The ICARUS experiment

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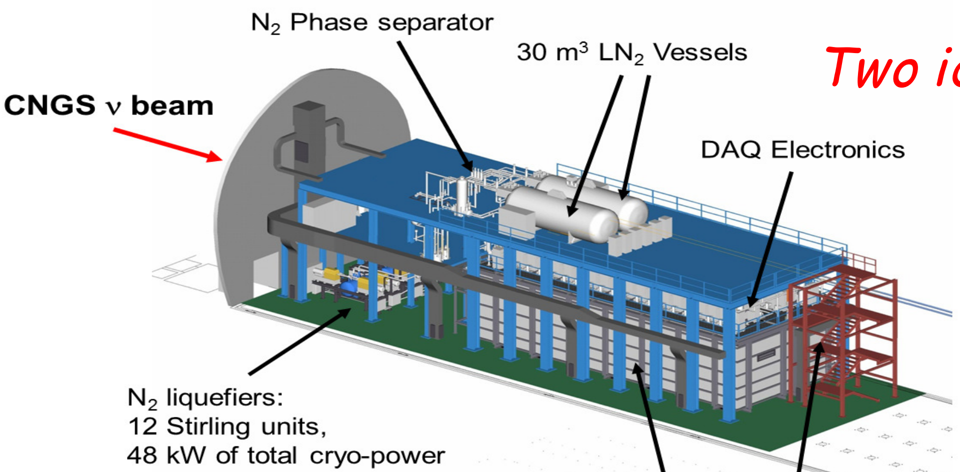
Outline

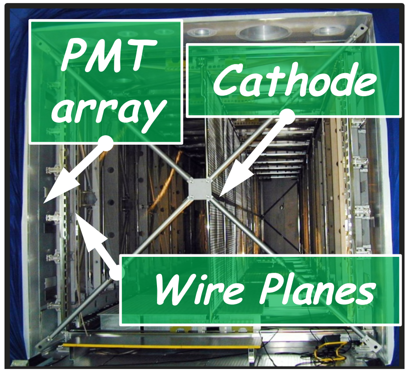
- ✓ ICARUS LAr-TPC technology: ICARUS T600 performance and results @ LNGS.
- ✓ Generalities on the ICARUS T600 overhauling .
- ✓ Search for sterile neutrinos. at FNAL: the Short Baseline Neutrino Experiment.
- ✓ T600 current status.
- ✓ Conclusions.

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.



Schematic view of the whole ICARUS T600 plant in the Hall B at LNGS.



≈2 10^4 ionization electrons per MeV

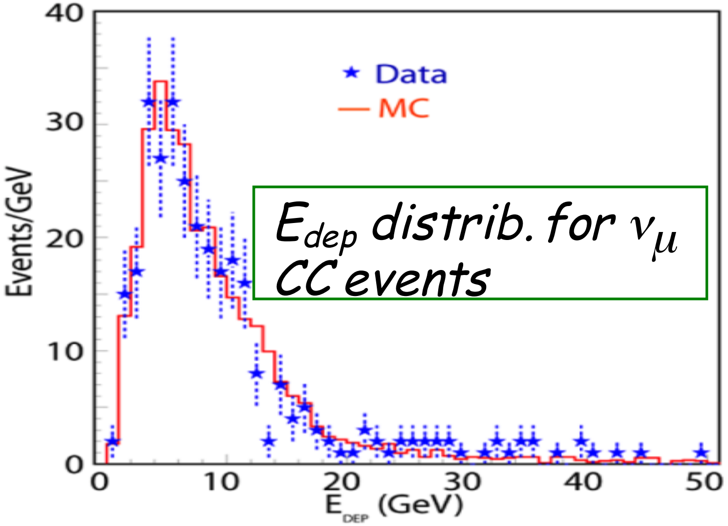
Abundant λ=128 nm light (~10^4 γ/ MeV)

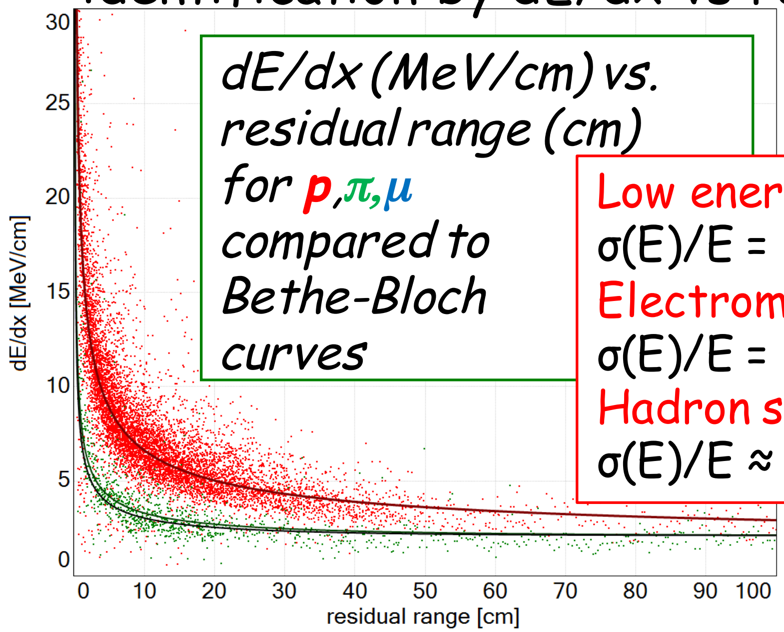
Two identical modules: 476 t total active mass:

- 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.

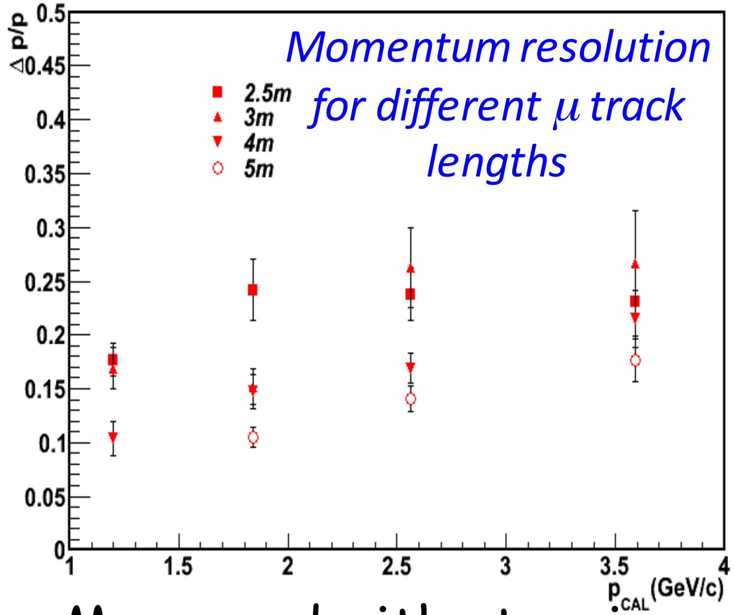
ICARUS LAr-TPC performance (CNGS ν's and cosmics)

- *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 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):





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)

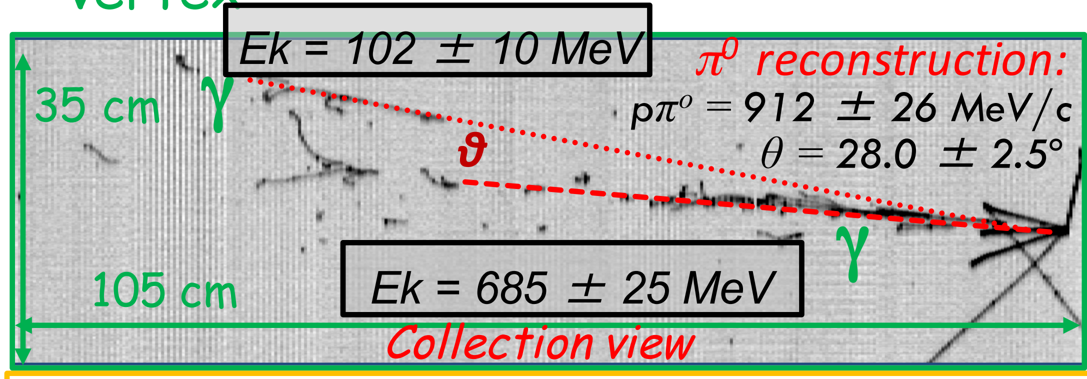


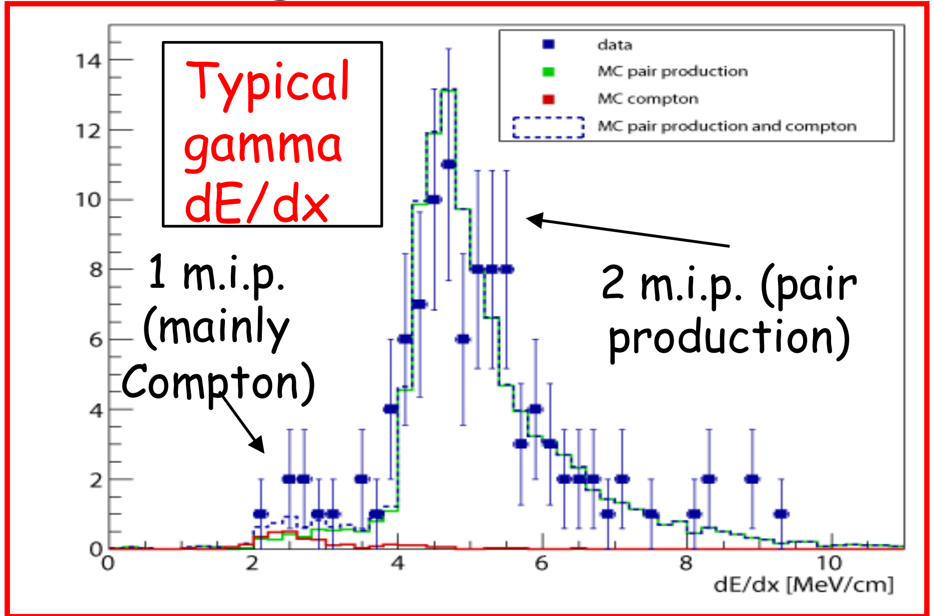
Measured with stopping μ comparing p_{MCS} with calorimetric measure

