ICARUS status and near future

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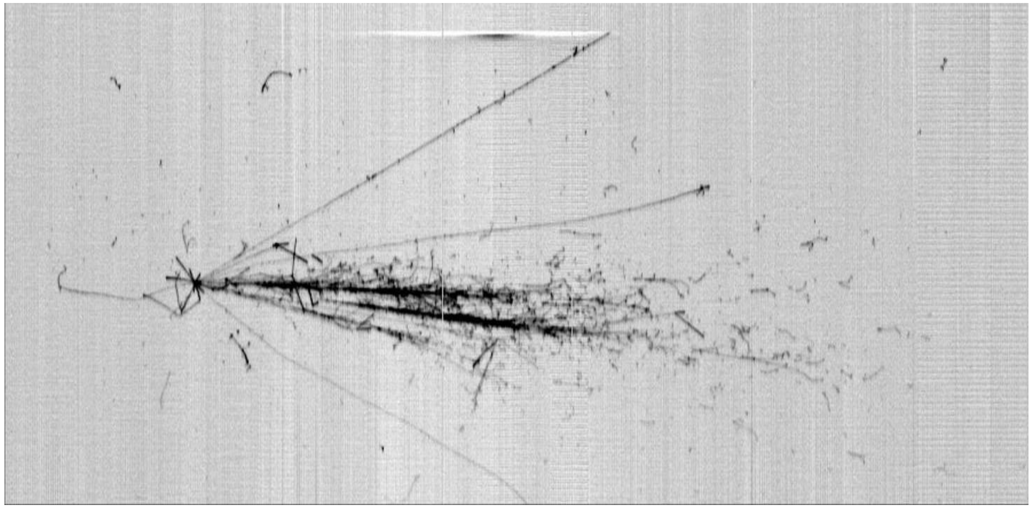
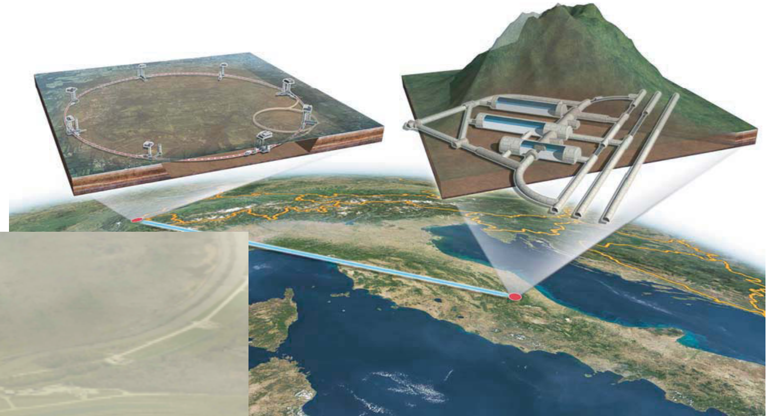
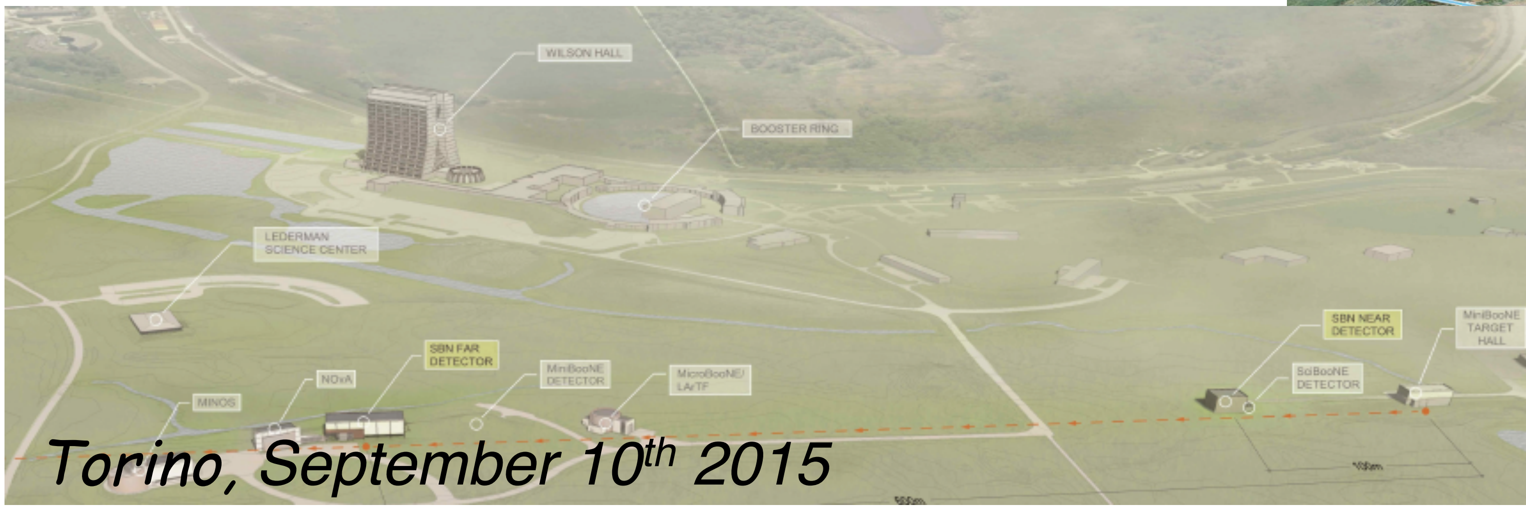
On Behalf of the
ICARUS Collaboration







Torino, September 10^{th} 2015

The ICARUS Collaboration

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+ ICAR-US : 6 new US groups: Colorado Univ., Pittsburgh Univ., SLAC, FNAL, Argonne, Los Alamos

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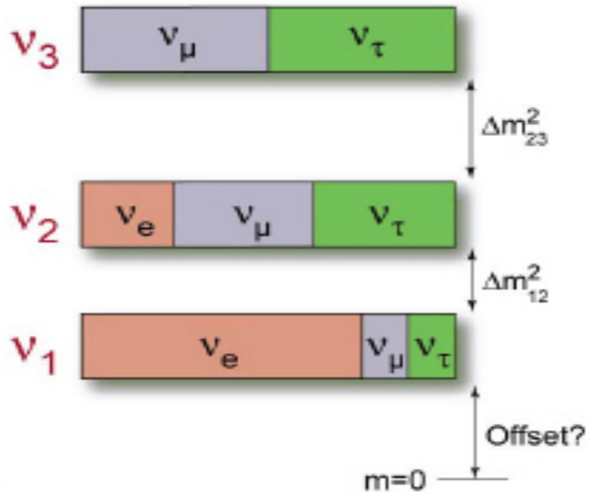
Anomalies in the neutrino sector

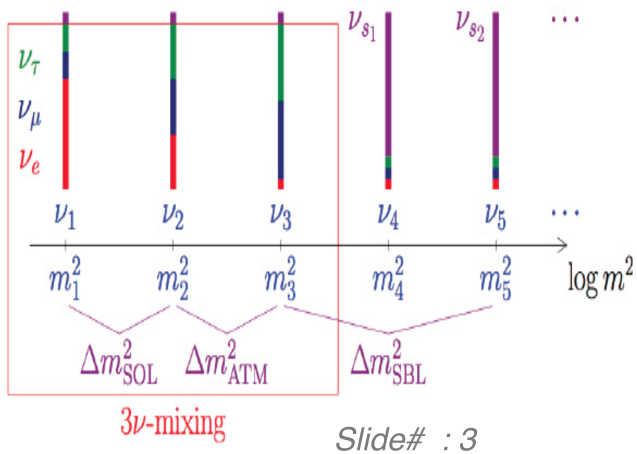
- Neutrino oscillations established a coherent picture with mixing of 3 physical $\nu_e\,\nu_\mu\,\nu_\tau$ with small mass differences Δm^2_{31}~2.4×10^{-3} eV^2, Δm^2_{21}~8×10^{-5} eV^2 and relatively large mixing angles, $\sin^2 2\theta_{13} \sim 10^{-1}$;

but mass hierarchy, δ_{CP}, ν mass values, Dirac/Majorana ν?



✓3 angles θ_{12}, θ_{13}, θ_{23}
✓2 mass diff.s Δm^2_{12}, Δm^2_{23}

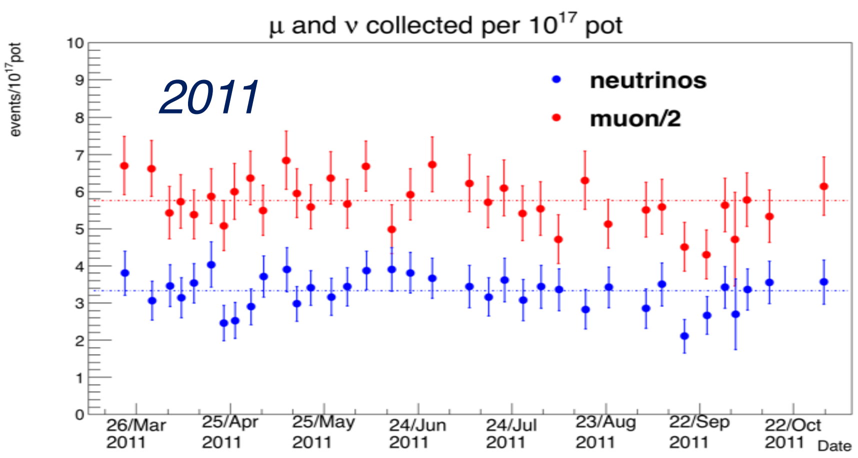
- There are however a number of *"anomalies"* which, if confirmed experimentally, could hint at (at least) an additional 4th neutrino, with non-standard oscillations at small distances with Δm^2_{new}~1 eV^2, small $\sin^2 2\theta_{new}$:
  - (1) observation of ν_μ->ν_e *excess signals* from LSND, MiniBooNE at accelerators (LSND effect: 3.8 σ)
  - *signal* in anti-ν_e events (2) detected from near-by nuclear reactors where the observed to predicted event rate is R=0.938±0.023 and (3) from Mega-Curie k-capture calibration sources in solar ν_e experiments with R=0.86±0.05;

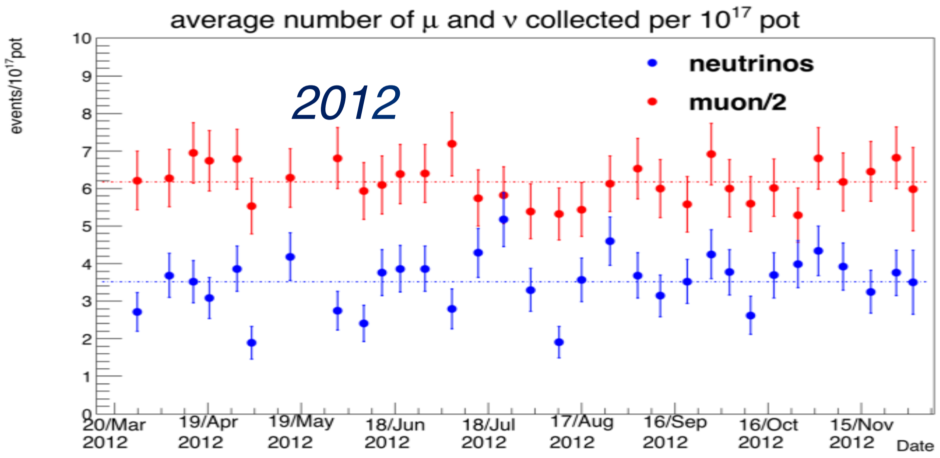


- According to Planck measurement, Big Bang cosmology, at most one sterile ν is expected, m< 0.4 eV.

