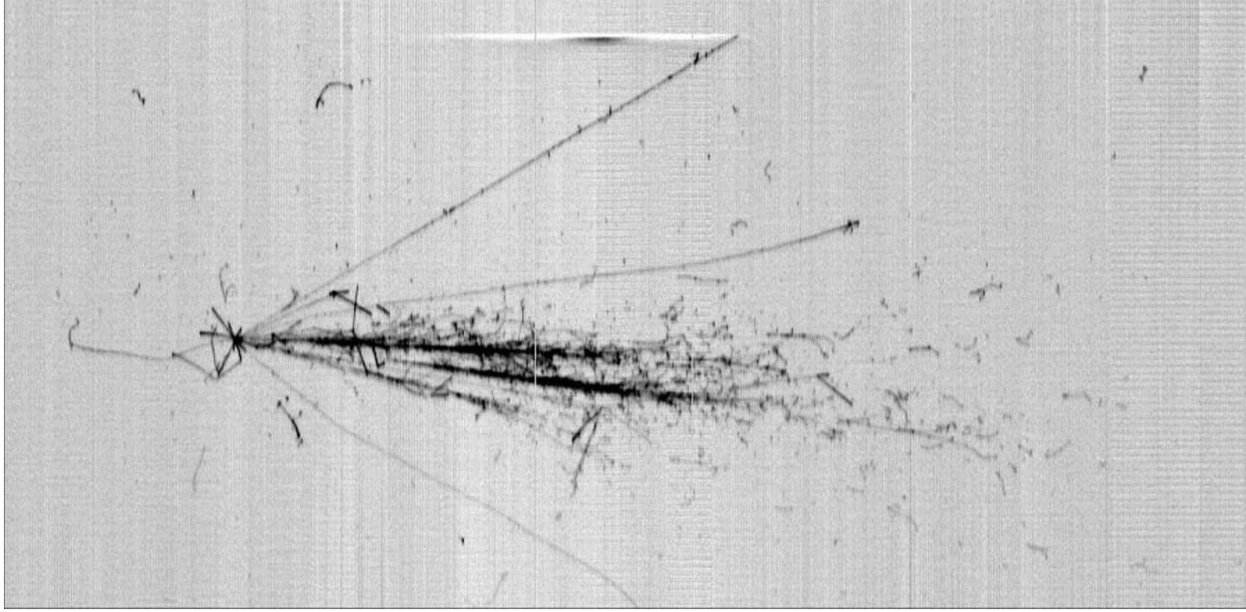
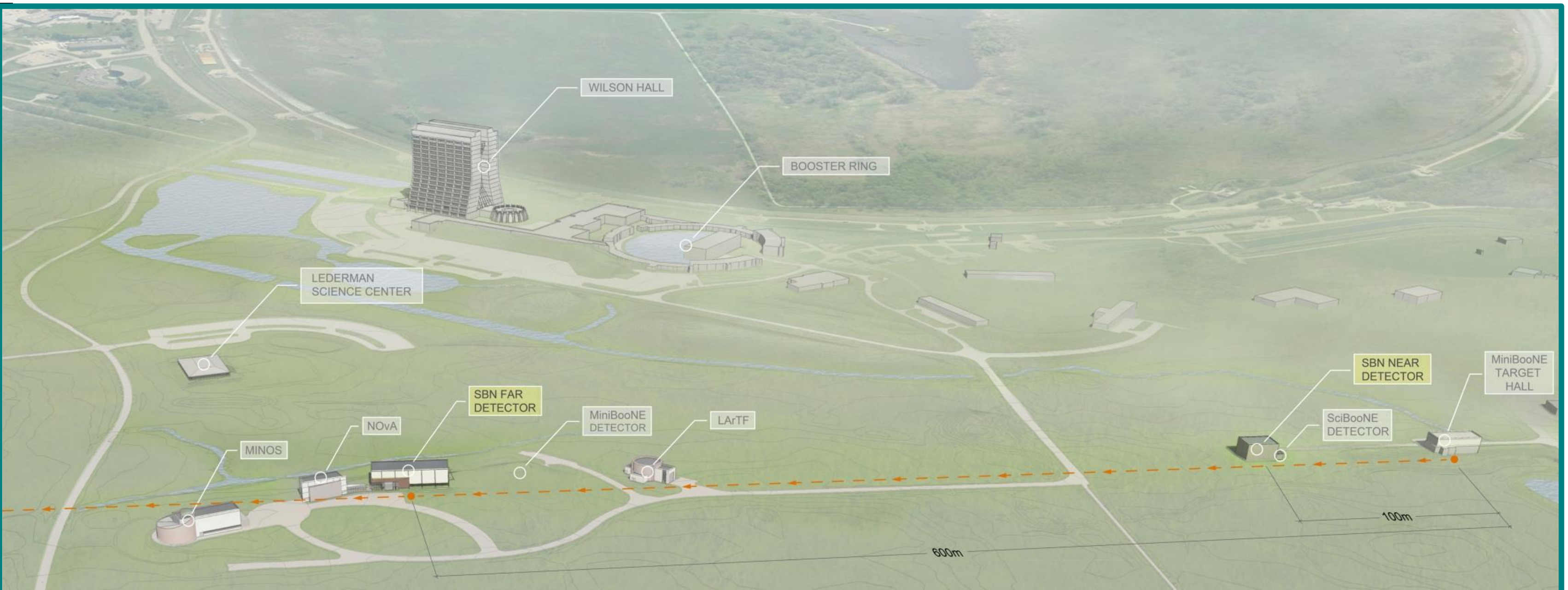
ICARUS T600: physics results and future activities



4th International Conference on New Frontiers in Physics
ICNFP2015 – 26/08/2015



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on behalf of the ICARUS Collaboration

ICARUS/WA104 Collaboration

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+ 6 US groups who recently joined:
Colorado Univ., Pittsburg Univ., SLAC,
FNAL, Argonne, Los Alamos : **ICAR-US**

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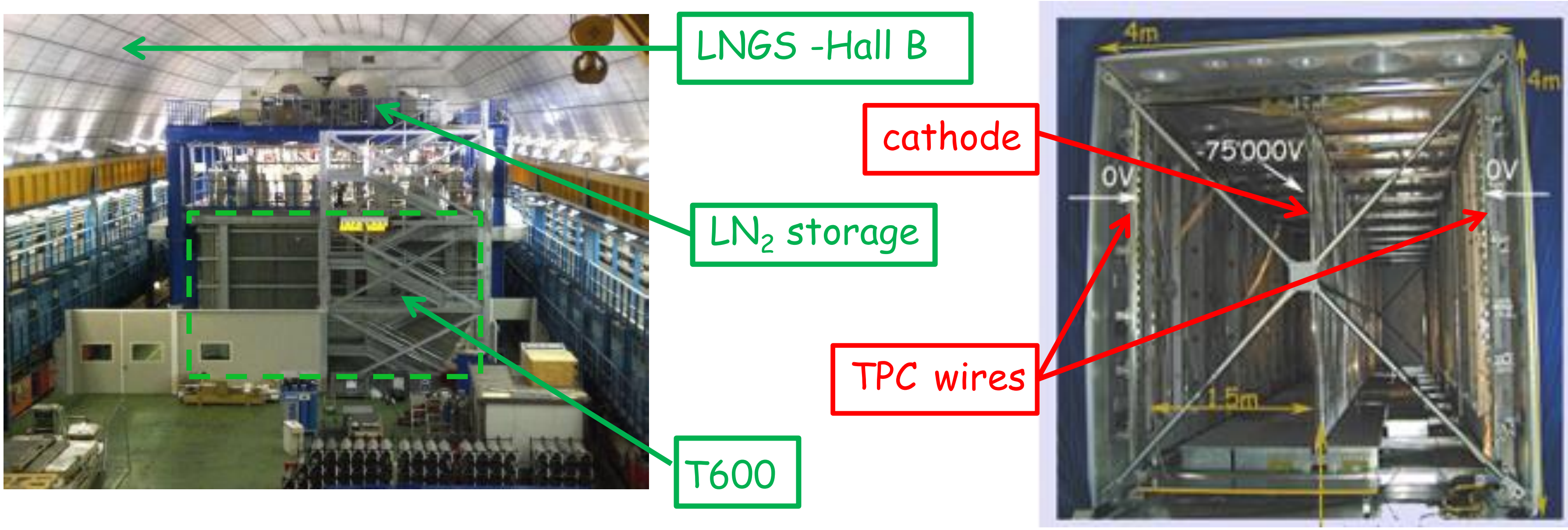
Premise

- 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.
- The detector is now at CERN (project WA104) for a major overhaul before being deployed to Fermilab.
- The Collaboration intends to undertake 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 (earlier: LAr1-ND); mid=MicroBooNE; far=ICARUS.
- This presentation will address the main physics motivations for the Short Baseline experiment at FNAL with the T600 as Far Detector, and show the on-going activities at CERN within the WA104 program.

