

Sterile neutrino searches with the ICARUS detector

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*on behalf of the ICARUS
Collaboration*



NOW 2018, Ostuni, September 10th

OUTLINE

- LAr-TPC technology: ICARUS T600 performance and results @ LNGS.
- Search for sterile neutrinos at FNAL: ICARUS in the Short Baseline Neutrino experiment scenario.
- Generalities on the ICARUS T600 overhauling.
- T600 current status.
- Conclusions.

Present ICARUS Collaboration

Brookhaven National Laboratory (BNL), USA

Colorado State University, USA

Fermi National Laboratory (FNAL), USA

University of Houston , 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

University of Pittsburgh , USA

University of Rochester , USA

SLAC, Stanford, CA, USA

University of Texas (Arlington), USA

*CERN and others INFN groups involved
in the SBN program*

Spokesman: C. Rubbia , GSSI

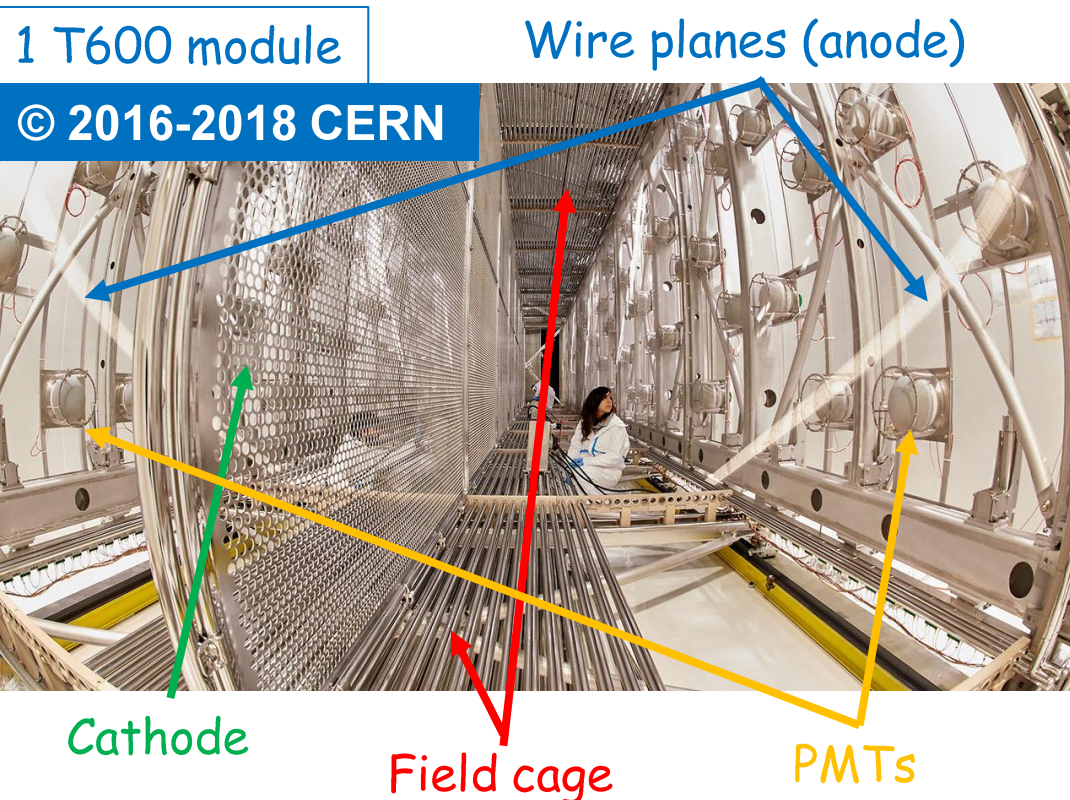
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ICARUS T600: the first large Liquid Argon TPC (760 t of LAr)

- ICARUS-T600 LAr TPC is a high granularity, uniform, self-triggering detector with 3D imaging and calorimetric capabilities, ideal for ν physics. It allows to accurately reconstruct a wide variety of ionizing events with complex topology.
- Exposed to CNGS beam, ICARUS, concluded in 2013 a very successful 3 years run at Gran Sasso INFN underground lab, collecting 8.6×10^{19} pot event statistics, with a detector live time $>93\%$, and cosmic ray events.

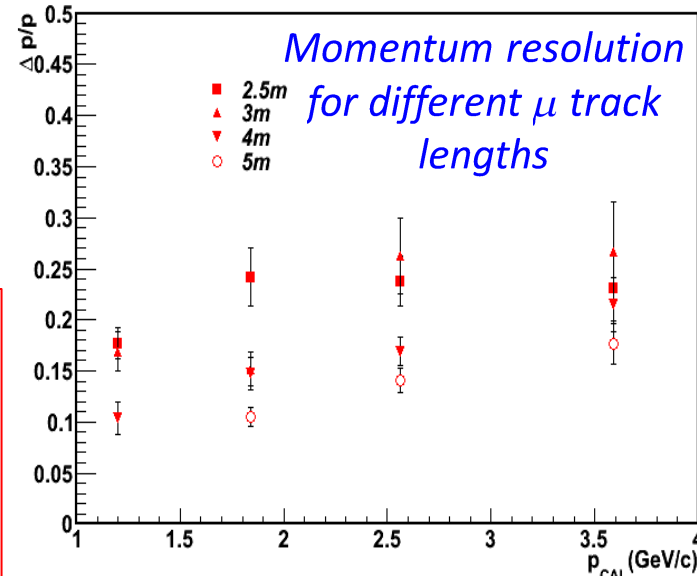
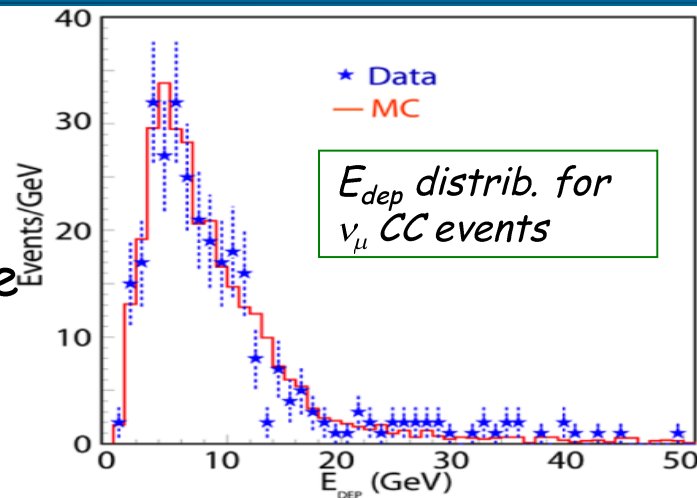
Two identical modules: 476 t tot active mass:



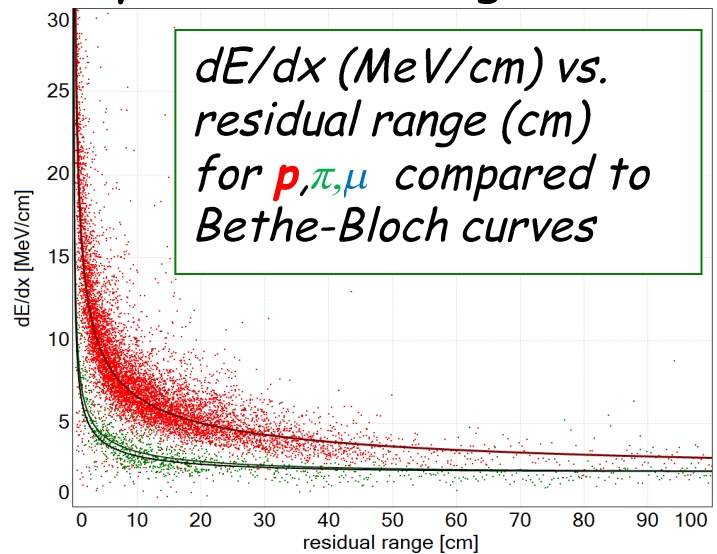
- 2 TPC's per module, with a common central cathode (punched 58% transparency) : $E_{\text{Drift}} = 0.5 \text{ kV/cm}$, $v_{\text{Drift}} \sim 1.6 \text{ mm}/\mu\text{s}$, 1.5 m drift length;
- 3 "non-destructive" readout wire planes per TPC, ≈ 54000 wires at $0^\circ, \pm 60^\circ$ w.r.t. horizontal: Induction 1, Induction 2 and Collection views;
- Ionization charge continuously read ($0.4 \mu\text{s}$ sampling time);
- 74 (LNGS) / 360 (FNAL) 8" PMTs, coated with TPB wls. for t_0 , timing and triggering.

