ICARUS

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CERN and INFN-Pavia

on behalf of

ICARUS/WA104 Collaboration

Workshop on Neutrino Telescopes - Venice – March 3, 2015

ICARUS-WA104 Collaboration

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Foreword

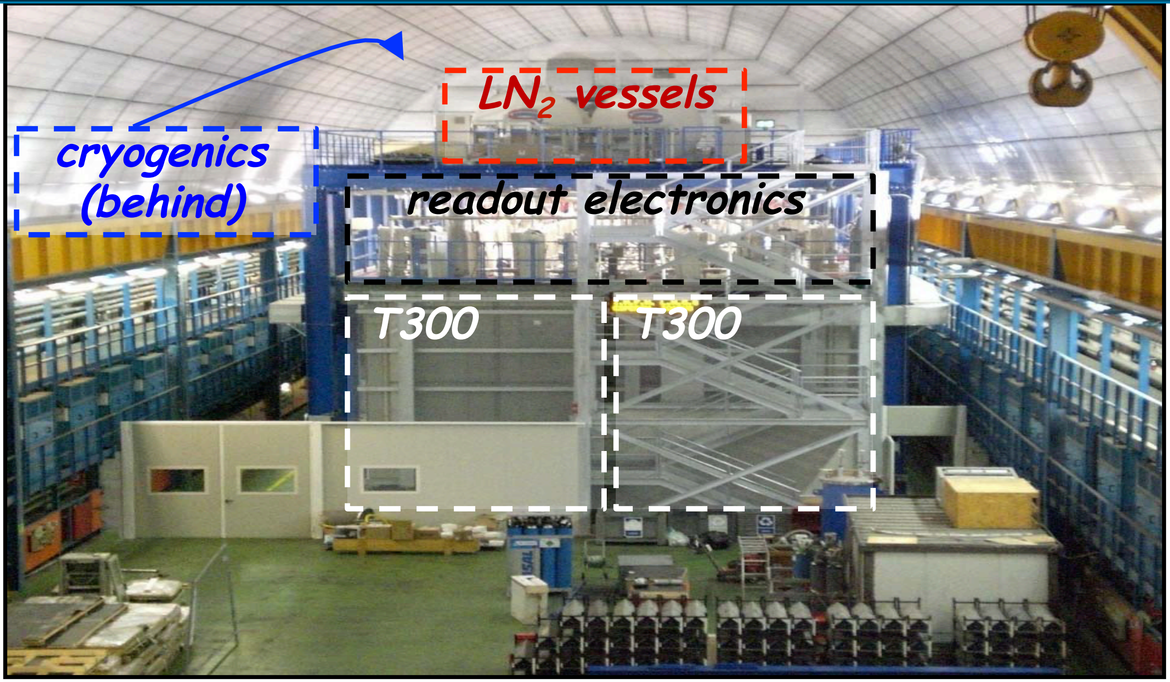
- In 2013 ICARUS concluded a very successful, long duration run with the T600 detector at the LNGS underground laboratory taking data both with the CNGS neutrino beam and with cosmic rays. Several relevant physics and technical results were achieved.
- It is mainly thanks to the continuing efforts of the ICARUS Collaboration and to the support of INFN, that the LAr TPC technology has been taken to full maturity. The T600, with about 500 ton of sensitive mass, is the largest LAr TPC ever constructed.
- A highly sensitive search for $\nu_\mu - \nu_e$ oscillation in the appearance mode was proposed already in 2009 by the ICARUS Coll. to test at CERN the LSND claim (arXiv:0909.0355, SPSC-P-345, SPSC-P-347)
- The proposed dual detector experiment allows to separately identify the Δm^2 and $\sin^2(2\theta)$ by the (simultaneous) observation at different distances of neutrino interaction with:
  - appropriate L/E oscillation path lengths to ensure appropriate matching to the Δm^2 window for the expected anomalies;

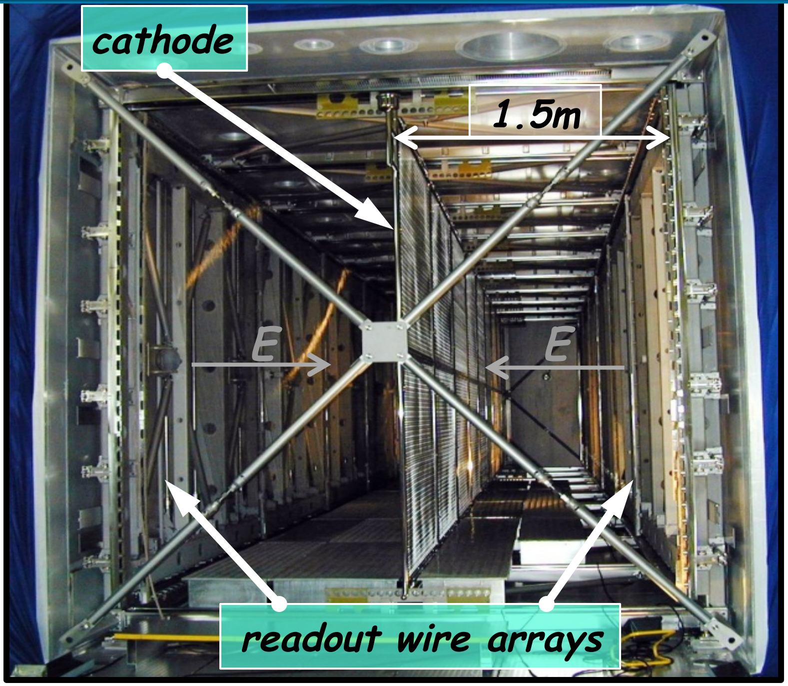
Foreword

- "Imaging" detector capable to identify unambiguously all reaction channels with a LAr-TPC;
- Very high rates due to large masses, in order to record relevant effects at the % level (>10^6 ν_μ, ≈10^4 ν_e events);
- Both initial ν_e and ν_μ components cleanly identified;

- After clarification of the CERN strategy on neutrino physics (2014-18 MTP) a similar dual detector experiment was proposed at the FNAL Booster beam (ICARUS at FNAL, Dec.2013). Two new proposals were then submitted to FNAL-PAC about one year ago.
- A joint ICARUS/LAr1-ND/MicroBooNE effort is taking place to develop a collaborative, international program at FNAL's BNB (and NuMI off-axis) with three detectors at different baselines by 2018 (near: Lar1-ND, mid: MicroBooNE, far: ICARUS);
- A common Conceptual Design Report has been submitted to the FNAL PAC in January 2015:
  - **The Proposal got level 1 approval.**

ICARUS-T600 detector



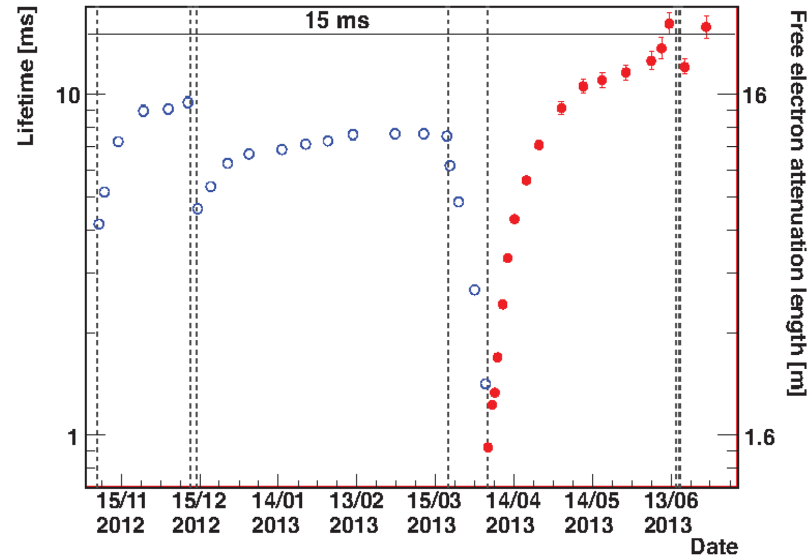


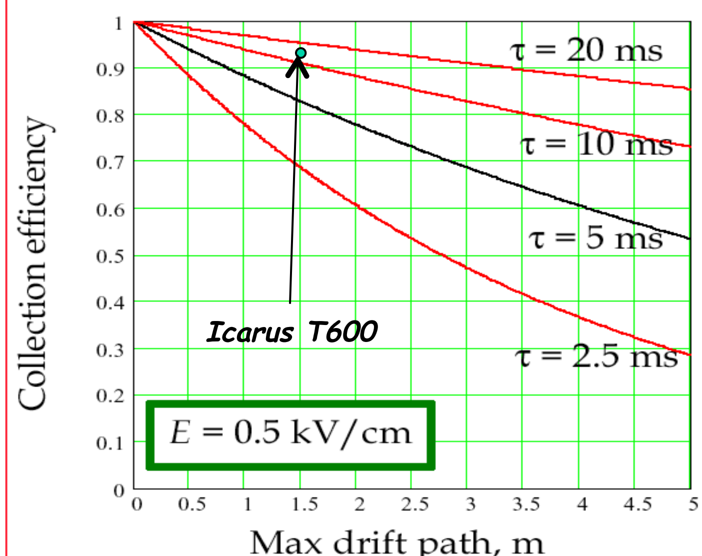
- *Two identical modules (T300)*
  - 3.6x3.9x19.6 = 275 m^3 each
  - Liquid Ar active mass: ~476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV; E = 0.5 kV/cm
  - drift velocity = 1.55 mm/μs
  - Sampling time 0.4 μs (sub-mm resolution in drift direction)
- *4 wire chambers*
  - 2 chambers per module
  - 3 "non-distructive" readout wire planes per chamber wires at 0, ±60° (ind1, ind2, coll view)
  - ~ 54000 wires, 3 mm pitch and plane spacing
  - Charge measurement on collection plane
- *20+54 8" PMTs for scintillation light detection*
  - VUV sensitive (128nm) with TPB wave shifter