The ICARUS detector @ LNGS



Two identical modules…
- $3.6 \times 3.9 \times 19.6$ m ≈ 275 m^3
- Total active mass ≈ 476 ton

… and four wire chambers
- Two TPCs for each module, divided by the cathode -> 1.5 m drift length
- HV = -75 kV -> E_{drift} = 0.5 kV/cm
- v_{drift} = 1.55 mm/μs

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

Electronics
- FADC 10bit 1mV/ADC ~ 1000e^-/ADC

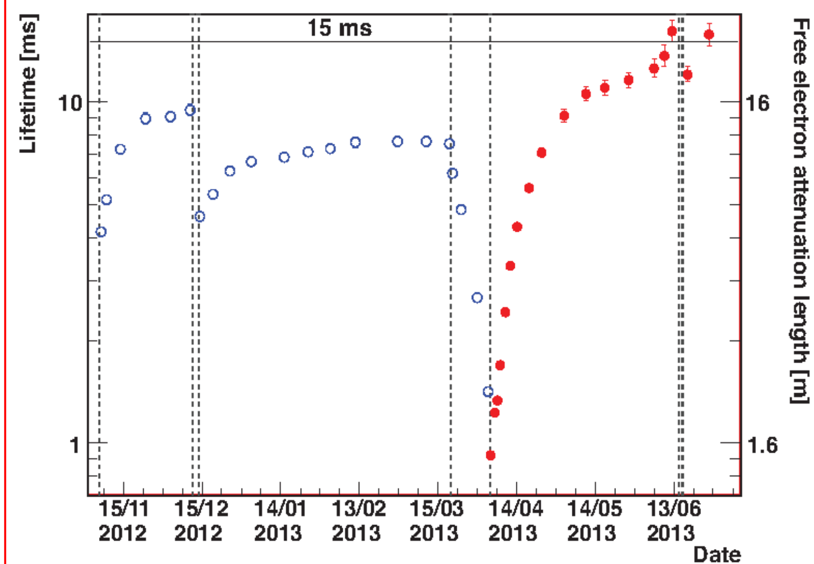
The way towards large-scale detectors: high LAr purity

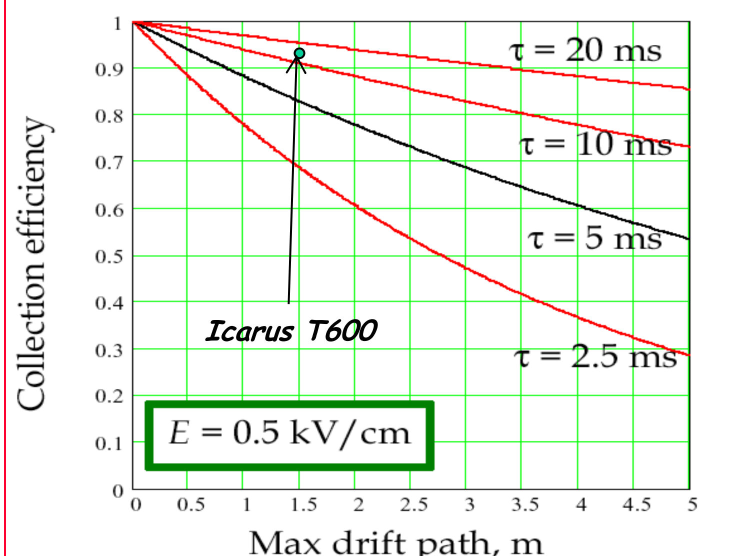
Level of electronegative impurities in LAr must be kept exceptionally low, in order to ensure un-attenuated drift of ionization electrons along meters-long distances.

New industrial purification methods have been developed to continuously filter and recirculate both in liquid (100 m^3/day) and gas (2.5 m^3/hour) phases.

- τ_e > 7 ms measured during ICARUS run at LNGS → 12% max charge attenuation.
- τ_e > 16 ms (< 20 ppt O_2 equiv.) in East cryo since April 4th, 2013 (new pump installed).
- τ_e ~ 21 ms previous reference obtained at the Icarino LAr-TPC (120 l) at INFN LNL.

ICARUS has demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors (~ 5 m drift).

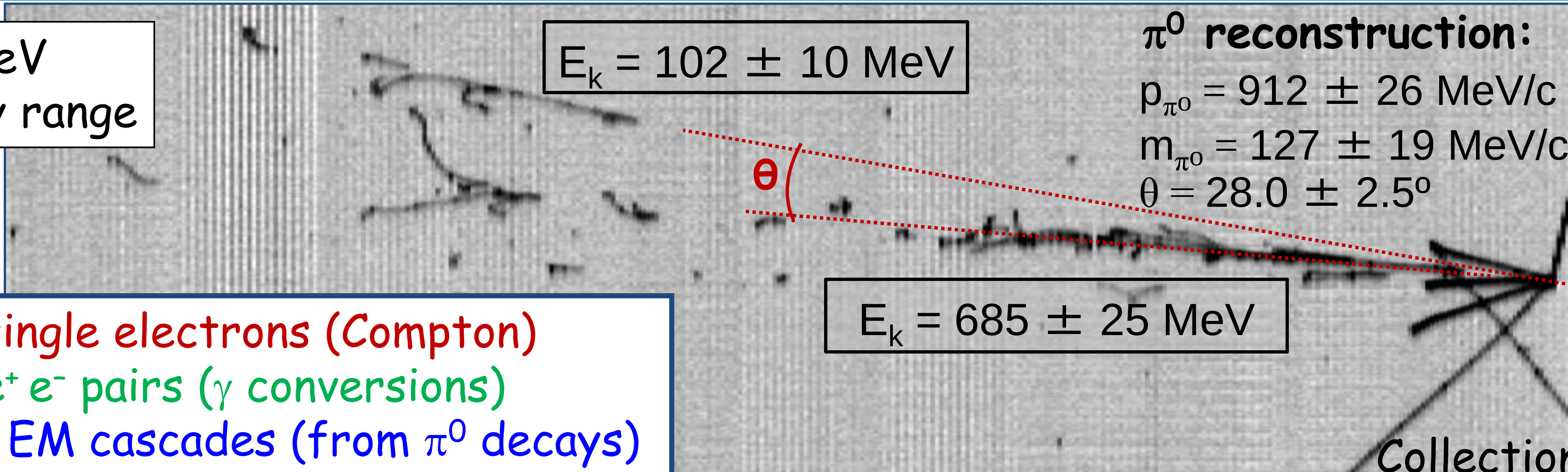




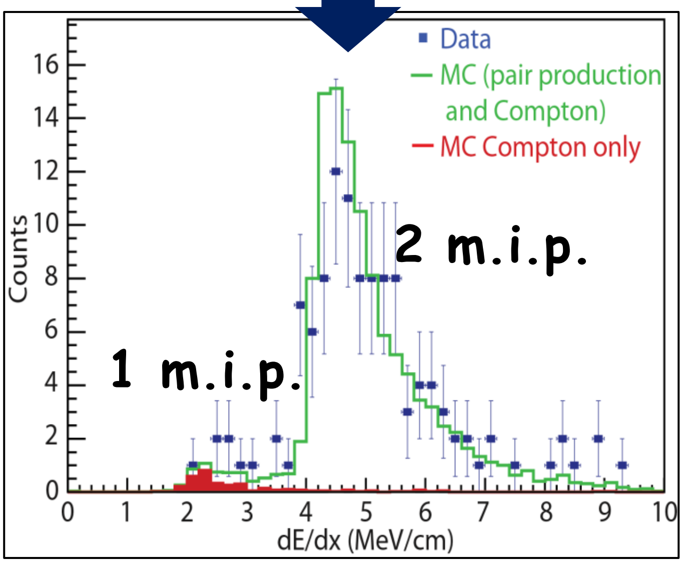
Drifting charge attenuation versus drift path at different electron lifetimes

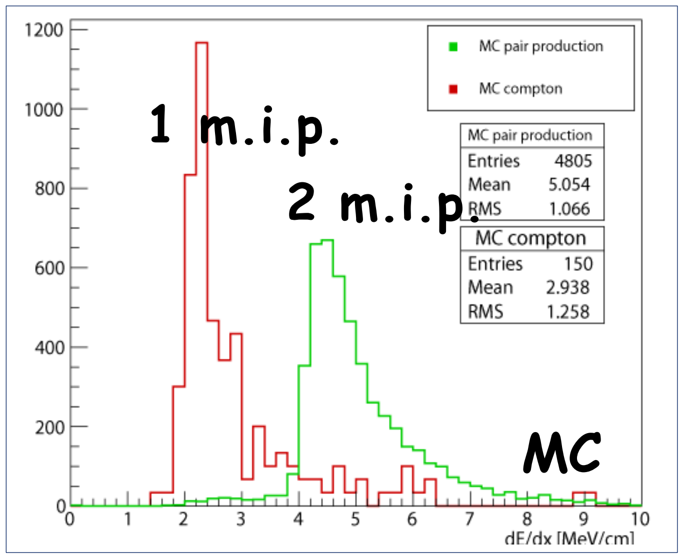
e/γ separation in Liquid Argon

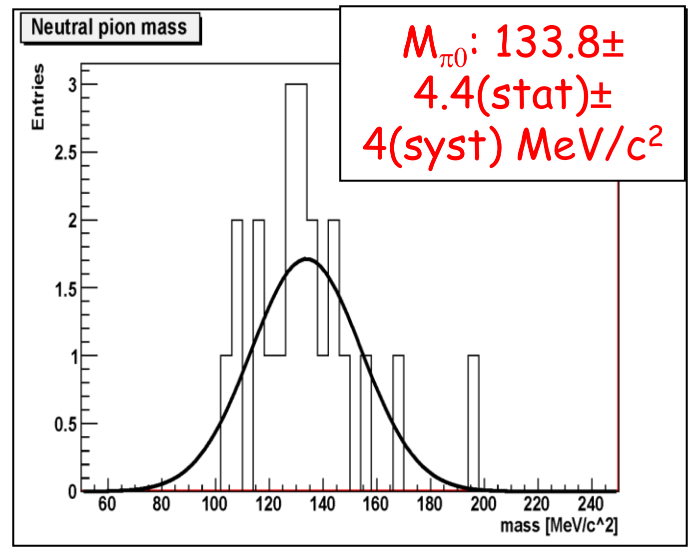
Sub-GeV
Energy range



- MC: single electrons (Compton)
- MC: $e^+ e^-$ pairs (γ conversions)
- data: EM cascades (from π^0 decays)







LAr unique features allow e/γ separation and π^0 reconstruction
-> Estimated bkg. (from MC/scanning) from π^0 in NC and ν_μ CC: **negligible**

CNGS-related 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", submitted to JINST.

Anomalies in the neutrino sector

Different anomalies have been collected in the last years in the neutrino sector, despite the well-established 3-flavour mixing picture within the Standard Model:

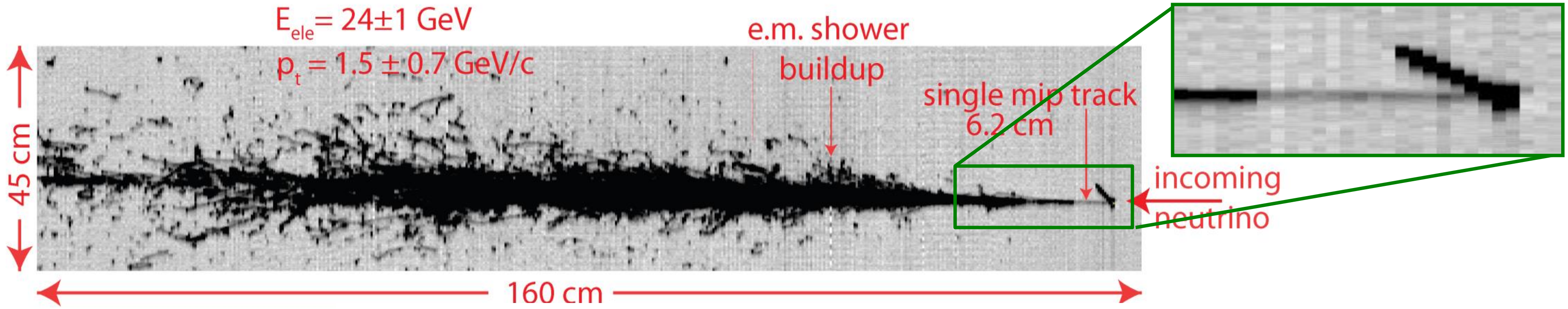
- appearance of $\bar{\nu}_e$ (excess) from muon neutrino beams in accelerator experiments (LSND + MiniBooNE, combined evidence > 3σ);
- disappearance of $\bar{\nu}_e$-events, hinted by nuclear-reactor experiments;
- disappearance of ν_e, hinted by solar neutrino experiments during calibration with Mega-Curie k-capture neutrino sources (SAGE, GALLEX).