ICARUS LAr-TPC performance (CNGS ν 's and cosmics)

- **Tracking device:** precise 3D event topology, $\sim 1 \text{ mm}^3$ resolution for any ionizing particle;
- **Global calorimeter:** full sampling homogeneous calorimeter; total energy reconstructed by charge integration with excellent accuracy for contained events; momentum of non contained μ by Multiple Coulomb Scattering (MCS) with $\Delta p/p \sim 15\%$ *;
- **Measurement of local energy deposition dE/dx :** remarkable e/γ separation ($0.02 X_0$ sampling, $X_0=14 \text{ cm}$) and a powerful particle identification by dE/dx vs range:



Validation on p_{MCS} of stopping μ 's, compared with calo estimate.



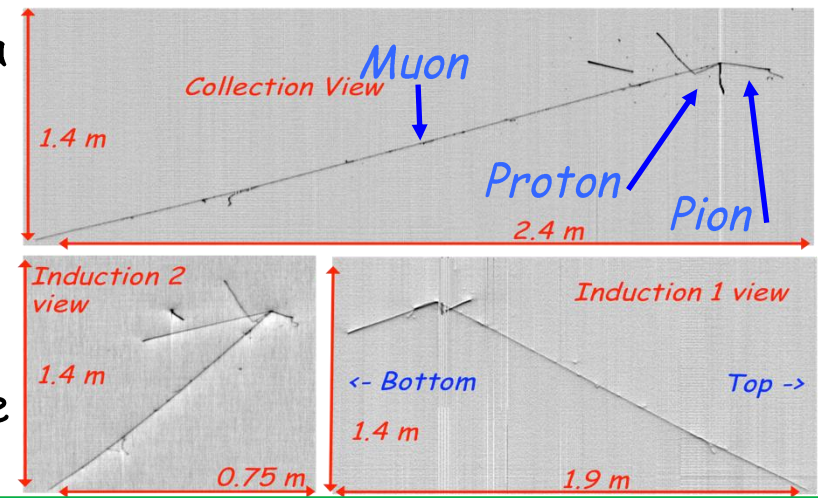
Low energy electrons:
 $\sigma(E)/E = 11\%/\sqrt{E(\text{MeV})} + 2\%$
Electromagnetic showers:
 $\sigma(E)/E = 3\%/\sqrt{E(\text{GeV})}$
Hadron showers:
 $\sigma(E)/E \approx 30\%/\sqrt{E(\text{GeV})}$

Atmospheric neutrino events @ LNGS

- ICARUS collected @ LNGS also atmospheric ν_e and ν_μ CC interactions.
- Globally 6 ν_μ CC and 8 ν_e CC atmospheric neutrino events identified (18 expected events evaluated taking into account detection efficiencies).
- These events are particularly suitable to emulate the ν interactions expected with FNAL beams because of the similar energy range

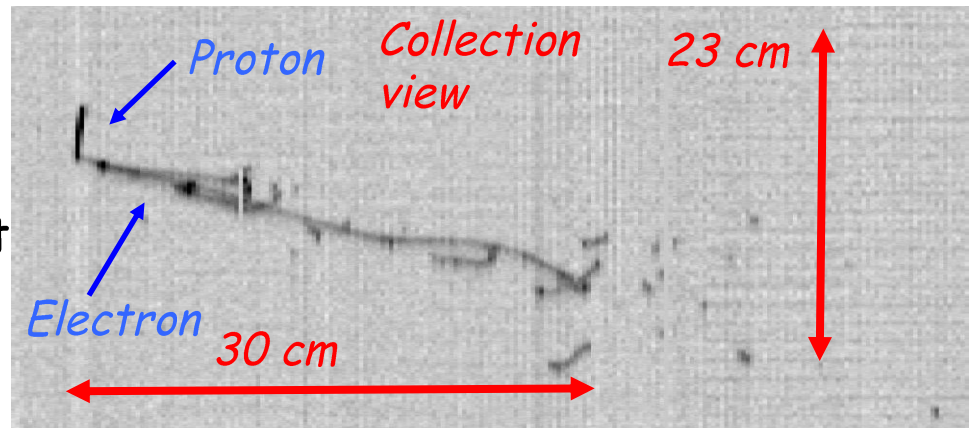
Example of upward-going ν_μ CC event with a deposited energy ~ 1.7 GeV:

- 4m escaping μ , 1.8 ± 0.3 GeV/c from MCS;
- Two pions ($E_{\text{dep}} \sim 80$ MeV) and a proton ($E_{\text{dep}} \sim 250$ MeV) at vertex.
- Reconstructed $E_\nu \sim 2$ GeV with $\sim 78^\circ$ zenith angle



Downward-going, quasi elastic ν_e event.
deposited energy: 240 MeV

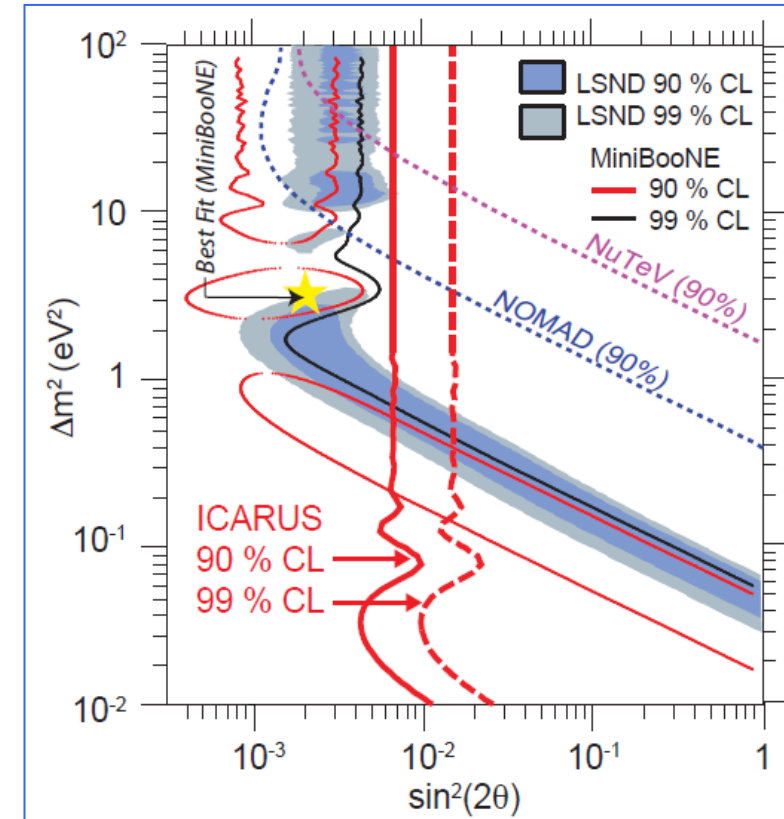
- $dE/dx \sim 2.1$ MeV/cm measured on first wires corresponds to a m.i.p.
- Short proton track recognized.



