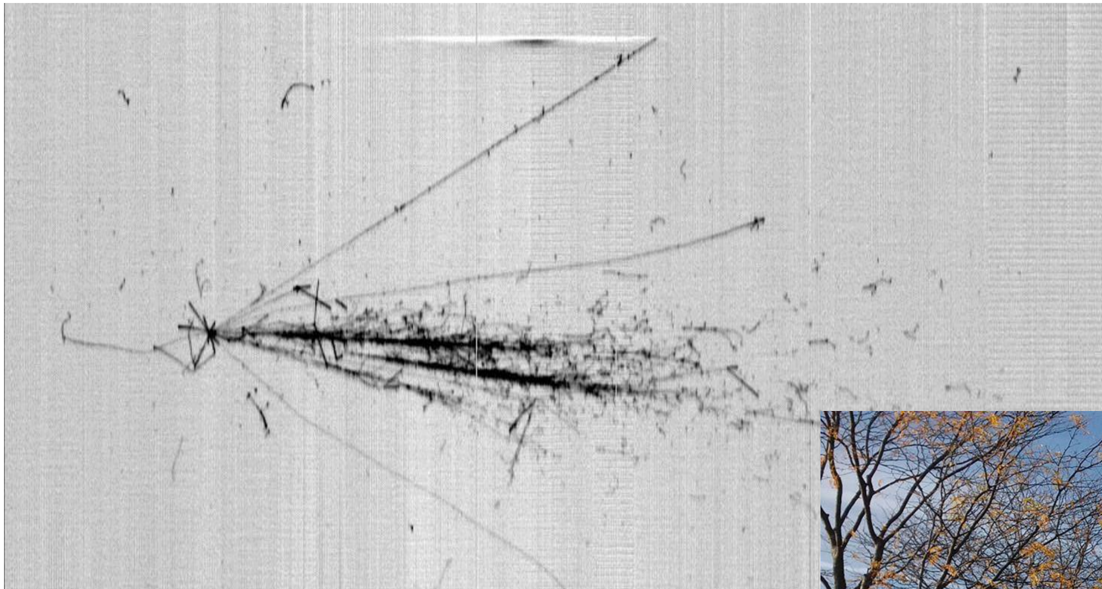
ICARUS: a new challenge within the Fermilab Short Baseline Neutrino Program

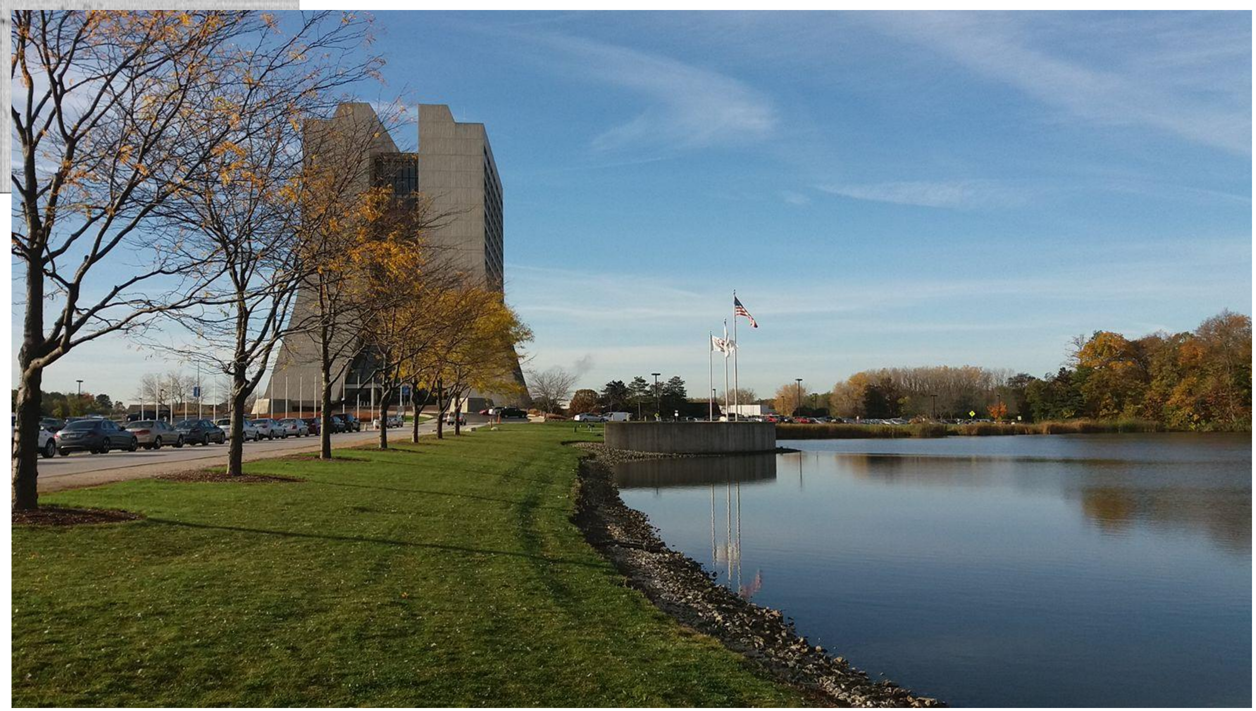


Andrea Rappoldi
INFN Pavia

on behalf of the
ICARUS collaboration

New Trends in High-Energy Physics

Odessa
May 12-18, 2019



Outline

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

The ICARUS collaboration

O(100) scientists

Italy

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

U.S.A.

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

Spokesman: C. Rubbia (GSSI)

Mexico

CINVESTAV

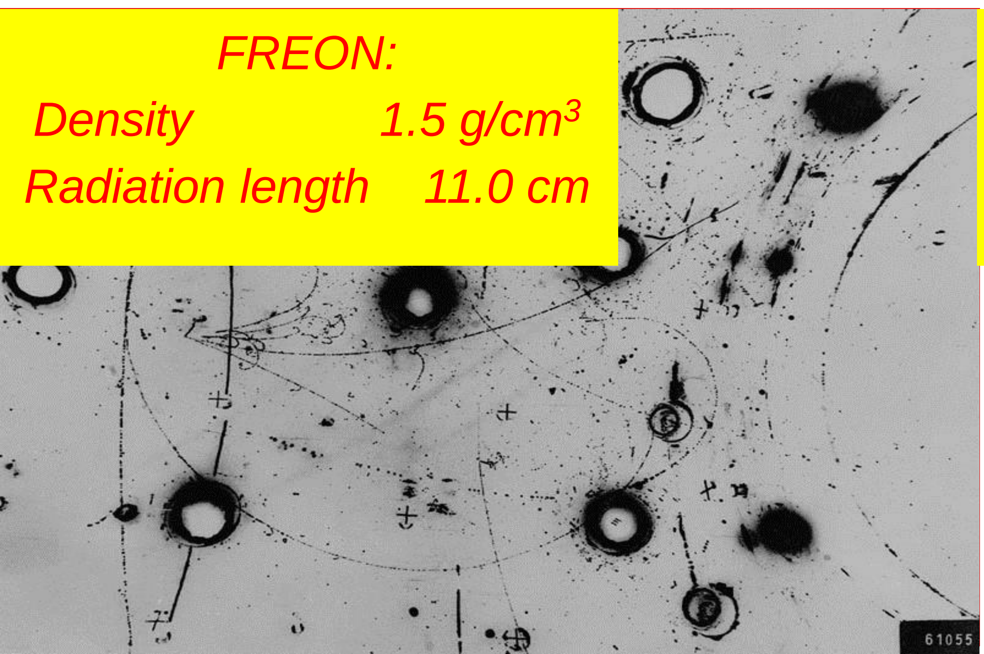
Neutrino Platform NP01

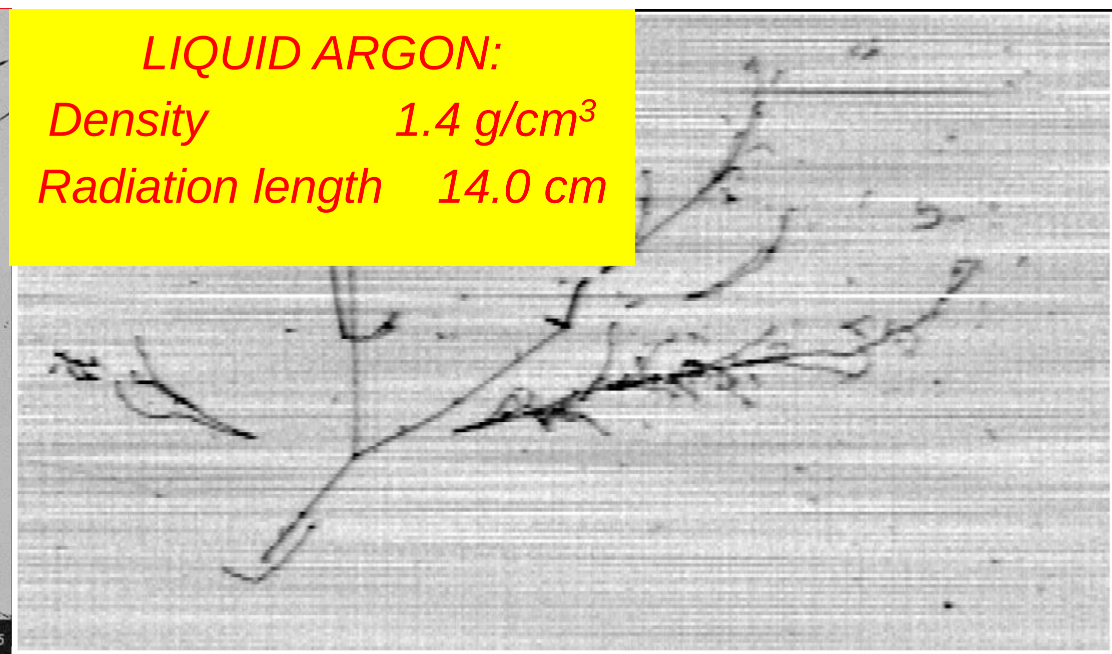
INTENSE

This work was supported by the EU *Horizon 2020* Research and Innovation Programme under the Marie Sklodowska-Curie Grant Agreement No. 822185

Liquid Argon TPC: an "electronic bubble chamber"

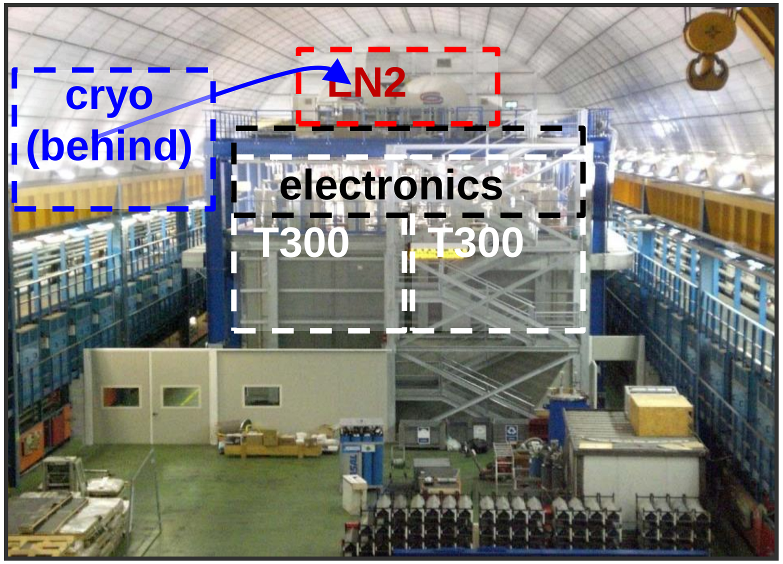
- First proposed by C. Rubbia in 1977: long R&D at INFN and CERN culminated in first large-scale experiment: ICARUS-T600 at LNGS (2010)
- LAr TPCs are suitable detectors for neutrino physics:
  - 3D reconstruction with high (mm^3) spatial granularity
  - Homogeneous, full-sampling calorimetry for contained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

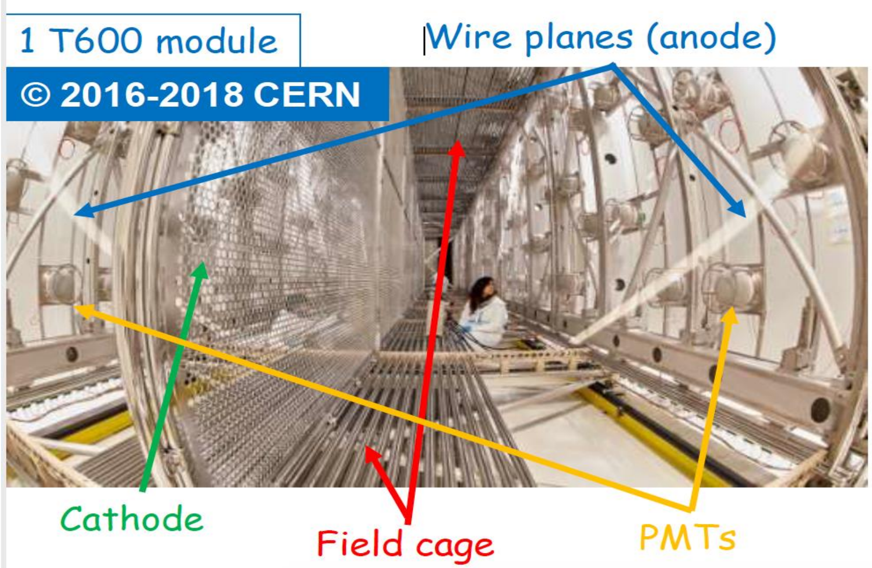




ICARUS-T600 at LNGS

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



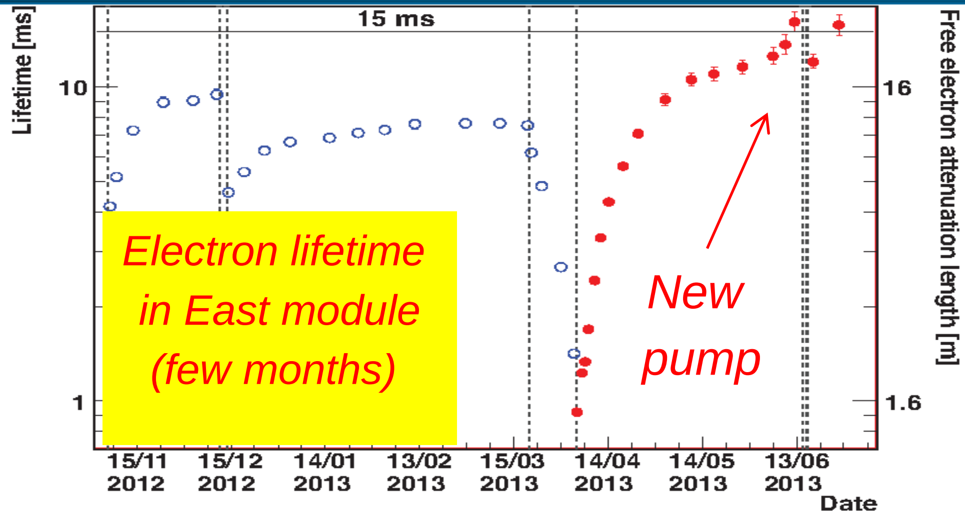


- ICARUS was exposed to CNGS beam and cosmics for 3 years (2010-2013)
- Run confirmed expected performance and obtained important physics results
- It proved the maturity of the LAr-TPC technique for large-scale experiments

