Status and plans of the ICARUS experiment

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(on behalf of the ICARUS Collaboration)

SPSC, June 23rd 2015, CERN

ICARUS Collaboration

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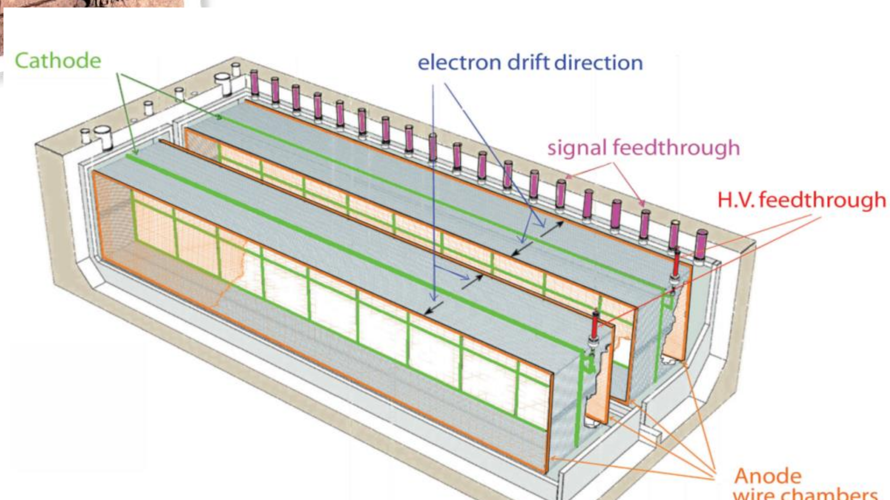
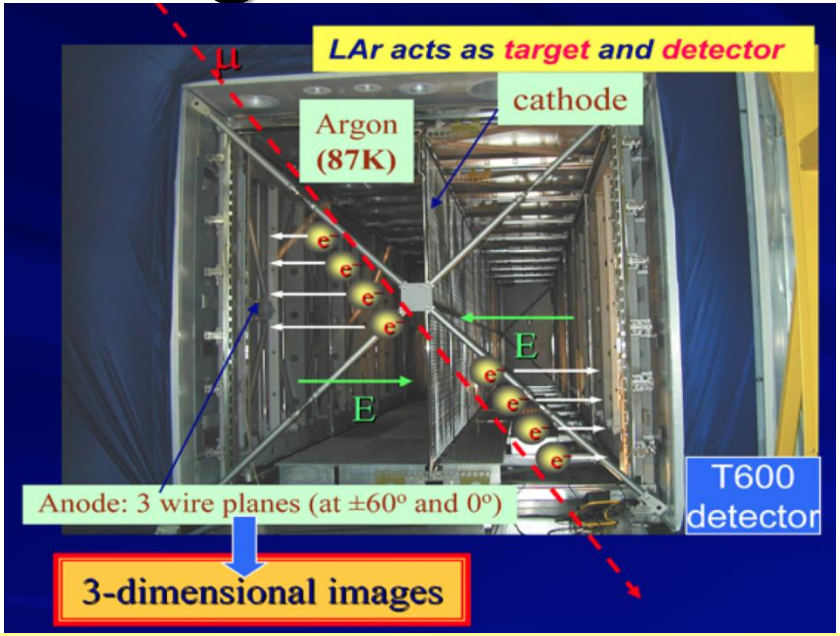
Introduction

- Three years (May 2010 – June 2013) of continuous and safe underground operation of the ICARUS detector in Hall B of the LNGS lab. resulted in plenty of high quality data, both from LNGS beam and cosmics.
- Such a long period allowed for detailed studies of all technical aspects of the Lar TPC detection technique,… and
- Development of advanced reconstruction algorithms.
- A total of 8.6×10^{19} protons on target has been collected, with a detector live time > 93%. 7.93×10^{19} pot are available (i.e. scanned and preliminary classified) for analysis.
- Also atmospheric neutrinos have been studied with exposure to cosmic rays (0.73 kton year).
- In this talk status and plans of the ICARUS experiment will be presented.

ICARUS T600: first large LAr TPC



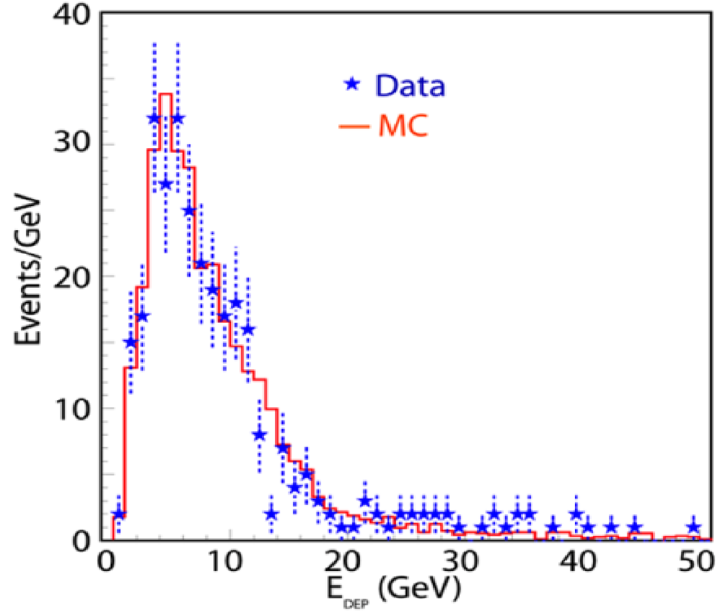
LAr TPC → C.Rubbia's idea (1977)



- 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)

Key feature: LAr purity from electro-negative molecules (O_2, H_2O, CO_2).

ICARUS LAr TPC: performance



Total energy reconstr. from charge integration

- Full sampling, homogeneous calorimeter with excellent accuracy for contained events

Tracking device

- Precise 3D topology and accurate ionization
- Muon momentum via multiple scattering

Measurement of local energy deposition dE/dx

- e/γ remarkable separation (0.02 X_0 samples)
- Particle identification by dE/dx vs range

Low energy electrons:

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

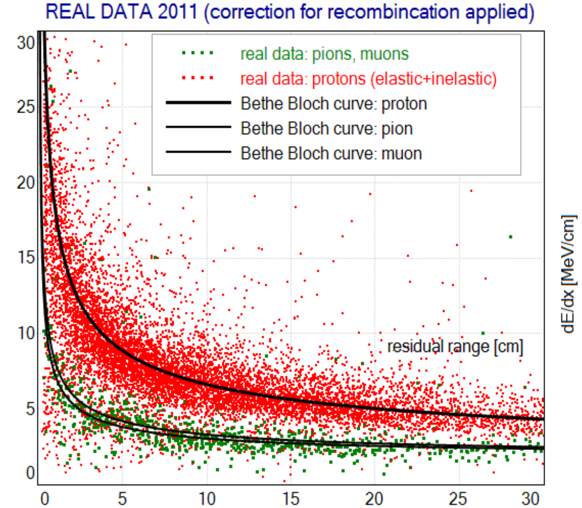
Electromagn. showers:

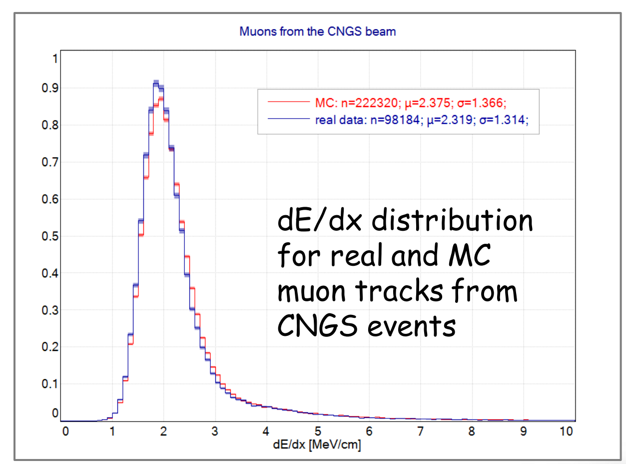
$\sigma(E)/E = 3\%/\sqrt{E(GeV)}$

Hadron showers:

$\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$

REAL DATA 2011 (correction for recombincation applied)

