

ICARUS

Andrea Zani - CERN

On behalf of

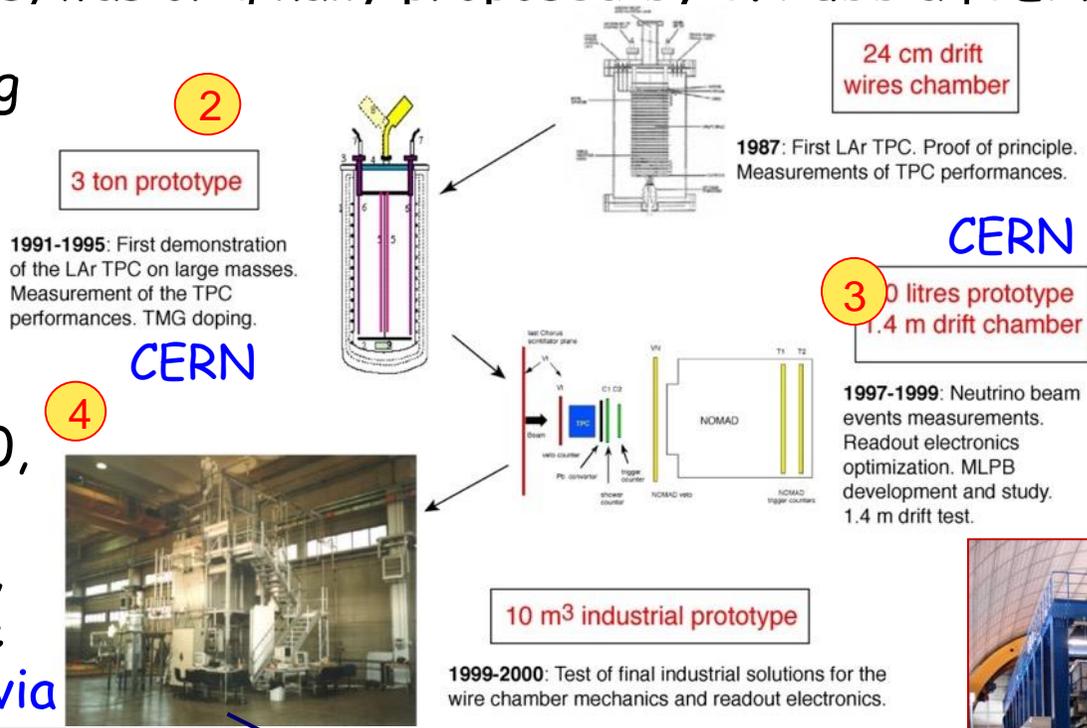
ICARUS/WA104 Collaboration

Workshop on Neutrino Telescopes - Venezia March 13-17, 2017

A premise: the ICARUS LAr-TPC development

- Cherenkov radiation detection has been for years one of the key choices for exploring neutrinos with k-ton water/ice detectors.
- As an alternative, the Liquid Argon Imaging technology LAr-TPC, an "electronic bubble chamber" which permits to identify unambiguously each ionizing track in complex ν events, was originally proposed by C. Rubbia [CERN-EP/77-08].

- With the continuing effort of ICARUS Collab. and INFN support, LAr-TPC technology has been taken to full maturity with T600, the largest LAr-TPC ever operated, ~500 t of sensitive mass.



CERN
CERN
Pavia

ICARUS-T600 experiment 2010-13

Cooperation with industry:
AirLiquide, Breme, Cinel, CAEN

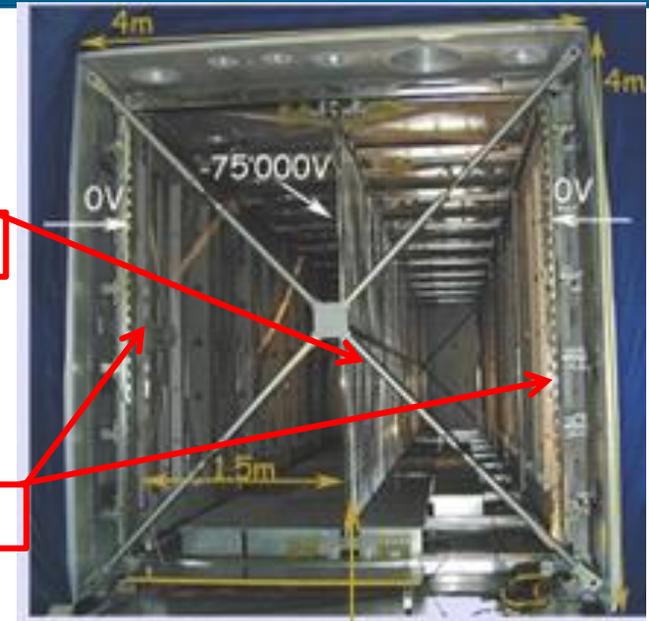
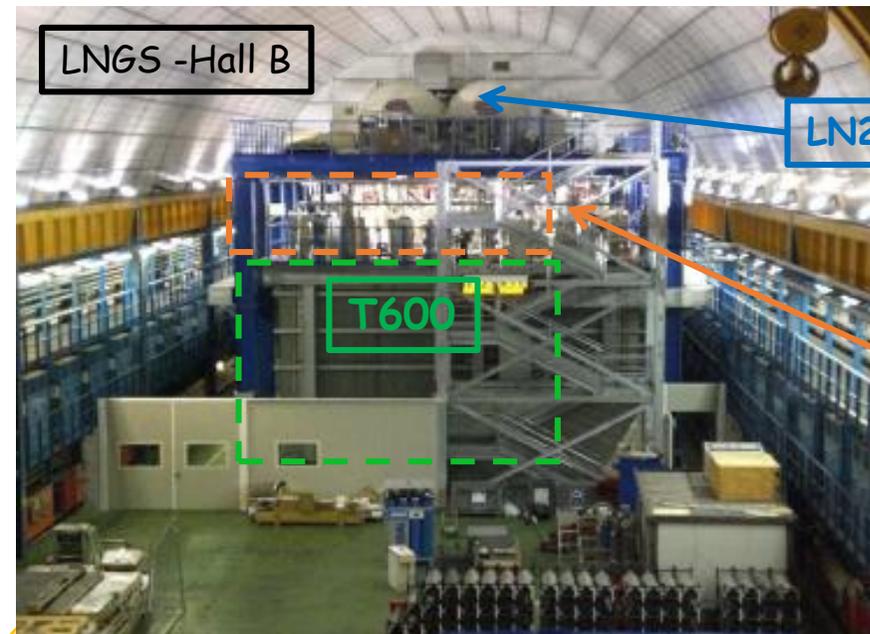


The path to larger LAr detectors

ICARUS: a summary

- T600 detector concluded in 2013 a successful three year long run at LNGS taking data both with CNGS ν beam and cosmic rays. Several relevant physics and technical results have been achieved:
 - ICARUS demonstrated its excellent performance as tracking device and homogeneous calorimeter with a remarkable PID capability, exploiting the measurement of dE/dx vs. range.
 - Reconstruction of ν interaction vertex and measurement of e.m. showers by primary electrons and invariant mass of γ pairs, allowed to reject bkg. in the study of $\nu_{\mu} \rightarrow \nu_e$ in LSND-like transitions, to unprecedented level.
- ICARUS will be exposed at shallow depth to ~ 0.8 GeV FNAL Booster ν beam 600 m from target to perform a highly sensitive search for $\nu_{\mu} \rightarrow \nu_e$ oscillation to test LSND claim in the framework of SBN program.
- ν oscillations are searched for, comparing the measured spectra with the un-oscillated ones at nearest sites SBND (110 m), MicroBooNE (470 m). At shallow depth a large cosmic bkg. will occur during 1 ms LAr-TPC readout, implying new experimental conditions where a cosmic tagger is mandatory.
- In addition ICARUS will detect the ~ 2 GeV NUMI Off-axis ν 's, an asset for LBNF/DUNE project.
- T600 detector is now at CERN for overhauling before being deployed at FNAL.

The ICARUS detector @ LNGS



Two identical modules, 4 wire chambers

- $3.6 \times 3.9 \times 19.6 \text{ m} \approx 275 \text{ m}^3$
- Total active mass $\approx 476 \text{ ton}$
- 2 TPCs per module, with common central cathode $\rightarrow 1.5 \text{ m}$ drift length
- $E_{\text{drift}} = 0.5 \text{ kV/cm}$, $v_{\text{drift}} = 1.55 \text{ mm}/\mu\text{s}$ (sub-mm resolution in drift direction).

TPC Warm Electronics

- Continuous read-out, digitization, waveform recording, $0.4 \mu\text{s}$ sampling time (sub-mm resolution in drift direction).

Detectors

- 3 "non-destructive" readout wire planes per TPC, wires at $0^\circ, \pm 60^\circ$ (Ind1, Ind2, Coll. View)
- ≈ 54000 wires ($150 \mu\text{m}$ \varnothing , 3 mm pitch)
- $54+20$ photomultipliers ($8'' \varnothing$) + wls (TPB), sensitive at 128 nm (VUV)

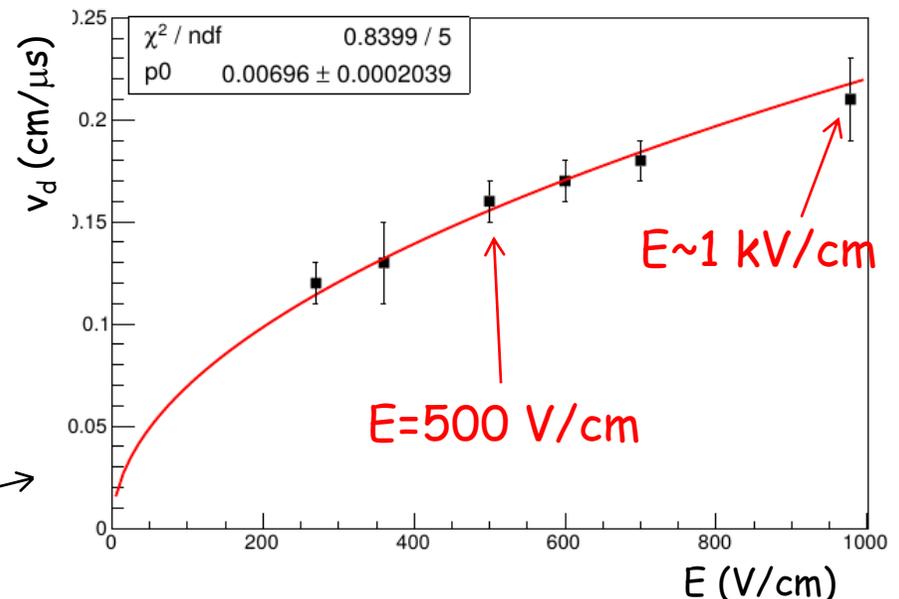
Cryogenics

- Liquid and gas Ar recirculation;
- Passive insulation + dual phase N_2 shield
- High purity $\sim 20 \text{ ppt}$ O_2 equiv. ($\tau_e > 16 \text{ ms}$).

The ICARUS experiment @ LNGS

- Smooth ICARUS operations under **stable running conditions for >3 years, at the nominal $E=500$ V/cm drift field** without any failure, allowed to collect ~ 3000 ν events ($8.6 \cdot 10^{19}$ pot) from the CNGS beam with **remarkable detector live-time > 93 %**, and cosmic events (**0.73 kt year exposure**).
- ICARUS performed a **sensitive search for LSND-like anomaly with CNGS beam** reducing the LSND experimental window to a narrow region at $\Delta m_s^2 \approx 1 \text{ eV}^2$.
- ICARUS contributed also to **solve the superluminal ν claim**:
 - Disproving the claim by the lack of Cherenkov-like radiation by CNGS ν 's and setting the limit: $\delta = (v_\nu^2 - c^2)/c^2 < 2.5 \cdot 10^{-8}$ 90% CL
 - Measuring with ns resolution CERN to LNGS ν t.o.f. excluding ν velocities $> c$ by more than $1.35 \times 10^{-6} c$ at 90% C.L.
- Different operating conditions have been successfully tested in the last months of run, proving that **ICARUS can safely stand up to ~ 1 kV/cm drift field** without any discharges;

