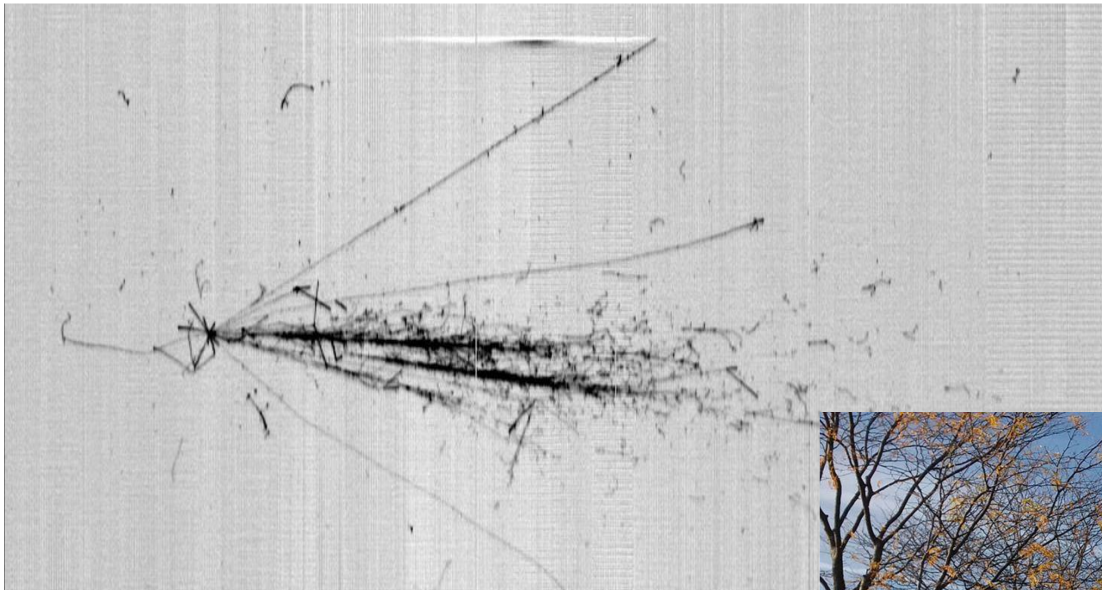
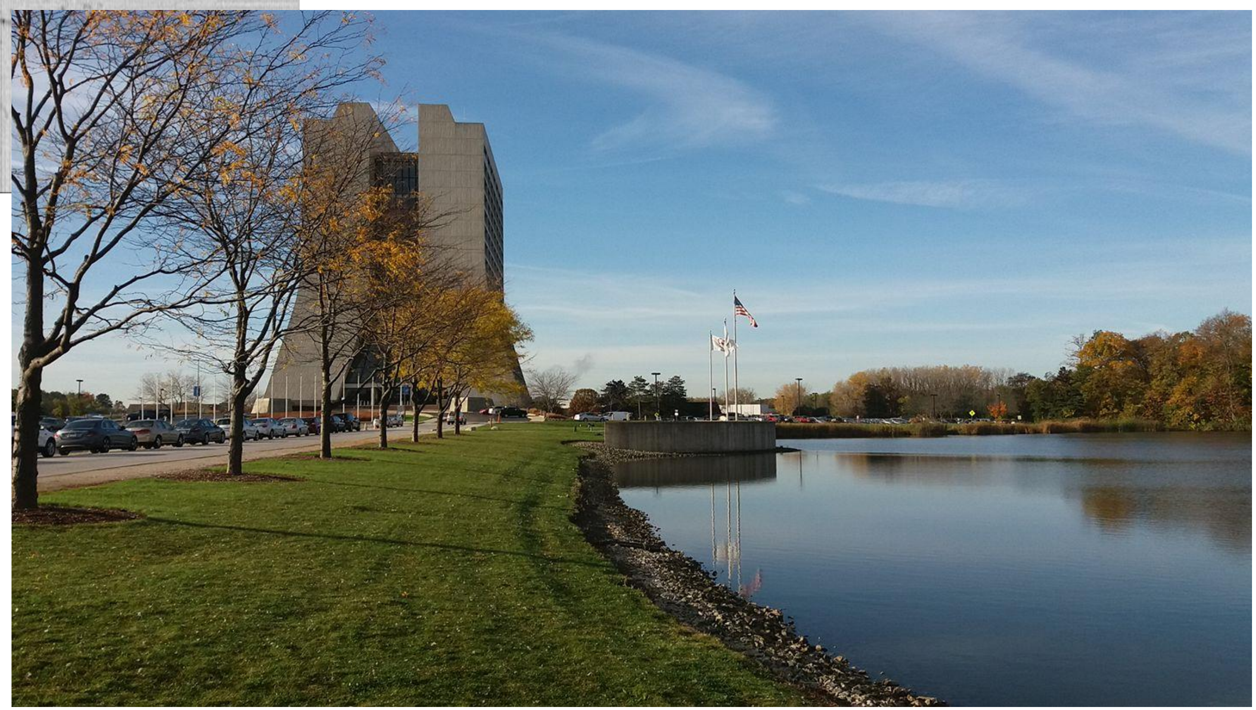
Sterile Neutrino searches with the ICARUS detector



Andrea Falcone
University and INFN
Milano Bicocca

on behalf of the
ICARUS collaboration



International Conference on New Frontiers in Physics

Kolymbari (Greece)
August 21-29, 2019

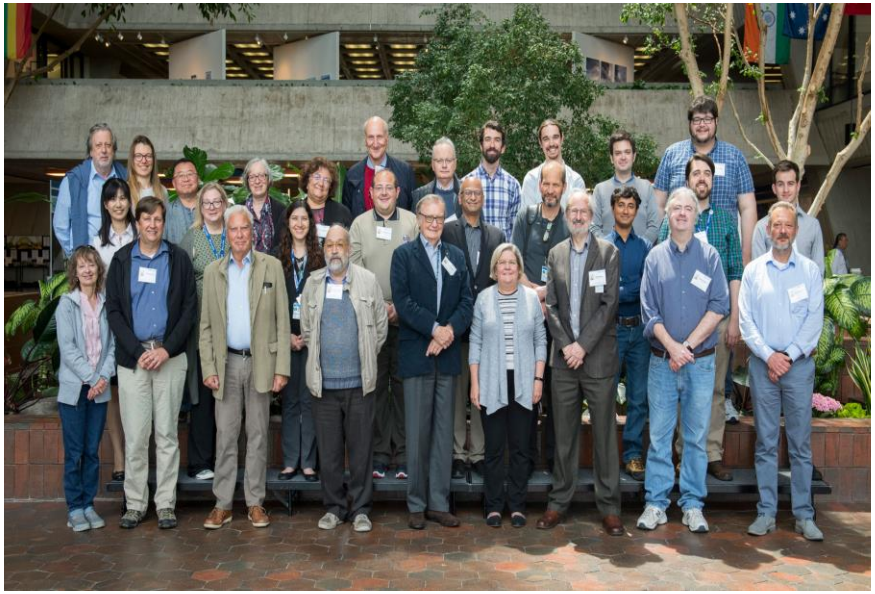
The ICARUS collaboration

The full list of the Collaboration: https://icarus.fnal.gov/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)