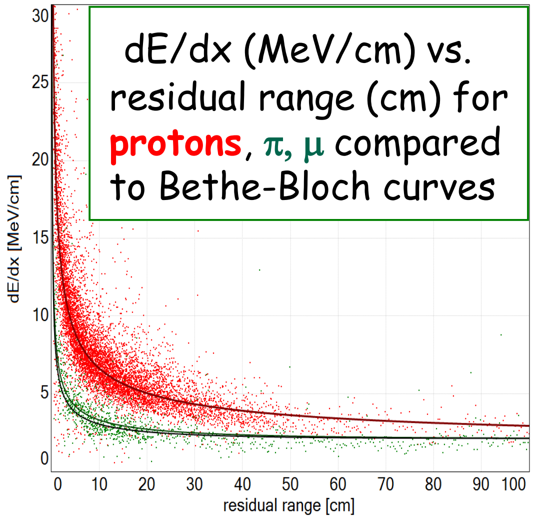
ICARUS paved the way to the next generation long-baseline project: DUNE

ICARUS reconstruction performances

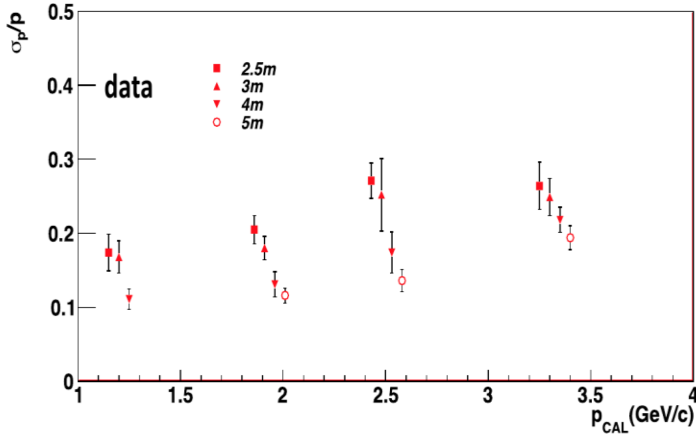
- High electron lifetime: > 7 ms (impurity concentration < 40 ppt)
  Crucial step towards future larger detectors
  2014 JINST 9 P12006



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

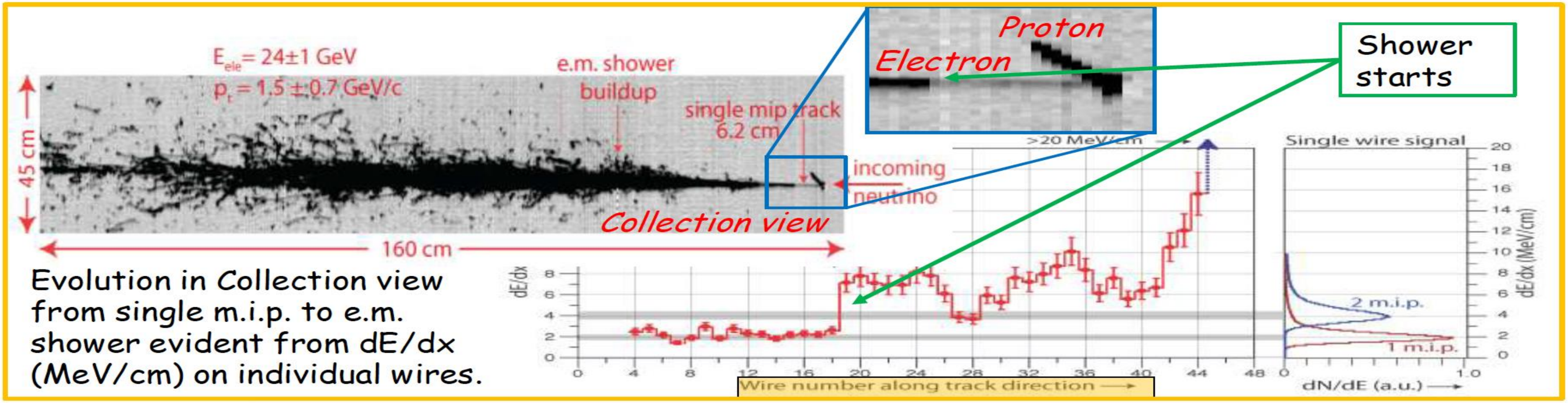


- Momentum of escaping muons can be measured by multiple Coulomb scattering. Average ~ 15% resolution on stopping muons (0.5÷5 GeV/c)
  JINST 12P04010

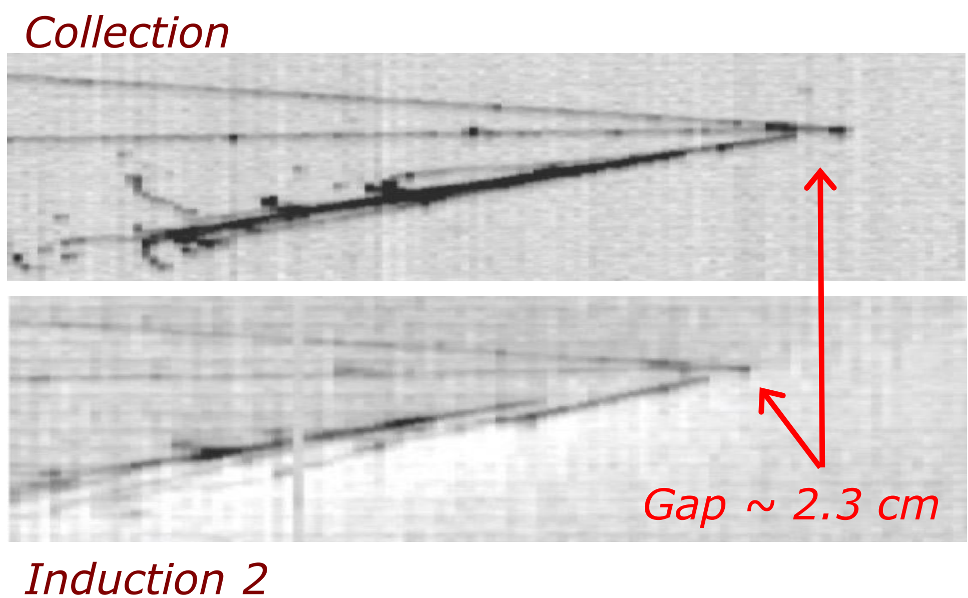


e/γ separation and ν_e identification

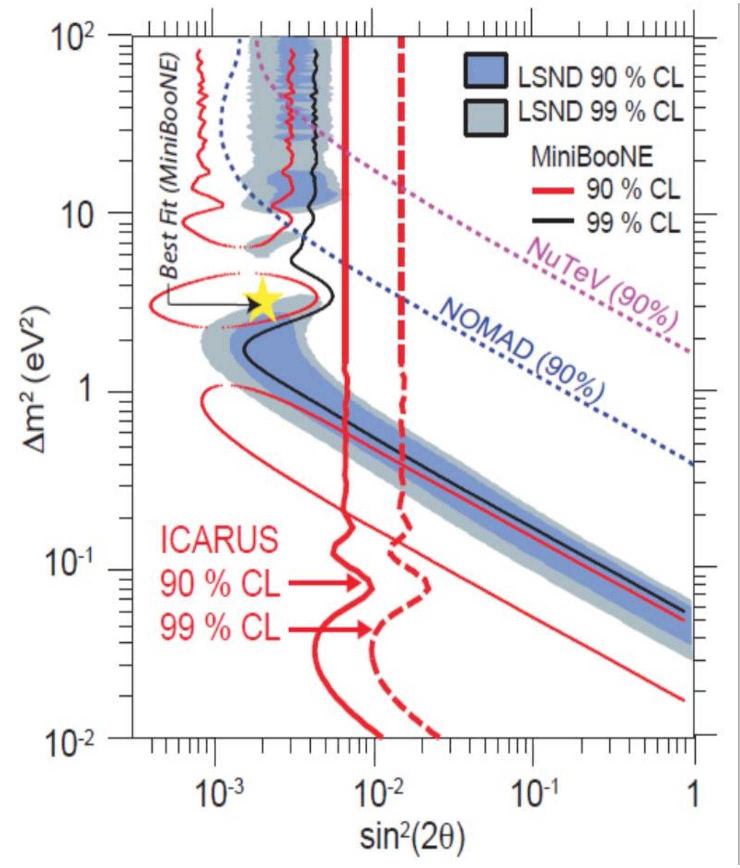
High-energy CNGS ν_e CC interaction:



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



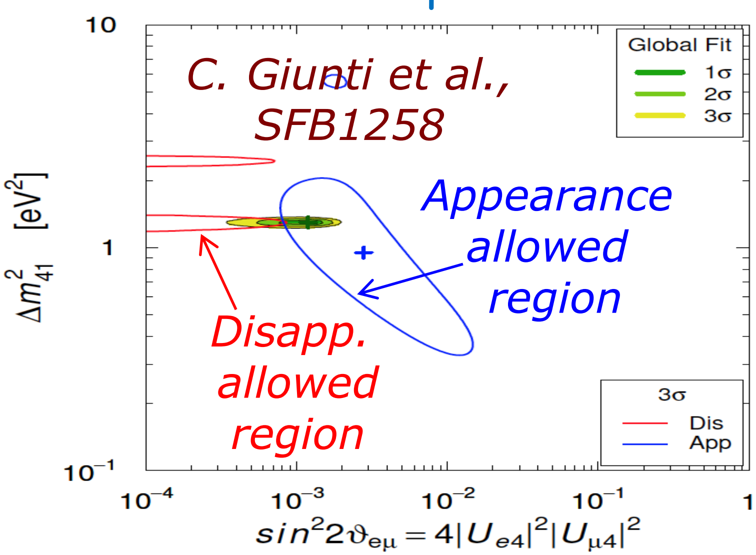
- ICARUS searched for sterile ν oscillations through ν_e appearance in the CNGS beam
- L/E ~ 36 km/GeV, far from LSND value ~ 1 km/GeV → "sterile-like" oscillation was averaged out, canceling energy dependence
- 7.9 10^{19} pots analyzed (~2650 ν interactions)
- Expected ~ 8.5±1.1 ν_e background events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



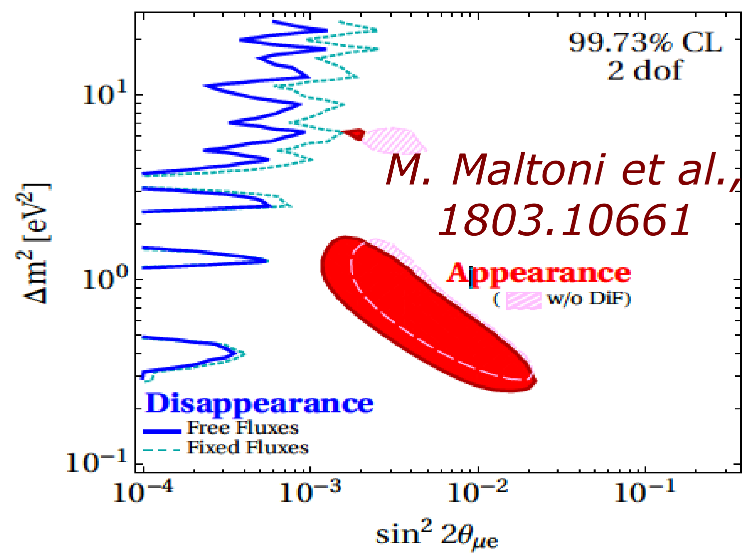
Eur. Phys. J. C (2013) 73:2599

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



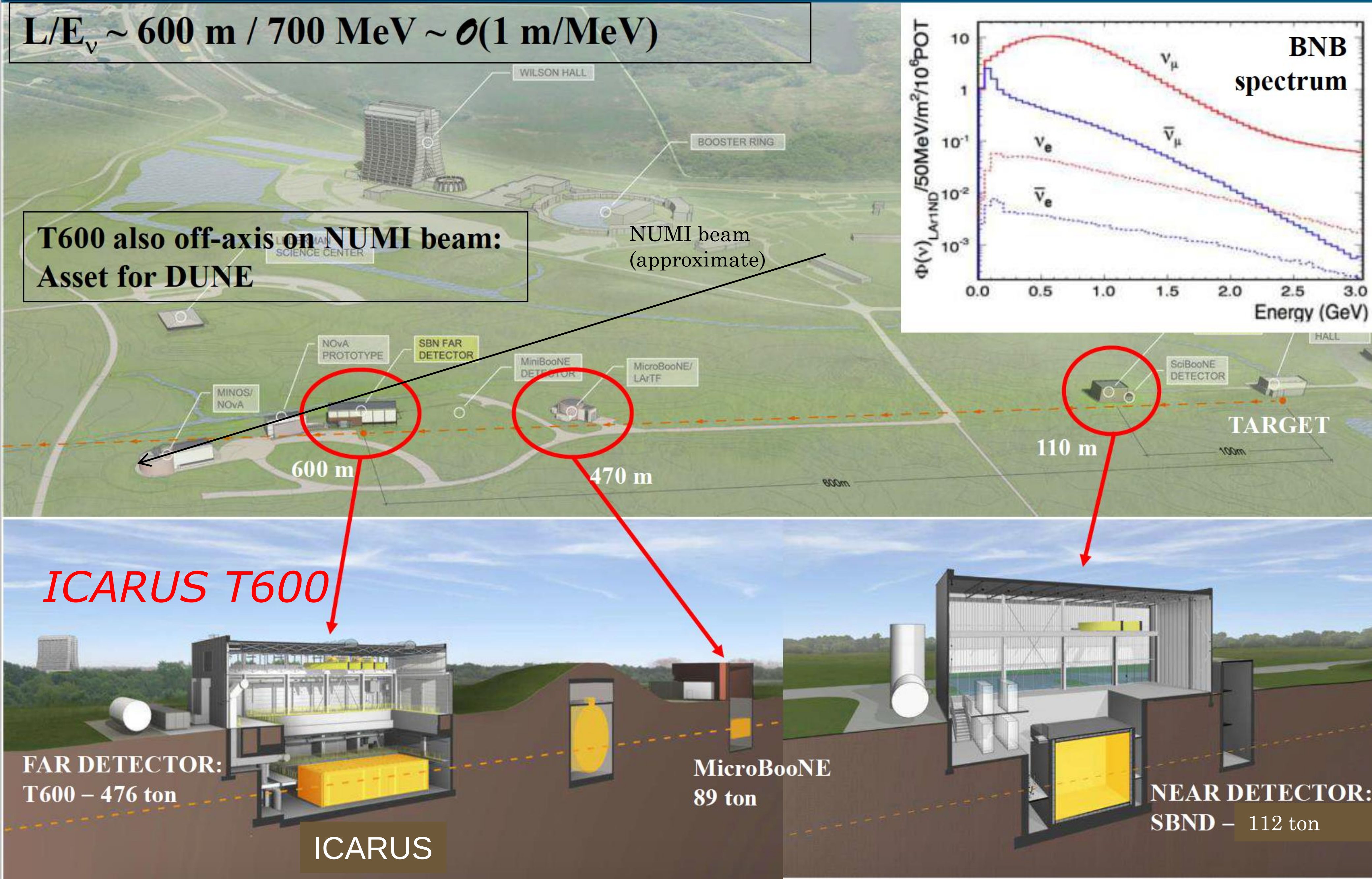
Combined analyzes



- 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



SBN Sterile neutrino search at FNAL Booster ν beamline

- The experiment will exploit 3 LAr-TPCs exposed to the FNAL Booster Neutrino Beam, (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