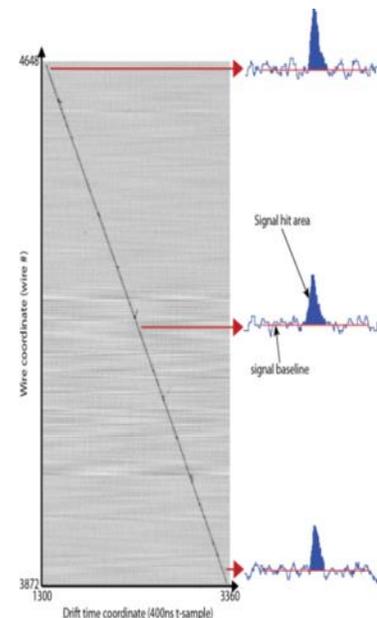
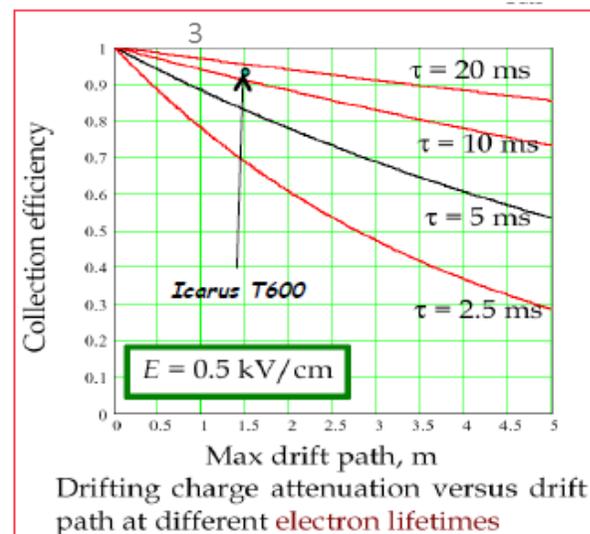
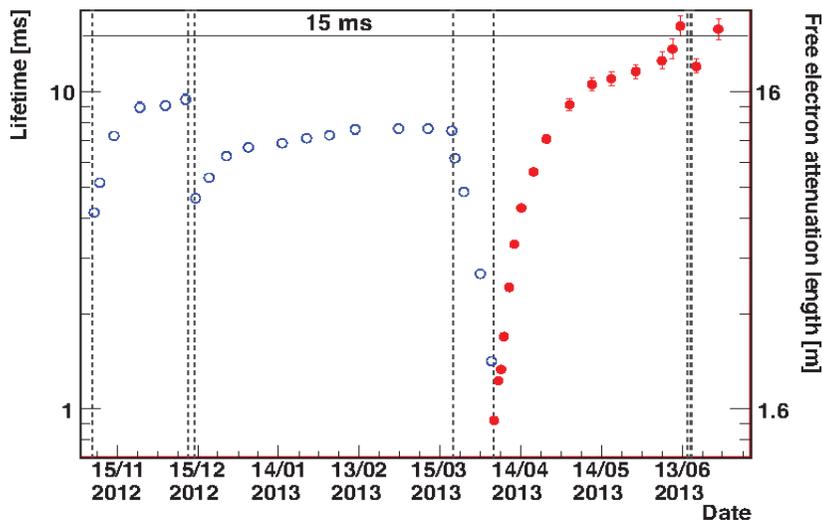
Measured e^- drift velocity
 v_{DRIFT} vs. E_{DRIFT} : $v_{\text{DRIFT}} \propto \sqrt{E}$



A key feature of LAr imaging: very long e^- mobility

- Level of electronegative impurities in LAr must be kept exceptionally low to ensure \sim m long drift path of ionization e^- signal without attenuation;
- New industrial/lab purification methods have been developed to continuously filter and re-circulate both liquid ($100 \text{ m}^3 / \text{day}$) and gas ($2.5 \text{ m}^3 / \text{hour}$) phases;
- e^- lifetime $>7 \text{ ms}$ ($<40 \text{ p.p.t [O}_2\text{] eq. impurities}$) measured with cosmic μ 's : **12% max. charge attenuation on 1.5 m drift.**

With a new not-immersed pump on East cryostat: $\tau_{e^-} > 15 \text{ ms}$!



ICARUS demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors with longer drift distances as required for LBNF/DUNE project.

ICARUS LAr-TPC performance

- Excellent detection properties:
 - **Tracking device:** precise 3D event topology with $\sim 1 \text{ mm}^3$ resolution for any ionizing particle;
 - **Global calorimeter:** full sampling homogeneous calorimeter; total energy reconstructed by charge integration with excellent accuracy for contained events;
 - **Measurement of local energy deposition dE/dx :** remarkable e/γ separation ($0.02 X_0$ sampling, $X_0=14 \text{ cm}$, particle id. by dE/dx vs range); dE/dx used to cross-check purity measurement.

Low energy electrons:

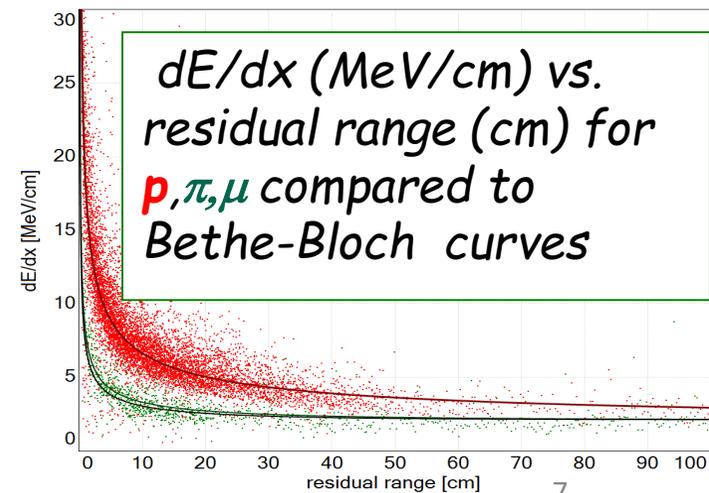
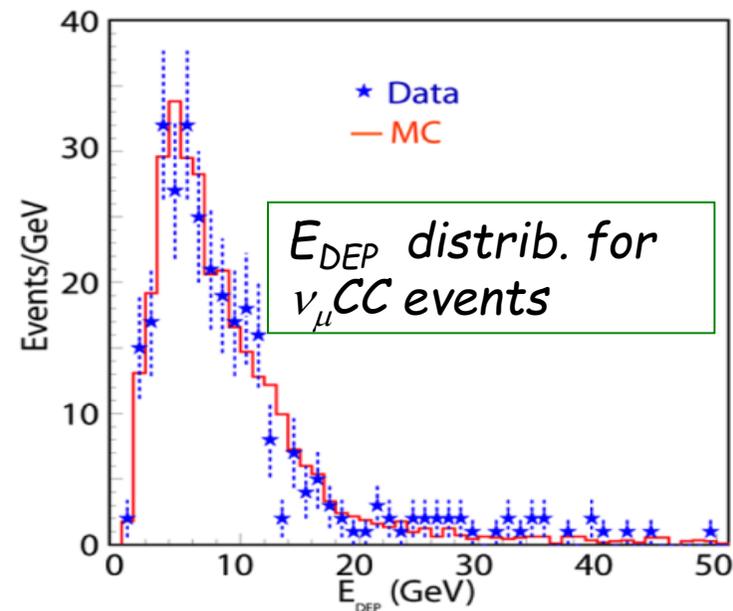
$$\sigma(E)/E = 11\%/\sqrt{E(\text{MeV})} + 2\%$$

Electromagnetic showers:

$$\sigma(E)/E = 3\%/\sqrt{E(\text{GeV})}$$

Hadron showers:

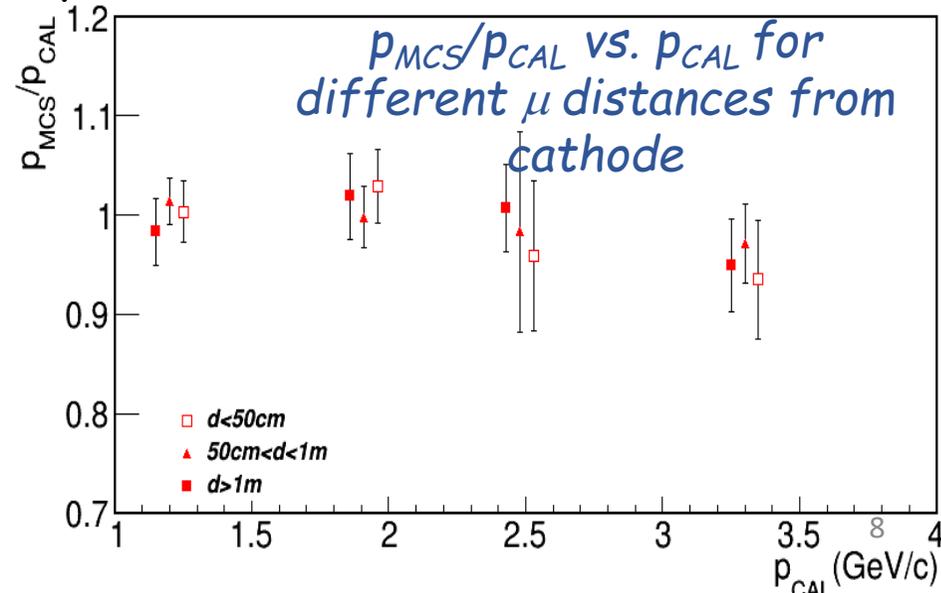
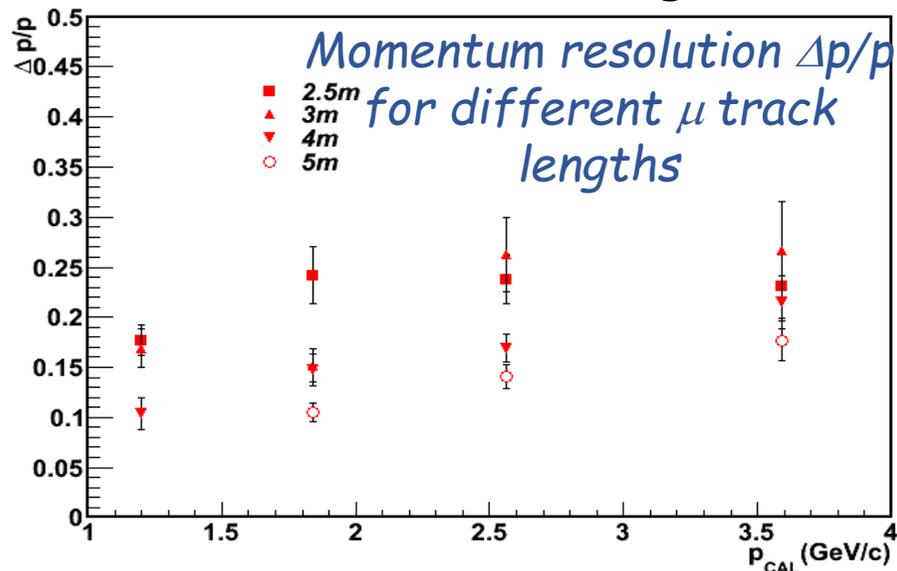
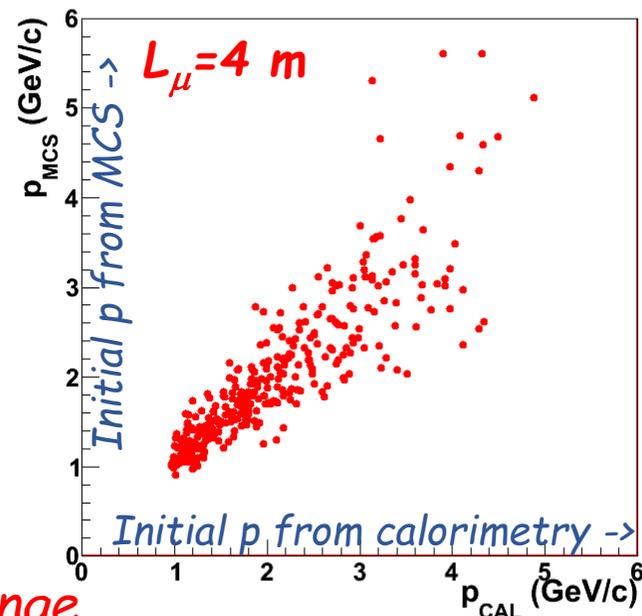
$$\sigma(E)/E \approx 30\%/\sqrt{E(\text{GeV})}$$



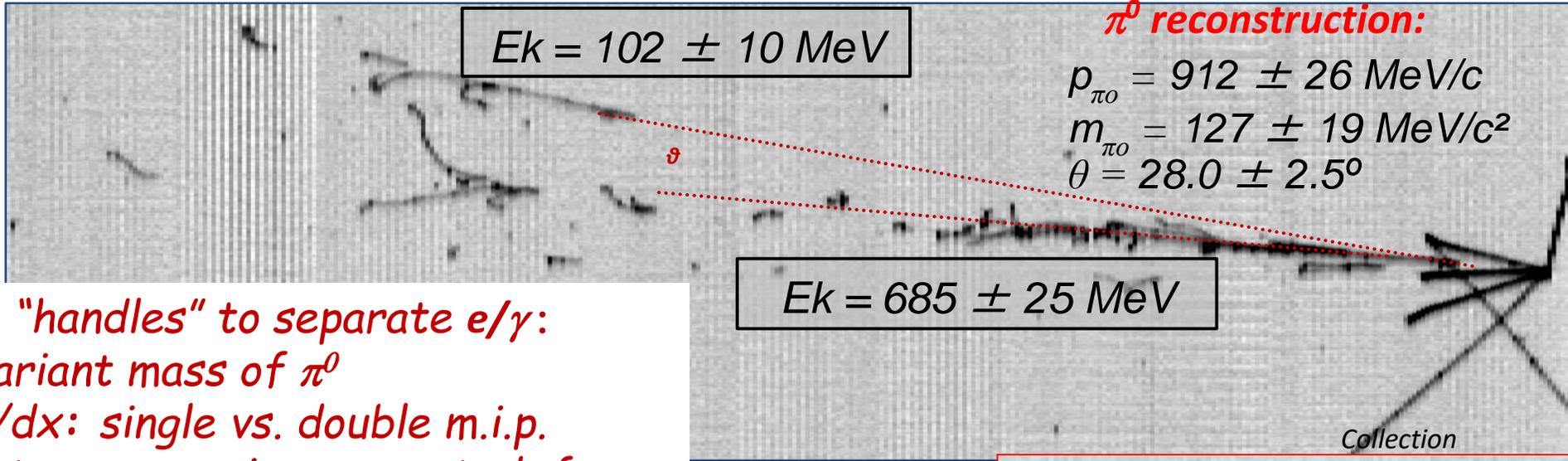
Measurement of muon momentum via multiple scattering (p_{MCS})

Measurement of μ momentum by multiple Coulomb scattering has been studied, comparing p_{MCS} with the corresponding calorimetric measurement p_{CAL} for stopping μ 's produced in CNGS ν_{μ} CC interactions in upstream rock and stopping/decaying inside T600:

- p_{MCS} in agreement with p_{CAL} within $\sim 5\%$, where electric drift field non-uniformities due to the not perfect cathode planarity $\Delta x \sim \pm 15$ mm, have been accounted for (measured at CERN);
- momentum resolution $\Delta p/p \sim 15\%$ in 0.4-4 GeV/c range of interest for short/long base-line experiments; [arXiv.1612.07715](https://arxiv.org/abs/1612.07715)



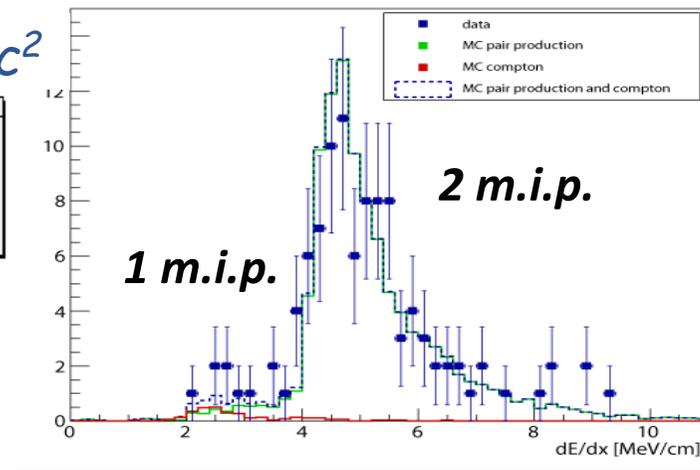
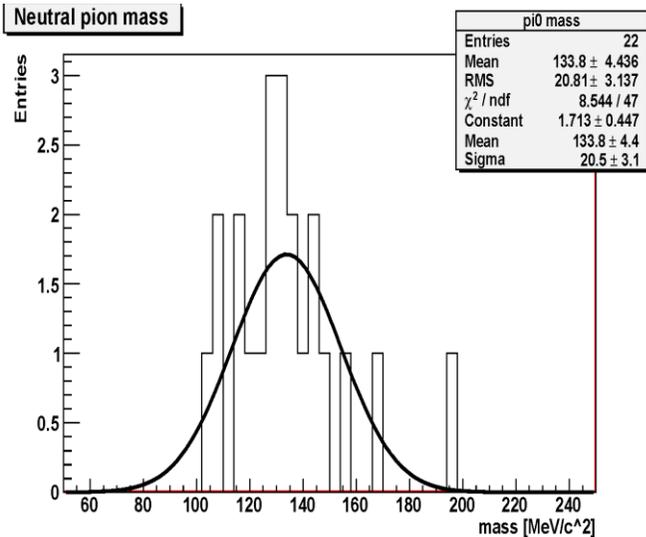
Unique feature of ICARUS: e/γ separation, π^0 reconstruction



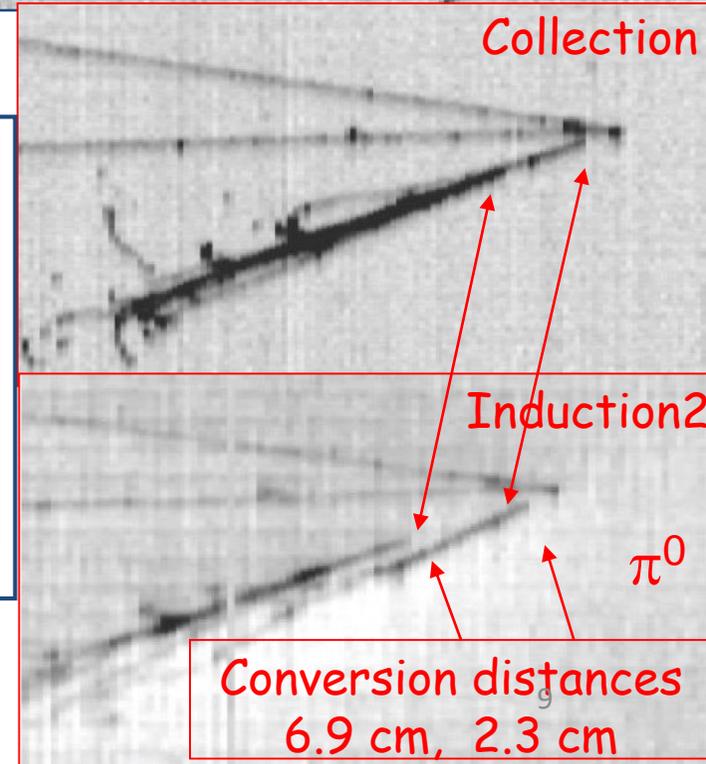
Three "handles" to separate e/γ :

- invariant mass of π^0
- dE/dx : single vs. double m.i.p.
- photon conversion separated from primary vertex

$M_{\gamma\gamma}: 133.8 \pm 4.4 \pm 4 \text{ MeV}/c^2$

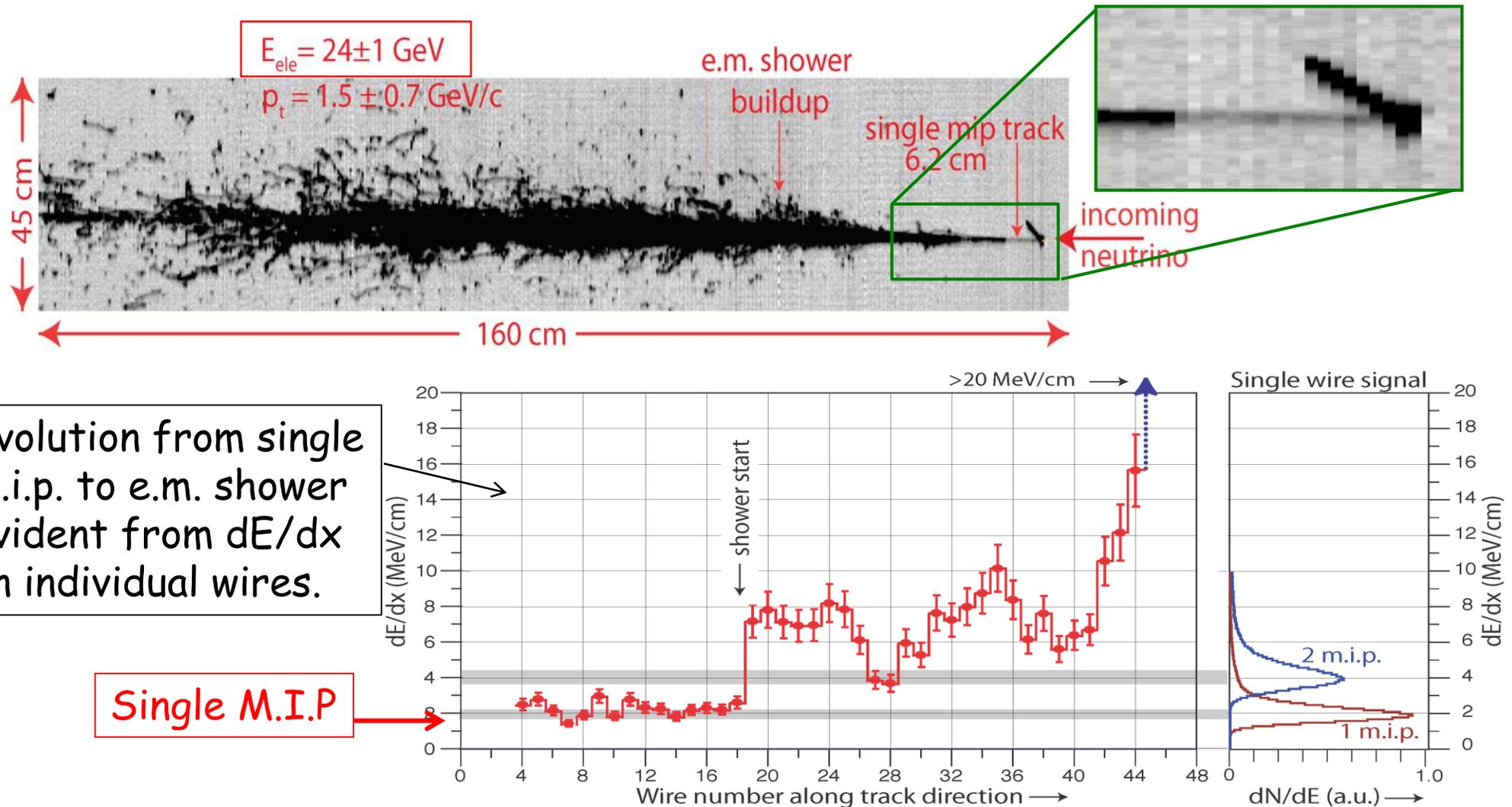


Crucial for NC rejection in ν_e -physics



ν_e CC identification in CNGS beam

- The unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.

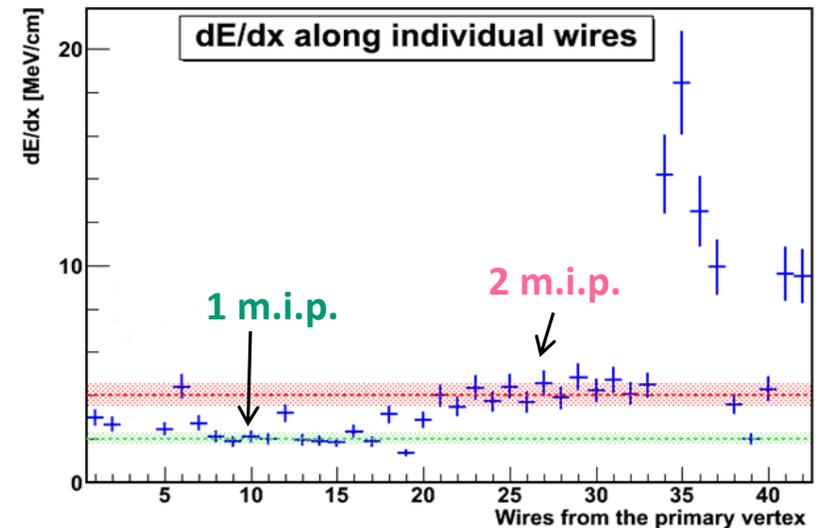
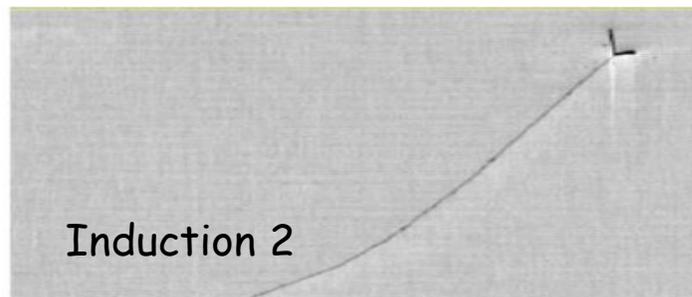
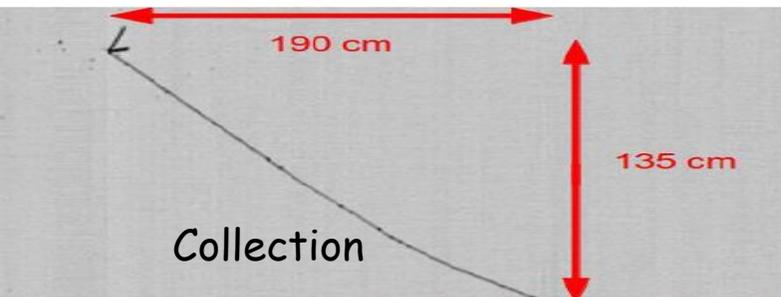
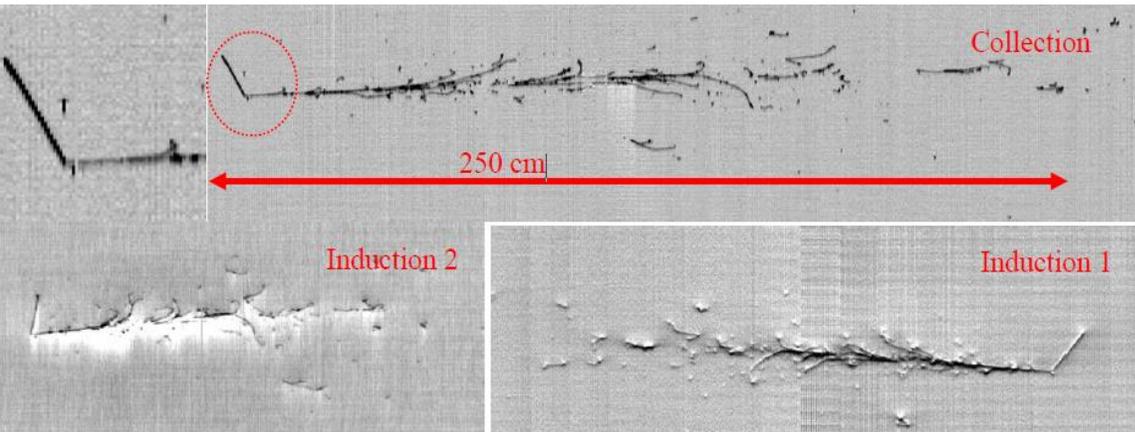


Atmospheric ν studies

- Search for atmospheric ν events in LNGS data (0.73 kt- year exposure) is being carried on with an automatic filter to reject incoming charged cosmics and provide neutral interaction candidates to be visually studied.
- A significant **test bench for the development of the search algorithms** needed at FNAL as **atmospheric events cover the energy range** of the SBN program.