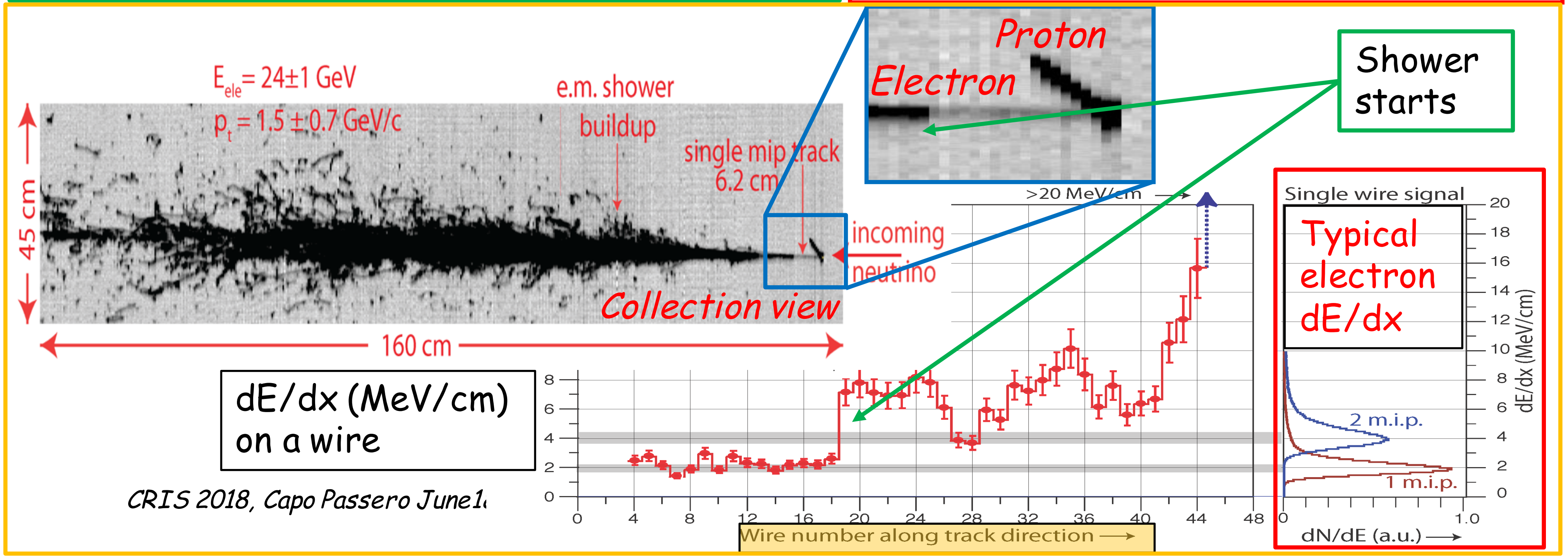
ν_e CC identification in CNGS beam: Electron/gamma separation

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





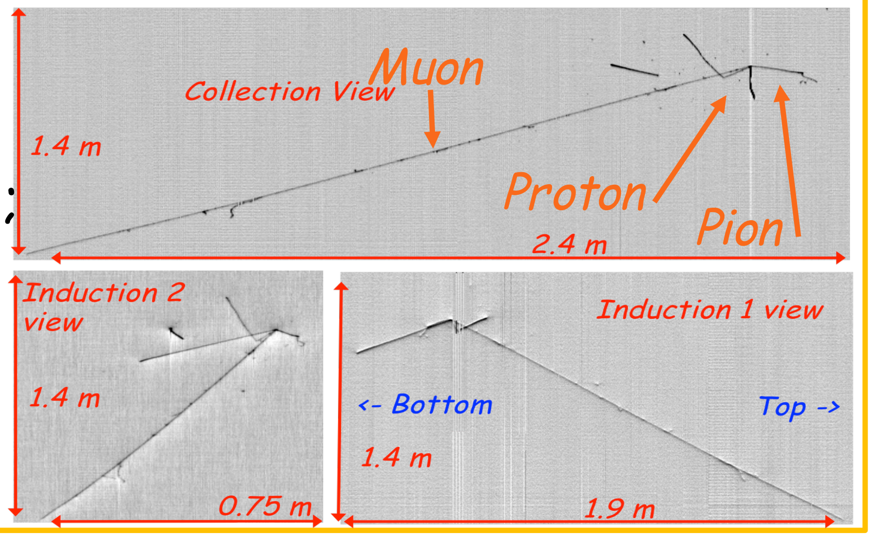


Atmospheric neutrino events @ LNGS

- 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

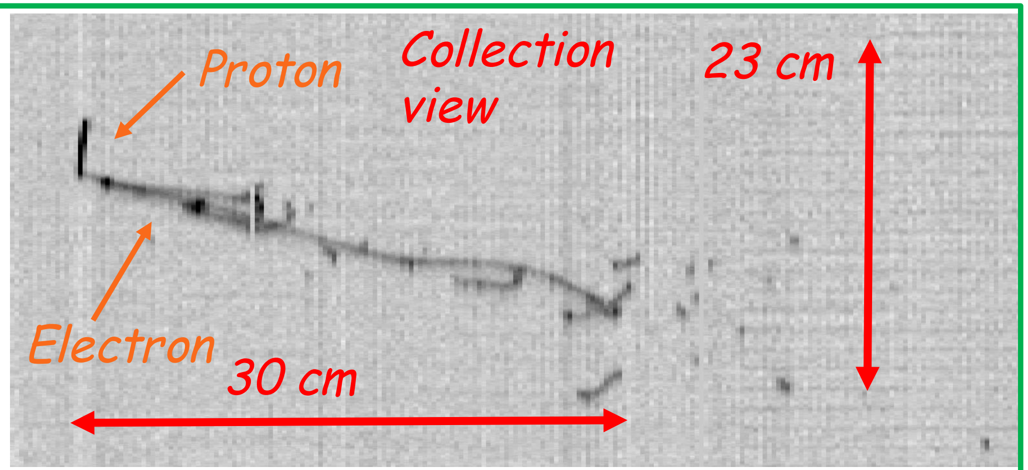
Example of upward-going ν_μ CC event with a deposited energy ~ 1.7 GeV:

- 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



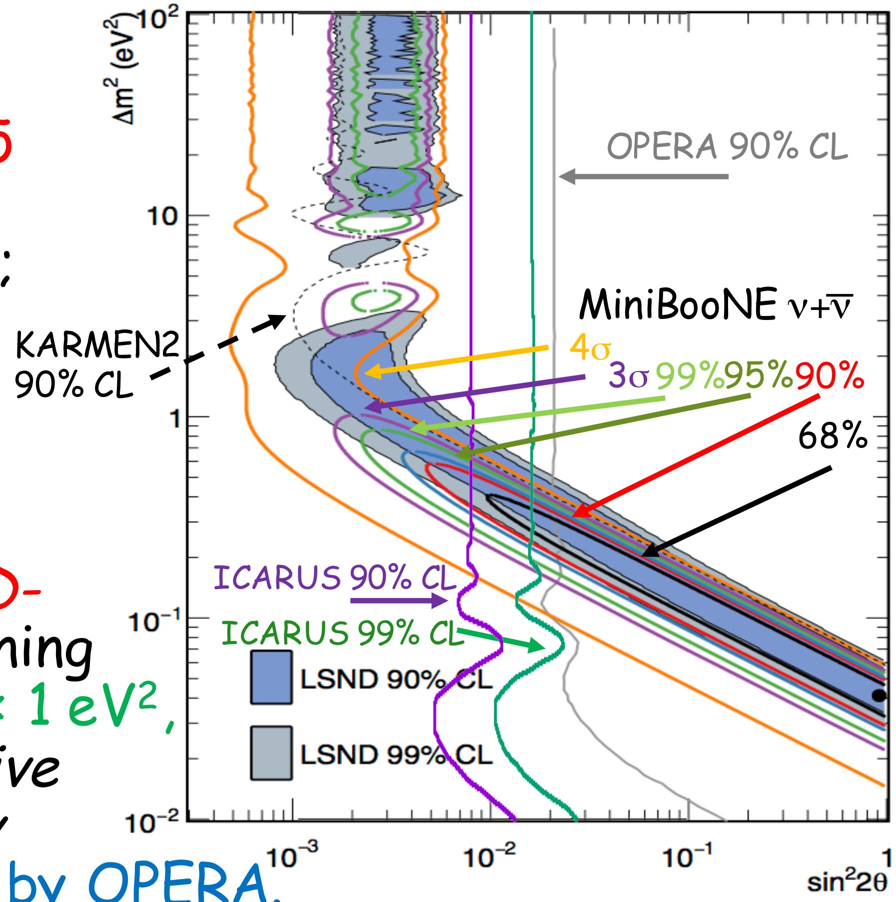
Downward-going, quasi elastic ν_e event: deposited energy 240 MeV

