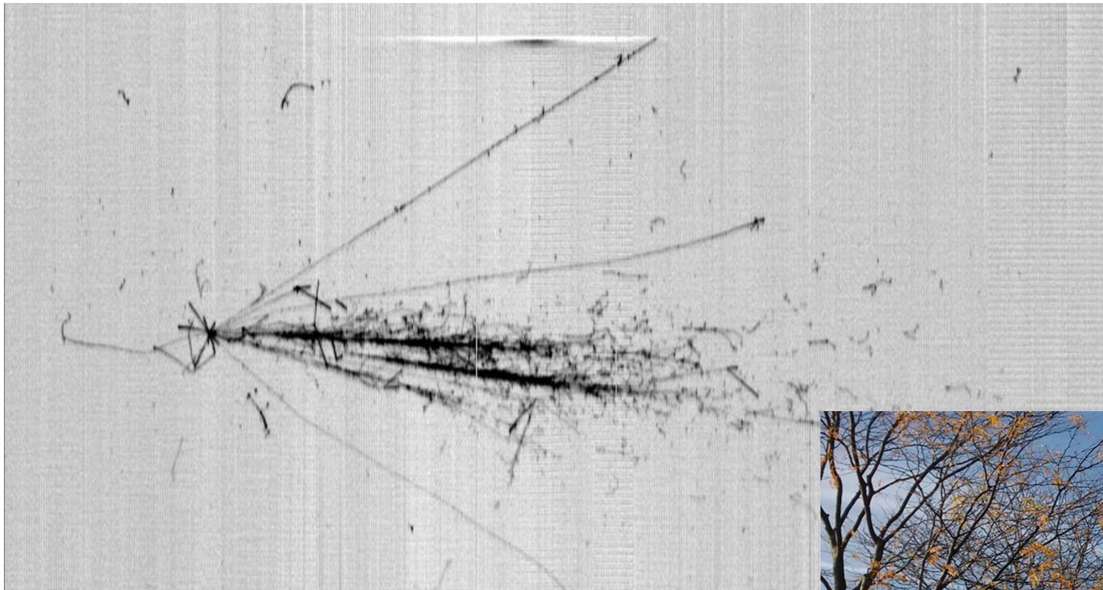
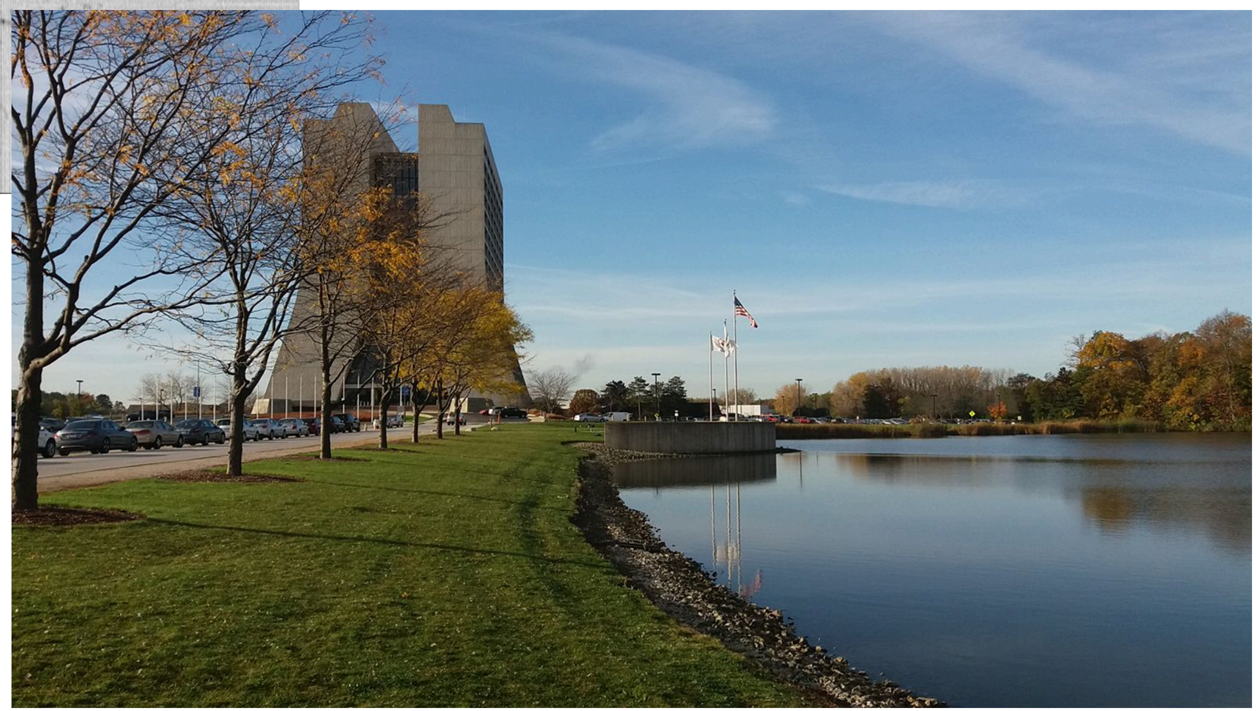
Sterile neutrino searches with the ICARUS detector



F. Varanini
INFN Padova

on Behalf of the ICARUS Collaboration



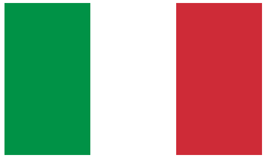
New Trends in High-Energy Physics

Budva (Montenegro)
September 28th 2018

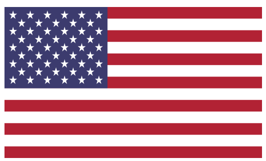
Outline

- Liquid Argon TPCs: performance and results at LNGS
- The sterile neutrino puzzle
- The SBN experiment at FNAL Booster: ICARUS as far detector
- The ICARUS detector refurbishing at CERN (2015-17)
- Status of installation at FNAL: looking forward to data taking
- Conclusions

The ICARUS collaboration



Catania (INFN and Univ.)
GSSI
LNGS
INFN Milano Bicocca
INFN Napoli
Padova (INFN and Univ.)
Pavia (INFN and Univ.)



Brookhaven (BNL)
Colorado State
FNAL
Houston
Pittsburgh
Rochester
SLAC
Texas (Arlington)

Spokesman: C. Rubbia (GSSI)

The Liquid Argon TPC

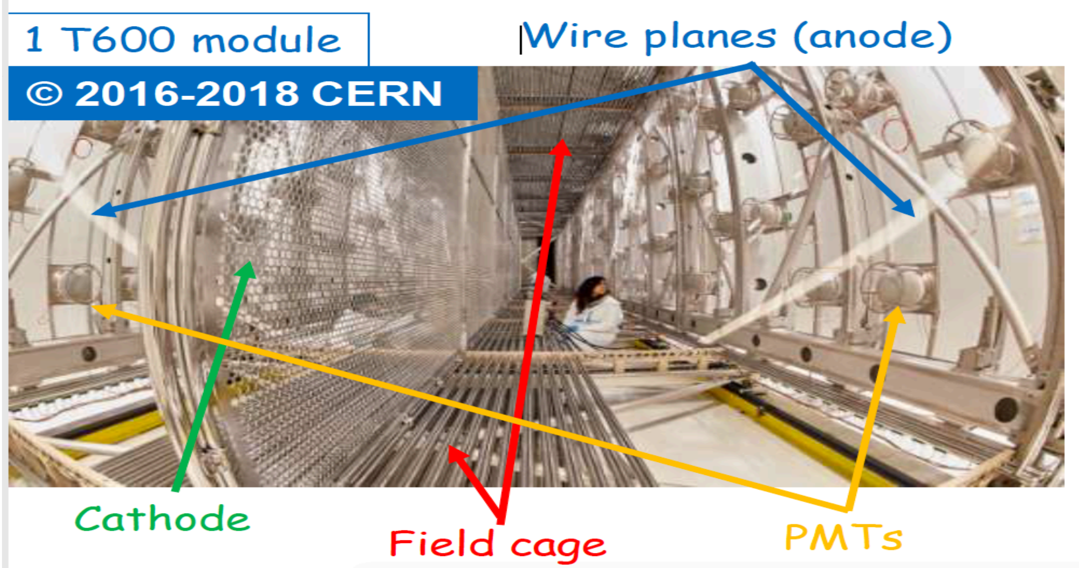
- LAr-TPCs are ideal detectors for neutrino physics and other rare phenomena, like nucleon decay:
  - Excellent 3D imaging capability (resolution~wire pitch, order of millimeter)
  - Uniform, full-sampling calorimetry (thanks to collection of drift electrons)
  - Argon acts both as massive target and detection medium
  - Relatively cheap -> can be scaled to huge masses (kton and beyond)

  LAr scintillation light provides fast signals for timing/triggering

- First proposed in a seminal paper by C. Rubbia in 1977
- Long R&D effort by INFN, in collaboration with industry, culminating in the first large-scale LAr-TPC physics experiment: ICARUS-T600, running in the LNGS underground lab from 2010 to 2013

