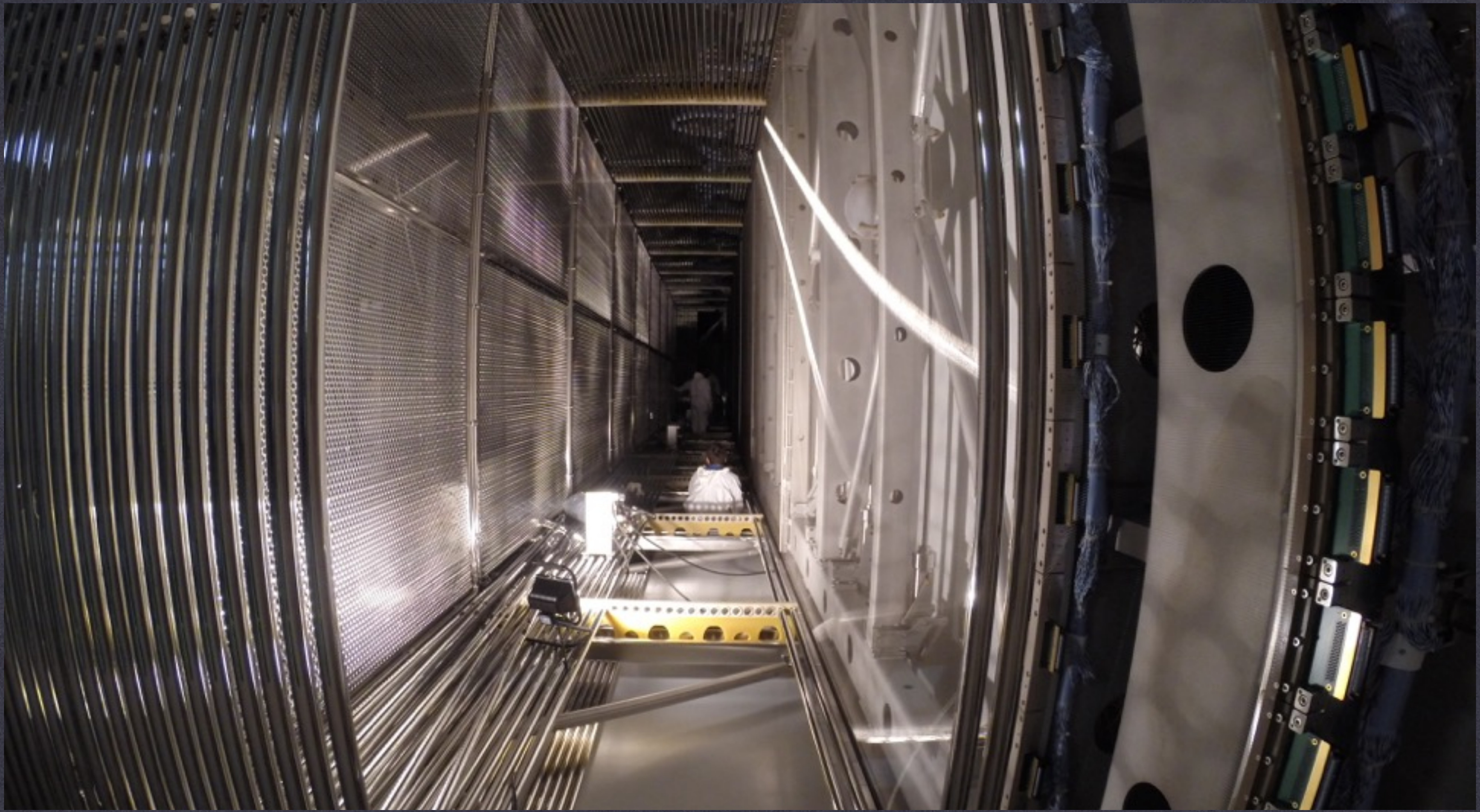
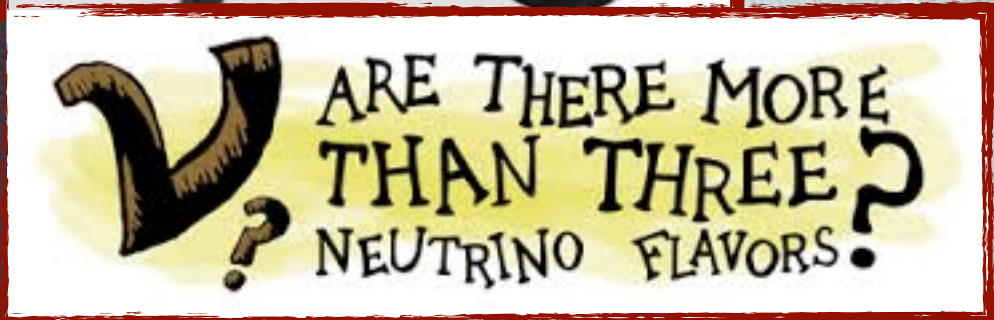


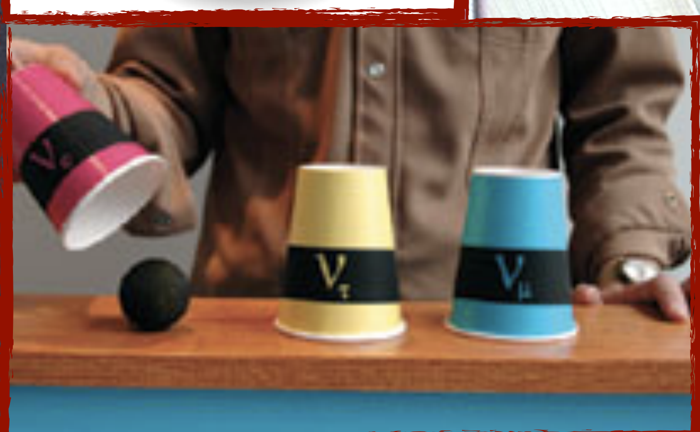
ICARUS-T600

Insights in the largest LAr-TPC detector

April, 21st 2016

ANGELA FAVA



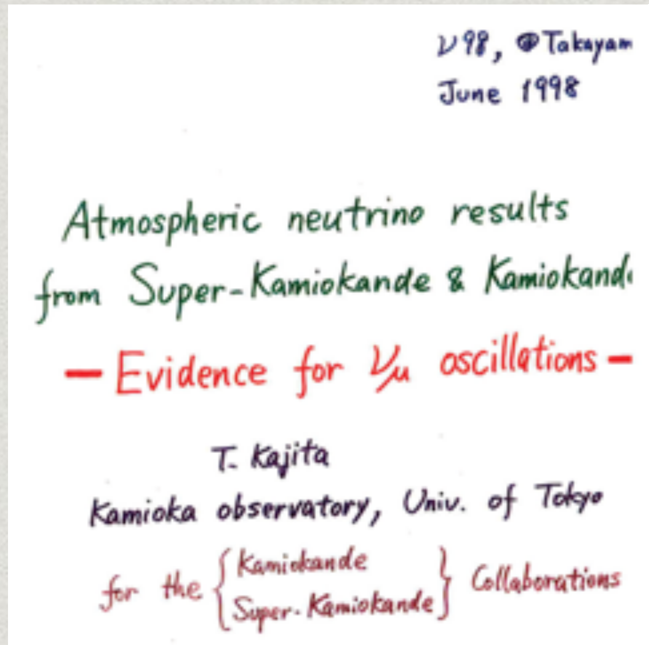


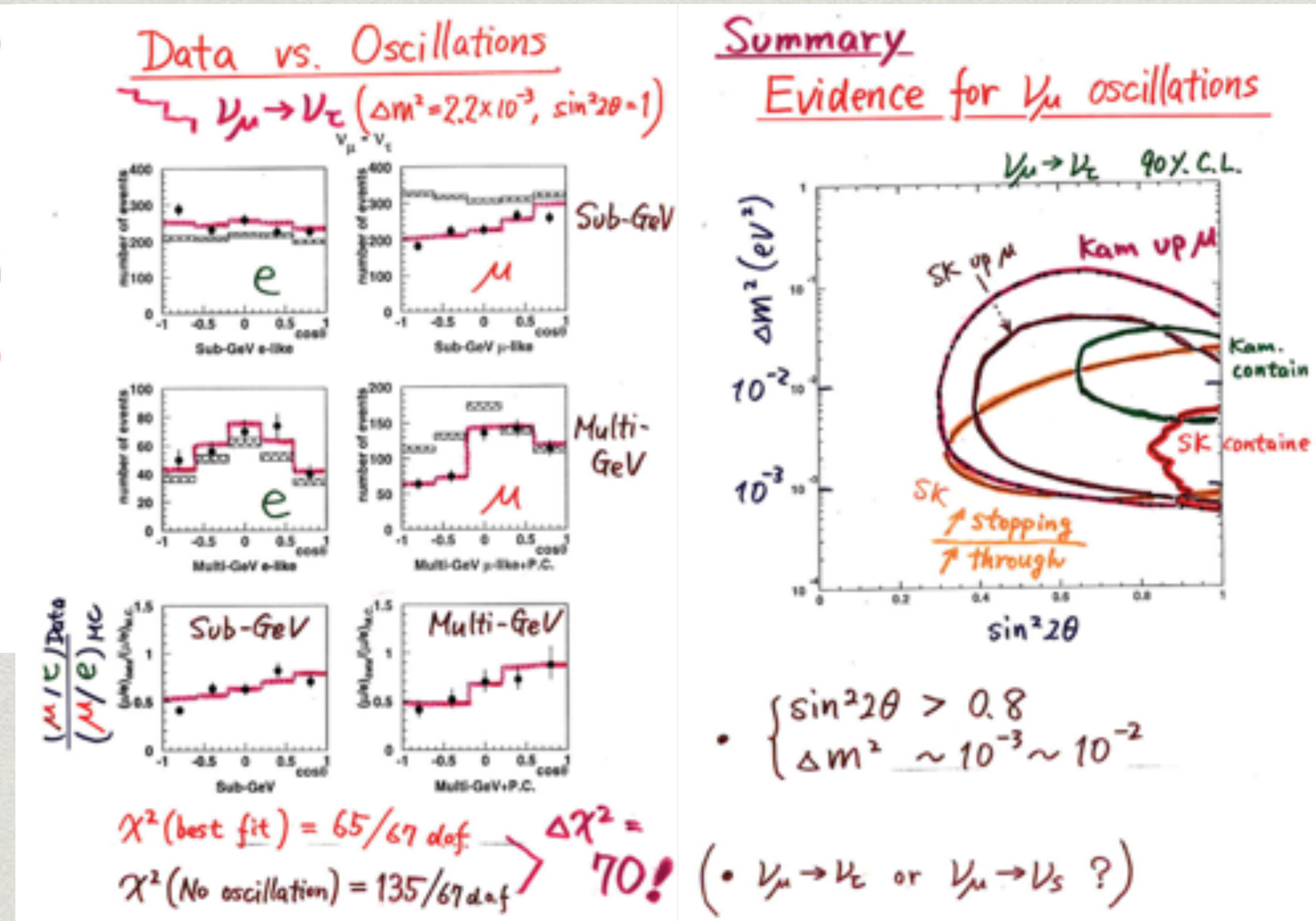
PHYSICS AND TECHNOLOGY LANDSCAPE

Neutrinos: the Standard Model misfits

Neutrinos were introduced in Standard Model of Particle Physics as spin 1/2 left-handed, **massless,** electrically neutral particles, existing in 3 flavours and coupled to corresponding leptons in SU(2).

The experimental discovery of ν oscillations is the first trouble caused by neutrinos to SM, since it implies non-zero masses.





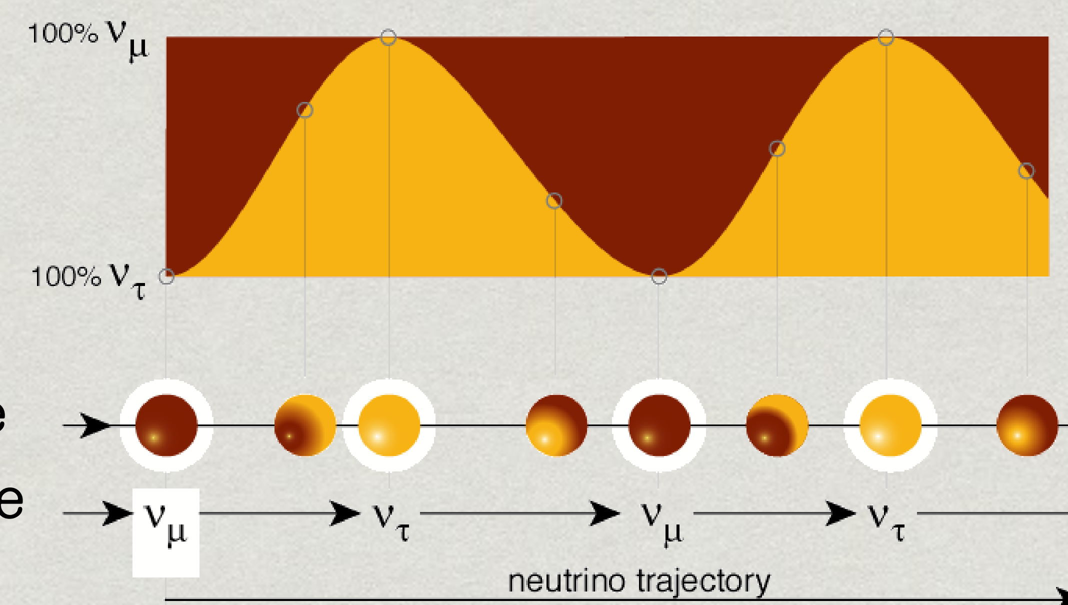
Indeed, oscillation is interpreted as flavour eigenstates ν_α being a superposition of mass eigenstates ν_i:

$$| \nu_\alpha > = \Sigma_{j=1,2,3} U_{\alpha j} |\nu_j>$$

each one propagating in time with his own motion equation (vacuum and ultra-relativistic approx):

$$|\nu_j(t)> = e^{-i(m_j^2/2p)t} |\nu_j>$$

Therefore, the resulting oscillation probability $P_{\alpha\rightarrow\beta} = |<\nu_\beta|\nu_\alpha(t)>|^2$ depends on the parameters of the mixing matrix U, the squared mass difference and the ratio of the propagation length over the energy.



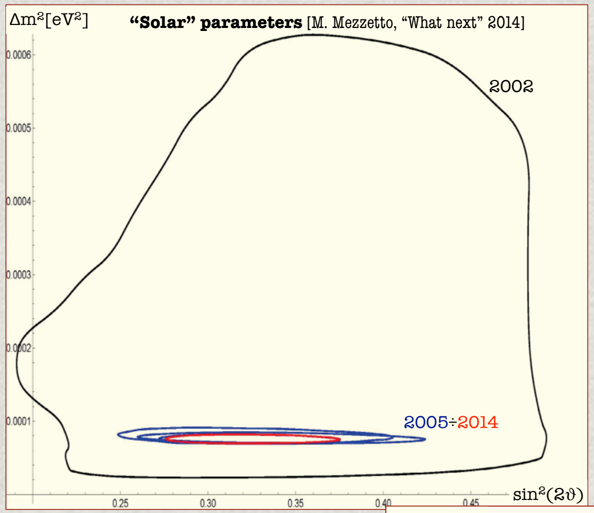
Towards a “precision measurement” era

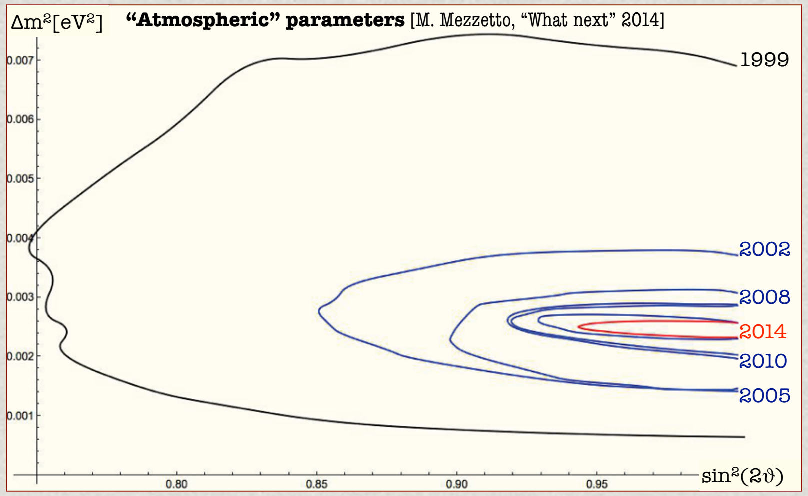
In recent years several experiments have been devoted to the determination of the squared mass differences and the parameters of the mixing matrix with increasing precision.

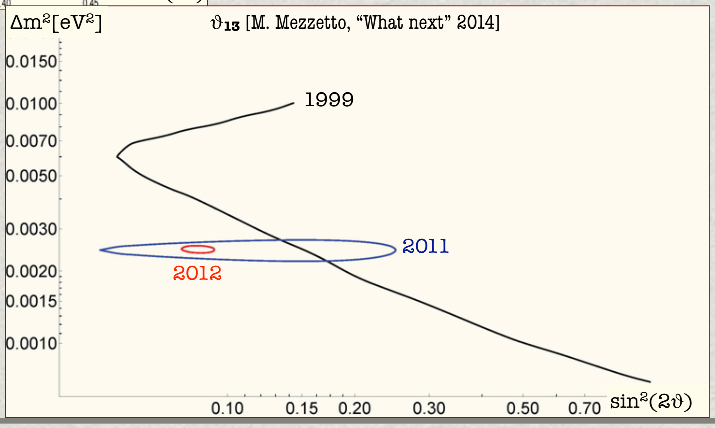
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

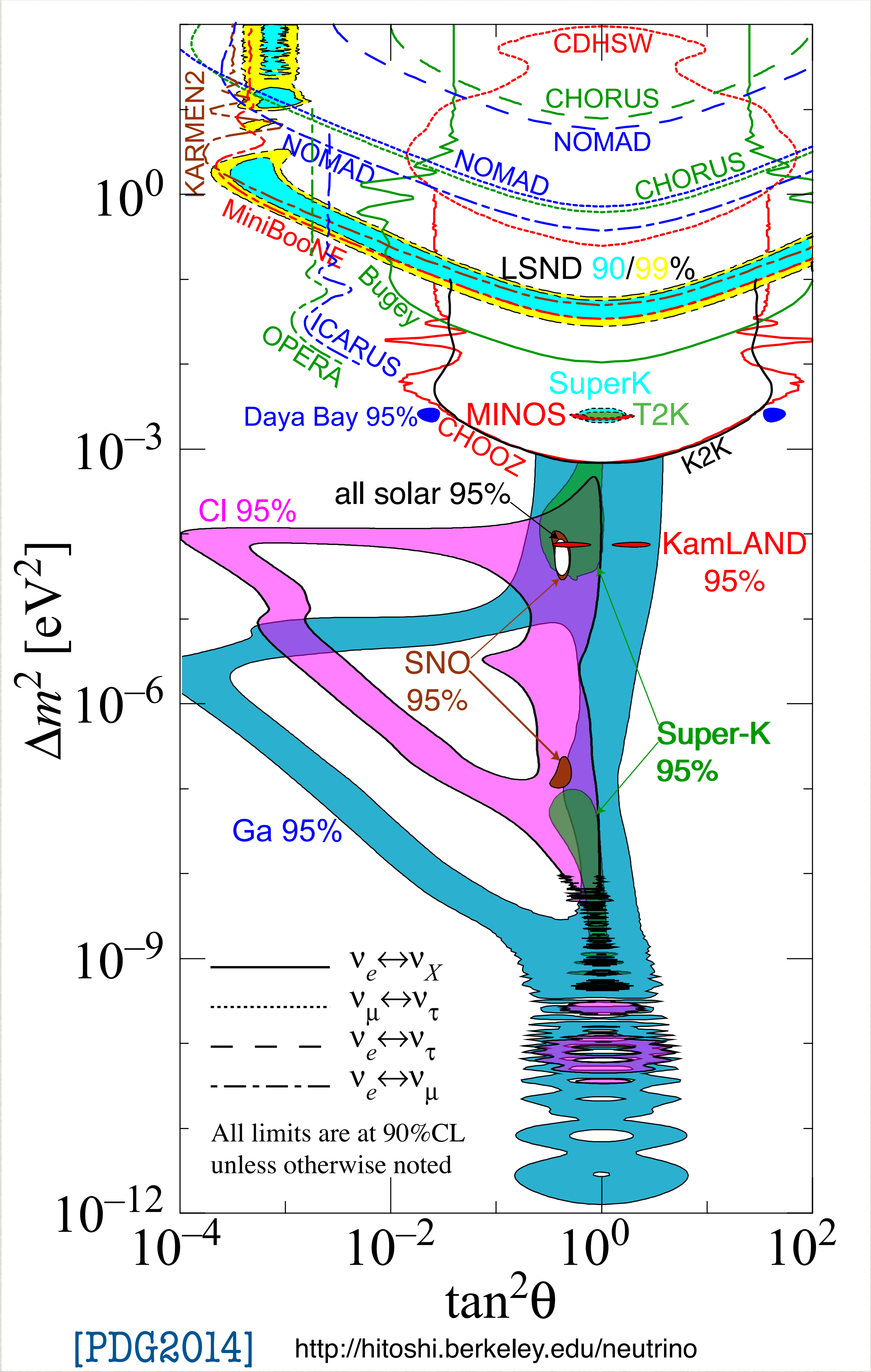
x $\mathrm{diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$

where $c_{ij}=\cos\vartheta_{ij}$, $s_{ij}=\sin\vartheta_{ij}$, δ is the Dirac CP violation phase and α_{ij} the Majorana CP violation phases.