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



The LAr-TPC technology and ICARUS-T600

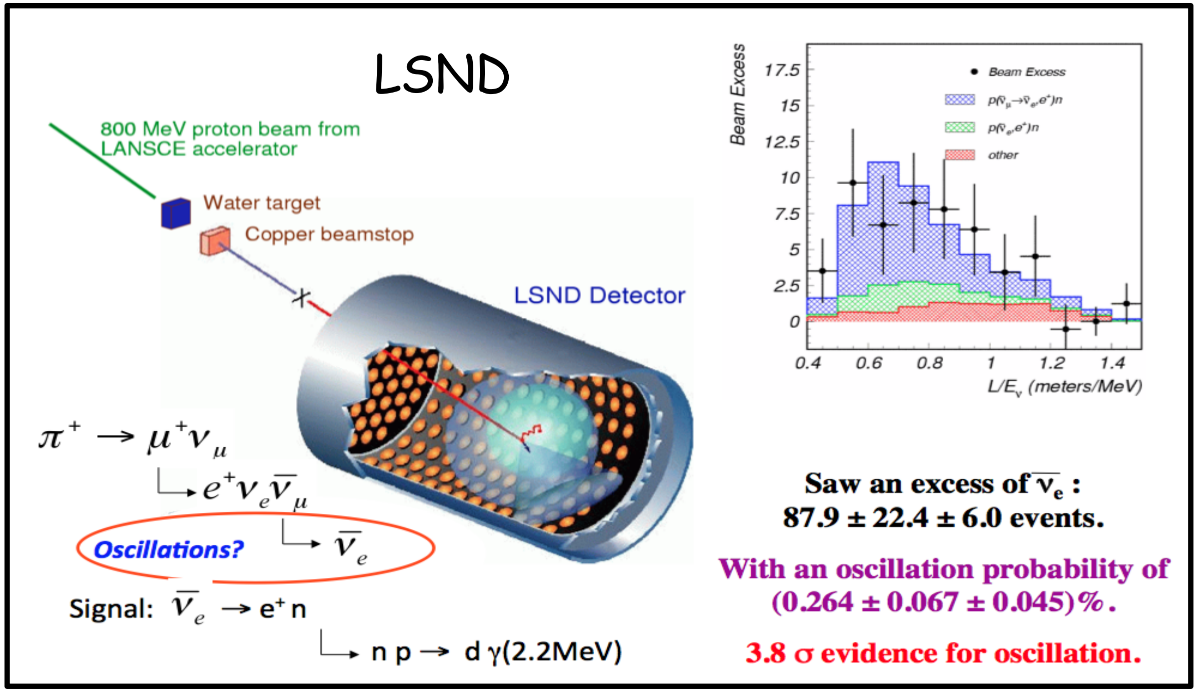
- ICARUS run at LNGS allowed to reach several physics/technical result demonstrating the maturity of the LAr-TPC technology:
  - *An exceptionally low level ~20 p.p.t. [O_2] eq. of electronegative impurities in LAr;* the measured e^- lifetime τ_{ele} >15 ms ensured few m long drift path of ionization e^- signal without attenuation;
  - *Demonstrated detector performance*, especially in ν_e identification and π^o background rejection in $\nu_\mu - \nu_e$ study to unprecedented level;
  - *Performed a sensitive search for LSND-like anomaly with CNGS beam,* constraining 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.

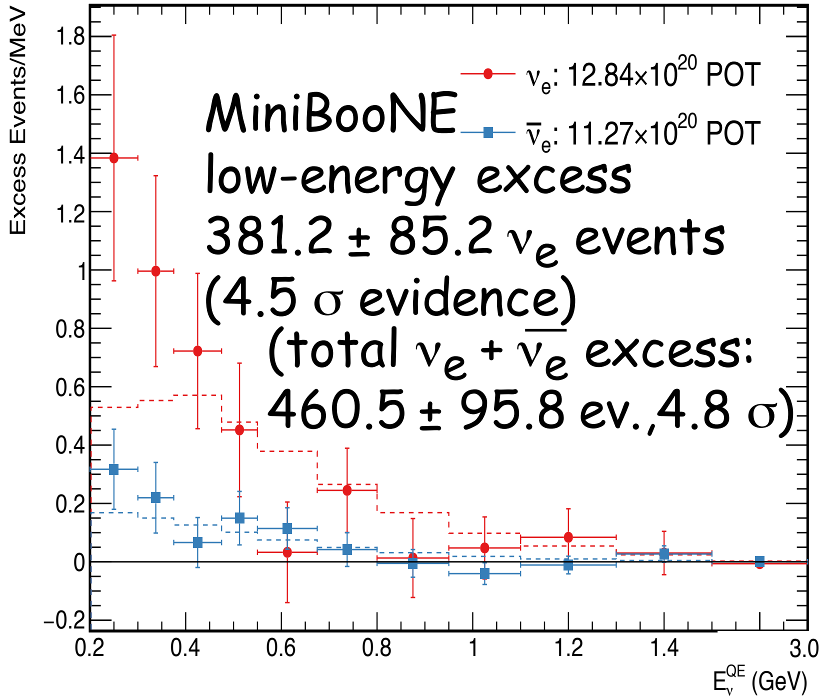


- These results marked a milestone for LAr-TPC technology with a large impact on neutrino and astro-particle physics projects: SBN short base-line neutrino program at FNAL with 3 LAr-TPC's (SBND, MicroBooNE and ICARUS) and the multi-kt DUNE LAr-TPC.

"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 ν_e from ν_μ beams in accelerator experiments (LSND 3.8σ, MiniBooNE 4.8σ (ν_e + anti-ν_e));
  - disappearance of anti-ν_e, hinted by near-by nuclear reactor experiments (formerly, ratio observed/predicted event rate R = 0.943 ± 0.023, Mention et. al, 2011);
  - disappearance of ν_e, hinted by solar ν experiments during their calibration with Mega-Curie sources (SAGE, GALLEX, R = 0.84 ± 0.05).



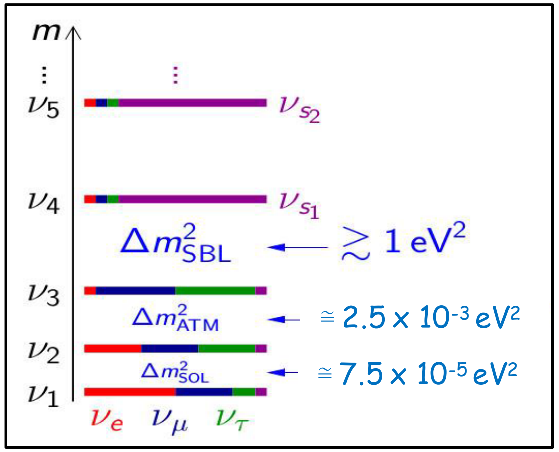


1805.12028 [hep/ex], neutrino2018

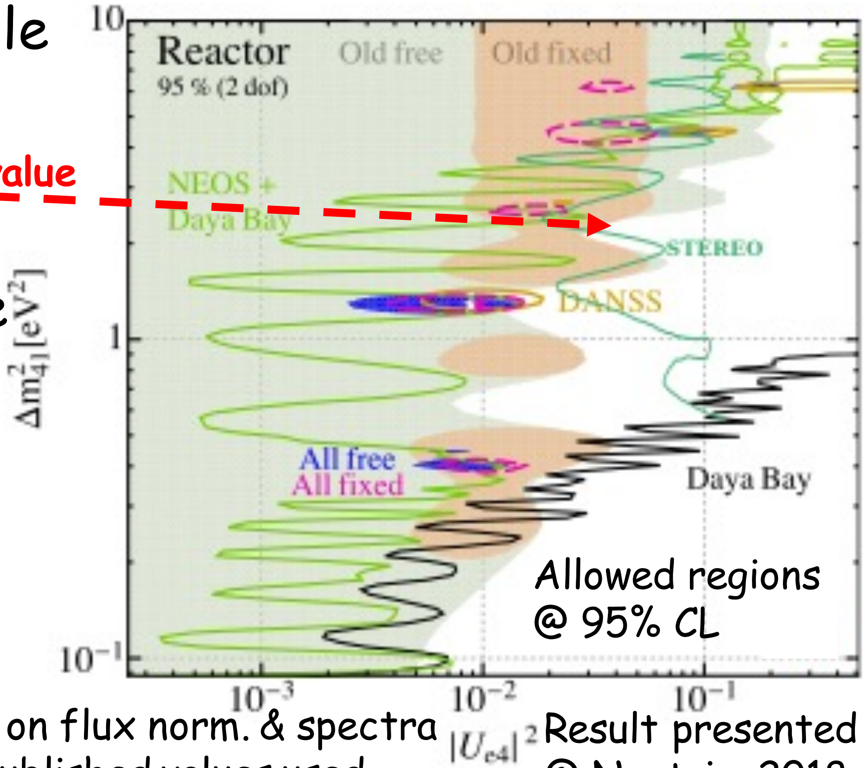
"Sterile neutrino puzzle" 2/2

- 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 indicates $\Delta m^2_{new} \leq 1\ eV^2$, small mixing;
  - Planck data and Big Bang cosmology point to at most one further flavor with $m_{new} < 0.24\ eV$;
  - No evidence for ν_μ disappearance in MINOS and IceCube in 0.32-20 TeV;
  - Recent reactor data are intriguing but inconclusive (global analysis prefers sterile ν hypothesis at $\sim 3\sigma$ with $\Delta m^2 \sim 1.3\ eV^2$).