ICARUS-T600 at LNGS

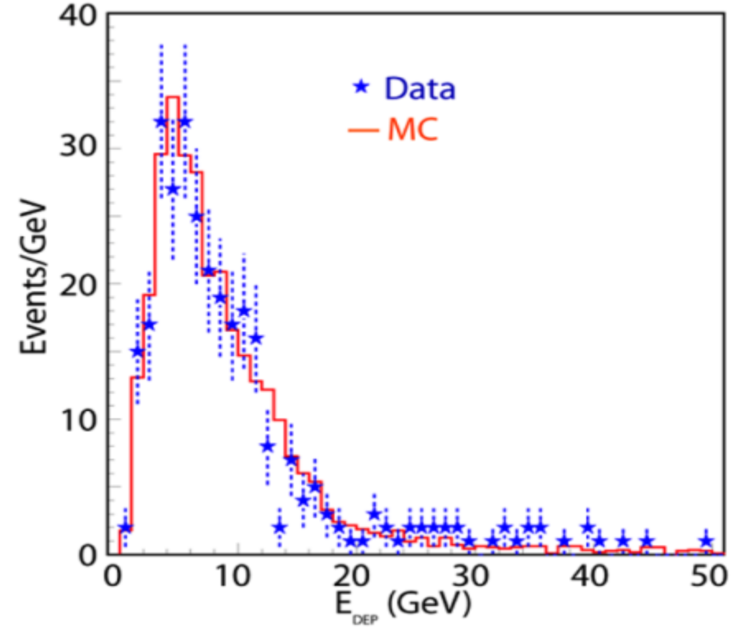
- 2 identical modules (476 t total mass), 2 TPCs per module sharing a central cathode, with 1.5 m drift length. Drift field is ~500 V/cm -> v_D~1.6mm/μs.
- 3 wire planes (0,±60° w.r.t. horizontal) with 3 mm pitch. Wire biasing guarantees non-destructive charge readout. Last plane (Collection) allows calorimetry. ~54000 total readout wires, with 400 ns sampling time
- VUV scintillation light is read out by PMTs coated with wavelength shifter(TPB)

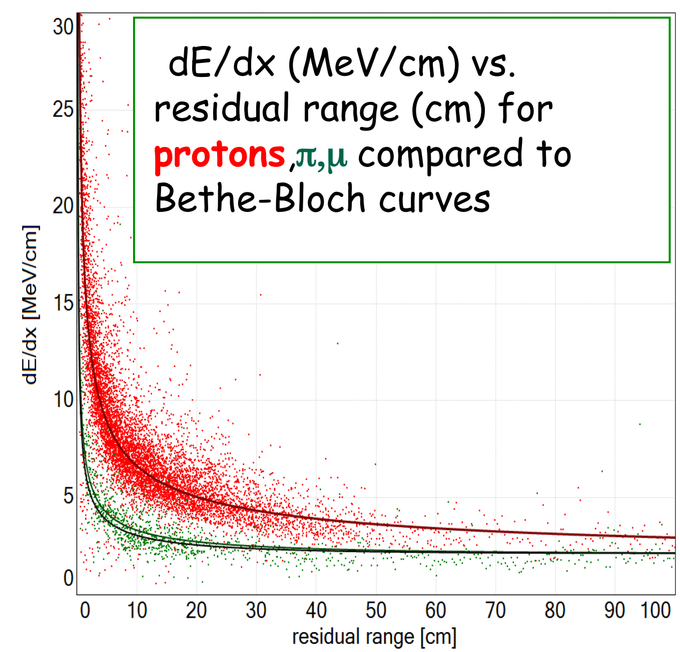


- ICARUS-T600 took data at LNGS underground lab from 2010 to 2013, exposed to both CNGS beam from CERN (8.6 10^{19} pot) and atmospheric neutrinos
- This very successful run (live time > 93%) proved the maturity of the LAr-TPC technology for physics experiments with large masses/long exposure time

ICARUS LAr-TPC performance

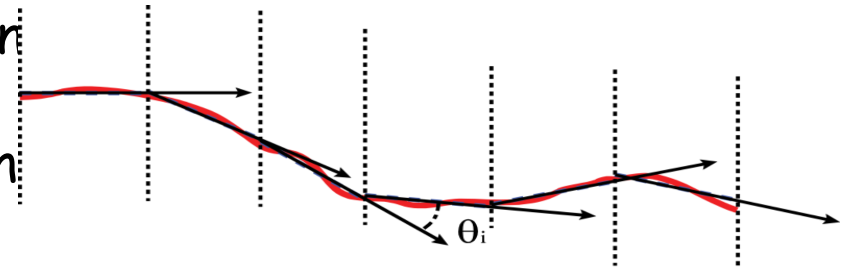
- *Tracking device:* 3D imaging at ~mm^3 level even for complex event topologies;
- *Global calorimeter:* homogeneous calorimetry by charge integration - excellent accuracy for contained events; momentum of non contained muons measured via Multiple Coulomb Scattering ($\Delta p/p$ ~15% in 0.5-5 GeV/c range);
- *Measurement of local ionization density dE/dx:* remarkable e/γ separation (0.02 X_0 sampling, X_0=14 cm). 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 shower (pure LAr):*
    $\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$





Measurement of muon momentum bymultiple scattering

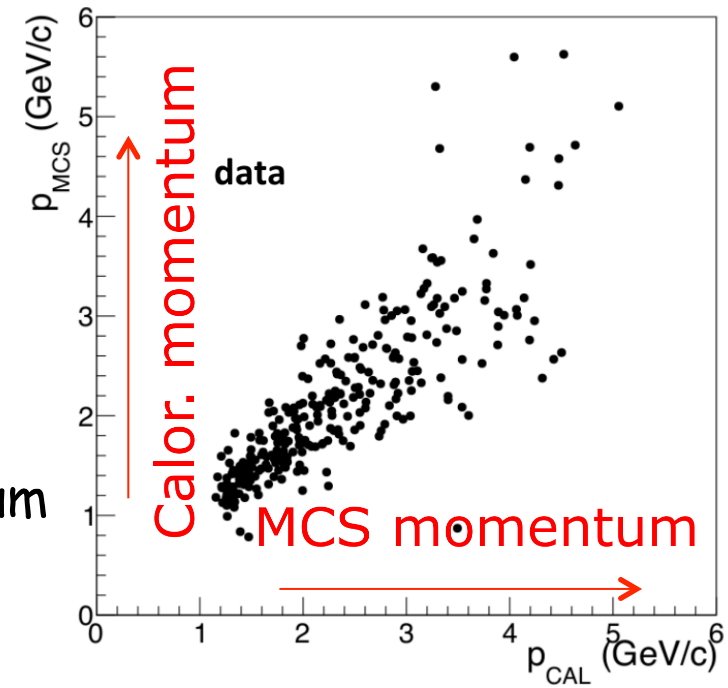
- Algorithm based on deflection angles θ between successive segments (length *l*) in Collection plane, compared with expected RMS for a given momentum



- Segment length chosen to enhance genuine MCS deflection w.r.t. apparent ones related to track measurement (errors evaluated event by event)

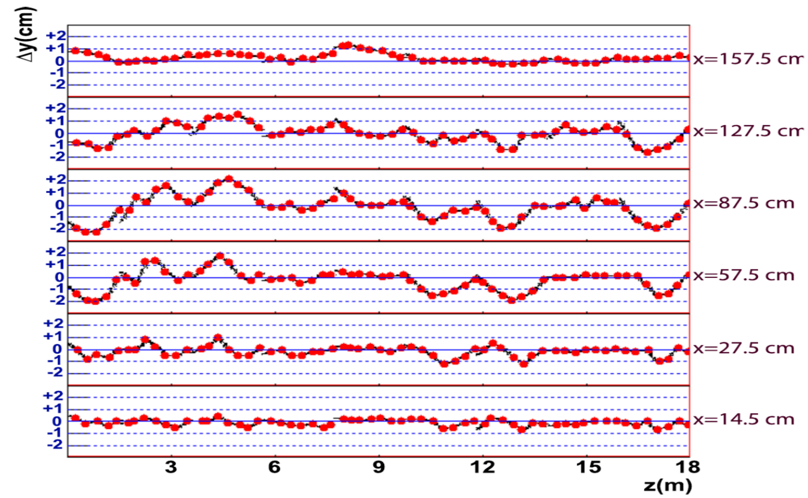
$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$