The exiting future of neutrino physics

A “standard” picture of neutrino oscillation has clearly emerged, demanding an extension of the Standard Model, although several open questions are still on the table:

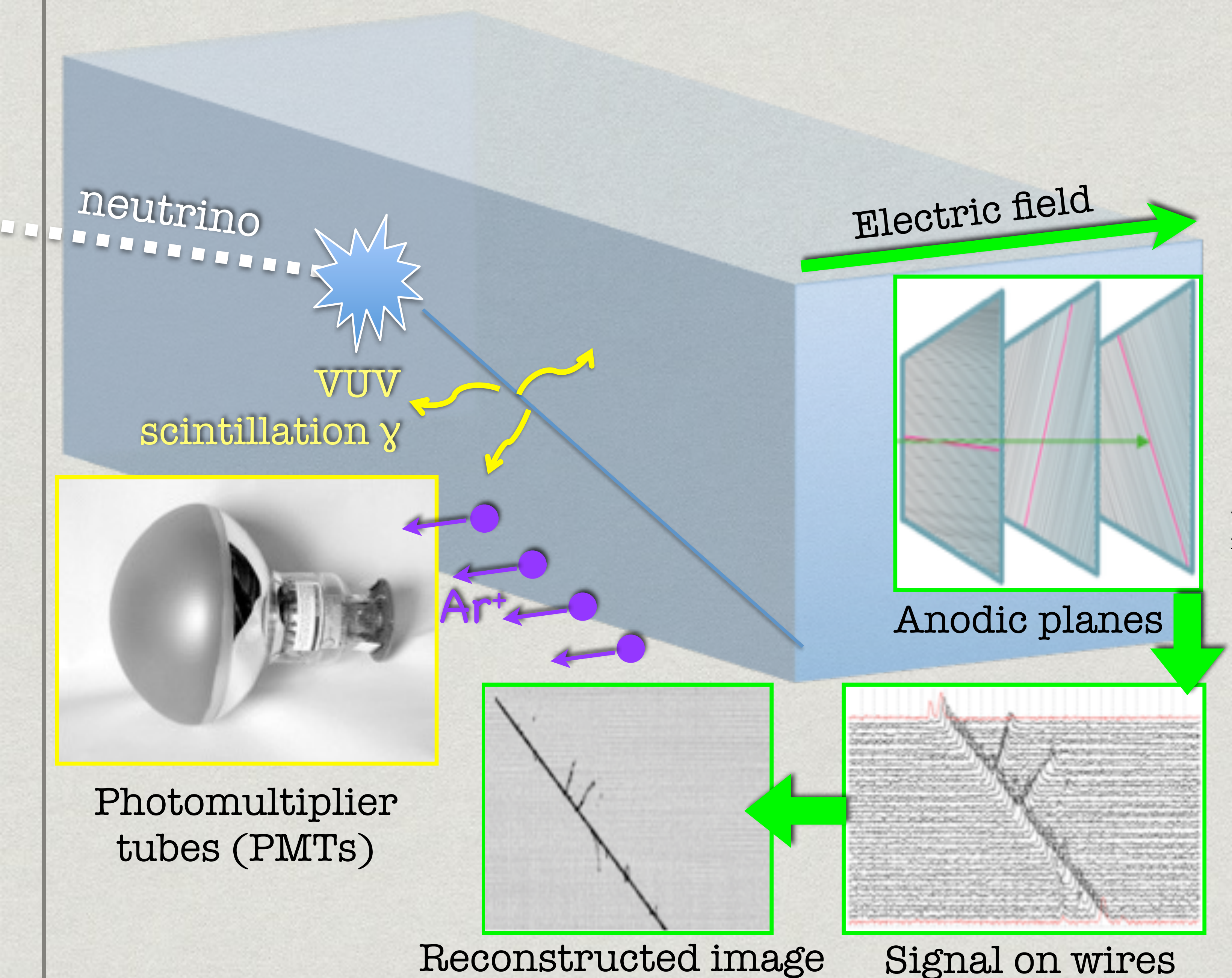
- what is the mass ordering or, in other words, is $\Delta m^2_{23} \lessgtr 0$?
- is CP-invariance violated in the lepton sector and, if so, how much?
- is the “atmospheric” mixing maximum or, if not, which is the ϑ_{23} octant?
- does the 3-flavour model provide a self-consistent description of the data?
- what is the absolute mass scale?
- are neutrinos Majorana or Dirac particles?

Beyond the 3-flavour mixing framework, some experimental anomalies have arisen curiosity on possible signatures of new Physics, such as the possible existence of “light” sterile neutrinos ($m \sim 1$ eV), unitarity violation of the mixing matrix and non standard neutrino interactions.

This intriguing scenario is being investigated with joint theoretical and experimental efforts; in particular, the thorough and redundant study of neutrino oscillations at different baselines both with natural (solar and atmospheric) and artificial (reactors and accelerators) sources plays a key role.

Liquid Argon TPC detector: a valuable investigation tool

- Liquid Argon Time Projection Chamber (LAr-TPC) detectors are very well suited for the experimental study of Neutrino Physics, combining a massive yet homogeneous target with excellent tracking and calorimetric capabilities.
- They represent a modern take on the successful Bubble Chamber technology, having introduced the possibilities to scale up to large masses and to electronically process the collected data while preserving high resolution imaging on an event-by-event basis.



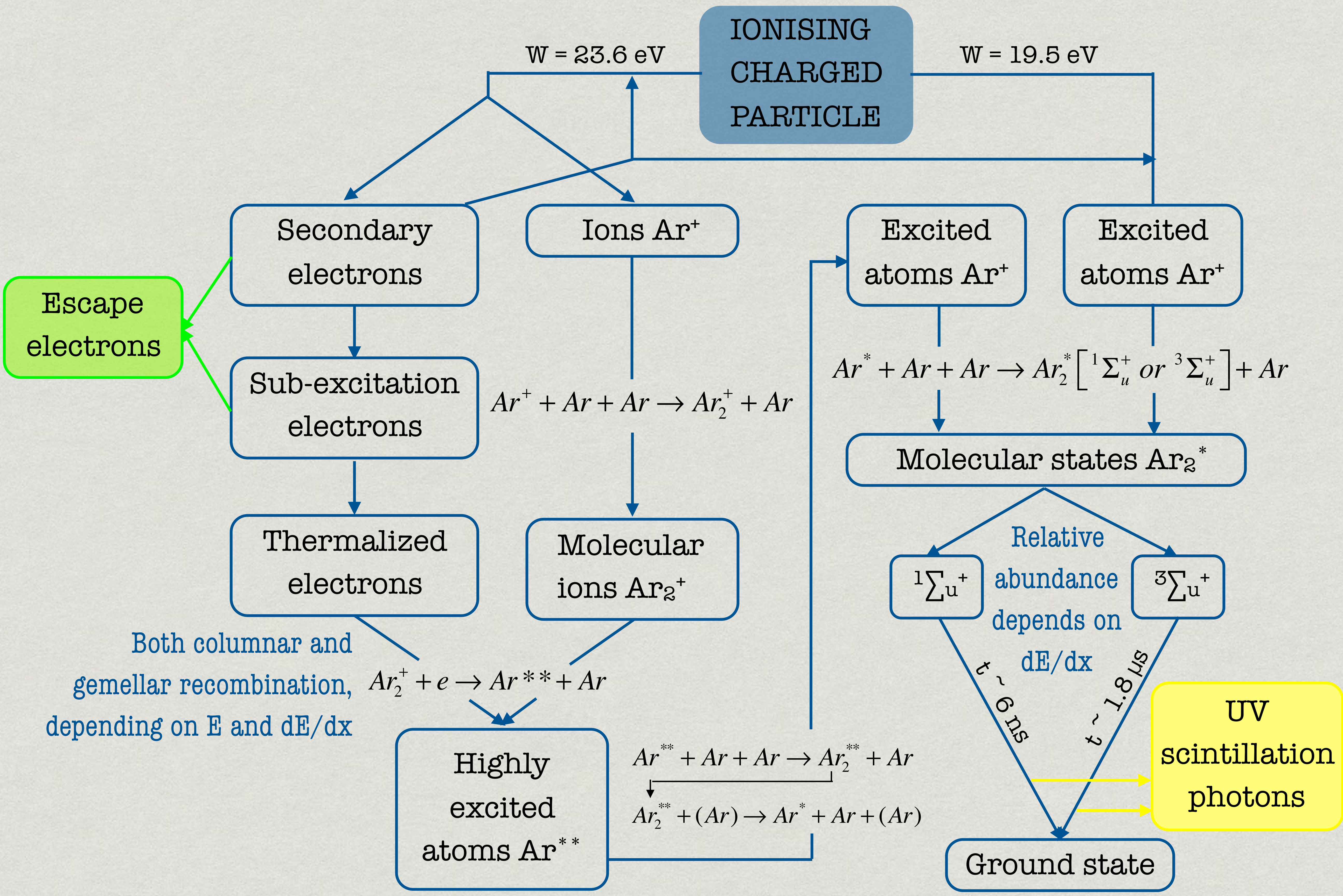
λ = 128 nm scintillation light:

- 40000 γ/MeV wo electric field
- Signal recorded by PMTs
- Response time ~ 6 ns ÷ 1.8 μs
- Affected by Rayleigh scattering and absorption by N_2
- Used for triggering

Ionisation electrons:

- 42000 e^-/MeV
- Drifted (E) toward planes of wires on which they induce a signal
- Response time = drift time (~ ms)
- Affected by diffusion, capture on LAr impurities and recombination
- Used for image reconstruction

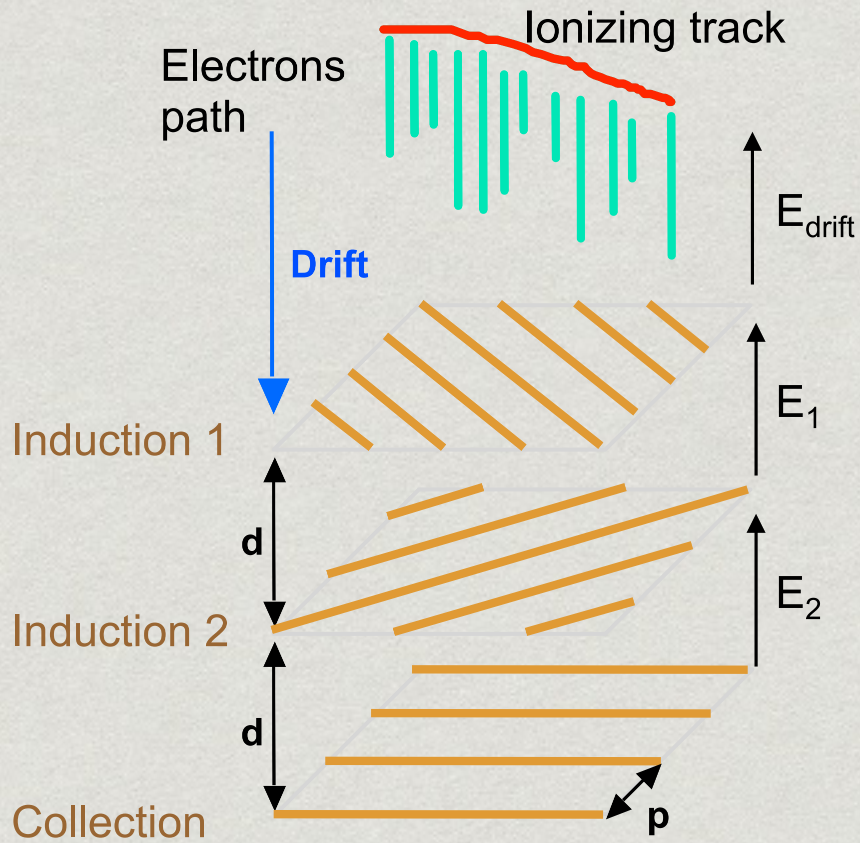
Processes of charged particles interaction with LAr

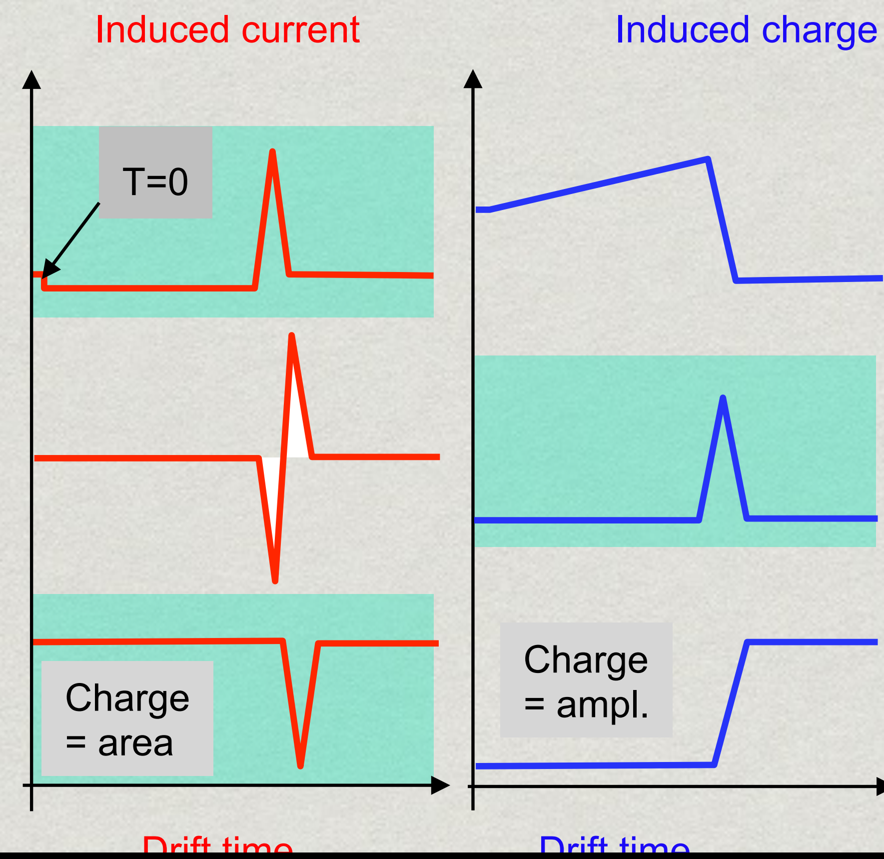


Signal recording: from drifting electrons to 3D image

In LAr ions mobility v^+ is much smaller than electrons' v^-: $v^-/v^+ \simeq 10^5$ ⇒ electron current is dominant.

Drifting e^- can traverse several wire planes, inducing a triangular shaped current signal, being finally collected on the last plane.





- Wire biasing has to be properly chosen to guarantee full transparency:

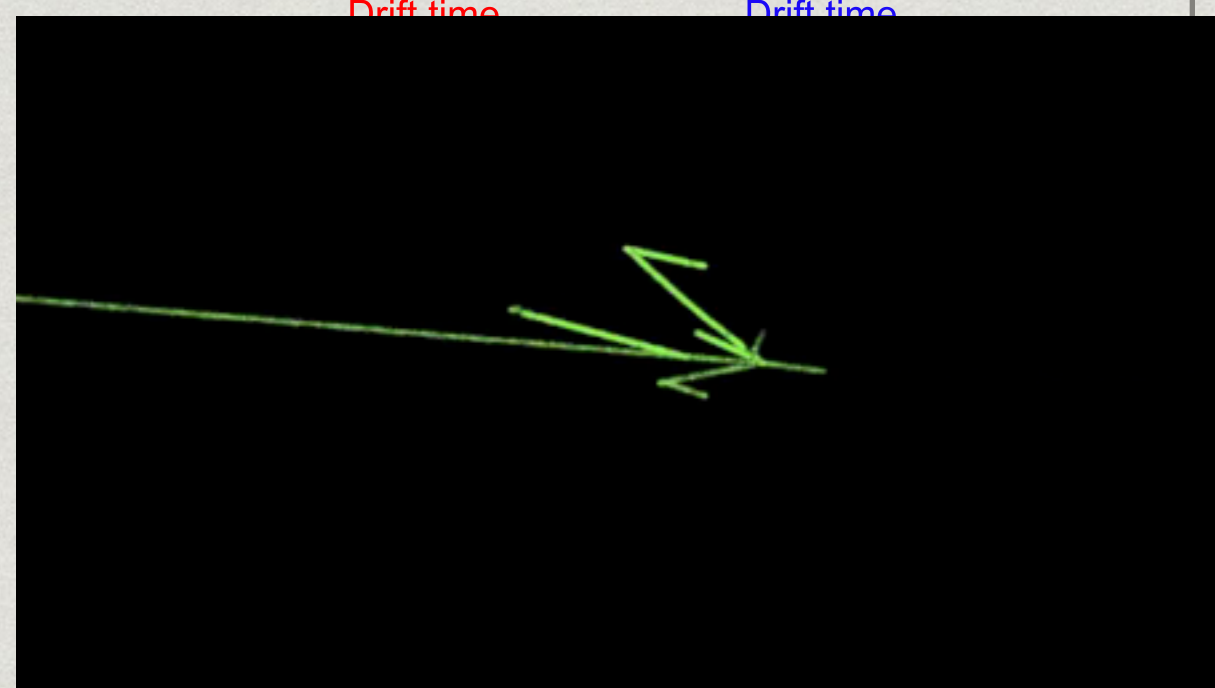
$$\frac{E_1}{E_2} > \frac{1+\rho}{1-\rho} \qquad \rho = \frac{2\pi r}{p}$$

r → wire radius; p → wire pitch

- Shielding inefficiency is unavoidable, due to a purely geometric effect:

$$\sigma = \frac{p}{2\pi d}\ln\left(\frac{p}{2\pi r}\right)$$

d → distance between wire planes



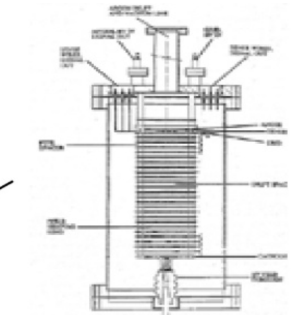
3D image reconstruction is obtained from full drift recording, by combining coordinates on different wire planes (with different wire orientations) at the same drift time. Ambiguity arises along the drift direction in absence of an external t = 0 information on trigger time.

(European) path to massive LAr-TPC detectors

First idea of LAr-TPC detector: H. Chen (1976) [FNAL P-496] and C. Rubbia (1977) [CERN-EP/77-08]

ICARUS first proposed to INFN in 1985 [ICARUS: Imaging Cosmics And Rare Underground Signals: INFN/AE-85/7]

1



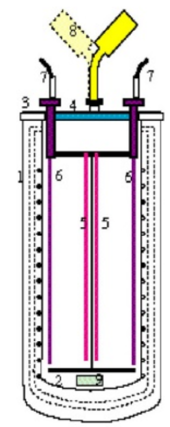
CERN

24 cm drift wires chamber

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.

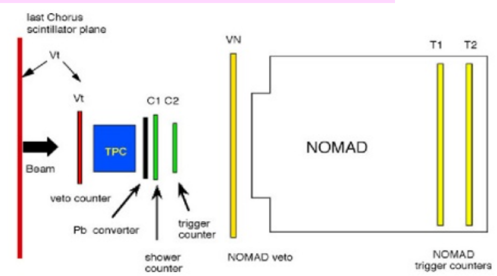
CERN

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.