Spokesperson: C. Rubbia, INFN GSSI
more than 90 collaboration members

International Partner

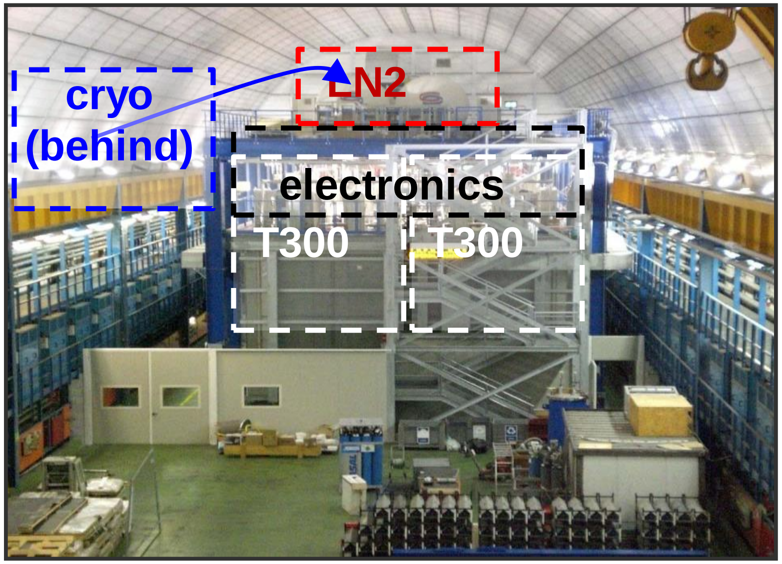
Neutrino Platform NP01

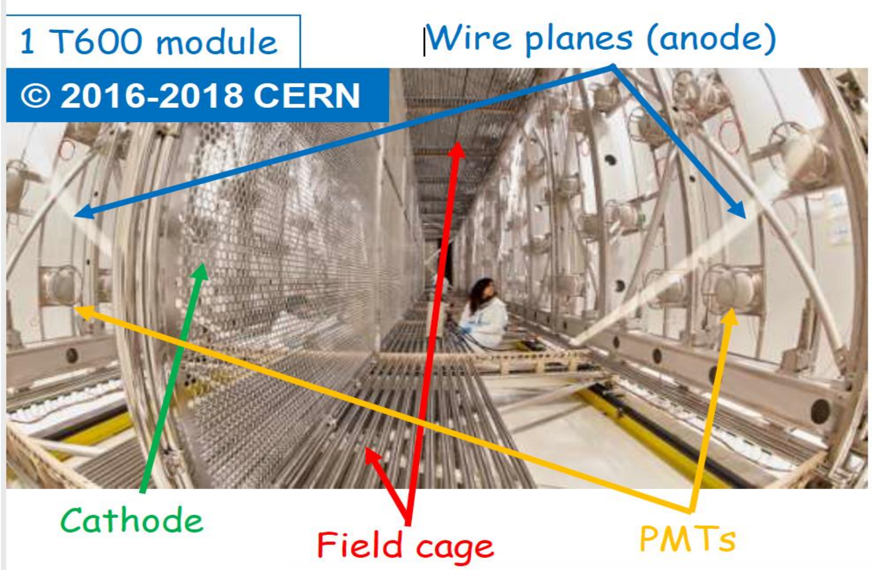
Many thanks for the major contributions to the Far Detector cryogenics and cosmic ray tagger from our partners at CERN, INFN-Bologna, INFN-Lecce, INFN-Milano, INFN-Napoli, INFN-Genoa, INFN-LNS.

Liquid Argon TPC: an "electronic bubble chamber"

- LAr-TPCs: 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 (2010-2013):

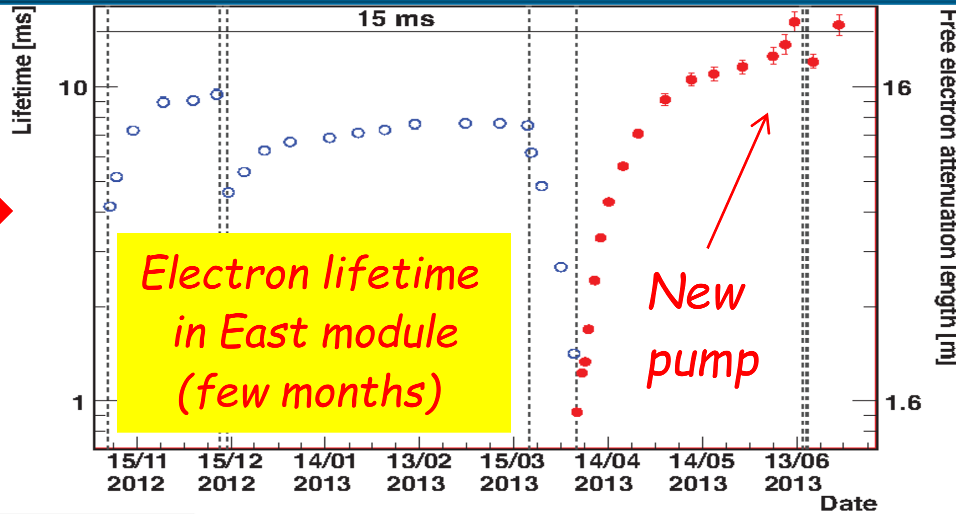




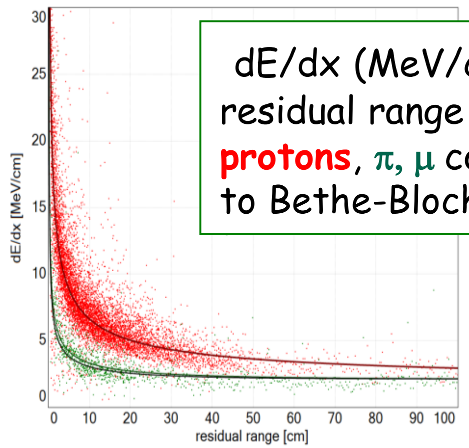
- ICARUS was exposed to CNGS beam and cosmics for 3 years, confirming expected performance and obtained important physics results.
- It proved the maturity of the LAr-TPC technique for large-scale experiments (DUNE).

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

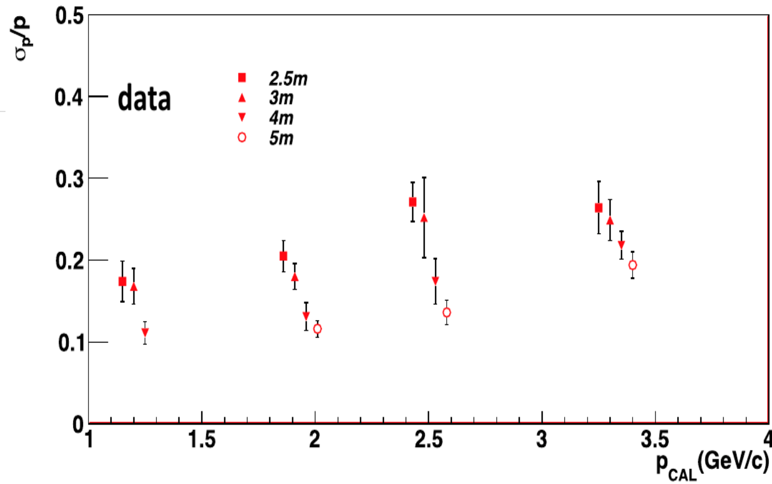


- Excellent spatial/calorimetric reconstruction. Accurate dE/dx measurement with fine sampling ($0.02X_0$). Particle ID from dE/dx vs. range
  AHEP (2013) 260820



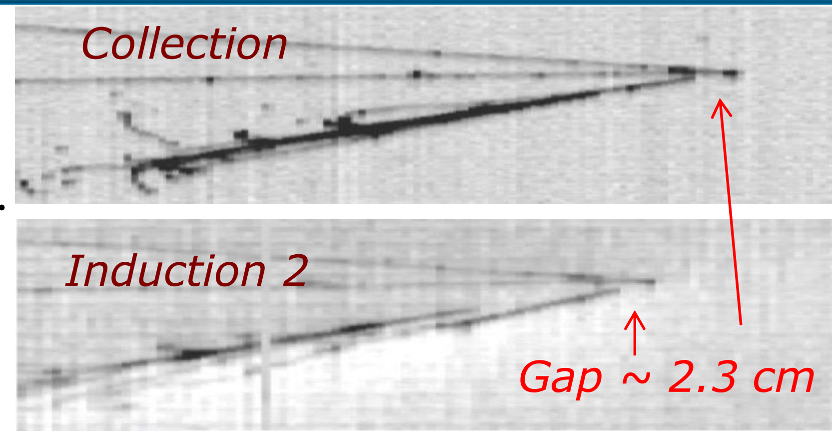
dE/dx (MeV/cm) vs. residual range (cm) for **protons**, π, μ compared to Bethe-Bloch curves

