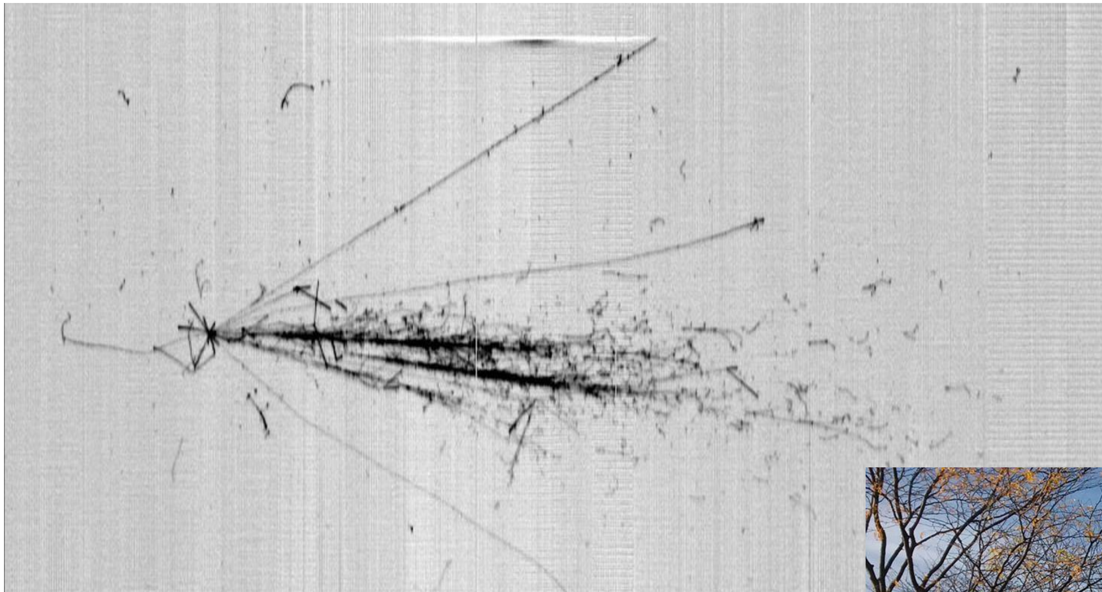
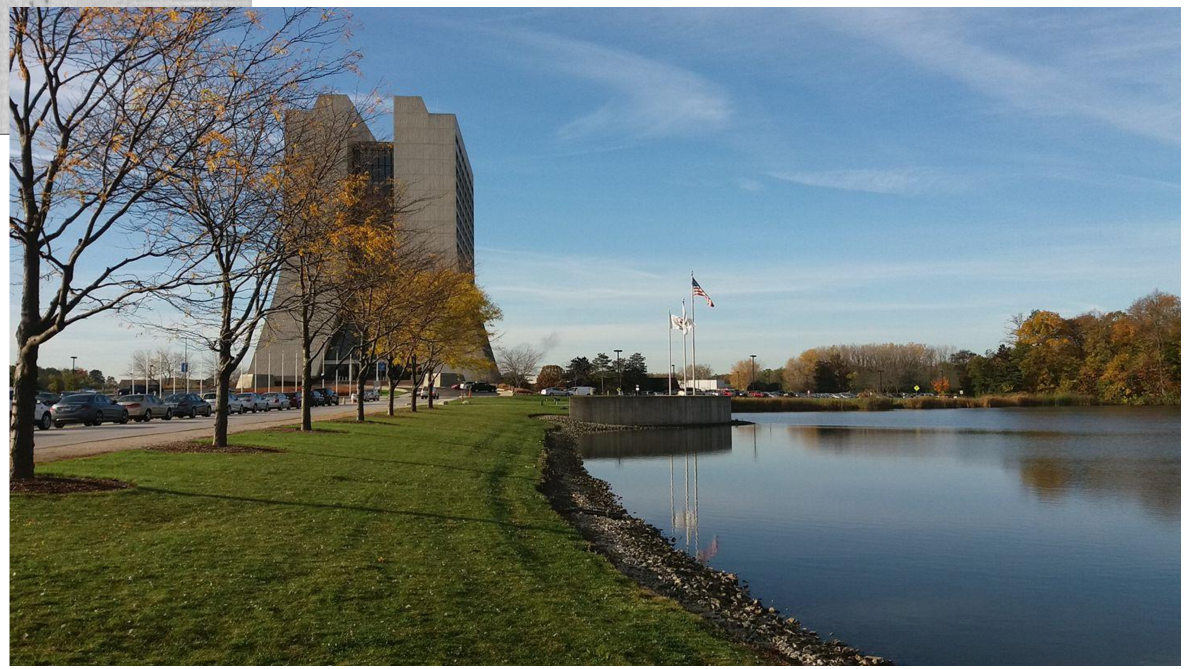
I neutrini sterili e il rivelatore Icarus a Fermilab



M. Bonesini
INFN Milano Bicocca



Seminario INFN
15 Giugno 2020

Requirements for a neutrino detector

Ultimately, two things:

- FLAVOUR IDENTIFICATION:
  - Efficiency and purity in identifying ν_μCC vs. ν_eCC vs. νNC
  - Crucial for any ν_e appearance searches
  - The separation between electrons and photons is critical
  - This requires both a good granularity (much less than X_0) and a precise calorimetry (to measure dE/dx)

- LARGE MASS/EXPOSURE:
  - cross-sections are typically very small (~10^{-38} cm^2 at SBN energies)
  - Small, subdominant oscillation effects are often searched for (as at SBN) ->large statistics is needed
  - This implies both huge size and long data-taking
  - A dense, relatively cheap target material is needed

Liquid Argon TPC

huge size and fine granularity may be combined

- Liquid Argon is a dense, cheap (~1$/liter) ionization medium: it allows masses up to several kton
- Multiple wire planes allow 3D reconstruction with ~mm resolution
- Collection of drifting ionization electrons permits a precise calorimetry
- Drift lengths can be several meters long (if Argon is sufficiently pure)
- Scintillation light at 128 nm provides fast signals for triggering/timing

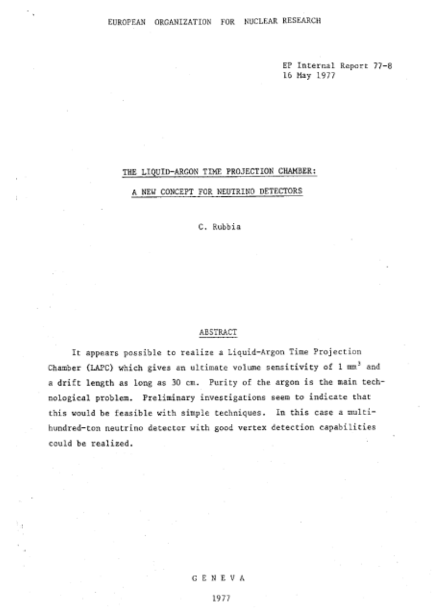
Only one major drawback: drift velocity is small (~1 mm/μs, drift time ~ ms)

Pile-up of cosmic rays can be a problem for surface operation

The first idea of a LAr TPC

The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)], was inspired by bubble chambers like Gargamelle:

"a novel device which combines the large amount of specific information of bubble chambers with the much larger mass, timing, and geometrical flexibility of a counter experiment"



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:
A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

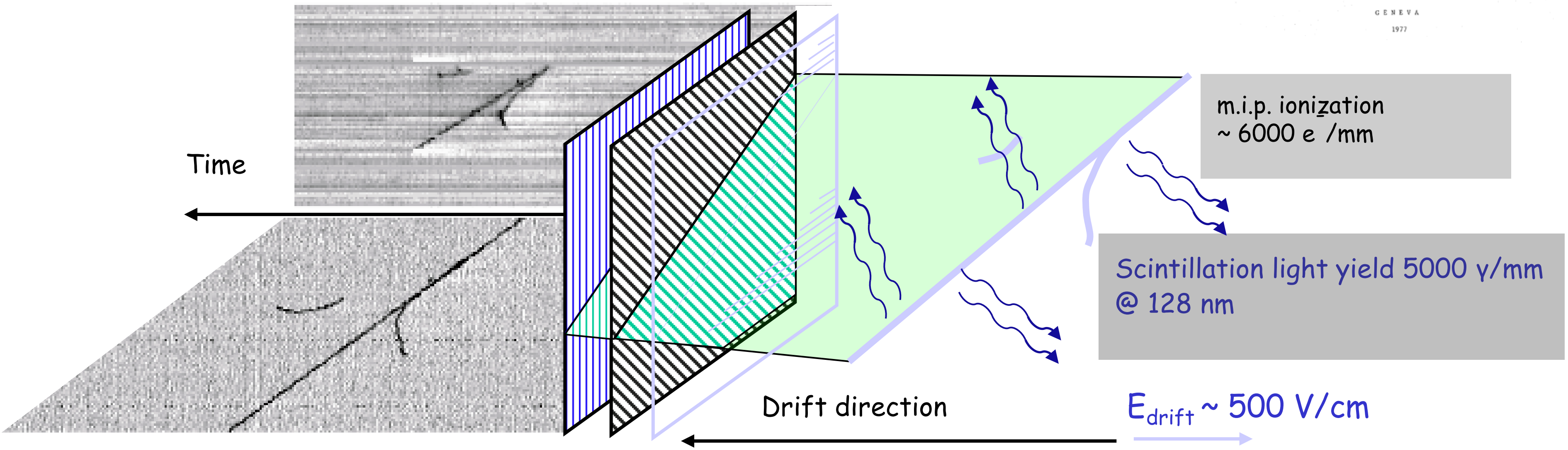
It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

G E N E V A

1977

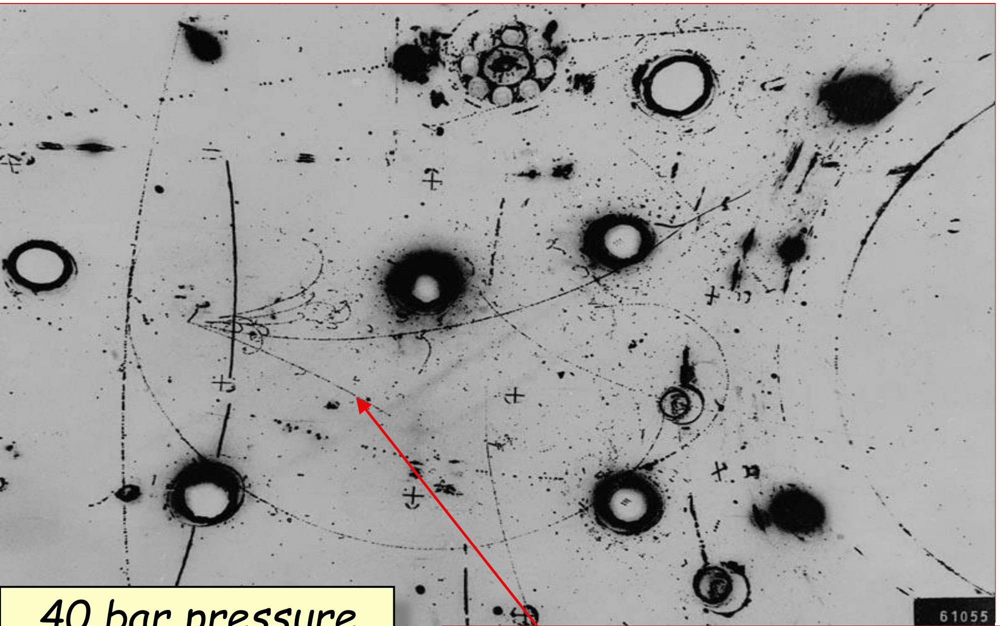
First proposed to INFN in 1985 [ICARUS: INFN/AE-85/7], is capable of providing a 3D imaging with high granularity (~ 1 mm) of any ionizing event ("electronic bubble chamber") with in addition:

- continuously sensitive, self triggering at atmospheric pressure
- excellent calorimetric properties, particle id. through dE/dx vs range



Drifting electrons are crossing transparent wire arrays oriented in different directions, where induction signals are recorded.

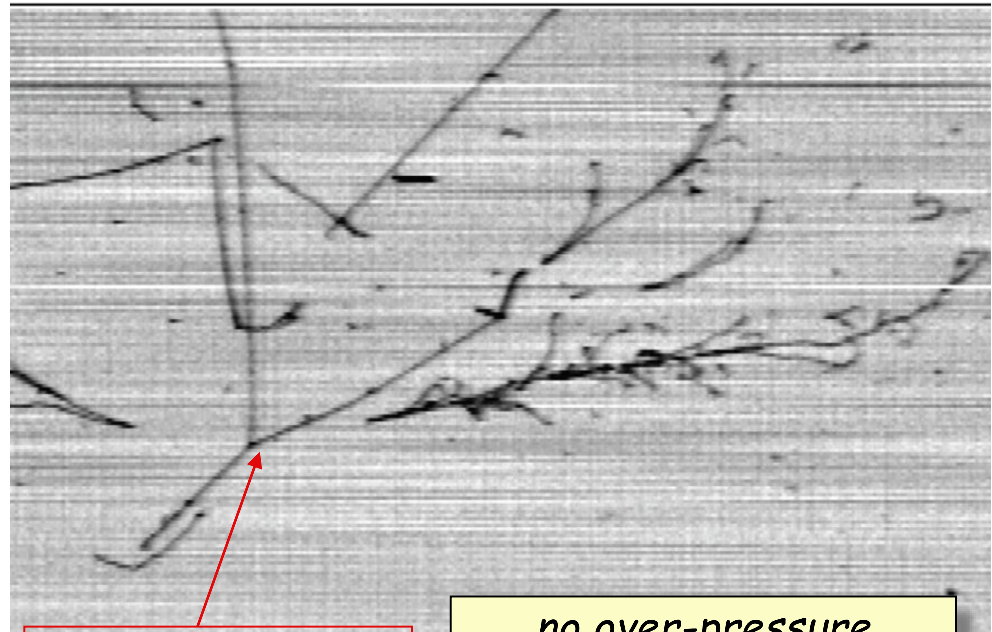
An "electronic bubble chamber"



40 bar pressure
Pulsed ≈ 1ms

Bubble diameter ≈ 3 mm
(diffraction limited)

Heavy freon



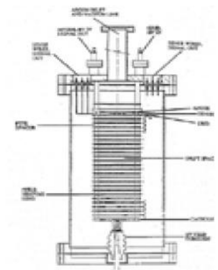
"Bubble" size
3 x 3 x 0.3 mm^3

no over-pressure
Continuously sensitive

Liquid argon

	Heavy freon	Liquid argon
Sensitive mass	3.0 ton	Many kton
Density	1.5 g/cm^3	1.4 g/cm^3
Radiation length	11.0 cm	14.0 cm
Collision length	49.5 cm	54 cm

The Icarus path to massive liquid Argon detectors



CERN

24 cm drift wires chamber

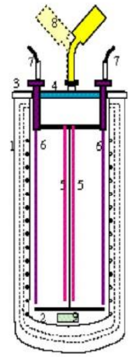
1

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

2

3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



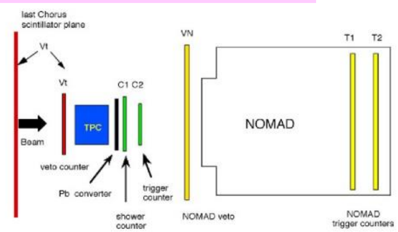
CERN

Laboratory work

3

CERN

50 litres prototype
1.4 m drift chamber



1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4

10 m^3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

ICARUS T600 experiment

2010 - 2013 : Data taking with CNGS beam

Pavia

T600 detector

2001: First T600 module

5

Cooperation with industry and several companies

6

LNGS Hall-B

Now at Fermilab on the SBN beamline

7

13-12-2013

ICARUS at FNAL

Proposal

The ICARUS Collaboration

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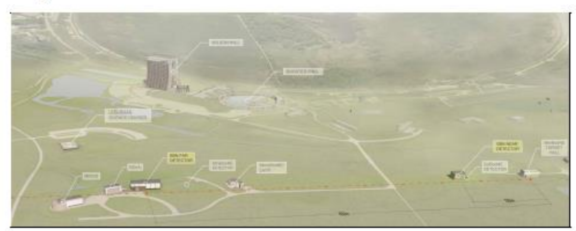
(a) Spokesperson

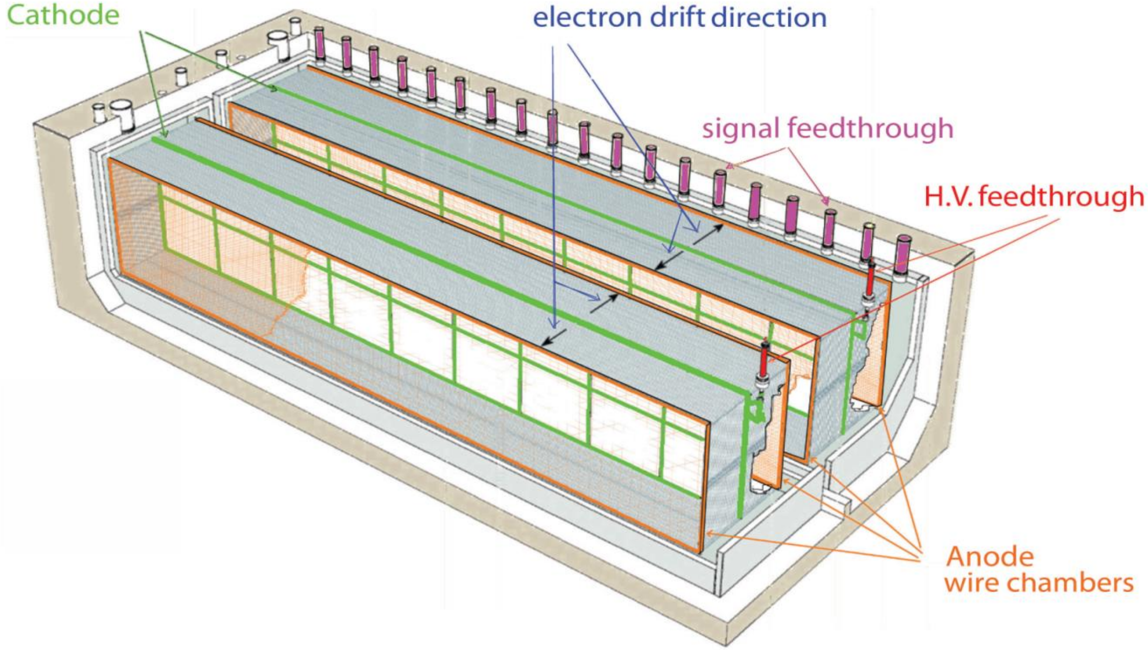
- First proposal in 2013 for operations at ground level (cosmics background)
- Joint effort with MicroBoone, LAr1-ND in 2015
- Overhauling at CERN as WA104/NP01 in 2015/17
- T600 arrived to Fermilab in August 2017
- Beginning installation at FNAL in 2018
- Data taking was scheduled for 2020 (before COVID-19 pandemia spread-up)
- As usual a long way between proposal and practical realization
- Some delays, remote shifts, but still in business