ICARUS results and search for an LSND-like effect

ICARUS run at LNGS allowed reaching several physics/technical results demonstrating the maturity of the LAr-TPC technology:

- An exceptionally low level ~ 20 p.p.t. $[O_2]$ eq. of electronegative impurities in LAr; the measured e- lifetime $\tau_{ele} > 15$ ms ensured few m long drift path of ionization e- signal without attenuation;
- Demonstrated detector performance especially in ν_e identification and π^0 bkg rejection in $\nu_\mu - \nu_e$ study to unprecedented level;
- Performed a sensitive search for LSND-like anomaly with CNGS beam, constraining the LSND window to narrow region at: $\Delta m^2 < 1$ eV², $\sin^2 2\theta \sim 0.005$ where all positive/ negative experimental results can be coherently accommodated at 90% C.L., confirmed by OPERA.



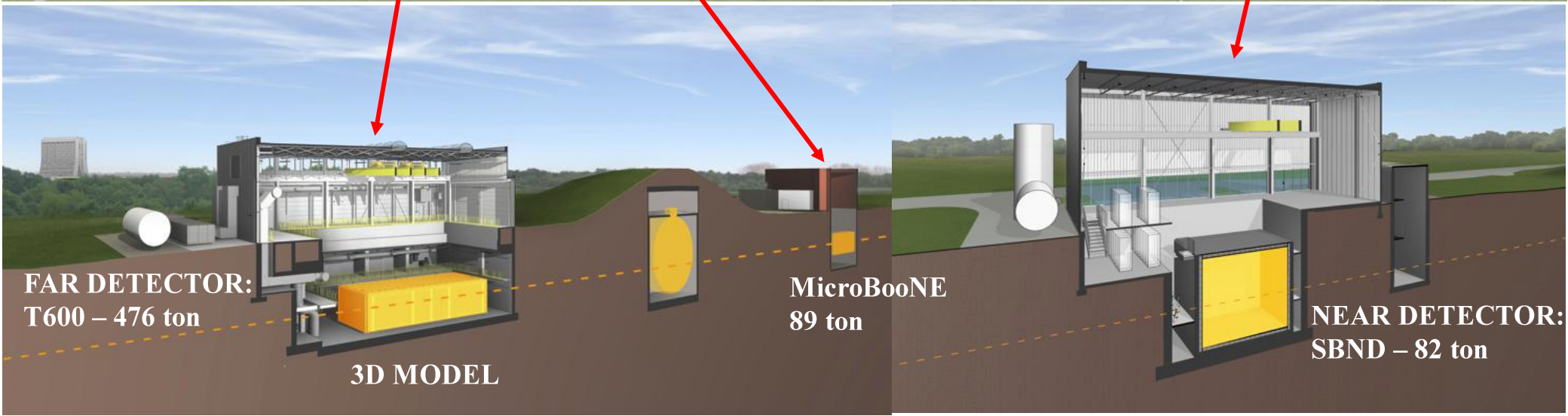
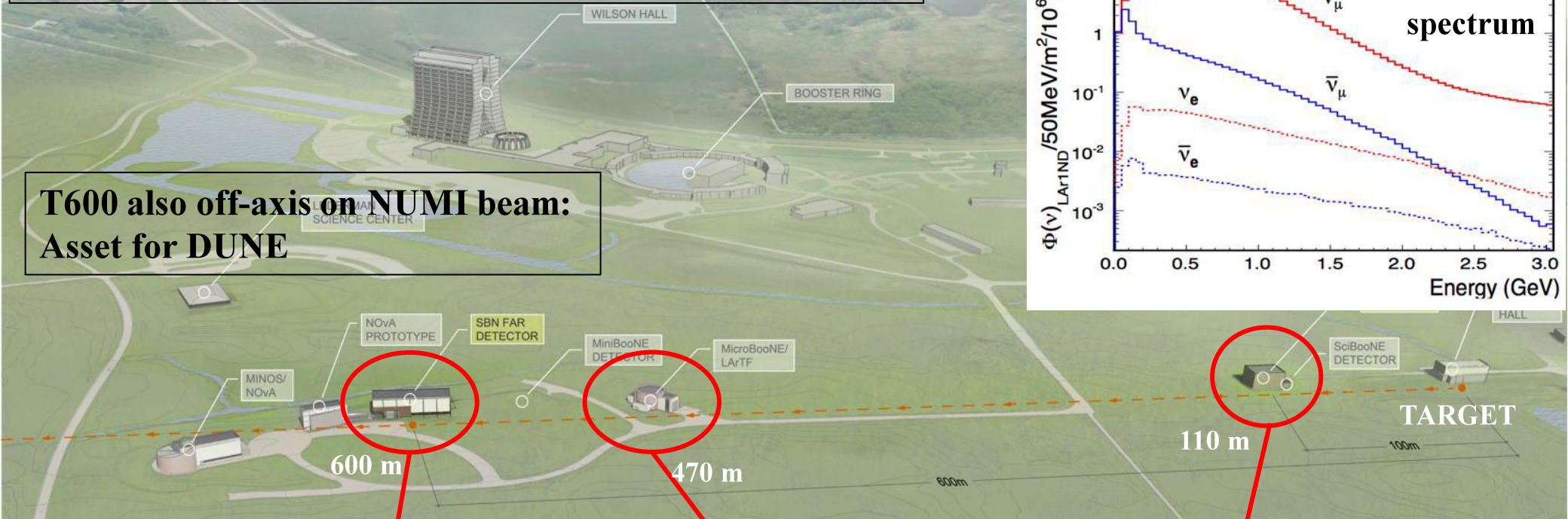
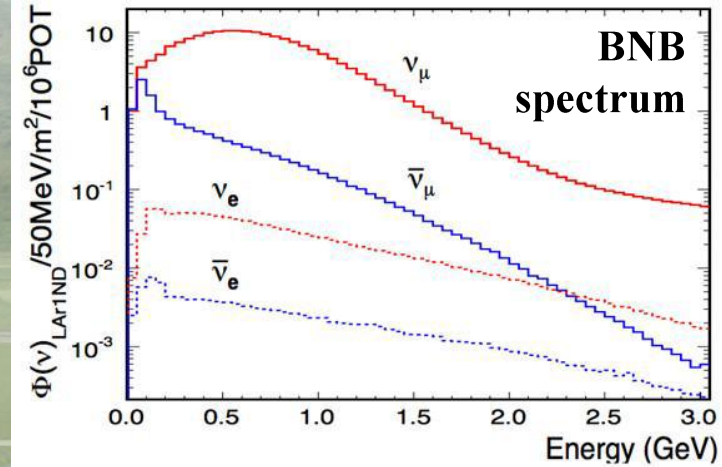
Eur. Phys. J. C (2013) 73:2599

Success of LAr-TPC technology with large impact on neutrino and astro-particle physics projects: SBN short base-line neutrino program at FNAL with 3 LAr-TPC's (SBND, MicroBooNE and ICARUS) and the multi-kt DUNE LAr-TPC.