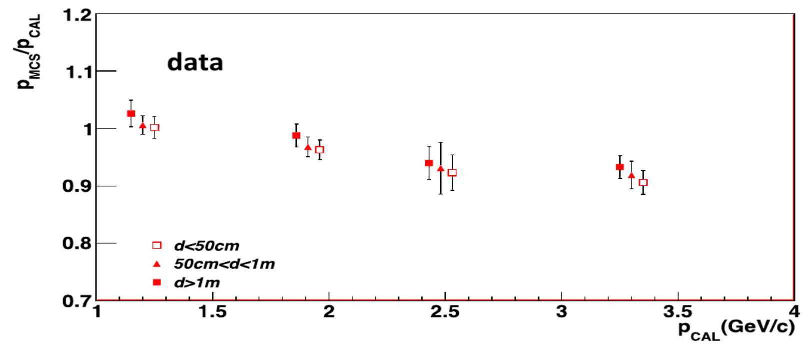
- Algorithm validated on ~400 muons from CNGS neutrinos interacting in upstream rock, stopping/decaying in T600 volume. They represent ideal validation sample:
  - Independent momentum estimate from calorimetry
  - Spectrum between ~0.5 and ~5 GeV/c, similar to muons from future short- and long-baseline neutrino experiment
- Agreement between MCS and calorimetric momentum is good, despite some distortion, observed at p>3 GeV/c, especially near the cathode



Measurement of muon momentum via multiple scattering

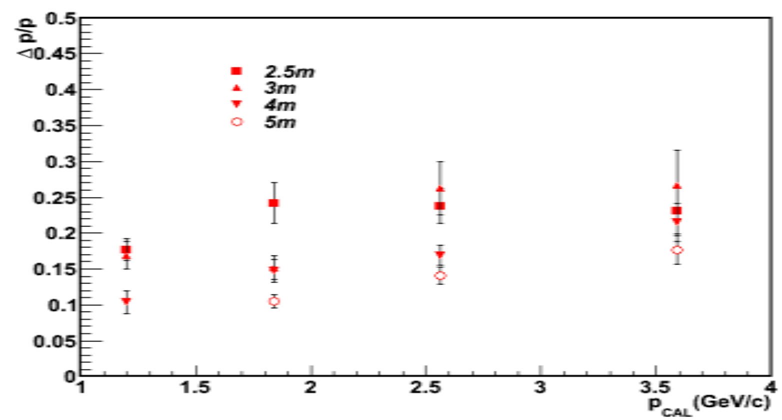
- In fact, a non-perfect planarity of the cathode (up to 2.5 cm) was observed, resulting in a distortion of the drift field
- This introduces "fake deflections", mimicking a larger MCS effect and a lower momentum
- An average MC-based correction can be obtained by simulating the drift field based on measured non-planarities. This allows to reduce the underestimation to max ~5%





- Muon momentum resolution depends on *p* and used track length (several values were tested); average is ~15% on stopping muon sample

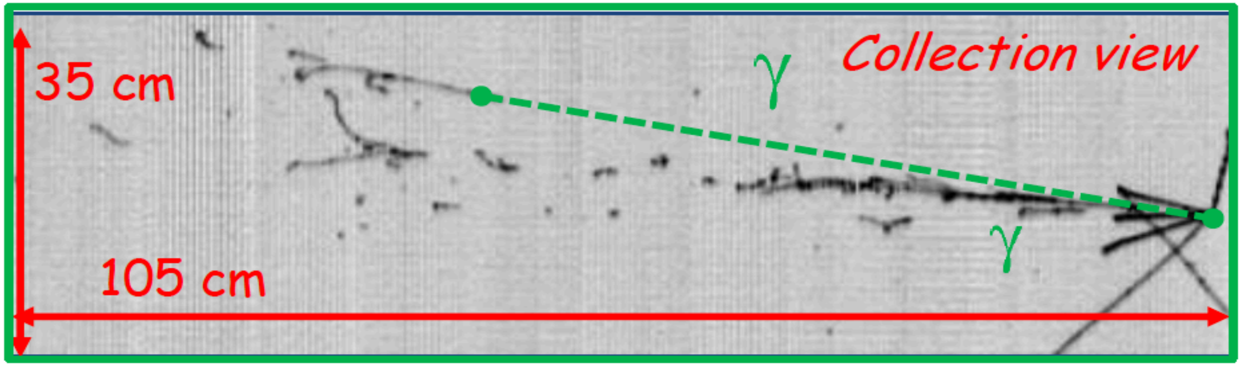
See paper JINST P04010 (2017) for details

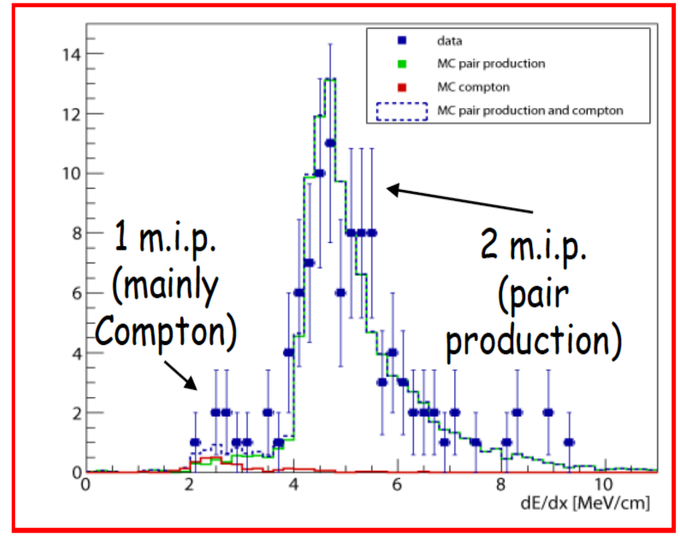


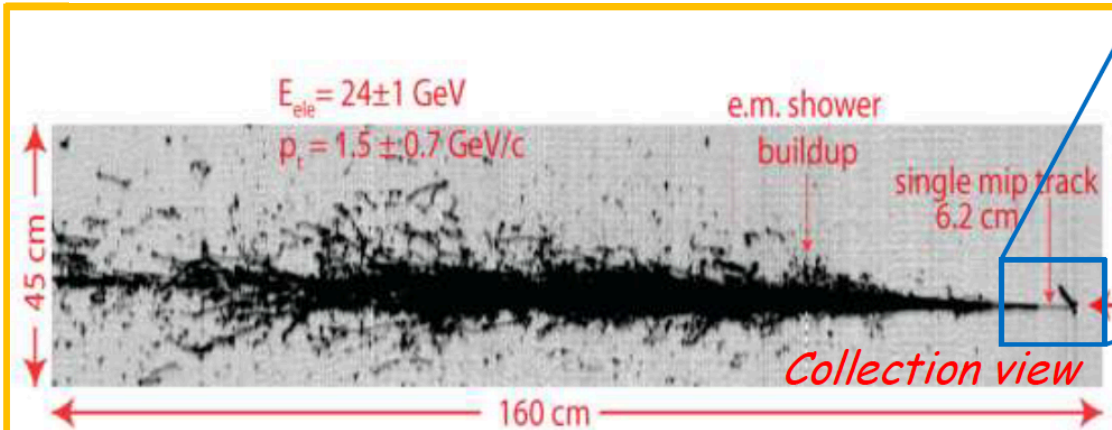
e/γ separation and ν_e identification

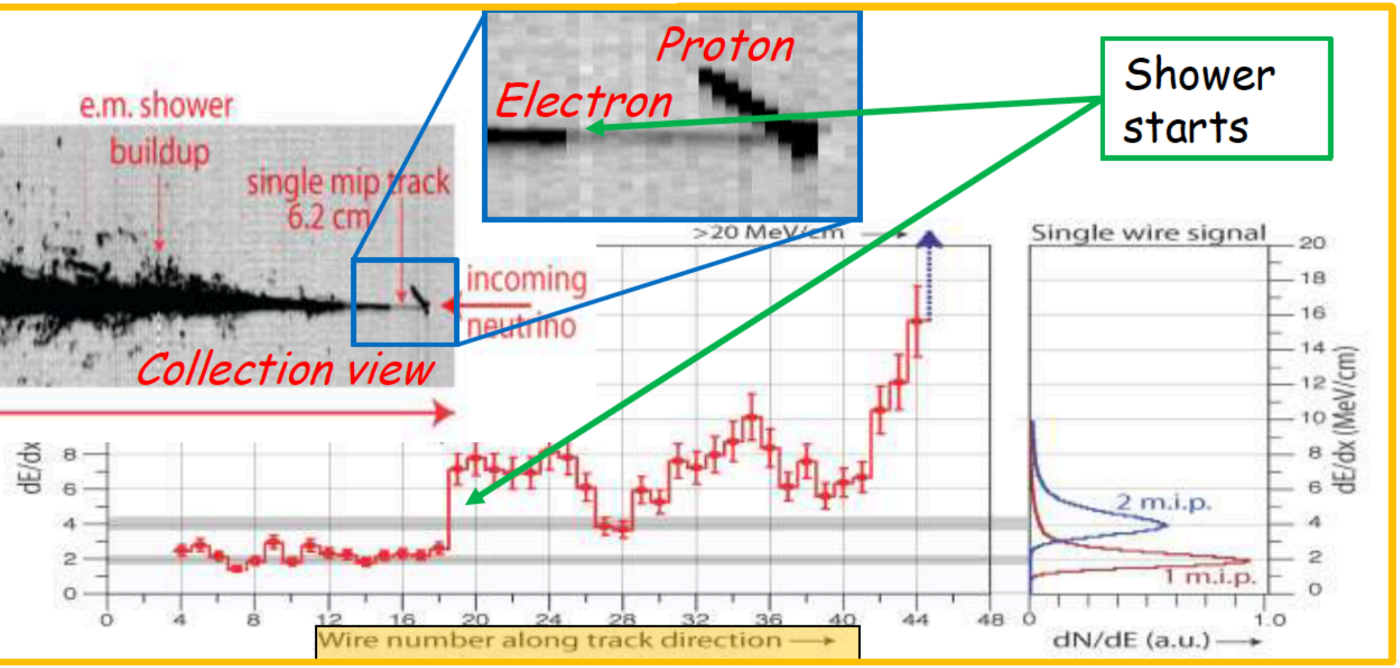
Three "handles" to tell e from γ and reject NC (π^0) background:

- Measurement of π^0 invariant mass
- dE/dx (single vs. double MIP)
- Visual identification of γ conversion "gap" at vertex









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

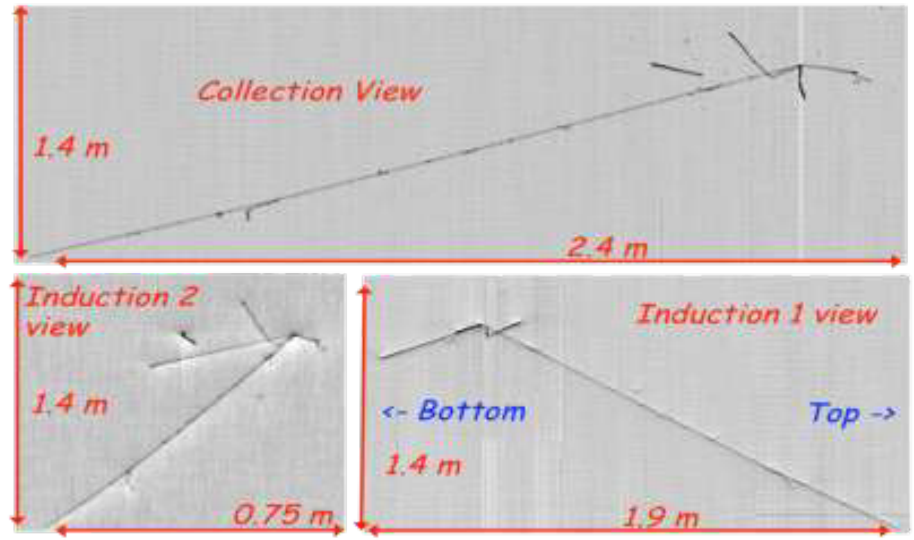
Atmospheric neutrinos at LNGS

- T600 was also exposed to atmospheric neutrinos (0.74 kt year) at LNGS
- 14 events (6 ν_μCC + 8 ν_eCC) identified vs. 18 expected (taking into account detection efficiencies and detector live time)
- Interesting sample to validate reconstruction: similar energy range as in SBN

2 examples:

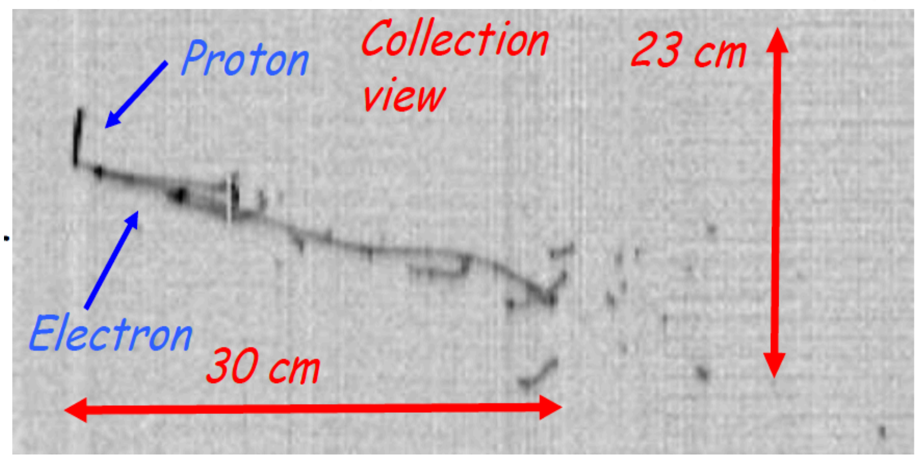
UP-GOING ν_μCC (E_{dep} ~1.7 GeV):

- *non-contained muon (1.8 GeV from MCS)*
- *2 pions (80 MeV) and a proton (180 MeV) at vertex*
- *Reconstructed E_ν~2GeV, zenith angle ~78°*



DOWN-GOING QE ν_eCC (E_{dep} ~240 MeV):

- *Identified as ν_e from single MIP dE/dx measured on first wires*
- *Short proton identified at vertex*

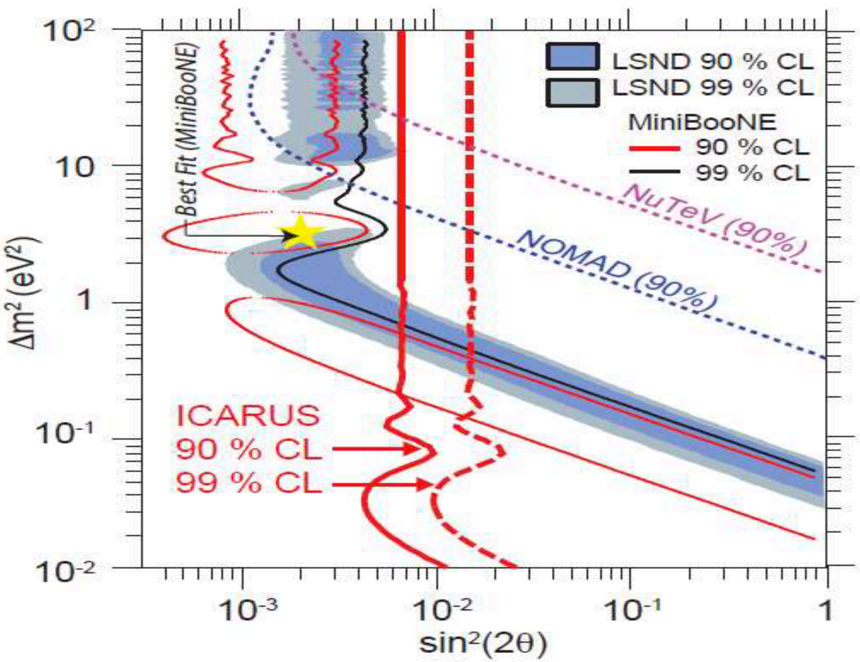


ICARUS at LNGS: results and perspectives

The T600 run proved the full maturity of LAr detection technology, obtaining several important scientific and technical results:

- An unprecedented argon purity: concentration of electronegative impurity at ~20 ppt (O_2eq.) or electron lifetime ~15ms.

  Maximum attenuation ~7% in ICARUS, paving the way for future larger TPCs
- Demonstrated reconstruction performances: especially in e/γ separation, and π^0 background rejection, superior to other technologies
- Results in sterile neutrino physics: LSND-like anomaly investigated by searching for νe appearance in the CNGS beam, constraining allowed parameter space to a small region around Δm^2~1eV^2, $\sin^2 2\theta$~0.005, confirmed by OPERA



ICARUS@LNGS opened the way for the next generation of LAr-TPC projects:

- *SBN for sterile neutrino searches at FNAL*
- *DUNE (35kt) for CP violation and neutrino mass hierarchy*

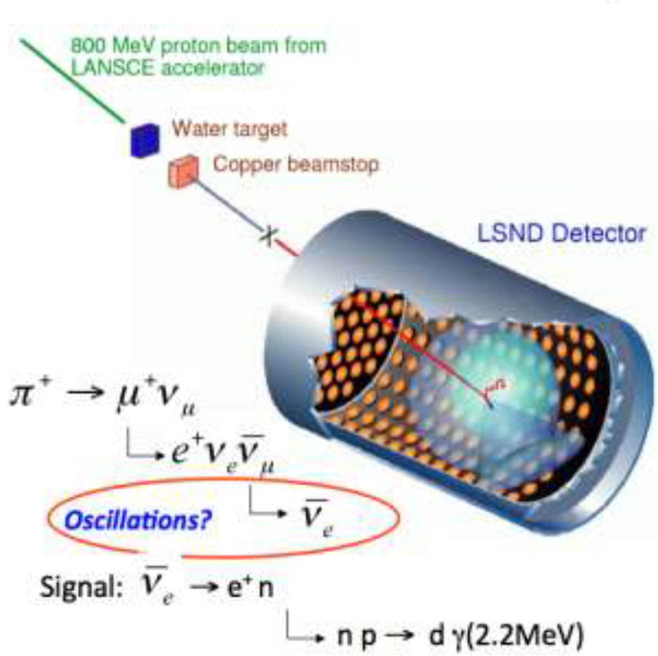
The sterile neutrino puzzle

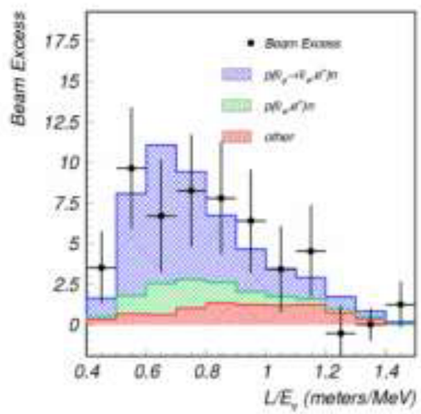
The 3-neutrino scenario is now well established and confirmed by lots of data.

