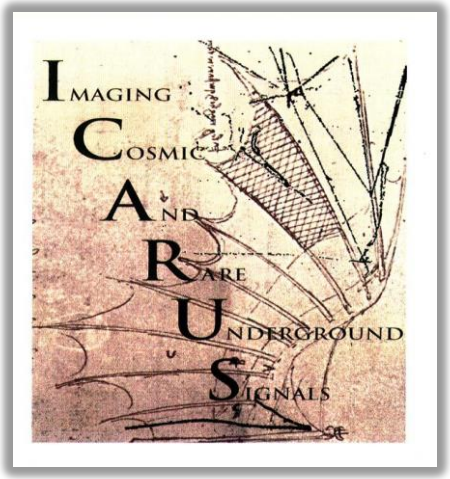
Status and plans of the ICARUS experiment



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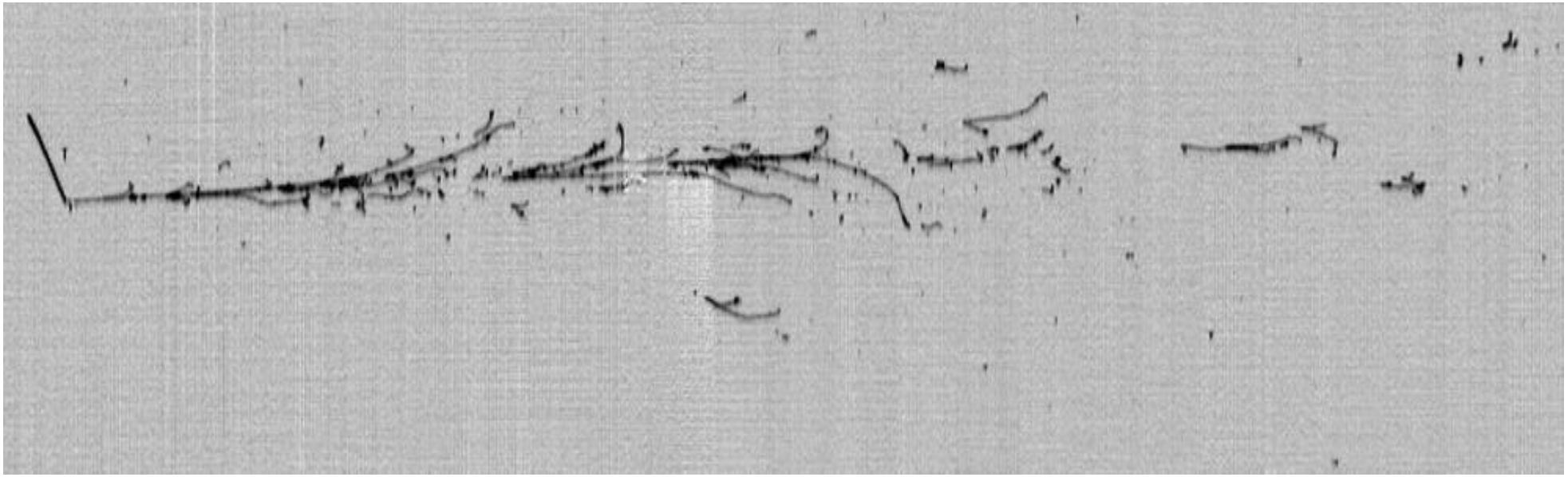
(on behalf of the ICARUS Collaboration)



SPSC, June 21st 2016, CERN

Introduction

- In June 2013 the ICARUS Coll., exploiting the biggest LAr TPC, with ~500 ton of sensitive mass, operating underground, concluded a long duration run collecting both:
  - CNGS beam: 8.6×10^{19} protons on target with a detector lifetime > 93%, 7.93×10^{19} are available (i.e. scanned and preliminary classified) for analysis; identification of 2650 neutrino interactions in the fiducial volume;
  - cosmics rays with exposure 0.73 kton year.

- ICARUS overhauling is ongoing at CERN (ICARUS/WA104 project) towards the SBN experiment at FNAL with three LAr detectors, to definitively set neutrino anomalies observed at accelerator, nuclear reactor and radioactive calibration sources of solar neutrino experiments.

- In this talk the status of the analysis (CNGS and cosmics data; muon momentum from multiple scattering) and plans of the ICARUS detector will be presented.