Short Baseline Neutrino (SBN) in a nutshell

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

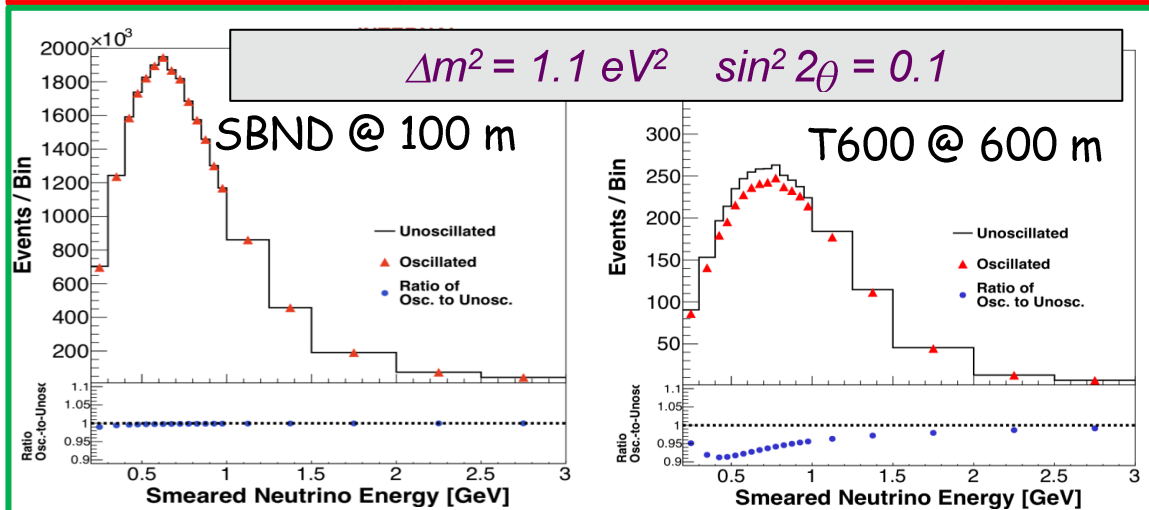
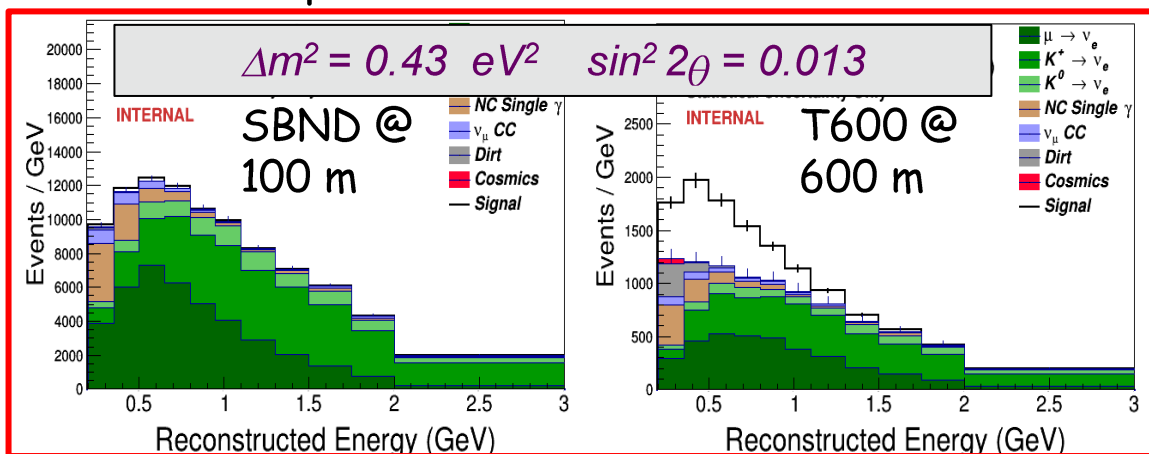
**T600 also off-axis on NUMI beam:
Asset for DUNE**



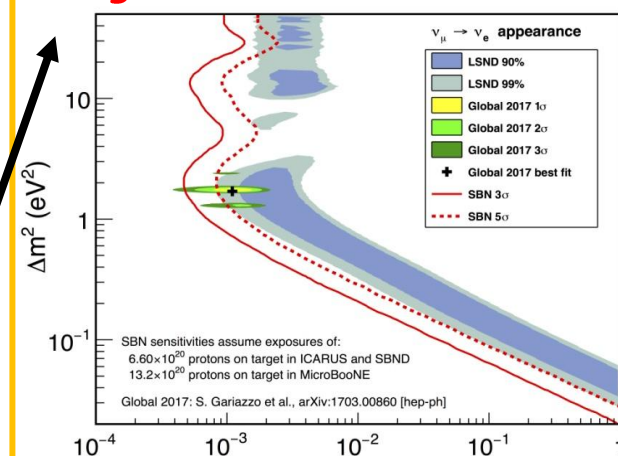
Sensitivity to Sterile neutrino @ SBN

SBN can clarify the issue by exploiting similar LAr-TPCs at different distances from the target

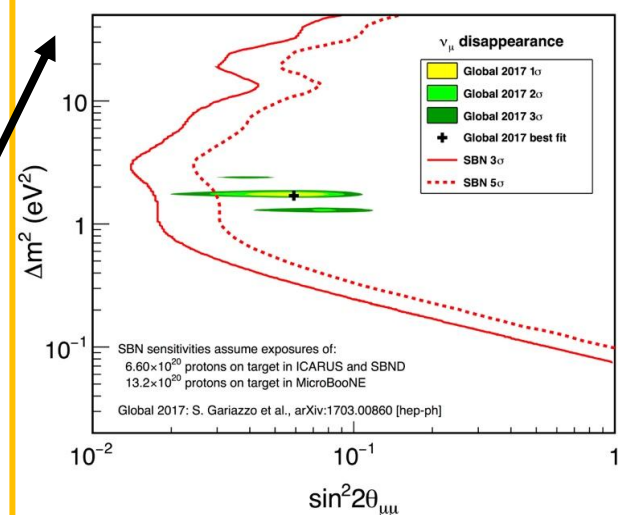
- SBND will give the "initial" BNB flux/composition
- ICARUS, as far detector, will characterize the ν oscillation parameters.



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



Both plots: 6.6×10^{20} pot (3 years)
 $3-5\sigma \nu_\mu$ disapp. SBN sensitiv.



T600 Overhauling at CERN (WA104/NP01)

- To face the new experimental situation at FNAL with respect to the LNGS run (*shallow depth data taking with higher beam rate*), the T600 detector needs important upgrades. The whole *apparatus underwent an intensive overhauling process at CERN*, before being shipped to FNAL.
- In 2015, T600 detector was moved to CERN for overhauling in the framework of CERN Neutrino Platform (*WA104/NP01 project*).
- The aim of these activities was to introduce technology developments *while maintaining the already achieved performance*:
 - New cold vessels, with a purely passive insulation, renovated cryogenic and LAr purification equipment;
 - Improvement of the cathode planarity;
 - *Upgrade of the light collection system* with high granularity/sensitivity and time resolution with ~ 1 ns precision;
 - *New faster, higher performance read-out electronics.*



