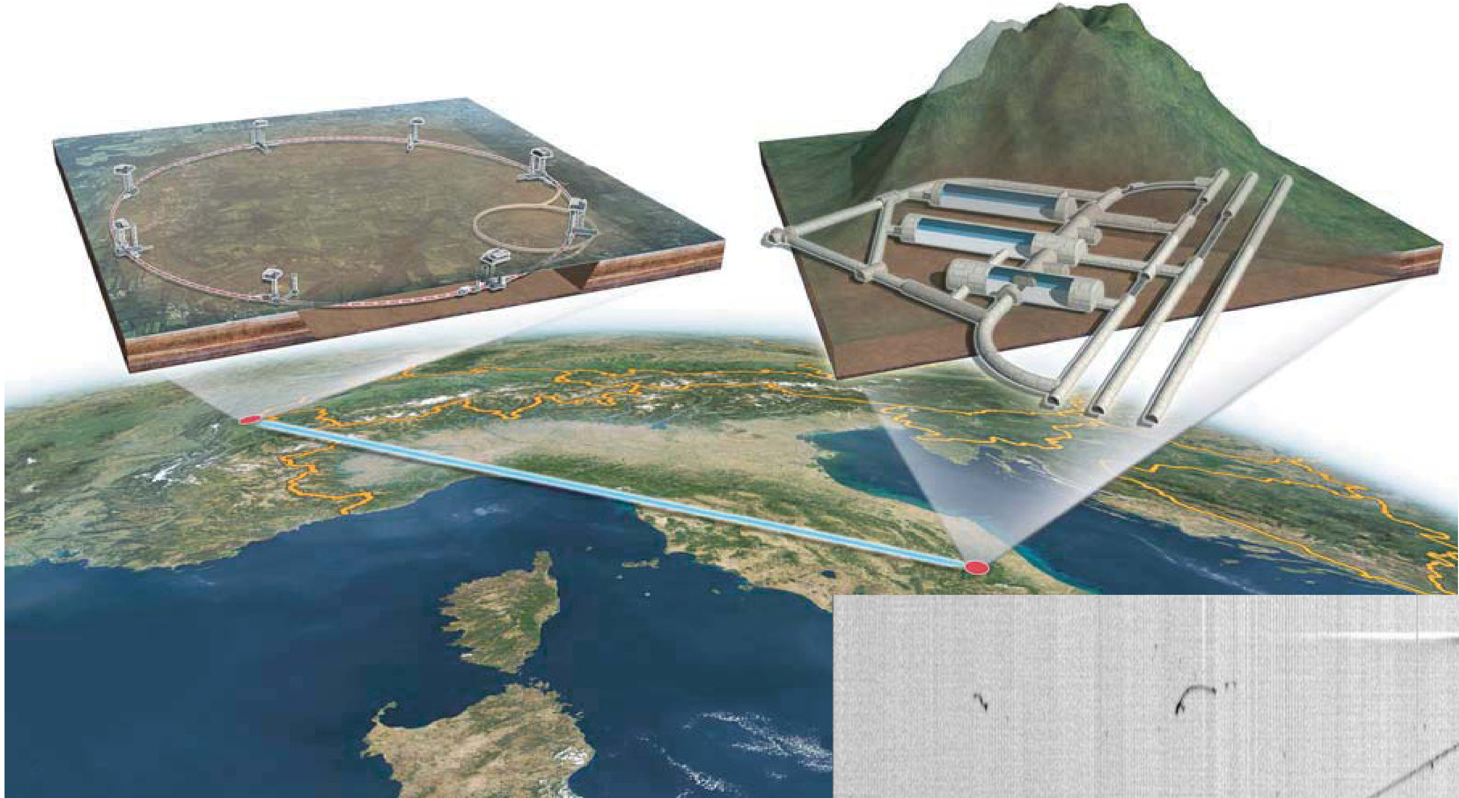
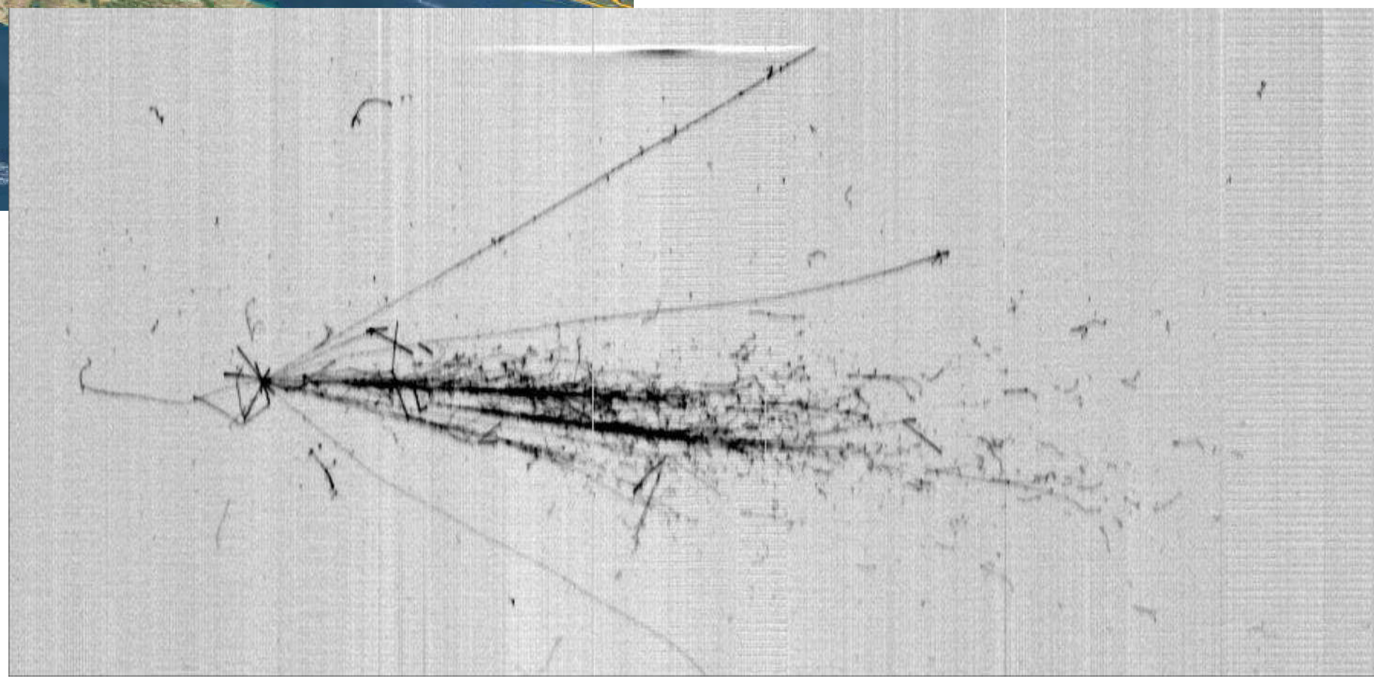
The role of the LAr-TPC technology for the present and future neutrino physics.



C. FARNESE
INFN Padova

On behalf of the ICARUS Collaboration

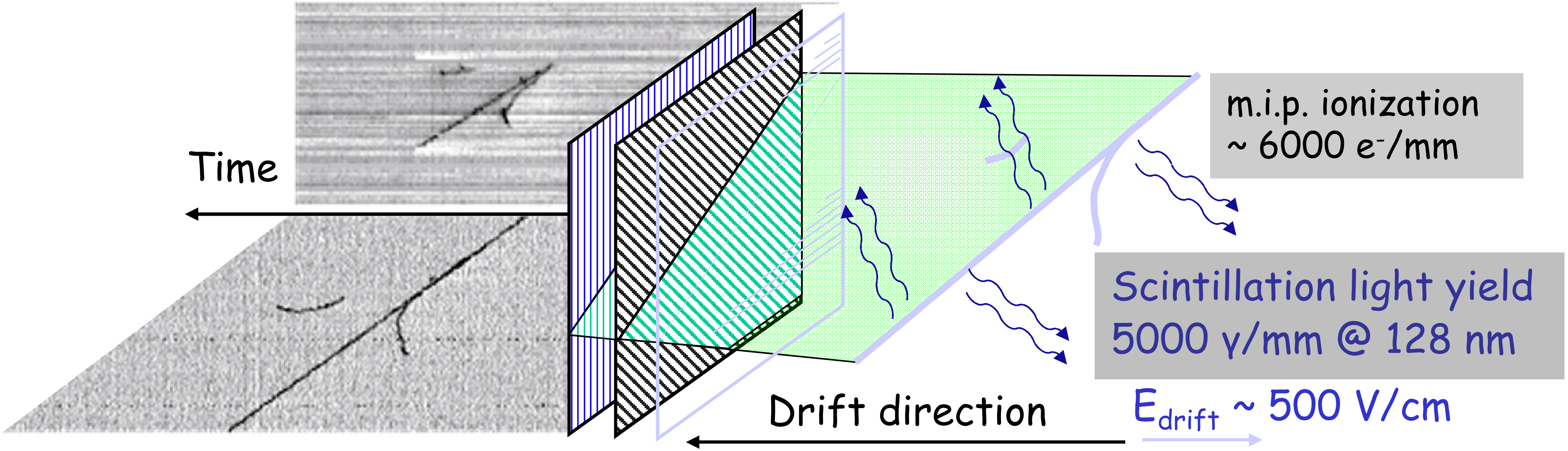


WHAT NEXT
Padova 1-2 Dec 2014

The initial idea of ICARUS: a powerful detection technique

The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)] first proposed to INFN in 1985 [ICARUS: INFN/AE-85/7] capable of providing a 3D imaging with high granularity (~ 1 mm) of any ionizing event ("electronic bubble chamber") with in addition:

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

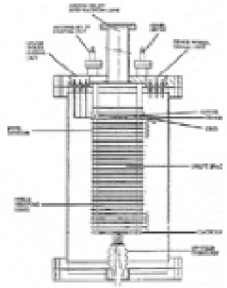


Drifting electrons are crossing transparent wire arrays oriented in different directions, where induction signals are recorded.

Medium	Liquid Argon	
Density	1.4	g/cm^3
Radiation length	14.0	cm
dE/dx	2.1	MeV/cm

The path to massive liquid Argon detectors

1



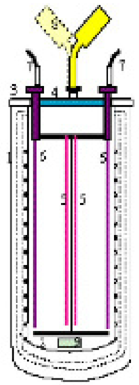
CERN

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.

