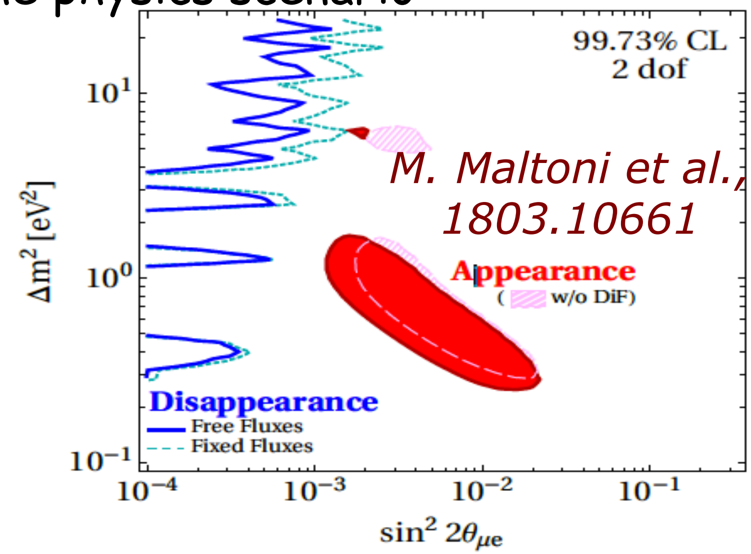


Eur. Phys. J. C (2013) 73:2599

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 $\nu\mu$ disappearance data (MINOS, IceCube)
- Tension between appearance and $\nu\mu$ disappearance results. Measuring both channels with the same experiment will help disentangle the physics scenario

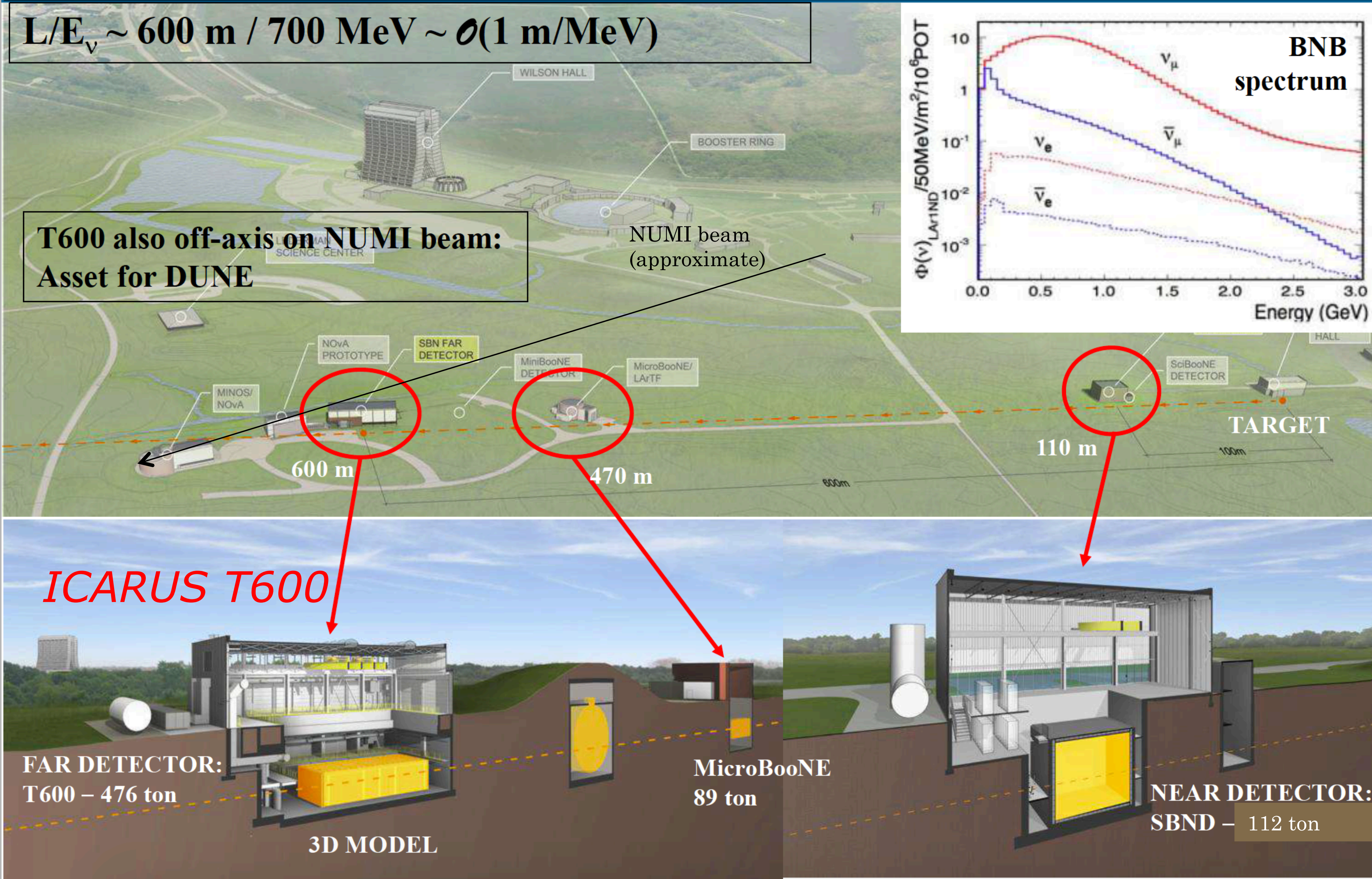




- A comparison between far/near detector is crucial for any accelerator experiment, with a better control of backgrounds and systematics

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

The SBN project



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% νe 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, mutually related through

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

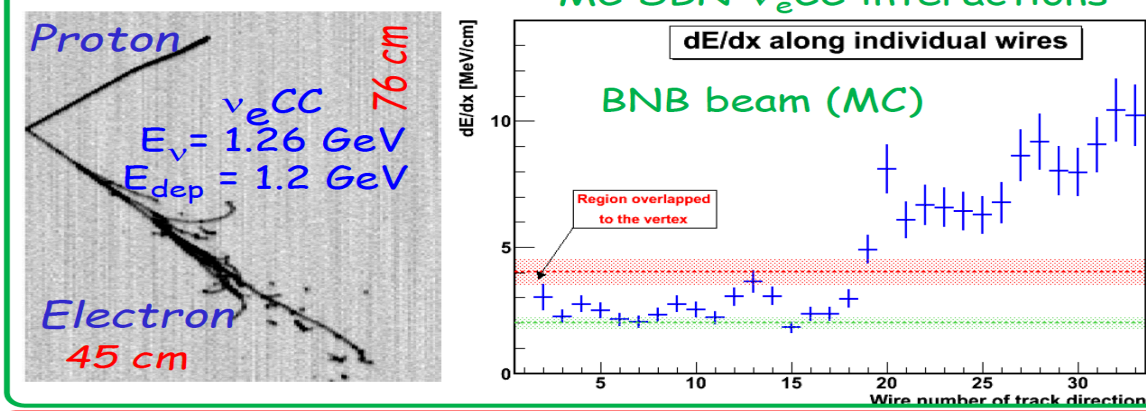
- In absence of "anomalies" the 3 detector signals should be a close copy of each other for all experimental signatures
- The great νe identification capability of LAr-TPC will help reduce the NC background

- During SBN operations, ICARUS will also collect ~2GeV neutrinos from NUMI 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 νe component with ~3GeV energy (in the DUNE range)