However, a few anomalies could point to flavour transition with $\Delta m^2 \sim eV^2$:

- νe appearance in $\nu\mu$ beams at accelerators (LSND 3.8σ excess, recent updates from MicroBooNE)
- Anti-νe disappearance at reactors (measured/predicted ratio R=0.938±0.024)
- Disappearance of νe from Mega-Curie sources used in calibration of solar neutrino experiments (SAGE/GALLEX, R=0.84±0.05)

The LSND Anomaly

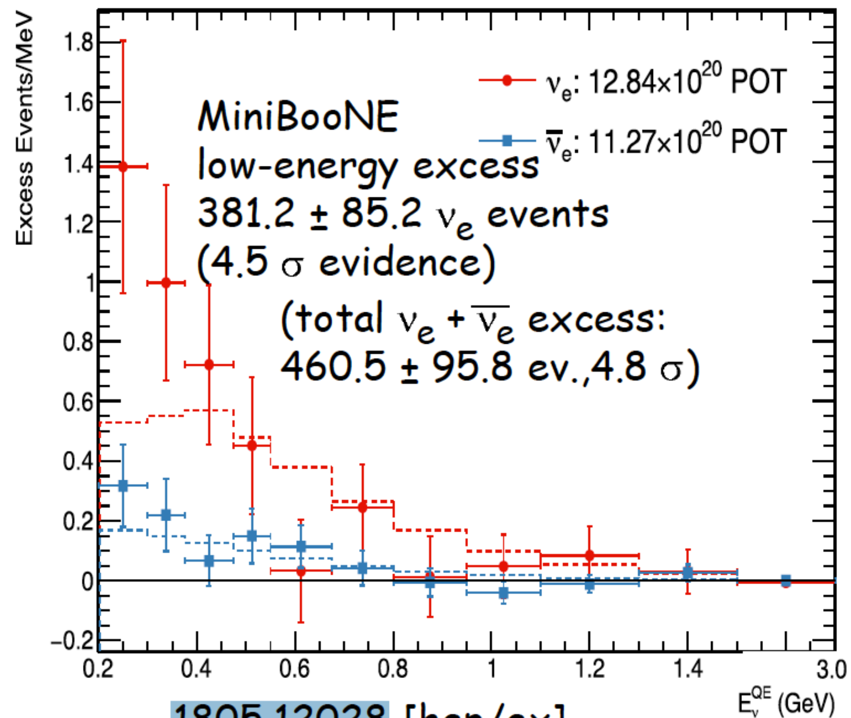




Saw an excess of $\bar{\nu}_e$: 87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

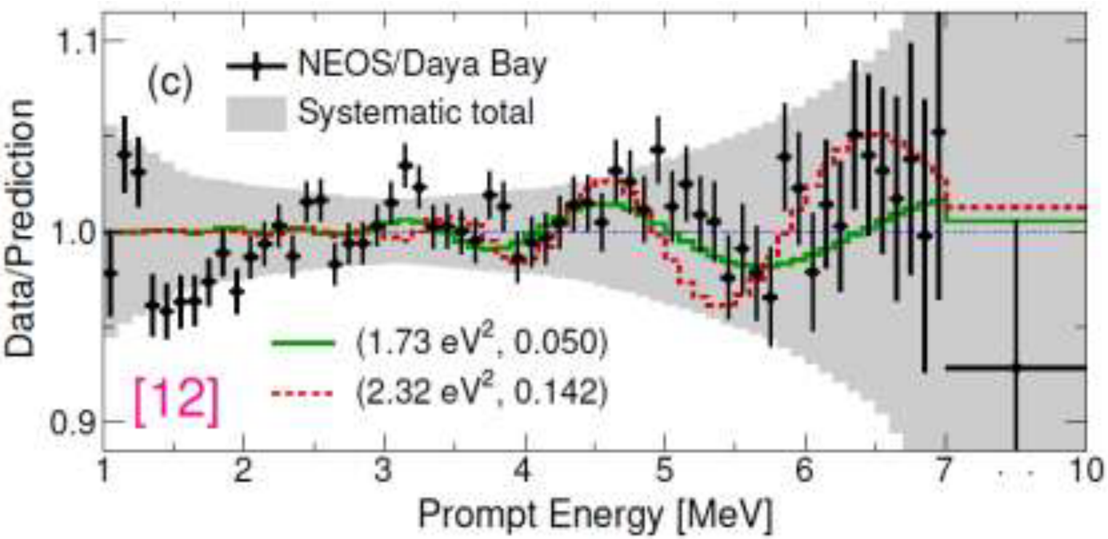


1805.12028 [hep/ex]

The sterile neutrino puzzle: more recent results

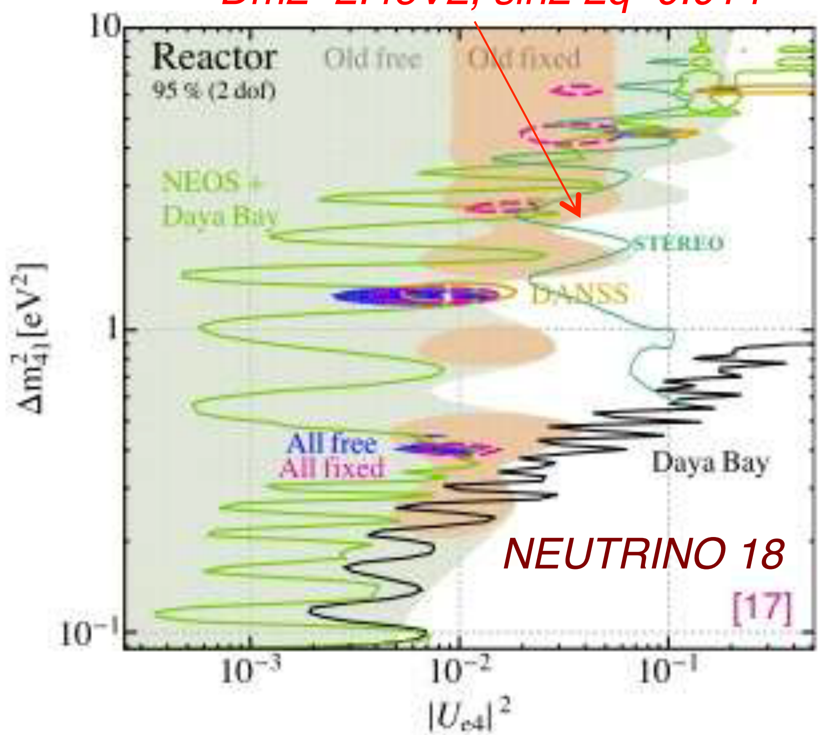
The current sterile scenario is definitely very complex:

- ICARUS and OPERA appearance results constrained Δm^2<=eV^2 and small angle
- Big Bang cosmology (Planck) allows at most one sterile flavour - mass <0.24 eV
- No evidence of $\nu\mu$ disappearance in MINOS and in IceCube (0.3-20 TeV)
- Recent reactor data (especially NEOS) are intriguing but not yet conclusive
- New claim by Neutrino-4: oscillations with Δm^2~7eV^2? arXiv 1809.10561
- New results are expected soon, especially from reactors



