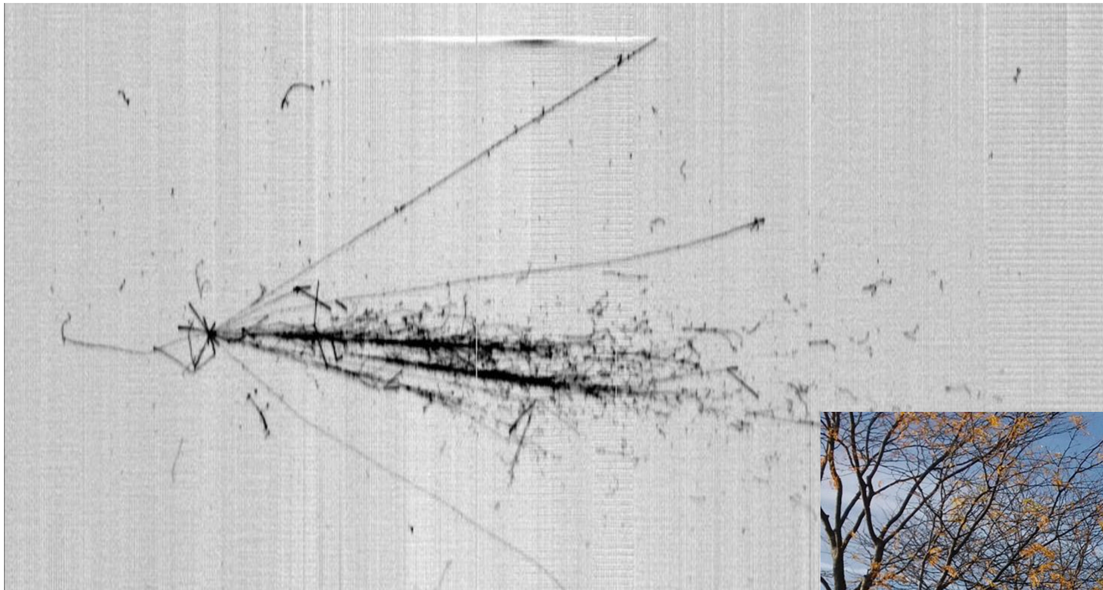
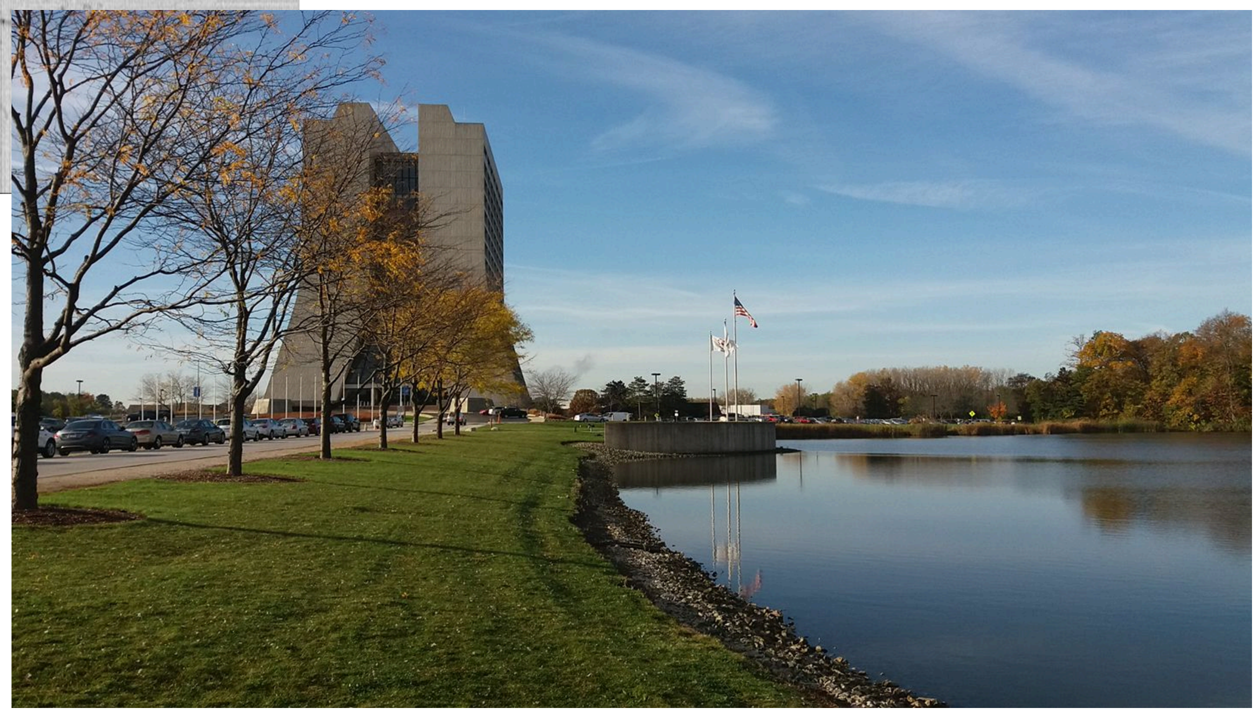
ICARUS: from the past to the future





F. Varanini
INFN Padova

on Behalf of the
ICARUS Collaboration

NPC seminar

FNAL
January 31st 2019

Outline

- Liquid Argon TPCs: the ideal detector for neutrino physics?
- The long history of Liquid Argon TPCs
- ICARUS at Gran Sasso: the first large-scale experiment
- Sterile neutrinos and the SBN project
- Making ICARUS better: from underground up to the surface
- Installation and commissioning here at FNAL

What are we looking for in a neutrino detector?

Ultimately, two things:

- FLAVOR IDENTIFICATION:
  - Efficiency and purity in identifying $\nu\mu$CC vs. νeCC vs. νNC
  - Crucial for any νe appearance searches
  - The separation between electrons and photons is especially 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 (like at SBN) ->large statistics is needed
  - This implies both huge size and long continuous data-taking
  - A dense, relatively cheap target material is needed

Liquid Argon TPC

This technique can combine these requirements: huge size and fine granularity

- 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 provides fast signals for triggering/timing purposes

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

- First conceptual proposal by Carlo Rubbia in 1977
- 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"

- Argon density and radiation/interaction lengths are very similar to Freon
- Predictions on detector performance and mass proved correct
- Drift length actually too pessimistic: we are doing an order of magnitude better!

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

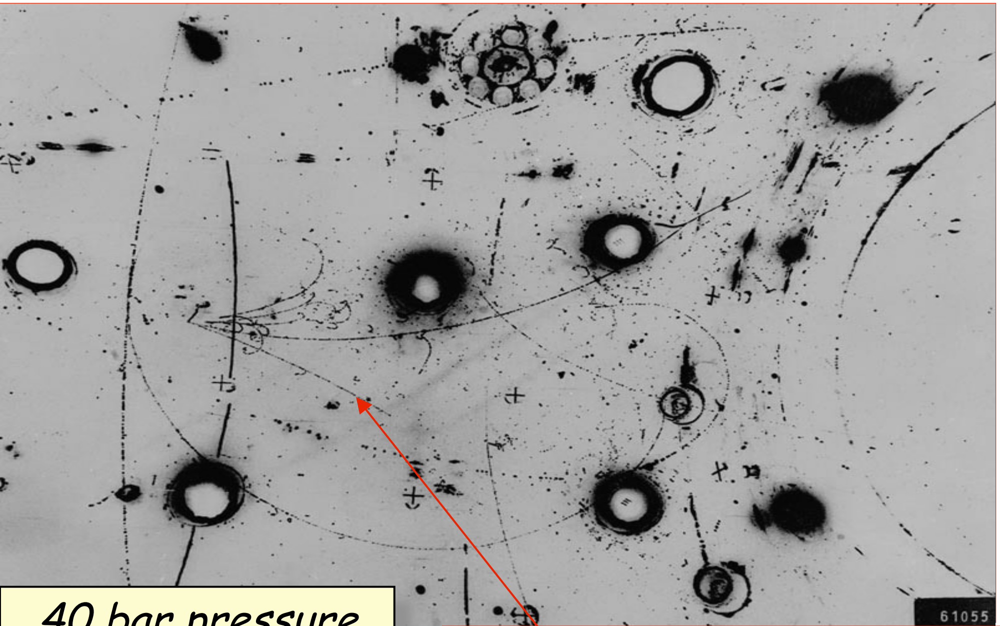
ABSTRACT

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.

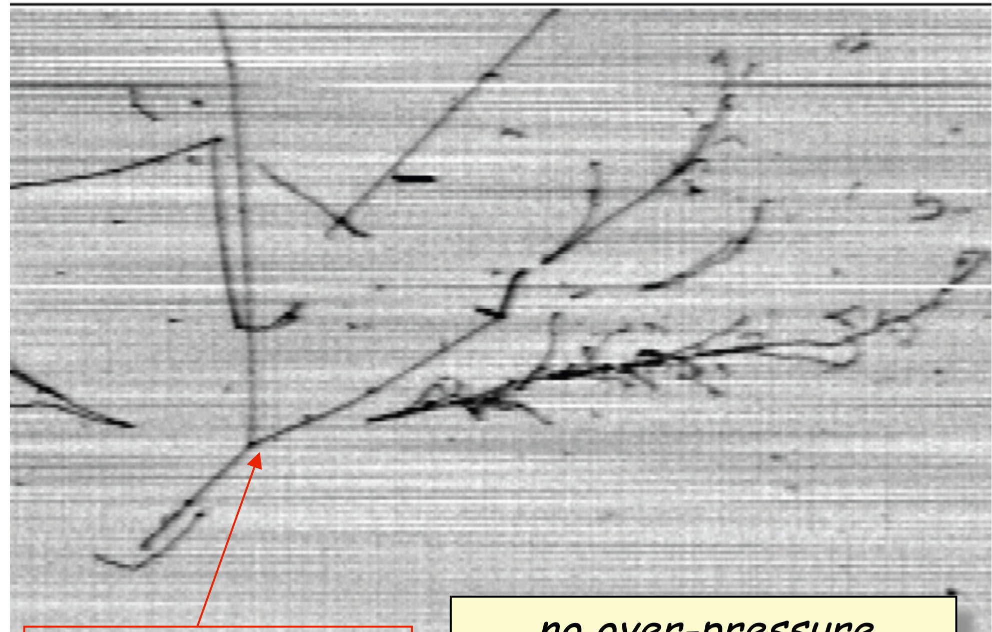
G E N E V A

1977

An “electronic bubble chamber”



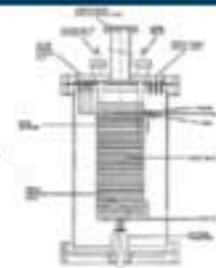
Heavy freon



Liquid argon

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

The path to larger LAr detectors



CERN

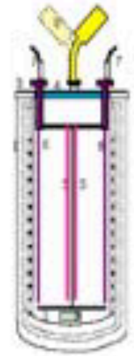
24 cm drift wires chamber

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.

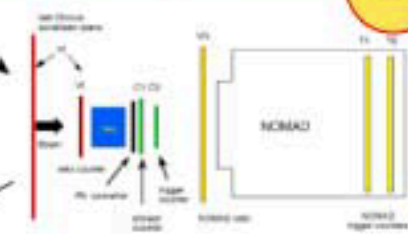
CERN

Laboratory work

CERN

3

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-... : Data taking with CNGS beam

Pavia

T600 detector

2001: First T600 module

5

Cooperation with industry
AirLiquide, Breme, Cinel, CAEN

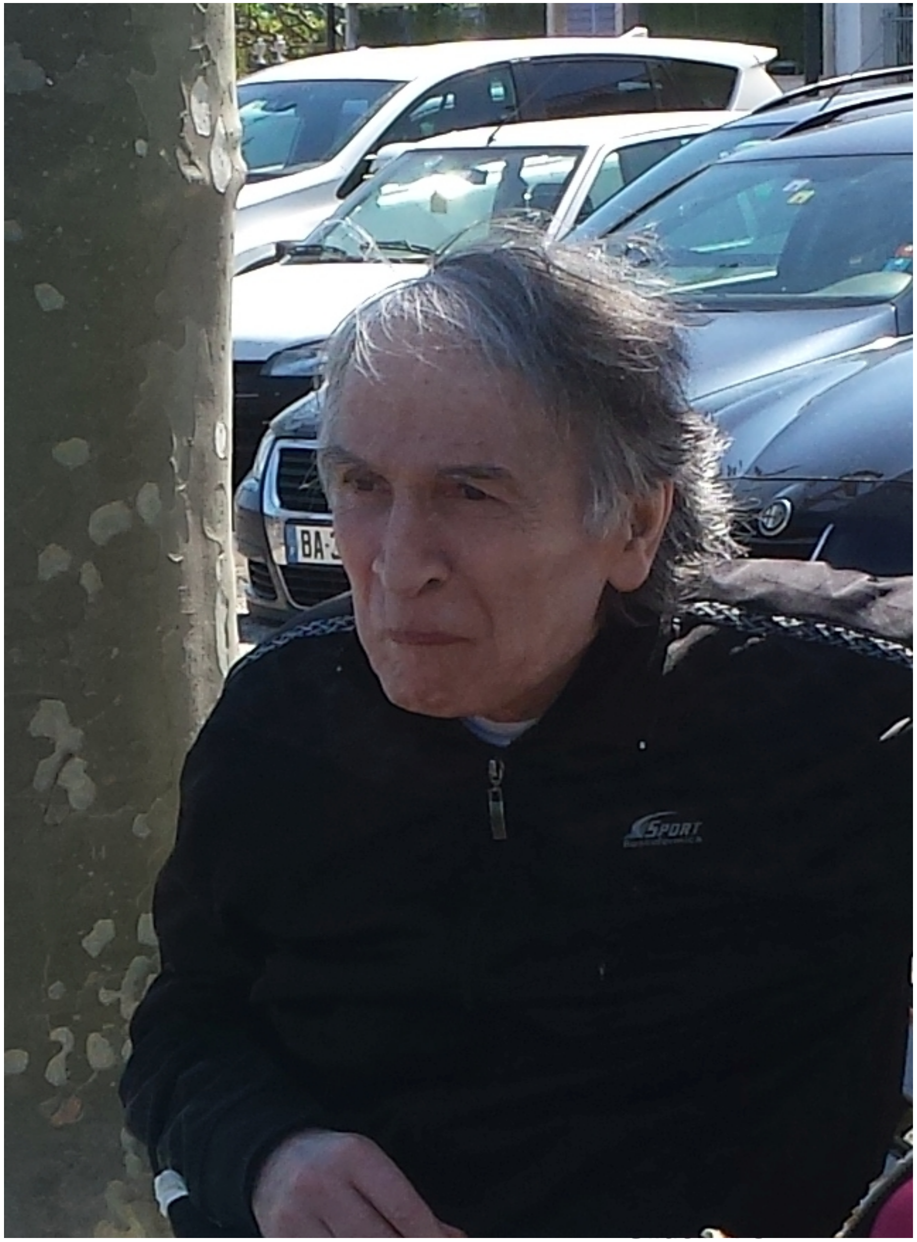
6

LNGS Hall-B

Pio Picchi (1942-2019)

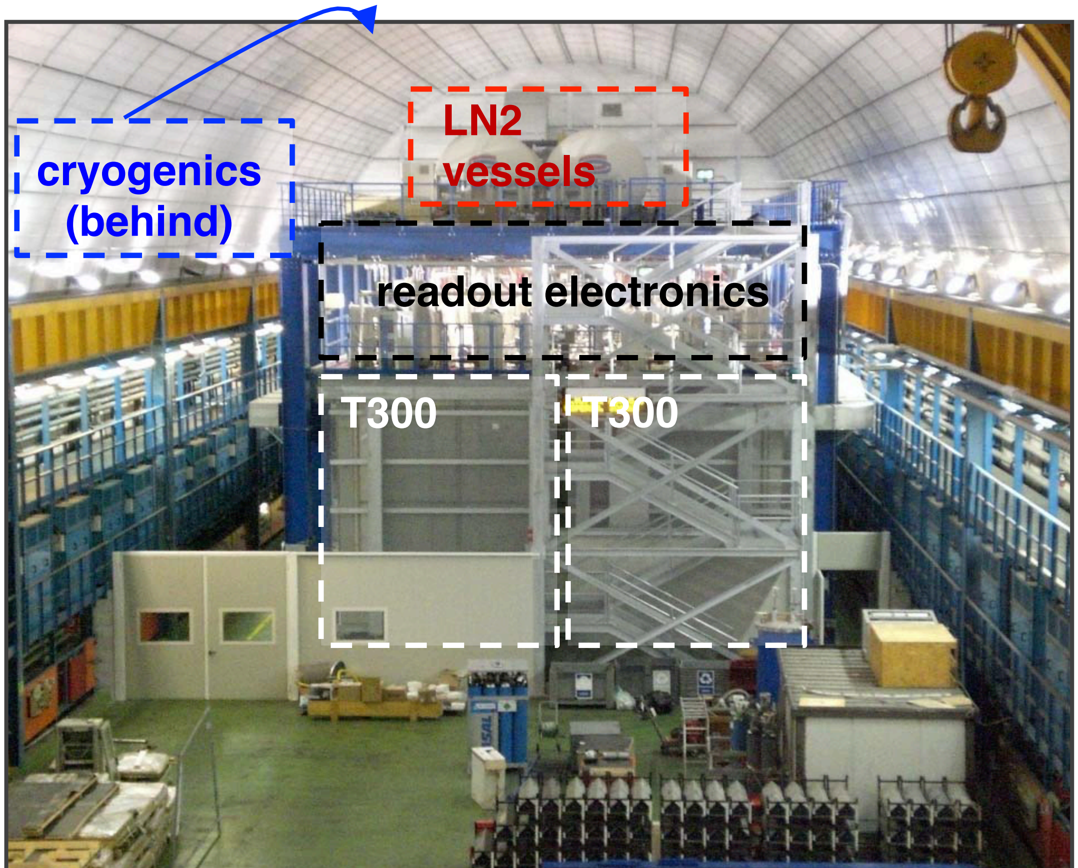
- Pio was the coordinator of the pioneering R&D prototypes on LAr-TPC at CERN during the 80s and 90s
- The success of ICARUS, paving the way to SBN and DUNE, prove the importance and vitality of the research activity that Pio pursued with great perseverance
- We who had the privilege to work with Pio remember his scientific imagination, humility, intellectual honesty, and his great kindness, patience and humor
- All these qualities never changed during the long years of his disease

