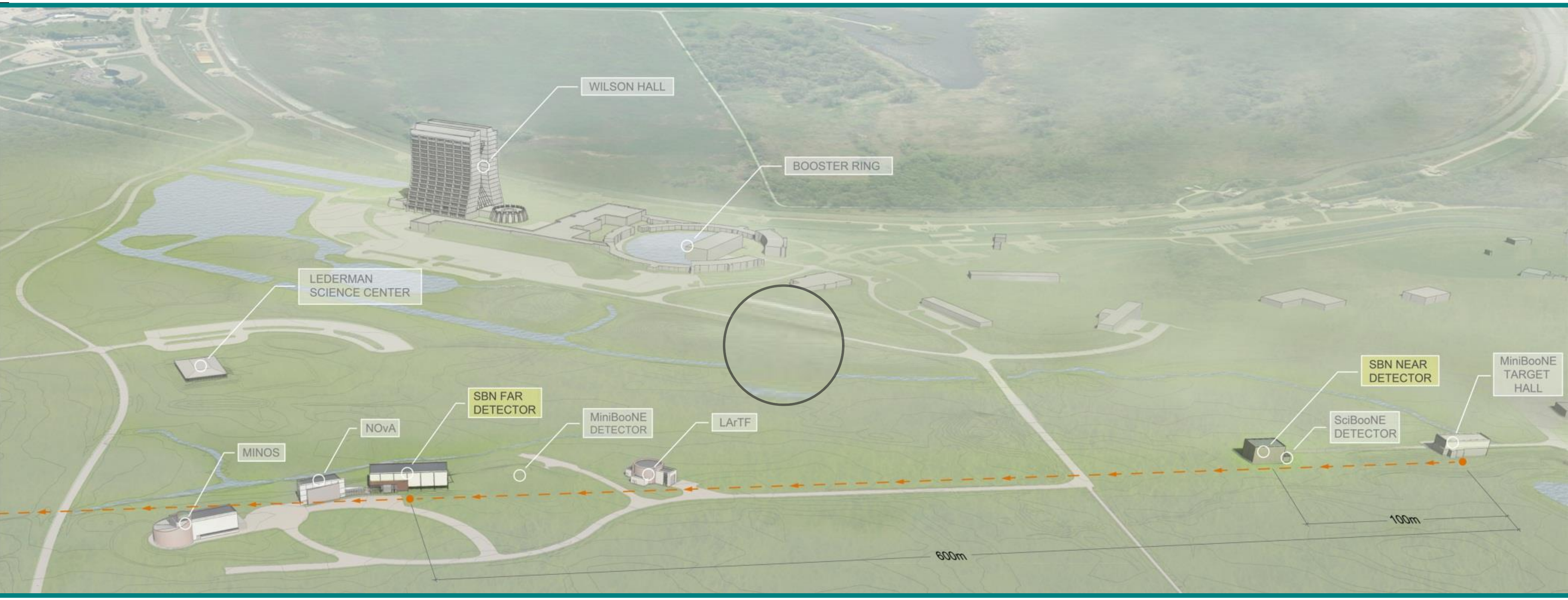
Sterile ν searches with the ICARUS detector

from CNGS to SBN



Andrea Zani (CERN)
on behalf of the ICARUS/NP01/WA104 Collaboration

FLASY 2018, Basel, 2-5 July 2018

Outline

- *ICARUS LAr-TPC technology:*
  ICARUS T600 performance and results @ LNGS;
  Sterile neutrino searches on CNGS data.

- *ICARUS T600 overhauling @ CERN.*

- *Search for sterile neutrinos @ FNAL:*
  the Short Baseline Neutrino Experiment.

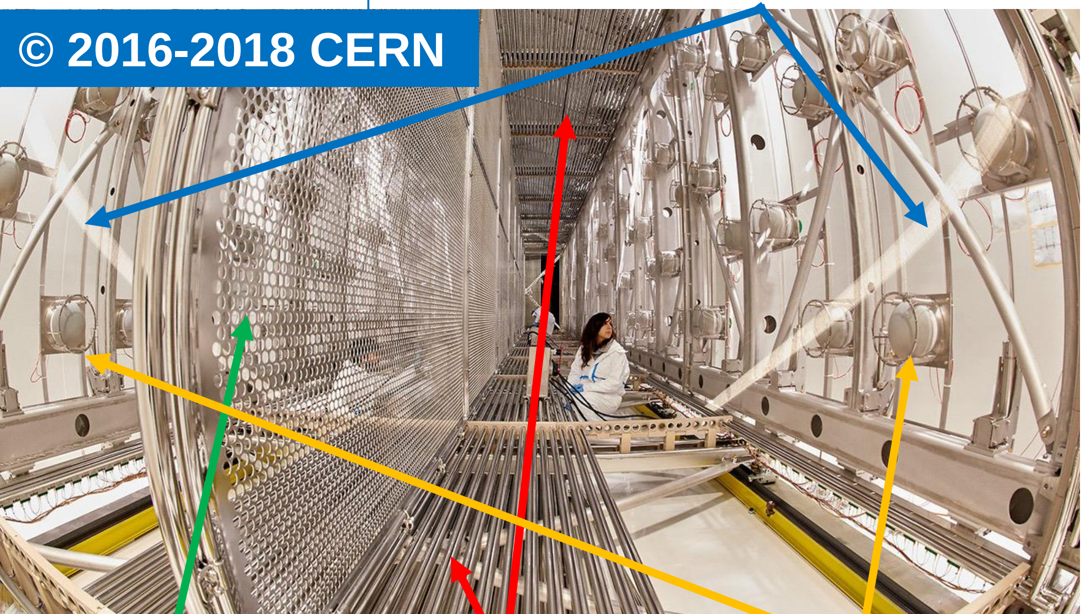
- *T600 current status.*
- *Conclusions.*

ICARUS T600: the first large Liquid Argon TPC

- ICARUS-T600 LAr TPC is a high granularity uniform self-triggering detector with 3D imaging and calorimetric capabilities, ideal for ν physics. It allows accurately reconstructing a wide variety of ionizing events with complex topology.
- Exposed to CNGS beam, ICARUS concluded in 2013 a very successful 3-year 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: 760t total LAr mass / 476t active

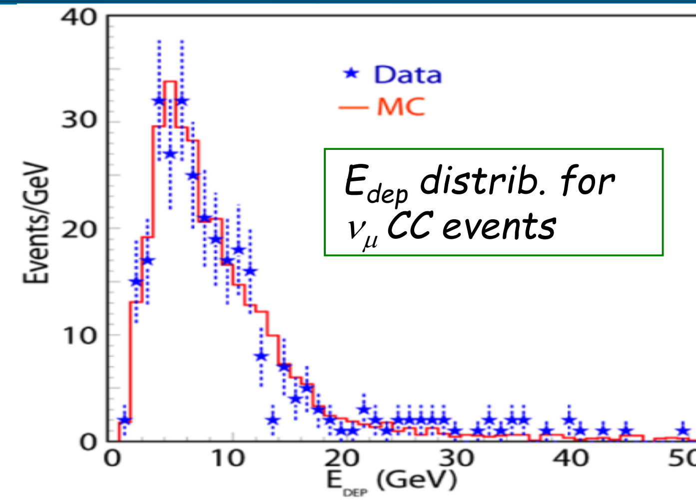
1 T600 module

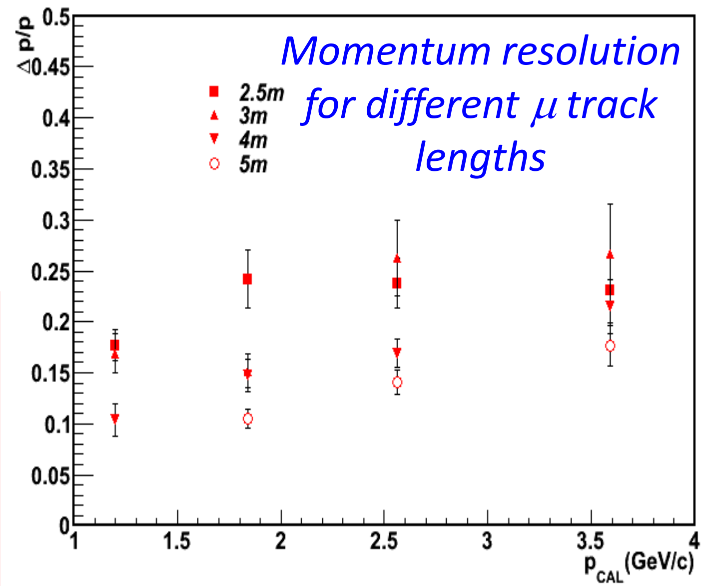


- 2 TPC's per module, with a common central cathode: E_{Drift}= 0.5 kV/cm, v_{Drift}~1.6 mm/μs, 1.5 m drift length;
- 3 "non-destructive" readout wire planes per TPC, ≈54000 wires at 0°, ±60° w.r.t. horizontal: Induction 1, Induction 2 and Collection views;
- Ionization charge continuously read (0.4 μs sampling time);
- 74 8" PMT's, coated with TPB wls, for t_0, timing and triggering.