The ICARUS Collaboration

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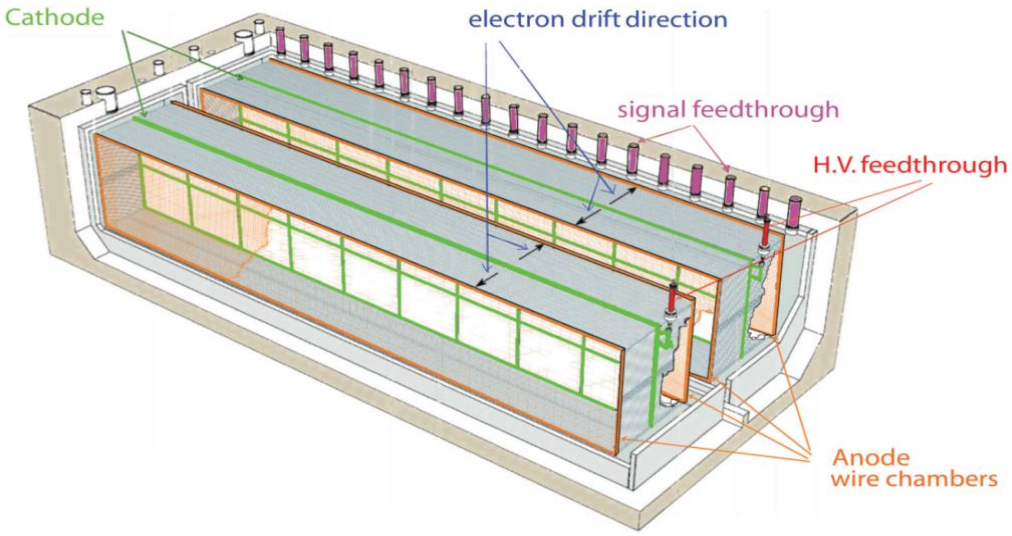
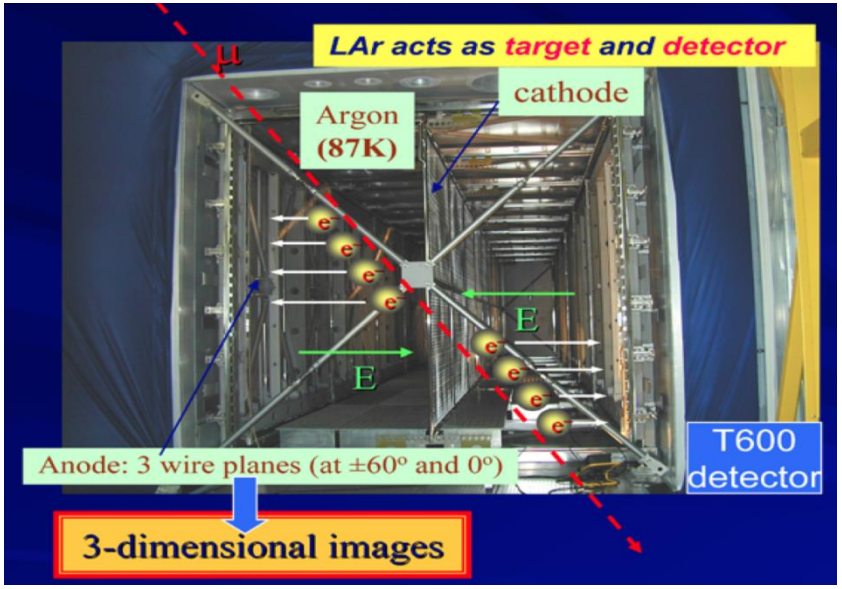
ICARUS T600: the largest LAr-TPC so far





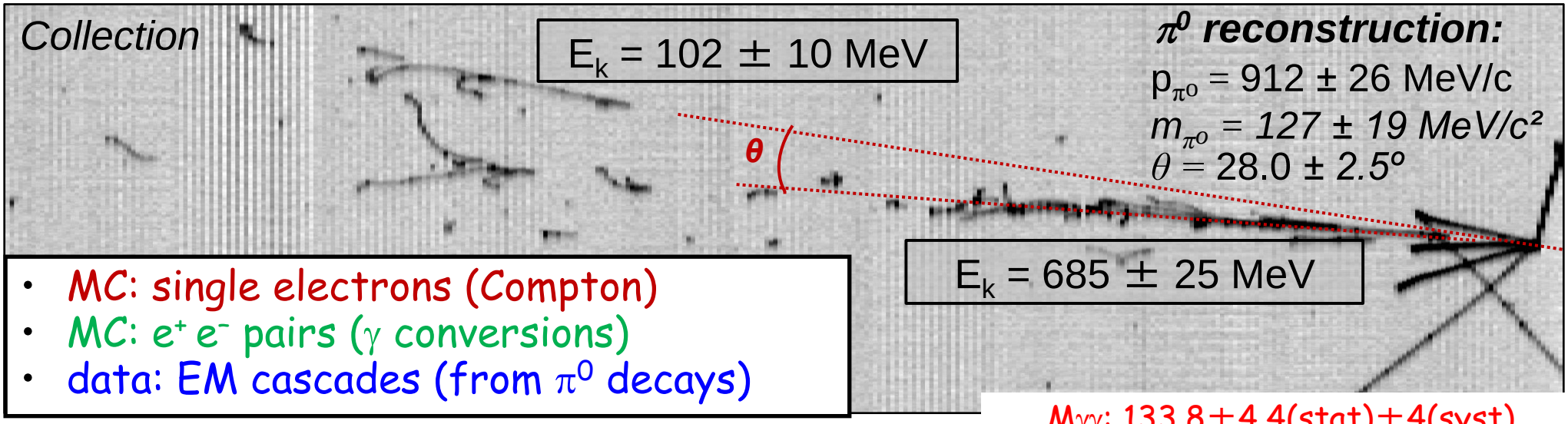
- **Two identical modules**
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- **4 wire chambers:**
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 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).