QE ν_e atm. candidate, $E_{dep} \sim 2.1$ GeV

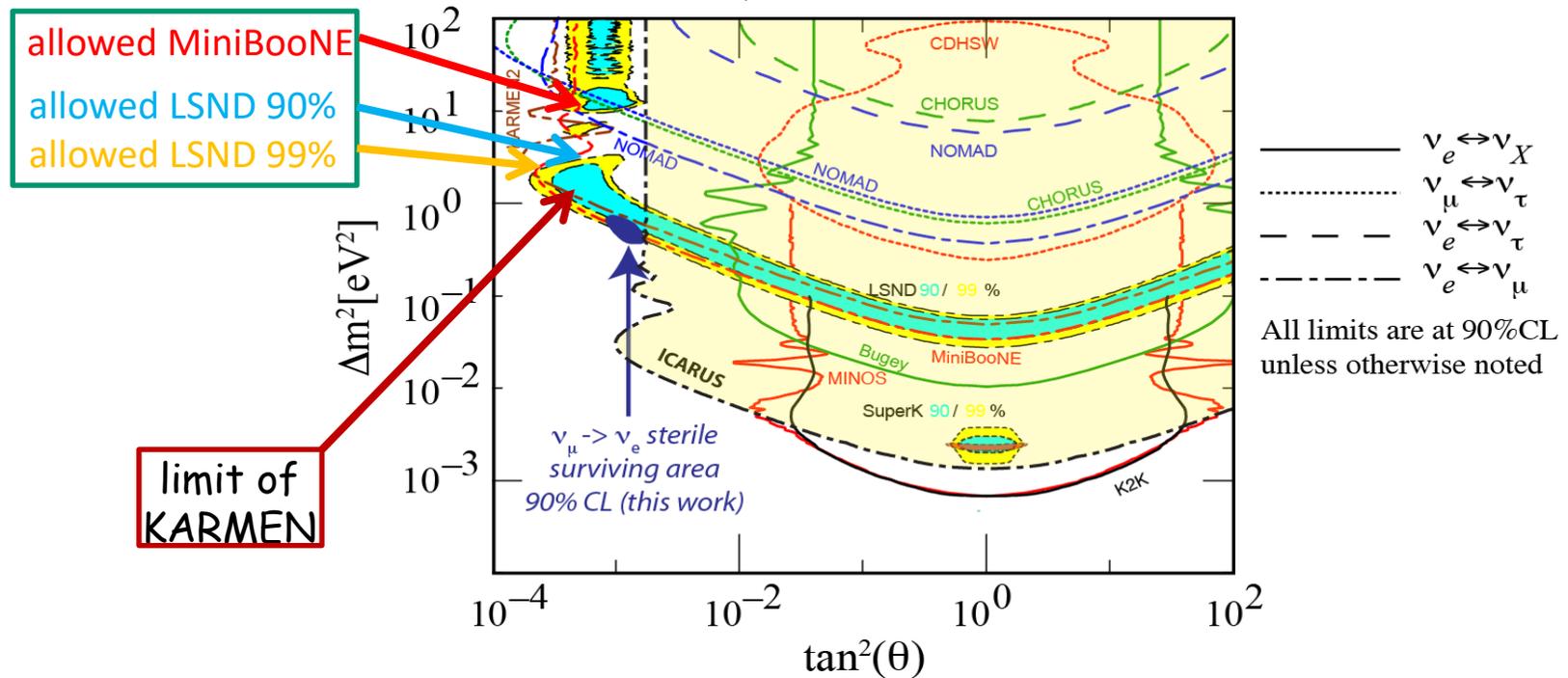
- Electron identified by single m.i.p.
- Proton with $E \sim 115$ MeV



ν_μ CC atm. candidate:
 $E_{dep} \sim 630$ MeV
 → 2.3 m μ track +
 2 charged tracks

LSND-like search by the ICARUS experiment at LNGS

- **ICARUS searched for ν_e excess** related to a LSND-like anomaly, on the ν_μ CNGS beam ($\sim 1\%$ intrinsic ν_e contamination, $L/E_\nu \sim 36.5$ m/MeV).
- Globally **7 e -like events were observed** in the full 7.93×10^{19} pot event statistics, consistently with the 8.5 ± 1.1 expected from intrinsic beam component + standard oscillations providing the limit:
 $P(\nu_\mu \rightarrow \nu_e) \leq 3.86 \times 10^{-3}$ at 90 % CL and $P(\nu_\mu \rightarrow \nu_e) \leq 7.76 \times 10^{-3}$ at 99 % CL

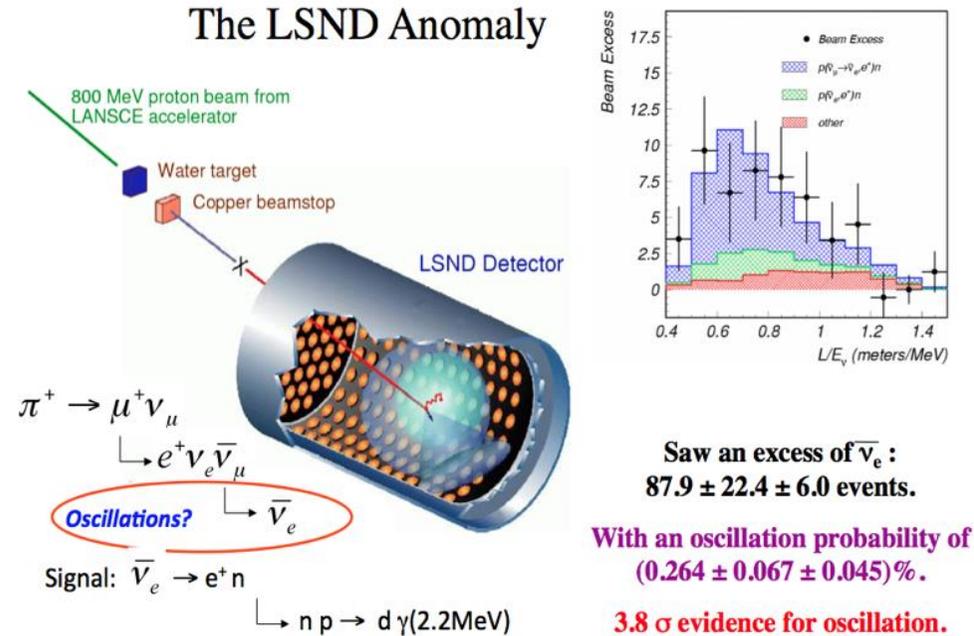


ICARUS, and OPERA, results constrain the allowed parameters to a narrow region around $\Delta m^2 \sim 0.5$ eV², $\sin^2 2\theta \sim 0.005$ where all the experimental results can be coherently accommodated at 90% C.L, calling for a definitive experiment

Persisting anomalies in the neutrino sector

- Neutrino oscillations established a coherent picture with the mixing of physical ν_e, ν_μ, ν_τ with small mass difference. However three main classes of anomalies have been reported, namely the observation of:

- **Electron- $\bar{\nu}$ excess signals** from muon- $\bar{\nu}$ at accelerators by LSND (3.8 σ) + MiniBooNE
- **Disappearance of anti- ν_e** by near-by nuclear reactor experiments (event rate $R = 0.938 \pm 0.023$).
- **Disappearance of ν_e** hinted by solar ν experiments in the calibration with Mega-Curie ν sources ($R = 0.86 \pm 0.05$).



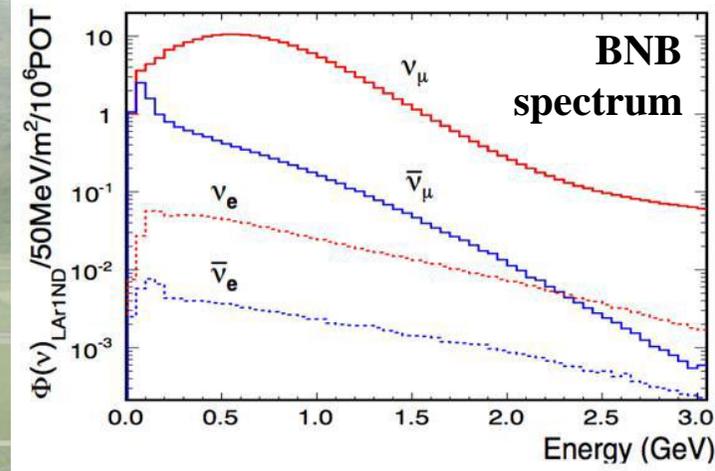
- These three independent signals may all point out to the **possible existence of at least a fourth non standard and heavier "sterile" neutrino state driving oscillations at small distances**, with Δm_{new}^2 of the order of $\approx 1 \text{ eV}^2$ and relatively small $\sin^2(2\theta_{new})$ mixing angles.
- Reported anomalies prompted very intense experimental activities with radioactive sources, reactors and accelerators to definitively clarify the situation both in appearance and disappearance modes.

Clarifying the neutrino anomalies

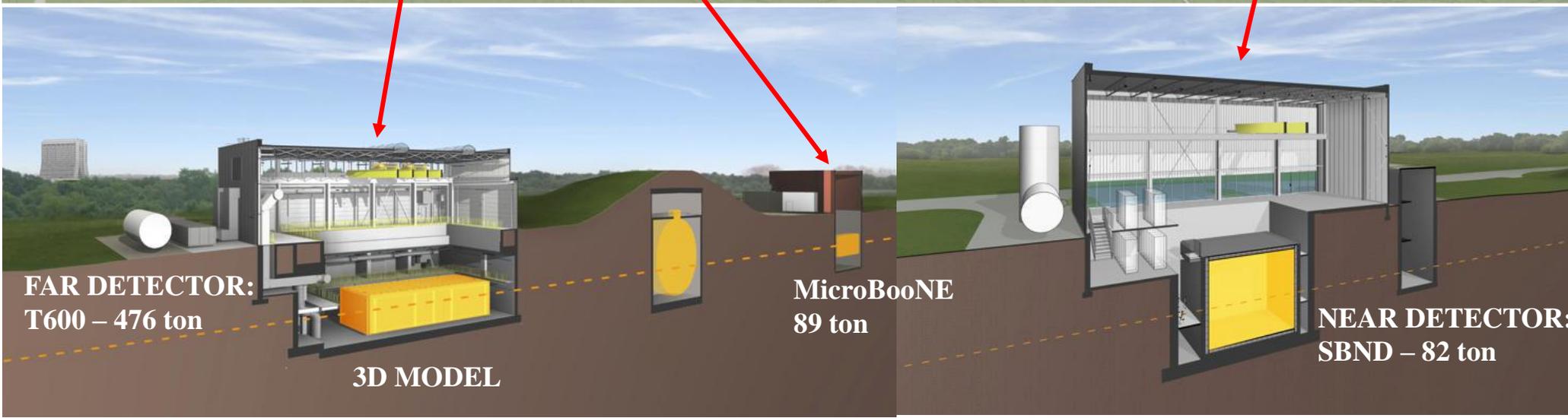
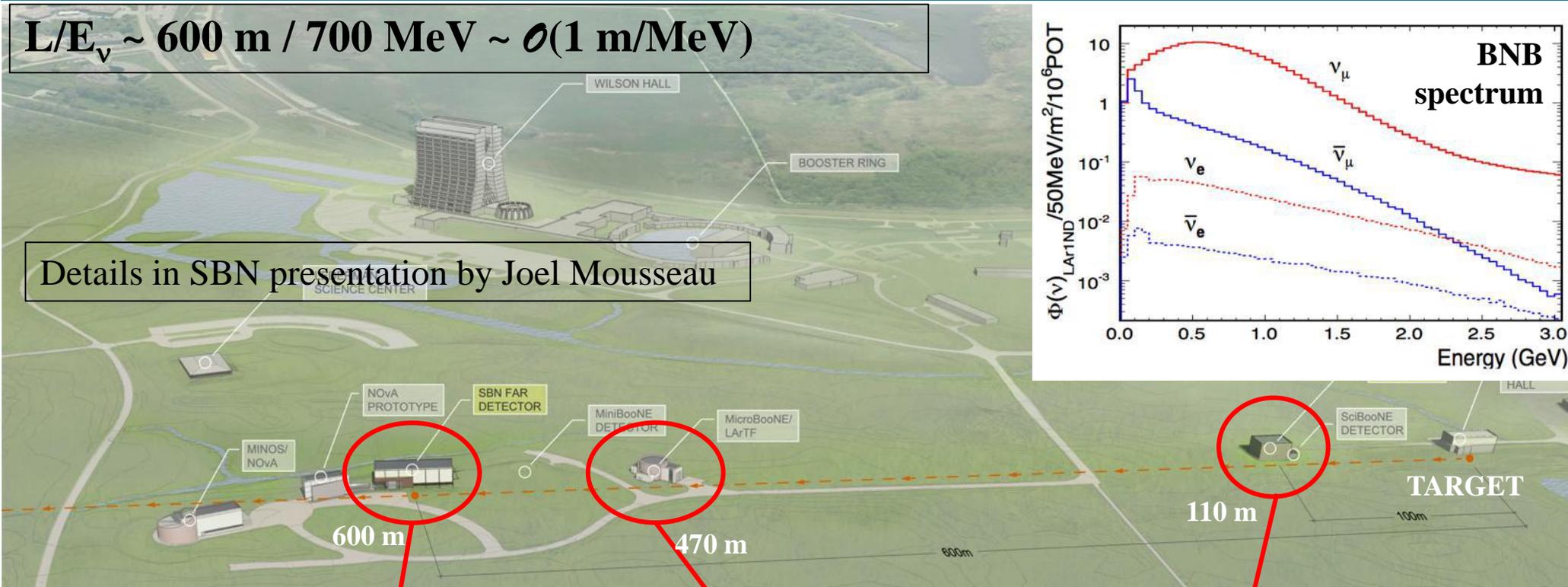
- Recent measurement by NEOS Collaboration of reactor anti- ν_e spectrum can be interpreted as a 2.1σ indication in favour of short baseline oscillations at a $\Delta m^2_{41} \sim 1.7 \text{ eV}^2$ and $\sin^2 2\theta_{ee} = 0.05$;
- **No evidence of ν_μ disappearance is found yet**, as shown in IceCube latest results in the 320 GeV-20 TeV E_ν range.
- Data from CMB expts, large scale structure and Lyman- α forest observation, naively bind for 3 massless + 1 massive sterile ν to $m_s < 0.26 \text{ eV}$ at 95% CL and should effectively **exclude sterile neutrino as explanation of LSND anomaly**. If LSND notwithstanding confirmed experimentally, cosmological data will have been proven wrong calling for a re-examine of this entire framework on which rest these very tight constraints.
- **A new experiment capable to clarify all these anomalies at $>5 \sigma$ level** is in preparation at FNAL, based on two main concepts and low energy ν and anti- ν from a proton accelerator:
 - **The comparison of ν spectra between identical detectors** at different distances. In absence of "anomalies", the spectra will be a precise copy of each other, without any MC comparison.
 - The novel, now fully operational large mass (0.7 k ton) **LAr-TPC** developed by the ICARUS Coll. which offers a "bubble chamber like" continuous sampling, homogeneous calorimeter with excellent event energy reconstruction.