A key feature of LAr-TPC technique: very long e^- mobility

- Level of electronegative impurities in LAr must be kept exceptionally low, in order to ensure ~m long drift path of ionisation e^- without attenuation.
- New industrial purification methods have been developed to continuously filter and recirculate both in liquid (100 m^3/day) and gas (2.5 x/hour) phases.
- τ_e > 7 ms measured during ICARUS run at LNGS → 12% max charge attenuation.
  τ_e > 16 ms (< 20 ppt O_2 equiv.) in East cryo since April 4th, 2013 (new pump installed).
- τ_e ~ 21 ms measured in the Icarino LAr-TPC (120 l) at INFN LNL.

ICARUS has demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors (~ 5 m drift).





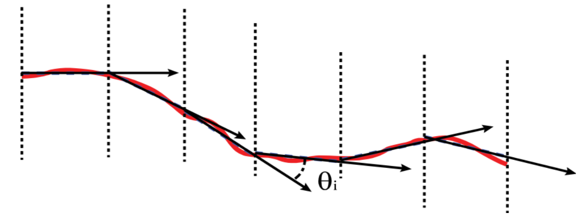
Drifting charge attenuation versus drift path at different electron lifetimes

ICARUS: the first large scale LAr physics experiment

- Exposed to CNGS ν beam (2010÷2012), collecting 8.6 x 10^{19} protons on target event statistics with a detector live time > 93%. Data taking also with c-rays to study atmospheric ν and p-decay (0.73 kty exposure).
- During its operation, ICARUS demonstrated excellent detection properties.
  - Tracking device: precise 3D topology, high spatial resolution (~ 1 mm^3), accurate ionization measurement.
  - Global calorimeter: total energy reconstruction is performed by charge integration, with 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): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$
  - Local calorimeter: measurement of dE/dx allows remarkable e/γ separation and particle identification (dE/dx vs range) .
  - Momentum of non contained μ determined via multiple Coulomb scattering (Δp/p ~16% in the 0.4-4 GeV/c range).

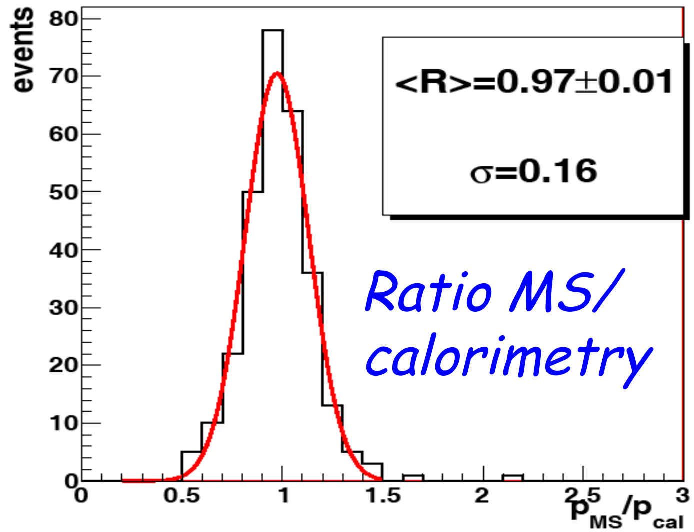
Measurement of muon momentum via multiple scattering

- RMS of deflection angle of μ, θ_{RMS}, depends on momentum p, spatial resolution σ and track segmentation.

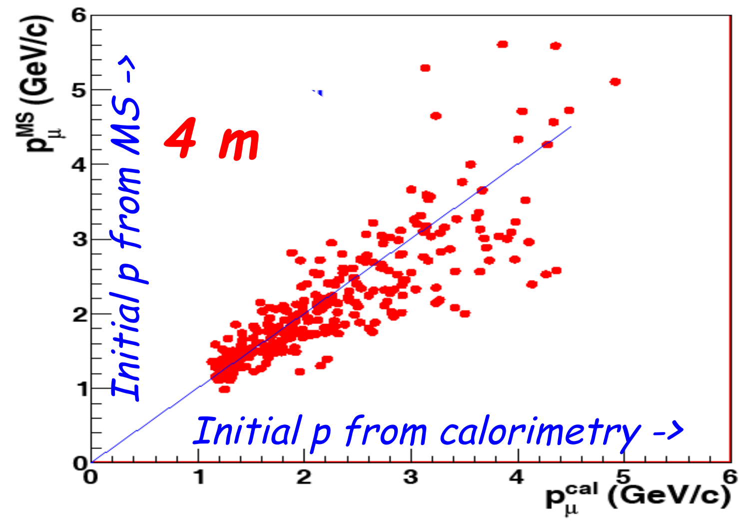


$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$

- The method has been tested on a sample of ~10^3 stopping μ's from CNGS ν interactions in upstream rock, comparing p^{MS} measured by MS with the corresponding calorimetric p^{CAL}