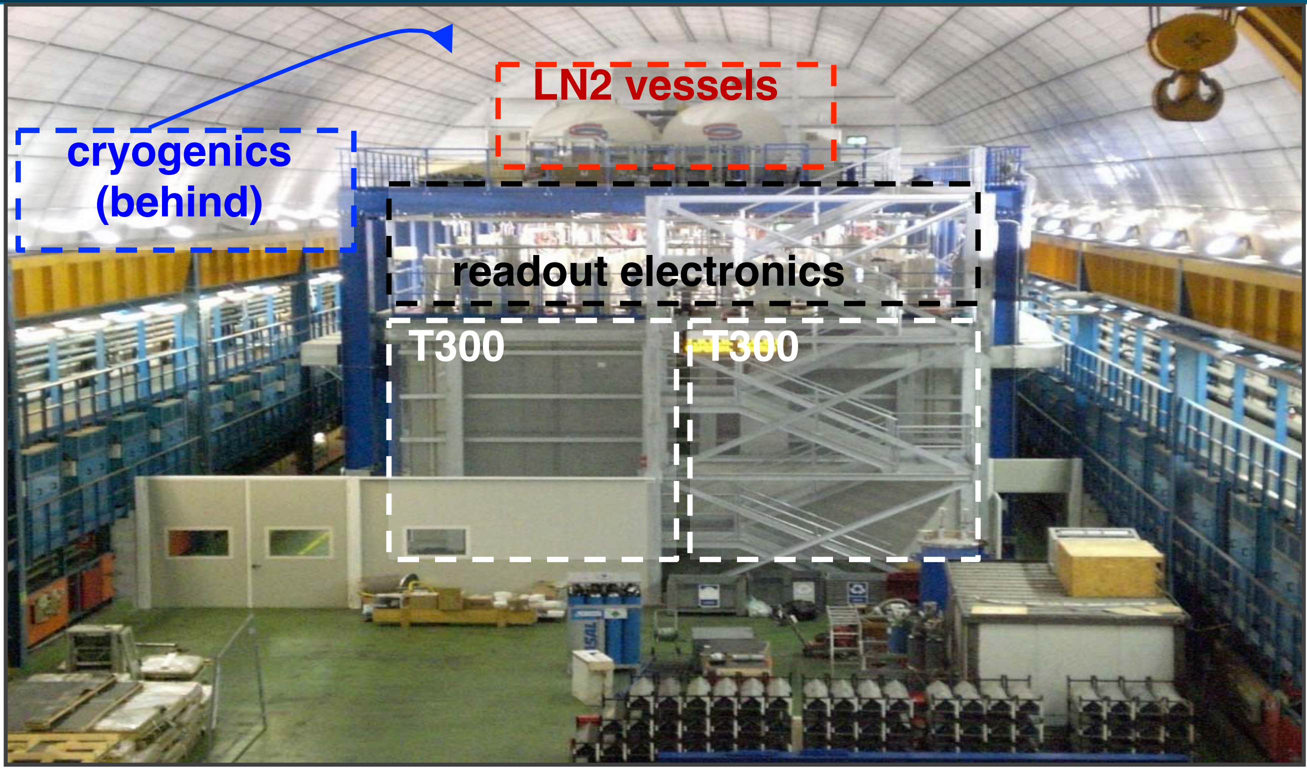
Evolution of LAr-TPC detectors

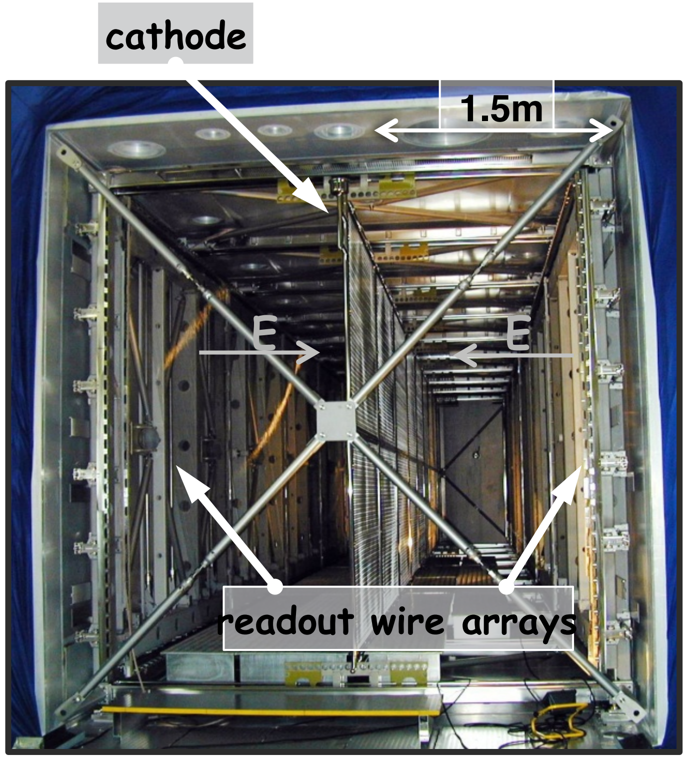
- Cherenkov detectors in water/ice and liquid scintillator detectors have been main technologies so far for neutrino and rare event physics. *Unfortunately these detectors do not permit to identify unambiguously each ionizing track.*
- *As an alternative, the Liquid Argon Imaging technology (LAr-TPC), effectively an electronic bubble-chamber, was originally proposed by C. Rubbia in 1977 [CERN-EP/77-08],supported by Italian Institute for Nuclear Research (INFN).*
- *Thanks to ICARUS collaboration, LAr-TPC has been taken to full maturity with the T600 detector (0.6 kton) receiving CNGS neutrino beam and cosmic rays.*
- *ICARUS concluded in 2013 a very successful 3 years long run at LNGS, collecting 8.6 x 10^{19} pot event with a detector live time > 93%, recording ~3000 CNGS neutrinos (in agreement with expectations) and cosmic rays (0.73 kty).*





ICARUS-T600 at LNGS laboratory





Two identical modules

- $3.6 \times 3.9 \times 19.6 \sim 275\ m^3$ each
- LAr active mass: 476 t
- Drift length: 1.5 m (1 ms)
- E=0.5 kV/cm, v_{drift}~1.5 mm/μs
- Sampling time 0.4μs (sub-mm resolution in drift direction)

Four wire chambers: 2 chambers/ module

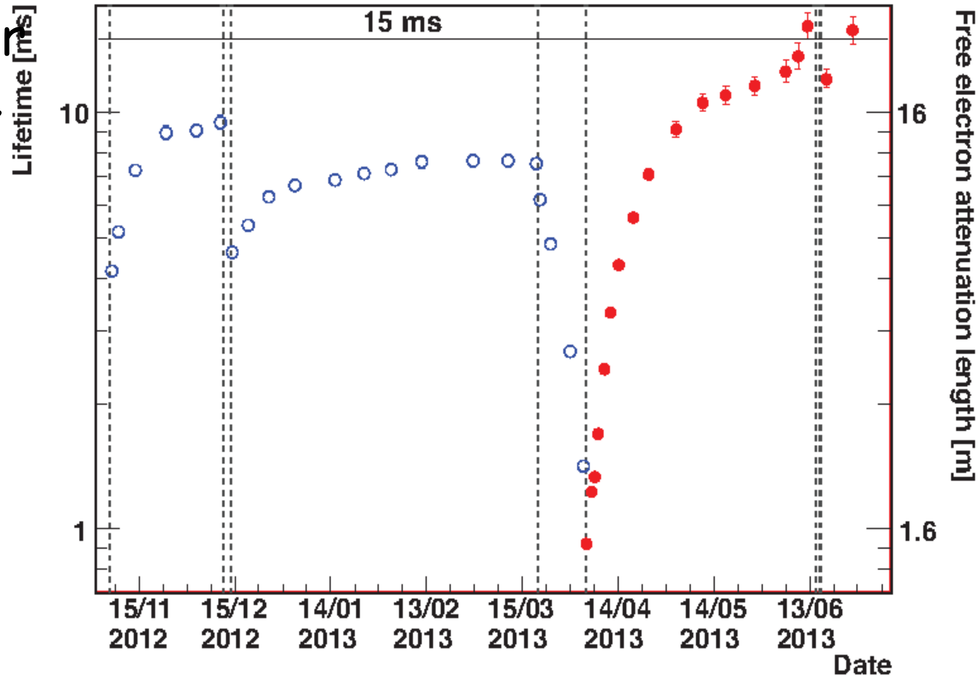
- 2 Induction + 1 Collection readout wire planes per chamber; ~54000 wires, 3 mm pitch and plane spacing, oriented at 0°,±60°;
- Charge measurement on last Collection plane

20+54 8" PMTs for scintillation light detection:

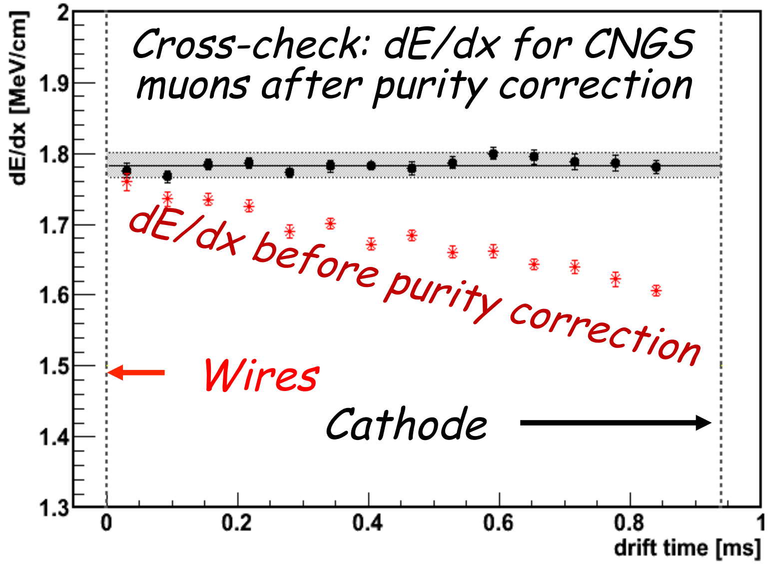
- VUV sensitive (128nm) with TPB wave shifter

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

- Level of electronegative impurities in LAr must be kept exceptionally low to ensure ~m long drift path of ionization e^- with very small attenuation.
- New industrial purification methods developed to continuously filter and re-circulate both in liquid (100 m^3/day) and gas (2.5 volumes/hour) phases.
- Electron lifetime measured during ICARUS run at LNGS with cosmic μ's: τ_{ele} >7 ms (~40 p.p.t. [O_2] eq) →12% max. charge attenuation.
- New pump installed on East cryostat since April 4th, 2013: τ_{ele} > 15 ms (~20 p.p.t.)

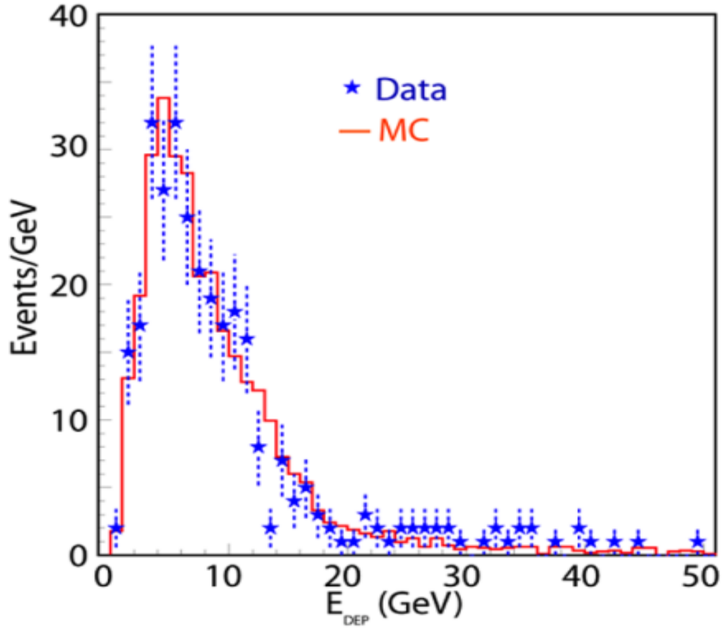


ICARUS demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors ~5 m drift as required for LBNF/DUNE project

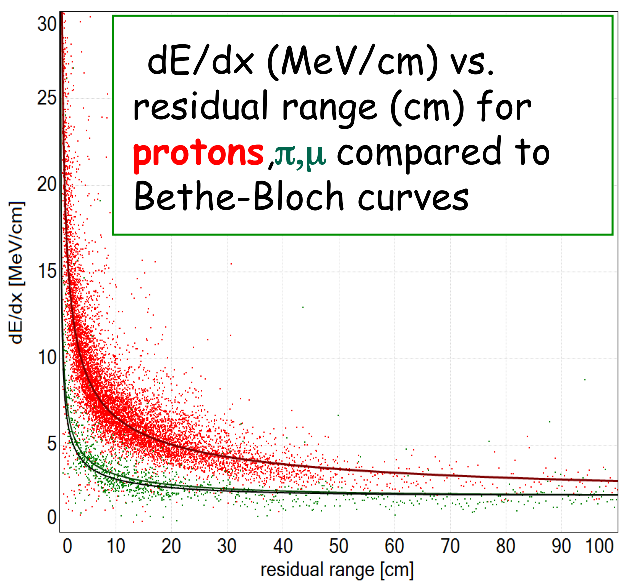


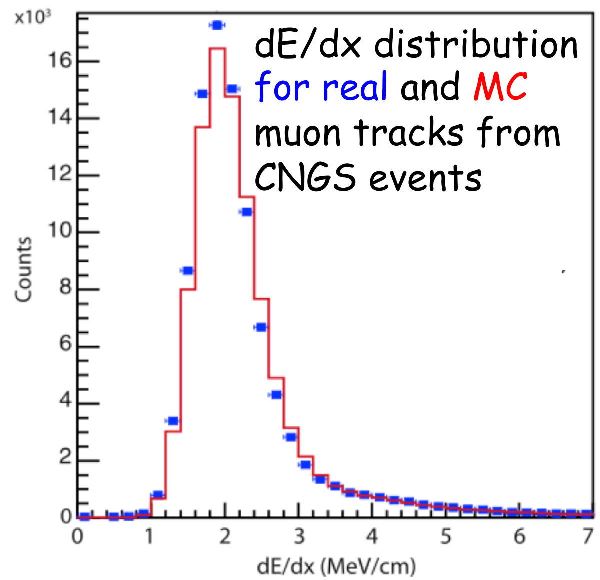
ICARUS LAr-TPC performance

- *Tracking device:* precise ~mm^3 resolution, 3D event topology, accurate ionization measurement;
- *Global calorimeter:* total energy reconstruction by charge integration - excellent accuracy for contained events; momentum of non contained μ determined via Multiple Coulomb Scattering $\Delta p/p$ ~15% in 0.4-4 GeV/c range;
- *Measurement of local energy deposition dE/dx:* remarkable e/γ separation (0.02 X_0 sampling, X_0=14 cm; particle identification by dE/dx vs range);