The Short Baseline Neutrino program

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

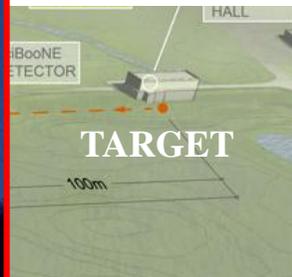
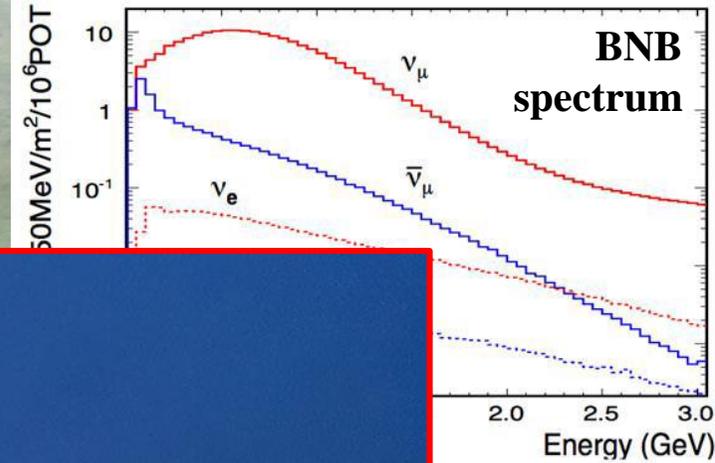


Details in SBN presentation by Joel Mousseau



The *Short Baseline Neutrino* program

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



SBND - 82 ton

FA
T60

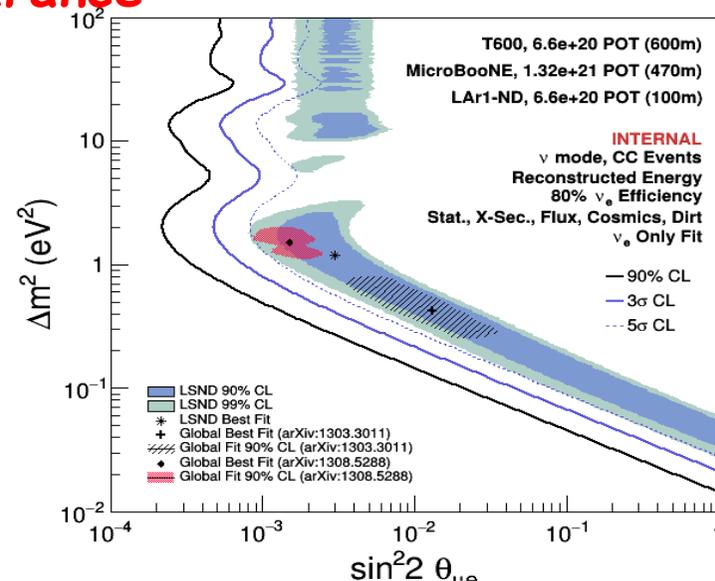
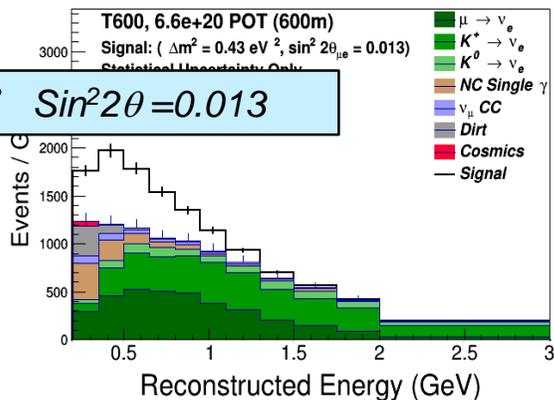
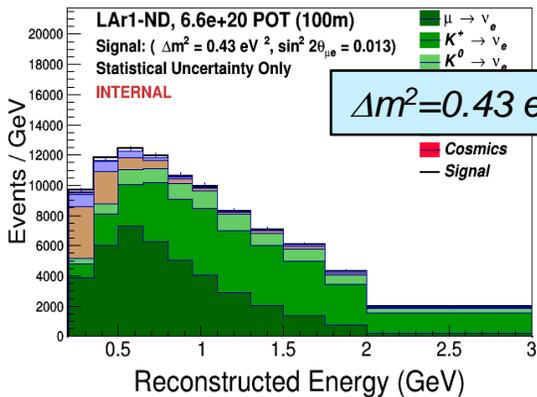
3D MODEL

Appearances and disappearances, $6.6 \cdot 10^{20}$ pot (3 years)

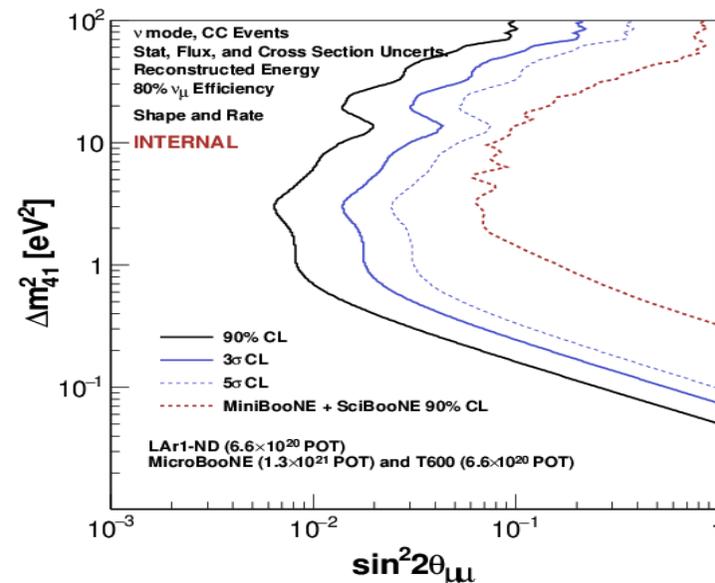
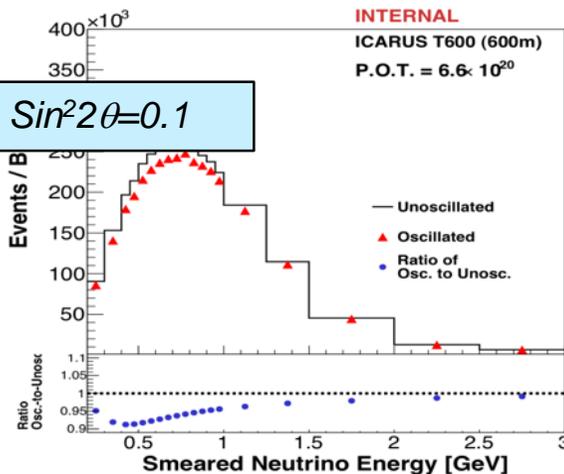
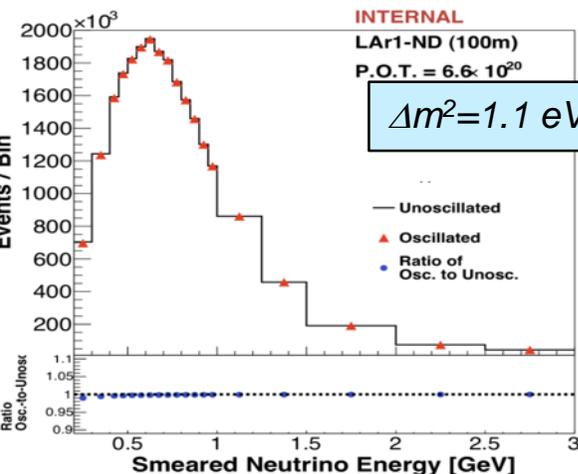
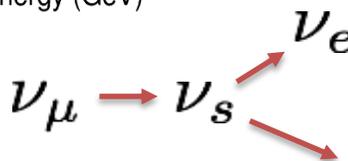
LSND 99%CL region: covered at $\sim 5\sigma$ in ν_e appearance

SBND @ 110 m

ICARUS-T600 @ 600 m



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



Sensitivity in ν_μ disappearance extended by factor 10 wrt present limits

WA104/NP01 - T600 overhauling at CERN

The T600 was moved from LNGS to CERN in December 2014 and is being upgraded by introducing technology developments **while maintaining the already achieved performance**:

- new cold vessels made of extruded aluminum profiles welded together;
- purely passive insulation (6.6 kW heat loss);
- Refurbishing at CERN of the cryogenic and purification equipment (included two-phase N₂ cooling shield);
- flattening of existing cathode panels to get improved planarity (by factor 10);
- upgrade of light collection system;
- new faster, higher-performance read-out electronics.



First cold vessel ready to house TPC. Leak tightness verified to $<10^{-7}$ mbar l/s. Structural test on the vessel by pumping down to 20 mbar. All measurements agree with calculation: 11 mm max. deformation.

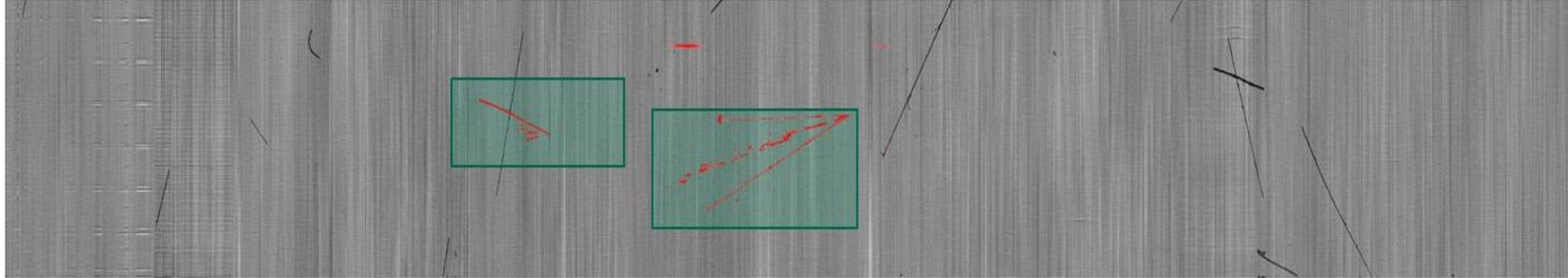
In addition an external **Cosmic Ray Tagging** system (**CRT**) will equip the T600. All activities of T600 refurbishing and CRT-top construction within the WA104/NP01 Neutrino Platform, are regulated by an MoU between CERN and INFN.

The ICARUS/WA104 Collaboration

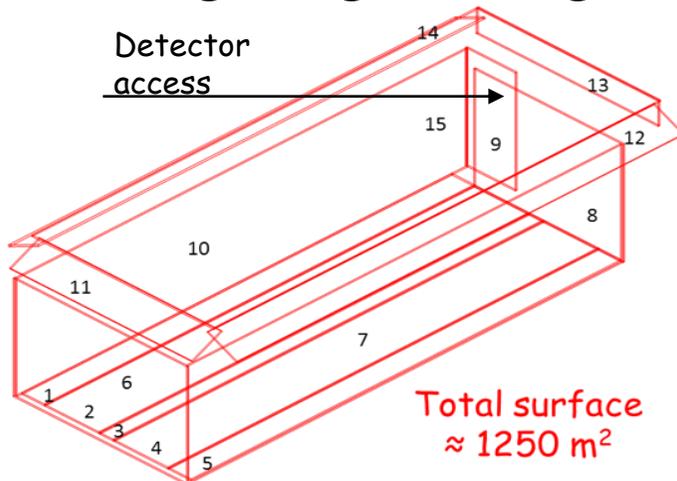
*Argonne National Laboratory (ANL), USA
Brookhaven National Laboratory (BNL), USA
CERN, Geneva, Switzerland
Colorado State University, USA
Fermi National Laboratory (FNAL), USA
INFN Sez. di Catania and University, Catania, Italy
INFN GSSI, L'Aquila, Italy
INFN LNGS, Assergi (AQ), Italy
INFN Sez. di Milano Bicocca, Milano, Italy
INFN Sez. di Napoli, Napoli, Italy
INFN Sez. di Padova and University, Padova, Italy
INFN Sez. di Pavia and University, Pavia, Italy
Los Alamos National Laboratory (LANL), USA
Pittsburgh University, USA
SLAC, Stanford, CA, USA
Texas University, Arlington, USA*

Event finding at shallow depth and Cosmic Ray Tagger

- Several uncorrelated cosmic rays (CR) will be recorded in T600 per triggering event within the 1 ms drift window readout: ~ 12 muon tracks per drift in each T300 were measured in Pavia test run on surface (2001).

