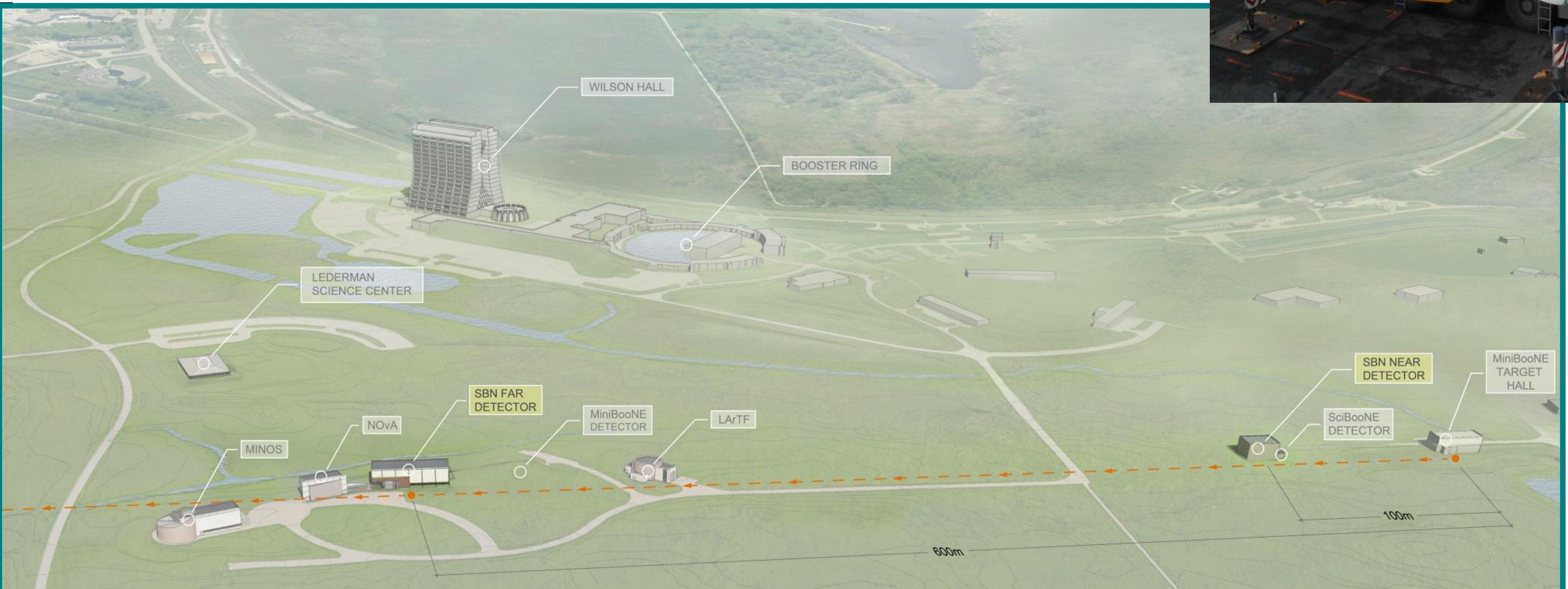
ICARUS T600, to FNAL thru CERN

PITT PACC SBN Physics Workshop
26-27/01/2016

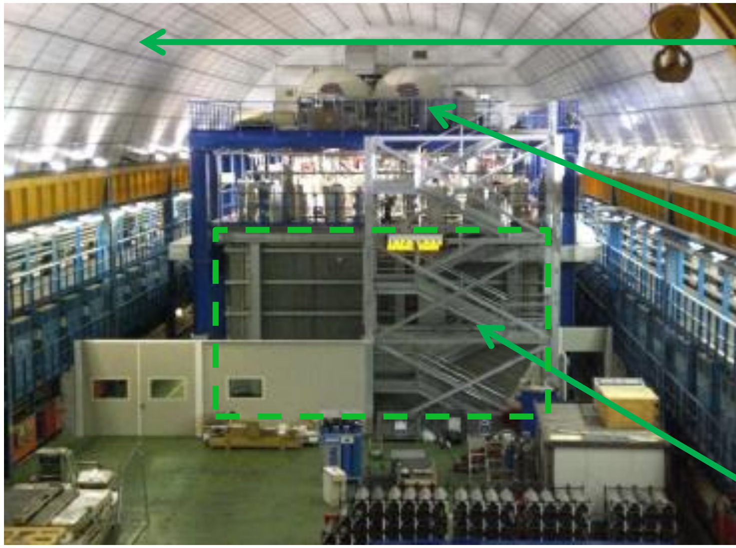
Andrea Zani (CERN) on behalf of
the ICARUS/WA104 Collaboration

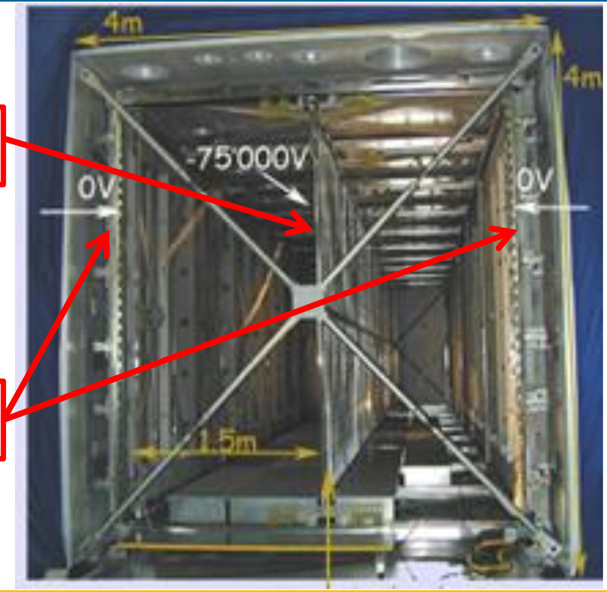


Premise

- In 2013 the ICARUS T600 detector concluded a successful, three-year long run at the LNGS underground laboratory, taking data both with the CNGS neutrino beam and with cosmic rays. Several relevant physics and technical results were achieved (**e-life time > 16 ms**).
- The detector is now at CERN (project WA104) for a major overhaul, before being deployed to Fermilab.
- The Collaboration intends to investigate the sterile neutrino hypothesis, and a joint ICARUS/SBND/MicroBooNE effort is taking place to develop an international, Short Baseline (SBN) program at FNAL's BNB (and NuMI off-axis) with three detectors at different baselines by 2018: near=SBND; mid=MicroBooNE; far=ICARUS.
- This presentation will concentrate on the ongoing refurbishment activities at CERN, that will prepare the detector for shipment at FNAL, within the end of 2016.

The ICARUS detector @ LNGS





Two identical modules…

- $3.6 \times 3.9 \times 19.6$ m ≈ 275 m^3
- Total active mass $\approx$ 476 ton

… and four wire chambers

- 2 TPCs per module, with common cathode -> 1.5 m drift length
- E_{drift} = 0.5 kV/cm; v_{drift} = 1.55 mm/µs

Detectors

- 3 wire planes per TPC (0°, ±60°)
- ≈54000 wires (150 µm Ø, 3 mm pitch)
- 54+20 photomultipliers (8″ Ø) + wls (TPB), sensitive at 128 nm (VUV)

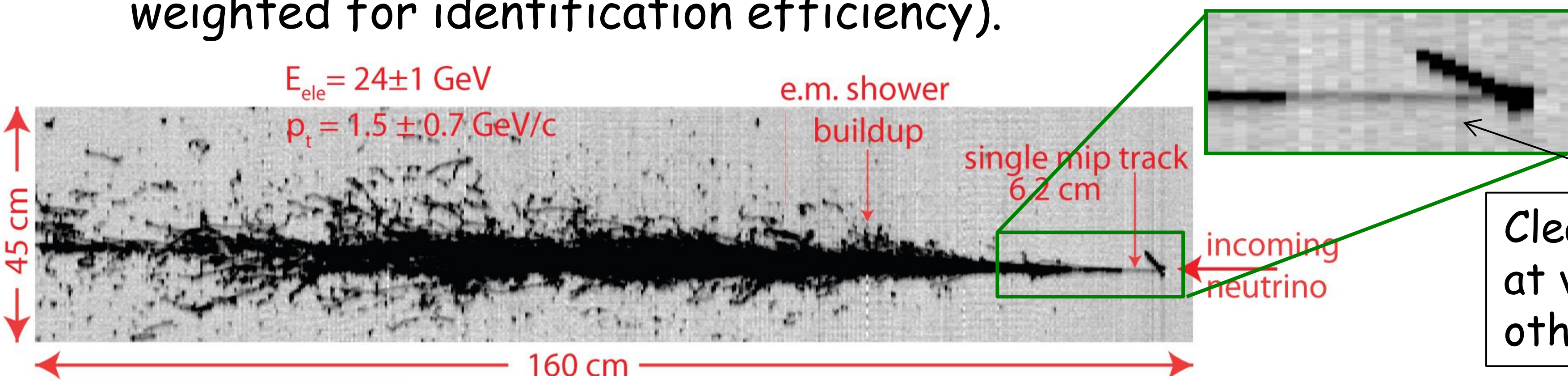
TPC Warm Electronics

- Continuous read-out, digitization, waveform recording

A total of 8.6×10^{19} protons on target (pot) was collected, for a detector live-time > 93%.