PAVIA

2001: Data taking with c-rays

Cooperation with industry and several companies

5

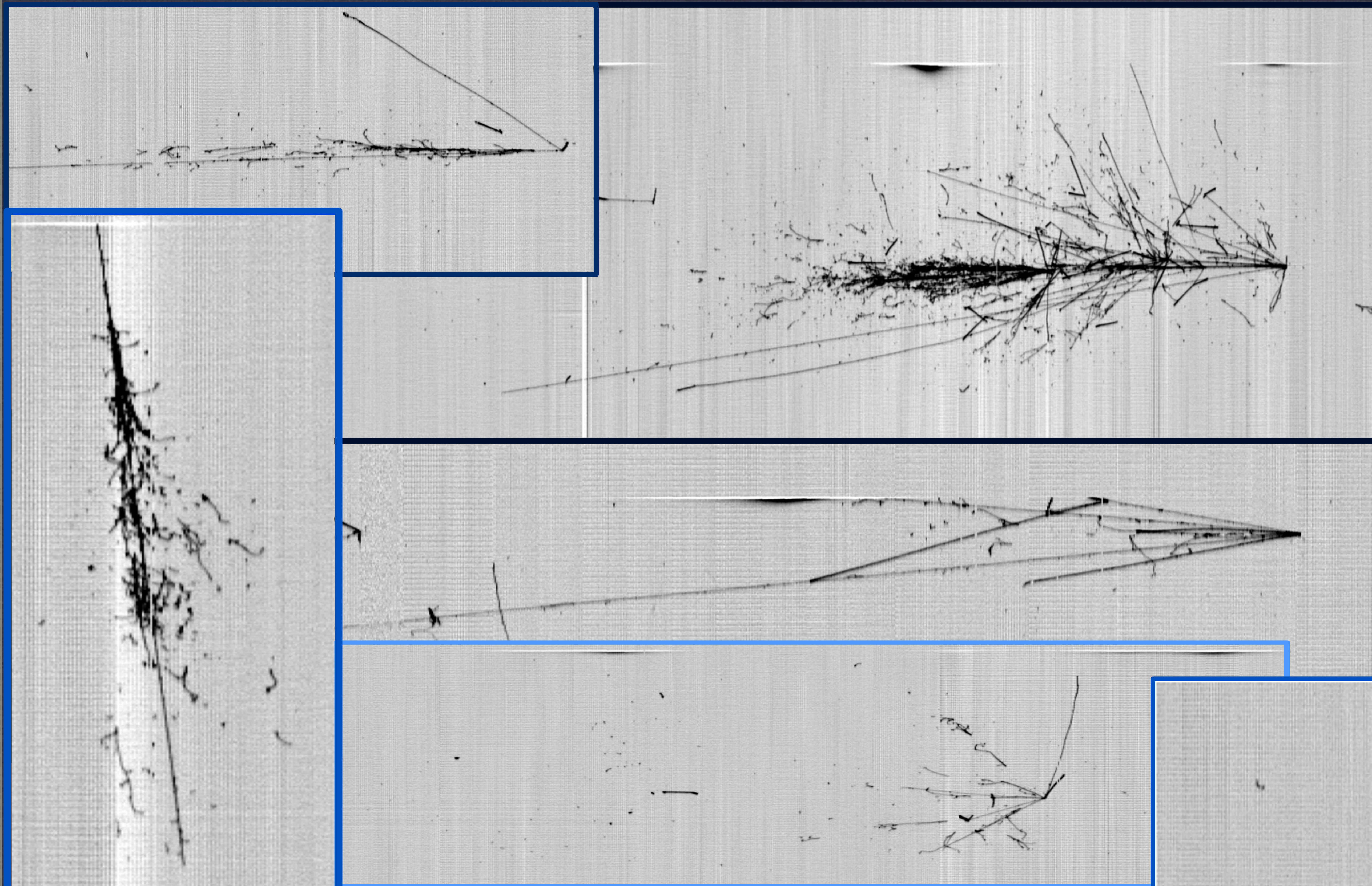
T600 detector

LNGS

2010 - 2013 : Data taking with CNGS beam

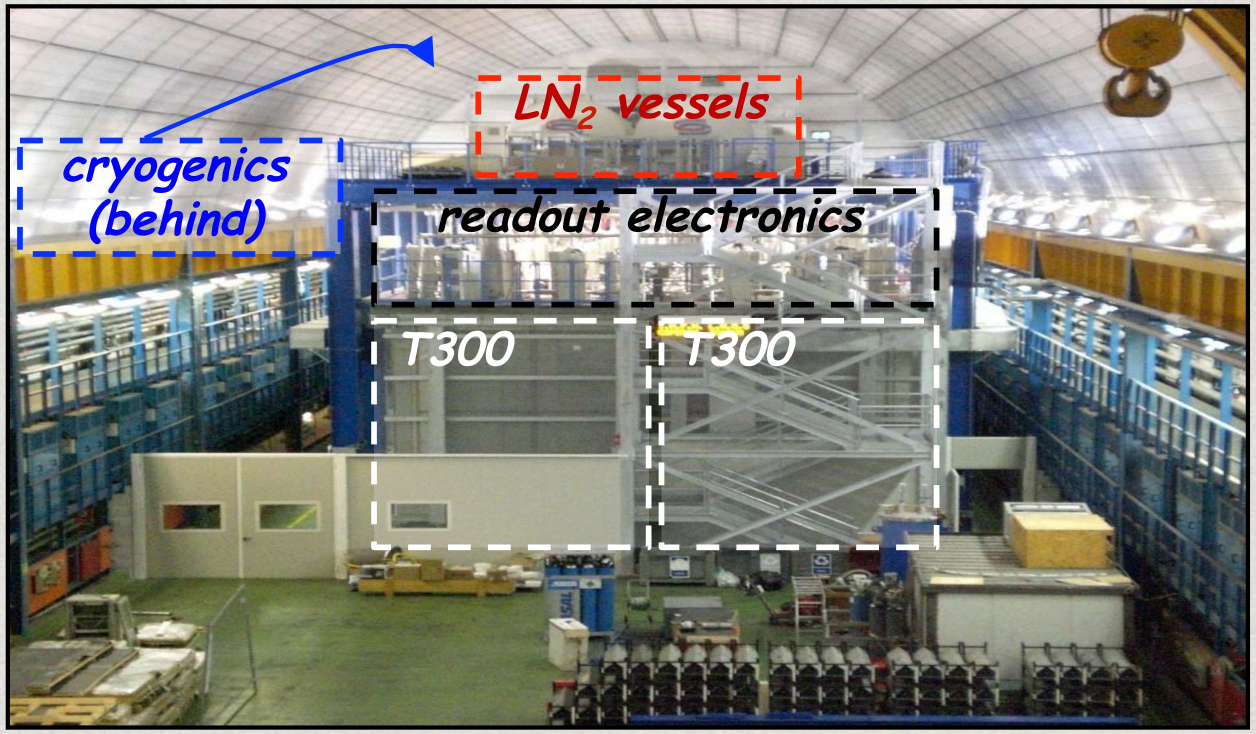
6

ICARUS T600 experiment



ICARUS-T600 @ LNGS

ICARUS-T600: state of the art of LAr-TPC technique



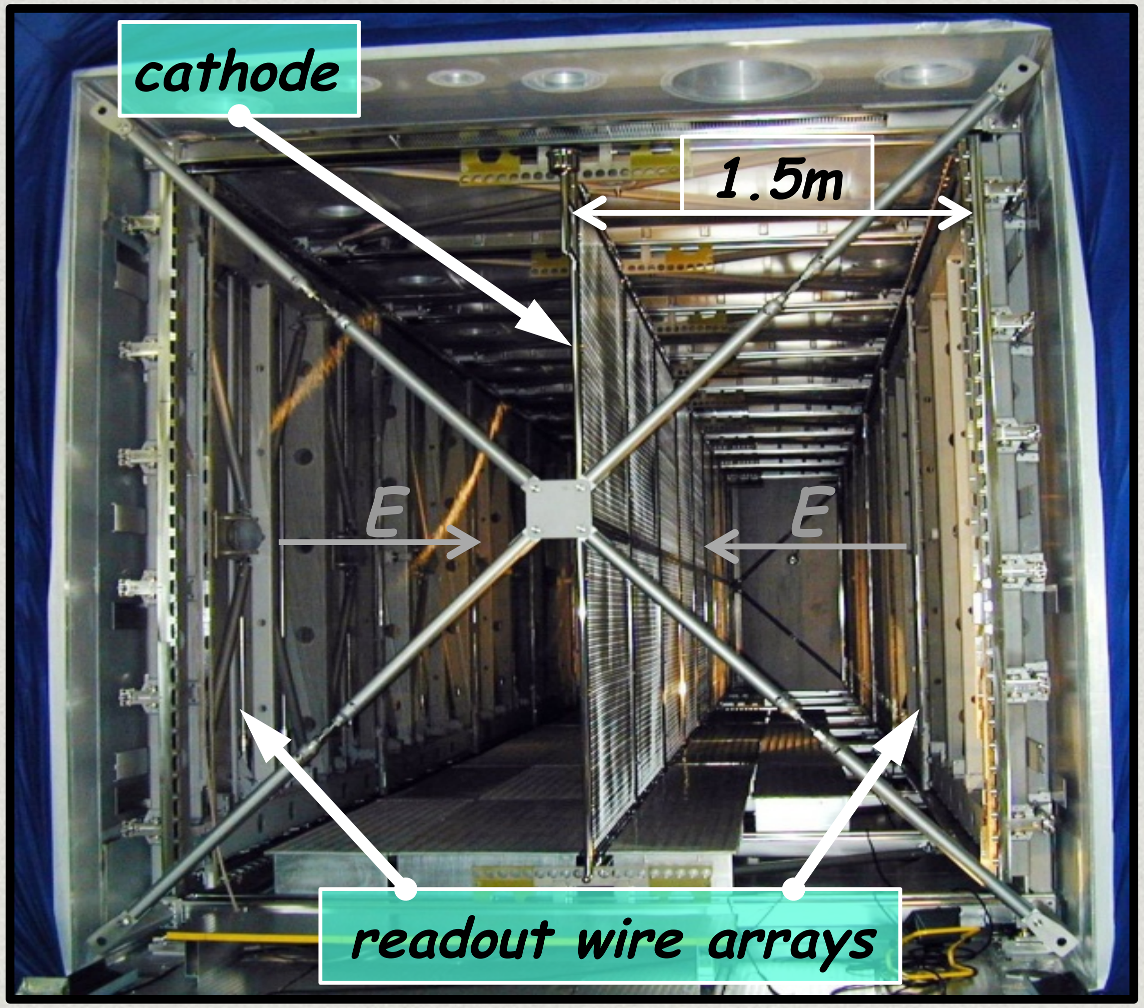
- 476 t LAr active mass
- 2 independent and identical T300 modules, 3.6x3.9x19.6 = 275 m^3 each
- 4 TPC chambers, 2 per T300
- Very elaborate cryogenic and purification systems, to guarantee continuous recirculation and filtering (Oxysorb/Hydrosorb) both in liquid and gas phases.

EACH TPC:

- 1.5 m drift length
- E = 0.5 kV/cm (cathode HV = -75 kV)
- 1.55 mm/μs e^- drift velocity (1 ms drift time)
- Anode: 3 wire planes 3 mm apart, > 13000 wires with 3 mm pitch, directions at 0, ±60°
- ~ 30% recombination for m.i.p.

SCINTILLATION LIGHT DETECTION:

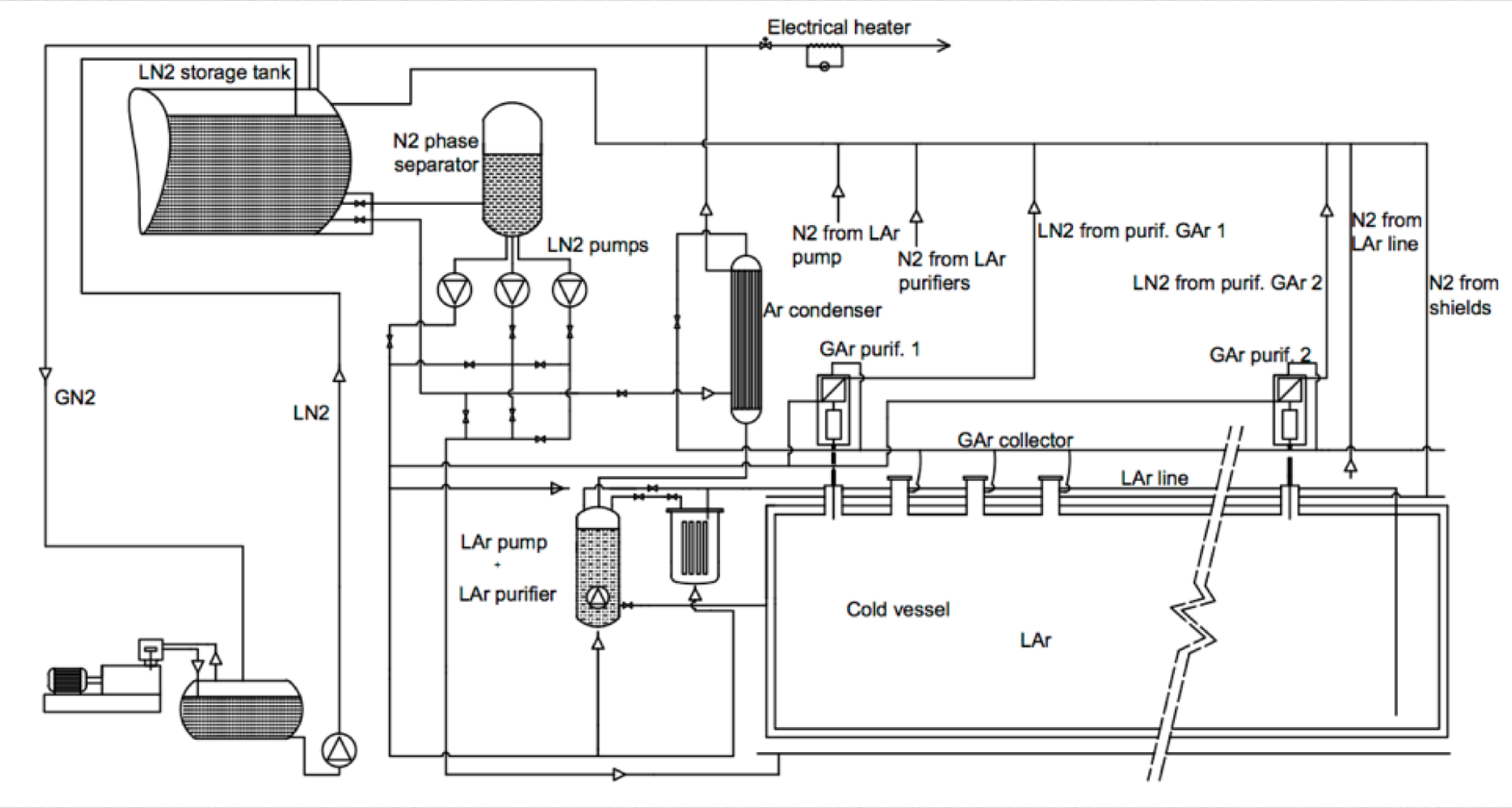
- 24000 γ/MeV light yield
- 74 photomultiplier tubes (PMTs), VUV sensitive with TPB wavelength shifter



A very elaborate cryogenic system

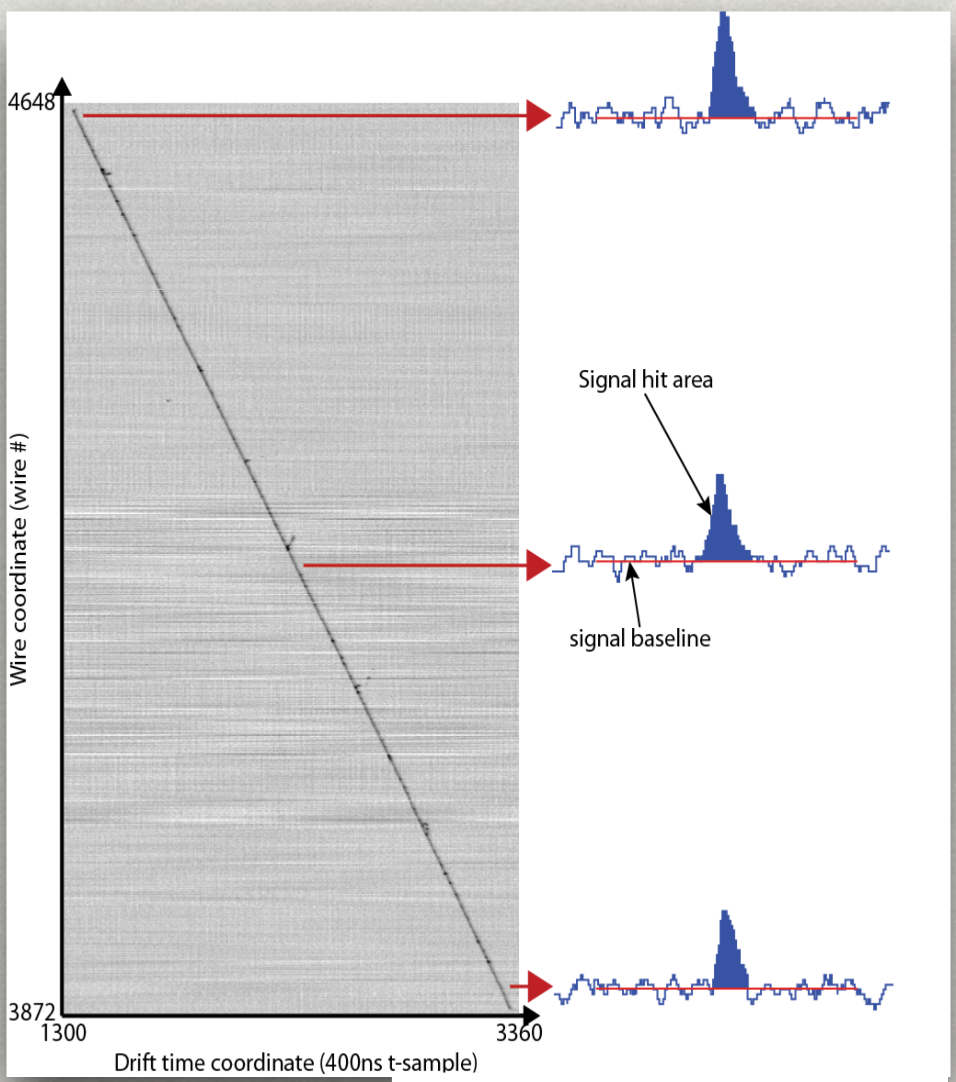
The ICARUS purification system is very complex, and demands a continuous operation both in the liquid and gas phases

- Purification (2.5 x/hour) of gas phase at the top (~40 Nm^3)
- Purification (100 m^3/day) of the bulk liquid volume (~550 m^3)



LAr purity: a key feature towards longer drift paths

- Concentration of electronegative impurities N in LAr must be kept exceptionally low, in order to ensure ~ m long drift path of ionisation electrons without attenuation:
  $\tau_e[ms] = 0.3/N[ppb[O_2]_{eq}]$
- In ICARUS-T600 run @ LNGS τ_e > 7 ms (40 ppt$[O_2]_{eq}$) was measured studying charge signal attenuation on traversing c-ray muons, corresponding to 12% max charge attenuation on 1.5 m drift path.
  Maximum τ_e > 16 ms reached in East cryostat since April 4th 2013 (new pump installed).