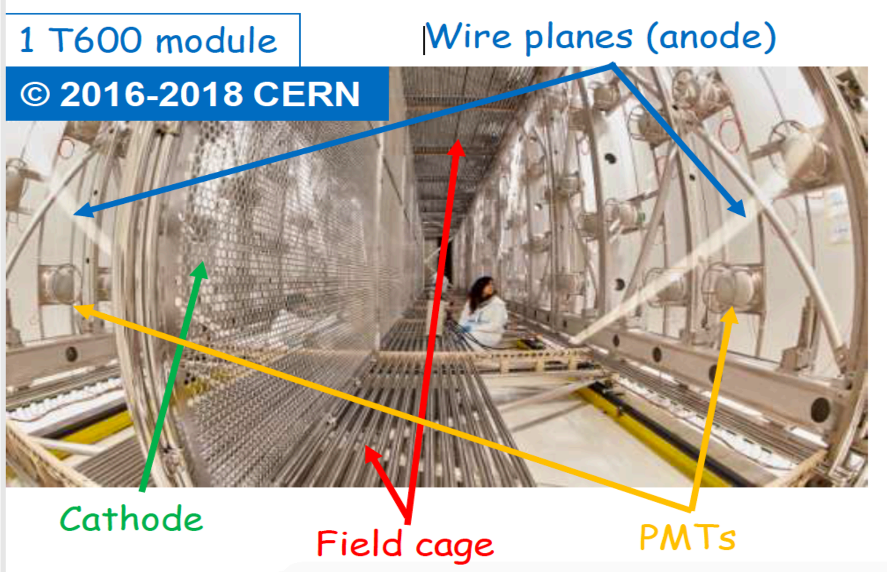
Thanks Pio!



ICARUS-T600 at LNGS

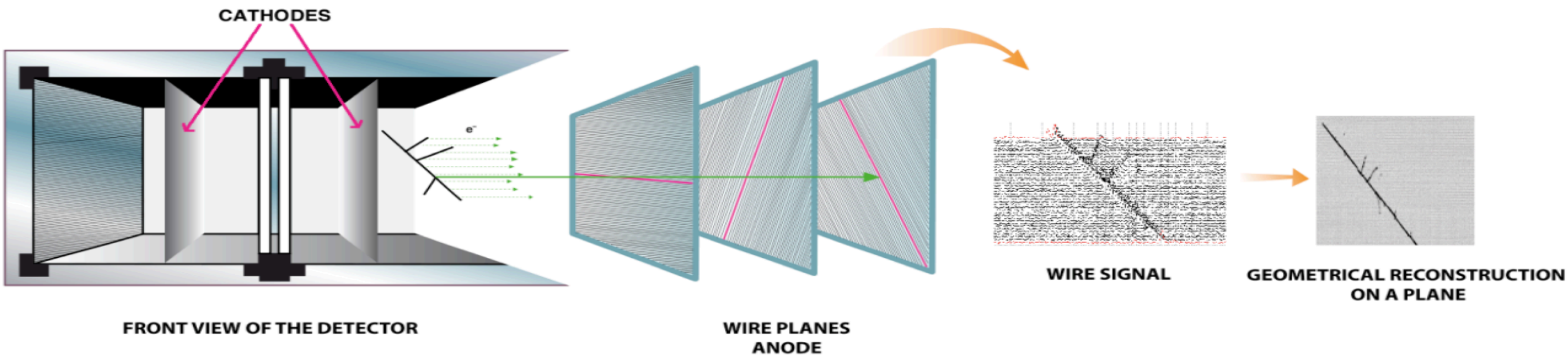
- First large-scale LAr-TPC in a neutrino beam
- 2 identical modules: each is 19.6x3.6x3.9 m^3. Size is limited by logistics: must be transported by truck and enter LNGS halls
- Active mass 476 tons; total LAr mass ~760 tons.
- Drift distance 1.5 m. A large step up from previous smaller prototypes
- Electric drift field is 500 V/cm -> drift velocity ~1.6 mm/μs



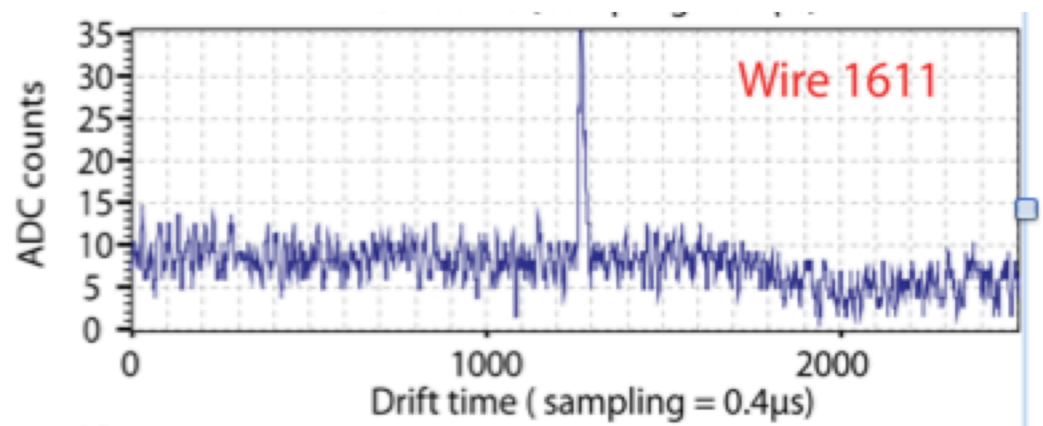


ICARUS-T600: TPC working principle

- 3 wire planes with 0°,+60°,-60° orientation w.r.t. horizontal; both pitch between wires and distance between planes are 3 mm
- Wire biasing guarantees (almost complete) plane transparency, and non-destructive readout in both Induction wire planes
- Last plane collects charge, allowing measurement of deposited energy
- ~54000 total readout wires, with 400 ns sampling time



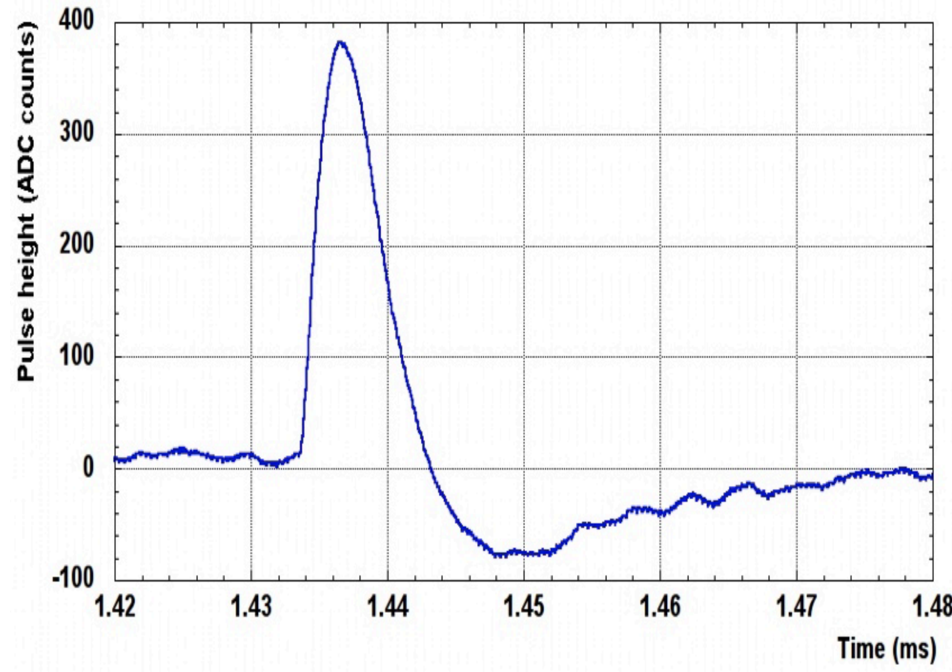
Typical signal in collection plane:



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

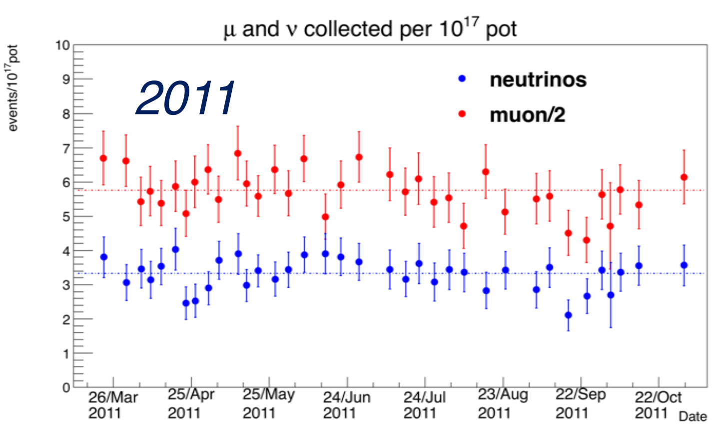
Example PMT signal after slow+fast component integration

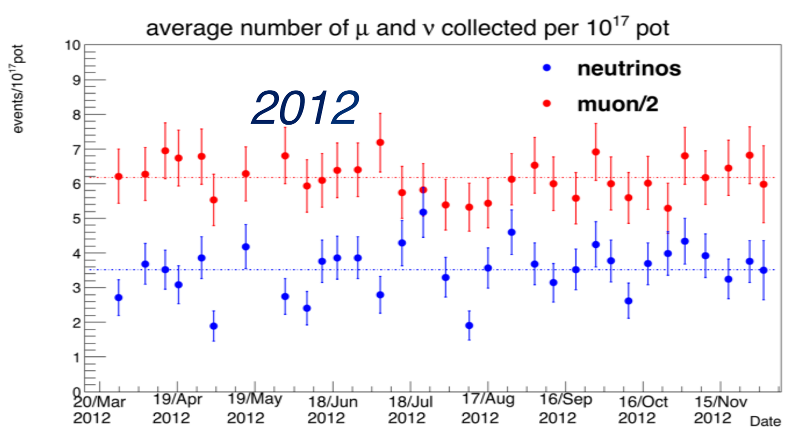


The ICARUS-T600 CNGS run

- ICARUS was exposed to the CERN to Gran Sasso (CNGS) ν_μ 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-T600 purity

Electronegative impurities (O_2, H_2O) in LAr can absorb drifting electrons and attenuate charge signals:

$$Q=Q_0\exp(-t/\tau_{ele})$$

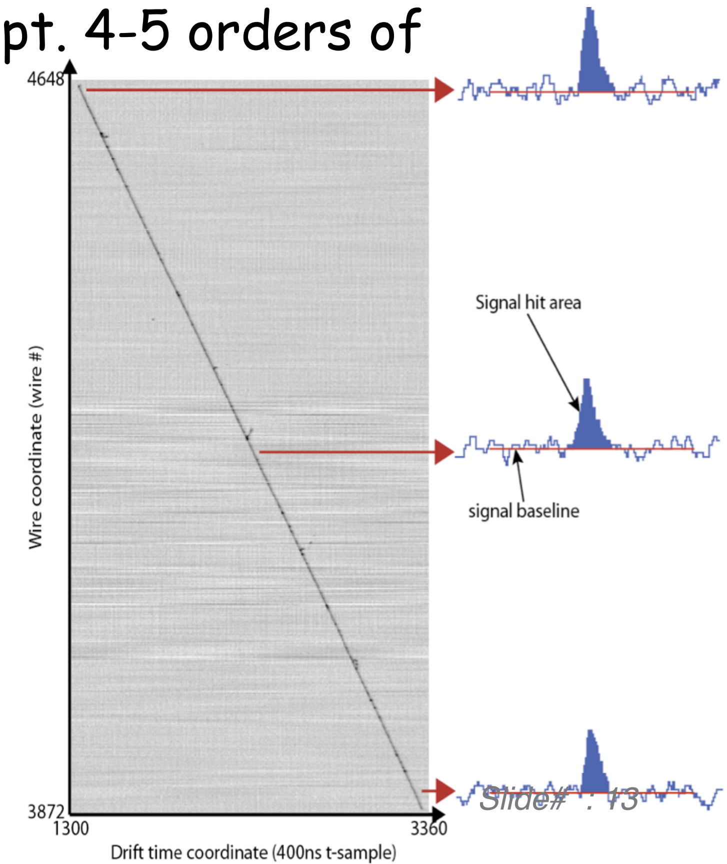
with τ_{ele} inversely proportional to contamination *C*:

$$\tau_{ele}[ms]\sim 300/C[ppt]$$

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

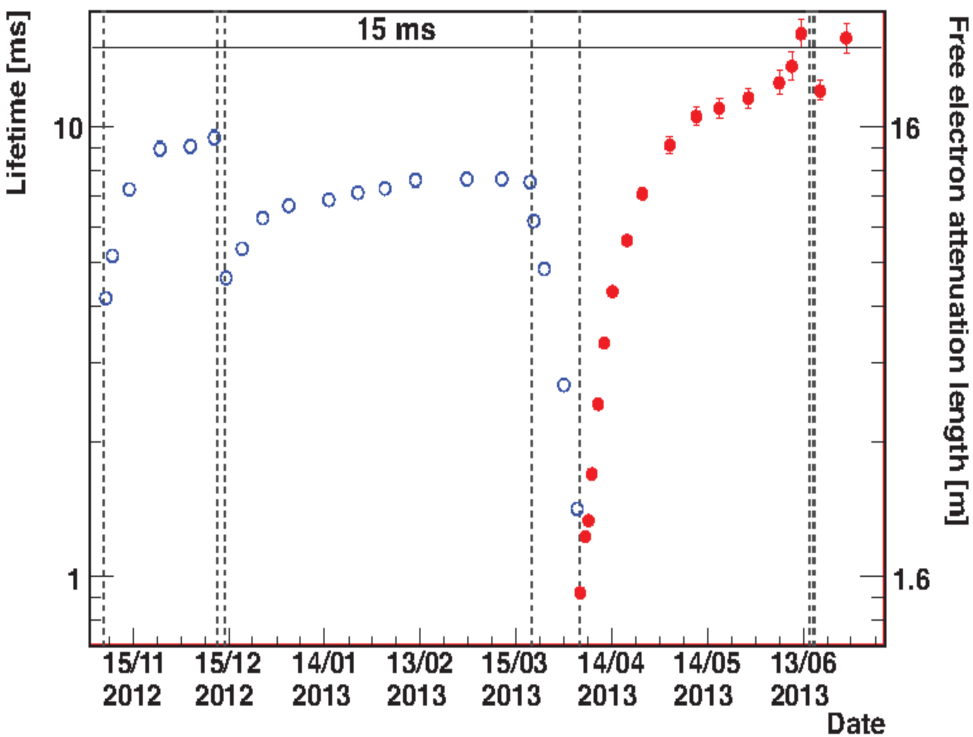
Achieving such an excellent electron lifetime was probably the hardest experimental challenge for ICARUS:

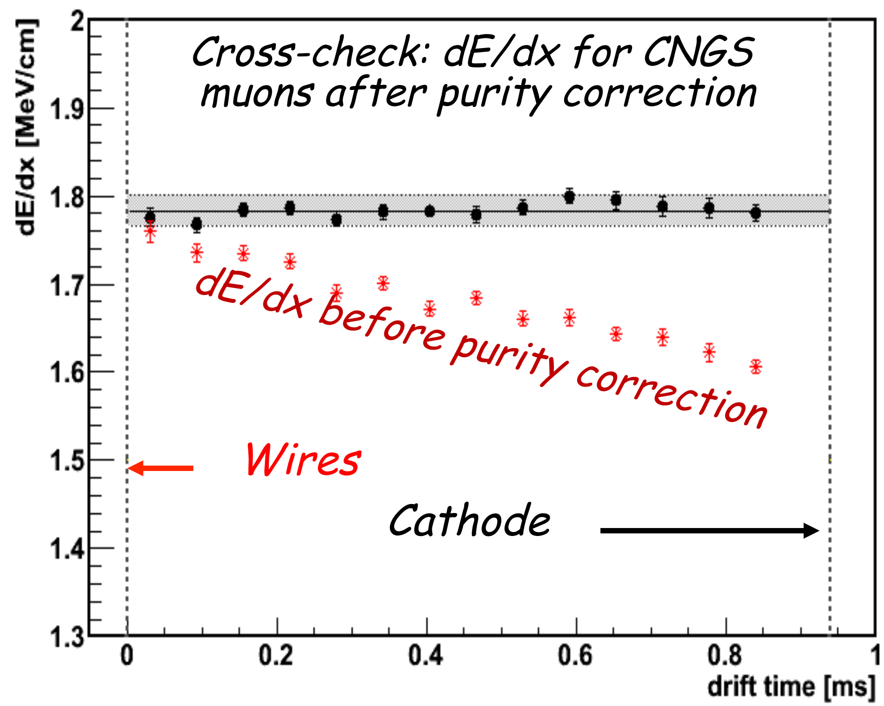
- Cooling and evacuation (to 10^{-4} mbar) before initial filling with clean LAr
- Continuous recirculation/filtering of both liquid (100 m^3/day) and gas Argon throughout data taking
- Development of algorithms for accurate purity measurement, even for τ_{ele} > 15 ms