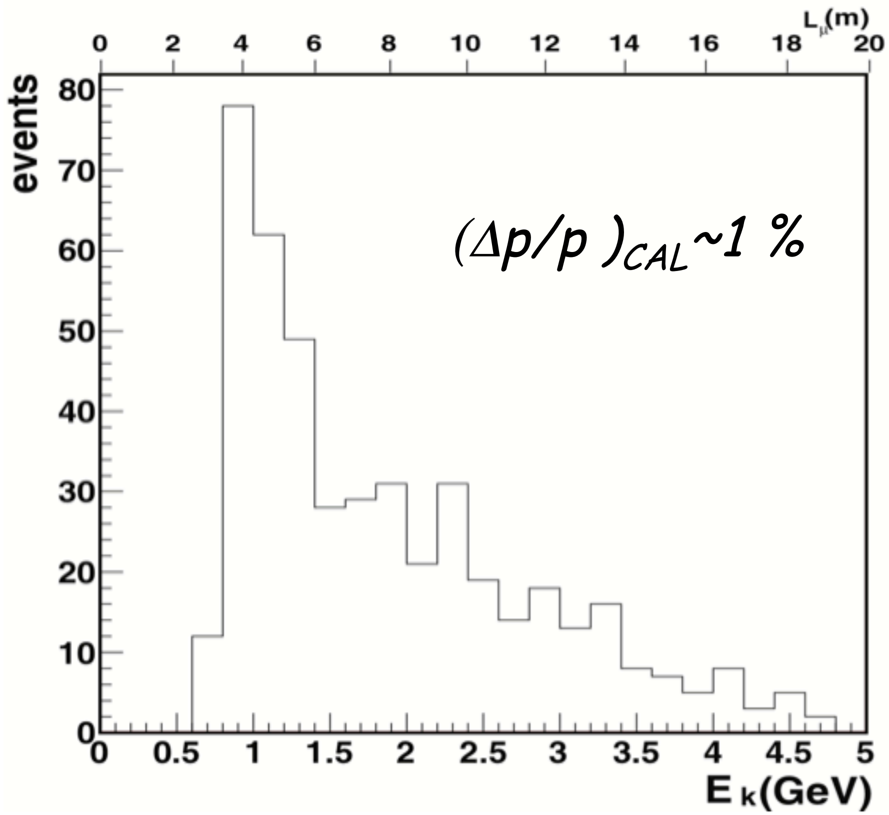
  - *Low energy electrons:* $\sigma(E)/E = 11\%/\sqrt{E(MeV)}+2\%$
  - *Electromagnetic showers:* $\sigma(E)/E = 3\%/\sqrt{E(GeV)}$
  - *Hadron shower (pure LAr):* $\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$





Measurement of muon momentum via multiple scattering

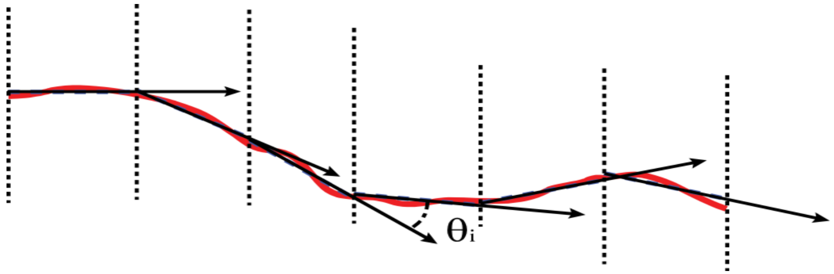
- Multiple Coulomb Scattering (MCS) is the only way to measure momentum of non-contained muons
- Algorithm validated on ~400 *stopping muons*: produced in ν_μCC interactions of CNGS neutrinos upstream of T600, and stopping/decaying inside the detector
- Stopping muons are an ideal subsample for validating MCS algorithm:
  - Independent momentum measurement from calorimetry
  - Momentum spectrum in a region of interest for future SB/LB neutrino experiments



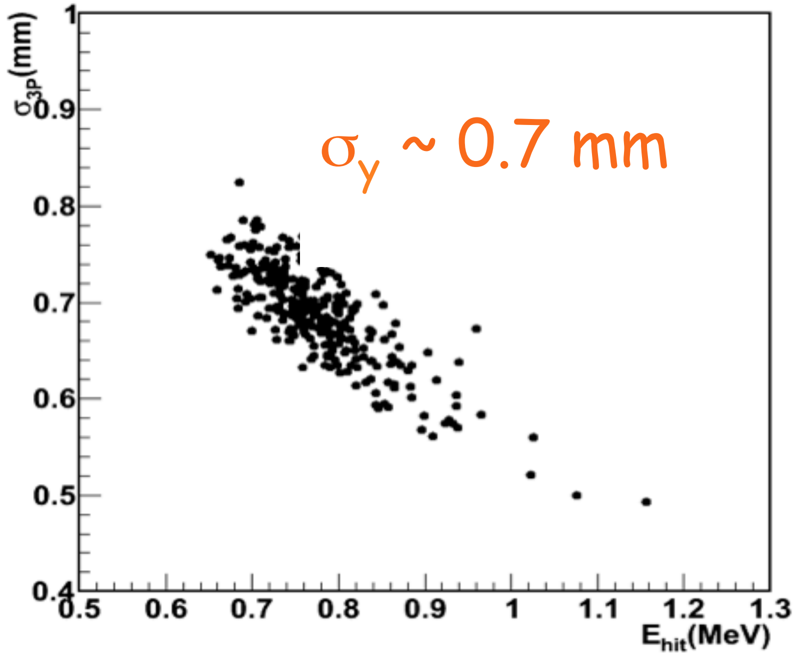
Last meter of muon tracks not used for MCS measurement, in order to emulate case of escaping muons

Muon momentum measurement algorithm

- Algorithm based on evaluation of θ_{RMS}: average RMS of deflection angles (in Collection view), compared with expectations for a given *p* (assuming Gaussian approximation of MCS)
- Three crucial ingredients:
  - Preliminary track cleaning, to avoid non-Gaussian tails (mainly δ-rays)
  - Precise track-to-track estimation of measurement errors (essentially on drift coordinate *y*)
  - Track segmentation, optimized to enhance MCS contribution while reducing statistically the effect of errors

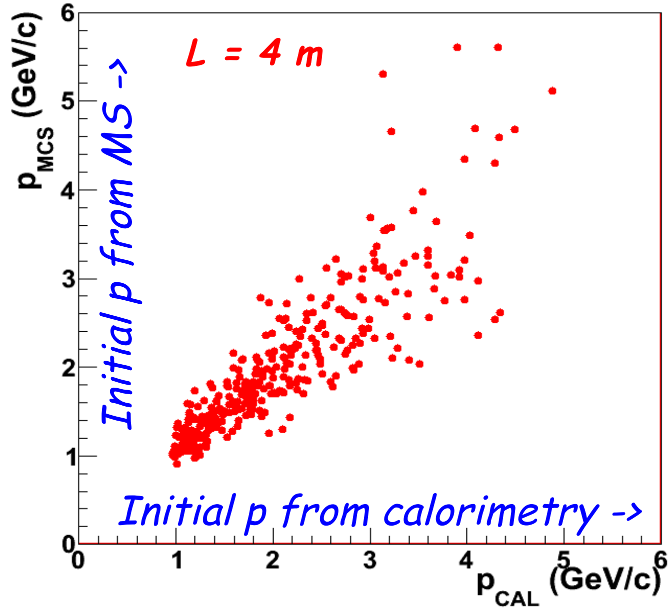


$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$

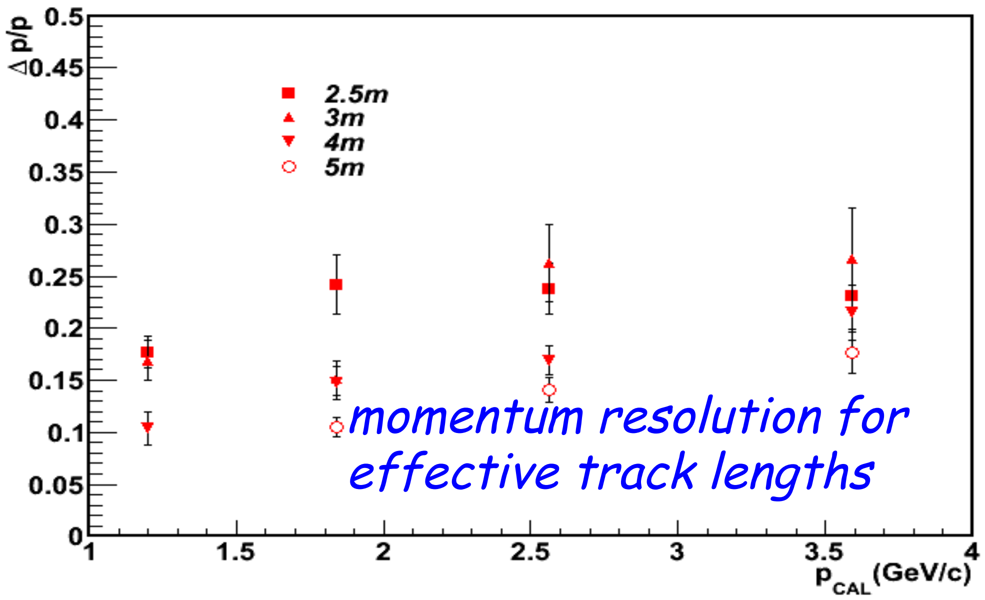


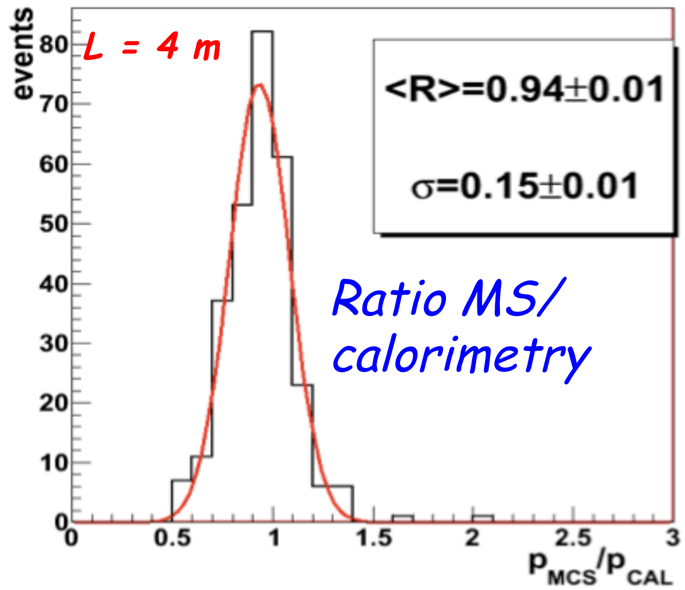
Muon momentum measurement results

- Good agreement between MCS and calorimetric measurements
- Average resolution of ~15% on the stopping muon sample
- Resolution depends both on momentum and effective muon track length used for measurement