Search for an LSND-effect with CNGS beam: no evidence

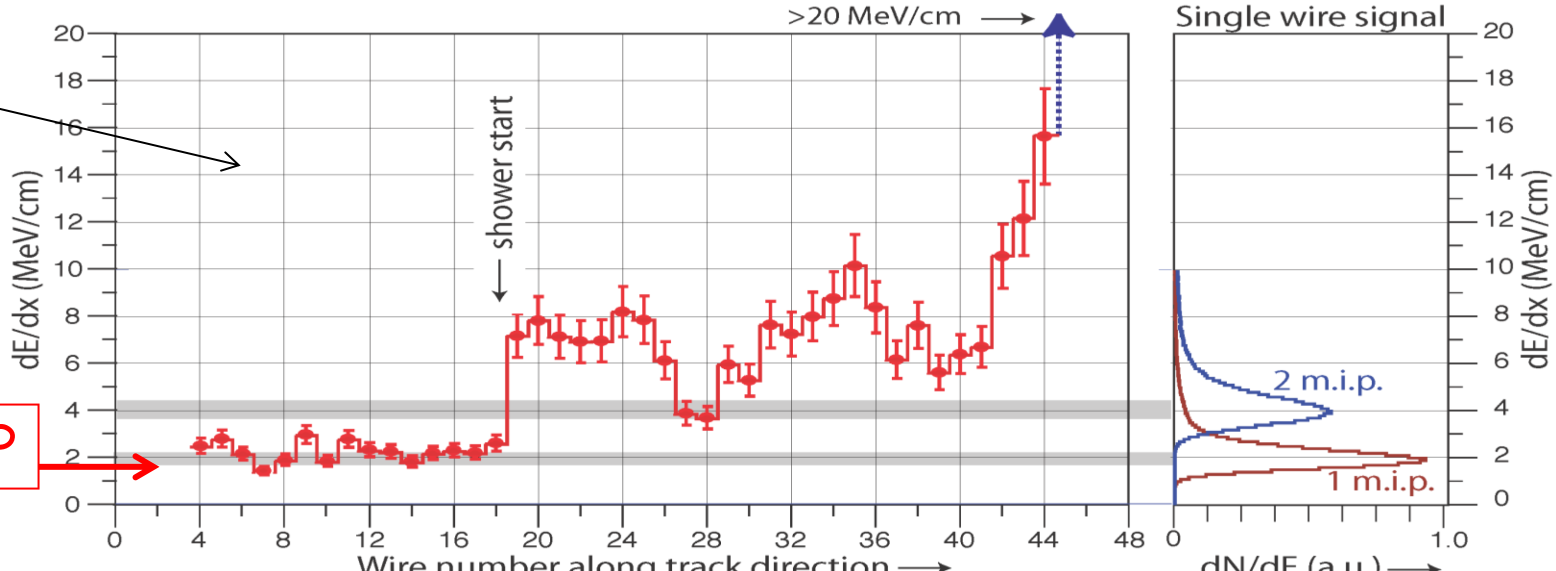
- ICARUS searched for a ν_e-excess, related to a LSND-like anomaly, on the CNGS ν_μ beam (~ 1% intrinsic ν_e contamination, L/E_ν ~36.5 m/MeV)
- **SEVEN ν_e events were found** in the overall sample of 2650 neutrino interactions (7.93×10^{19} pot) from the beam (8.4 ± 1.1 expected events, weighted for identification efficiency).



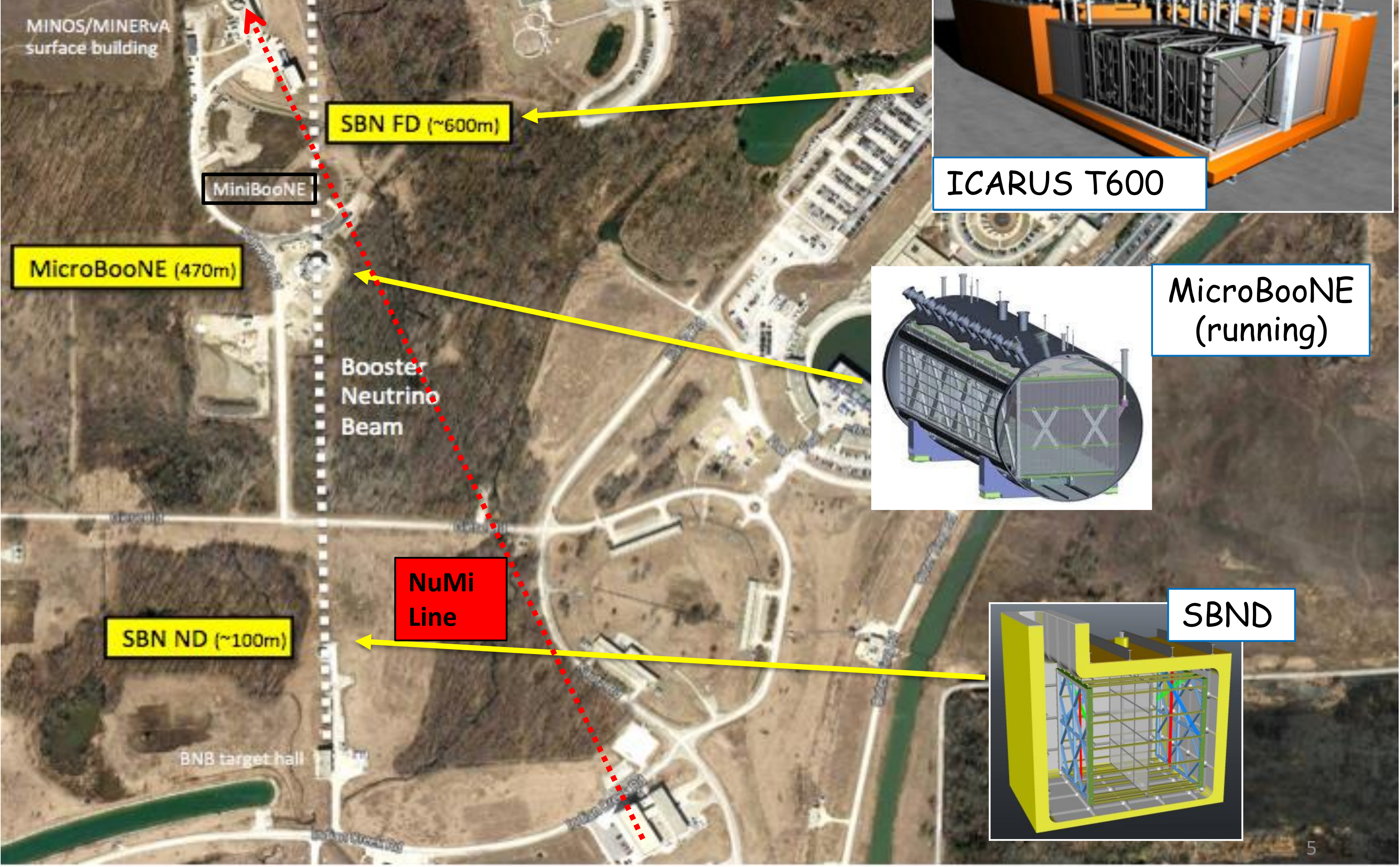
Clear separation at vertex from other tracks.

Evolution from single m.i.p. to e.m. shower evident from dE/dx on individual wires.

Single M.I.P

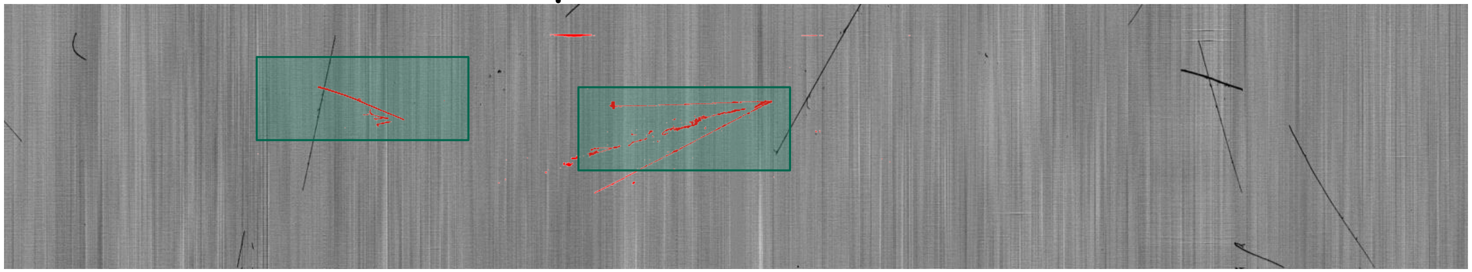


The future: SBN @ BNB



A new challenge: cosmic backgrounds at shallow depth

At shallow depths several uncorrelated cosmic rays (CR) will occur in the T600, during the 1 ms drift window readout, at each triggering event: during the Pavia test run on surface (2001), ~ 12 muon tracks per drift in each ICARUS half module were measured.