Measurement of electron lifetime

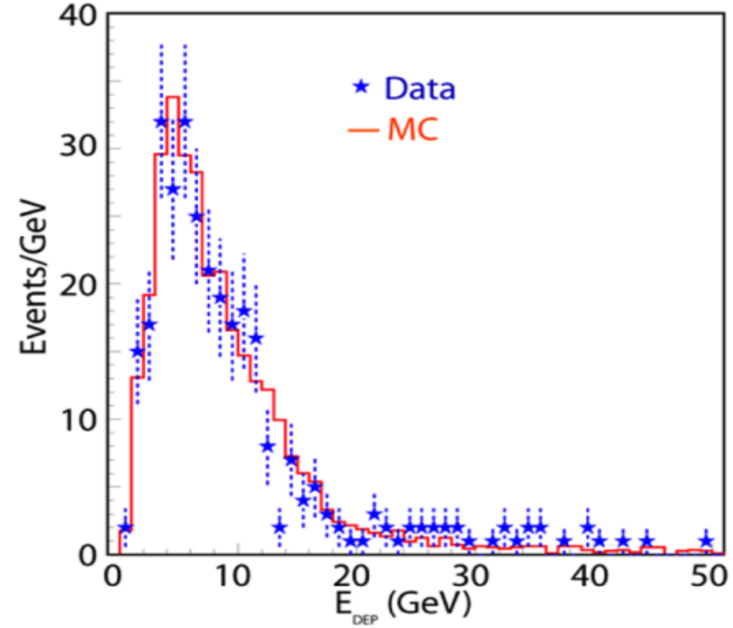
- Lifetime measurement based on exponential attenuation of signal area (deposited energy) in ~MIP cosmic ray muons, as a function of drift coordinate
- Lifetime constantly higher than 7 ms (40 ppt) during all run in both modules.
- Maximum attenuation along the whole drift distance ~12%.
- After installation of new (not immersed) pump lifetime reached ~15ms
- After correcting for purity, calorimetric response is uniform along drift



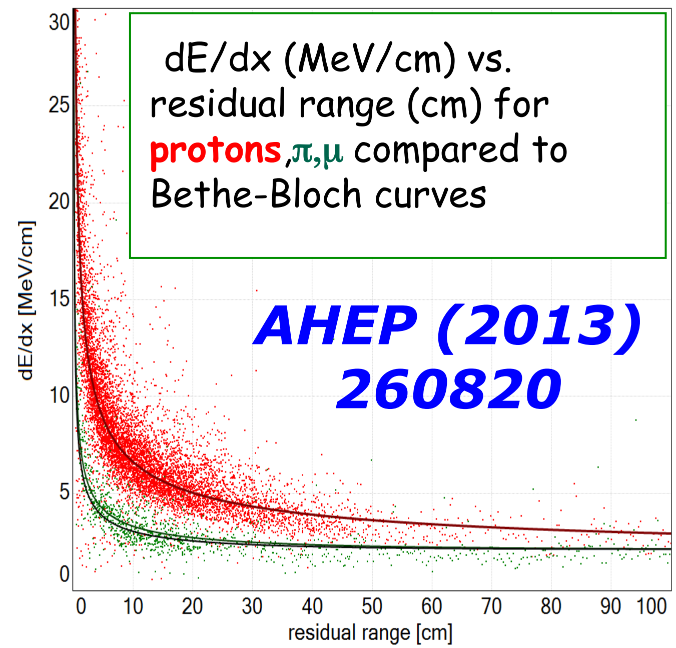


ICARUS general reconstruction performance

- *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;
- *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;

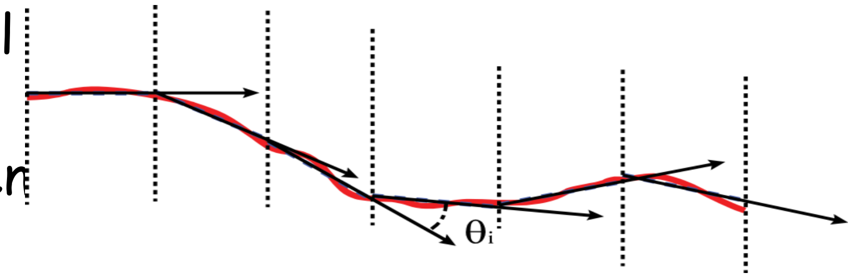


- *Low energy electrons:* $\sigma(E)/E = 11\%/\sqrt{E(MeV)}+2\%$
- *Electromagnetic showers:* $\sigma(E)/E = 3\%/\sqrt{E(GeV)}$
- *Hadron shower (pure LAr):* $\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$



Measurement of muon momentum by multiple scattering

- Measurement of non-contained muons is crucial to $\nu\mu$CC event reconstruction
- Algorithm based on deflection angles θ between successive segments in Collection

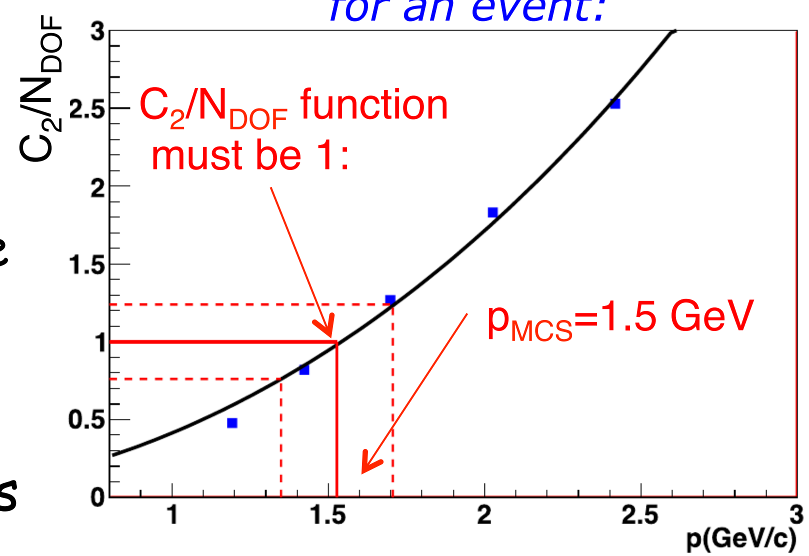


- Segment length chosen to enhance genuine MCS deflection w.r.t. apparent ones related to track measurement (evaluated event by event)

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

- χ^2-like function C_2/N_{DOF} extracted from deflections: should be 1 for "true" momentum
- C_2/N_{DOF} fitted as a function of the guessed initial momentum: the MCS momentum estimate is the value p_{MCS} such that $C_2/N_{DOF}=1$.
- Correlations among successive deflection angles are fully taken into account

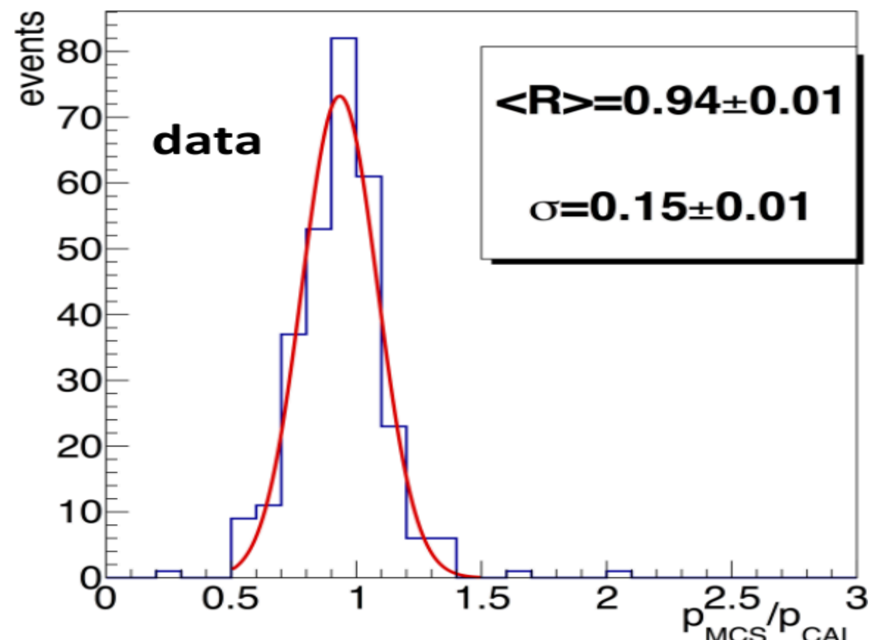
Example of C_2/N_{DOF} for an event:



Stopping muons

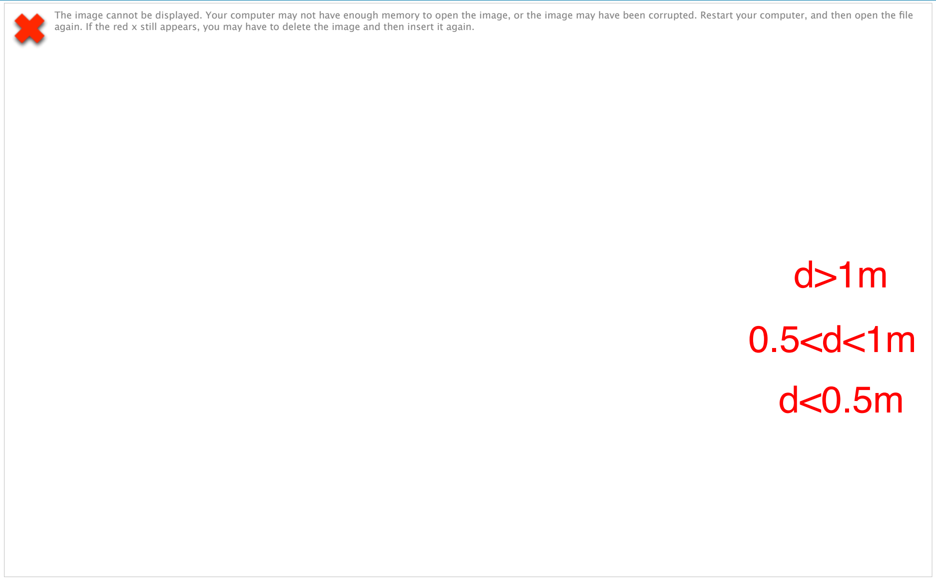
- MCS measurement was validated by comparison with calorimetric estimate of momentum on ~400 *stopping muons*
- They were produced from CC interactions of CNGS neutrinos in the upstream rock, and stop/decay in the LAr volume
- Spectrum between ~0.5 and 5 GeV -> good benchmark at SBN/DUNE momentum range

- The final meter of each track was not used for the MCS measurement, to "mimic" the case of a non-contained muon
- The MCS measurement then is not biased by "knowing" when the muon ranges out
- Agreement is generally good: ~15% average resolution (for muons longer than 5 meters)



Cathode non-planarity and field distortion

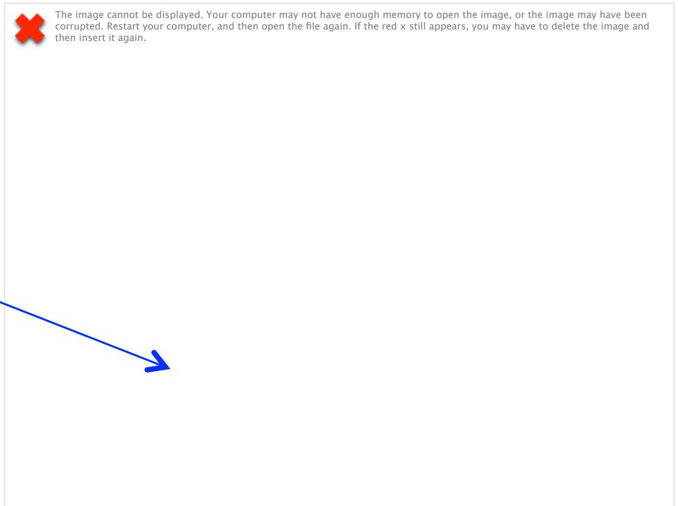
- An underestimation can be noticed for high momenta (>3 GeV) – larger for tracks at small distance *d* from the cathode



This is due to a non-perfect cathode planarity – that was independently measured with two different methods:

- INDIRECTLY using cathode-crossing cosmic rays
- DIRECTLY with a laser-meter (on empty detector, during the later T600 refurbishing at CERN)

- These estimates are well correlated and show deviations of the cathode positions along the drift coordinate, up to Δy ~2 cm

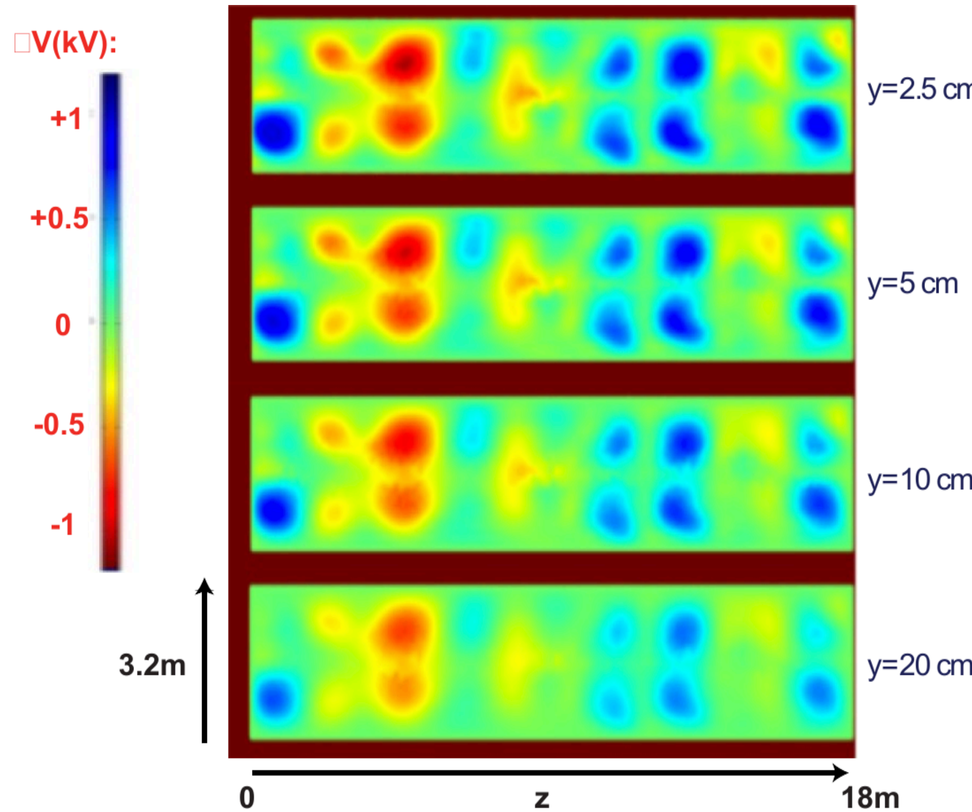


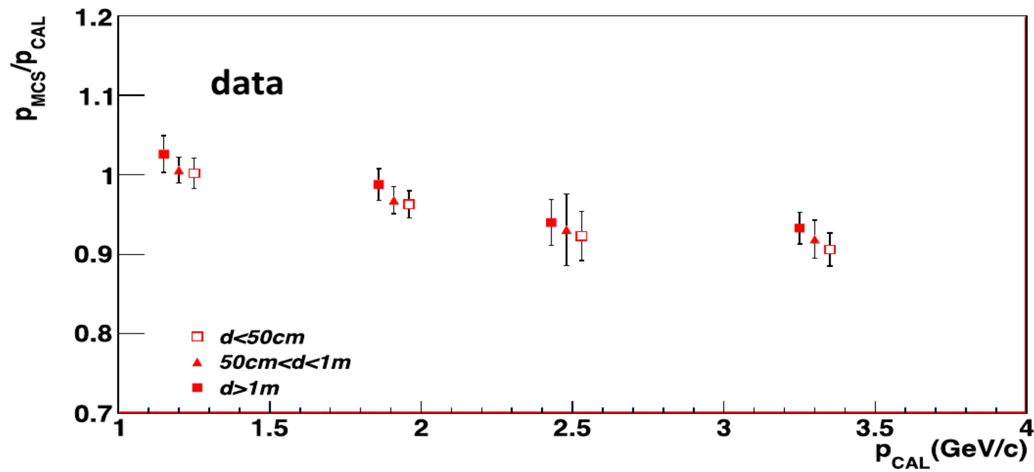
Cathode non-planarity produces drift field distortion, that give rise to fake track deflections, mimicking a lower value of p_{MCS}