SBL = Short base line
ATM = Atmospheric ν
SOL = Solar neutrino



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



Tension between appearance/disappearance results

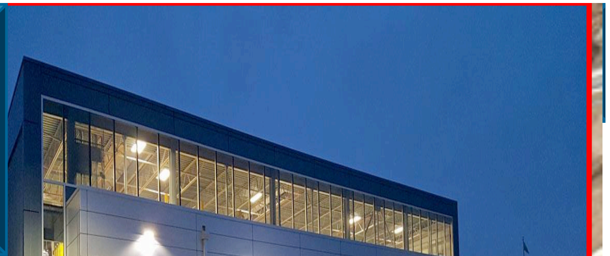
THE EXPERIMENTAL SCENARIO CALLS FOR A DEFINITIVE CLARIFICATION!

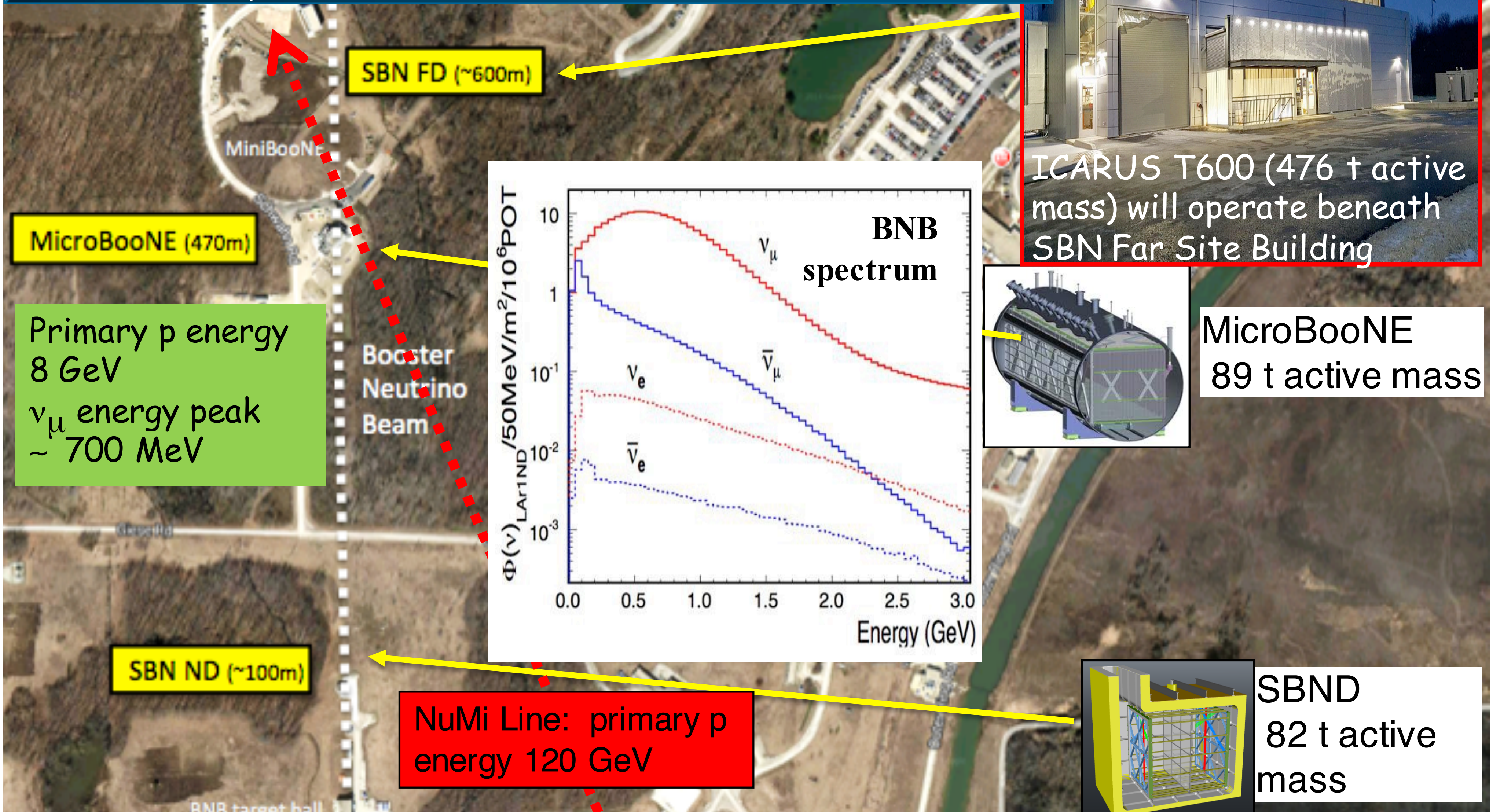
free=no assumption on flux norm. & spectra
fixed=prediction&published values used

Result presented @ Neutrino2018

SBN 0.8 GeV ν FNAL Booster: 3 shallow-depth LAr-TPCs as definitive answer to sterile ν puzzle

L/E_ν ~ 600 m / 800 MeV ~ 1m/MeV

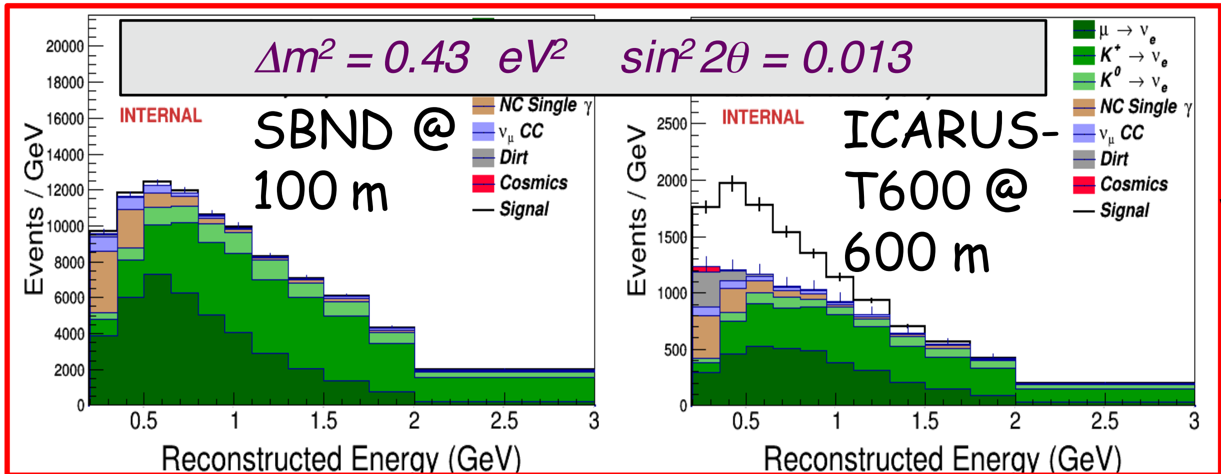


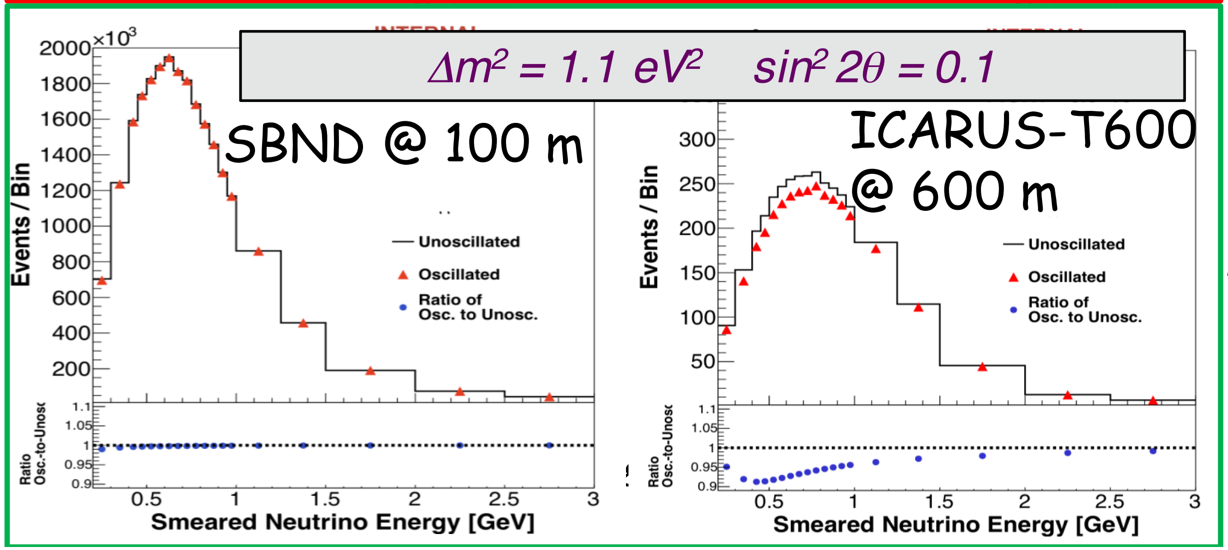


ICARUS T600 will collect also ~2 GeV ν_e NuMI Off-Axis: an asset for next LBNF-DUNE (ν cross-section in LAr measurements)

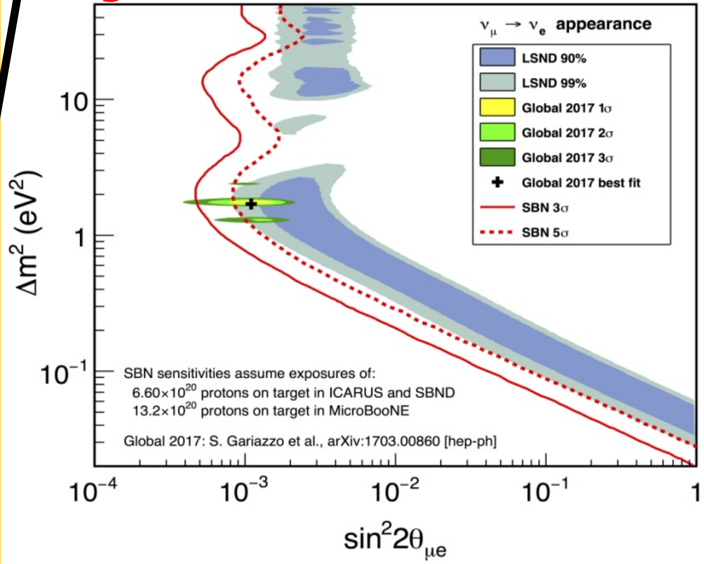
Sensibility and Sterile neutrino @ SBN

- 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, shall characterize the ν oscillation parameters.