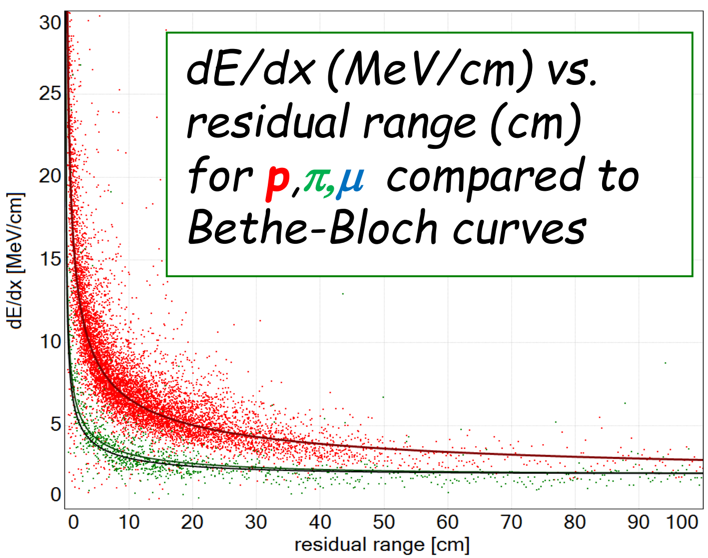
LAr-TPC performance (CNGS ν's and cosmics)

- *Tracking device:* precise 3D event topology, ~1 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 Δp/p ~15%;
- *Measurement of local energy deposition dE/dx:* remarkable e/γ separation (0.02 X_0 sampling, X_0 =14 cm and a powerful particle identification by dE/dx vs range):





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

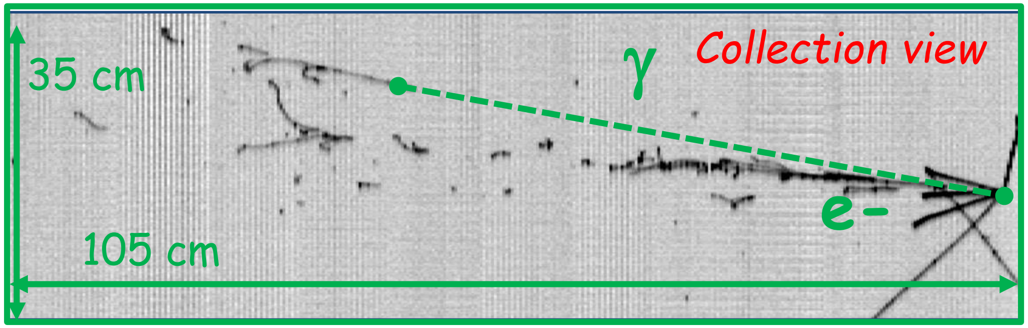


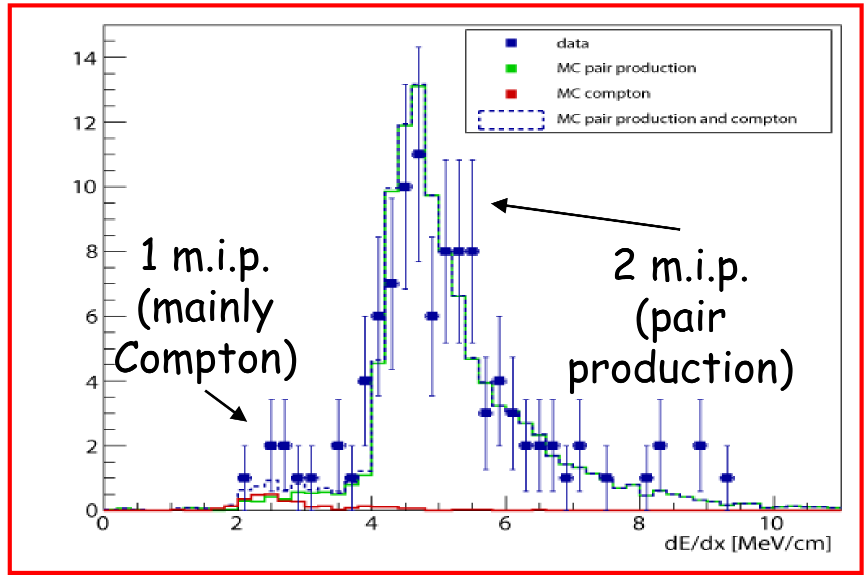
Low energy electrons: σ(E)/E = 11%/√ E(MeV)+2%
Electromagnetic showers: σ(E)/E = 3%/√ E(GeV)
Hadron showers: σ(E)/E ≈ 30%/√ E(GeV)

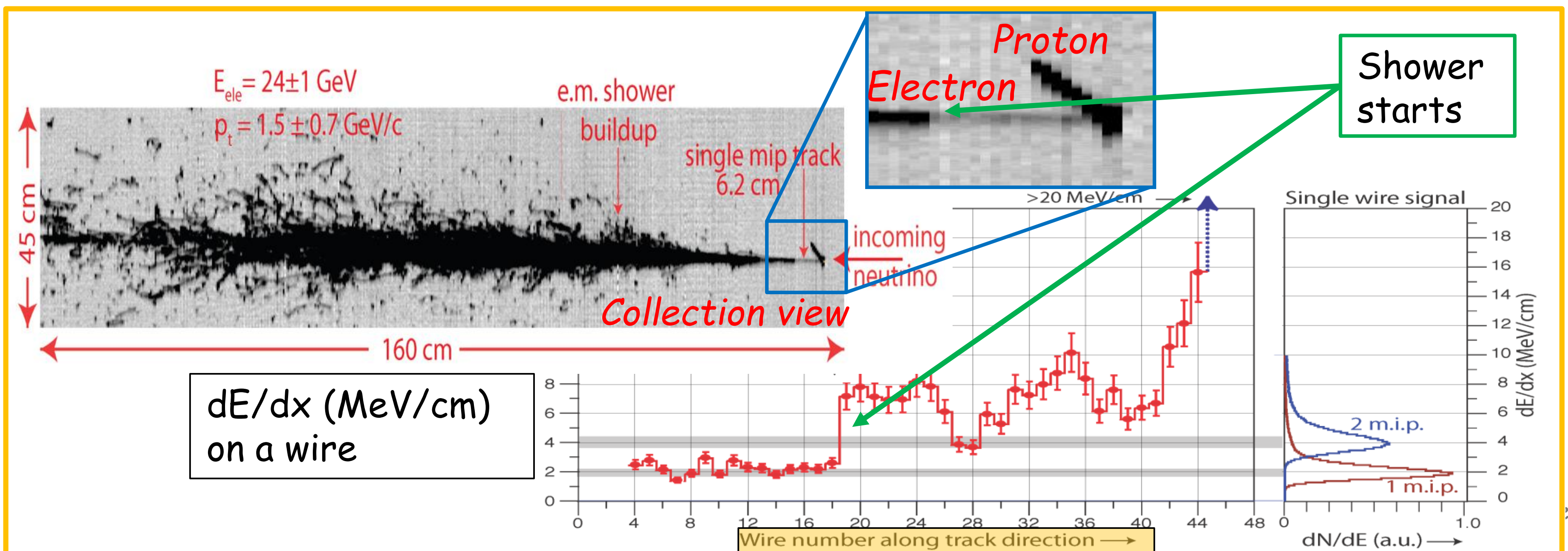
ν_eCC identification in CNGS beam: e/γ separation

Three "handles" to separate e/γ and reject NC background:

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







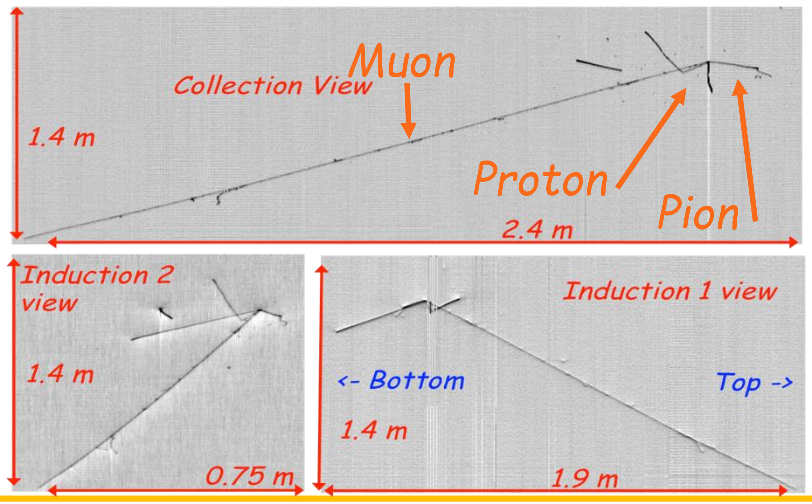
Atmospheric neutrino events @ LNGS

ICARUS collected @ LNGS also atmospheric ν_e and ν_μ CC interactions

These events are particularly suitable to emulate the ν interactions expected with FNAL beams (more on this later) because of the similar energy range

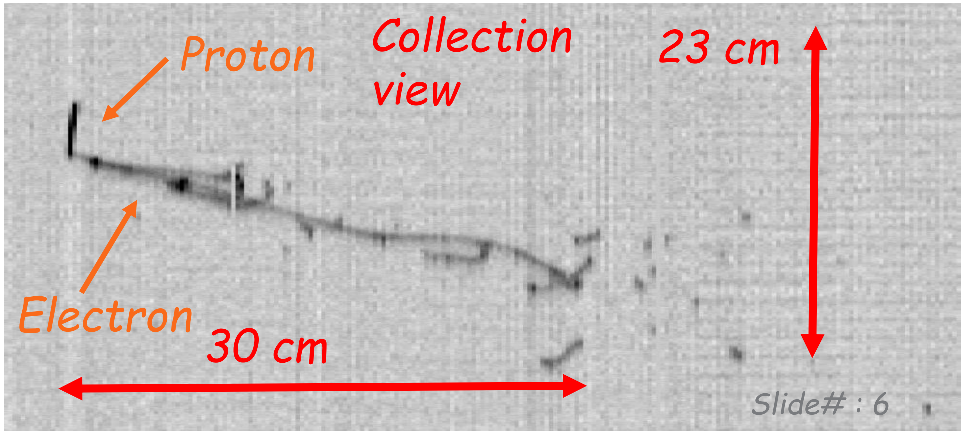
Example of upward-going ν_μ CC even with a deposited energy ~ 1.7 GeV:

- 4m escaping μ, 1.8±0.3 GeV/c from MCS;
- Two pions (E_{dep}~80 MeV) and a proton (E_{dep}~250 MeV) at vertex.
- Reconstructed E_ν~2 GeV with ~78° zenith angle