~40 p.p.t. [O_2] eq → τ_{ele} > 7 ms; ~20 p.p.t. → τ_{ele} > 15 ms

(15 ms reached at the end of data taking)

ICARUS: e/γ separation and π^0 reconstruction



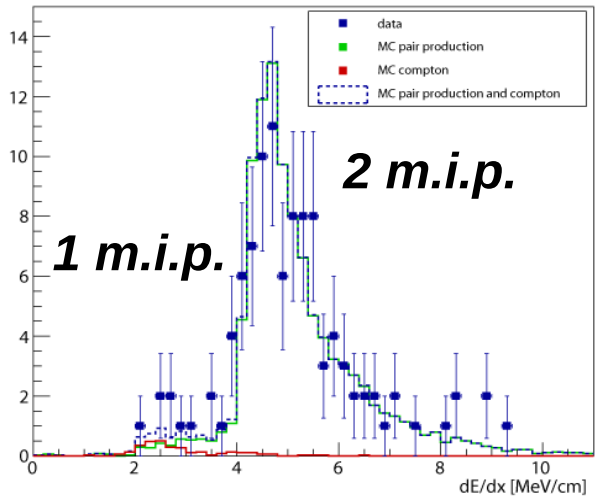
π^0 reconstruction:

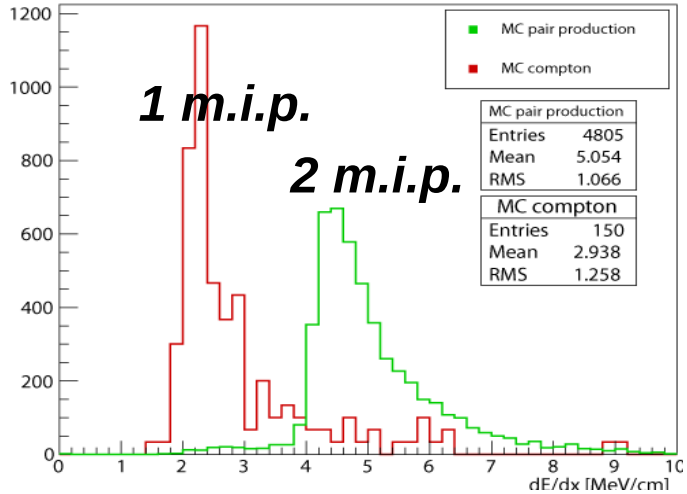
p_{π^0} = 912 ± 26 MeV/c

m_{π^0} = 127 ± 19 MeV/c²