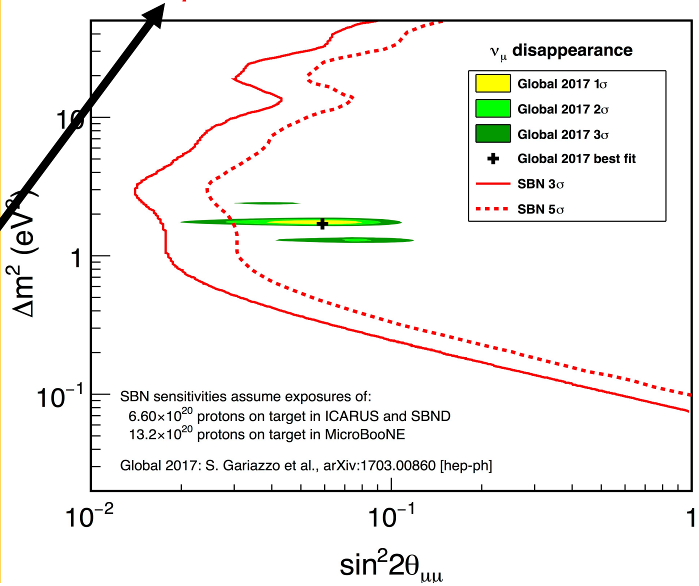


ν_e appearance: LSND 99% CL region covered at 5 σ level



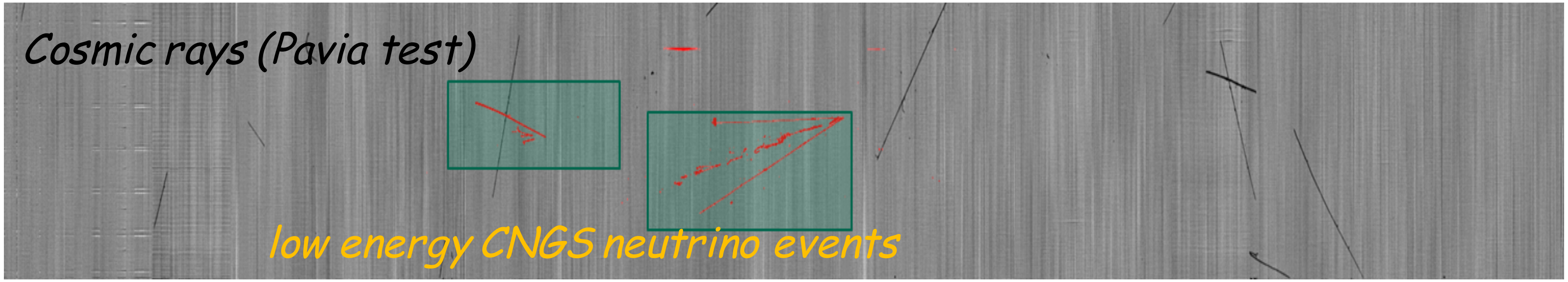
Both plots: 6.6×10^{20} pot (3 years)

3-5 σ ν_μ disapp. SBN sensitiv.

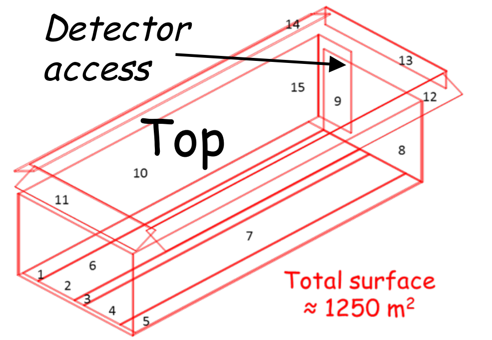


Taking data @ shallow depth: Cosmic Ray Tagger is mandatory

- ICARUS at FNAL is facing a more challenging experimental condition than at LNGS, requiring the recognition of ν interactions amongst 11 KHz of cosmics.
- *A 3 m concrete overburden* will remove contribution from charged hadrons/γ's.
- *Moreover ~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 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 ~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)

- 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* with both analogue/digital parts integrated in a single board in direct communication with ad-hoc signal feedthrough flanges.

T600 leaving from CERN June 12th 2017

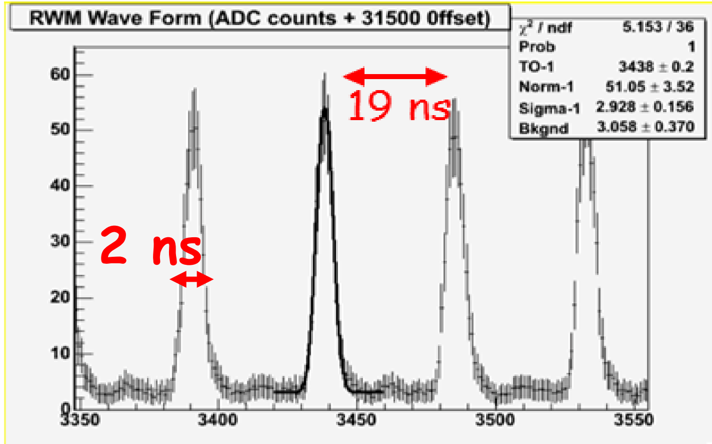
T600 in Antwerp: unloading from barge from Basel and loading into ship to Burns Arbors (Michigan lake)

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

The light collection system 1/2

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

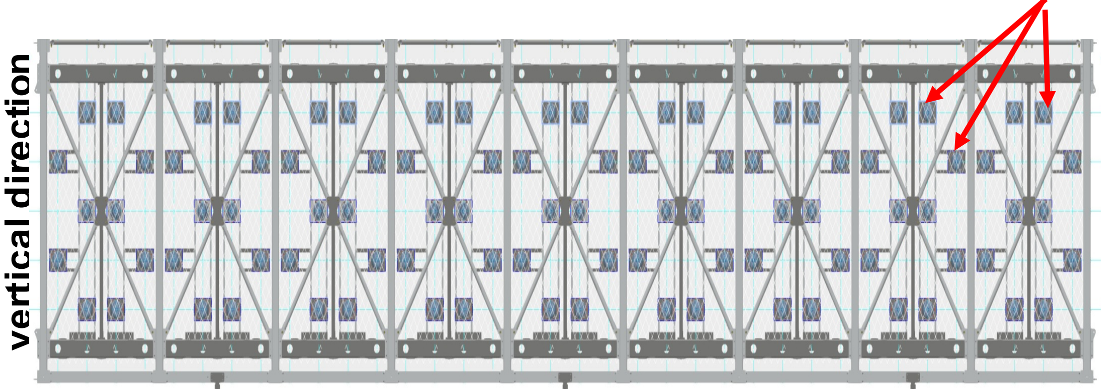


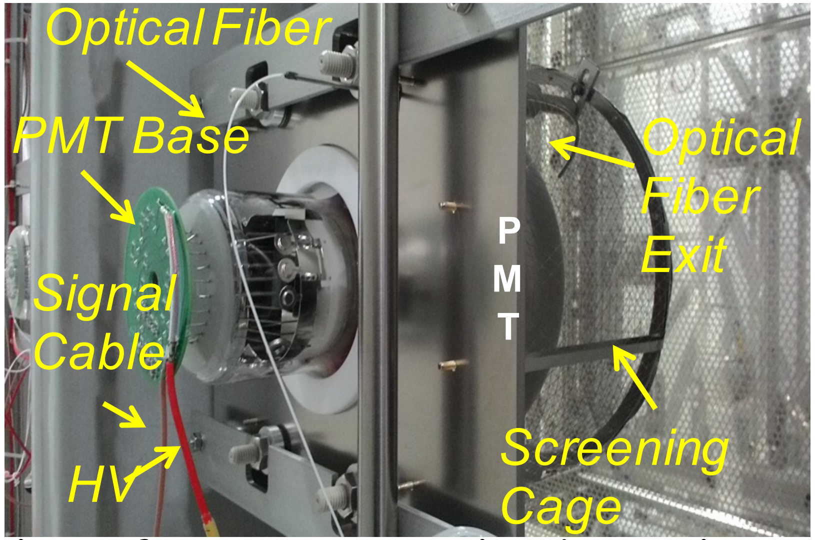
The light collection system is based on 360 PMT's, 90/chamber, to have:

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 (~mm), 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.