Correcting the cathode effect on MCS measurement

- Using measured cathode non-planarity, an electrostatic COMSOL simulation of the drift field was performed
- A map of the consequent distortions in track reconstruction was computed and added into MC simulation
- The effect on momentum measurement was parametrized as a function of momentum and cathode distance, and applied as a correction to real data
- The maximum underestimation was therefore reduced from ~20% to ~5%

JINST 12P04010



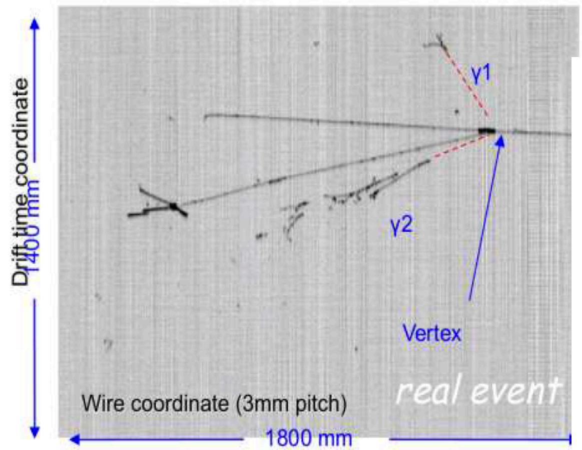


e/γ separation and ν_e identification

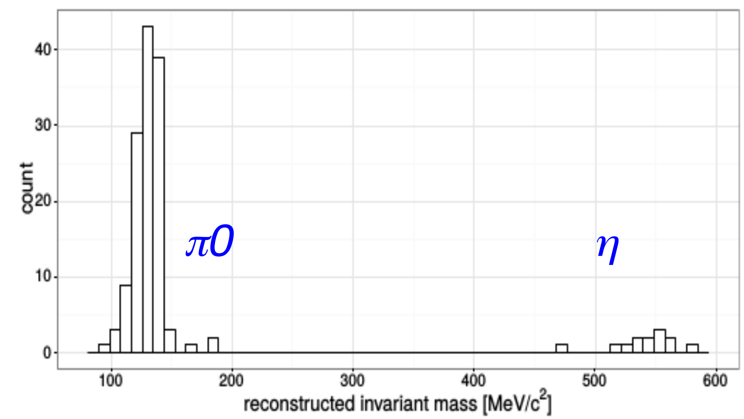
In order to identify a νeCC event, the shower produced by the electron must be selected, distinguishing it from a photon-initiated shower generated by a π0 in a NC interaction.

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

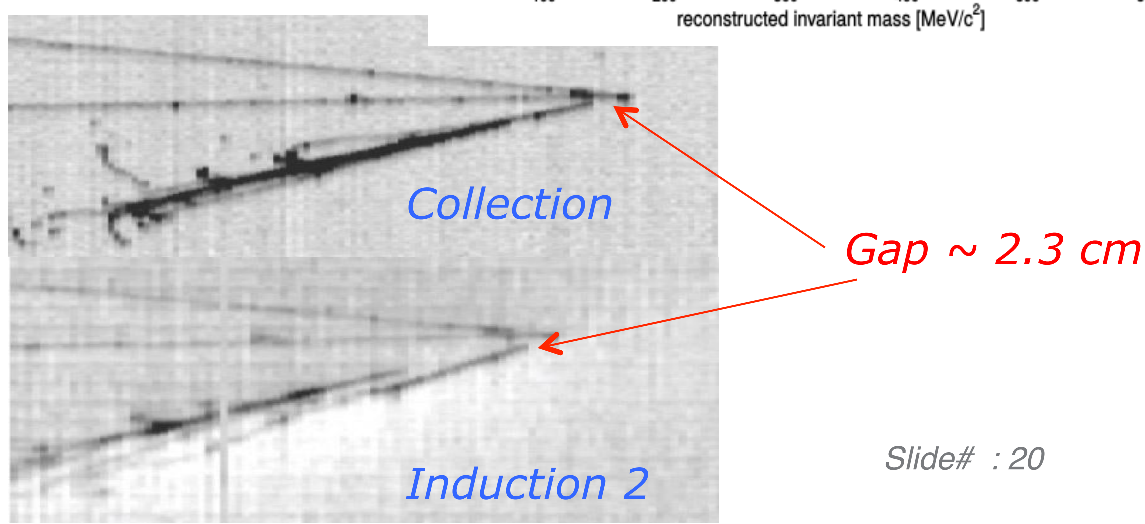
- π0 INVARIANT MASS : Measurement of position/energy of the showers from both γ's allows computing $M_{\pi 0}$



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



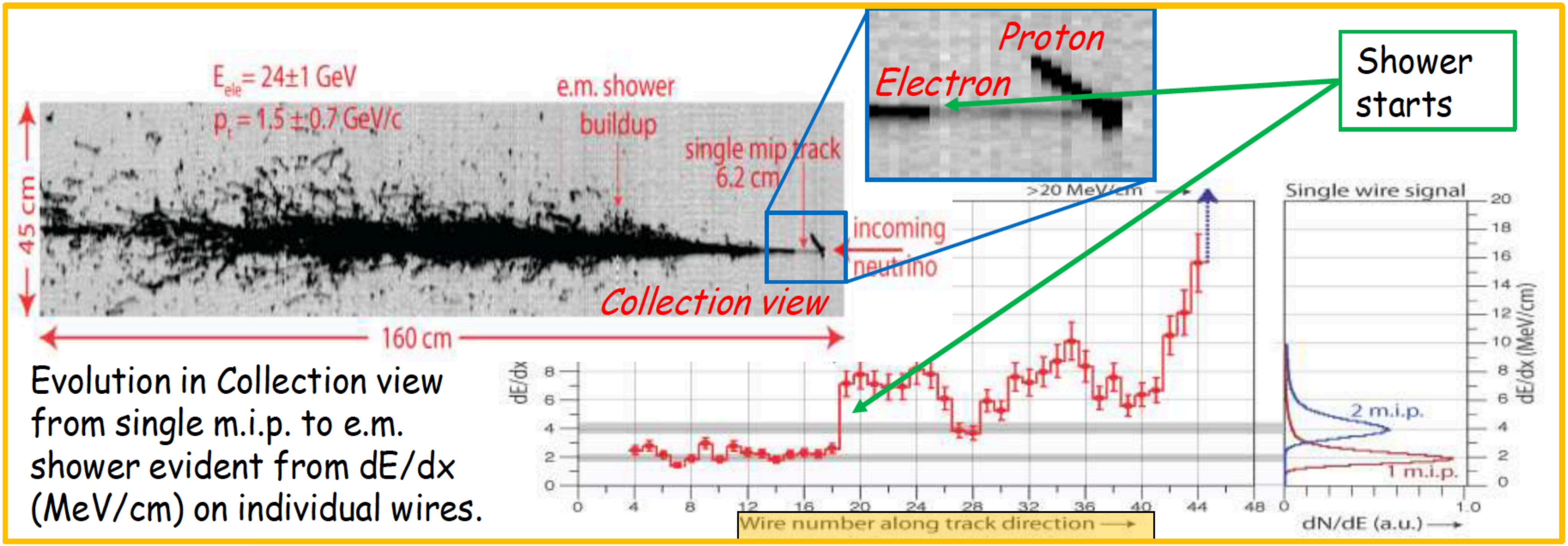
e/γ separation and ν_e identification

- 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:



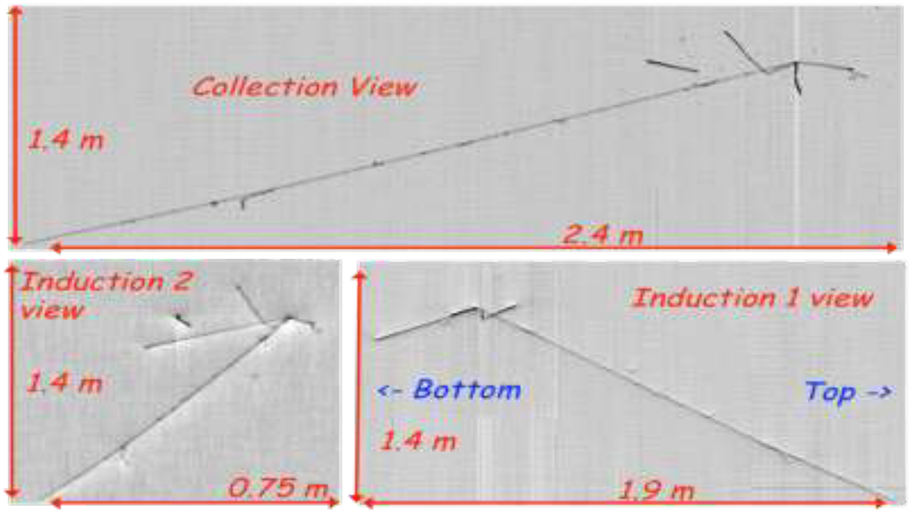
Atmospheric neutrinos at LNGS

ICARUS was also exposed to atmospheric neutrinos: first ever observations with a LAr-TPC!

2 examples:

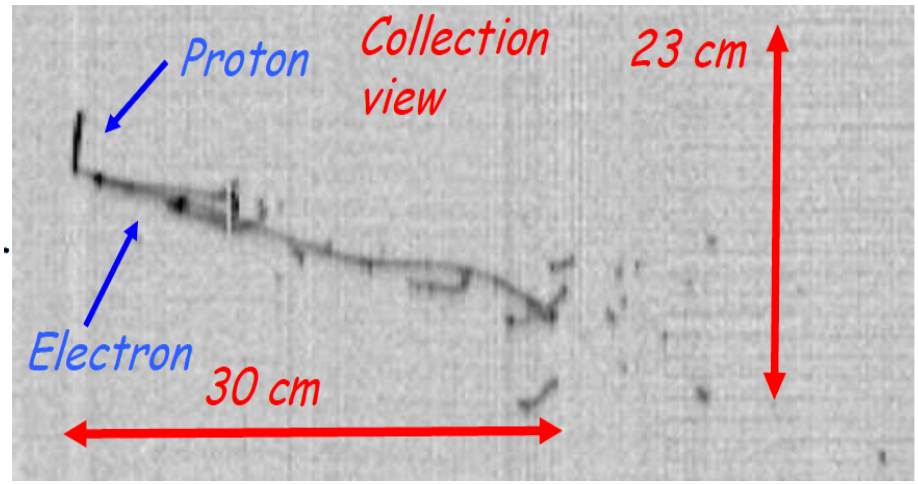
UP-GOING $\nu\mu$CC (E_{dep} ~1.7 GeV):

- *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°*



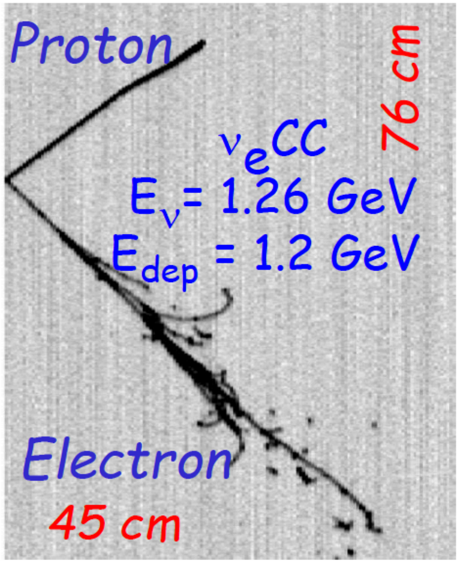
DOWN-GOING QE νeCC (E_{dep} ~240 MeV):

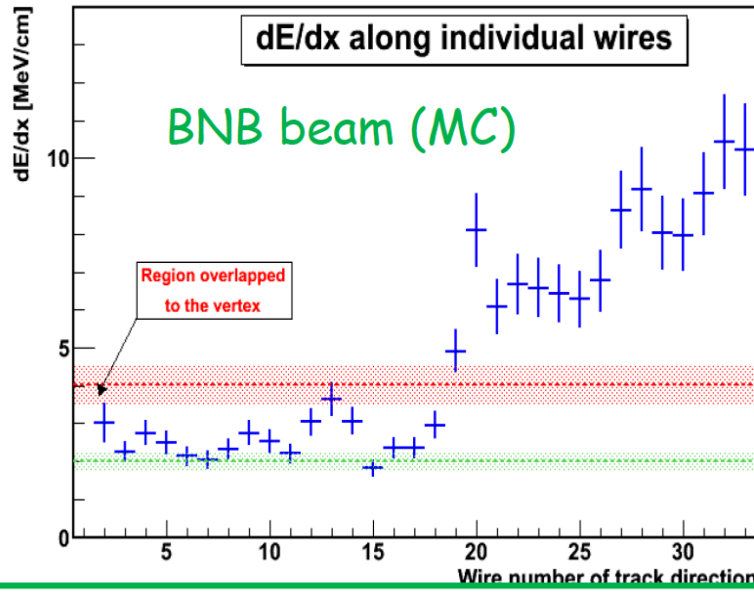
- *Identified as νe from single MIP dE/dx measured on first wires*
- *Short proton identified at vertex*



Atmospheric neutrinos and SBN

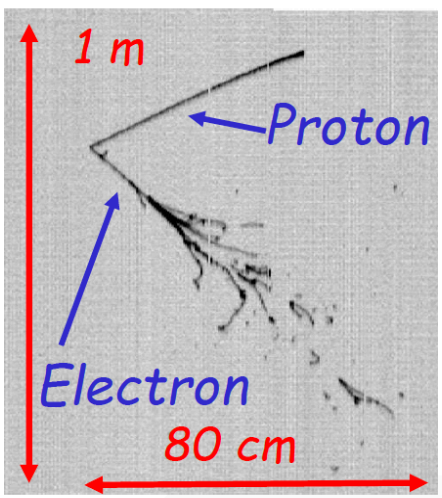
MC SBN ν_eCC interactions

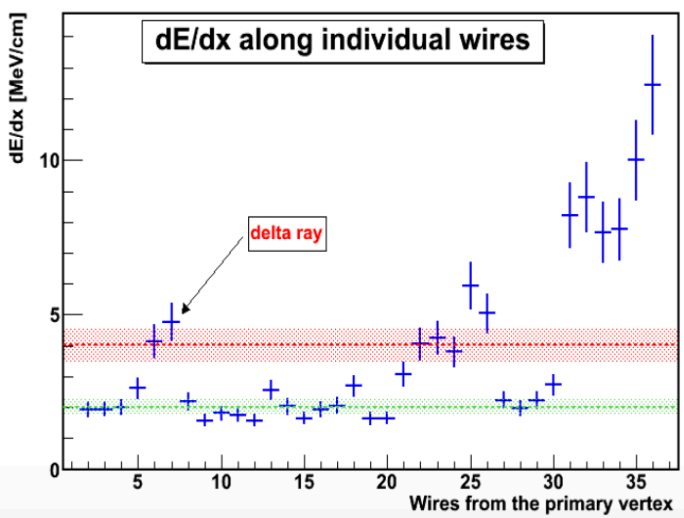




- very alike to typical atmospheric ν_eCC events @ LNGS (below)
- Similar results hold for ν_μCC interactions