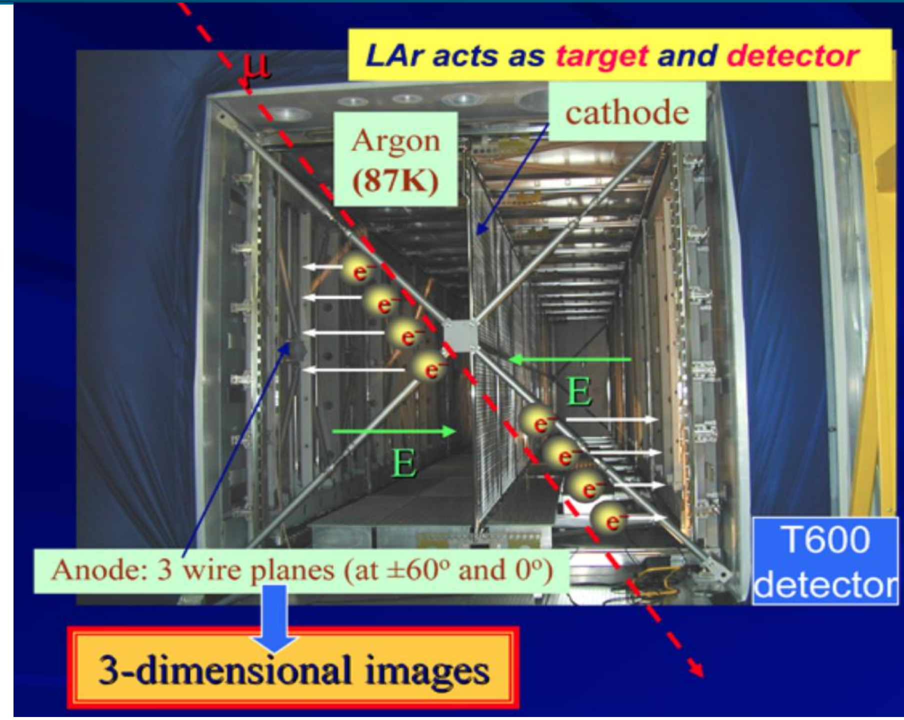
arXiv:1503.01520v1

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam



The ICARUS T600 detector at LNGS





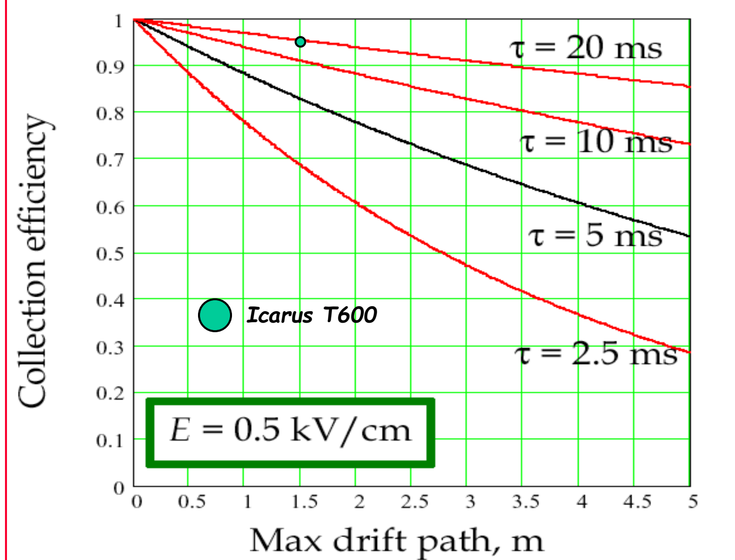
- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0,±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV sensitive (128nm) with wave shifter (TPB)

The key feature of LAr imaging: very long e-mobility

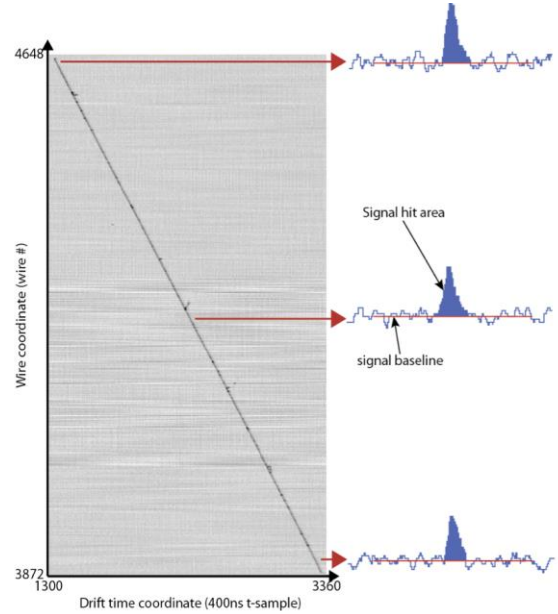
The main technological challenge is the capability of ensuring a sufficiently long lifetime of drifting electrons. Electronegative impurities (O_2, H_2O) in LAr can absorb drifting electrons and attenuate charge signals: $Q=Q_0 \exp(-t/\tau_{el})$ with t_{ele} inversely proportional to contamination C: $\tau_{el}[ms] \sim 300/C[ppt]$

$\tau \sim$ 1 ms implies an impurity concentration of ~100 ppt. 4-5 orders of magnitude smaller than commercial Argon

- 2001 technical run in Pavia, τ_{el} = 1.8 ms
- New industrial purification methods developed at an exceptional level: remnants of electronegative impurities (O_2) have to be initially and continuously purified.
- Electron signal attenuation of ~10 % for a longest drift of 5 meters, opening the way to exceptionally long drift distances.

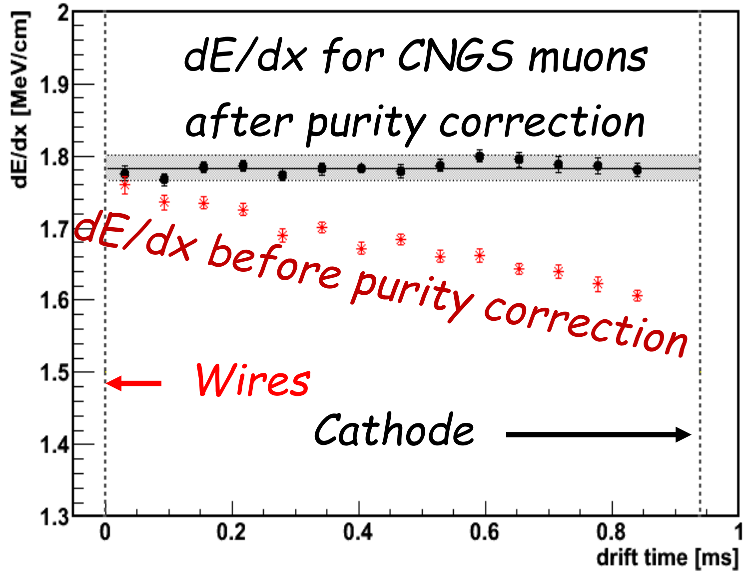


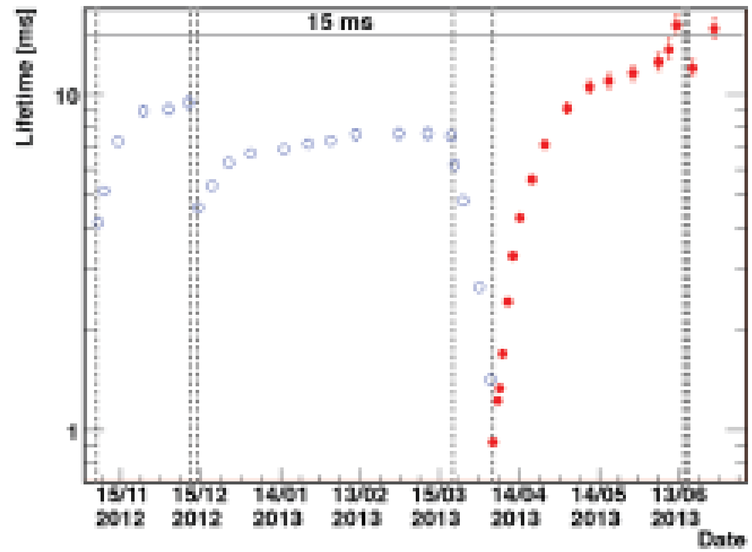
Drifting charge attenuation versus drift path at different electron lifetimes



ICARUS T600 LAr purity

- Electron lifetime measured during the ICARUS run at LNGS studying the charge signal attenuation on traversing cosmic-ray muons: τ_{el} > 7 ms (~40 p.p. trillion $[O_2]_{eq}$) →12% maximum charge attenuation
- Cross check with muons from CNGS ν interacting in the upstream rock: dE/dx signal correctly reconstructed constant along the drift coordinate
- τ_{el} uniform along the longitudinal direction
- New pump installed on East cryostat since April 4th, 2013: τ_{ele} > 15 ms !





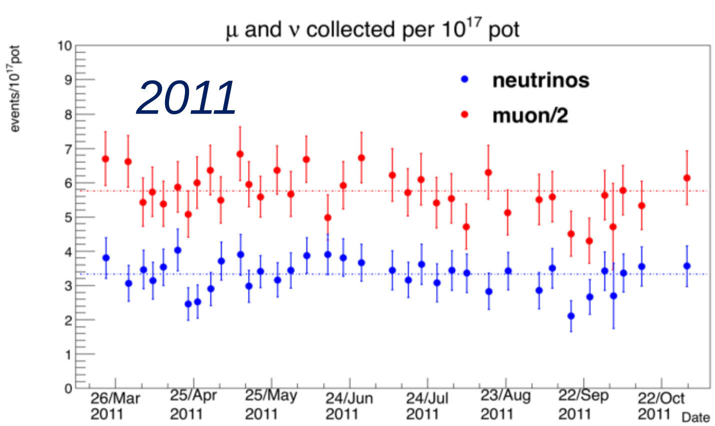
ICARUS has demonstrated the effectiveness of the single phase LAr-TPC technique, paving the way to huge detectors/~5 m drift as required for LBNE project

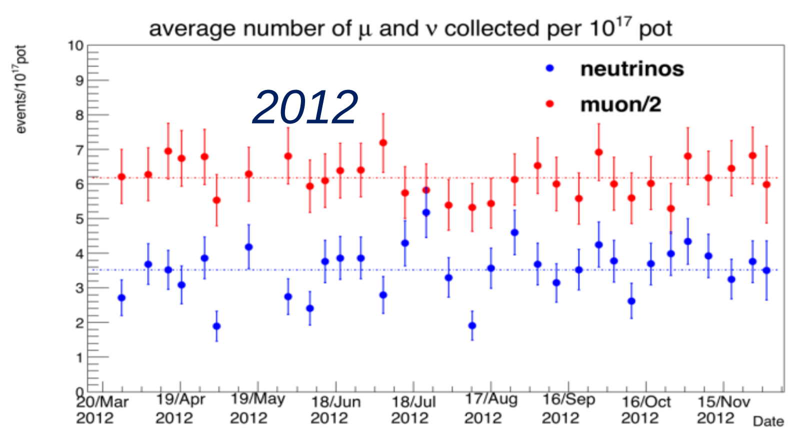
published on JINST

The ICARUS-T600 CNGS run

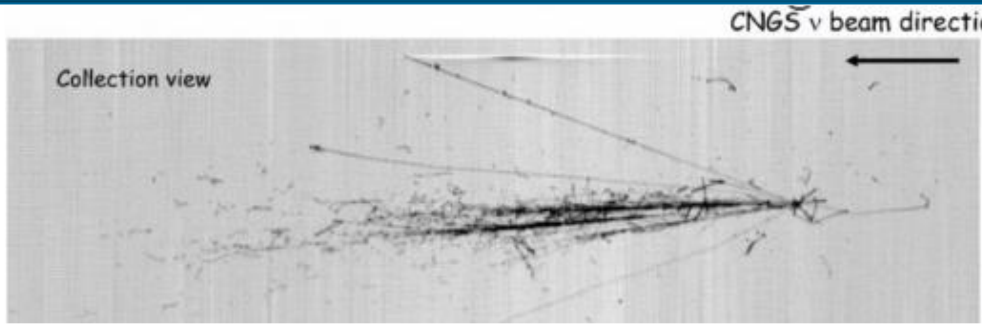
- ICARUS was exposed to the CERN to Gran Sasso (CNGS) $\nu\mu$ beam (732 km distance, $\langle E_\nu \rangle$ ~ 18 GeV) from May 2010 to June 2013
- Total collected pot $8.6\ 10^{19}$
- Excellent detector live time ~93%
- Data-taking was largely successful. It proved for the first time the feasibility of LAr-TPCs for physics experiments:
  - Large masses and long data-taking periods
  - Excellent electron lifetime >15 ms, allowing several meters of drift

ICARUS paved the way to the next generation long-baseline project: DUNE (a factor ~50 larger)





ICARUS reconstruction performances

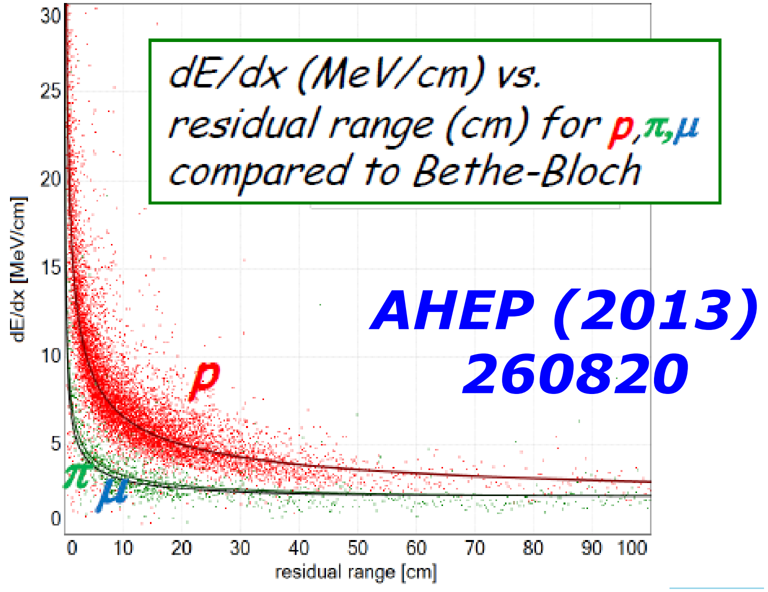


- *Tracking device:* 3D imaging at ~mm^3 level even for complex event topologies;
- *Global calorimeter:* homogeneous calorimetry by charge integration - excellent accuracy for contained events; momentum of non contained muons measured via Multiple Coulomb Scattering;
- *Measurement of local ionization 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):*

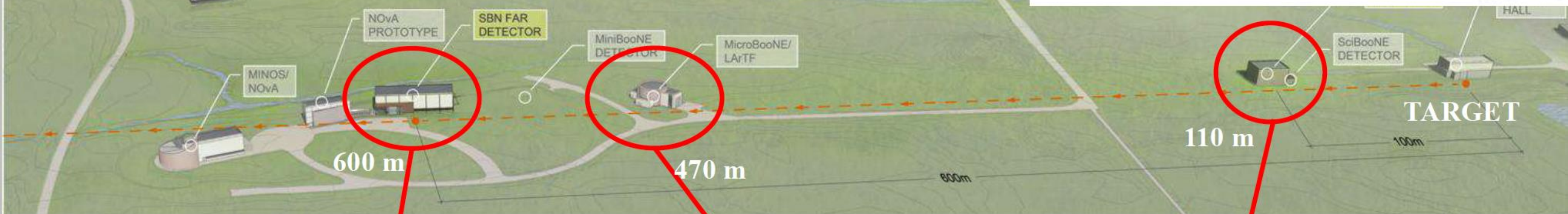
    $\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$