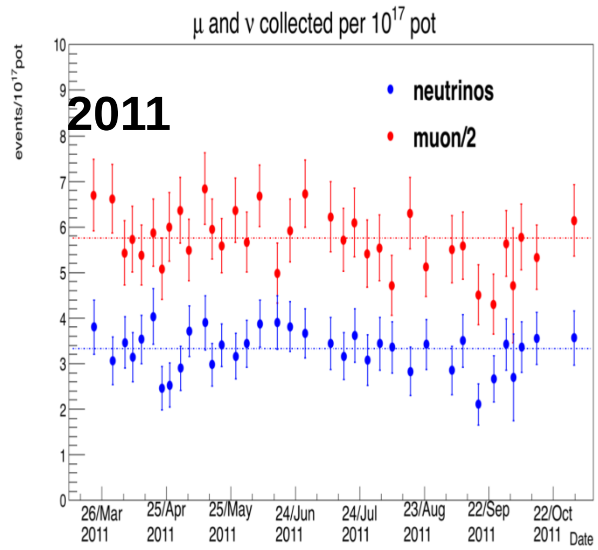


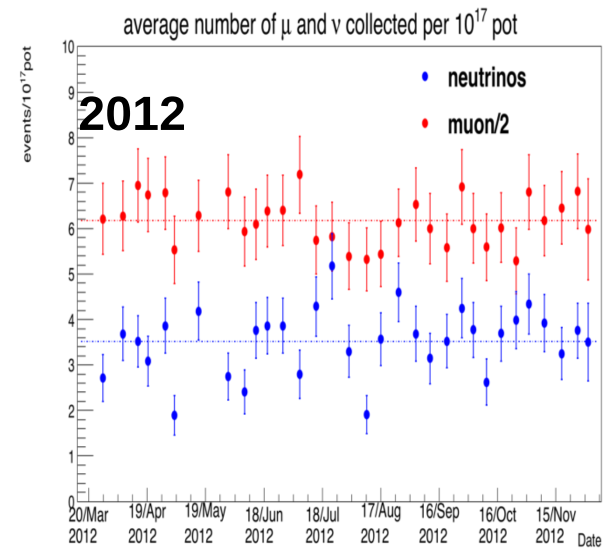


dE/dx distribution for real and MC muon tracks from CNGS events

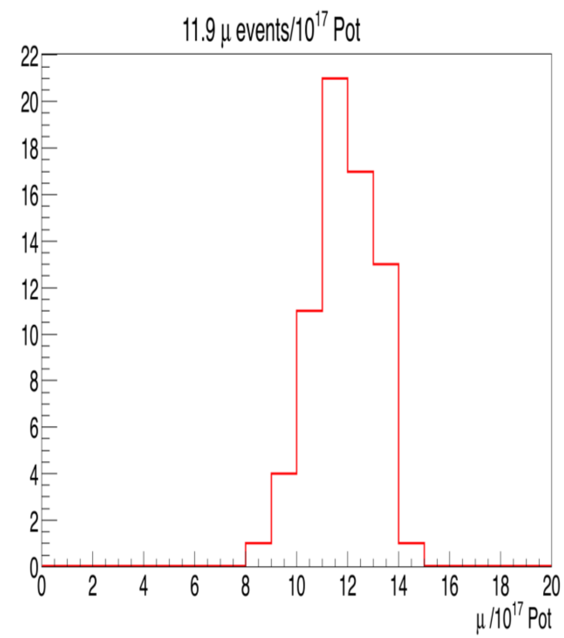
ICARUS: summary of collected data

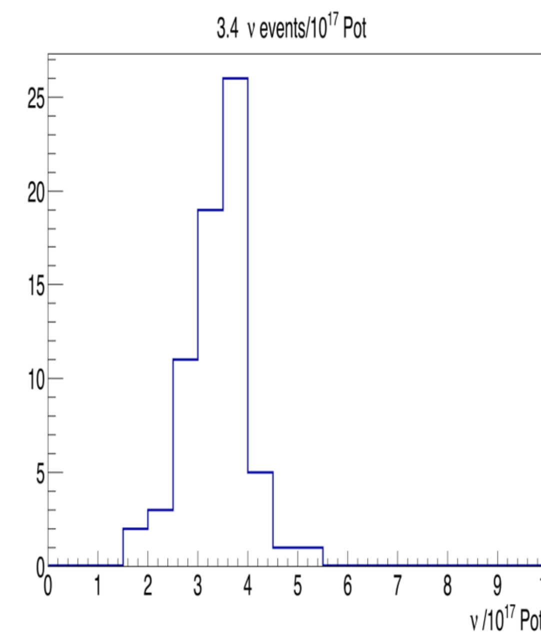
Neutrino interactions and rock muons (divided by2), normalized by pot statistics, and DAQ efficiency: each point refers to average over 10^{18} pot (only stat. errors), from 7.93×10^{19} pot





Distributions of collected neutrino interactions (3.4 on average) and beam related muons (12 on average) per 10^{17} pot





Consistent within 6% with MC predictions for Corresponding exposure

Search for LSND anomaly: additional electron neutrino event (1)

• First analysis (Eur. Phys. J. C73 (2013) 2345) was based on 1091 neutrino interactions (3.2×10^{19} pot) → 2 ν_e events found

• Extended analysis (Eur. Phys. J. C73 (2013) 2599) was based on 1995 neutrino interactions (6.0×10^{19} pot) → 4 ν_e events found

• At Neutrino 2014 conf. and SPSC 2014 analysis based 2450 neutrino interactions was presented (7.23×10^{19}pot) → 6 ν_e events found

• Additional electron neutrino event has been identified in the full available sample corresponding to the 7.93×10^{19} pot

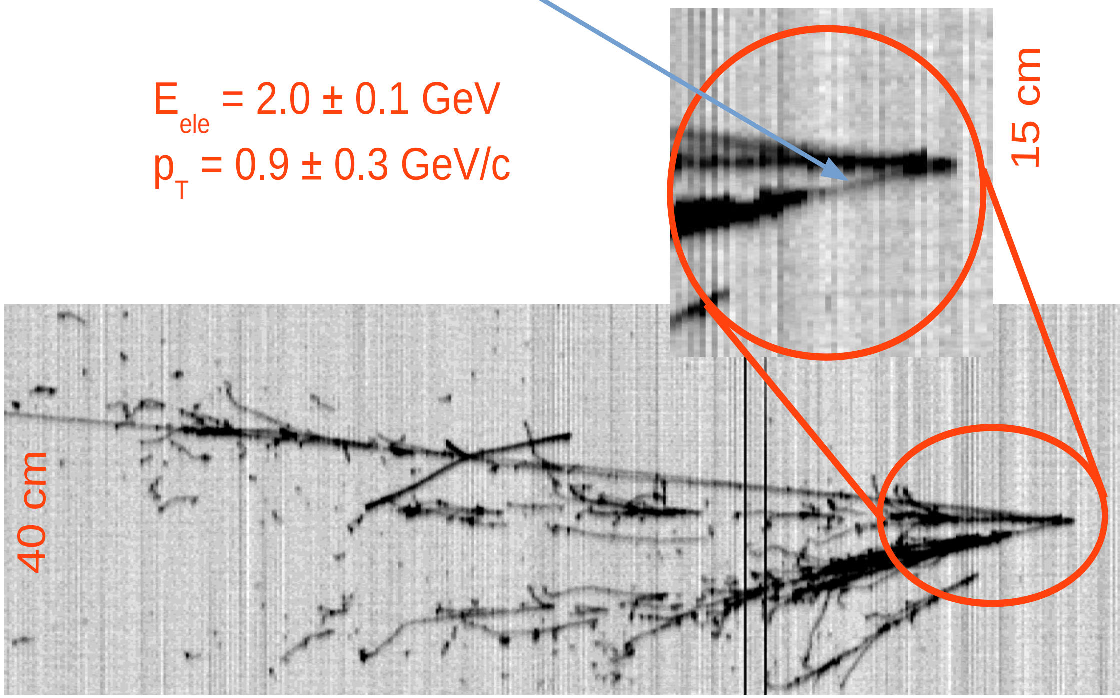
• The 7 observed electron like neutrino events are consistent with the 8.4 events expected: no evidence for sterile neutrino oscillation.

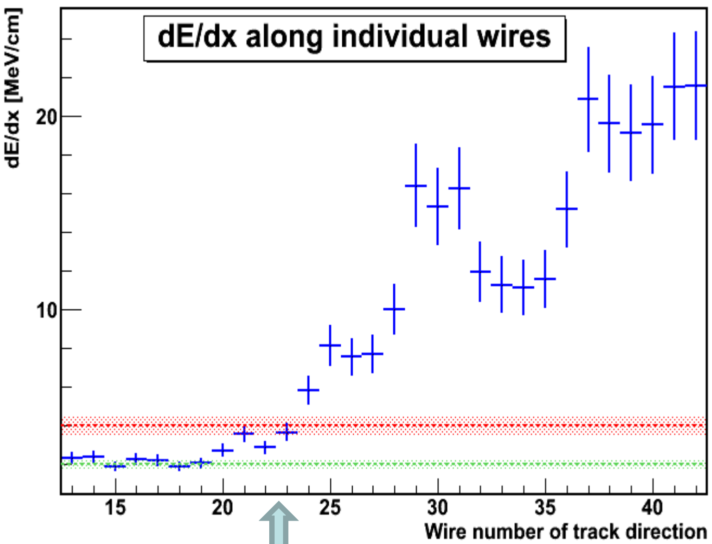
• ICARUS excludes large region of allowed parameters and permits to define a narrow region of agreement between different experiments (around $\Delta m^2 \approx 0.5$ eV^2 , $\sin^2 2\theta \approx 0.005$) which has to be explored in future.

Search for LSND anomaly: additional electron neutrino event (2)

E_{ele} = 2.0 ± 0.1 GeV

p_T = 0.9 ± 0.3 GeV/c

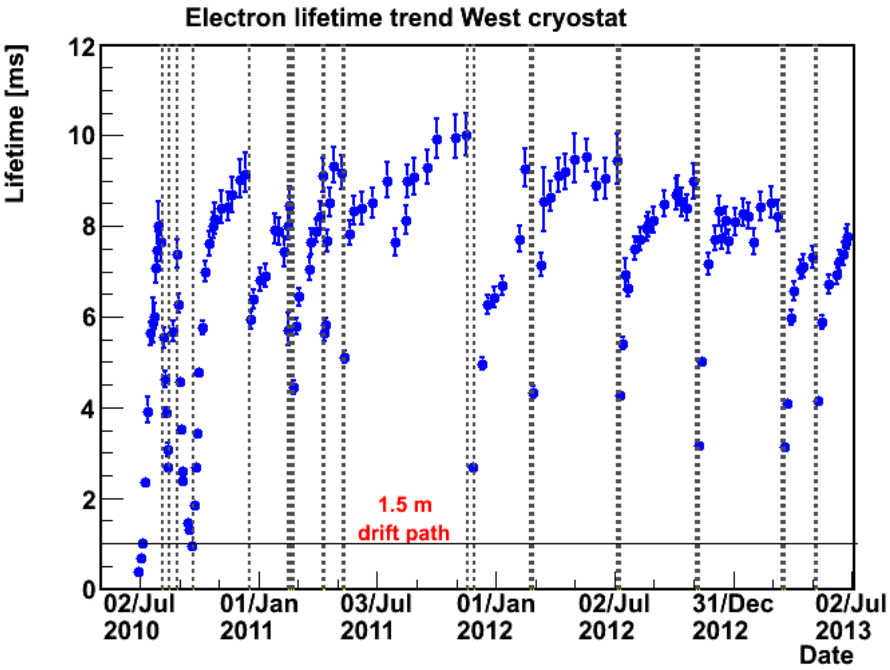


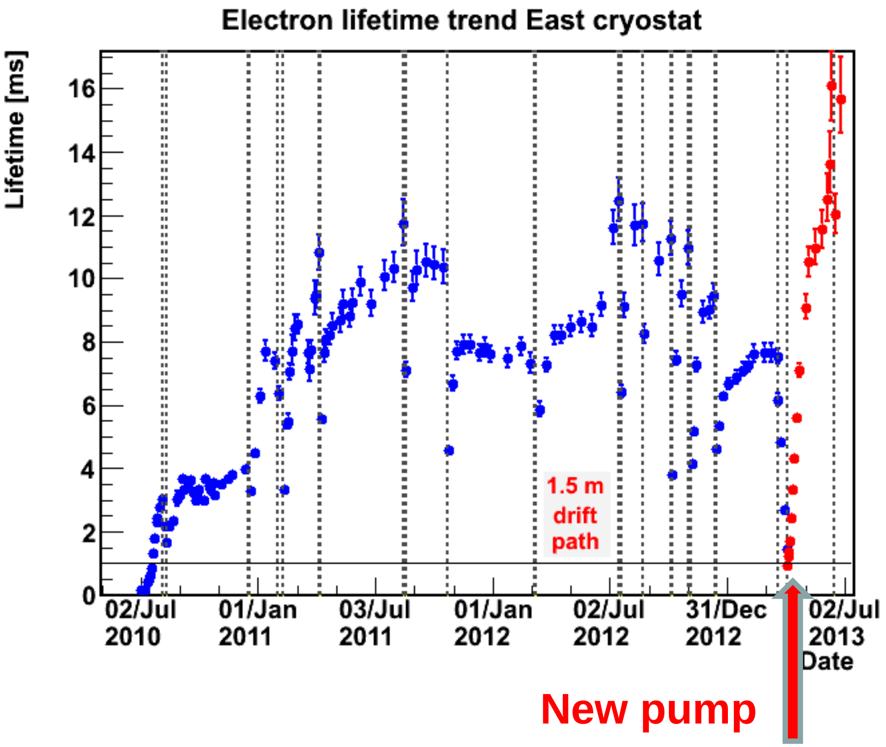


Evolution of dE/dx from a single track to an electromagnetic shower

ICARUS: LAr purity

- Operation of large TPC (~ 1 kton LAr, 1.5 m drift → 1 ms electron drift time) requires to reach and maintain very high level of LAr purity.
- Many years of R&D by ICARUS Coll. (from 50 liters to ~1 kton).
- In ICARUS detector it was achieved with use of commercial filters and liquid/gas recirculation (LAr continuously filtered).