These results seems to point to the existence of at least one more "sterile", heavier neutrino flavour, characterised by large mass-difference ($\Delta m^2_{new} \approx 1$ eV^2) and small mixing angle θ_{new} and driving oscillations at short distance.

On the other hand Planck data and Big Bang cosmology point to at most only one further flavour, with mass $m_{new} < 0.4$ eV.

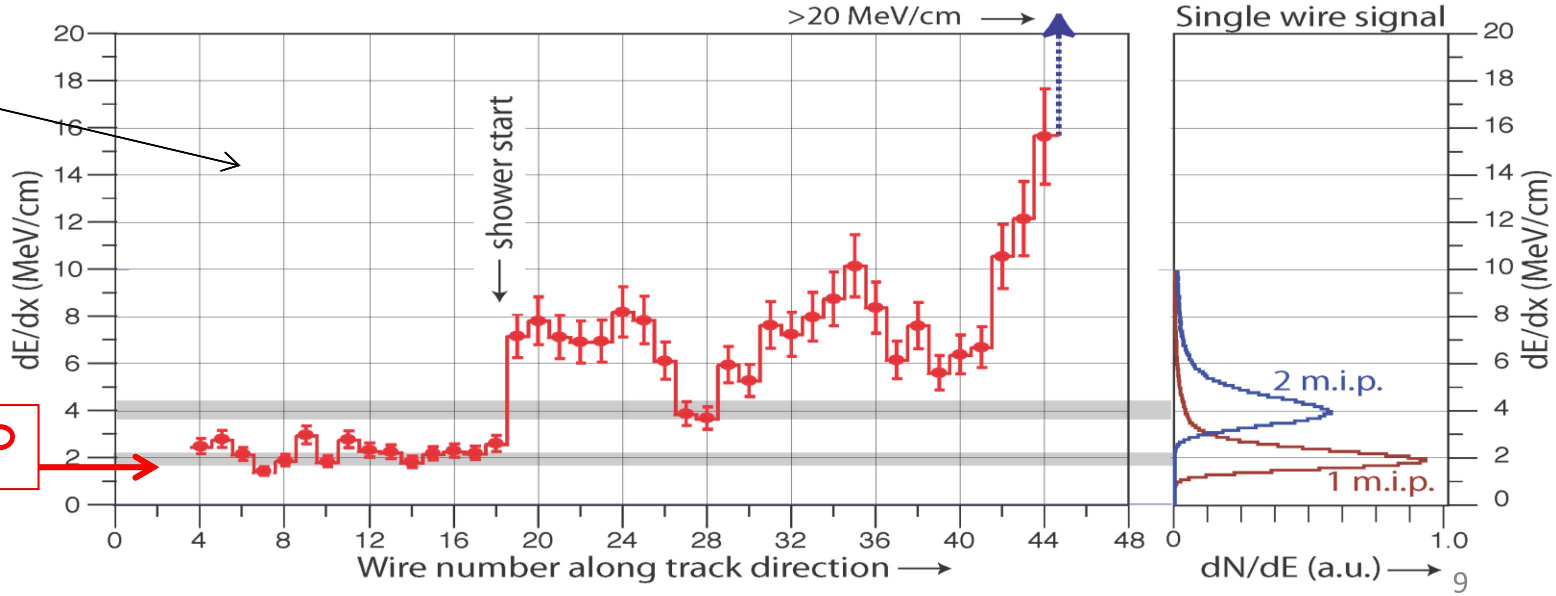
Electron neutrino events

- ICARUS searched for a ν_e-excess, related to a LSND-like anomaly on the CNGS ν 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 x 10^{19} pot) from the CNGS beam (8.4±1.1 expected events, weighted for identification efficiency).



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

Single M.I.P



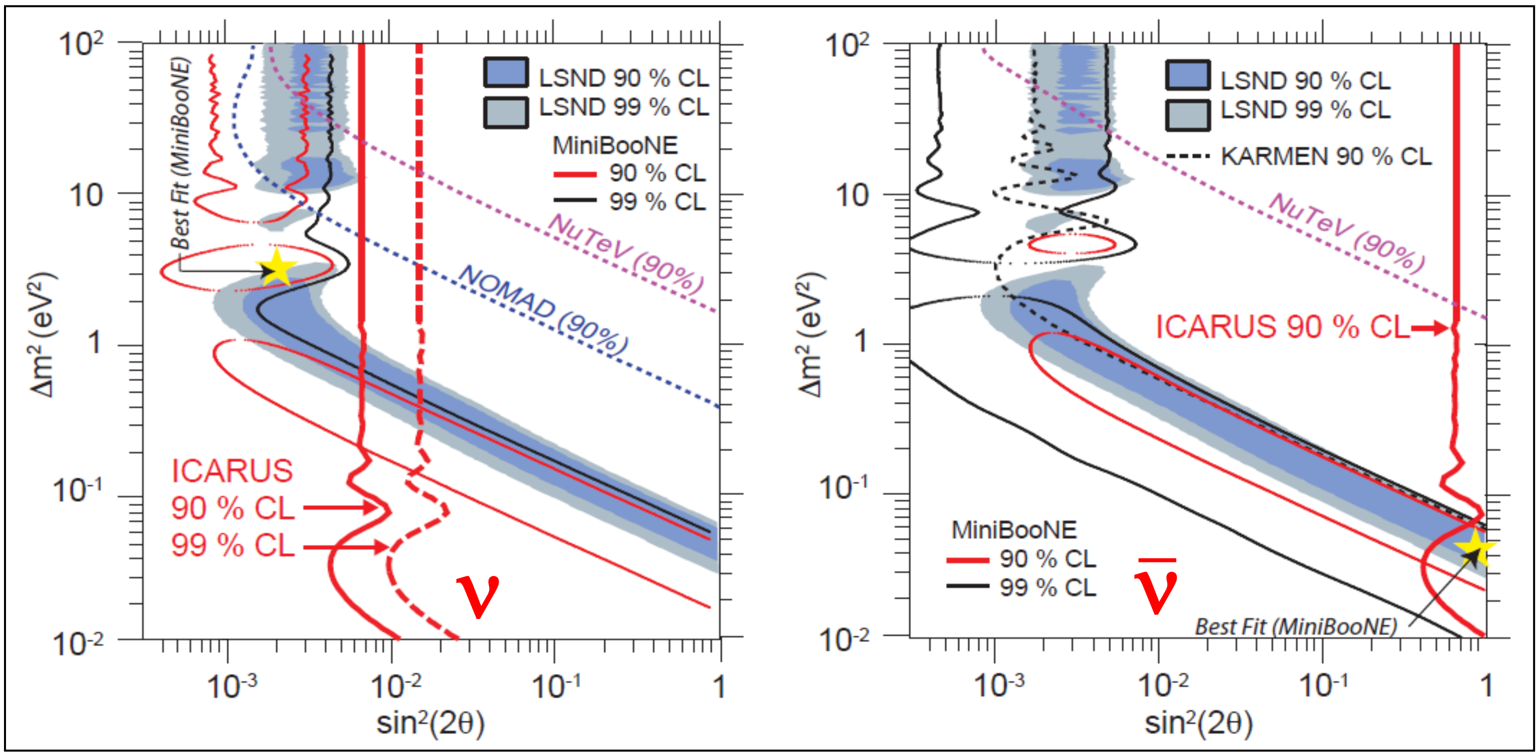
ICARUS results from CNGS beam: no exotic oscillation

- 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:

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



Bringing sterile neutrino searches to FNAL

A ultimate multi-station experiment exposed to FNAL Booster Neutrino Beam (BNB, ~ 0.8 GeV) was proposed to finally answer the "sterile neutrino puzzle".

A joint Conceptual Design Report was presented to FNAL PAC (Jan 15th , 2015), exploiting 3 LAr-TPCs at different distances from target: SBND (82 t active mass), MicroBooNE (89 t) and ICARUS T600 (476 t) at 150, 470 and 600 m.

The new program will allow separately identifying Δm^2 and $\sin^2(2\theta)$ by simultaneous observation at different distances of ν-interactions, exploiting:

- appropriate L/E range to match the Δm^2 window for the expected anomalies;
- "imaging" detectors capable to identify unambiguously all reaction channels with a LAr-TPC;
- very high rates due to large masses, in order to record relevant effects at the % level (>10^6 ν_μ, ≈10^4 ν_e events);
- both initial ν_e and ν_μ components cleanly identified.

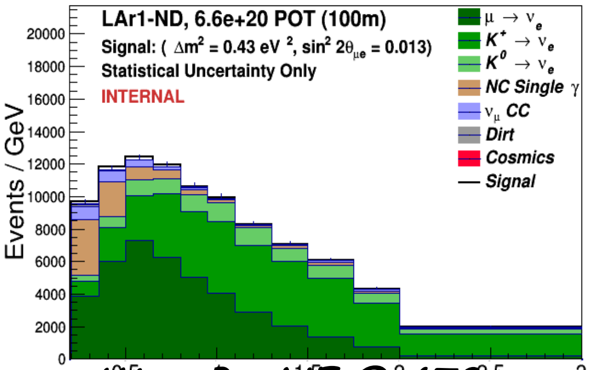
Intrinsic ν_e contamination can be changed via intervention on beam optics, if needed, to disentangle appearance/disappearance effects.