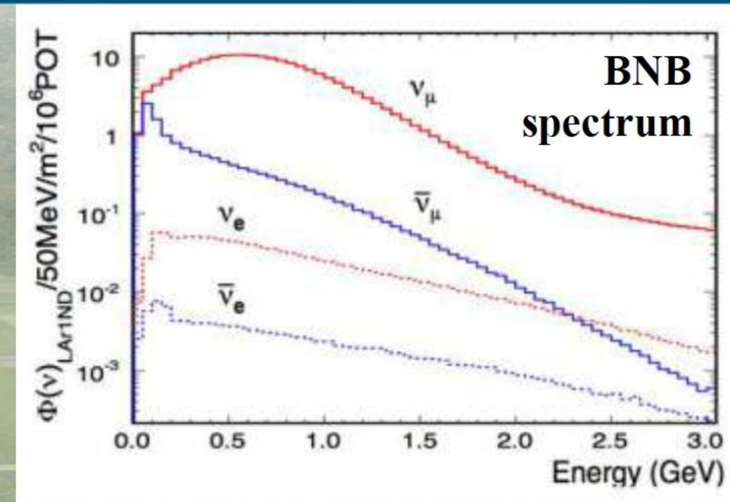


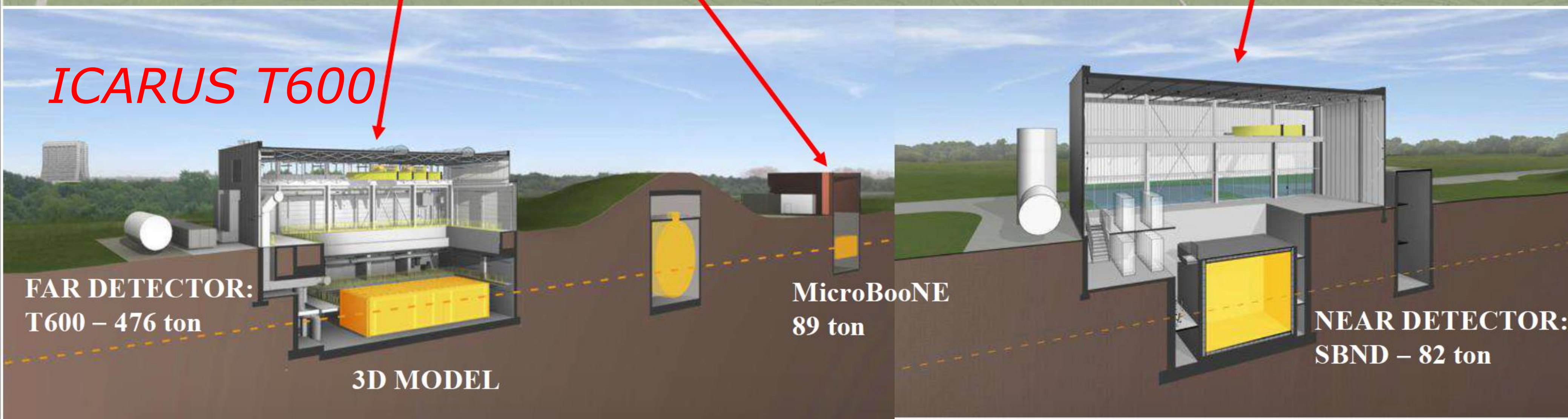
The SBN project at FNAL

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

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







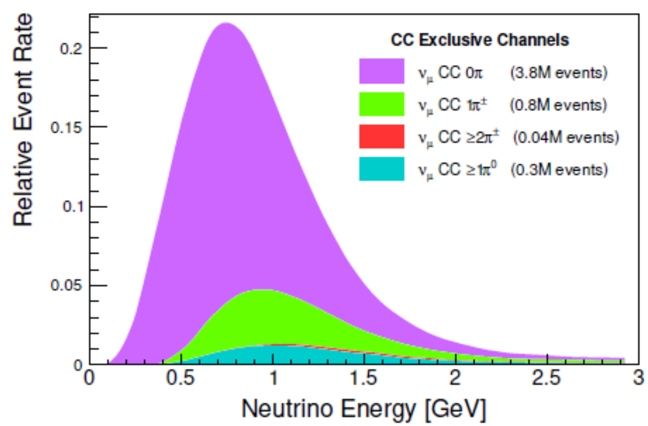
SBN features

- The Booster beam is well understood and has a small (~0.5%) ν_e contamination
- Oscillation will be studied both in ν_e appearance and ν_μ disappearance channels
- The use of 3 very similar detectors at different distances from target will greatly reduce systematics: SBND will provide crucial initial beam composition and spectrum, without relying on MC simulation
- In absence of oscillations, the spectra at the near/far detector should be identical: any difference in spectrum would be a sign of new physics
- The excellent νe identification capability of LAr-TPC will help reduce the NC background
- ICARUS will also measure off-axis NuMI neutrinos in a similar energy range as DUNE – important for measurement of neutrino cross-sections

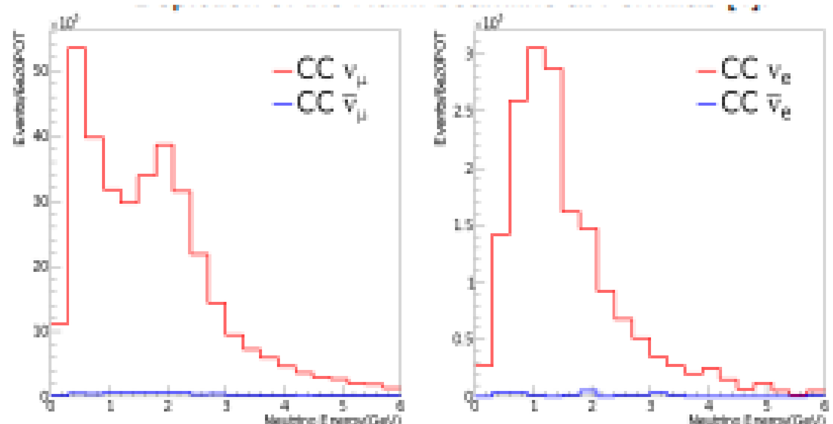
Physics at SBN

- High statistics measurements of neutrino Argon cross sections in the DUNE energy range with NuMI off-axis data

ν_μ from the Booster



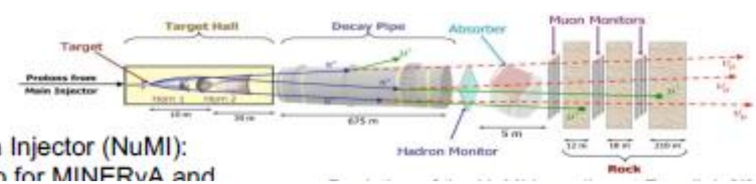
ν_μ, ν_e from the NUMI off axis



Charged-current neutrino interactions expected in ICARUS per year, assuming 6×10^{20} POT per year. A wealth of events in the $\geq$1 GeV range are expected.

- Rich BSM searches: dark matter, ….
- Sterile neutrinos: see later

ICARUS ~800 m from target, ~6^0 off-axis

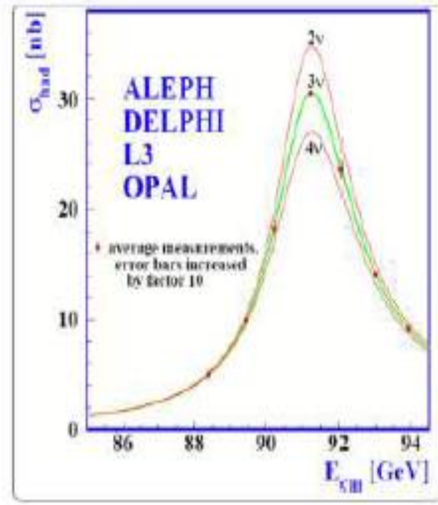


Neutrinos at the Main Injector (NuMI):
- ν beam at Fermilab for MINERvA and

Beyond three-flavours oscillations

- Sterile neutrinos were first hypothesized by B. Pontecorvo in 1957, as particles not interacting via any SM interaction but gravity.
- Four anomalies have been found in short baseline (SBL) experiments, which cannot be explained in the 3-flavour scenario

Experiment	Type	Channel	Significance
LSND anomaly	DAR accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8 σ
MiniBooNE anomaly	SBL accelerator	$\nu_\mu \to \nu_e$	4.5 σ
		$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8 σ
GALLEX/SAGE	Source – e	ν_e disappearance	2.8 σ
Reactors anomaly	b decay	$\bar{\nu}_e$ disappearance	3.0 σ

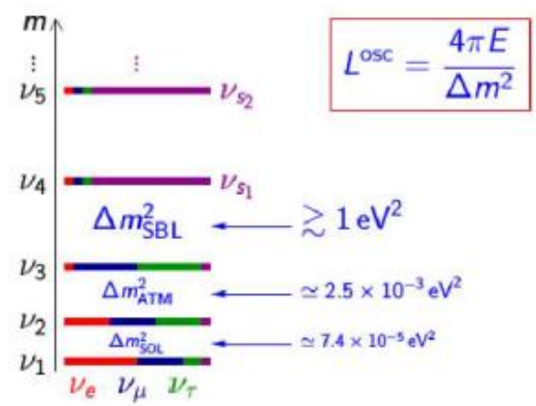


- The new hypothetical eigenstate must be a sterile, i.e. a singlet of the standard model gauge group

- Minimal extension (3+1) : one mass eigenstate ν_4 weakly mixed with the active neutrino flavours (ν_e,ν_μ,ν_τ) and separated from the standard mass eigenstates (ν_1,ν_2,ν_3) by a O(1 eV^2) difference

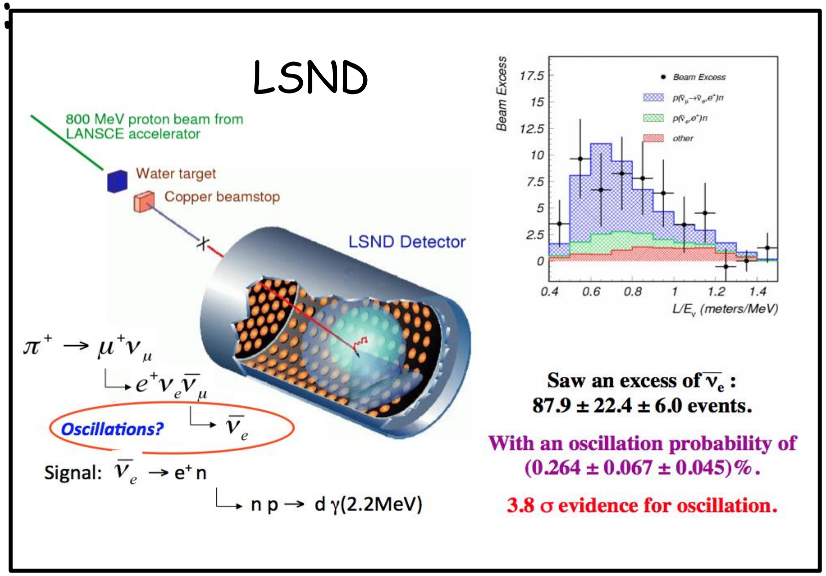
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$$

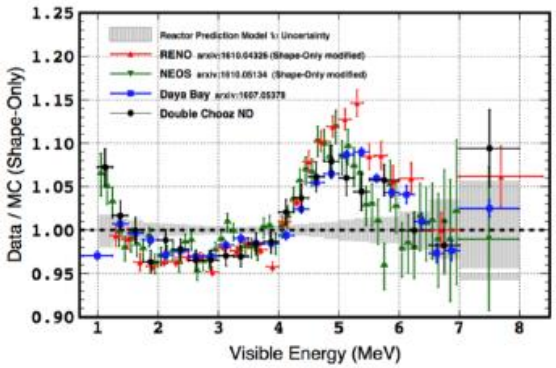
ϑ_{14}
ϑ_{24}
ϑ_{34}

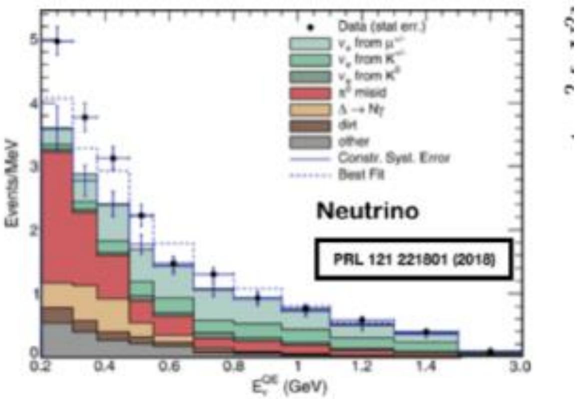


The Sterile Neutrino puzzle

- Anomalies have been collected so far in the neutrino sector, despite the well-established 3-flavour mixing picture with Δm^2_{31}~2.4×10^{-3} eV^2, Δm^2_{21}~8×10^{-5} eV^2 pointing to the existence of additional ν states:
  - $\overline{\nu}_e$ appearance from $\overline{\nu_\mu}$ beams in LSND experiment, 3.8 σ (1998)
  - MiniBooNE anomaly (2007) $\overline{\nu_\mu}$ beam, same L/E 4.7 σ excess
  - ν_e disappearance by SAGE, GALLEX experiments during their calibration with Mega-Curie sources, observed/predicted rate R = 0.84±0.05;
  - $\overline{\nu_e}$ disappearance nuclear reactor experiments: R = 0.934±0.024



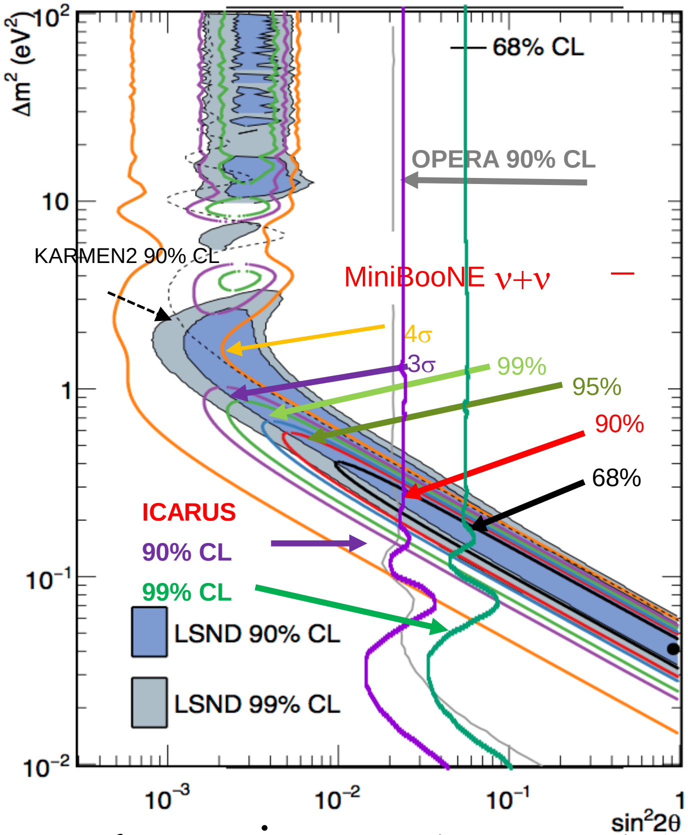


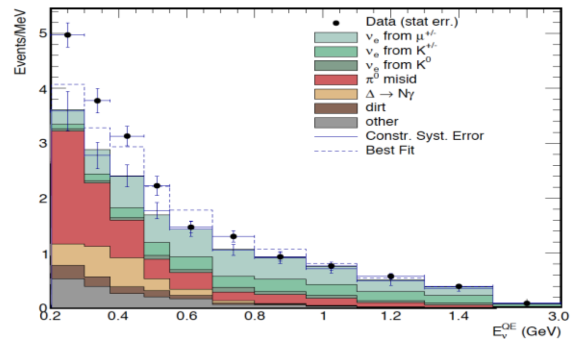


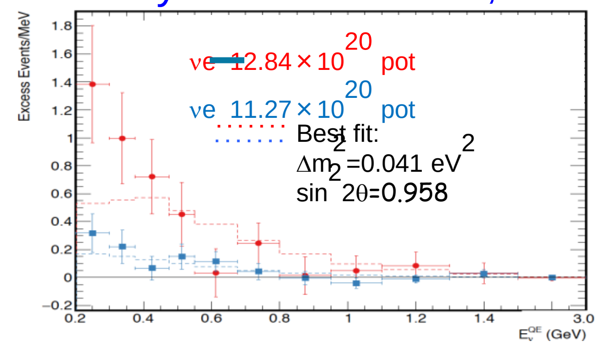
Recent results from MiniBooNE

- A significant excess of electron-like events in both beam polarities was observed by MiniBooNE (818 tons pure mineral oil) at FNAL Booster beam:

Phys. Rev. Lett. 121, 221801







- The 2 ν oscillation region indicated by MiniBooNE overlaps the initial LSND result, with a 6 σ significance for LSND + MB combined analysis.
- However a large part of this region already investigated/excluded by ICARUS LAr-TPC at LNGS exposed to CNGS beam EPJ C(2013) 73: 2599

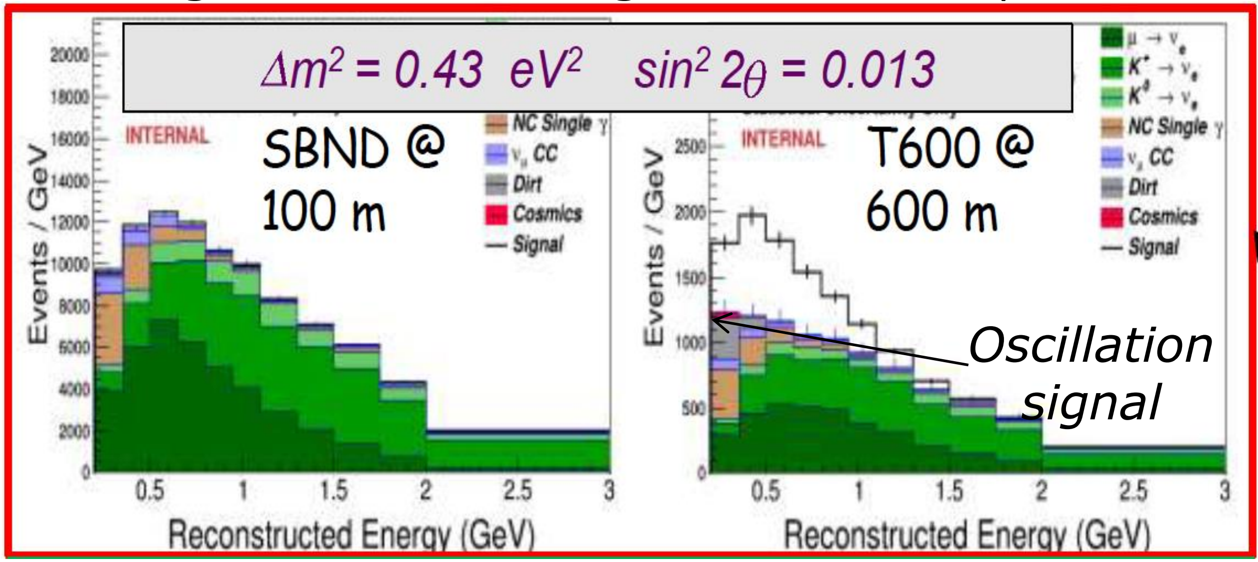
- … a scenario even more complex because the not observed corresponding ν_μ disapp. (MINOS, Icecube,…) and cosmology seems to disfavor additional ν states

Need of a definitive clarification: measuring both n appearance/disapp. With the same experiment at accelerator with L/E~ 1 km/GeV by comparing the ν fluence at two different distances