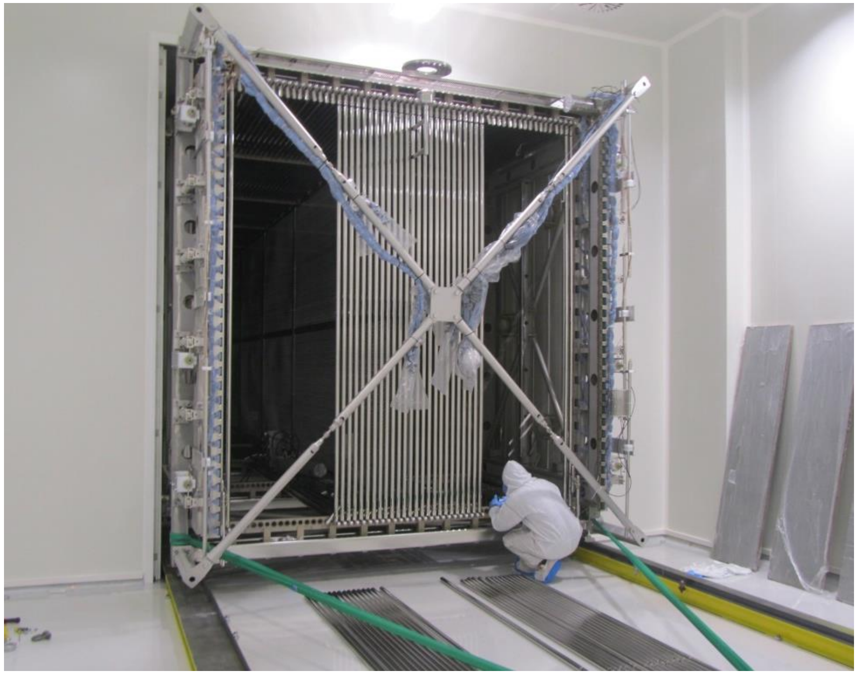
Various **strategies** can be devised **to reject cosmic backgrounds**:

- Unambiguous identification of the CR entering the active volume, with an external system that surrounds the TPC and yields timing information to be matched with the T600 wire/PMT data. Such *Cosmic Ray Tagger* (CRT) is foreseen to consist of plastic scintillators read by SiPM.
- ~ 1 ns timing accuracy for the internal PMT system, to exploit the bunched structure of the Booster p-beam within spill (2 ns-wide bunches every 19 ns).
- Identification of γ's associated to cosmic muons via geometrical selection directly on the TPC images.

In addition, automatic tools for event selection/reconstruction will be developed, to aid identifying neutrino events among millions of spurious cosmic triggers.

The present: ICARUS at CERN and the WA104 program

The T600 was moved from LNGS to CERN in Dec. 2014 and is being upgraded, by introducing technology developments while maintaining the already achieved performance(WA104 program):



- new cold vessels and purely passive insulation;
- refurbishing of the cryogenic and purification equipment;
- flattening of existing cathode panels, to get improved planarity (factor 5-10);
- upgrade of the light collection system;
- new faster, higher-performance read-out electronics.

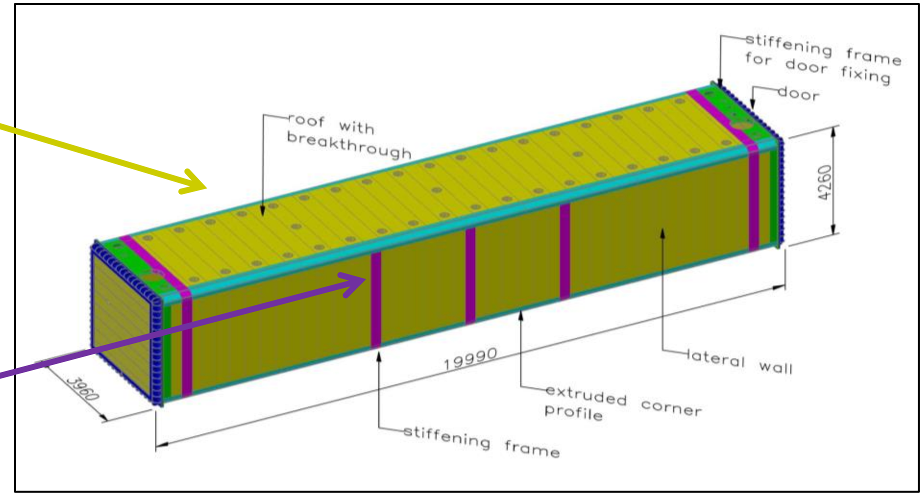
In addition, the mentioned CRT and filtering/selection tools are items common to the SBN program and they are being jointly developed by the 3 collaborations.

The WA104 program is regulated by a Memorandum of Understanding between CERN and INFN. Active, daily collaboration between ICARUS people and CERN personnel (Mech. Workshop, Cryogenics, TE department) is ongoing, and fundamental to successfully complete the refurbishment.

New Cold Vessels

New LAr containers (cold vessels) made by extruded aluminum profiles welded together, to form a vacuum-tight double-walled container.

Production of the extrusions has started. Welding of the stiffening frames (violet, holding LAr weight) is being done at CERN.



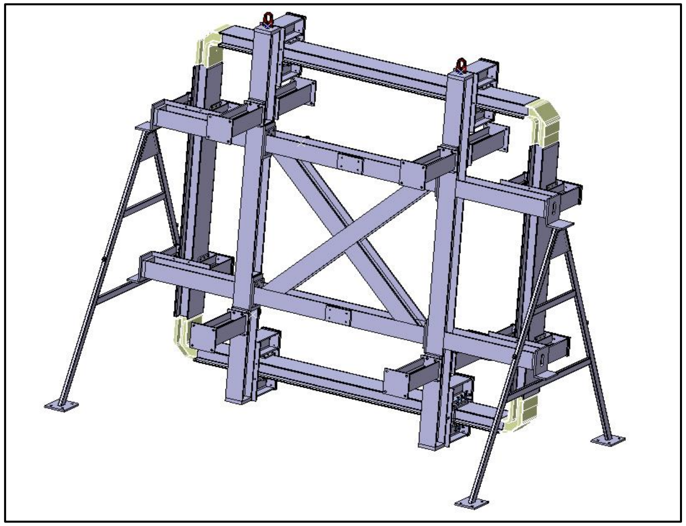
Panels pre-assembled by the company (STEP-G), while final assembly will be done at CERN, in building 156-185. A dedicated assembly structure has been put in place.

Completion of the first vessel foreseen by May 2016; the second one will be ready ~6 months later.

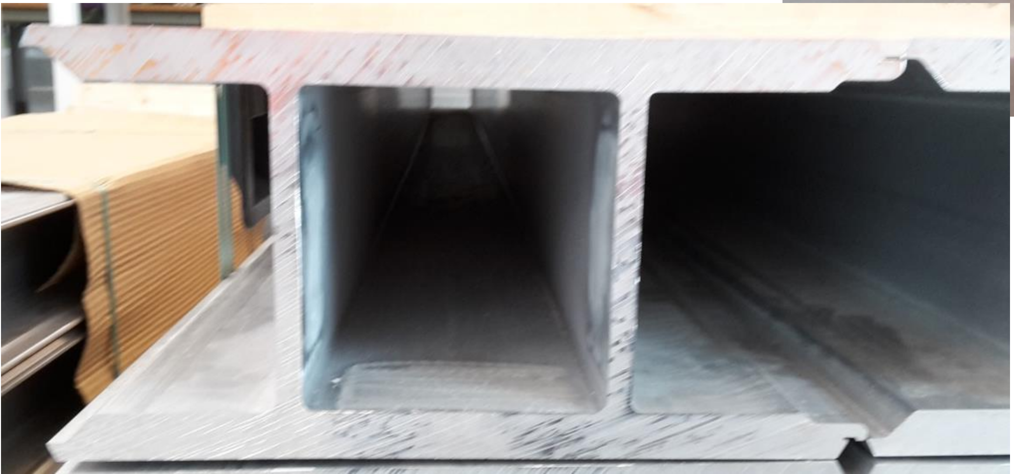
The roof of the first module (2 pieces) is currently being assembled.

Assembly in building 156

Dedicated tool for assembly of stiffening frames at CERN.

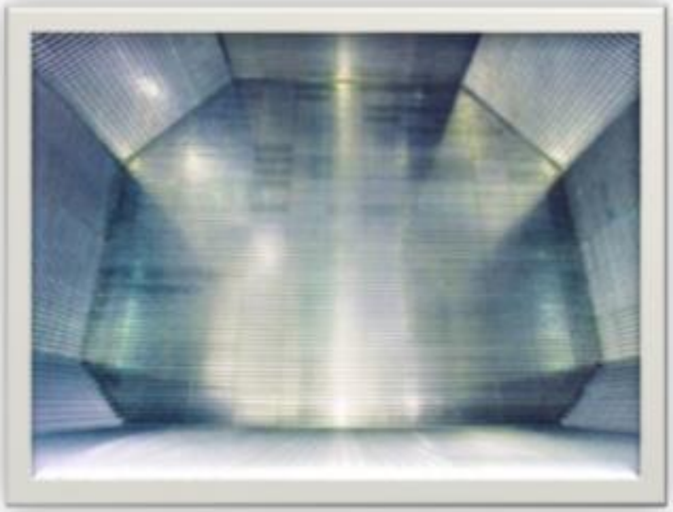


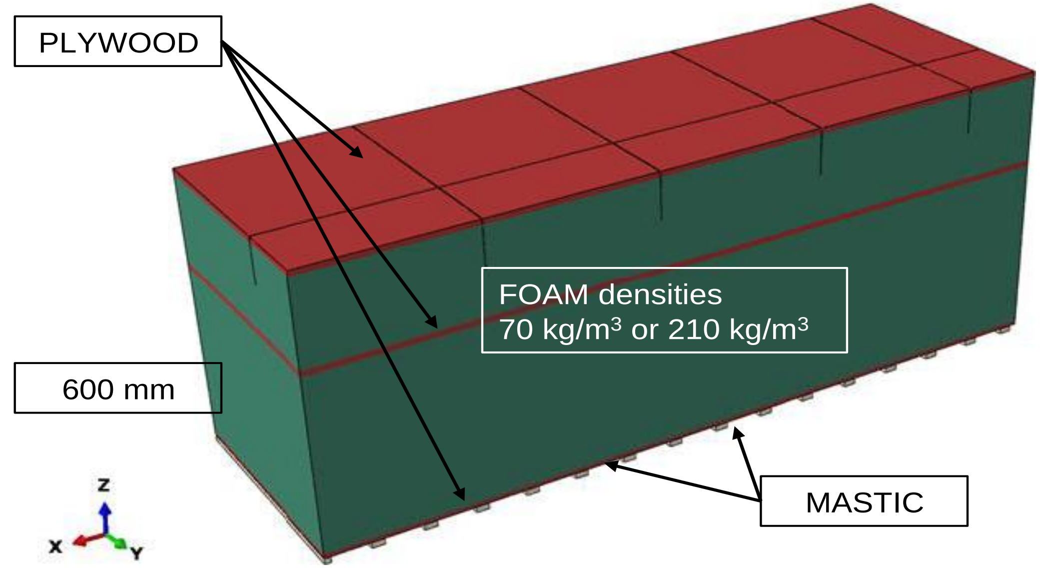
Detail of the extruded pieces



Dedicated tools and rotation system of the whole structure, to allow welding in flat position and achieve the requested highest quality level.

