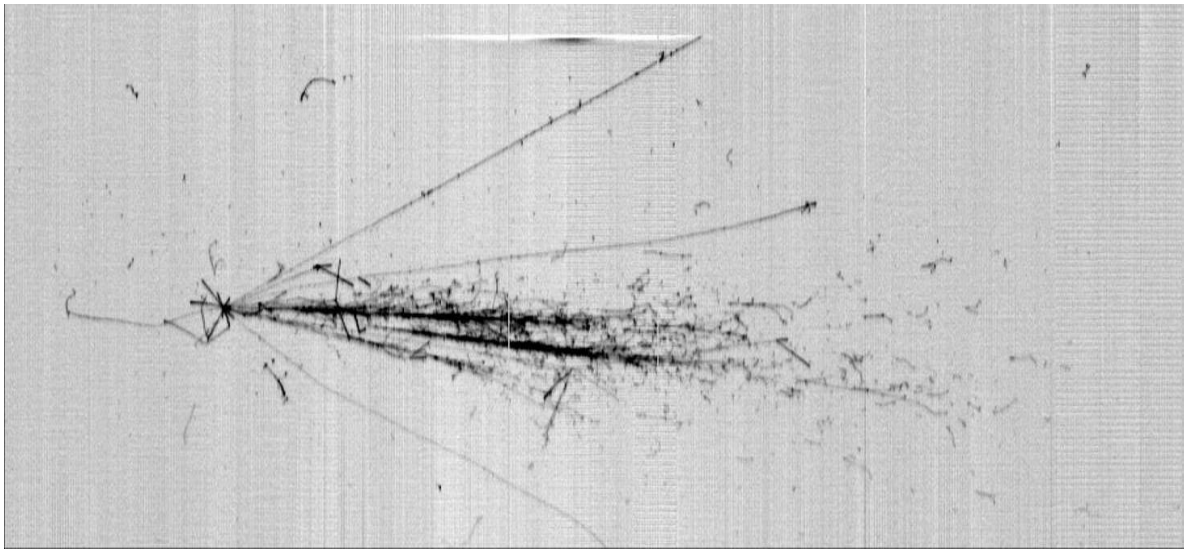
The ICARUS experiment

Between LNGS and FNAL



Christian Farnese
Università di Padova
and INFN

on behalf of the ICARUS
Collaboration

ICNFP 2018, Crete, July 12th

Outline

- LAr-TPC technology: ICARUS T600 performance and results @ LNGS.
- Search for sterile neutrinos at FNAL: the Short Baseline Neutrino Experiment.
- 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
Los Alamos National Laboratory (LANL), USA
University of Pittsburgh , USA
University of Rochester , USA
SLAC, Stanford, CA, USA
University of Texas (Arlington), USA

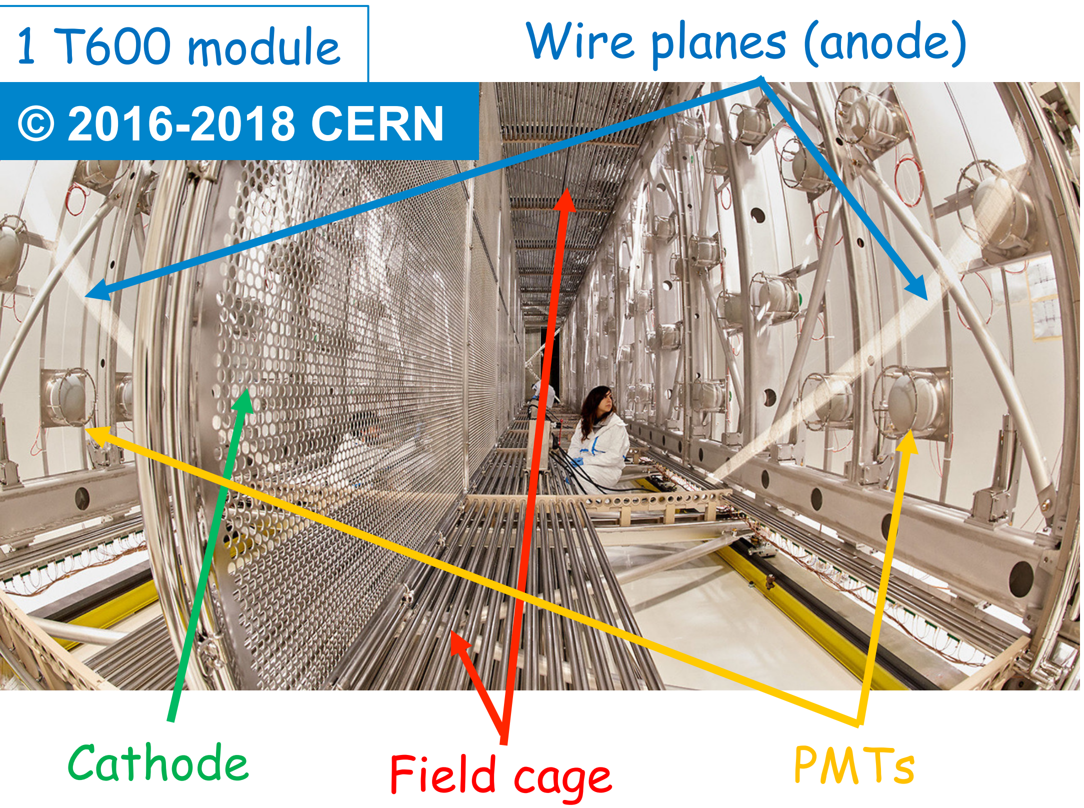
+CERN and others INFN groups involved in the SBN program

Spokesman: C. Rubbia , GSSI

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.

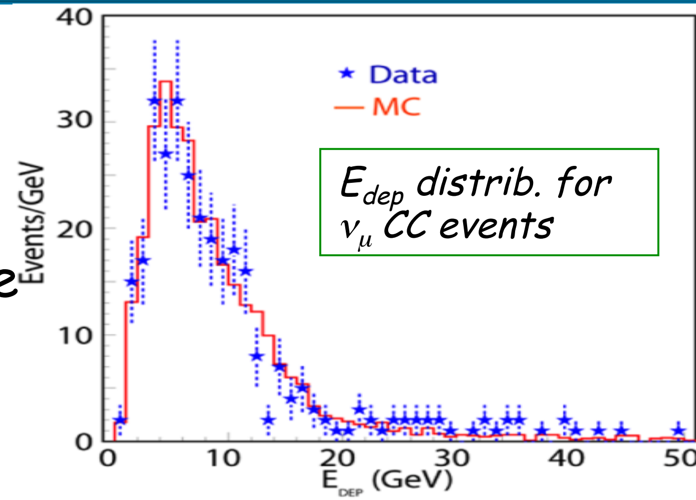
Two identical modules: 476 t total active mass:

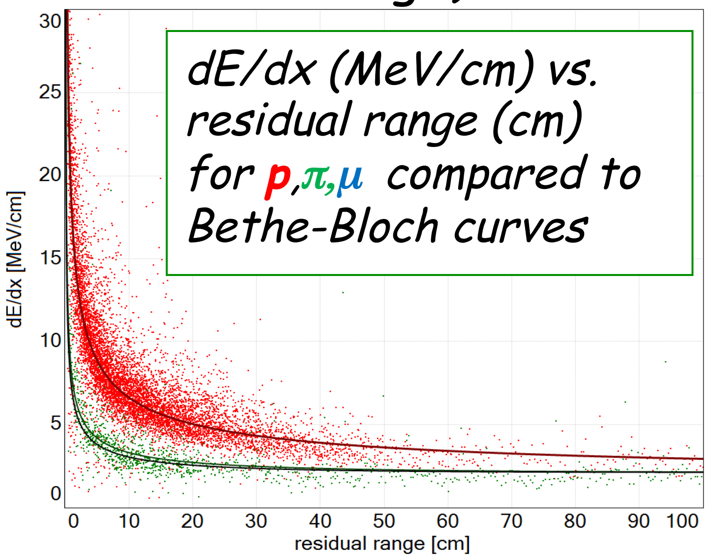


- 2 TPC's per module, with a common central cathode: E_{Drift}= 0.5 kV/cm, v_{Drift}~1.6 mm/μs, 1.5 m drift length;
- 3 "non-destructive" readout wire planes per TPC, ≈54000 wires at 0°, ±60° w.r.t. horizontal: Induction 1, Induction 2 and Collection views;
- Ionization charge continuously read (0.4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

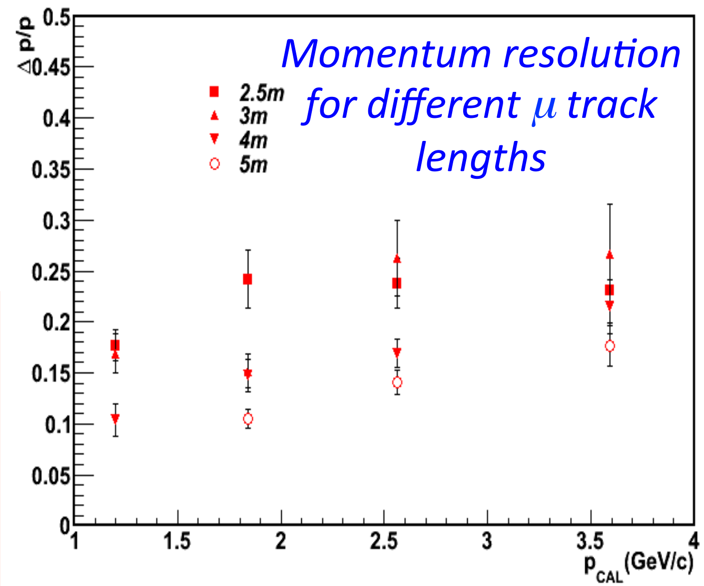
ICARUS LAr-TPC performance (CNGS ν's and cosmics)