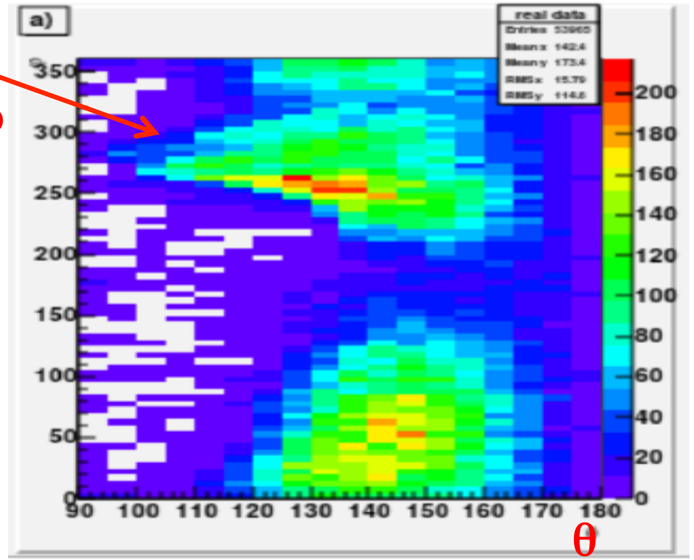
Some deviations for p > 3.5 GeV/c induced by non-perfect planarity of TPC cathode

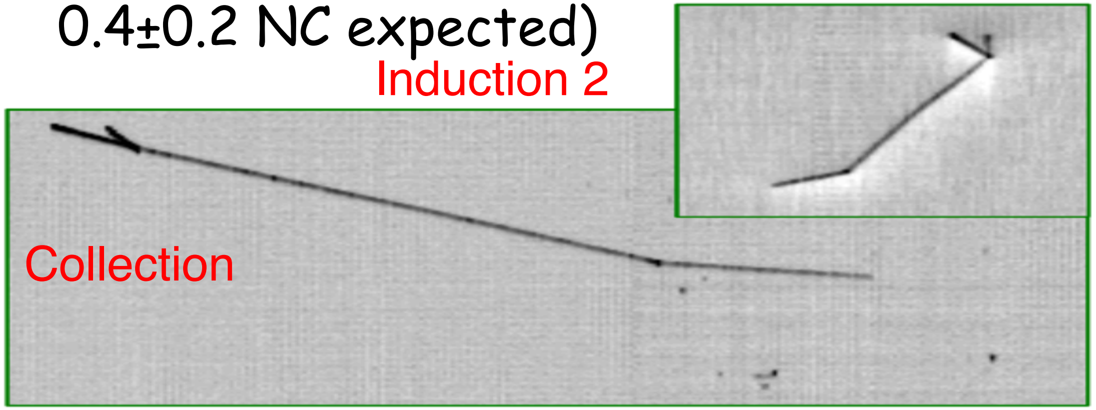




Search for atmospheric ν's

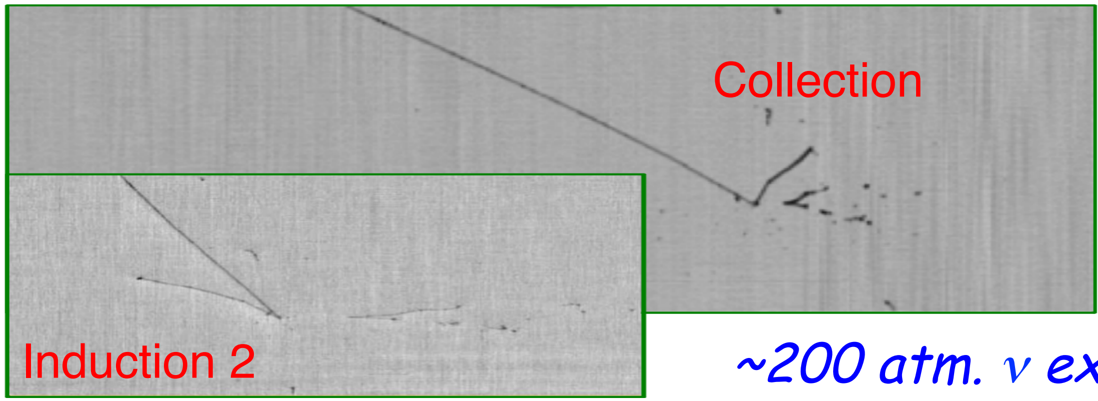
- Preparatory step: automatic 3D reco of cosmic μ's
- An algorithm for filtering of interaction vertex and multi-prong event topology has been developed, complemented by visual scanning;
- *Work in progress*: 2 muon-like and 2 NC-like atmosph. ν candidates have been identified in 3 week data recording (1 ± 0.4 μCC, 1 ± 0.4 eCC and 0.4 ± 0.2 NC expected)





NC atm. candidate: E_{DEP} ~ 200 MeV

- 2 charged particles emerge from interaction vertex
- π track: 63 cm (interacting and generating 2 protons)

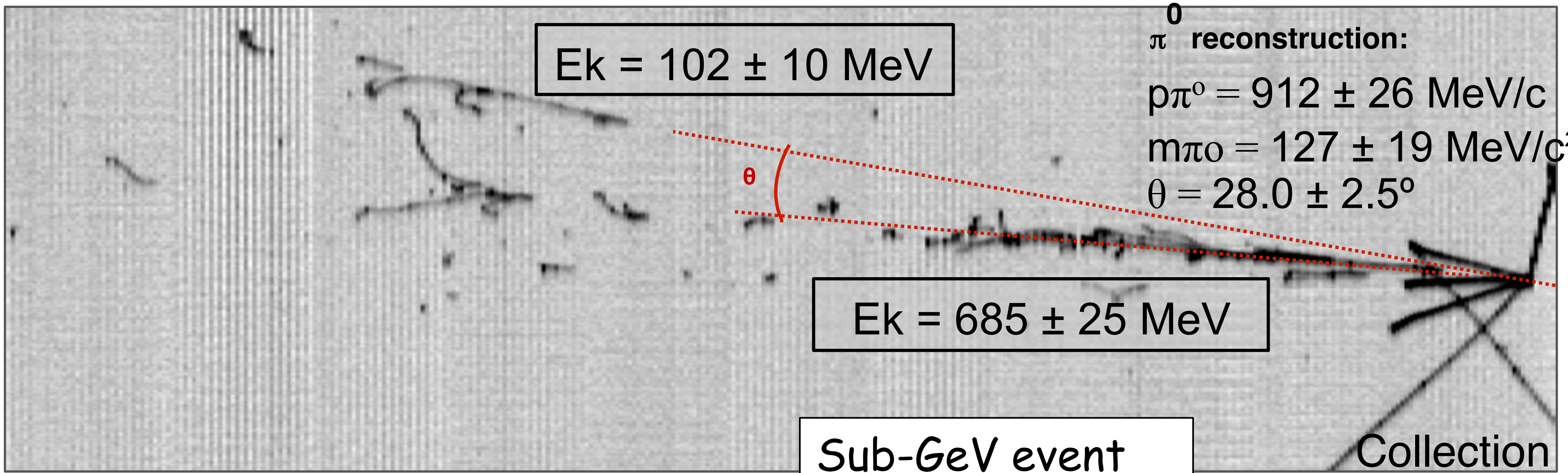


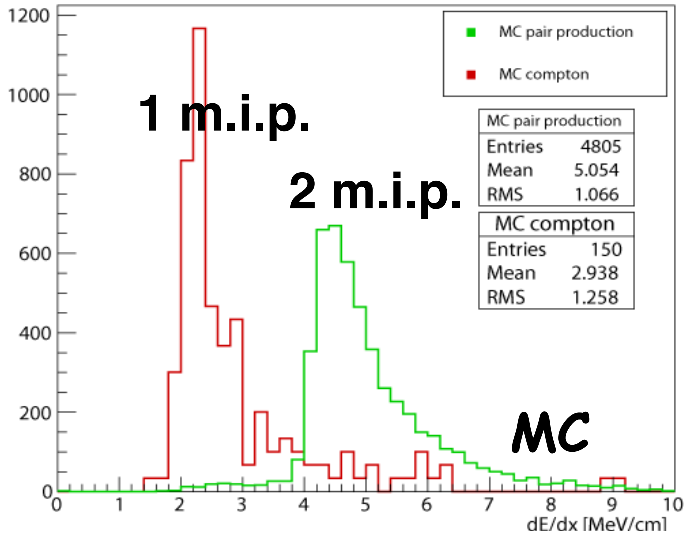
$\nu\mu$ CC atm. candidate: E_{DEP}~ 350 MeV

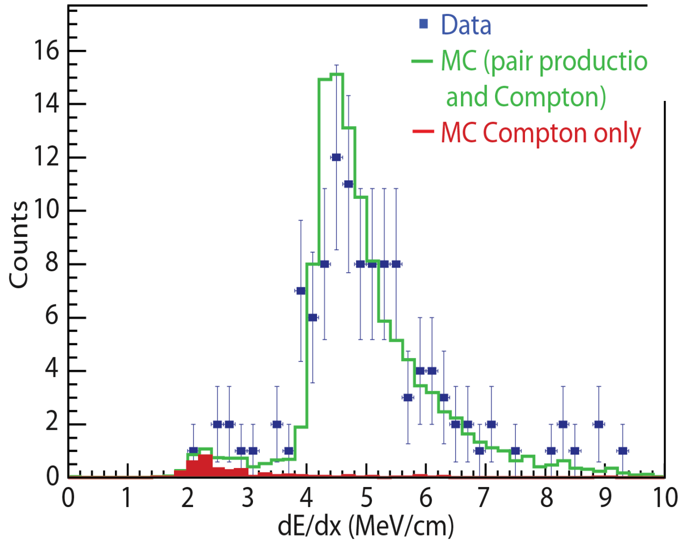
- μ and p/π tracks are visible
- μ track candidate: 124 cm

~200 atm. ν expected for 0.73 kt y exposure

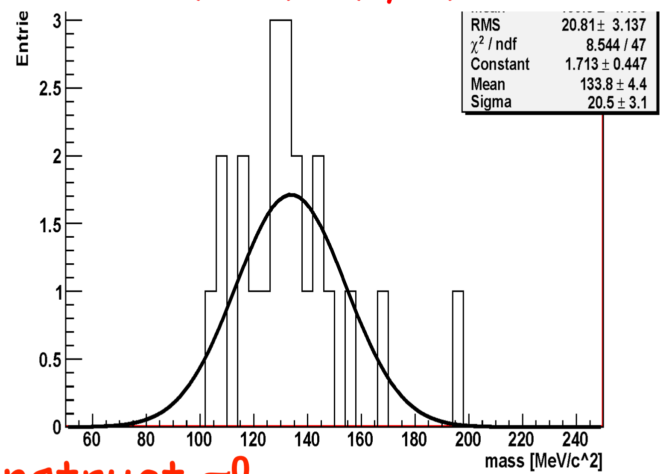
e/γ separation and π^0 reconstruction in ICARUS