Atmospheric neutrinos in LAr-TPC and SBN

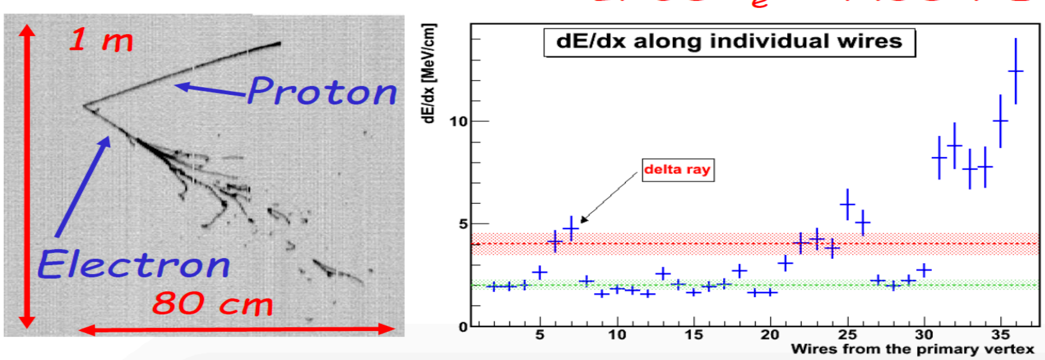
- ICARUS at LNGS was also exposed to atmospheric neutrinos (exposure ~0.74 kt year): first observation of atmospherics with a LAr-TPC
- 14 events found (8 νeCC + 6 νμCC) vs. 18 expected – accounting for triggering, filtering and scanning efficiencies
- Very good benchmark for the forthcoming SBN experiment: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

MC SBN ν_eCC interactions



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

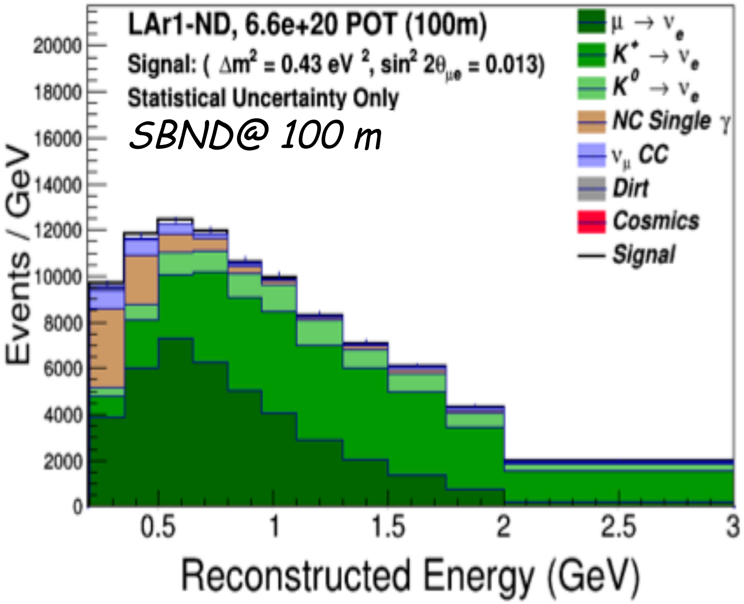
LNGS ν_e ATMOSPHERIC EVENT

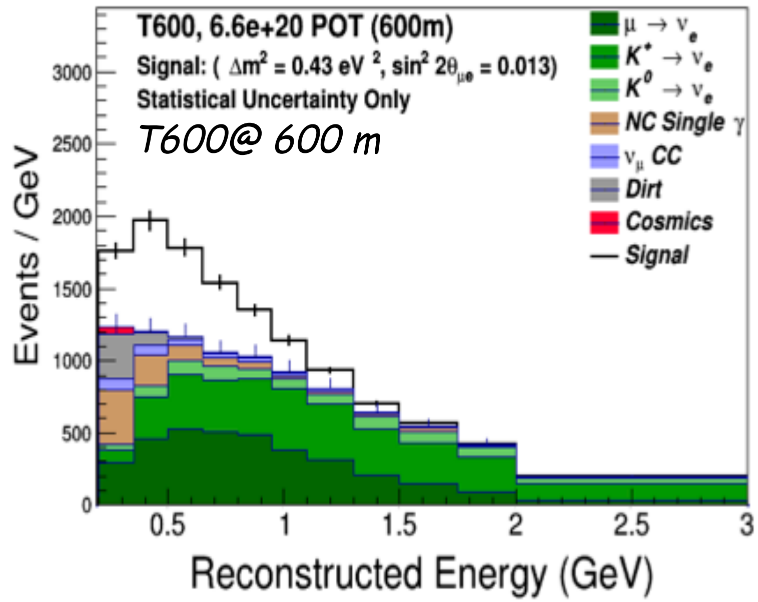


- Quasi-elastic ν_eCC E_{Dep}= 0.9 GeV.
- Proton identified by dE/dx.
- Electron identified by single m.i.p. before showering

SBN spectra (from the proposal: arXiv 1503.01520)

νe spectra (oscillation signal+backgrounds) for 3 years (6.6 10^{20} pot)

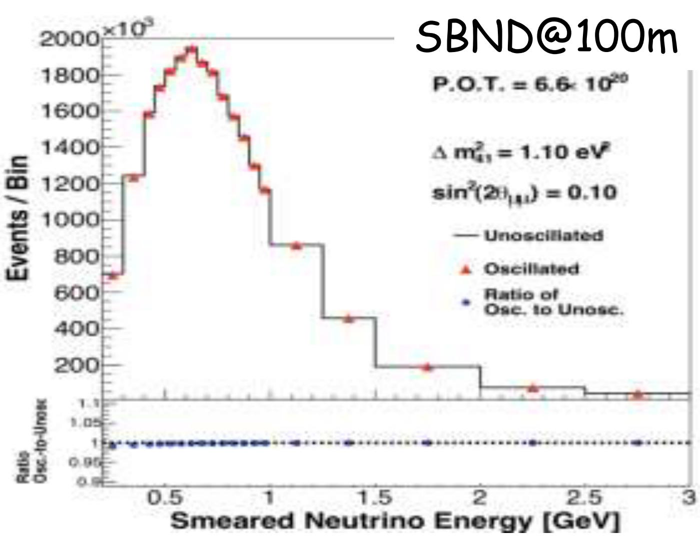


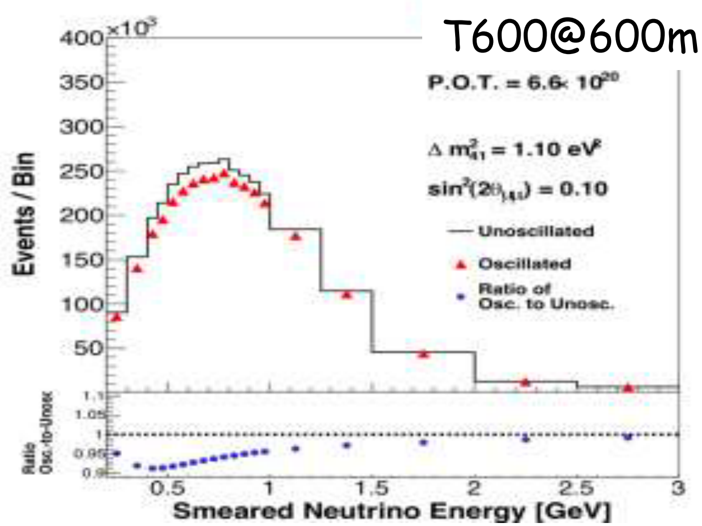


Example for
$\sin^2 2\theta=0.013$
$\Delta m^2=0.43 eV^2$

In absence of oscillations, spectra should be ~identical

νμ spectra (oscillation modulation) for 3 years (6.6 10^{20} pot)