The light collection system 2/2

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





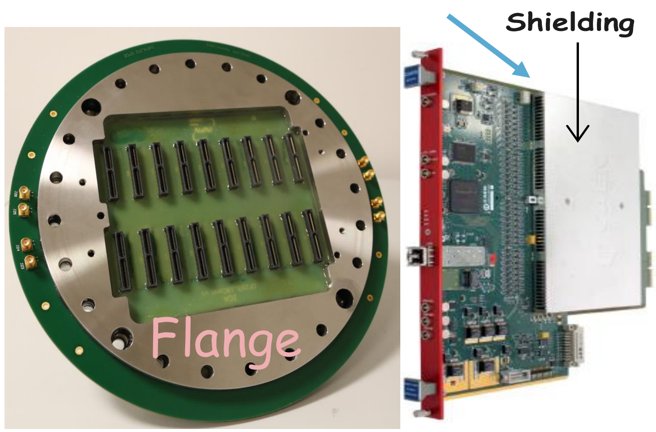
- Hamamatsu R5912-MOD (8", 10 dynodes) are rated for cryogenic temperature, as they feature a cathode with platinum under-layer.
- Each PMT is enclosed in a wire screening cage to prevent induction of PMT pulses on the facing TPC wires
- PMT sand blasted glass windows coated by ~200 $\mu g/cm^2$ of Tetra-Phenyl-Butadiene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

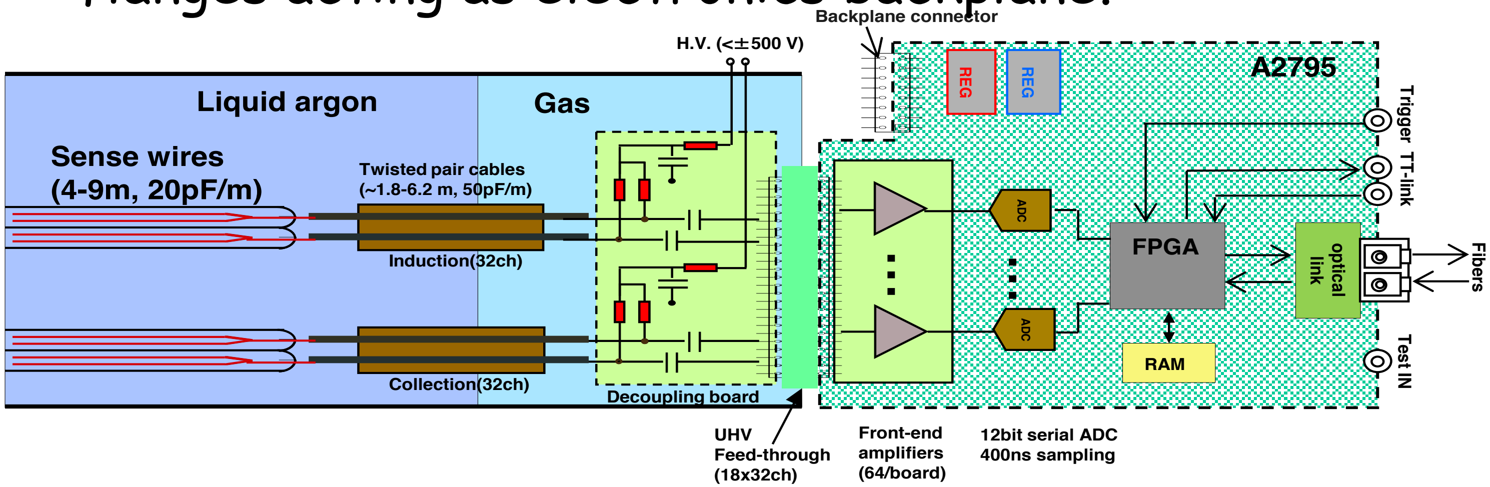
A clear cosmic μ's identification will be provided by genetic algorithms (~2% expected residual misidentification).

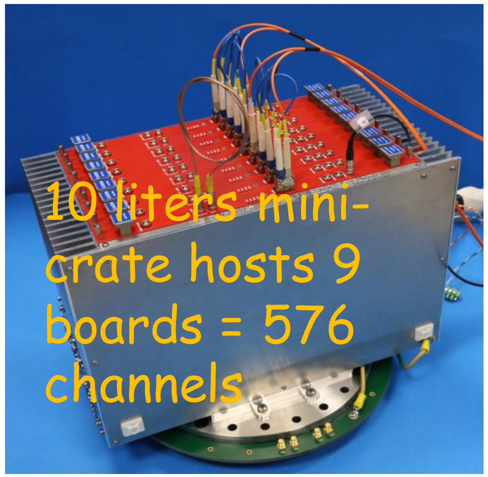
The new TPC read-out electronics

- ICARUS electronics at LNGS was based on analogue low noise "warm" front-end amplifier, a multiplexed 12-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 acting as electronics backplane.

CAEN A2795 board, 64 chs



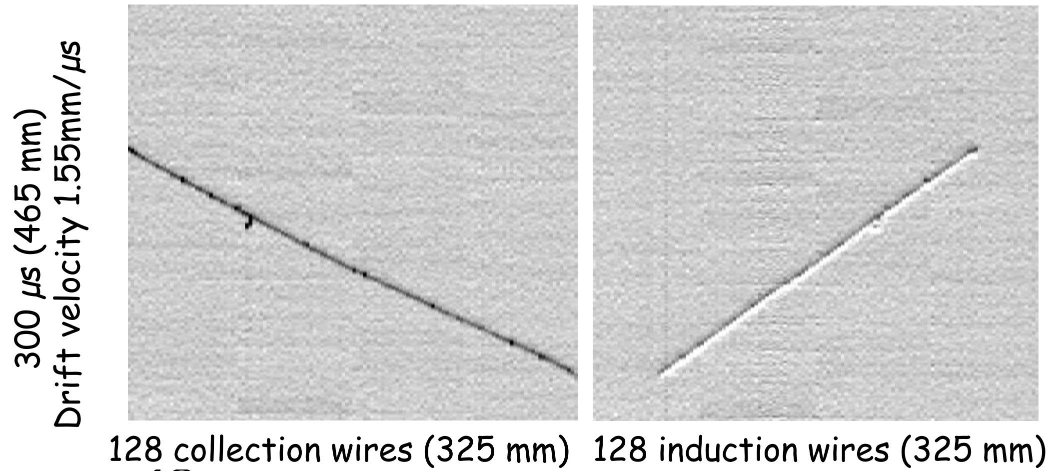




Improved front-end electronics for T600

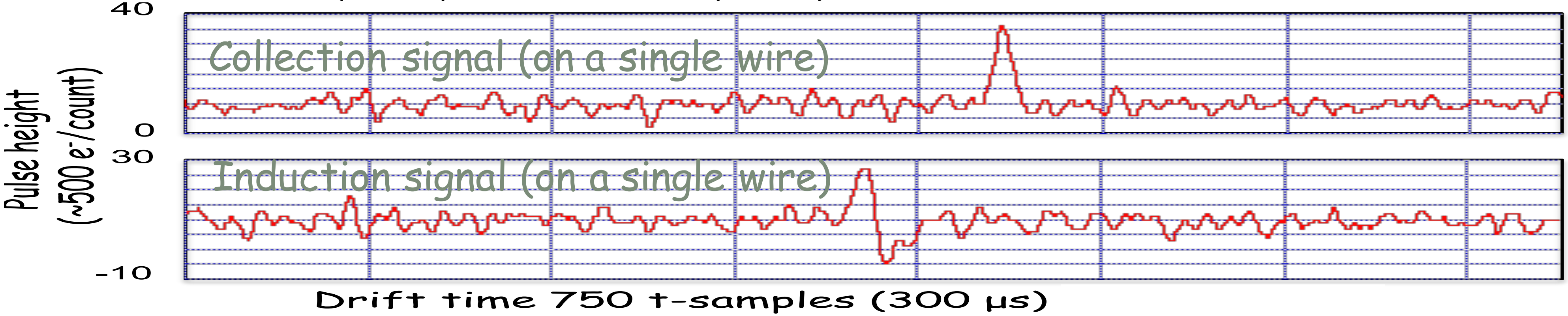
- Adopted improvements in the analogue front-end
  - A faster shaping time ~1.5 μs of analogue signals to match electron transit time in wire plane spacing;
  - A drastic reduction of undershoot in the preamp response as well as of the low frequency noise while maintaining a same or better S/N;
  - Same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

A better event reconstruction is then possible



Example of single m.i.p. track:

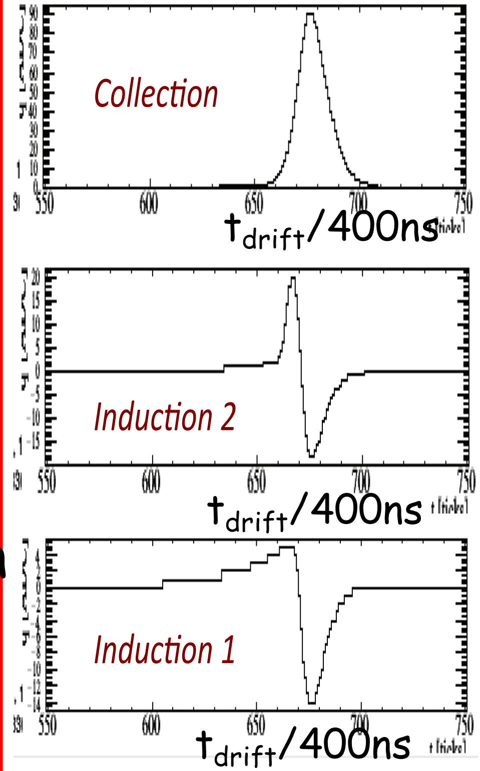
- Same ~2ADC counts (~1000 e-) noise for both Collect. & Induct.;
- Unipolar Collection signal: ~ 25 ADC counts;
- No filter applied to any data.