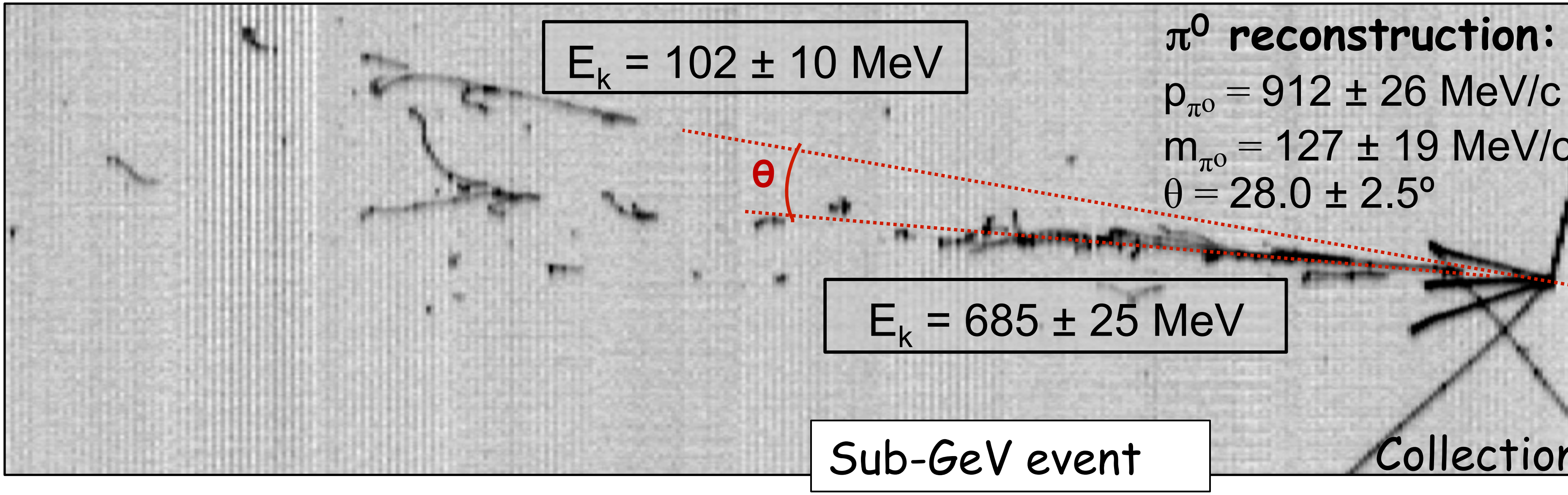


μ track length: > 5m
Used length: 4m



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

e/γ separation and π^0 reconstruction in ICARUS

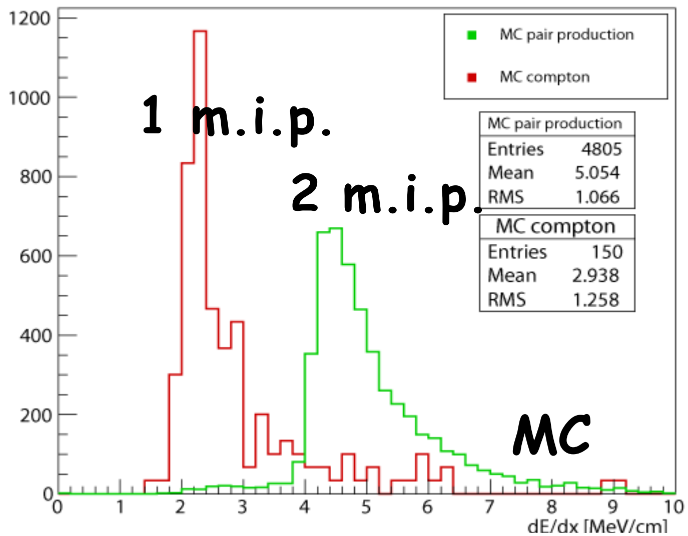


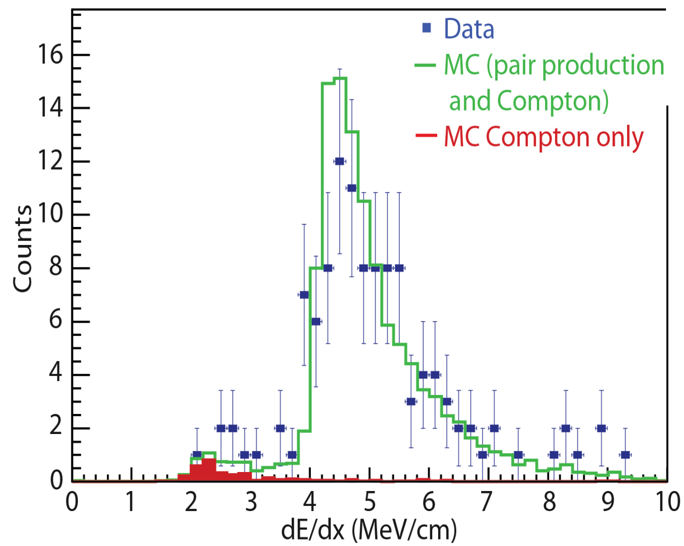
π^0 reconstruction:

$p_{\pi^0} = 912 \pm 26$ MeV/c

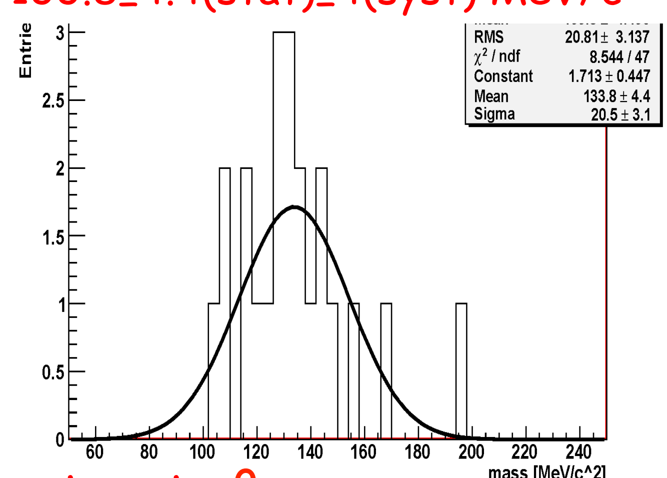
$m_{\pi^0} = 127 \pm 19$ MeV/c^2

$\theta = 28.0 \pm 2.5^o$





$M_{\gamma\gamma}$: 133.8±4.4(stat)±4(syst) MeV/c^2

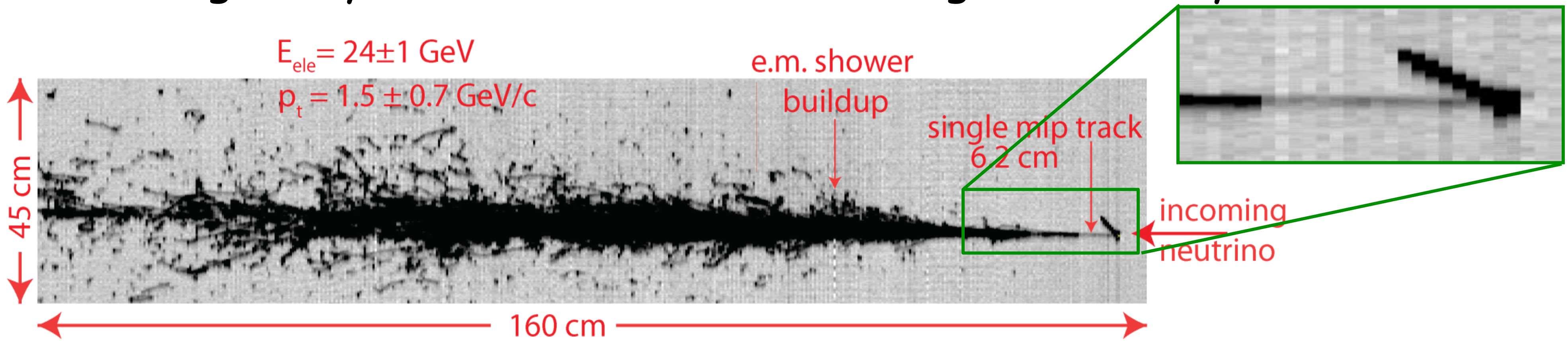


Unique feature of LAr to distinguish e from γ and reconstruct π^0

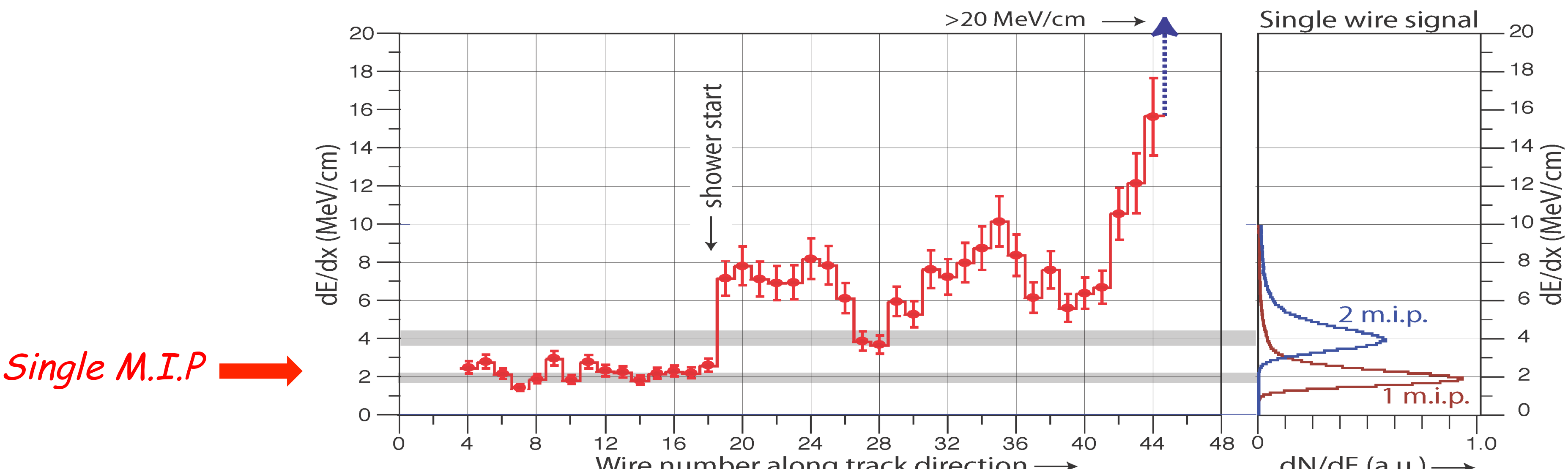
➔ Negligible background from π^0 in NC and ν_μ CC estimated from MC/scanning

ν_e identification in ICARUS LAr-TPC

- The unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.