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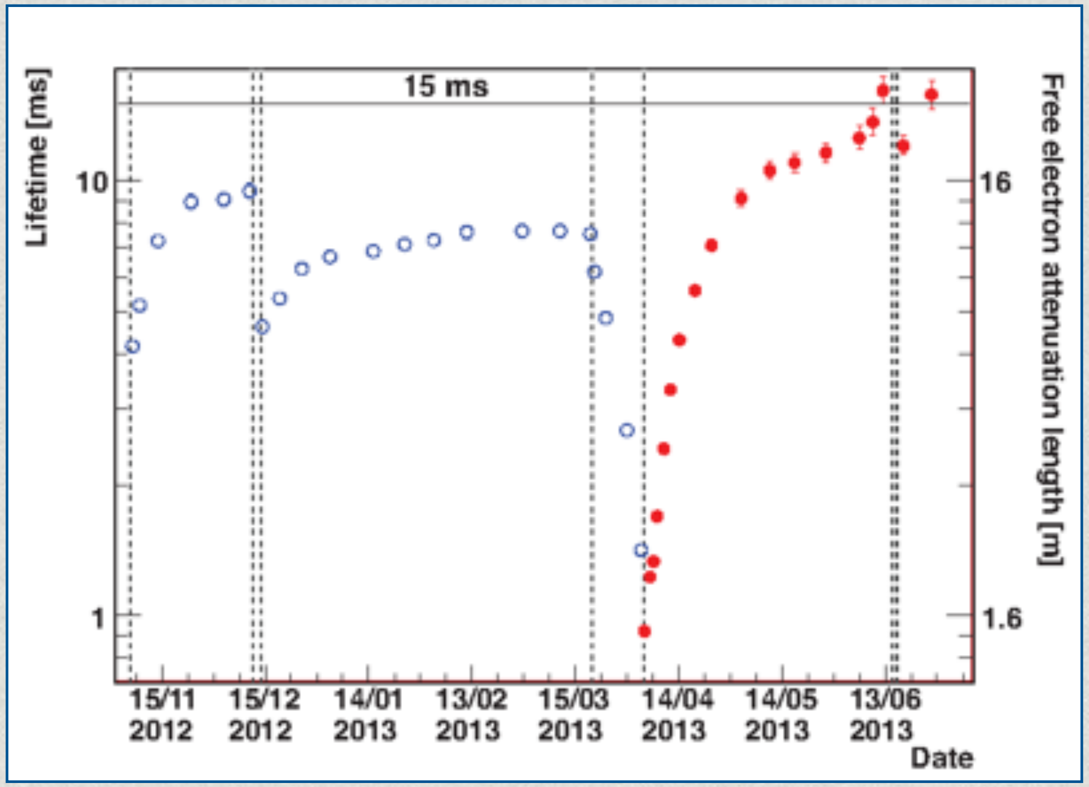


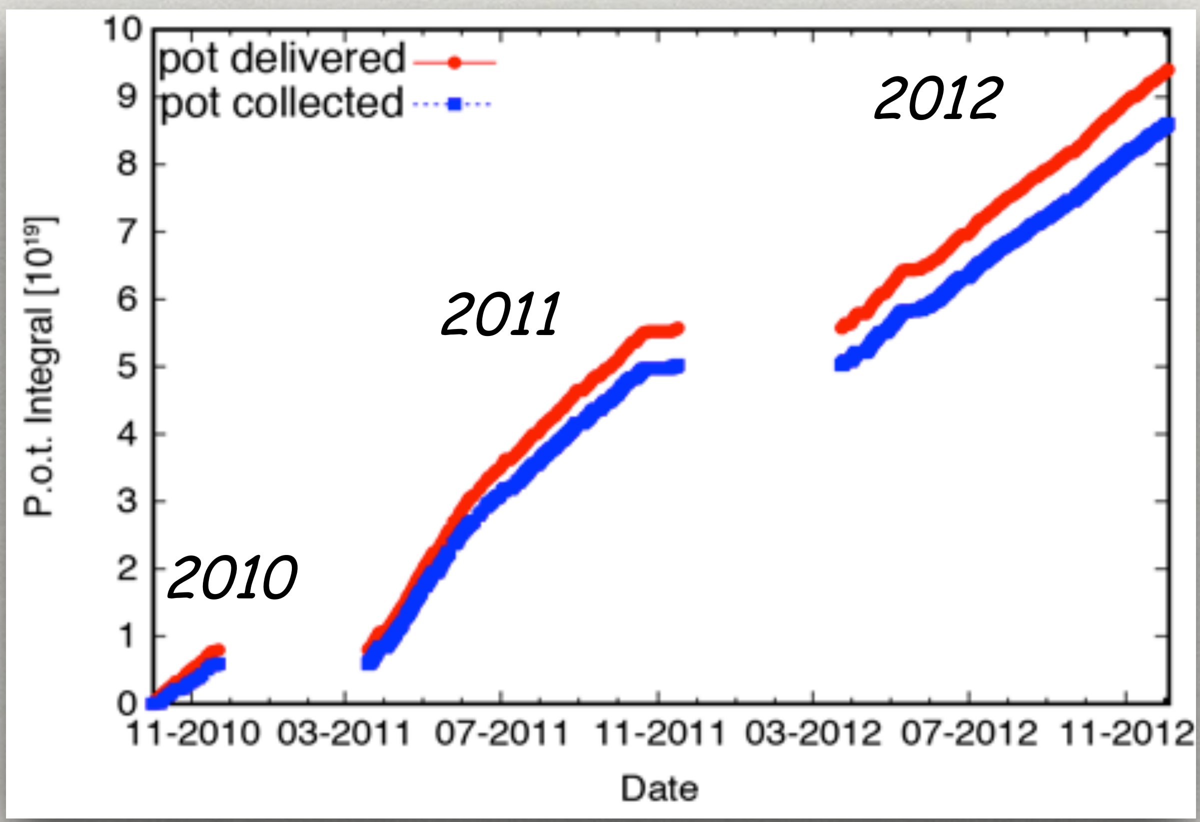
- This result is comparable with τ_e ~ 21 ms value measured in the Icarino LAr-TPC test facility (50 l) at INFN LNL.

Huge single phase LAr-TPC detectors, with ~ 5 m drift paths, are feasible!

A manifold assortment of particle interactions

- ICARUS-T600 was installed underground at INFN-LNGS and exposed to the CNGS (Cern to Gran Sasso) ν_μ beam: average energy $<E_\nu>$ = 17.4 GeV, intrinsic ν_e contamination ~ 0.8 %, baseline 732 km.

- In 2010÷2012 it collected 8.6 x 10^{19} protons on target (pot) statistics, with a remarkable detector live-time > 93%.
  3000 ν interactions in the LAr active volume, both CC and NC, were recorded, peaked in the 10÷35 GeV energy range.
  Additional ~ 12000 beam associated events were also collected: ~ 9000 μ generated by ν interaction with the upstream rock and ~ 3000 residuals of ν interaction outside of the LAr fiducial volume.

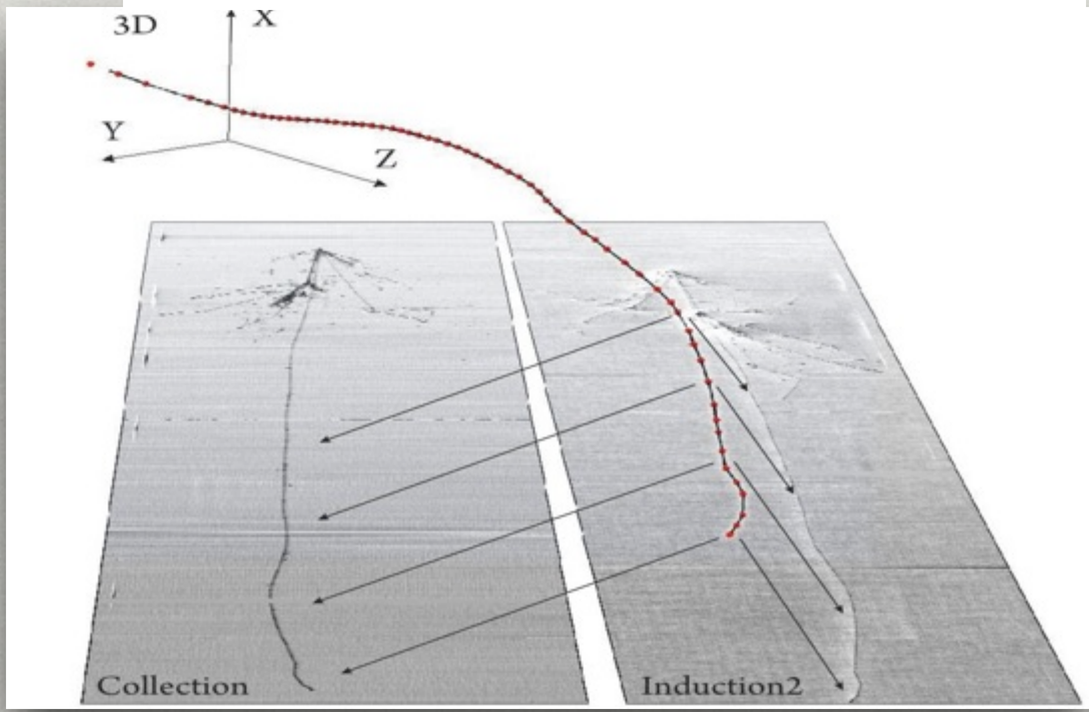


- In parallel, ICARUS-T600 recorded a large sample of cosmic-ray induced events (rate ~ 50 mHz), useful for studying atmospheric neutrino interactions, with energy ranging from few MeV up to tens GeV, and searching for nucleon decay candidates as localised events with energy deposition < 1 GeV.

Tracking and calorimetric properties

- Tracking performance.
  Precise 3D reconstruction, with ~ 1 mm^3 spatial resolution, is obtained with simultaneous 3D polygonal fit: 2D hit-to-hit associations are no longer needed.

Adv. High Energy Phys. 2013 (2013) 260820



- Calorimetric performance
  - Total energy reconstruction, performed by charge integration, has excellent accuracy for contained events.

    Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$

    Electromagnetic showers: $\sigma(E)/E = 3\% / \sqrt{E(GeV)}$

    Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

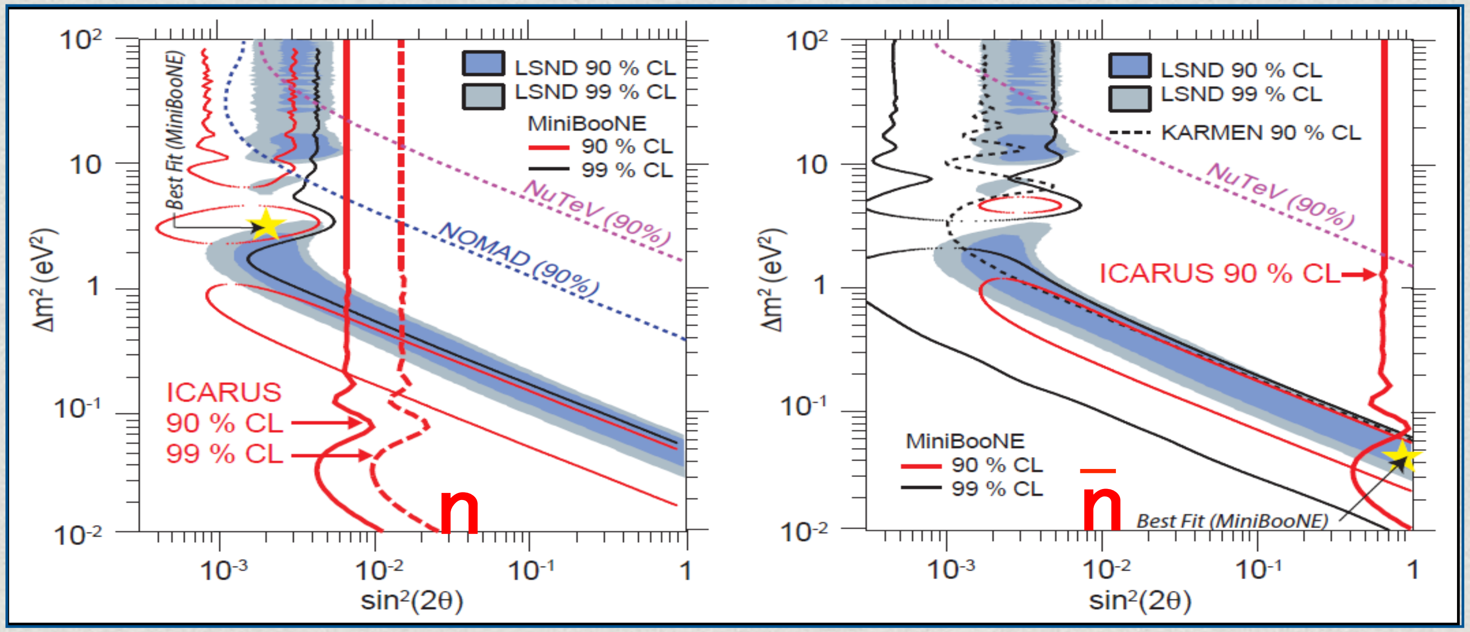
  - Measurement of dE/dx allows remarkable e/γ separation and particle identification (dE/dx vs range).
  - Momentum of non contained μ is determined via multiple Coulomb scattering with a resolution $\Delta p/p$ ~16% in the 0.4-4 GeV/c range.

Search for a LSND-like signal on CNGS ν beam

- Analysed sample: 2450 neutrino events corresponding to 7.23×10^{19} pot (84% of fully collected statistics).
- Expected number of ν_e events in this sample:
  - 7.0 ± 0.9 due to the ~ 1% intrinsic electron neutrino beam contamination.
  - 2.9 ± 0.7 due to ϑ_{13} oscillations (L/E_ν ~ 36.5 m/MeV), $\sin^2(\vartheta_{13}) = 0.0242 \pm 0.0026$.
  - 1.6 ± 0.1 from $\nu_\mu \rightarrow \nu_\tau$ oscillations with subsequent e production.
- Total number of expected events: 11.5 ± 1.2, which reduces to 7.9 ± 1.0, when accounting for recognition efficiency (systematics only).
- 6 electron neutrino events have been identified → compatible with expectations (33% probability to observe ≤ 6 ν_e events).
- ICARUS new limits, weighted for efficiency, on the oscillation probability:

$P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3}$ (90 % C.L.)

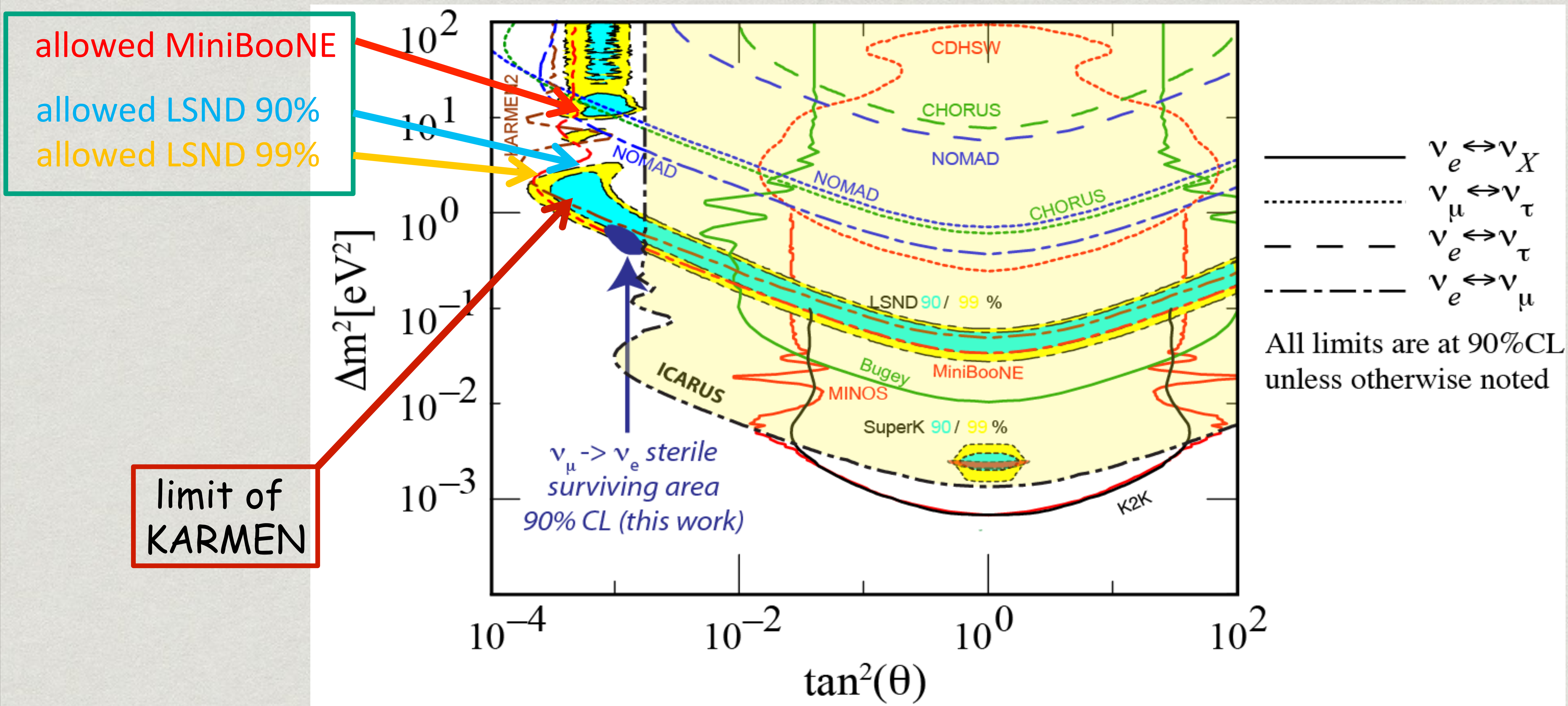
$P(\nu_\mu \rightarrow \nu_e) \leq 7.60 \times 10^{-3}$ (99 % C.L.)



In case the effect is only due to anti-ν_μ (CNGS beam contamination ~2%), the derived oscillation probability is: $P(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e) \leq 0.32$ (90 % C.L.), corresponding to 4.2 ev.

Search for a LSND-like signal on CNGS ν beam

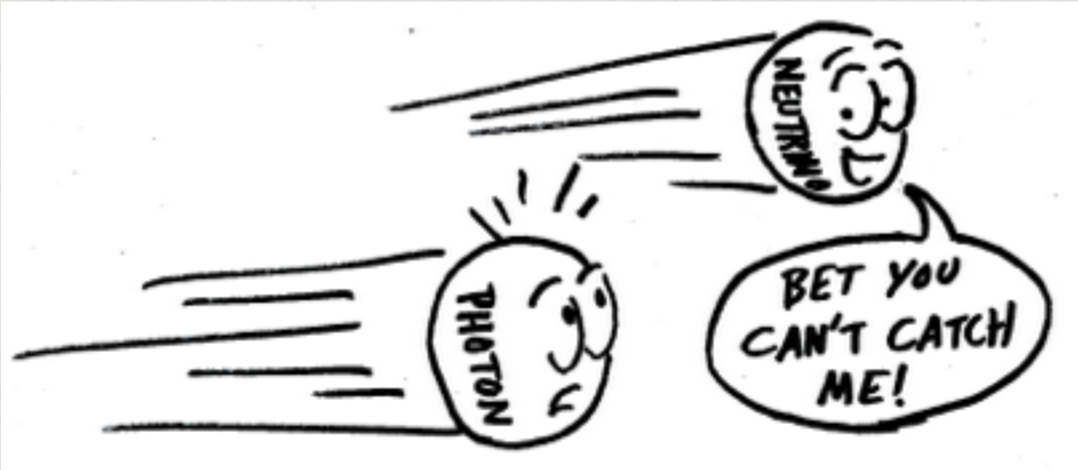
- ICARUS result indicates a very narrow region of the parameter space ($\Delta m^2 \approx 0.5$ eV^2, $\sin^2(2\vartheta) \approx 0.005$), where all experimental results can be accommodated at 90% CL.



ICARUS talk @ Neutrino2014 Conference

Experimental determination of neutrino time of flight

- Two measurement campaigns of neutrino velocity were carried out with ICARUS-T600 detector in 2011 and 2012, triggered by the surprising result, reported by OPERA experiment, of a superluminal excess in neutrino propagation from CERN to LNGS.



- The difference between the expected time of flight, accounting for a propagation over the CERN to LNGS baseline L at the speed of light, and the one actually measured

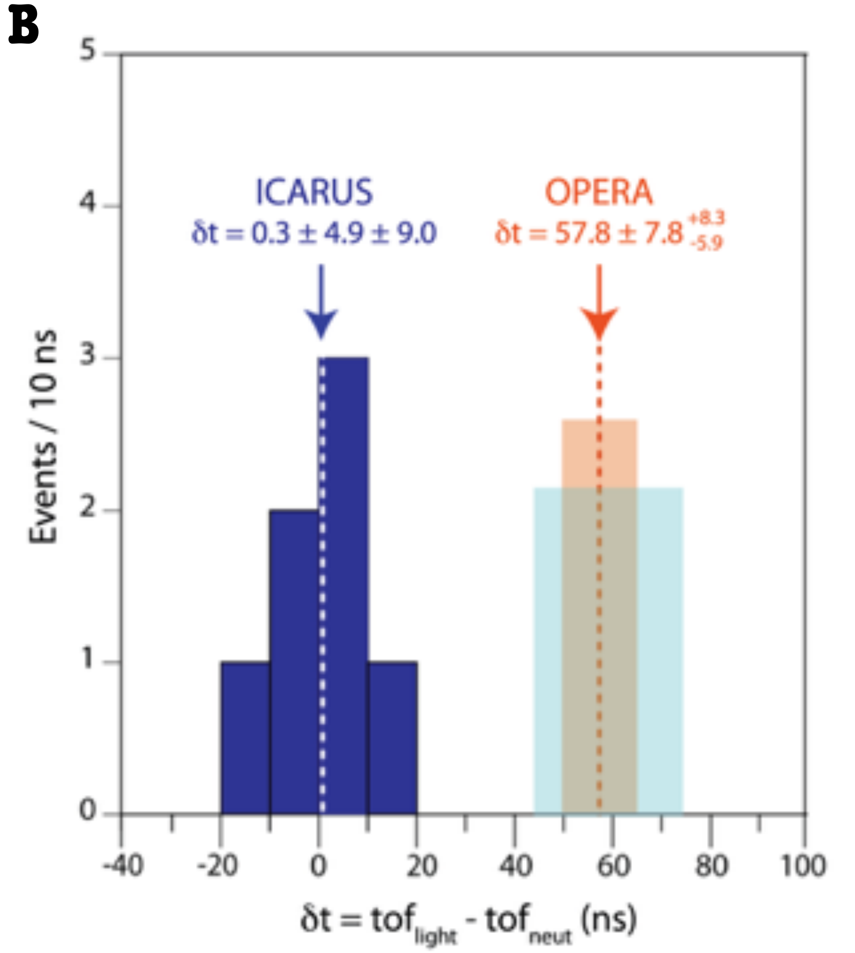
$$\delta t = L * c - tof_{exp}$$

  has been computed for each beam related event detected with ICARUS-T600.
- Distance between the Beam Current Transformer (BCT) detector at CERN and the upstream wall of ICARUS detector at LNGS was estimated with few cm accuracy, relying on the results of dedicated geodetic campaigns.
- Neutrino time of flight was determined as the difference between the **interaction time, recorded with ICARUS-T600 in the LNGS absolute timebase and extrapolated to the upstream wall**, and the proton transit time at the BCT, provided by CERN in its absolute timebase.
- Synchronisation between CERN and LNGS timebases within few nanoseconds uncertainty was obtained resorting to a common GPS-based timing system, developed by a joint effort of the two Laboratories with OPERA (and Borexino in 2012) Collaboration.

Einstein is still alive!