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

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



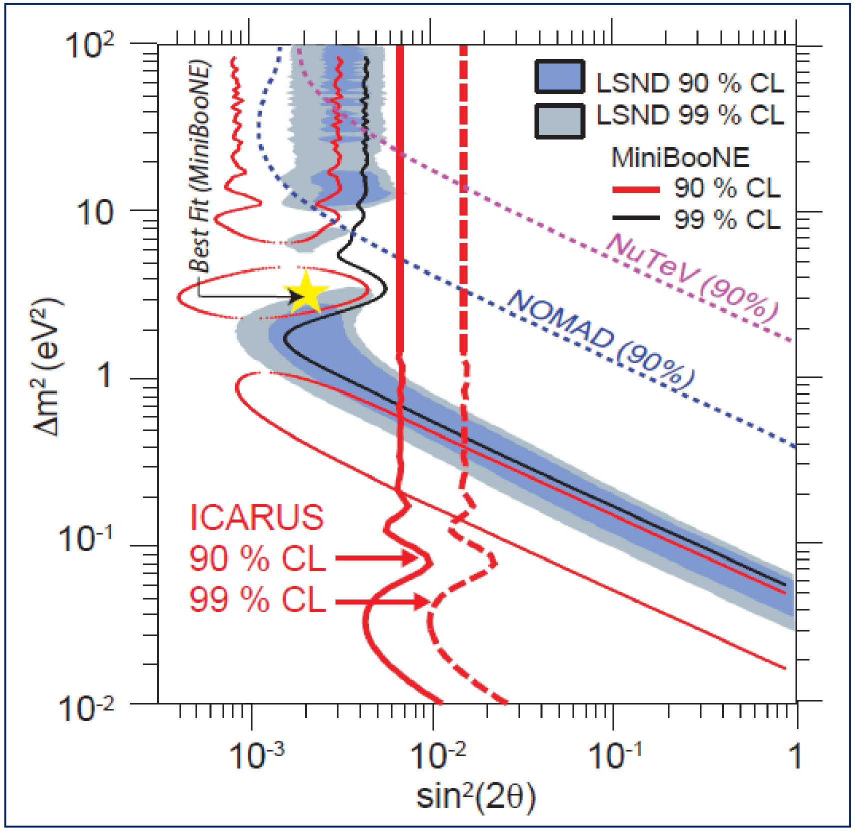
ICARUS LAr-TPC technology achievements

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 τ_{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^o bkg rejection in $\nu_\mu \rightarrow \nu_e$ study to unprecedented level;
- Performed a sensitive search for LSND-like anomaly with CNGS beam, constraining the LSND window to narrow region at:

  $\Delta m^2 < 1$ eV^2, $\sin^2 2\theta \sim 0.005$

  where all positive/ negative experimental results can be coherently accommodated at 90% C.L., confirmed by OPERA.



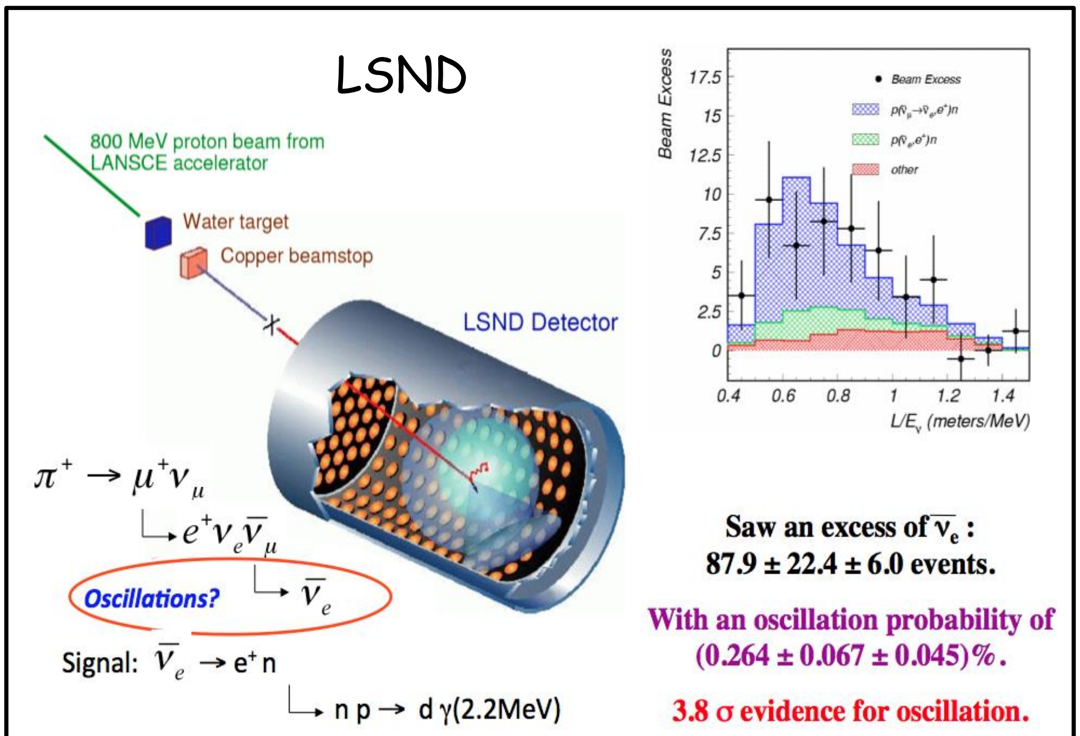
Eur. Phys. J. C (2013) 73:2599

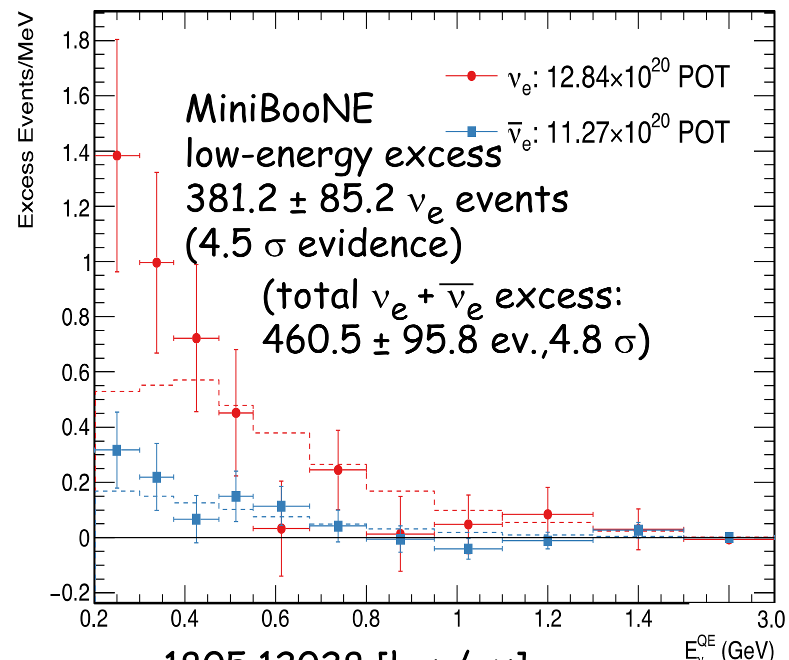
Success of LAr-TPC technology with large impact on neutrino and astro-particle physics projects: Short Baseline Neutrino program at FNAL (SBN) with 3 LAr-TPC's (SBND, MicroBooNE and ICARUS) and the multi-kt DUNE LAr-TPC.

Sterile neutrino puzzle - I

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

- appearance of $\nu_e/\overline{\nu}_e$ from ν_μ beams in accelerator experiments (LSND + MiniBooNE, combined evidence from new MiniBoonE results > 6σ);
- disappearance of $\overline{\nu}_e$, hinted by near-by nuclear reactor experiments (ratio observed/predicted event rates R = 0.938 ± 0.024);
- disappearance of ν_e, hinted by solar ν experiments during their calibration with Mega-Curie sources (SAGE, GALLEX, R = 0.84 ± 0.05).





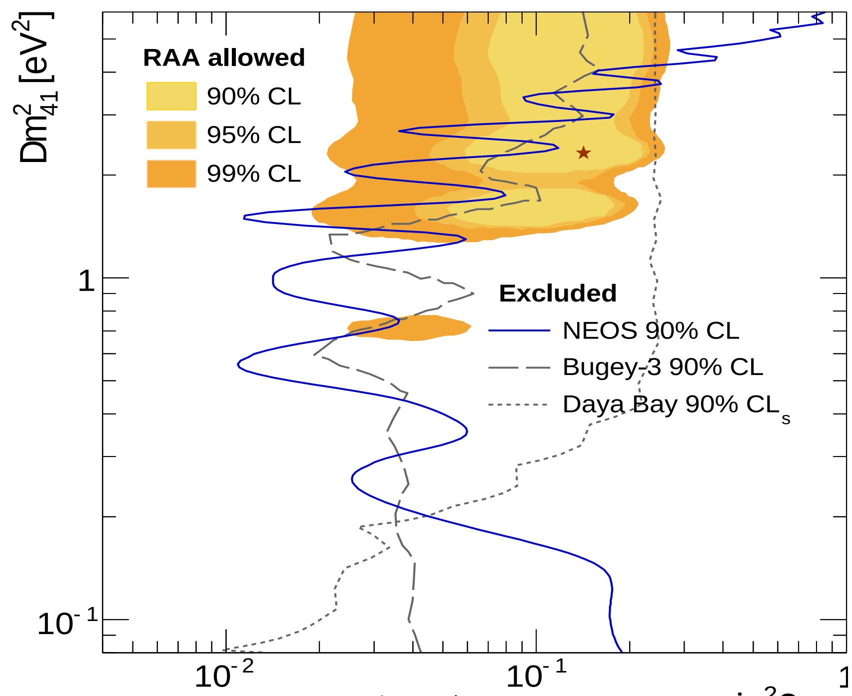
1805.12028 [hep/ex]

Sterile neutrino puzzle - II

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 (NEOS, DANSS) can be inserted in 3+1 frameworks supporting one sterile neutrino, but they are not conclusive.
- ν_e appearance results of accelerator-based experiments are in tension with mentioned ν_μ disappearance data.