- **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 $\Delta p/p$ ~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):





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

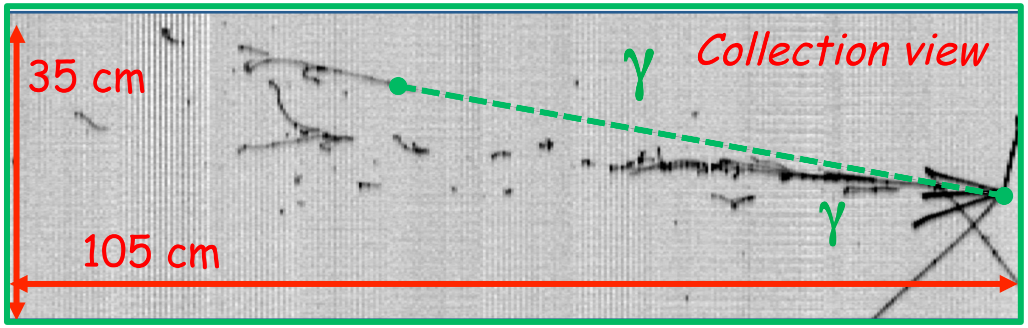


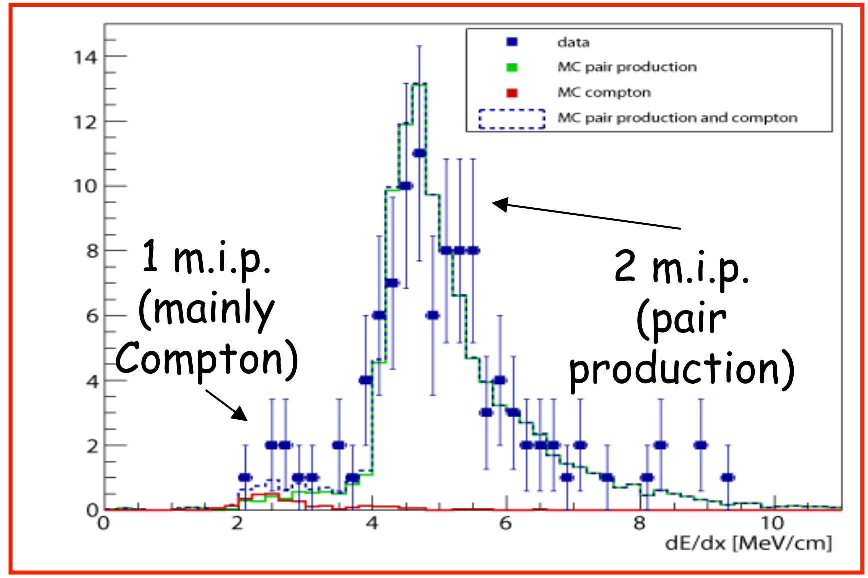
Validation on p_{MCS} of stopping μ's, compared with calo estimate.

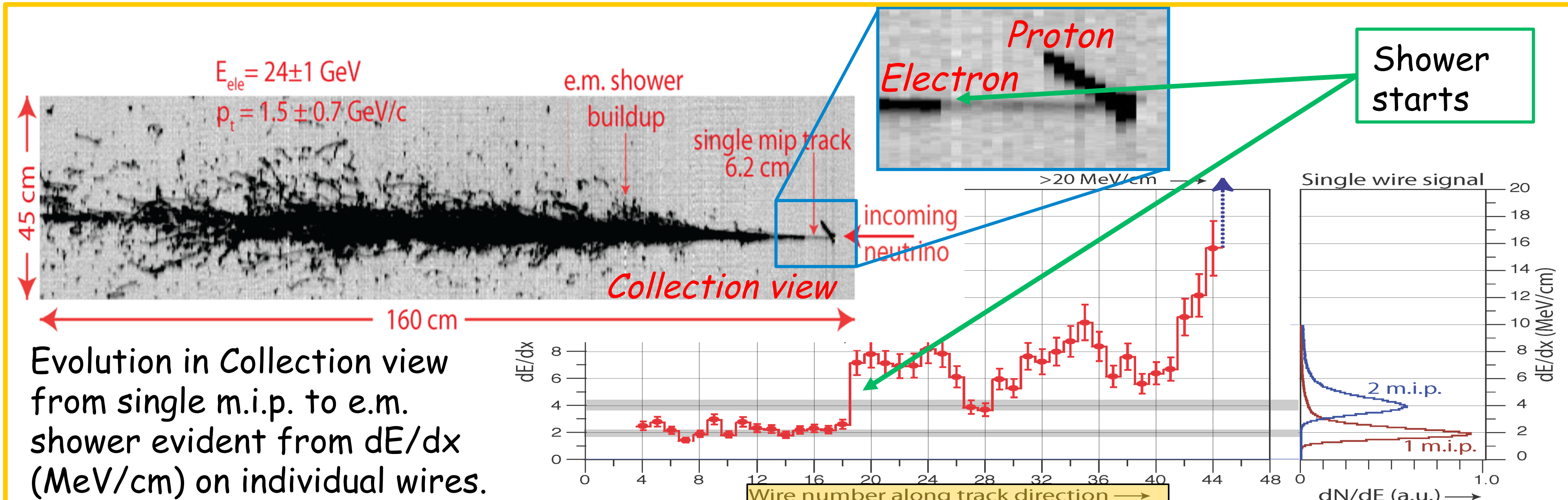
νe CC identification in CNGS beam: Electron/gamma separation

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







Evolution in Collection view from single m.i.p. to e.m. shower evident from dE/dx (MeV/cm) on individual wires.

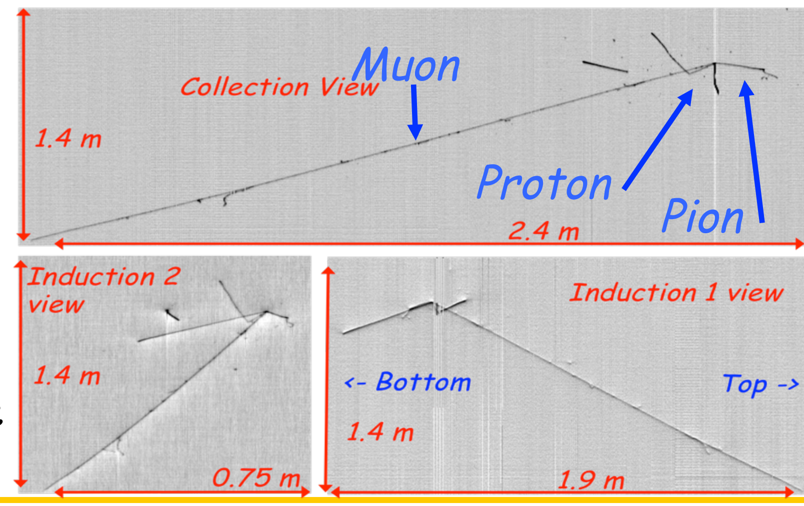
Atmospheric neutrino events @ LNGS

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

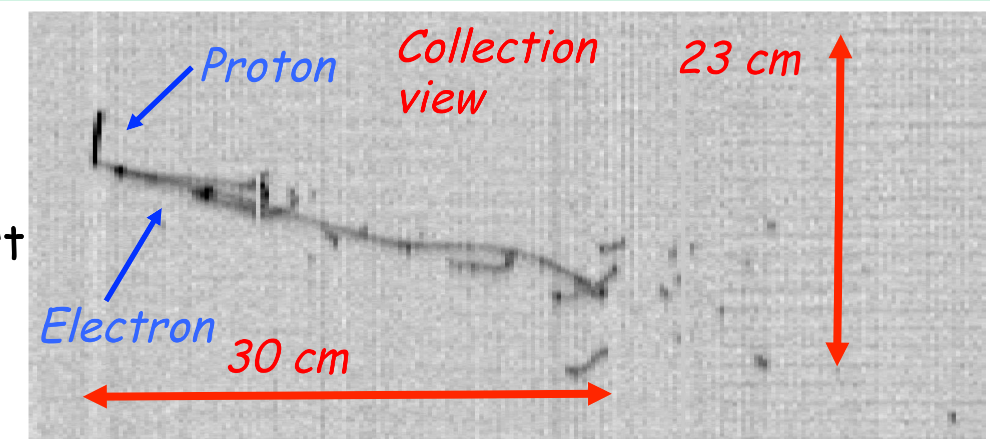
Example of upward-going ν_μ CC even with a deposited energy ~ 1.7 GeV:

- 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

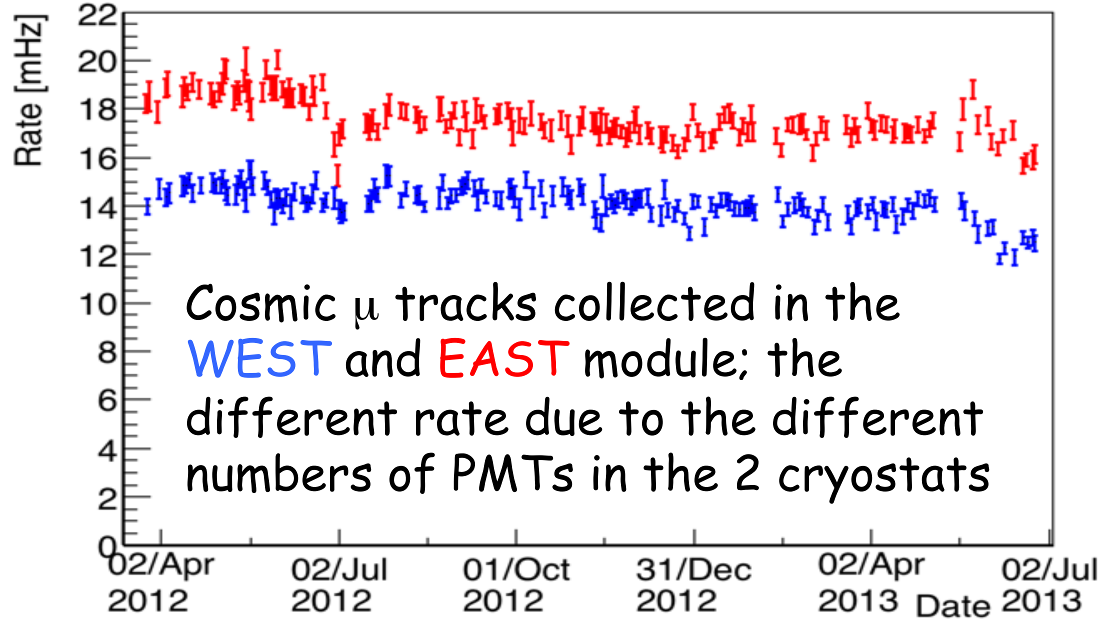
- dE/dx ~ 2.1 MeV/cm measured on first wires corresponds to a m.i.p.
- Short proton track recognized.

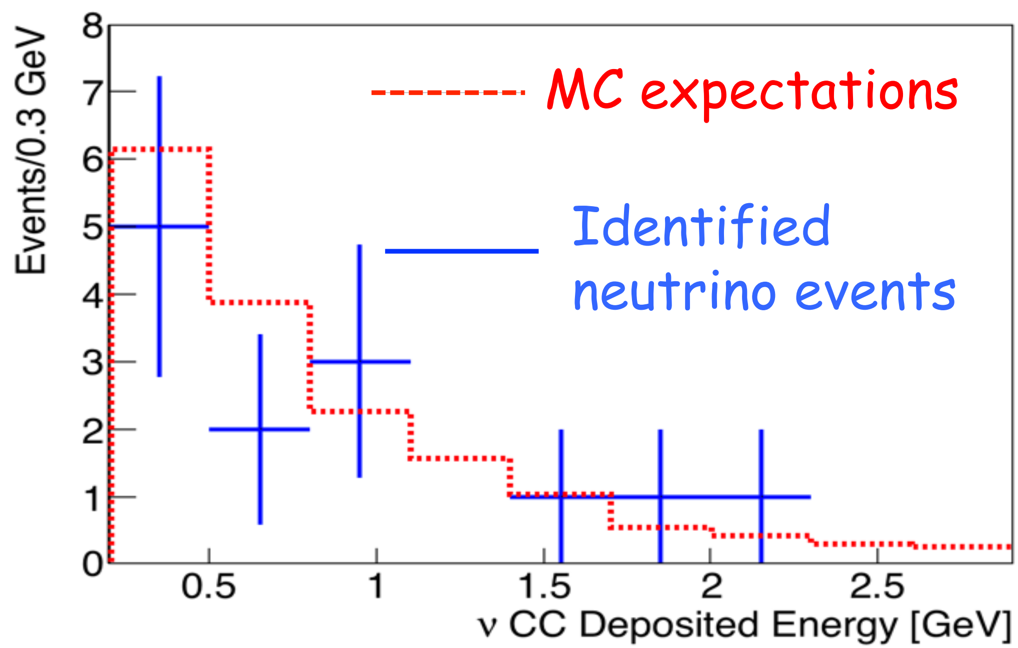


Atmospheric neutrino events @ LNGS – preliminary

- Cosmic ray events recorded in ~0.48 kton y exposure (2012-2013 run) analyzed to identify atmospheric ν events.
- Incoming c-rays identified and rejected by factor ~100
- ν CC candidates with E_{dep}>200 MeV are automatically pre-selected (~80%/~25% efficiency for νe/νμ), then validated by visual scanning;
- Globally 6 νμCC and 8 veCC atmospheric neutrino events identified, to be compared with 18 expected events, evaluated taking into account of the trigger, filtering and scanning efficiencies;

see C.Farnese's poster "Atmospheric neutrino search in the ICARUS T600 detector"

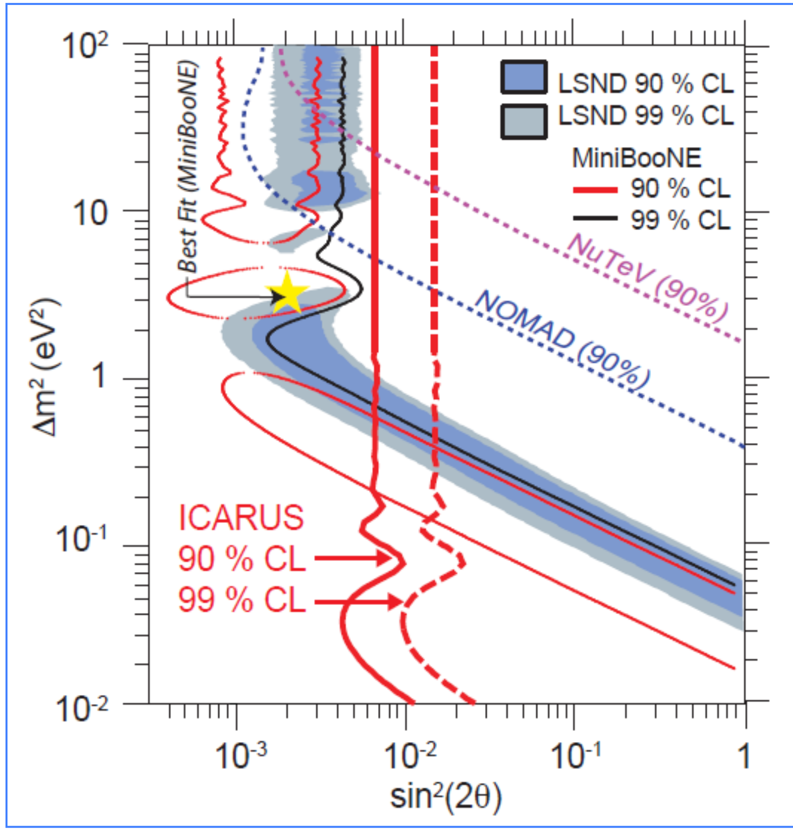




ICARUS results and search for an LSND-like effect

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 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^0 bkg rejection in ν_μ-ν_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.*