New thermal insulation

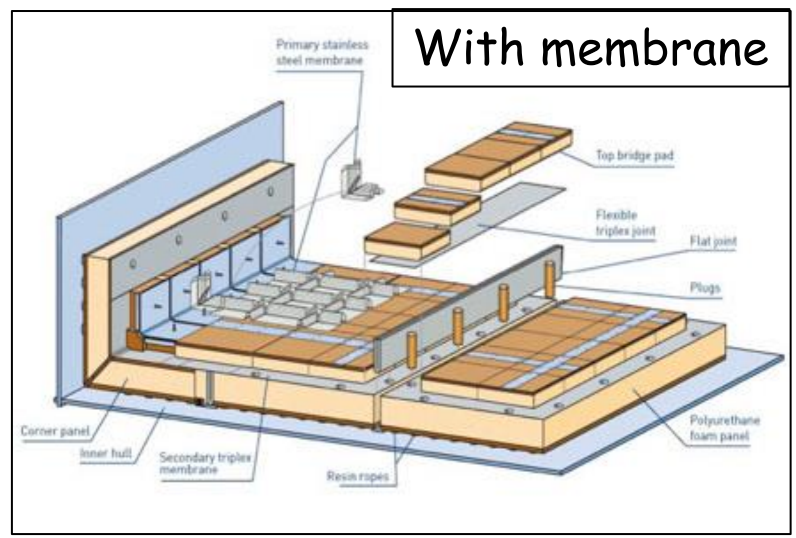




Purely passive insulation chosen for the installation, coupled to standard two-phase N_2 cooling shield, redesigned and tested at CERN.

Technique developed for 50 years with membrane and widely used for large industrial storage vessels and ships for liquefied natural gas. Expected heat loss through the insulation: ≈ 6.6 kW (10-15 W/m²)

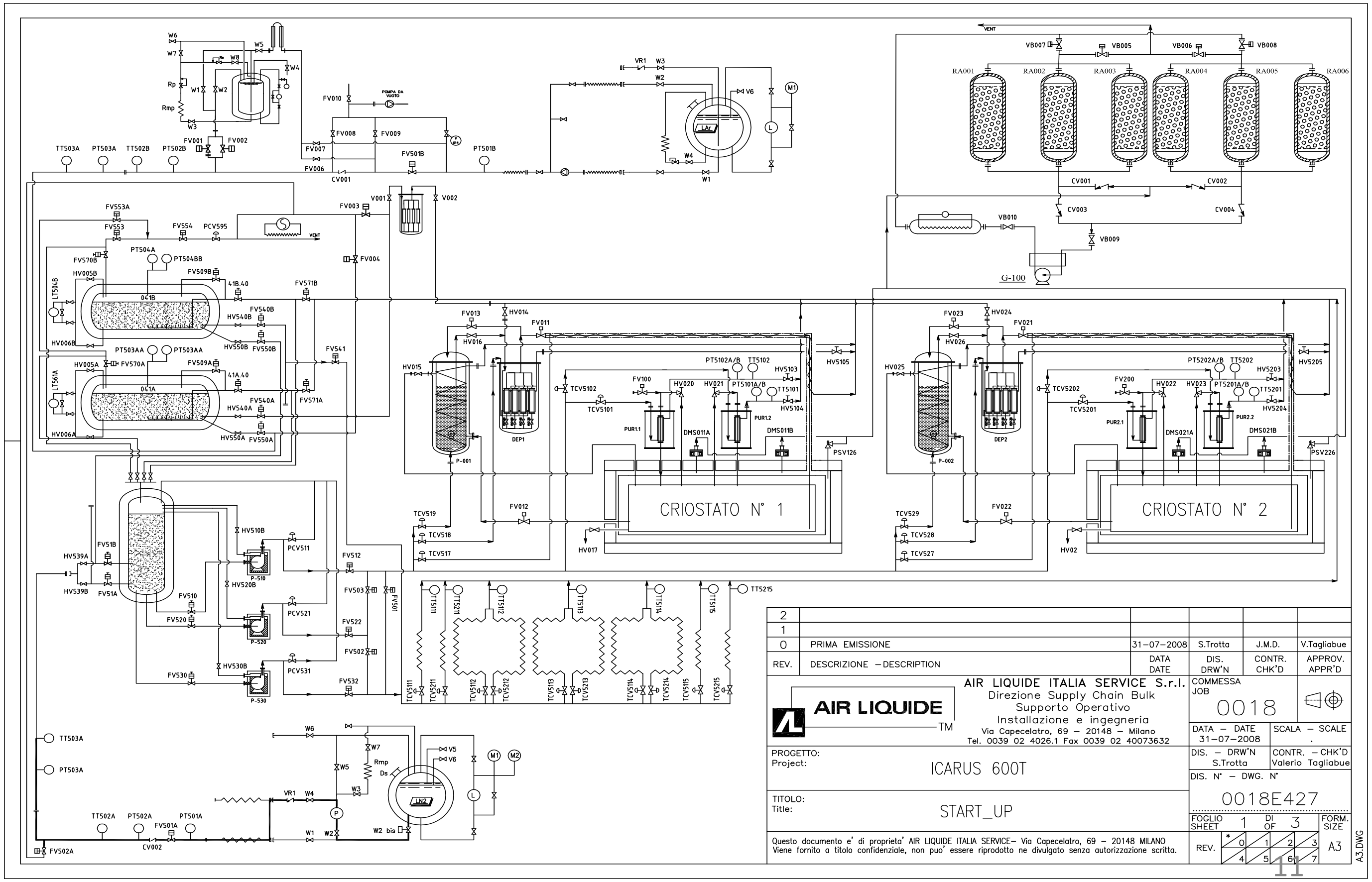
No internal membrane is required



New cryogenic plant

- The original layout of the T600 cryogenic/purification plant will be re-organized into self-consistent sub-units (skids) to be built and fully tested at CERN, prior to delivery to FNAL. Re-usable components from the old installation are being selected.
- Intensive discussions have started with CERN Cryo group (daily meetings), to prepare the P&ID of the cryogenic system(s) for the SBN program.

General, non-detailed P&ID of ICARUS at LNGS. New version (also for all other cryogenic systems provided by CERN) due within April-May.



Cathode planarization

Cathode panels of the first T300 module underwent a successful thermal treatment by personnel of the CERN Main Workshop: the residual non-planarity is within few mm.

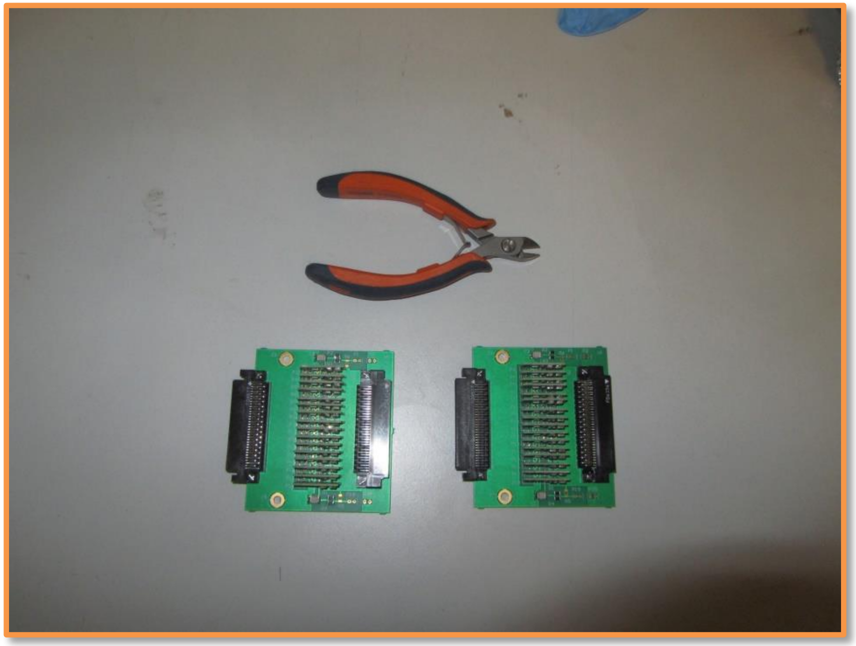
The "flattening" operation was completed at the end of September. The panels were taken to an external company for cleaning and electro-polishing.

All the panels have been re-installed in the first T300 module and a detailed survey of the present planarity is ongoing.