SBN appearance sensitivity

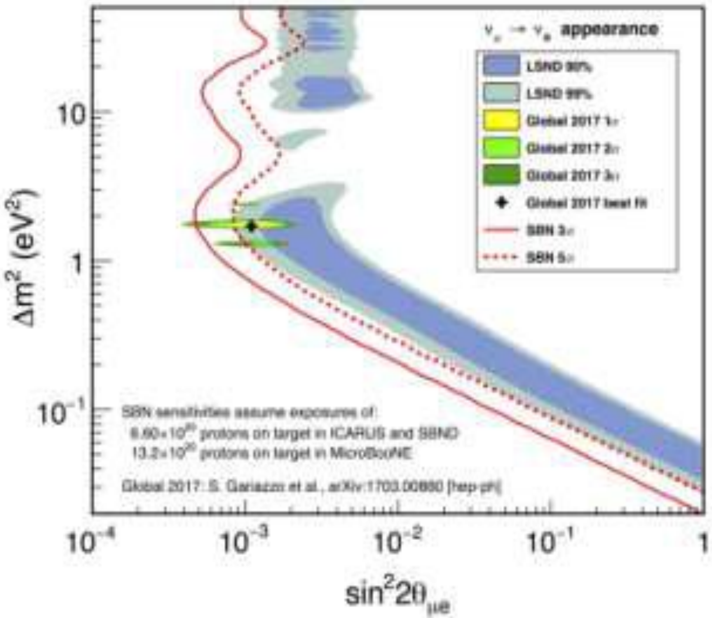
SBN will be able to cover the LSND region with a 5σ significance in 3 years (6.6 10^{20} pot) in ν_e appearance mode

Near and far detector ν_e spectra for a (Δm^2,$\sin^2 2\theta$) value (close to current best fit):



Sensitivity compared with LSND allowed region:

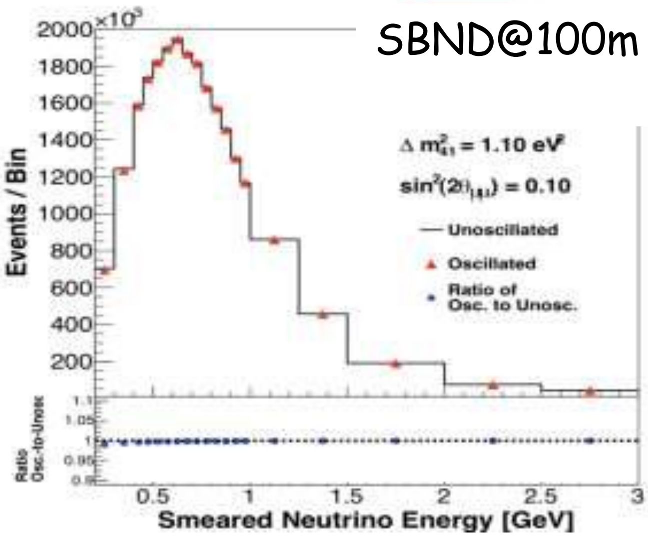
from SBN proposal arXiv:1503.01520

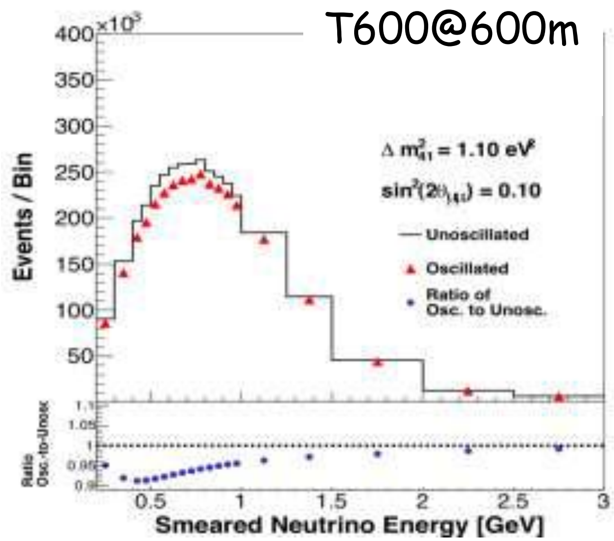


SBN disappearance sensitivity

- In the ν_μ disapperance channel, in 3 years (6.6 10^{20} pot), SBN will improve the present disappearance sensitivity by a factor ~10

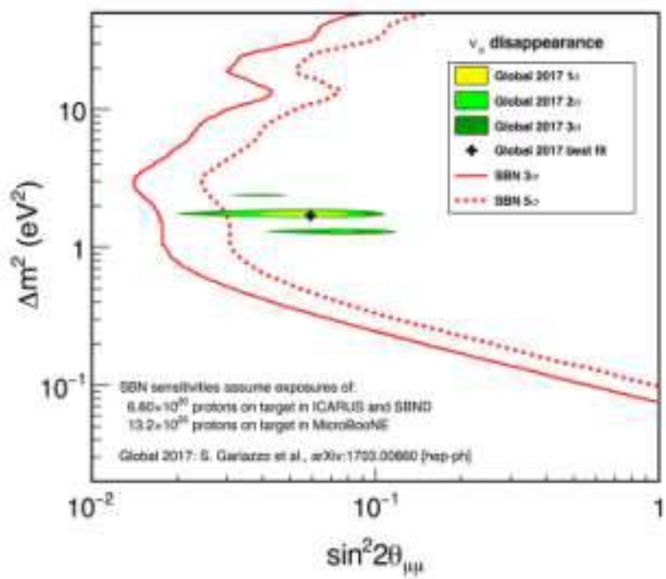
ν_μ unoscillated and oscillated spectra in the near and far detector, for an example (Δm^2,$\sin^2 2\theta$) value (close to current best fit). Energy smearing included (see SBN proposal)





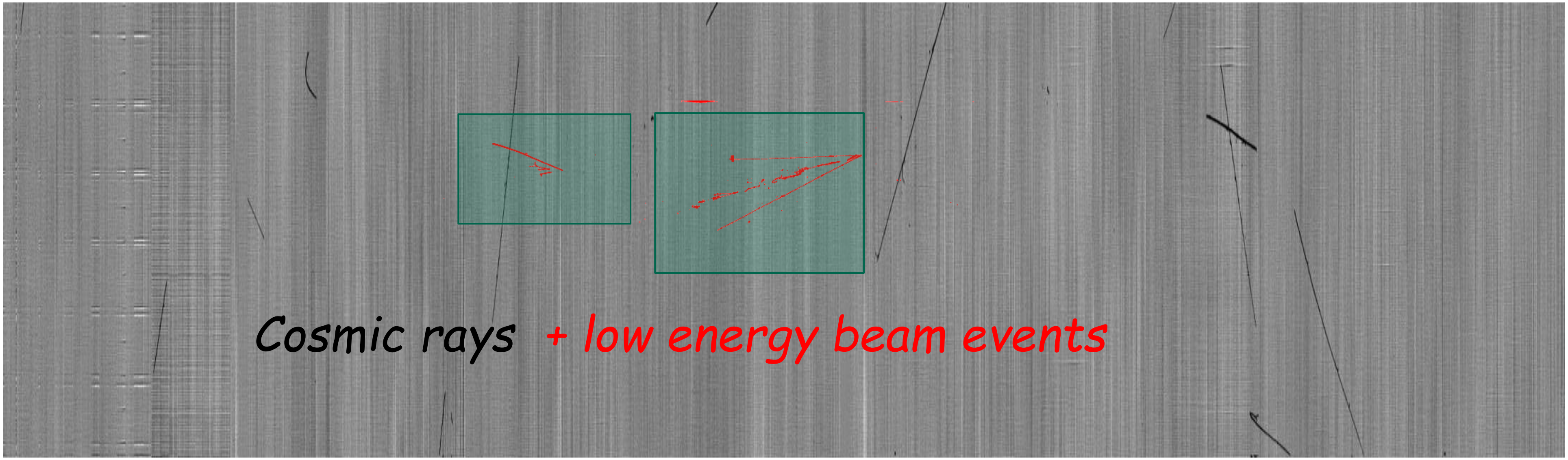
Sensitivity compared to 2017 best fit values

from SBN proposal arXiv:1503.01520



Experimental challenge: a LAr-TPC on surface

- ICARUS will take data at shallow depth (only 3 m concrete overburden)
- It will be the first operation of a large-scale LAr-TPC on surface with a ν beam
- ~11 muon tracks will hit each ICARUS module in the ~1 ms drift window: the associated γs can produce electrons (via Compton/pair production) that represent a critical background to ν_e searches



- LAr ionization by cosmic rays also produces ions that accumulate in time, and may distort the electric field (Space Charge).
- The effect on ICARUS was measured in a few mm in a surface test run

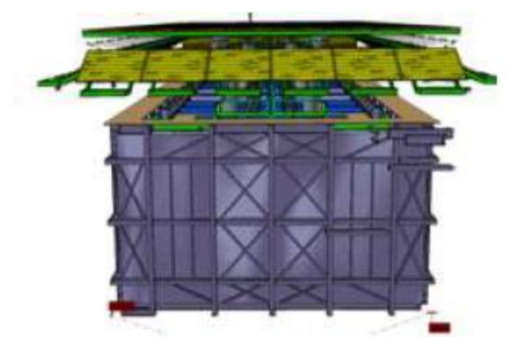
How to reduce the cosmic background?

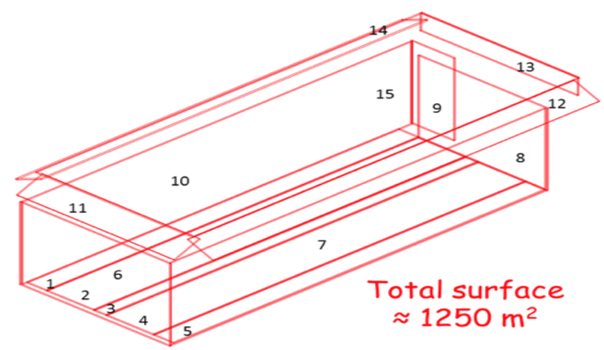
Cosmic-related BG will be dominated by "out-of-time" photons, due to the cosmic ray interactions randomly overlapped to the beam neutrino interaction.

This contribution can be significantly suppressed by unambiguously identifying the timing of each ionizing event occurring during the drift time.

This will require information on a much faster time scale that the ~ms drift time:

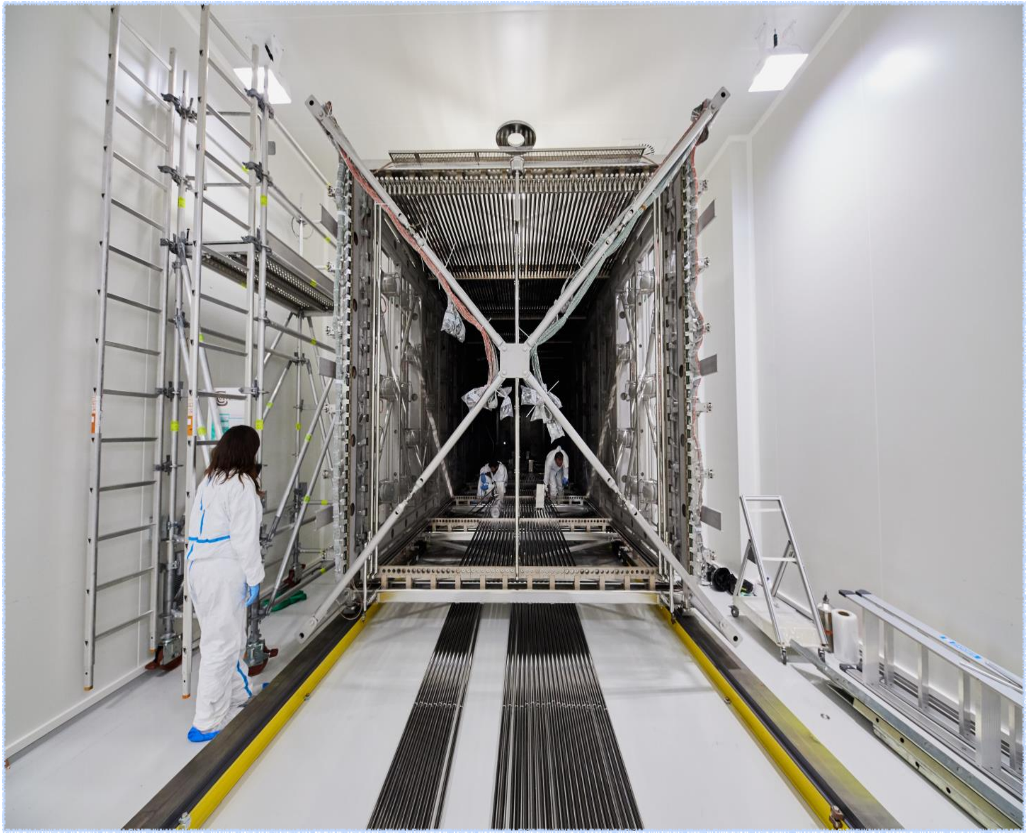
- A much-improved light detection system: the number of PMT have been increased to 360 (90 in each TPC) with excellent timing capabilities (~ns);
- An external Cosmic Ray Tagging system (CRT) to detect incoming particles and measure their direction of propagation by time of flight (top/side/bottom 4π)





Improving ICARUS: the overhauling at CERN

- 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) from 2015 to 2017.
- 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 plant
  - 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 re-installed after flattening and electro-polishing

- 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

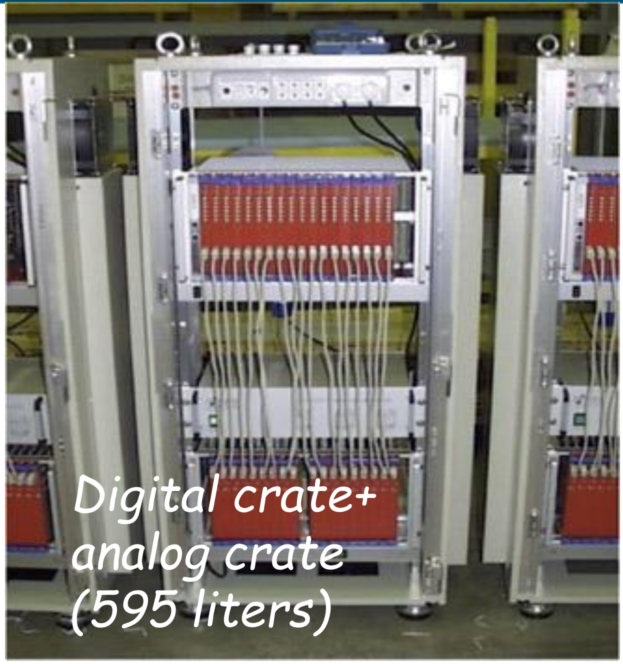
Upgrade of the TPC read-out system

ICARUS electronics at LNGS was based on:

- "warm" low-noise front-end amplifier
- Multiplexed 10-bit ADC
- Digital VME module for local storage, data compression, trigger information

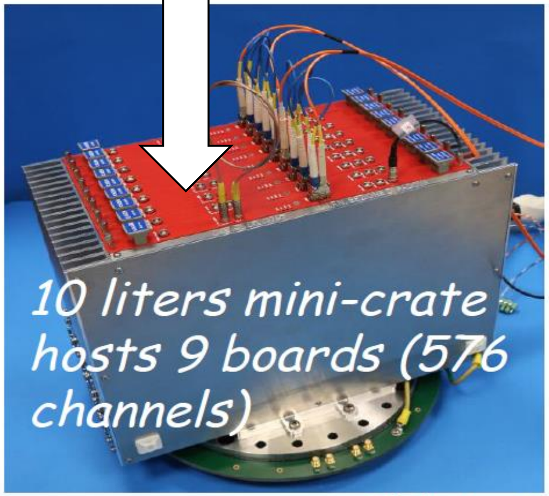
Performances proved adequate for track reconstruction and MCS measurement:

S/N~9 in Collection, resolution σ_y ~ 0.7 mm along drift



However, in view of the SBN experiment some components were modernized and improved:

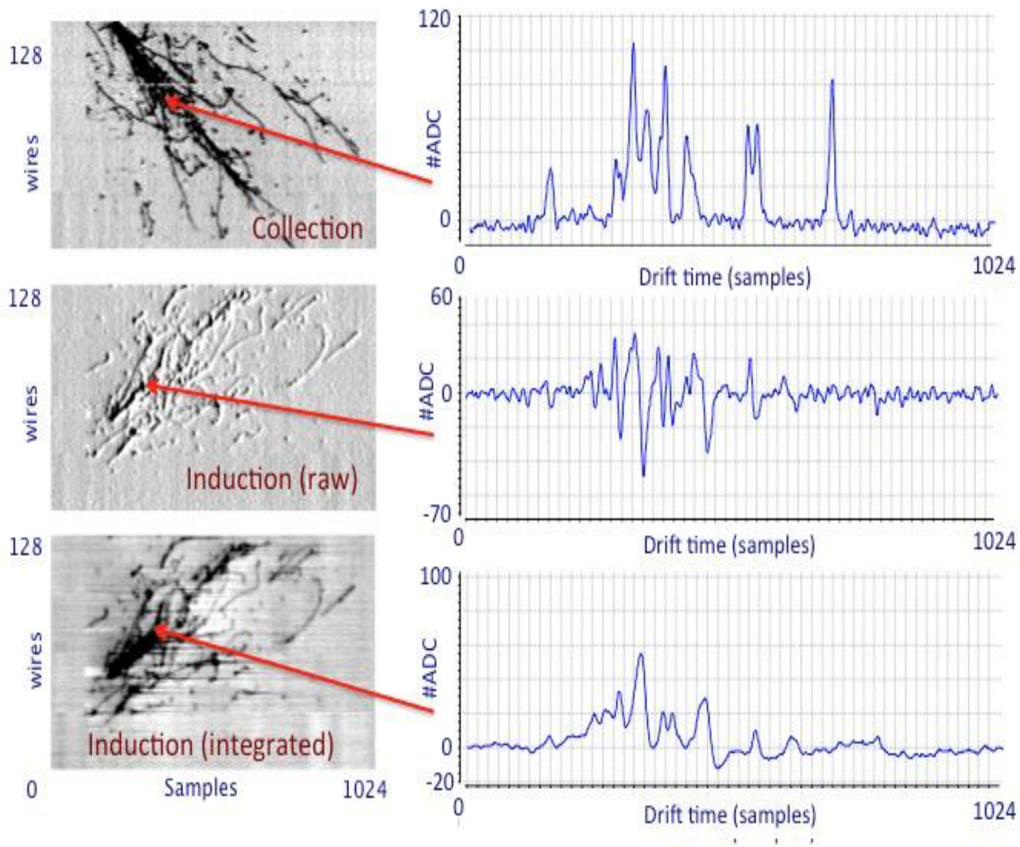
- Serial 12-bit ADC, fully synchronous in the whole detector -> ~20% improvement in MCS resolution
- Serial bus architecture increases bandwidth to ~10 MHz
- More compact layout: both analog+digital electronics hosted on a single flange