Best fit

Dm2=2.4eV2, sin2 2q=0.014

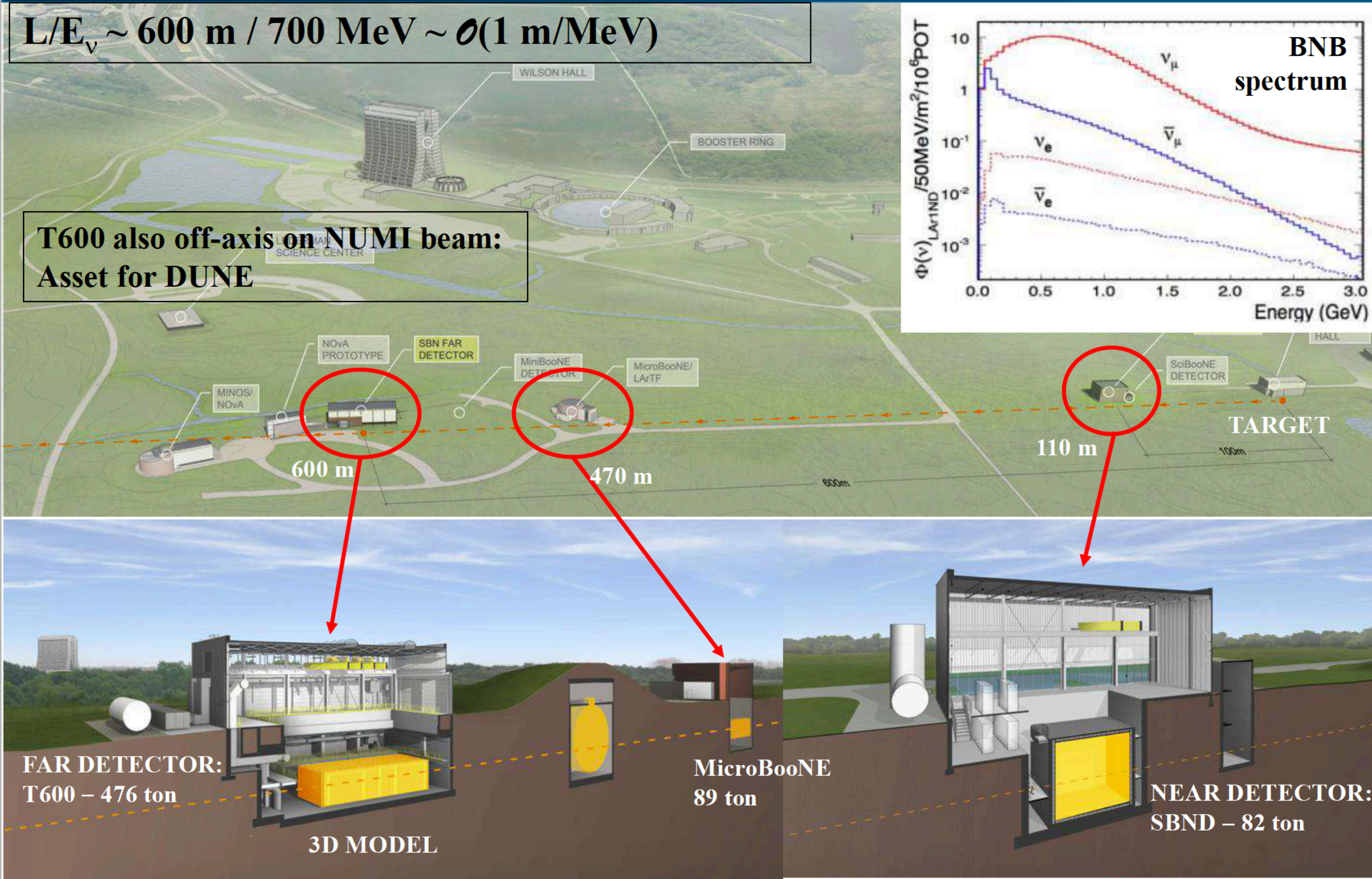


This scenario calls for a definitive clarification

The SBN project

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

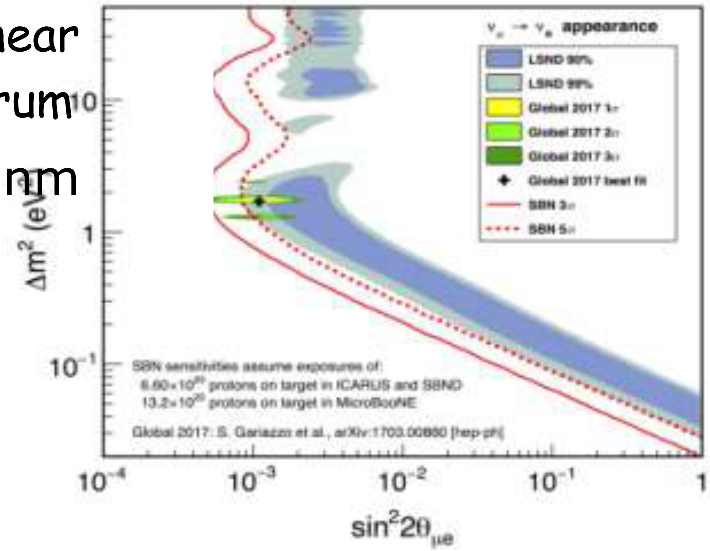
T600 also off-axis on NUMI beam: Asset for DUNE

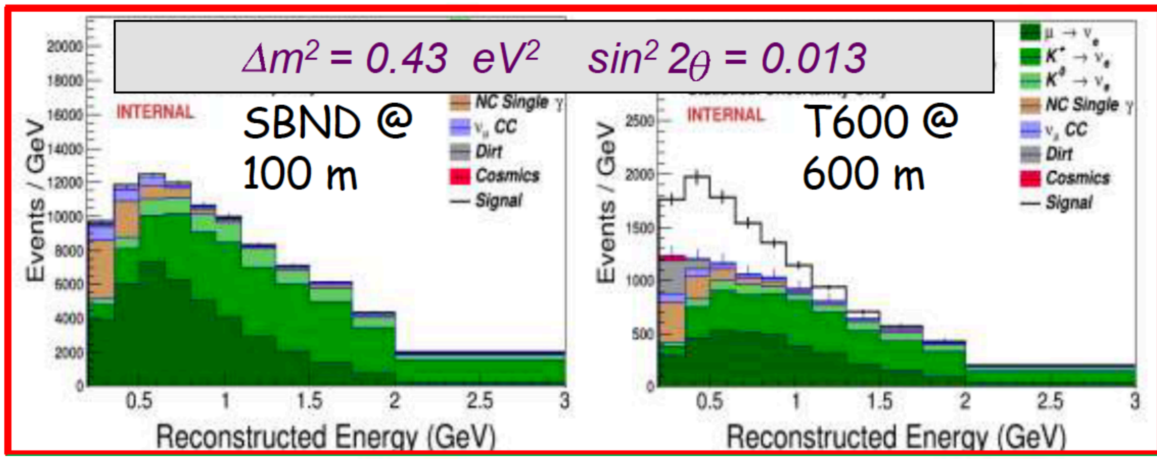


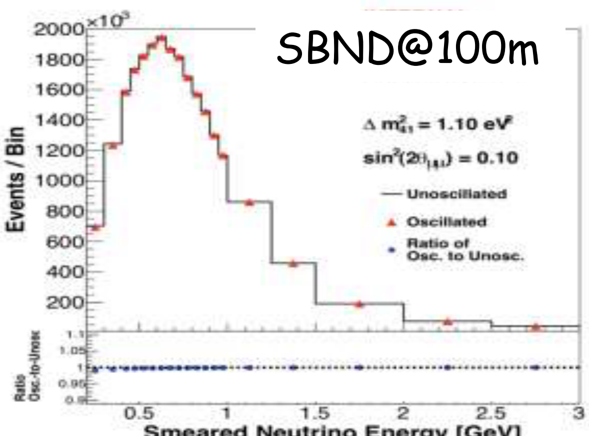
SBN sensitivity

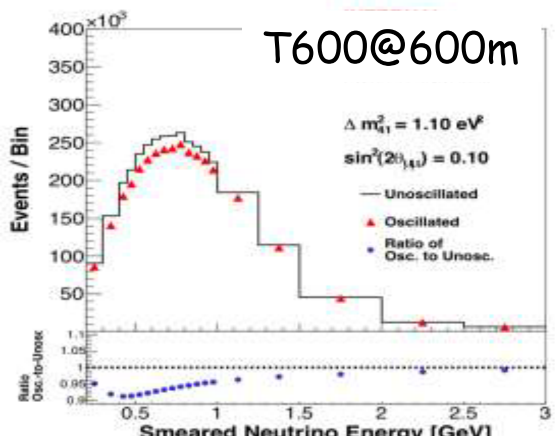
- SBN will use 3 very similar LAr-TPCs at different distances from target
- This similarity will greatly reduce systematics: SBND (near detector) will provide "initial" flux composition and spectrum
- Oscillation will be studied both in νe appearance and νm disappearance channels