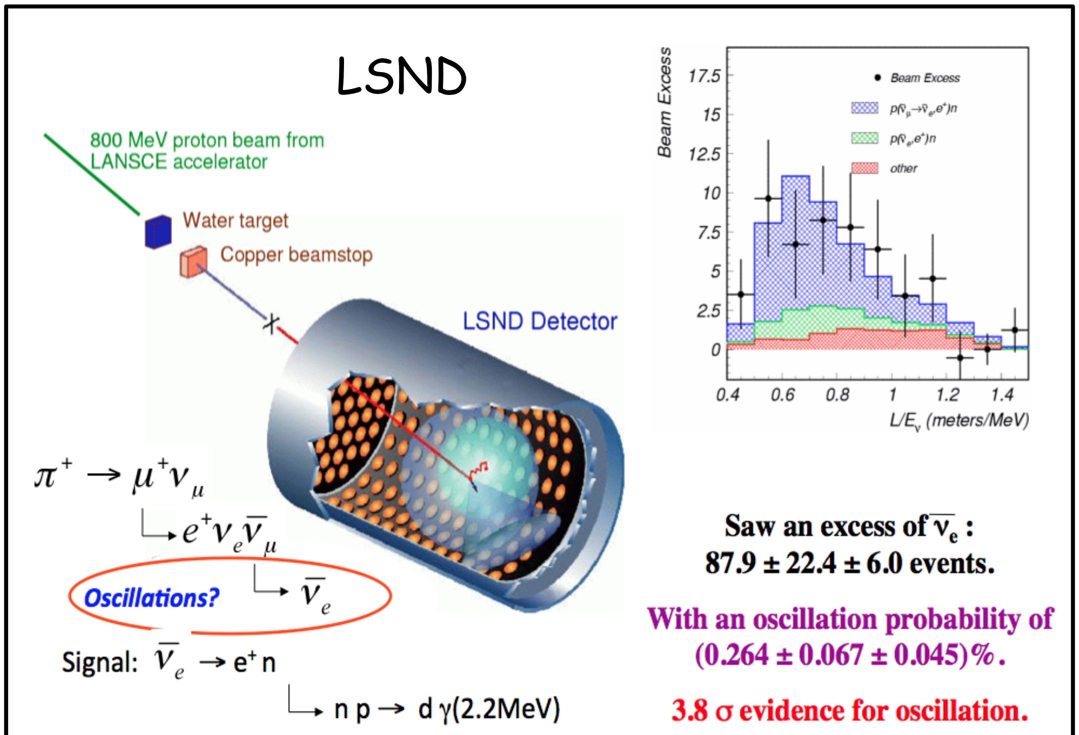
Eur. Phys. J. C (2013) 73:2599

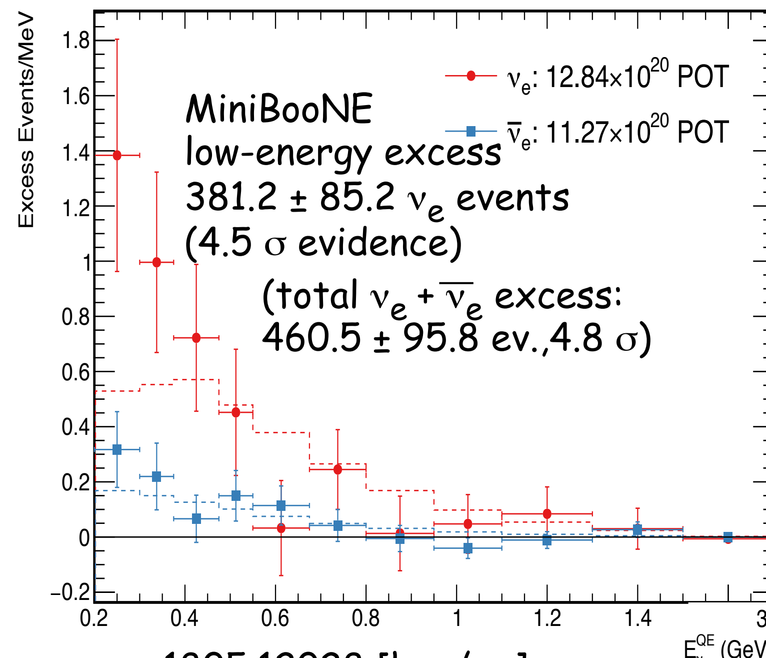
Success of LAr-TPC technology with large impact on neutrino and astro-particle physics projects: SBN short base-line neutrino program at FNAL with 3 LAr-TPC's (SBND, MicroBooNE and ICARUS) and the multi-kt DUNE LAr-TPC.

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





1805.12028 [hep/ex]

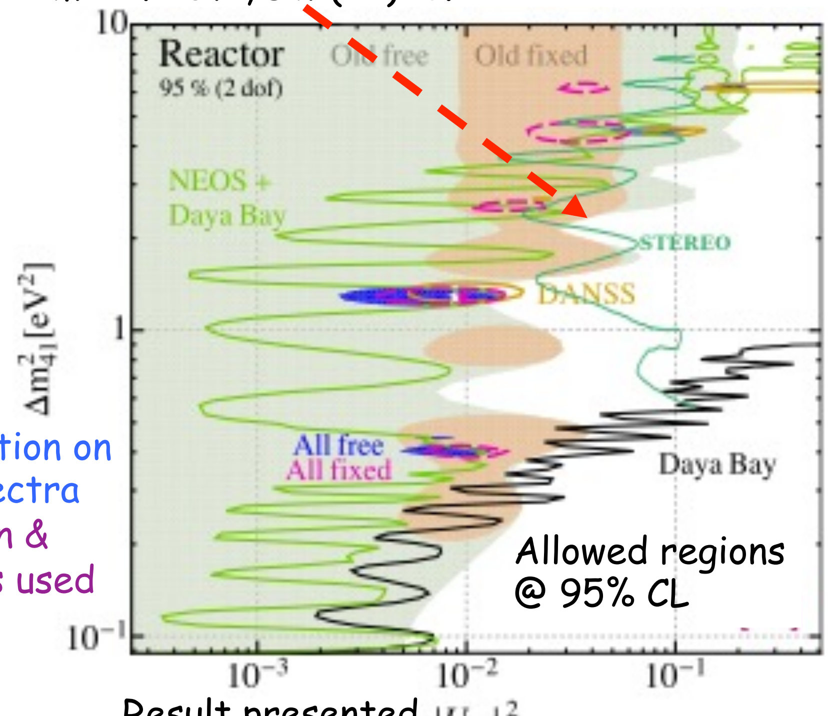
“Sterile neutrino puzzle” 2/2

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 $\nu\mu$ 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.

Reactor Antineutrino Anomaly best fit value

$\Delta m^2 \sim 2.4\ eV^2$, $\sin^2(2\theta) \sim 0.14$

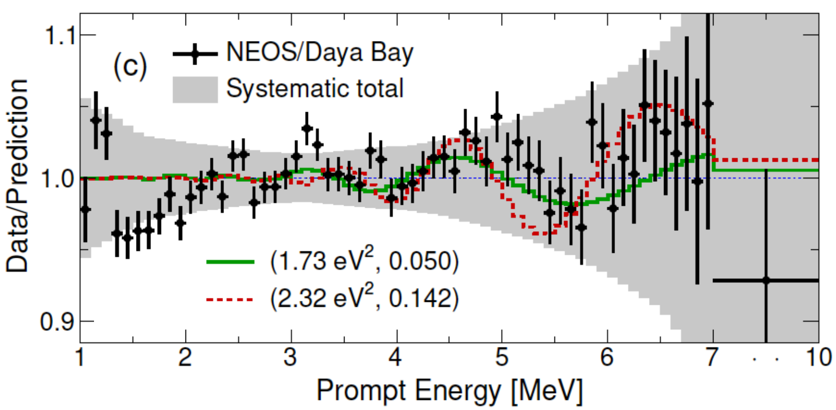


Allowed regions @ 95% CL

Result presented @ Neutrino2018

free=no assumption on flux norm. & spectra

fixed=prediction & published values used

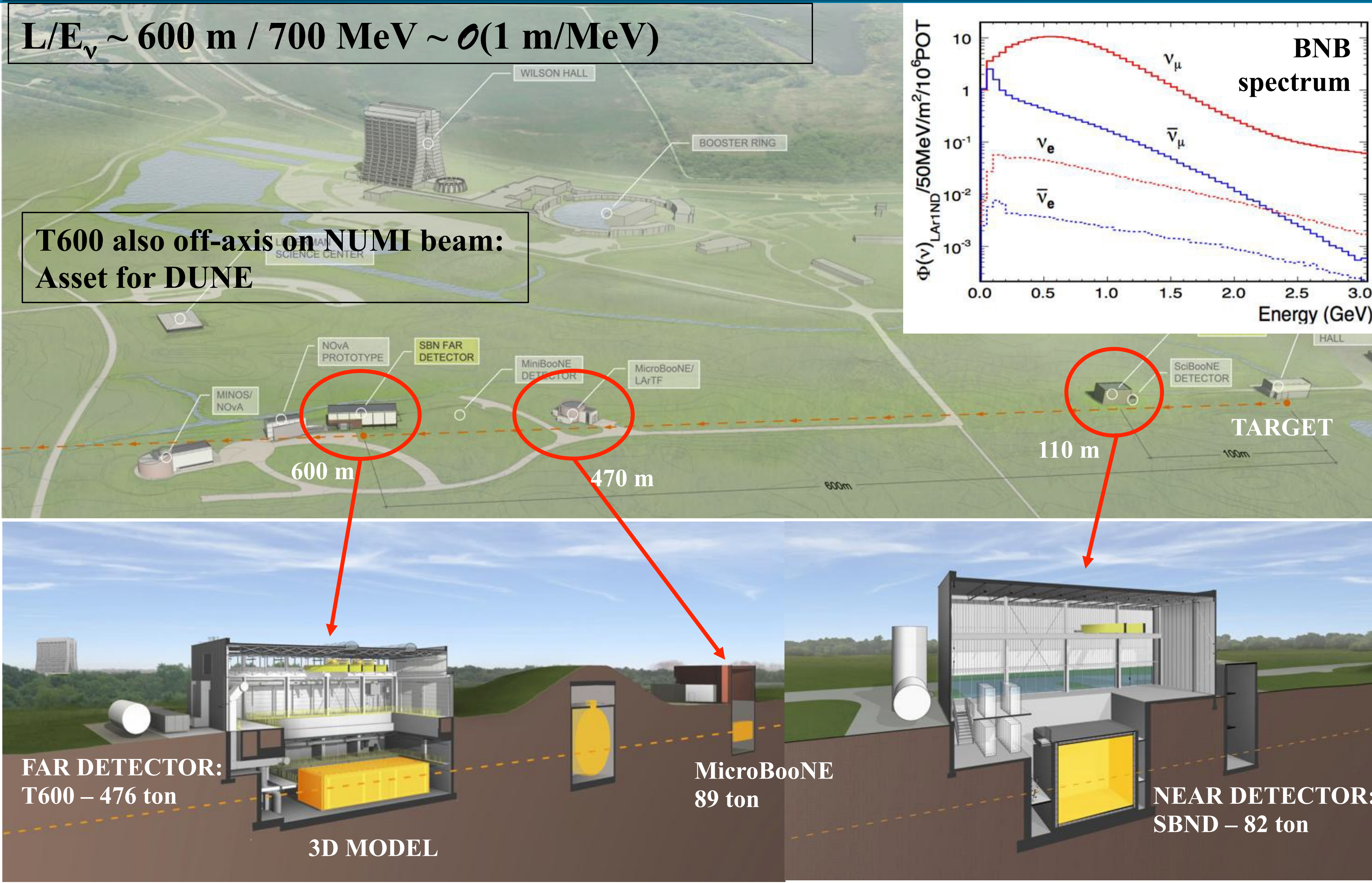


THE EXPERIMENTAL SCENARIO CALLS FOR A DEFINITIVE CLARIFICATION!