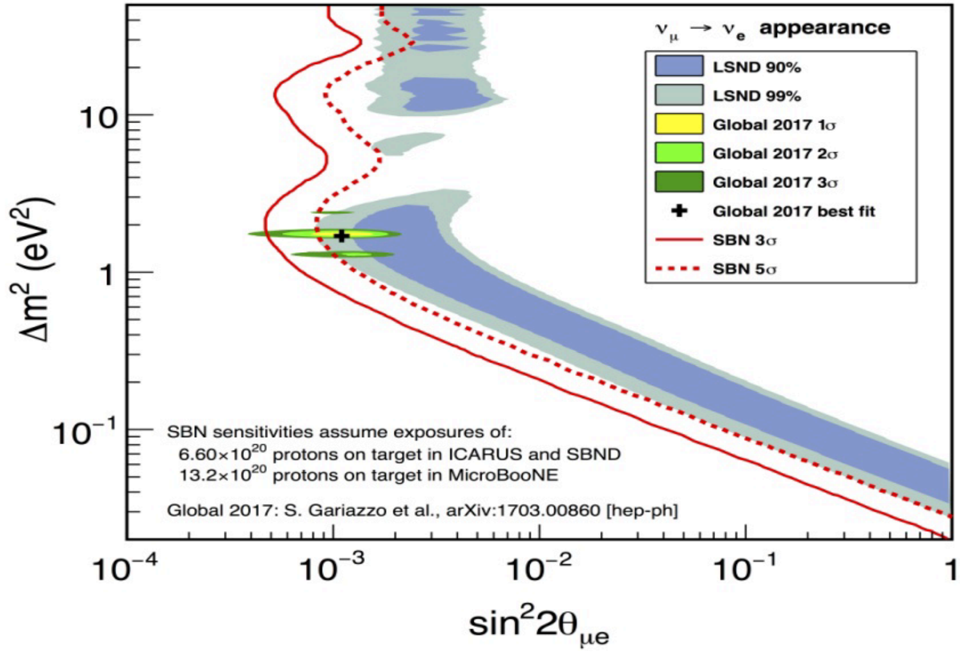
Example for
$\sin^2 2\theta=0.01$
$\Delta m^2=1.10 eV^2$

In absence of oscillations, spectra should be ~identical

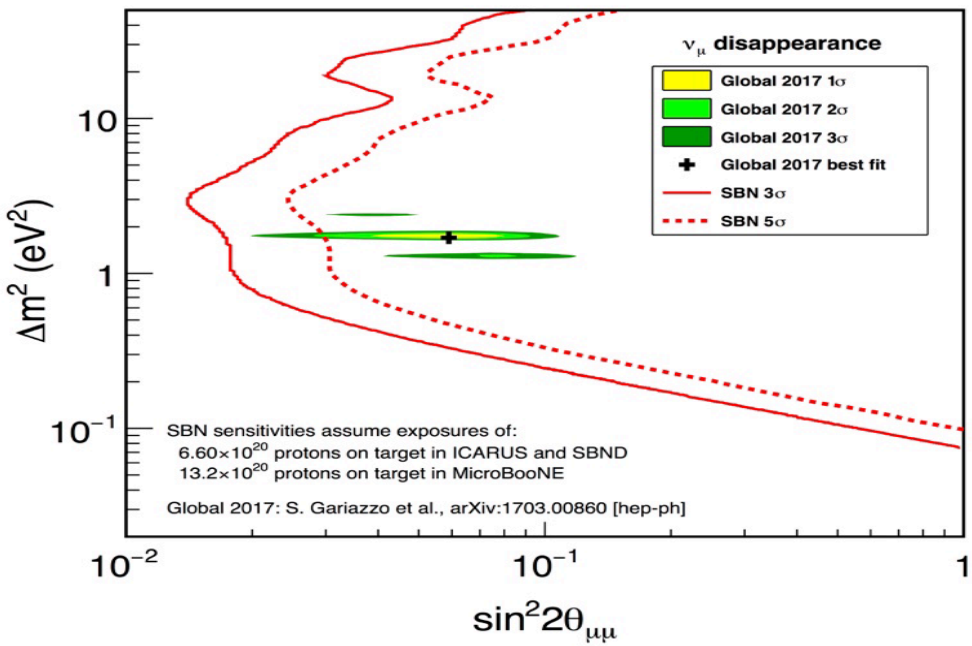
SBN sensitivities (from the proposal: arXiv 1503.01520)

Appearance sensitivity for 3 yr ($6.6\ 10^{20}$ pot) at BNB

LSND 99%CL region will be covered at ~5σ level

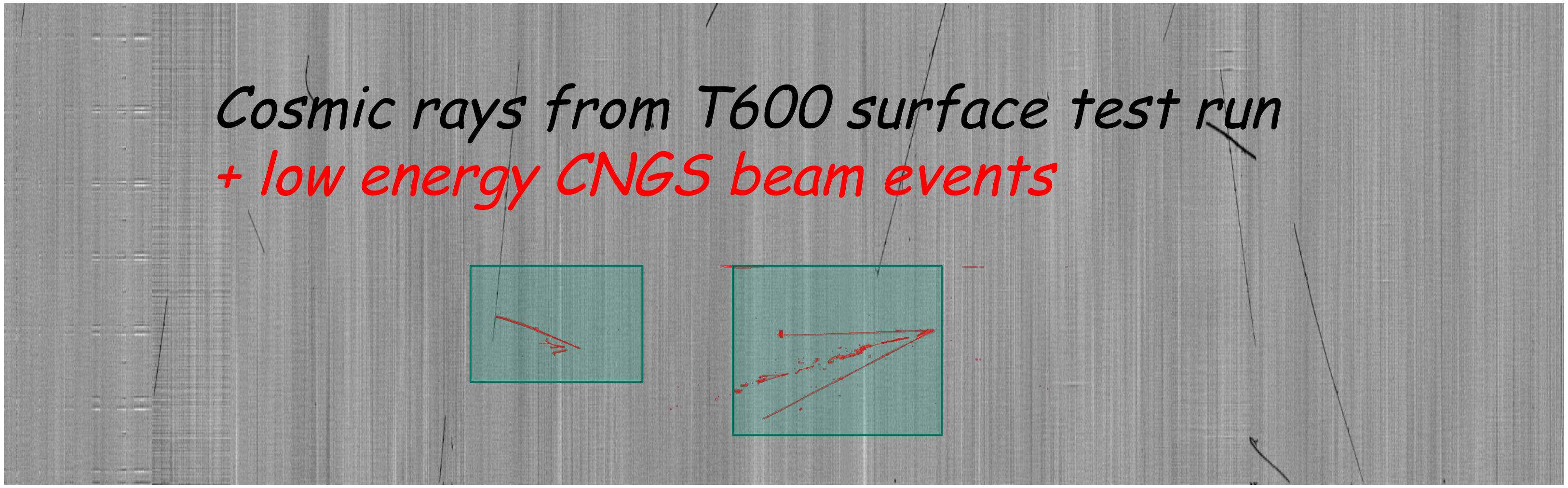


Exploiting high rates/detector correlations, $\nu\mu$ disappearance sensitivity will be extended by one order of magnitude beyond present limit in 3 yr



A new experimental challenge: a LAr-TPC on surface

- ICARUS will take data at shallow depth (only 3 m concrete overburden)
- ~11 muon tracks will hit each ICARUS module in the ~1 ms drift window and be randomly overlapped to the beam neutrino interaction