Reactor Antineutrino Anomaly



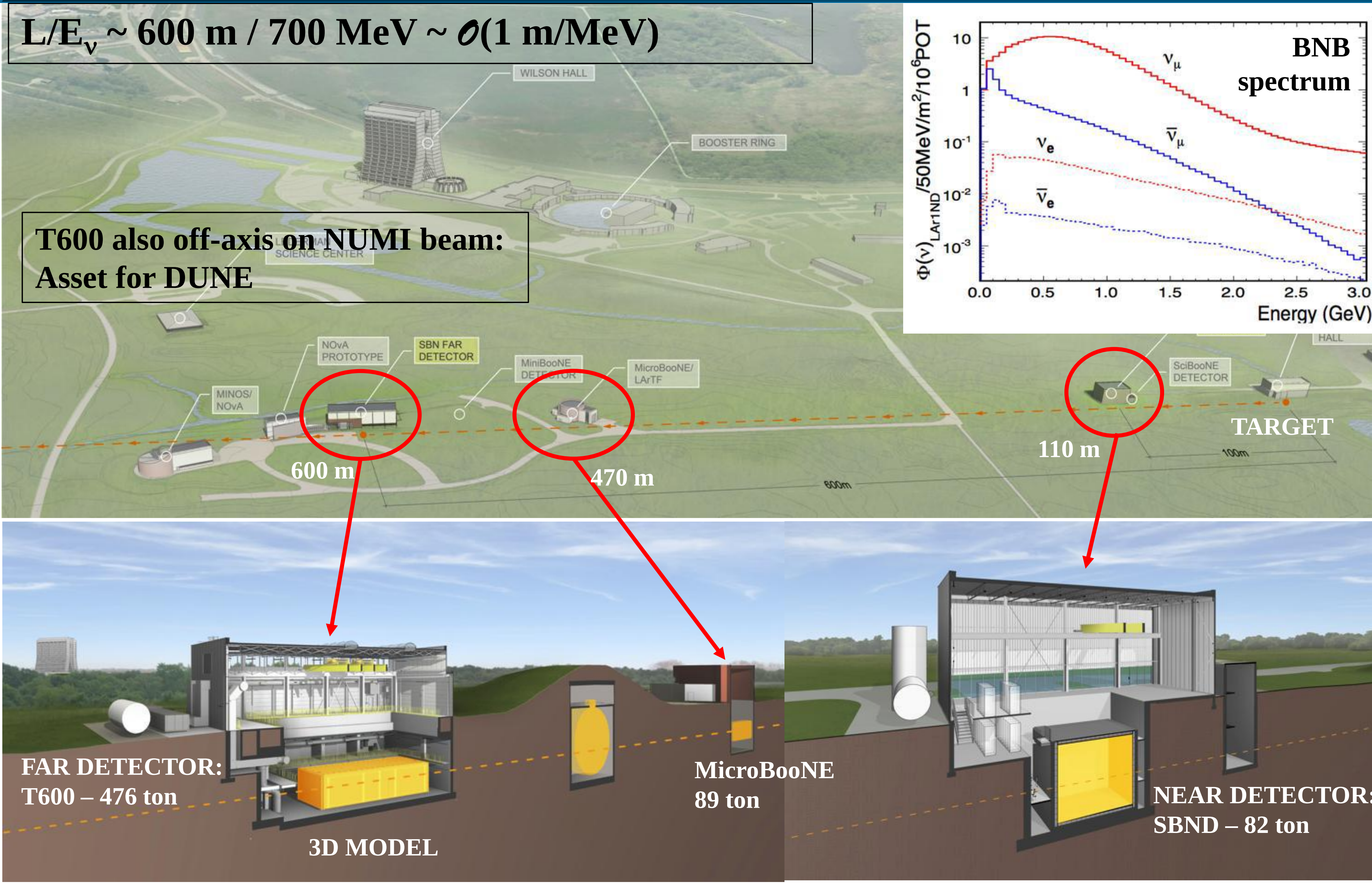
1610.05134 hep/ex

THE EXPERIMENTAL SCENARIO CALLS FOR A DEFINITIVE CLARIFICATION!

Short Baseline Neutrino (SBN) in a nutshell

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

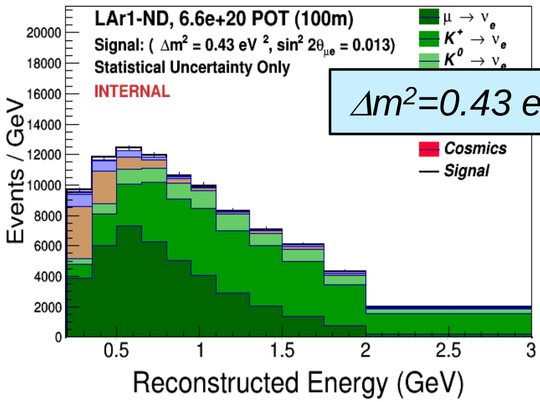
T600 also off-axis on NUMI beam:
Asset for DUNE



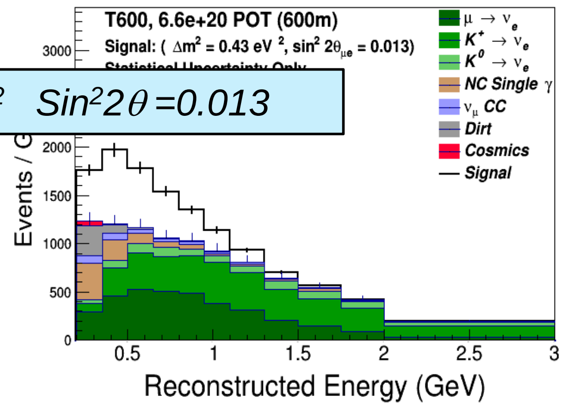
Appearances and disappearances, 6.6×10^{20} pot (3 years)

LSND 99%CL region covered at ~5σ in ν_e app.

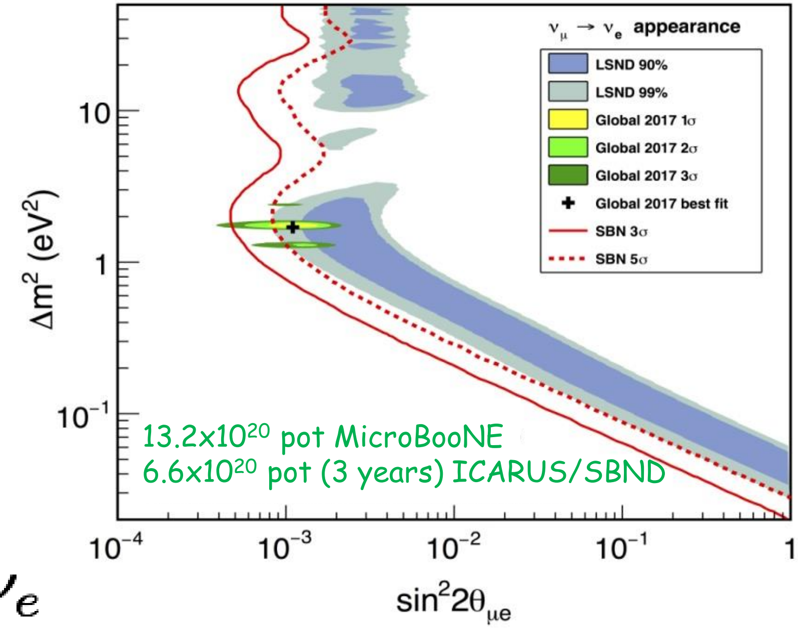
SBND @ 110 m



ICARUS-T600 @ 600 m



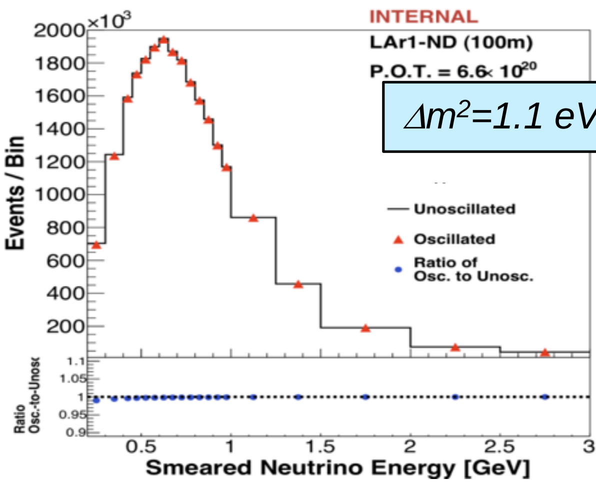
Δm^2=0.43 eV^2 Sin$^2 2\theta$=0.013

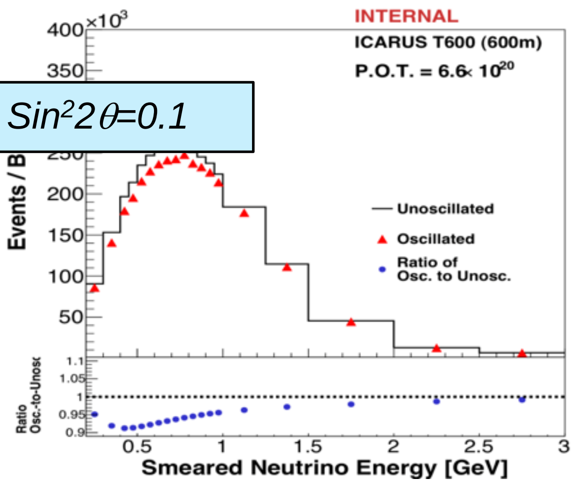


$$\sin^2(2\vartheta_{\mu e}) \le \frac{1}{4}\sin^2(2\vartheta_{\mu x})\sin^2(2\vartheta_{ex})$$

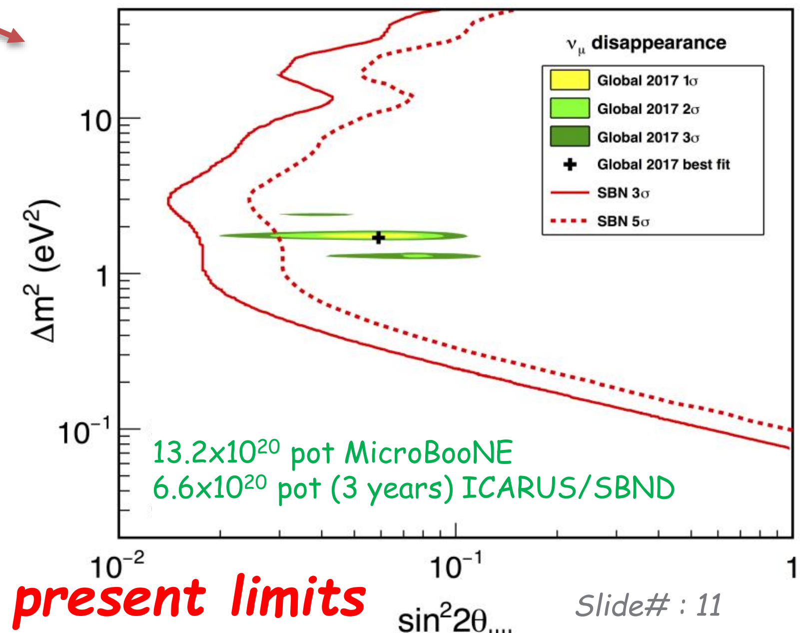
$$\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$$

arXiv: 1703.00860 [hep-ph]