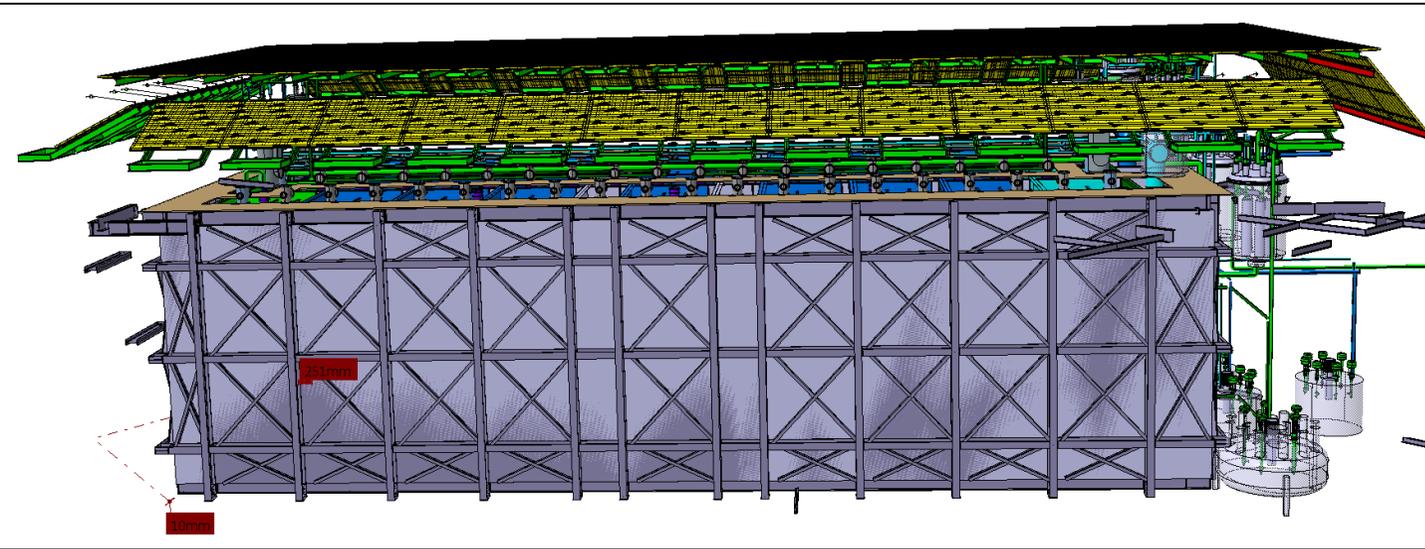


- The reconstruction of true 3D position of the triggering event, requires to associate precisely the timing of each track in the TPC image by:
 - Exploiting the PMT ~ 1 ns time resolution;
 - Recognizing incoming cosmic particles by an external CRT system.



- ✓ A CRT, made of Scintillating bars will surround the T600 (aim: 98% coverage). Bars will be equipped with optical fibers to convey light to SiPM arrays.
- ✓ Top coverage under CERN and INFN responsibility.
- ✓ FNAL is recovering modules previously used by MINOS for sides and Double Chooz for bottom.

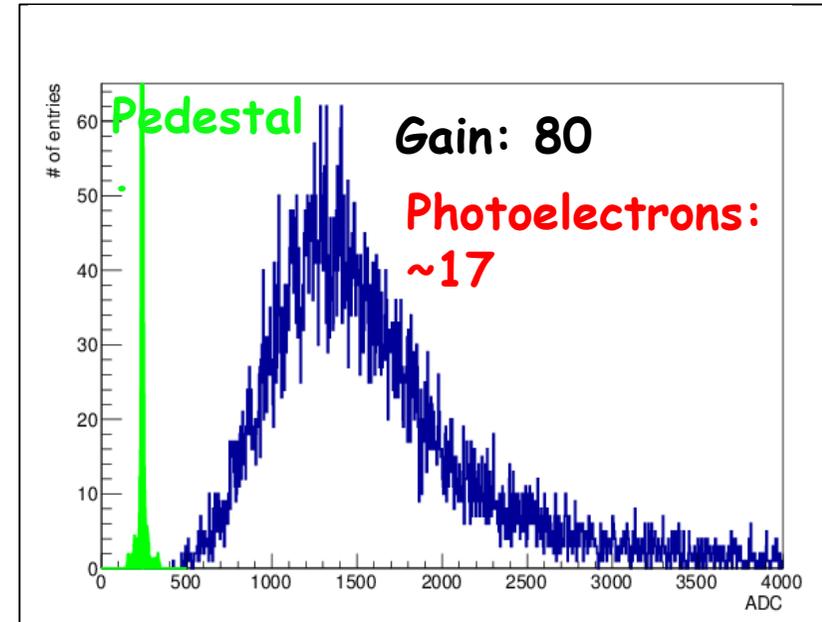
Top CRT Design



84 + 38 modules.
Each module has
8(X) + 8(Y) bars for
2D localization.
Around 2000 in total.

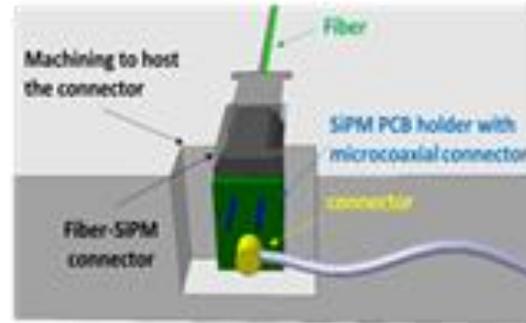
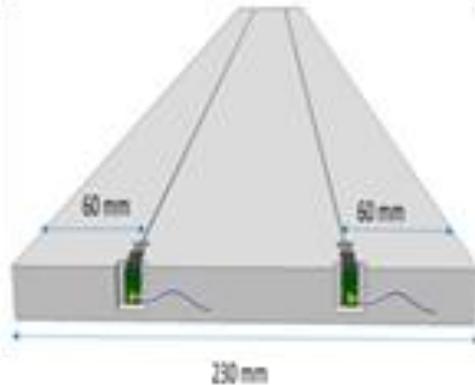
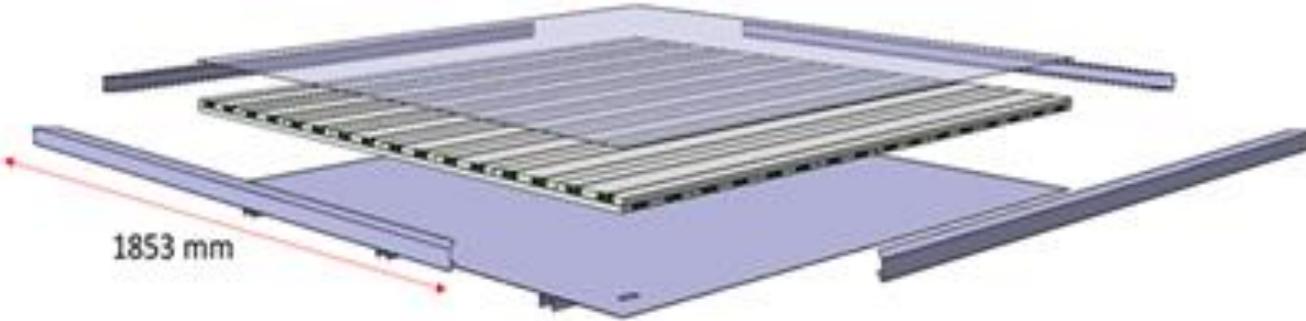
Module design
optimization ongoing.

- Various scintillation bars tested at CERN with cosmic rays (doped polystyrene and PVT)
- Scint. bars read by multicladd WLS fibers connected to SiPM's with an active area of $1.3 \times 1.3 \text{ mm}^2$.
- P.e. distribution (see e.g. picture on the right) is made with 1 cm thick bars.
- **Tagging efficiency of the top section: 80%**



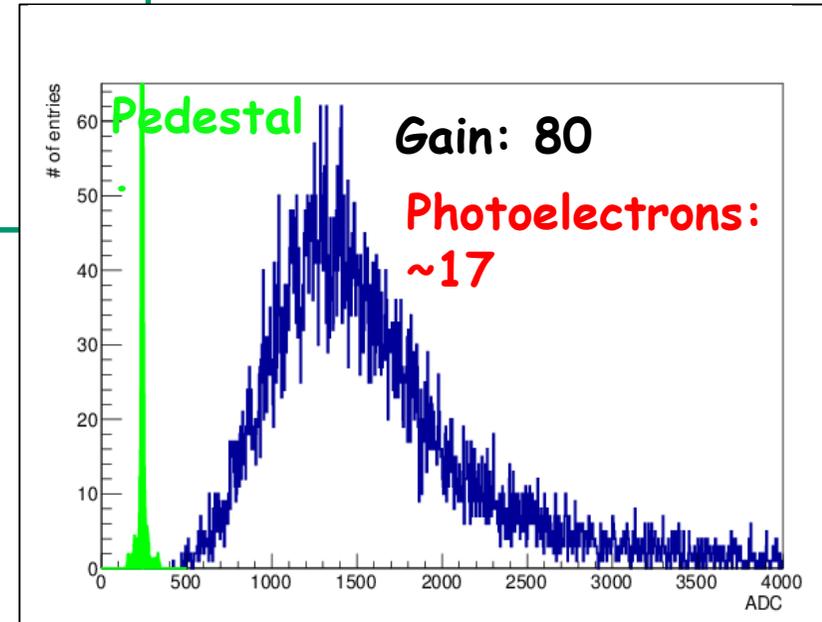
Top CRT Design

In total 125 modules for CRT top unit → 2000 scintillator bars



84 + 38 modules.
Each module has 8(X) + 8(Y) bars for 2D localization.
Around 2000 in total.

Module design optimization ongoing.



- Scint. bars read by multicladd WLS fibers connected to SiPM's with an active area of $1.3 \times 1.3 \text{ mm}^2$.
- P.e. distribution (see e.g. picture on the right) is made with 1 cm thick bars.
- Tagging efficiency of the top section: 80%

Upgraded light collection system

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

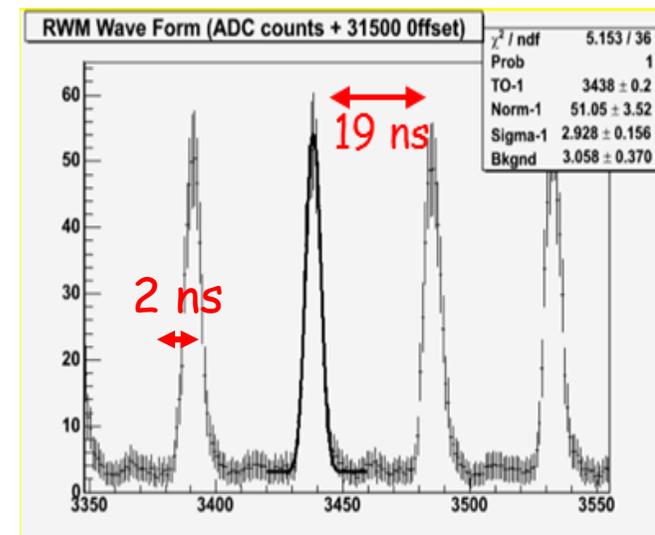
- higher quantum efficiency (QE);
- improved photo-cathode coverage;
- new PMTs shielding, to avoid induced spurious signals on TPC wires;
- new readout electronics, \sim ns resolution to exploit the BNB bunched structure.

PMT number and layout have been defined by Monte Carlo studies aiming at:

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

The light collection system consists of 90 PMTs per TPC (360 total) which guarantee a photo-cathode Coverage $> 5\%$ and a longitudinal event localization better than 0.5 m, assuming conservative 5% effective QE.

BNB Bunch Structure



Upgraded light collection system

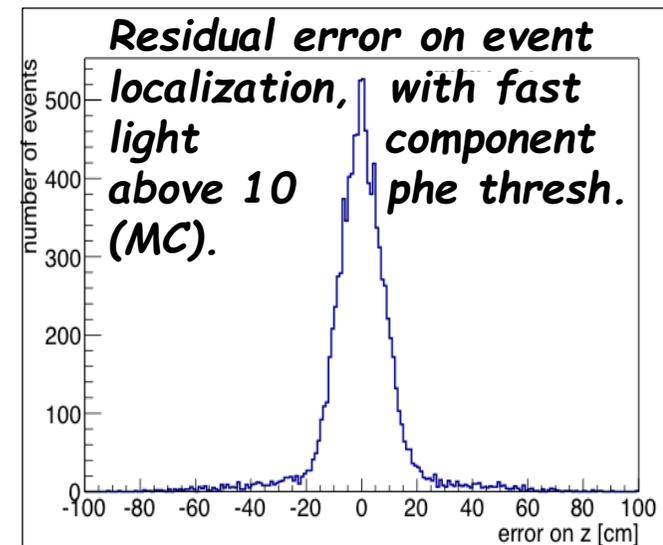
Large surface, Hamamatsu 8" PMTs are adopted as in LNGS, but major improvements in space/time event localization capabilities are required to reject cosmic backgrounds:

- higher quantum efficiency (QE);
- improved photo-cathode coverage;
- new PMTs shielding, to avoid induced spurious signals on TPC wires;
- new readout electronics, \sim ns resolution to exploit the BNB bunched structure.