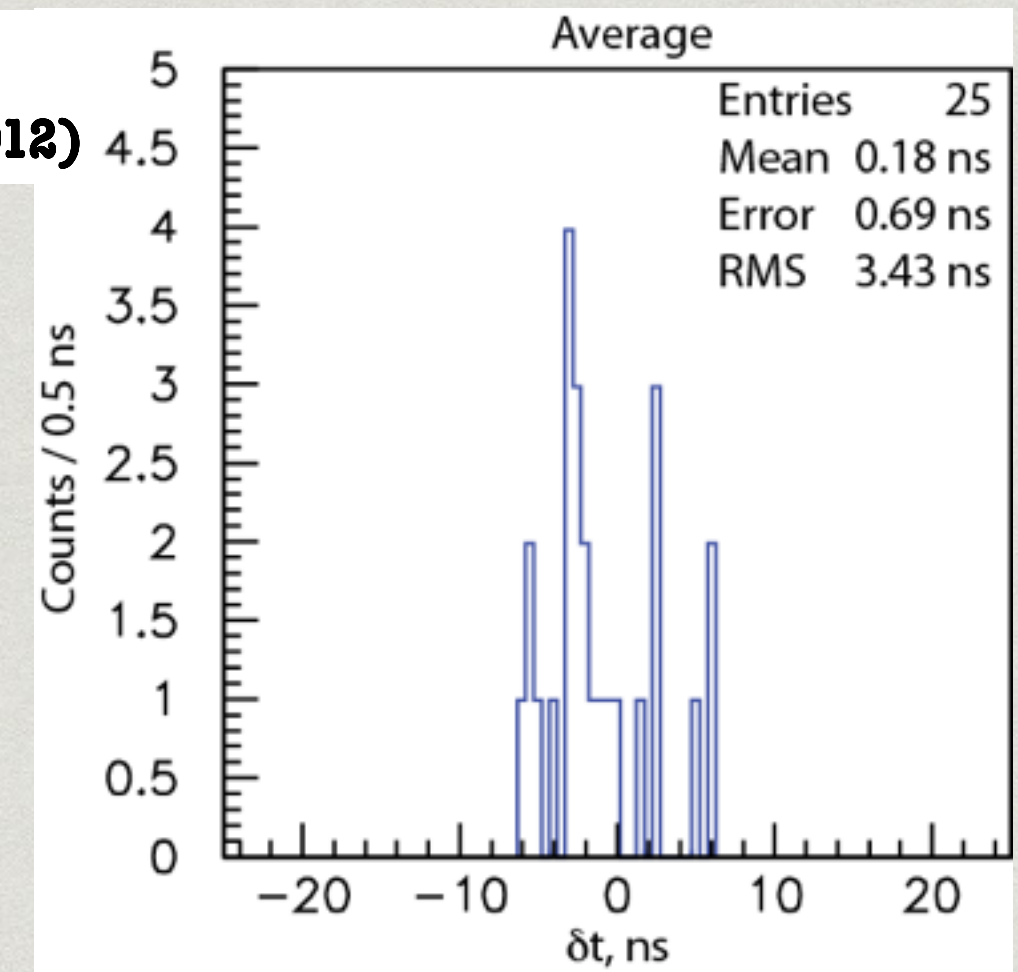
- 2011 run –> 7 beam-related interactions were collected (2.2×10^{16} pot), resulting in: 2 ν_μCC, 1 νNC and 4 μ's from ν interacting in upstream rock.
- 2012 run –> 25 beam-related interactions were collected (1.8×10^{17} pot), resulting in: 6 ν_μCC, 2 νNC and 17 μ's from ν interacting in upstream rock (1 stopping).
- Beyond having confirmed the compatibility of the neutrino velocity with the speed of light, the final measurement shows a remarkable precision, paving the way to the exploitation of the fine bunched structure of neutrino beams.

Physics Letters B 713, 17 (2012)



$\delta t = [0.3 \pm 4.9\ (stat) \pm 9\ (syst)]$ ns

JHEP 11, 049 (2012)



$\delta t = [0.18 \pm 0.69\ (stat) \pm 2.17\ (syst)]$ ns


[ICARUS Collaboration]

ICARUS NEXT FLIGHT

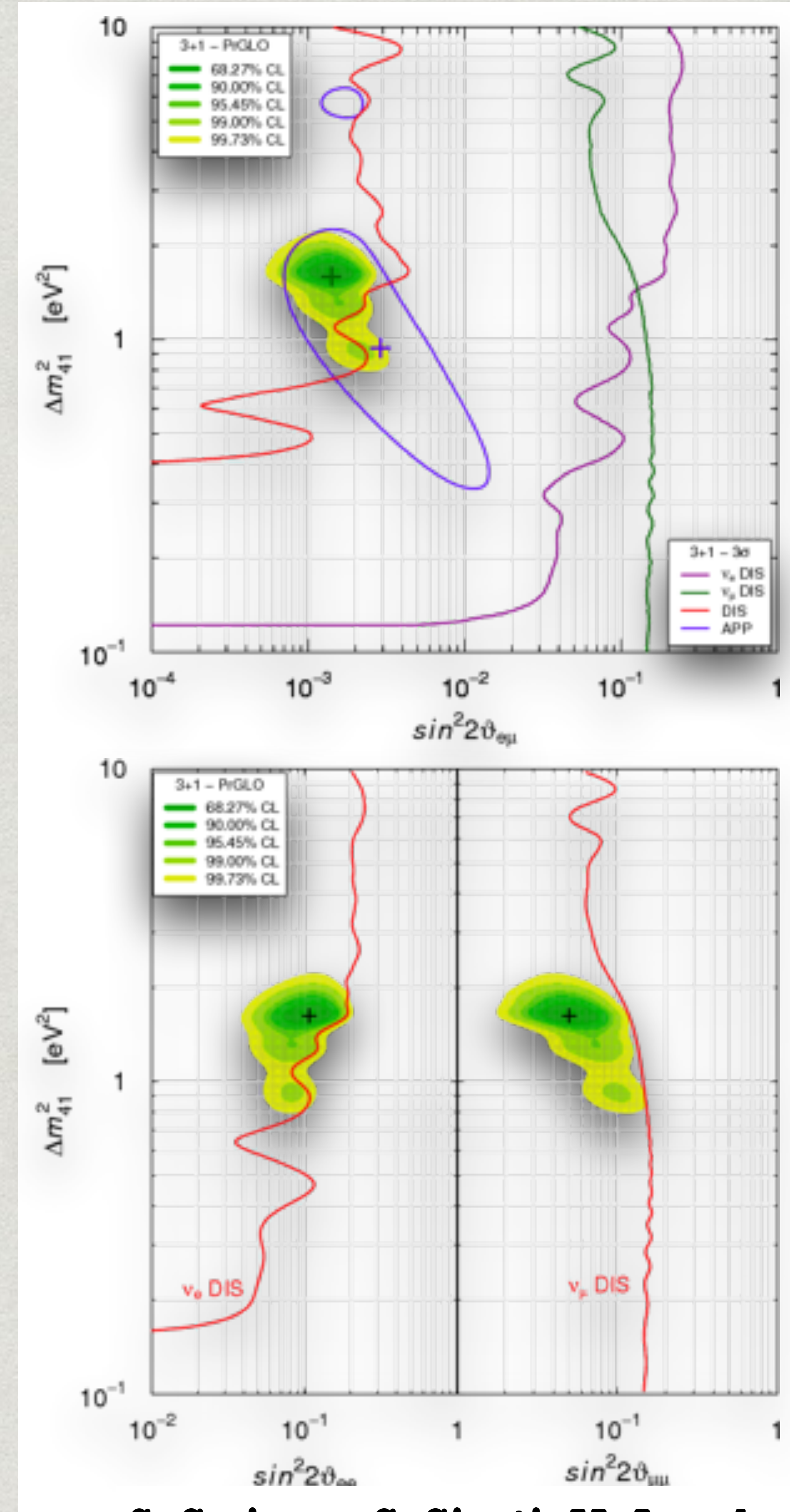
The Short Baseline Neutrino program at Fermilab Booster beam to search for "sterile" neutrino oscillations

The puzzling picture of short baseline ν oscillations

Three independent classes of anomalous results, not fitting into the "standard" landscape of 3-flavour ν mixing, have been reported by multiple experiments studying ν oscillations:

- disappearance signature in the anti-ν_e events detected from near-by nuclear reactors, with R = 0.938 ± 0.023 ratio between observed and predicted event rates;
- disappearance signature in the ν_e events from Mega-Curie k-capture calibration sources in experiments devoted to the detection of solar ν_e, with R = 0.86 ± 0.05;
- appearance signature of ν_e/anti-ν_e from experiments studying ν_μ/anti-ν_μ beams produced at particle accelerators, with 3.4 σ (MiniBooNE) / 3.8 σ (LSND) evidence for oscillations.

While each of these measurements alone lacks the significance to claim a discovery, together they all point to the possible existence of at least a fourth non standard and heavier "sterile" neutrino state driving oscillations at small distances, with Δm^2_{new} of the order of ≈ 1 eV^2 and relatively small $\sin^2(2\vartheta_{new})$ mixing angle.

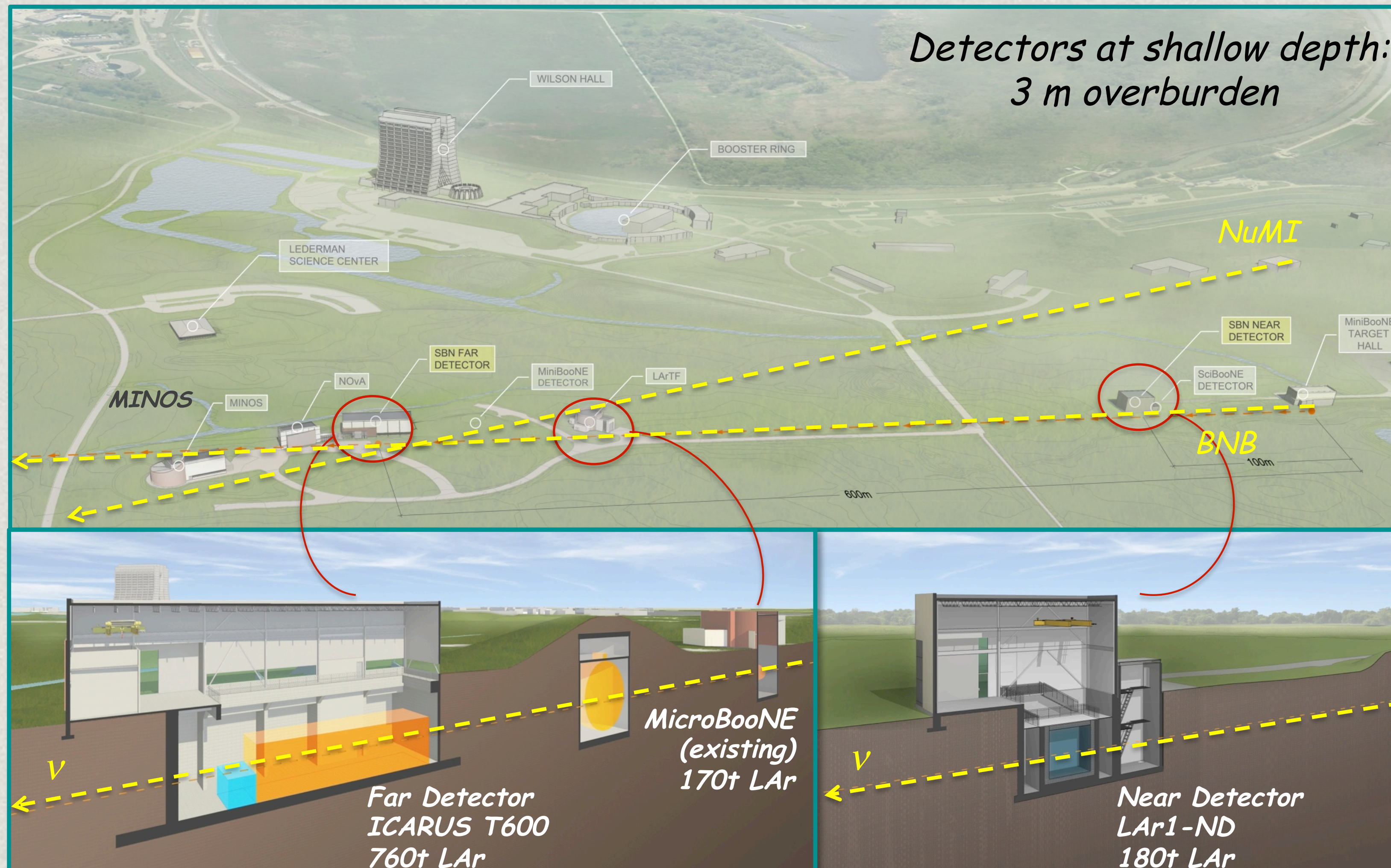


S. Cariazzo, C. Giunti, M. Laveder
arXiv:1507.08204

The proposed SBN experiment at Fermilab

An ultimate experiment with multiple LAr-TPCs exposed to FNAL Booster ν beam ($<E_\nu>$ ~ 0.8 GeV) has been proposed to FNAL PAC on Jan 15th 2015 as definitive answer to the "sterile neutrino puzzle", being rewarded with a recommendation for Stage-1 approval.

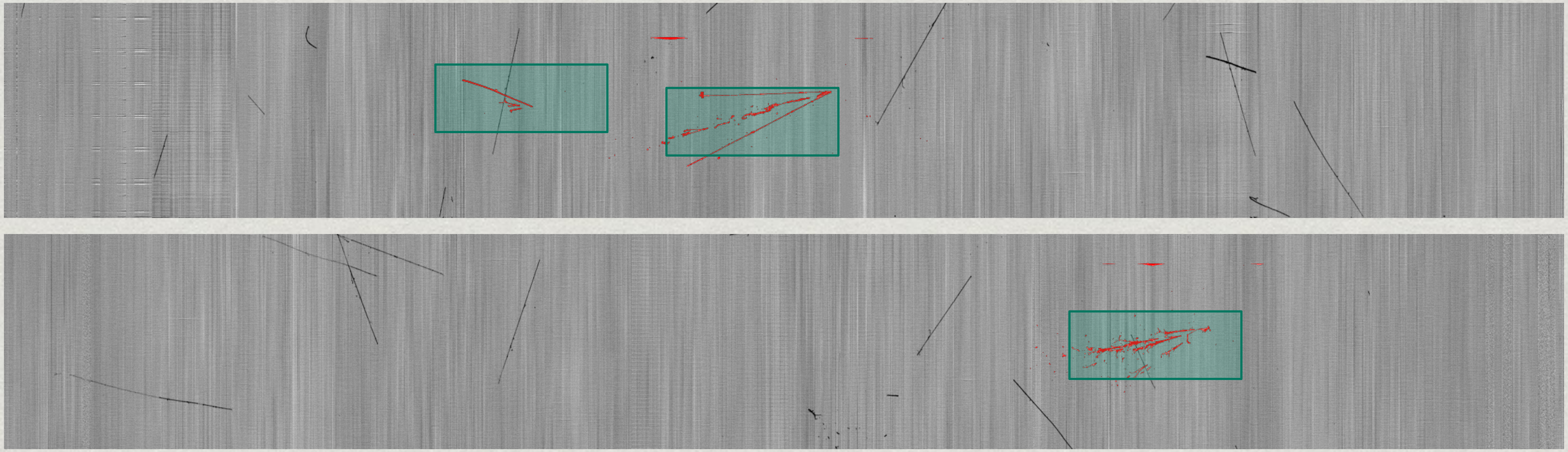
- SBND detector to be built anew, with 82 t LAr active mass, at 110 m from target;
- MicroBooNE detector (89 t), installed at 470 m and ready for commissioning;
- ICARUS T600 (476 t), presently at CERN for refurbishing, at 600 m.



Both ν_e appearance and ν_μ disappearance will be independently measured by comparing the event spectra recorded with the three detectors. The exploitation of the same ν beam and detection technique will allow for the cancelation of many systematic errors.

Challenges of operating at shallow depth

- SBND, MicroBooNE and ICARUS will be exposed to the BNB near the surface, under 3 m of concrete overburden, therefore being exposed to a high rate of cosmic rays.
- This situation will have a twofold effect.
  - A significative amount of spurious triggers will be caused by cosmic μ's in coincidence with the beam spill (1.6 μs duration): in ICARUS-T600 5 times more cosmic ray than neutrino interaction events are expected.
  - Several uncorrelated c-rays will occur in the LAr active volume during the drift window readout at each triggering event: ~ 11 tracks per 1.5 m drift are expected in the whole ICARUS-T600, relying on experience of data taking on surface in 2001 (Pavia, Italy).
- Photons associated with cosmic μ represent a serious background for the ν_e appearance search, since electrons they generate in LAr can mimic a ν_eCC signal.

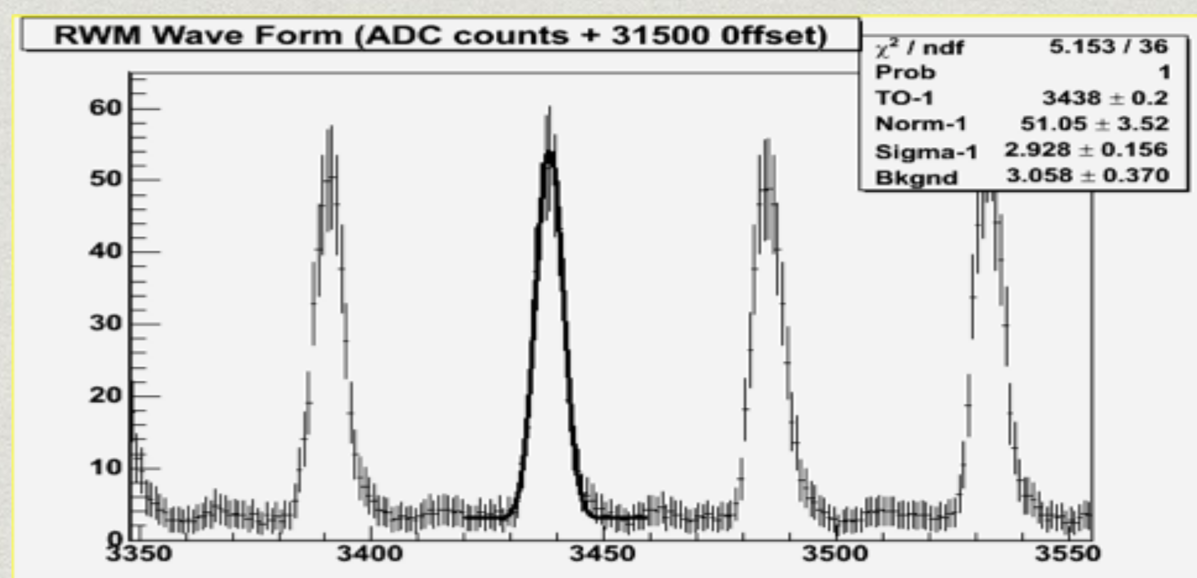


Cosmic rays (PV) + low energy CNGS beam events

Need for precise timing with the scintillation light system

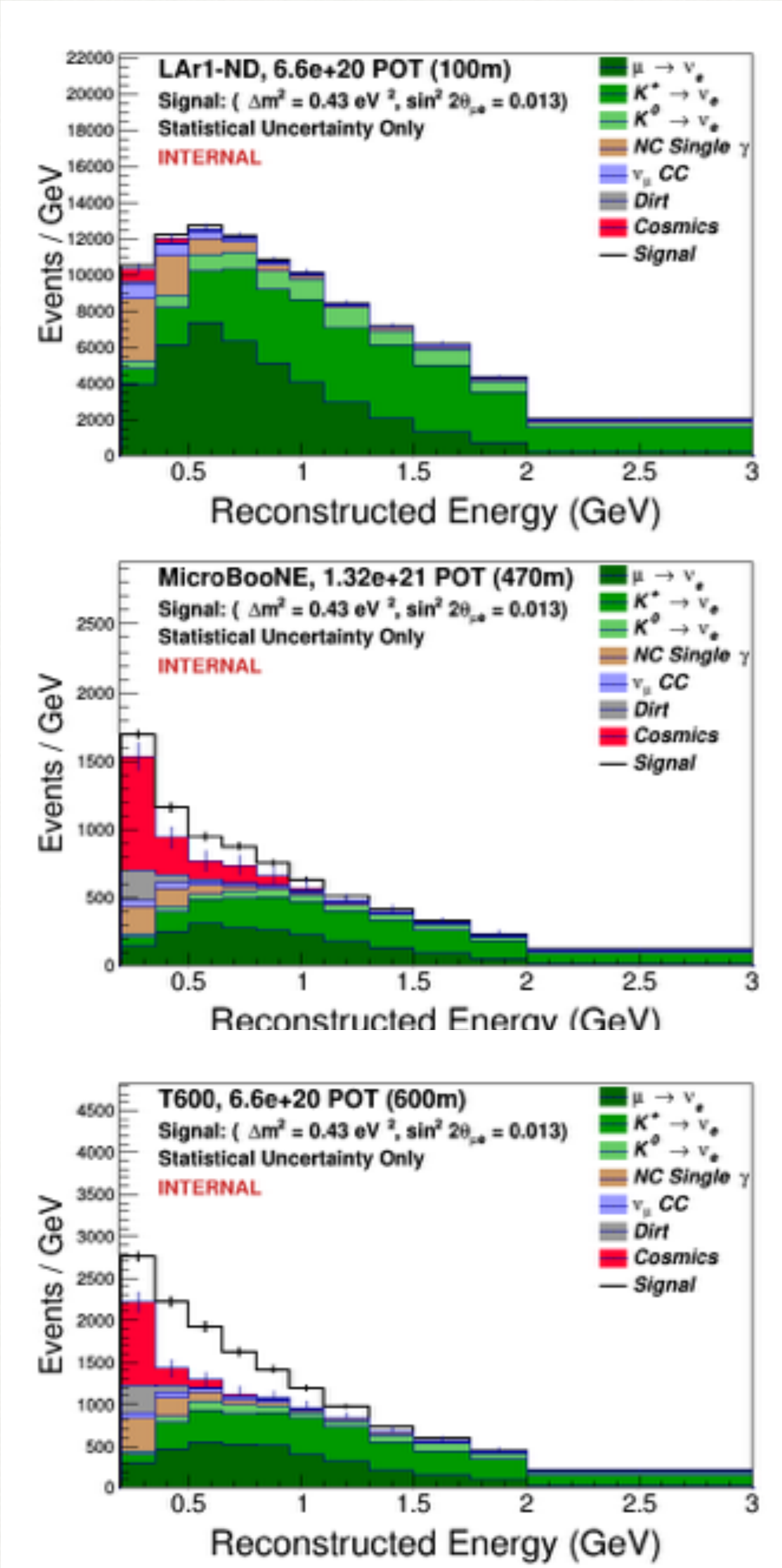
- In order to strongly mitigate this cosmogenic background, timing of each element of the TPC image with respect to the trigger time must be precisely determined.
  The absolute time information can't be gathered directly from the 3D reconstruction of the signals collected on the TPC wires, due to its ambiguity in the drift direction. Therefore the 1-to-1 match of each ionisation charge signal (wires) with the corresponding scintillation light one (PMTs) will resort only on the combination of the 3D position reconstructed with both systems, thus requiring high performance of the light scintillation system both in space and time resolution.
  This challenging identification process would be largely facilitated by an external timing provided by a Cosmic Rays Tagging system around the LAr active volume.