LNGS ν_e ATMOSPHERIC EVENT

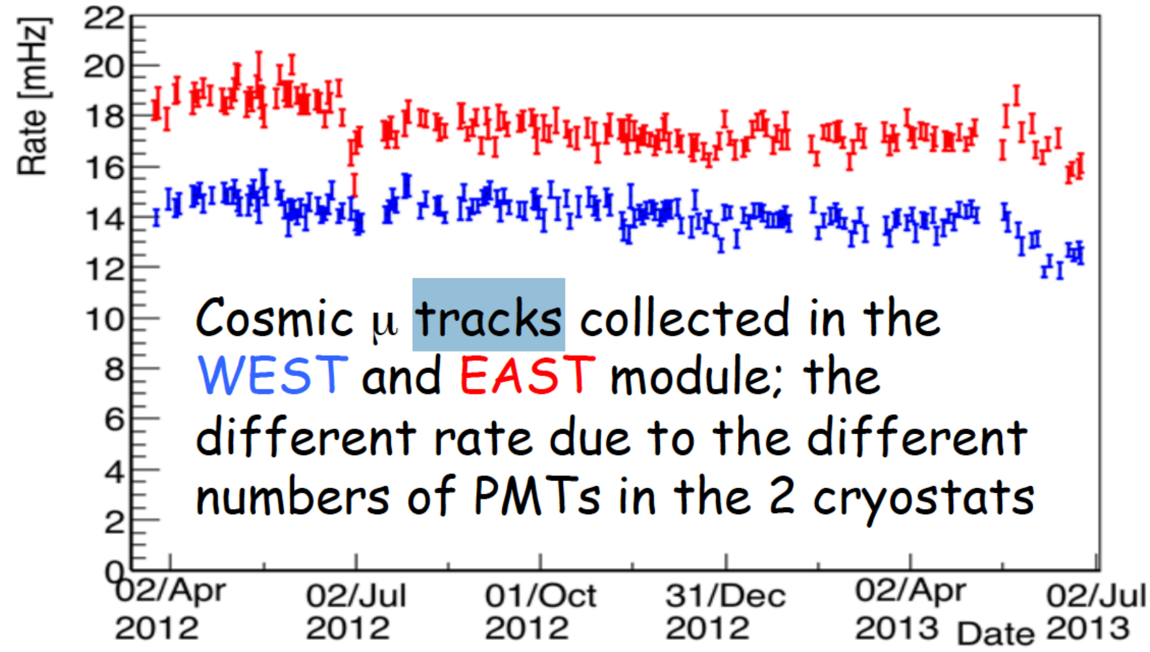




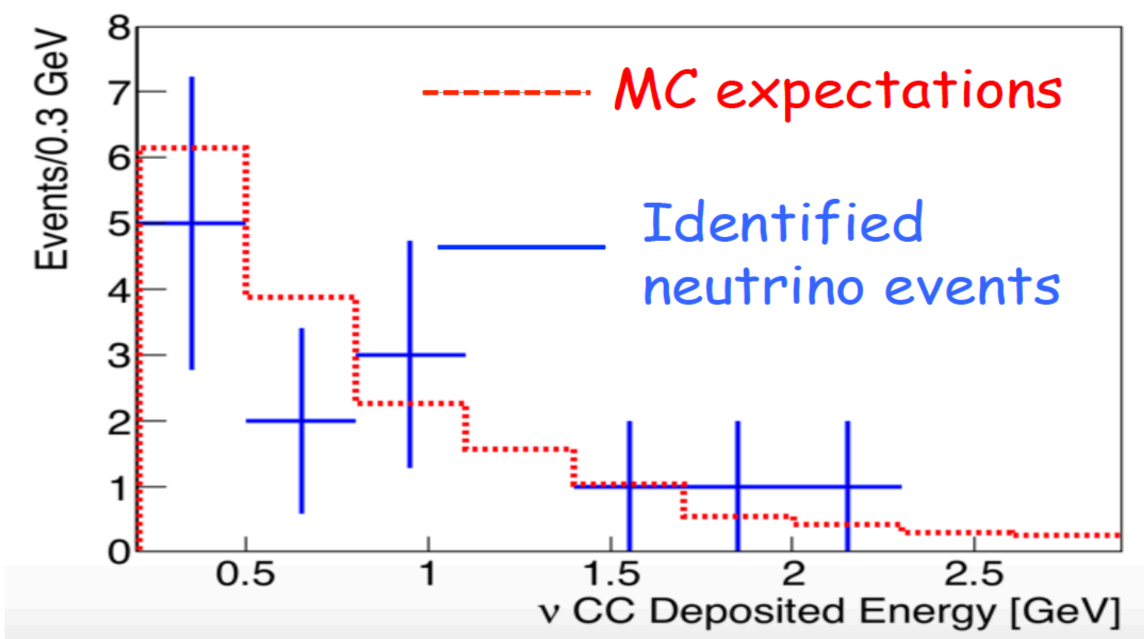
- Quasi-elastic ν_eCC E_{Dep}= 0.9 GeV.
- Proton identified by dE/dx.
- Electron identified by single m.i.p. before showering

Atmospheric neutrino summary at LNGS

- Data from 2012-13 run (~0.48 kt yr) analyzed
- Incoming cosmic rays rejected by a factor ~100
- Automatic preselection of νμ and νe candidates (with 80% and 25% efficiency); then validated by visual scanning

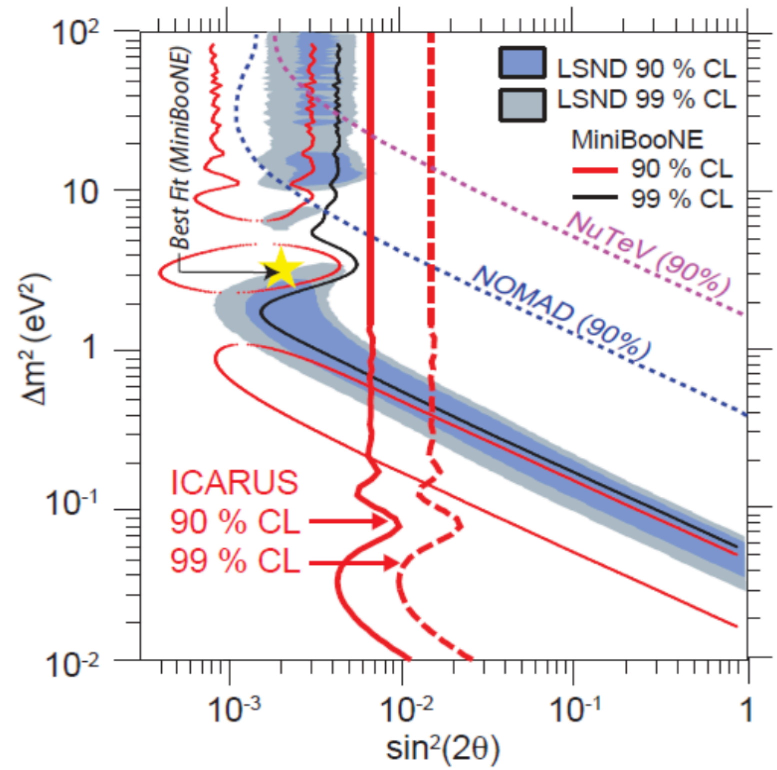


- Similar energy range to SBN. Useful to test filtering/ reconstruction tools
- 14 events found (8 νe+6 νμ) vs. 18 expected – accounting for triggering, filtering and scanning efficiencies



ICARUS search for sterile neutrinos

- ICARUS searched for sterile ν oscillations through νe appearance in the CNGS beam
- L/E~36 m/MeV, far from the LSND value -> "sterile-like" oscillation was averaged out, canceling energy dependence
- 7.9 10^{19} pots analyzed (~2650 ν interactions)
- Expected ~8.5±1.1 νe background events in absence of anomaly, mostly from intrinsic νe beam contamination (taking into account ~74% efficiency estimated on MC)
- 7 events observed - no evidence of oscillation



- Most of LSND allowed region excluded – except for small area around $\sin^2\theta$~0.005, Δm^2~0.1 eV^2
- Similar result by OPERA with same CNGS beam and different detection technique

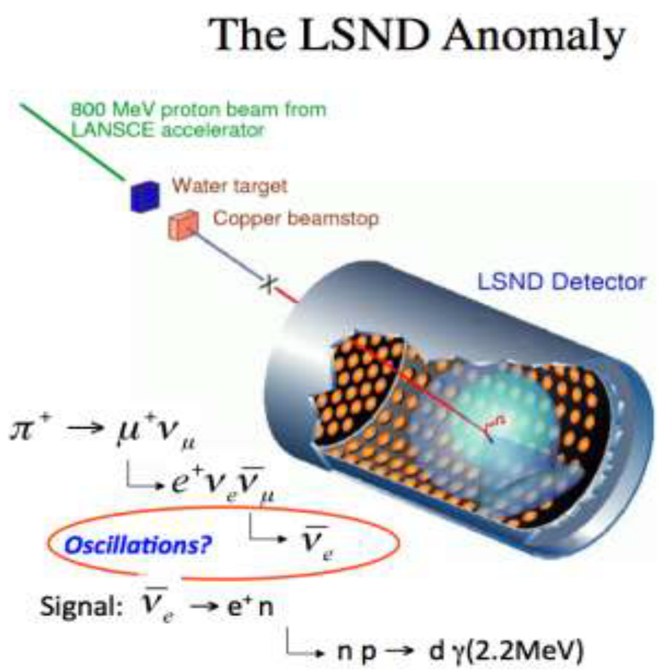
Eur. Phys. J. C (2013) 73:2599

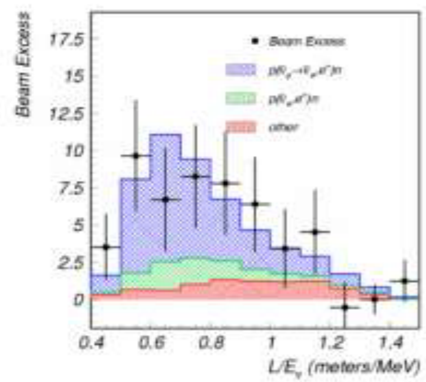
The sterile neutrino puzzle

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

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

- νe appearance in $\nu\mu$ beams at accelerators (LSND 3.8σ excess)
- MiniBooNE newest result shows 4.5σ νe low energy ecess
- Anti-νe disappearance at reactors (measured/predicted ratio $R=0.938 \pm 0.024$)
- Disappearance of νe from Mega-Curie sources used in calibration of solar neutrino experiments (SAGE/GALLEX, $R=0.84 \pm 0.05$)

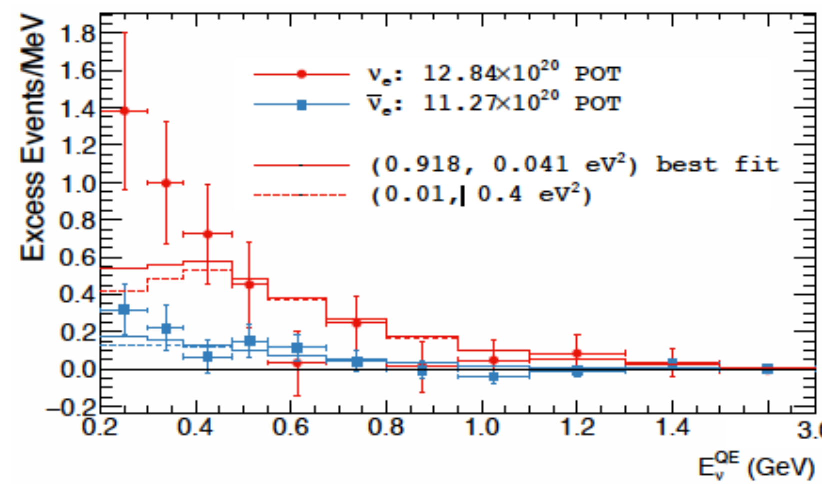




Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

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

3.8 σ evidence for oscillation.



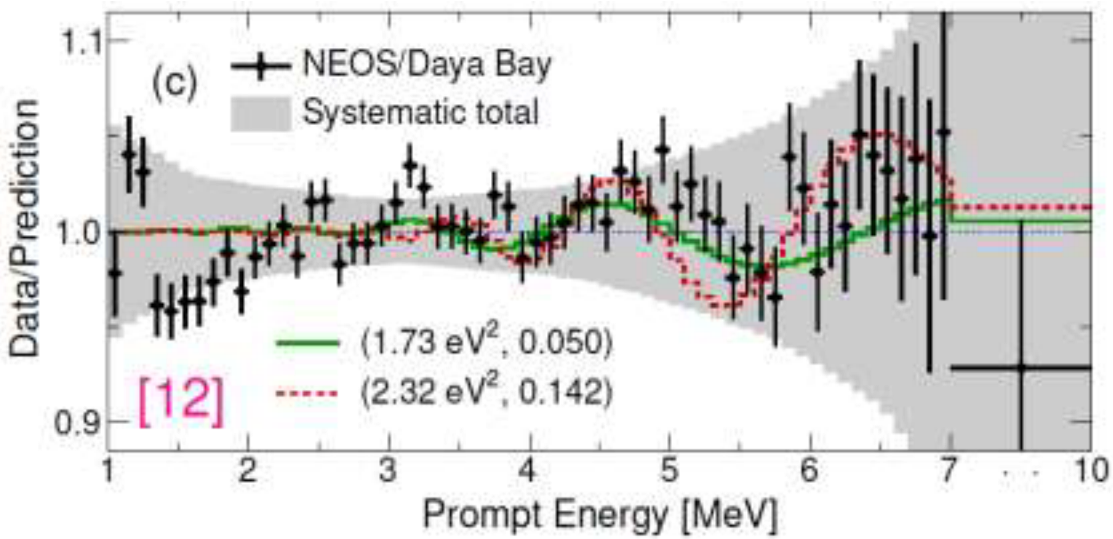
Phys.Rev.Lett.121 (2018) No.22, 221801

The sterile neutrino puzzle: more recent results

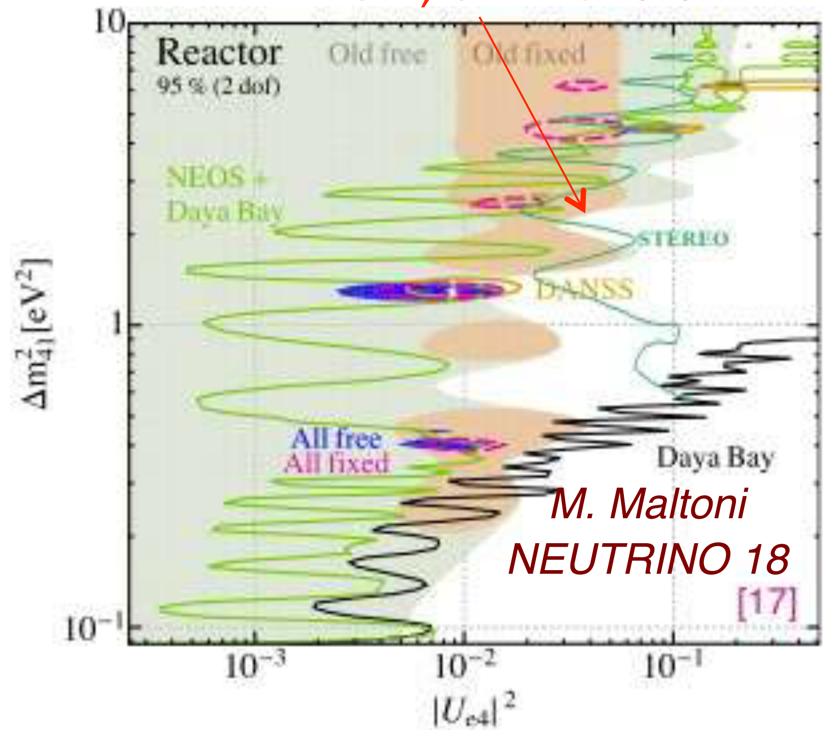
The current sterile scenario is definitely very complex:

- Big Bang cosmology (Planck) allows at most one sterile flavour - mass <0.24 eV
- No evidence of $\nu\mu$ 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 Δm^2~$7 eV^2$?