SBN @ BNB

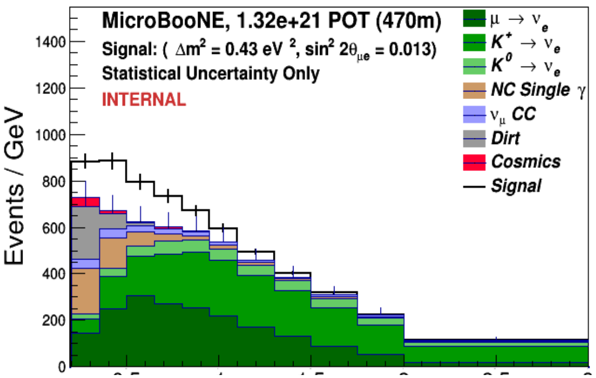
MINOS/MINERvA surface building
SBN FD (~600m)
MiniBooNE
MicroBooNE (470m)
Booster Neutrino Beam
NuMi Line
SBN ND (~100m)
BNB target hall
ICARUS T600
MicroBooNE (running)
SBND

$\nu_\mu \rightarrow \nu_e$ appearance sensitivity

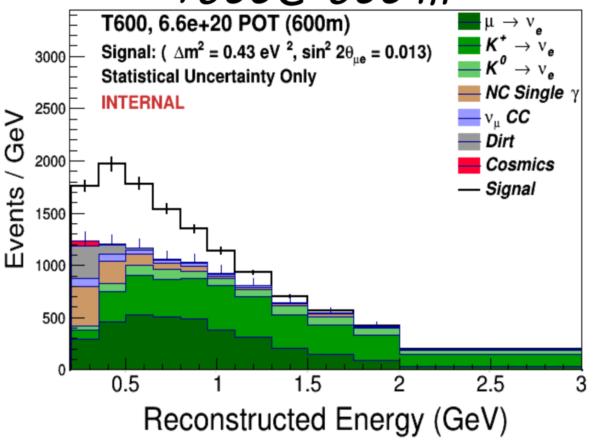
SBND @ 100 m



MicroBooNE @ 470 m



T600@ 600 m



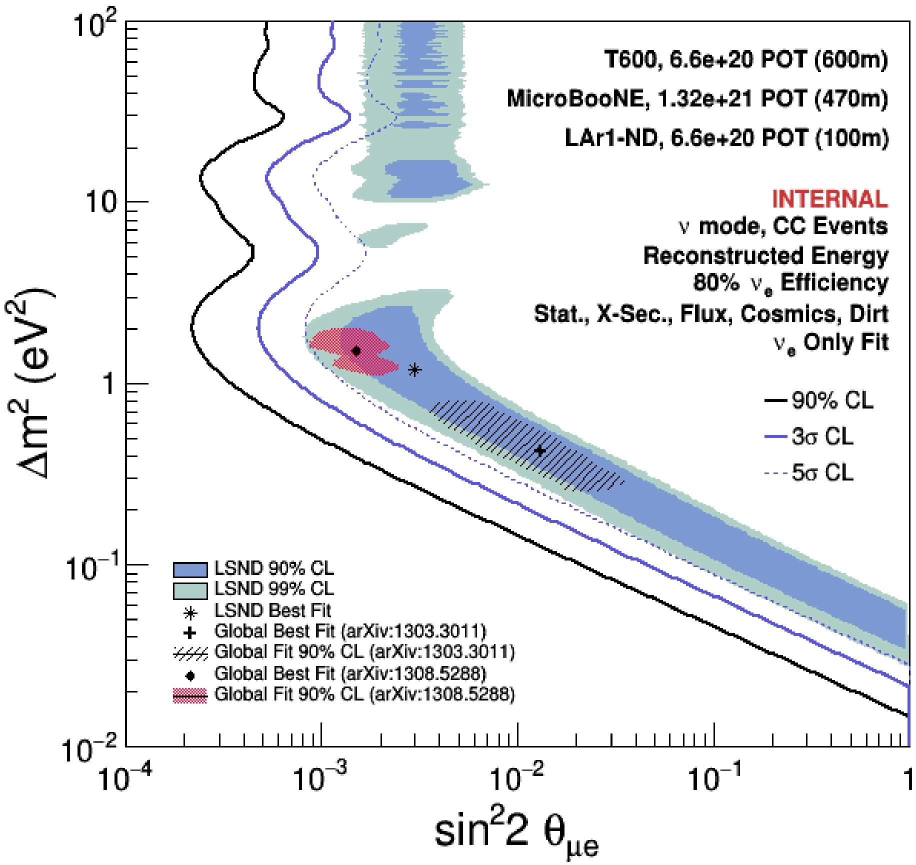
Expected exposure sensitivity of $\nu_\mu \rightarrow \nu_e$ oscillations for 3 years - 6.6 10^{20} pot BNB (6 years for MicroBooNE).

Example for

($\sin^2(2\theta)=0.013$

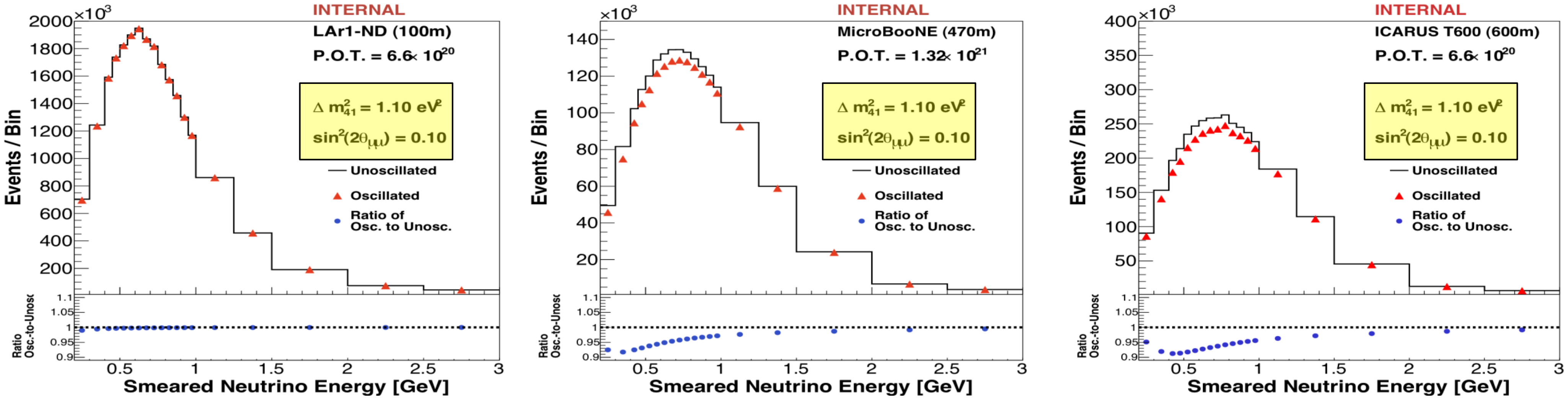
$\Delta m^2=0.43$ eV^2)

In absence of oscillations, the spectra should be copies of each other.



The LSND 99%CL region is covered at the ~5σ level

Novel analysis channel: ν_μ disappearance

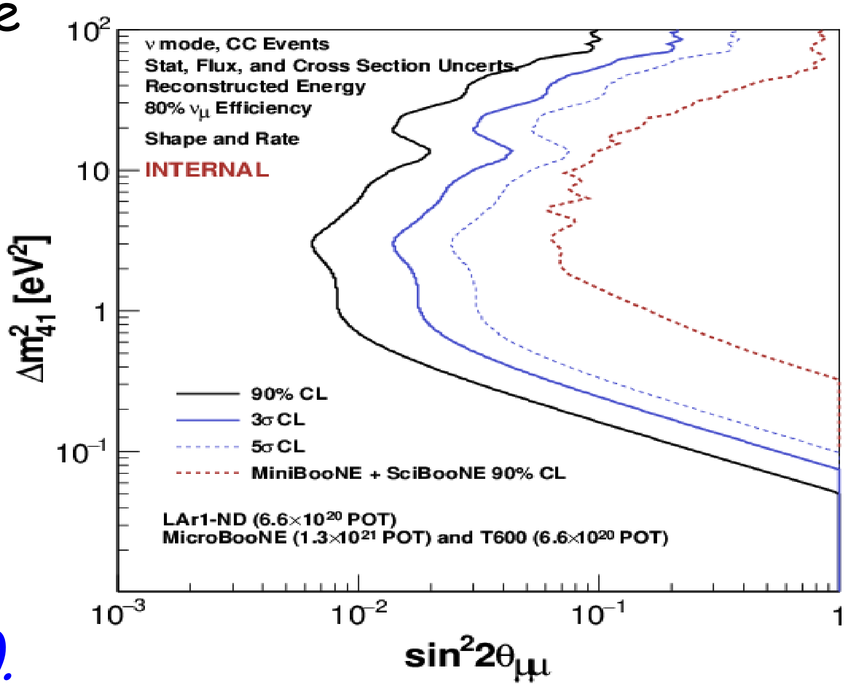


- ν_μ disappearance connected to ν_e appearance via the relation:

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

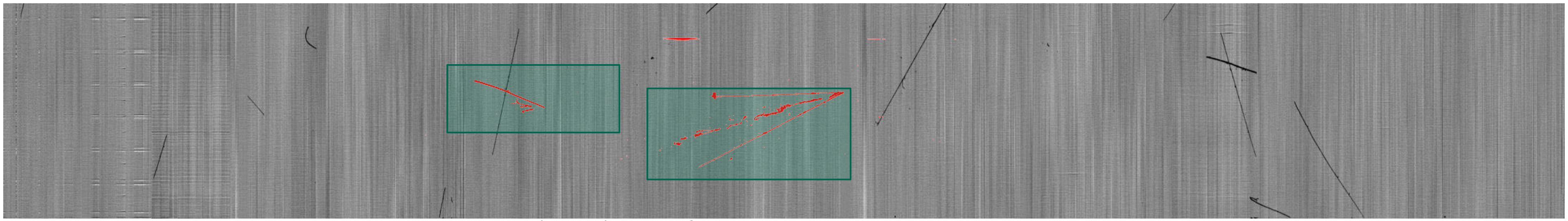
- However for $\Delta m^2 < 0.5$ eV^2, disappearance at 600 m will be limited at lowest ν energy bins 0.2-0.4 GeV.