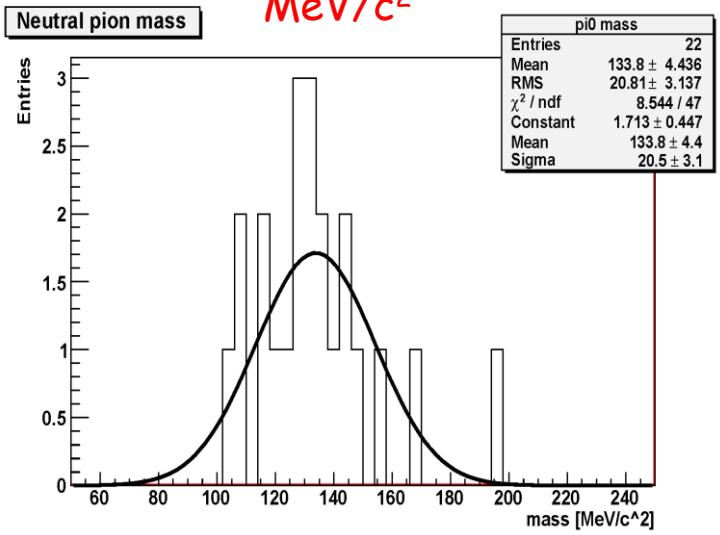
θ = 28.0 ± 2.5°

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





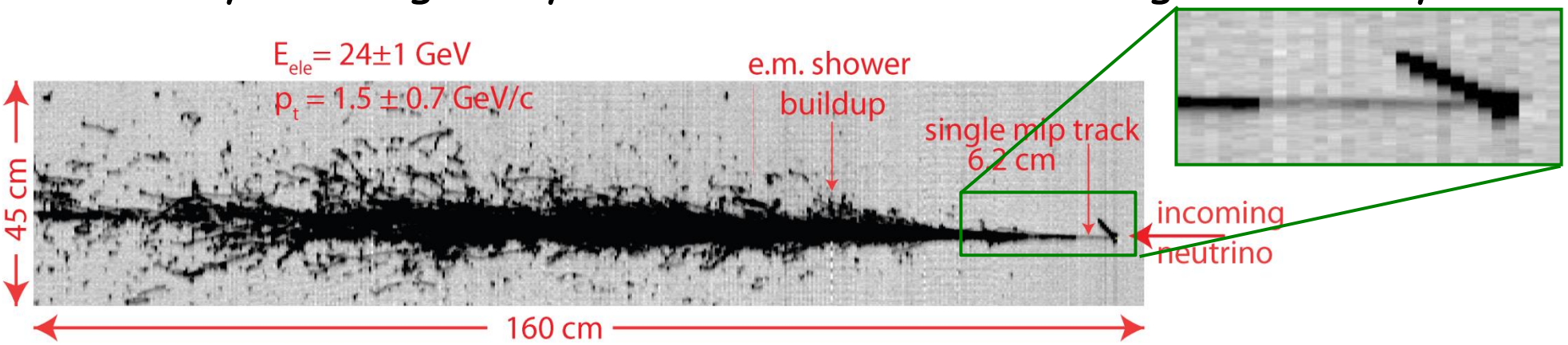
Mγγ: 133.8±4.4(stat)±4(syst) MeV/c²



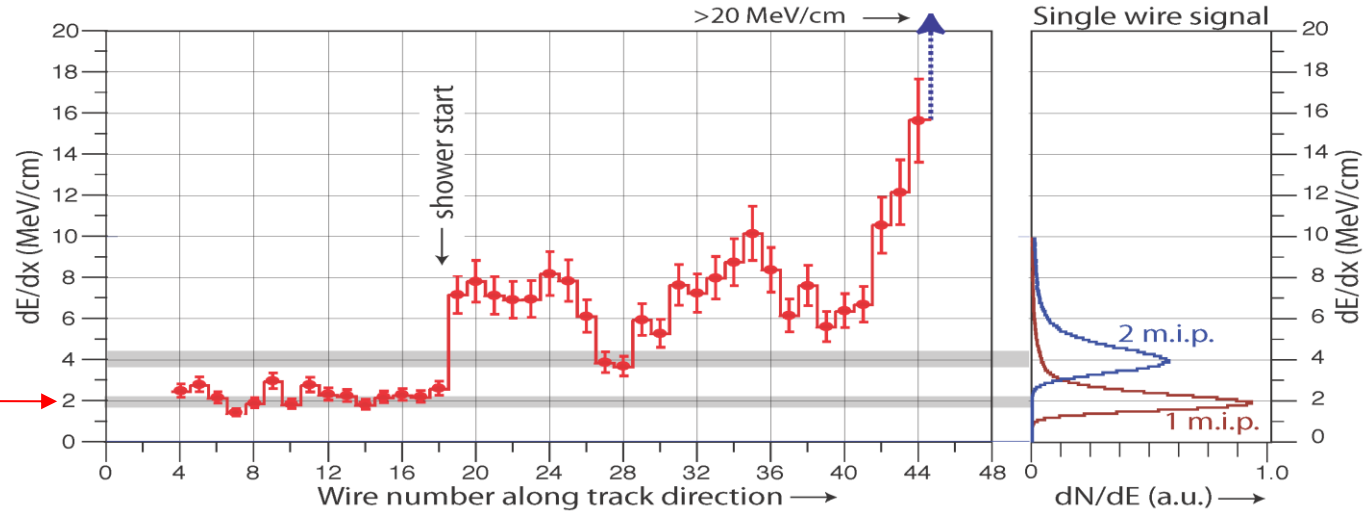
LAr TPC: very good e/γ separation: excellent rejection of NC background to ν_e events