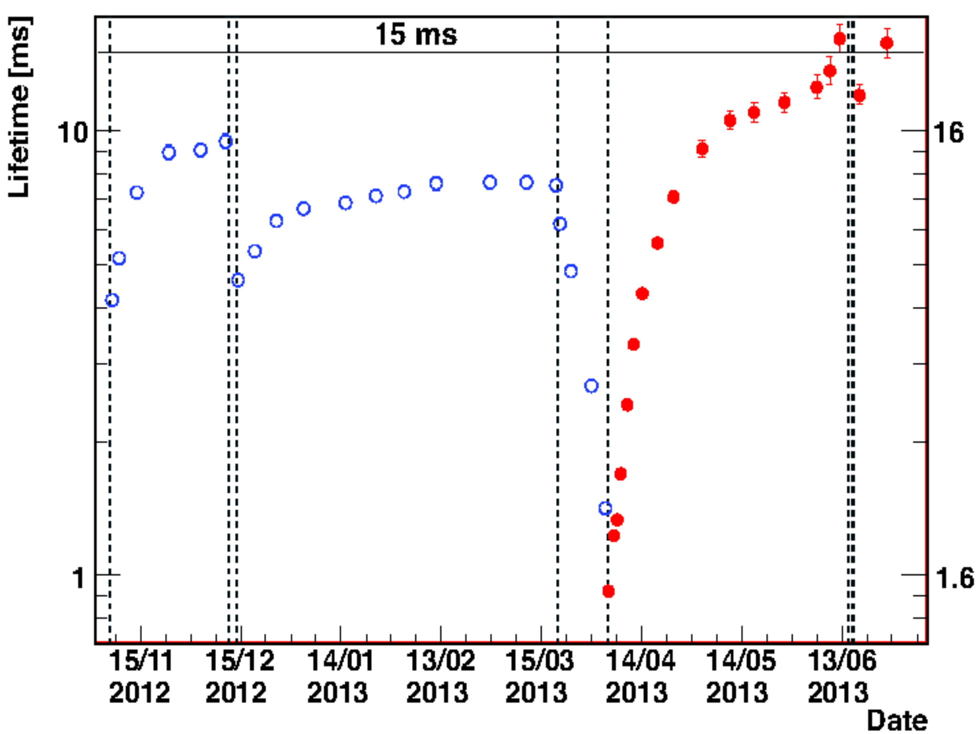


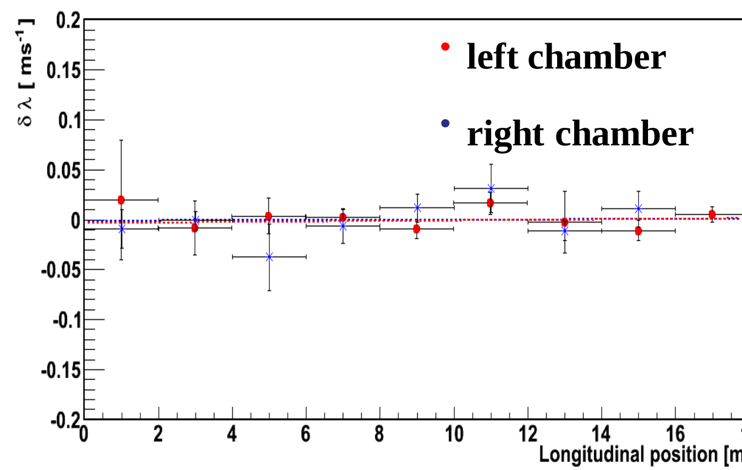


Average purity level ~40 ppt (O_2 equivalent) → Max. charge attenuation at 1.5m: 12%

ICARUS: LAr purity – new pump

- A new pump, with not immersed motor, has been installed on East cryostat near run-end.
- Electron life time exceeded 16 ms (signal attenuation of 6% for the maximum drift distance of 1.5 m), value so far reached only in small size prototypes → important for future very large LAr detectors (drift distance of several meters).





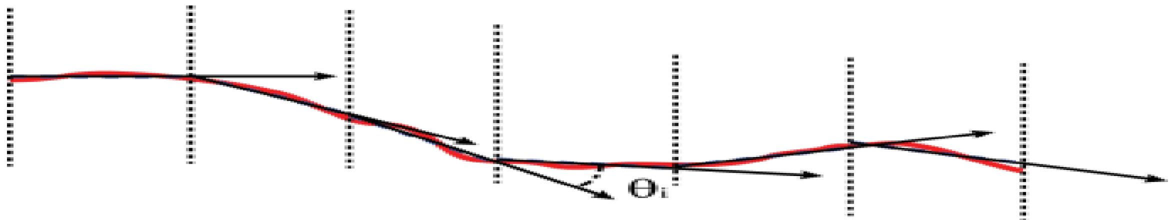
Measured variation of the level of the East cryostat impurities , verified with ~1000 vertical cosmic muon tracks

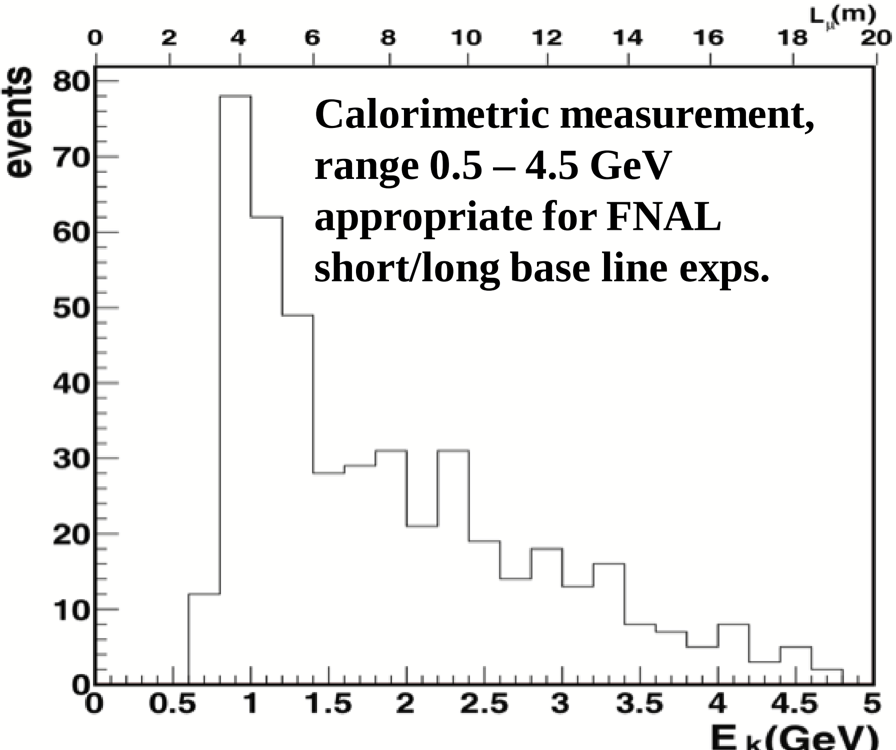
published, JINST 9 (2014) P12006

Muon momentum measurement via multiple scattering (1)

In absence of a magnetic field, multiple Coulomb Scattering (MCS) can be used to determine the initial μ momentum in LAr

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





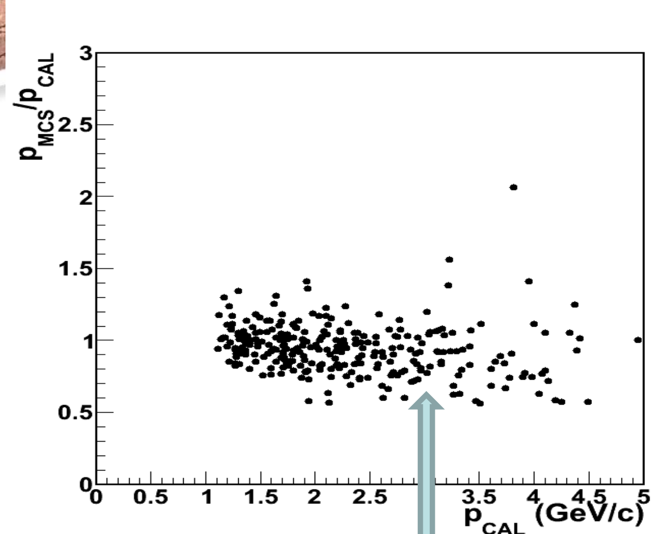
RMS of deflection angle θ depends on μ momentum p, on the segment length l and on the spatial resolution σ (radiation length in LAr X_0 = 14 cm)

Validation of the MCS method in T600 with the use of stopping muons sample (track length min. 2.5m, about 3 radiation lengths in LAr) from CNGS neutrinos interactions in the upstream rock, comparing the p_{MS} with the corresponding calorimetric determination p_{CAL}.