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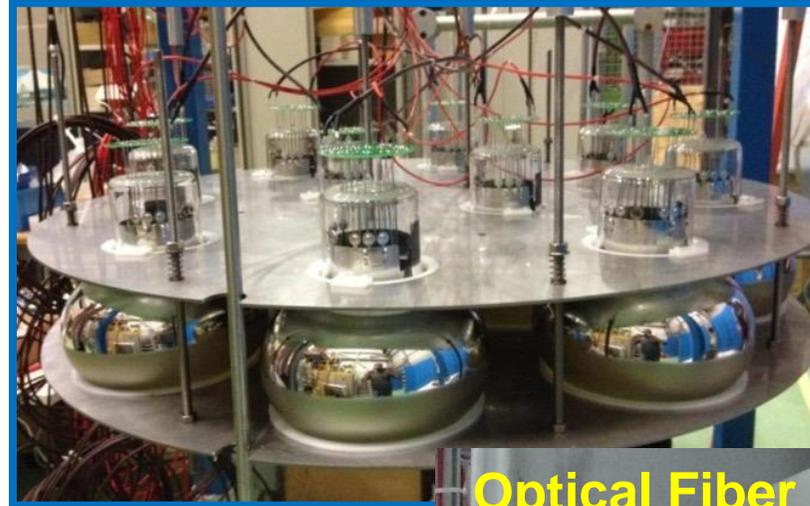
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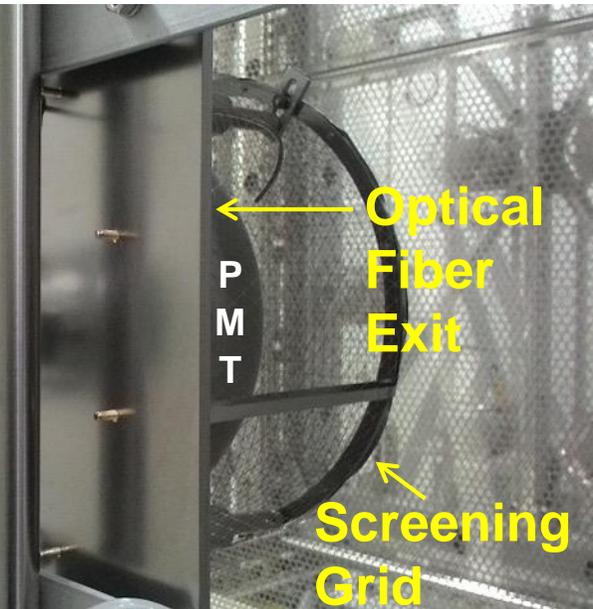
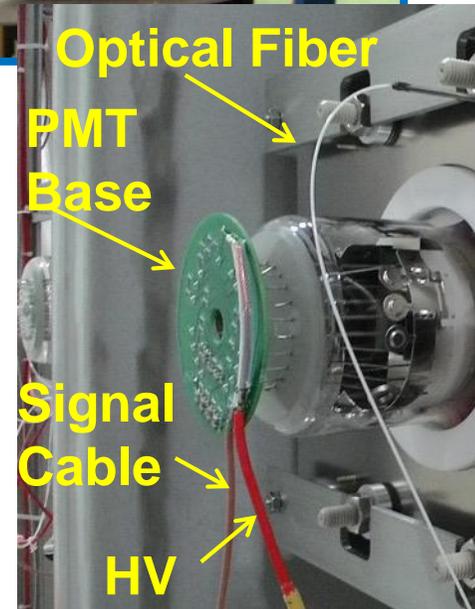
PMT tests and installation

- All PMTs have been characterized at room temperature, gain set to 10^7 e⁻/phe with ~1500 V.
- Average gain loss in LAr ~ 50%, recovered by raising HV of ~ 150 V (10% PMTs characterized).

*Set-up for LAr test:
gain, linearity
and dark counts*



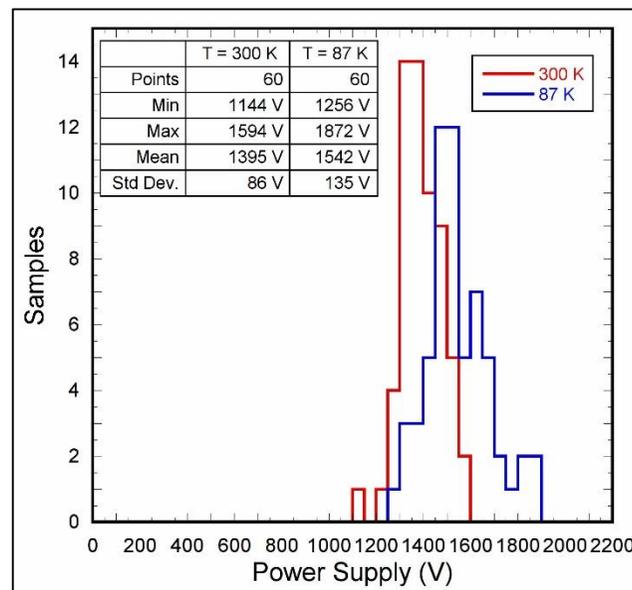
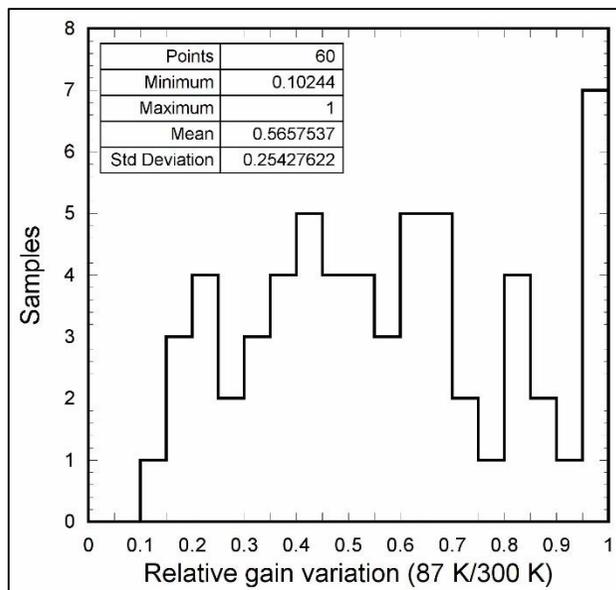
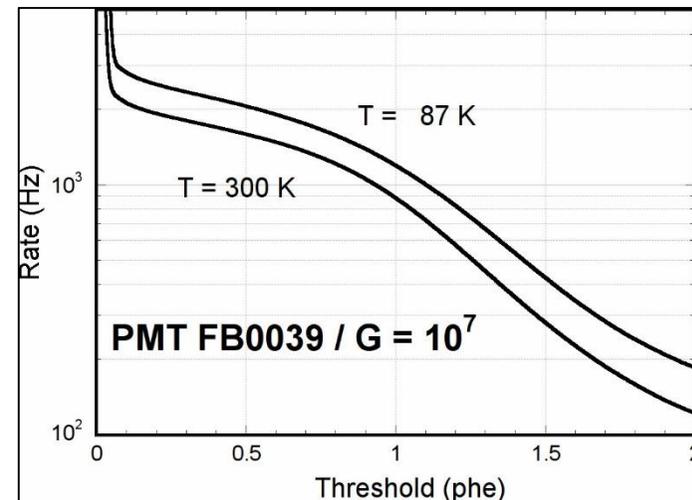
- 200 $\mu\text{g}/\text{cm}^2$ TPB layer evaporated on tubes, for VUV light shifting to visible spectrum;
- Calibration system with optical fibers and laser.



PMT test results

Test results on the PMT sample characterized both at room and Liquid Argon temperature.

Gain variation of the PMT Gain and voltage difference at room and LAr temperature, in order to have $G = 10^7$.

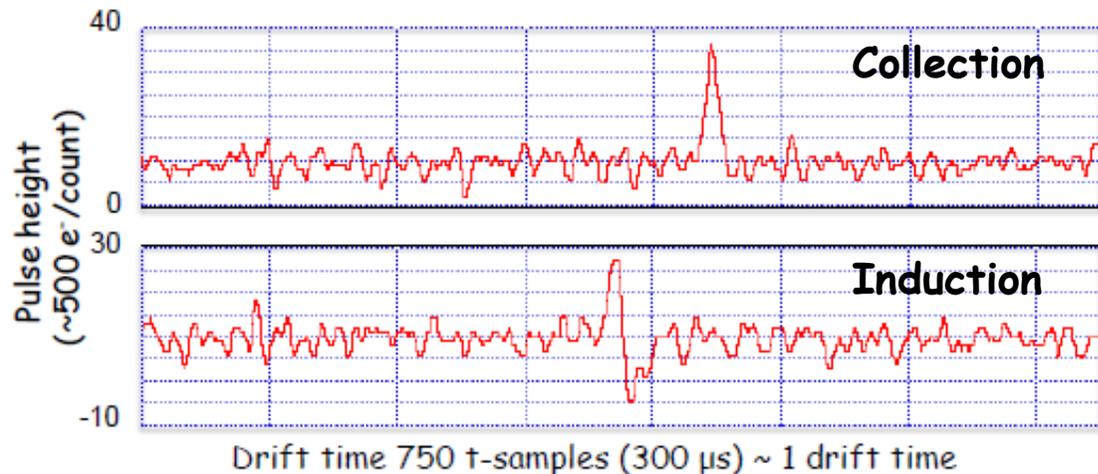
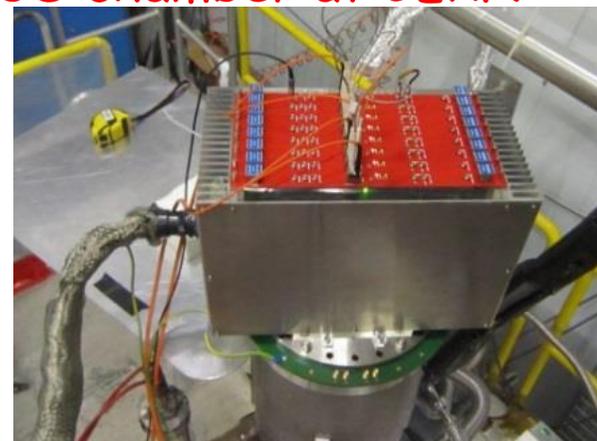
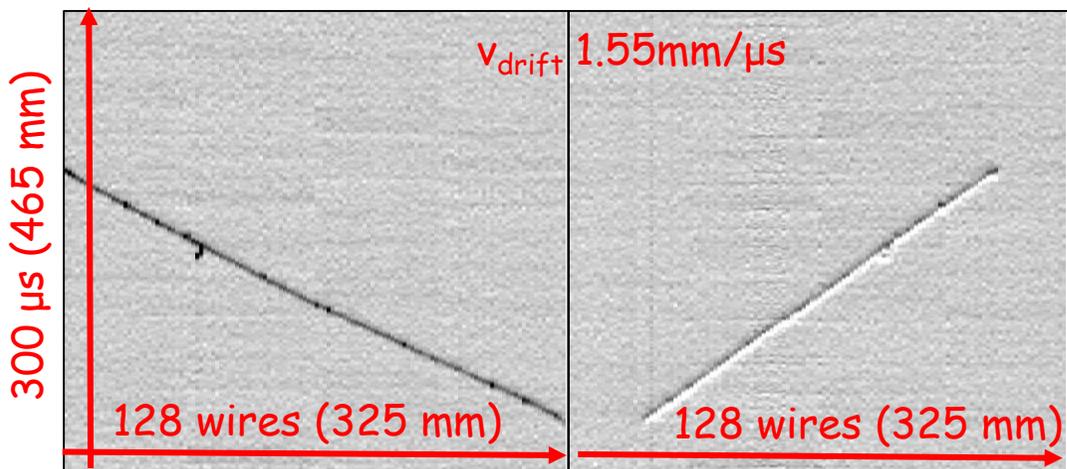


Dark count rate at room and LAr temp on a sample PMT, at gain $G = 10^7$.

New TPC-redout electronics

- 1 mini-crate mounted on each of 96 flanges, houses 9 boards, 64 channels each, to serve 576 channels (~52000 channels total).
- Each board hosts 64 front-end low noise charge sensitive pre-amplifiers, 64 serial 12 bit ADC (2.5 MHz), FPGA, memory, and optical link interface.

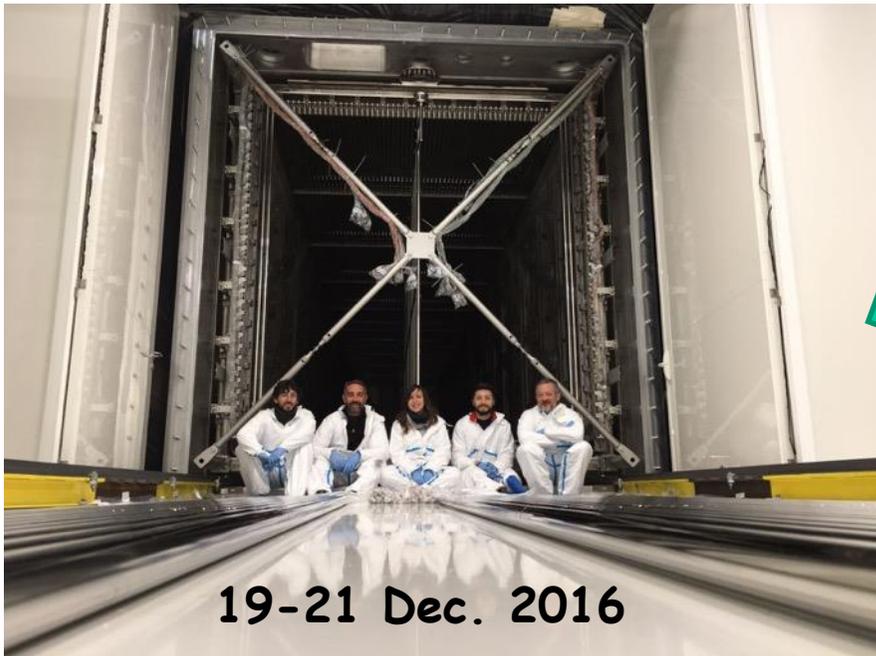
Heavily tested collecting cosmics with the **50l ICARUS chamber at CERN**



A single m.i.p. track event:

- Same ~ 2 ADC counts ($\sim 1000 e^-$) noise for both Coll & Ind;
- unipolar Coll. signal: ~ 25 ADC #;
- Symmetric bipolar Ind. signal with slightly reduced amplitude, as expected.