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

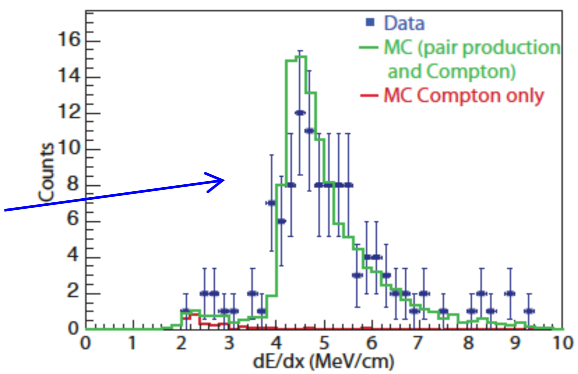


e/γ separation and ν_e identification

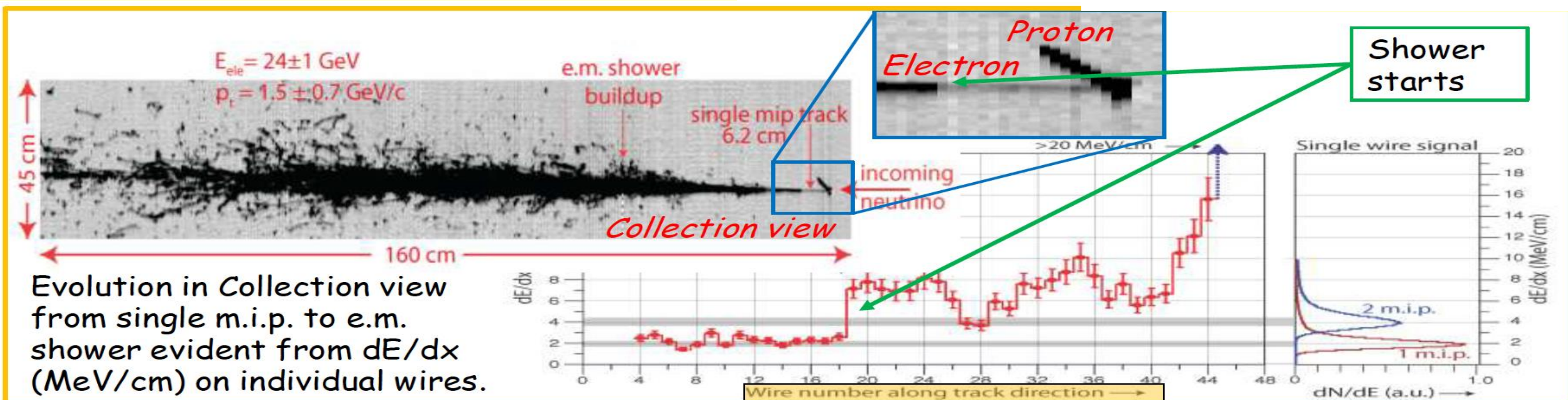
- ν_e CC event (electron-initiated EM showers) separation from NC background with π^0 (γ-initiated showers): crucial for oscillation physics.
- LAr-TPC provides 3 handles:
  - Visual identification of γ conversion gap.
  - Reconstruction of π^0 invariant mass.
  - dE/dx: calorimetric accuracy and fine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



dE/dx of sub-Gev photons:



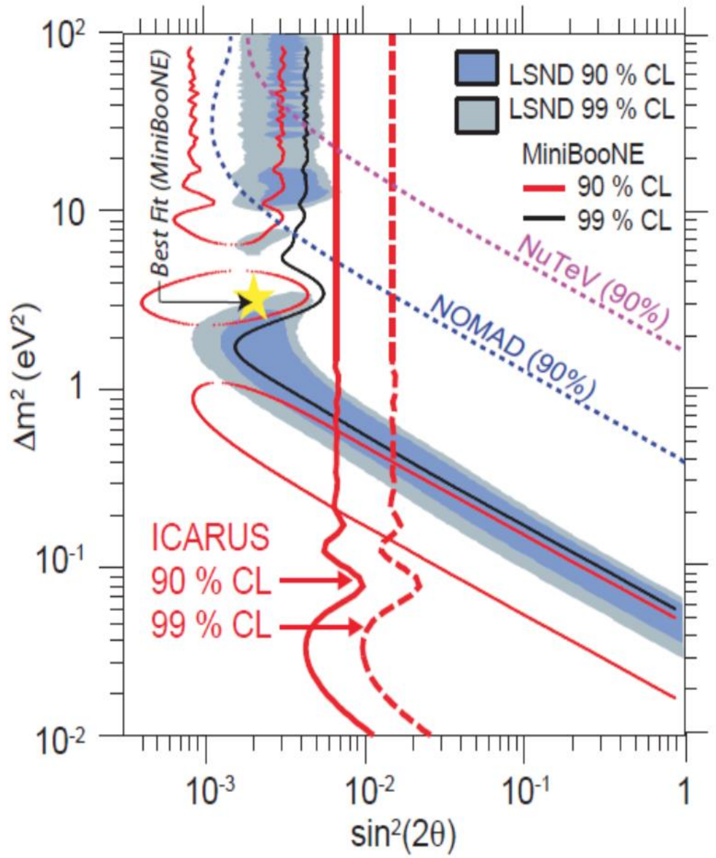
High-energy CNGS ν_e CC interaction:



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

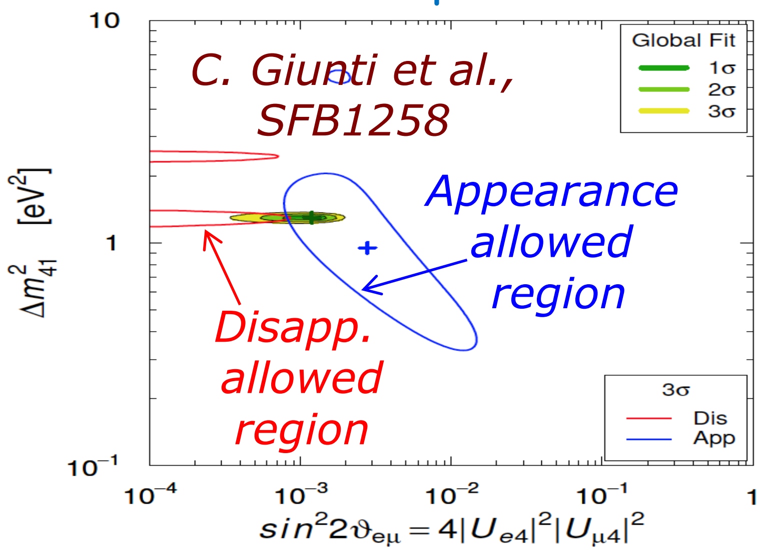
- ICARUS searched for sterile ν oscillations through ν_e appearance in the CNGS beam.
- L/E ~ 36 km/GeV, far from LSND value ~ 1 km/GeV -> "sterile-like" oscillation was averaged out, canceling energy dependence.
- 7.9 10^{19} pots analyzed (~2650 ν interactions).
- Expected ~ 8.5 $\pm$ 1.1 ν_e background 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.



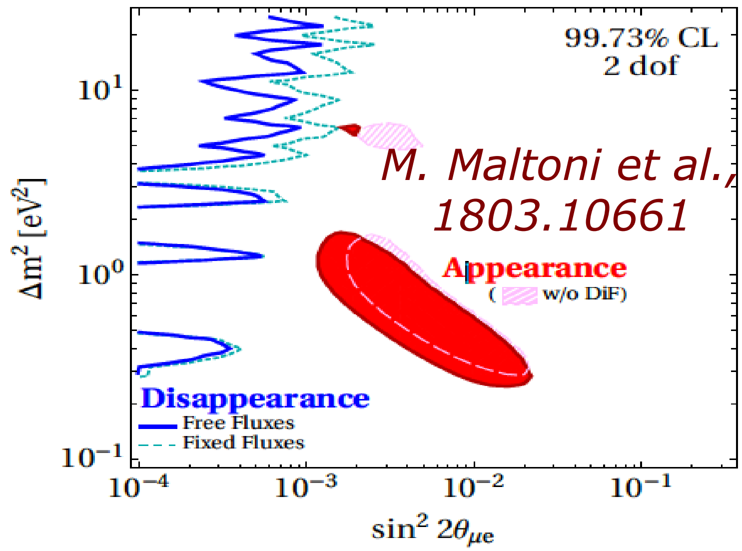
Eur. Phys. J. C (2013) 73:2599

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 appearance and ν_μ disappearance results. Measuring both channels with the same experiment will help disentangle