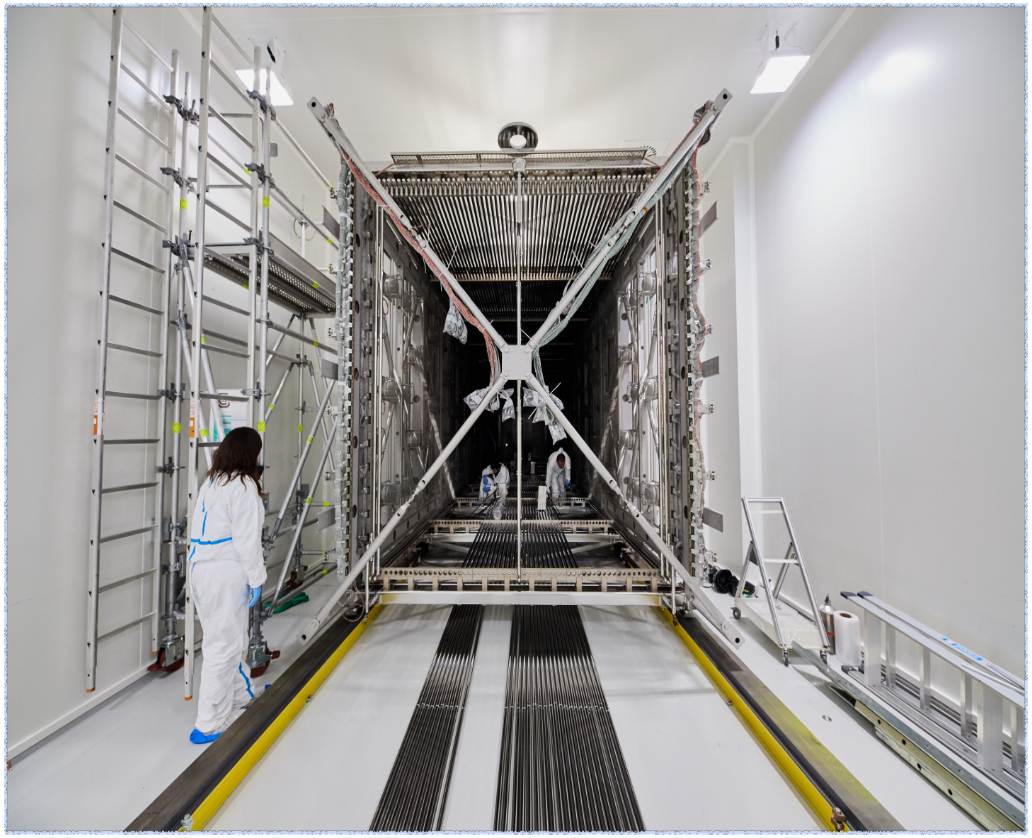


- Cosmic-related photons can mimic νe interactions (via Compton or asymmetric pair production) and result in significant background
- They can be mitigated by unambiguously identifying the timing of each (cosmic and beam) ionizing event occurring during the ~ms TPC drift window
- This requires signals on a faster time scale than the TPC including:
  - A vastly improved LAr scintillation light detection system
  - A Cosmic Ray Tagger (CRT) around the detector

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.
- Several technology developments were introduced *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



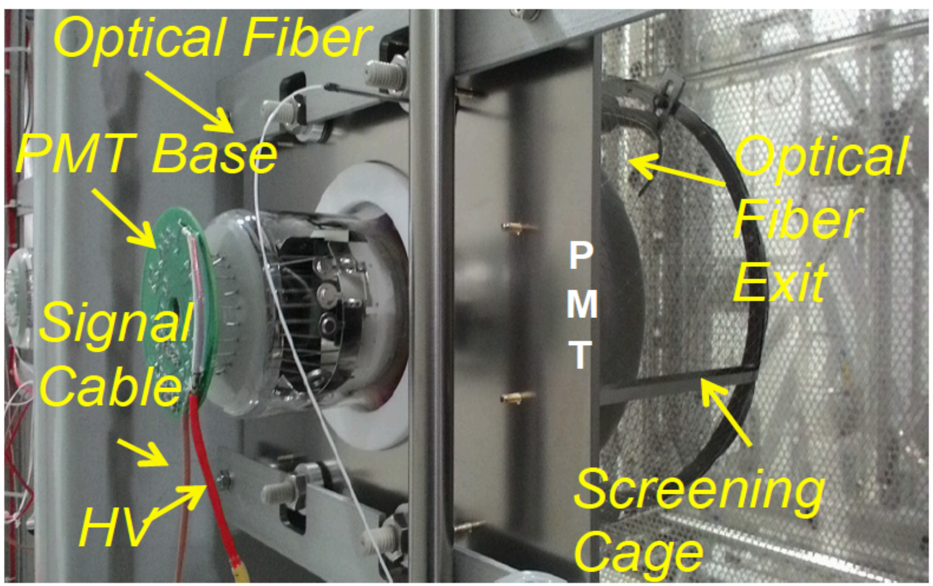
Upgrade of the light collection system

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:

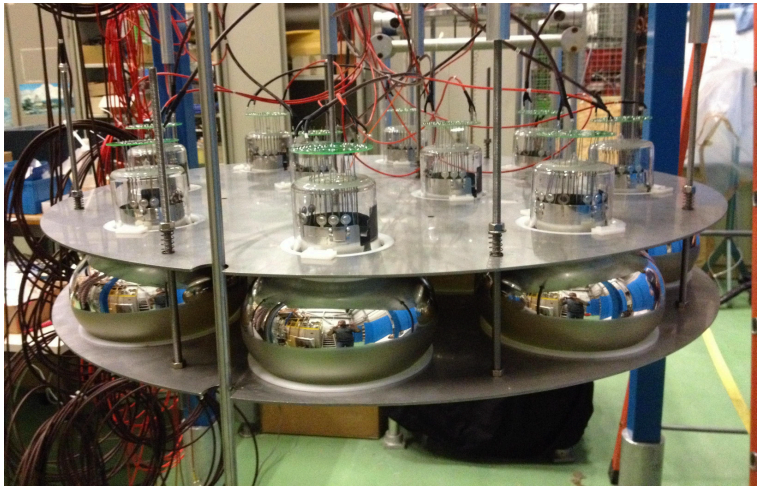
- Sensitivity to LE events (~100 MeV)
- Good spatial resolution (<~50 cm)
- ~ns timing resolution
- Possible cosmics identification by PMT space/time pattern



Timing/gain equalization will be performed by laser light pulses (λ=405 nm, FWHM <100 ps, peak power ~400 mW)

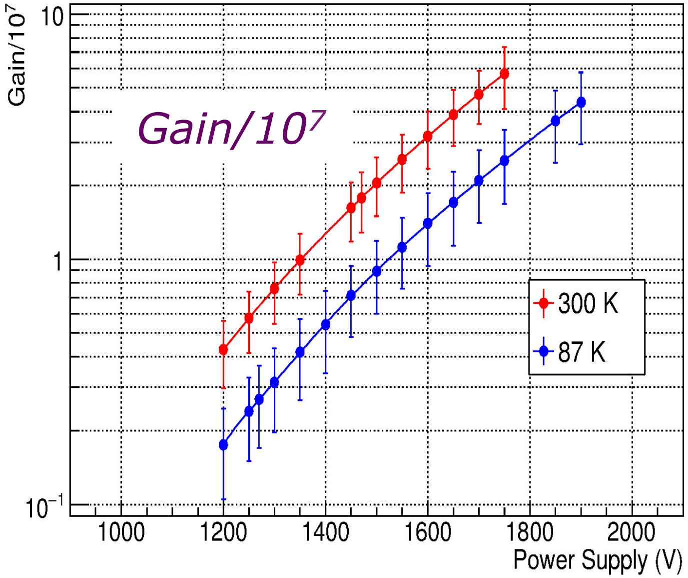
PMT tests at CERN

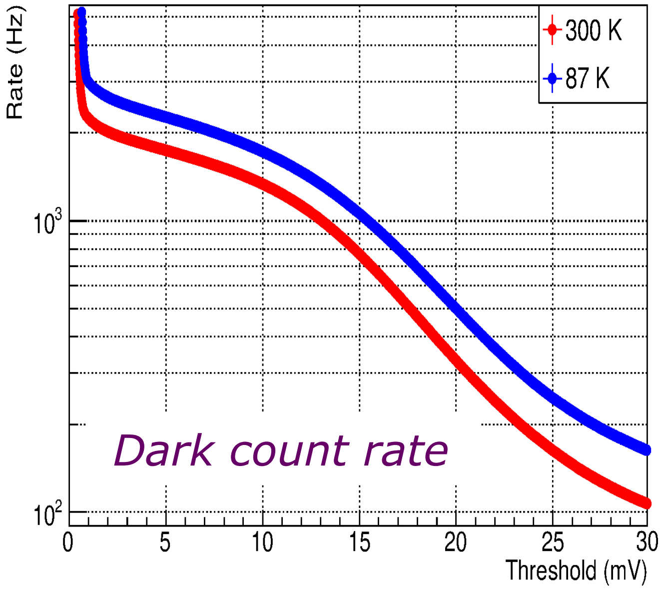
- All PMTs tested at room temperature in a dedicated dark room at CERN
- A subset of 60 PMTs tested immersed in LAr to compare the PMT performance in cryogenic environment to room temperature
- All PMTs illuminated with laser light pulses