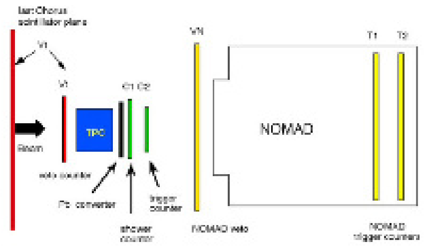
CERN

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

T600 detector

2001: First T600 module

5

Cooperation with industry and several companies

6

ICARUS T600 experiment

2010 - 2013 : Data taking with CNGS beam

LNGS Hall-B

The ICARUS Collaboration

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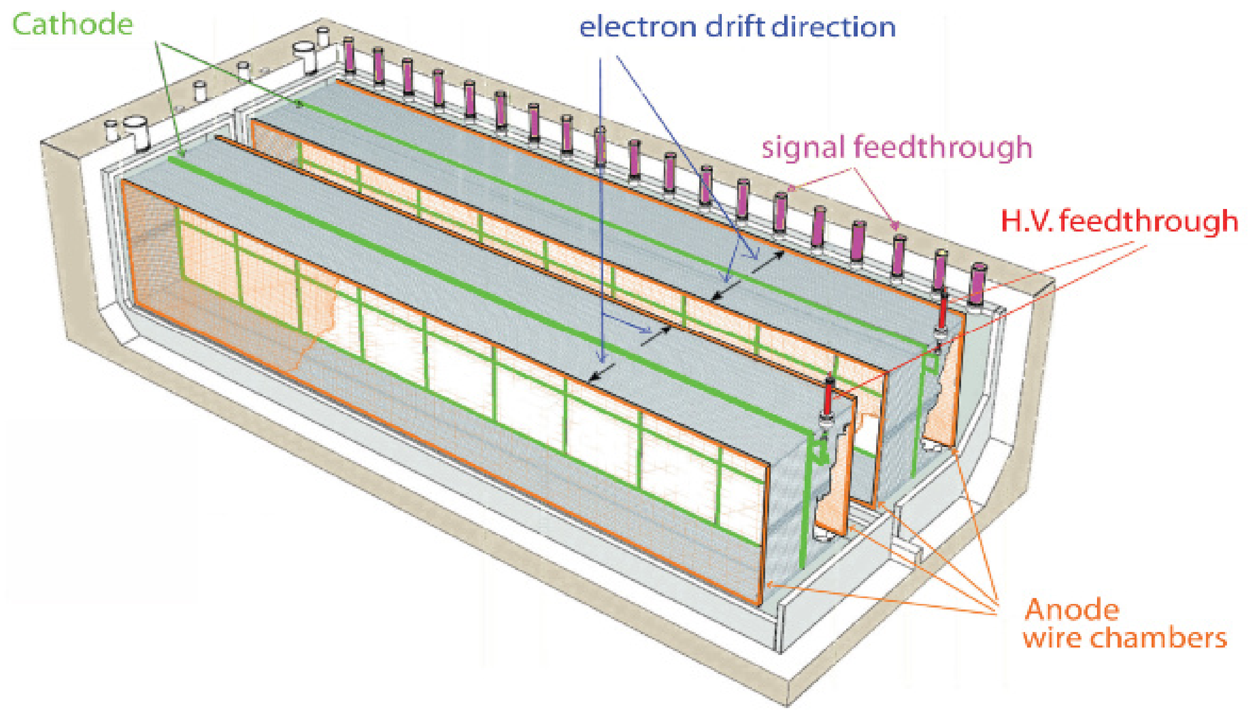
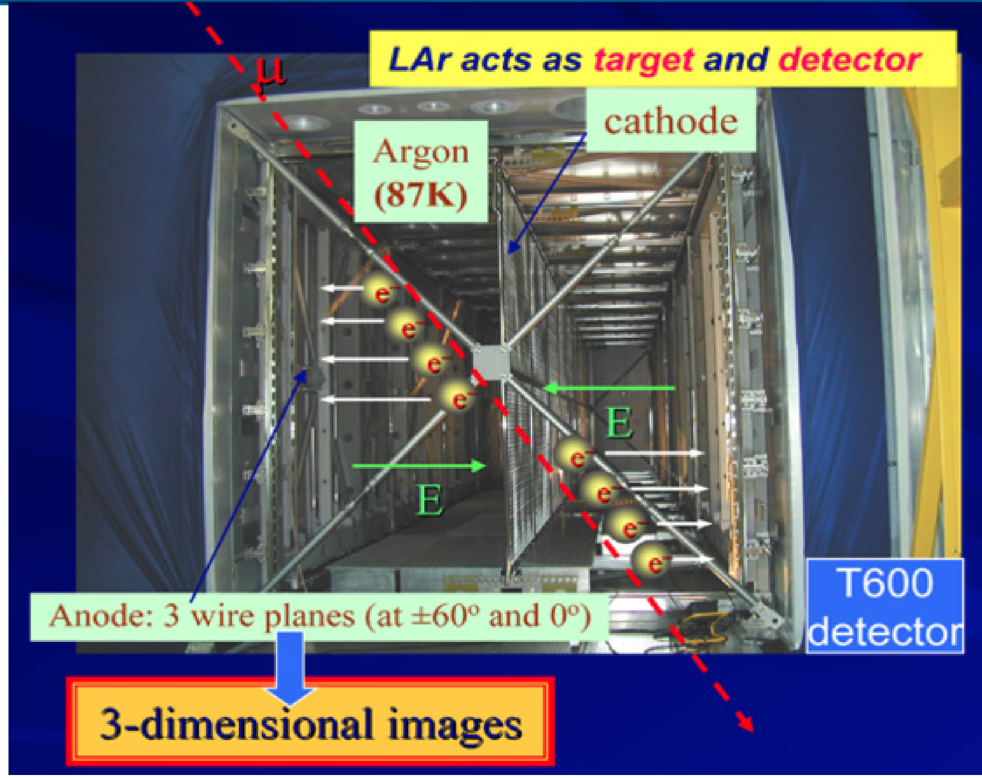
q GSSI, Gran Sasso Science Institute, L'Aquila, Italy

The ICARUS T600 detector

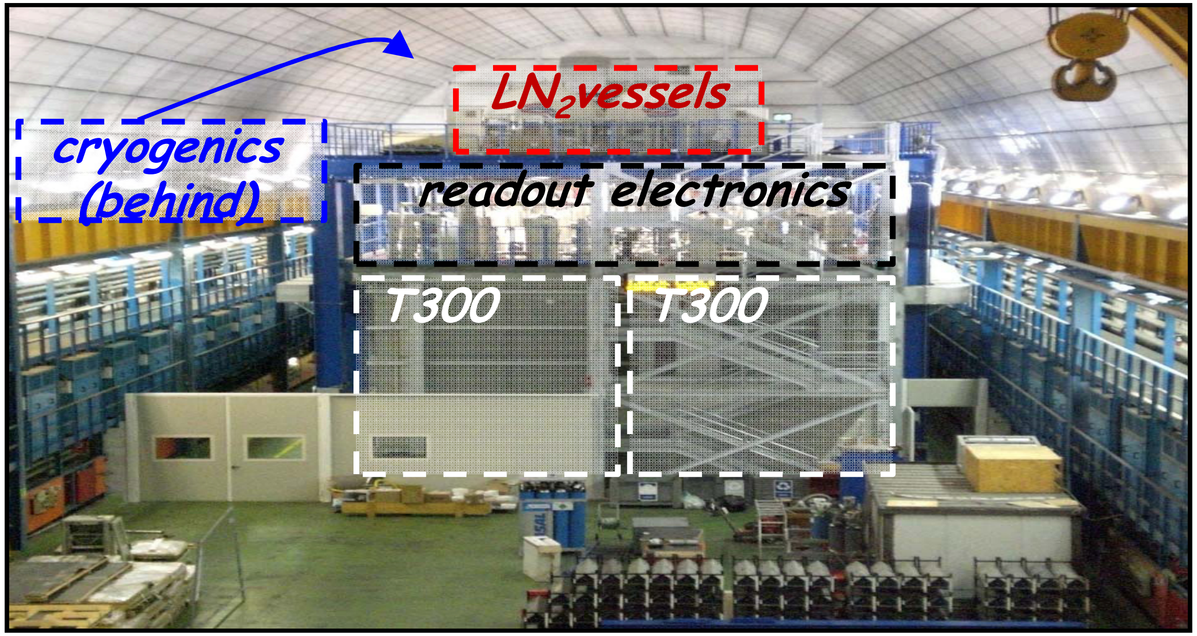




- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0,±60°
  - ≈ 54000 wires,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

The first large scale LAr physics experiment

- ICARUS represents a major milestone in the practical realization of a large scale LAr detector.
- ICARUS has been successfully exposed to CNGS beam from Oct 1st 2010 to Dec. 3rd 2012
- **$8.6\ 10^{19}$ protons on target** collected with a remarkable **detector live time > 93 %**



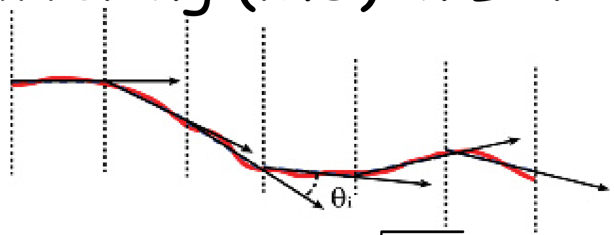
- Data taking conducted in parallel with c-rays to study atmospheric ν and p-decay (0.73 kty exposure)
- The main features of the detector are
  - Calorimetric determination of the e.m. and hadronic cascades

    Low energy electrons: $\sigma(E)/E = 11\% / \surd E(MeV) + 2\%$
    Electromagn. showers: $\sigma(E)/E = 3\% / \surd E(GeV)$
    Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \surd E(GeV)$
  - Determination of muon momentum by multiple scattering

Measurement of muon momentum via multiple scattering

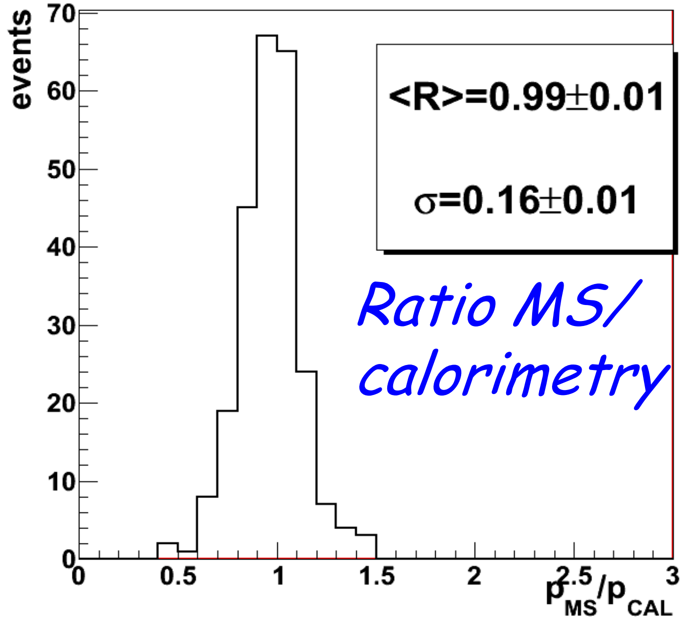
In absence of a magnetic field, the initial μ momentum is determined through the reconstruction of multiple Coulomb Scattering (MS) in LAr

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

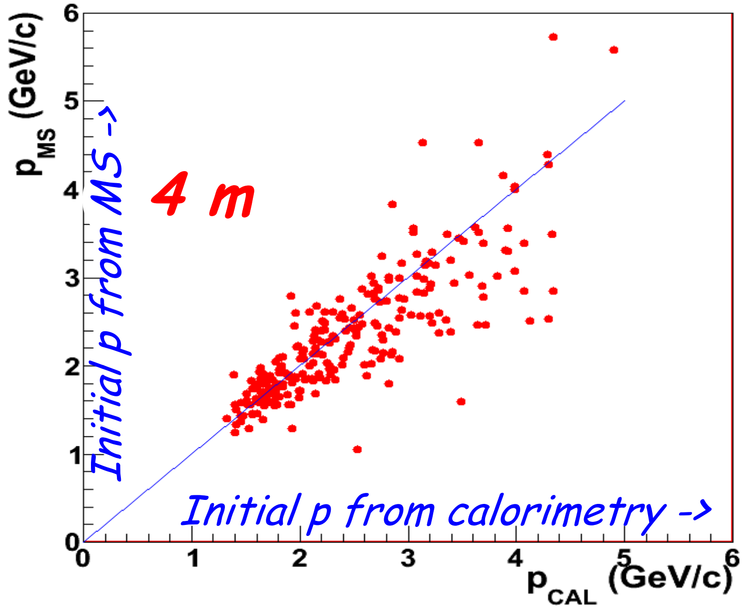


$$\theta_{RMS} \div \frac{13.6 MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$

Method tested on ~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

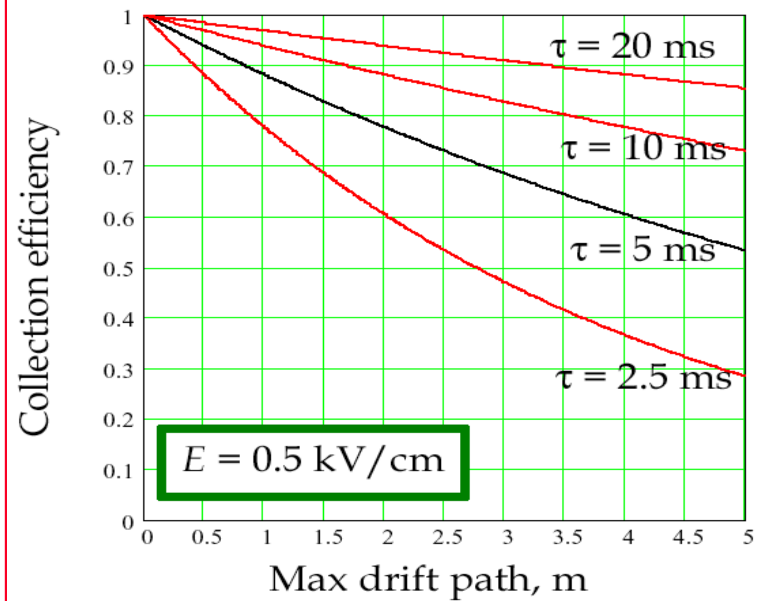


~16% resolution has been obtained in the 0.4-4 GeV /c momentum range of interest for the future short/long base-line experiments