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

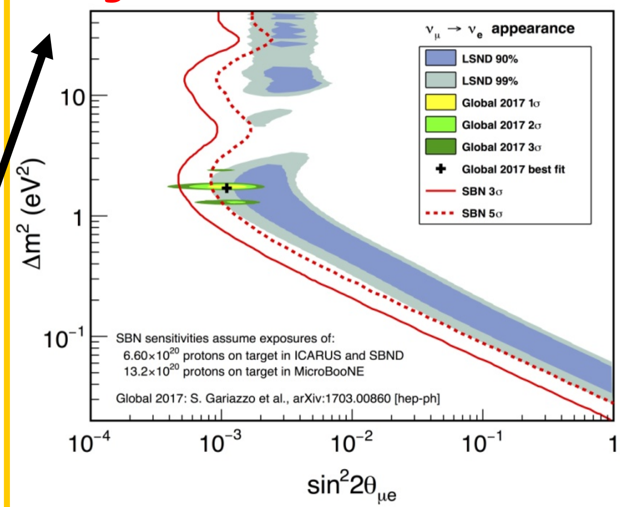


Sensitivity to Sterile neutrino @ SBN

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

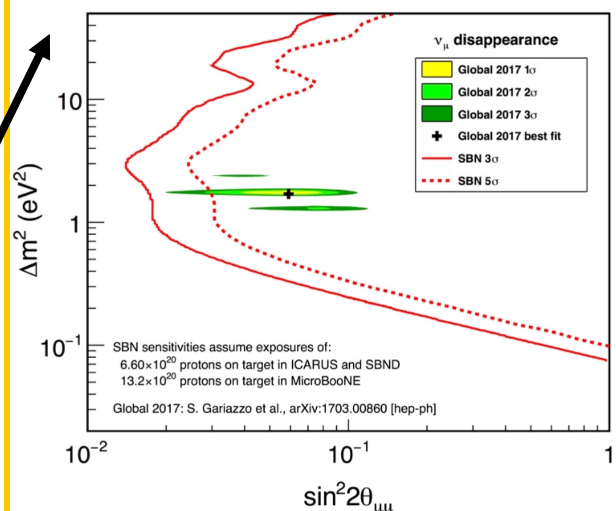
- SBND will give the "initial" BNB flux/composition
- ICARUS, as far detector, will characterize the ν oscillation parameters.

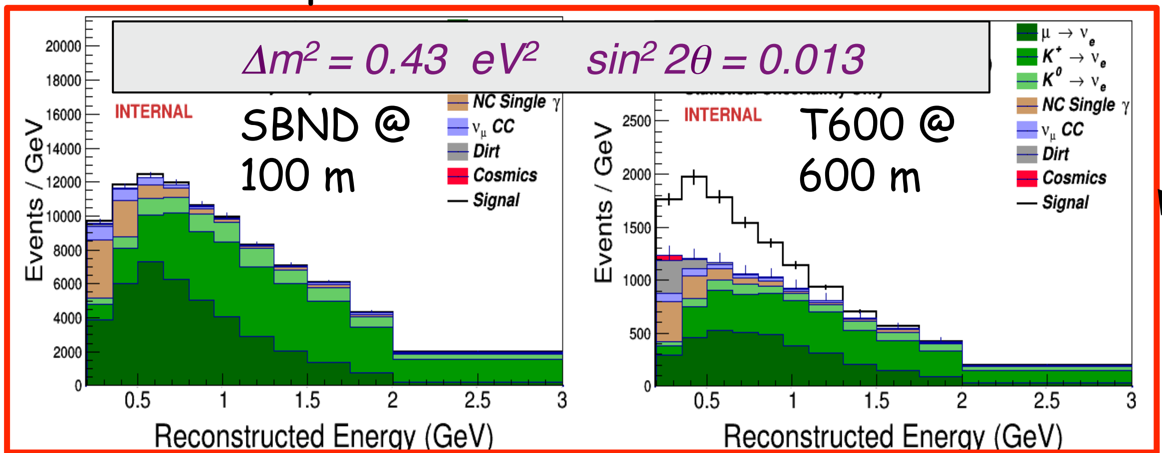
ν_e appearance: LSND 99% CL region covered at 5 σ level

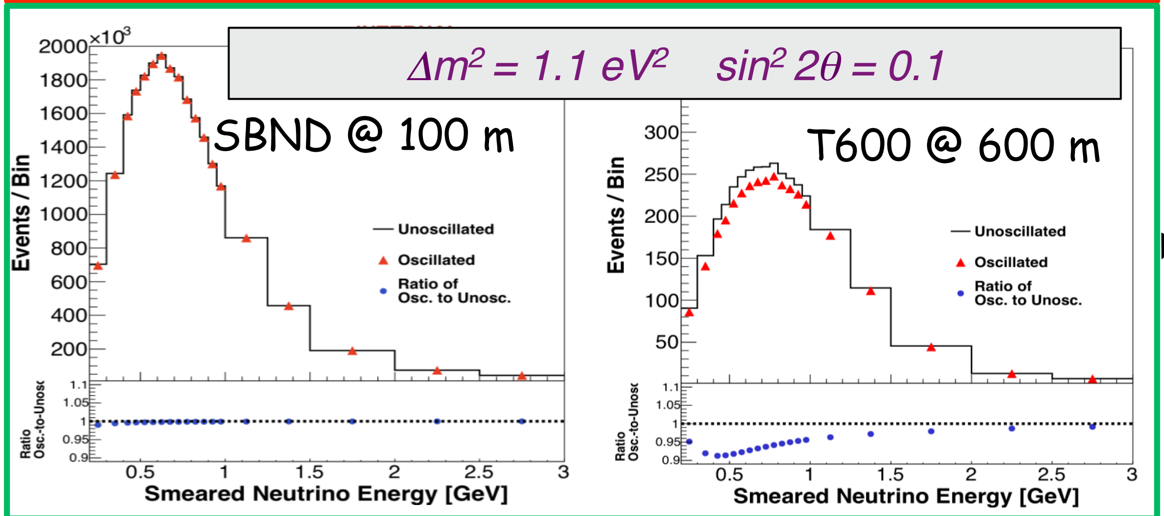


Both plots: 6.6×10^{20} pot (3 years)

3-5 σ ν_μ disapp. SBN sensitiv.



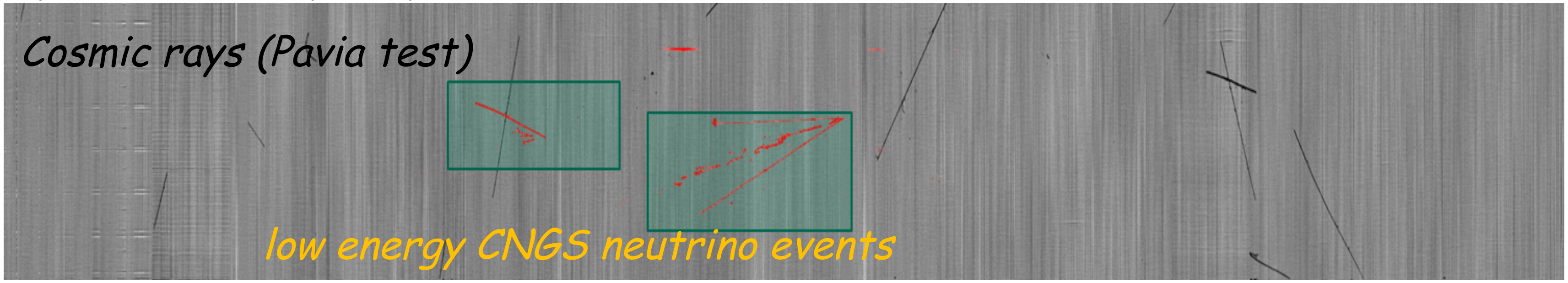




Taking data @ shallow depth

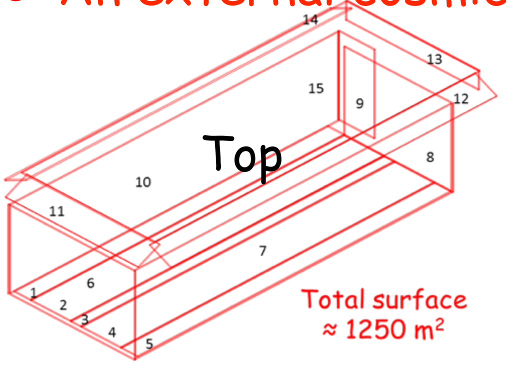
ICARUS at FNAL is facing a more challenging experimental condition than at LNGS, requiring the recognition of ν interactions amongst 11 KHz of cosmic rays.