In order to amplify the effect, we may move at a later stage one ICARUS T300 module to 1500 m distance (to be decided).

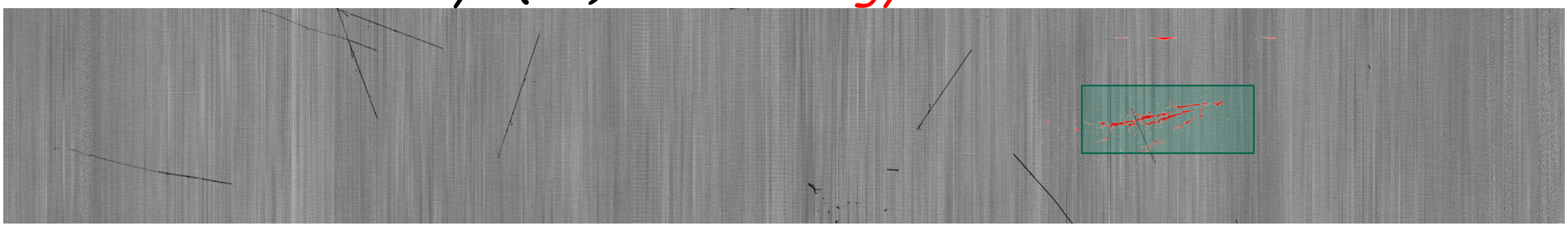


A new challenge: backgrounds at shallow depths

- 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.



Cosmic rays (PV) + low energy CNGS beam events



- This is a new scenario w.r.t. LNGS, where each trigger contained only one event (were it neutrino interaction or background).
- To reconstruct the true 3D position of each object, it is necessary to associate precisely the timing of the related track in the TPC image, w.r.t. the trigger time.

Background mitigation strategies

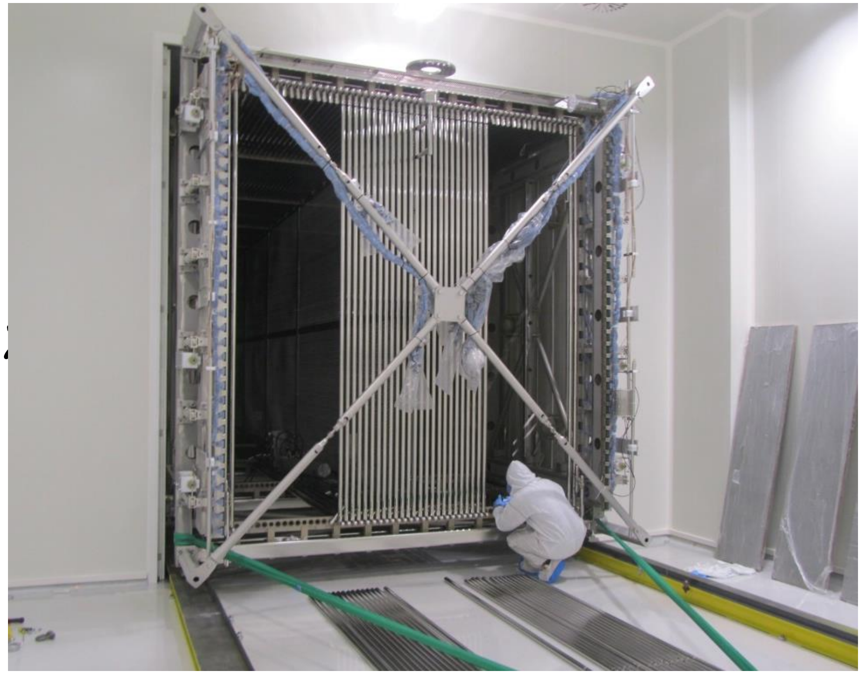
A potentially serious background source is due to photons, associated to cosmic μ's, producing electrons via Compton effect or pair production: this can mimic ν_eCC interactions (appearance signal).

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. Almost full geometrical coverage (95%) is being suggested.
- ~ 1 ns timing accuracy in light detection for the internal PMT system: this will enable exploiting 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.

At CERN: the WA104 program



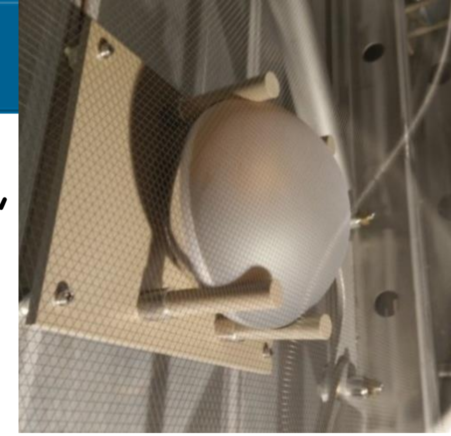
The T600 was moved to CERN in Dec. 2014 and is being upgraded, by introducing technology developments while maintaining the already achieved performance(WA104 program):

- new cold vessels and purely passive insulation;
- refurbishing of the cryogenic and purification equipment;
- existing cathode panels flattened, to provide 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 all the three SBN detectors, and they are being jointly developed by the three collaborations.

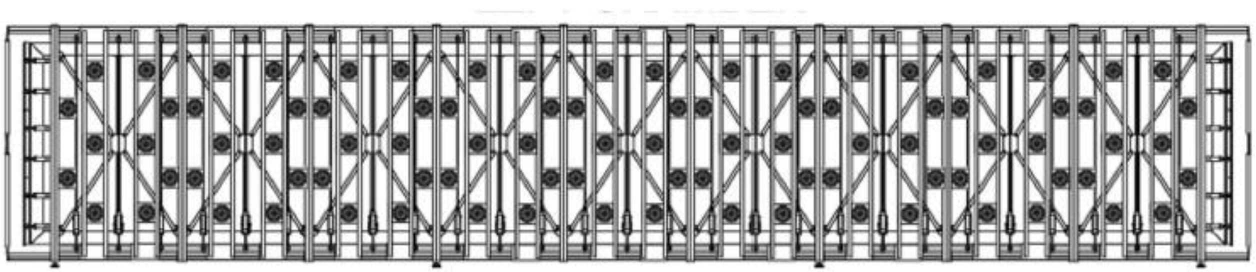
The WA104 program is regulated by a Memorandum of Understanding between CERN and INFN.

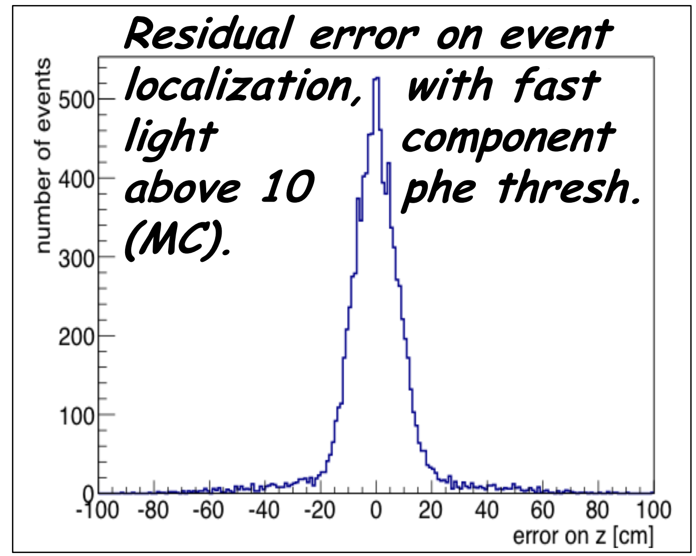
Upgraded Light Collection System



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%. For instance, a layout with 90 PMTs per TPC, compatible with present mechanical structure, allows obtaining longitudinal resolution < 0.5 m
  (MC simulation with 5% effective QE).



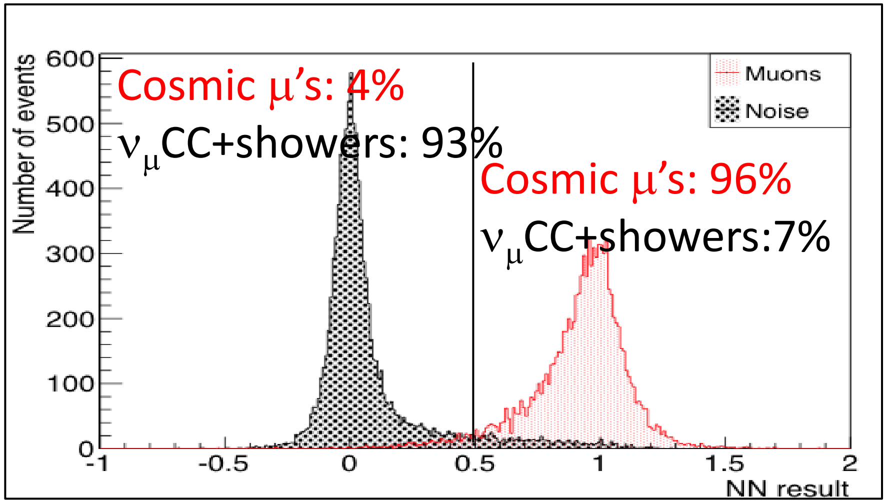


- new voltage divider and shielding, to avoid induced spurious signals on TPC wire planes;
- better performance readout electronics, with ~ ns resolution, to exploit the FNAL bunched beam structure.

Upgraded Light Collection System - II

A Monte Carlo simulation has been developed, with two main goals:

- derive spatial localization capability with the chosen model/disposition in the detector, as shown in the previous slide;
- learn how to identify tracks and e.m. showers, starting with light signals, with a neural network approach.



The PMTs chosen for the overhauled detector are Hamamatsu R5912 – 10 dynodes. Once they are shipped at CERN, they will be:

- tested at room temperature, to characterise them;
- tested at LAr temperature (only selected samples) to verify their operation in real experimental conditions
- evaporated with Tetra-Phenyl Butadiene (TPB), in order to be able to collect Liquid Argon scintillation light, produced in the Vacuum Ultra-Violet at λ = 128 nm.

At the same time PEEK/Stainless Steel supports are being produced at CERN, to hold the PMTs on the TPC mechanical structure.