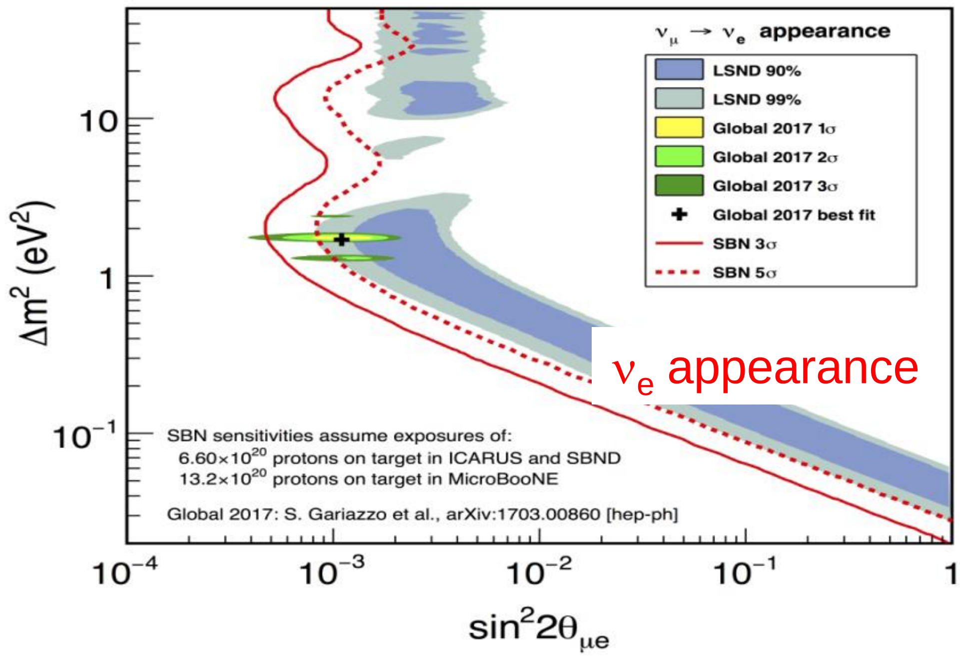
- Using the same detector technology for all the 3 detectors will greatly reduce the systematic errors: SBND (near detector) will provide the "initial" beam composition and spectrum

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

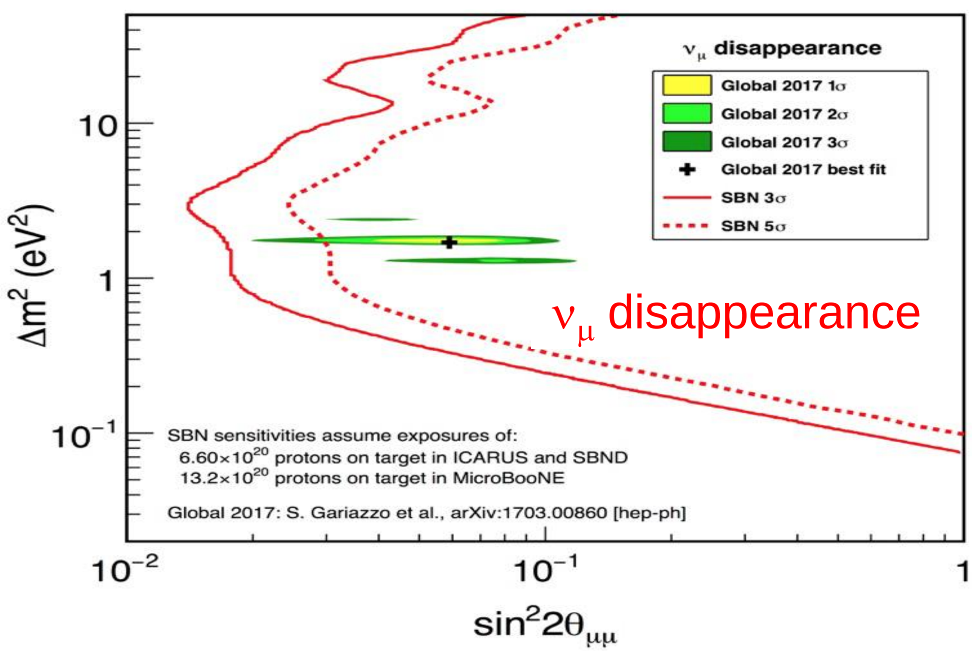
- During SBN operations, ICARUS will also collect ~ 2 GeV neutrinos from NuMI (Neutrino Main Injector) Off-Axis beam. This will be an asset for the future long-baseline project:
  - ν interaction cross-section measurements and identification/reconstruction studies
  - In particular, a large ν_e component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

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

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

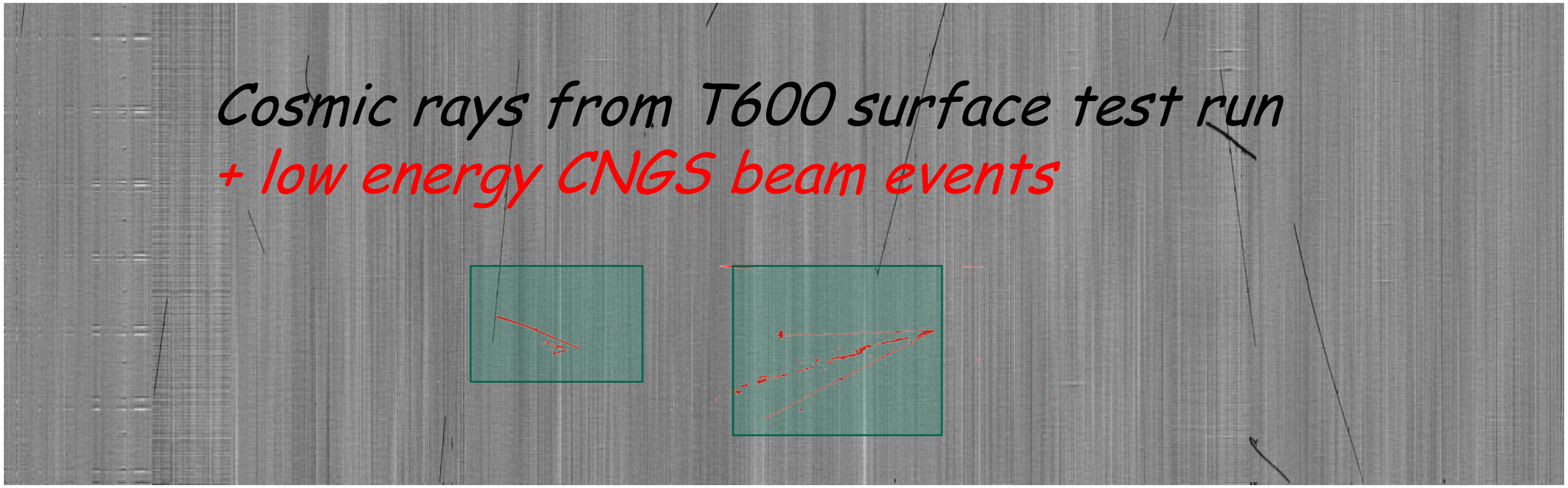


Exploiting high rates and detector correlations, ν_μ disappearance sensitivity will be extended by one order of magnitude beyond present limit in 3 yr



The new experimental challenge: a LAr-TPC on surface

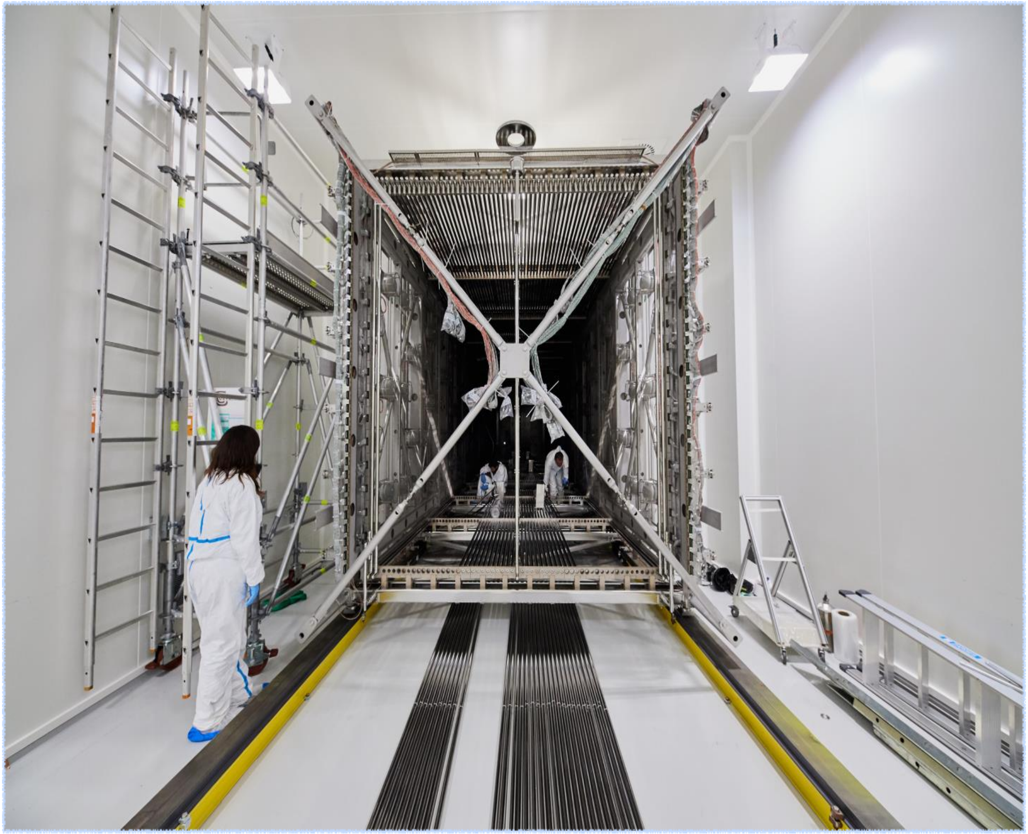
- ICARUS will take data at shallow depth (only 3 m concrete overburden)
- ~ 11 muon tracks will hit each ICARUS module in the ~1 ms drift window and be randomly overlapped to the beam neutrino interaction



- Cosmic-related photons can mimic ν_e 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 O(1) ms TPC drift window
- This requires signals on a faster time scale than the TPC including:
  - improved LAr scintillation light detection system
  - Cosmic Ray Tagger (CRT) surrounding 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



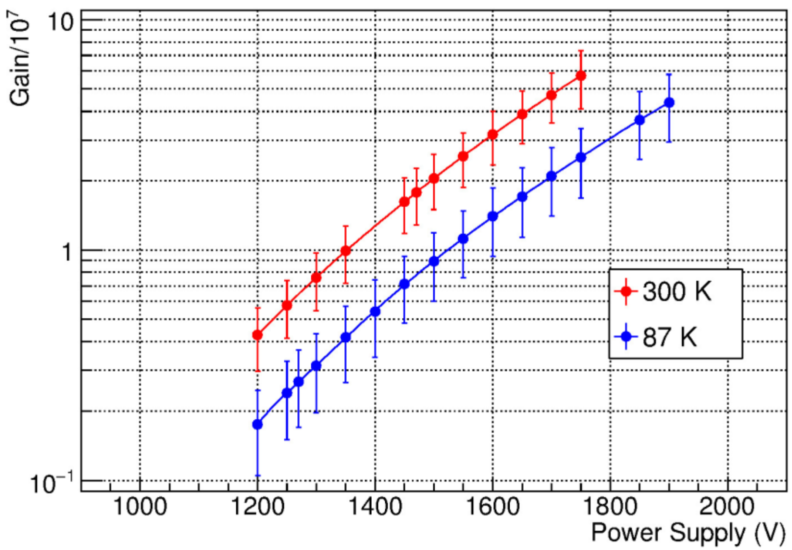
Upgrade of the light collection system

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 uses 90 8″ 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



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

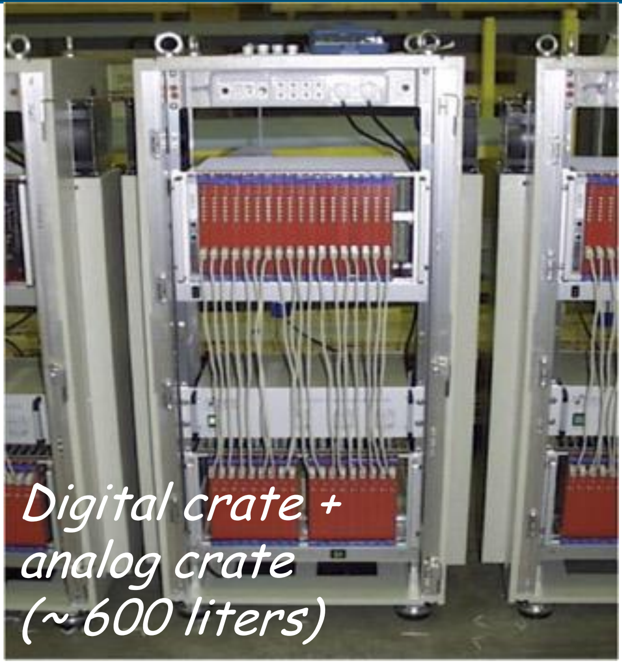
Upgrade of the TPC read-out electronics

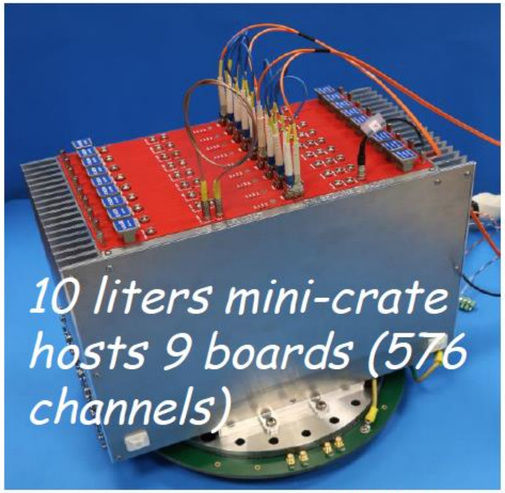
ICARUS electronics at LNGS was based on:

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

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





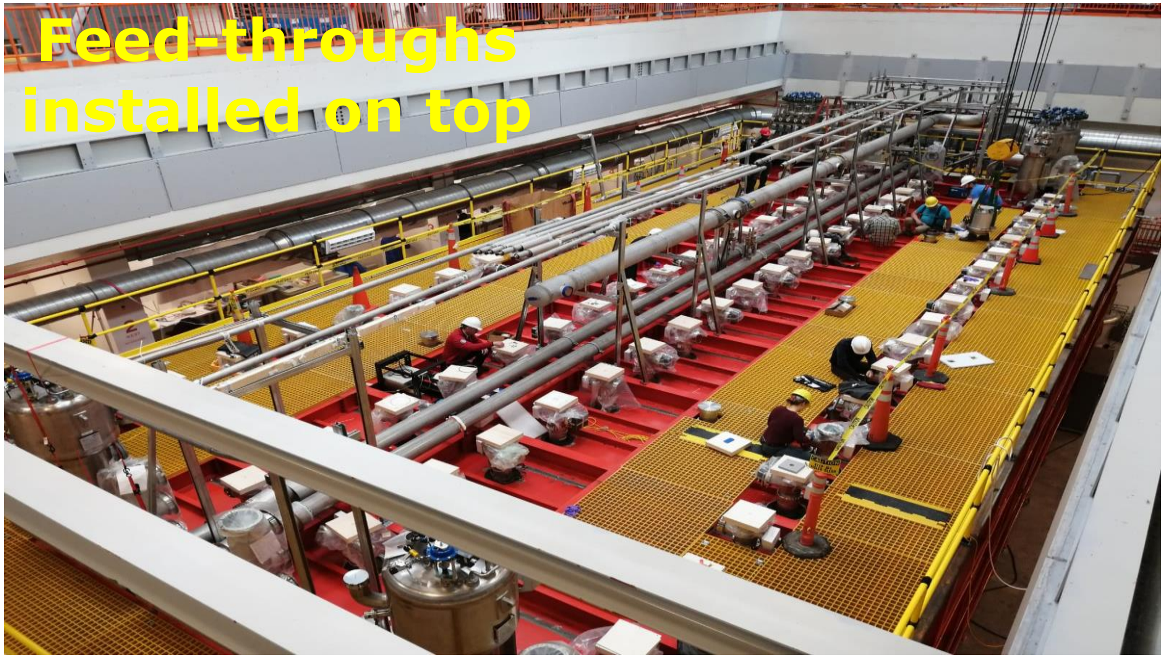
Volume 60 times smaller

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

JINST 13 (2018) P12007

ICARUS installation at FNAL

- 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



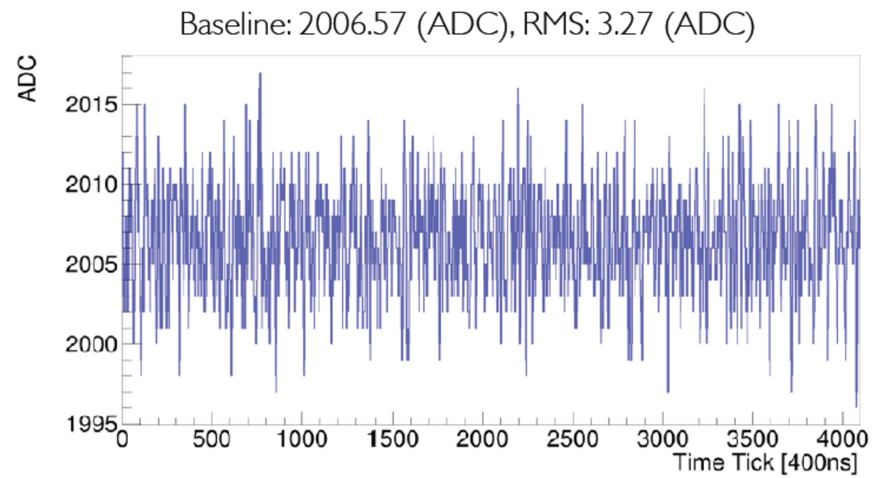
- PMT electronics and trigger being tested at cryogenic temperatures at CERN
- Installation of proximity cryogenics started in February
- Side CRT installation also ongoing
- Director's Review in December 2018 recognized the great progress of SBN

Preliminary Readout Test

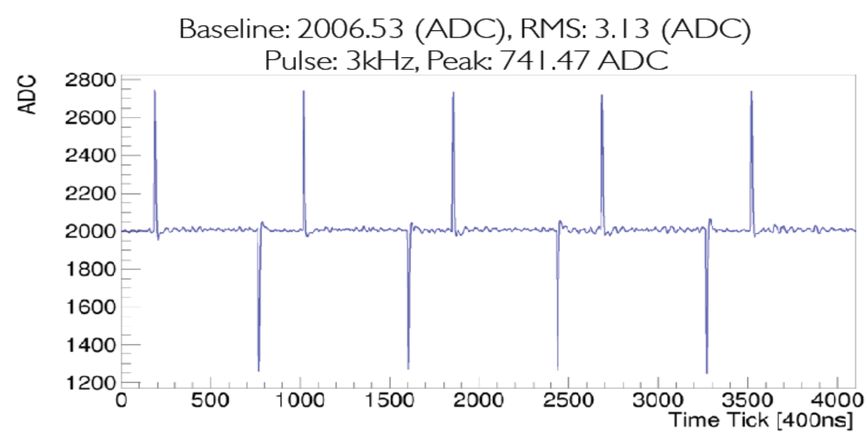
- A test of the full readout chain, from wires to DAQ, was performed in December on one mini-crate (576 channels + optical links)
- Allowed to check readout and set baseline for future noise monitoring
- Noise measured on random triggers and test pulses
- Grounding conditions different from ICARUS data-taking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

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

Noise Waveform



Injected Pulses



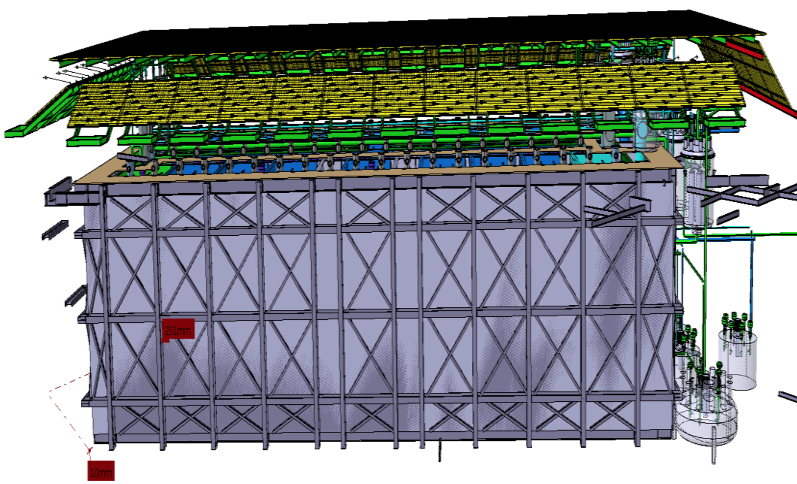
The Cosmic Ray Tagging system (CRT)

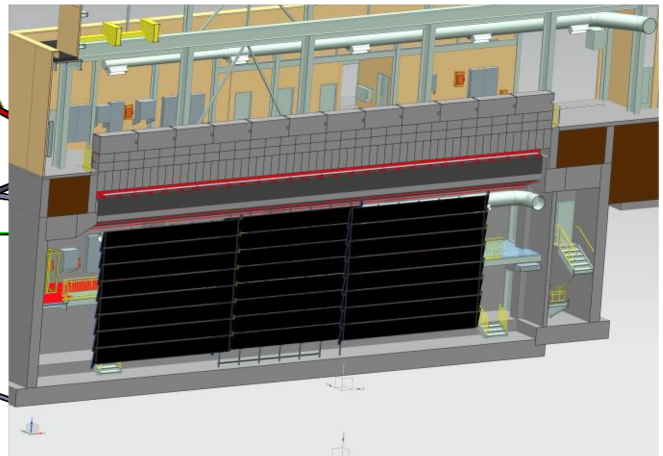
- Surrounds the cryostat with two layers of plastic scintillators: 1100 m^2
- Tags incident cosmic or beam-induced muons with high efficiency (95%) giving spatial and timing coordinates of the track entry point
- Reconstructed CRT hits are matched to activity in the LAr volume
- Few ns time resolution allows measuring direction of incoming/outgoing particle propagation via time of flight

TOP
~ 400 m^2: roof+angled parts
Will catch~80% cosmic ms
SiPM readout

SIDES
~ 500 m^2 on four sides
SiPM readout

BOTTOM
~ 200 m^2, already installed
2 parallel layers
PMT readout

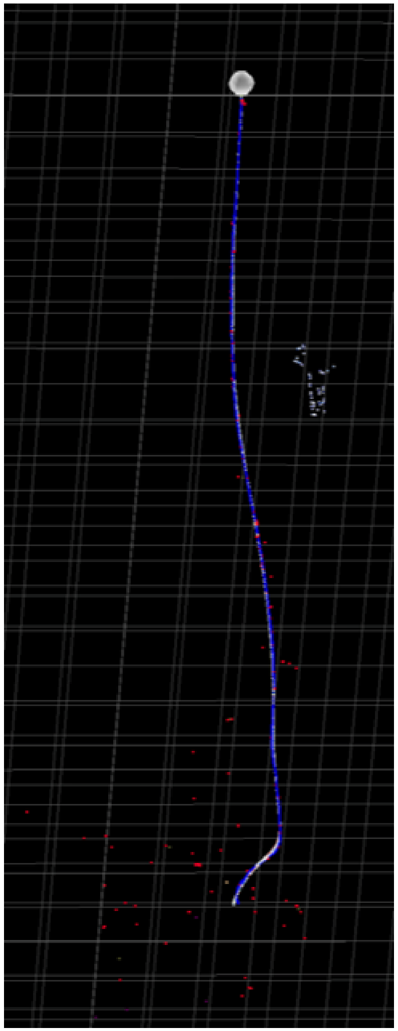




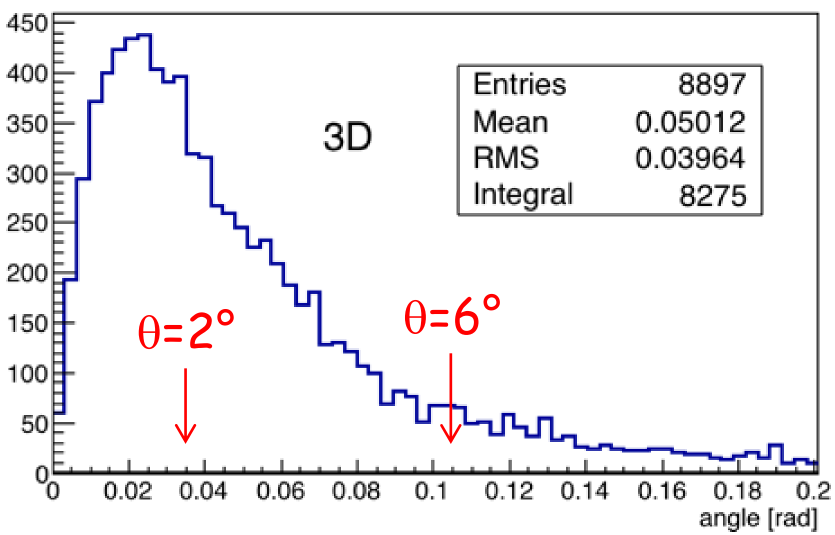
Reconstruction and analysis in SBN

- 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

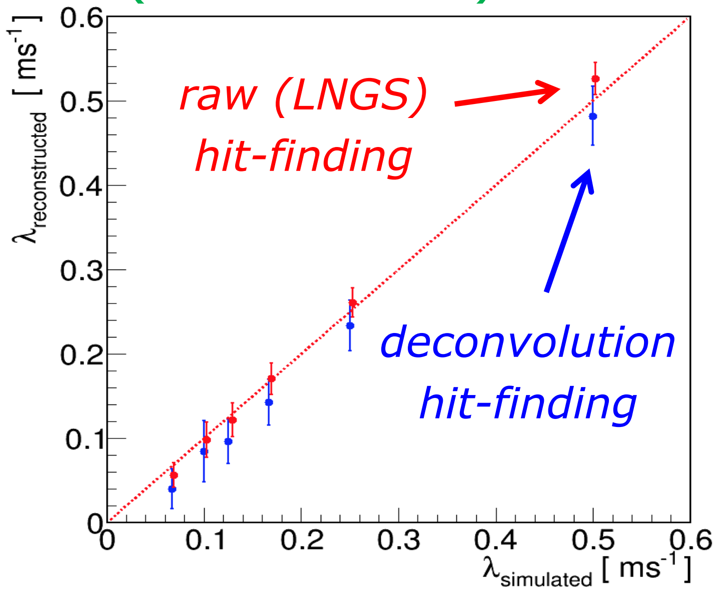
3D reco of stopping muon



angle between sim/reco direction for EM showers



electron lifetime (reco vs. sim)



ICARUS transportation (from CERN to FNAL)