Mγγ: 133.8±4.4(stat)±4(syst) MeV/c2

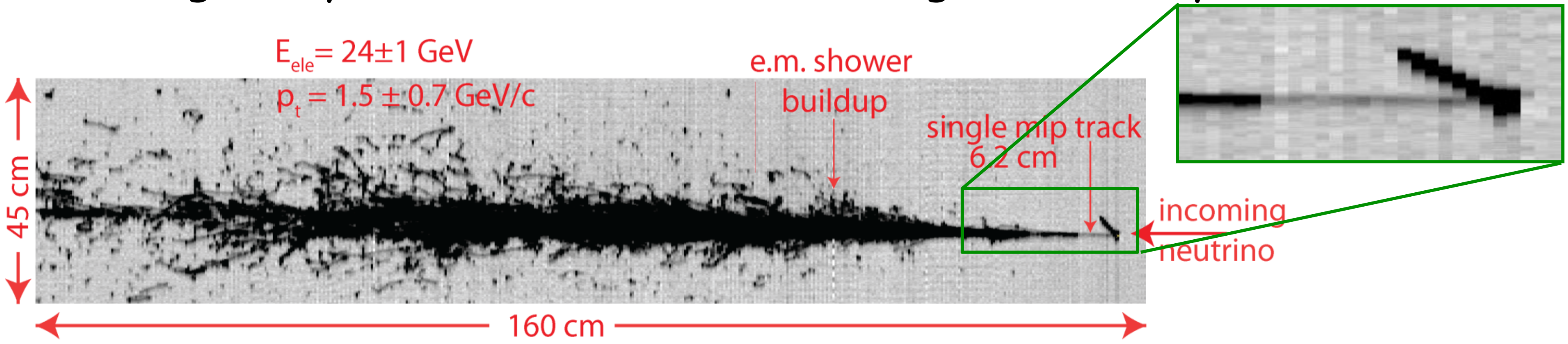


Unique feature of LAr to distinguish e from γ and reconstruct π^0

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

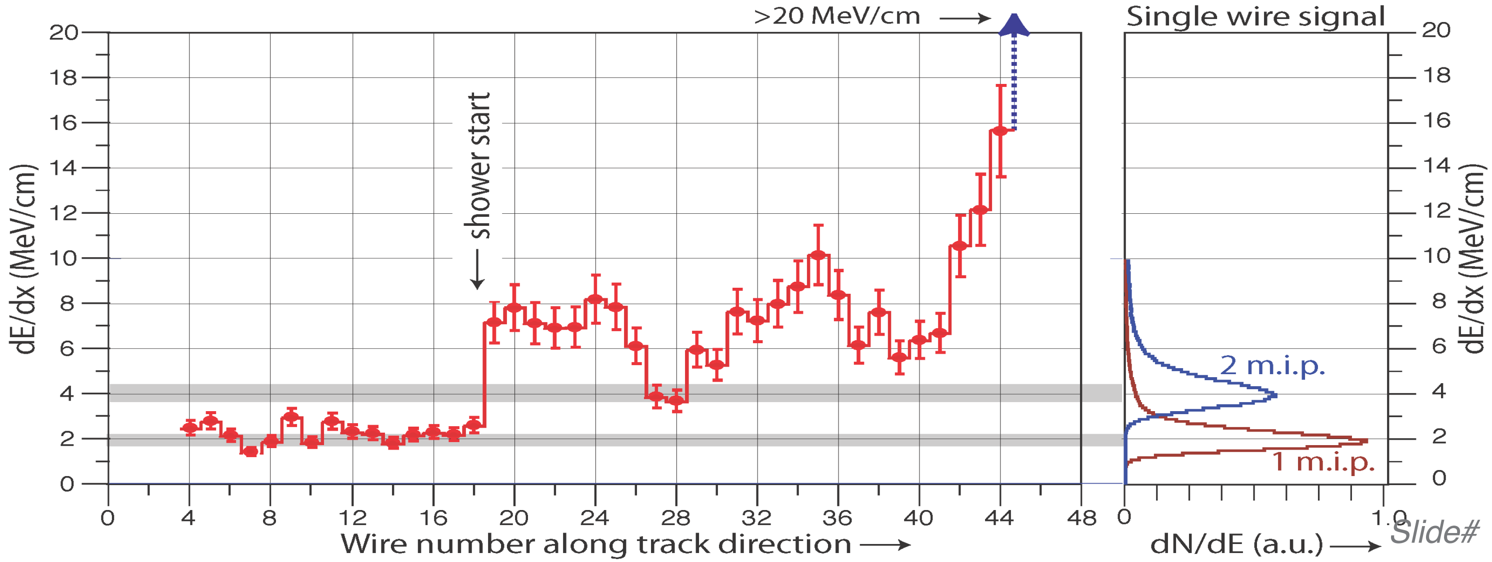
ν_e identification in ICARUS LAr-TPC

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



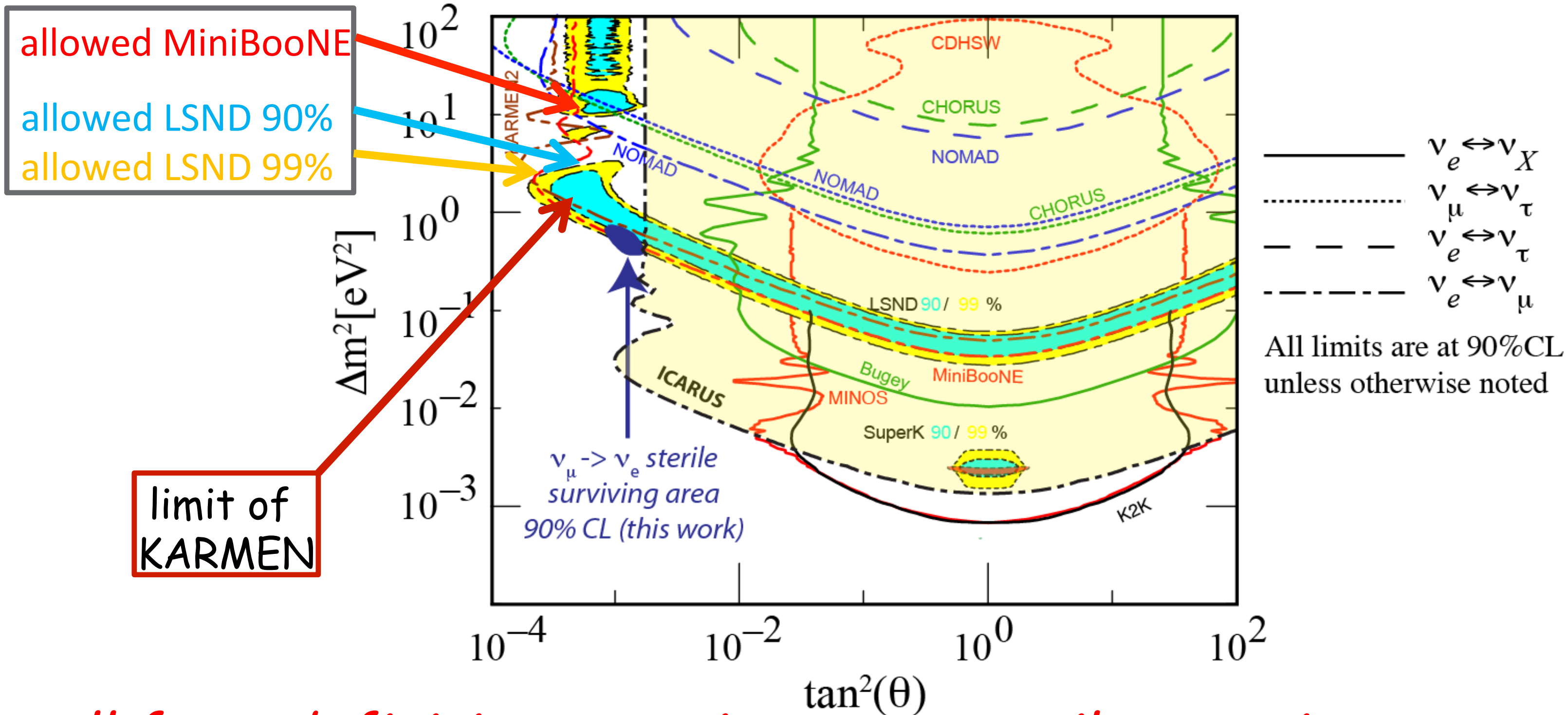
- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.

Single M.I.P



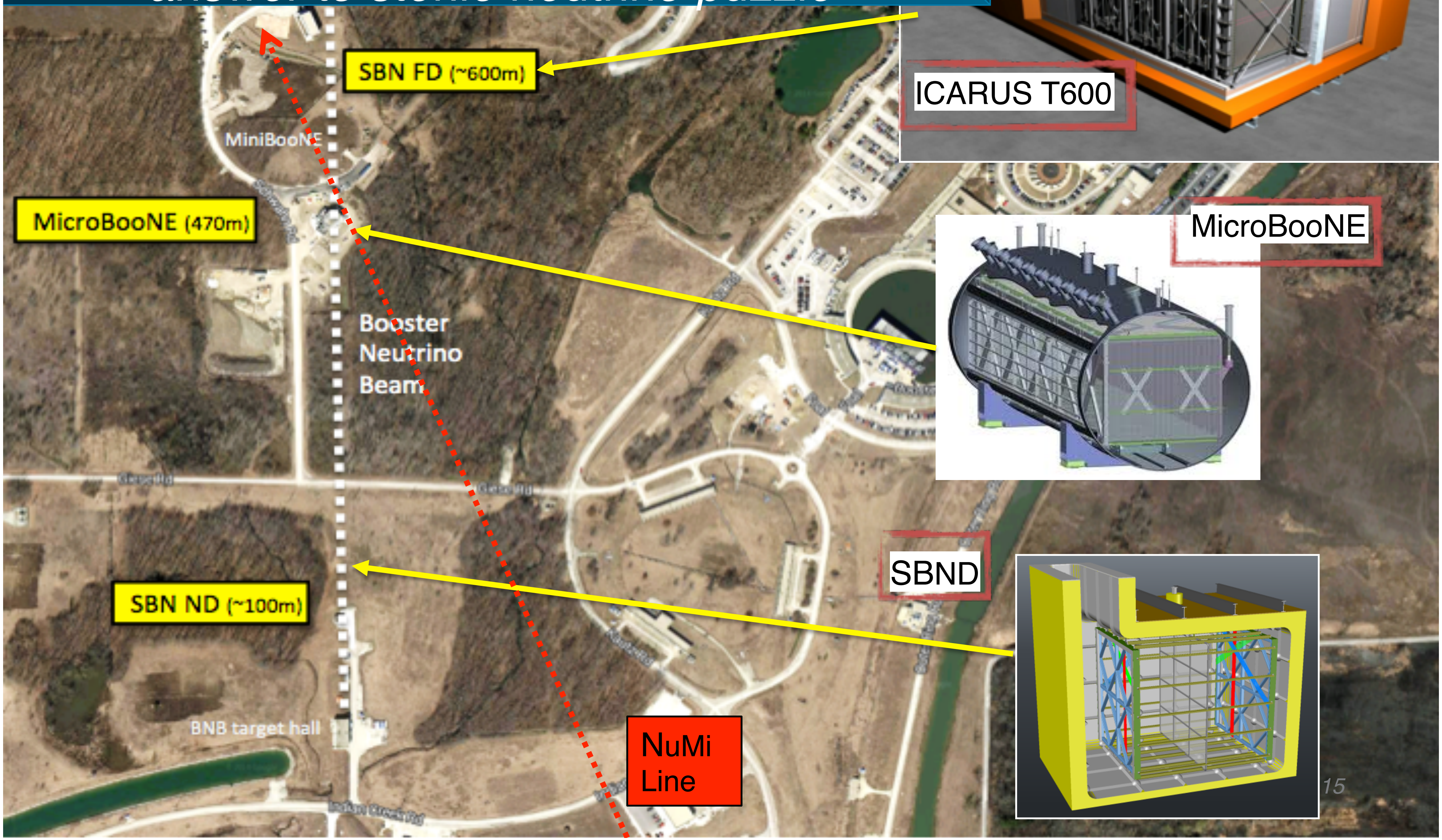
Search for LSND-like anomaly by ICARUS at LNGS

- ICARUS searched for ν_e excess related to LSND-like anomaly on the CNGS ν beam (~ 1% intrinsic ν_e contamination, L/Eν ~36.5 m/MeV)
- Analysis on 7.23 x 10^{19} pot event sample provided the limit on the oscillation probability $P(\nu_\mu \rightarrow \nu_e) \leq 3.85\ (7.60) \times 10^{-3}$ at 90 (99) % C.L.
- ICARUS result indicates a very narrow region of parameter space, Δm^2~0.5 eV^2, $\sin^2 2\theta$~0.005 where all experimental results can be accommodated at 90% CL



The result call for a definitive experiment on sterile neutrino to clarify all the reported neutrino anomalies

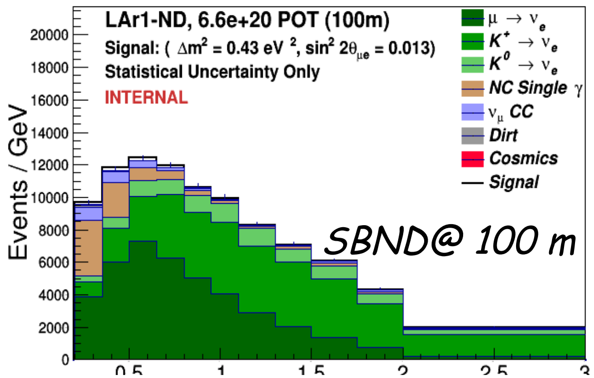
SBN experiment*: 3 LAr-TPCs at FNAL Booster beam (E_ν~0.8 GeV) for a definitive answer to sterile neutrino puzzle*

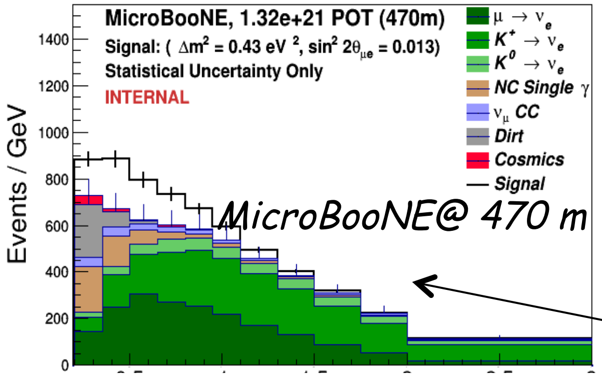


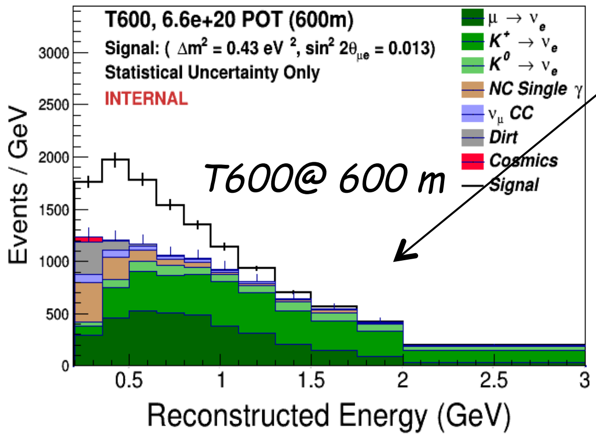
SBN Sterile neutrino search at FNAL Booster ν beamline

- Joint ICARUS/SBND/MicroBooNE CDR received *Stage 1 Approval from FNAL PAC Jan 2015*. Three LAr-TPC's at different distances from target: SBND (82 t active mass), MicroBooNE (89 t) and ICARUS (476 t) at 100, 470 and 600 m
- The experiment will likely clarify LSND/MiniBooNE , Gallex, reactor anomalies by precisely/independently measuring both ν_e appearance and ν_μ disappearance, mutually related through $\sin^2(2\vartheta_{\mu e}) \leq \frac{1}{4}\sin^2(2\vartheta_{\mu x})\sin^2(2\vartheta_{ex})$
  - In absence of "anomalies", 3 detector signals should be a close copy of each other for all experimental signatures. Intrinsic ν_e with a disappearance signal (if f.i. confirmed by reactors) may result in a reduction of a superimposed LSND ne signal: effects can be disentangled by changing intrinsic ne beam with different beam optics (horn/ decay tunnel length).
- During its SBN operations, ICARUS will collect also ~ 2 GeV ν_eCC events with NUMI Off-Axis beam, an asset for the long baseline LAr project at FNAL.
  - accurate determination of cross sections in LAr ;
  - experimental study of all individual CC/NC channels to realize algorithms to improve the identification of neutrino interactions.