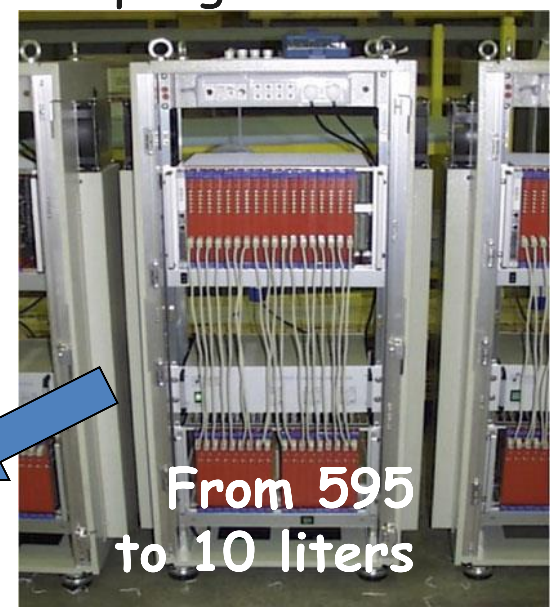
Updated electronic chain

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.

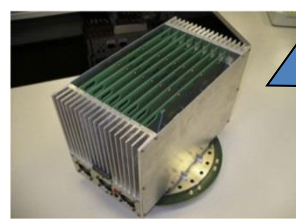
Some limitations: asynchronous sampling of channels within 400 ns sampling time, which slightly affects Multiple Scattering measurement, and data throughput mainly due to the choice of VME standard (8-10 MB/s).

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

- adoption of high frequency serial ADCs with synchronous sampling;
- housing and integration of electronics onto detector;
- 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 and the whole chain housed on a flange-mounted crate.



A solution with cold front-ends (by BNL) was also tested at CERN but will not be employed during the SBN program.



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 ν_μ beam, to test the so-called "LSND effect", to no positive outcome.
- To confirm/exclude the sterile neutrino hypothesis, the ICARUS detector will take part in the dedicated FNAL Short Baseline Neutrino program, consisting of three LAr-TPC detectors (T600, MicroBooNE, SBND) aiming at the search for non-standard oscillations.
- Such experiment will allow fully covering the parameter space for the $\nu_\mu \rightarrow \nu_e$ appearance and ν_μ disappearance channels.
- During the SBN program, the T600 will also collect ν_eCC events with the NUMI Off-Axis beam peaked at ~ 2 GeV, to provide initial data for the future Long Baseline DUNE experiment.
- The T600 detector is now undergoing a major technological overhaul at CERN and is expected to be deployed at FNAL by the end of 2016 for installation, commissioning and start of data taking with ν beam by the end of 2017.


Thank you !

Back Up

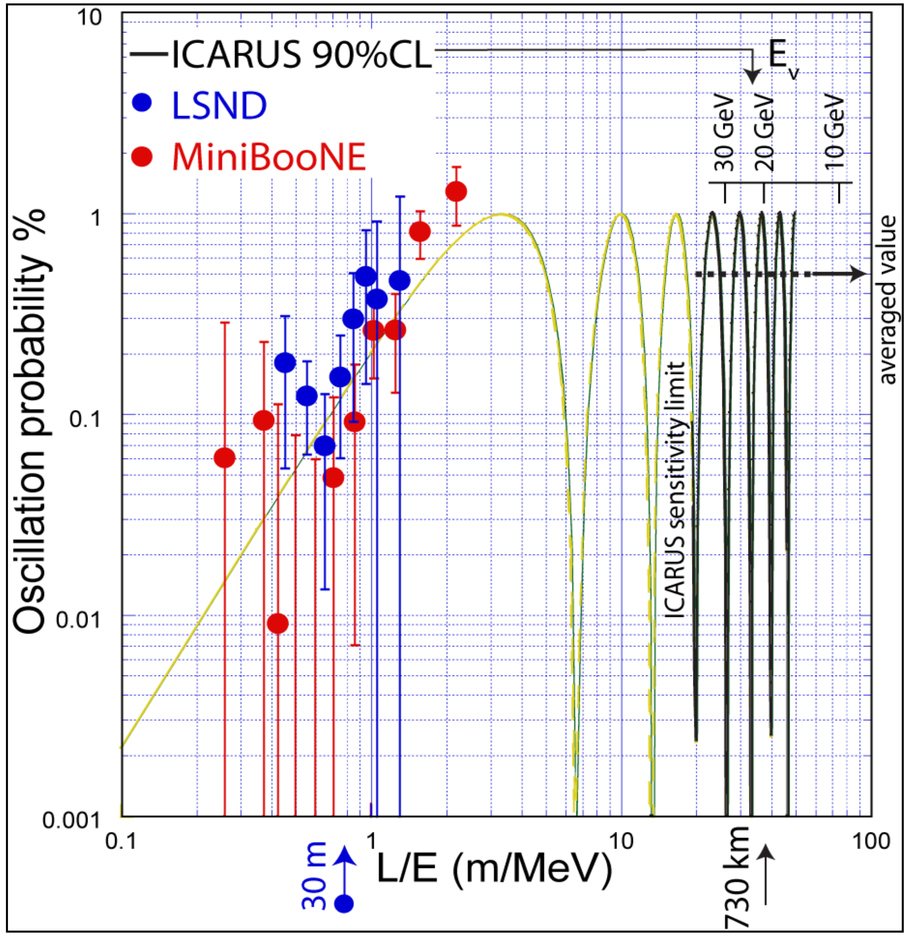
Search for a LSND-like effect with the CNGS beam

The ICARUS Collaboration has searched for a ν_e excess signal during the LNGS run: the CNGS facility delivered an almost pure ν_μ beam, with E_ν in (10 ÷ 30) GeV range and 1% intrinsic ν_e contamination.
CERN to Gran Sasso distance: L=732 km.

- Main difference w.r.t. LSND: L/E_ν range (≈ 1 m/MeV at LSND; ≈ 36.5 at CNGS)

-> LSND short distance signal averages here to $\sin^2(1.27\Delta m^2_{new}\, L/E_\nu) \sim 1/2$ and $\langle P \rangle_{\mu\to e} \sim 1/2 \sin^2(2\theta_{new})$

- Moreover, in ICARUS L/E_ν region, contributions from standard oscillations [mostly $\sin(\theta_{13})$] are not yet too relevant.

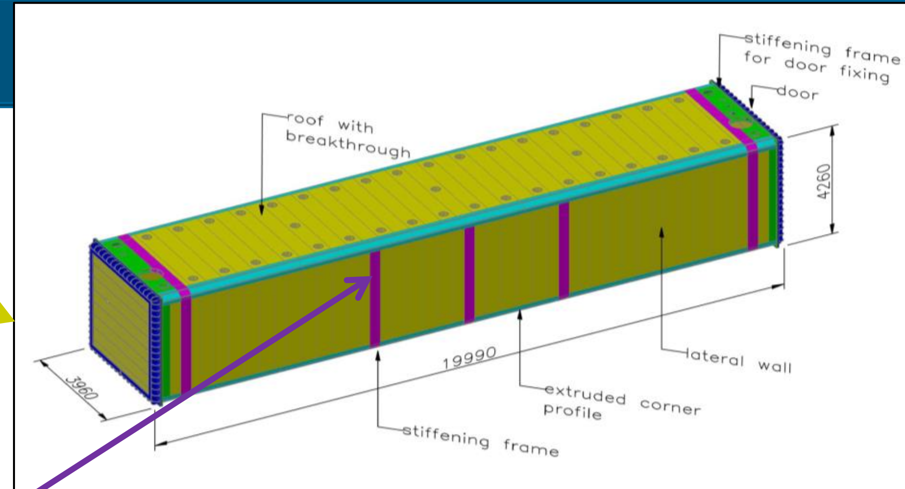


- Unambiguous identification of e-events, with high efficiency, made possible by unique detection properties of LAr-TPC technique.

From LNGS to FNAL… via CERN

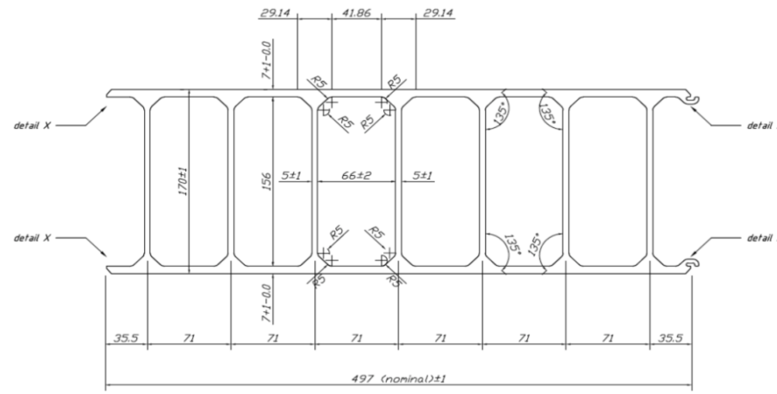
- *LAr-TPCs are the leading technology for future short/long baseline accelerator-driven neutrino physics*, as fully demonstrated by the successful run of the ICARUS-CNGS2 experiment.
- On its way to FNAL, the ICARUS Collaboration has started the **WA104 project at CERN**, regulated by a Memorandum of Understanding between INFN and CERN, aimed at a major overhaul of the detector modules, prior to deployment in the SBN program.
- ICARUS Italian members (and INFN) also got involved in the US Long Baseline program, taking part in the recent DUNE/LBNF project: during SBN operations ICARUS will collect also ν_eCC events with the NUMI Off-Axis beam peaked at ~ 2 GeV.
- These activities represent as well an opportunity to further develop the LAr-TPC technique in view of the ultimate realization of the LBNF detector, with:
  - accurate determination of cross sections in liquid Argon;
  - experimental study of all individual CC and NC channels;
  - realization of sophisticated algorithms to improve the automatic identification of neutrino interactions.

New Cold Vessels

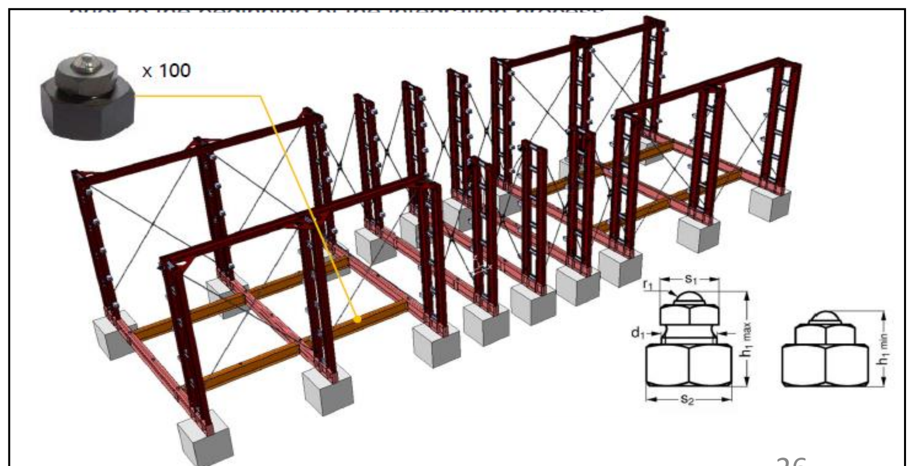


New LAr containers (cold vessels) made by extruded aluminum profiles welded together, to form a vacuum-tight double-walled container.