- Further rejection of spurious triggers will come from the exploitation of the bunched structure of the Booster proton beam within each spill (2 ns wide bunches every 19 ns), requiring a ~ ns accuracy of the internal timing system.



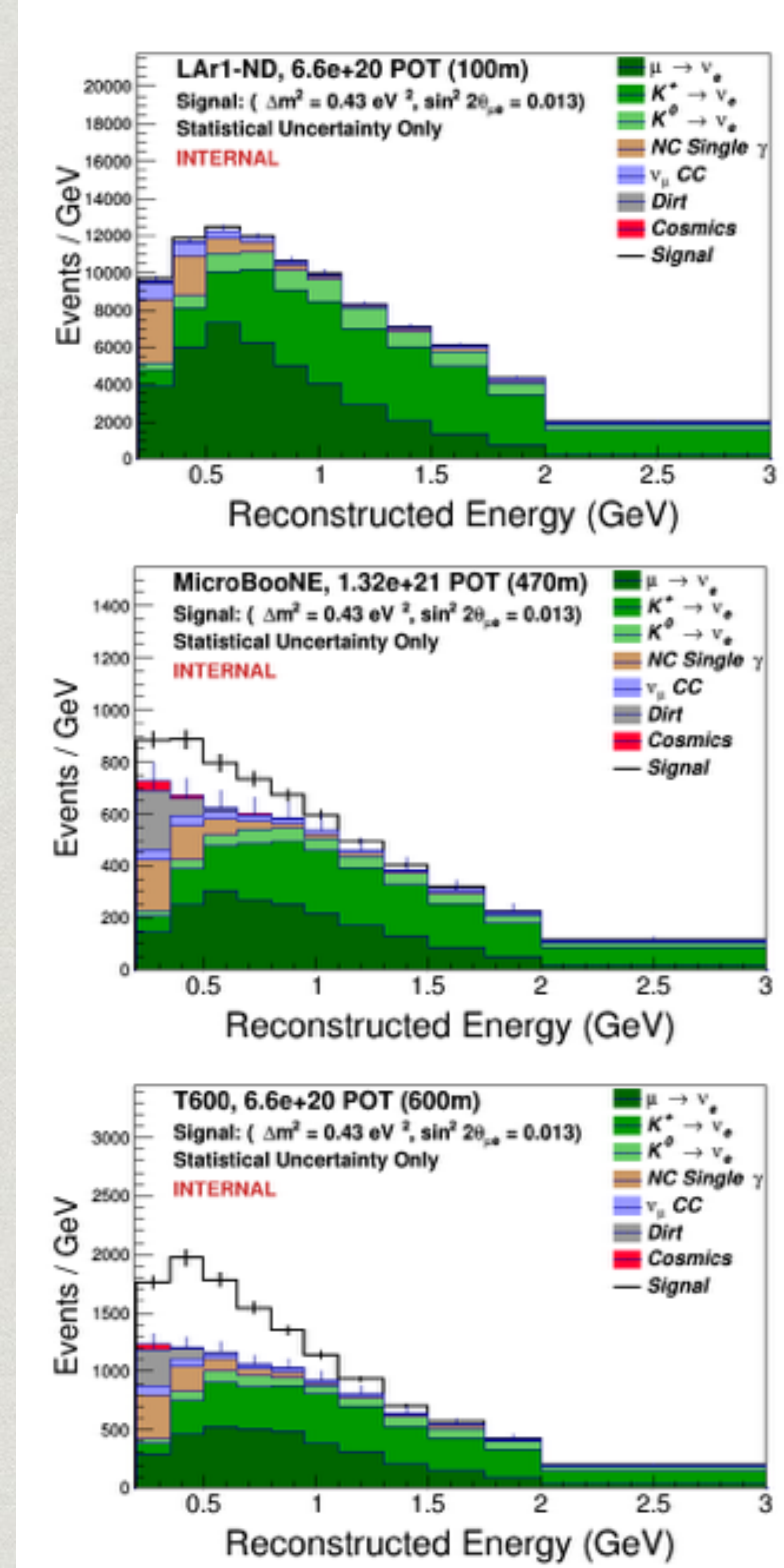
The experience gained with the operation of ICARUS-T600 detector will represent an asset. In particular the measurement of neutrino velocity with the CNGS beam demonstrates the feasibility of a ~ ns precision in timing with scintillation light signal.

Cosmogenic background rejection at SBN

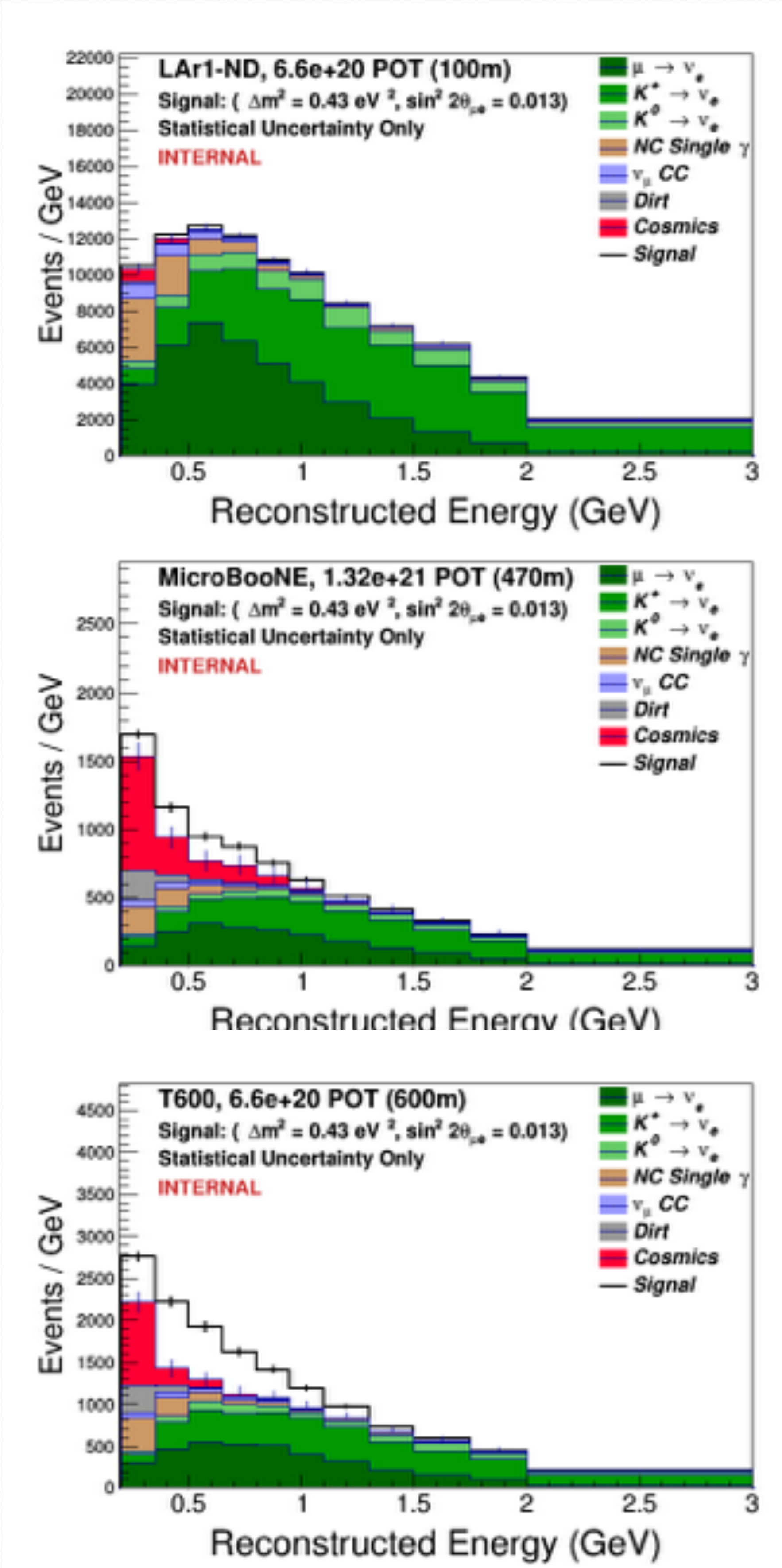


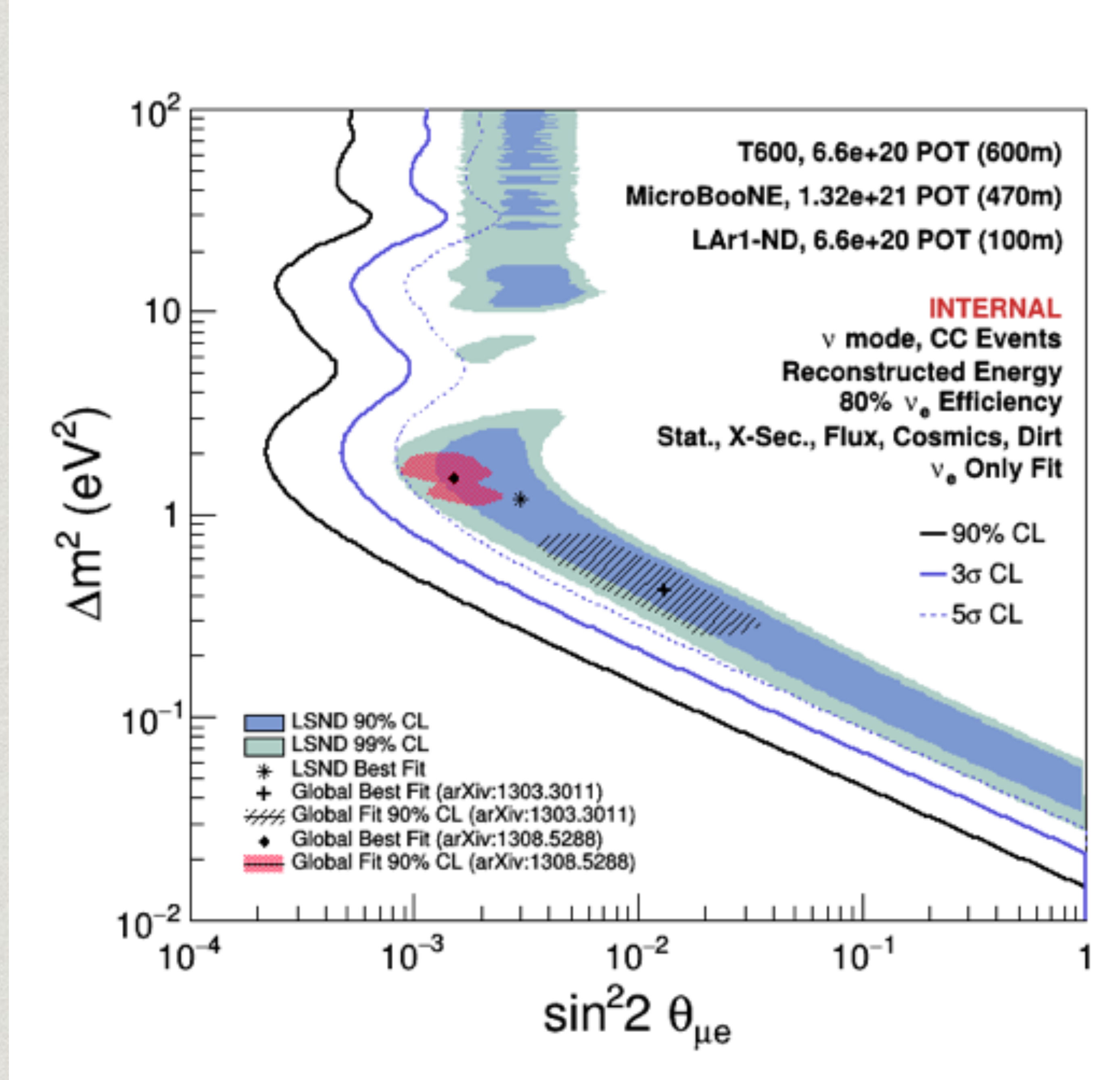
Assuming a cosmogenic background rejection capability of 95% (conservative!), by combining information from internal scintillation light and external tagging

Small effect on signal: reduction at 1% level



Sensitivity of SBN program in ν_eCC appearance channel





The LSND 99% C.L. region will be covered at ~ 5 σ level in 3 years of data taking with positive focusing of the BNB (~ 6.6 x 10^{20} pot).

Relevance of ν_μCC disappearance measurement

- In the framework of 3+1 model (only 1 light sterile neutrino), three mixing angles are introduced describing ν_μ disappearance ($\theta_{\mu x}$), ν_e disappearance (θ_{ex}) and appearance ($\theta_{\mu e}$) cross-related through the relation

$$\sin^2(2\theta_{\mu e}) = 1/4 \sin^2(2\theta_{\mu x}) \sin^2(2\theta_{ex})$$

- As a consequence, a possible ν_e excess due to the existence of sterile neutrinos will necessary be due to the combined effect of ν_e appearance and disappearance

$$S = R\nu_\mu(E)\left[\frac{1}{4}\sin^2(2\theta_{\mu x}) - \frac{R\nu_e}{R\nu_\mu}(E)\right]\sin^2(2\theta_{ex})\sin^2(1.27\,\Delta m_{41}\,L/E)$$

- The interplay between these 2 effects can be disentangled by independently measuring ν_μ disappearance (or measuring ν_e appearance varying the intrinsic ν_e contamination of the beam)