- 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 νe search since e's produced via Compton scatt./ pair prod. can mimic a genuine νe 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 ~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.

ICARUS T600 Overhauling at CERN (WA104/NP01)

T600 leaving from CERN June 12th 2017

To face the new experimental situation at FNAL (shallow depth data taking with higher beam rate) 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

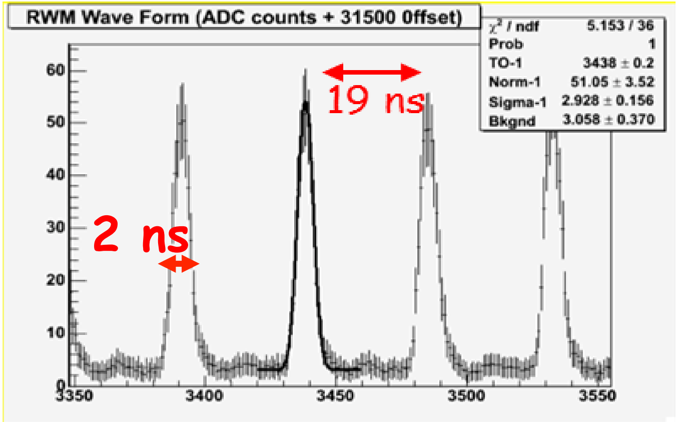
T600 in Antwerp: unloading from barge from Basel and loading into ship to Burns Harbor (Michigan lake)

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

The light collection system

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

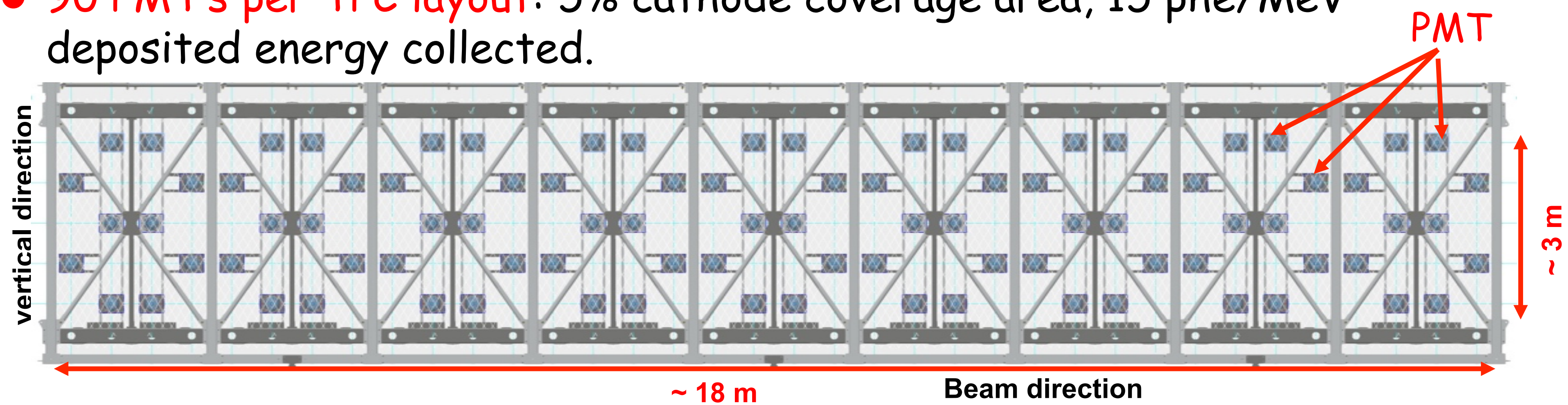


The light collection system is based on 360 PMT's, 90/chamber, to have:

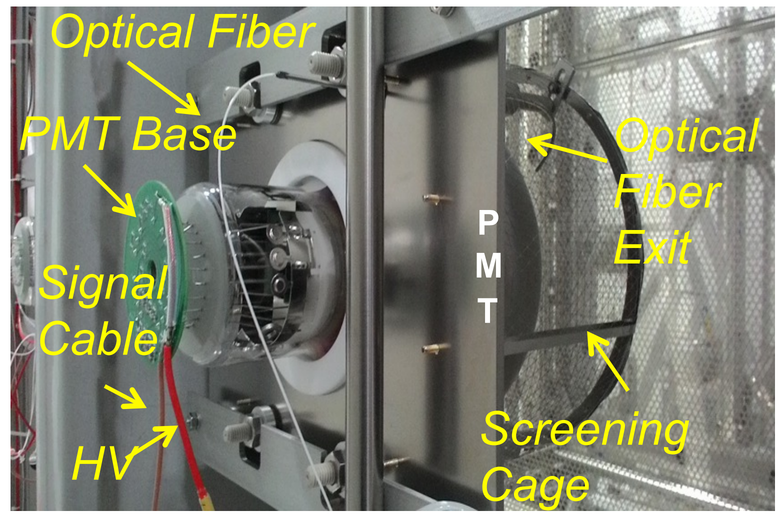
1. High detection coverage, to be sensitive to the lowest-expected neutrino energy deposition in the TPC (approximately 100 MeV), also using the light fast-component only;
2. High detection granularity, longitudinal resolution is better than 0.5 m (effective Q.E. = 5%).
3. Fast response time/ high time 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.

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 ~200 $\mu g/cm^2$ of Tetra-Phenyl-Butadiene wavelength shifter to detect the λ = 128 nm scintillation light in LAr.



Possible cosmic μ's identification provided by pattern/time recognition of PMT signals

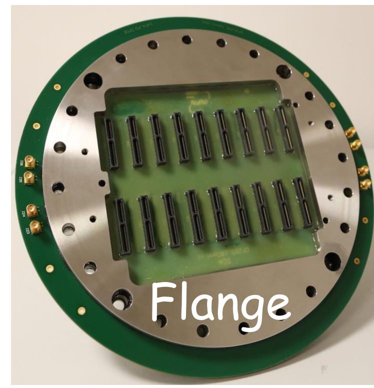
The new TPC read-out electronics

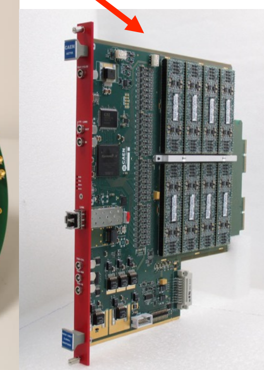
- ICARUS electronics at LNGS was based on analogue low noise “warm” front-end amplifier, a multiplexed 10-bit 2.5 MHz ADC and a digital VME module for local storage, data compression, trigger information:

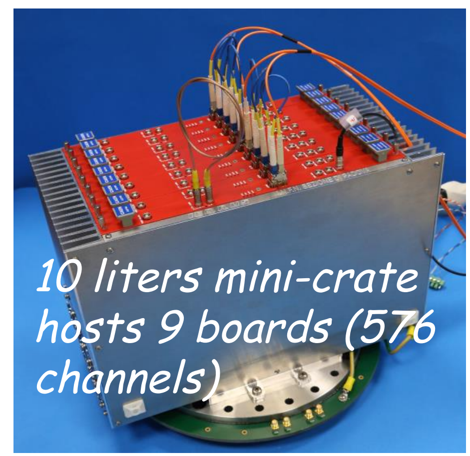
  S/N ~9 in Collection, ~0.7 mm single hit resolution, resulting in a precise spatial event reconstr. and μ momentum measurement by MCS.