Appearance: LSND 99%CL region covered at 5σ in 3 yrs

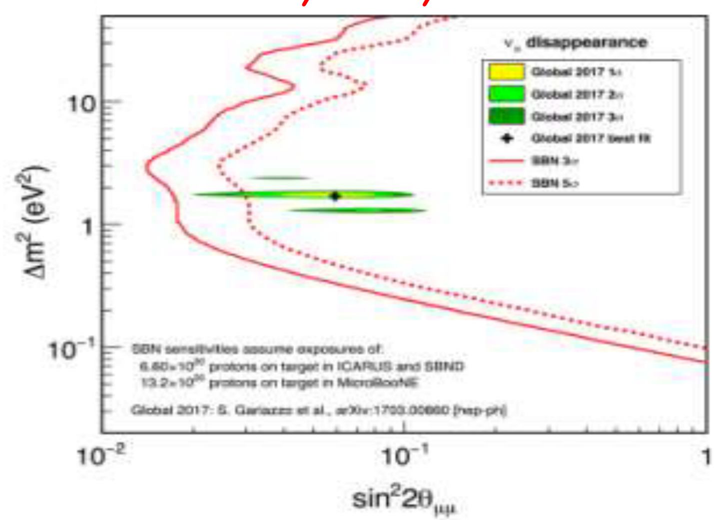






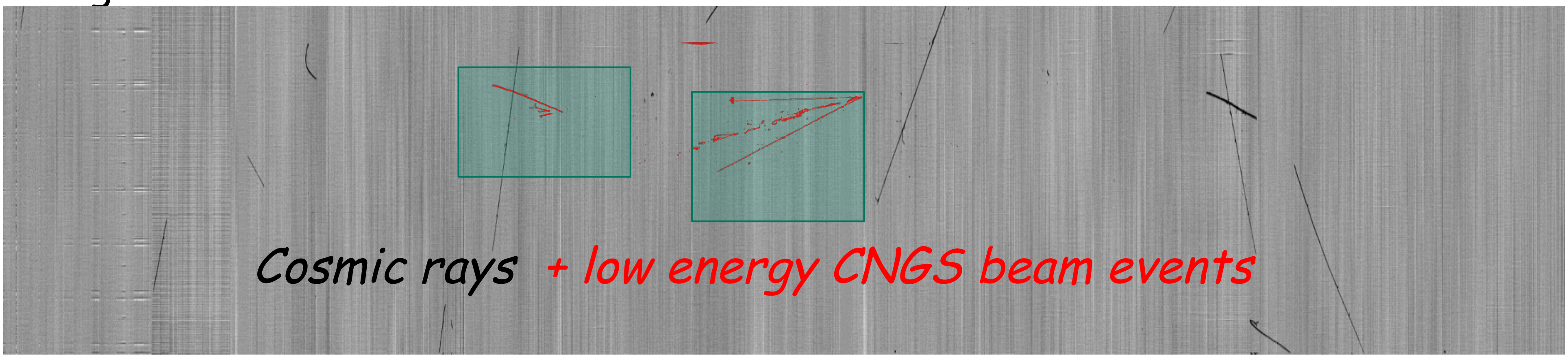


Disappearance: 3-5σ sensitivity in 3 yrs



A new experimental challenge: a LAr-TPC on surface

- ICARUS at SBN will take data at shallow depth (only 3 m concrete overburden)
- ~11 muon tracks will hit each TPC in the ~1 ms drift window: the associated γs can produce electrons (via Compton/pair production) that represent a critical background to νe searches

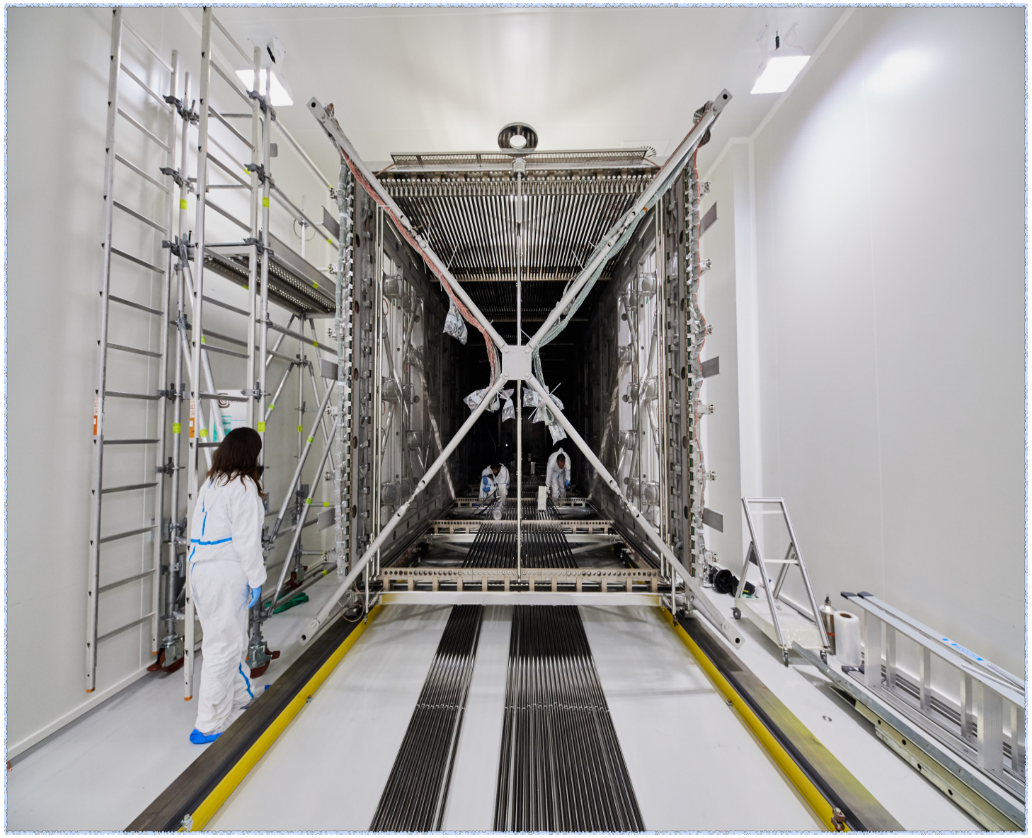


To reject this background and identify triggering events, it's crucial to know unambiguously the timing of each track in the TPC image. New "handles" can provide crucial information:

- Light signals from a much-improved PMT 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 with 98% coverage (1250 m^2) are equipped with optical fibers to convey light onto SiPM arrays. Top under INFN/CERN responsibility, bottom and sides under FNAL.

T600 overhauling at CERN (WA104/NP01)

- To face the new experimental conditions at FNAL (shallow depth, higher beam rate) T600 underwent intensive overhauling at CERN, before shipping to US.
- Overhauling took place in the CERN Neutrino Platform framework (WA104) starting in 2015.
- The goal was to introduce technology developments *while maintaining the already achieved performance:*
  - new cold vessels, with a purely passive insulation;
  - Renovated LAr cryogenics/ purification equipment;
  - Improvement of the cathode planarity
  - new faster, higher-performance read-out electronics;
  - Upgrade of the PMT system: higher granularity and ~ns time resolution



Upgrades in cryogenics/mechanics

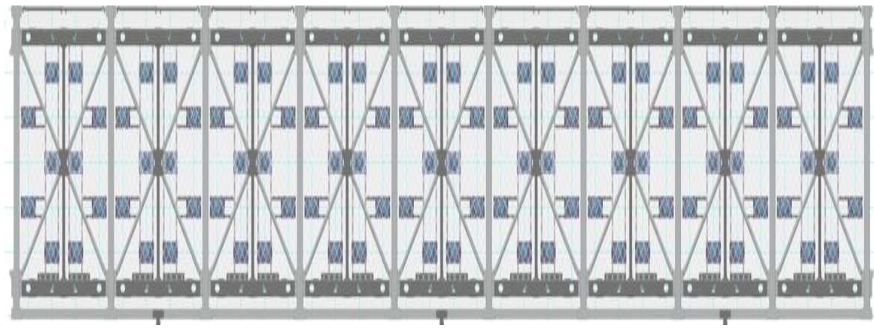
- Purely passive insulation was chosen, coupled with standard N_2 cooling shield, redesigned and tested at CERN
- New cold vessels made of extruded Aluminum profiles, welded together at CERN

- Cathode panels were flattened by thermal/ mechanical treatment, reducing the residual non-planarity by a factor ~10
- This allows to extend range of MCS momentum well over the typical momentum range of future SBL/LBL neutrino experiments

Upgrade of the light collection system

In shallow depth operation, the light collection system is required to:

- Precisely identify the time of occurrence (t_0) of any ionizing event in the TPC
- Determine the event rough topology for selection purposes
- Generate a trigger signal for read-out, combining information from:
  - Pattern/majority of fired PMT signals
  - Signal from external CRT
  - Beam spill bunched structure



The system features 360 PMTs (90 per chamber, 15 phe/MeV), providing:

- High coverage (5% cathode area), allowing sensitivity down to lowest expected depositions from neutrino events (~100 MeV)
- High spatial granularity, longitudinal resolution better than 50 cm
- High time resolution (~ns) and fast response,
- Possible identification of cosmics by PMT space/time pattern.