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 voltage

JINST 13 (2018) P10030

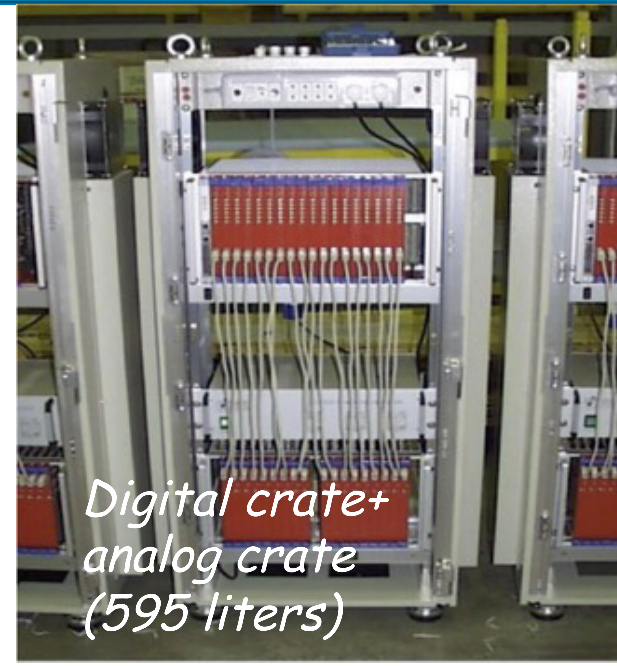
Upgrade of the TPC read-out electronics

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 MCS measurement:

Minimal MIP S/N~7 in Collection, resolution σ_y ~ 0.7 mm along drift

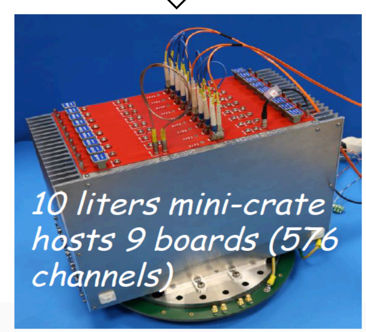


However, in view of the SBN program, some components were modernized and improved:

- 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 50-liter TPC@CERN:

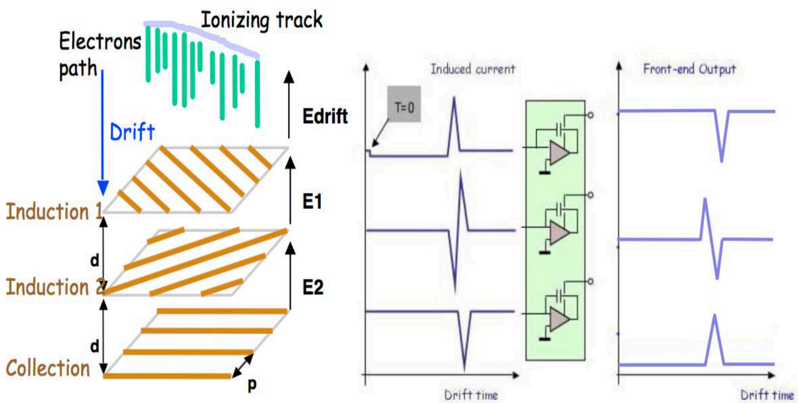
JINST 13 (2018) P12007



Front-end electronics for ICARUS@SBN

The analog front-end shaping was also modified:

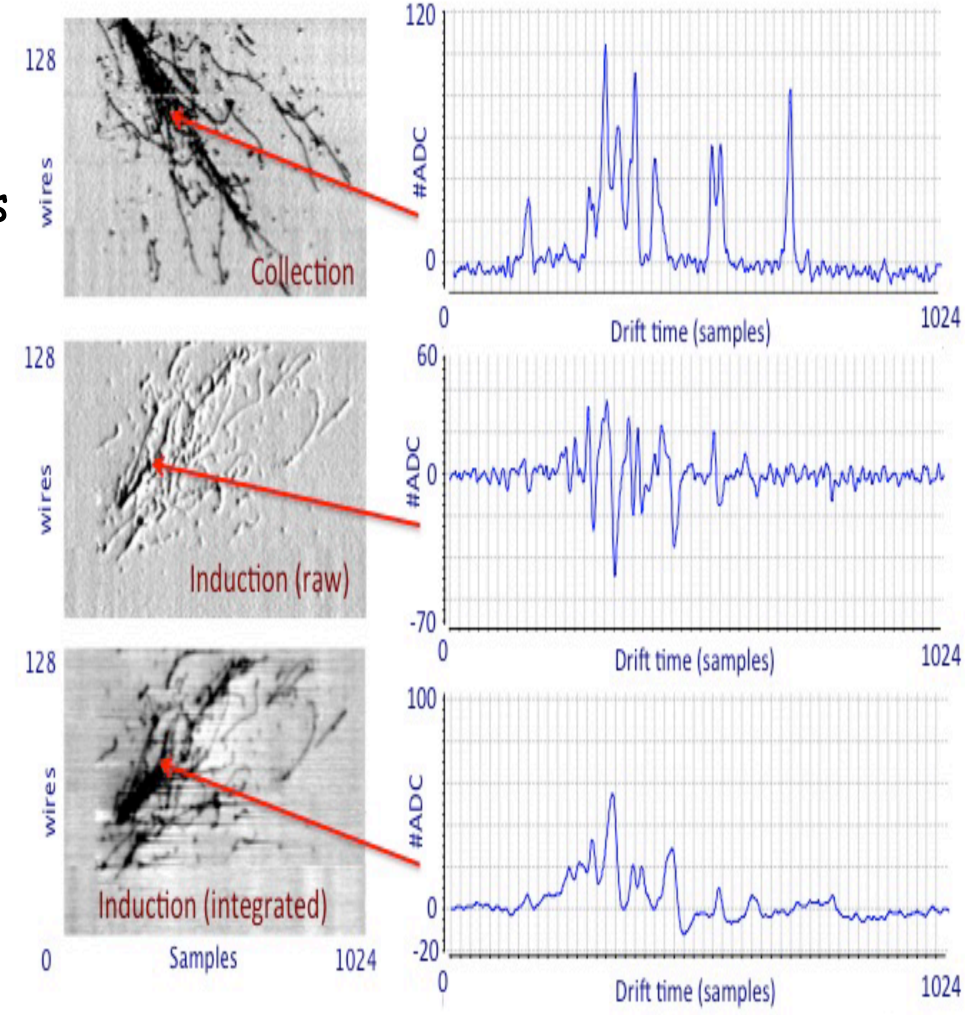
- Lower noise ~1200 e- equivalent (~20% S/N improvement w.r.t. LNGS electronics)
- Shorter shaping time (~1.5 μs for all planes) matching electron transit time between planes
- Drastic reduction of undershoot after large signals: better description of crowded vertex region