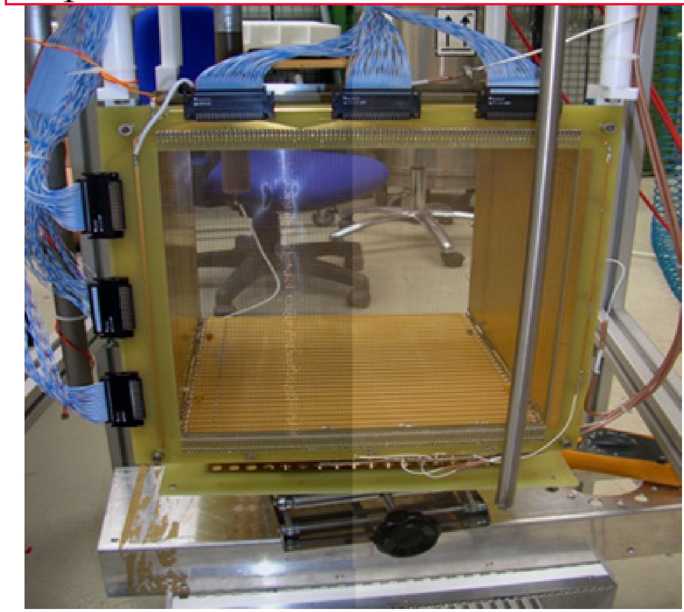
paper in preparation

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

- The main technological challenge of the development of the cryogenic LAr TPC is the capability of ensuring a sufficiently long free lifetime of the drifting electrons.
- 2001 technical run in Pavia, τ_{ele} = 1.8 ms
- New industrial purification methods developed at an exceptional level: remnants of electronegative impurities (O_2) have to be initially and continuously purified.
- Extremely high τ_{ele} ≈21 ms (≈15 ppt molecular impurities) measured with cosmic μ's in a 50 litres LAr-TPC in INFN-Legnaro ICARINO.
- Electron signal attenuation of ~10 % for a longest drift of 5 meters, opening the way to exceptionally long drift distances.

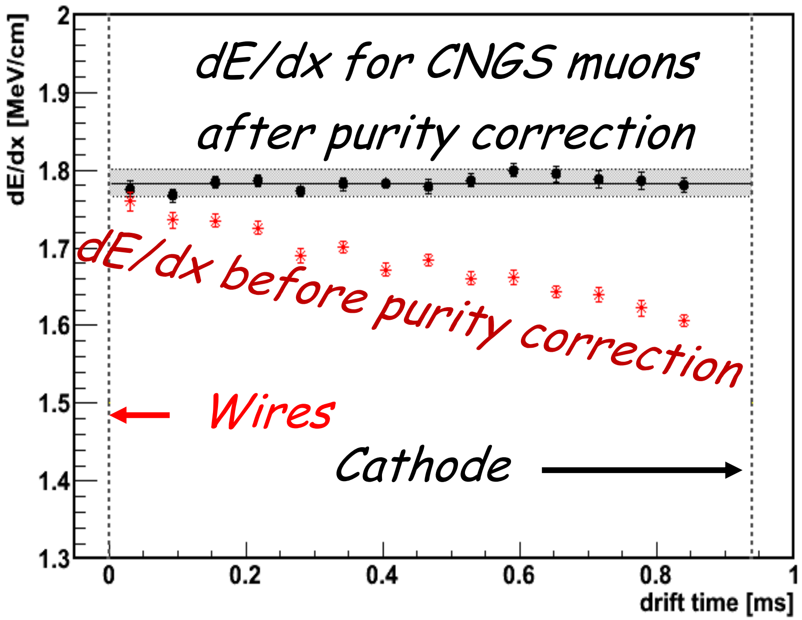


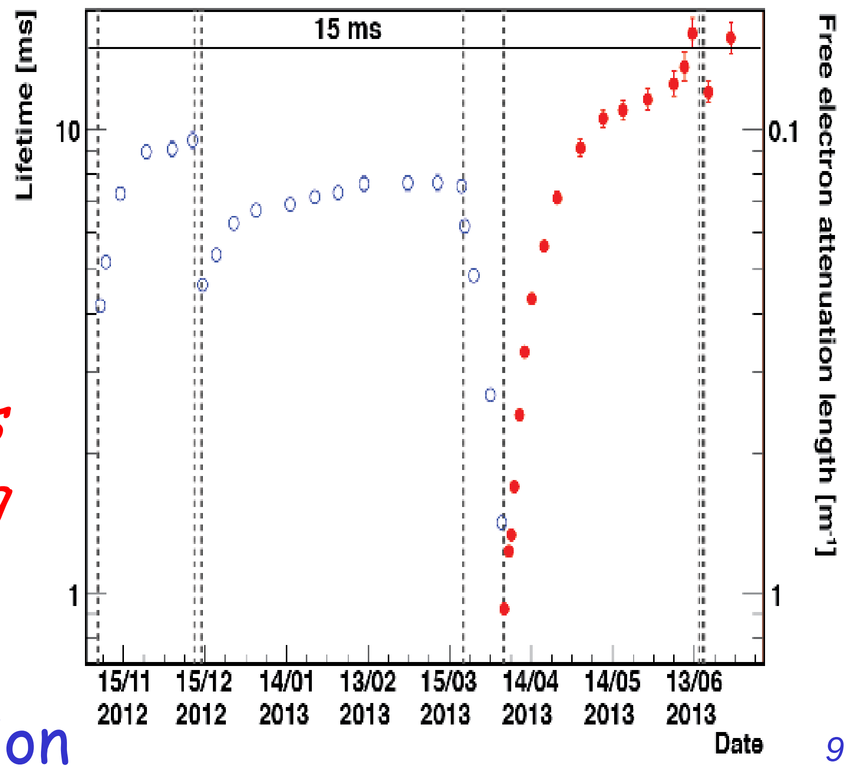
Drifting charge attenuation versus drift path at different electron lifetimes



ICARUS T600 LAr purity

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



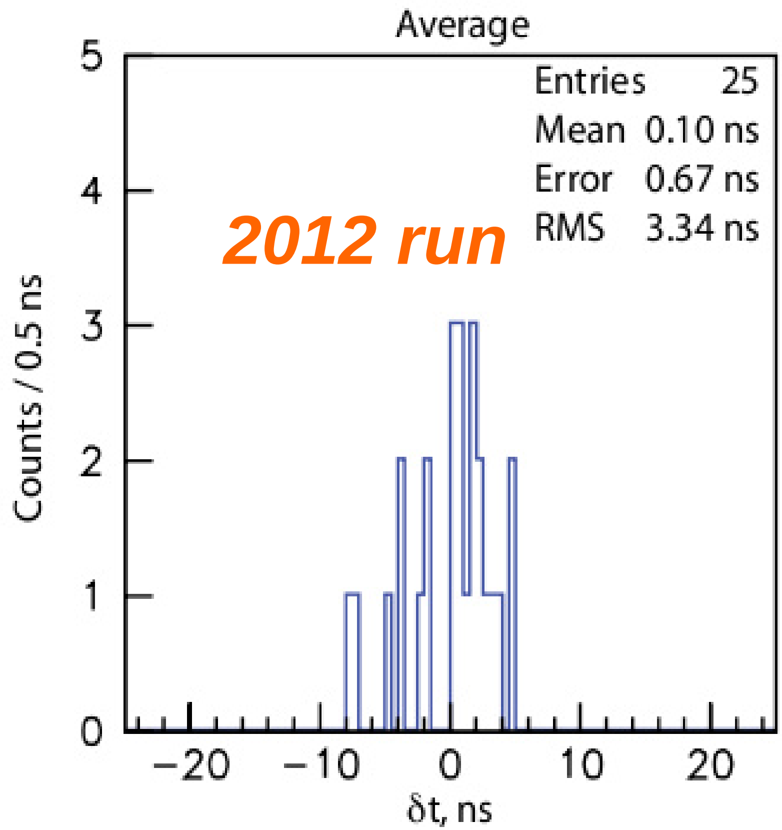


ICARUS has demonstrated the effectiveness of the single phase LAr-TPC technique, paving the way to huge detectors/~5 m drift as required for LBNE project

arXiv:1409.5592 under publication

Some physics results: neutrino velocity

- Search for superluminal ν's radiative processes in the framework of Cohen-Glashow prediction: negative result Phys.Lett.B-711 (2012) 270
- Direct measurement of ν velocity with CNGS bunched beam Phys Lett. B713 (2012), 17 , JHEP11 (2012) 049.
  - Arrival time determined by prompt scintillation light signals (~ns resolution) and accurate localization of events.
  - 2011 bunched beam: 4 bunches/spill, 3 ns FWHM, 524 ns separation
  - 2012 : new beam structure: 64 bunches, 3 ns width, 100 ns spacing. Four timing systems available.



$\delta t = tof_c - tof_\nu = 0.10 \pm 0.67\ (stat.) \pm 2.39\ (syst.)\ ns$

[2011 result: +0.3 ± 4.9 (stat.) ± 9.0 (syst.) ns]

$\delta(v/c) = (v_\nu - c)/c = 0.4 \pm 2.8\ (stat.) \pm 9.8\ (syst.)\ 10^{-7}$

Results confirmed by BOREXINO-LVD-OPERA

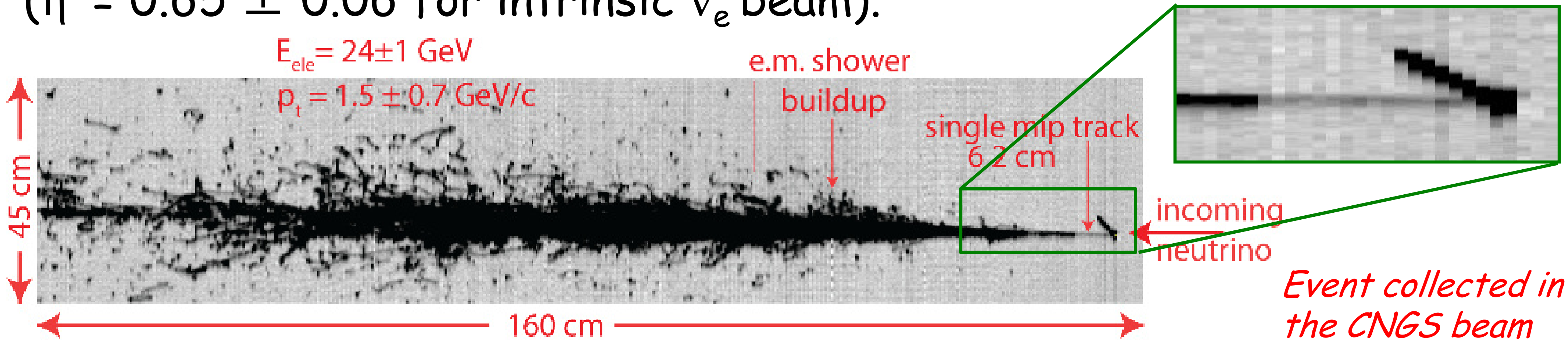
Sterile neutrino puzzle

- Sterile neutrinos were first hypothesized by B. Pontecorvo in 1957, as particles not interacting via any SM interaction but gravity. Nonetheless they could mix with standard neutrinos via a mass term.
- *Recently experimental ν anomalies started to build up, which could be explained with the oscillation into sterile neutrinos:*
  - Anomalous anti-ν_e production from anti-ν_μ beam at short distances detected by LSND experiment and later confirmed by MiniBooNE with ν_μ/amti-ν_μ beams → $\Delta m^2_{new} \approx 10^{-2} \div 1$ eV^2 .
  - Anti-ν_e disappearance from reactors
  - ν_e disappearance from very intense e-conversion ν sources in Gallium experiments (designed to detect solar ν_e) → $\Delta m^2_{new} >> 1$ eV^2.
- *The CNGS facility delivered an almost pure ν_μ beam in 10-30 GeV E_ν range (beam associated ν_e ~1%) at a distance L=732 km from target.*
- Unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency

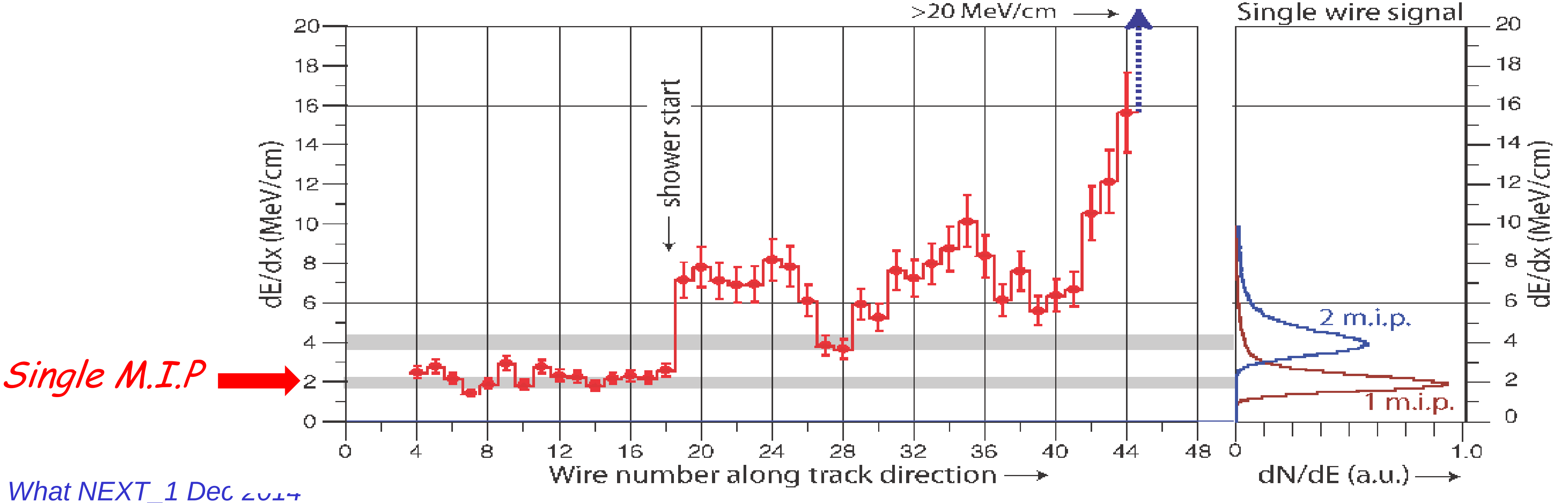
→ ***Search for ν–e events***

Search for ν–e events in CNGS beam

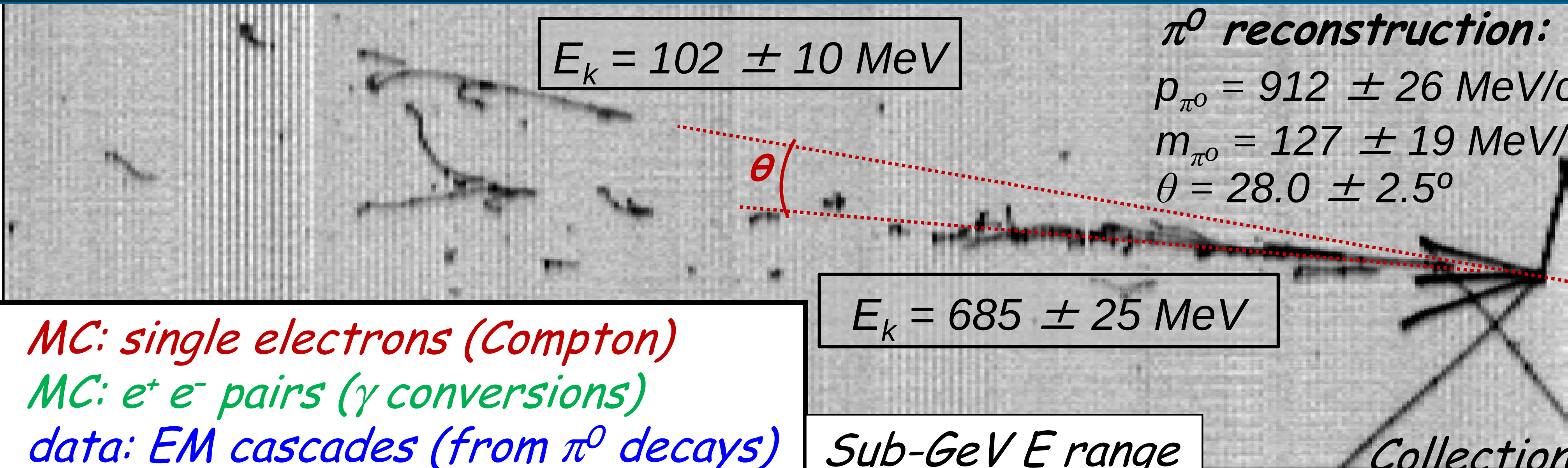
"Electron signature" for ν_e CC event : energy < 30 GeV, charged isolated track from primary vertex, compatible with a m.i.p., subsequently building un into a shower; *e*-identification efficiency $\eta = 0.74 \pm 0.05$ ($\eta' = 0.65 \pm 0.06$ for intrinsic ν_e beam).



Event collected in the CNGS beam

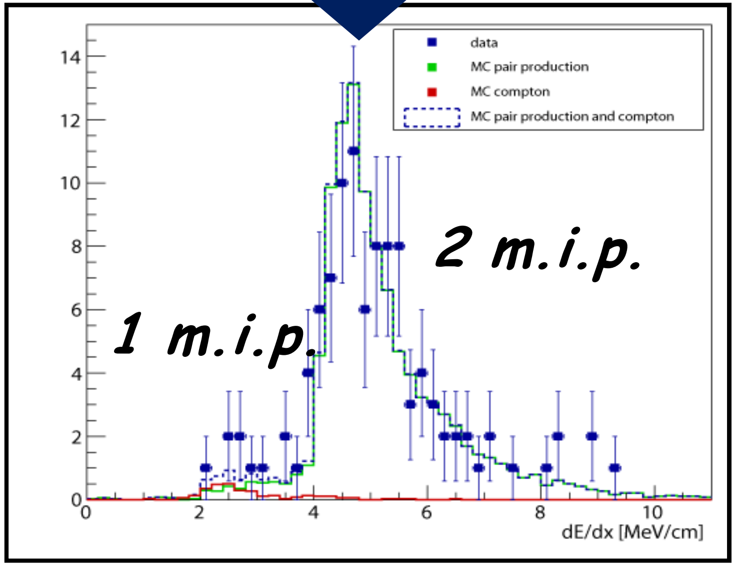


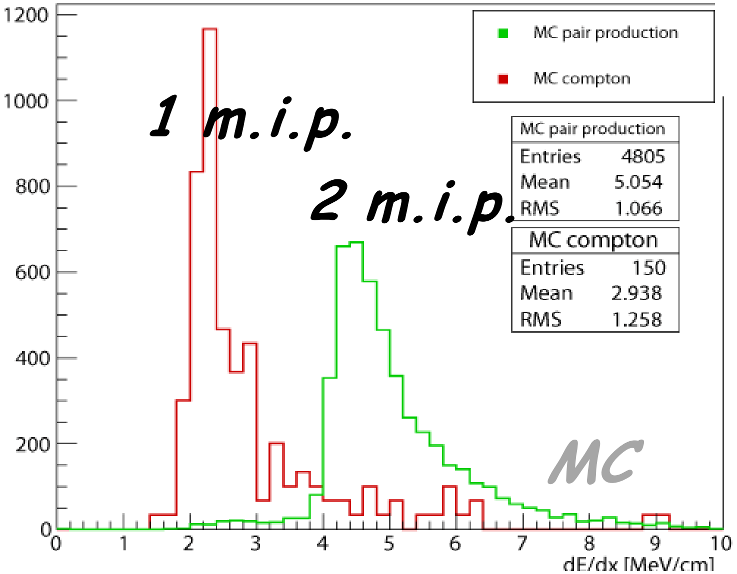
e/γ separation and π^0 reconstruction in ICARUS



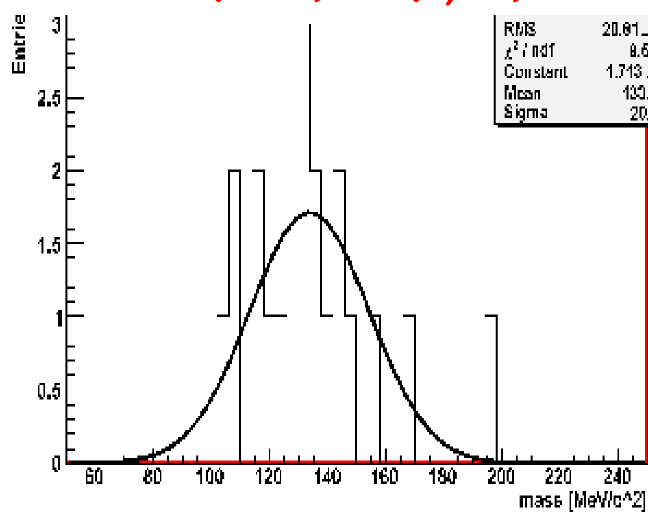
- *MC: single electrons (Compton)*
- *MC: $e^+ e^-$ pairs (γ conversions)*
- *data: EM cascades (from π^0 decays)*

Sub-GeV E range





Mγγ: 133.8±4.4(stat)±4(syst) MeV/c²



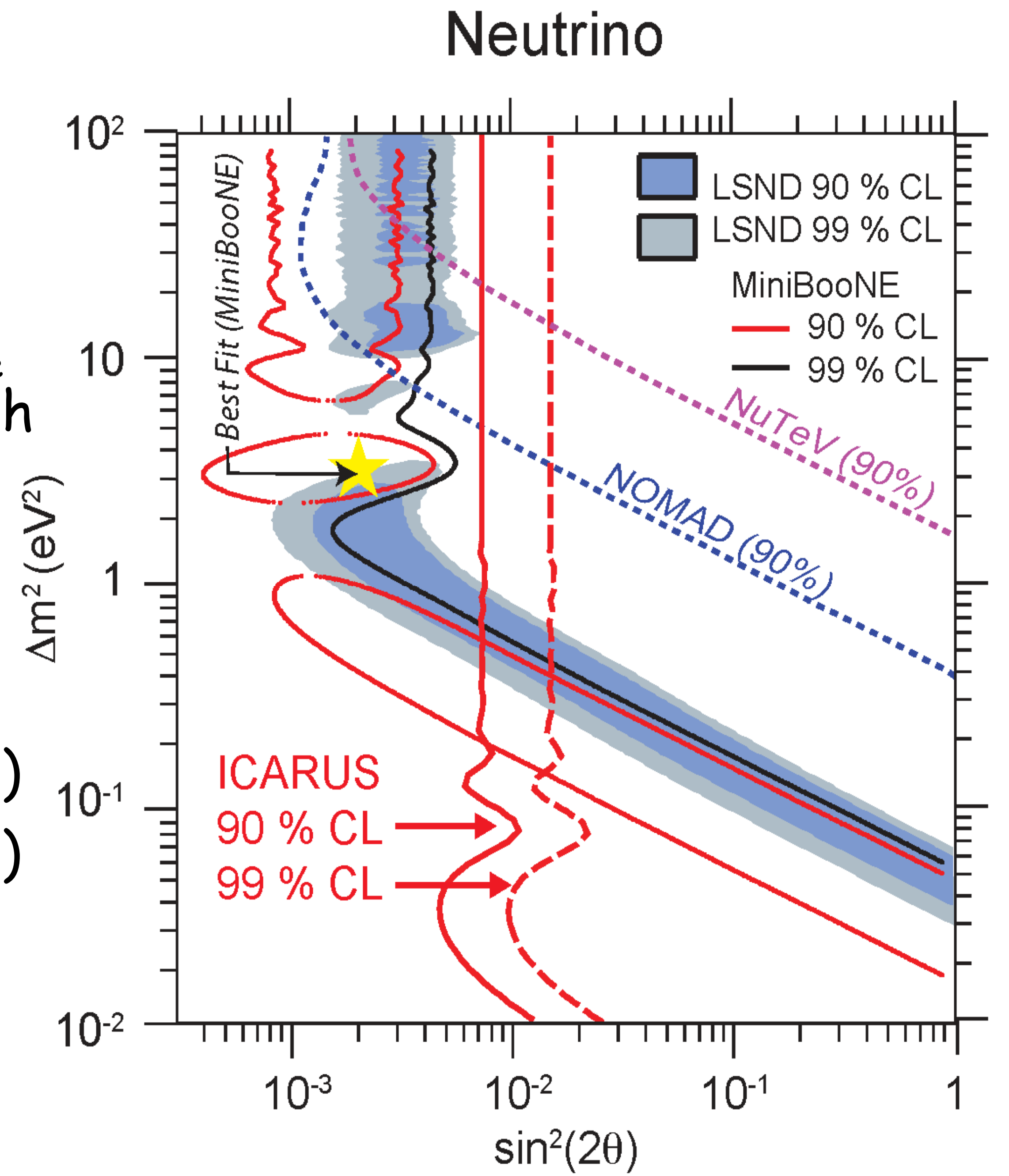
Unique feature of LAr to distinguish e from γ and reconstruct π^0