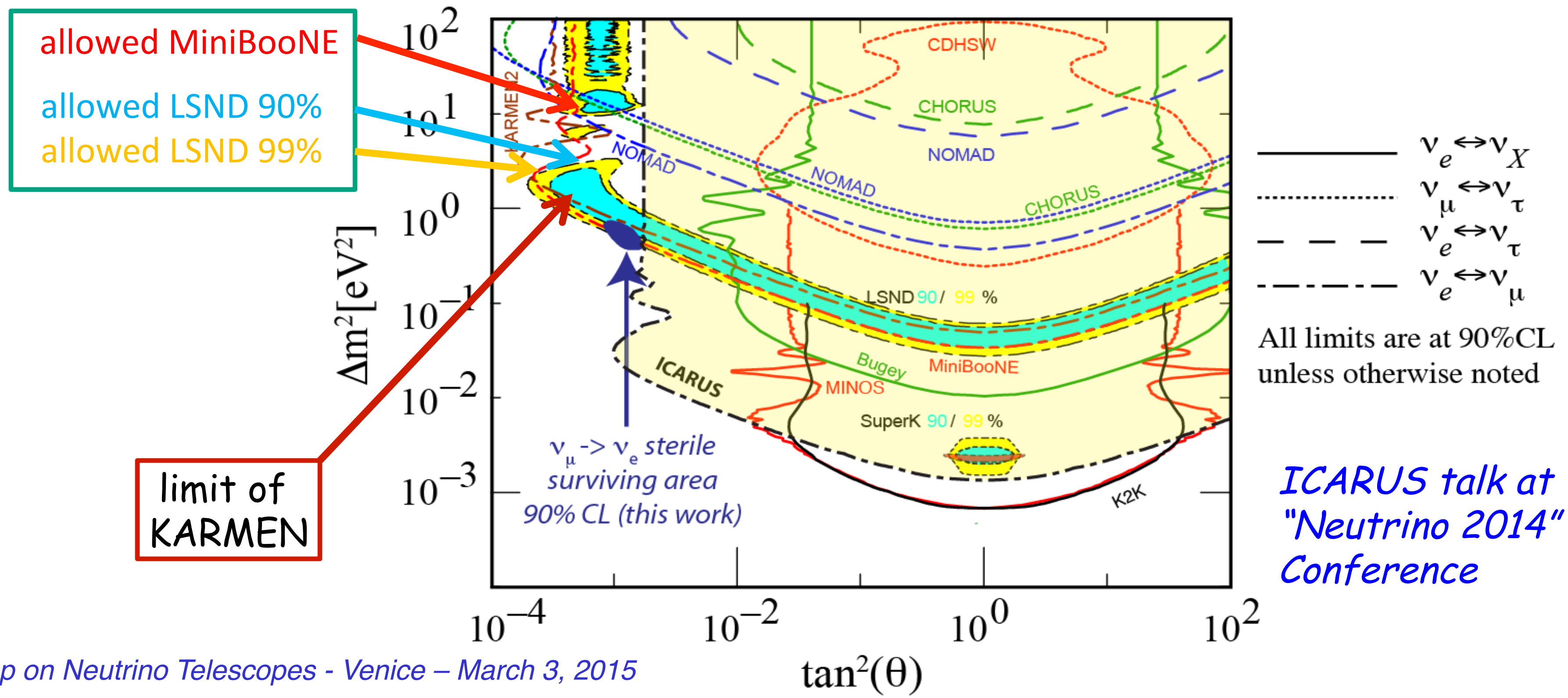


- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.



LSND-like search by the ICARUS experiment at LNGS

- ICARUS searched for ν_e excess related to a LSND-like anomaly, on the ν_μ CNGS beam (~ 1% intrinsic ν_e contamination, L/E_ν ~36.5 m/MeV).
- Analysis on 7.23×10^{19} pot event sample provided the limit on the oscillation probability $P(\nu_\mu \to \nu_e) \leq 3.85\ (7.60) \times 10^{-3}$ at 90 (99) % C.L.
- 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 at "Neutrino 2014" Conference

Persisting anomalies in the neutrino sector

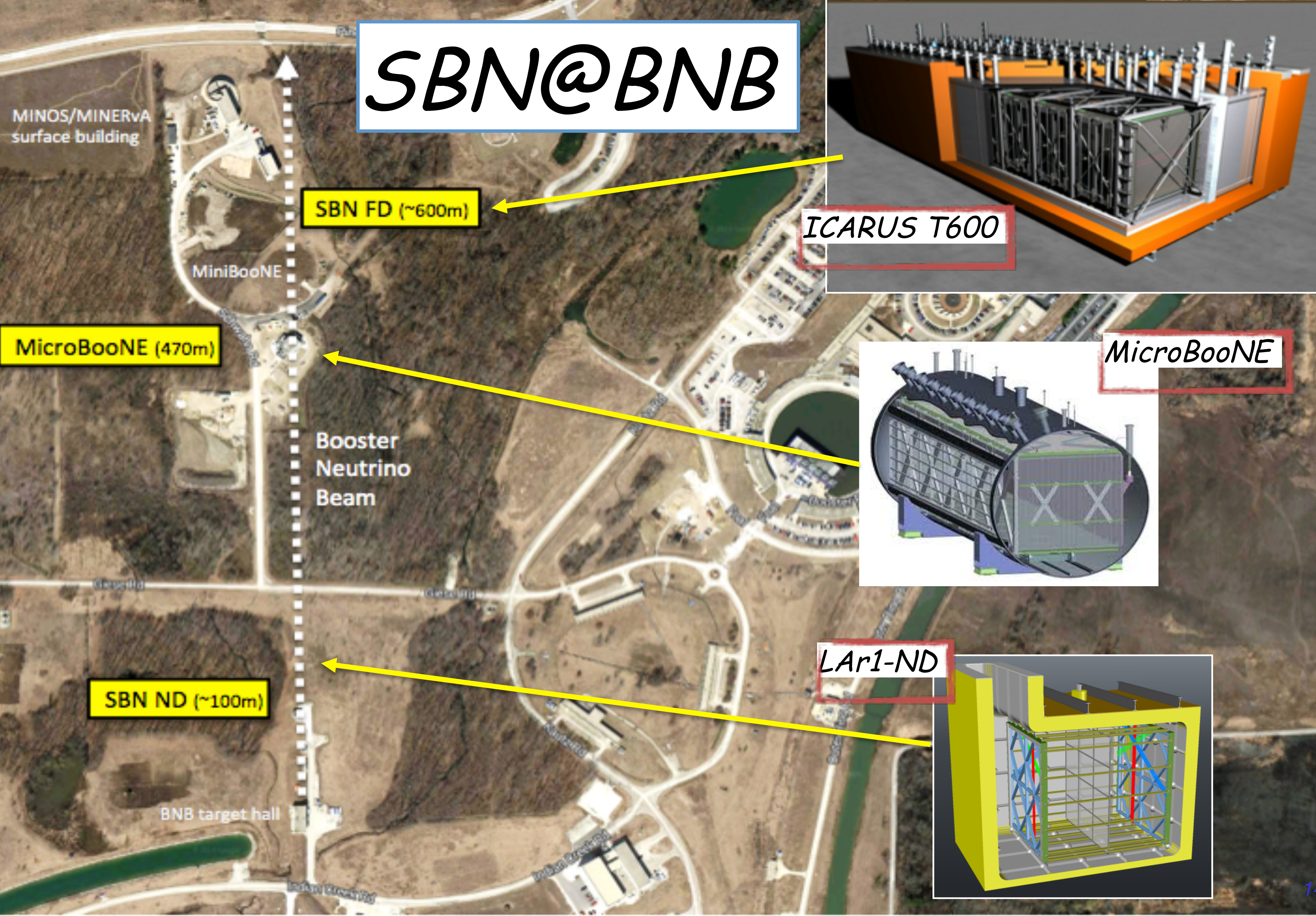
- Three main classes of anomalies have been reported, namely the apparent disappearance signal in the anti-ν_e events
  - (1) detected from near-by nuclear reactors, where the observed to predicted event rate is $R = 0.938 \pm 0.023$ and
  - (2) from Mega-Curie k-capture calibration sources in the experiments to detect solar ν_e with $R = 0.86 \pm 0.05$, and, in addition,
  - (3) observation of excess signals of ν_e electrons from muon neutrinos from particle accelerators (the LSND effect: 3.8 σ evidence for oscillations).
- These three independent signals may all point out to the possible existence of at least a fourth non standard and heavier "sterile" neutrino state driving oscillations at a small distances, with Δm^2_{new} of the order of $\approx 1\ eV^2$ and relatively small $\sin^2(2\vartheta_{new})$ mixing angles.
- According to Planck measurement and Big Bang cosmology, at most one sterile ν is expected, with $m < 0.4$ eV.

Sterile neutrino search at the FNAL Booster ν beamline

- An ultimate experiment with multiple LAr-TPCs exposed to FNAL Booster ~ 0.8 GeV neutrino beam has been proposed as definitive answer to the "sterile neutrino puzzle".
- The Conceptual Design Report, a joint ICARUS/LAr1-ND/MicroBooNE effort presented to FNAL PAC (Jan 15th, 2015), will exploit three LAr-TPC detectors at different distances from target: *LAr1-ND (82 t active mass), MicroBooNE (89 t) and ICARUS T600 (476 t) at 150, 470 and 600 m.*
- The experiment will likely clarify both LSND/MiniBooNE and Gallex/reactor anomalies by precisely and independently measuring both ν_e appearance and ν_μ disappearance, mutually related through the relation

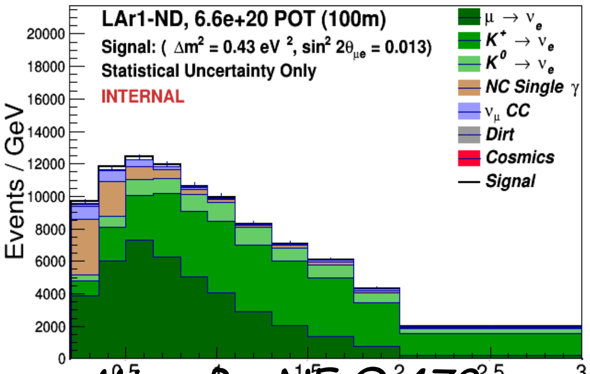
$$\sin^2(2\vartheta_{\mu e}) \leq \frac{1}{4}\sin^2(2\vartheta_{\mu x})\sin^2(2\vartheta_{ex})$$

- In absence of "anomalies", the three detector signals should be a closer copy of each other for all experimental signatures. However, the intrinsic ν_e events with a disappearance signal (if f.i. confirmed by reactors) may result in the reduction of a superimposed LSND ν_e signal. These two effects can be disentangled by changing the intrinsic ν_e beam contamination with different beamline optics (horn and decay tunnel length).