A new front-end electronics

The analog front-end shaping was also modified:

- Faster shaping time ~1.5μs for all wire planes, to match electron transit time;
- Drastic reduction of the undershoot around signals, allowing a better reconstruction of signals in the crowded vertex region;



- Electronics was tested on a small LAr-TPC test facility at CERN (~50 litres)
- Noise ~2ADC#(1200 e-) in all planes
- Typical Collection S/N~15 (depending on track angle), improved w.r.t. LNGS read-out

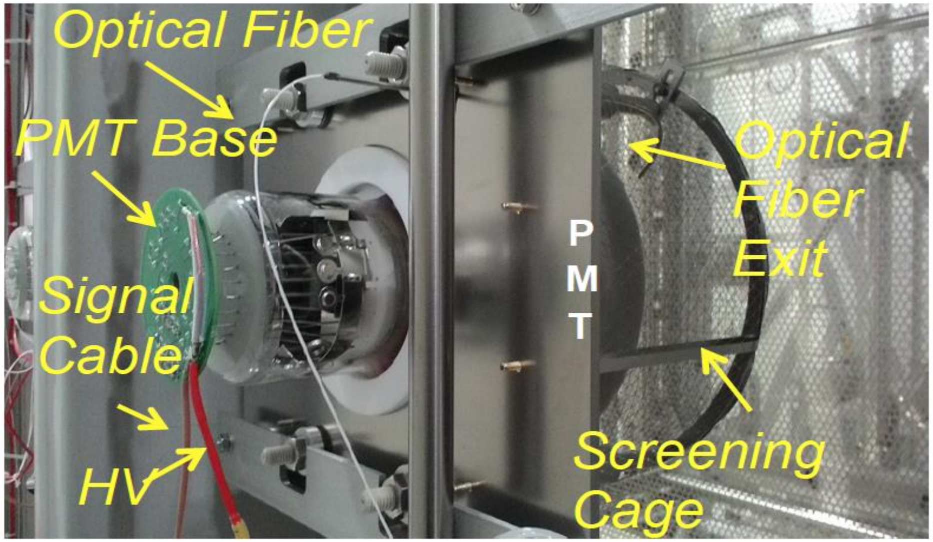
EM shower

Upgrade of the light collection system (CT,MIB,PV)

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:
  - PMT pattern/majority signal
  - Signals from external CRT

JINST 13 (2018) P10030

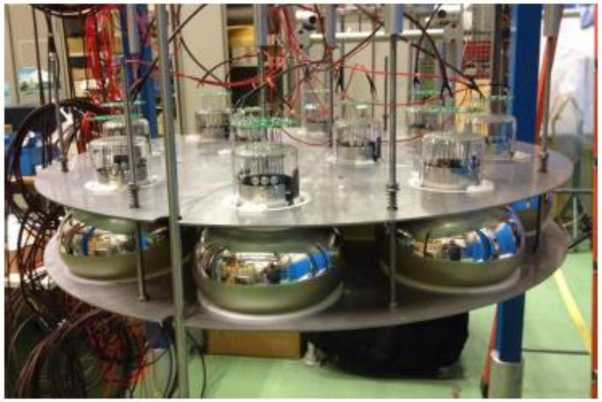


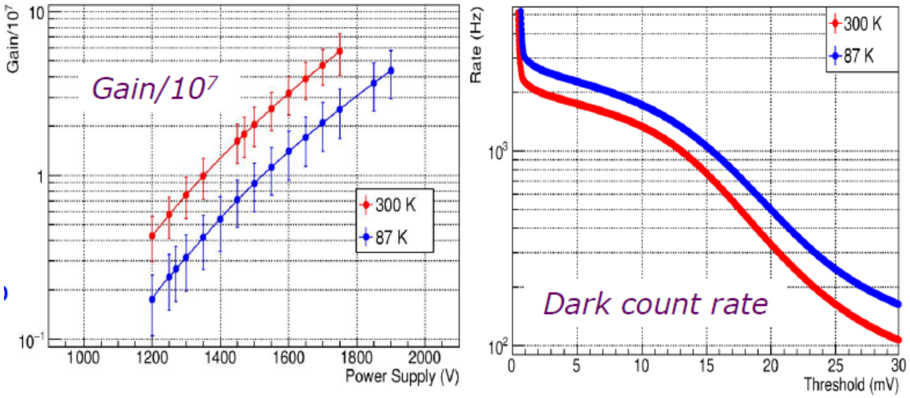
The system will provide:

- 90 PMTs per TPC (5% coverage) sensitivity to low energy events (~100 MeV)
- 15 photoelectrons per MeV of deposited energy
- High spatial granularity, longitudinal resolution better than 50 cm
- High time resolution (~ns) and fast response, to determine timing of ionizing event (possibly exploiting the ~ns beam bunch structure). 500 MHz sampling
- Possible identification of cosmics by PMT space/time pattern

Icarus PMTs

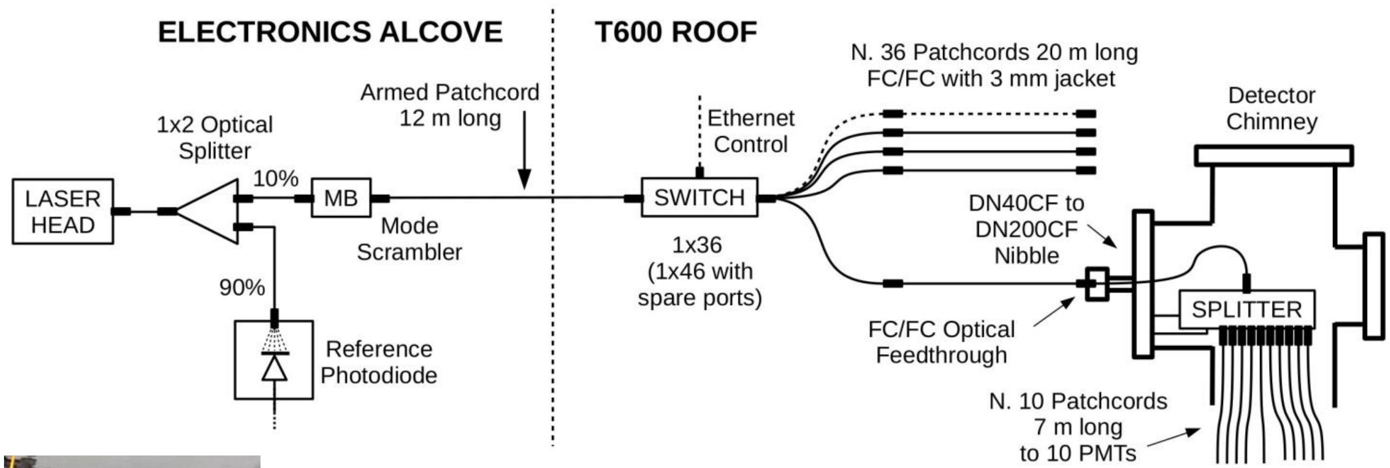
- LAr scintillation light in the VUV range (peaks at ~128 nm): wavelength shifter (TPB) deployed on PMT window to shift it to the visible range
- All PMTs tested at room temperature in a dark room at CERN
- A subset of 60 PMTs tested in Lar for performance comparisons
- Each PMT characterized at 300K and 87K for gain, dark count rate, peak to valley rate and uniformity of photocathode response
- Gain reduction at 87K may be compensated by an increase of ~100 V in power supply voltage



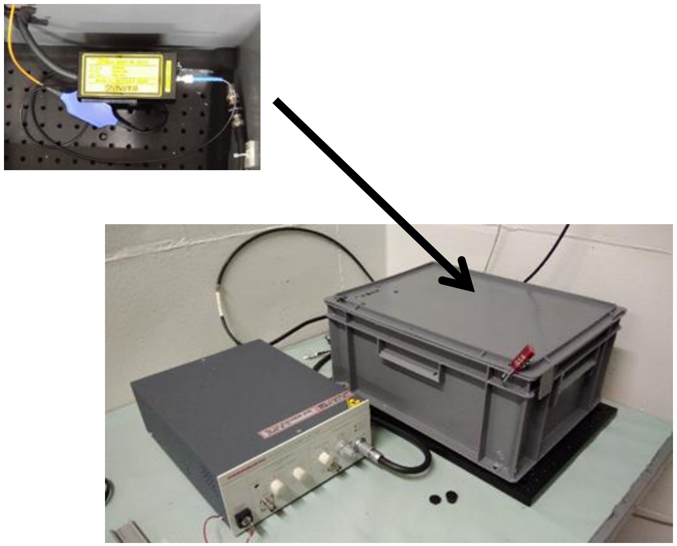


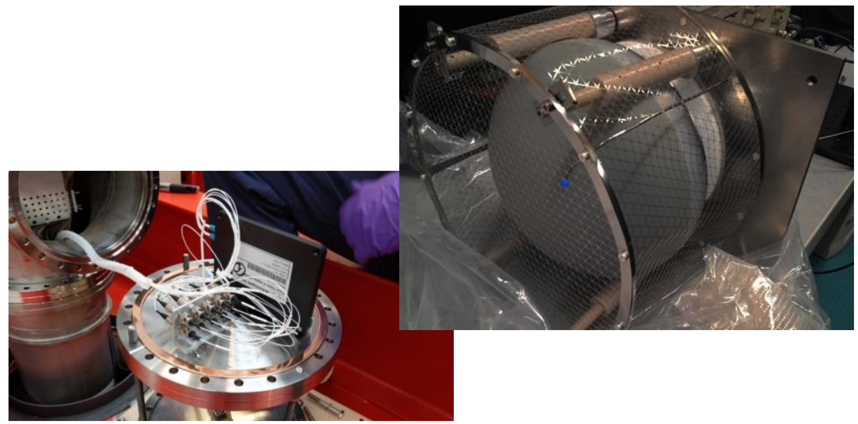
JINST 13 (2018) P10030

Laser calibration system (MIB)



- Timing/gain equalization will be performed with laser pulses.
- distributed to the 360 channels via optical switch, fiber patch cords, 1x10 fused fiber splitters





Laser source: Hamamatsu PLP10, λ=405 nm, FWHM <100 ps, peak power ~120 mW

All the components have been tested and characterized before installation.

ICARUS-T600 Trip to FNAL

leaving from CERN, June 12th 2017

June - July 2017 from CERN to FNAL

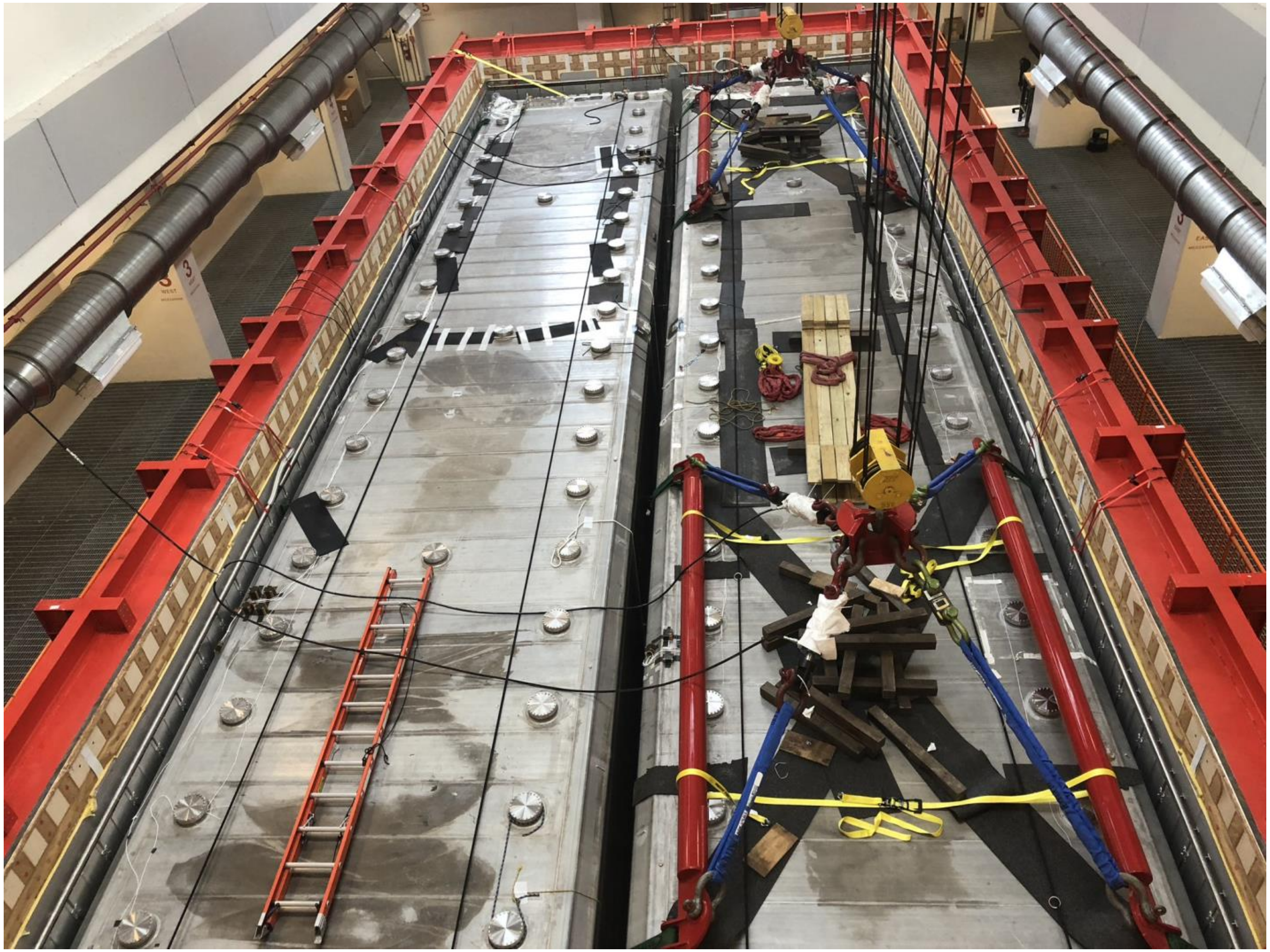
Antwerp: unloading from barge from Basel and loading into ship to Burns Harbor (Indiana)

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

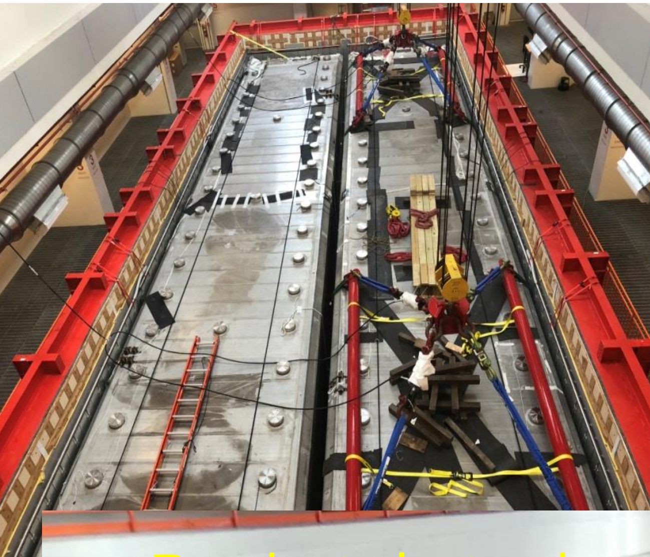
Icarus on the movie

- The video from FNAL illustrates some steps in the ICARUS installation at FNAl

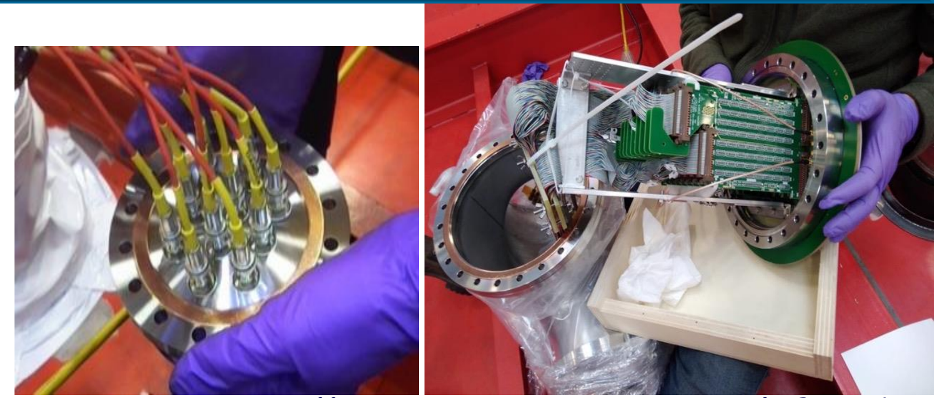
Rigging ICARUS into its place (August 14, 2018)



ICARUS installation @FNAL



Placement of ICARUS inside the warm vessel after the overhauling at CERN (Aug. 2018)