➔ Estimated bkg. from π^0 in NC and ν_μ CC: negligible

ICARUS result on the search of the LSND-anomaly

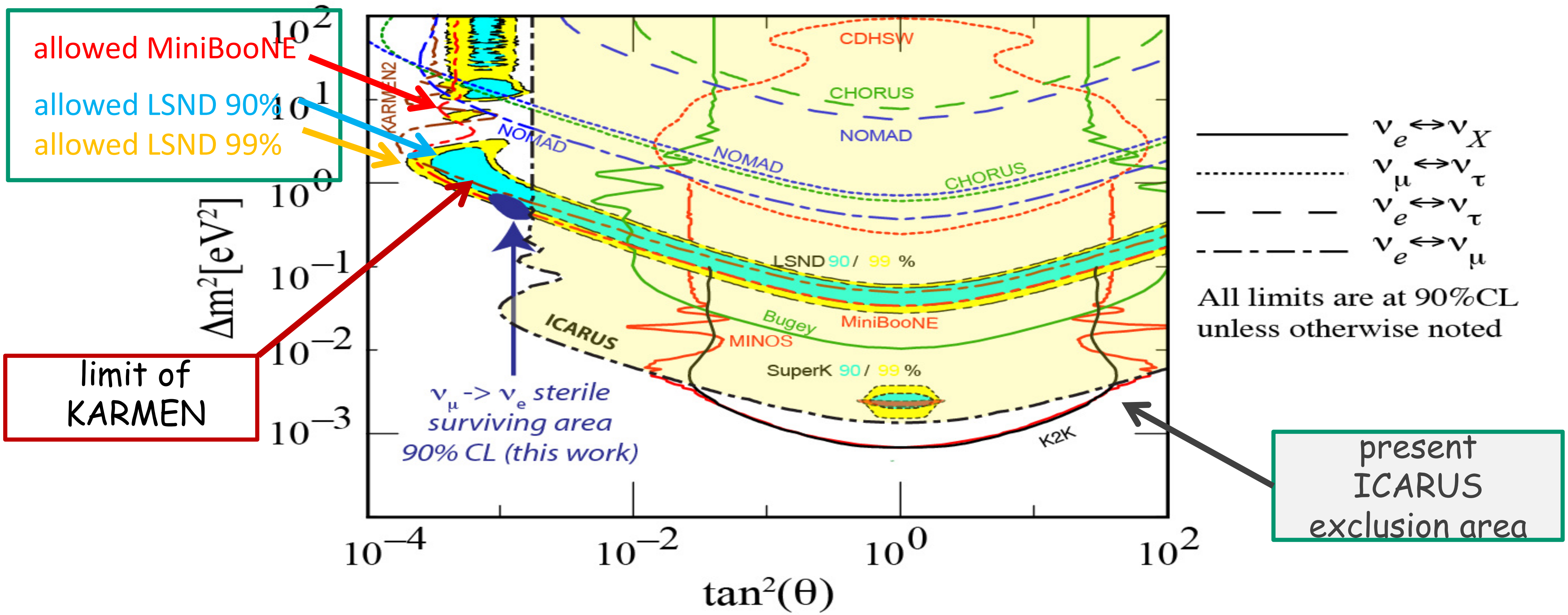
- Analysis on 2450 ν events (7.23×10^{19} pot out of the full statistics of 8.6×10^{19} pot): 6 ν_e events observed in agreement with expectations due to conventional sources (7.9±1.0).
- These provide the limits on the oscillation probability:
  - $P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3}$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

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



Results confirmed by OPERA

LSND-like exclusion from the ICARUS experiment



ICARUS result strongly limits the window of parameters for *the* LSND anomaly to a very narrow region *($\Delta m^2 \approx 0.5\ eV^2$ and $\sin^2 2\theta \approx 0.005$)* for which there is an overall agreement (90% CL) *of*

- *the present ICARUS limit*
- *the limits of KARMEN*
- *the positive signals of LSND and MiniBooNE*

Future steps: clarifying the anomalies

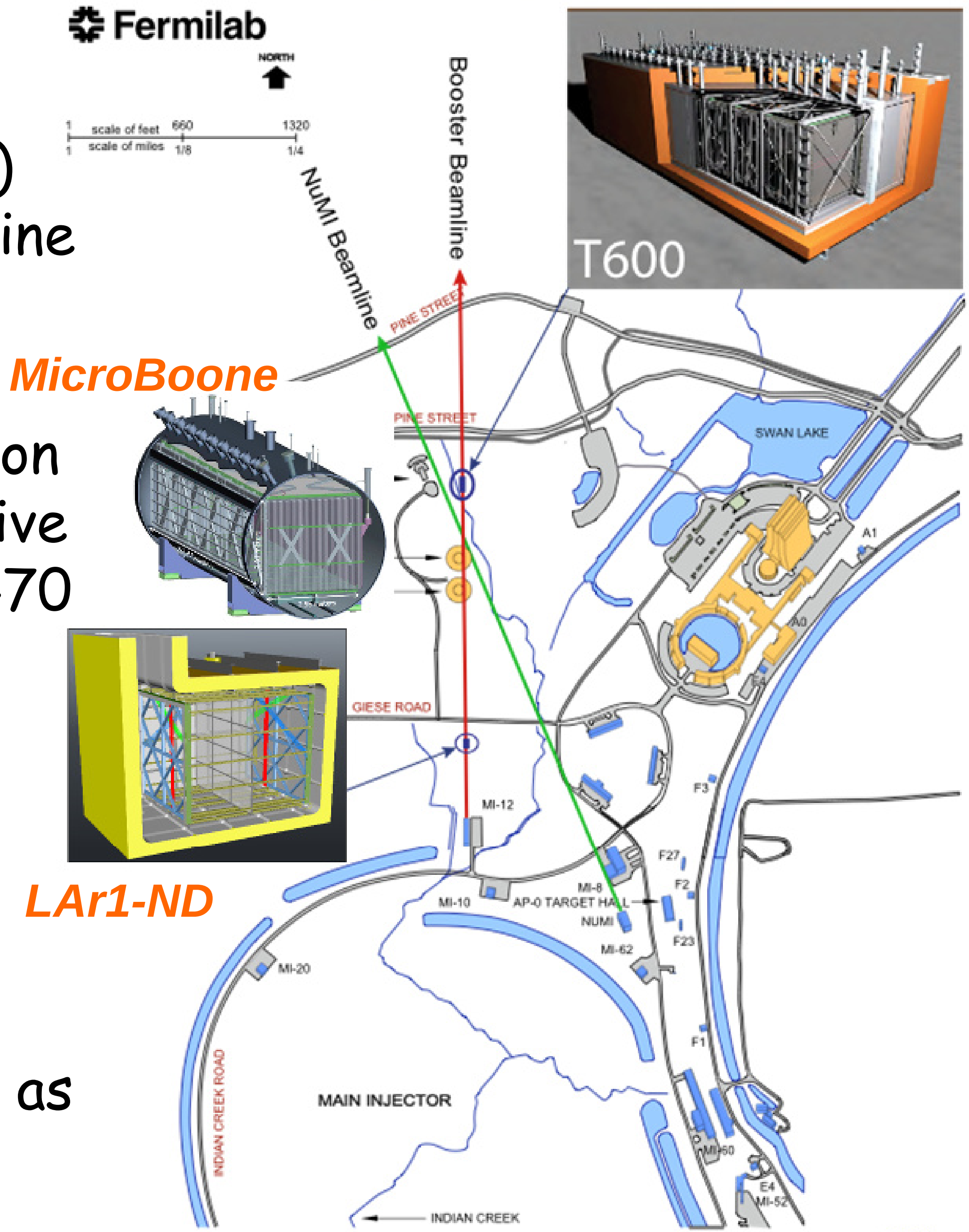
- ICARUS experiment has conclusively demonstrated that LAr-TPC is *the leading technology for future short/long baseline accelerator driven ν physics*. The detector is a "bubble chamber like" sampling, homogeneous calorimeter with excellent accuracies and the total energy reconstruction of the event from charge integration.
- A new experiment, capable to clarify all the ν anomalies at the appropriate > 5 sigma level is therefore highly desirable.
- Such an experiment is based on two main, innovative concepts and a low energy ν and anti-ν beam.
  - The first new concept is the comparison for spectral differences of two (or more) identical detectors located at two different distances. In the case of absence of "anomalies", the two distributions will be a precise copy of each other, without any Monte Carlo comparison.
  - The second new concept is the now fully operational large mass Liquid LAr-TPC detectors developed by the ICARUS collaboration.

Basic features of the proposed experiment

- The experiment, initially proposed for CERN and now under consideration at FNAL, may be able to give a likely definitive answer to the 4 following queries:
  - The LSND+MiniBooNe both antineutrino and neutrino $\nu_\mu \rightarrow \nu_e$ oscillation anomalies;
  - The Gallex+Reactor oscillatory disappearance of the initial ν-e signal, both for neutrino and antineutrinos
  - an oscillatory disappearance maybe present in the ν-μ signal, so far unknown.
  - Accurate comparison between neutrino and antineutrino related oscillatory anomalies, maybe due to CPT violation.
- In addition, the proposed experiment ensures the bulk of the preparatory phase of the LNBE Coll., accumulating ν events *for test and analysis purposes as a running premise to LBNE*, providing:
  - An accurate determination of cross sections in Argon;
  - The experimental study of all individual CC and NC channels;
  - The realization of sophisticated algorithms for the most effective identification of the events.

Experiment layout at the FNAL neutrino beam lines

- ICARUS T600 detector may be located at shallow depth (3m deep) along the Booster Neutrino Beam line at ~600 m distance from target.
- Two LAr-TPCs with a smaller sensitive mass will be also located on axis: LAr1-ND at 110m with an active mass of 82 t and MicroBooNE at 470 m with an active mass of 89 t.
- T600 at FNAL will also provide additional information in the framework of LBNE with ν's from the off-axis kaon-neutrino NUMI beam peaked at ~2 GeV and an enriched flux of ν_e events as large as ~ 5%.