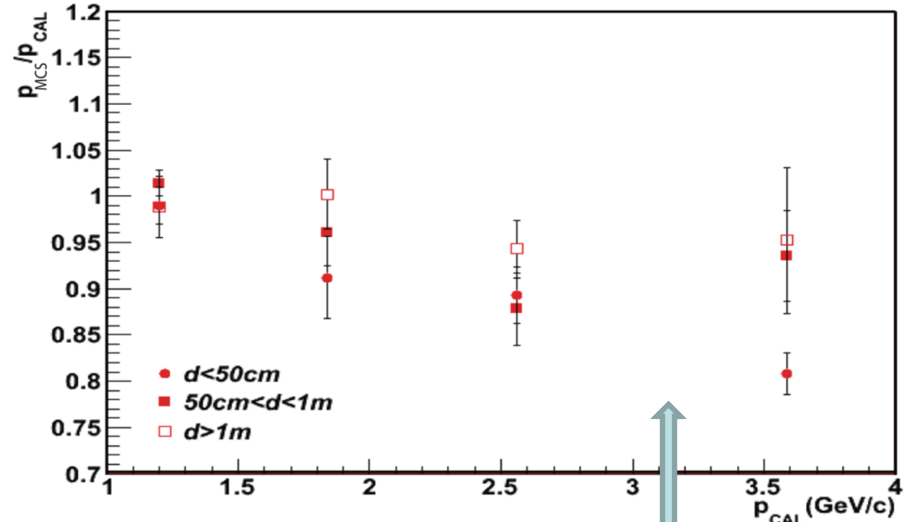
Muon momentum measurement via multiple scattering (2)

- Visual selection of muon tracks (no hadronic interaction along the track) within the CNGS events
- Automatic track reconstruction in 3D followed by visual inspection
- Removal of δ electrons (large energy deposition on wires)
- Fixed track length of 4 m is used in the measurement
- The last meter of a muon track was not used in MCS measurement (MCS deflections are extremely large)
- MCS measurement performed on the muon track projection on the two dimensional Collection plane (hit position uncertainty ~0.7 mm – mainly from the drift coordinate)
- Observed deflection angles, apart from MCS, contains also the single point space resolution (~ 2mrad) and the board to board synchronization (~ 1mrad). Both, are momentum independent.

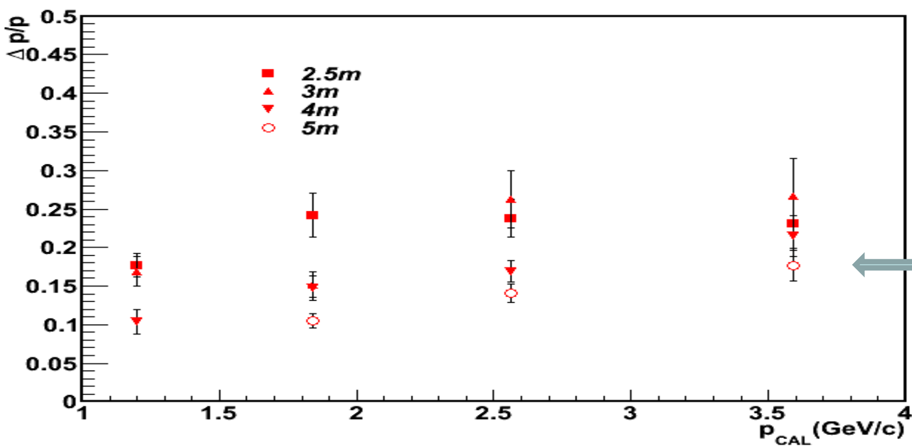
Muon momentum measurement via multiple scattering (3)



p_{MCS}/p_{CAL} decreases with p_{CAL}



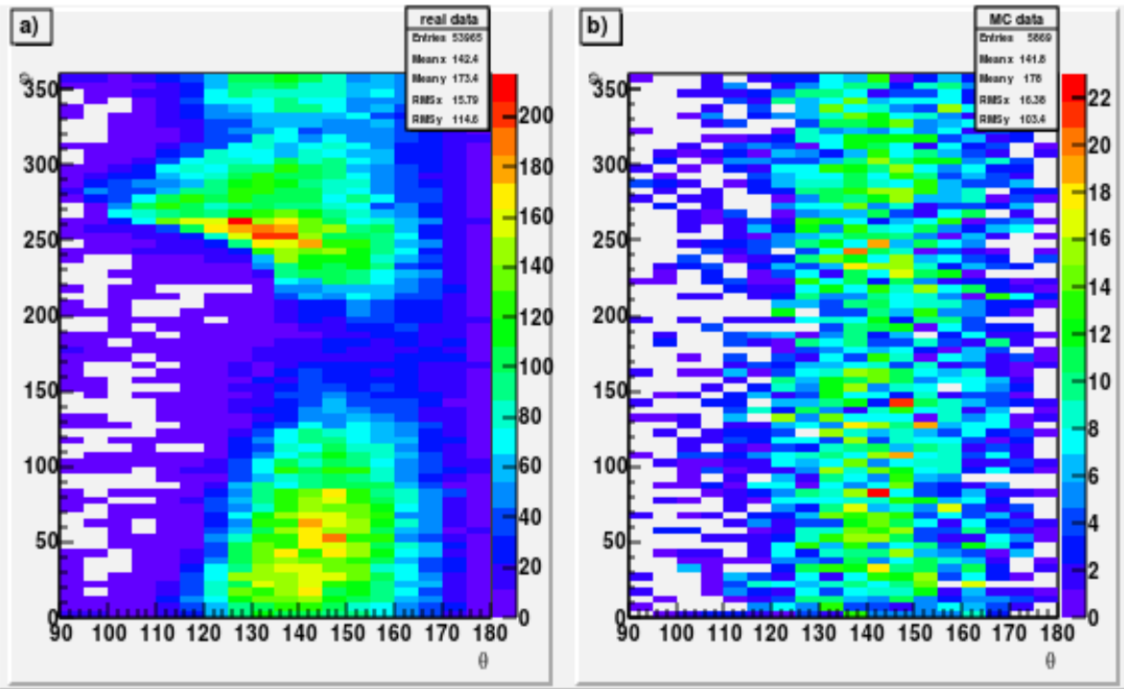
dependence on the track distance from the cathode induced by electric field distortion due to the non-perfect planarity of TPC cathode, as seen after detector decommissioning and checked with simulations

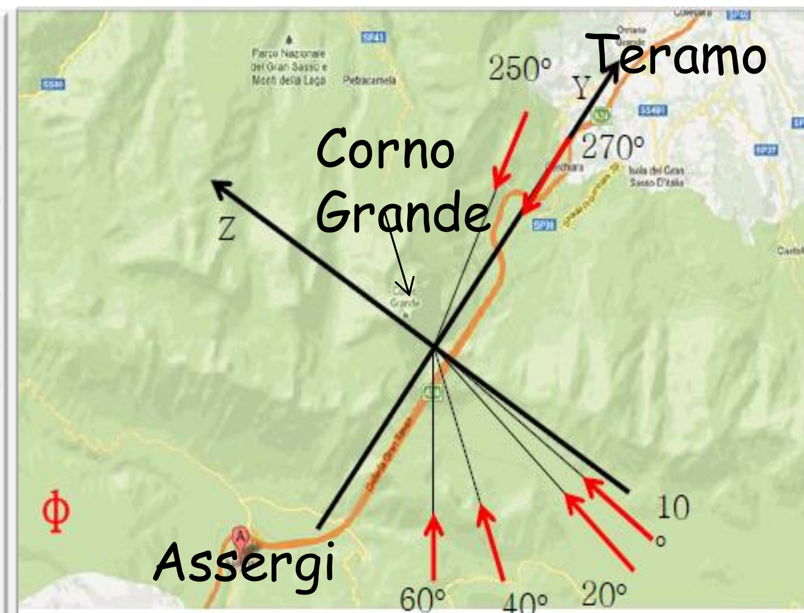


momentum resolution for several values of muon track lengths

Cosmic muons studies

- Preparatory step for search of atmospheric neutrinos
- Automatic 3D reconstruction of cosmic muon: found track with start and end of 3D reconstructed points closer than 5cm from detector walls. Selection of ~93% of cosmic muons.
- Full (geometry, trigger and reconstruction efficiency, noisy or missing crates, …) MC detector simulation.
- Evidence of Teramo anomaly (variation of mountain thickness)
- Statistics doubled since last SPSC report.