ν_e identification in CNGS beam: **very high energy**

- 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

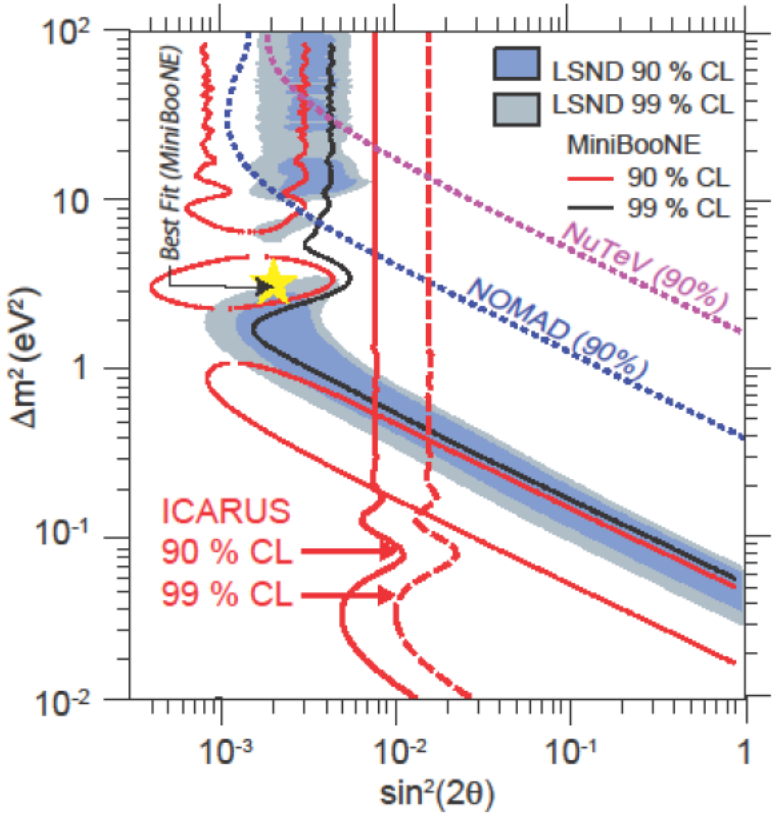
- ICARUS searched for ν_e excess related to LSND-like anomaly on the CNGS ν beam (~1% intrinsic ν_e contamination, L/E_ν ~ 36 km/GeV). No excess was observed: number of ν_e events as expected in absence of LSND signal.
- Analysis on 7.93 x 10^{19} pot event sample provided the limit on the oscillation probability $P(\nu_\mu \rightarrow \nu_e) \leq 3.86\ (7.76) \times 10^{-3}$ at 90 (99) % C.L.

- ICARUS result indicates a very narrow region

  $\Delta m^2 \sim 0.5\ eV^2$, $\sin^2 2\theta \sim 0.005$

  where all experimental results can be be accommodated at 90% CL.

Need for a definitive experiment on sterile neutrinos to clarify all the reported neutrino anomalies .



Update of CNGS analysis (1)

The collected 2650 CNGS ν events offers the opportunity to detect oscillations into sterile states **also** in disappearance down to $\Delta m^2 \approx 10^{-2}$ ($L/E_\nu \sim 36$km/GeV) with a sensitivity on effective $\sin^2 2\Theta_{\mu\mu}$ determined:

- **essentially** by systematic uncertainty on CNGS neutrino flux, which f.i. can be obtained from the μ flux measured in muon stations at CERN), neutrino interaction cross section and events reconstruction, *and*
- only **weakly** (~2-3%) by the collected statistics.

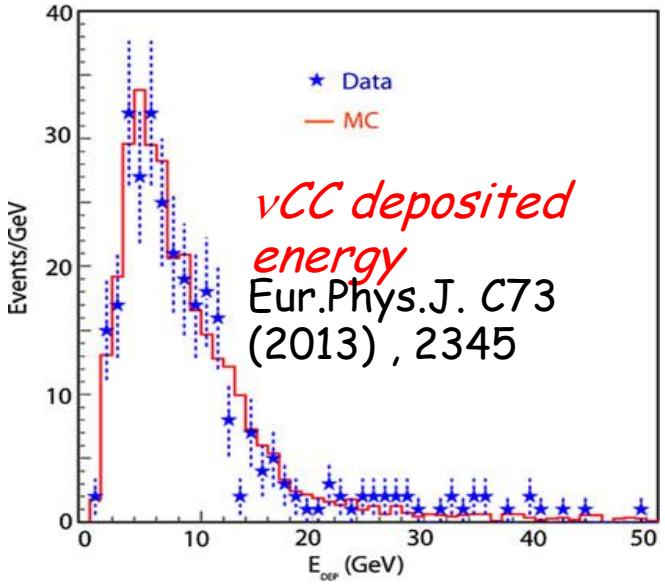
Direct comparison between expected and observed ν_μ CC interactions was checked on the events selected requiring a minimal 2.5 m track length resulting in the:

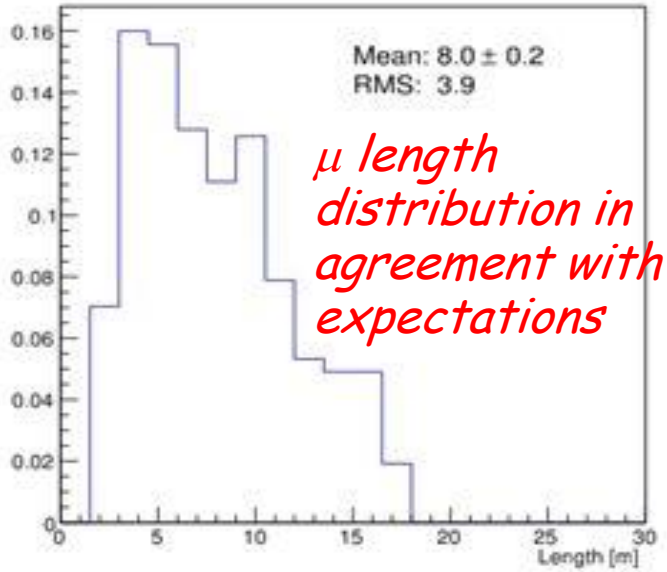
- identification of μ with ~70 % efficiency for genuine ν_μ CCs, and
- rejection of NC events by a factor ~60.