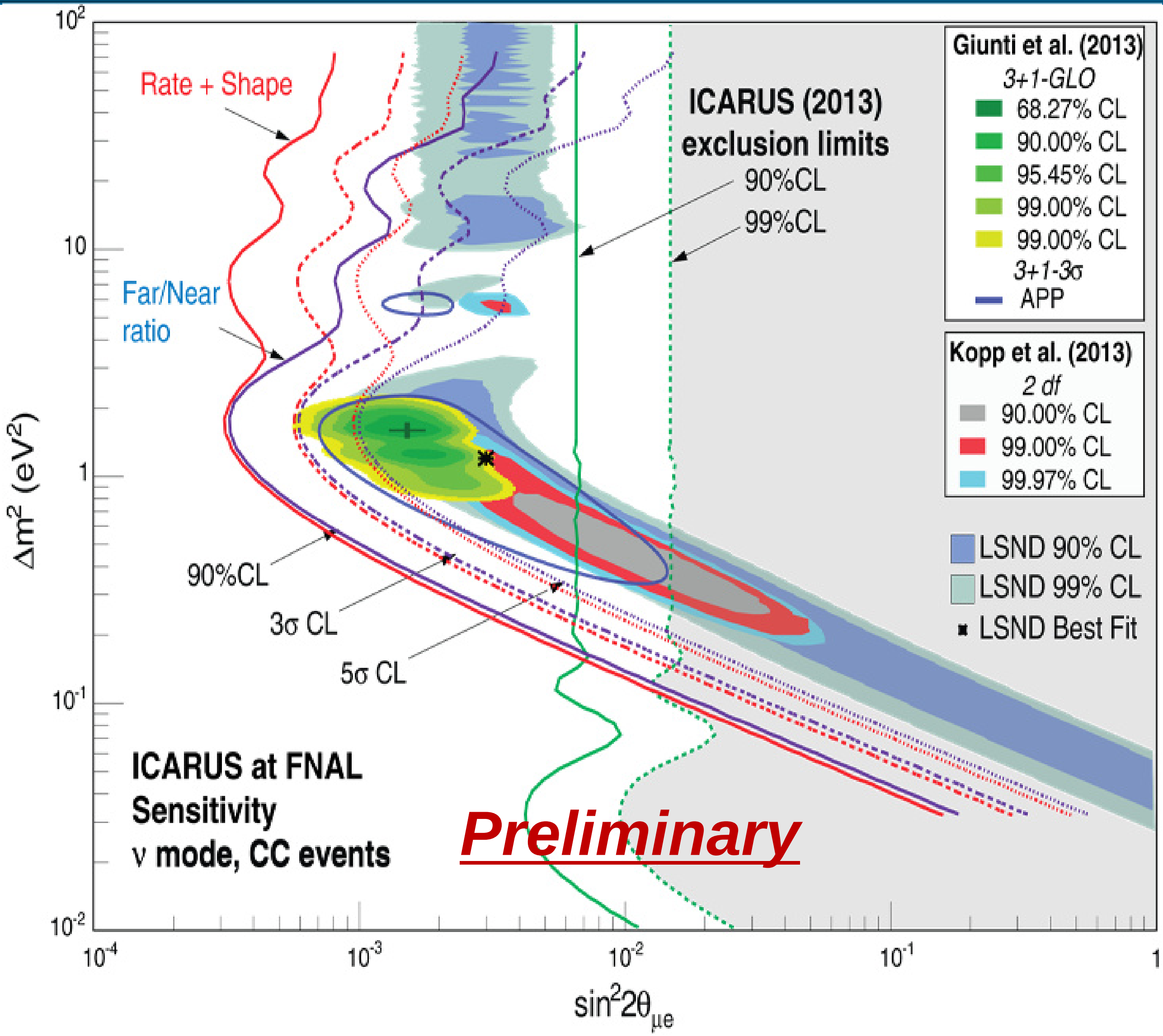


Ongoing study activities

- A joint activity between INFN FNAL and CERN is launched to finalize the experimental design with a particular attention to:
  - The level of background induced from cosmic rays and the strategies to mitigate it;
  - Detailed estimate of the residual flux uncertainties in the prediction of the far/near neutrino flux ratio;
  - The required cryogenic infrastructures needed at FNAL to integrate the LAr-TPC detectors.
- In the low energy Booster beam, cosmic neutrons and γs could affect significantly the experimental $\nu_\mu \rightarrow \nu_e$ sensitivity
  - the Compton signals may lead to a singly ionizing electron.
  - ≈ 11 cosmic μs expected in T600 at shallow depth in 1 ms drift time.
  - The new 'Cosmic Rays Tagging System' around the LAr sensitive volume, will reduce the cosmic backgrounds.
- ν_eCC identification efficiency under study considering also the wide angular distribution of the electron showers around the beam direction.

A definitive assessment of the LSND anomaly

- Expected LSND like sensitivity with 5σ CL of the NEAR detector and of T600 to $\nu_\mu \to \nu_e$ oscillations *after 3 years - 6.6 10^{20} pot BNB positive focusing at the present FNAL beam rates*
- Signal is computed as difference between Far and Near detectors with a small correction for the expected Near to Far beam shape differences
- *The predicted signal regions are well covered within 5σ.*



Exposure: 6.6 10^{20} pot – 3 years

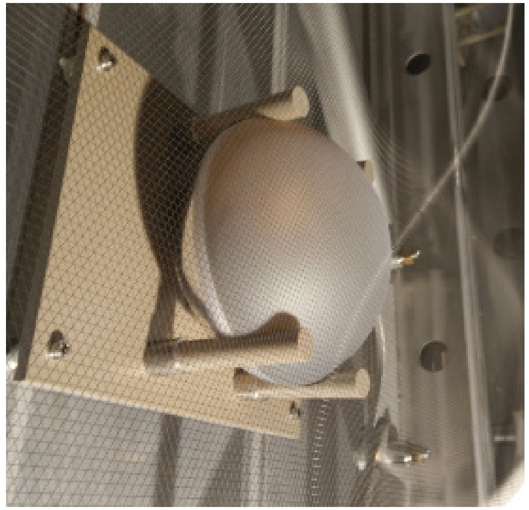
T600: 430 t fiducial mass at 600 m
LAr1-ND : 50 t fiducial mass at 150 m

Improving the T600 detector: WA104 Project at CERN

- WA104 program at CERN: two-years to prepare the ICARUS detector for the forthcoming search of sterile neutrinos within the FNAL Short Baseline neutrino program.
- First TPC movement completed on Nov. 21. Transport of the 2nd TPC foreseen on Dec. 10.

- At CERN, the following main operations will be carried out on the TPCs:
  - Cathode deformation mapping, new design with better planarity;
  - New cold vessels, new purely passive insulation and corresponding new supporting structure (warm vessel);
  - Upgrade of the light collection system;
  - New faster, higher-performance read-out electronics solution.

Upgraded light collection system (Photomultipliers)



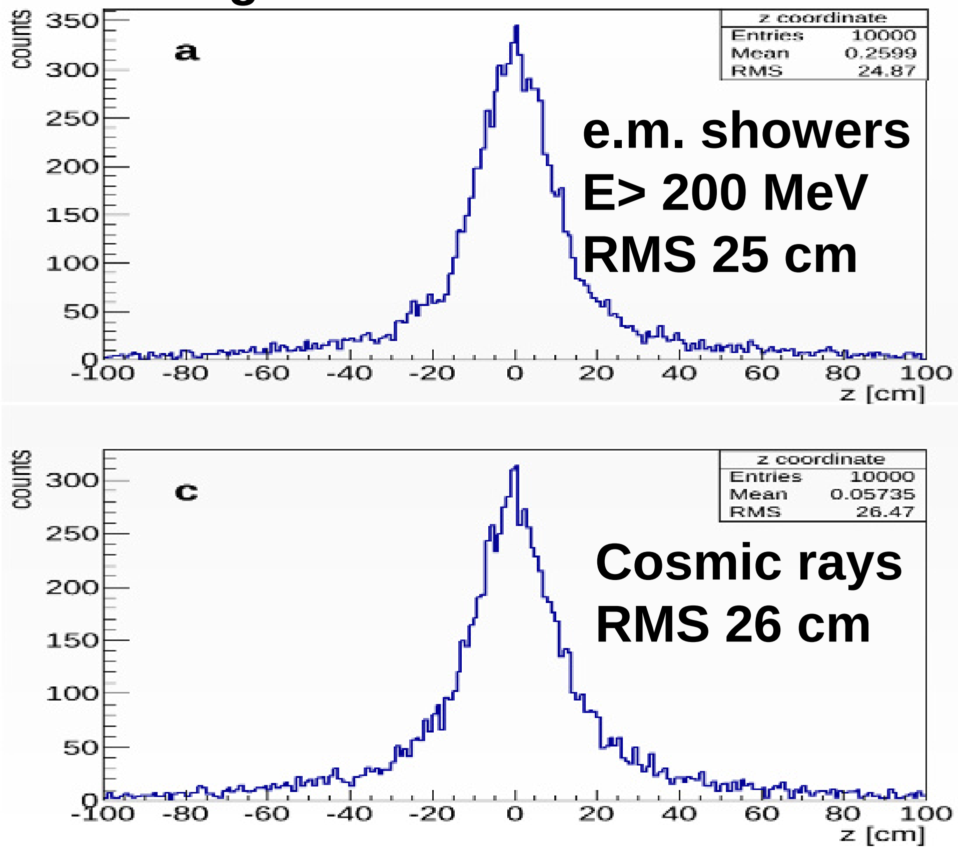
Upgrade of the light collection system:

- ~100 PMT ("8) per TPC, large surface, >QE
- Implementation of electrostatic shields, to prevent inducted spurious signals on wire planes.
- Read-out electronics: ~ ns resolution with GHz digitizer.

Ongoing activities

- Evaluation of tracks localization based on light signal intensities, as a function of the PMT number/ arrangement: space resolution better than 0.5 m;
- Characterization of different new PMTs looking for the best solution in the overhauled TPCs.

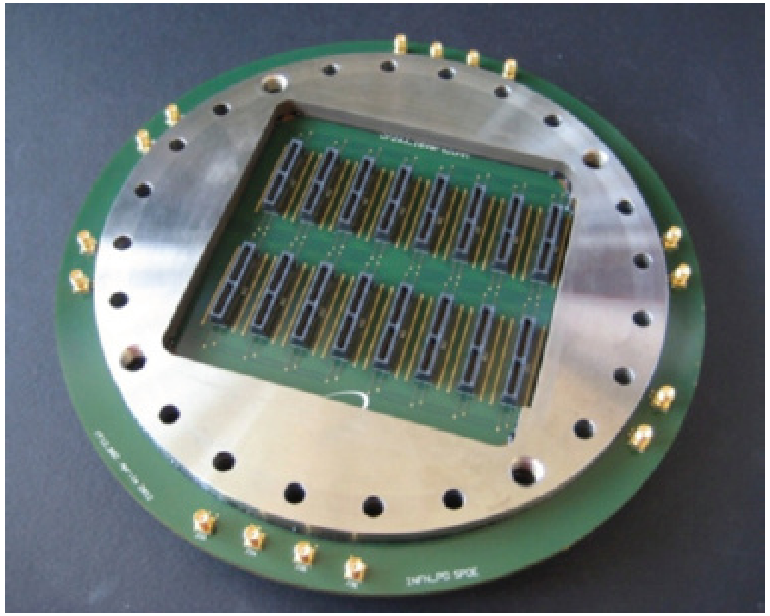
longitudinal coordinate

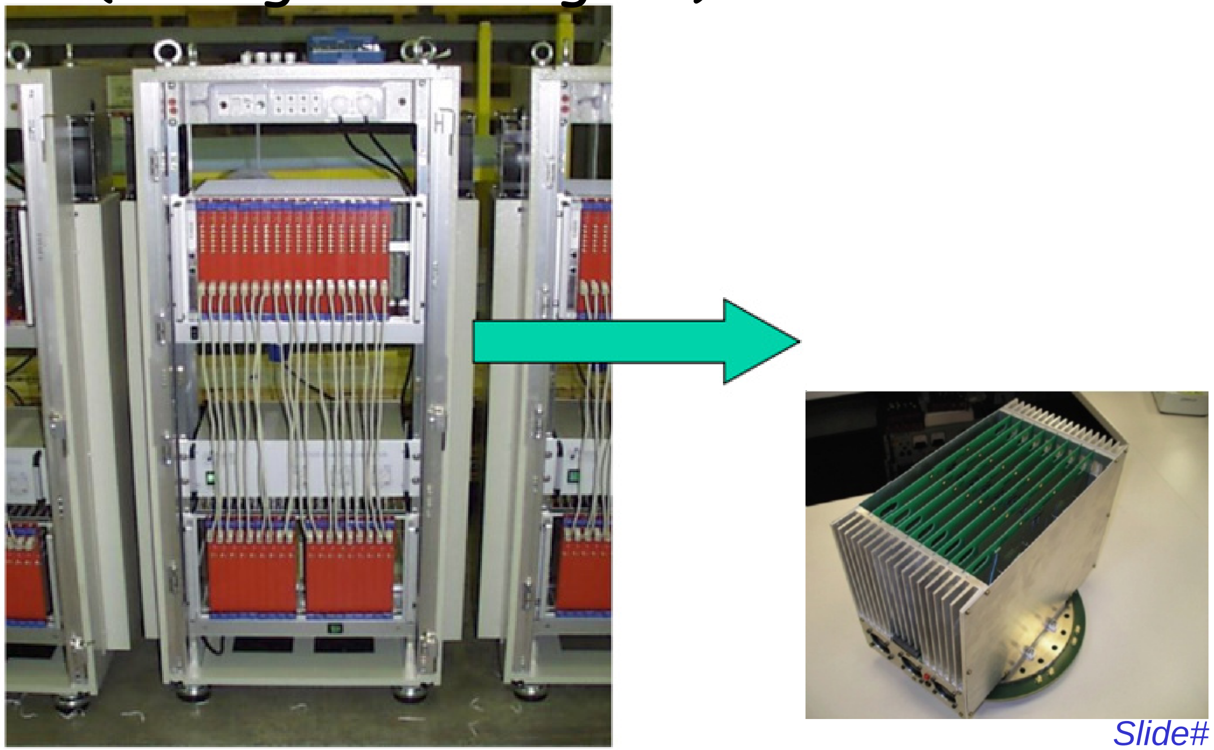


New electronics

New design developed for the electronics chain, featuring:

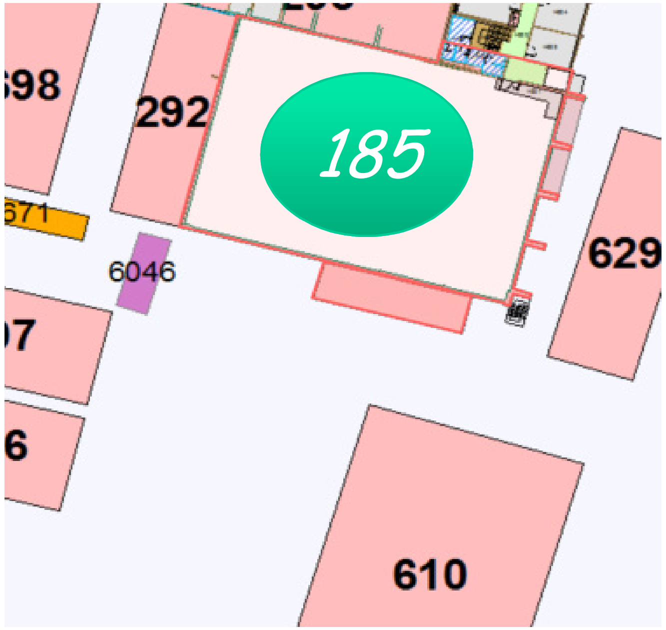
- more compact electronics for both analogue and digital, flange integrated (CF200 – INFN Proprietary design, figures below);
- serial ADCs (1/chan) instead of multiplexed ones used in LNGS run (-> synchronous sampling time, 400 ns);
- modern serial switched I/O for data flow + optical link (for Gb/s transmission rate).
- First prototype of new boards (analogue and digital) under test in LNL.