Δm^2=1.1 eV^2 Sin$^2 2\theta$=0.1

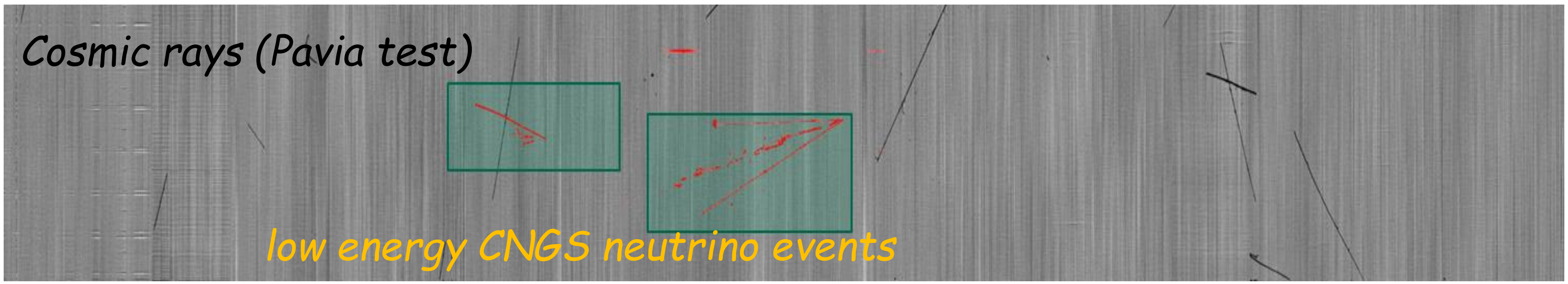


Sensitivity in ν_μ dis. extended by factor10 wrt present limits

Taking data @ shallow depth

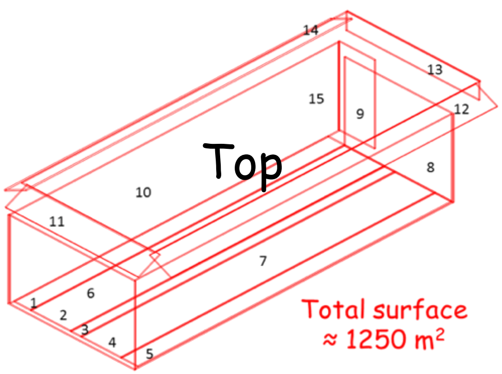
ICARUS at FNAL is facing a more challenging experimental condition than at LNGS, requiring the recognition of ν interactions amongst 11 KHz of cosmic rays.

- *A 3 m concrete overburden* will remove contribution from charged hadrons/γ's.
- *~11 μ 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 scattering/pair production can mimic a genuine ν_e CC.*



Rejecting cosmic background, i.e. identifying the triggering events, requires to precisely know the time of each track in the TPC image. This is achieved with:

- *A much improved light detection system, with ~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 PM arrays.

✓ Top coverage under INFN/ CERN responsibility. FNAL is recovering modules by MINOS/Double Chooz for side/bottom.

T600 Overhauling at CERN (WA104/NP01)

ICARUS T600 detector underwent an intensive overhauling at CERN in 2015/17 in the framework of CERN Neutrino Platform (WA104/NP01 project) before being shipped to FNAL:

- *New cold vessels,* purely passive insulation;
- *Renovated cryogenic / LAr purification* equipment;
- *Flattening of TPC cathode*: few mm planarity;
- *Upgrade of light collection system*;
- *New higher performance TPC read-out electronics*

T600 leaving from CERN June 12th 2017

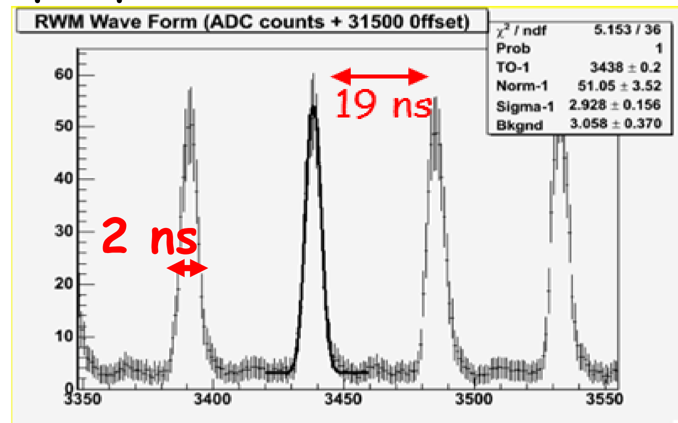
T600 in Antwerp: unloading from barge from Basel and loading into ship to Burns Harbor (Michigan lake)

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

Light collection system - I

In ICARUS, light collection is used 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

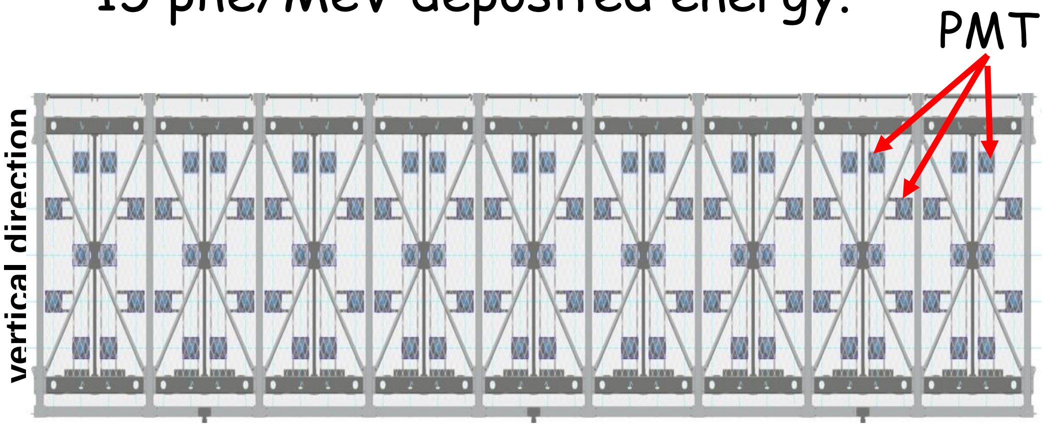


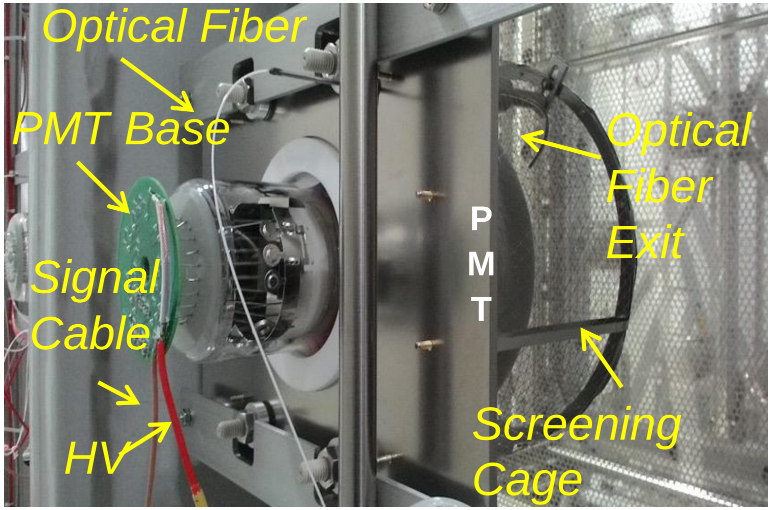
The light collection system is based on 360 PMT's, 90/chamber, to have:

1. High detection coverage, to be sensitive to the lowest-expected neutrino energy deposition in the TPC (approximately 100 MeV), also using the light fast-component only;
2. High detection granularity, longitudinal resolution is better than 0.5 m (effective Q.E. = 5%).
3. Fast response time/ high time resolution (≈1 ns), with a PMT timing calibration provided by a laser system (Hamamatsu PLP10, λ~450 nm, FWHM<100 ps, peak power ~400 mW) + 50 μm optical fiber.

Light collection system - II

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





- Hamamatsu R5912-MOD (8", 10 dynodes) are rated for cryogenic temperature, as they feature a 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 sand blasted glass windows coated by ~200 $\mu g/cm^2$ of Tetra-Phenyl-Butadiene (TPB) wavelength shifter to detect the λ = 128 nm scintillation light in LAr.

A clear cosmic μ's identification (vs elm showers) will be achieved with neural networks (~2% expected residual misidentification).

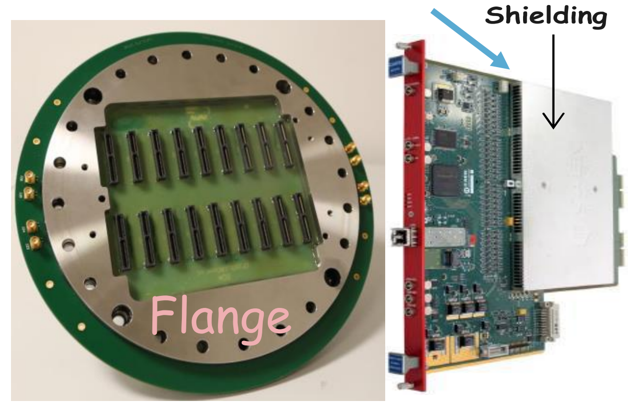
New TPC read-out electronics

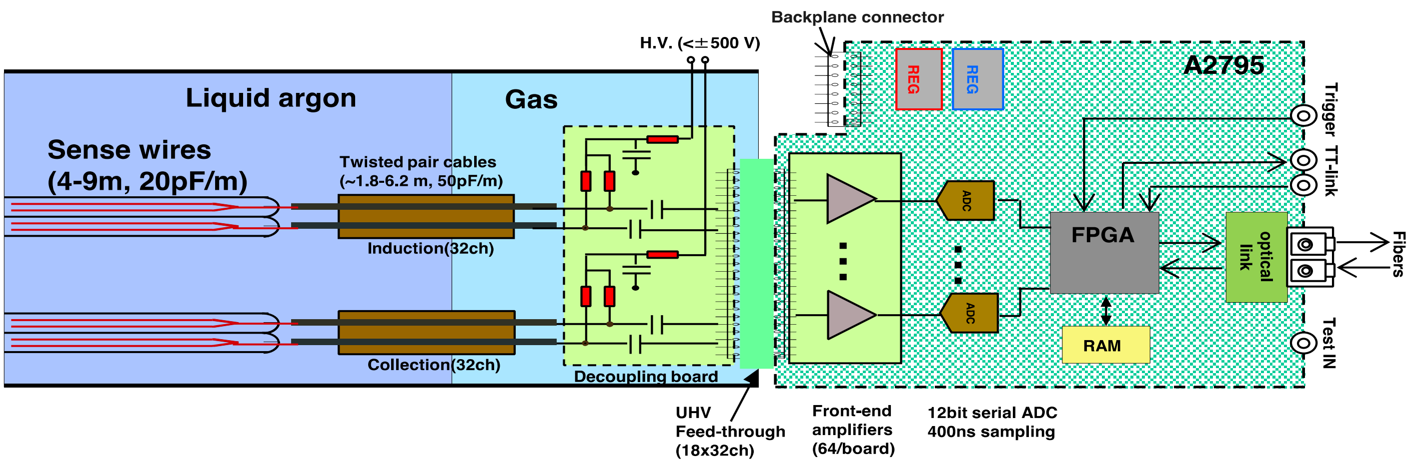
- ICARUS electronics at LNGS was based on analogue low noise "warm" front-end amplifier, a multiplexed 10-bit 2.5 MHz ADC and a digital VME module for local storage, data compression, trigger information:

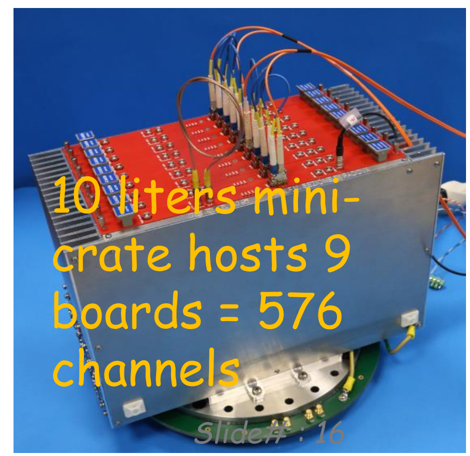
  S/N ~9 in Collection, ~0.7 mm single hit resolution, resulting in a precise spatial event reconstr. and μ momentum measurement by MCS.