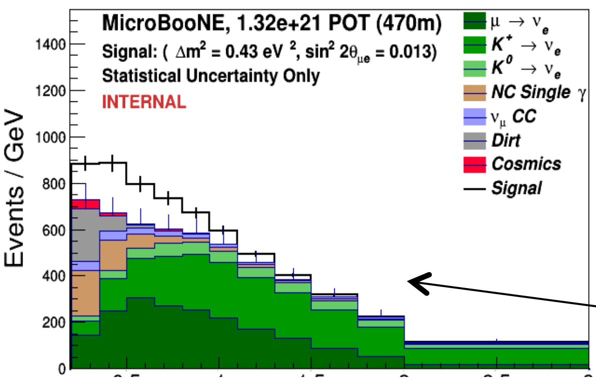

SBN@BNB
MINOS/MINERvA surface building
SBN FD (~600m)
ICARUS T600
MiniBooNE
MicroBooNE (470m)
MicroBooNE
Booster Neutrino Beam
SBN ND (~100m)
LAr1-ND
BNB target hall

$\nu_\mu \rightarrow \nu_e$ appearance sensitivity

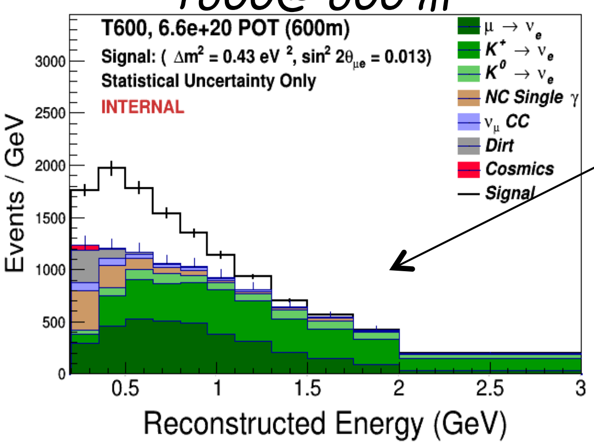
LAr1ND @ 100 m



MicroBooNE @ 470 m



T600@ 600 m

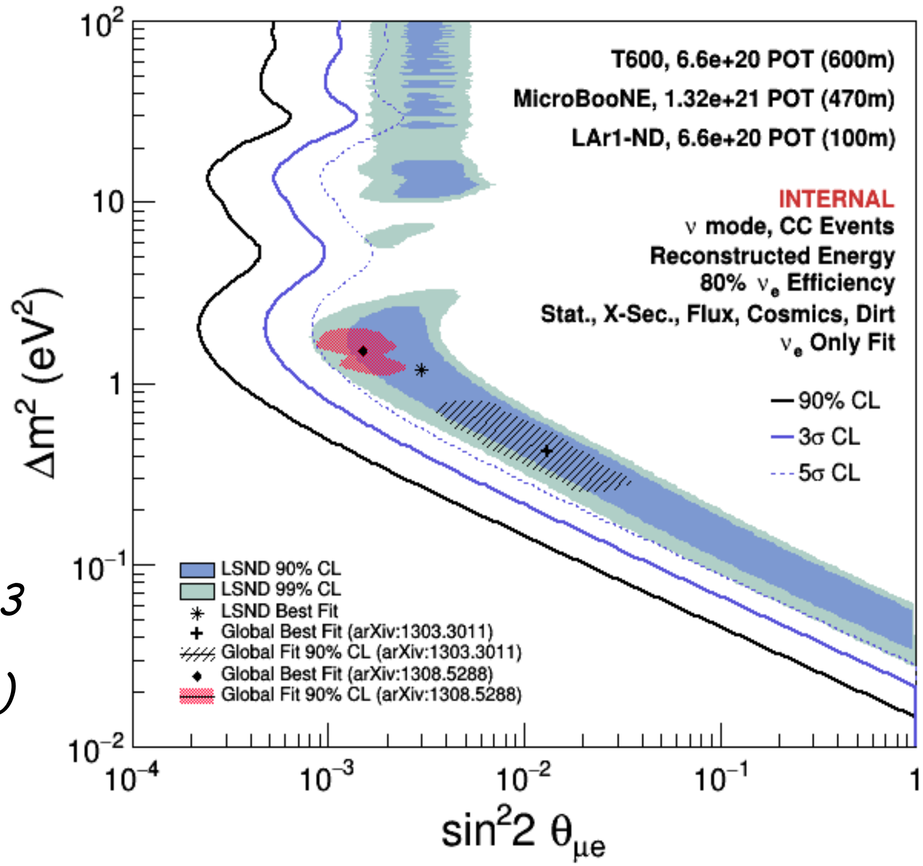


- Expected exposure sensitivity of $\nu\mu \rightarrow \nu e$ oscillations for 3 years - 6.6 10^{20} pot BNB positive focusing (6 years for MicroBooNE).

Example for

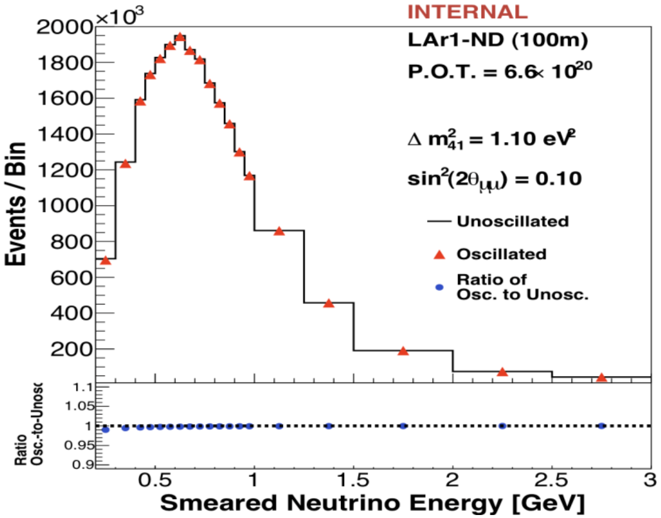
($\sin^2(2\theta)$=0.013

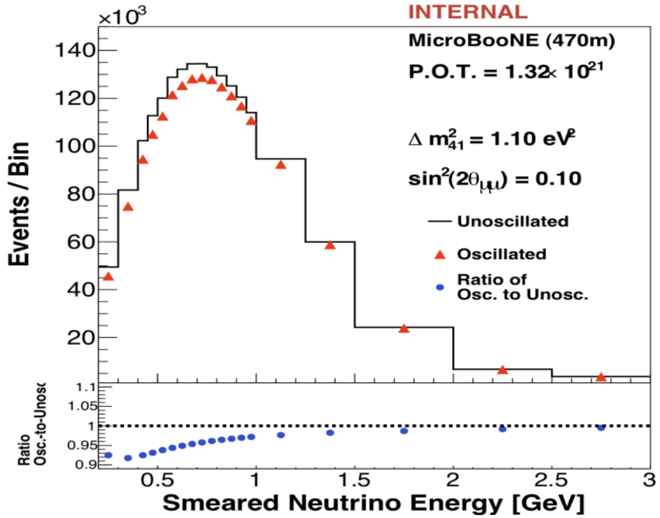
Δm^2=0.43 eV^2)