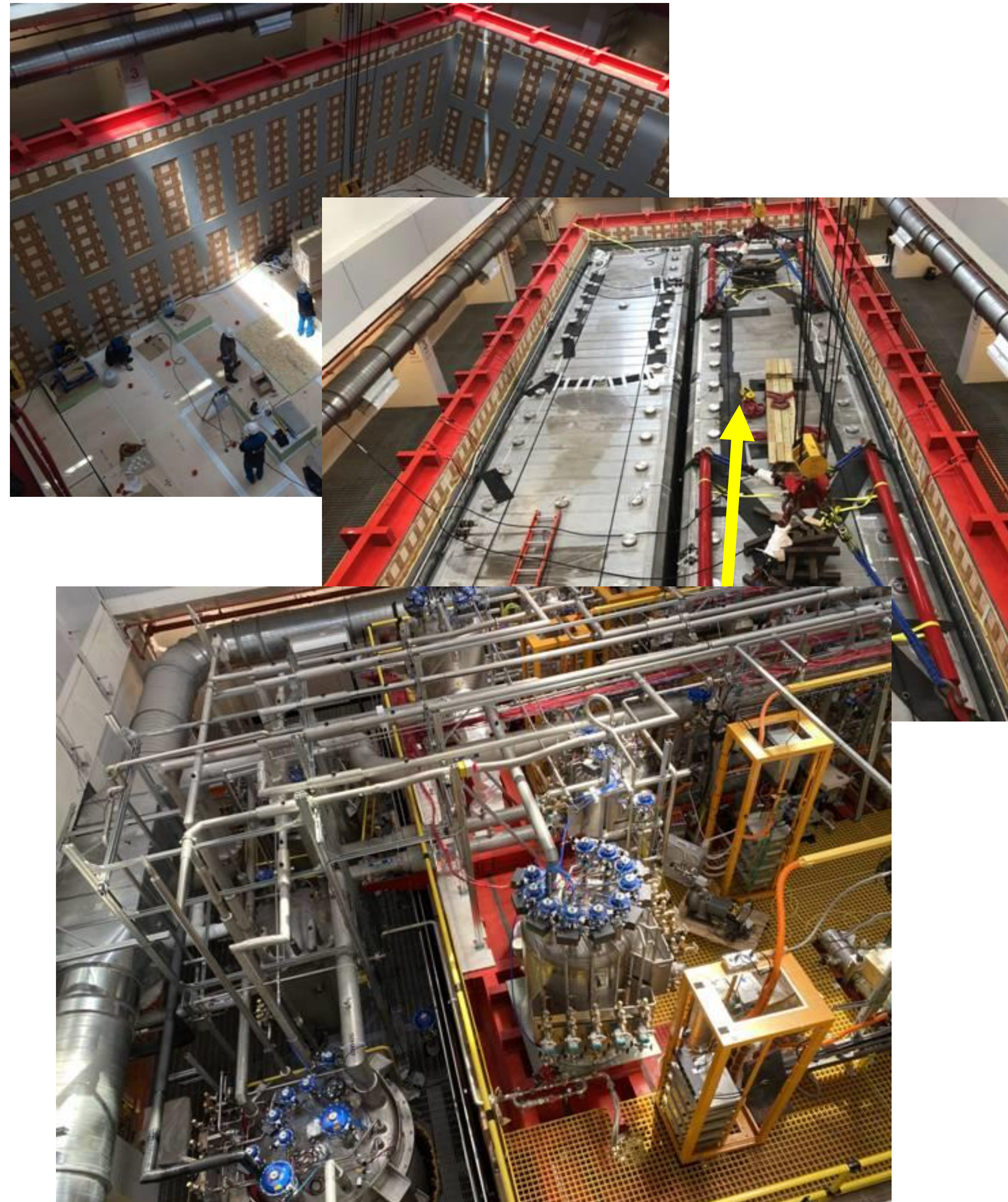
Installing PMT, TPC signal feed-through flanges (Jan. 2019)

Installing the readout electronics (Summer 2019)

- ✓ *All PMT digitizers, HV electronics and laser system installed*
- ✓ *TPC readout electronics (mini-crates, CAEN boards and Power Supplies) installed and verified;*
- ✓ *Internal/external signal connections verified.*
- ✓ *Signal, TT-link cables deployed and connected*

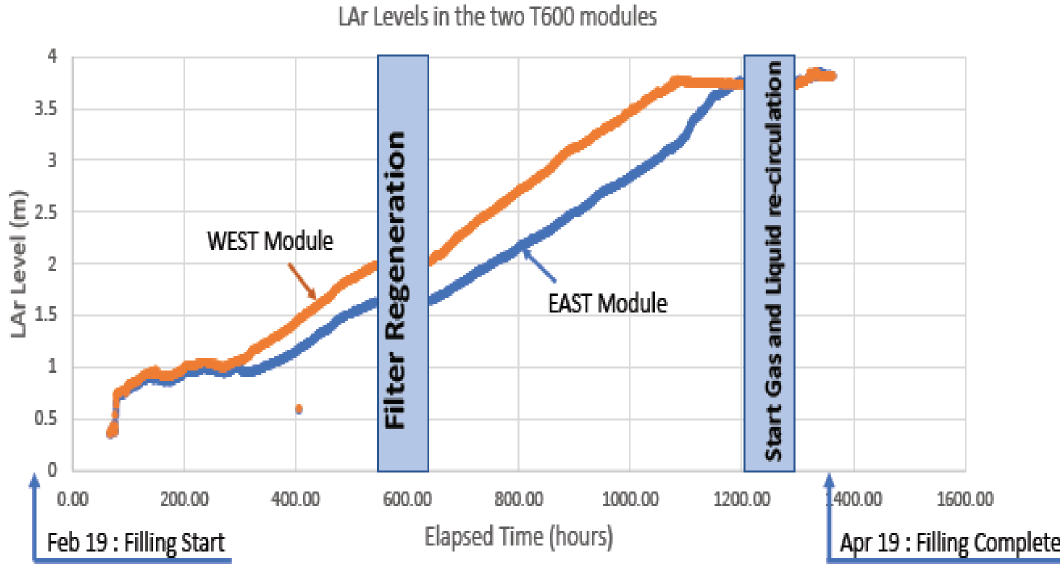
The new ICARUS T600 Cryogenics:

- A Passive Thermal Insulation layer and the relative supporting mechanical structure (Warm Vessel) surrounding and mechanically supporting the main argon volumes and the systems located on top and in close proximity of them;
- An Argon System, providing containment, initial purification during the filling and continuous purification through re-circulation of the main Liquid Argon volumes.



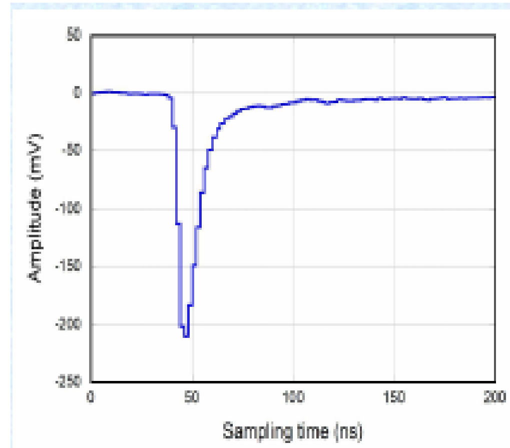
The ICARUS T600 Cryogenic Commissioning

- On Febr. 13th vacuum pumping was stopped and the T600 filled with ultra-purified Ar gas. Then cool down lasted for 5 days by circulating LN2 in cold shields, a large heat exchanger surrounding the 2 LAr volumes. The thermal gradient was kept uniform within 35 K, to preserve the mechanical alignment of TPC wires;
- At the end of the cooling phase the filling with ultra-purified LAr started. The high quality commercial LAr, daily delivered and certified by the vendor, was systematically verified onsite before unloading the truck in the storage tank;
- LAr was then ultra-purified by primary + secondary filter in series before being injected in the main volumes. At half of the filling, the primary filter was regenerated. The filling lasted for ~50 days; it was completed on April 21st.
- In the final stage both Ar re-circulation systems (liquid and gas) are taken progressively online and the operational parameters are adjusted to the steady state conditions.

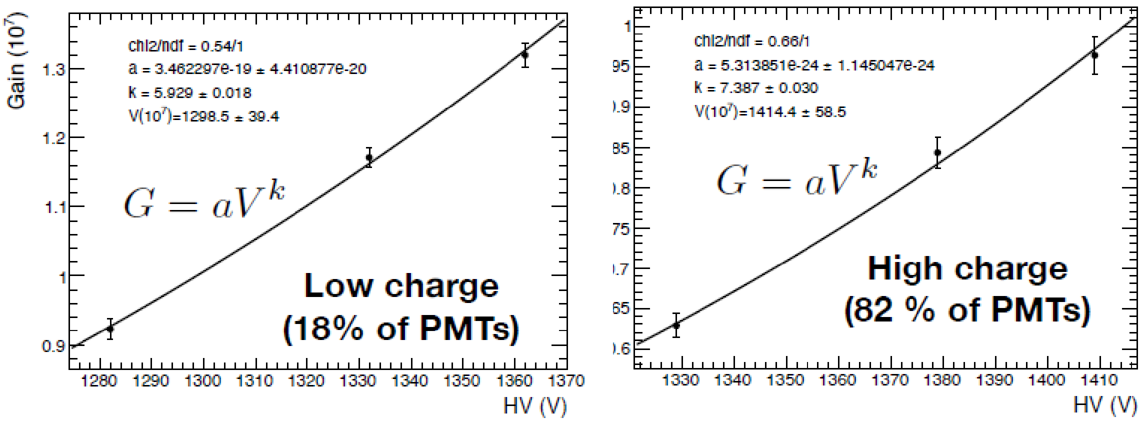


PMT characterization and performances

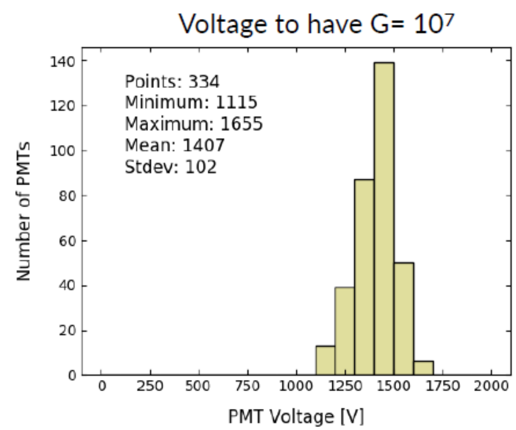
- All 360 PMTs were characterized after installation, before cooling down with laser system.
  - A 0.7-2 x 10^7 gain is achieved on average for ~1.4 kV voltage in the whole PMT set;
  - PMT dark count values measured in 1-2 kH range.

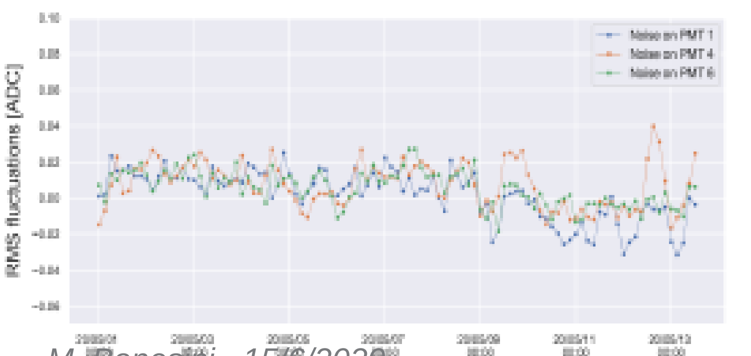


PMT signal shape with a laser pulse



Gain at three different voltages





RMS fluctuations for different PMTs in LAr

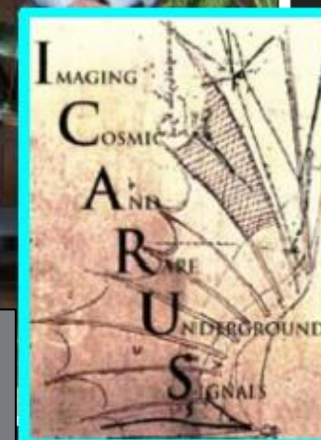
Conclusions

- ICARUS-T600 successful 3-year run at LNGS proved that LAr-TPC technology is mature and ready for large-scale neutrino physics experiments
- ICARUS searched for possible LSND-like anomaly through νe appearance in the CNGS beam. No excess found, identifying a small allowed parameter region where sterile neutrinos have to be searched.
- The SBN project at FNAL will be able to clarify the sterile neutrino puzzle, by looking at both appearance and disappearance channels with three LAr-TPCs
- ICARUS-T600 was extensively refurbished at CERN (2015-17) and is now being installed at the Far Site on the BNB beamline
- The detector is ready to take data, but we are on wait for COVID-19.
- As Milano Bicocca group we are actively engaged in the PMT sub-system, analysis and experiment running

Thank you!

- *The full list of the Collaboration* https://icarus.fnal.gov/collaboration

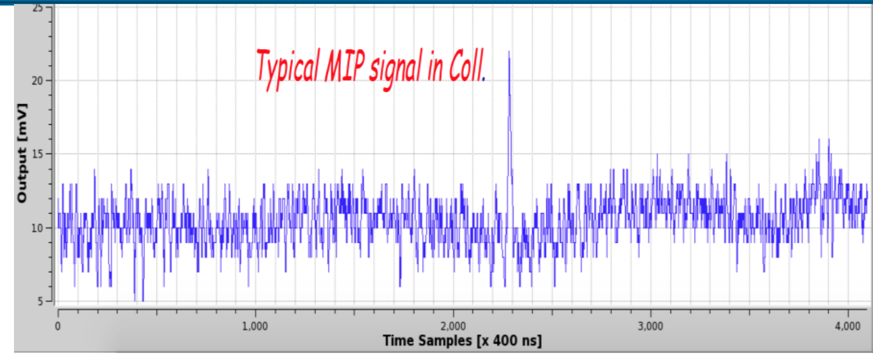
Come with us: thesis available

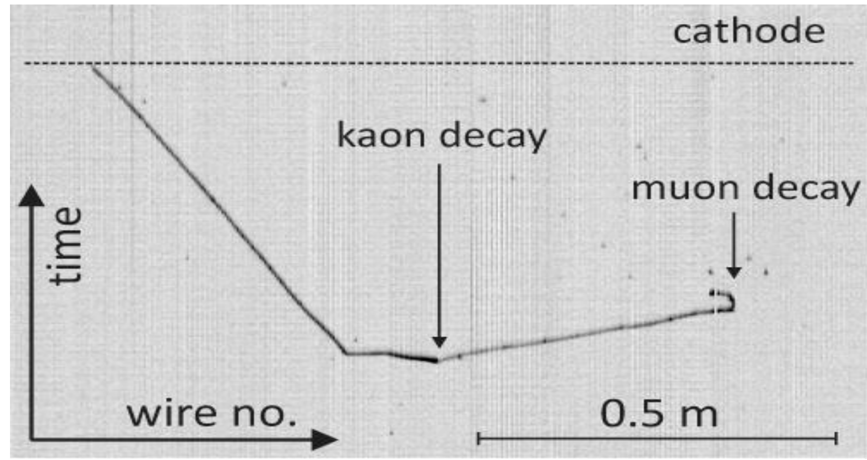


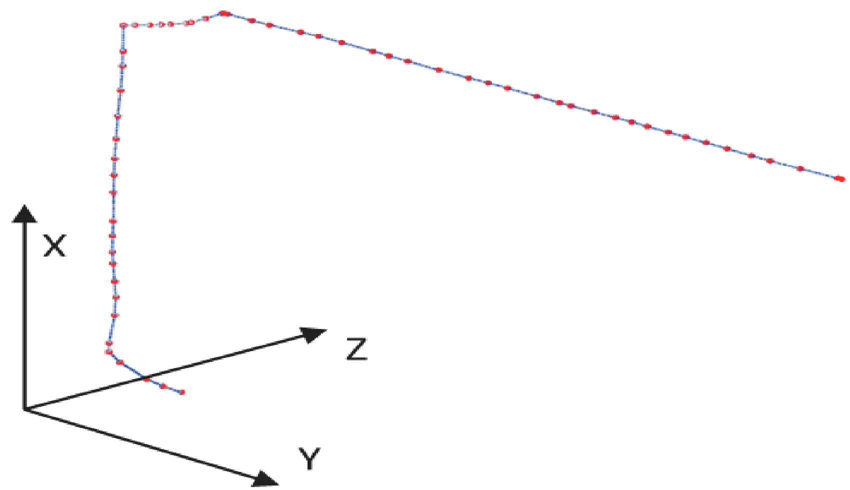
***** Additional slides *****

ICARUS reconstruction and analysis

- LAr-TPC reconstruction starts from single wire waveforms: ADC# as function of sample
- SIGNAL PROCESSING on wires: noise filtering, possible deconvolution, hit finding
- CLUSTERING of hits, based on 2D (wire-sample) topology in each plane
- 3D TRACKS/SHOWERS are identified based on geometrical features of clusters and matching between wire planes
- Higher-level reconstruction extracts physics quantities from tracks and showers:
  - Track fitting
  - Calorimetry
  - MCS momentum measurement
  - Particle ID
- In ICARUS@LNGS, higher level reconstruction had significant input from visual scanning