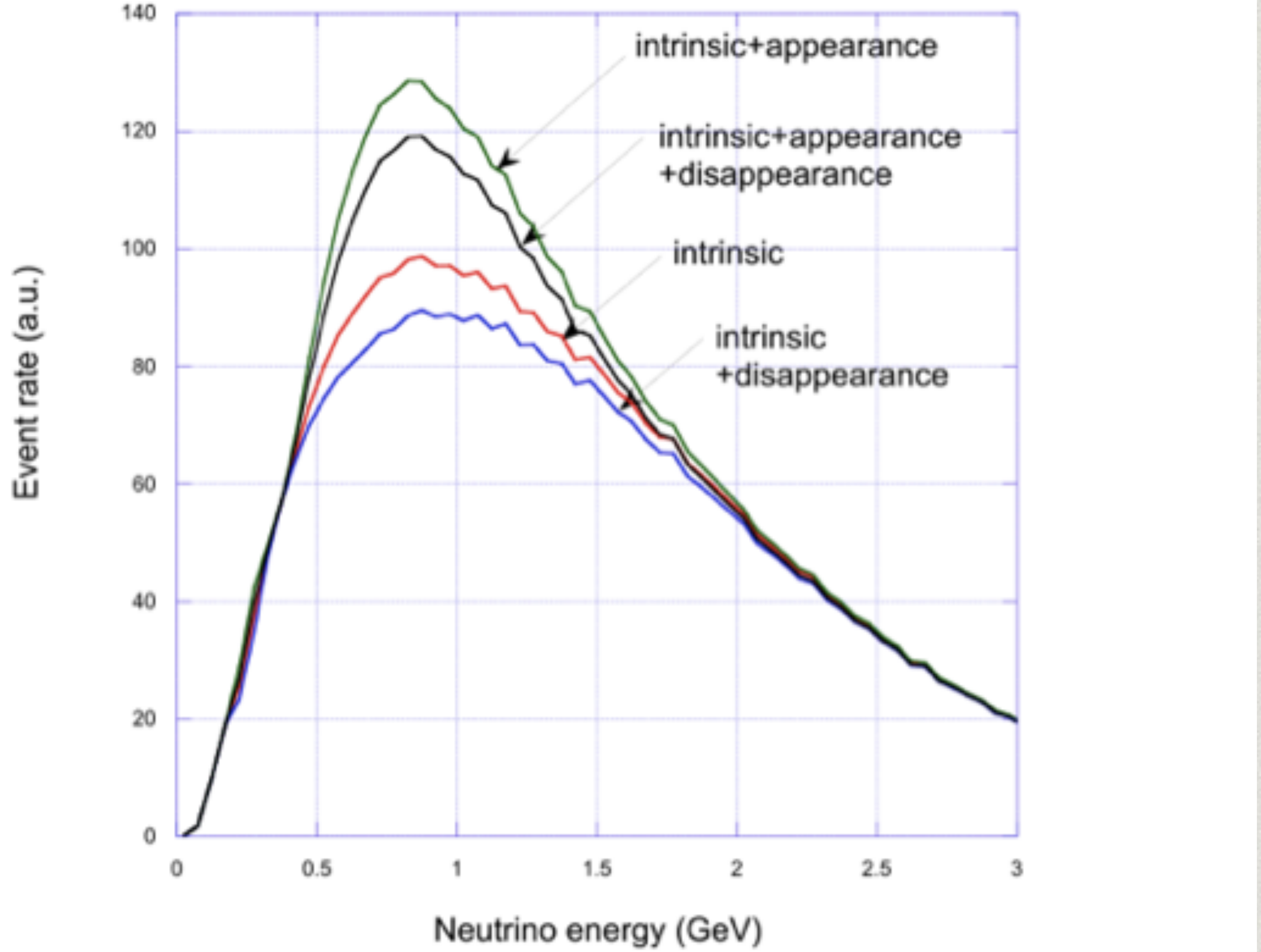
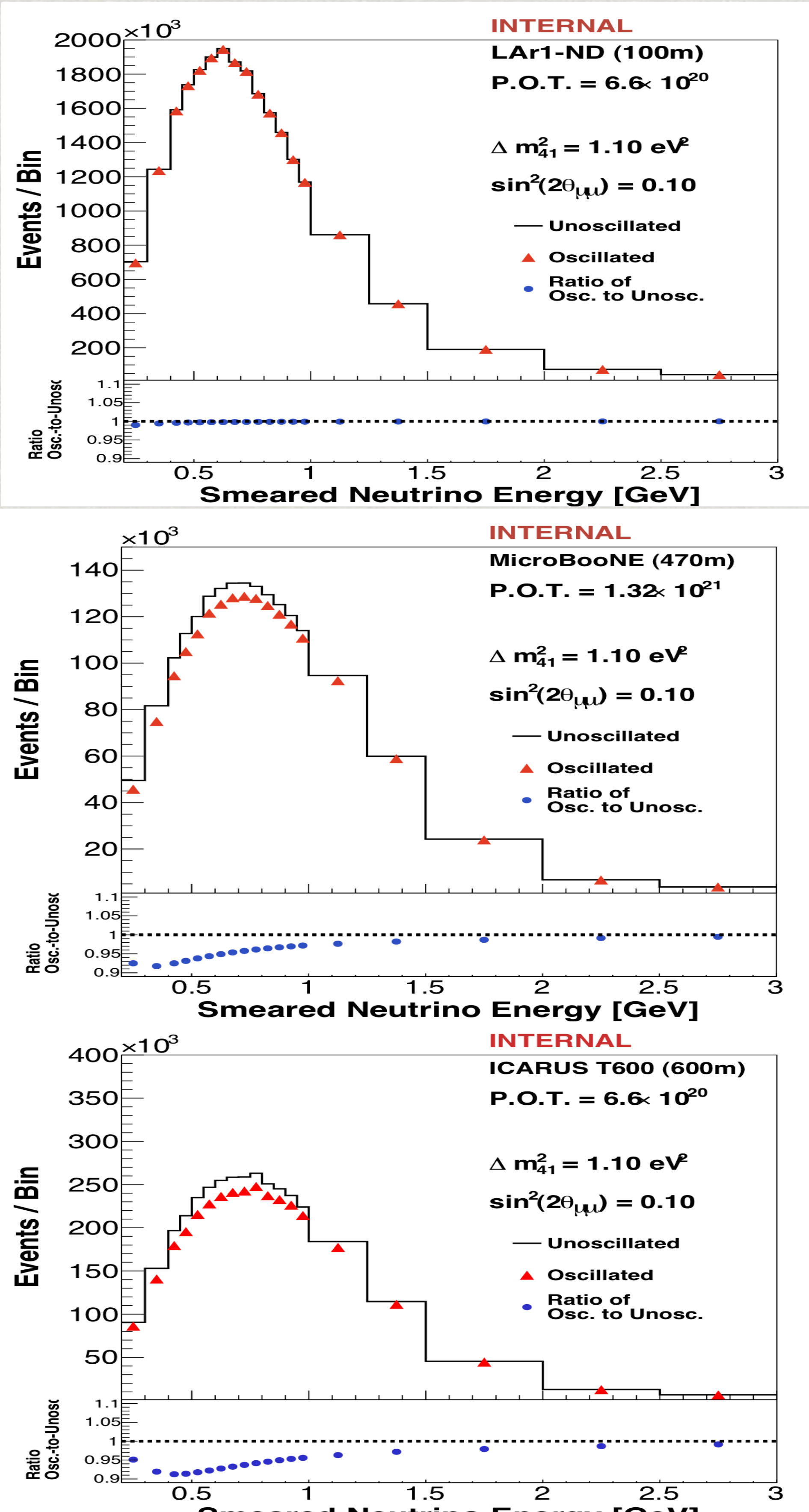
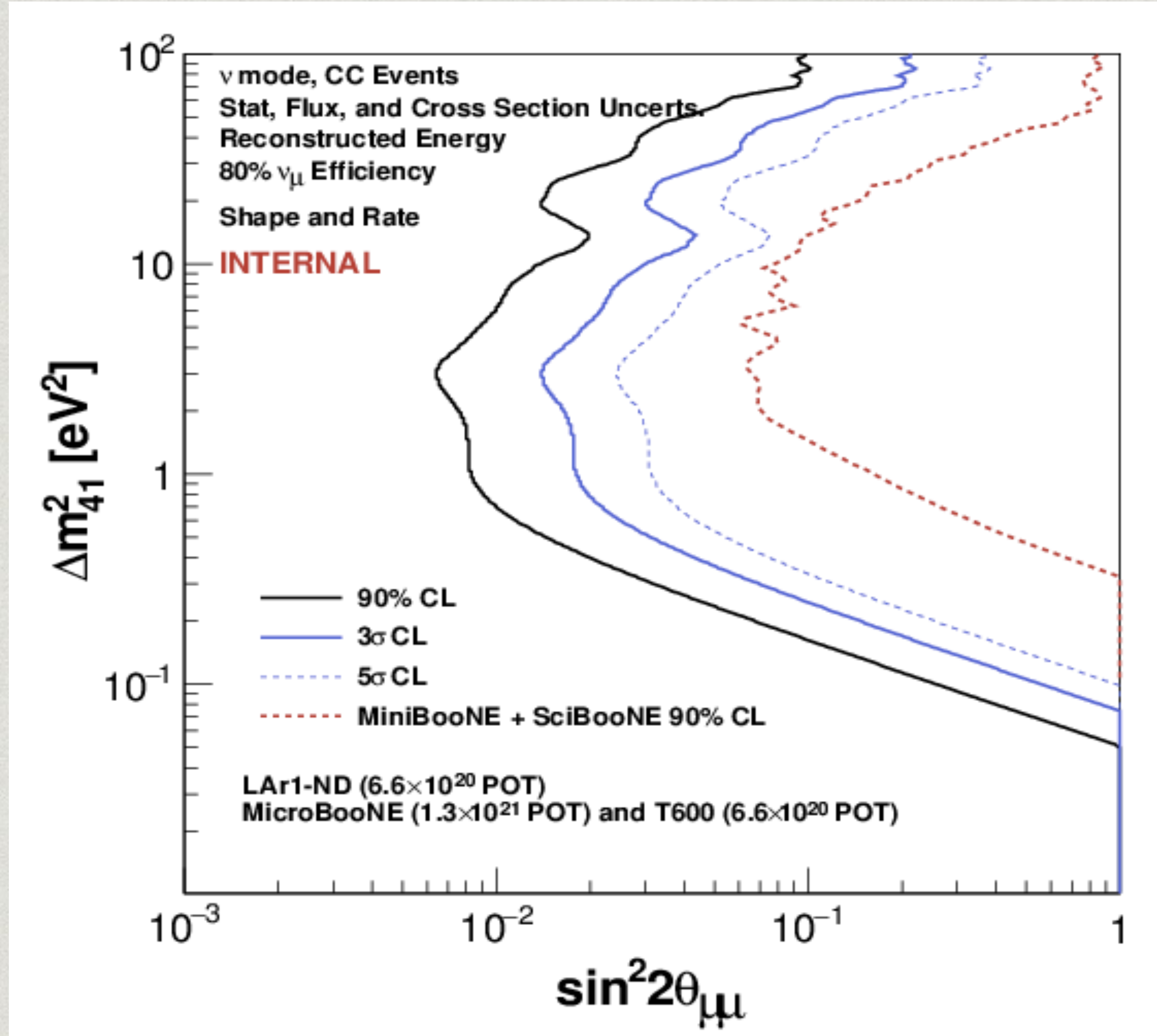


FIGURE 1. Contribution to the ν_e excess in the Booster neutrino spectrum in case of a detector placed at ~ 600 m from the beam target, as foreseen for the ICARUS T600, for the best fit of Giunti-Laveder 3+1 neutrino model (arxiv1308.5288) predicting $\Delta m^2_{41} \sim 1.5\, eV^2/c^2$ and $\sin^2(2\theta_{\mu e}) \sim 1.25\ 10^{-3}$, $\sin^2(2\theta_{ex}) \sim 10^{-1}$, $\sin^2(2\theta_{\mu x}) \sim 5\ 10^{-2}$.

Sensitivity of SBN program in ν_μCC disappearance channel

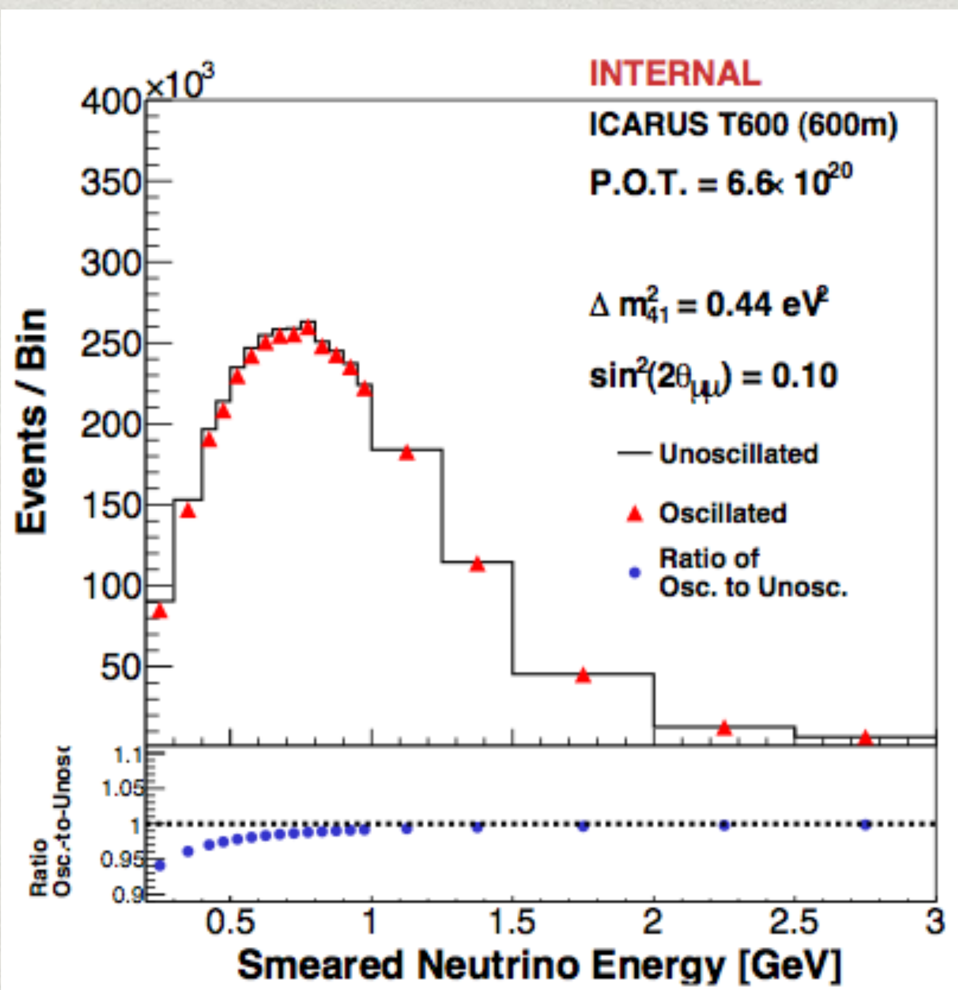




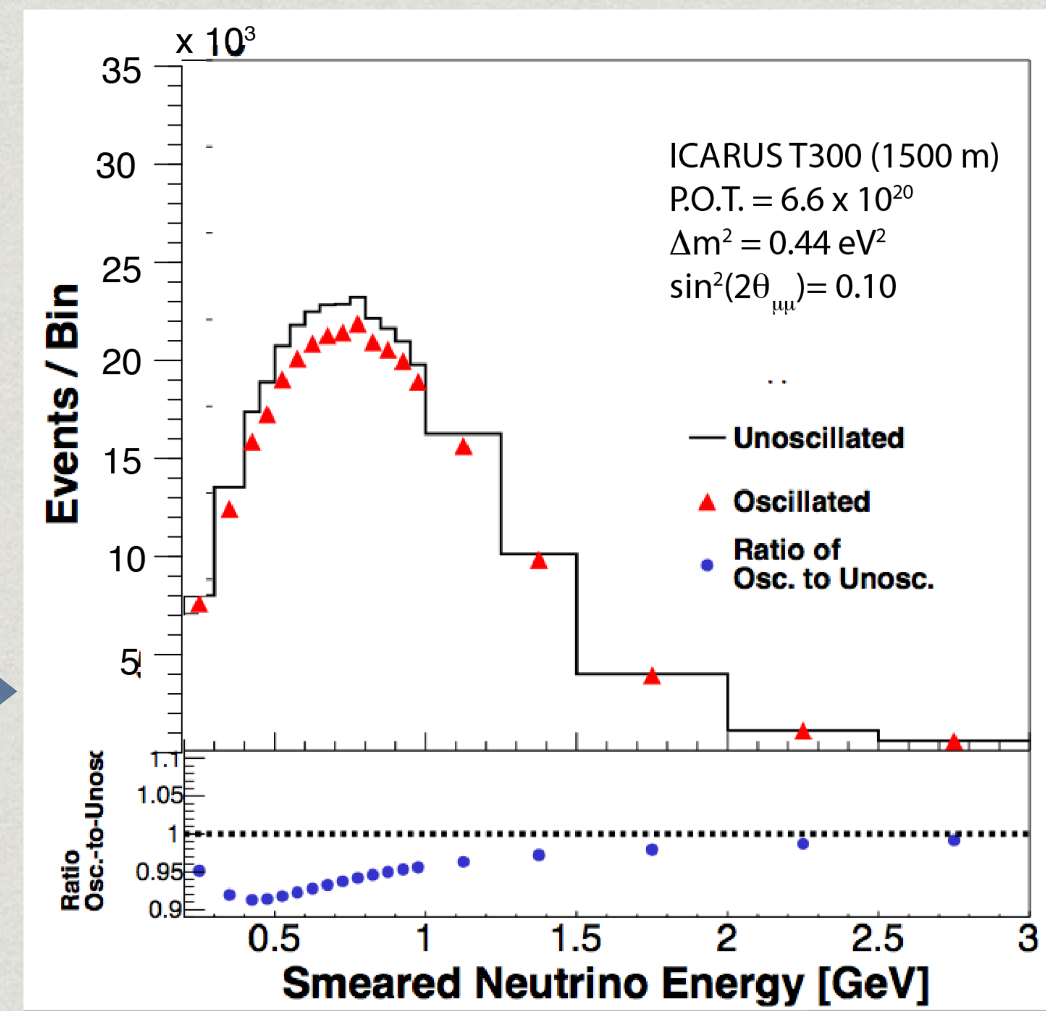
Sensitivity to ν_μ disappearance will be extended by 1 order of magnitude beyond SciBooNE+MiniBooNE limits in 3 years of data taking with positive focusing of the BNB (~ 6.6 x 10^{20} pot).

Additional considerations on ν_μCC disappearance search

- In case Δm^2 turns out to be small, f.i. of the order of 0.4 eV^2 according to the limits from Big Bang Cosmology, the ν_μ disappearance effect at 600 m will be limited at the lowest neutrino bin energies, namely 0.2÷0.4 GeV.
- In this scenario one of the T300 could be moved to a distance of the order of 1500 m at a later stage of the SBN program, in order to improve the sensitivity,.



Moving ICARUS-T300 from 600 m to 1500 m



T600 exposure to NuMI beam

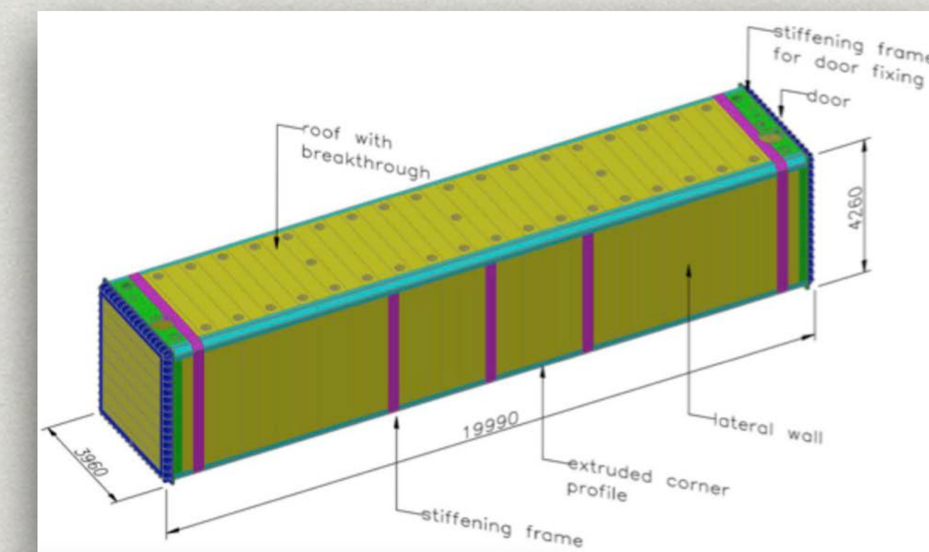
- The NuMI beamline is fed by 120 GeV protons with 4 x 10^{13} protons per pulse. The secondary beam includes a double-horn focusing system which allows for different energy configurations.
- Given the NuMI repetition rate (0.53 Hz) and its spill duration (8.6 s), one trigger every 12 s is expected in the T600, mainly due to cosmic rays occurring in the coincidence gate. About 1 neutrino event from the NuMI beam every 150 s is foreseen.
- The T600 will collect a large neutrino event statistics in the 0÷3 GeV energy range with an enriched component of electron neutrinos (several %) from the dominant three body decay of secondary K, accounting for the large off-axis angle.
- A careful and detailed analysis of these events will allow an evaluation of detection efficiency and background reduction by kinematical cuts, in several neutrino interaction channels, at the energy of the second oscillation maximum in the signal expected at the long baseline neutrino oscillation Program.

WA104 Project at CERN: overhauling of the T600

- The T600 was moved from LNGS to CERN in Dec. 2014 and is being upgraded, by introducing technology developments while maintaining the already achieved performance (**WA104 program**):
  - new cold vessels and purely passive insulation;
  - refurbishing of the cryogenic and purification equipment;
  - flattening of existing cathode panels, to get improved planarity (factor 5-10);
  - upgrade of the light collection system;
  - new faster, higher-performance read-out electronics.
- In addition, the Cosmic Ray Tagger and filtering/selection tools are items common to the whole SBN program and they are being jointly developed by the 3 Collaborations.
- The WA104 program is regulated by a Memorandum of Understanding between CERN and INFN. Active, daily collaboration between ICARUS people and CERN personnel (Mech. Workshop, Cryogenics, TE department) is ongoing, and fundamental to successfully complete the refurbishment.

New cold vessels and insulation

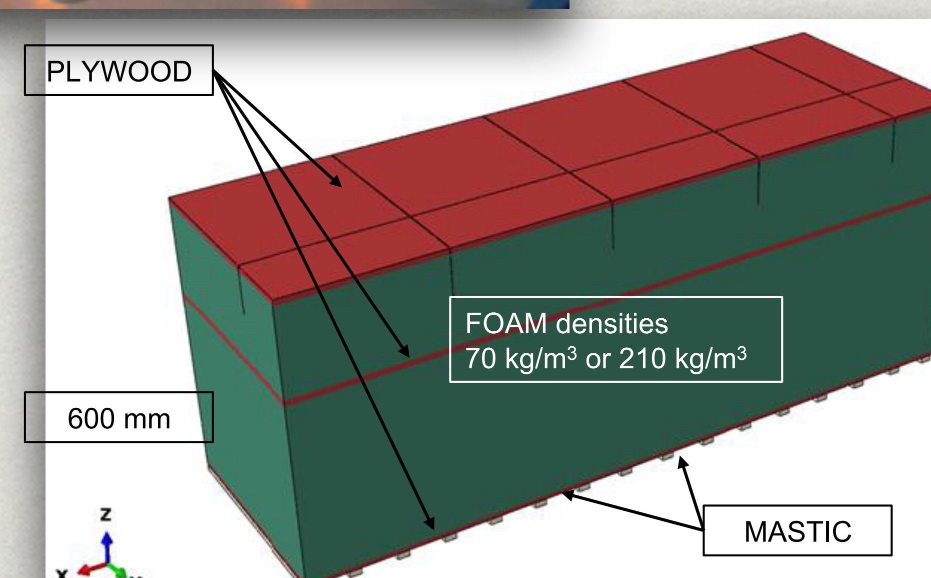
- New LAr containers (cold vessels) made by extruded aluminum profiles welded together, to form a ultra clean and ultra vacuum-tight double walled container compliant with EU & US rules.



- Panels pre-assembled by the company (STEP-G) undergo final assembly at CERN, buildings 156 and 185. Dedicated tools and rotation system allow welding in flat position and achieving the requested highest quality level.

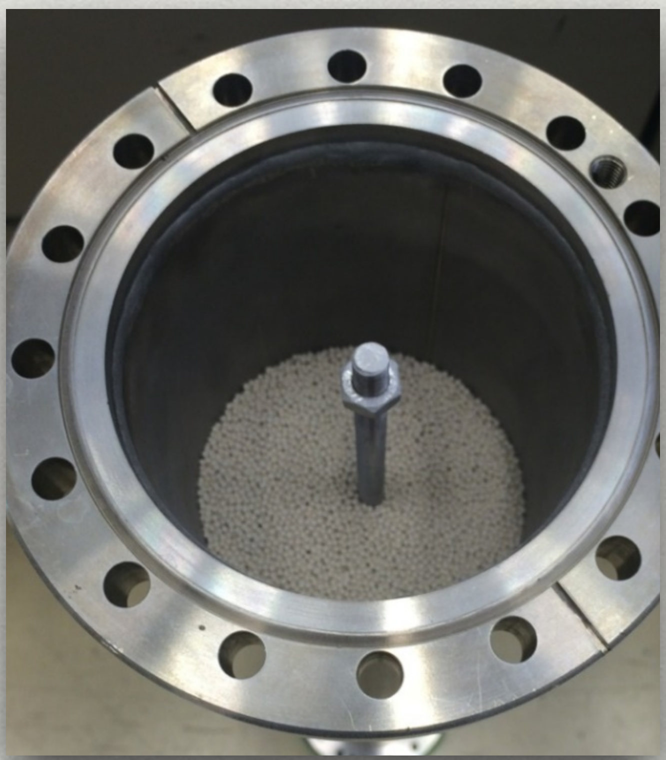
- The top of the first module (T300) is completely welded and the U-frames are under production: it will be completed by June.