Upgrade of the light collection system

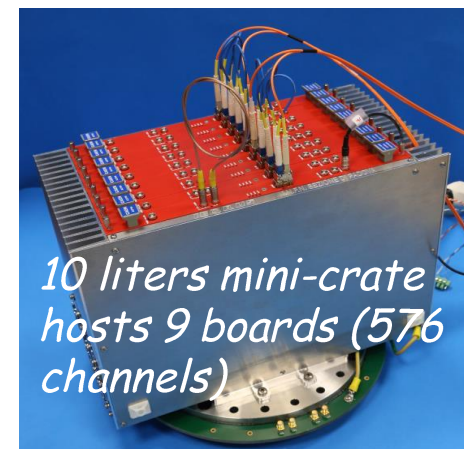
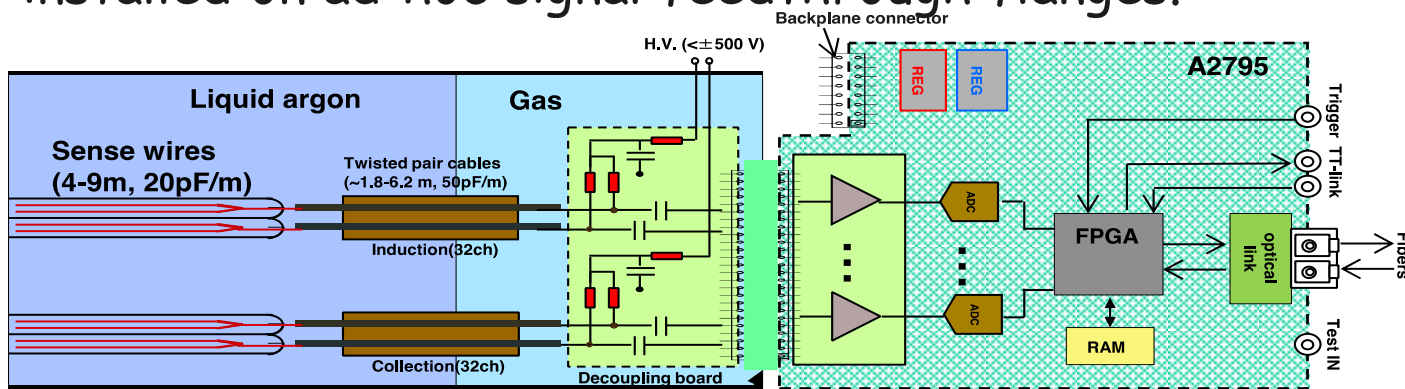
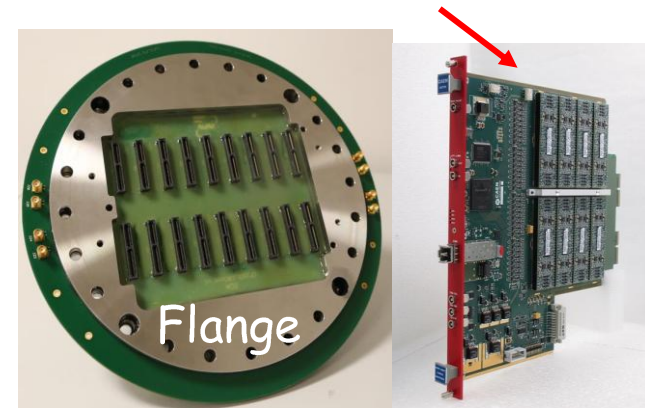
- The T600 light detection system is devoted to:
 - Identify precisely **the time of occurrence (t_0) of each interaction**;
 - Identify the **event topology** for fast selection purposes;
 - Generate **a trigger signal** to enable the event read-out by combining the PMT signal pattern to the BNB/NuMI beam spills (≈ 1 ns precision) and the veto from the external Cosmic Ray Tagger (CRT).
- The light collection system is based on 360 PMTs (90/chamber).
 - Hamamatsu R5912-MOD (8", 10 dynodes) rated for cryogenic temperature;
 - PMT glass windows coated by $\sim 200 \mu\text{g}/\text{cm}^2$ of Tetra-Phenyl-Butadiene wavelength shifter to detect the $\lambda = 128$ nm scintillation light in Lar;
 - A PMT timing calibration provided by a laser calibration system (Hamamatsu PLP10, $\lambda \sim 450$ nm, FWHM < 100 ps, peak power ~ 400 mW) + $50 \mu\text{m}$ optical fibers.



The new TPC read-out electronics

- ICARUS electronics at LNGS was based on analogue low noise "warm" front-end amplifier, a multiplexed 10-bit 2.5 MHz ADC and a digital VME module for local storage, data compression, trigger information:
S/N ~9 in Collection, ~0.7 mm single hit resolution, resulting in a precise spatial event reconstruction and μ momentum measurement by MCS.
- Improvements concern:
 - *Serial 12 bits ADC, one per ch, 400 ns **synchronous sampling** on the whole detector;*
 - *Serial bus architecture with Gbit/s optical links to increase the bandwidth (10 MHz);*
 - *Both analogue/digital electronics housed in a single board inserted in a new mini-crate directly installed on ad-hoc signal feedthrough flanges.*

CAEN A2795 board, 64 chs



ICARUS Trip to FNAL



T600 leaving from CERN June 12th 2017



June - July 2017
from CERN to FNAL



T600 in Antwerp: unloading from barge from Basel and loading into ship to Burns Harbor (Michigan lake)



T600 arriving at SBN Far site building @FermiLab, July 26th 2017

ICARUS @ FNAL - Status

- Warm vessel floor/walls were assembled/installed in the pit in the Far Detector (FD) building in 2017.
- Bottom CRT modules (200 m² total area) already installed in 2017.
- Assembly of cold shields (bottom and side) completed and installed (May 2018).
- Installation of detector supports, sealing of main vessels doors and Helium leak tests completed (June 2018).
- Rigging of the two modules and placement in the pit completed (August 2018).



- Chimney and read-out cable recovery September 2018.
- Top part of cold shield will be then installed and tested, followed by installation of top part of warm vessel.
- Activities on top of detector will follow (cryo, purification and vacuum systems, ext. cabling, read-out & decoupling boards, feedthrough flanges, optical fibers,...).
- Vacuum pumping should start and last until ready to start cool-down.

Detector commissioning will consist of three phases:

- Cryogenic commissioning: Vacuum, Cooling, Filling, Purification, Stabilization.
- TPC and PMT system commissioning: HV system, PMT's supply, calibrations, DAQ & trigger commissioning.
- CRT commissioning: in parallel with the activities for the completion of cryogenic plant, TPC and PMT system commissioning.

Data taking (early 2019).

Conclusions

- The LAr-TPC detection technique has been taken to full maturity with ICARUS-T600.
- ICARUS completed in 2013 a successful continuous 3-year run at LNGS exposed to CNGS neutrinos and cosmic rays, and performed a sensitive search for a potential ν_e excess related to the LSND-like anomaly defining a narrow region at $(\Delta m^2, \sin^2 2\theta) \sim (1 \text{ eV}^2, 0.005)$.
No excess evidence, as confirmed by OPERA.
- The T600 underwent a major overhauling at CERN and has been transported to FNAL to be exposed to Booster and NuMi neutrinos.
- SBN experiment will provide a clarification of the sterile neutrino issue, both in appearance and disappearance modes.
- Installation in the Far Site building is in progress. A strong effort is being carried on by INFN, CERN and FNAL to start the commissioning and data taking in early 2019.

Thank you !

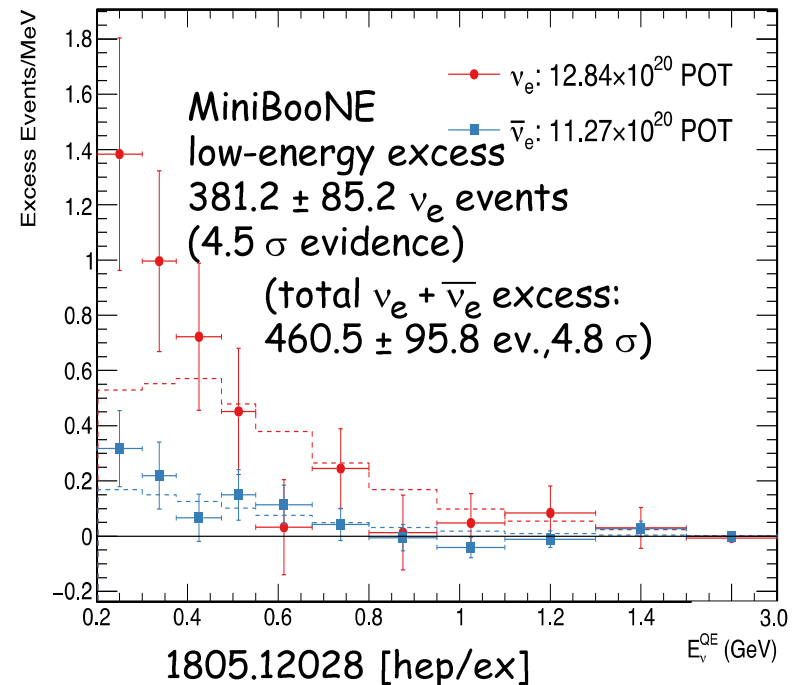
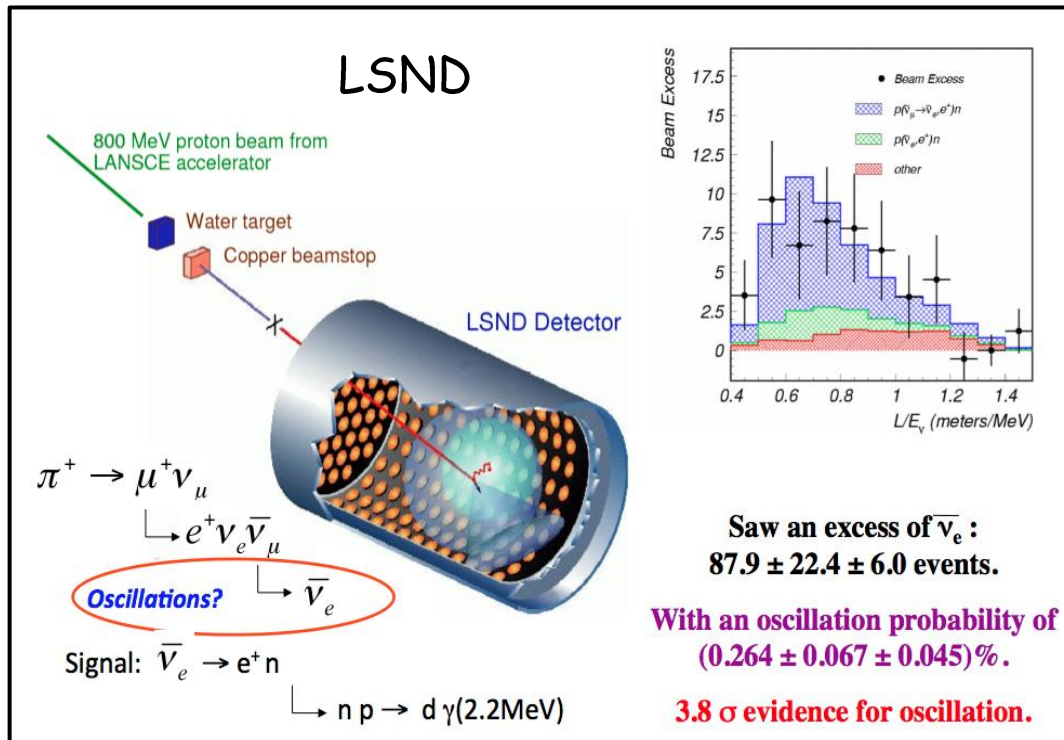