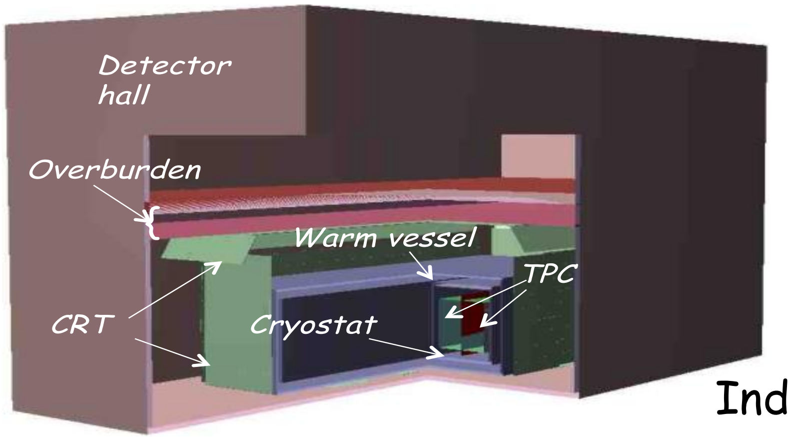


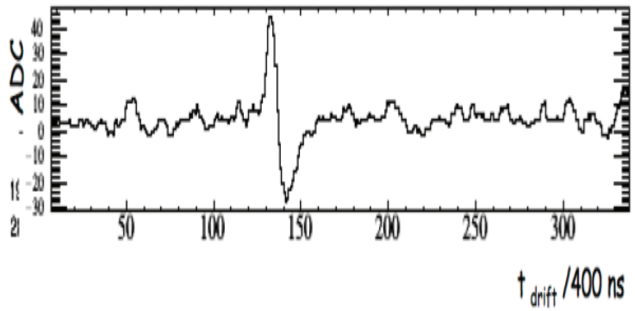
ICARUS @ SBN software status 1/2

- ICARUS adopts a framework (LarSoft) common to SBN experiments, providing tools to simulate, reconstruct/ identify events (cosmic μ's, e.m. showers, neutrinos, …).
- Experimental geometry setup is described in LarSoft.
- Some reconstruction/analysis tools (particle ID, 3D and shower axis reconstructions, momentum from Multiple Coulomb Scattering…) are inherited from previous LNGS ICARUS software and are being ported to LarSoft.
- Scintillation light in LAr is parameterized to simulate PMT signals for any MC event, to study event recognition with genetic algorithms, and for trigger simulation.
- MC simulations include new wire electronic response/ realistic noise, as well as PMT scintillation light signals.

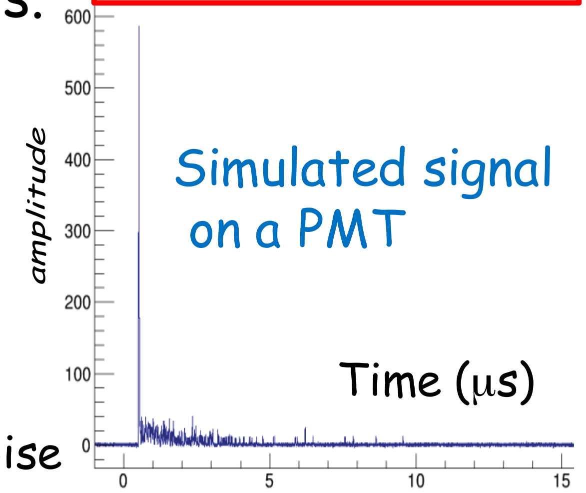
Typical wire shape for 1 m.i.p. μ





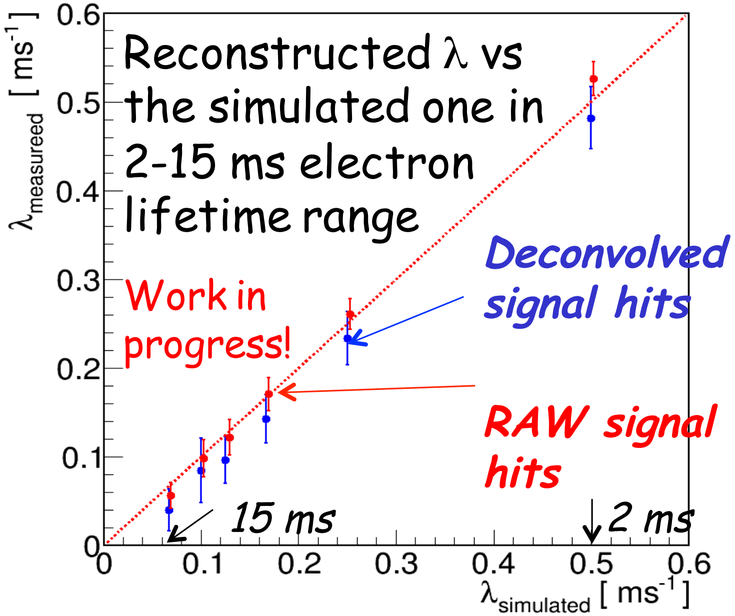


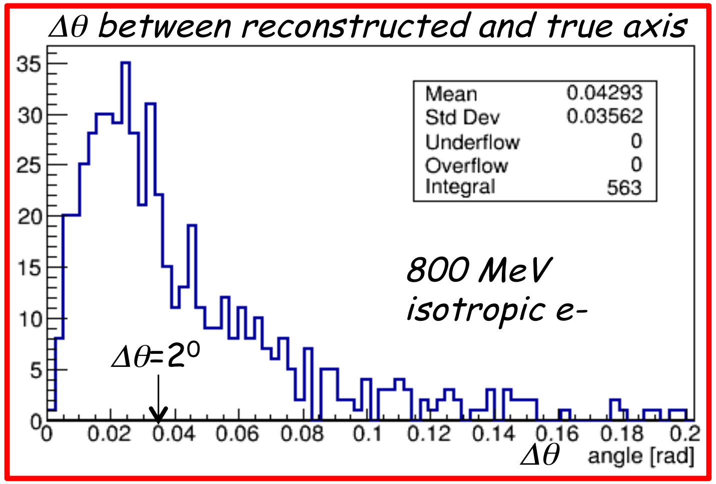
Ind.2 signal simulation, including noise