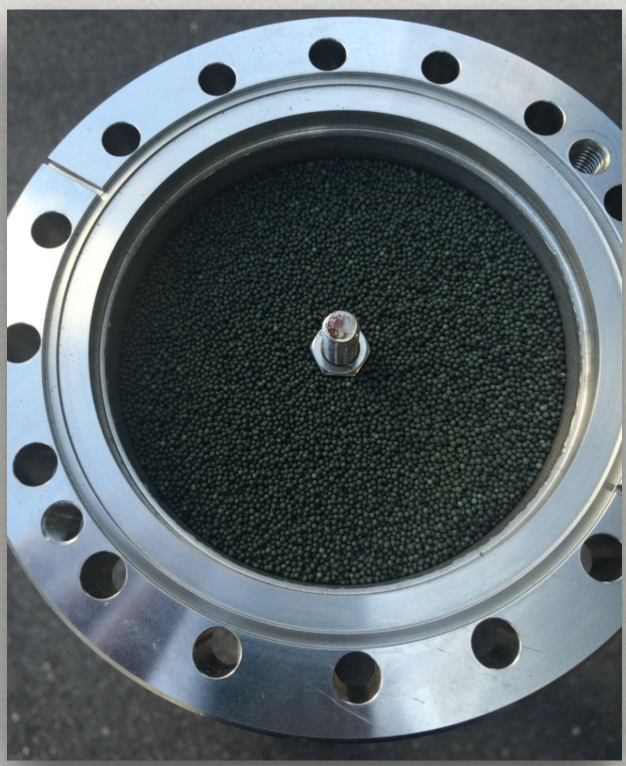
- Purely passive insulation has been chosen for the installation, coupled to standard two-phase N_2 cooling shield, without need for internal membranes.
  Expected heat loss through the insulation: ≈ 6.6 kW (10 - 15 W/m^2).



Refurbishing of the cryo/purification equipment

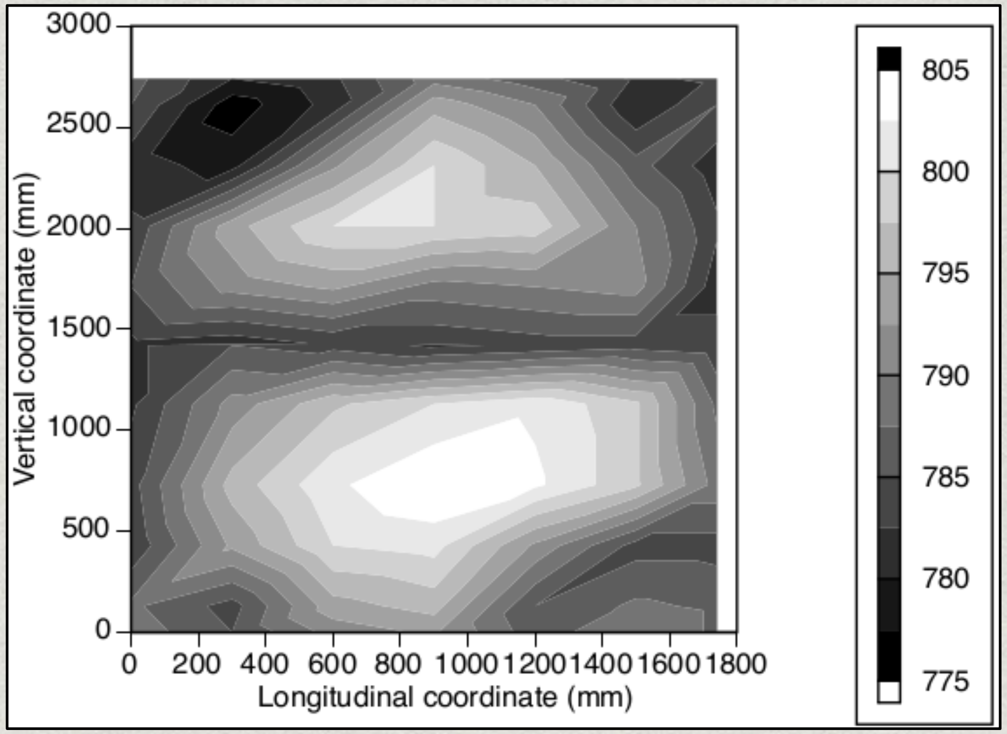
- The layout of T600 cryogenic/purification plant will be reorganised into self-consistent sub-units (skids) to be built and fully tested at CERN, prior to delivery to FNAL.
- Maintenance of cryogenic pumps and valves from the Gran Sasso installation was started in 2015, in order to select parts to be recovered for operations @ FNAL.
- Process and Instrumentation diagrams (P&ID) and technical specifications for the ICARUS detector are being finalised in collaboration between ICARUS and CERN Cryolab group. Tender opening is foreseen for June 20th.
- New filters for LAr purification, made of molecular sieve and alumina pellets with a rough layer of copper deposited on surface (10% mass of Cu), designed by Fermilab people, are being tested and characterised in the 50 l LAr-TPC test facility at CERN building 182.
  They might be used to replace Oxysorb/Hydrosorb filters used at LNGS, whose content of hexavalent chromium has raised safety issues for use in US labs.





Cathode planarisation

- Unexpected deviations observed in muon momentum measurements (multiple scattering) of μ stopping tracks travelling at d < 50 cm from the cathode, triggered the suspect of cathode distortions affecting the uniformity of the electric drift field.
- This effect was confirmed, and quantified in maximum 3 cm deviations from planarity, by means of measurements with a laser meter carried out at CERN.



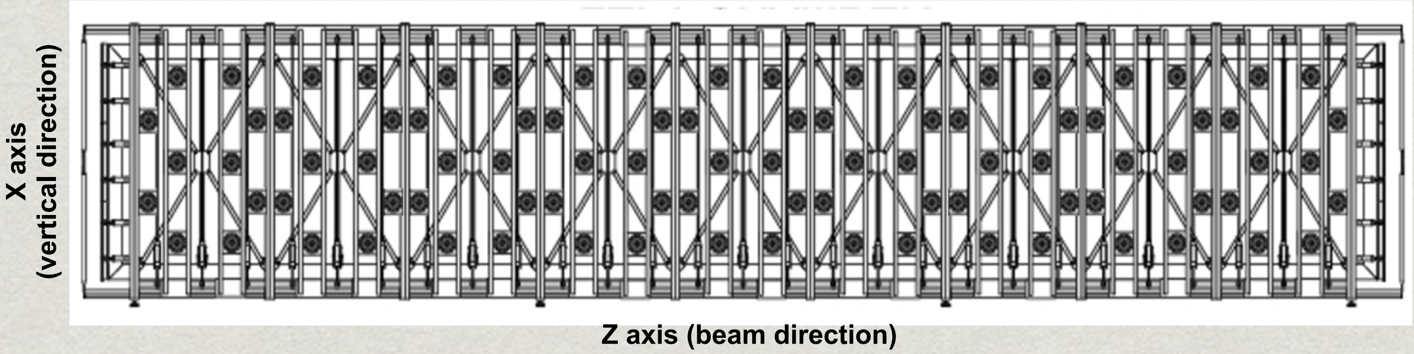
- Cathode panels of the first T300 module underwent a successful thermal treatment, including local heating and pressing, by personnel of the CERN Main Workshop: the residual non-planarity is within few mm.
- All the panels of the first T300 module were "flattened" and reinstalled in the detector after cleaning and electro-polishing.

Upgrade of the light collection system

- The light detection system is devoted to:
  - generation of a trigger signal with a sensitivity down to 100 MeV energy deposition in LAr;
  - identification of the time of occurrence of each interaction with ns resolution, in order to exploit the available 2ns/19ns bunched beam structure;
  - initial identification of event topology for fast event selection.

- 90 8" HAMAMATSU R5912-MOD PMTs will be installed in each TPC behind the wire planes, covered with 200 μg/cm^2 of TPB wavelength shifter. The resulting photo-cathode coverage corresponds to 5% of the wire plane area.

  15 photo-electrons are expected per MeV of deposited energy in a single TPC (9 phe/MeV for events close to the cathode).



- Each PMT is equipped with a customised cryogenic base. The biasing of dynodes is obtained through a passive resistive voltage divider, directly mounted on the PMT flying-leads. Divider components were selected for operation at cryogenic temperature.
- New mechanical supports for the PMT installation were designed, with a wire shielding cage which prevents the induction of PMT pulses on the facing collection planes.

PMT testing at CERN

All PMTs are being tested and characterised at room temperature in consecutive bunches of 16. A pulsed LASER source (405 nm) illuminates each PMT by means of an optical fiber.

CERN building 3179.

10% of PMTs are also tested at cryogenic temperature, 10 at a time (all PMTs are mechanically tested in LN_2 by Hamamatsu)

CERN building 182.

Completion in few weeks.

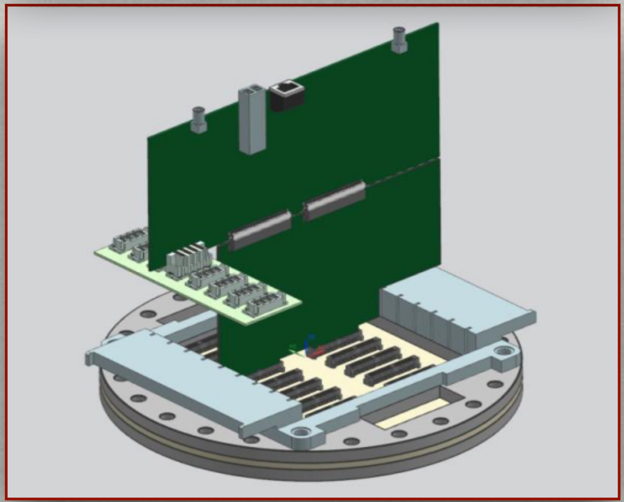
All the PMTs are being coated with TPB by evaporation under vacuum, at the rate of 5 per day.

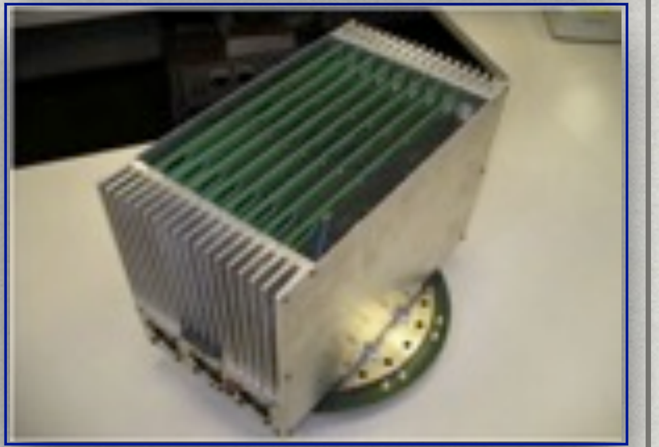
CERN building 169.

Completion by the end of May 2016.

An upgraded TPC readout electronics

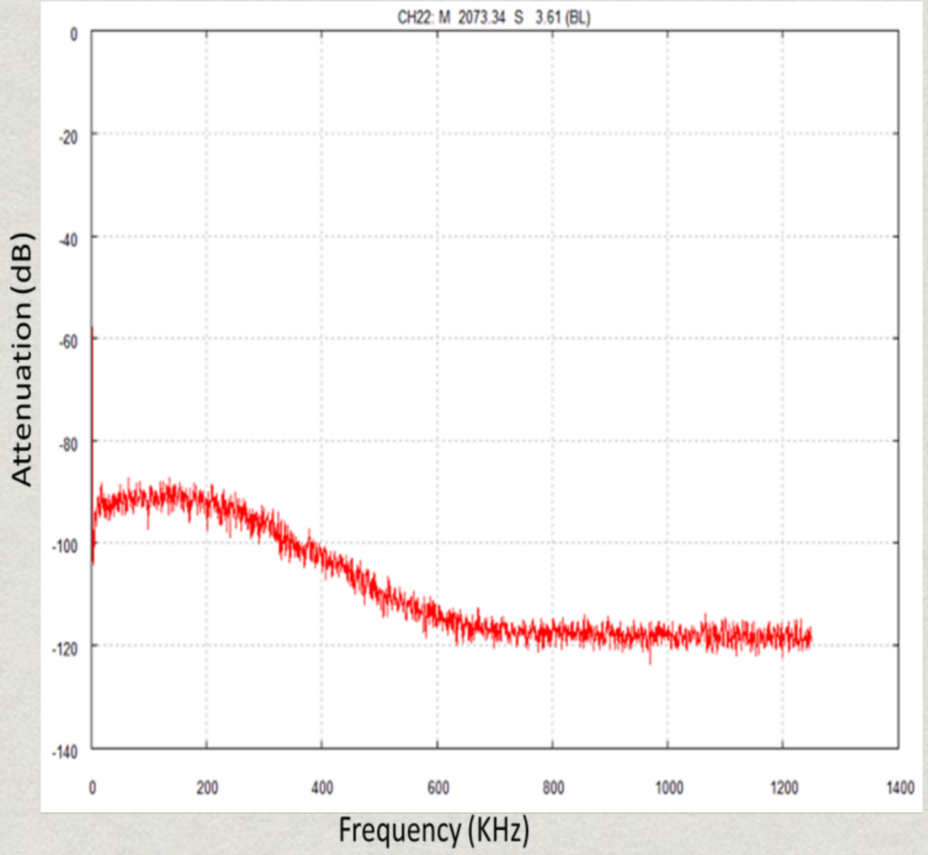
- Architecture of ICARUS-T600 front-end electronics, inherited from the one adopted in LNGS run, is a continuous waveform recording based on analogue low noise "warm" amplifiers, 2.5 MHz AD converters and programmable FPGAs.
- Improvements concern:
  - synchronous high frequency 12-bit serial ADCs instead of 10-bit multiplexed ones;
  - modern serial bus architecture (instead of VME), with optical links for faster transmission rate (Gbit/s).
  - new compact design, with both analogue and digital processing for 64 channels handled by a single board (CAEN A2795) plugged directly on a flange-mounted crate hosting 9 boards.
- The backplane of the crate is used for distributing to all 9 boards the power lines, both analogue and digital, and the TT-Link 1 wire single bus carrying a 10 MHz clock with modulated duty cycle.



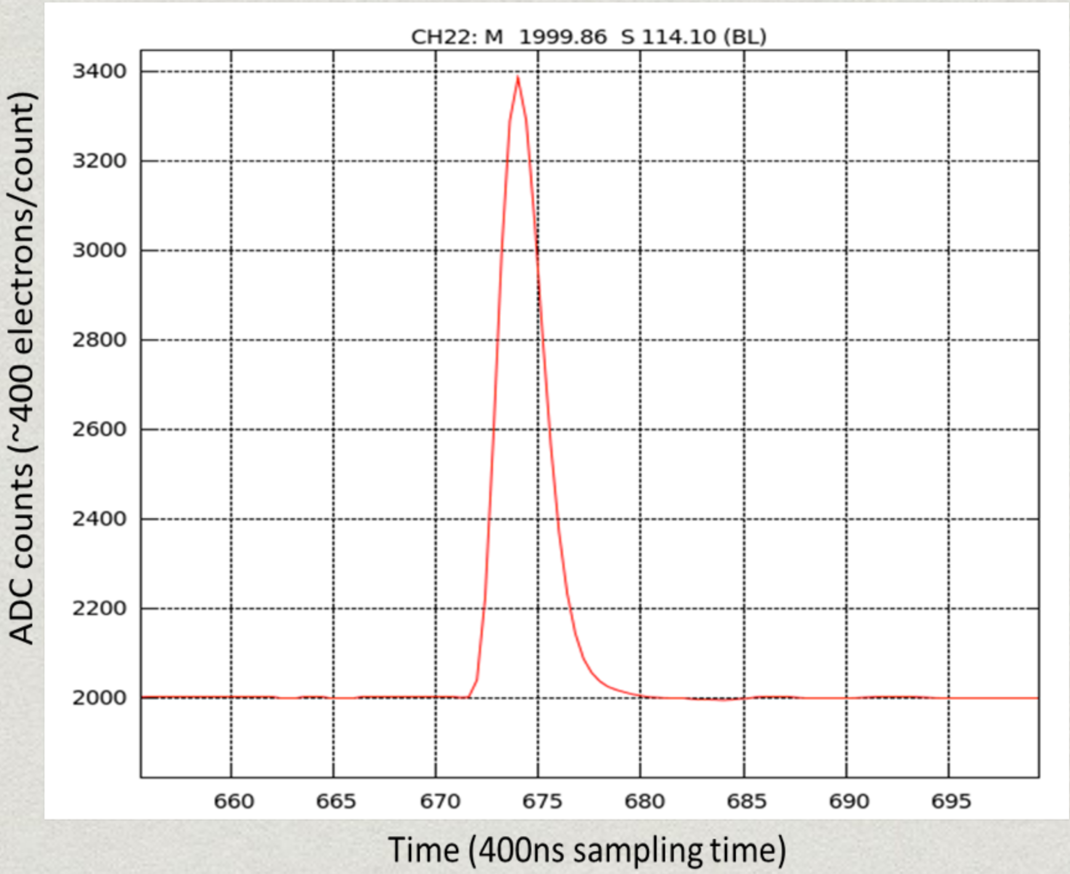


Optimisation still ongoing

- The new electronics response is designed to be faster without undershoot:
  - signal integration by pre-amplifier (long shaping time) is followed by zero-pole cancellation circuit;
  - a short shaping time has been chosen to preserve bipolar signals in Induction view, allowing for numerical integration of the digitised output.
- Tests are ongoing in parallel on 2 50 l LAr-TPC test facilities, one in Italy (INFN Legnaro Laboratories) and the other at CERN building 182.



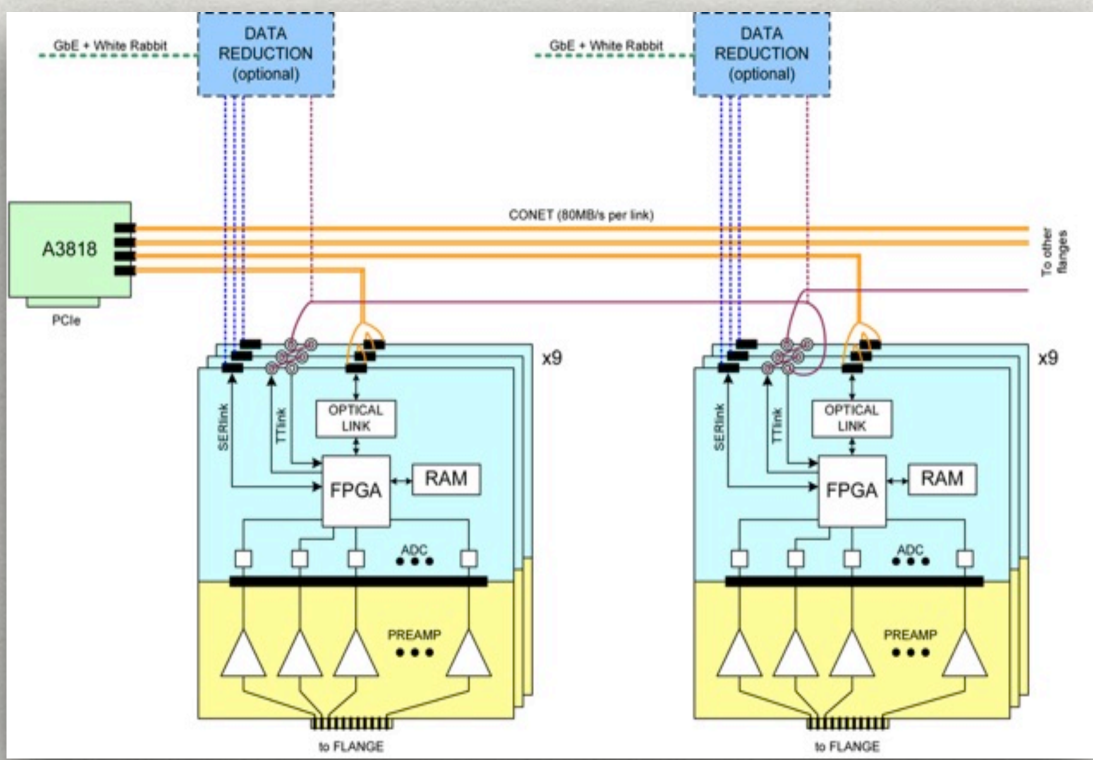
Typical FFT for collection channel connected to small test chamber.



Test pulse with italian test-stand in dry conditions, C_{det}= 410pF, 400 el/count.

DAQ architecture

- Performance, in terms of throughput, has been improved replacing the VME (~10 MB/s) and the sequential order single board access mode inherent to the shared bus architecture, with a modern switched I/O.
  Such I/O transaction can be carried over bi-directional optical links at 1.25 Gbit/s.



- The FPGA onboard is programmed to drive the optical link over a proprietary CONET-2 (Chainable Optical NETwork) protocol, handled at the other end by the CAEN PCI express board A3818 installed in a commercial PC.
  The CONET-2 protocol can stand 80 MB/s transfer rate with at most 8 boards connected in daisy chain: this is compatible with the 47 MB/s data throughput foreseen for recording 1.6 full drift windows at each extraction of the BNB in case of an upgrade of the beam repetition rate to 15 Hz.

- All data fragments (including PMTs and cosmic ray tagger) will be merged together at the level of event building, realisable in multiple nodes over a shared file-system.

- A DAQ demonstrator of the basic functionality has been setup at LNL and CERN for integrating multiple TPC front-end units with the PMT system.

WORK IN PROGRESS...