Sample of such 1285 „pure" ν_μ CC events has been identified in the 2011/12 runs (6.7×10^{19} pot)

Update of CNGS analysis (2)

- So far, 493 out of 1285 events have been visually reconstructed (separately muon track and hadronic jet). As already published the νCC deposited energy spectrum shows good agreement with expectations.
- *Next steps: reconstruction of all events, estimation of muon momentum, energy deposition of hadronic part, and finally neutrino energy distribution.*





Detailed analysis of ν_μ CC events, together with robust prediction of CNGS neutrino flux allowing to predict number of events at LNGS, are key ingredients for the study of neutrino disappearance.

Towards ν_μ disappearance study: neutrino beam calculation

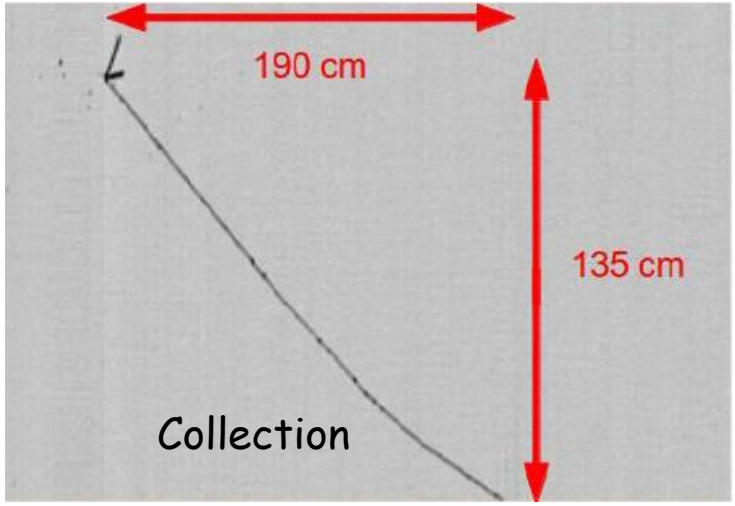
- The measured muon fluxes at two muon stations at CERN can be used to determine CNGS neutrino flux at LNGS for both experiments: OPERA and ICARUS. These measurements can be also used to estimate systematic uncertainties of the neutrino flux at Gran Sasso site.

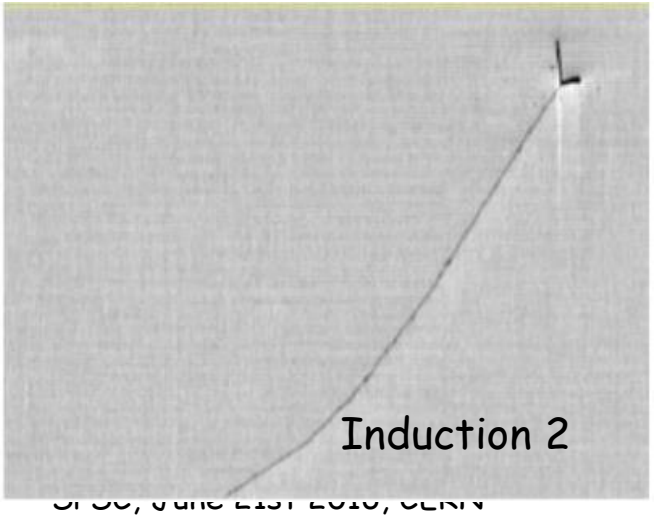
- The absolute comparison of the horizontal and vertical distributions of the signals of the CNGS muon pits detectors with the full beam line simulation have shown an agreement within few percent in the first muon pit, and ranging from few percent to 10% in the second one.

- Therefore, the analysis of two muon measurements at CERN stations needs to be finalized in order to extract neutrino flux sent to Gran Sasso.