- Improvements concern:
  → *Serial 12 bits ADC*, one per ch, 400 ns sampling synchronous on the whole detector;
  → *Serial bus architecture* with Gbit/s optical links to increase the bandwidth (10 MHz);
  → Both analogue/digital electronics are housed in a single board inserted in a new mini-crate directly installed on ad-hoc signal feedthrough flanges

CAEN A2795 board, 64 chs



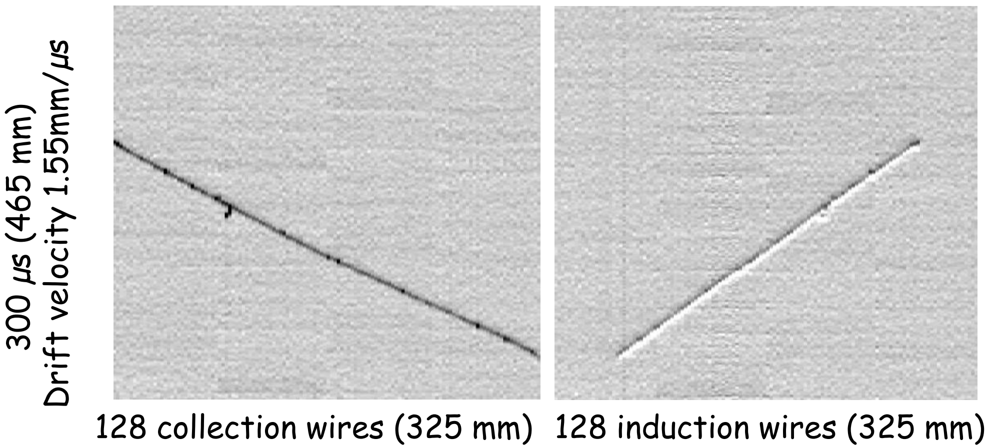




Improved front-end for T600 (tested at CERN)

- Adopted improvements in the analogue front-end:
  - → faster shaping time ~1.5 μs of analogue signals to match electron transit time in wire plane spacing;
  - → drastic reduction of undershoot in the preamp response as well as of the low frequency noise, while maintaining same or better S/N;
  - → same preamplifier for Ind/Coll planes, so induction view can be used for dE/dx measurement as well.

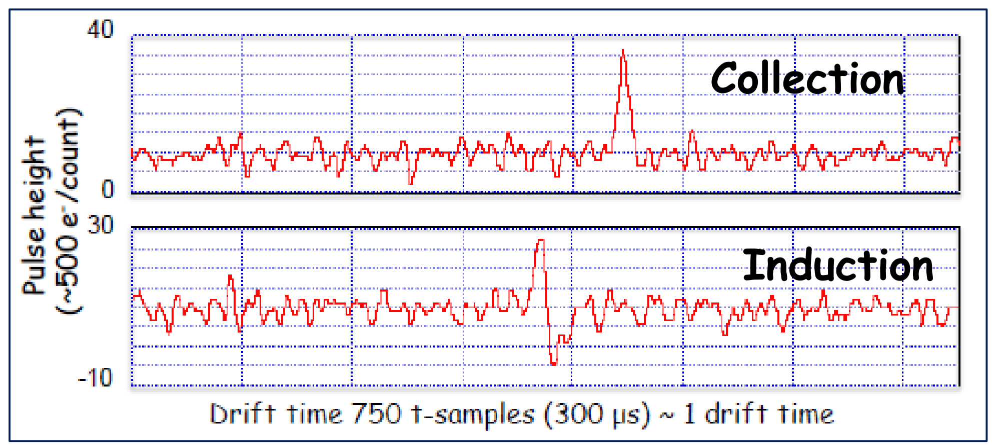
A better event reconstruction is then possible



- Unipolar Coll signal: ~ 25 ADC counts;
- Symmetric bipolar Ind. Signal;
- No filter applied to any data.

Example of single m.i.p. track:

- Cosmic μ's collected with 50l LAr-TPC (FLIC) at CERN;
- Same ~2ADC counts (~1000 e-) noise for both Collect. & Induct.;

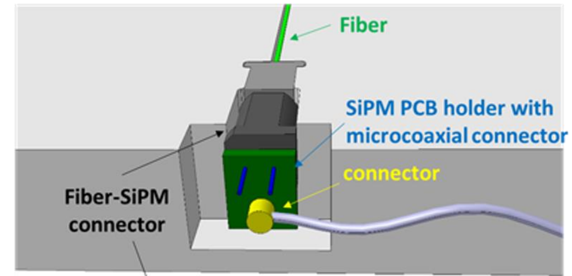


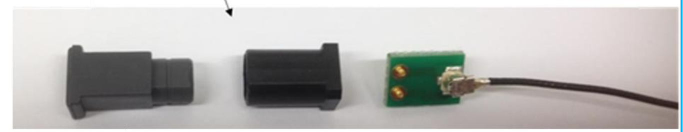
Cosmic Ray Tagger – Top section

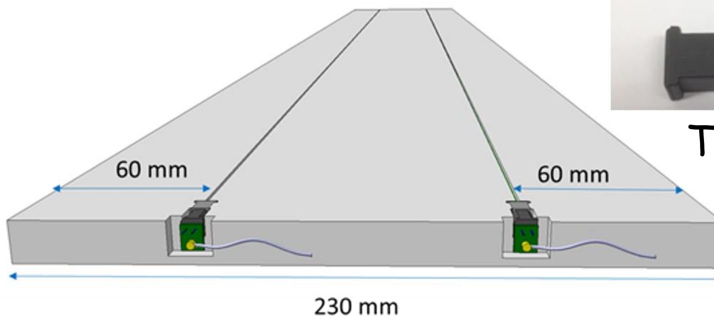
84 + 38 modules.
Each module has 8(X) + 8(Y) bars for 2D localization.
Around 2000 bars in total.

Bar production and quality controls in two stations:

- Prague (NUVIA bars);
- Dubna (bars from ISMA, Kharkov, Ukraine).

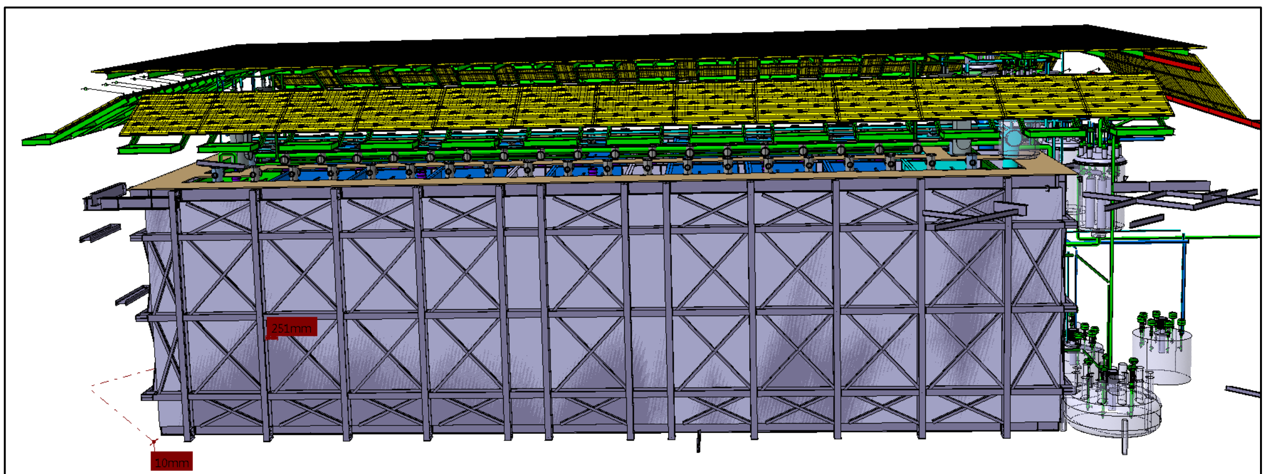






Top CRT single module detail
Bars painting @ CERN
Assembly @ INFN-Bo/LNF

Fibers: Kuraray Y11, multiclad, Ø = 1 mm



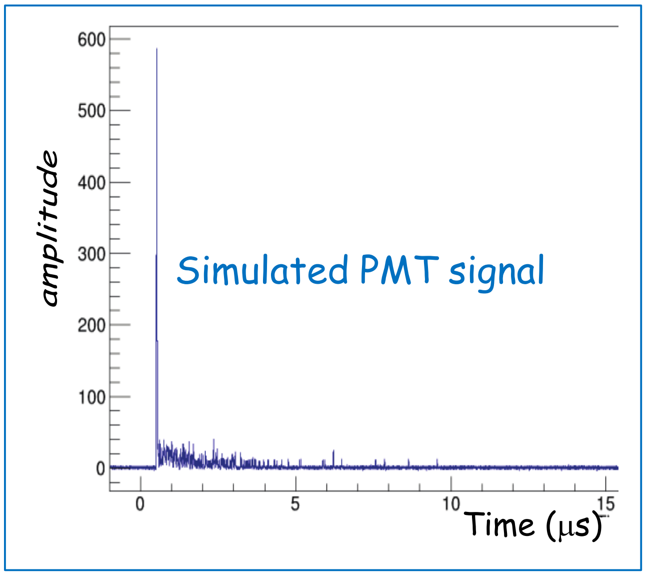
SiPMs: Hamamatsu MPPC S13360-1350CS, active area of 1.3 x 1.3 cm^2.