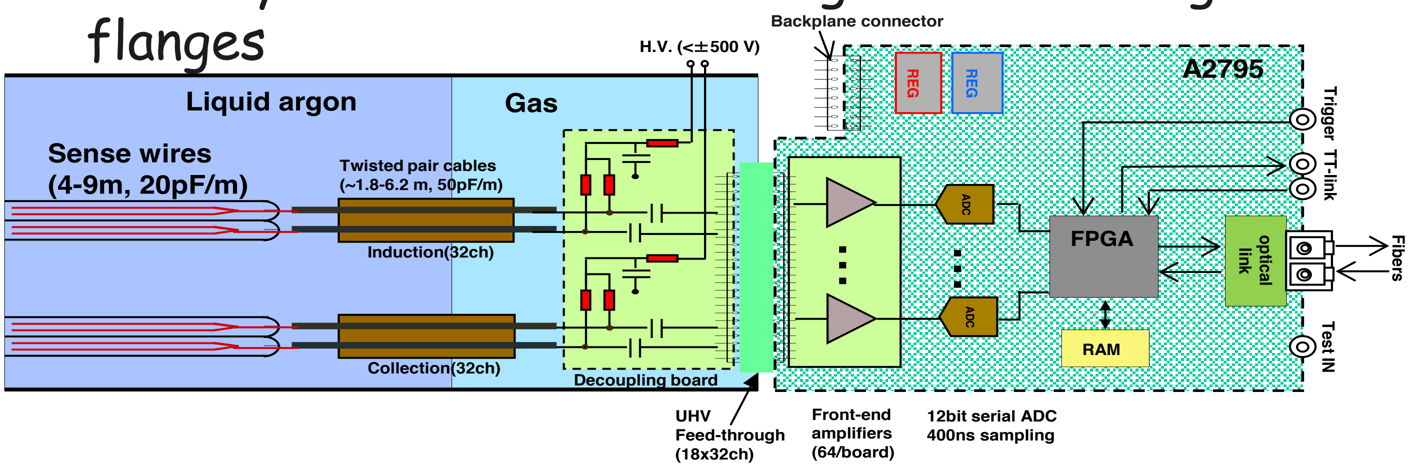
- Improvements concern:
  - *Serial 12 bits ADC*, one per ch, 400 ns sampling synchronous on the whole detector;
  - *Serial bus architecture* with Gbit/s optical links to increase the bandwidth (10 MHz);
  - Both analogue/digital electronics are housed in a single board inserted in a new mini-crate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

CAEN A2795 board, 64 chs



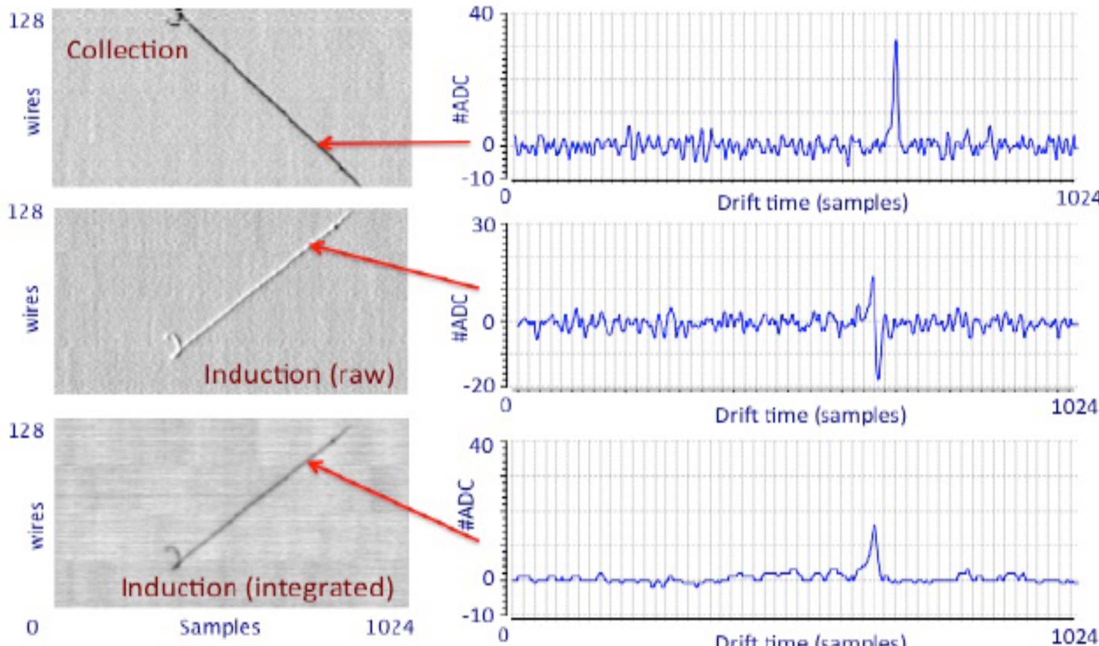






Improved front-end electronics for T600

- In the newT600 analogue front-end the adopted improvements concern:
  - A faster shaping time ~0.6 μs 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.



Single 45° m.i.p. μ track

- Same ~2ADC counts (~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 ~ 10 is recognized in Induction view

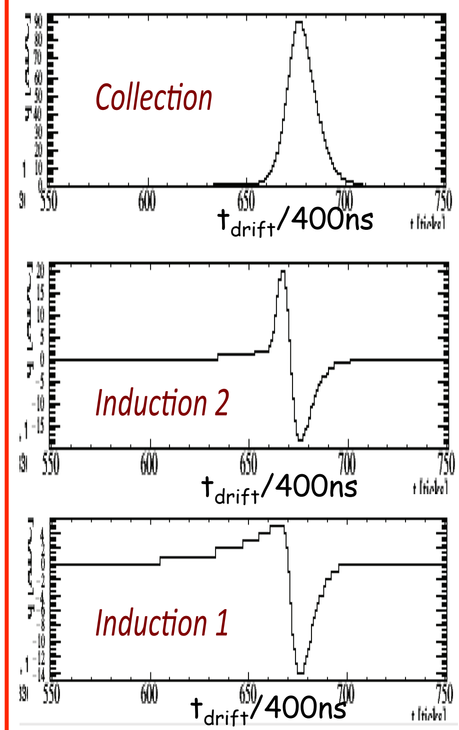
Better event reconstruction provided!

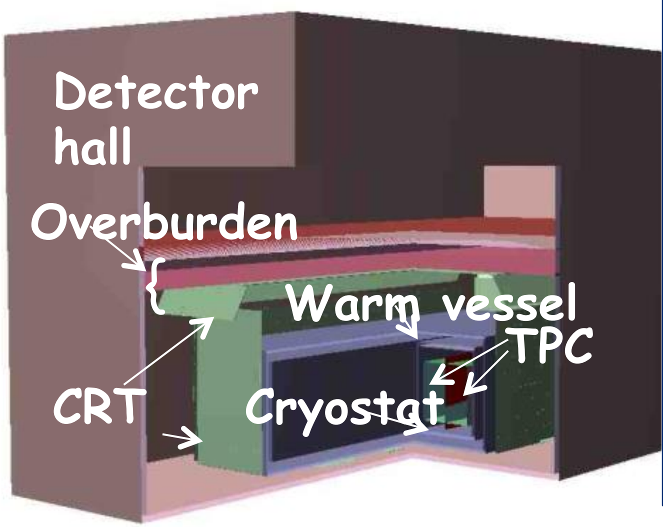
arXiv:1805.03931
Paper submitted to JINST

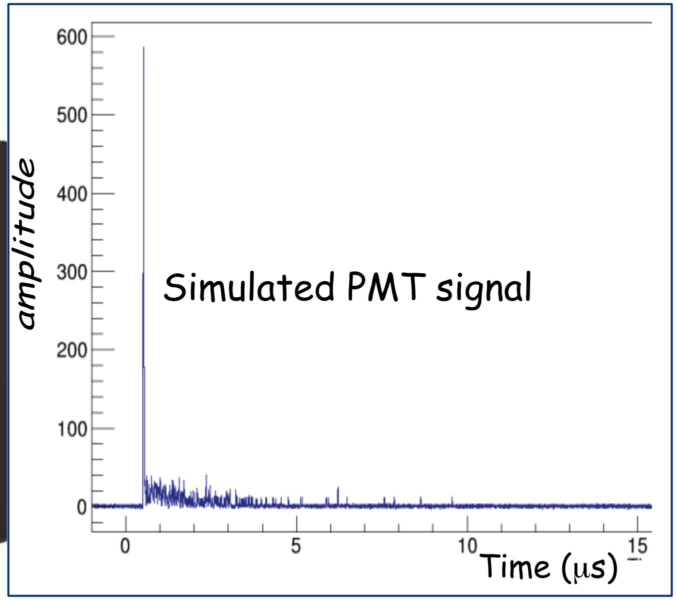
ICARUS event reconstruction @ SBN 1/2

- 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.