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





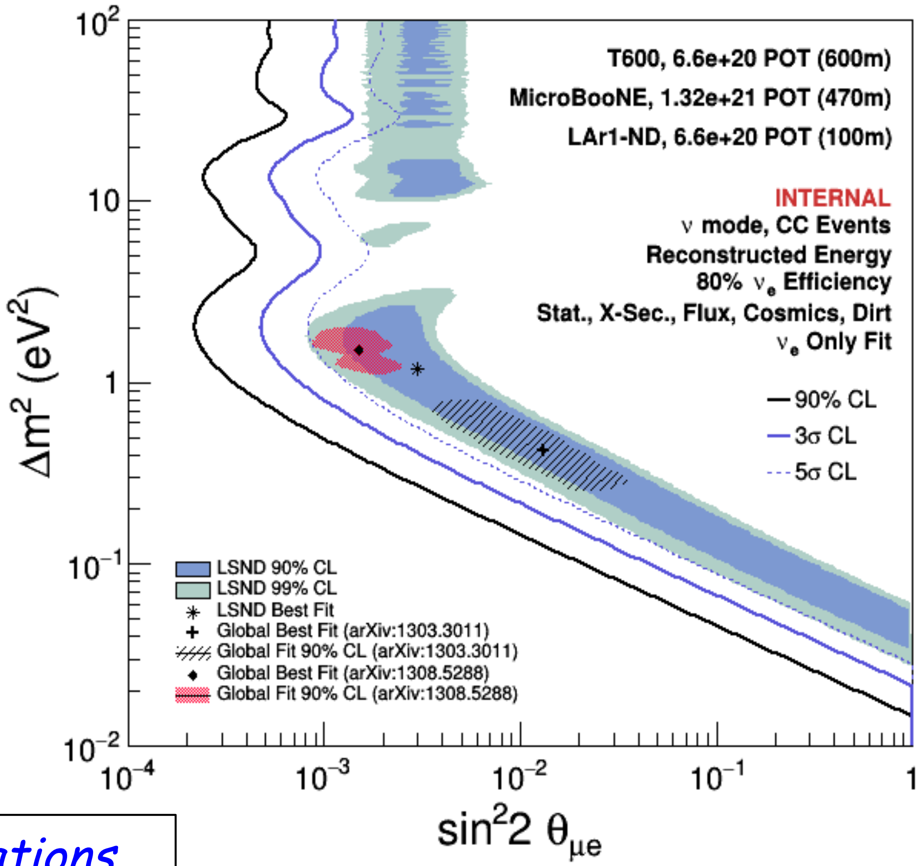


- Expected exposure sensitivity of $\nu_\mu \rightarrow \nu_e$ oscillations for 3 years - 6.6 10^{20} pot BNB positive focusing (6 years for MicroBooNE).

Example for

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

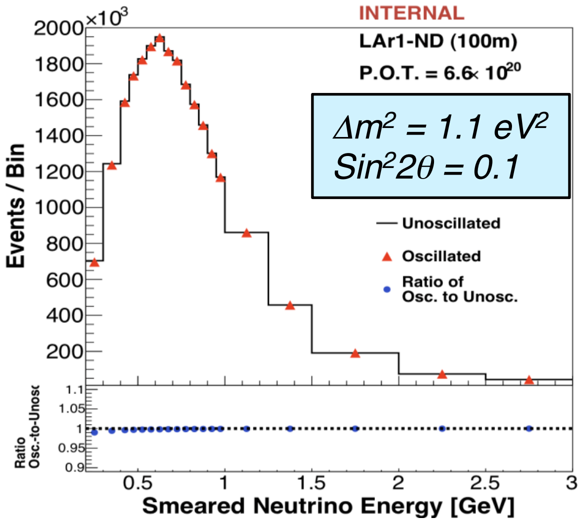
Δm^2=0.43 eV^2)

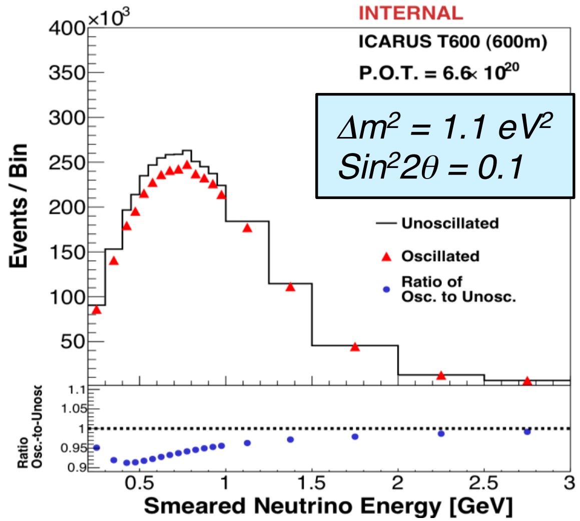


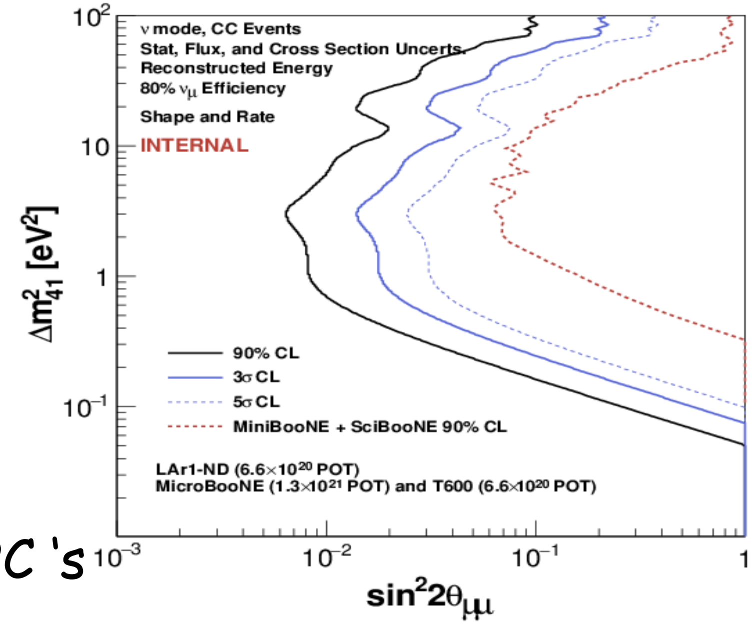
In absence of oscillations, the spectra should be copies of each other

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

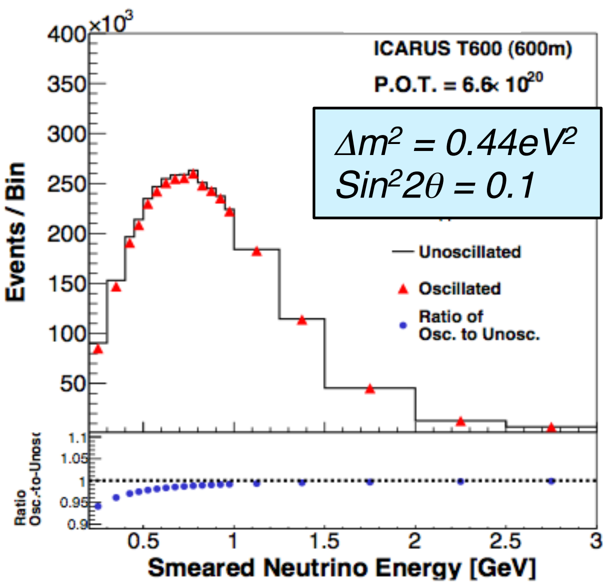
ν_μ disappearance sensitivity

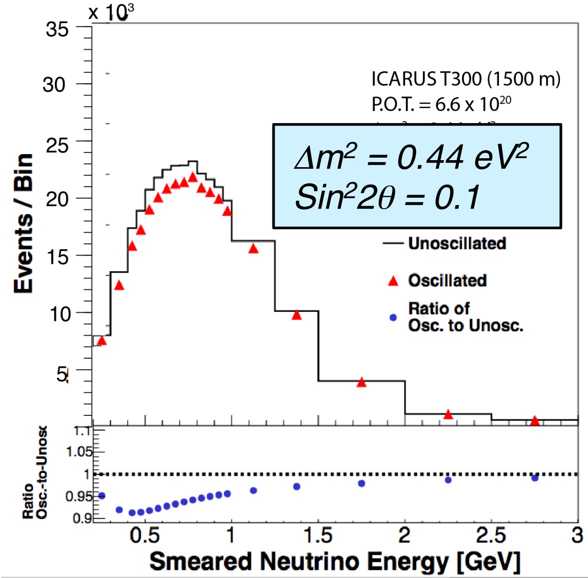






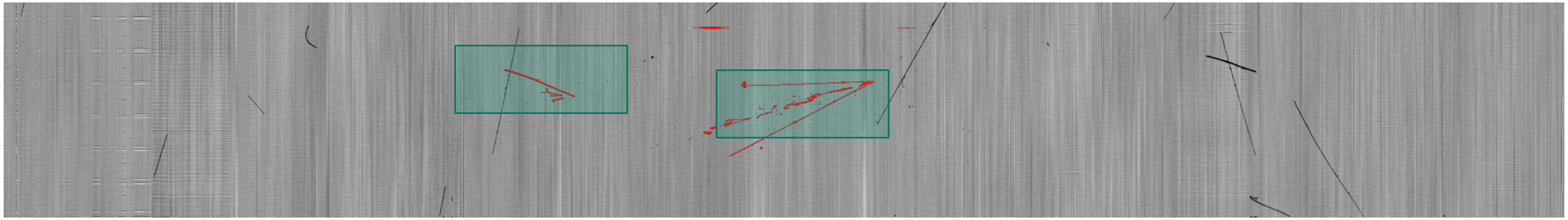
- High event rates/ correlations between 3 LAr-TPC 's will allow extending sensitivity by one order of magnitude beyond present limit
- However for $\Delta m^2 < 0.5\ eV^2$ ν_μ disappearance at 600 m will be limited at lowest ν energy bins (0.2-0.4 GeV).
- *In order to amplify the effect we may move at a later stage one ICARUS T300 module to 1500 m distance.*





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

- At shallow depth ~12 uncorrelated cosmic rays will occur in T600 during 1 ms drift window readout at each triggering event.
- This represents a new problem compared to underground operation at LNGS: the reconstruction of the true position of each track requires precisely associating to each element of TPC image the occurrence time with respect to trigger time.