Module production underway.

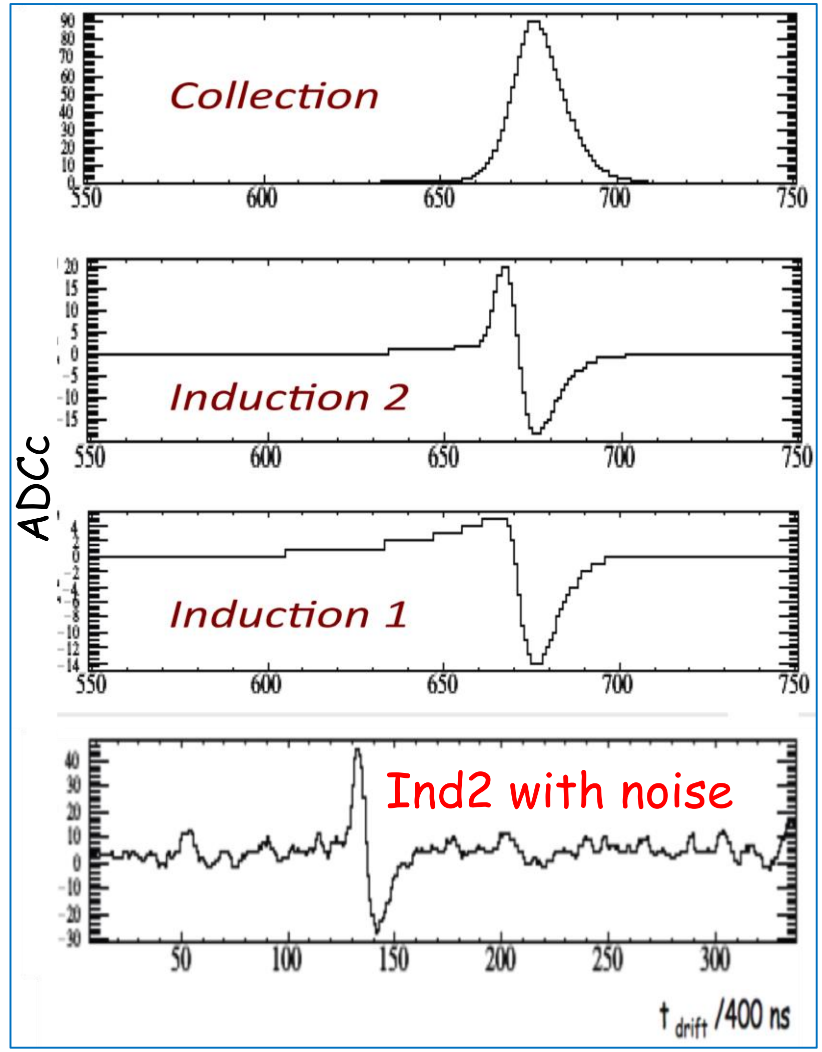
Estimated tagging efficiency of the Top-CRT alone is 80%.

T600 @ SBN software status - I

- Common SBN framework (LarSoft) provides tools to simulate, reconstruct/identify events (cosmic μ's, elm showers, neutrinos, …).
- Exp. geometry setup is described in LarSoft.
- Some reco/analysis tools inherited from LNGS ICARUS software and ported to LarSoft.
- LAR scintillation light simulated for studies on event recognition with neural networks, and trigger configuration.



Typical Signal Shape – m.i.p. μ (ADCc)

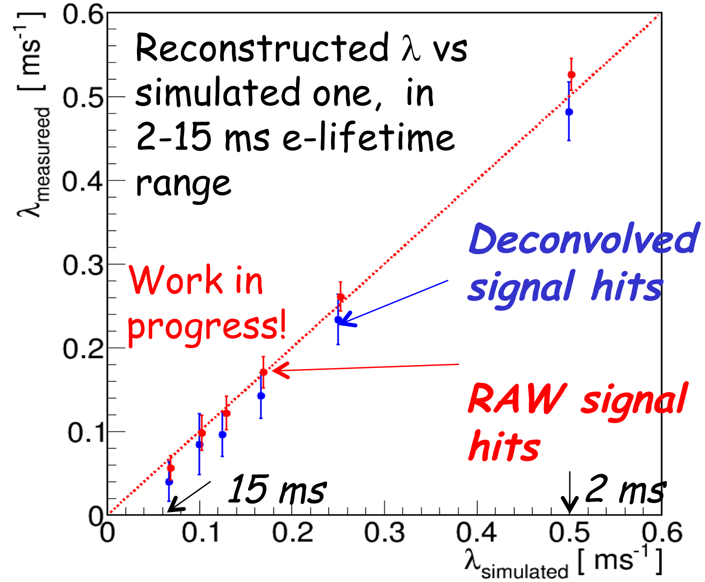


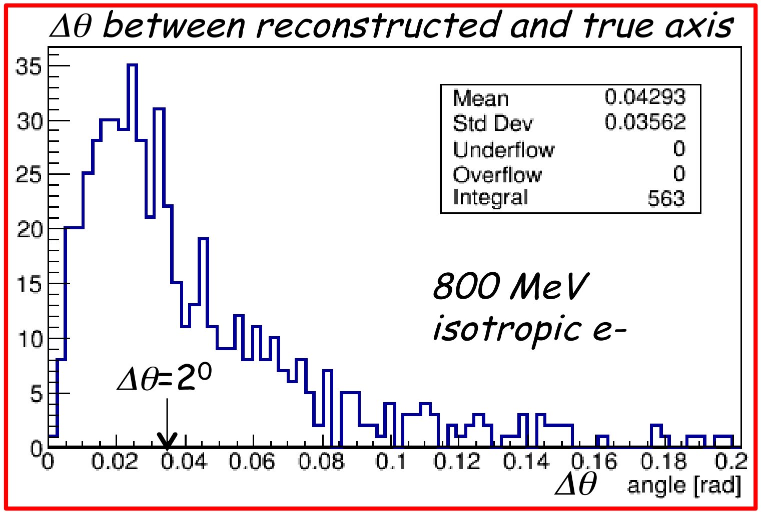
- MC simulations include new wire electronic response/realistic noise, as well as PMT scintillation light signals.

T600 @ SBN software status - II

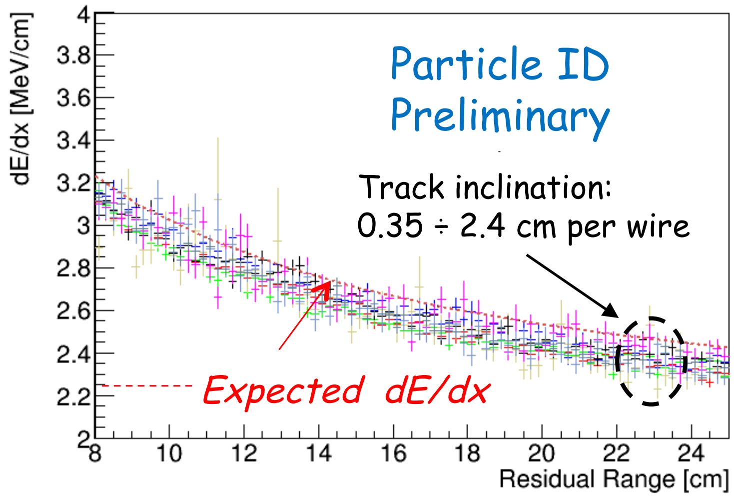
Some advanced tools already ported in LarSoft:

- LAr purity $\lambda=1/\tau_{ele}$ (τ_{ele}: electron lifetime) measurement from charge attenuation of cosmic μ's tracks along the drift
  ➔ Track selection at shallow depth difficult due to crowded events and lower energy μ's
- Particle ID, based on dE/dx vs range
- Electromagnetic shower axis identification
  ➔ Provides 3D reconstruction of shower