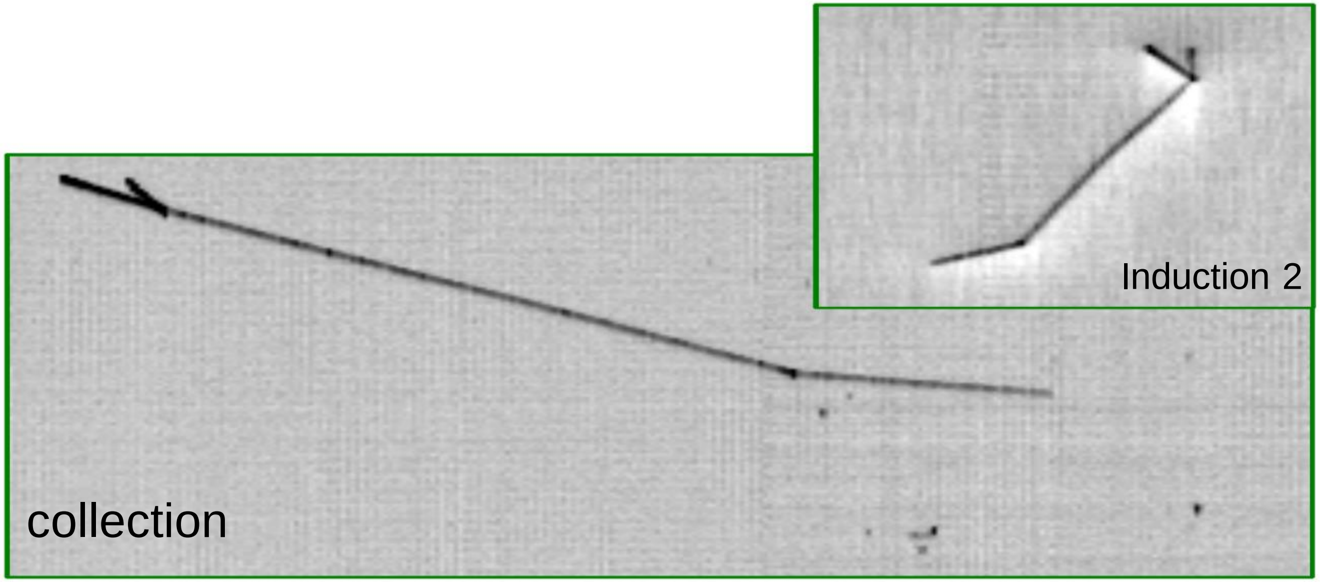




Search for atmospheric neutrinos

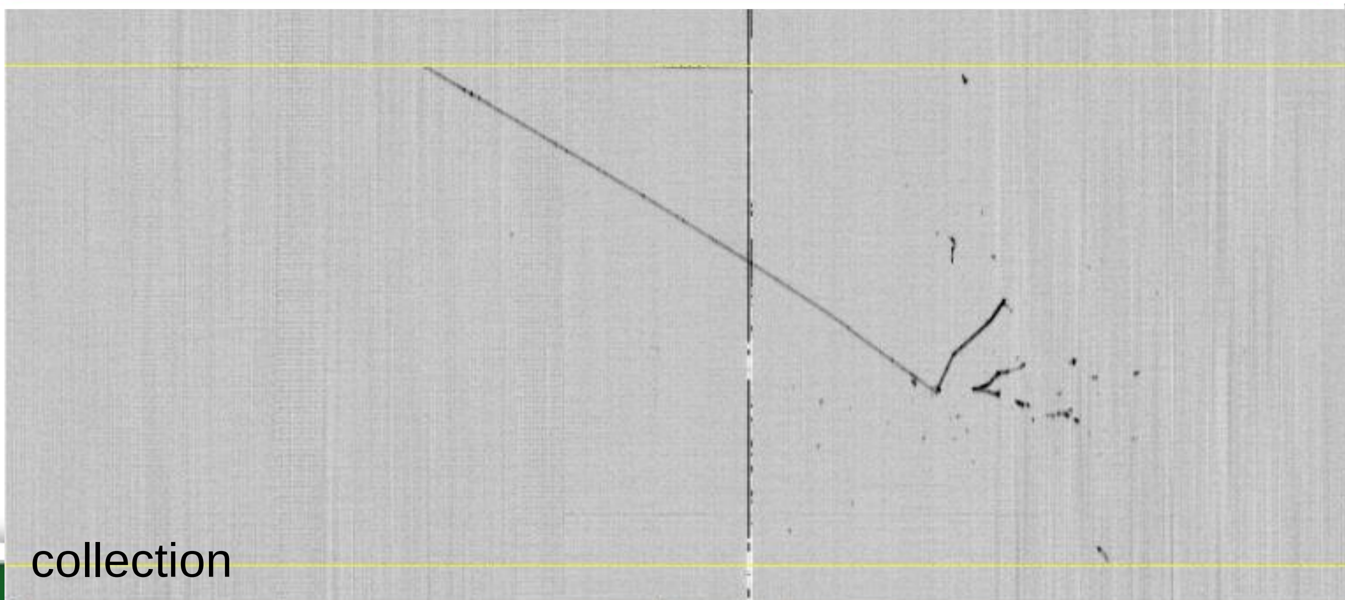
- About 200 atmospheric neutrino interactions are expected for 0.73 kt year ICARUS T600 exposure at LNGS,
- Algorithm for automatic search for an interaction vertex and multi-prong event topology, complemented by visual scanning was developed,
- Identification efficiency determined with MC: ~41% for multi-prong ν_μ CC, ~52% for ν_e CC and ~15% for NC,
- Work in progress: so far ~ 77000 triggers (~ 20 days) was filtered resulting in ~ 5400 multi-prong neutrino event candidates for scanning
- 2 muon-like, 0 electron-like and 2 NC-like atmospheric neutrino events have been observed (1.0 ± 0.4, 1.0 ± 0.4 and 0.4 ± 0.2 expected)

Atmospheric neutrinos: 2 candidates



NC atm. event:

- **2 charged particles emerge from int. vertex**
- **pion track: 63 cm (interacting and generating 2 protons)**
- **measured deposited energy: ~200 MeV**



ν_μ CC atm. event:

- **muon and proton/pion tracks are visible**
- **muon track: 124 cm**
- **measured deposited energy: ~ 350 MeV**

(no quenching correction)

ICARUS future: sterile neutrino search within FNAL SBN program

ICAR-US: 6 new US institutions (Los Alamos NL, Colorado State Univ., SLAC, Univ. of Pittsburg, FNAL and Aragonne NL) joined recently the ICARUS Coll.

- **To answer definitively the „sterile neutrino puzzle" an experiment with three LAr-TPCs, exposed to FNAL ~0.8 GeV neutrino beam, has been proposed.**
- **SBND (82 tons of active mass), MicroBooNE (89 tons) and ICARUS T600 (476 tons) will be installed at 100m, 470m and 600m from target, respectively**
- **Common Conceptual Design Report *A proposal for a Three Detector Short-Baseline Neutrino Program in the Fermilab Booster Neutrino Beam*, submitted to the FNAL-PAC in January 2015, underwent level 1 approval.**
- **The aim of the experiment is to clarify both, LSND/MiniBooNE and Gallex/reactor anomalies , by independent measurement of both, ν_e appearance and ν_μ disappearance mutually linked by the equation:**

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

- **In absence of anomalies, signals from three detectors should be a copy of each other. However, the intrinsic ν_e events with a disappearance signal may result in the reduction of a superimposed appearance LSND signal.**
- **By changing the intrinsic ν_e beam contamination (horn focusing and decay pipe length) these two effects can be disentangled.**

U.S. Groups join ICARUS (ICAR-US)

Sunday, April 26, 2015 9:42 AM

Dear Colleagues

this is to let know that all the ICARUS participating groups have been formally consulted and have unanimously agreed to extend the ICARUS collaboration to you and your teams. Argonne National Laboratory, Colorado State University, Los Alamos National Laboratory, FermiLab, University of Pittsburgh and SLAC are presently new participants in the Collaboration.

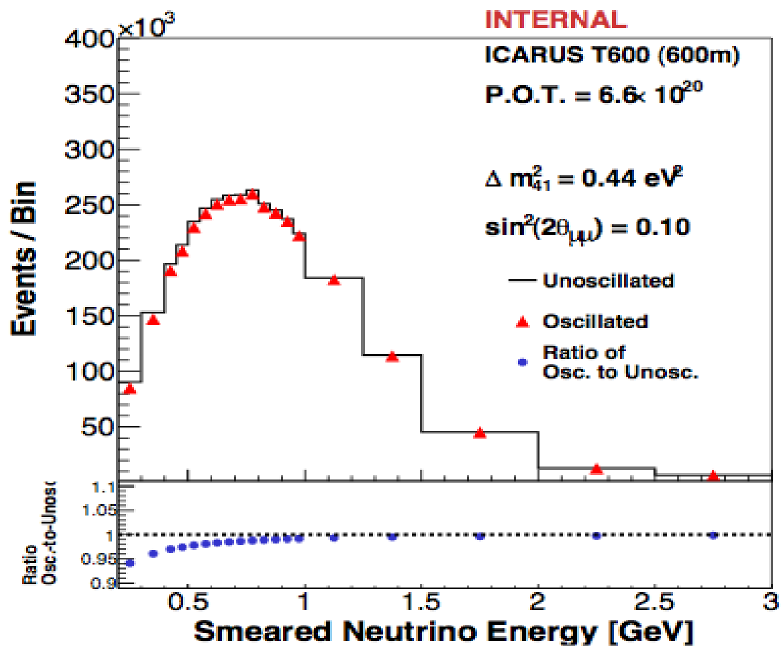
Welcome in ICARUS !