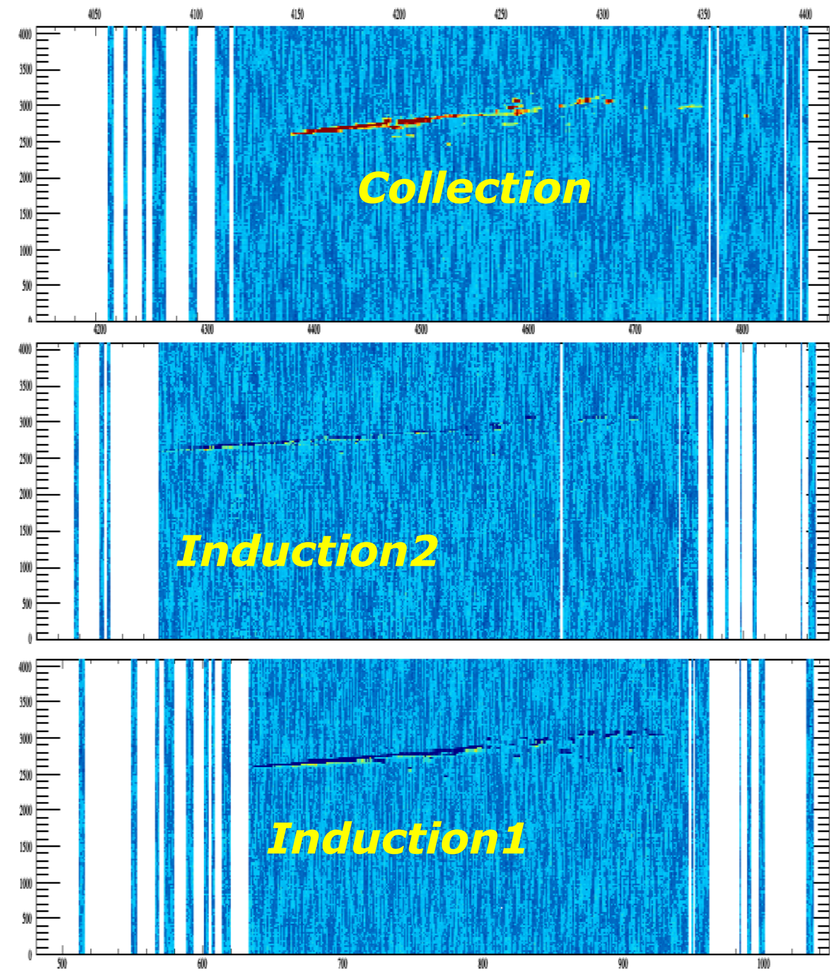




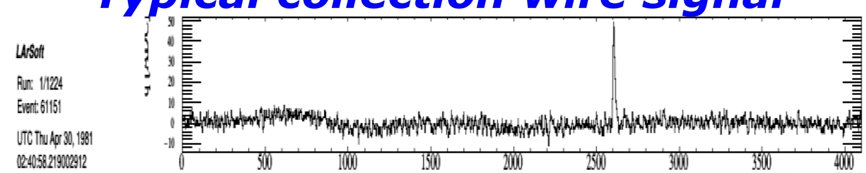
SBN reconstruction and analysis

- LNGS experimental experience will be crucial in developing SBN analysis tools
- Conditions however will be different
  - Much larger event statistics
  - Overlap of cosmics on neutrino events
- The combination of TPC, PMT and CRT data will be needed to fully exploit information
- Common analysis with near detector will be crucial to control SBN systematics
- ICARUS joined Larsoft framework, in order to share tools and algorithms with SBND and perform cross-checks
- Full simulation produced - realistic geometry and signal/noise from TPC, PMT, CRT
- First large-statistics ICARUS MC studies are currently ongoing

Simulated electron (E~800MeV,l~1.2m)



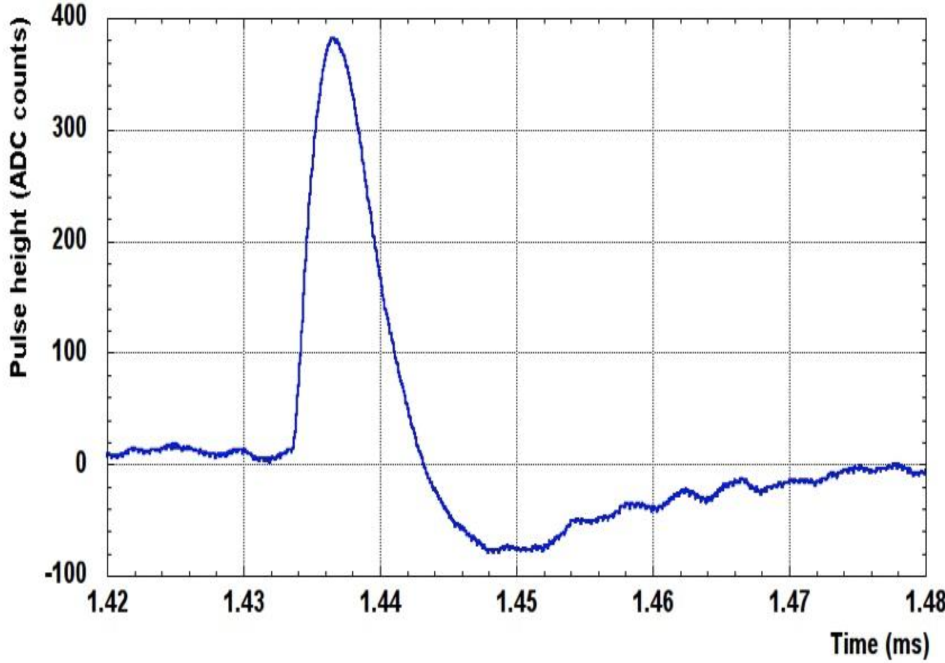
Typical collection wire signal



ICARUS-T600 at LNGS: light detection system

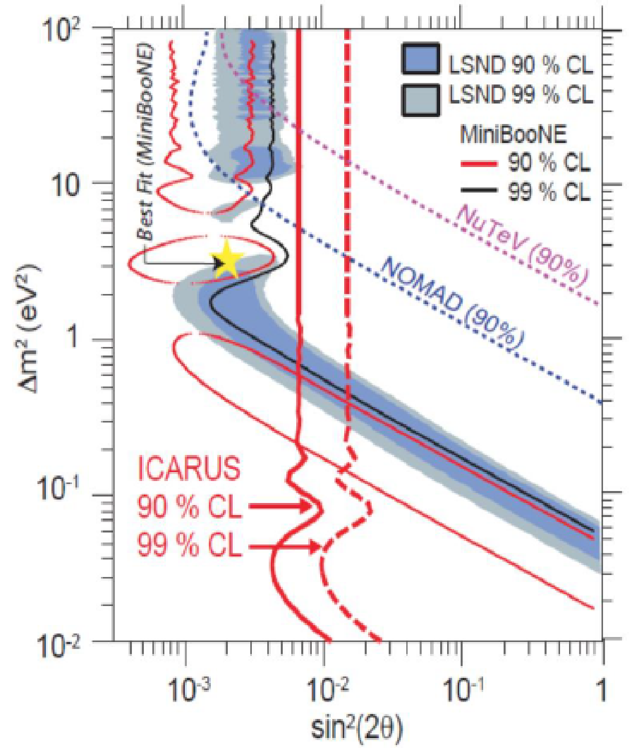
- LAr is a good scintillator: ~5000 photons/mm for a MIP track
- Two components: fast (~ 6 ns) and slow (~ 1.6 μs)
- Light signal is much faster than charge: can provide trigger signal (alone or in coincidence with beam gate)
- 74 PMTs (54 in the East module + 20 in the West): 8-inch diameter.
- LAr scintillation light in the VUV range (peaked at ~128 nm): wavelength shifter (TPB) deployed on PMT window to shift it to the visible range

Example PMT signal after slow+fast component integration



Icarus search for sterile neutrinos at CNGS

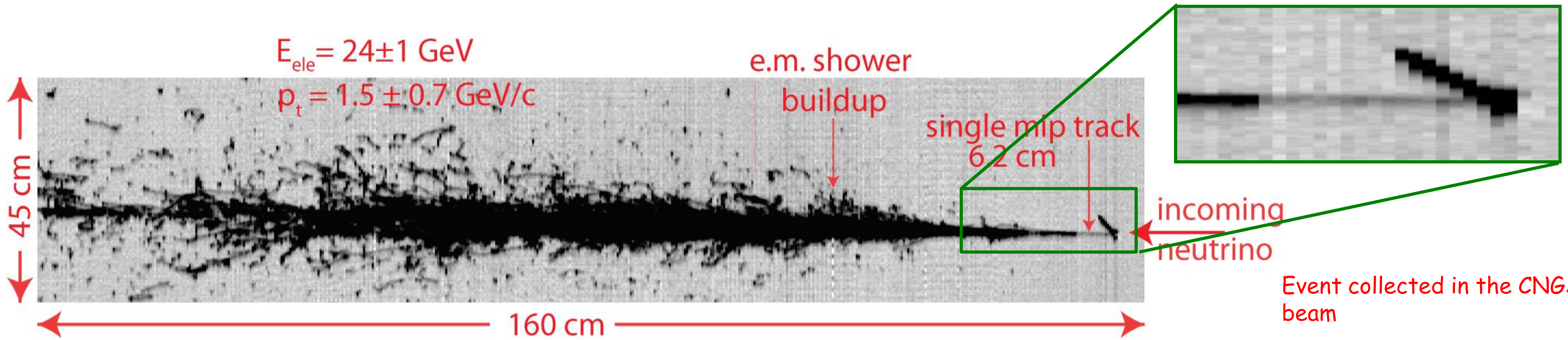
- ICARUS searched for sterile ν oscillations through ν_e appearance in the CNGS beam.
- L/E ~ 36 km/GeV, far from LSND value ~ 1 km/GeV -> "sterile-like" oscillation was averaged out, canceling energy dependence.
- 7.9 10^{19} pots analyzed (~2650 ν interactions).
- Expected ~ 8.5 ± 1.1 ν_e background events in absence of anomaly, mostly from intrinsic ν_e beam contamination.
- Estimated ν_e identification efficiency ~74% with negligible background from misidentification.
- 7 events observed → no evidence of oscillation.
- Most of LSND allowed region is excluded - except for small area around $\sin^2 2\theta \sim 0.005$, $\Delta m^2 < 1$ eV^2
- Similar result by OPERA with same CNGS beam and different detection technique.



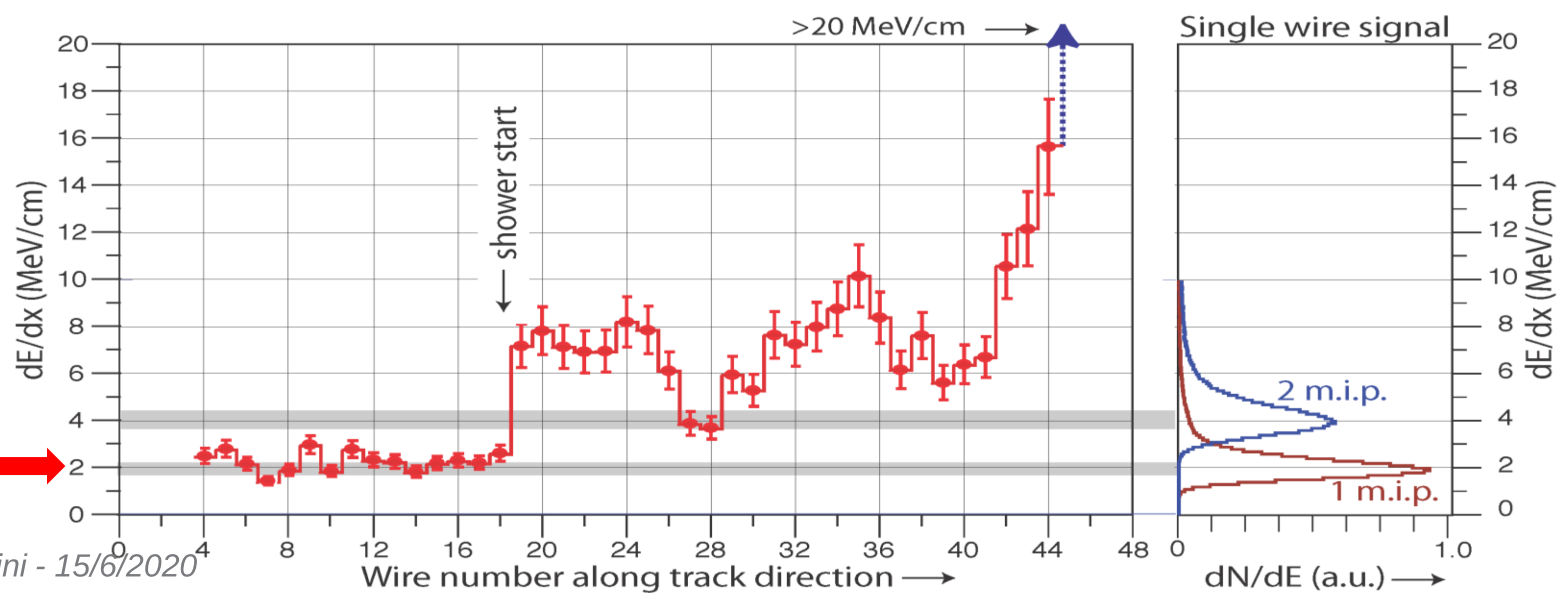
Eur. Phys. J. C (2013) 73:2599

Search for ν–e events in CNGS beam

"Electron signature" for νe CC event : energy < 30 GeV, charged isolated track from primary vertex, compatible with a m.i.p., subsequently building un into a shower; e-identification efficiency $\eta = 0.74 \pm 0.05$ ($\eta' = 0.65 \pm 0.06$ for intrinsic νe beam).



Event collected in the CNGS beam



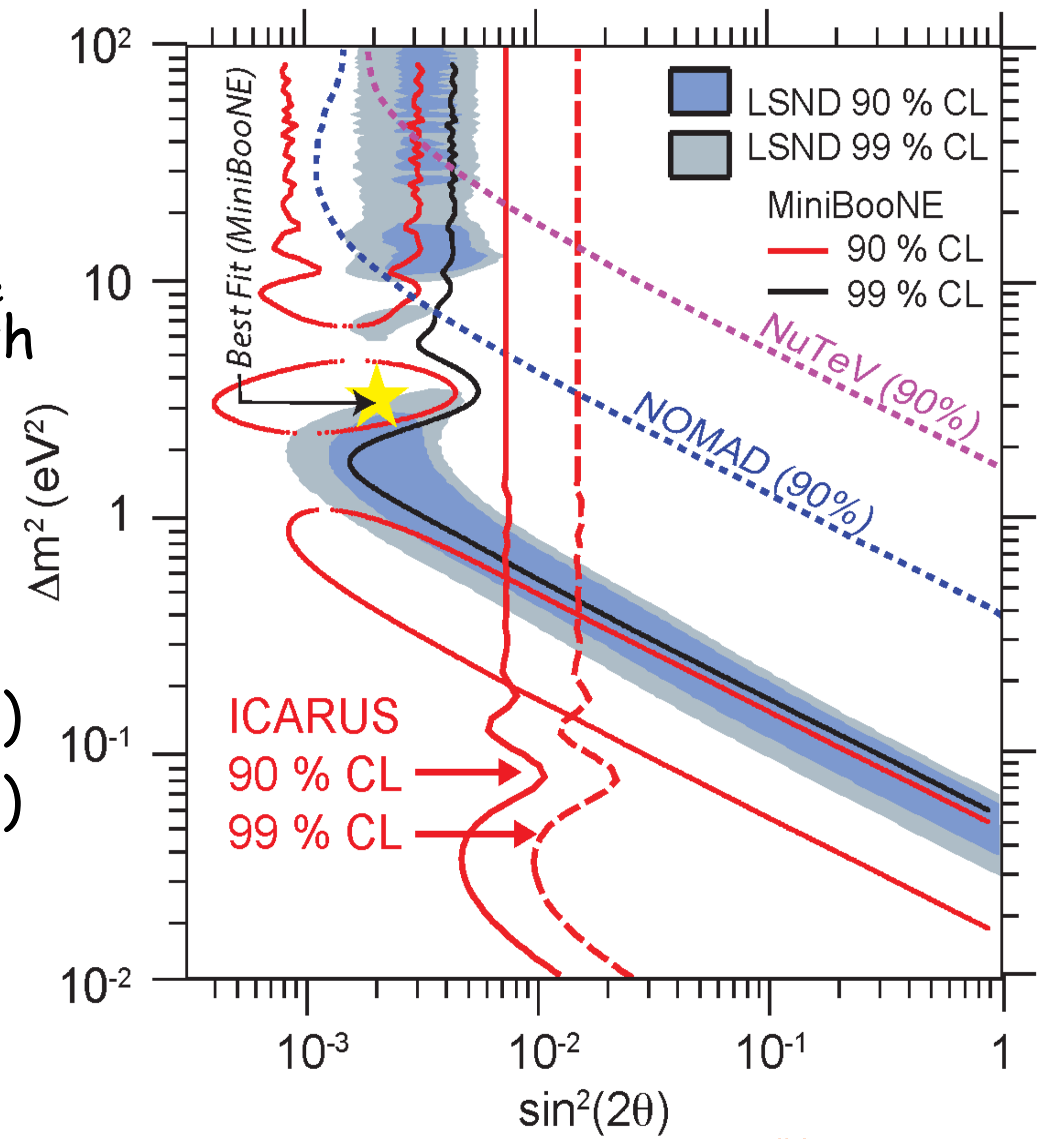
Single M.I.P

ICARUS result on the search of the LSND-anomaly

- Analysis on 2450 ν events (7.23×10^{19} pot out of the full statistics of 8.6×10^{19} pot): 6 ν_e events observed in agreement with expectations due to conventional sources (7.9 ± 1.0).
- These provide the limits on the oscillation probability:
  - $P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3}$ (90 % C.L.)
  - $P(\nu_\mu \rightarrow \nu_e) \leq 7.60 \times 10^{-3}$ (99 % C.L.)