Combined analyzes



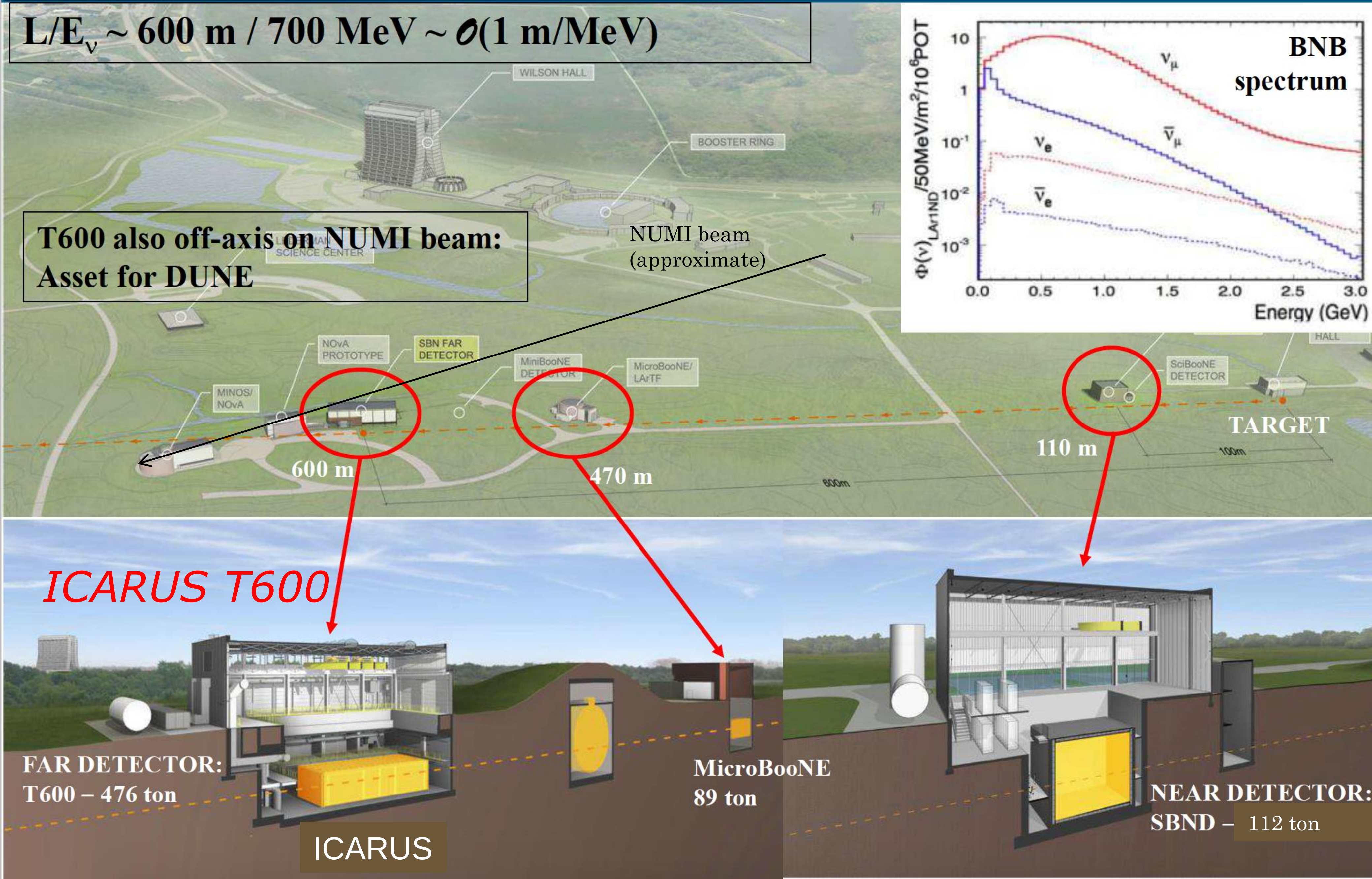
- A comparison between far/near detector is crucial for any accelerator experiment, with a better control of backgrounds and systematics

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

The SBN project

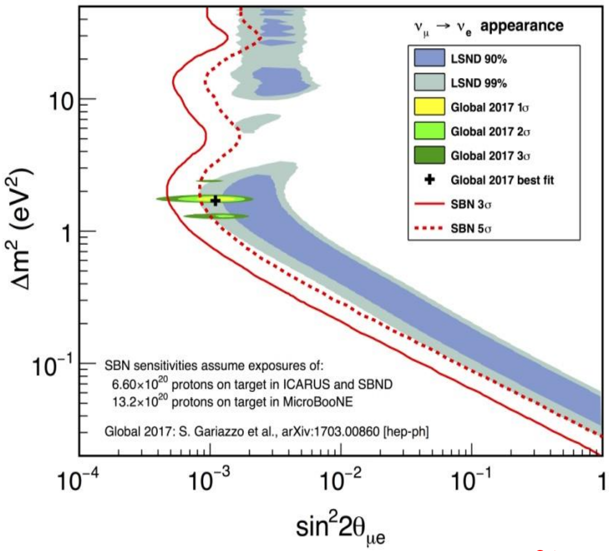
$L/E_\nu \sim 600$ m / 700 MeV $\sim \mathcal{O}(1$ m/MeV)

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

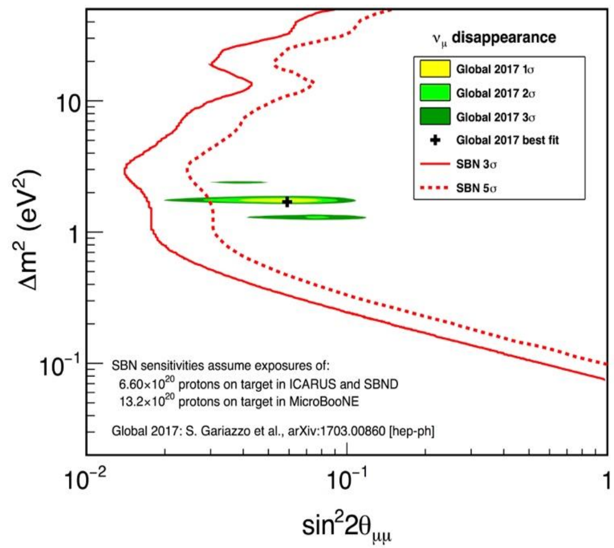


SBN Sterile neutrino search at FNAL Booster ν beamline

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



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

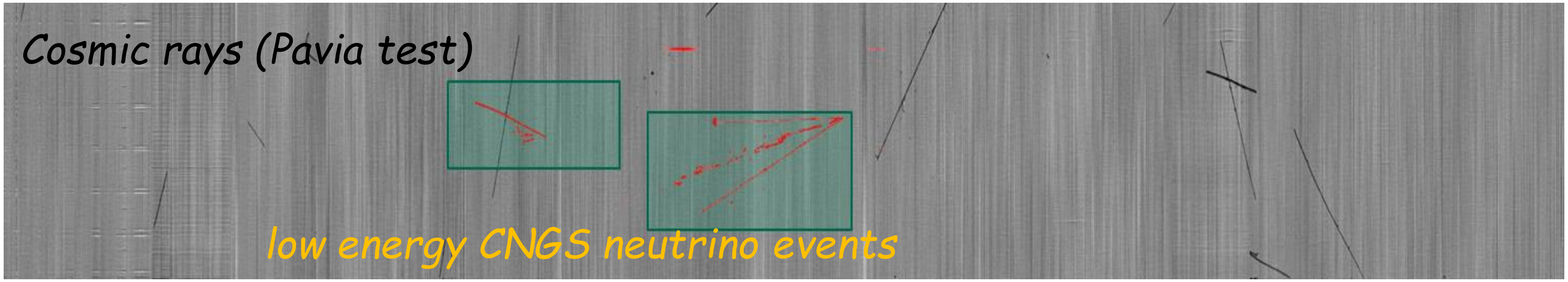


3-5 σ ν_μ disapp. SBN sensitiv.

- 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 as DUNE.

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 among 11 kHz of cosmic rays.



- Therefore, 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.

- 3 m concrete overburden to remove contribution from charged hadrons/γ's.
- External cosmic ray tagger to correlate residual muons with TPC signals.