WA104 facility at CERN, building 185

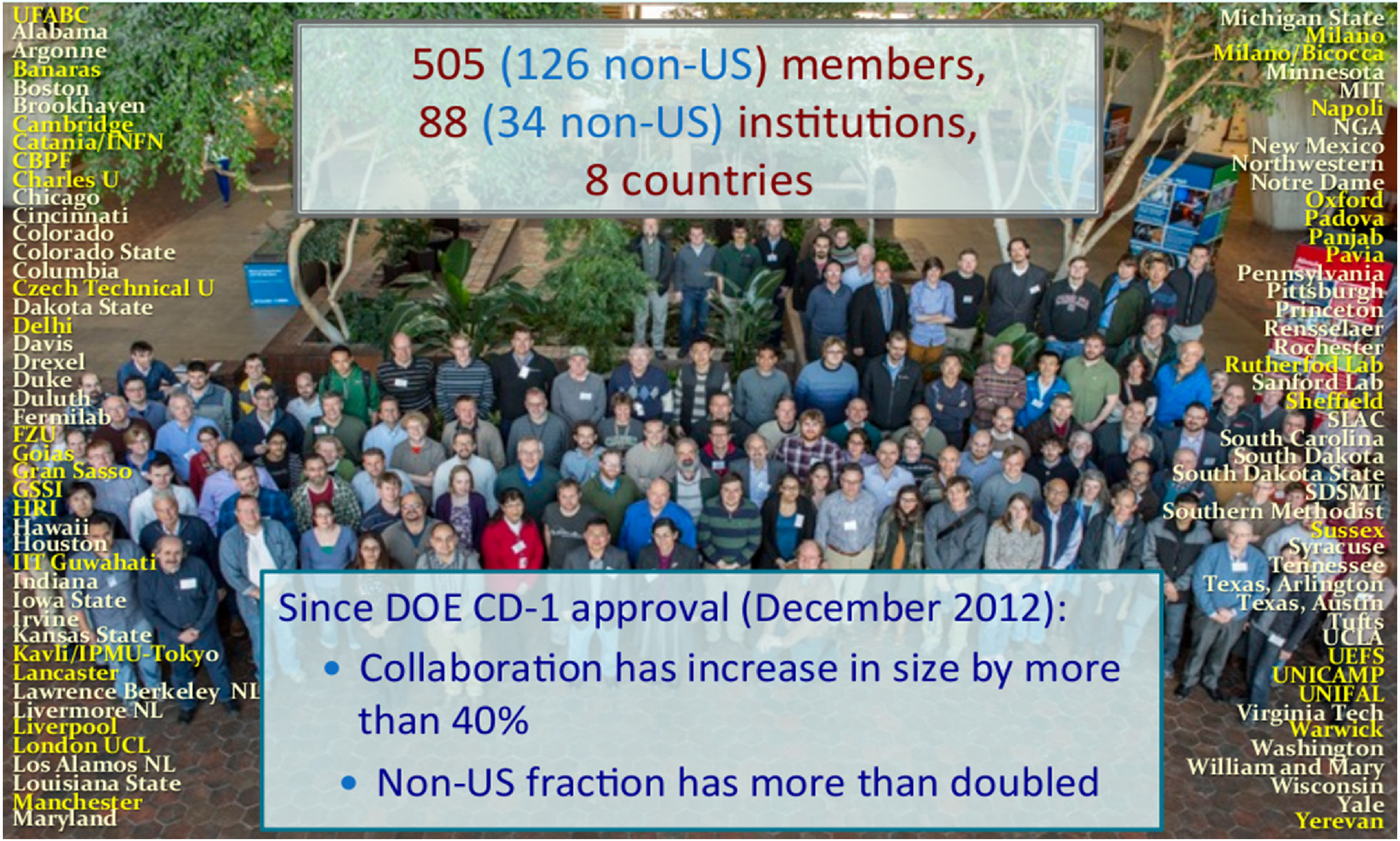
- Activities will be carried on at existing CERN building 185. A dedicated clean room, to house the TPCs during operations, is about to be completed.



- Design and construction of a new, 4π 'Cosmic Rays Tagging System' (CRTS) around the LAr sensitive volume, to tag cosmic rays and associated e.m. activity crossing the active volume in the SBN sterile neutrino search at FNAL (surface detector location).

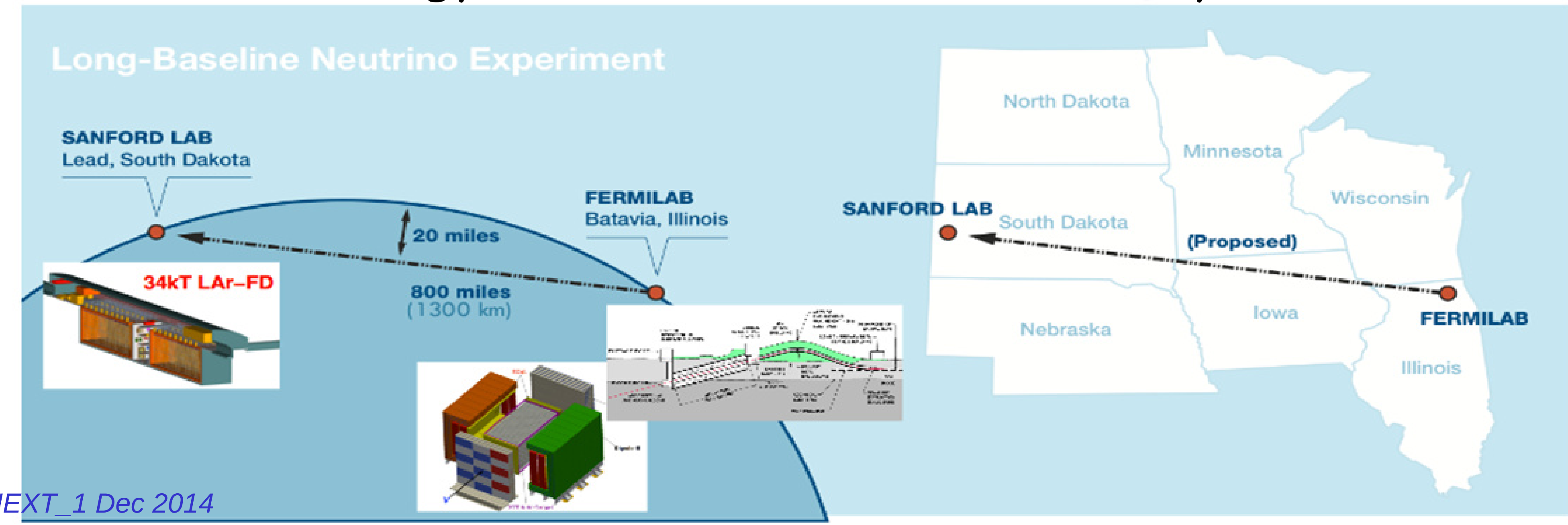
- Further R&D activities will be carried on in parallel (including some specifically related to future LBNF program):
  - LAr magnetization;
  - Consequent replacement of PMTs with different light detectors (SiPM)
  - LAr doping, Argon purification.

WHAT NEXT? The Long-Baseline Neutrino Experiment



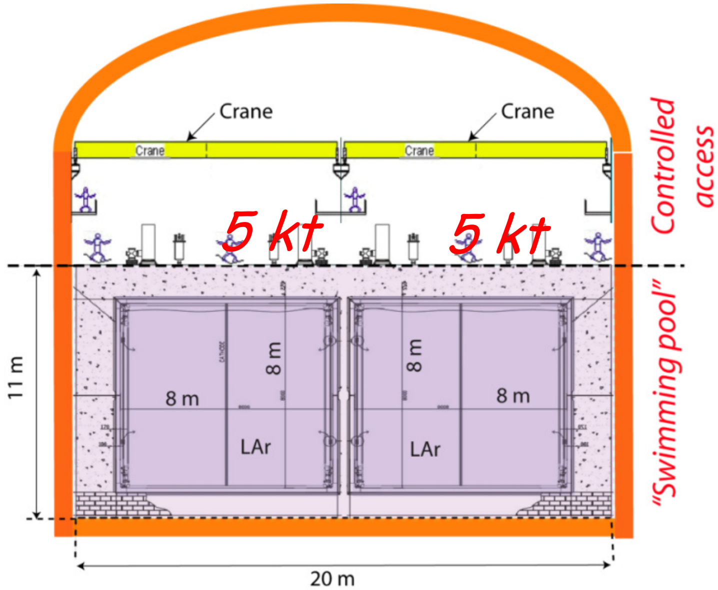
WHAT NEXT? The Long-Baseline Neutrino Experiment

- Neutrino beam from FNAL to SURF: 1300 km baseline
  - Protons 60-120 GeV, 1.2→2.3 MW, from upgraded Main Injector PIP-II, 10 s pulses every 1.0 to 1.33 s
  - Neutrinos: sign selected, horn focused, energy range 0.5-5 GeV;
- NEAR detector: Fine-Grained Tracker at 460 m from the target;
- FAR detector: LBNF single phase LAr TPC based on the ICARUS/Modular design and technology; GOAL: 34 kton fiducial mass (total 50 kton);
- Baseline and ν energy chosen to maximize sensitivity to CP violation



Going to larger masses: the ”Modular” approach

- *C. Rubbia et al., “A new very massive modular Liquid Argon Imaging Chamber to detect low energy off-axis neutrinos from the CNGS beam” Astroparticle Physics 29, 174-187(2008)*
- A modular structure with several separate vessels, each of a few thousand tons, is to us a more realistic solution.
- Each 5 kton unit is a scaled-up version of ICARUS (x 2.66^3):
  - 8 X 8 m^2 LAr cross section and ~60 m length
  - Two gaps within a same cryogenic volume: 10’740 ton
  - 4 m drift (2.66 ms), E_{drift} = 0.5 kV/cm, H.V.: -200 kV
  - 3-D imaging like ICARUS, 6 mm pitch (~50000 chs)
  - PM’s will extract the trigger and timing LAr signal.