Production of the extruded has started. Welding of the stiffening frames (violet, holding LAr weight) will be done at CERN.

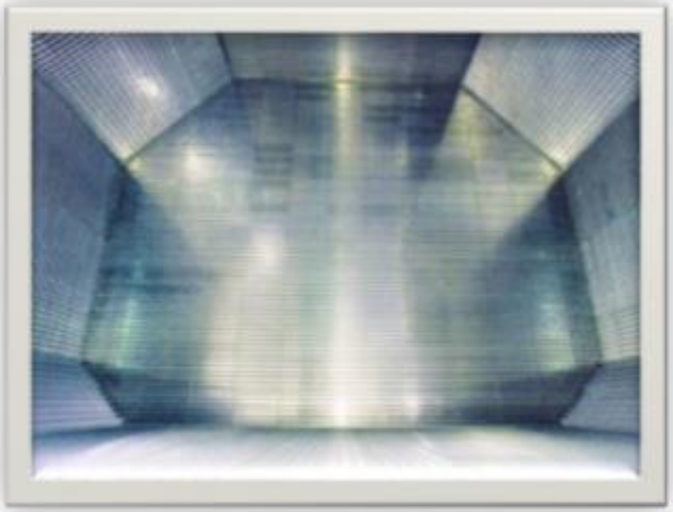


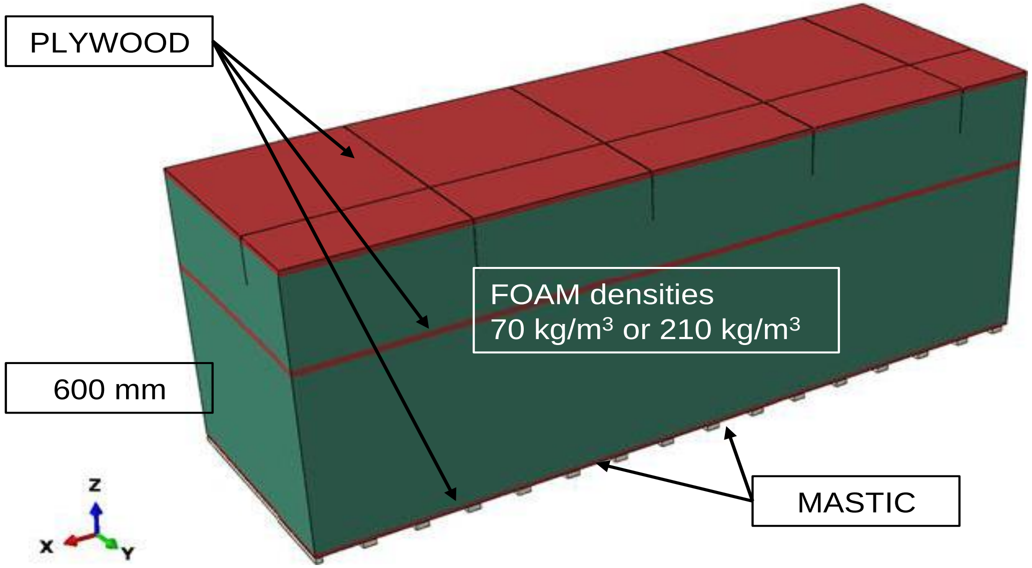
Pre-assembly of panels will be done by the company producing the extruded, while final assembly will be done at CERN, in building 185. Studies are on-going for the assembly structure.



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

New thermal insulation

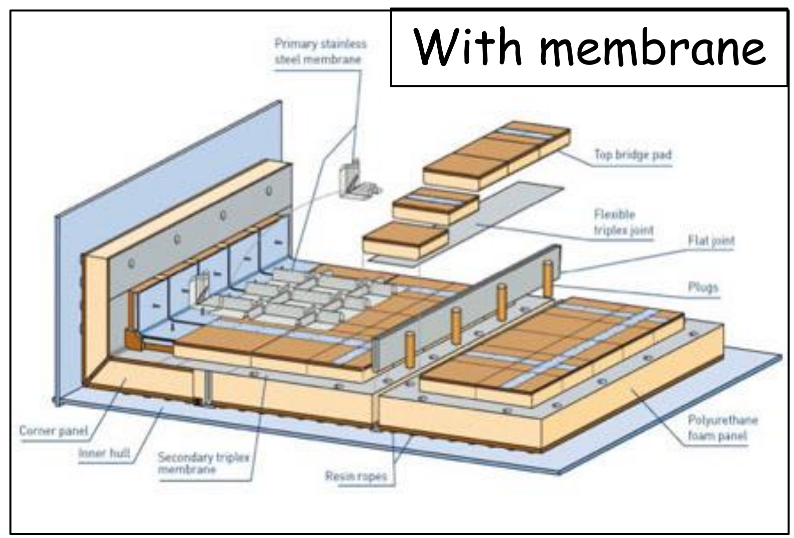




Purely passive insulation chosen for the installation, coupled to a renovated, standard cooling shield with two-phase Nitrogen;

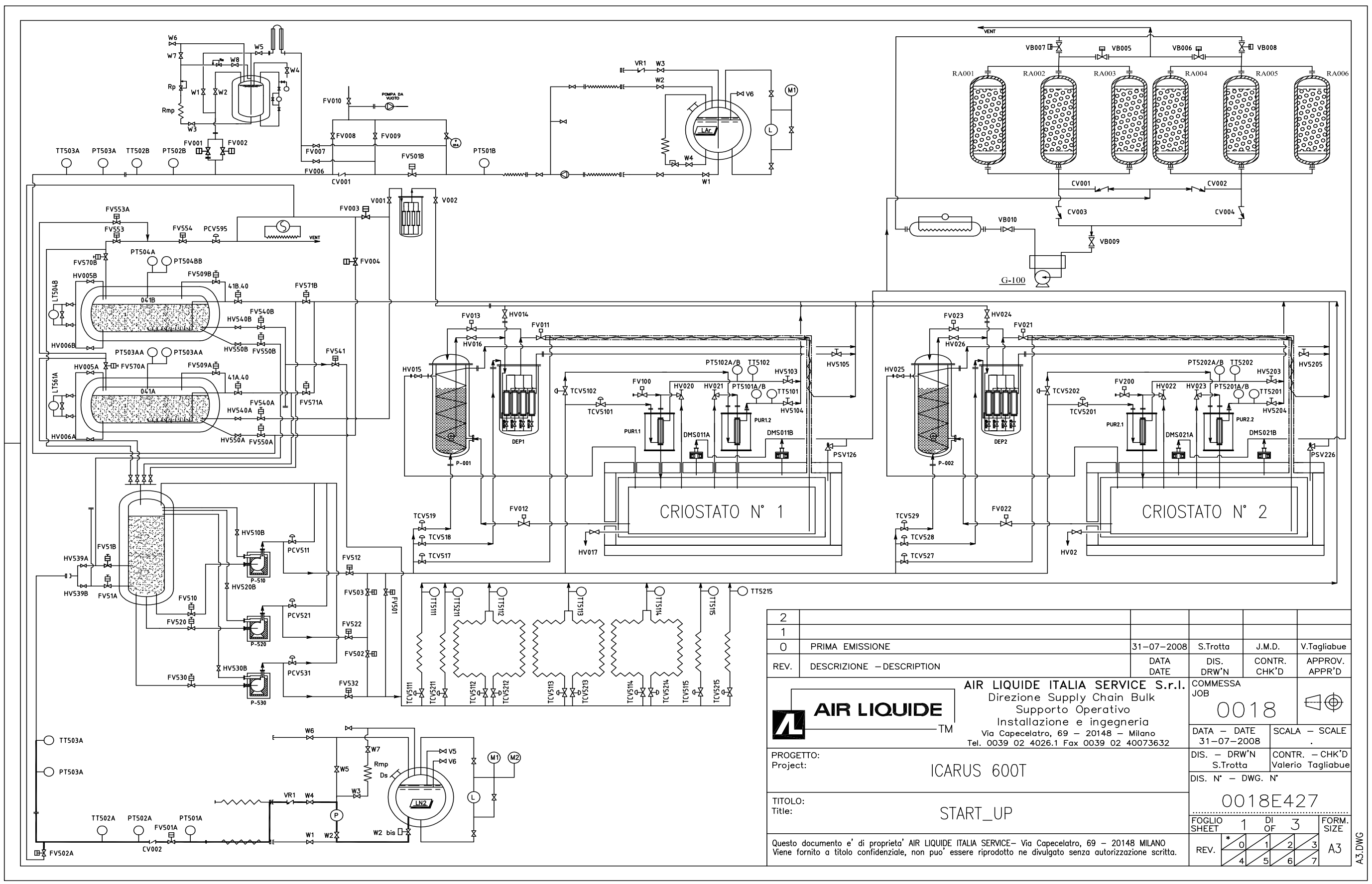
Technique developed for 50 years with membrane and widely used for large industrial storage vessels and ships for liquefied natural gas. Expected heat loss through the insulation: ≈ 6.6 kW (10-15 W/m^2)

No internal membrane is required



New cryogenic plant

- The original layout of the T600 cryogenic/purification plant is being revised: it will be re-organized into self-consistent sub-units (skids) to be built and fully tested here, prior to delivery to FNAL. Re-usable components from the old installation are being selected.
- Once a preliminary layout is defined, detailed drawings and 3D models will be prepared.