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

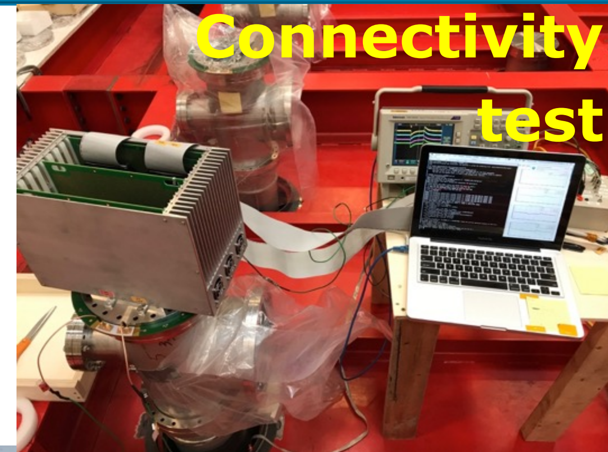
- Possible off-line integration with suitable LF filtering
- Allows calorimetric measurement in this plane too (with ~2 worse resolution than Collection)
- May improve νe identification efficiency by ~20%

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

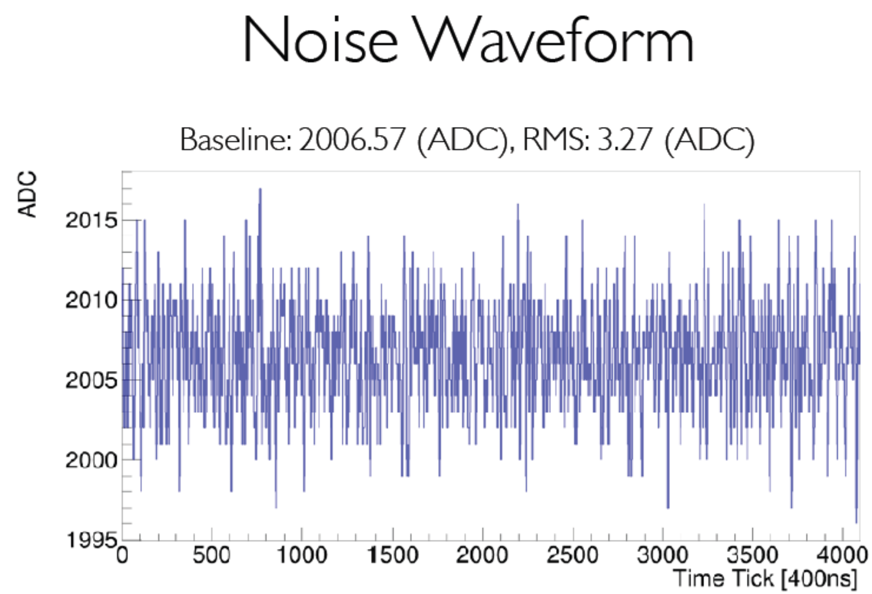


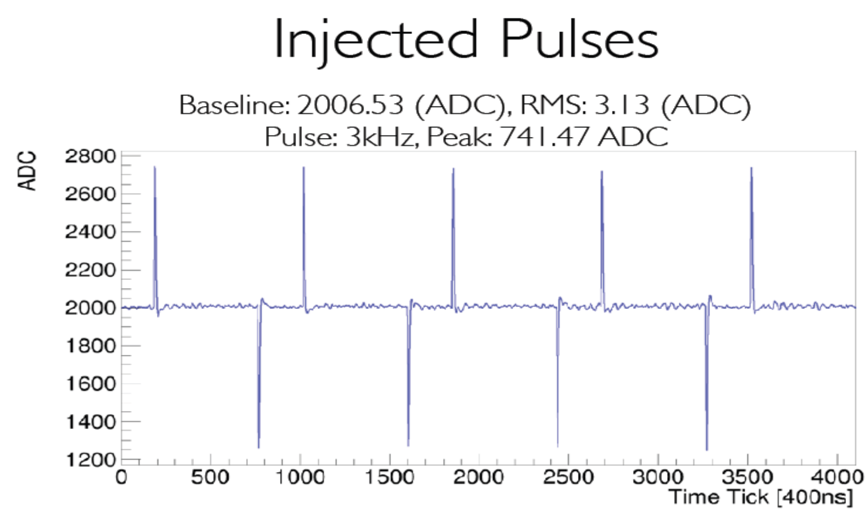
- PMT electronics and trigger being tested at cryogenic temperatures at CERN
- Installation of proximity cryogenics started in February
- Side CRT installation also ongoing
- Director's Review in December 2018 recognized the great progress of SBN

Vertical Slice Test

- A test of the full readout chain, from wires to DAQ, was performed in December on one mini-crate (576 channels + optical links)
- Allowed to check readout and set baseline for future noise monitoring
- Noise measured on random triggers and test pulses
- Grounding conditions were very different from ICARUS data-taking conditions and far from optimal
- Noise RMS ~1700 e-, not too far from ~1200 e- measured in CERN 50-liter setup

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





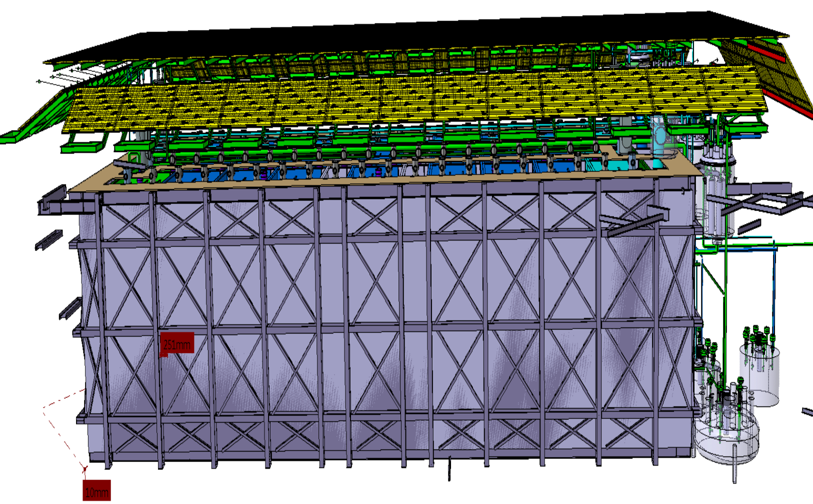
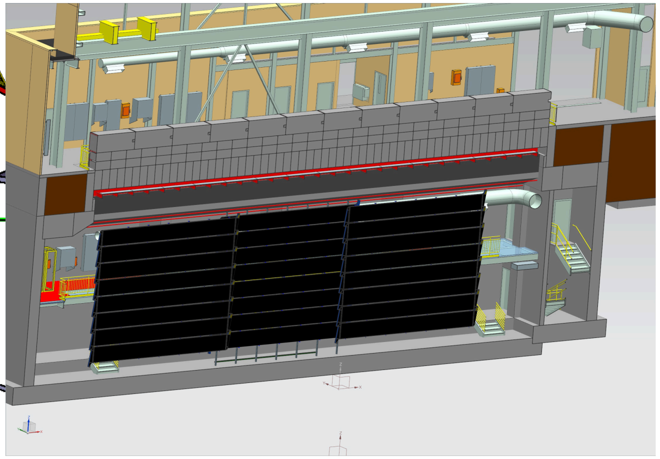
The Cosmic Ray Tagging system (CRT)

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

SIDES(FNAL+CSU):
~500 m^2 on four sides
Old MINOS veto modules
parallel strips
SiPM readout

BOTTOM(FNAL):
~200 m^2, already installed
D-Chooz veto modules
2 parallel layers
PMT readout