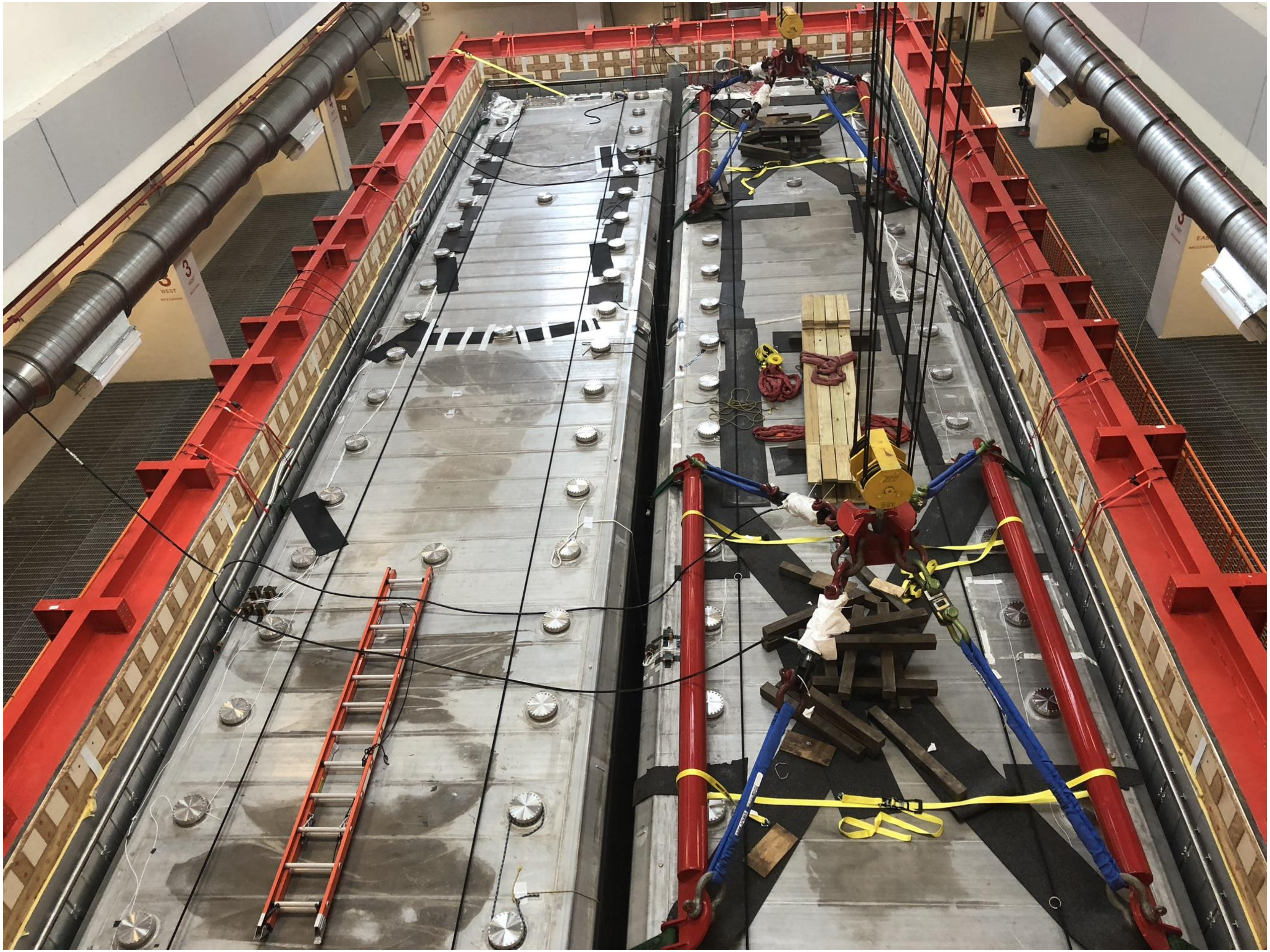
leaving from CERN, June 12th 2017

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

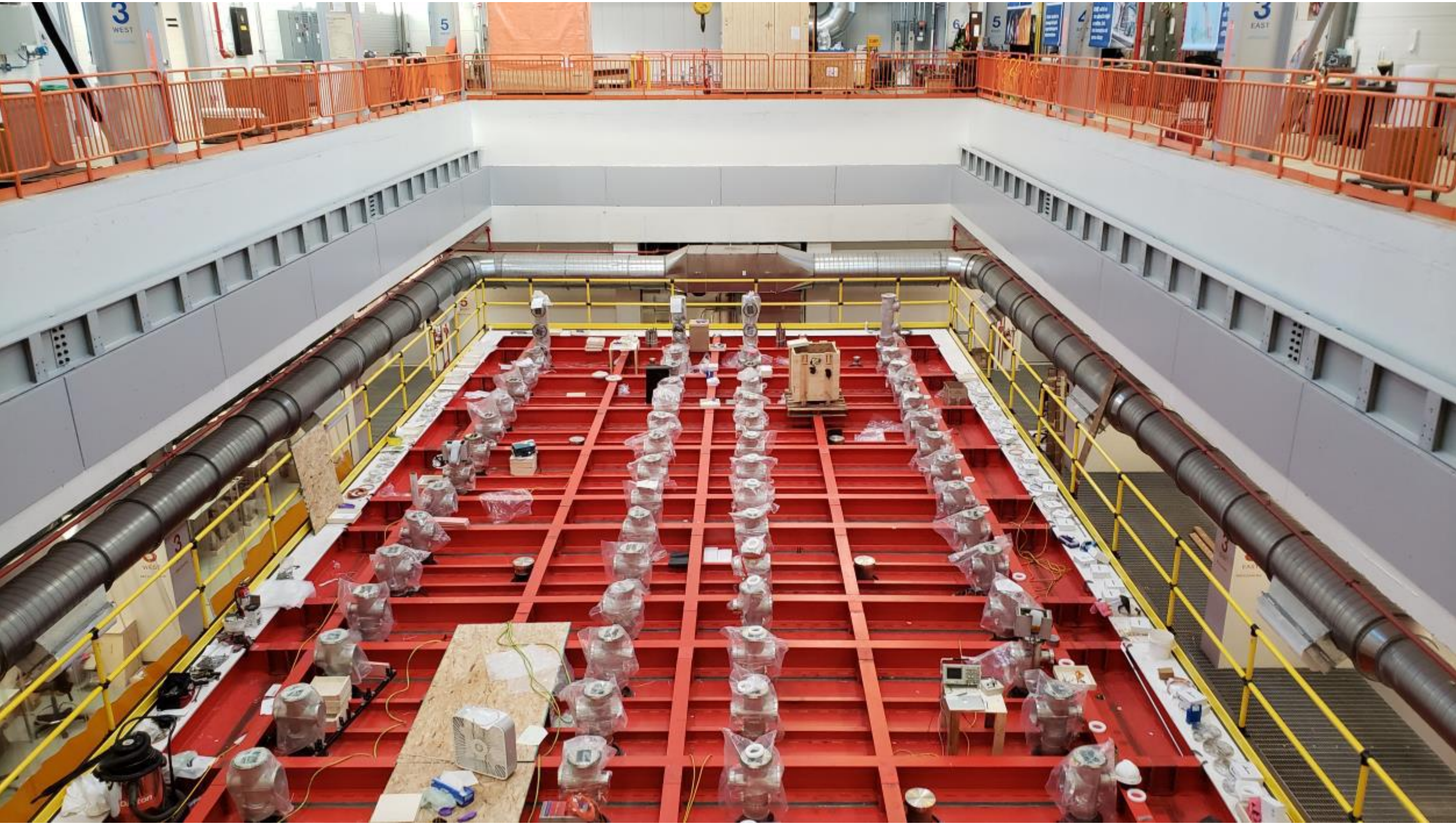
SBN far site building at FermiLab

Placement of ICARUS (August 2018)



Chymney installation (October 2018)

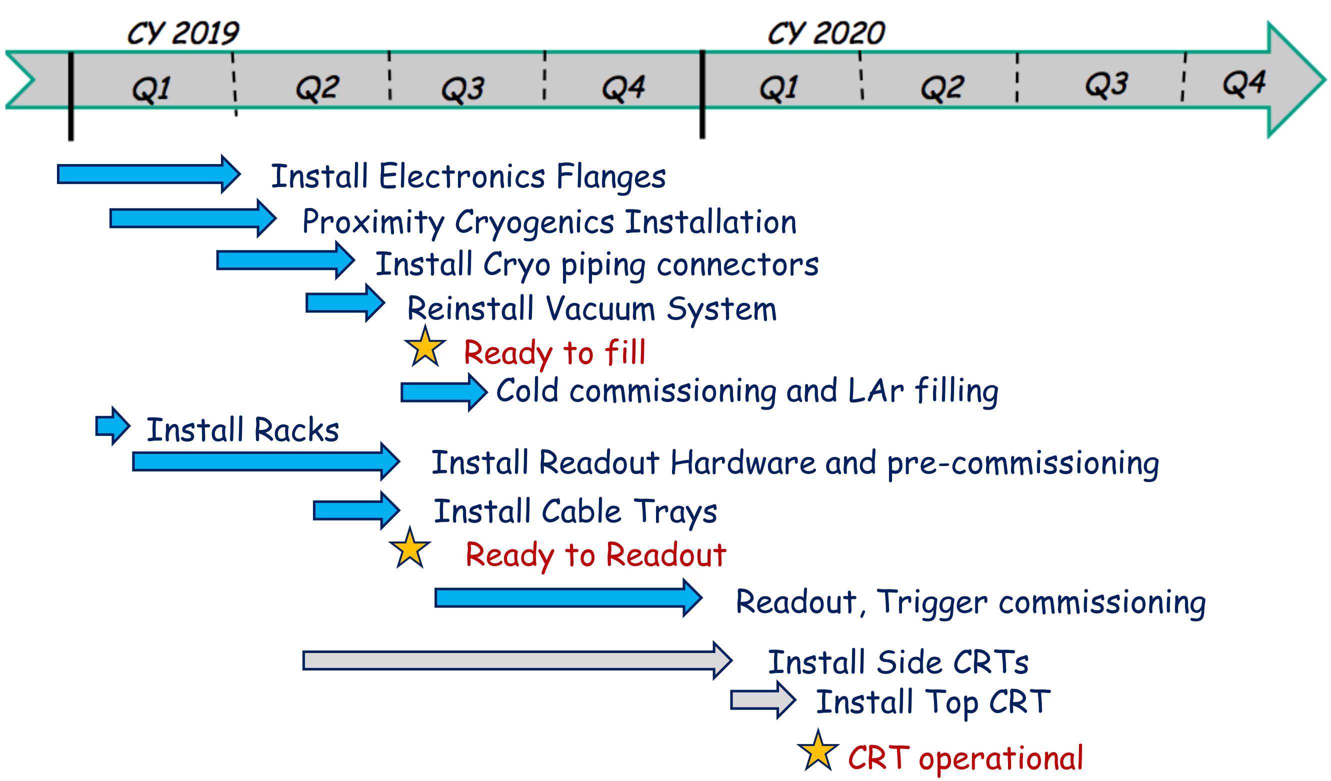
Feedthrough installation (December 2018)



Positioning the readout system (May 2019)

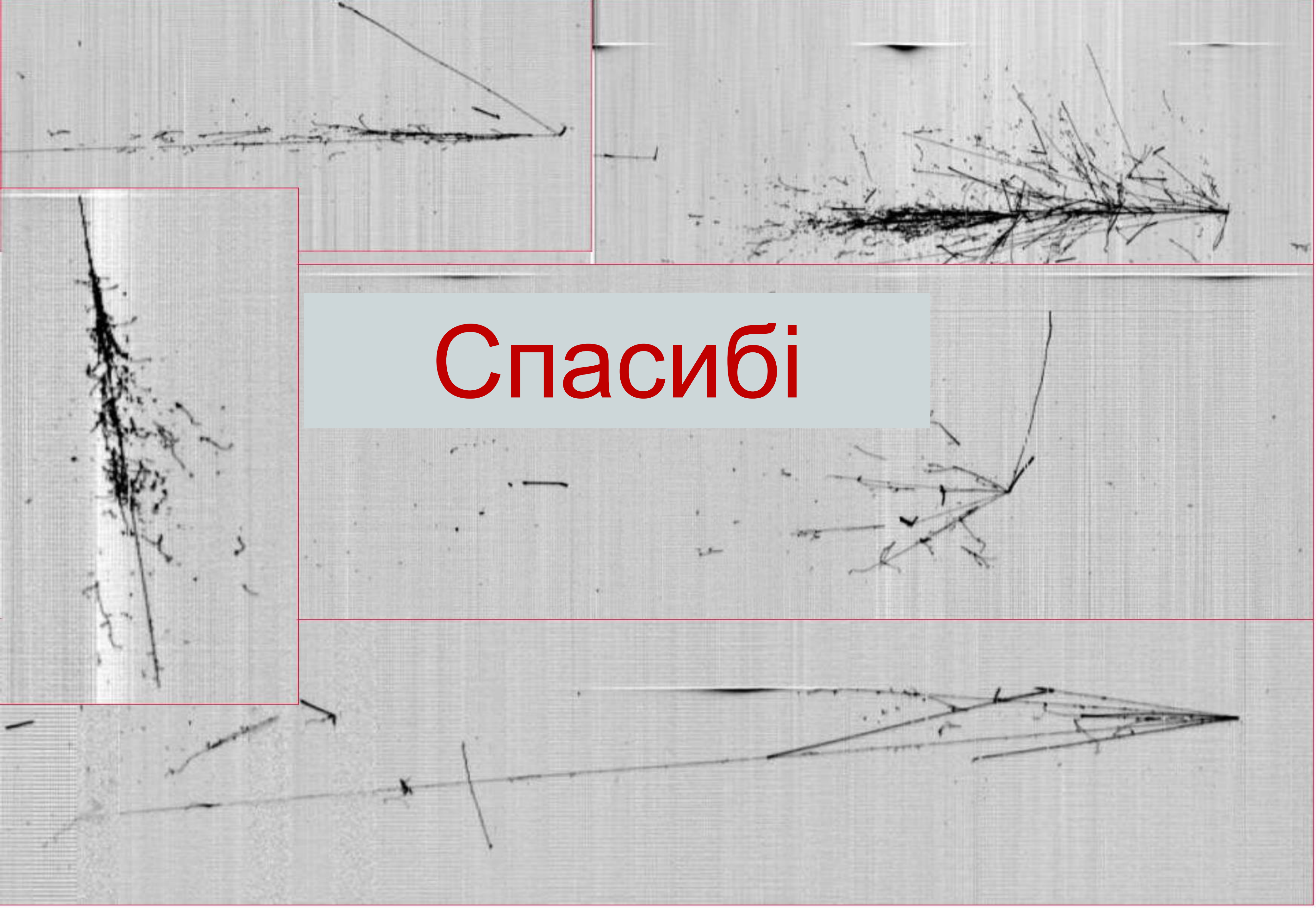
ICARUS at FNAL – plans and commissioning

- 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 at the end of July 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 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 !