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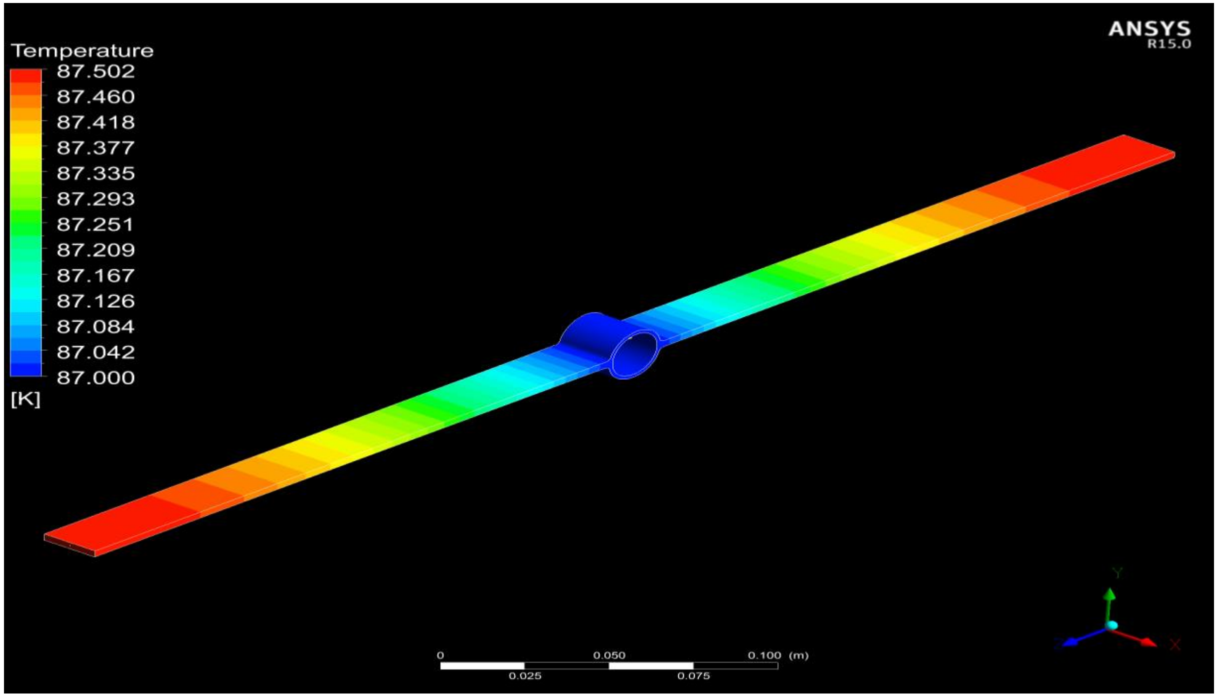
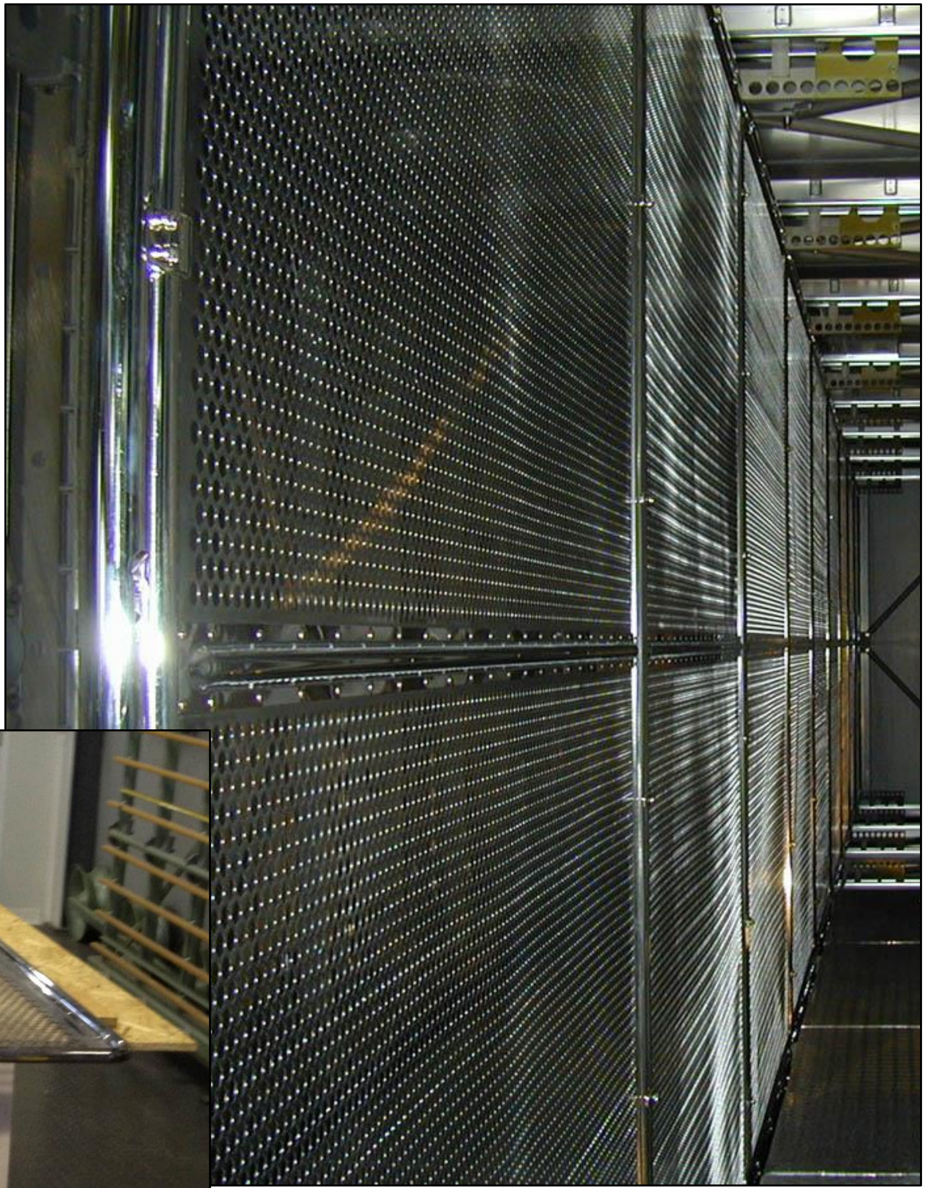
- Once a preliminary layout is defined, detailed drawings and 3D models will be prepared.
- At the same time, a new two-phase Nitrogen cooling shield, made of thin Al panels, is being developed. A sample of shield was built at CERN and is now under testing, to verify the computing model.



Cathode

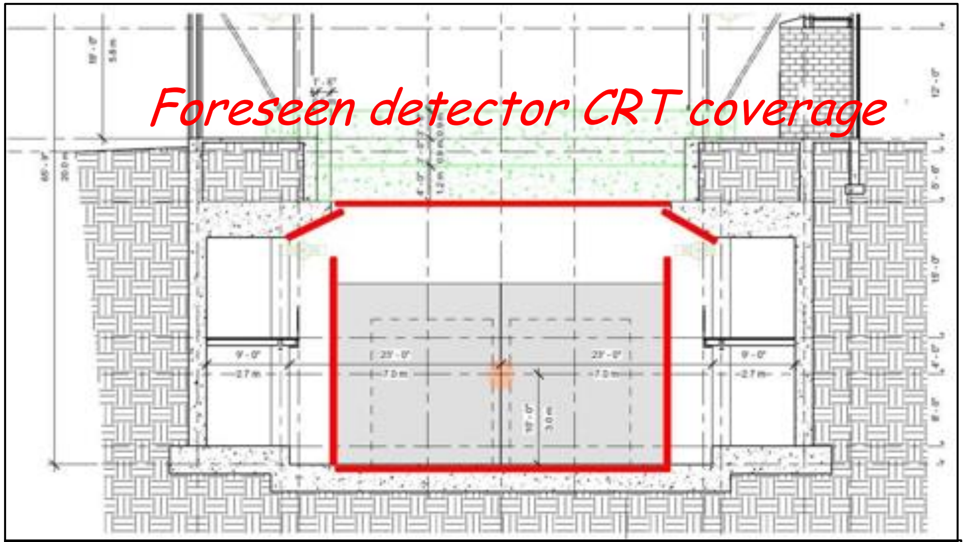
- The old cathode panels were dismounted, but they will be re-installed, once flattened (thermally) with the help of CERN main workshop.
- Original deformations were reduced, on the first panel, from around 2.5 cm to few mm.

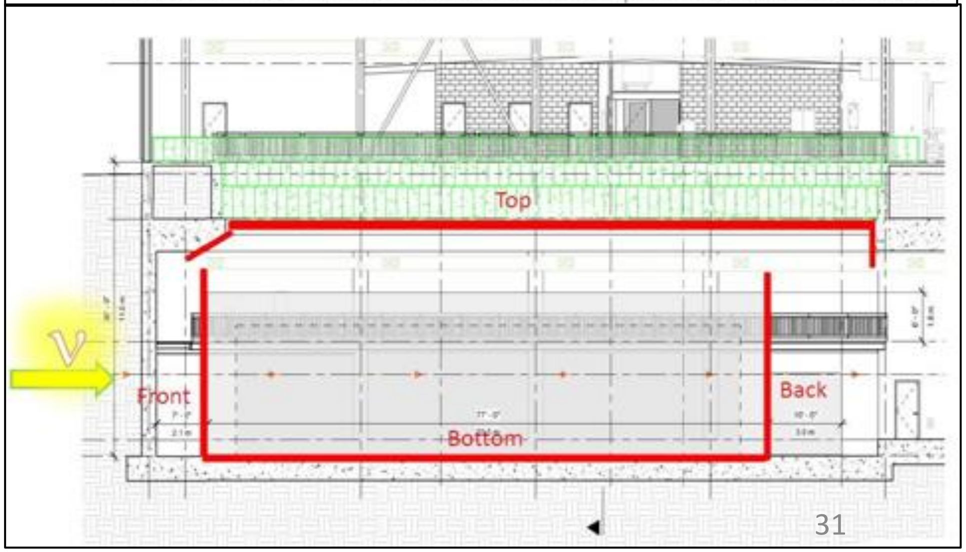


Cosmic Ray Tagger

Design and development of the CRT is under way, as a common tool to be applied to the three SBN detectors (T600, SBND, MicroBooNE).

The present solution involves plastic scintillators, with embedded optical fibres read by SiPMs.





The amount of coverage results from the balance between the need to efficiently tag external CR muons and not veto internal νCC events with outgoing muons.

Presently 95% coverage is foreseen; US groups and CERN are working on material testing and electronics development