BACKUP SLIDES

“Sterile neutrino puzzle” 1/2

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

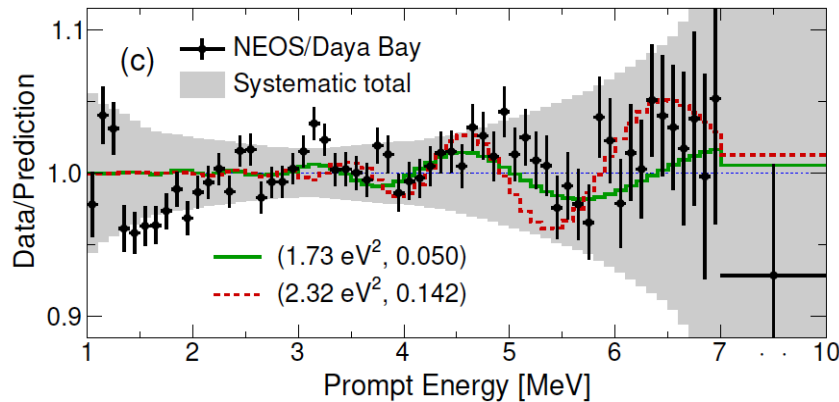
- **appearance of ν_e from ν_μ beams** in accelerator experiments (LSND 3.8σ evidence for oscillation, recent updates from MiniBooNE);
- **disappearance of anti- ν_e** , hinted by near-by nuclear reactor experiments (ratio observed/predicted event rates $R = 0.938 \pm 0.024$);
- **disappearance of ν_e** , hinted by solar ν experiments during their calibration with Mega-Curie sources (SAGE, GALLEX, $R = 0.84 \pm 0.05$).



“Sterile neutrino puzzle” 2/2

Results **hint to a new “sterile” flavor**, described by $\Delta m^2 \sim eV^2$ and small mixing angle, driving oscillations at short distance:

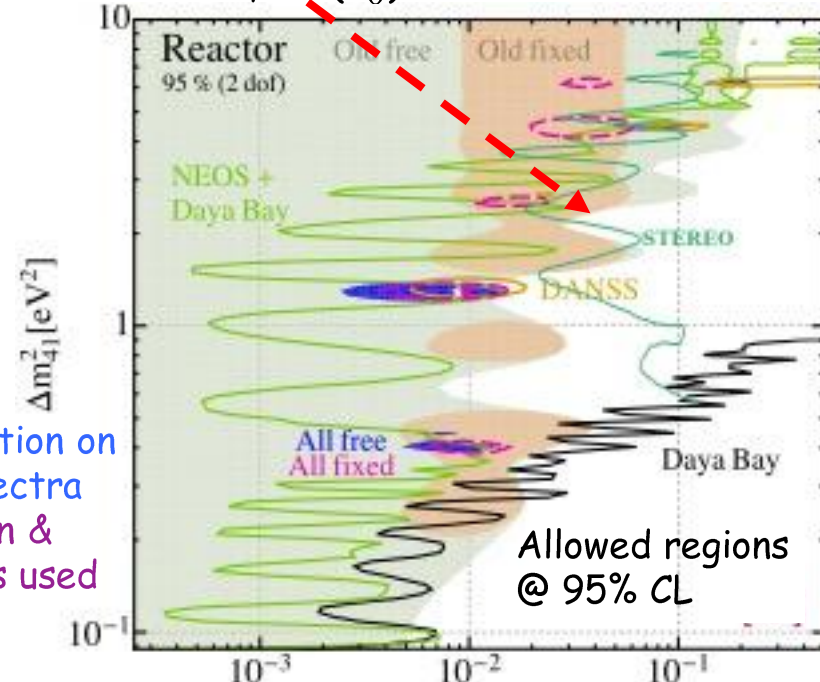
- ICARUS constrained $\Delta m^2_{new} \leq 1 eV^2$, small mixing;
- Planck data and Big Bang cosmology point to at most one further flavor with $m_{new} < 0.24 eV$;
- No evidence of ν_μ disappearance in MINOS and IceCube in 0.32-20 TeV;
- Recent reactor data (especially NEOS) are intriguing but still not conclusive.
- New results are expected from ongoing and upcoming experiments at reactors.



free=no assumption on flux norm. & spectra
 fixed=prediction & published values used

THE EXPERIMENTAL SCENARIO CALLS FOR A DEFINITIVE CLARIFICATION!

Reactor Antineutrino Anomaly best fit value
 $\Delta m^2 \sim 2.4 eV^2$, $\sin^2(2\theta) \sim 0.14$

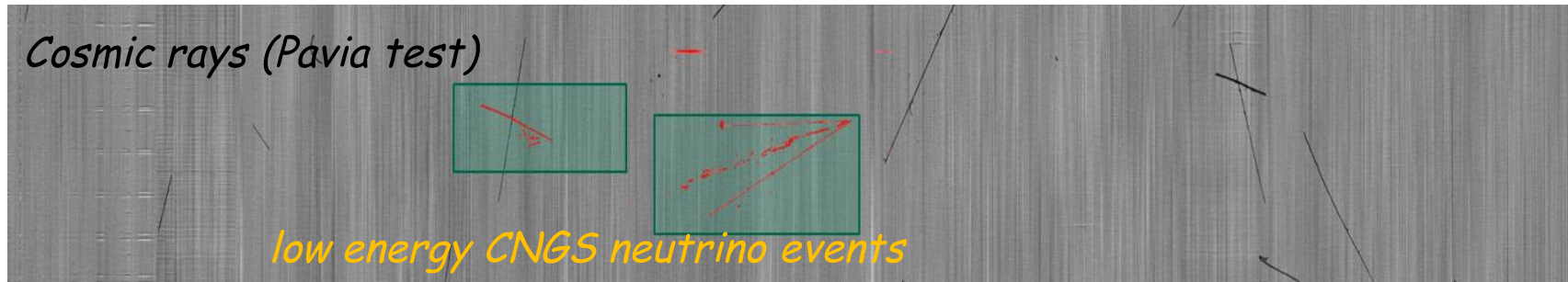


Result presented @ Neutrino2018

Taking data @ shallow depth

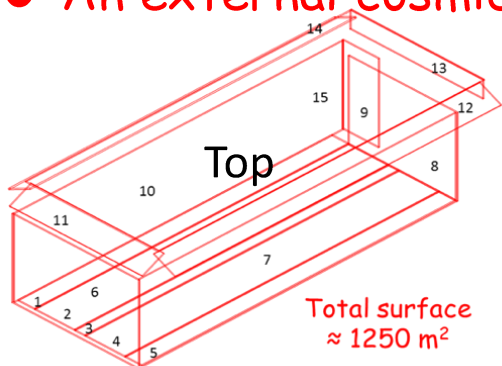
ICARUS at FNAL is facing a more challenging experimental condition than at LNGS, requiring the recognition of ν interactions amongst 11 KHz of cosmic rays.