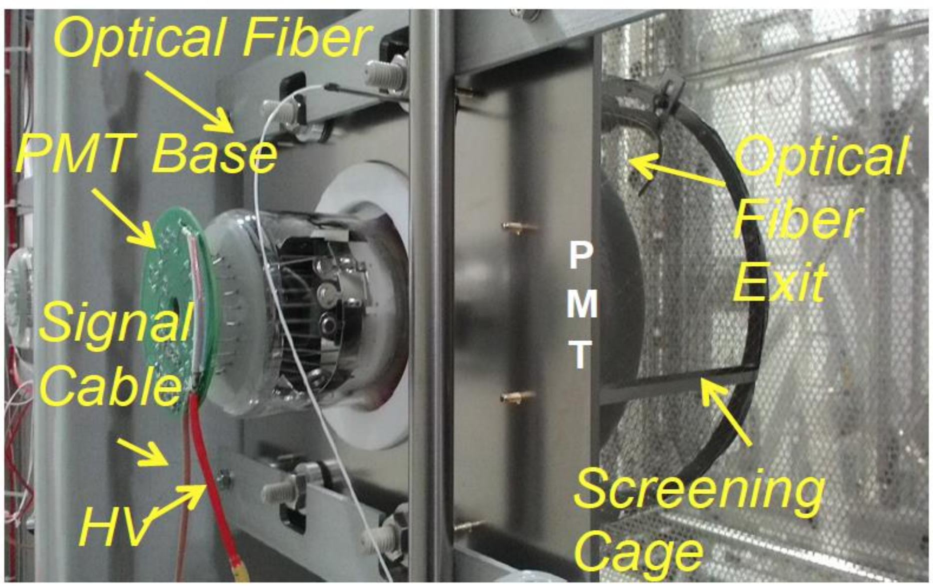
Upgrade of the light collection system

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

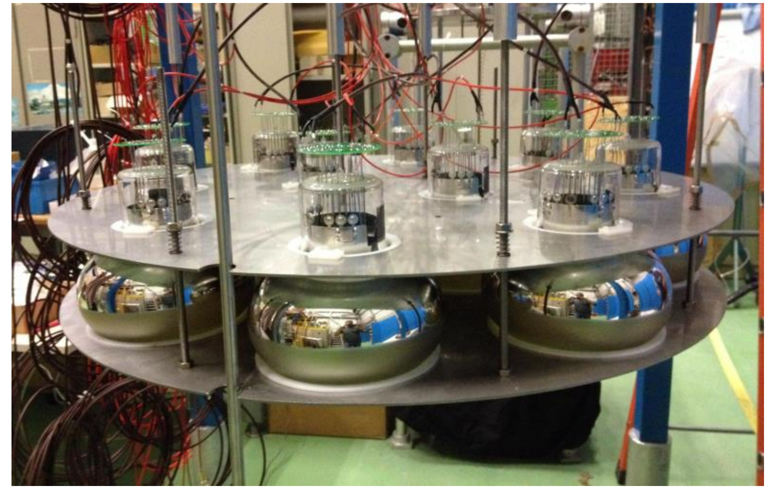
λ = 405 nm

FWHM < 100 ps

peak power ~ 400 mW

PMT tests at CERN

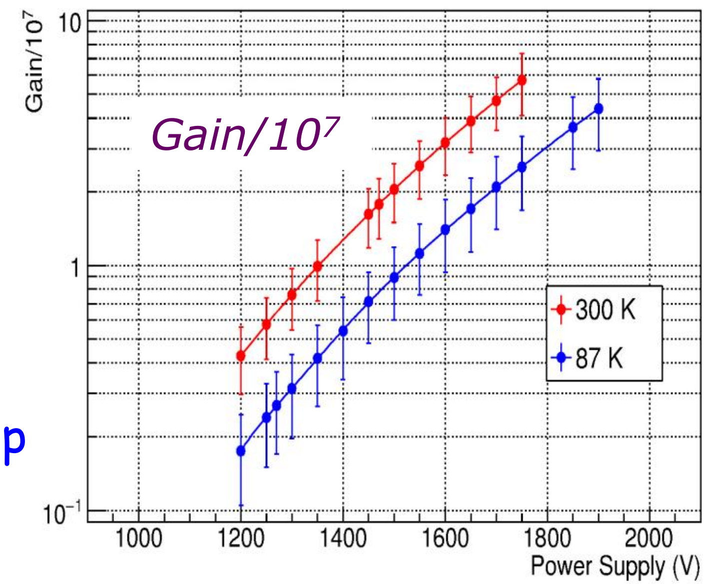
- All PMTs tested at room temperature in a dedicated dark room at CERN
- A subset of 60 PMTs tested immersed in LAr to compare the PMT performance in cryogenic environment to room temperature
- All PMTs illuminated with laser light pulses

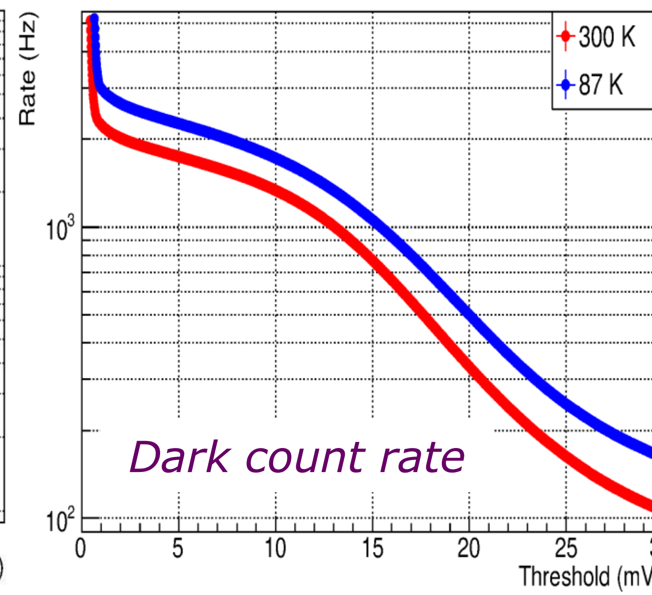


PMTs were characterized individually at 300K and 87K:

- 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



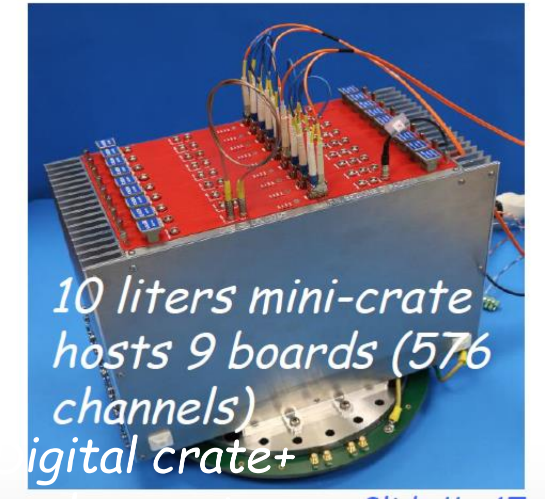


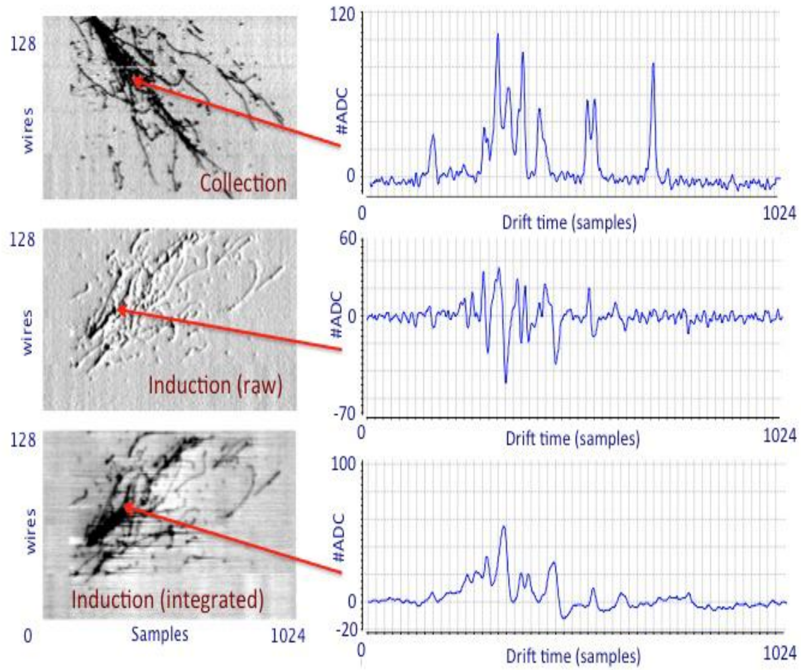
JINST 13 (2018) P10030

Upgrade of the TPC read-out electronics

New TPC readout electronics

- Outside the cryostat
- Serial 12-bit ADC, fully synchronous in the whole detector
- CAEN A2795 64-chan modules.
- 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

- Lower noise ~ 1200 e- equivalent (~20% S/N improvement w.r.t. LNGS electronics).
- Shorter shaping time (~ 1.5 μs for all planes) and drastic reduction of undershoot after large signals.
- Induction 2 signal keeps bipolar shape → allows calorimetric measurement in this plane, to improve ν_e identification efficiency by ~20%.