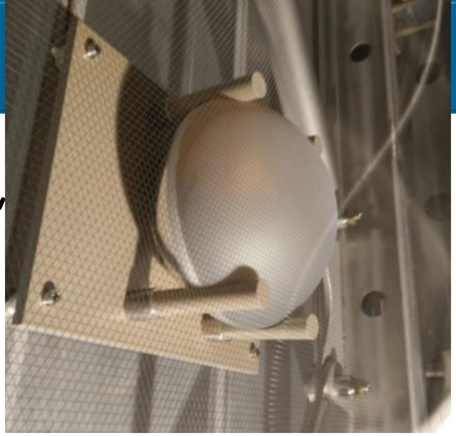
Cathode panels after flattening and electro-polishing

Detector re-cabling

- The design of the decoupling boards is complete and the components selection for the biasing chain is also complete.
- Prototypes have been installed to check for mechanical interferences and to fix the details of the mechanical supports.
- Pre-series have been delivered; a second batch was also produced and delivered.
- New cables have been selected and tested in LAr. Production of the cable bundles is ongoing.



Upgraded Light Collection System

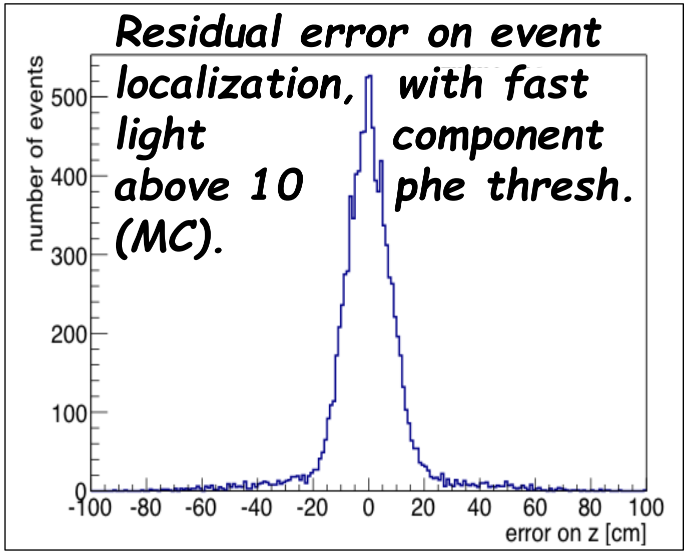


Large surface, Hamamatsu 8" PMTs will be adopted, as in LNGS, but major improvements in space/time event localization capabilities will be required to reject cosmic backgrounds:

- higher quantum efficiency (QE);
- improved photocathodic coverage > 5%. Chosen layout foresees 90 PMTs per TPC. From MC simulation (assuming conservative 5% effective QE), obtained longitudinal resolution is < 0.5 m.
- new voltage divider / shielding, to avoid induced spurious signals on TPC wires;
- new readout electronics, with ~ ns resolution, to exploit the BNB bunched structure.

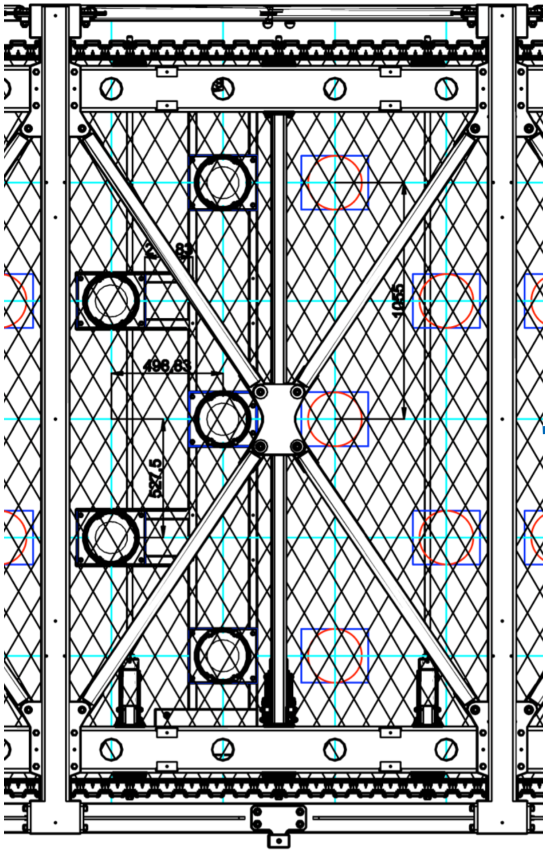
PMT number and layout defined by dedicated Monte Carlo, with two main goals:

- maximizing spatial localization capability;
- performing μ-tracks / e.m. showers separation with light signals, with a neural network approach, to help reducing cosmic backgrounds.

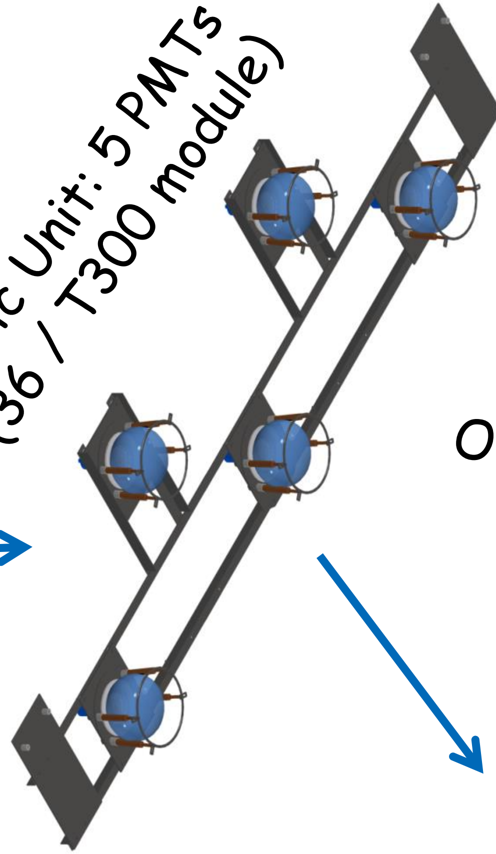


PMT mechanics

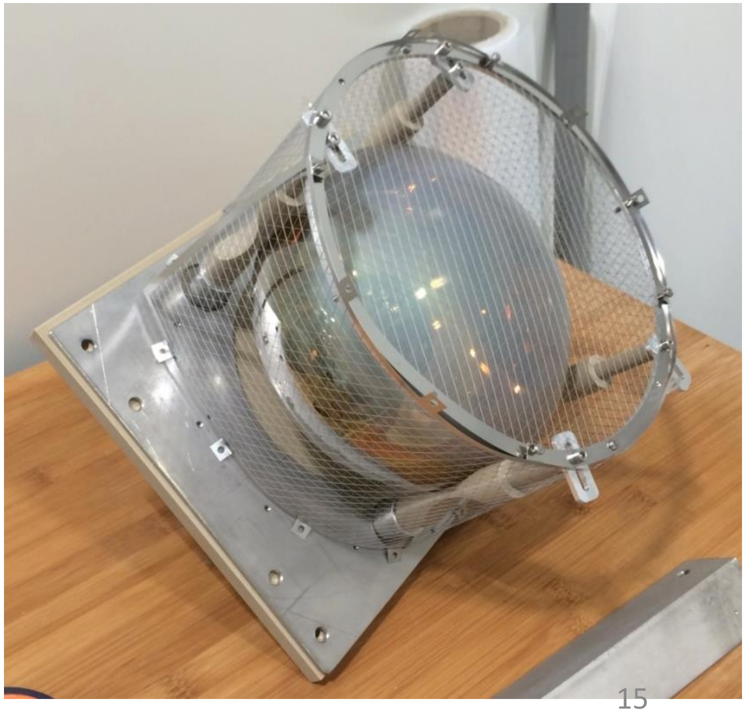
10 PMTs per 2-meter Section (2 basic units)



Basic Unit: 5 PMTs (36 / T300 module)



One PMT with support structure and shielding grid



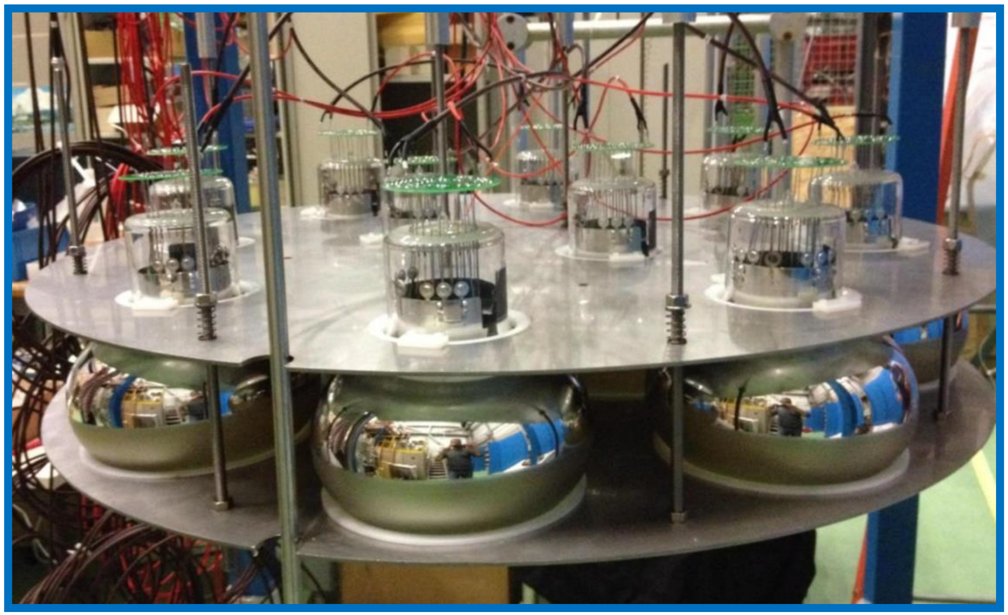
Test installation of one basic unit, to check for mechanical interferences and to perfect assembly sequence.