Towards automatic neutrino search: atmospheric ν

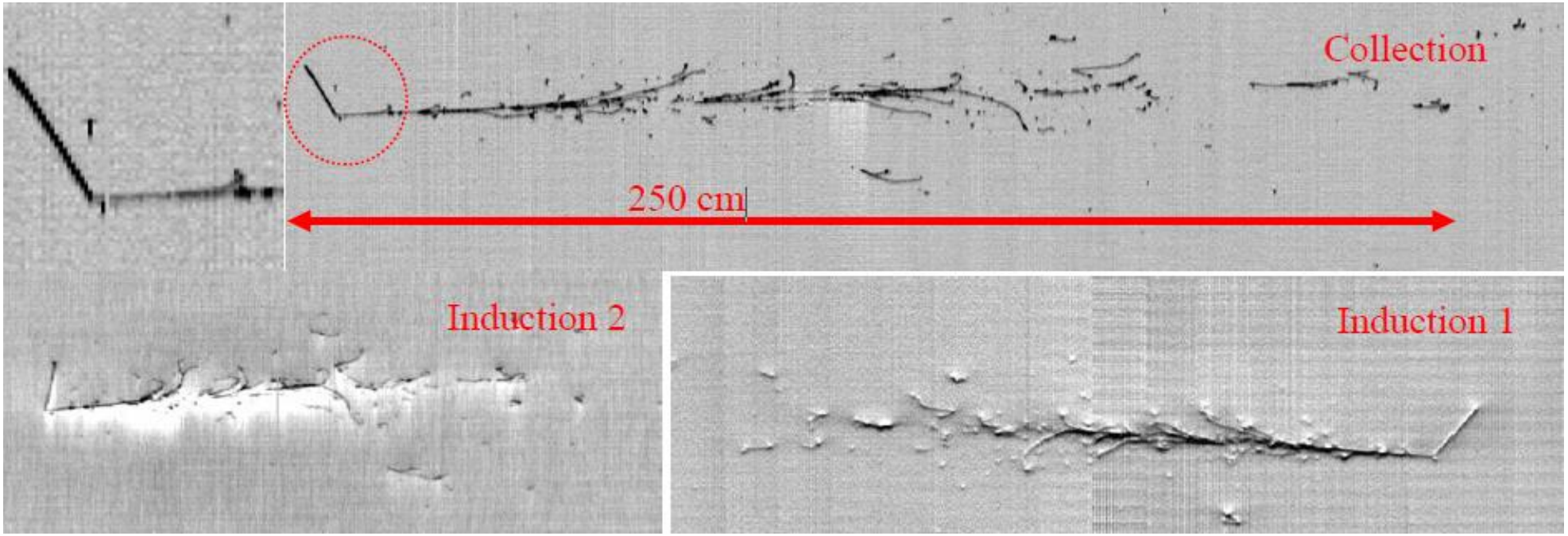
- LNGS data are being filtered by an automatic algorithm looking for interaction vertex and multi-prong (at least 2 charged primary) event topology to strongly reduce the scanning time.
- 3 μ-like, 2 e-like within a total sample of 12 observed atm. ν candidates have been identified so far in 25% of collected statistics (10 ± 2 multi-prong events are expected).
- Since the SPSC 2015 presentation a drastic reduction (7% to 0.5%) of events undergoing visual scanning has been achieved by the development of selection filter algorithms.
- new selection algorithm maintaining low the fraction of events needing visual scanning but with higher efficiency for ν_{atm} are under validation