ICARUS transportation (from CERN to FNAL)

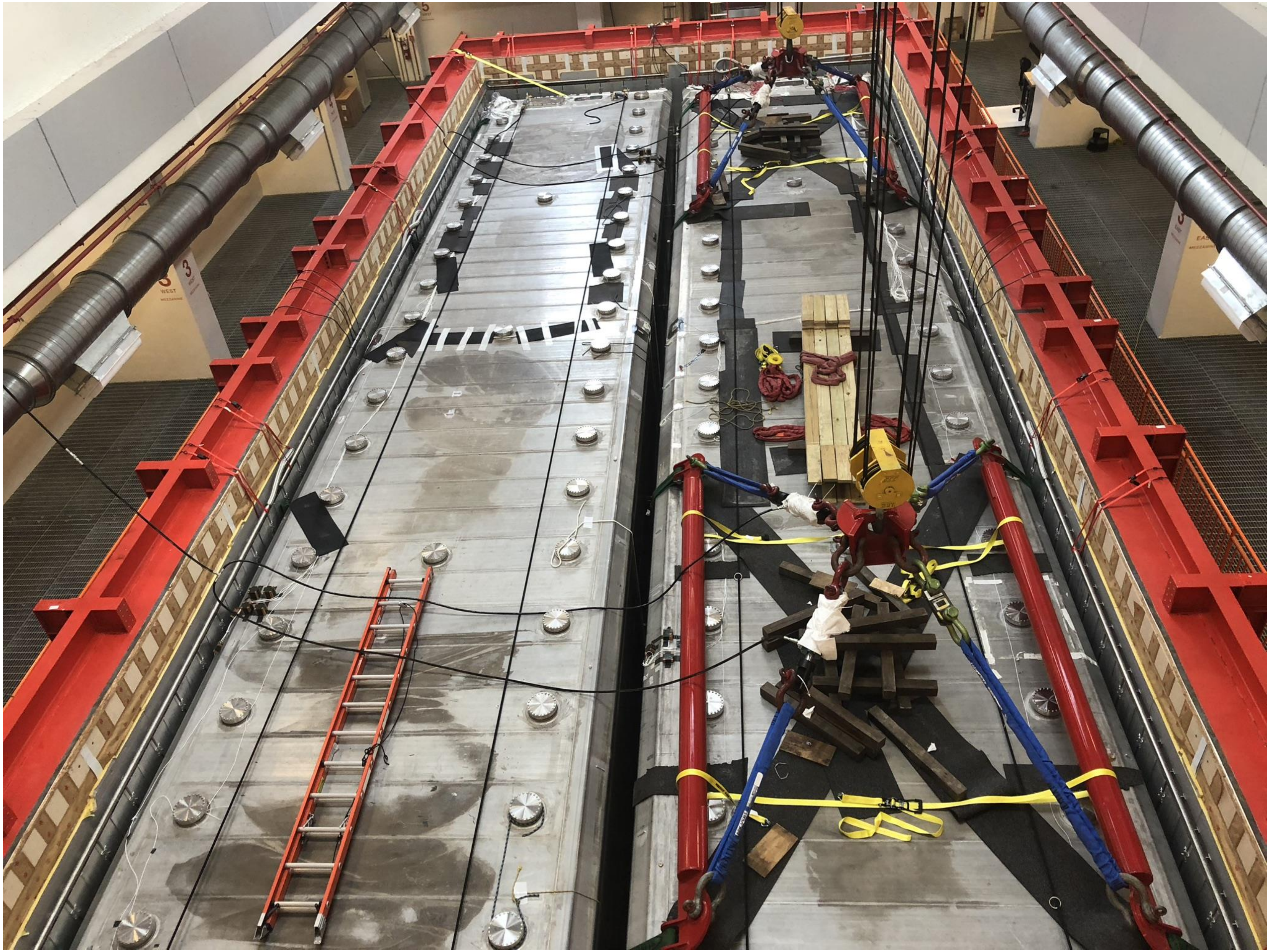
leaving from CERN, June 12th 2017

Antwerp: unloading from barge from Basel and loading into ship to Burns Harbor (Indiana)

arriving at SBN Far site building at FermiLab, July 26th 2017

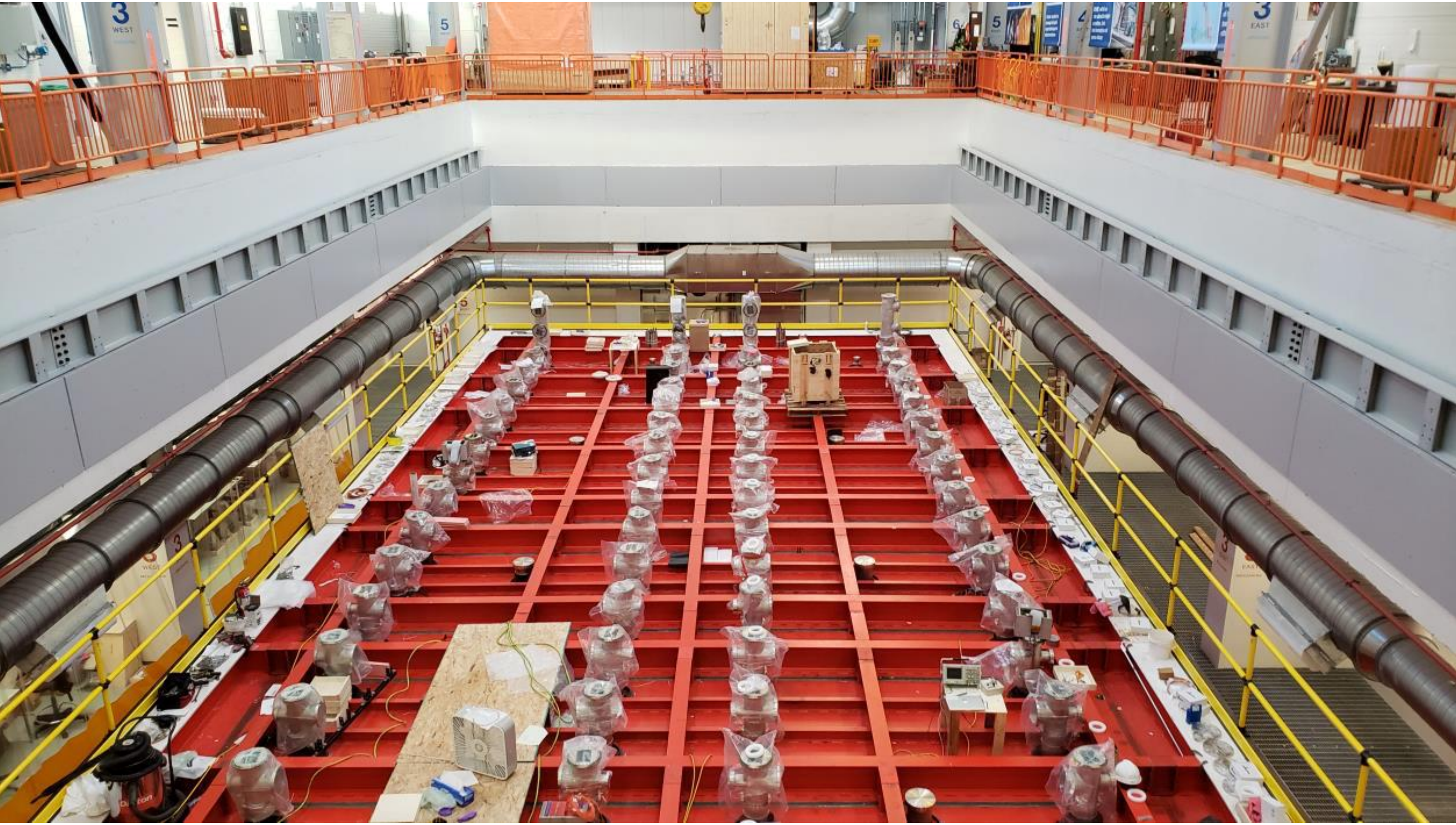
SBN far site building at FermiLab

Placement of ICARUS (August 2018)



Chimney installation (October 2018)