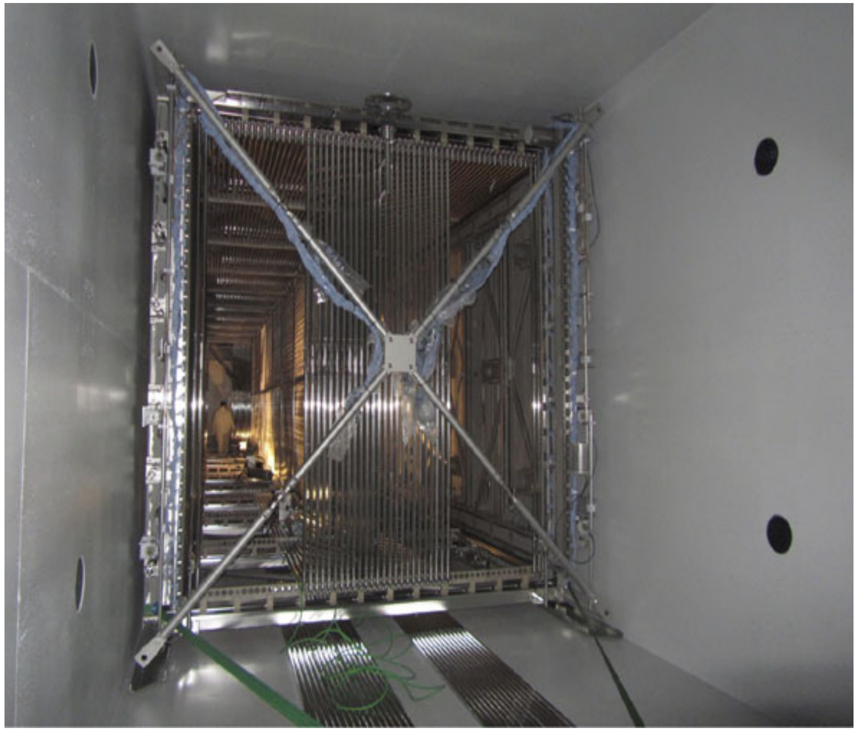


Cosmic rays + low energy CNGS beam events

- Moreover, γ's associated with cosmic μ's represent a serious background for the νe appearance search since *electrons* generated in LAr via Compton scattering/ pair production can mimic a νe CC genuine signal.
- A 4π Cosmic Rays Tagger (total surface ~ 1200 m^2) of plastic scintillators around the LAr active volume will unambiguously identify all cosmic ray particles entering the detector providing timing/ position to be combined with the TPC reconstructed image.

WA104 Project at CERN: overhauling of the T600

- INFN has signed a MoU for WA104 project at CERN for T600 overhauling in the framework of CERN Neutrino Platform for LAr-TPC development for short/ long baseline neutrino experiment

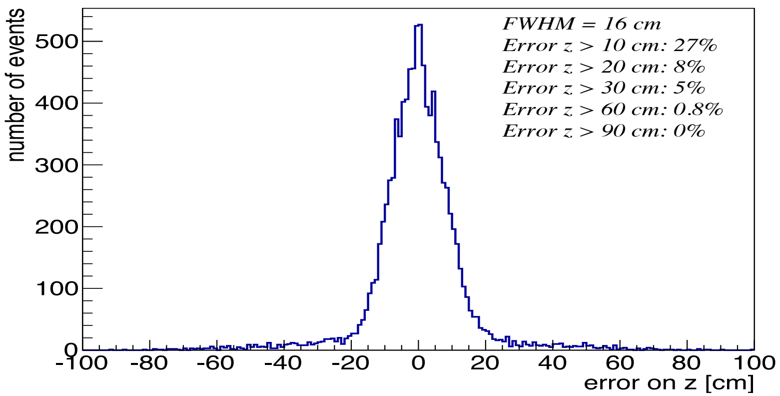


- T600 is being upgraded introducing technology developments while maintaining the already achieved performance:
  - new cold vessels, with a purely passive insulation;
  - refurbishing of cryogenics / purification equipment;
  - a cathode with better planarity;
  - upgrade of the light collection system;
  - new faster, higher-performance read-out electronics.
- Common items for ICARUS and other SBN LAr-TPCs: muon tagging systems to be designed/constructed; tools for event reconstruction have to be developed

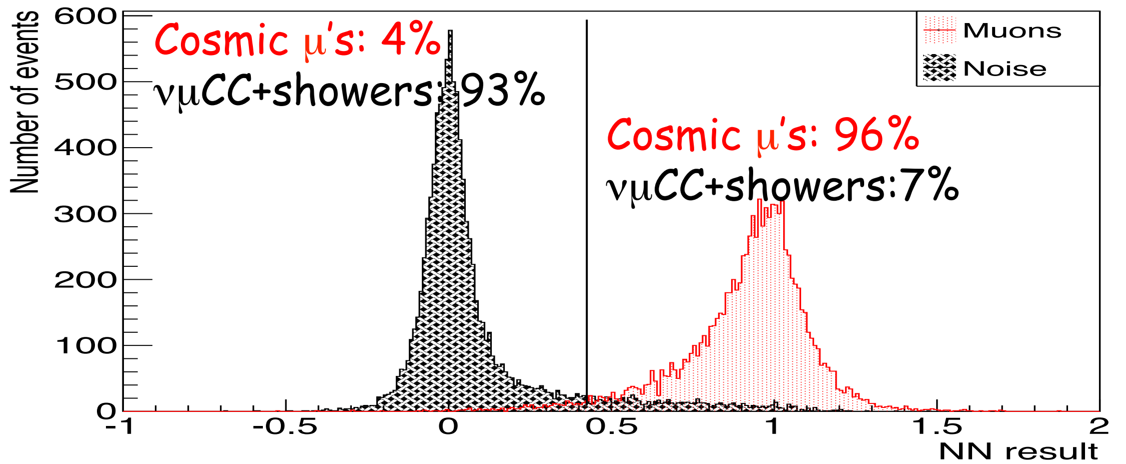
The detector is expected to be transferred to FNAL before end 2016 for installation, commissioning and start of data taking (end 2017).

Upgrade of the light collection system

- Main requirements for the refurbished light detection system:
  - High detection coverage, to be sensitive to low E_ν deposition (~ 100 MeV)
  - High detection granularity, to localize events and unambiguously associate the collected light to deposited charge;
  - Fast response - high time resolution, to be sensitive to timing of each event in the T600 DAQ windows (~ 1 ms); a ~1 ns precision is advisable to exploit the 2ns/19ns bunched beam structure .
- The present T600 light detection system can be extended to 90 PMT per TPC, (5% area coverage). ~15 phe/MeV allowing to efficiently trigger LE events.



95 % events localized within 30 cm



Neural Networks can provide a clear cosmic muon identification (~2% wrong ID)

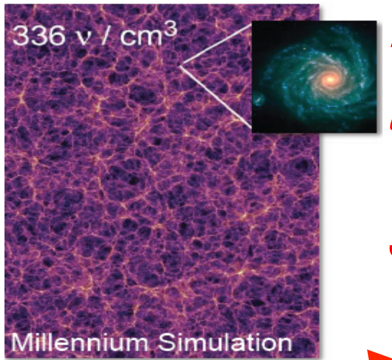
Conclusions

- Exposed in Hall B of the Gran Sasso underground Lab. to CNGS neutrino beam from CERN, the ICARUS T600 neutrino experiment with 760 ton of highly purified LAr has successfully completed a three years physics program at LNGS. Together with all previous test beam runs, this allowed the definitive assessment of detection capabilities of LAr-TPC technology.
- The T600 detector has now been moved to CERN for a significant overhauling in view of the SBN neutrino experiment on the FNAL Booster and NUMI beams based on three detectors at different baselines (near: SBND, mid: MicroBooNE, far: ICARUS).
- *The experiment is expected to start data taking by end 2017 aiming to the definitive clarification of the LSND signal in terms of ν oscillations (ν_e appearance). It will also provide a significant amount of data in the energy range of interest for the next Long Baseline experiment.*
- A second phase is also under consideration with a fourth LAr detector at a longer distance ($\geq$1500 m) extending the sterile ν search to lower Δm^2 as indicated by cosmology (ν_μ disappearance).

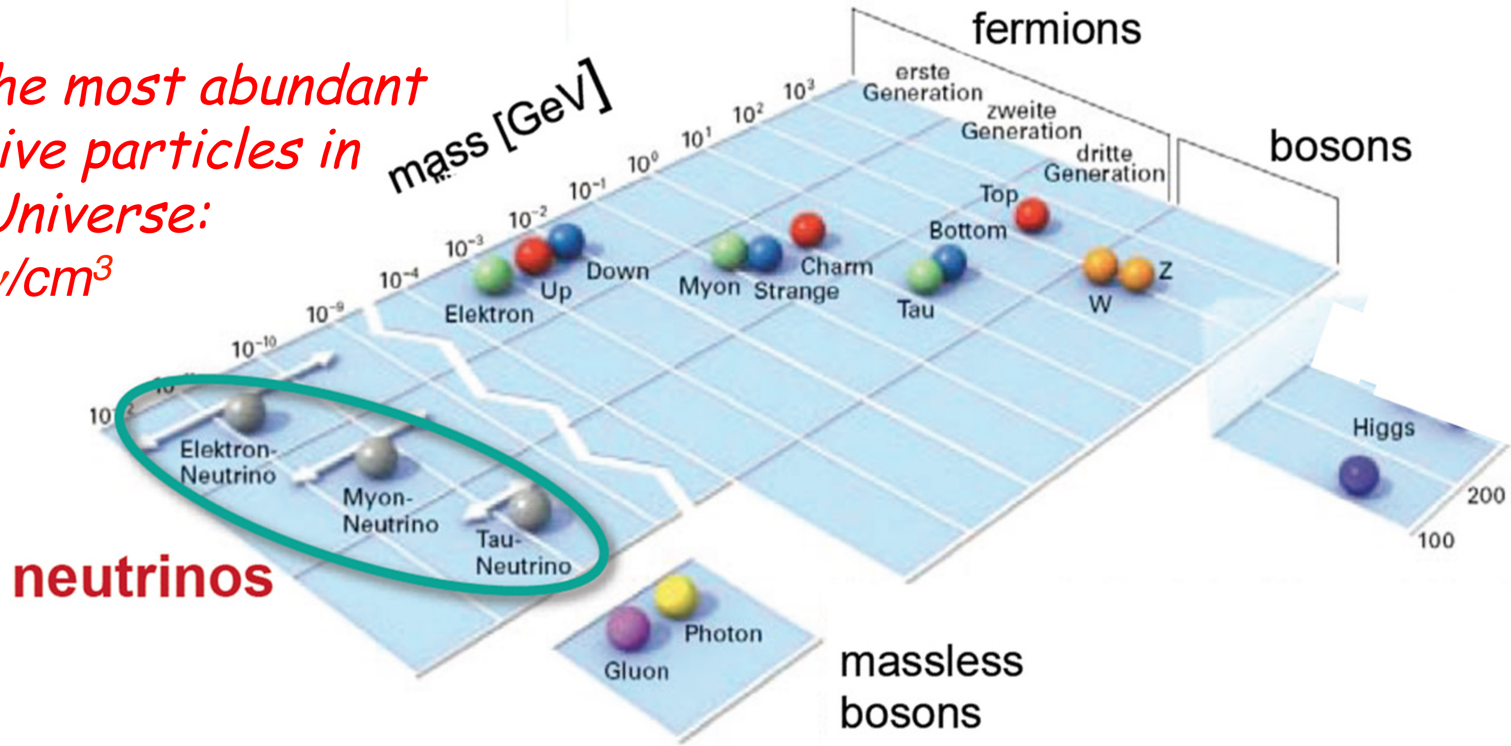
Backup

The high energy frontier

- Neutrino masses and oscillations represent today a main experimental evidence of physics beyond SM. Being the only elementary fermions whose basic properties are still largely unknown, νs are naturally one of the main priorities to complete our knowledge of SM.



νs :the most abundant massive particles in the Universe:
336 ν/cm³

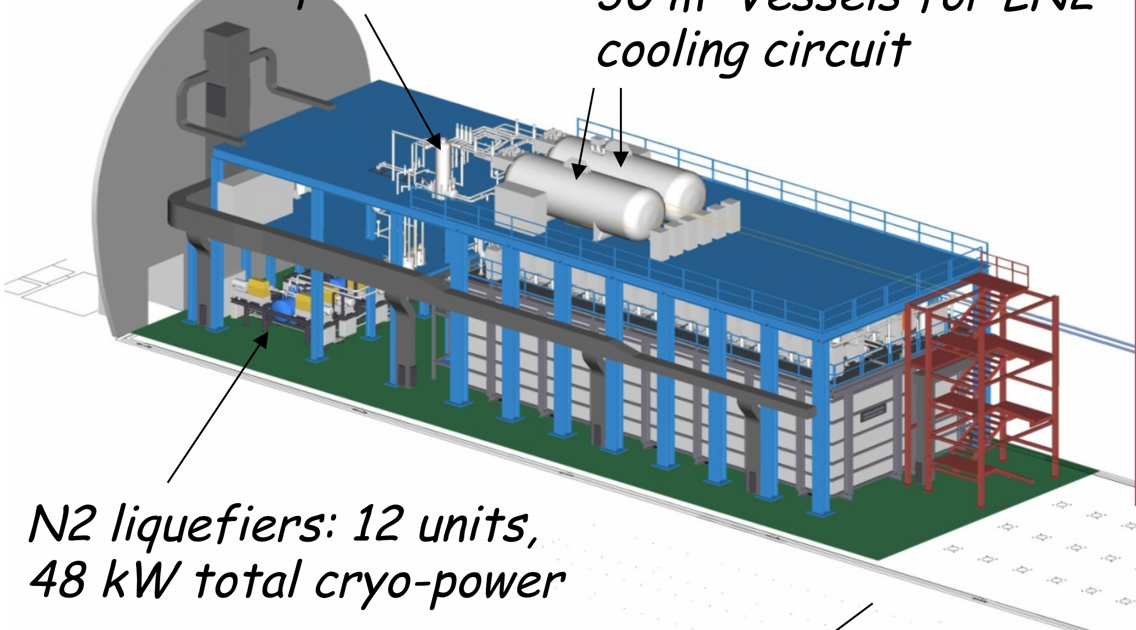


- The incredible smallness of ν masses compared to other elementary fermions points to some specific scenario awaiting to be elucidated.