PMT test areas

All PMTs are characterized at warm temperature (CERN bg. 3179 – Ideasquare)

10% of them is also turned on in LAr (bg. 182) – all PMTs are mechanically tested in LN_2 by Hamamatsu.

Tubes are coated under vacuum with a TPB layer, ~200 $\mu g/cm^2$ thick (bg. 169 – TE lab.).



Updated electronic chain

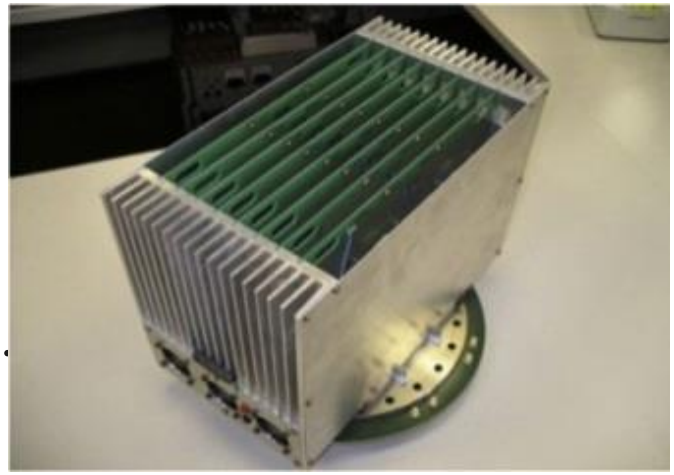
ICARUS-T600 electronics are based on analogue low noise "warm" front-end amplifier, a multiplexed 10-bit 2.5 MHz AD converter and a digital VME module for local storage, data compression & trigger information.
A signal to noise ratio better than 10 was obtained during the LNGS run.

Some limitations: asynchronous sampling of channels within 400 ns sampling time, which slightly affects Multiple Scattering measurement, and data throughput mainly due to the choice of VME standard (8-10 MB/s).

A new fully warm chain is then being developed, and improvements will concern:

- adoption of high frequency serial ADCs with synchronous sampling;
- adoption of a modern serial bus architecture with optical links for faster transmission rate (Gbit/s).
- new compact design: digital part in a single FPGA; whole chain housed on a flange-mounted crate.

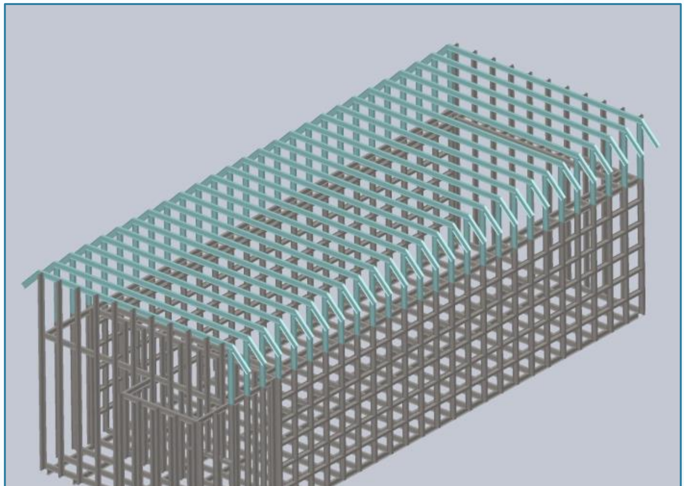
Tests carried on mainly in LNL-Padova with a ~50l TPC.

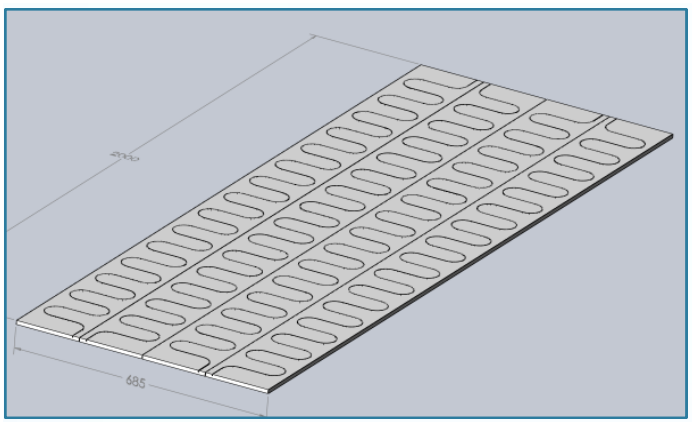


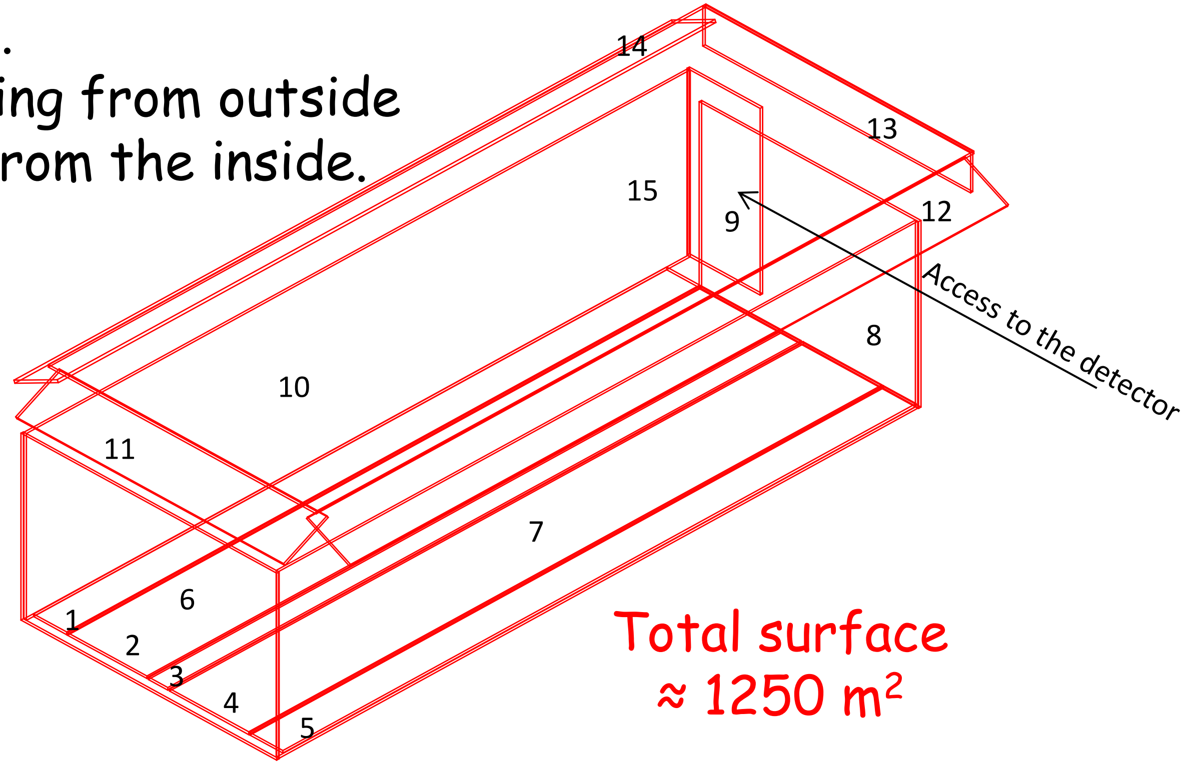
A solution with cold front-ends (by BNL) was also tested at CERN with the FLIC 50l TPC, but it will not be employed by ICARUS during the SBN program (chosen by MicroBooNE and SBND).

Cosmic Ray Tagger

Largest possible coverage (> 98%).
Timing to recognize particles coming from outside the detector from those coming from the inside.