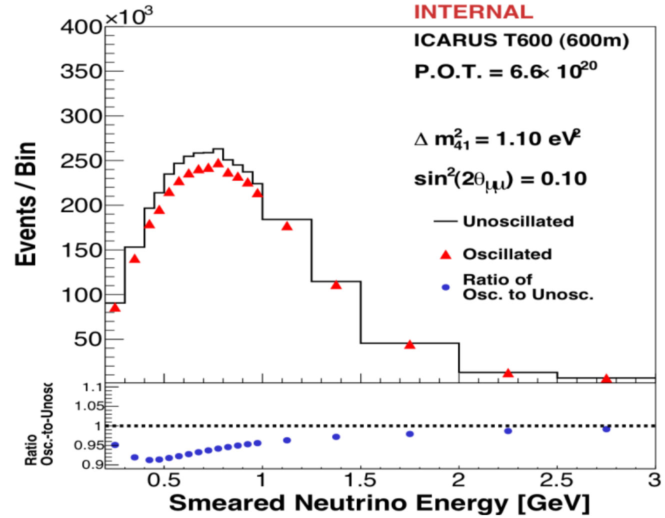


The LSND 99%CL region is covered at the ~5σ level

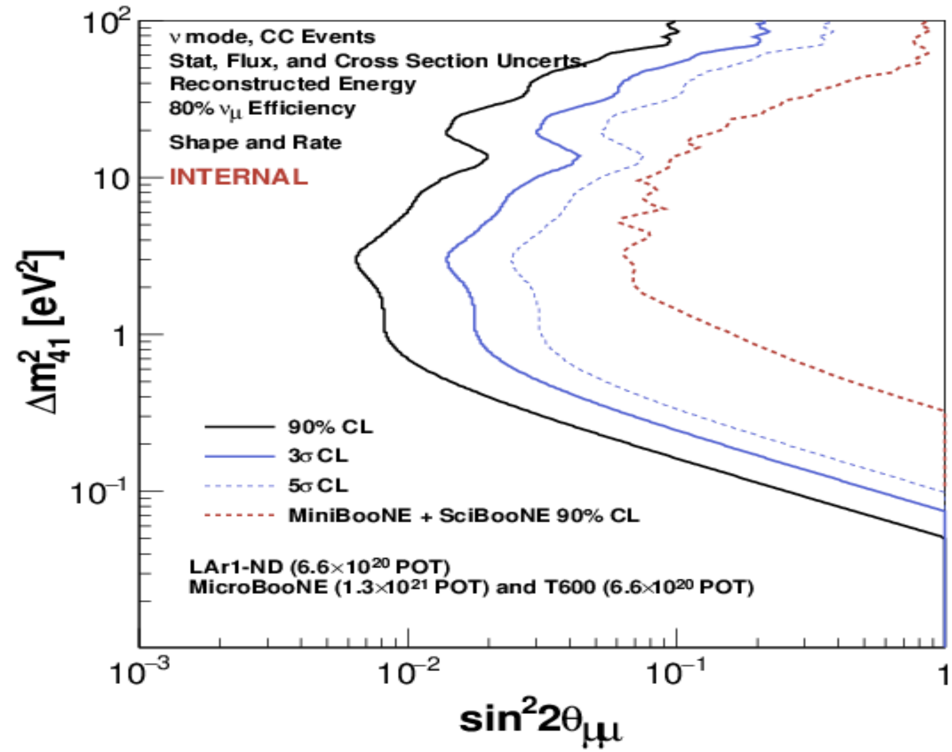
νμ disappearance sensitivity





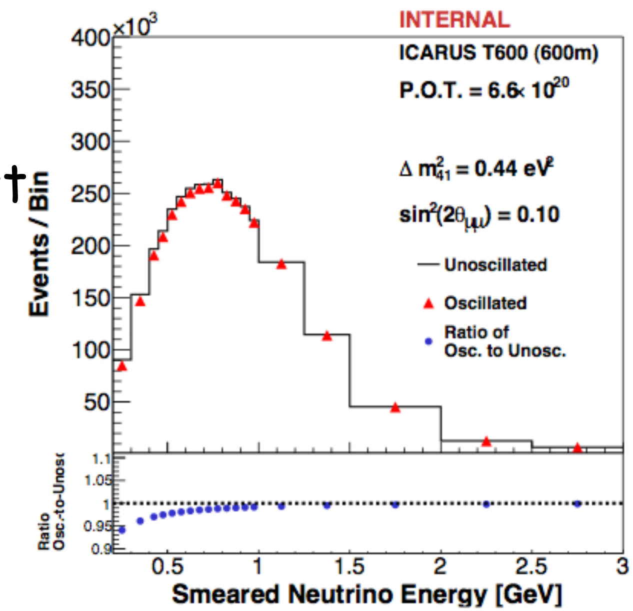


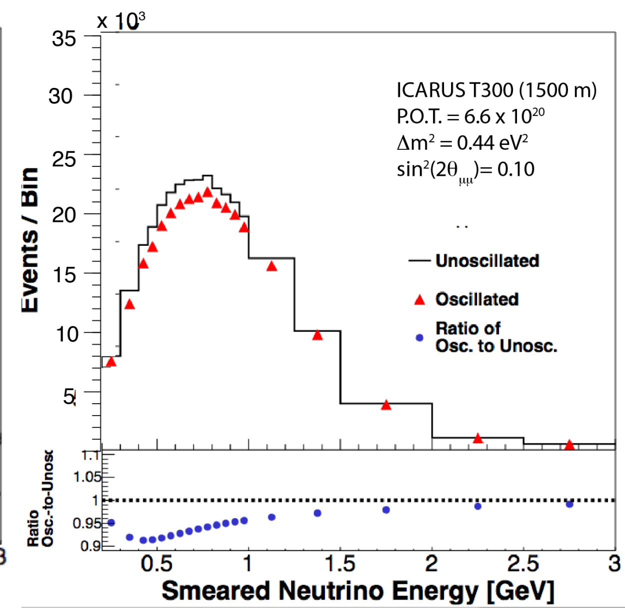
- Disappearance analysis can profit from high rates and correlations between the three LAr-TPC detectors
- SBN can extend sensitivity by 1 order of magnitude beyond SciBooNE+MiniBooNE



A second stage

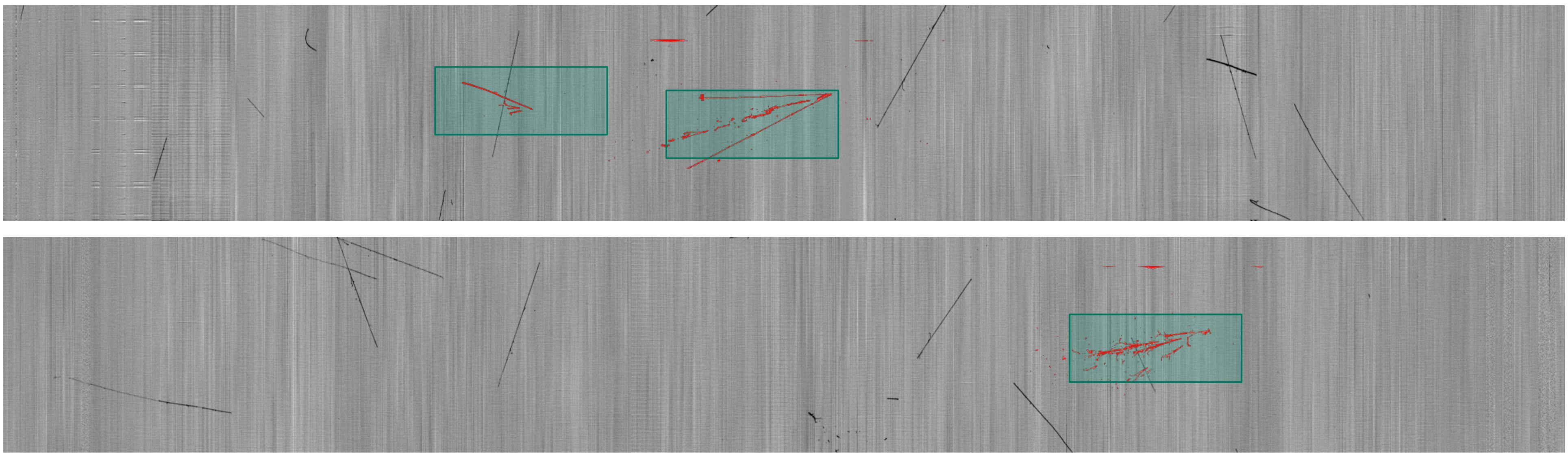
- Within 3+1 model, the most relevant and solid result is LSND, where $sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \approx 1.5\ 10^{-3}$. If LSND is confirmed, both ν_e and ν_μ disappearance are present, since $sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 (1-|U_{e4}|^2)$ and $sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 (1-|U_{\mu 4}|^2)$
- Reactor experiments presently claim $sin^2 2\vartheta_{ee} \approx 0.12$, $|U_{e4}|^2 = 0.03$.
- From LSND and assuming naively muon-electron universality, we expect at FNAL $sin^2 2\vartheta_{ee} = sin^2 2\vartheta_{\mu\mu} \approx 0.08$, about ½ of the present reactor data and Mega-sources much smaller than claimed.
- For $\Delta m^2 < 0.5\ eV^2$ the ν_μ disappearance effect at 600 m will be limited at the lowest ν energy bins 0.2-0.4 GeV.
- In order to amplify the effect, we install at a later stage an additional detector to 1500 m distance.





Facing a new situation: the LAr-TPC near the surface

- At shallow depths several uncorrelated cosmic rays will occur in T600 during the 1 ms drift window readout at each triggering event: ~ 12 muon tracks per drift in each ICARUS half module were measured on surface (Pavia 2001).
- This represents a new problem compared to underground operation at LNGS since, in order to reconstruct the true position of each track, it is necessary to associate precisely the related timing of each element of the TPC image with respect to the trigger time.