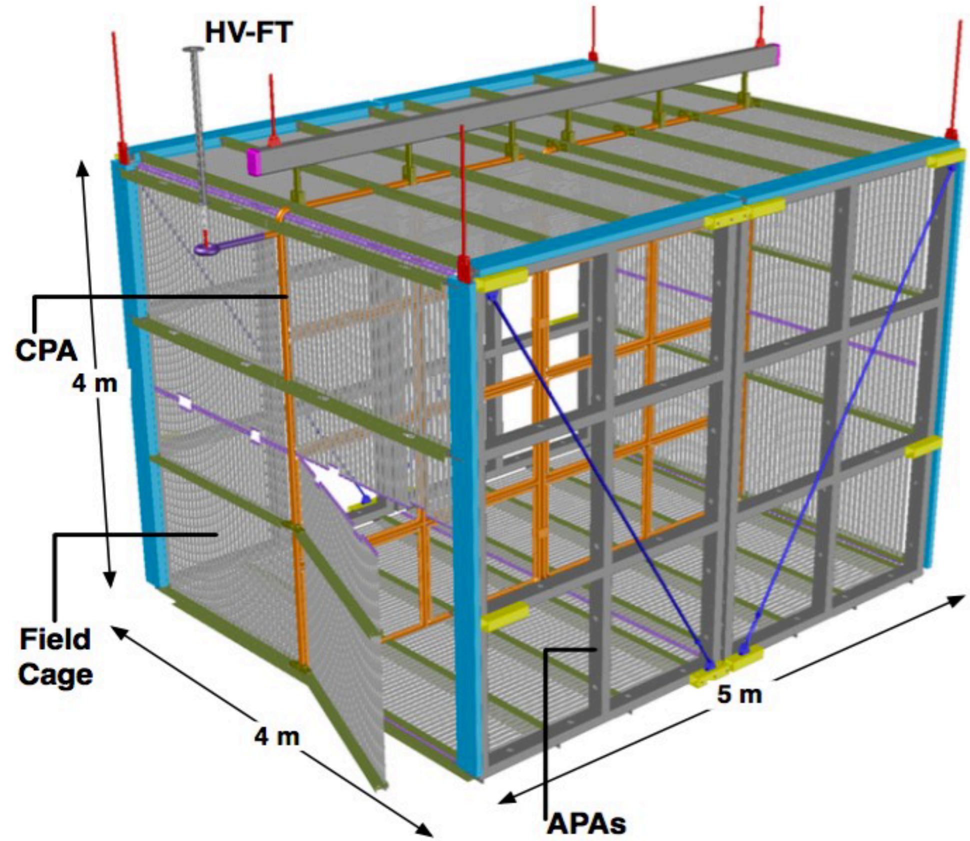




The Short Baseline Near Detector (SBND)

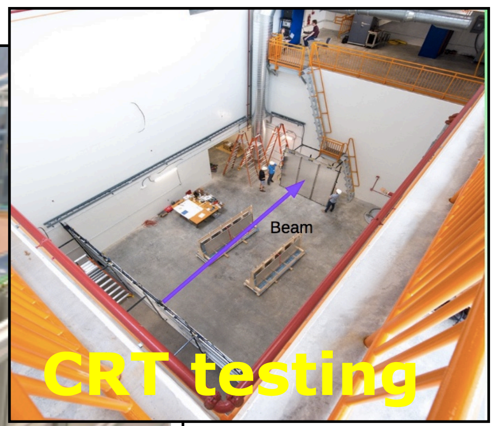
- 2 TPCs with 2 m drift length; 112 t of active LAr mass (4x4x5 meters)

Very similar LAr-TPC to ICARUS, with a few differences:

- Membrane cryostat
- Cold read-out electronics
- Hybrid photon detection system:
  - PMTs coated with TPB
  - Light guide bars coupled to SiPMs
  - ARAPUCA light traps coupled to SiPMs



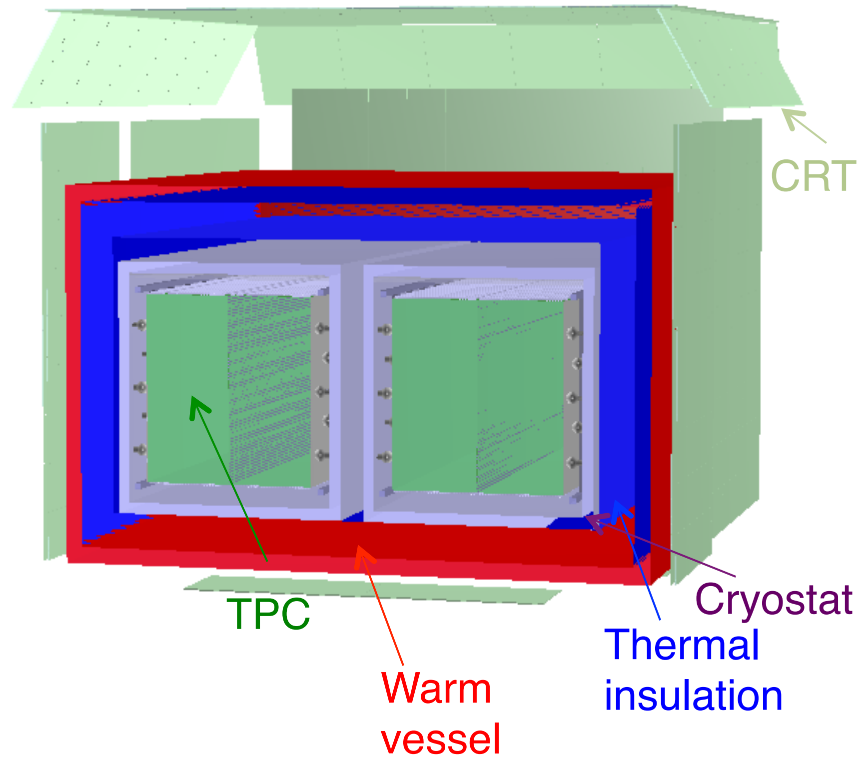
- All detector components completed or under construction
- TPC assembly ongoing at FNAL
- Commissioning expected by the end of 2020



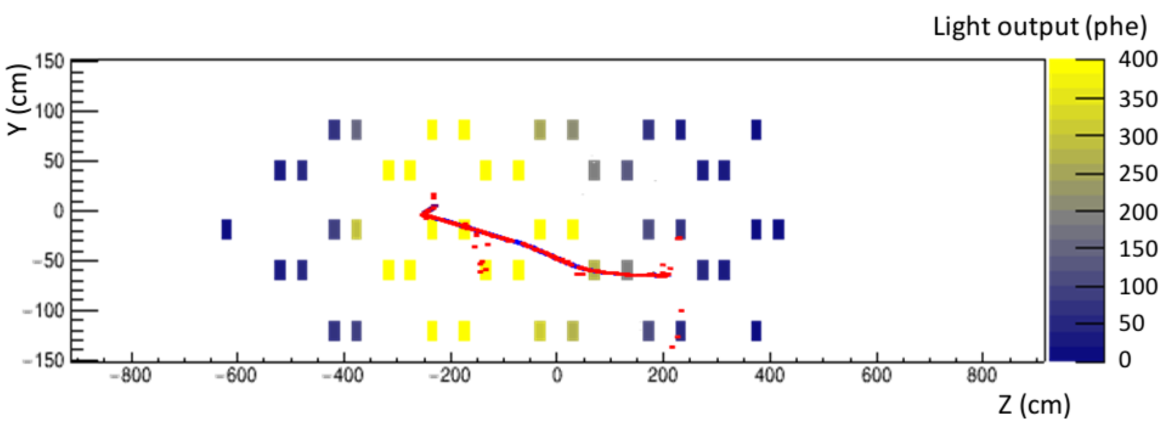
ICARUS simulation and reconstruction

- LNGS experience will be fundamental for SBN analysis
- However, different experimental conditions:
  - Much larger event statistics
  - Overlap of cosmics on ν events
  - Rich information from light and CRT
- Full simulation performed with realistic geometry and signals from all subdetectors (TPC,PMT,CRT)
- Signal/noise modelization uses information from LNGS and small prototypes at CERN