Support structure: Warm vessel+ extensions





Total surface
≈ 1250 m²

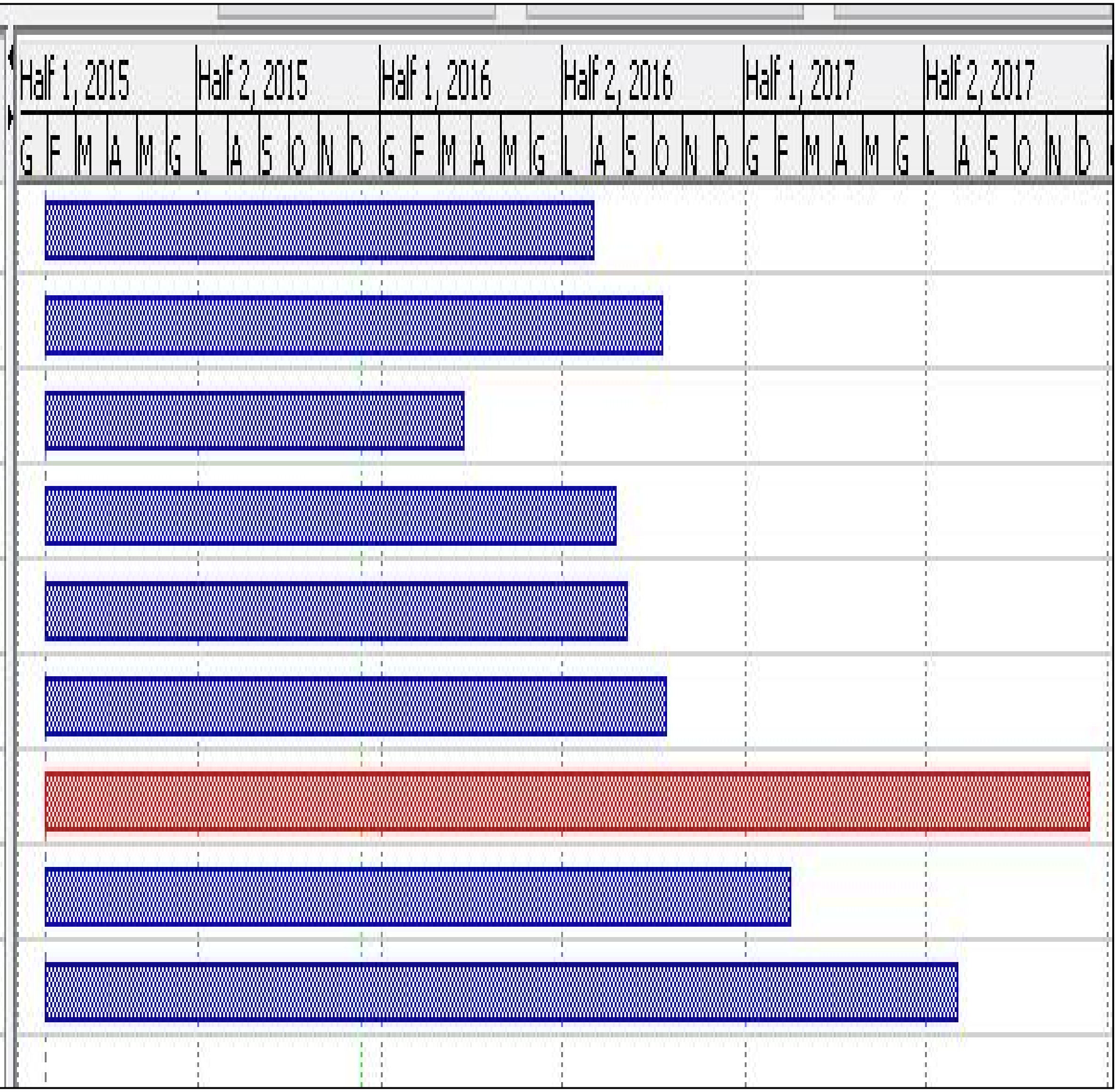
- Scintillator + WLF fiber + SiPMs
- Two configurations considered
  - X-T – single layer
  - X-Y double layer
  - Physics performance vs. cost
- Integration with Warm Vessel to be finalized
- Design and fund to be completed for ICARUS
- Provided by Bern to SBND and MicroBooNE

Far Detector Building Construction at FNAL

Construction proceeds according to schedule; beneficial occupancy in Oct. 2016.
Discussions ICARUS-CERN-FNAL for Integration and Installation started:
again, continuous interactions are fundamental to succeed!

Overall Schedule

Name	...	Start	Finish
FIRST COLD VESSEL	...	28/01/15 8.00	02/08/16 17.00
SECOND COLD VESSEL	...	28/01/15 8.00	10/10/16 17.00
FIRST TPC	...	28/01/15 8.00	25/03/16 17.00
SECOND TPC	...	28/01/15 8.00	26/08/16 17.00
WARM VESSEL	...	28/01/15 8.00	05/09/16 17.00
CRYOGENICS	...	28/01/15 8.00	14/10/16 17.00
COSMIC TAGGER	...	28/01/15 8.00	15/12/17 17.00
TRANPORT TO FNAL	...	28/01/15 8.00	16/02/17 17.00
ASSEMBLY AT FNAL	...	28/01/15 8.00	04/08/17 17.00



Conclusions

- The ICARUS detector has successfully operated for three years at the LNGS, providing multiple results on neutrino physics and LAr-TPC technology.
- A study of exotic oscillations, mediated by sterile ν's, was carried on with the CNGS beam, to test the so-called "LSND effect", with no anomalies detected. To further investigate the sterile neutrino hypothesis, the ICARUS detector will take part in the dedicated FNAL Short Baseline Neutrino program.
- The T600 detector is now undergoing a major technological overhaul at CERN and is expected to be moved to FNAL by the end of 2016 for installation, commissioning and start of data taking with ν beam by the end of 2017.
- The overhauling is proceeding according to schedule and in line with the budget, with the only exception of the Cosmic Rays Tagger.
- The first T300 module will be ready in the first months of 2016. The second one will take advantage of all the preparatory work of the first one and will require only six months to be completed. Both modules will be ready for transport in second half 2016.
- Aim of the Collaboration is to start data taking with the BNB during 2017.


Thank you !

Main recent ICARUS publications

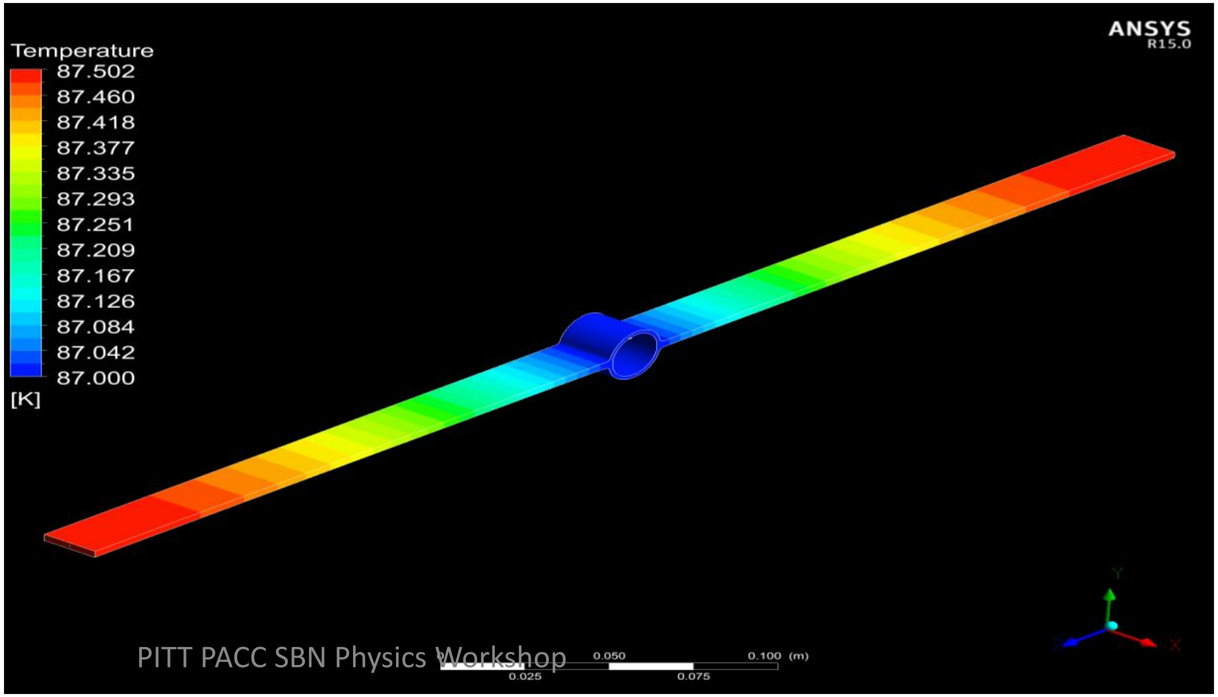
1. "Underground operation of the ICARUS T600 LAr-TPC: first results", JINST 6 (2011) P07011.
2. "A search for the analogue to Cherenkov radiation by high energy neutrinos at superluminal speeds in ICARUS", PLB 711 (2012) 270.
3. "Measurement of neutrino velocity with the ICARUS detector at the CNGS beam", PLB 713 (2012) 17.
4. "Precision measurement of the neutrino velocity with the ICARUS detector in the CNGS beam", JHEP 11 (2012) 049.
5. "Precise 3D Reconstruction Algorithm for the ICARUS T600 Liquid Argon Time Projection Chamber Detector", AHEP 2013 (2013) 260820.
6. "Experimental search for the LSND anomaly with the ICARUS detector in the CNGS neutrino beam", EPJ C73 (2013) 2345.
7. "Search for anomalies in ν_e appearance from ν_μ beam", EPJ C73 (2013) 2599.
8. "The trigger system of the ICARUS detector for the CNGS beam", JINST 9 (2014) P08003.
9. "Experimental observation of an extremely high electron lifetime with the ICARUS-T600 LAr-TPC", JINST 9 (2014) P12006.
10. "Operation and performance of the ICARUS-T600 cryogenic plant at Gran Sasso underground Laboratory", JINST 10 (2015) P12004.

Back Up

New cryogenic plant

- The original layout of the T600 cryogenic/purification plant will be re-organized into self-consistent sub-units (skids) to be built and fully tested at CERN, prior to delivery to FNAL. Re-usable components from the old installation are being selected.
- Intensive discussions have started with CERN Cryo group (daily meetings), to prepare the P&ID of the cryogenic system(s) for the SBN program.
- A new two-phase N_2 cooling shield, made of thin Al panels, is being developed. A sample of shield was built at CERN and tested, to verify the computing model. Its design is being integrated in the P&ID

Sample of cooling shield, computed temperature profile. Note that the shield is not used in membrane cryostats.