MODULAr: 8 x 8 m^2

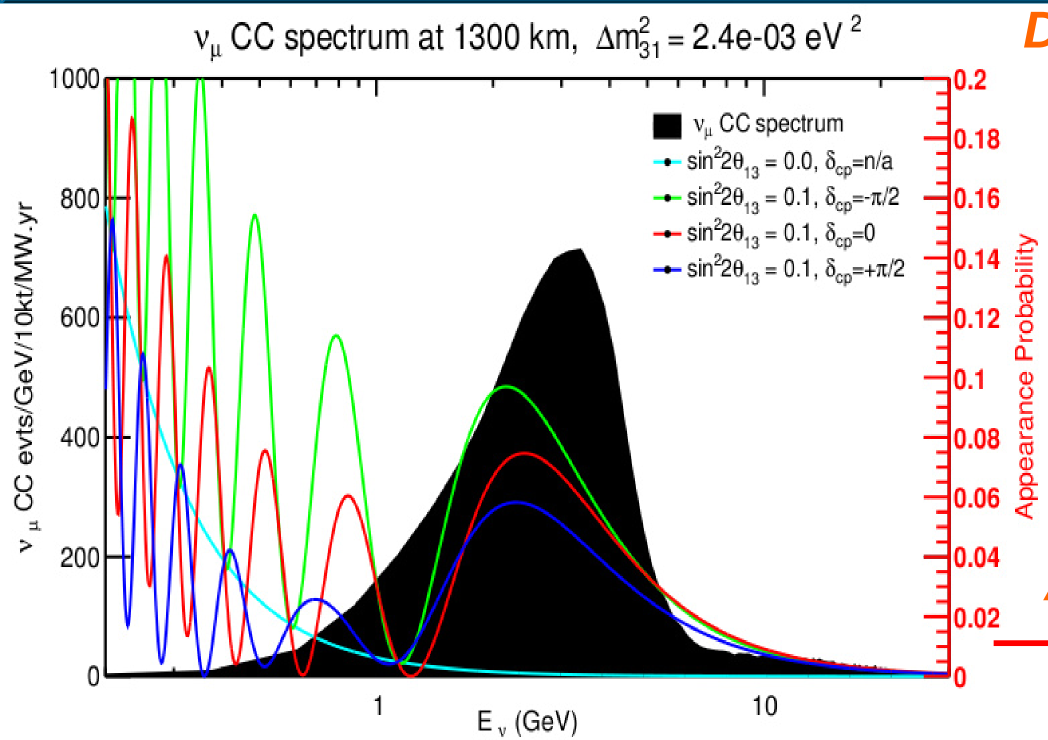
ICARUS: 3 x 3 m^2

Long-Baseline Neutrino Experiment: scientific motivation

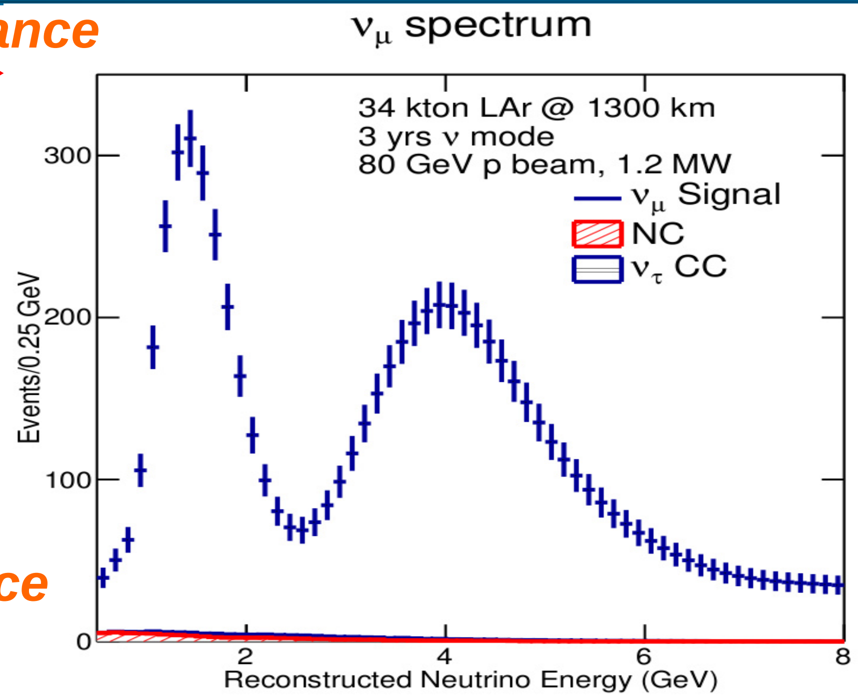
- CP violation in the neutrino sector;
- Neutrino Mass Hierarchy;
- Testing the Three-Flavor Paradigm
  - Precision measurements of known fundamental mixing parameters for neutrinos and anti-neutrinos;
  - New physics: non-standard interactions, sterile neutrinos (based on the study of the beam + atmospheric neutrino sources);
  - Precision neutrino interactions studied (in particular in the near detector)
- Fundamental physics enabled:
  - Nucleon decay search
  - Grand Unification Theory
  - Supernova neutrino burst – evolution of a stellar collapse

WA 104 project at CERN and the presence of the ICARUS detector at the short baseline experiment at FNAL neutrino beam can provide fundamental informations to reach these scientific goal.

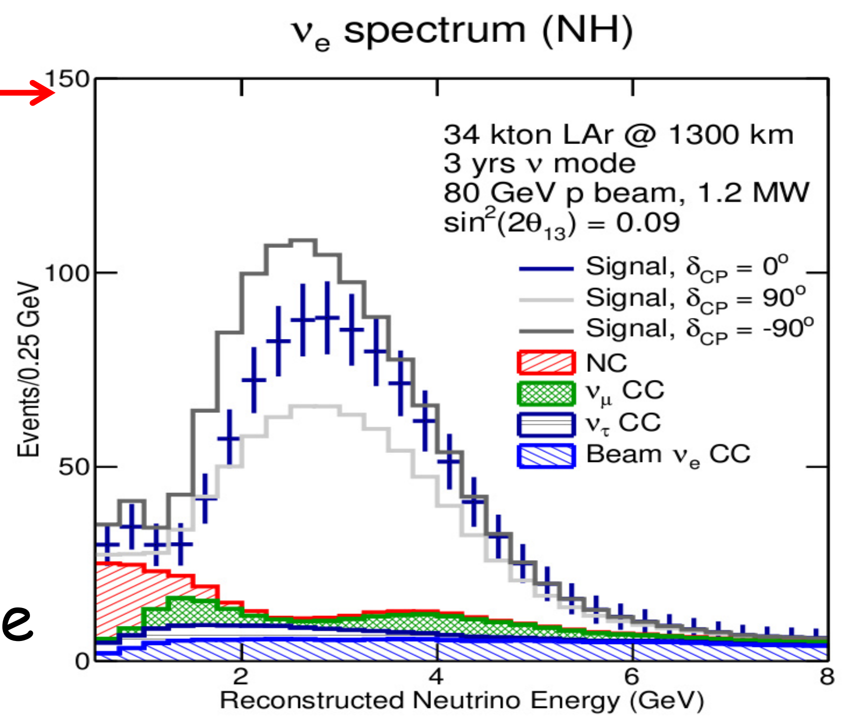
Long-Baseline Neutrino Experiment: experimental technique



Disappearance



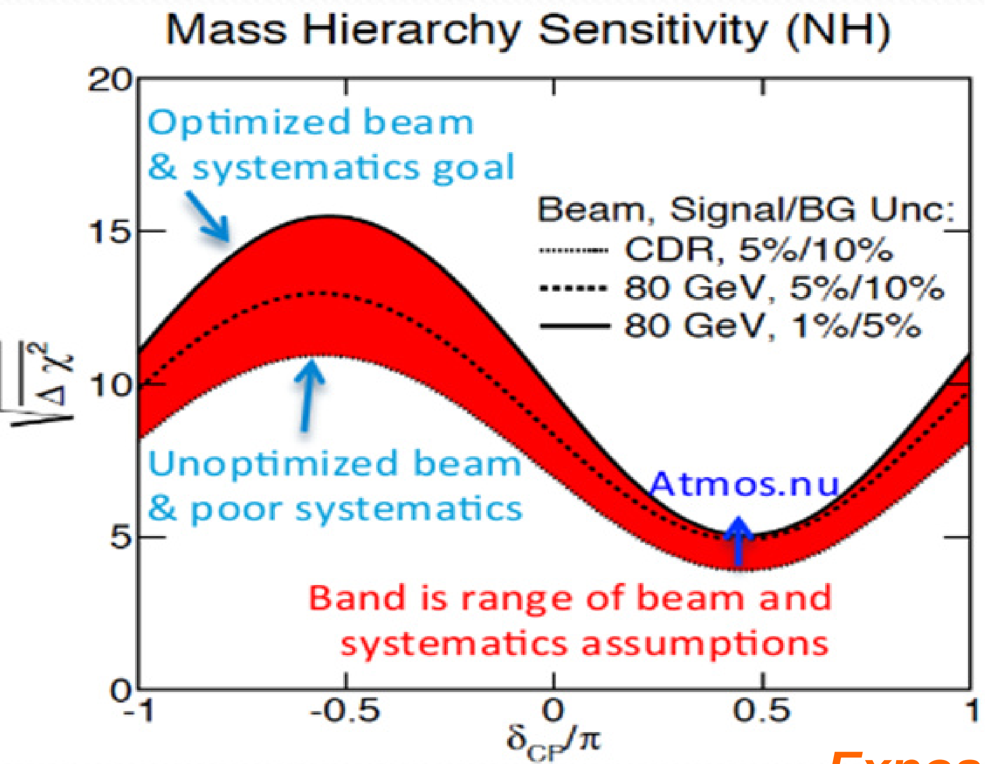
Appearance

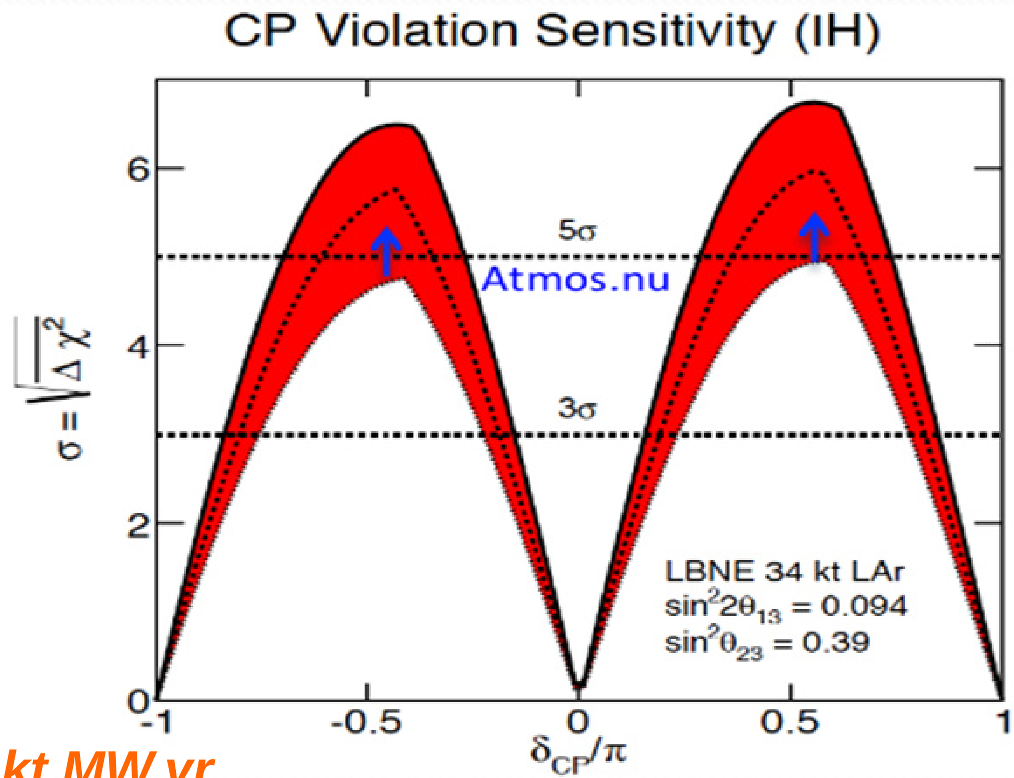


- δ_{CP} measurement requires a precise determination of the other mixing parameters and the explicit observation of an asymmetry between P(ν → ν) and P(anti-ν →anti-ν);
- The excellent energy and directional resolution of the LArTPC will provide unique sensitivity to the $\nu_\mu \rightarrow \nu_e$ appearance

Mass Hierarchy and CP violation sensitivity

From R.Wilson talk at NEUTRINO 2014





Exposure 245 kt.MW.yr
34 kt * 1.2 MW * (3 ν +3 $\bar{\nu}$) yr

- Mass hierarchy is very well determined over most of the δ_{CP} range;
- CP Violation > 3 σ over most of the range and > 5 σ for maximal CPV
- The atmospheric neutrinos in LBNE, if combined with the neutrino beam, can provide an increase of the CP violation sensitivity;


Thank you !