- A 3 m concrete overburden will remove contribution from charged hadrons/ γ 's.
- $\sim 11 \mu$ tracks will occur per triggering event in 1 ms TPC drift readout: associated γ 's represent a serious background source for ν_e search since e 's produced via Compton scatt./ pair prod. can mimic a genuine ν_e CC.



Rejecting cosmic background, i.e. reconstructing the triggering events, requires to precisely know the time of each track in the TPC image:

- A much improved light detection system, with \sim ns time resolution;
- An external cosmic ray tagger (CRT) to detect incoming particles and measure their direction of propagation by time-of-flight:



- ✓ Scintillating bars surrounding T600 (aim: 98% coverage) equipped with optical fibers to convey light to SiPM arrays.
- ✓ Top coverage under INFN/ CERN responsibility. FNAL is recovering modules by MINOS/Double Chooz for side/bottom.

Cryogenics and Mechanics Upgrades

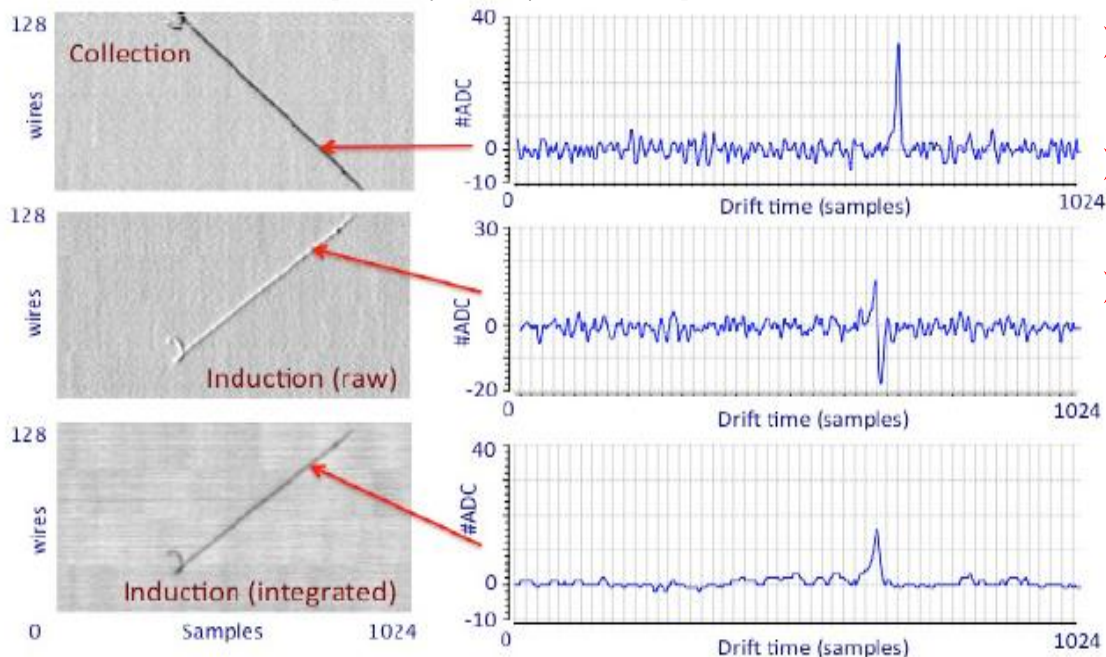
- Purely passive insulation chosen for the installation, coupled to standard two-phase N_2 cooling shield, redesigned and tested at CERN.
- New cold vessels, made of extruded aluminum profiles welded together at CERN.



- Non-perfect planarity of the cathode (up to ~ 25 mm) resulted in field distortions which affects e-drift velocity for particles travelling close to the cathode.
- Cathode panels underwent thermal treatment reducing the non-planarity to within few mm.
- These interventions extend the muon momentum measurement by MCS well above the range required by the next short/long base-line ν experiments.

Improved front-end electronics for T600

- The new T600 analogue front-end features:
 - A faster shaping time $\sim 0.6 \mu\text{s}$ of analogue signals to match electron transit time in wire plane spacing;
 - A drastic reduction of undershoot in the preamp response as well as of the low frequency noise while maintaining a same or better S/N;
 - A same preamp for Induction1,2 and Collection wires allowing dE/dx measurement in Induction2 too.
- In addition the full 400 ns synchronous signal sampling on the whole detector will allow slightly improving the resolution on μ momentum by MCS.



- Same ~ 2 ADC counts ($\sim 1500 e^-$) noise for Collect. & Induct.;
- Unipolar Coll signal: ~ 25 ADC counts; Symmetric bipolar Ind. Signal
- After signal integration by a running sum and baseline restoring, a $S/N \sim 10$ is recognized in Induction view