Eur.Phys.J.C (2013) 73:2345
Eur.Phys.J.C (2013) 73:2599

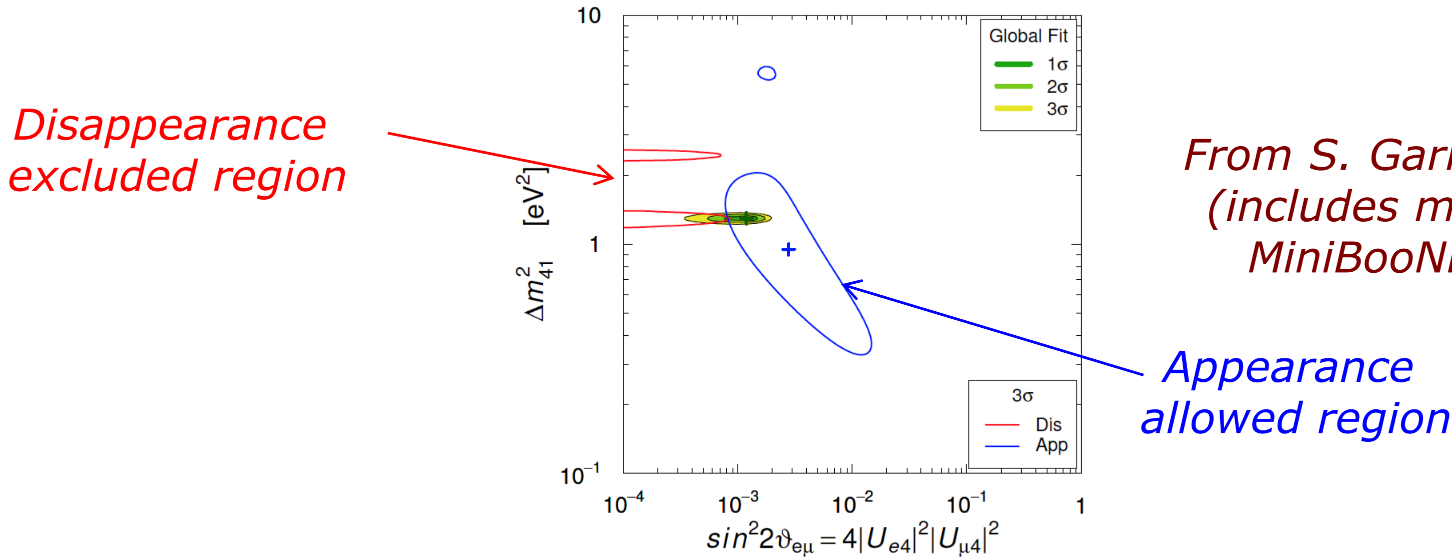
Neutrino



Results confirmed by OPERA

Perspectives for sterile neutrino physics

- The sterile neutrino picture is far from understood and needs a definitive clarification
- Tension between appearance and ν_μ disappearance results. Measuring both channels with the same experiment will help disentangle the physics scenario



From S. Gariazzo, 2018 (includes most recent MiniBooNE result)

- Control of backgrounds and systematics will be fundamental: a near detector will be necessary for any accelerator experiment

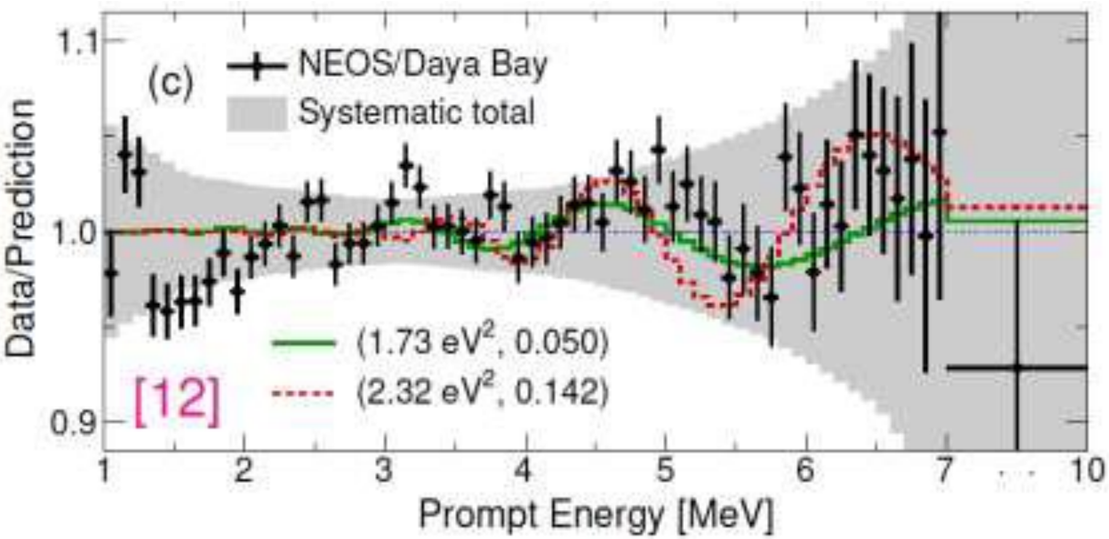
SBN satisfies these requirements: it could have a crucial role in solving the sterile neutrino puzzle!

Results from reactors

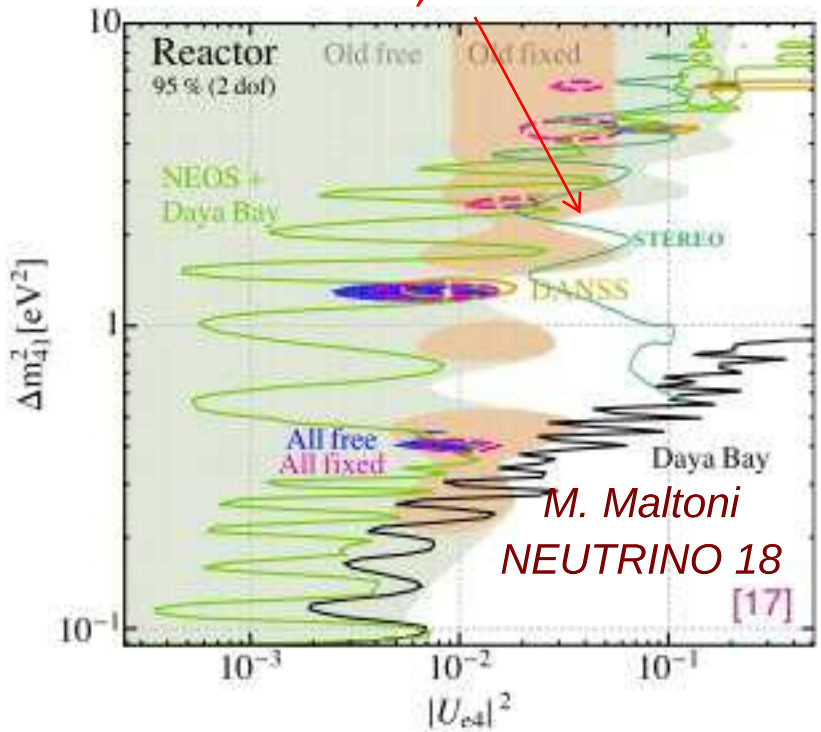
The current sterile scenario is definitely very complex:

- Big Bang cosmology (Planck) allows at most one sterile flavour - mass <0.24 eV
- No evidence of ν_μ disappearance in MINOS and in IceCube (0.3-20 TeV)
- Recent reactor data (NEOS/DANSS) are intriguing but not yet conclusive
- New claim by Neutrino-4: oscillations with $\Delta m^2 \sim 7 eV^2$?

see JHEP08(2018)010,JHEP06(2017)135



Best fit
$\Delta m^2=2.4 eV^2$, $\sin^2 2\theta=0.014$

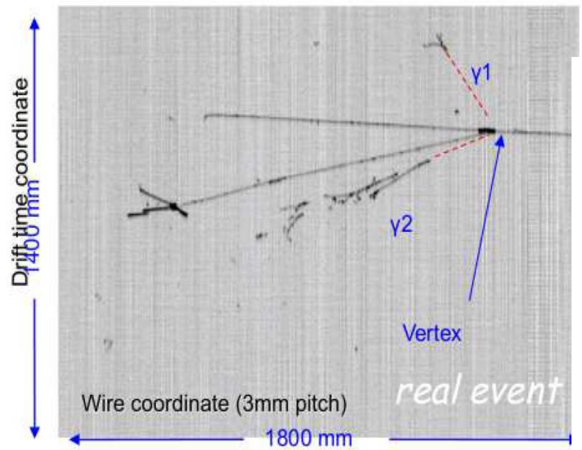


e/γ separation and ν_e identification

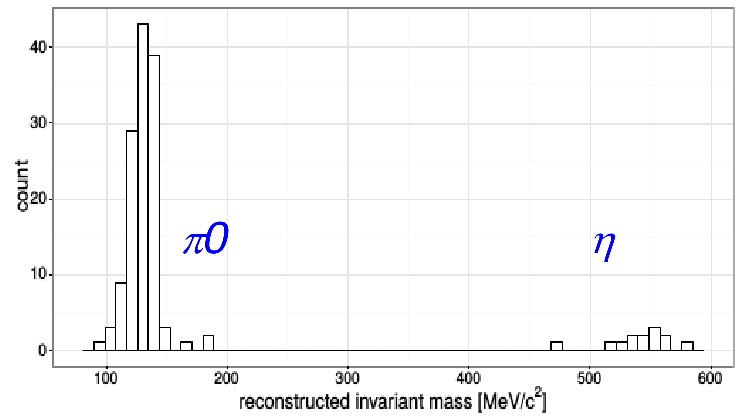
In order to identify a ν_eCC event, the shower produced by the electron must be selected, distinguishing it from a photon-initiated shower generated by a π^0 in a NC interaction.

3 "handles" are available in ICARUS to perform this discrimination:

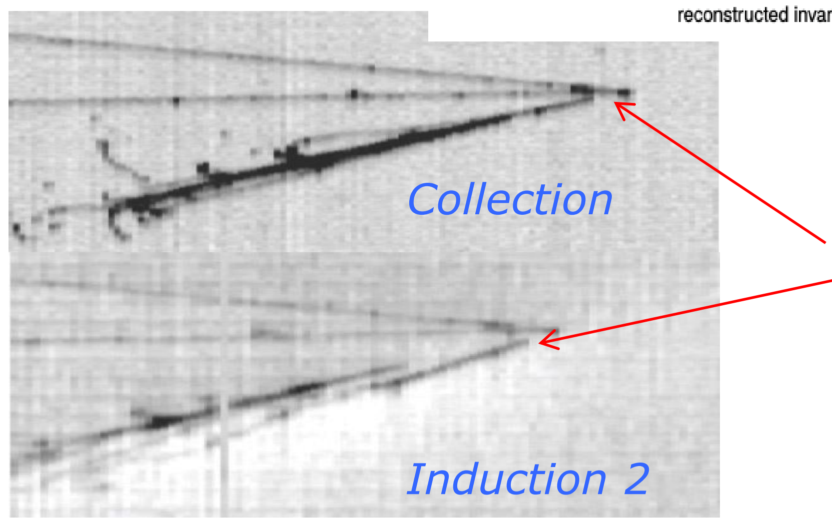
- π^0 INVARIANT MASS : Measurement of position/energy of the showers from both γ's allows computing $M_{\pi 0}$



Reconstructed invariant mass in CNGS events



- CONVERSION GAP: the excellent LAr-TPC granularity allows seeing the gap (few cm) between primary vertex and photon pair production



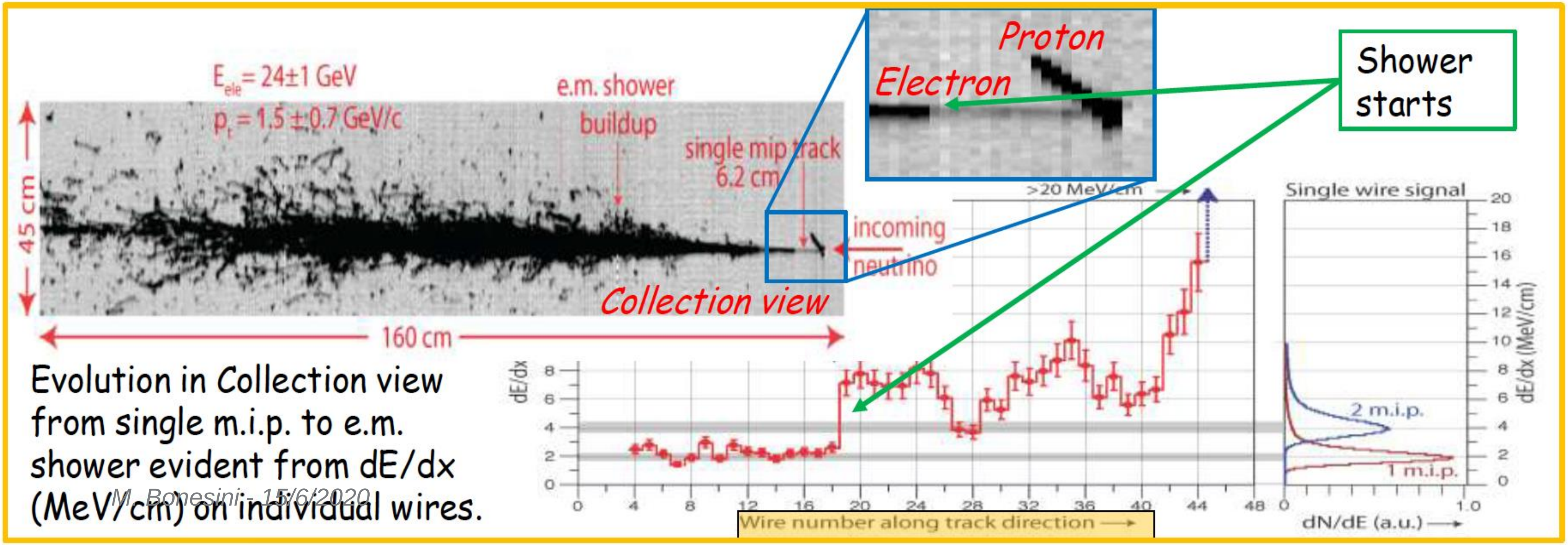
e/γ separation and ν_e identification

- dE/dx MEASUREMENT:

The great spatial and calorimetric reconstruction, and the fine sampling (2% X0) allow measuring dE/dx on each wire, before the beginning of shower development.

An electron is identified by a single MIP deposition (~2.1 MeV/cm).
Individual delta rays can be flagged and excluded from the analysis.

An example of a high-energy CNGS beam νeCC interaction:

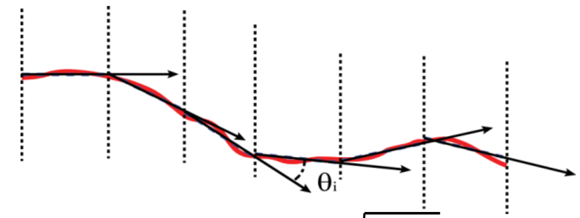


Evolution in Collection view from single m.i.p. to e.m. shower evident from dE/dx (MeV/cm) on individual wires.

Measurement of muon momentum via multiple scattering

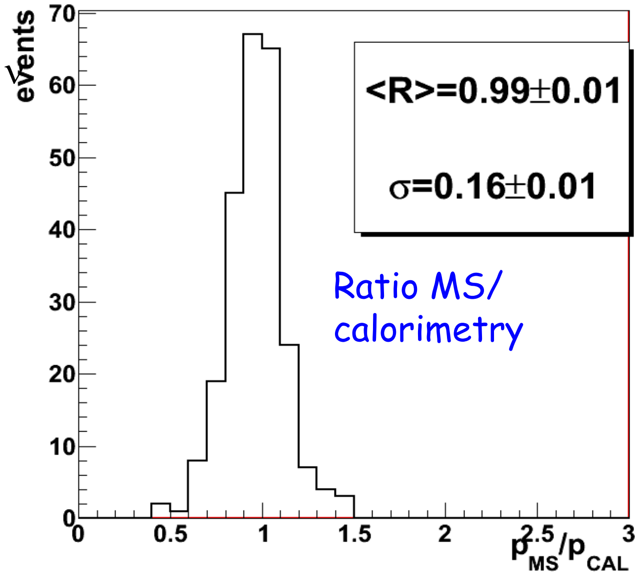
In absence of a magnetic field, the initial μ momentum is determined through the reconstruction of multiple Coulomb Scattering (MS) in LAr

RMS of θ deflection of μ depends on p, spatial resolution σ and track segmentation

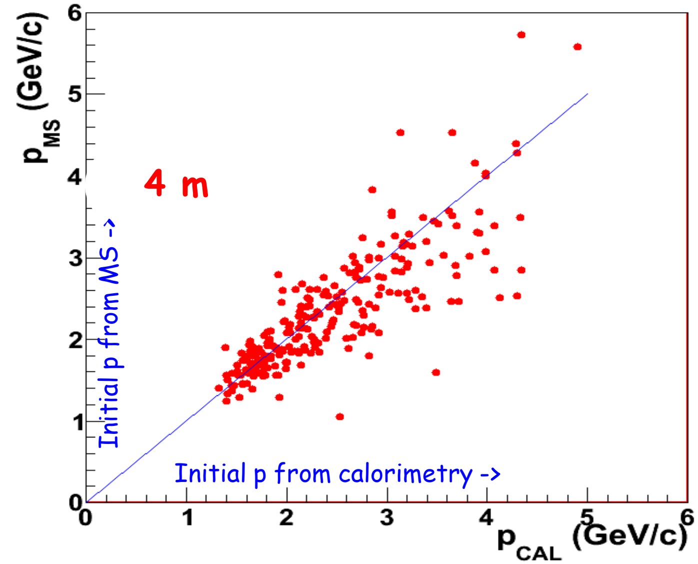


$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$

Method tested on ~10^3 stopping μ's from CNGS interactions in upstream rock, comparing PMS measured by MS with the corresponding calorimetric PCAL



μ track length: > 5m Used length: 4m



~16% resolution has been obtained in the 0.4-4 GeV /c momentum range of interest for the future short/long base-line experiments

paper in preparation

The ICARUS T600 Current Status

- Due to the COVID-19 outbreak all activities have been suspended at Fermilab except for essential work to be conducted on site, consistent with the current Illinois "stay at home" announcement:
  - The laboratory is closed to users and all employees telecommute from home;
  - Only specific **essential personnel** is authorized to be on-site;
  - There will be no beam from the accelerators by October 2020;
  - All the experimental plants are set in "safe mode".
- Most of ICARUS operations are mainly being performed from remote since March 23th, including remote survey shifts from the Collaboration. The cryogenic commissioning was supported by a joint effort of Cern/Fermilab cryogenic teams. On site presence is limited to a maximum of 2 people for routine checks.
- Plans to re-start onsite operations after lifting of the present restrictions are being developed in conjunction with the Fermilab management. The completion of TPC/PMT cabling with final tuning and adjustment of grounding would require the presence on site of experts.
- The TPC/PMT noise must be carefully studied during the HV activation. Moreover the direct investigation of the noise source and the possible strategies for its mitigation require TPC/PMT experts facing in person the actual situation.

ICARUS installation at FNAL - status

- T600 installed inside warm vessel in August 2018
- Installation of TPC/PMT feedthrough flanges completed by December 2018
- "Vertical slice test" performed on a small electronics subset: preliminary results show good connectivity and satisfactory noise level
- PMT electronics and trigger are being tested at CERN
- Side CRT installation is currently ongoing (January 2019)
- Installation of proximity cryogenics system is also progressing
- SBN Director Review in December 2018 recognized the experiment's progress