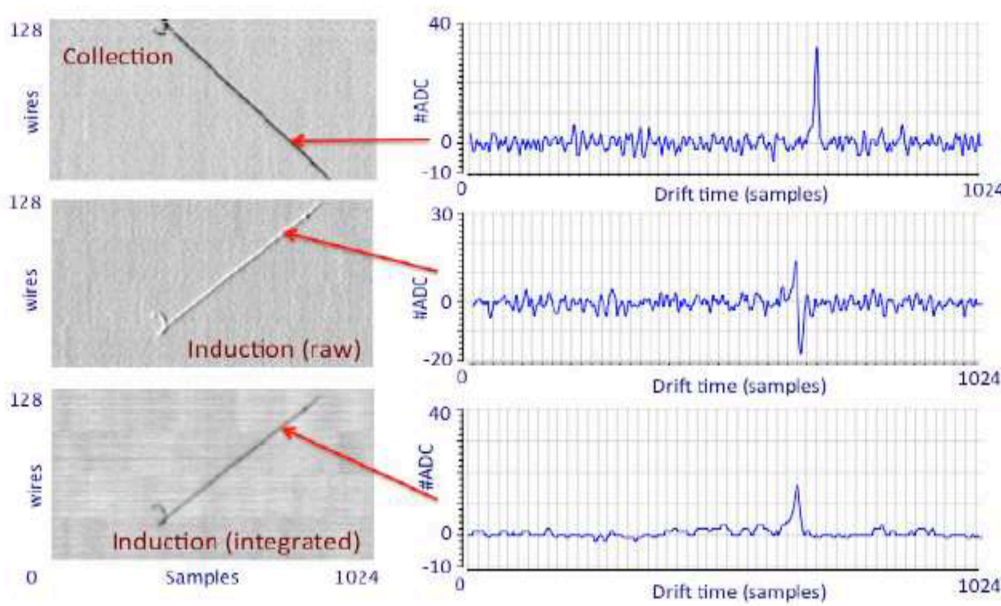
Paper submitted to JINST! arXiv:1807.08577

Upgrade of the read-out electronics

Analogue front-end has been redesigned, in order to improve reconstruction:

- Faster shaping time ~1.5μs for all wire planes, to match electron transit time between wire planes;
- Drastic reduction of the undershoot around signals, allowing a better reconstruction of signals in the crowded vertex region;
- Possibility to integrate Induction-2 signals, providing calorimetric measurement in this plane too.

Moreover, synchronous sampling on the whole detector will allow an improvement in the resolution of MCS muon momentum measurement.

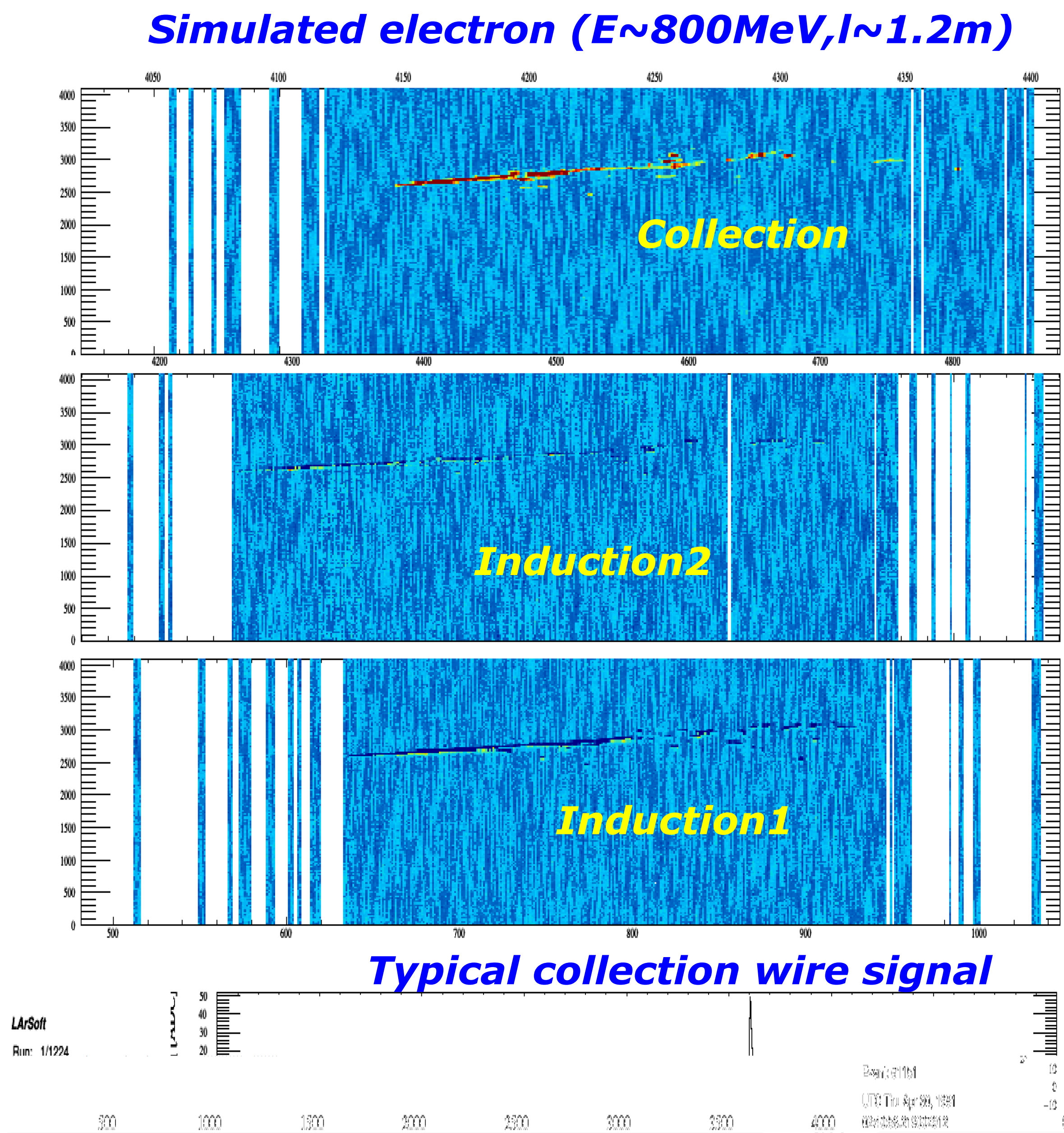


- Noise ~2ADC#(1500 e-) in all planes
- Collection signal is unipolar – S/N~15
- Induction signal is bipolar- after offline integration (running sum+BL restoring) it provides S/N~10

Paper submitted to JINST!
arXiv:1805.03931

Simulation and reconstruction

- A common software framework (Larsoft) is used by the three SBN detectors, allowing easy comparison and sharing of algorithms
- Simulation performed in Geant4, with ICARUS geometry included. First large-statistics MonteCarlo production (~10^5 events) produced for various samples (electron, muons, cosmics, neutrinos) is being analyzed
- All data from wires, PMT, CRT are included in the simulation. Wire description includes realistic noise and new electronics response



ICARUS-T600 Trip to FNAL

leaving from CERN, June 12th 2017

June - July 2017
from CERN to FNAL

Antwerp: unloading from barge from Basel and loading into ship to Burns Harbor (Indiana)

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

ICARUS installation at FNAL - status

- Warm vessel floor and walls were assembled/installed in the pit at the Far Detector building during 2017
- Bottom CRT modules (200 m^2) were also installed in the FD during 2017
- Assembly of cold shields (bottom and side) was completed by May 2018.
- Installation of detector supports, sealing of main vessel doors and Helium leak tests were finished by June 2018.
- Rigging of both modules and placement in the pit was done by August 2018.
- Work on top of detector (chimney installation) is ongoing

ICARUS at FNAL – plans and commissioning

- Chimneys installation and readout cable recovery complete – He leak tests to be finished by September
- Top side of cold shield will then be installed/tested, followed by top of warm vessel
- Activities on the top will then be able to begin during fall: feedthrough flanges, top of CRT
- Pre-commissioning (cryogenics/purification/vacuum system, read-out/ electronics, etc.) at beginning of 2019
- Vacuum pumping should start ~March 2019, until TPCs are ready to cool down.

Commissioning will be organized in three phases:

- CRYOGENICS: vacuum (1 month), cooling (15 days), filling (15 days), purification (1 month), stabilization (1 month)
- TPC/PMT (2 months): HV system, PMT supply, calibrations, DAQ/trigger commissioning
- CRT (in parallel with the other two phases)

Conclusions

- ICARUS-T600 successful 3-year run at LNGS proved that LAr-TPC technology is fully mature and ready for next generation (DUNE)
- ICARUS searched for possible LSND-like anomaly through νe appearance in the CNGS beam. No excess found, identified a small allowed parameter region where the sterile neutrinos have to be searched.
- The SBN experiment at FNAL will be able to clarify the sterile neutrino puzzle, by looking at both appearance and disappearance channels with three LAr-TPCs (ICARUS acting as far detector)
- ICARUS-T600 was extensively refurbished at CERN (2015-17) and is now being installed at the Far Site on the BNB beamline
- The strong cooperative effort by INFN, CERN and FNAL will allow to start commissioning and data taking in early 2019.

Thank you!

Hvala!

Спасибо!