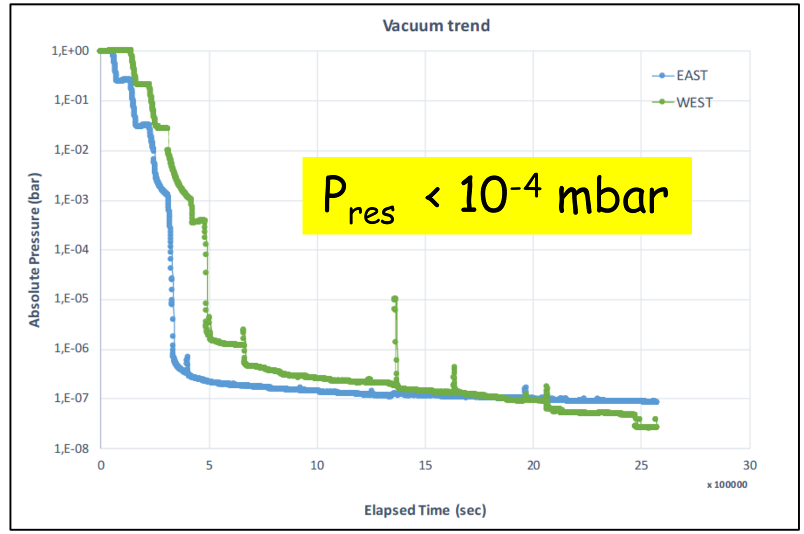
Feedthrough installation (December 2018)



Positioning the readout system (May 2019)

ICARUS installation at FNAL - status

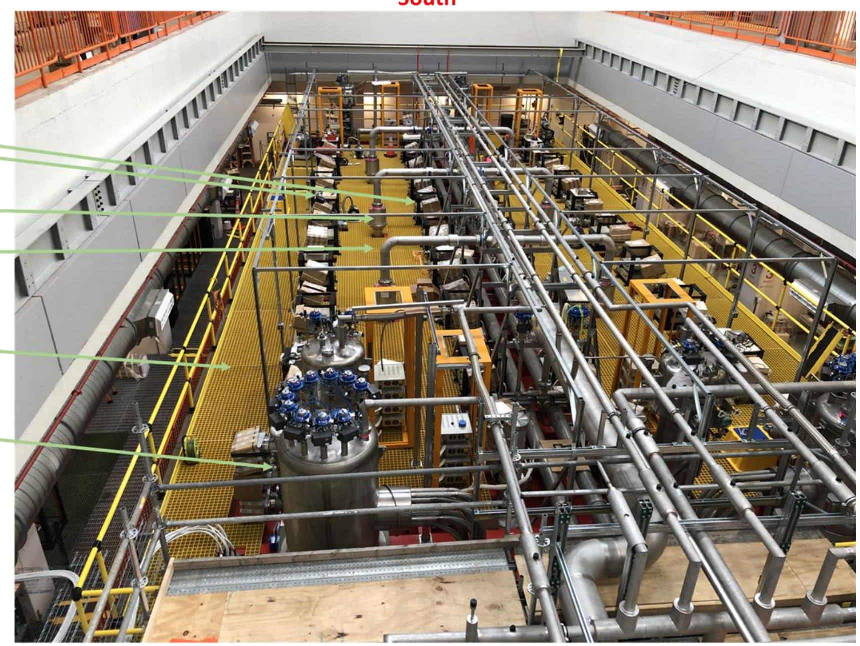
- Top cold shields and top CRT support installed.
- Installation of proximity cryogenics completed.
- ICARUS Vacuum phase started June 5th!
- Side CRT installation also ongoing.
- Director's Review in December 2018 recognized the great progress of SBN.



Connectivity test

Side CRT installation

South

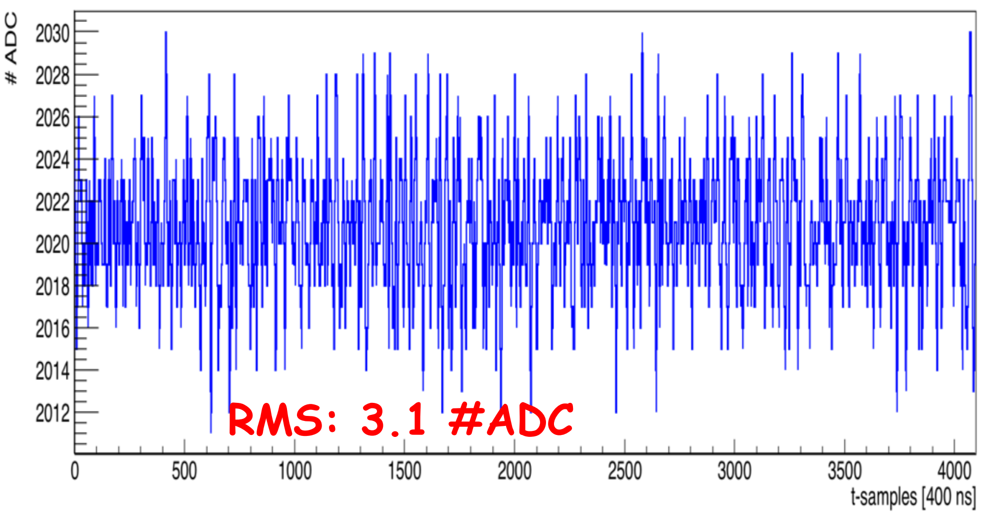


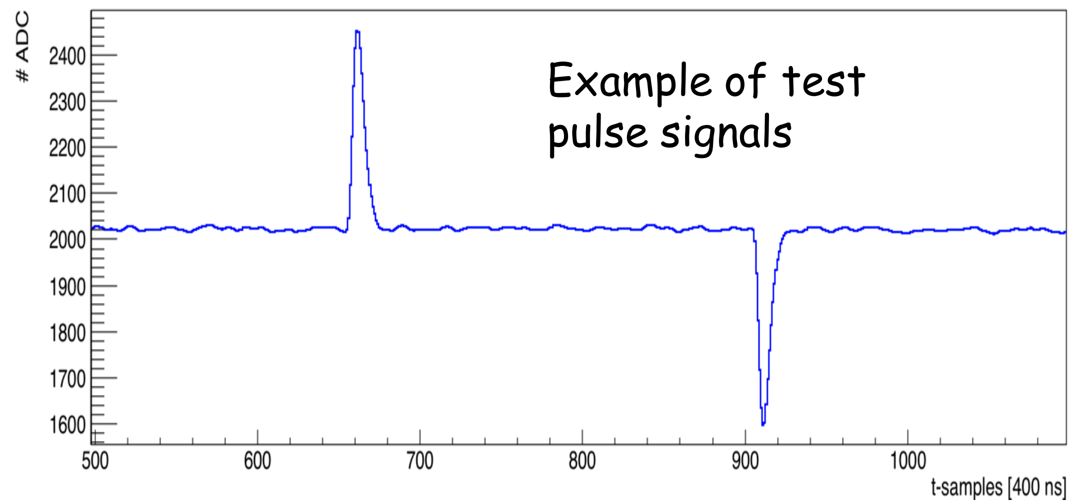
North

Standard crosses
Safety valves
Argon exhaust piping
Decking
Cold shields valve boxes

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!

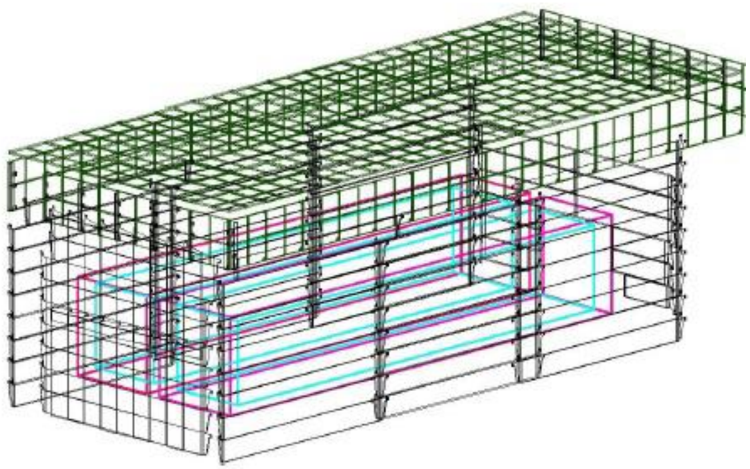
The Cosmic Ray Tagging system (CRT)