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

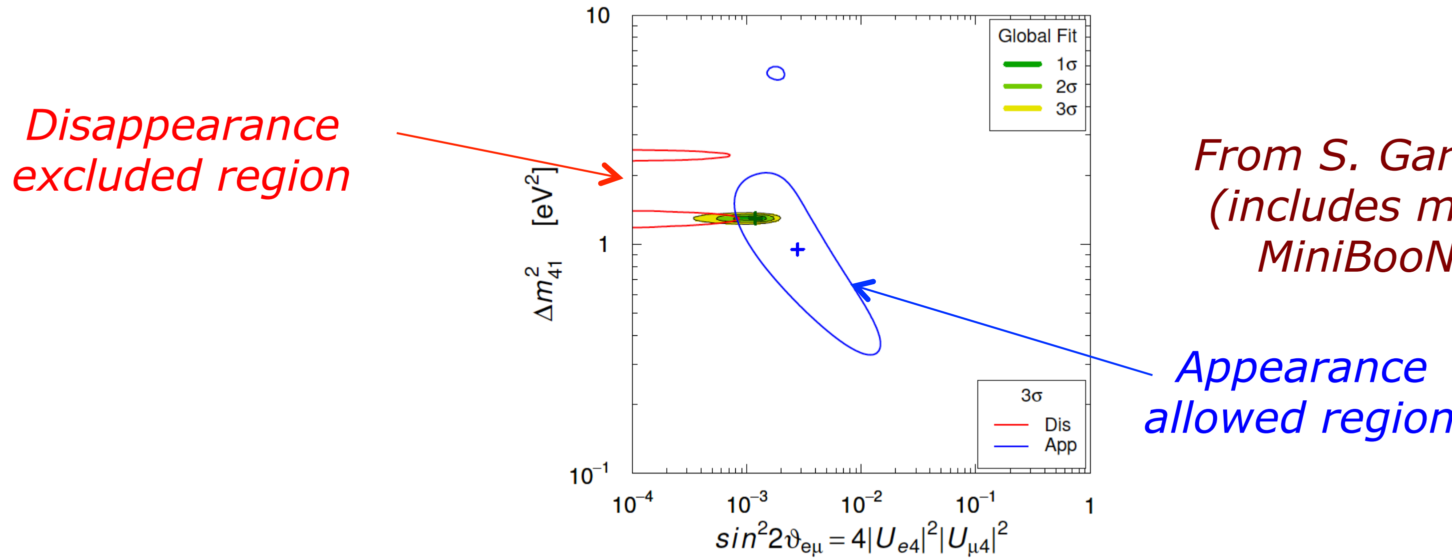


Best fit
Δm^2=2.4eV^2, sin^2 2θ=0.014



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

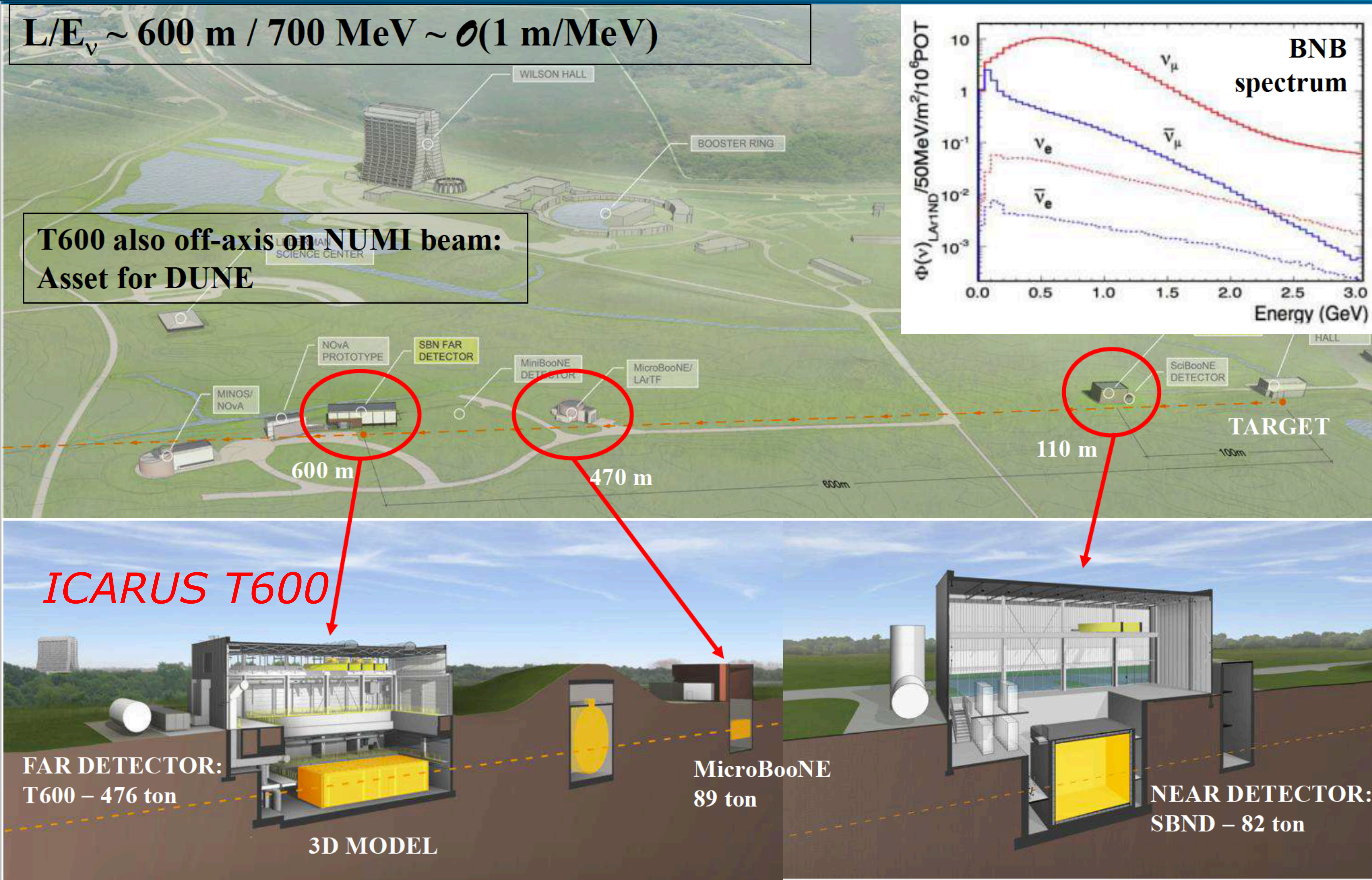


From S. Gariazzo, 2018 (includes most recent MiniBooNE result)

- 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!

The SBN project



SBN features

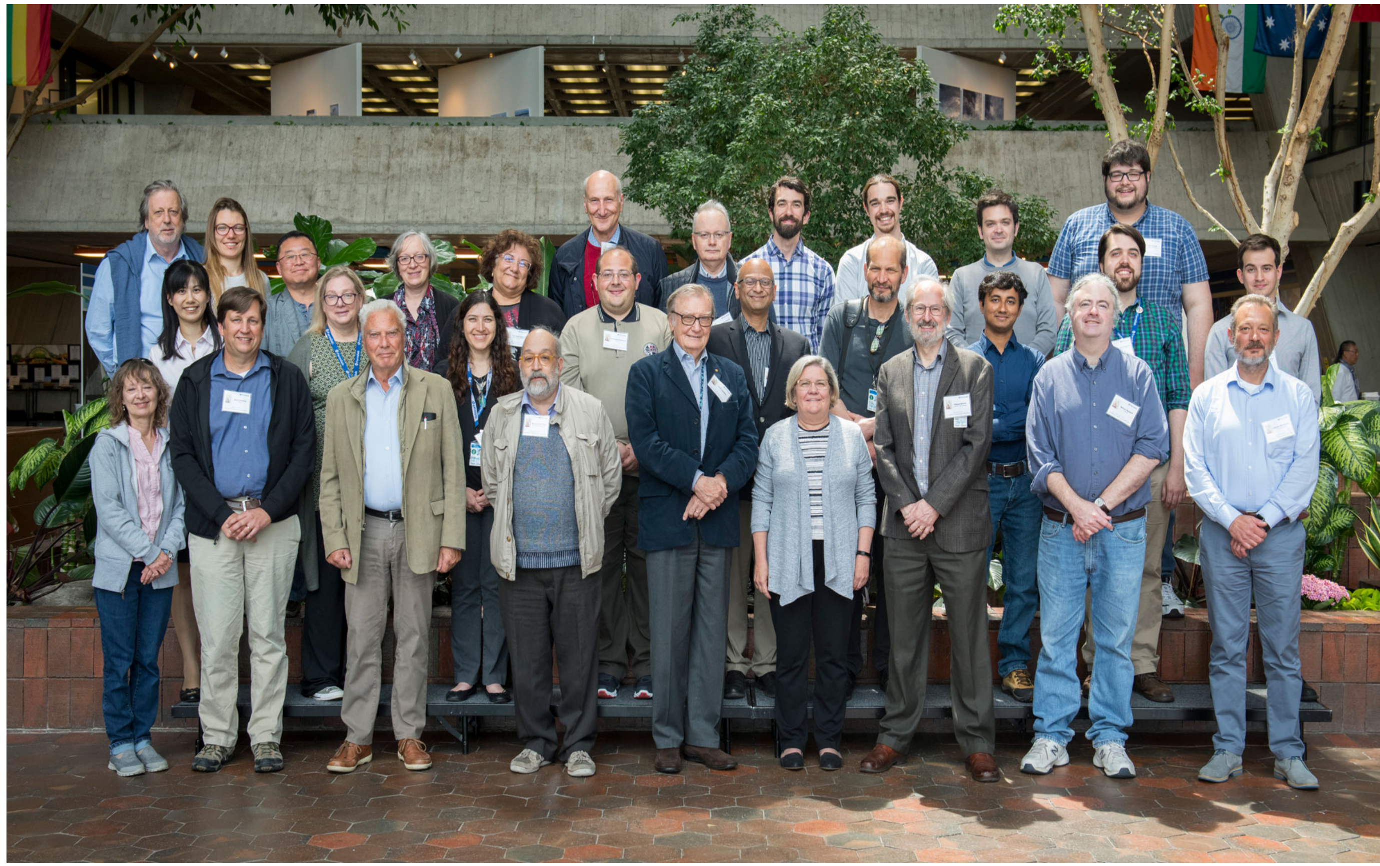
- The Booster beam is well understood and has a small (~0.5%) νe contamination
- Oscillation will be studied both in νe appearance and $\nu\mu$ disappearance channels
- The use of 3 very similar detectors at different distances from target will greatly reduce systematics: SBND will provide crucial initial 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

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)

Just a small subset…

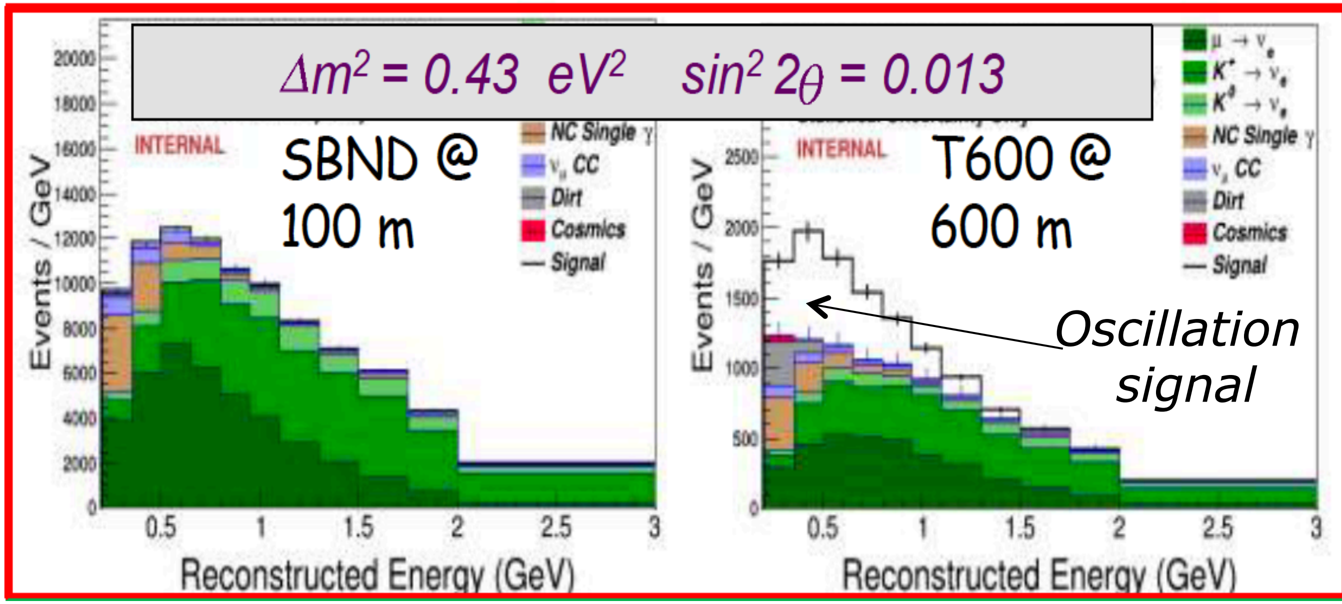


Spokesman: C. Rubbia (GSSI)

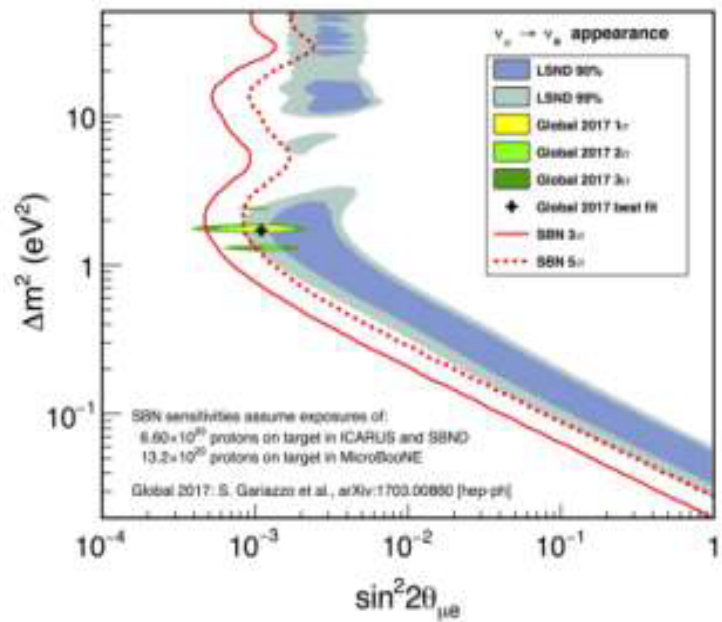
SBN appearance sensitivity

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

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



Sensitivity compared with LSND allowed region:

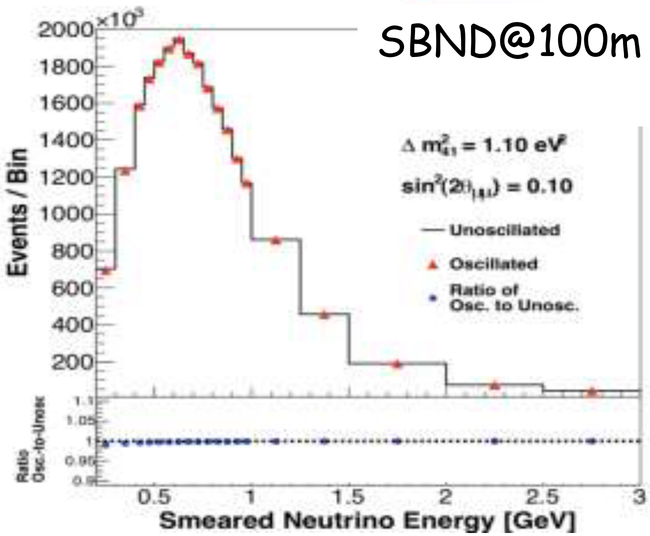


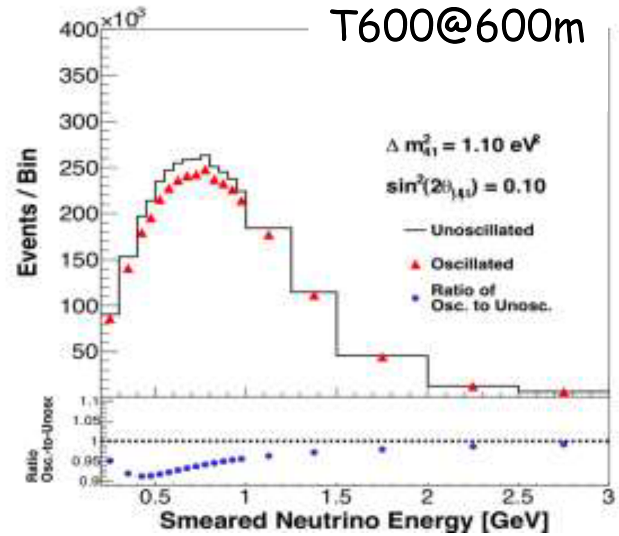
from SBN proposal arXiv:1503.01520

SBN disappearance sensitivity

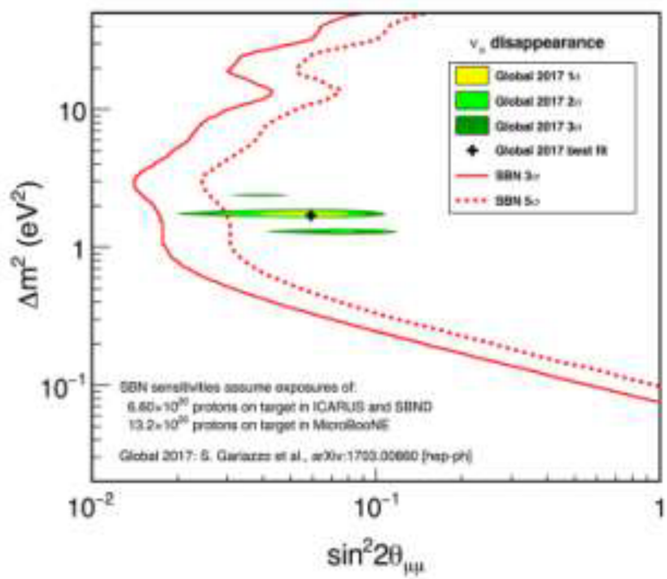
- In the $\nu\mu$ disapperance channel, in 3 years (6.6 10^{20} pot), SBN will improve the present disappearance sensitivity by a factor ~10

$\nu\mu$ 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)





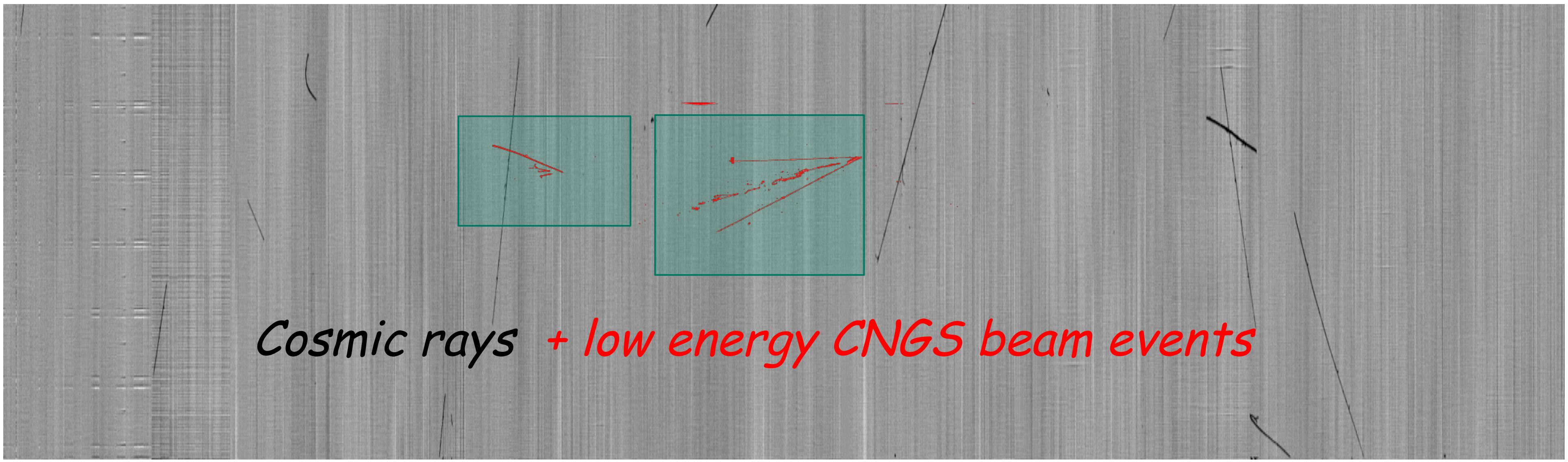
Sensitivity compared to 2017 best fit values



from SBN proposal arXiv:1503.01520

A new 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 νe 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

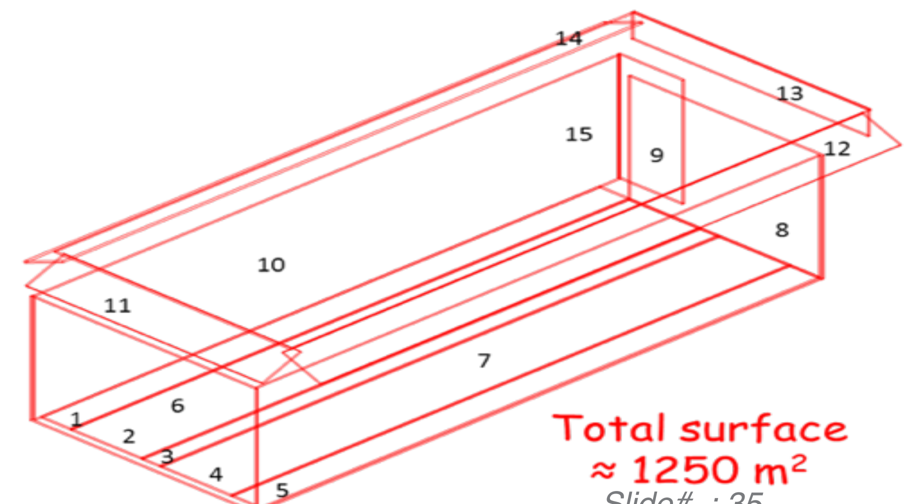
How to reduce the cosmic background?