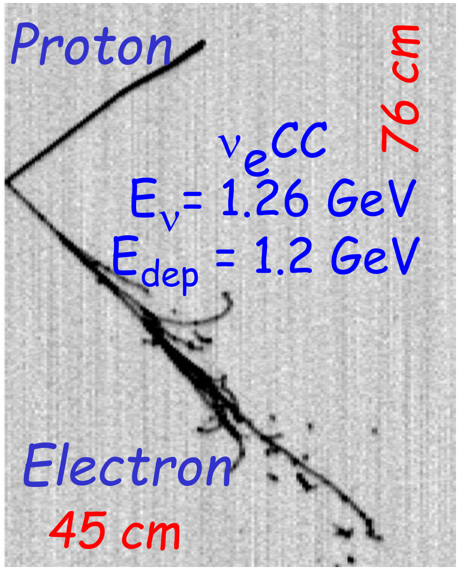
dE/dx vs range for μ's

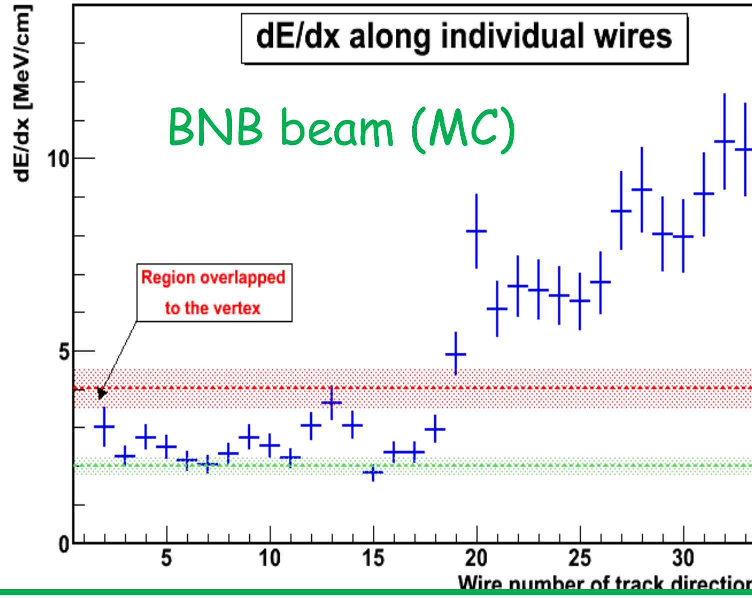


Software is mature enough to realistically simulate events with BNB beam

BNB (MC) and real atmospheric ν_eCC events comparison

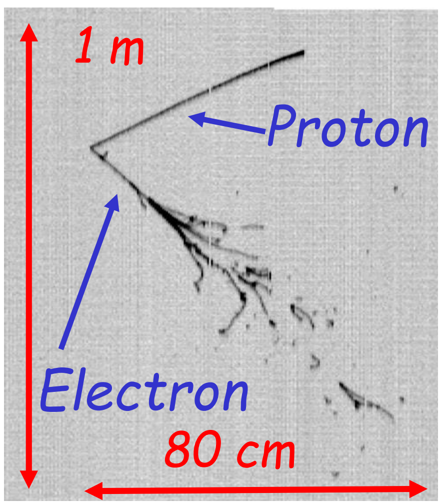
MC SBN ν_eCC interactions

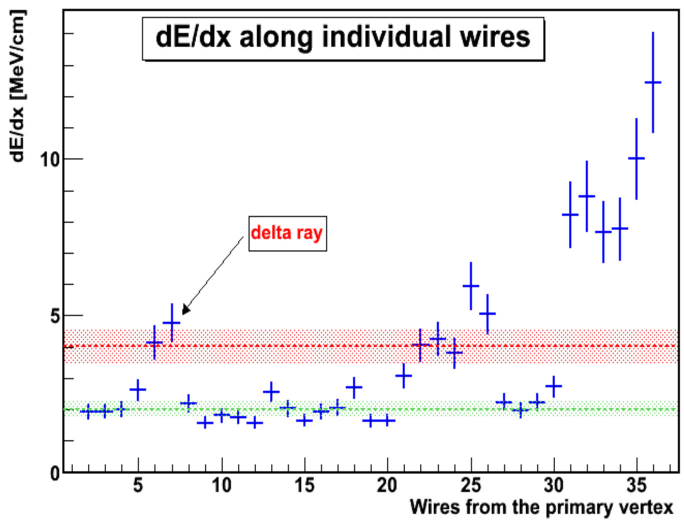




- very alike to typical **atmospheric ν_eCC events @ LNGS** (below)
- Similar results hold for ν_μCC interactions

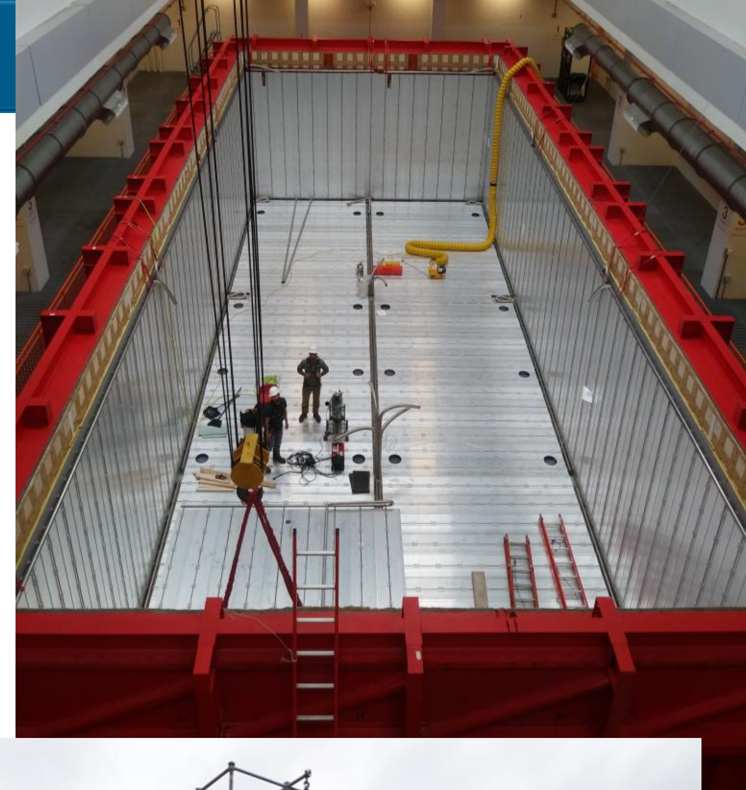
LNGS ν_e ATMOSPHERIC EVENT





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

T600 @ FNAL – Status



- Warm vessel floor/walls were assembled inside the Far Detector (FD) building at FNAL by summer 2017.
- 14 modules of the bottom CRT (200 m^2 total area) were installed by summer 2017.
  - → Each module (4m x 1.6m x 3.2cm) consists of 2 layers of 32 parallel scintillator strips (5 cm width), read out by a 64-pixel multi-anode PMT.
- Assembly of cold shields; installation of bottom/side completed by May/June 2018.
- Installation of detector supports is in progress. As of May 30^{th}.
- Main vessels doors must be welded to main bodies: Welding is in progress. Helium leak tests will follow (June 2018).

"Caged" ICARUS, waiting cover to start doors welding

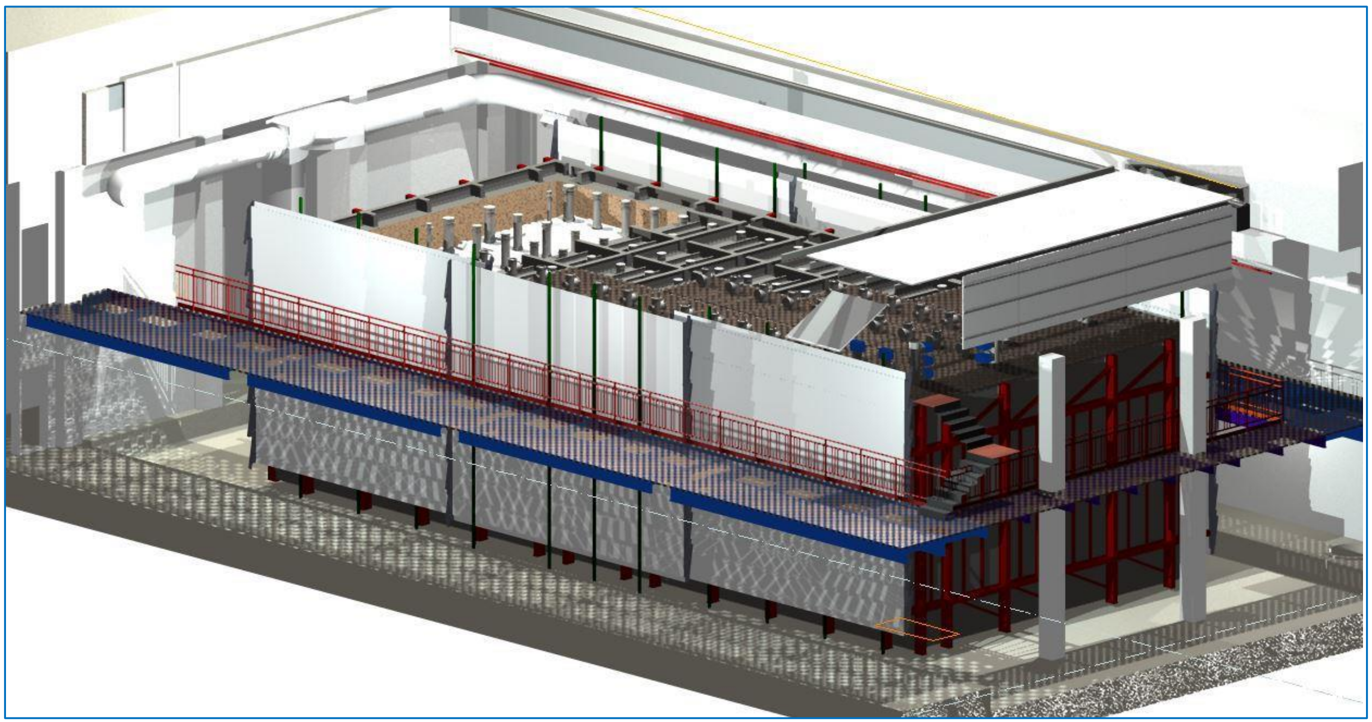
T600 @ FNAL – 2018 plans

- Cold Vessels will be equipped with strain gauges for monitoring of stress during vacuum/cool-down/filling. Validation of mech. engineering models very useful also for next-gen LAr-TPC experiments (DUNE) – July 2018.
- Detectors insertion in Warm Vessel – End of July 2018.
- Chimney installation for electronics housing, followed by connectivity/ /continuity tests (from cold vessels to outside of thermal insulation).
- Top part of cold shield will be installed and tested, followed by installation of top part of warm vessel (starting Aug-Sep 2018).
- Read-out board production should start in fall for side CRT (double layer, ~1000m^2 total):

  → each module (8m x 80.5cm x 1 cm) has 20 parallel scintillator strips, SiPM-based readout.
- From Fall 2018, activities on top of detector will start (installation of cryo, purification and vacuum systems, ext. cabling, read-out & decoupling boards, feedthrough flanges, optical fibers,…).
- Vacuum pumping should start by late 2018 / early 2019 and last until ready to start cool-down.

T600 @ FNAL – Commissioning

- Cryogenic commissioning steps: Vacuum (1 month minimum), Cooling (15 days), Filling (15 days), Purification (1 month), Stabilization (1 month).
- TPC and PMT system commissioning (2 months in total): HV system, PMT's supply, calibrations, DAQ & trigger commissioning.
- Side+bottom CRT can be installed and commissioned in parallel with the activities for the completion of cryo, TPC and PMT system commissioning.
- Top CRT "barn-style" installation should start by Dec 2018 and be completed after stabilization of cryo and purification systems;



Conclusions

- LAr-TPC detection technique 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 a LSND-like anomaly, defining a narrow allowed region at $(\Delta m^2, \sin^2 2\theta) \sim (1\ eV^2, 0.005)$.
  No excess evidence, as confirmed by OPERA.
- The T600 underwent a major overhauling at CERN and was transported to FNAL to be exposed to Booster and NuMi neutrinos, as part of the Short Baseline Neutrino Program (SBN), along with SBND & MicroBooNE.
- SBN experiment will provide a clarification of the sterile neutrino issue, both in appearance and disappearance modes.
- Installation of the T600 in the Far Site building @ FNAL is in progress:

→ vacuum pumping should start at the earliest in winter 2018.

→ Detector commissioning while waiting for clearance by FNAL (by Jan - Feb 2019) to start cool-down .Then data taking for physics!

Thank you !