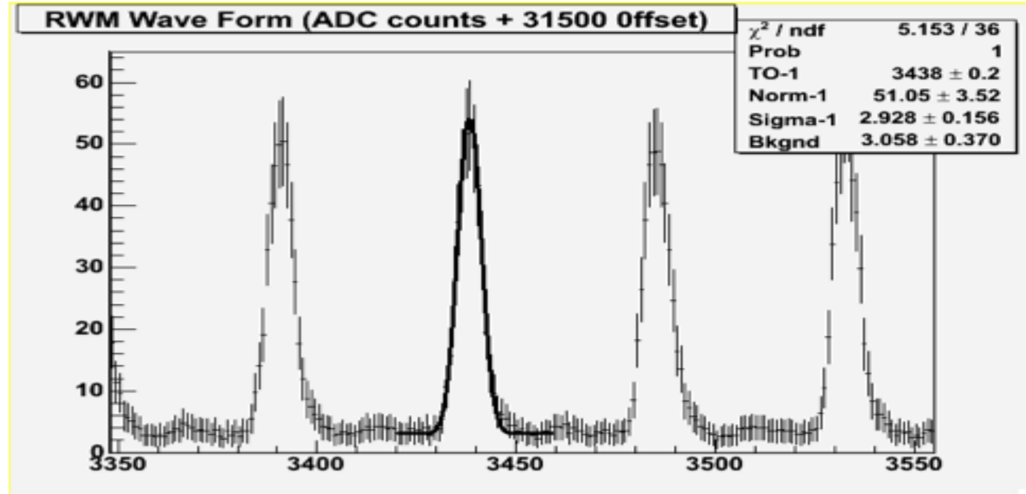
Cosmic rays (PV) + low energy CNGS beam events

Cosmogenic background mitigation

- Photons associated with cosmic μ represent a serious background for the ν_e appearance search, since electrons generated in LAr via Compton scattering / pair production can mimic a $\nu_e CC$ signal.
- In order to strongly mitigate the cosmogenic background, all the c-ray particles entering the detector must be unambiguously identified. This can be achieved by implementing a Cosmic Rays Tagging around the LAr active volume that provides an external timing of each track to be combined with the TPC reconstructed image. This system could consist either of external RPCs or plastic scintillation counters or internal readout plates detecting ionization signals.
- The adoption of a muon tagging system with 95% detection efficiency of single muon hit could ensure 99% efficiency in c-rays identification in T600, relying on double crossing of muons (only 15% are expected to stop in LAr).

Further mitigation of cosmogenic background

- Further rejection capabilities will come from precise timing information from internal scintillation light detectors. A ~ 1 ns accuracy will enable exploiting the bunched structure of the Booster p beam within spill (2 ns wide bunches every 19 ns).

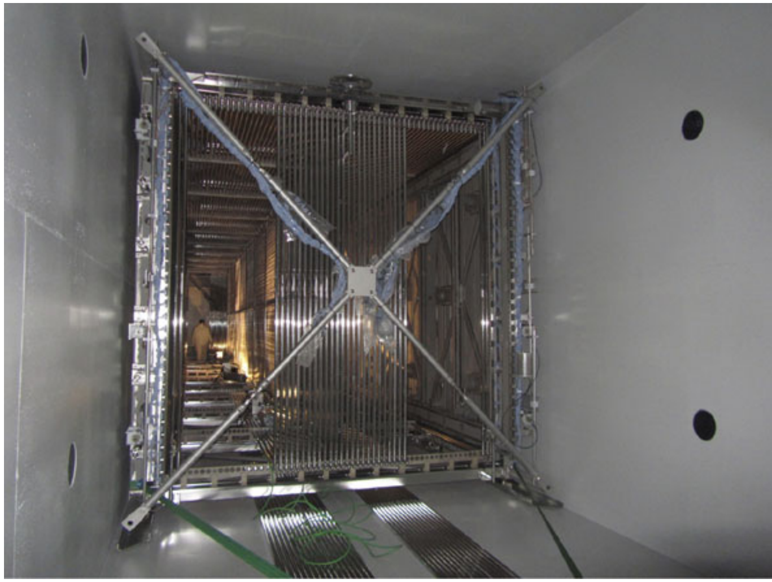


- Additional background mitigation strategies, exploiting the topological capability of the LAr-TPC, will be also applied to identify photons inside LAr active volume associated with cosmic muons.
- This requires the development of automatic tools to efficiently select, identify and reconstruct the neutrino interactions among the millions events triggered by cosmics (to be compared with the ~ 3000 ν events collected by ICARUS during CNGS run at LNGS!).

A continuing neutrino program

- The recent success of ICARUS-CNGS2 experiment has conclusively demonstrated that LAr-TPC is *the leading technology for future short/long baseline accelerator driven neutrino physics.*
- INFN has signed a Memorandum of Understanding for **WA104 project at CERN** and just concluded an important cooperation agreement for a short baseline experiment in the framework of the US-LBNF collaboration, involving the long term realization of a truly large mass, LAr-TPC detector.
- During its operation in the Short Baseline Neutrino Oscillation Program **SBN at Fermilab**, ICARUS will collect also ν_eCC events with the NUMI Off-Axis beam peaked at ~ 2 GeV, which will be an asset for the LBNF project.
- These activities represent as well an opportunity to further develop the LAr-TPC technique in view of the ultimate realization of the LBNF detector, with:
  - accurate determination of cross sections in liquid Argon;
  - experimental study of all individual CC and NC channels;
  - realization of sophisticated algorithms to improve the automatic identification of neutrino interactions.

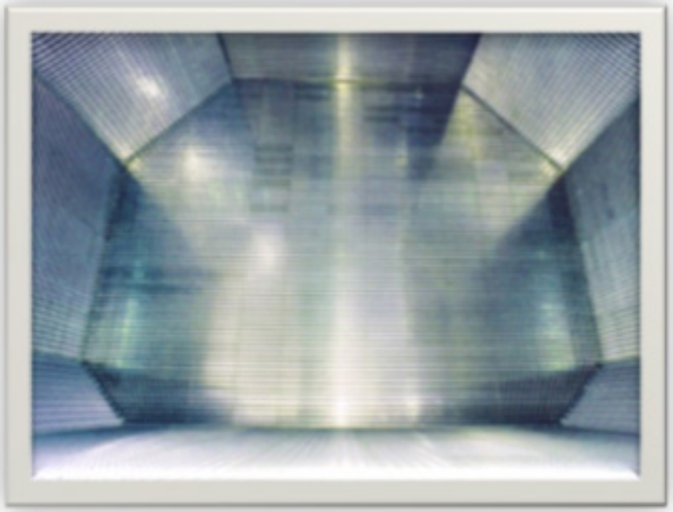
WA104 Project at CERN: overhauling of the T600

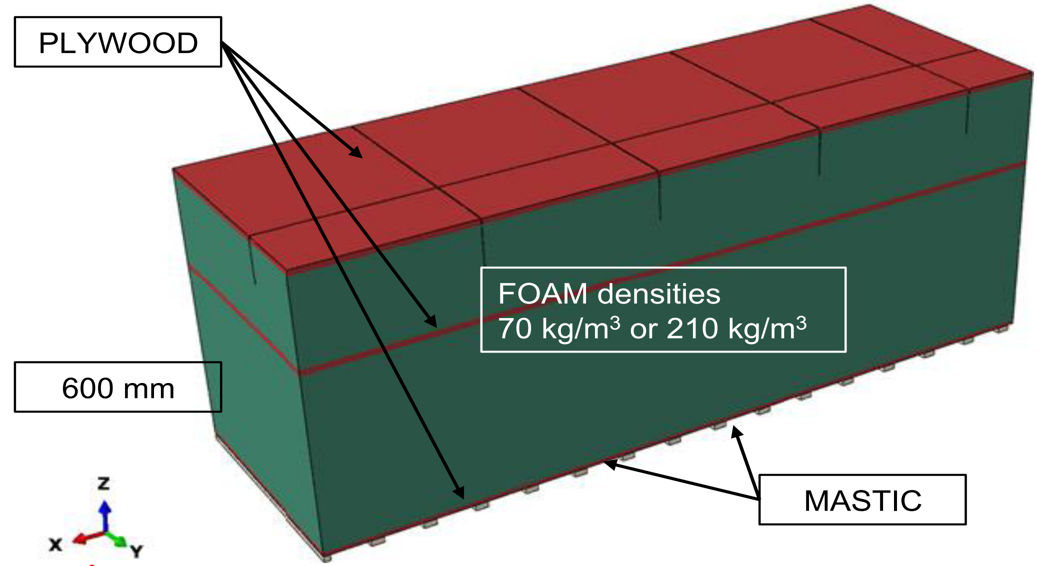


- The T600, already moved to CERN, is being upgraded introducing technology developments while maintaining the already achieved performance:
  - new cold vessels and new purely passive insulation;
  - refurbishing of the cryogenic and purification equipment;
  - new cathode with better planarity;
  - upgrade of the light collection system;
  - new faster, higher-performance read-out electronics.
- In parallel, the muon tagging system will be designed and constructed.
- Fully automatic tools for event reconstruction have to be developed.
- The detector is expected be transferred to FNAL before end of 2016 for installation, commissioning and start of data taking with ν beam.