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.

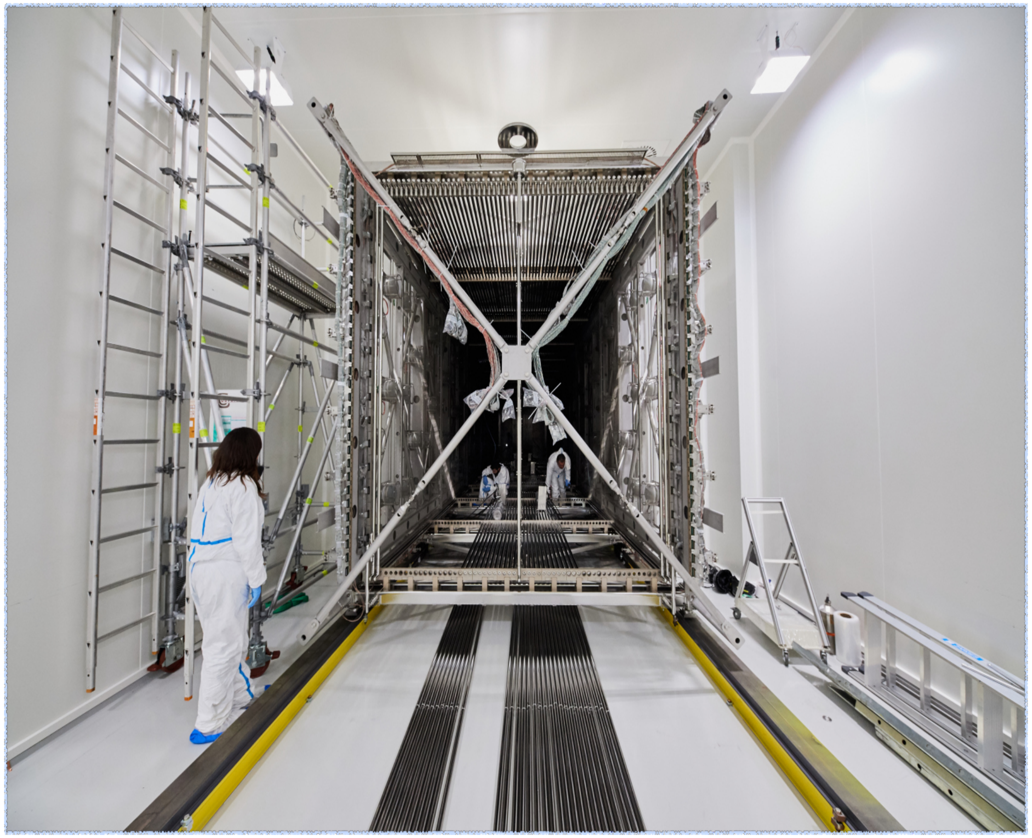
This will require information on a much faster time scale that the ~ms drift time:

- 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.



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 equipment;
  - Improvement of the cathode planarity
  - new faster, higher-performance read-out electronics;
  - Upgrade of the PMT system: higher granularity and ~ns time resolution



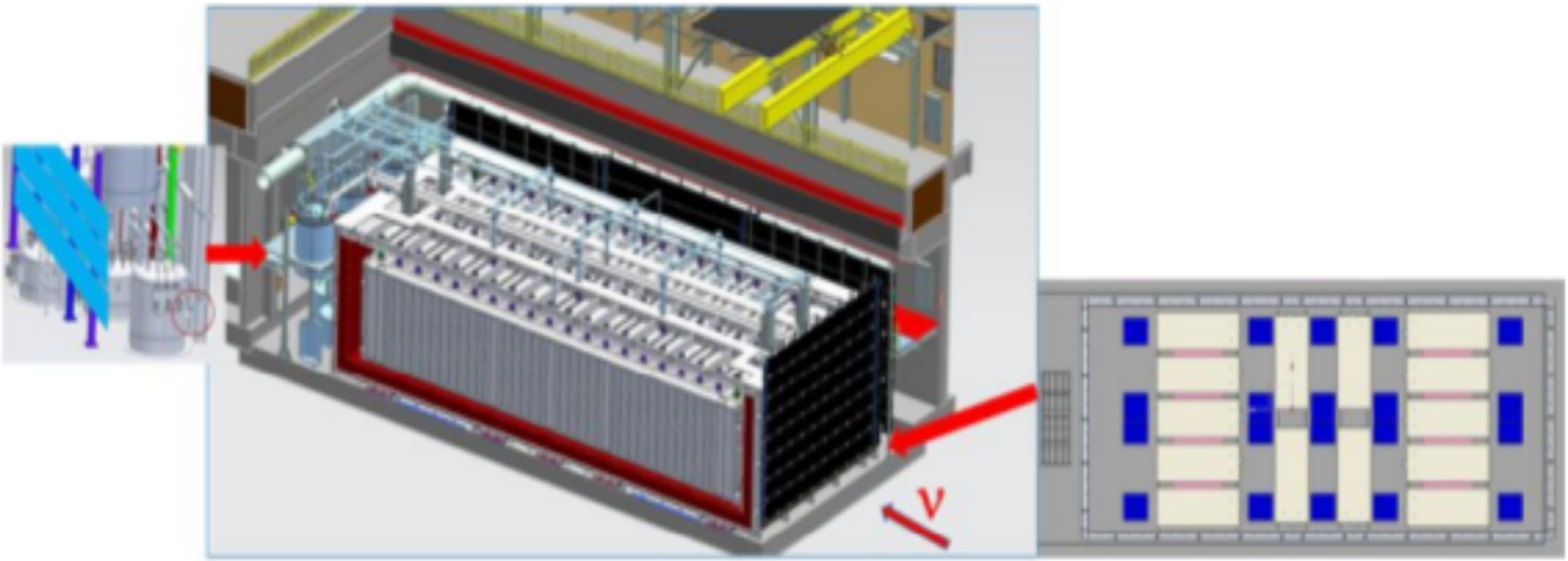
Upgrades in cryogenics/mechanics

- 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

The Cosmic Ray Tagging system (CRT)

- Surrounds the cryostat with two layers of plastic scintillators: 1200 m^2
- Tags incident cosmic or beam-induced muons with high efficiency (95%) giving spatial and timing coordinates of the entry point
- Reconstructed CRT hits are matched to activity in the LAr volume



- 3 different subsystems (top, bottom, sides) to cope with large area
- Top and sides use SiPMs for light collection, while bottom uses PMTs

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

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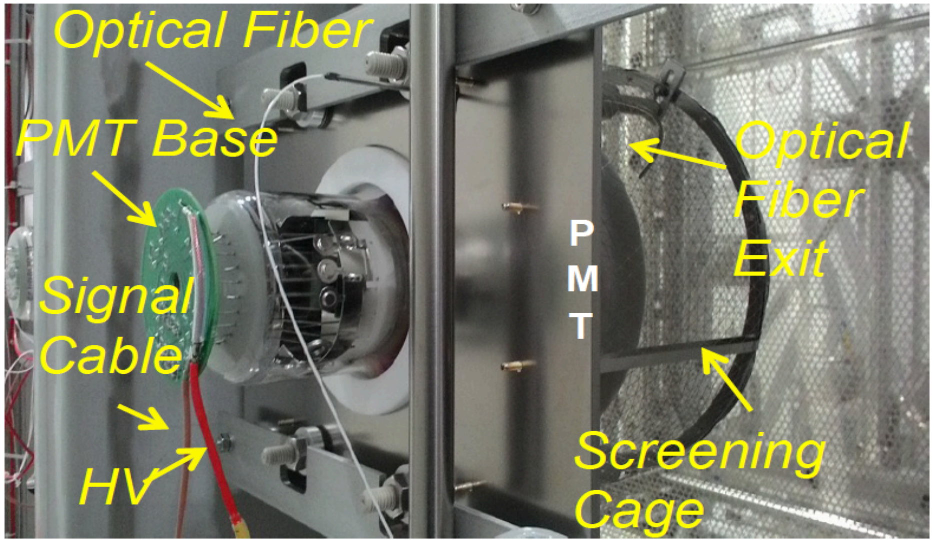


The system will provide:

- 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

Upgrade of the TPC read-out system

ICARUS electronics at LNGS was based on:

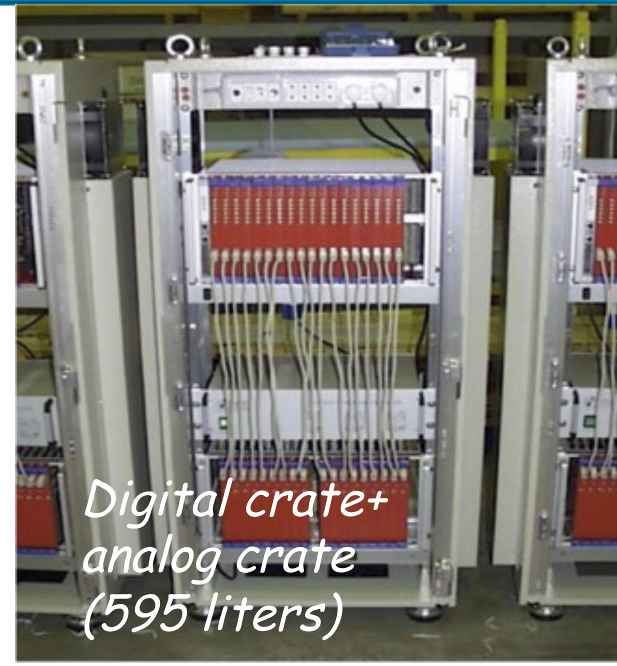
- "warm" low-noise front-end amplifier
- Multiplexed 10-bit ADC
- Digital VME module for local storage, data compression, trigger information

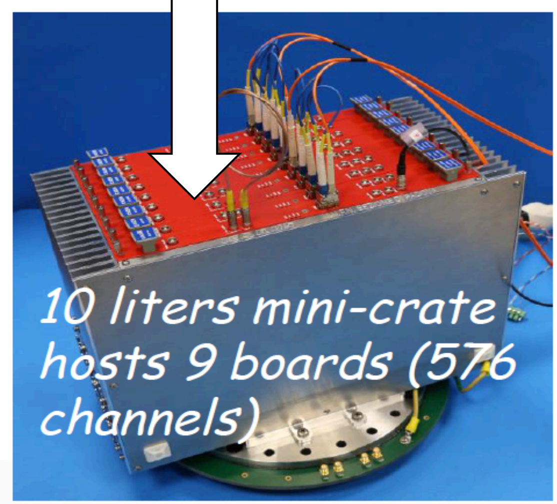
Performances proved adequate for track reconstruction and MCS measurement:

Minimal MIP S/N~7 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

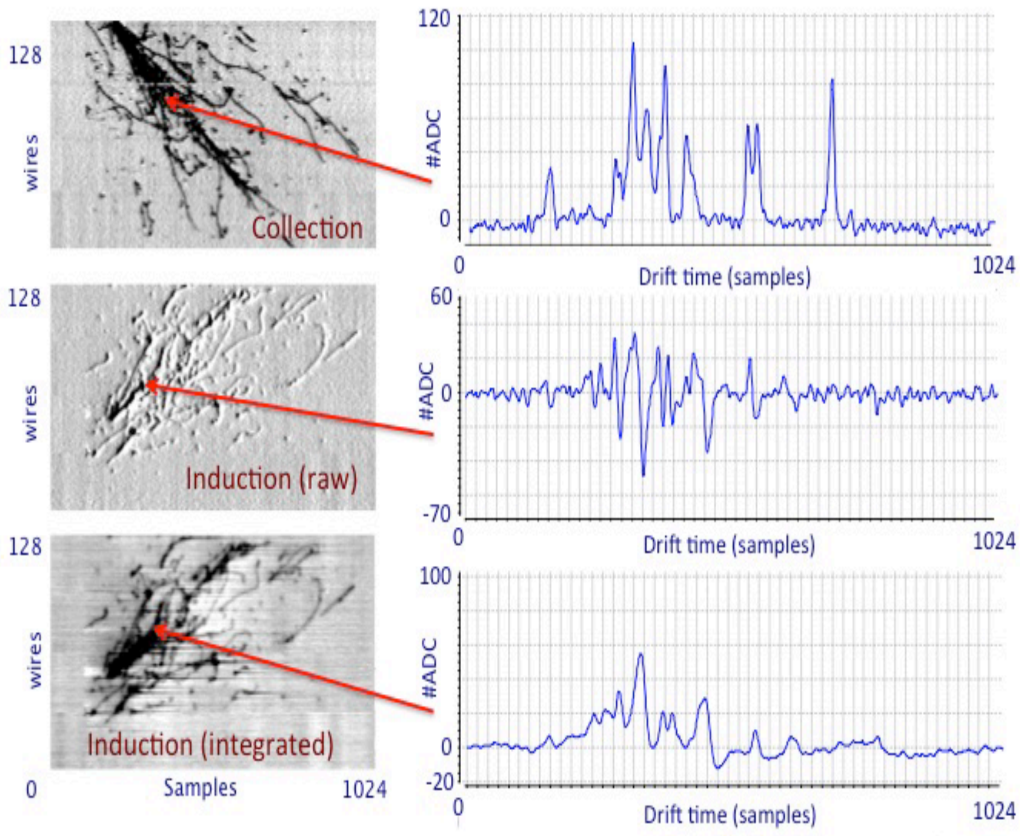




A new front-end electronics

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;

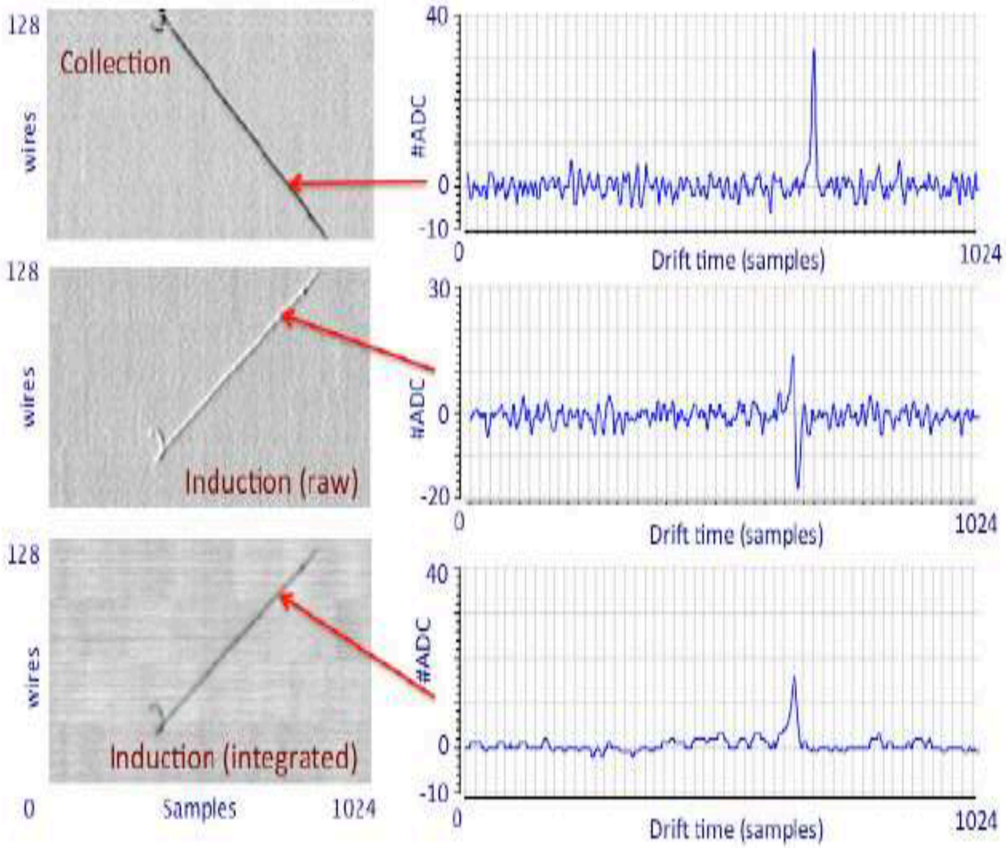


EM shower

- Electronics was tested on a small LAr-TPC test facility at CERN (~50 litres)
- Noise ~2.2ADC#(1200 e-) in all planes -> higher S/N
- Typical Collection S/N~14 (depending on track angle)