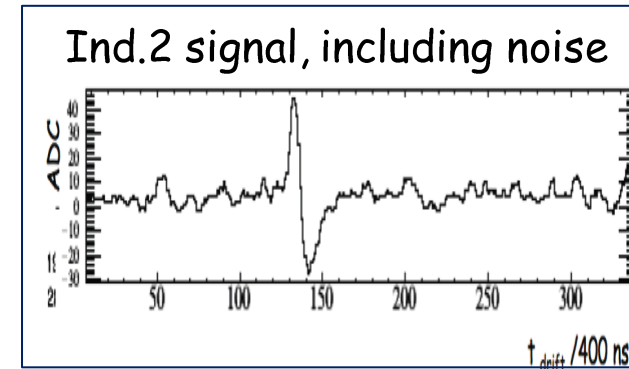
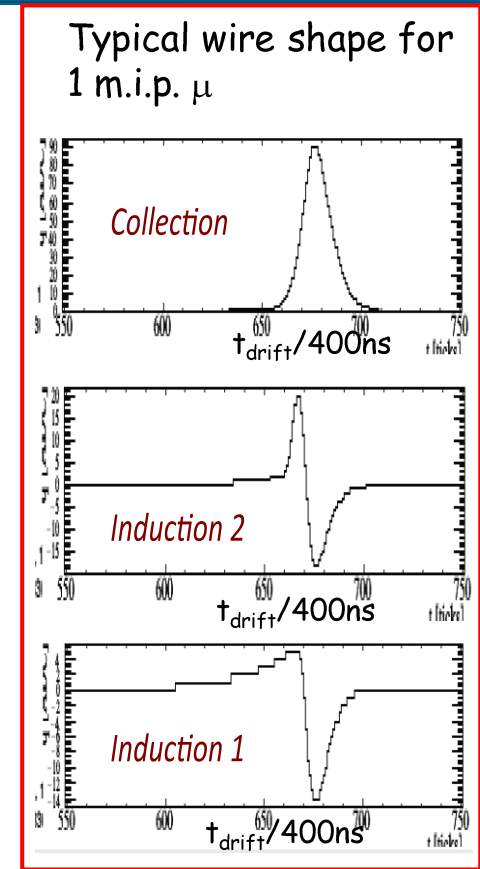
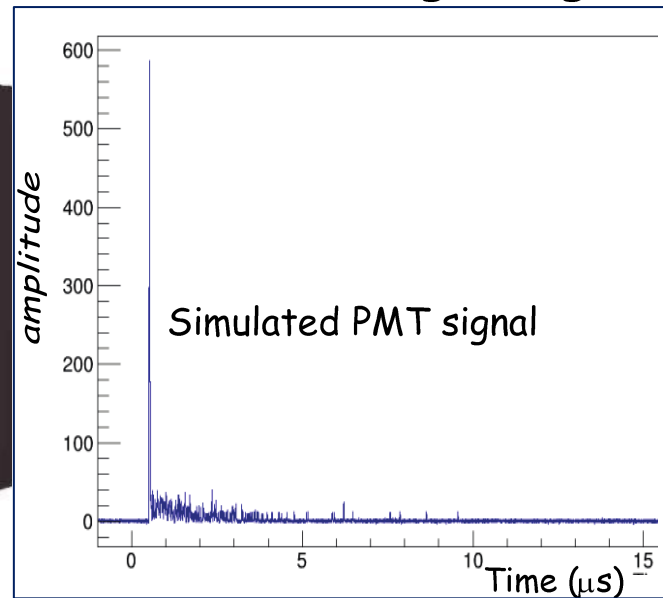
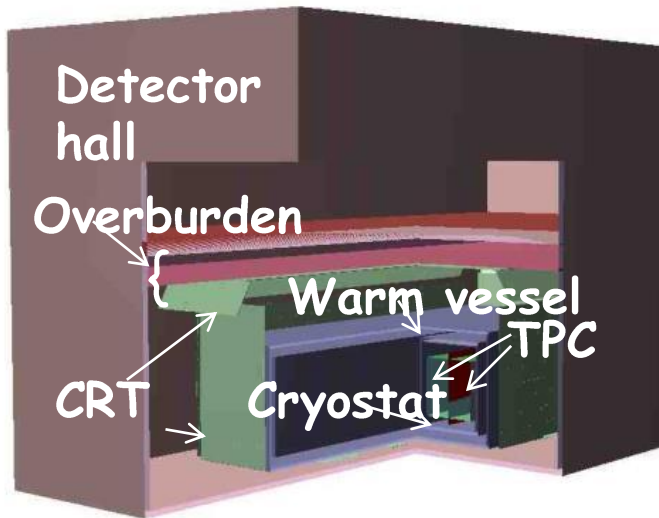
**Better event
reconstruction provided!**

ICARUS Collab. arXiv:1805.03931
Paper submitted to JINST

Single 45° m.i.p. μ track

ICARUS event reconstruction @ SBN

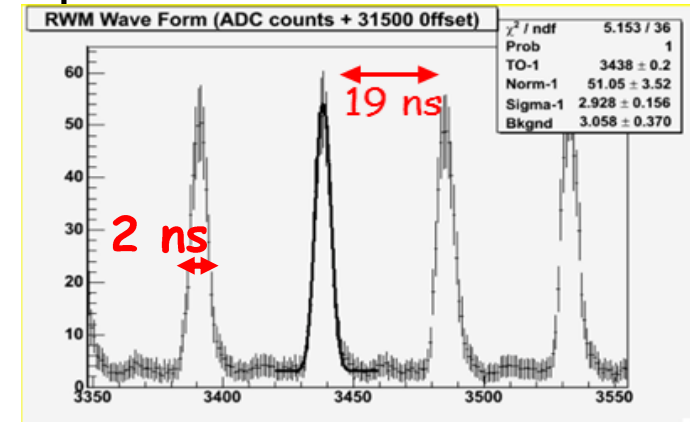
- Common SBN framework (LarSoft) used, providing tools to simulate (Geant4), reconstruct/identify events (cosmic μ 's, e.m. showers, neutrinos, ...).
- Experimental geometry setup is described in LarSoft.
- Scintillation light in LAr is parameterized to simulate PMT signals for any MC event, to study trigger and event recognition.
- MC simulations include new wire electronic response, realistic noise, as well as PMT scintillation light signals.



Software is mature enough to realistically simulate events with BNB beam Slide#: 24

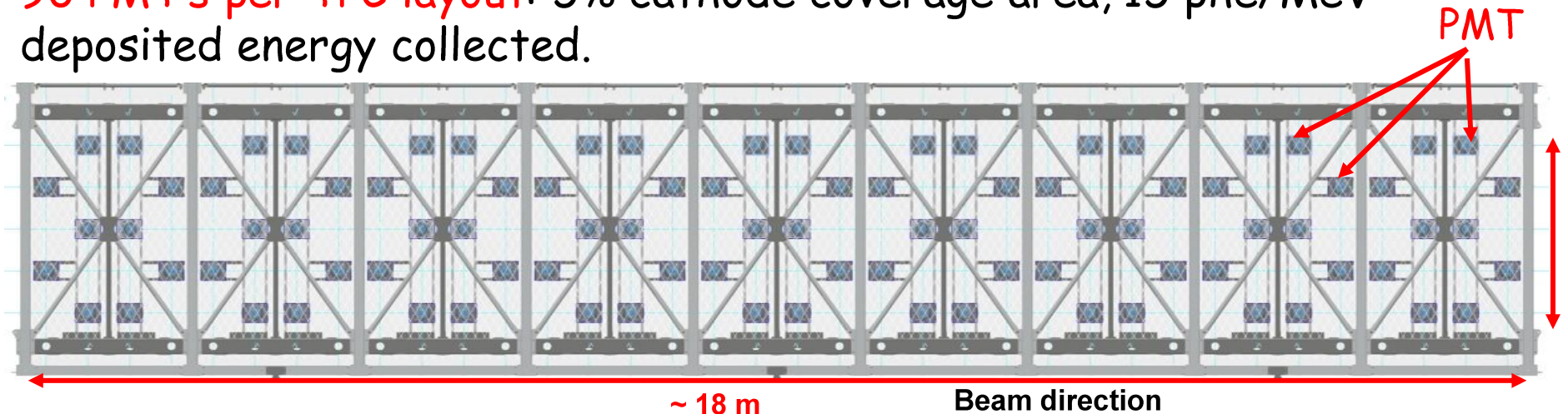
Upgrade of the light collection system

- The T600 light detection system is devoted to:
 - Identify precisely **the time of occurrence (T_0) of each interaction**;
 - Identify the **event topology** for fast selection purposes
 - Generate **a trigger signal** to enable the event read-out by combining:
 - ✓ Pattern/majority of hit PMT signals;
 - ✓ BNB/NuMI bunched beam spill;
 - ✓ Veto from CRT.
- The light collection system is based on 360 PMTs (90/chamber) provides:
 - ✓ High detection coverage, to be sensitive to the lowest-expected neutrino energy deposition in the TPC (approximately 100 MeV), even using the light fast-component only;
 - ✓ High detection granularity and longitudinal resolution is better than 0.5 m.
 - ✓ Fast response time/ high time resolution (≈ 1 ns), with a PMT timing calibration provided by a laser system (Hamamatsu PLP10, $\lambda \sim 450$ nm, FWHM < 100 ps, peak power ~ 400 mW) + 50 μ m optical fiber.
 - ✓ Possible cosmic identification by pattern/time recognition of PMTs.



PMT layout

- 90 PMT's per TPC layout: 5% cathode coverage area, 15 phe/MeV deposited energy collected.



- Hamamatsu R5912-MOD (8", 10 dynodes) rated for cryogenic temperature (cathode with platinum under-layer).
- Each PMT is enclosed in a wire screening cage to prevent induction of PMT pulses on the facing TPC wires.
- PMT glass windows coated by $\sim 200 \mu\text{g}/\text{cm}^2$ of Tetra-Phenyl-Butadiene wavelength shifter to detect the $\lambda = 128 \text{ nm}$ scintillation light in LAr.