First module moved into cold vessel



19-21 Dec. 2016



Moving forward

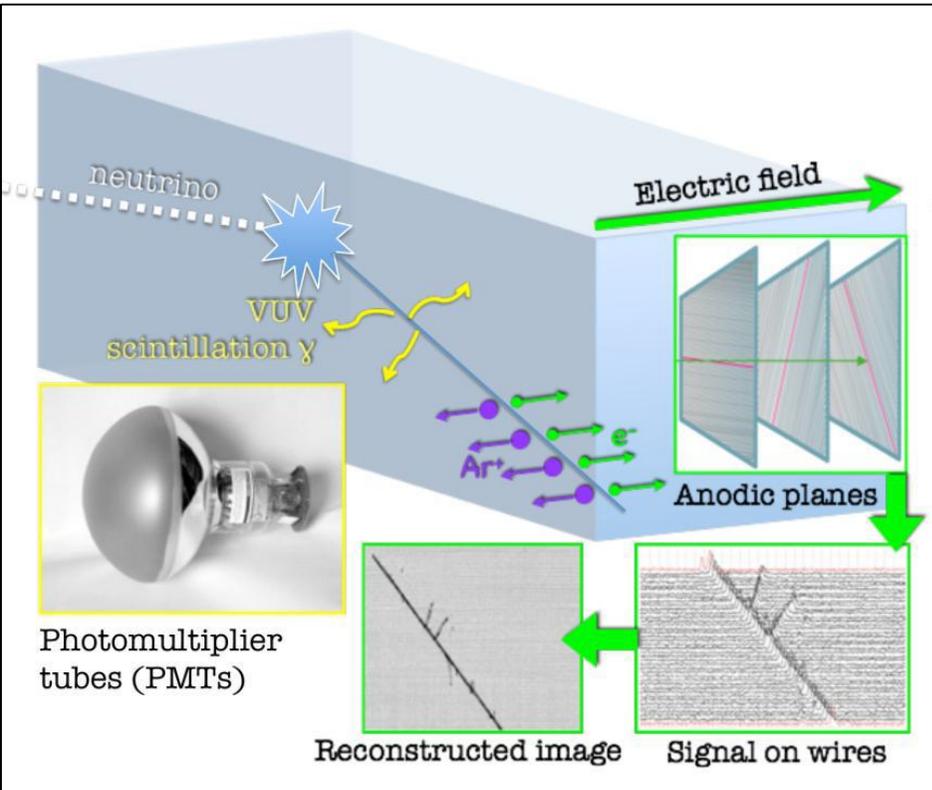
- The ICARUS T600 detector remains to date the only large volume LAr-TPC having successfully operated, for a three years in Gran Sasso underground Lab collecting both CNGS neutrinos and cosmic rays.
- ICARUS major overhauling in CERN in the framework of the WA104 MoU between INFN and CERN is ongoing in view of its deployment at FNAL. It will be exposed to the Booster neutrino beam at FNAL, within the SBN program, aiming at a definite answer to sterile ν hypothesis.
- The T600 will also collect $\sim 2\text{GeV}$ neutrinos from NUMI off-axis beam to measure cross sections in LAr, and study all CC/NC channels, to improve neutrino identification: an asset for DUNE-LBNF project.
- The overhauling is almost complete and time for T600 to leave for FNAL is approaching.
- A strong effort is being carried on by INFN, CERN and FNAL to prepare the installation and commissioning of ICARUS in the far position on the Booster beam, to start data taking in early 2018.

Thank you!



Back up

LAr-TPC technology



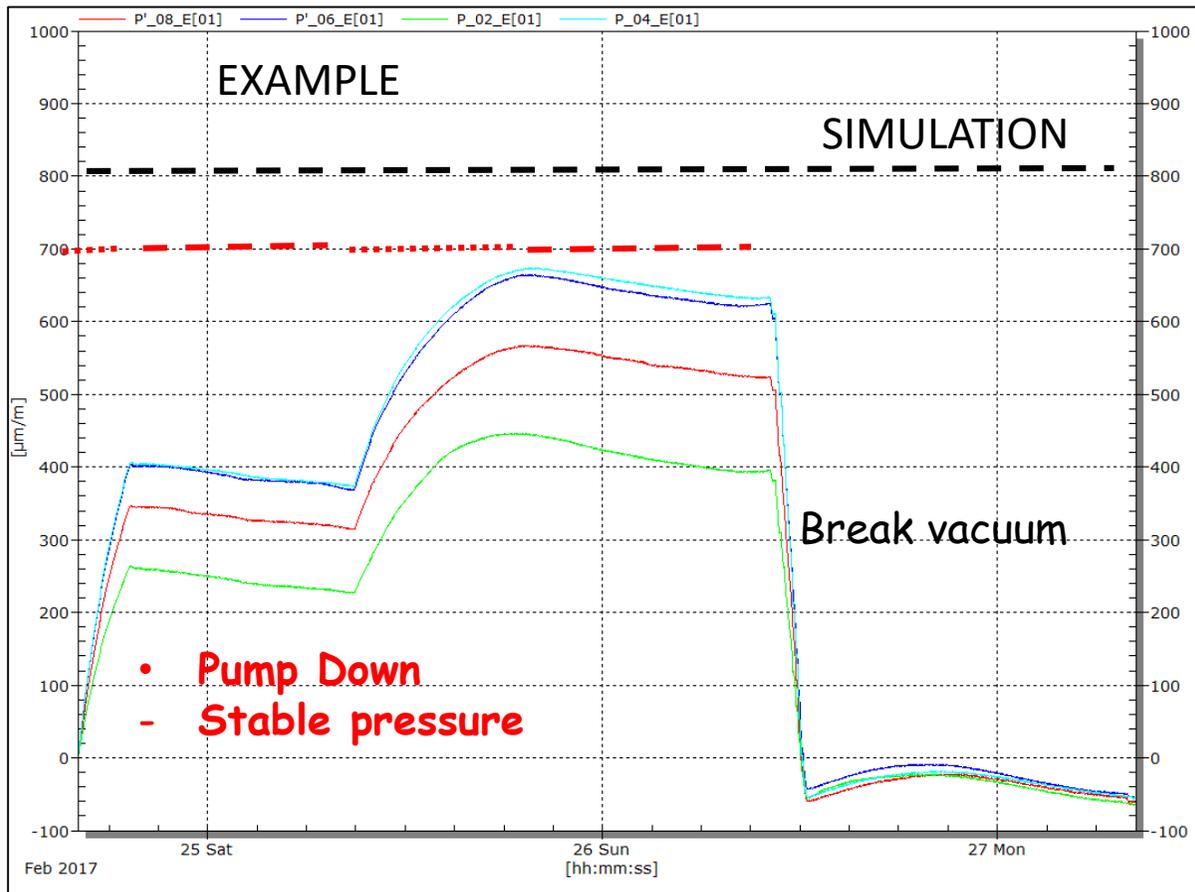
- 2D projection for each of 3 wire planes
- 3D spatial reconstruction from stereoscopic 2D projections
- Charge measurement from Collection plane signals
- Absolute drift time from scintillation light collection

A m.i.p. interacting particle in LAr produces (with $E_{\text{drift}} = 0.5 \text{ kV/cm}$):

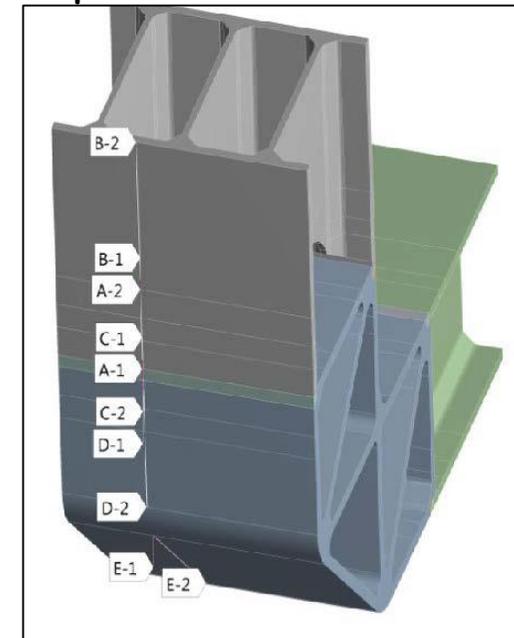
- **Ionization electrons:** $\sim 6000/\text{mm}$, drifted to the anode, ($v_{\text{drift}} = 1.55 \text{ mm}/\mu\text{s}$).
- **Scintillation photons:** $\sim 5000/\text{mm}$; VUV light (128 nm), with two components (decay times 6 ns and 1.5 μs).

Cold vessels vacuum tests

Strain on selected positions on the outer walls of the cold vessel was measured. Results expressed in terms of local deformation: $\mu\text{m}/\text{m}$. All sensors show values below or simulated ones, for application of 95% load (simul: $\Delta p=1$ bar; test: pumping from 970 atmospheric to 20 mbar).



Test duration: two days
Pump down time < 20 h



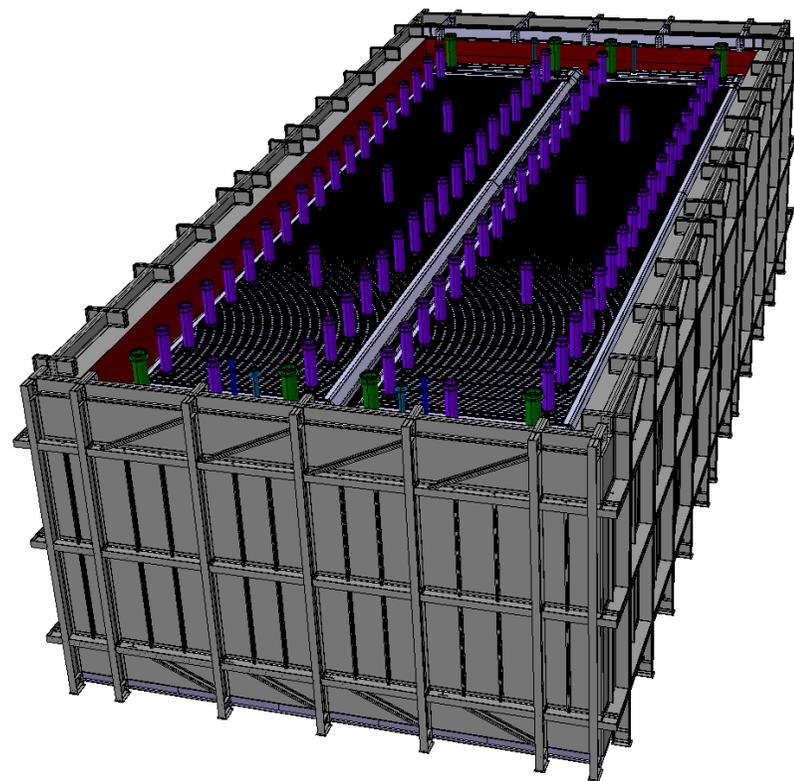
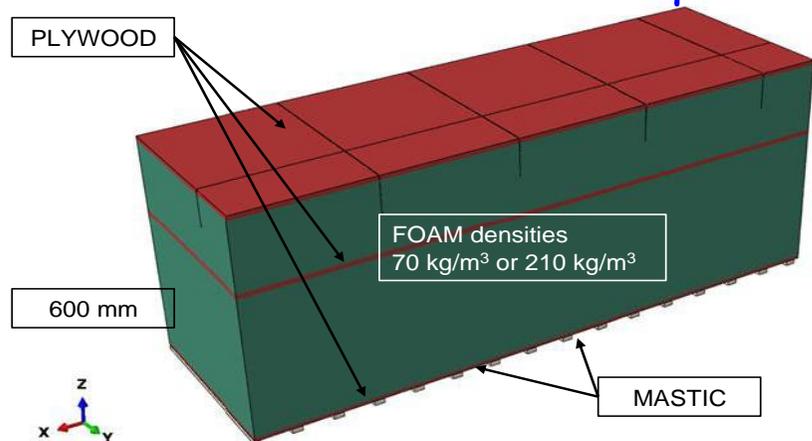
Warm vessel and insulation

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 LNG, now also for Neutrino Platform cryostats (see Nessi's talk).

Expected heat loss through the insulation: ≈ 6.6 kW ($10\text{-}15$ W/m²)

No internal membrane is required here



Warm vessel produced in Europe and sent to FNAL for installation (starting soon).

Electronics test with the 50l chamber at CERN

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.

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

- 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.

The new warm chain has been repeatedly tested at CERN, collecting cosmic rays with the **50 Liters ICARUS Chamber**. The chamber is an ICARUS test stand for new detectors and materials since 20 years.

The chamber is now also an asset for the Neutrino Platform, used for multiple purposes, e.g., testing Cold Front End boards produced by BNL, coupled with ICARUS warm chain.