ICARUS-T600 @ LNGS Hall B: 0.77 kton LAr-TPC

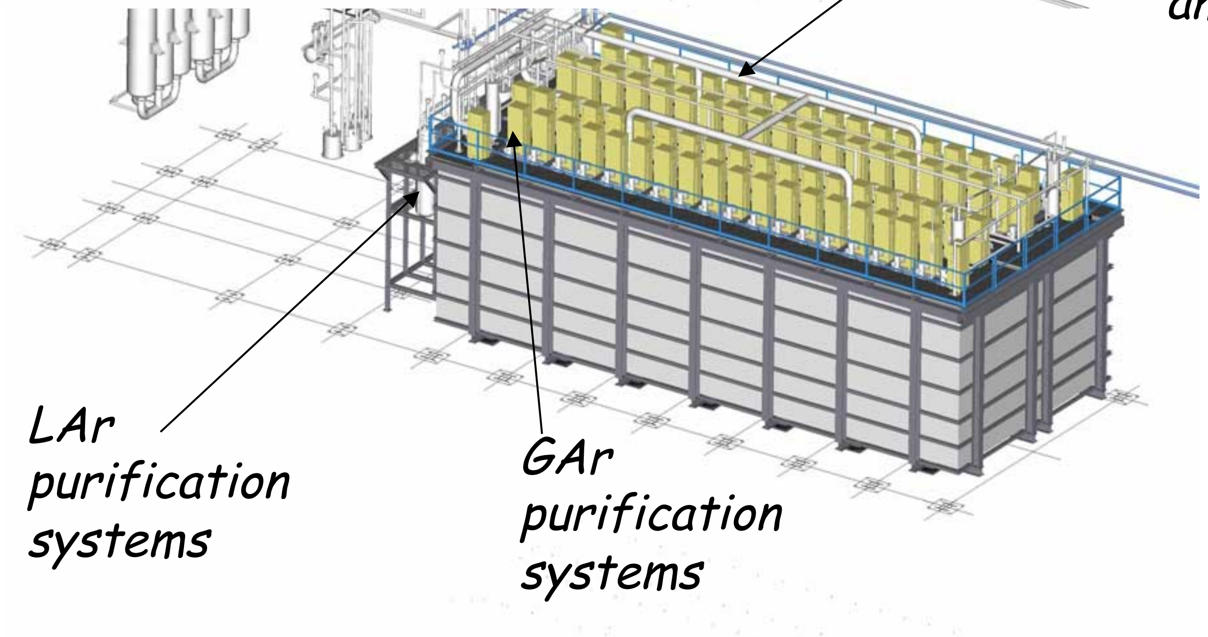
N2 Phase separator

30 m³ Vessels for LN2 cooling circuit



N2 liquefiers: 12 units, 48 kW total cryo-power

54000 electronic ch, low noise charge amplifiers + digitizers, S/N > 10

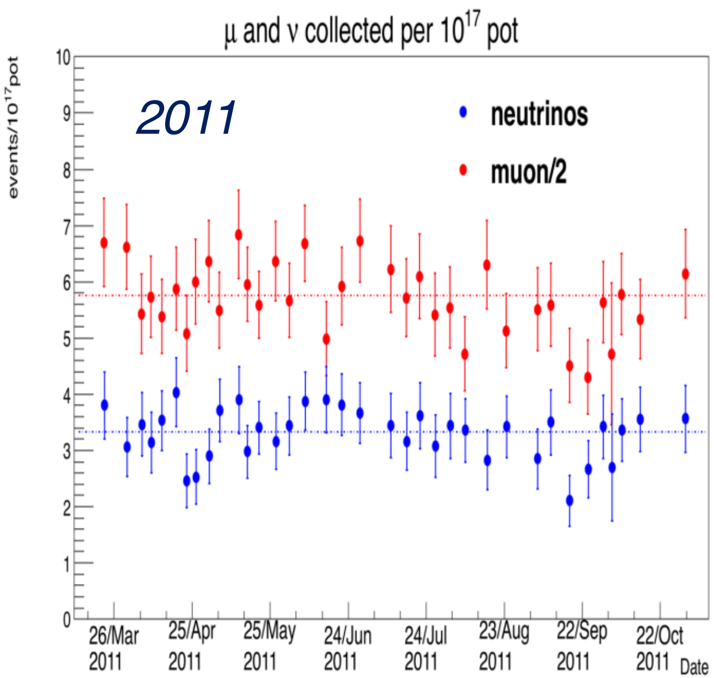


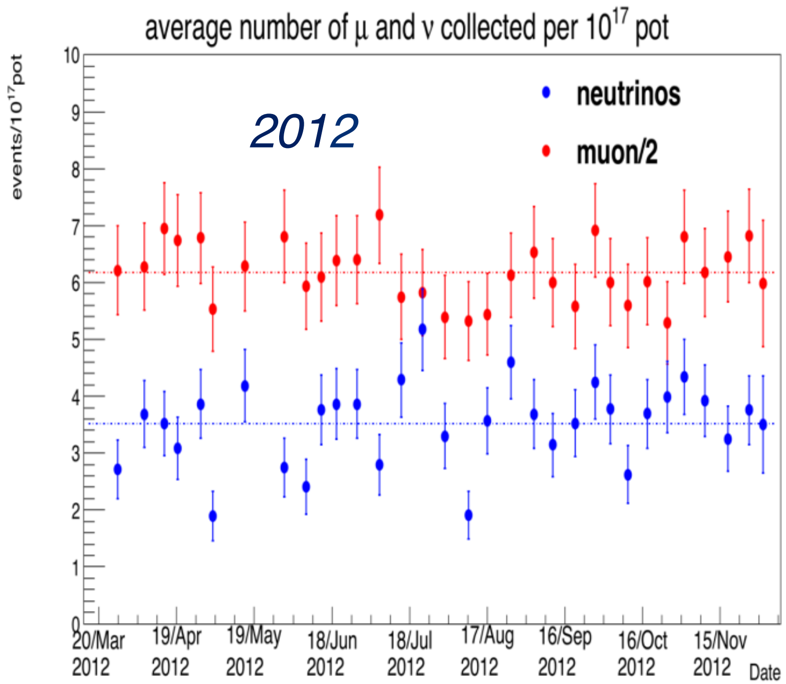
LAr purification systems

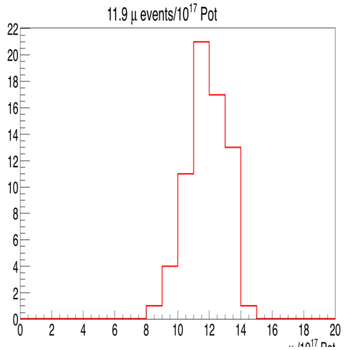
GAr purification systems

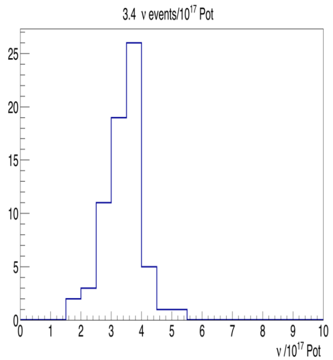
ICARUS: summary of collected data with CNGS

- A total sample of 2650 ν interactions corresponding to 7.93 10^{19} over 8.6 10^{19} pot collected has been filtered, scanned & preliminarly analyzed
- Distributions of collected neutrinos and of beam related μs normalized by 10^{17}pot statistics and DAQ efficiency: 3.4 νs 12 μs events on average





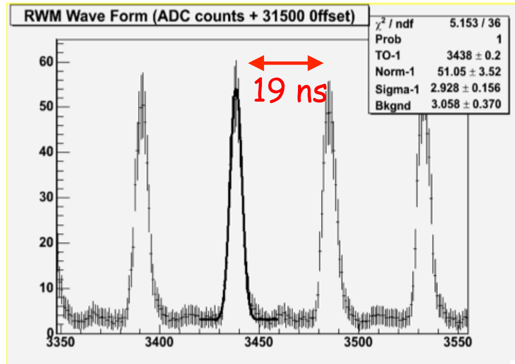




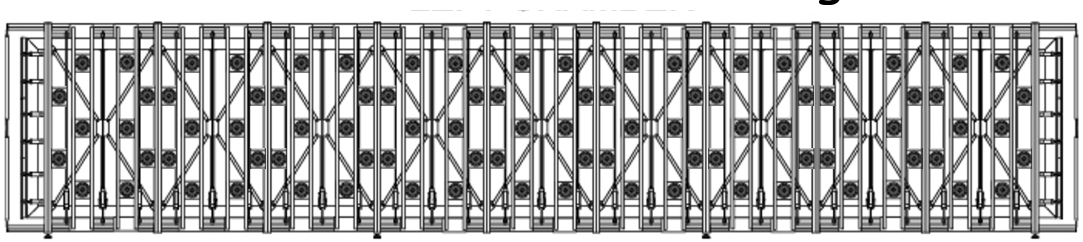
Data are consistent within 6% with MC predictions for corresponding exposure

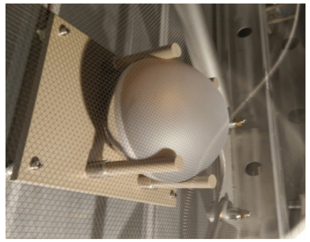
Upgrade of the light collection system

- Main requirements for the refurbished light detection system:
  - ➢ High detection coverage, to be sensitive to low Eν deposition in the TPC (~ 100 MeV) and to reject ^{39}Ar background;
  - ➢ High detection granularity, to localize events/ unambiguously associate the collected light to deposited charge;
  - ➢ Fast response - high time resolution, to be sensitive to time and evolution of each event in the T600 DAQ windows (~ 1.5 ms); a ~1 ns precision is advisable to exploit the available 2ns/19 ns bunched beam structure .



- The present T600 light detection system can be easily extended with additional 8" PMTs with TPB wavelength shifter, up to 90 devices per TPC.

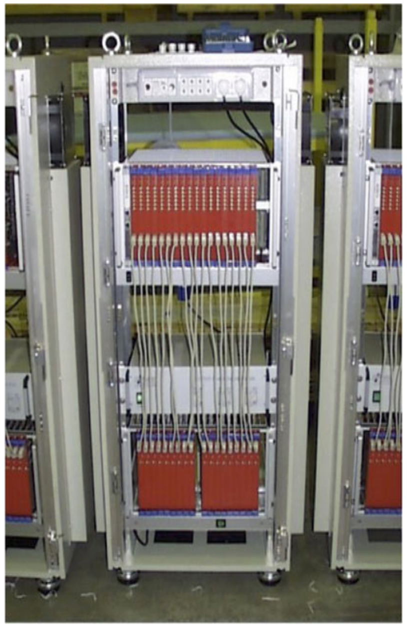




- The photo-cathode coverage corresponds to 5% of the wire plane area. ~ 15 (11) phe/MeV are collected at 1.5 (3) m drift allowing to trigger low energy events with fairly high threshold and PMT multiplicity.

An upgraded electronics

- Architecture of ICARUS 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.
- A signal to noise ratio > 10 and ~ 0.7 mm single point resolution were obtained in LNGS run, resulting in precise spatial event reconstruction and muon momentum by multiple scattering.
- *Some limitations:* asynchronous sampling of channels within 400 ns sampling-time slightly affecting MCS measurement, data throughput mainly due to VME.
- *Some relevant ongoing changes/improvements:*
  - Serial ADCs (10-12 bits, one per channel) in place of the multiplexed ones;
  - *Synchronous* sampling of all channels (400 ns sampling time) of whole detector;
  - Digital part contained in a single, high performance FPGA per board, that handles signal filtering, organizes information provided by the serial ADCs;
  - Housing/ integration of electronics onto detector; serial bus with optical links for faster transmission.



From 595 to 10 liters