- 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

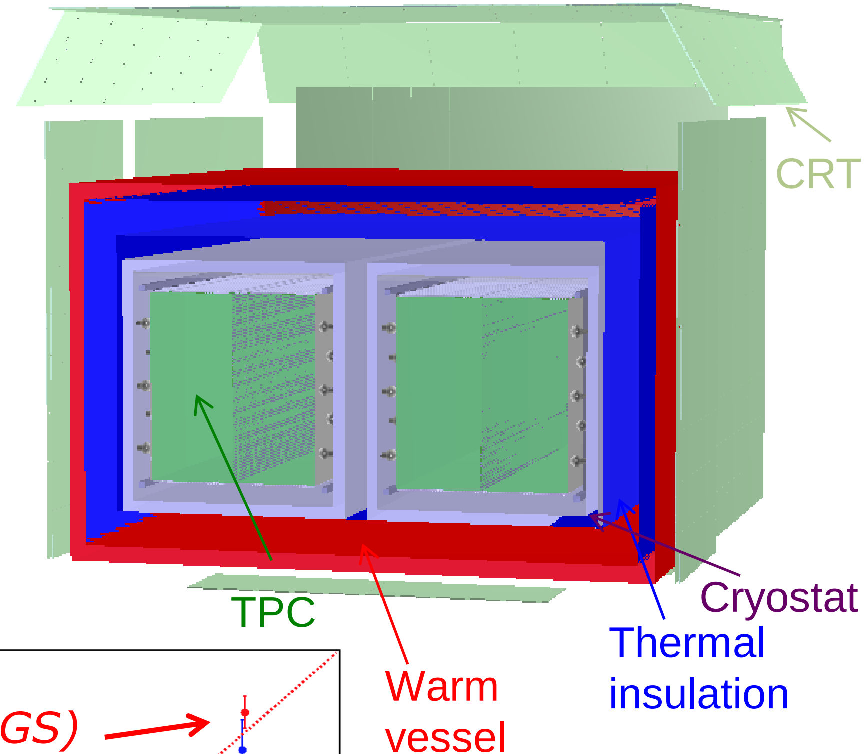
BOTTOM:
~ 200 m^2, already installed
D-Chooz veto modules
2 parallel layers
PMT readout

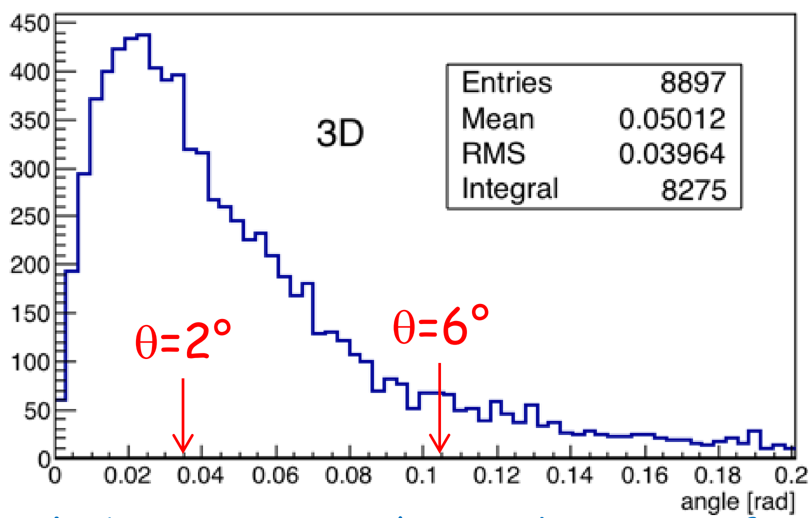


Reconstruction and analysis in SBN

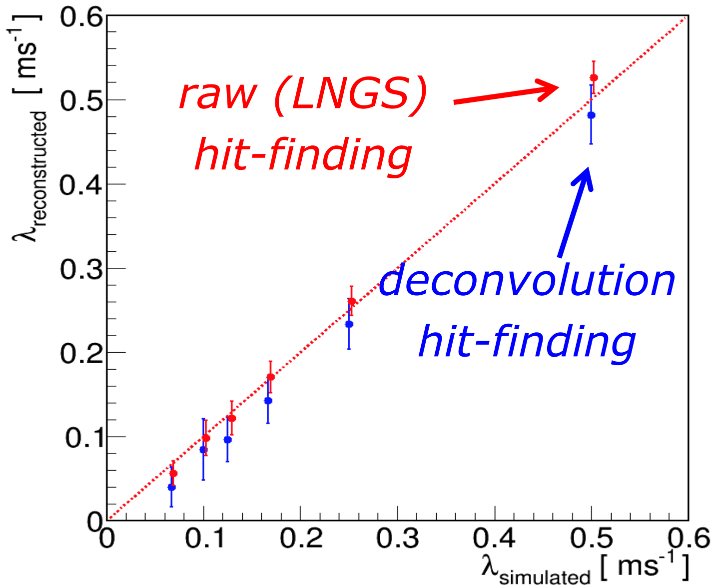
- A detailed understanding of detector-related systematics and their correlation across near/far detectors will be crucial to SBN physics.
- Common reconstruction tools and oscillation analysis are therefore fundamental.
- ICARUS joined the LArSoft framework: mutual sharing of algorithms and tools and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





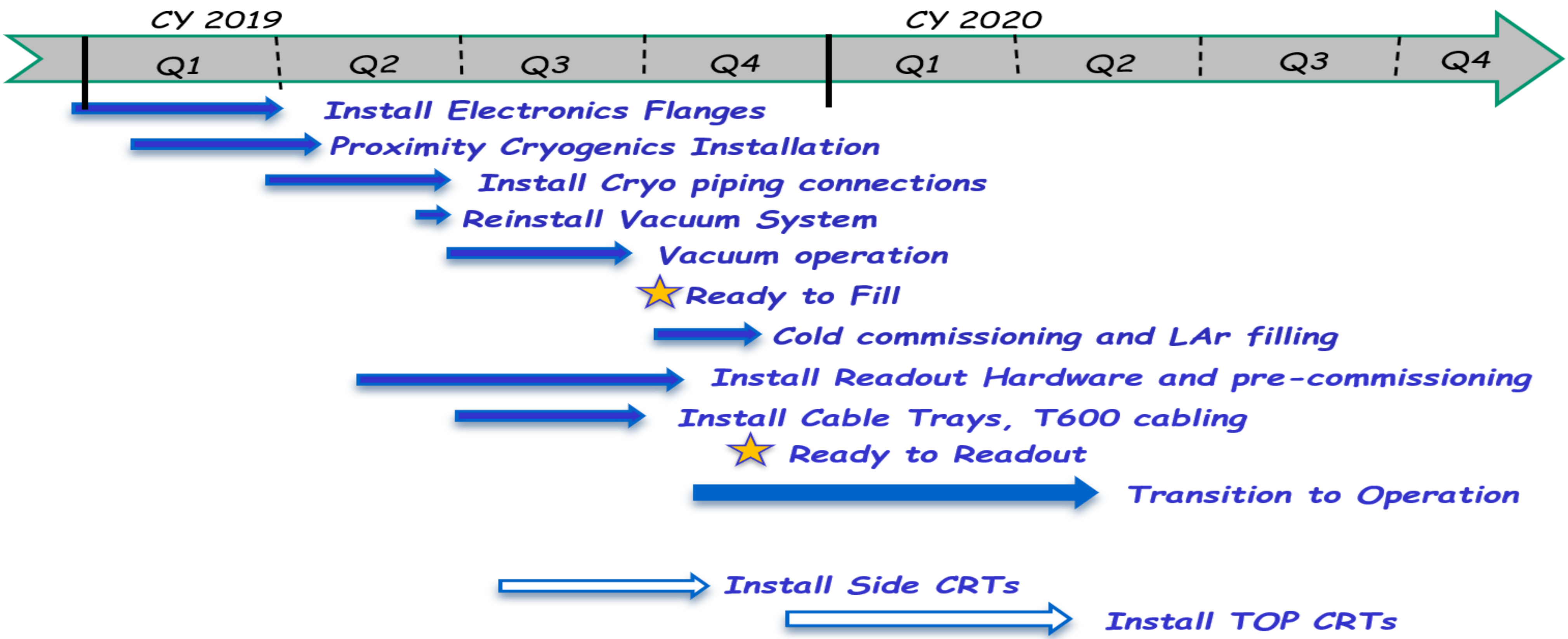
angle between sim/reco direction for EM showers



electron lifetime (reco vs. simulation)

ICARUS at FNAL – plans and commissioning

- TPC/trigger electronics installation to be completed and tested by October 2019.
- PMT electronics installation also to be completed during the summer.
- ICARUS expected to be ready to fill by fall.
- 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 !

Thanks!