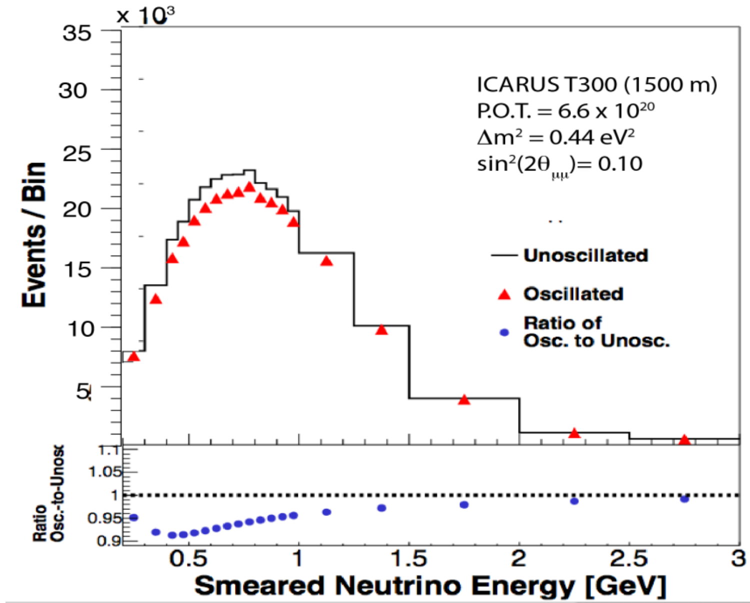
Sincerely

Carlo Rubbia

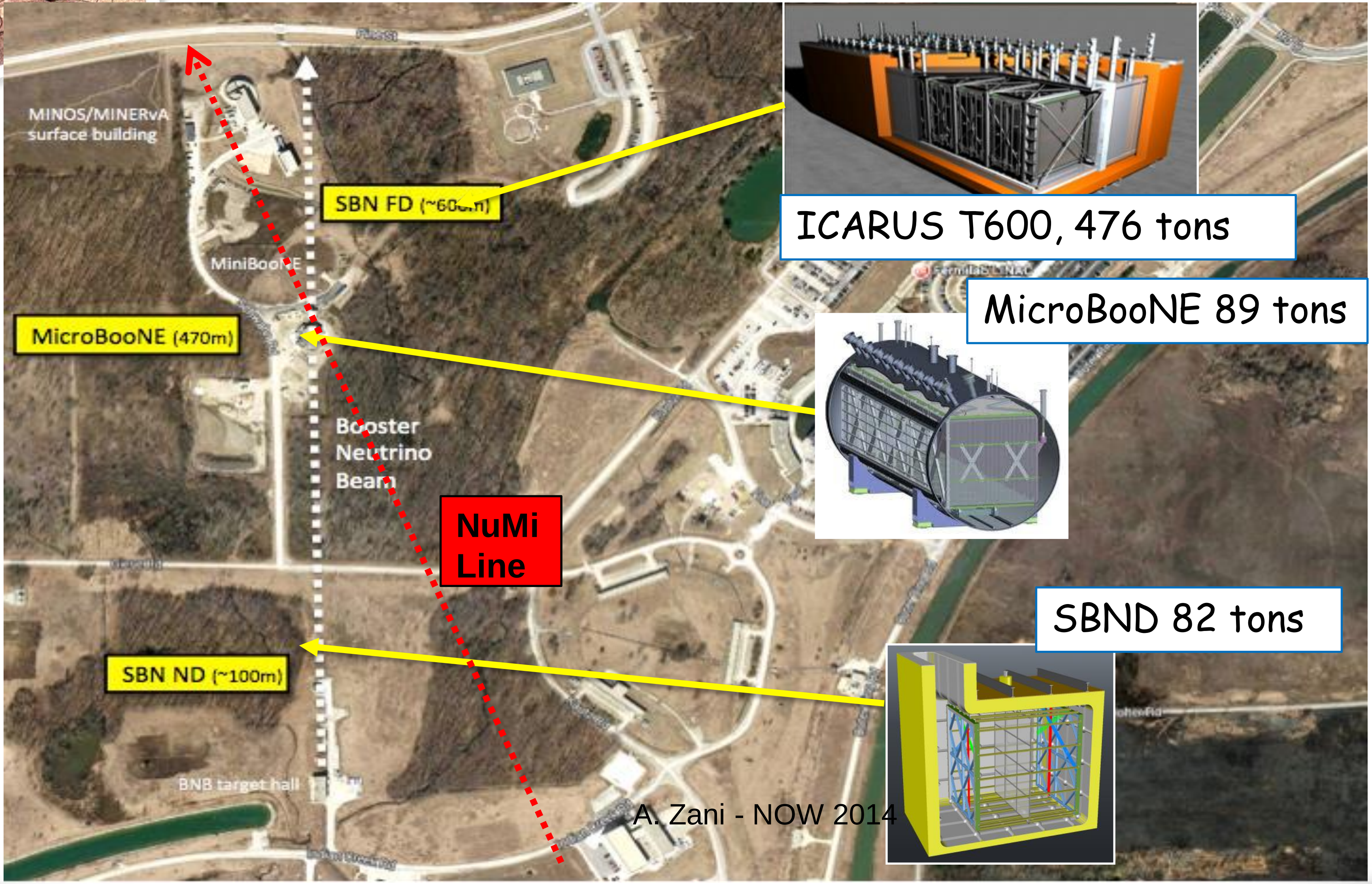
ν_μ disappearance measurement at FNAL

- If LSND result is confirmed ($\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \sim 1.5 \times 10^{-3}$), within 3+1 model, both ν_e and ν_μ disappearance are present since: $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{\mu4}|^2)$ and $\sin^2 2\theta_{\mu\mu} = 4|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$
- Present reactor experiments claim: $\sin^2 2\theta_{ee} \sim 0.12$, $|U_{e4}|^2 \sim 0.03$
- For $\Delta m^2 < 0.5$ eV^2 the ν_μ disappearance effect at 600 m will be limited at the energy bins 0.2 – 0.4 GeV
- At a later stage one ICARUS T300 module may be moved to 1500 m from the target to enhance the effect

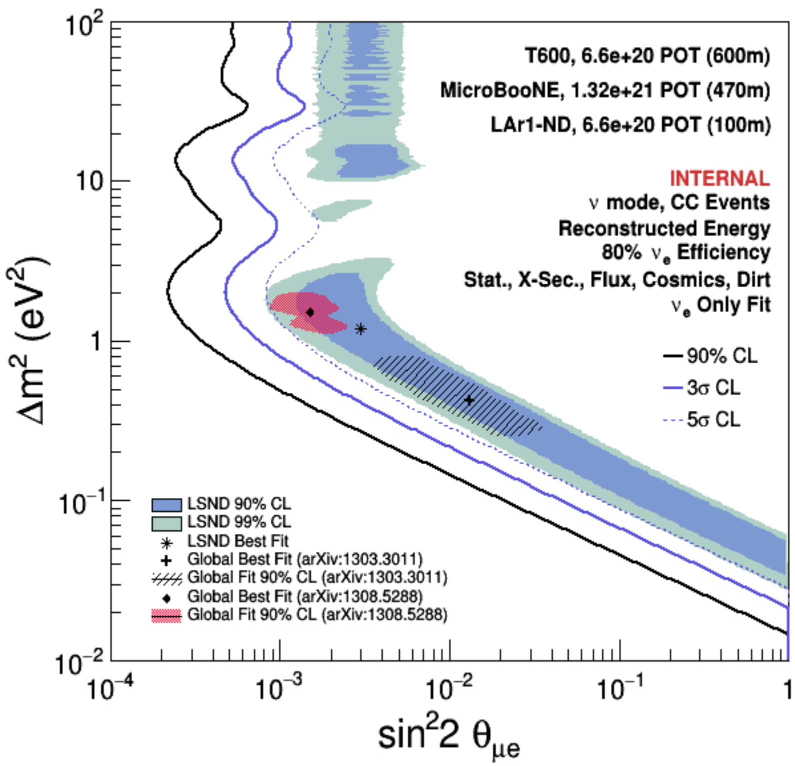


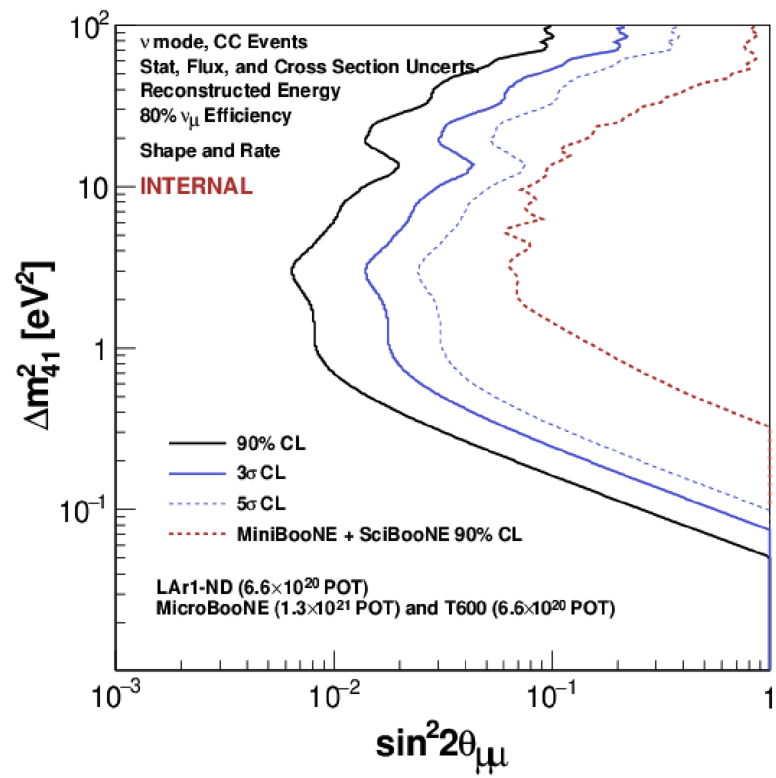


Layout of three LAr TPCs at FNAL



Expected sensitivity: 3 years, 6.6×10^{20} pot



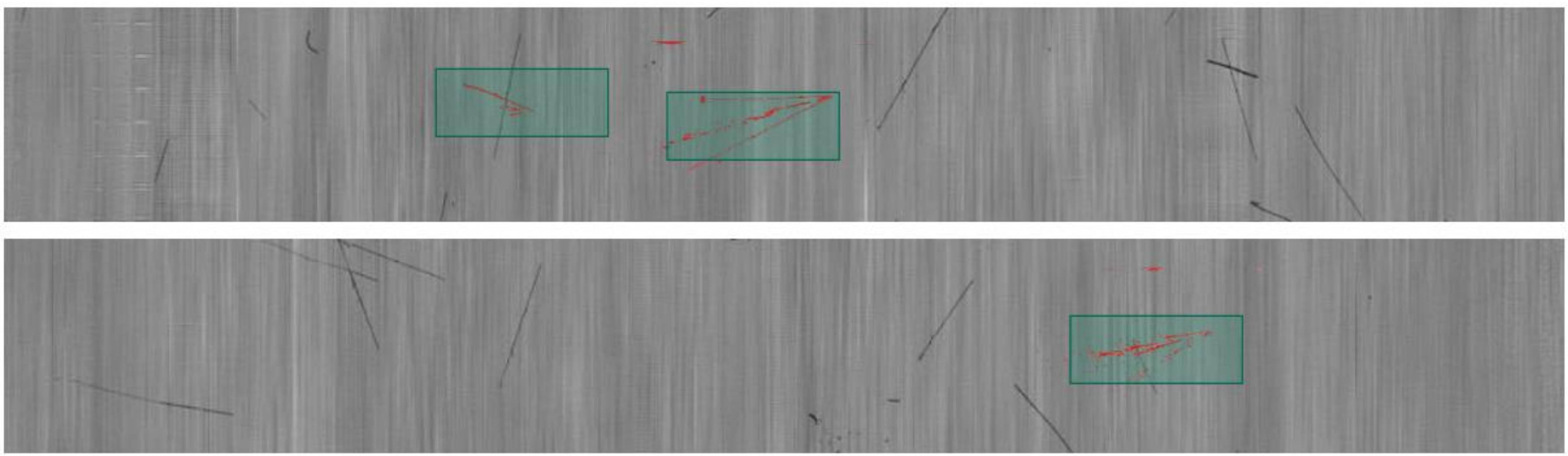


$\nu_\mu \rightarrow \nu_e$ oscillations
(6 years of MicroBooNE)

ν_μ disappearance
(6 years of MicroBooNE)

ICARUS at shallow FNAL depth: new challenge (1)

- **Several (~12 muons from Pavia 2001 surface measurement) uncorrelated cosmic rays will occur in T600 during 1 ms window readout at each triggering event**
- **Therefore, it is necessary to associate precisely the related timing of each element of TPC image with respect to the trigger line.**
- **Moreover, photons associated with cosmic muons represent a serious background for the ν_e appearance search, since electrons generated in LAr via Compton scattering or pair production can mimic ν_e CC interaction.**



Cosmic rays (PV) + low energy CNGS beam events

ICARUS at shallow FNAL depth: new challenge (2)

- **An unambiguous identification of all cosmic ray particles entering the detector has to be applied. A Cosmic Rays Tagging, around the Lar active volume is under study. It will provide an external timing of each track, which will be combined with the TPC reconstructed image.**
- **99% efficiency in cosmic rays identification can be achieved with a 95% detection efficiency (relying on double crossing of muons) of single muon hit**
- **Also a ~1 ns accuracy of internal scintillation light detectors, will enable to exploit the bunched structure of the Booster p beam (2 ns wide bunches every 19 ns)**

ICARUS T600 detector improvement in order to prepare it for operation at shallow depth is going on within the CERN ICARUS/WA104 experiment with strong support from CERN groups

ICARUS/WA104 program at CERN

- Established through the CERN/INFN MoU
- T600 overhauling by introducing technology achievements while maintaining the already achieved performance
- New cold vessels and new purely passive insulation
- Partial reconstruction of cryogenic and purification systems
- Substitution of TPC cathodes with better planarity
- An improved scintillation light collection system
- New faster, higher-performance read-out electronics
- Design and construction of muon tagging system
- Development of fully automatic tools for event reconstruction
- Two years schedule to be completed by the end of 2016, followed by the detector transportation to FNAL
- Reported at previous SPSC session.