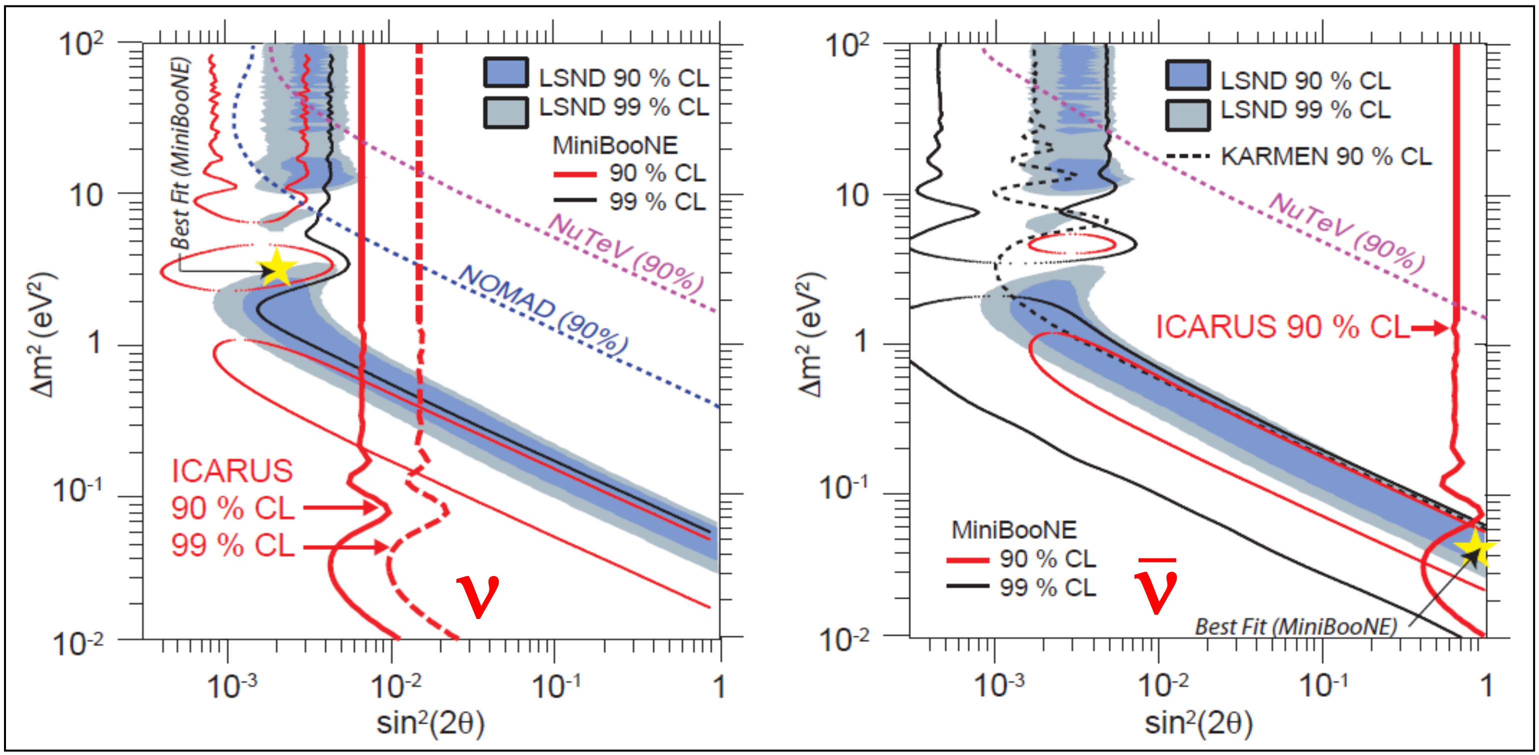
ICARUS results from CNGS beam: no exotic oscillation

- ICARUS limits on neutrino events due to LSND anomaly are: 5.2 (90% C.L.), or 10.3 (99% C.L.), the corresponding oscillation probability being:

  $P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3}$ (90% C.L.) $P(\nu_\mu \rightarrow \nu_e) \leq 7.60 \times 10^{-3}$ (99% C.L.)

- Similar results were obtained by the Opera experiment. Combining all positive and negative world results, only a narrow region of overall agreement between different experiments remains, centered around:

  $\Delta m^2_{new} \approx 0.5\ eV^2$, $\sin^2 2\theta_{new} \approx 0.005$.



Sterile Neutrino searches at the FNAL BNB ($E_\nu \sim 0.8$ GeV)

- The experiment will likely clarify LSND/MiniBooNE , Gallex, reactor anomalies by precisely/independently measuring both ν_e appearance and ν_μ disappearance, mutually related through the relation:

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

  - In absence of "anomalies", the 3 detector signals should be a close copy of each other, for all experimental signatures. The possibility to change intrinsic ν_e contamination, by acting on beam optics as horn and decay tunnel length, may help disentangling conflicting effects, like ν_e disappearance (if confirmed by reactors) and the possibly superimposed excess ν_e signal (LSND-like).

- During its SBN operations, ICARUS will collect also ~ 2 GeV ν_eCC events from the NUMI beam, Off-Axis, an asset for the long baseline DUNE project.
  - accurate determination of cross sections in LAr ;
  - experimental study of all individual CC/ NC chs to realize algorithms to improve the identification of n interactions.

SBN Director's Review Main Recommendations

ICARUS and the SBN program in general successfully underwent the FNAL Director's Review in December. Among the recommendations from the revising committee, the main ones, that require strong and fast reaction from the Collaboration, concern:

- the request to add contingency to the program, in terms of time and funding;
- creation/improvement of interfaces among all the entities involved, funding agencies, labs, collaborations;
- the need to complete the Cosmic Ray Tagger, with priority to the T600: the present available funding (1.2M€) in fact should cover only half of the installation;
- the idea to upgrade the beam in 2019, which requires the Near Detector to be operational earlier than that date, so that all three detectors can take data in the original beam configuration.

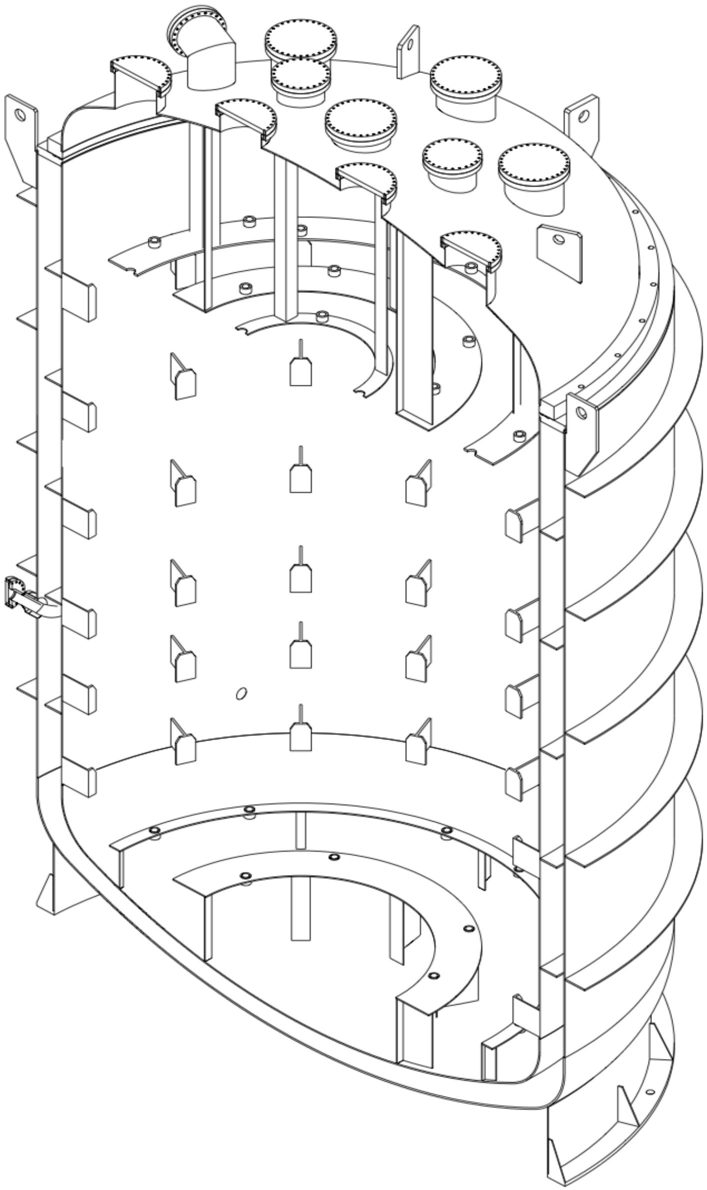
Understanding the cosmic induced background

- A direct measurement of cosmic rays induced background before the start of operation on the Booster neutrino beam, in our view, can and must be done in order to assess:
  - the correct thickness of the overburden;
  - the correct performance of the Cosmic Rays Tagger;
  - the validity of the reconstruction and event selection algorithms.

- The direct availability of data from detectors like MicroBooNE, MiniBooNE, ... is crucial for a correct comparison of data and Monte Carlo's.

- However, a dedicated measurement can be performed, at CERN, using already existing cryogenic and purification equipment. The existing equipment has to be complemented with a TPC (≈10 m^3 active volume), an adequate shielding using existing concrete blocks and a Cosmic Rays Tagger.

The WArP cryostat



Internal vessel diameter	2900 mm
External vessel diameter	3200 mm
Max ext vessel diameter	3440 mm
Internal vessel thickness	6/7 mm
External vessel thickness	6/10 mm
Max internal height	4996 mm
Max external height	5090 mm
Cylindrical useful part height	3755 mm
Cooling worm-pipe diameter	22x1.5 mm
LAr recirculation flange from cap flange 170 mm dim.	2630 mm
Internal vessel volume	**29 m^3**
Vacuum insulation volume	6 m^3
Cryostat mass (empty)	8800 kg
LAr level from cap flange	500 mm
Max LAr level from bottom	3693 mm
LAr volume	**22.8 m^3**
LAr mass	**32000 kg**

ICARUS/WA104 Collaboration

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+ 8 US groups who recently joined:
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