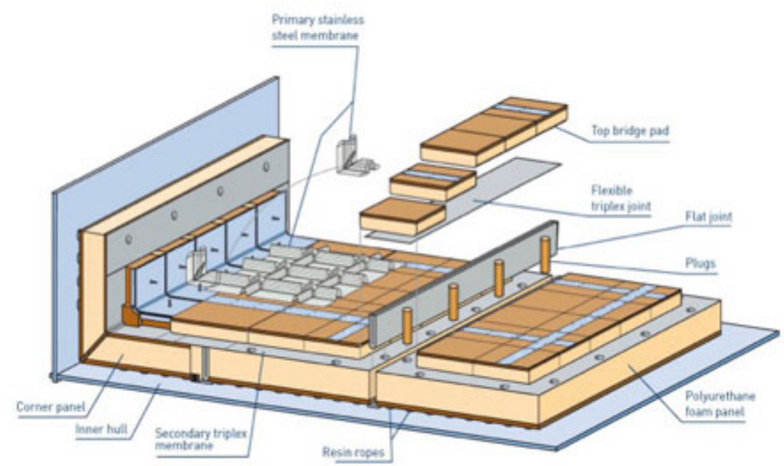
Transfer of ICARUS-T600 from LNGS to CERN

New Thermal Insulation



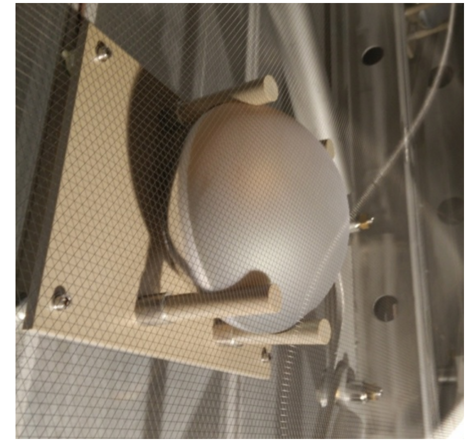


- Purely passive insulation chosen for the installation at CERN, coupled to standard cooling shield with boiling Nitrogen;
- Technique developed for 50 years and widely used for large industrial storage vessels and ships for liquefied natural gas.
- Expected heat loss through the insulation: T600 ≈ 6.6 kW
- No internal membrane is required

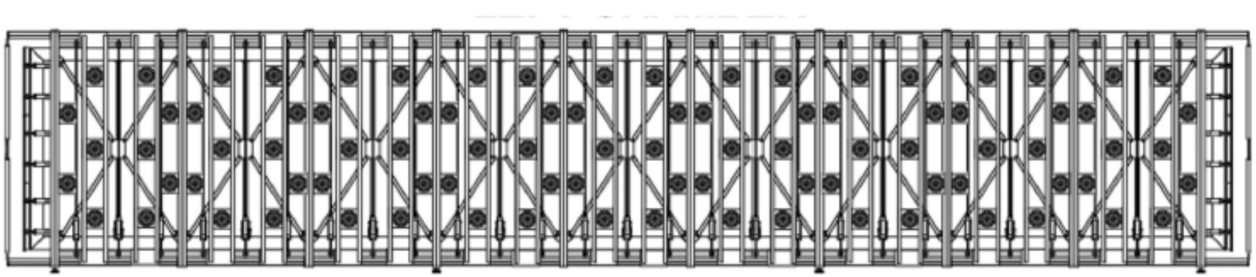


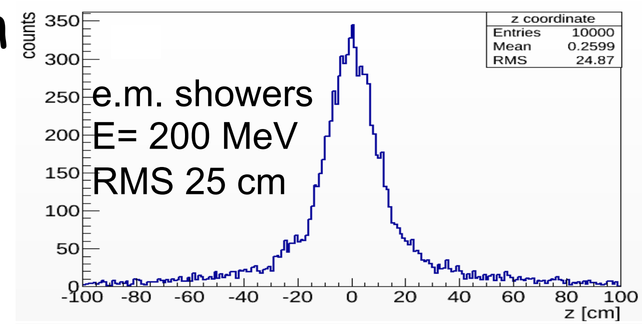
Upgrade of the light collection system

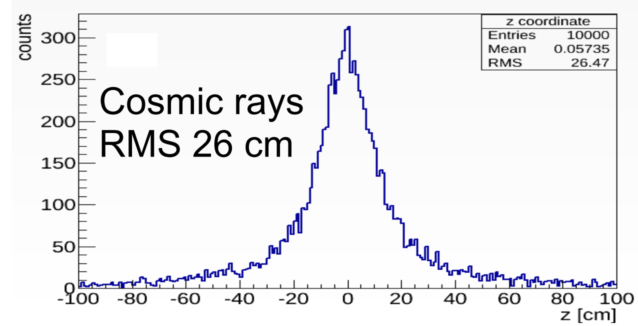
Large surface 8" PMTs will be adopted as in T600, but major improvements in space/time event localization capabilities are required to reject cosmogenic bckg:



- higher quantum efficiency (QE);
- improved photocathode coverage > 5%. F.i. a 90 PMTs per TPC layout, compatible with present mechanical structure, allows to obtain longitudinal resolution < 0.5 m (MC simulation with 5% effective QE).







longitudinal coordinate

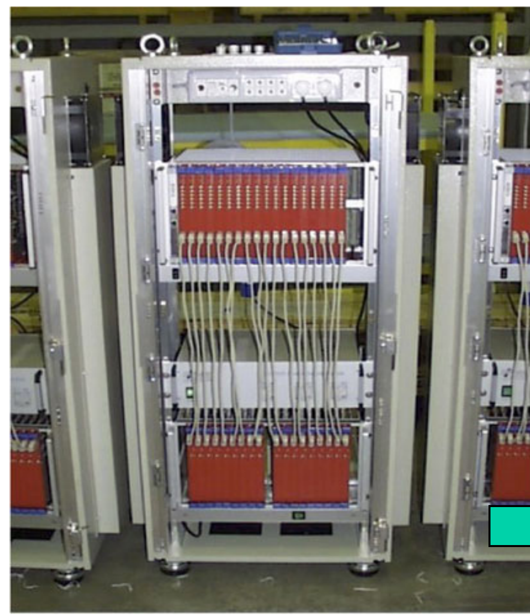
- new PMT voltage divider, to prevent induced spurious signals on TPC wire planes;
- better performance readout electronics, with ~ ns resolution, to exploit the bunched beam structure.

The need for an upgraded electronics

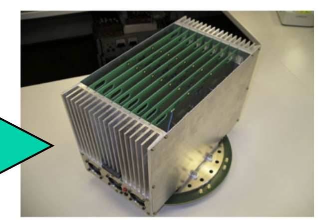
- Architecture of ICARUS-T600 electronics is based on analogue low noise "warm" front-end amplifier, a multiplexed 10-bit 2.5 MHz AD converter and a digital VME module for local storage, data compression & trigger information.
- A signal to noise ratio better than 10 and a ~ 0.7 mm single point resolution were obtained during the LNGS run, resulting in precise spatial reconstruction of events and allowing to measure muon momentum by multiple scattering (MS) with $\Delta p/p$ ~16% in the 0.4-4 GeV/c range.
- Even though well suited for larger size LAr-TPC, ICARUS-T600 electronics is affected by some limitations, like the asynchronous sampling of all channels within 400 ns sampling time, which slightly affects the MS measurement, and data throughput mainly due to the choice of VME standard (8-10 MB/s).
- Some conceivable improvements concern:
  - adoption of high frequency serial ADCs with synchronous sampling;
  - housing and integration of electronics onto detector;
  - adoption of a modern serial bus architecture with optical links for faster transmission rate (Gbit/s).
- A cold front-end option, with warm digital processing, is being investigated. Prototypes, developed in collaboration with BNL, will be tested at CERN.

New simplified/compact design

- A relevant change concerns the adoption of serial ADCs (10-12 bits, one per channel) in place of the multiplexed ones used in T600 al LNGS.
- The main advantage is the *synchronous* sampling of all channels (at 400 ns sampling time) of the whole detector, relevant for instance to the improvement of the muon momentum measurement by MS.
- The digital part is fully contained in a single high performance FPGA per board, that handles signal filtering and organizes the information provided by the serial ADCs.
- A new, compact design, has been conceived to host both analogue and digital electronics directly on the ad-hoc flanges.
- Prototype boards are under test at INFN-LNL.



From 595 to 10 liters



Conclusions

- Exposed in the underground Hall B of the Gran Sasso Laboratory at 730 km to the neutrino beam from CERN, the ICARUS T600 neutrino experiment made of 770 ton of highly purified LAr has successfully completed a three years physics program at CNGS.
- The T600 detector has now been moved to CERN for a significant overhauling in view of a short baseline neutrino experiment on the FNAL Booster and NUMI beams based on three detectors at different baselines (near: Lar1-ND, mid: MicroBooNE, far: ICARUS).
  The experiment is expected to start data taking by end 2017.
- Aim of the experiment is the definitive clarification of the LSND signal in terms of neutrino oscillations (ν_e appearance). The experiment will also provide a significant amount of data in the energy range of interest for future Long Baseline experiments.
- A second phase of the experiment is also under consideration with a fourth detector at a longer distance (≥1500 m) to extend the sterile neutrino search to lower Δm^2 as indicated by cosmology (ν_μ disappearance).


Thank you !