Concluding remarks

- ICARUS is the largest LAr TPC operated underground.
- ICARUS has been acquiring data without interruption for more than 3 years with both CNGS beam and cosmics, proving the maturity of this detection technique → important for next generation experiments.
- ICARUS search for sterile neutrino excluded a large fraction of parameters defining a narrow space of agreement between different experiments (around $\Delta m^2 \approx 0.5$ eV^2 , $\sin^2 2\theta \approx 0.005$) which has to be explored in the future.
- ~15% resolution of the muon momentum measurement by Coulomb Multiple Scattering is achieved in the momentum range of interest for future experiments exploiting LAr TPCs.
- LAr purity corresponding to the electron lifetime exceeding 16 ms was achieved opening the way for next generation LAr TPC detectors.
- Overhauling of the ICARUS T600 detector, within the CERN/INFN ICARUS/WA104 project is continued at CERN.
- Beyond 2016 plan for the ICARUS T600 : far detector in the framework of FNAL Short Baseline Neutrino Program.

Some backup slides

ICARUS – published papers

- **Search for superluminal neutrinos:**

1. **Cherenkov-like emission of e^+e^- pair: PL B711 (2012) 270**
2. **Measurement of neutrino tof: PL B713 (2012) 17**
3. **Precision measurement of neutrino tof: JHEP 11 (2012) 049**

- **Search for „LSND" anomaly:**

1. **Limited statistics result: Eur. Phys. J. C73 (2013) 2345**
2. **Improved statistics result: Eur. Phys. J. C73 (2013) 2599.**

- **„Technical" aspects of the experiment:**

1. **Underground operation: JINST 6 (2011) P07011**
2. **3D reconstruction: Adv. High Energy Phys. (2013) 260820**
3. **Trigger system: JINST 9 (2014) P08003**
4. **Electron lifetime: JINST 9 (2014) P12006**

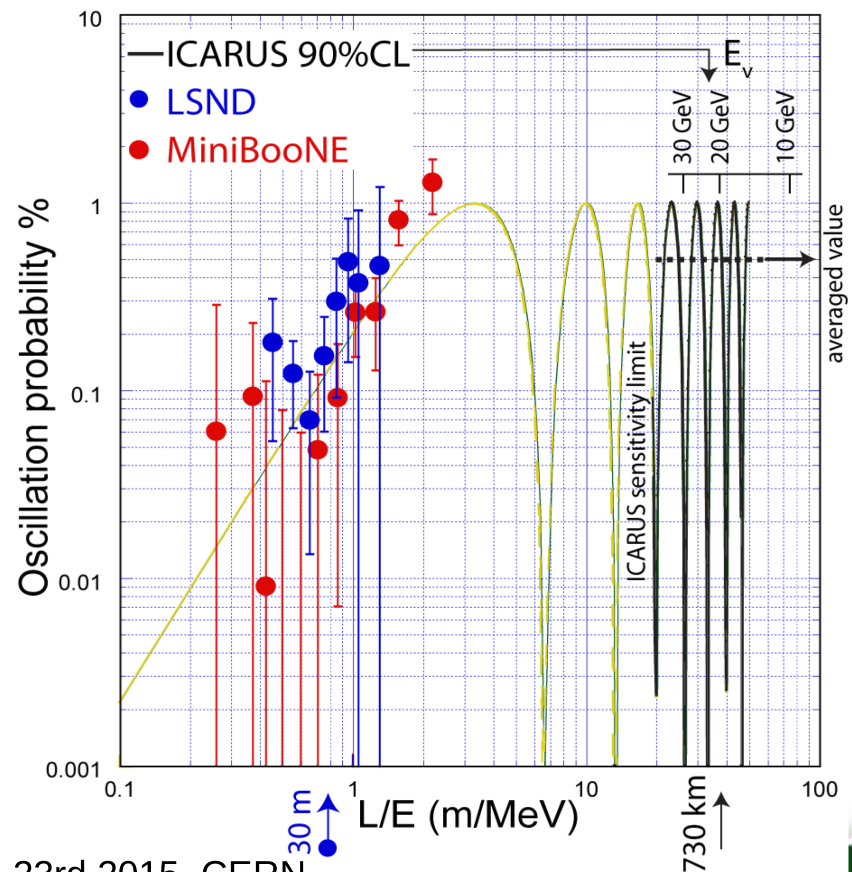
ICARUS: search for LSND anomaly

- The LSND has observed an excess of anti-ν_e nuetrino events in anti-ν_μ beam: 87.9 ± 22.4 ± 6.0 (3.8σ), later partly confirmed by MiniBooNE with both ν_μ/anti-ν_μ beams: **$\Delta m^2_{new} \approx 10^{-2} \div 1$ eV²** implied.

LSND: L/E=1 m/MeV

ICARUS: L=730km, E_ν є [10,30] GeV, almost pure ν_μ beam (ν_e≈1%)
L/E ≈ 36.5 m/MeV, i.e. fast oscillations as a function of E_ν averaging to
$\sin^2(1.27\Delta m^2 L/E) \approx 1/2$
$\langle P\rangle_{\nu_\mu \rightarrow \nu_e} \approx 1/2 \sin^2(2\theta_{new})$

A sterile neutrino signal would appear for ICARUS as an excess of ν_e events.



ν_e CC event recognition becomes crucial, and possible due to unique LAr feature.

ICARUS: ν_e signal selection

• Visual selection of electron neutrino event candidates in the following fiducial volume for shower id: > 5 cm from walls and 50 cm downstream.

• Energy cut: < 30 GeV (≈50% reduction on ν_e beam, but only 15% reduction of signal events.

Signal events selection criteria:

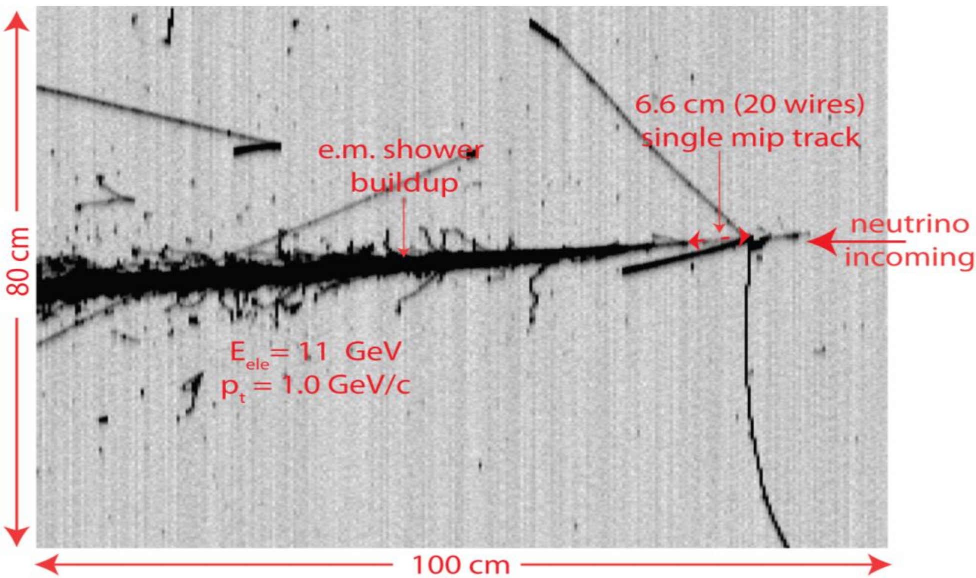
• Single m.i.p. from vertex, al least 8 wires long (dE/dx ≤ 3.1 MeV/cm, excluding δ-rays), later developing into EM shower.

• Minimum spatial separation (150 mrad) from other tracks coming from vertex, at least in one of 2 transverse views.

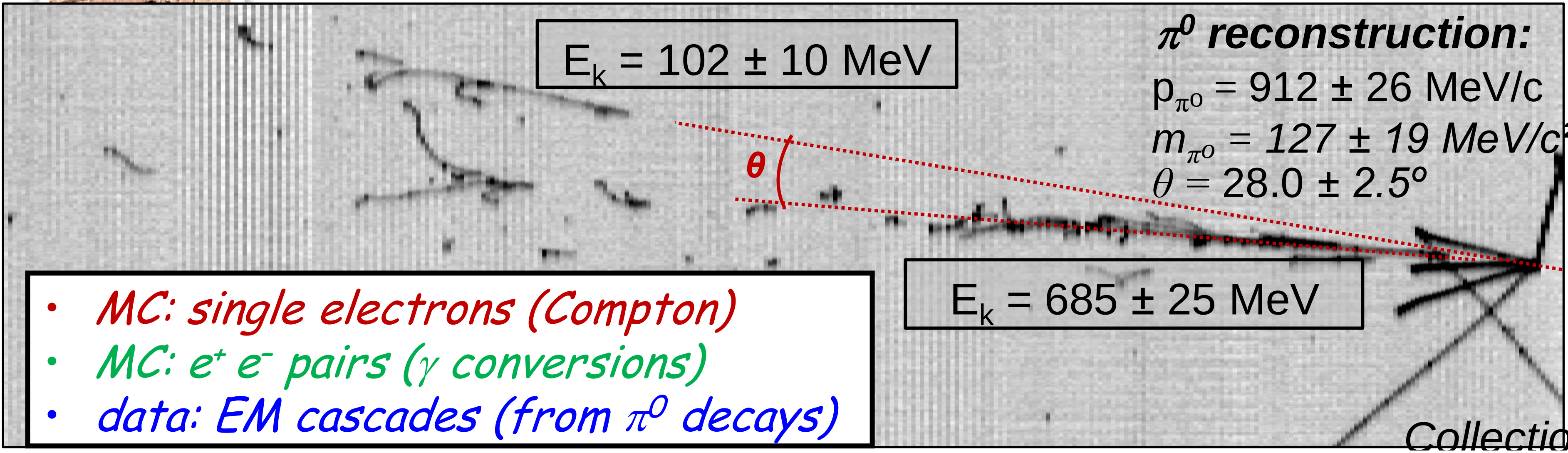
• visibility cuts: (3 independent scanners), leading to 0.74 ± 0.05 efficiency;

•No ν_e-like events selected among NC simulated sample of 800 events.