Спасибі

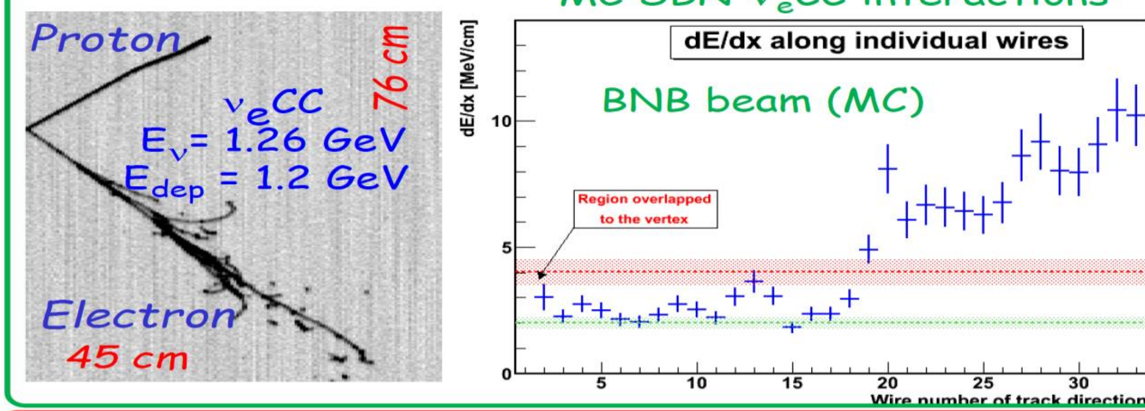
Backup slides

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

ν_e

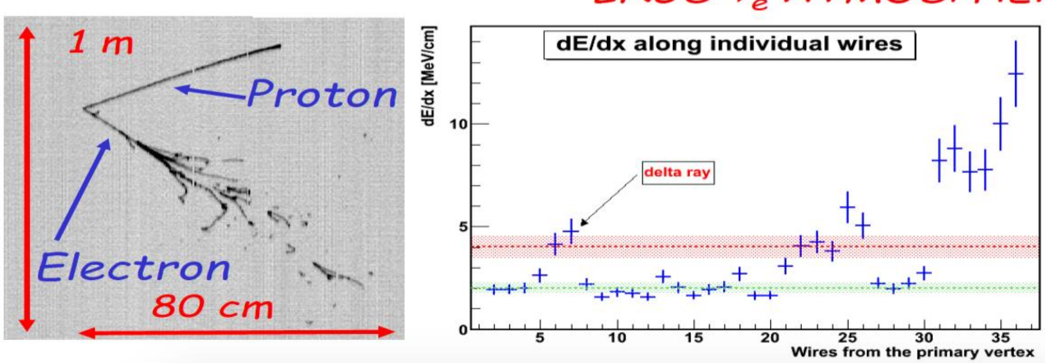
MC SBN ν_eCC interactions



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

ν_e

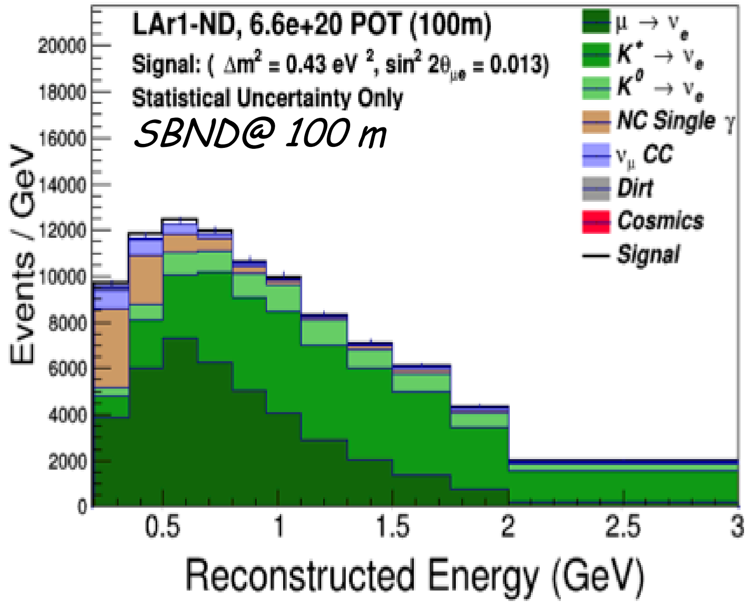
LNGS ν_e ATMOSPHERIC EVENT

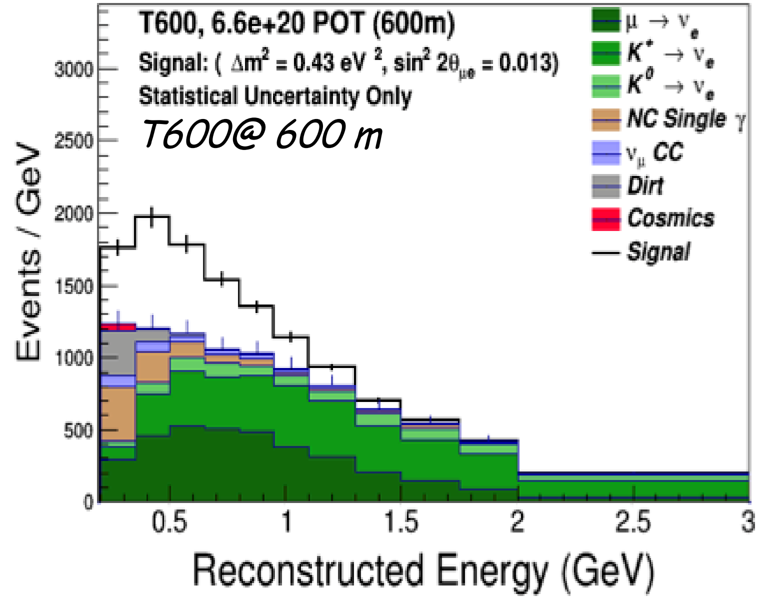


- Quasi-elastic ν_eCC E_{Dep}= 0.9 GeV.
- Proton identified by dE/dx.
- Electron identified by single m.i.p. before showering

SBN spectra (from the proposal: arXiv 1503.01520)

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

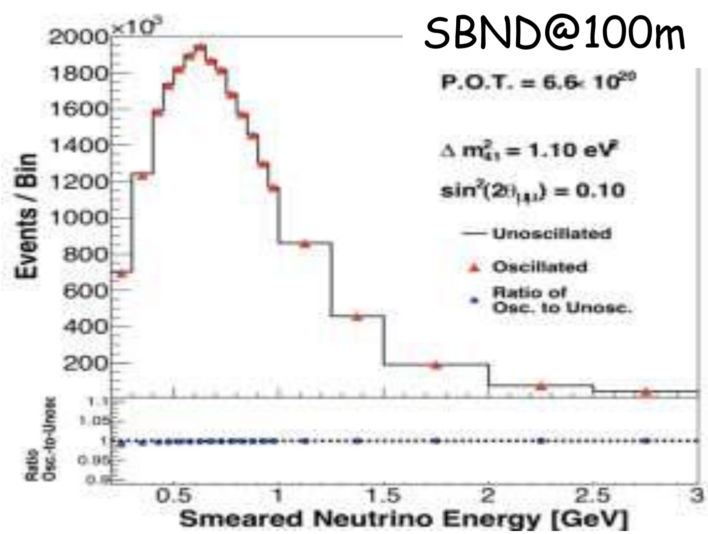


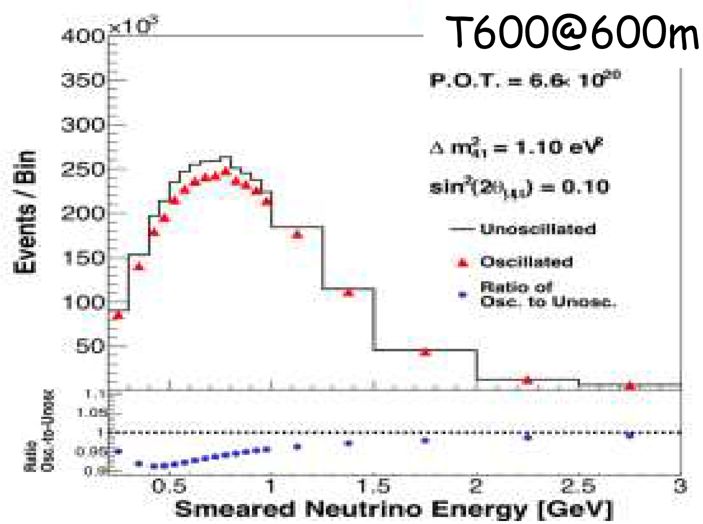


Example for
$\sin^2 2\theta = 0.013$
$\Delta m^2 = 0.43\ eV^2$

In absence of oscillations, spectra should be ~identical

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





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

In absence of oscillations, spectra should be ~ identical

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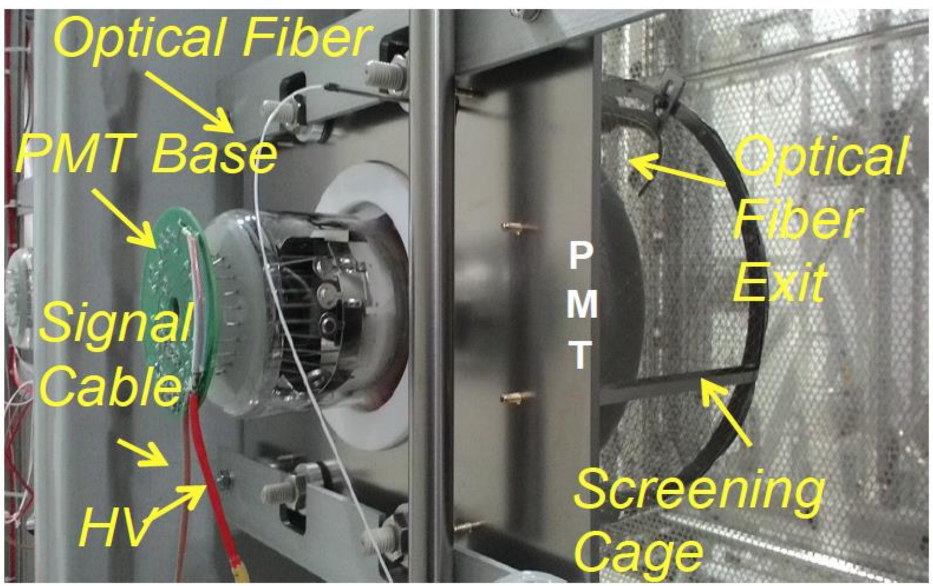


Timing/gain equalization will be performed with laser pulses

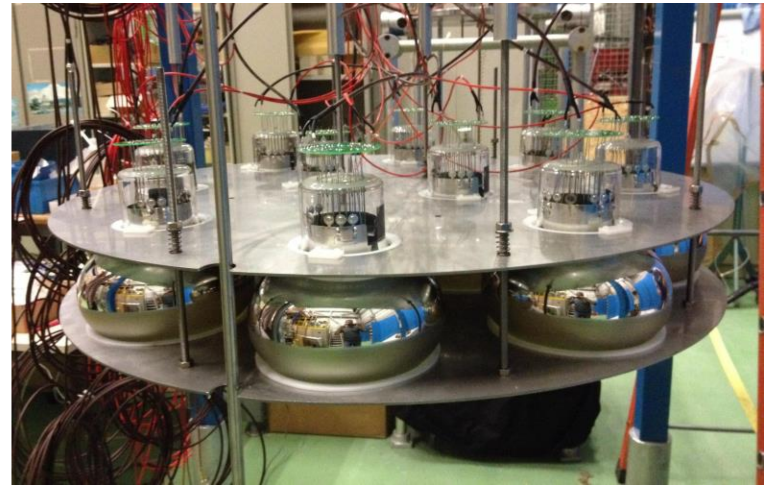
λ = 405 nm

FWHM < 100 ps

peak power ~ 400 mW

PMT tests at CERN

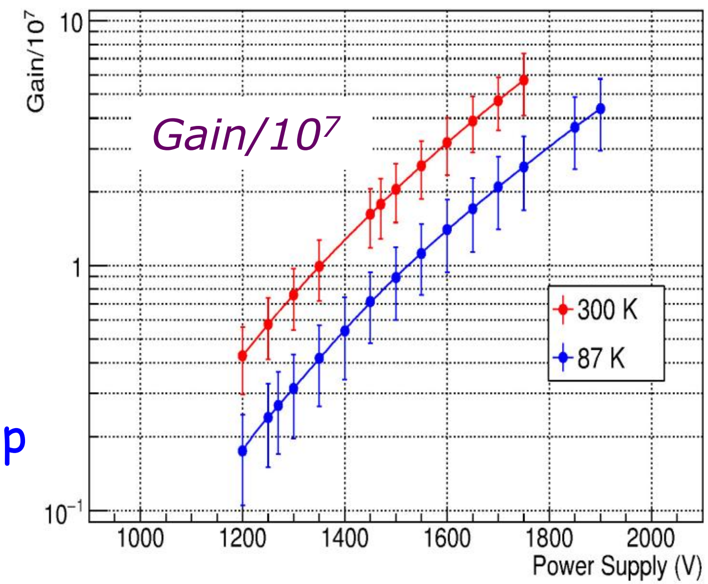
- All PMTs tested at room temperature in a dedicated dark room at CERN
- A subset of 60 PMTs tested immersed in LAr to compare the PMT performance in cryogenic environment to room temperature
- All PMTs illuminated with laser light pulses

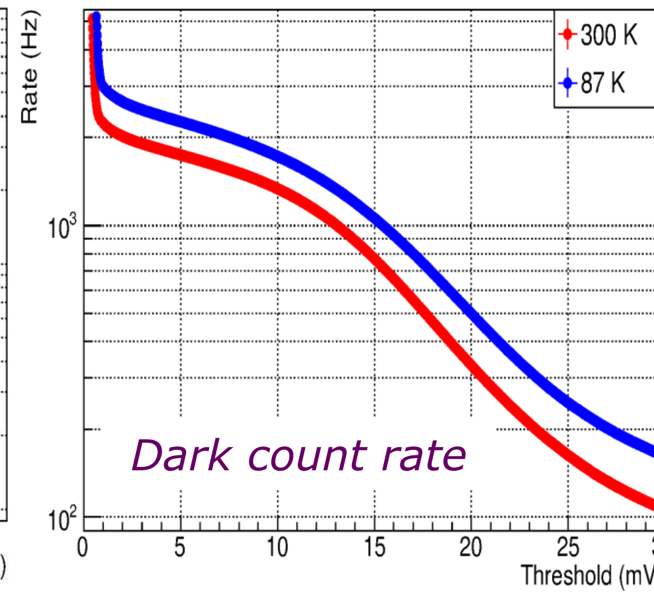


PMTs were characterized individually at 300K and 87K:

- 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





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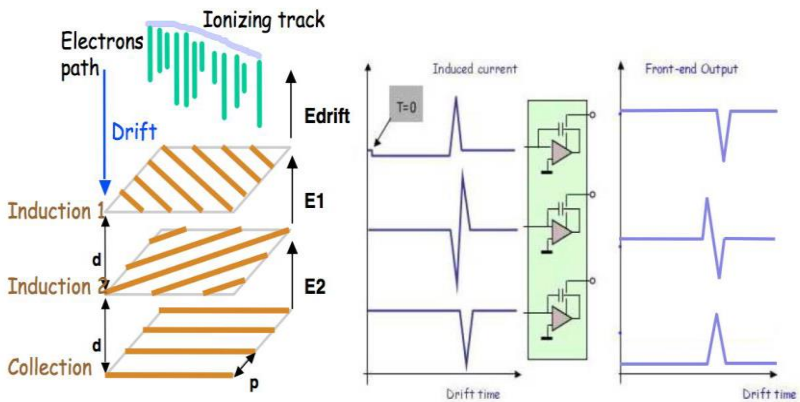
Front-end electronics for ICARUS@SBN

The analog front-end shaping was also modified:

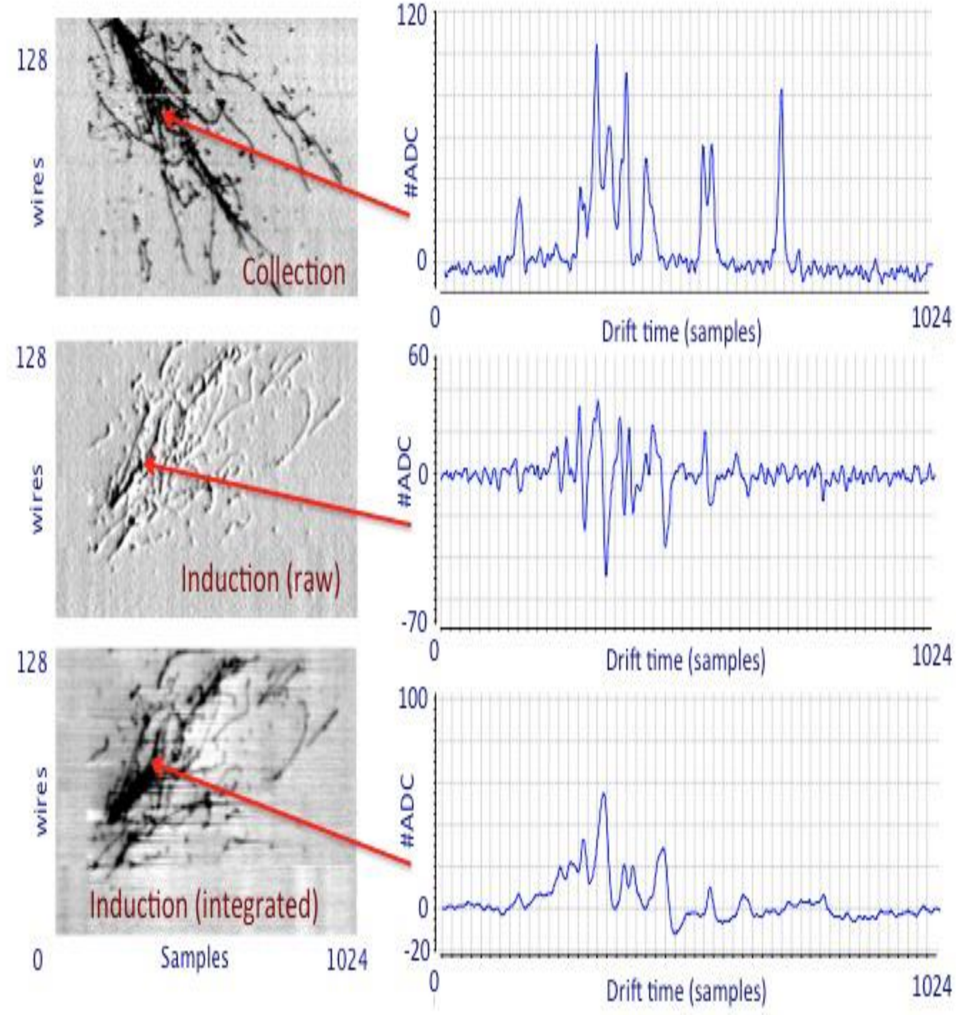
- Lower noise ~ 1200 e- equivalent (~20% S/N improvement w.r.t. LNGS electronics)
- Shorter shaping time (~ 1.5 μs for all planes) matching electron transit time between planes
- Drastic reduction of undershoot after large signals: better description of crowded vertex region



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 ν_e identification efficiency by ~ 20%

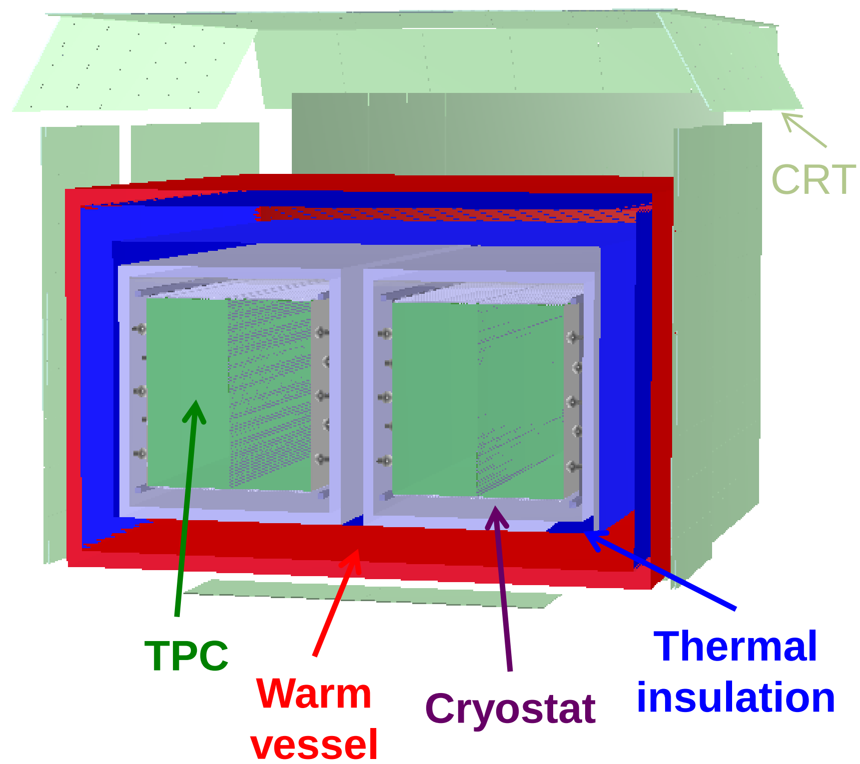
Tests on 50-liter TPC at CERN:



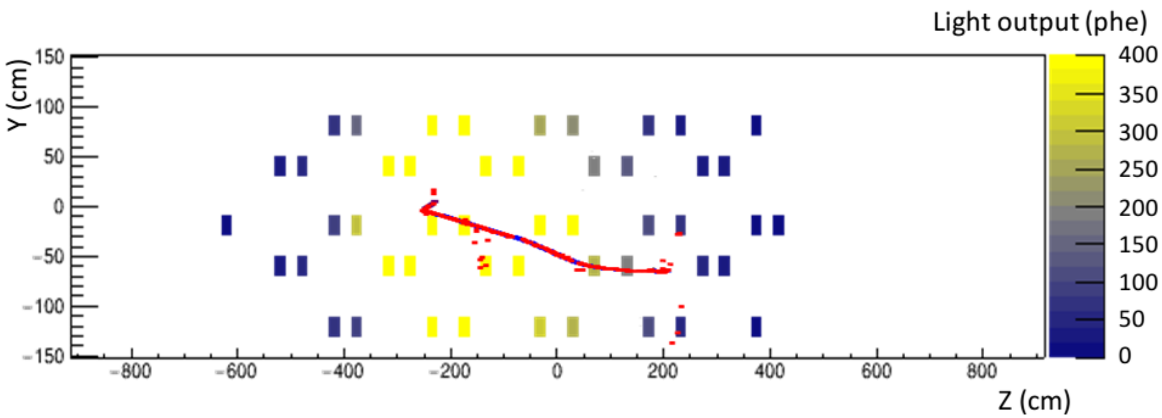
ICARUS simulation and reconstruction

- 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



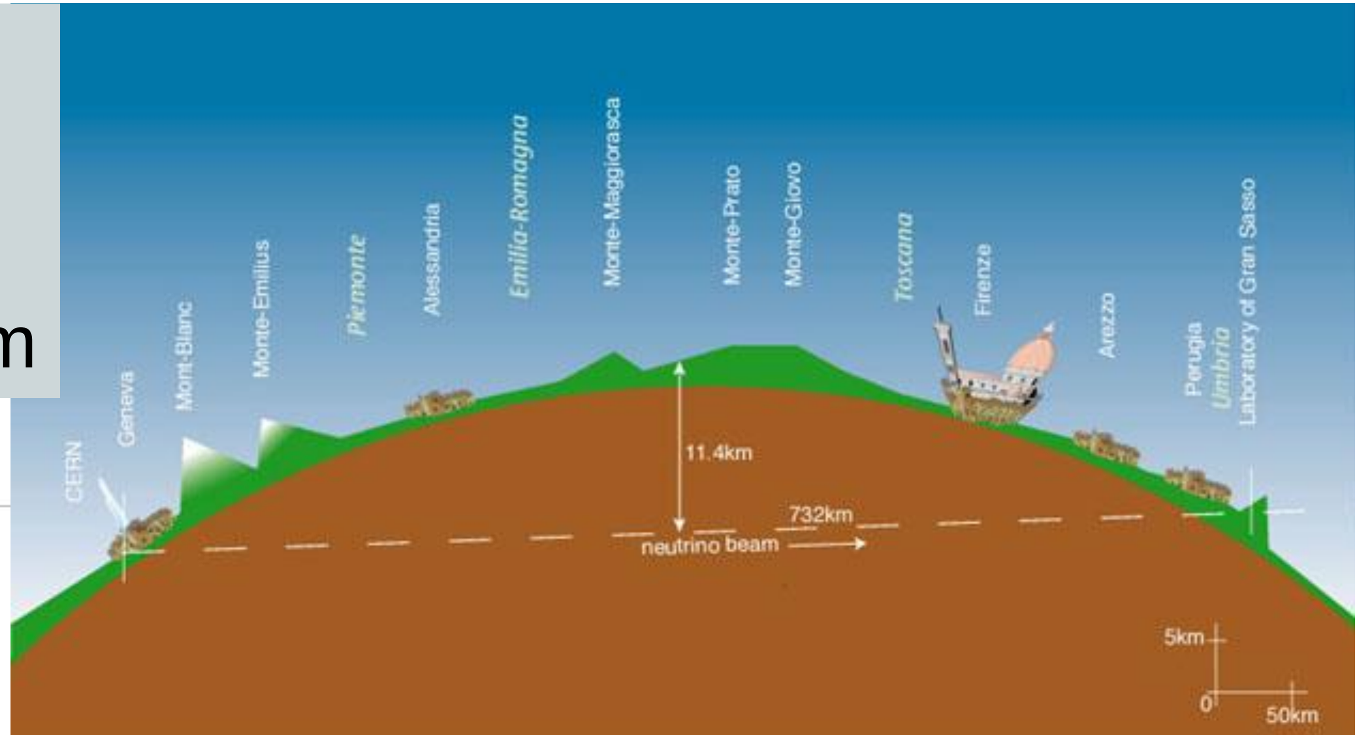
PMT vs. TPC information

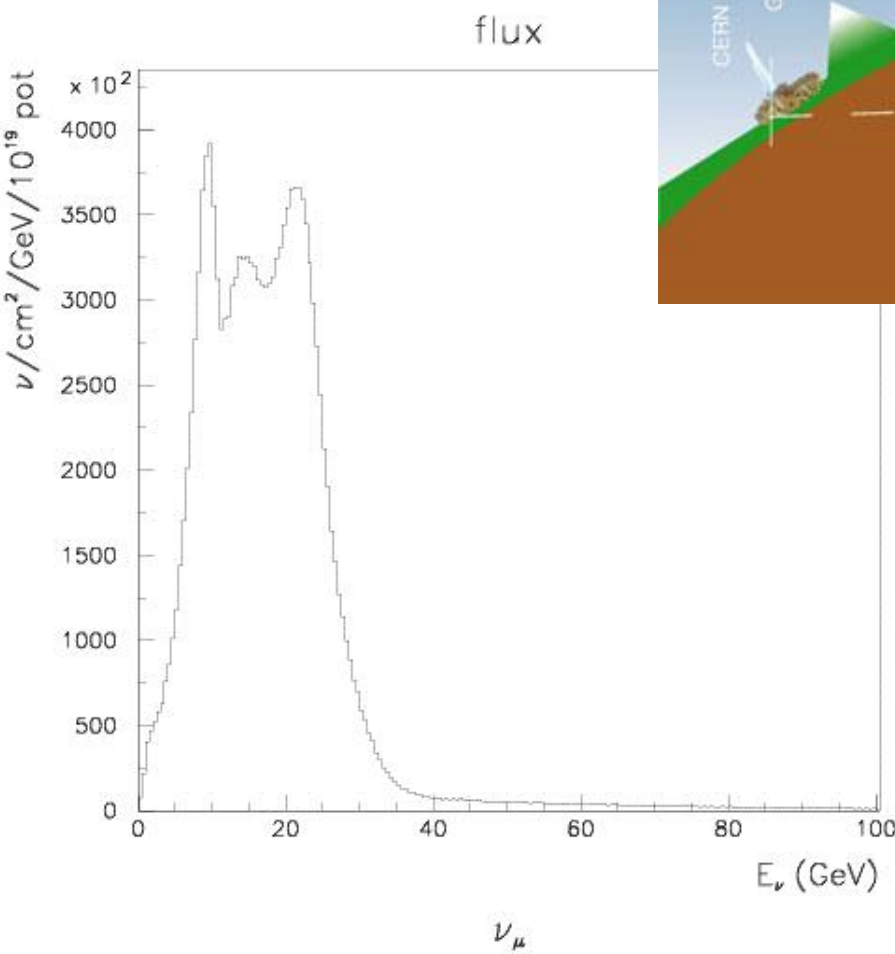


- ν_μ CC interaction with ~ 1.4 GeV deposited energy
- 49 PMTs have visible signal (over 10 phe)
- Fired PMTs extend over ~ 8m