Induction calorimetry

- The new "fast" shaping in Induction 2 preserves bipolar signal shape, unlike in old LNGS read-out (~30μs)
- Off-line integration of the signal is possible (with LF noise filtering), to obtain an area proportional to deposited energy and allow a calorimetric measurement
- Expected improvement in νe identification efficiency, up to ~20%



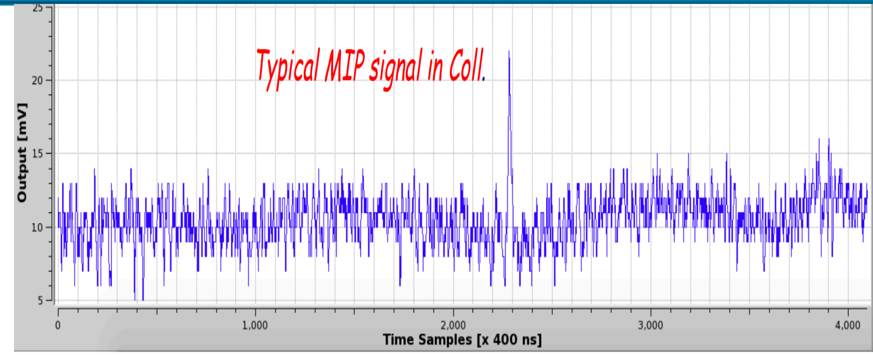
MIP muon track at 45°

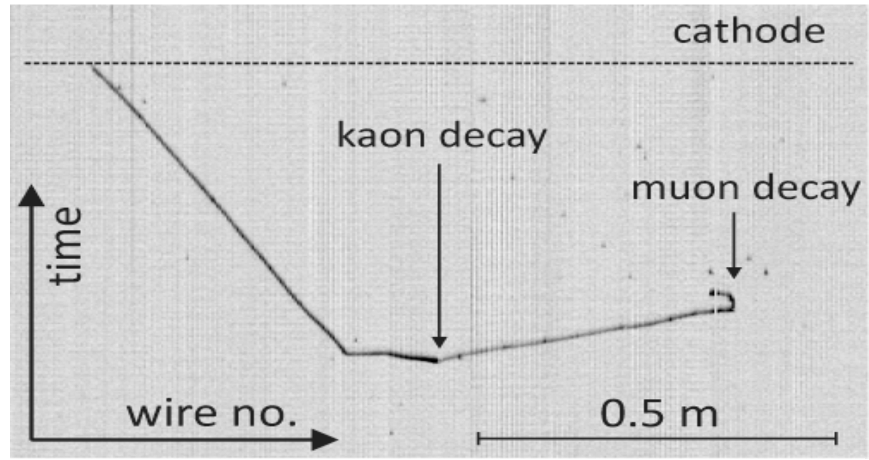
- Preliminary studies on CERN test facility data: S/N~10 in Induction 2, improvement w.r.t. CNGS (~7 for similarly inclined tracks)
- Induction calorimetric resolution a factor ~2 worse than Collection
- Studies on SBN simulation are ongoing

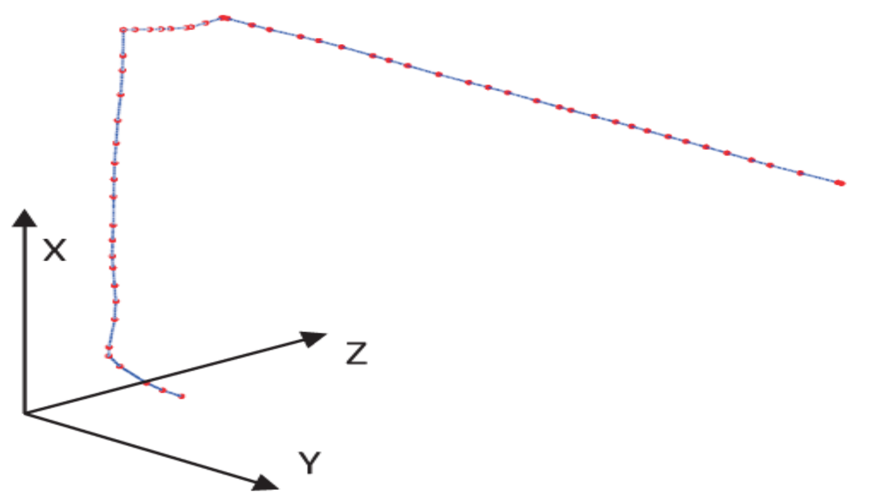
JINST 13 (2018) P12007

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



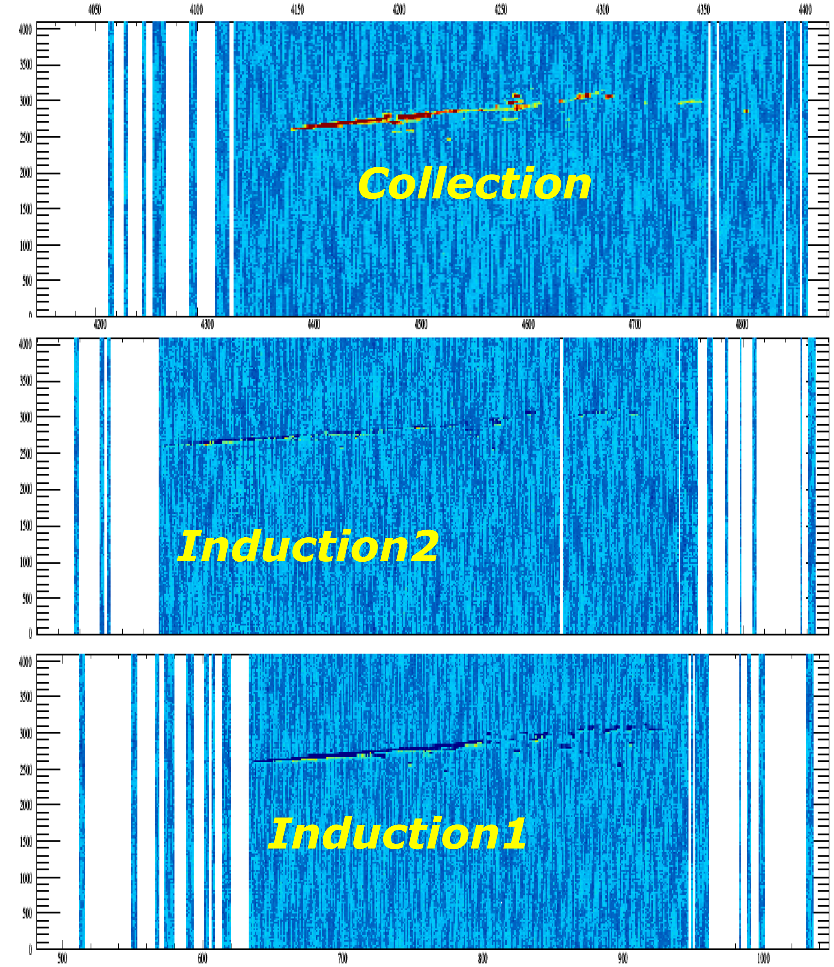




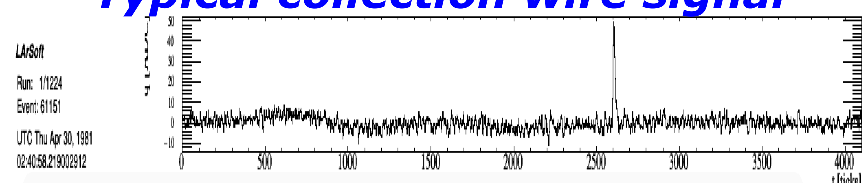
SBN reconstruction and analysis

- 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



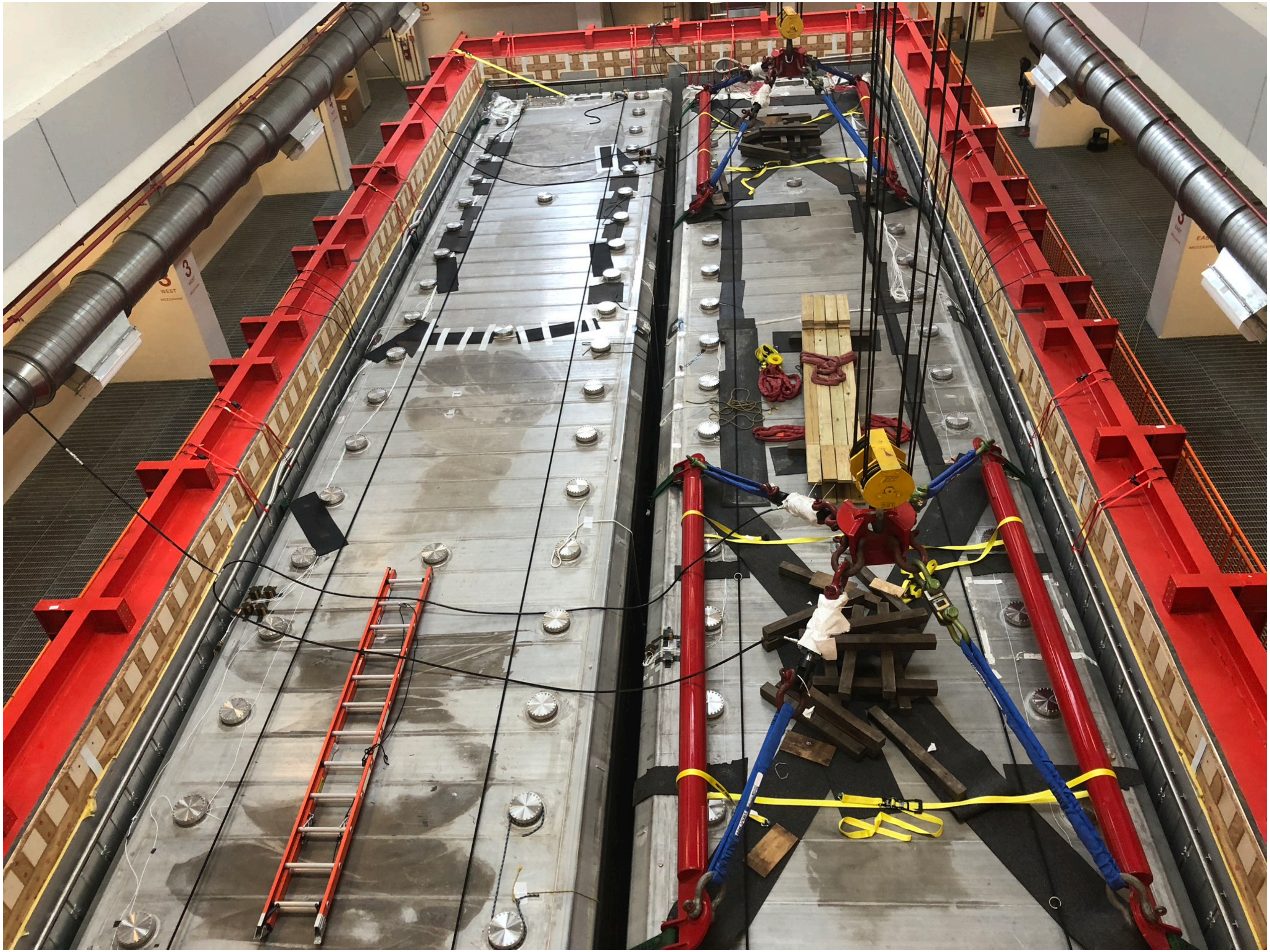
ICARUS-T600 Trip to FNAL

leaving from CERN, June 12th 2017

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

Rigging ICARUS into its place (August 14, 2018)

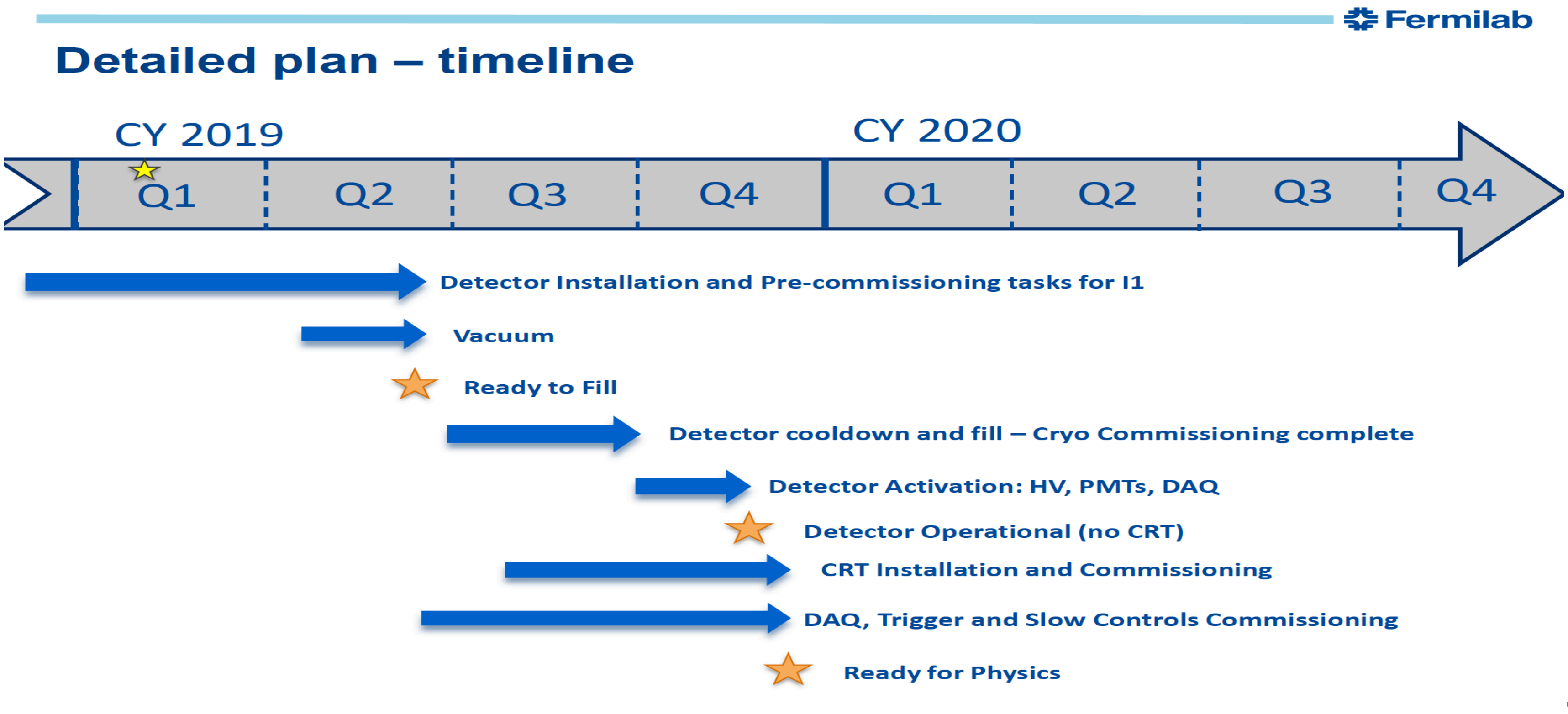


ICARUS installation at FNAL - status

- 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 (February 2019)
- Installation of proximity cryogenics system is also progressing
- SBN Director Review in December 2018 recognized the experiment's progress

ICARUS at FNAL – plans and commissioning

- TPC/trigger electronics installation to be completed and tested in spring 2019
- PMT electronics installation also to be completed during the spring
- ICARUS expected to be ready to fill by June 2019
- After cryogenics commissioning, cooldown and filling, ICARUS T600 should be operational during the last quarter of 2019
- Commissioning of CRT, DAQ, trigger and slow controls will follow
- Data-taking for physics is expected by the end of this year



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 is a crucial part of this effort, working in close collaboration with SBND. The analysis effort is common and very intense.
- 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 commissioning and data taking during 2019.

Thank you!