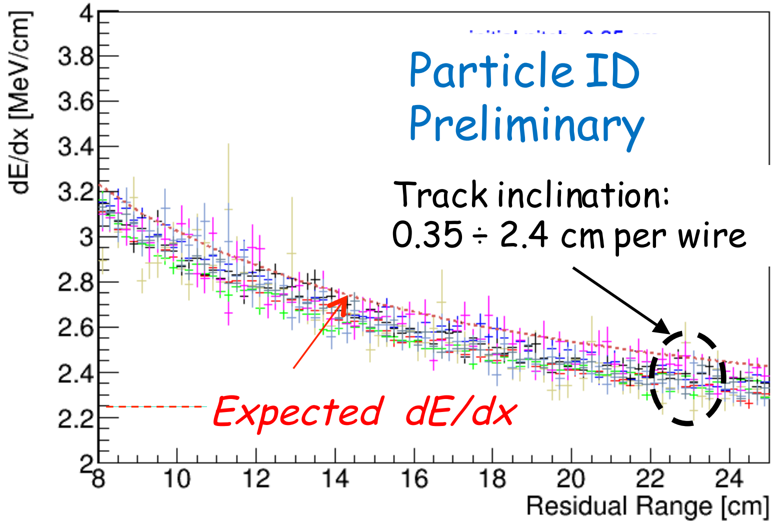
Software status 2/2

- Examples of 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



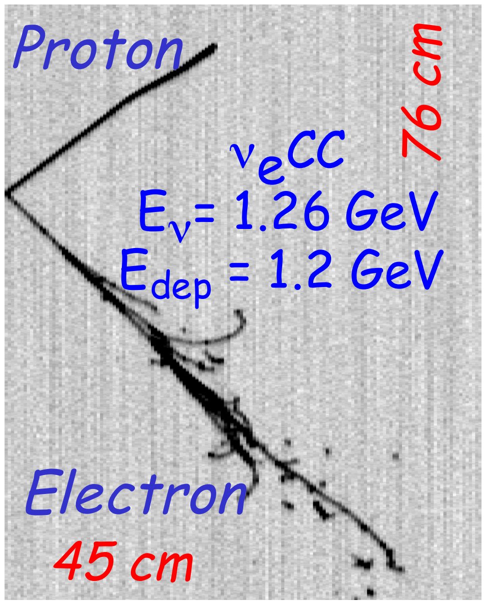


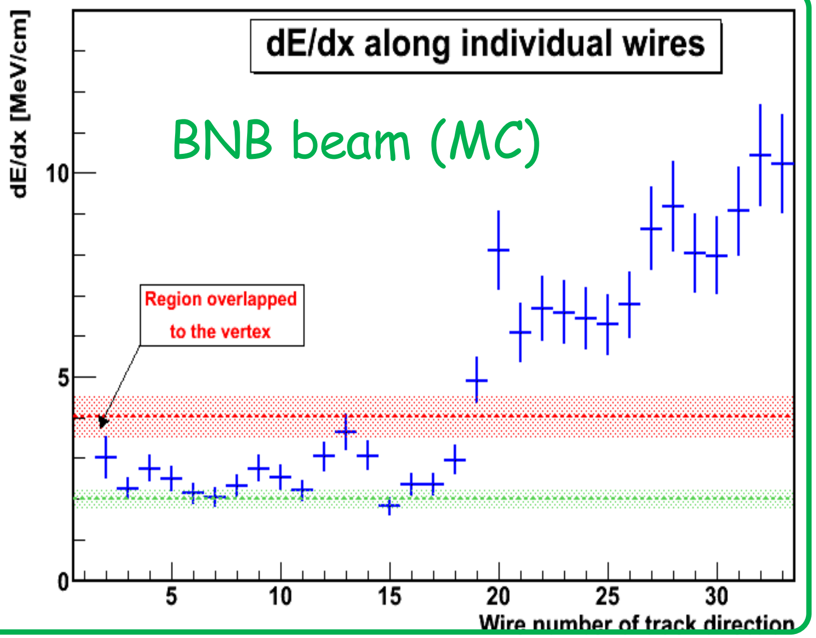
dE/dx vs range for μ's



Software is mature enough to realistically simulate events with BNB beam

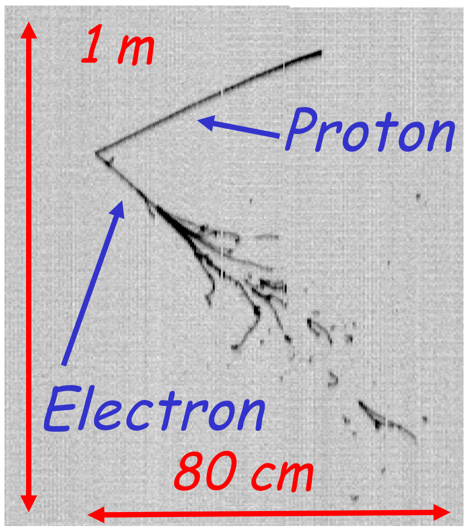
BNB (MC) and real atmospheric ν_eCC events comparison

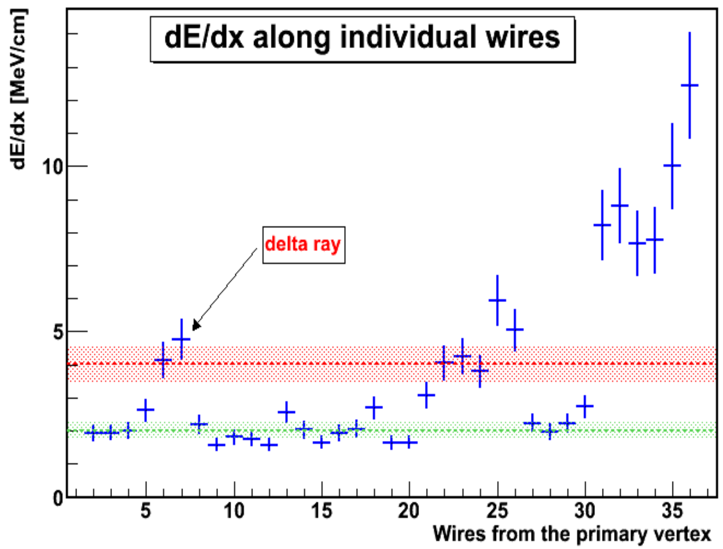




- MC SBN ν_eCC interactions (on the left) are very alike to typical atmospheric ν_eCC events @ LNGS (below)
- Similar results hold for ν_μCC interactions

LNGS ν_e ATMOSPHERIC EVENT

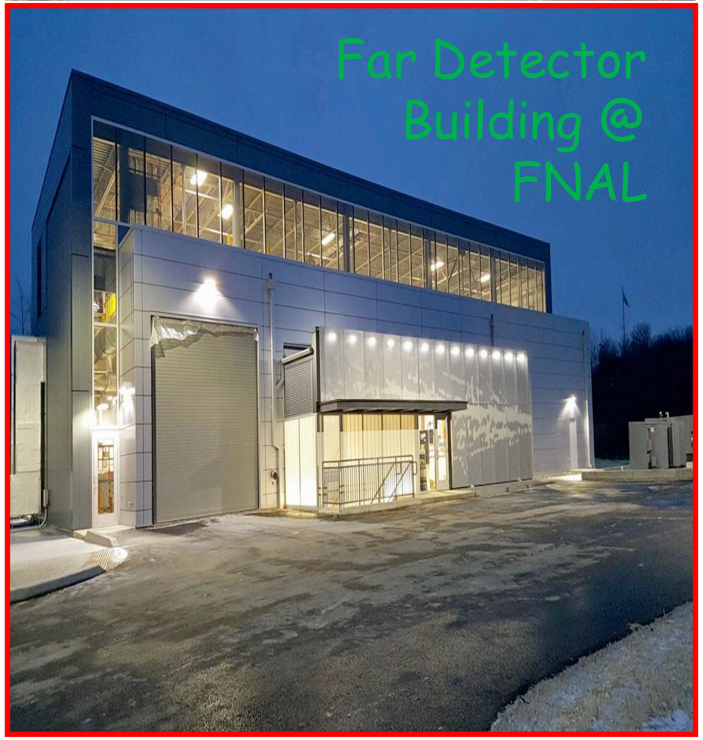




- Quasi-elastic ν_eCC E_{Dep}= 0.9 GeV.
- Proton identified by dE/dx.
- Electron identified by single m.i.p. before showering

Current status of ICARUS installation @ FNAL 1/3

- The lower part of the warm vessel had been assembled inside the Far Detector (FD) building at FNAL by summer 2017.
- 14 modules of the bottom CRT (200 m^2 total area) have been 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 completed by May 2018.
- Before moving cold vessels in the final position (expected by middle July 2018), the main doors of the vessels have to be sealed. A helium leak tests is being performed and should be completed by this week (~mid June 2018)
- Installation of detector supports is in progress.

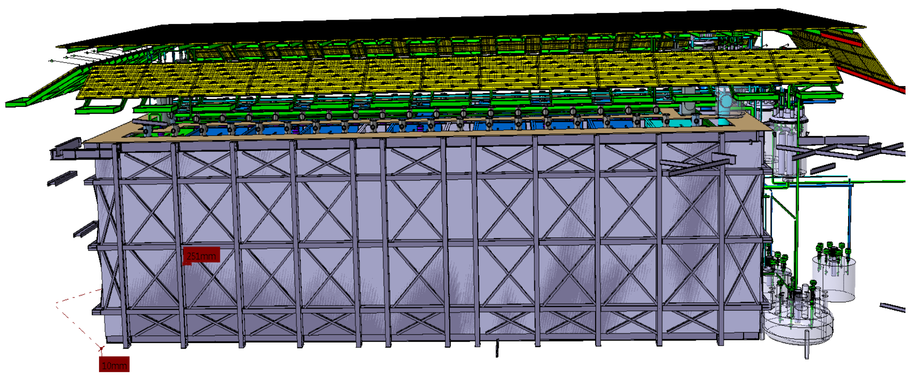


Current status of ICARUS installation @ FNAL 2/3

- Connectivity tests have to be performed as part of the installation of chimneys (cold vessel to outside of thermal insulation connections), by beginning August 2018.
- Top part of cold shield will be installed and tested, followed by installation of top part of warm vessel (August 2018).
- Side CRT (double layer, ~1000m^2 total) should start read-out board production in fall
  - Each module (8m x 80.5cm x 1 cm) has 20 parallel scintillator strips, SiPM-based readout.
- From Sept. 2018, activities on top of detector will start (cryo, purification and vacuum systems, ext. cabling, feedthrough flanges with decoupling boards, optical fibers, read-out,…)
- Vacuum pumping should start by Nov 2018 and last until ready to start cool-down (Jan 2019), which is bound to "clearance to start operation" issued by Fermilab.

Current status of ICARUS installation @ FNAL 3/3

- Meanwhile:
  - Testing of DAQ, noises, PMTs, Slow controls, etc. should continue.
  - Cryo systems installation and pre-commissioning will be completed.
- Detector commissioning consists of three phases:
  - Cryogenic commissioning (2 months in total): Cooling (15 days), Filling (15 days), Purification (1 month), Stabilization (1 month).
  - TPC and PMT system commissioning (2 months in total): HV for the E field drift, PMT's supply, calibrations, DAQ & trigger commissioning.
  - CRT 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 (~400m^2, 125 modules, 64 scint. strips per module, SiPM-based readout, 2 fibers/strip) "barn-style" installation should start in 2019.



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 LSND-like ν_e excess defining a narrow region at (Δm^2, $\sin^2 2\theta$) ~ (1 eV^2, 0.005). Result confirmed by OPERA.
- ICARUS underwent a major overhauling at CERN and was transported to FNAL to be exposed to Booster and NuMi neutrinos, to provide a clarification of the sterile neutrino issue, both in appearance and disappearance modes (SBN experiment).
- ICARUS installation in the Far Site building @ FNAL is in progress
  - Done: lower part of warm vessel, 14 modules of bottom CRT in summer 2017, cold shields: assembly in May 2018, installation by mid Jun 2018.
  - Now: Installation of detector supports.
  - Next steps:

    ➔ Installation of: chimneys (Aug 2018), top of cold shield, warm vessel (Aug 2018); activities on top (cryo, purification, vacuum systems…) (from Sep 2018); vacuum pumping should start by Oct-Nov 2018.

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


Thank you !