CNGS

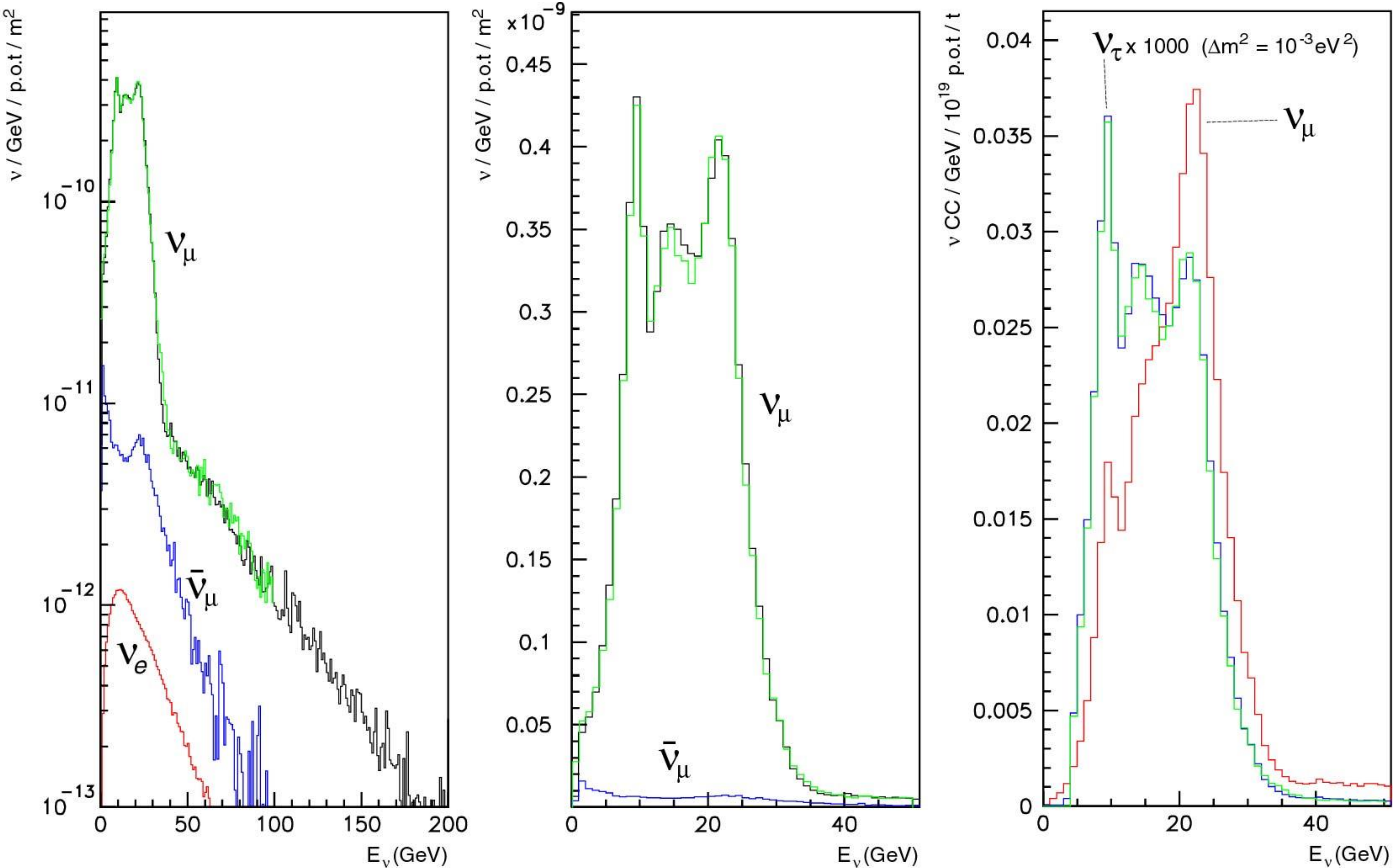
CERN Neutrino
to Gran Sasso beam



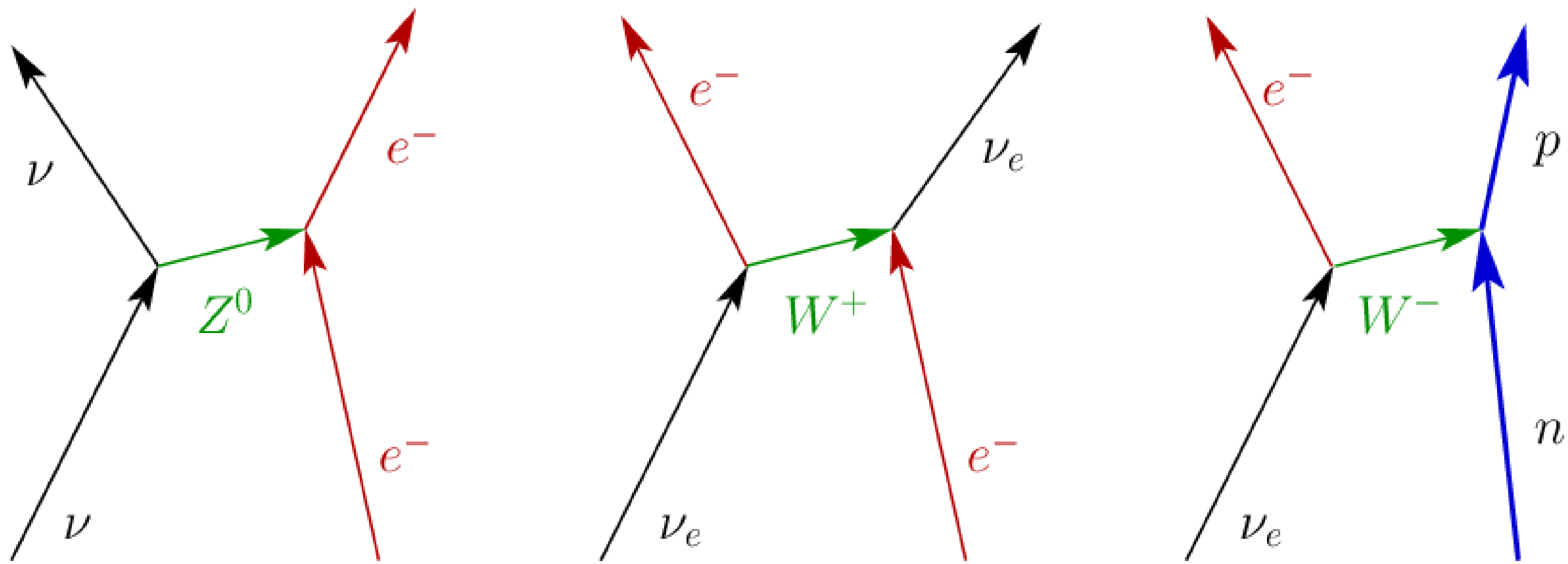


$L/E = 730/20 \sim 36$ km/GeV

CNGS beam spectrum



Neutrino interactions

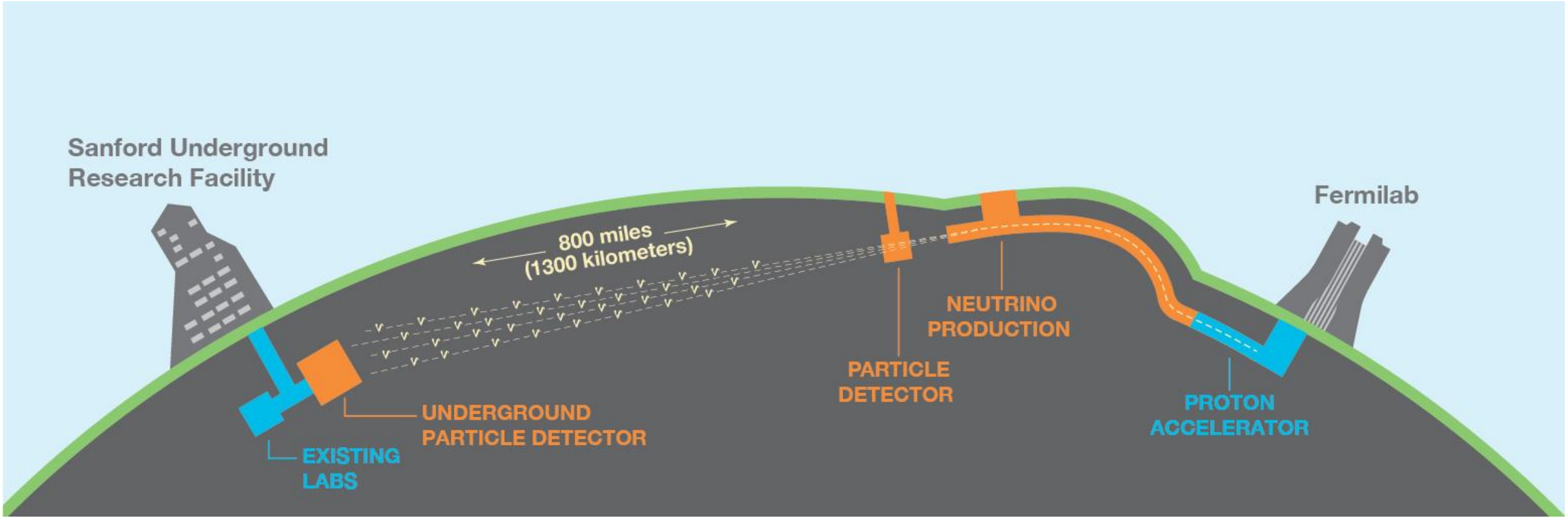


Neutral Current

Charged Current

DEEP UNDERGROUND NEUTRINO EXPERIMENT

[https://www.dunescience.org]



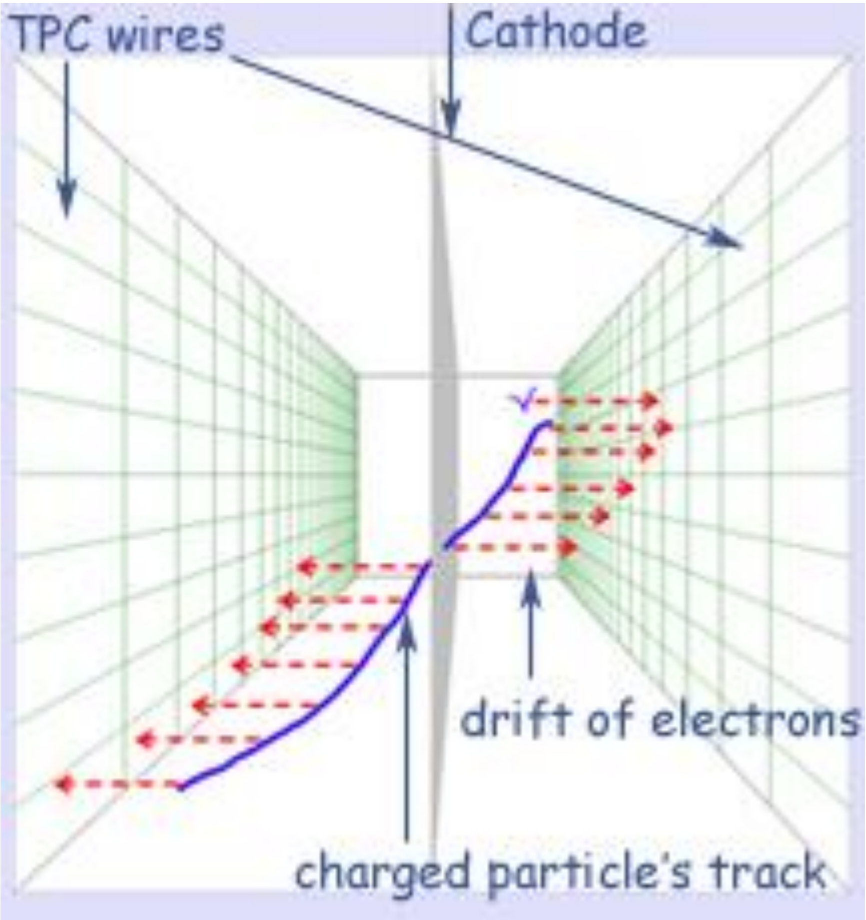
Origin of Matter Could neutrinos be the reason that the universe is made of matter rather than antimatter? By exploring the phenomenon of neutrino oscillations, DUNE seeks to revolutionize our understanding of neutrinos and their role in the universe.

Unification of Forces With the world's largest cryogenic particle detector located deep underground, DUNE can search for signs of proton decay. This could reveal a relation between the stability of matter and the Grand Unification of forces, moving us closer to realizing Einstein's dream

Black Hole Formation DUNE's observation of thousands of neutrinos from a core-collapse supernova in the Milky Way would allow us to peer inside a newly-formed neutron star and potentially witness the birth of a black hole.

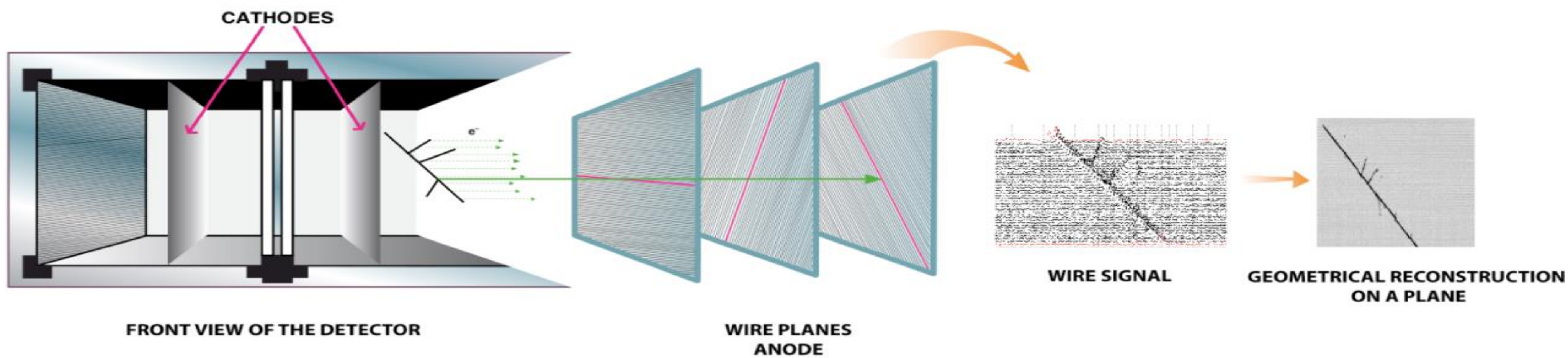
LAr TPC principle of operation

TPC = Time Projection Chamber



ICARUS-T600: LAr TPC working principle

- 3 wire planes with 0°, +60°, -60° orientation w.r.t. horizontal; both pitch between wires and distance between planes are 3 mm
- Wire biasing guarantees (almost complete) plane transparency, and non-destructive readout in both Induction wire planes
- Last plane collects charge, allowing measurement of deposited energy
- ~ 54000 total readout wires, with 400 ns sampling time



Typical signal in collection (last) plan