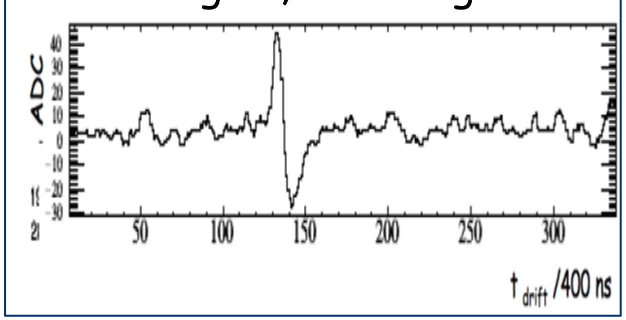
Typical wire shape for 1 m.i.p. μ







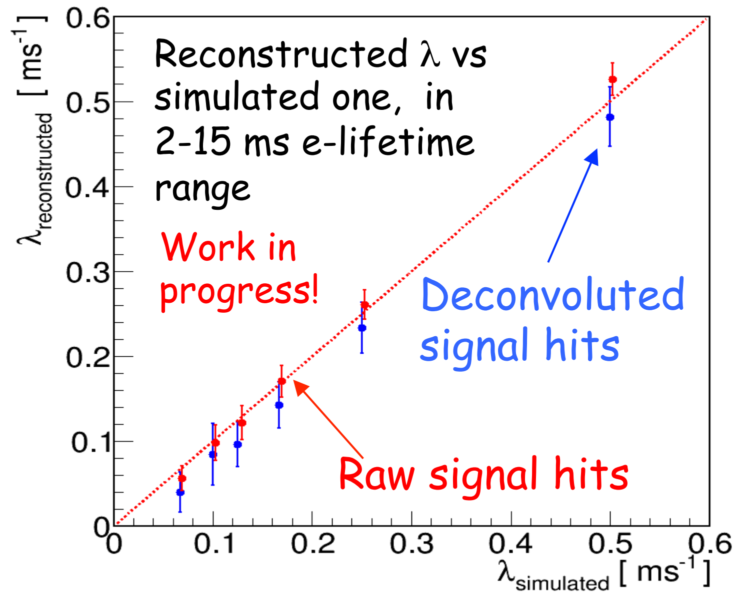
Ind.2 signal, including noise

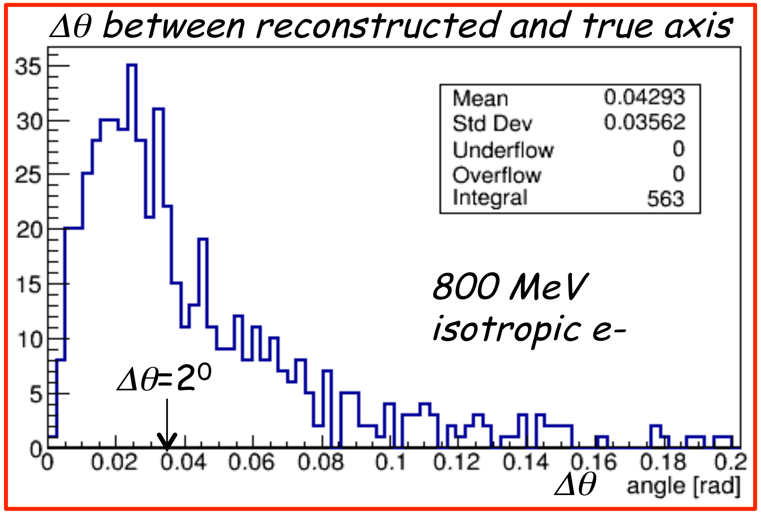


ICARUS event reconstruction @ SBN 2/2

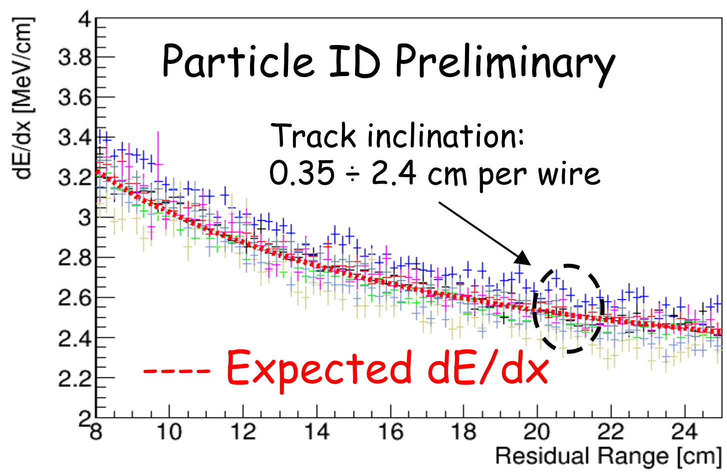
Some advanced tools already ported in Larsoft:

- 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





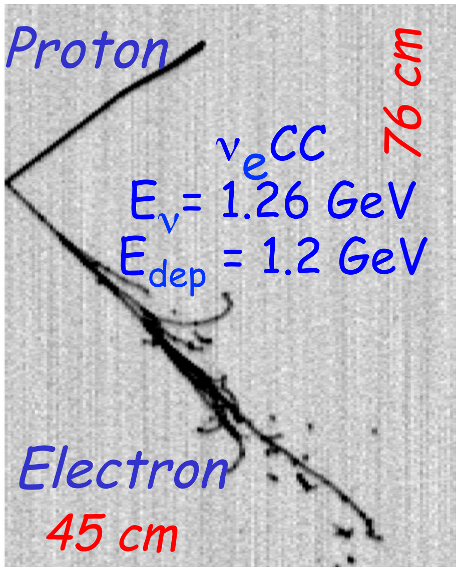
dE/dx vs range for μ's

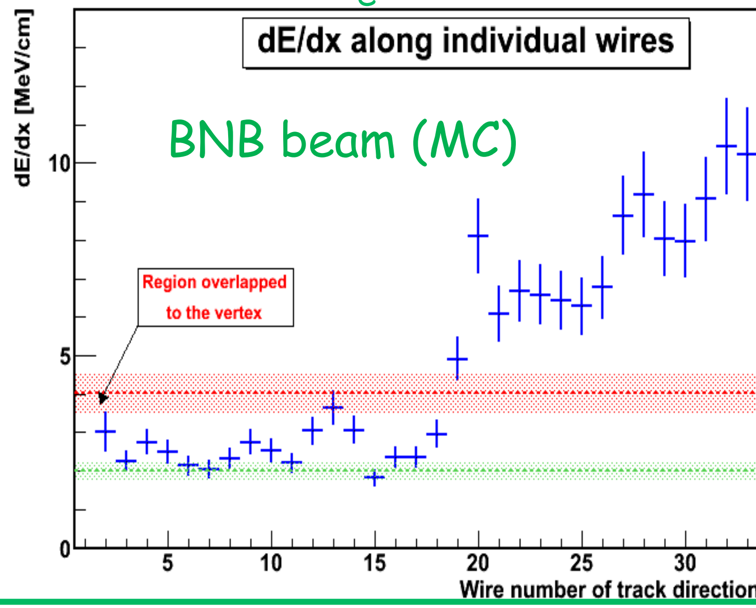


Software is mature enough to realistically simulate events with BNB beam

BNB (MC) and real atmospheric ν_eCC events comparison

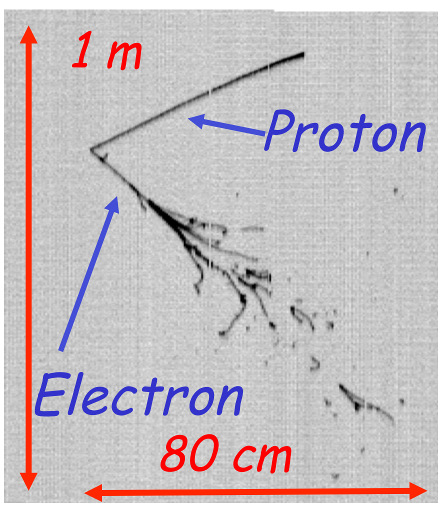
MC SBN ν_eCC interactions

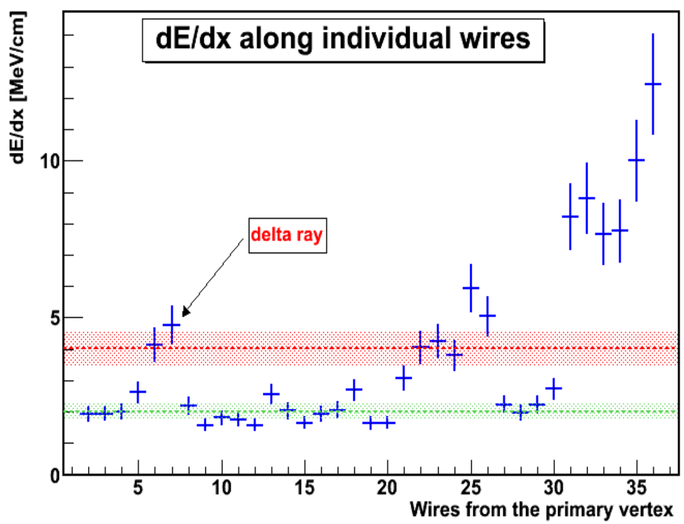




- very alike to typical atmospheric νeCC events @ LNGS (below)
- Similar results hold for νμCC interactions

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

ICARUS @ FNAL 1/2 - Status

- Warm vessel floor/walls were assembled/installed in the pit in the Far Detector (FD) building in 2017.
- Bottom CRT modules (200 m^2 total area) already installed in 2017.
- Assembly of cold shields completed (May 2018), now under leak test.
- Installation of detector supports is in progress. Should be done by July 2018.
- Main vessels doors sealed. Helium leak tests ongoing…

ICARUS Vessel 2 parked west of SBN Far Detector Building

Warm vessel, cold shield (June 2018)

ICARUS @ FNAL 2/2 – 2018 plans and commissioning

- Detectors insertion in Warm Vessel –July-August 2018
- Top part of cold shield will be then installed and tested, followed by installation of top part of warm vessel (August – September 2018).
- From Fall 2018, activities on top of detector will start (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.

Detector commissioning will consist of three phases:

- Cryogenic commissioning: Vacuum (1 month), 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.
- CRT commissioning: in parallel with the activities for the completion of cryo, TPC and PMT system commissioning.

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 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 @ 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 !