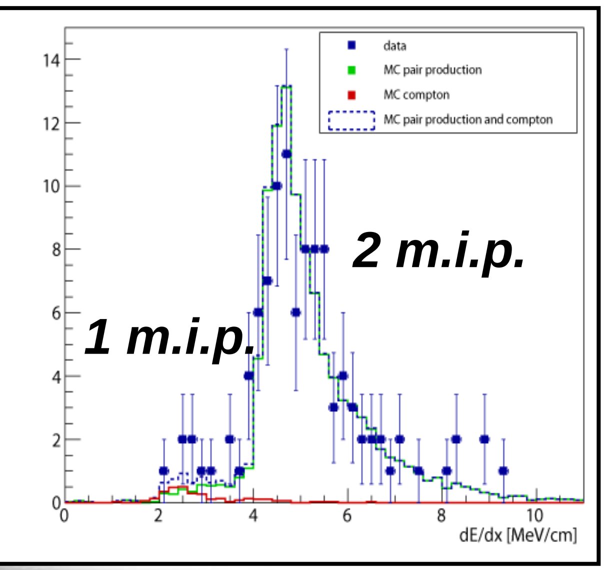
• ν_μ CC events identified by L > 2.5 m primary track without hadronic interaction

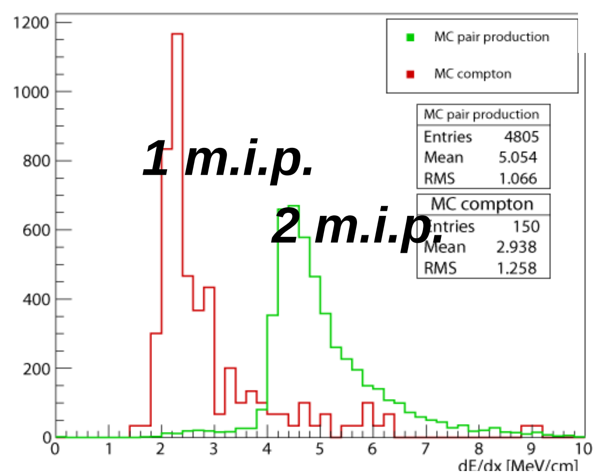


ICARUS: e/γ separation

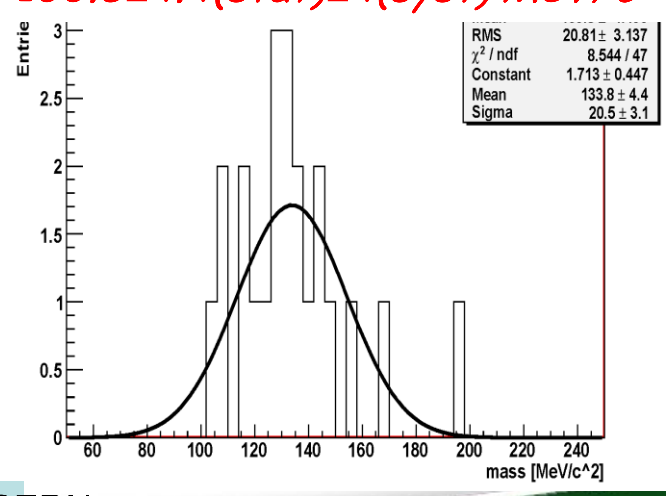


- *MC: single electrons (Compton)*
- *MC: $e^+ e^-$ pairs (γ conversions)*
- *data: EM cascades (from π^0 decays)*





Mγγ:
133.8±4.4(stat)±4(syst) MeV/c²



LAr TPC: very good e/γ separation

Data sample and event rate

• Analysis presented here is based on 2450 neutrino events corresponding to 7.23 x 10^{19} pot (84% of fully collected statistics).

• Previously published result (Eur. Phys. J. C73 (2013) 2599) was based on 1995 neutrino interactions (6.0 x 10^{19} pot).

•Expected number of ν_e events in this sample:

- •7.0 ± 0.9 due to the intrinsic electron neutrino beam contamination.
- •2.9 ± 0.7 due to θ_{13} oscillations, $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$.
- •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 (probability to observe ≤ 6 ν_e events is ~33%).

•No evidence of oscillation into sterile neutrinos was found in the analysed sample.

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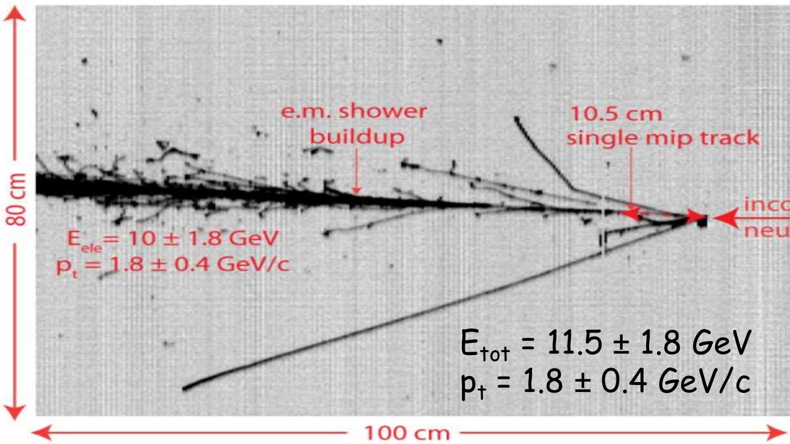
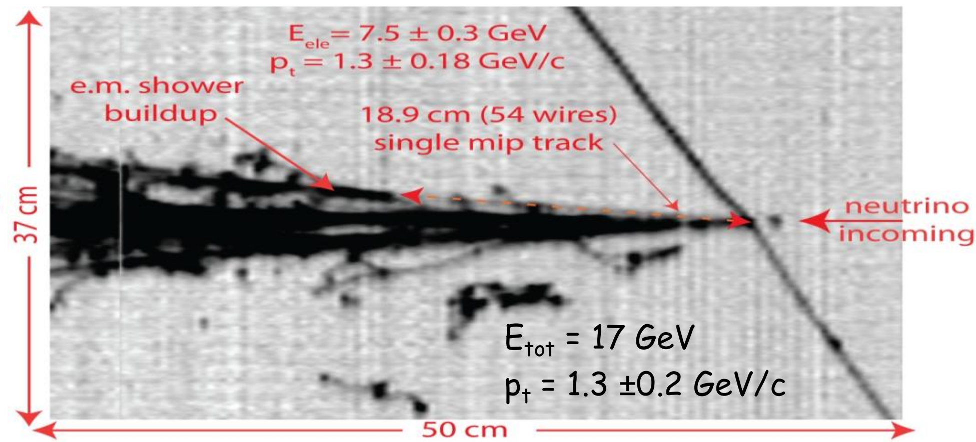
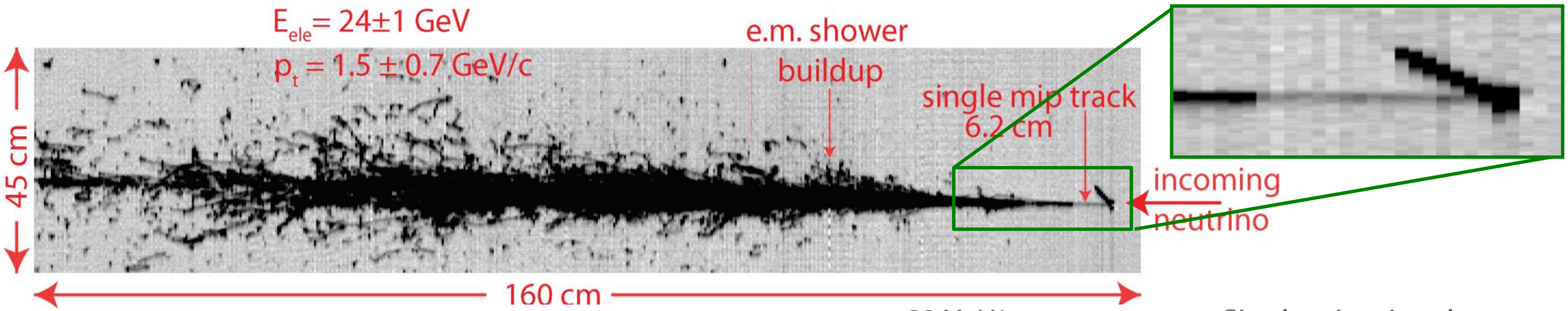
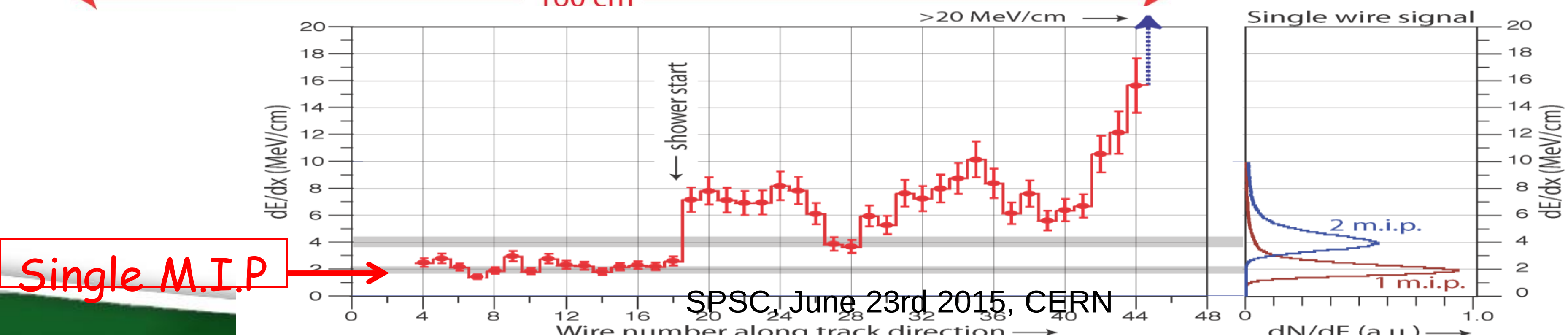
Examples: 3 out of 6 CC ν_e events









ICARUS: no LSND-type signal

ICARUS new limits, weighted for efficiency, on neutrino events due to LSND anomaly are: 5.2 (90 % C.L.), or 10.3 (99 % C.L.), with the following limits on the oscillation probability:

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

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

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.

Only a narrow region of overall agreement between different experiments remains, centered around $\Delta m^2 \approx 0.5$ eV^2 , $\sin^2 2\theta \approx 0.005$.