Scheme of detector geometry



PMT vs. TPC information

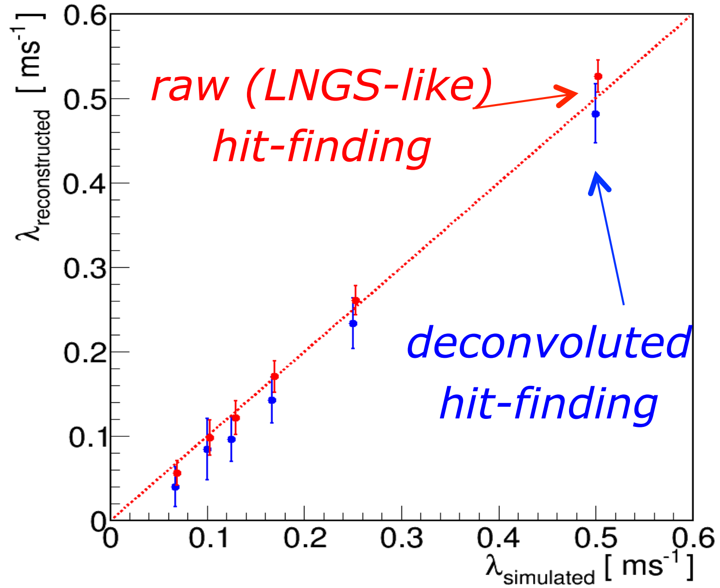


- νμCC interaction with ~1.4 GeV deposited energy
- 49 PMTs have visible signal (over 10 phe)
- Fired PMTs extend over ~8m

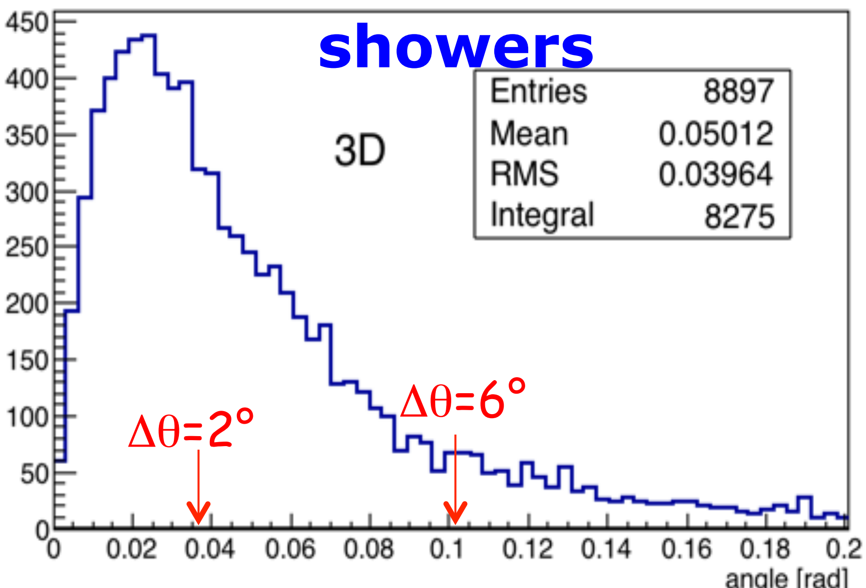
Reconstruction and analysis in SBN

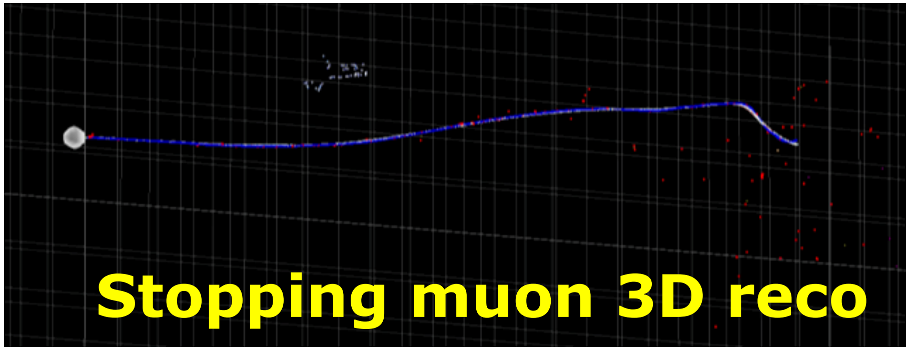
- A detailed understanding of detector-related systematics and their correlation across near/far detectors will be crucial to SBN physics
- Common reconstruction tools and oscillation analysis are therefore fundamental
- ICARUS joined the *larsoft* framework: mutual sharing of algorithms and tools and cross-check between different reconstruction approaches

Reco vs. sim electron lifetime



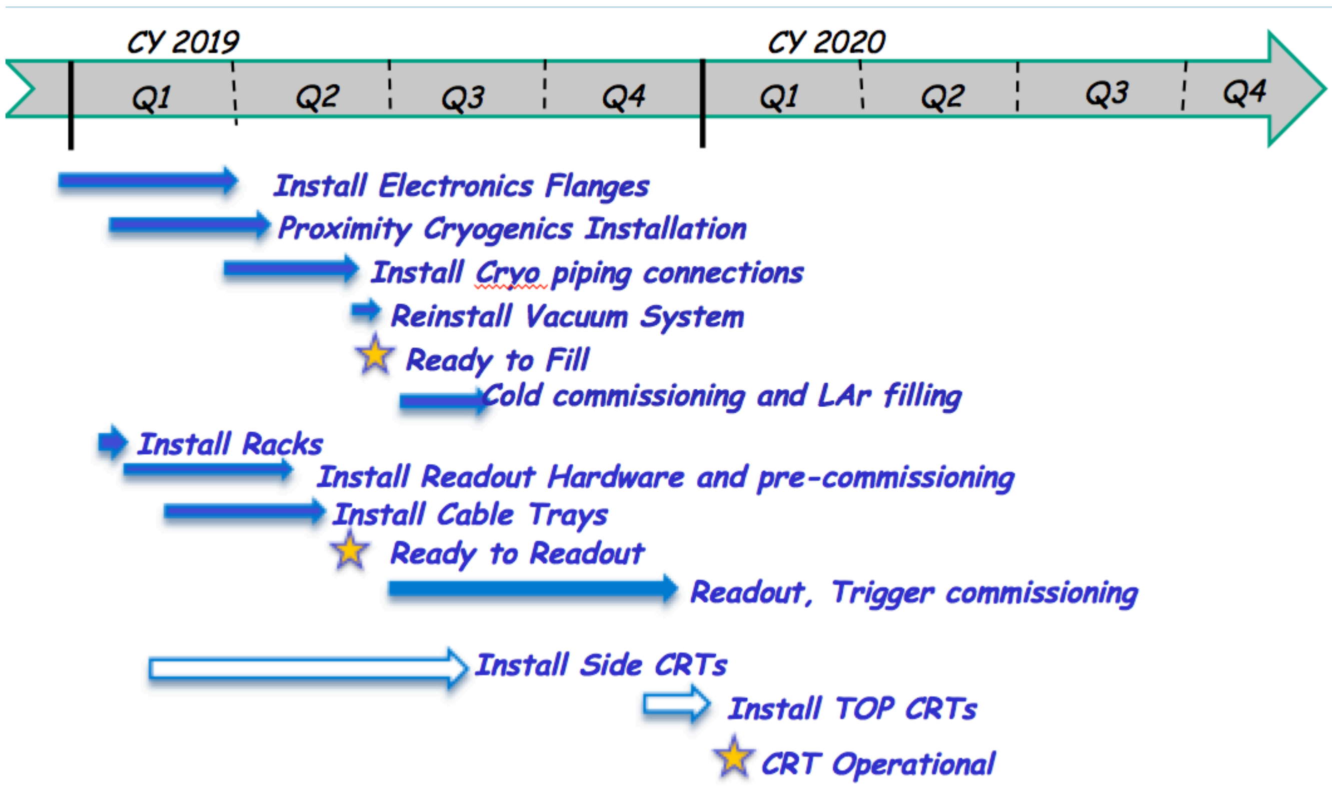
Angle between sim/reco direction for EM showers





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 June 2019
- After cryogenics commissioning, cooldown and filling, ICARUS T600 should be operational during 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 νe 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 2020.
- ICARUS will see first neutrinos by the end of this year!


Thank you !