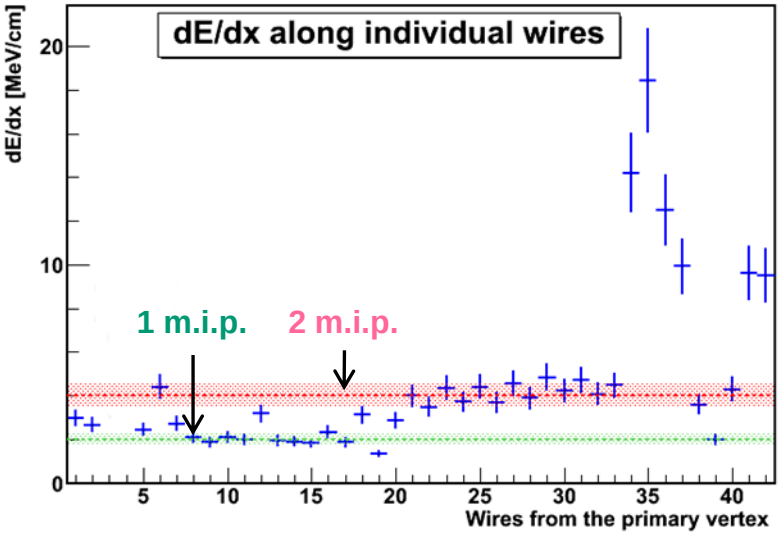




ν_μ CC atm. candidate:
E_{dep} ~ 630 MeV
- 2.3 m μ track and 2 charged tracks

The first observed „LAr TPC" atmospheric ν_e CC event



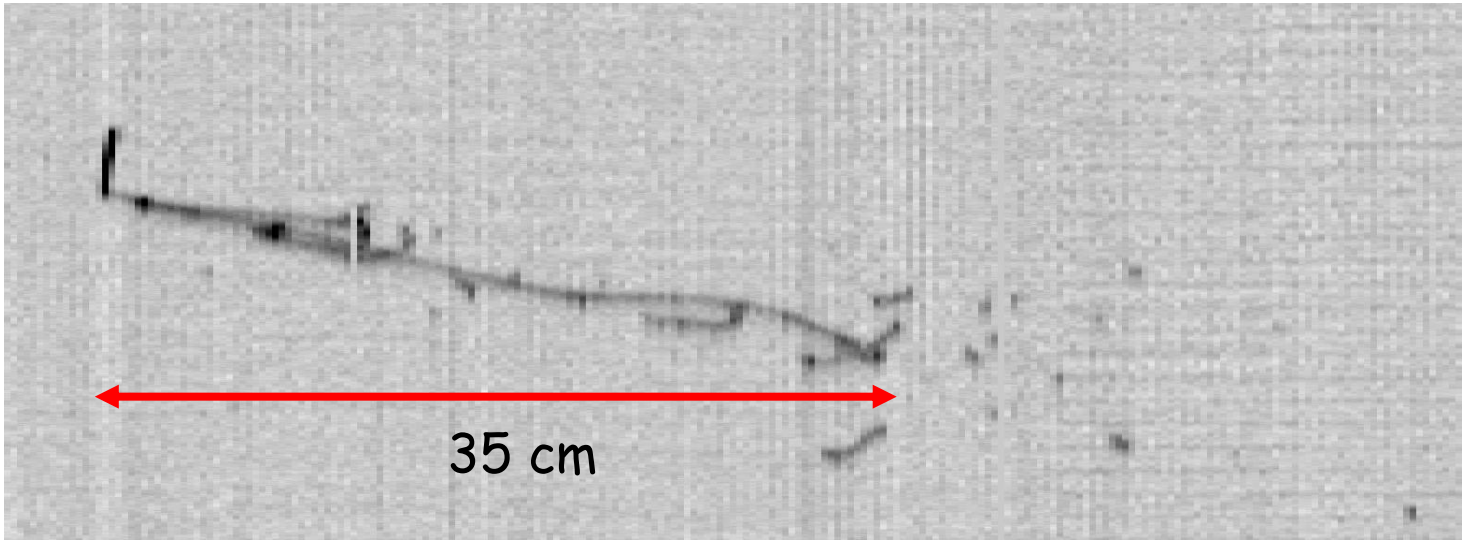


Deposited energy: ~ 2.1 GeV:

- E.m. shower (~ 2 GeV): clear single m.i.p from vertex;
- Identified short proton track (~ 0.1 GeV).

Automatic search for ν_e CC with E_{dep} of the order of several GeV is feasible.

The second atmospheric ν_e CC event: **very low energy**



Downward-going, quasi-elastic event, deposited energy: ~ **240 MeV**

- dE/dx measured on the first wires (2.1 MeV/cm) corresponds to a m.i.p. particle
- One short proton track.

ICARUS LAr TPC: unambiguous identification and measurement capability of ν_e interactions down to sub GeV energy range.

ν_{atm} and ν_e reconstruction in ICARUS LAr TPC: summary

- Thanks to the excellent detector capabilities electron neutrino interactions can be identified and reconstructed in a very broad energy range, from few hundreds of MeV in atmospheric neutrinos to tens of GeV in CNGS neutrino beam, with excellent precision.

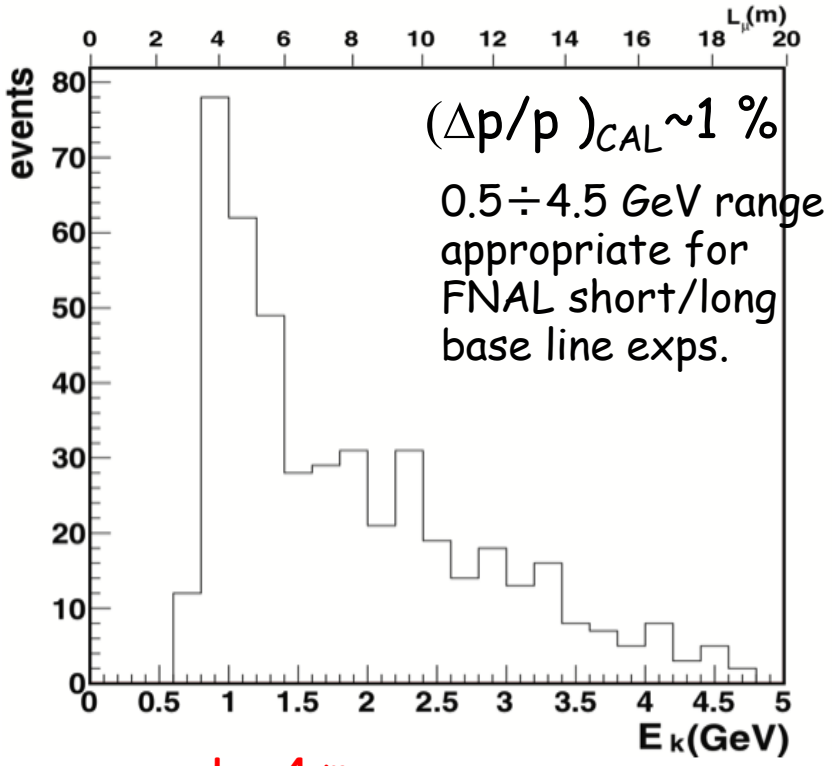
- Due to the similar energy range, the study of atmospheric neutrino interactions collected by ICARUS at Gran Sasso, is an asset for the SBN program of sterile neutrino search at FNAL, permitting tuning and validation of selection and reconstruction algorithms.

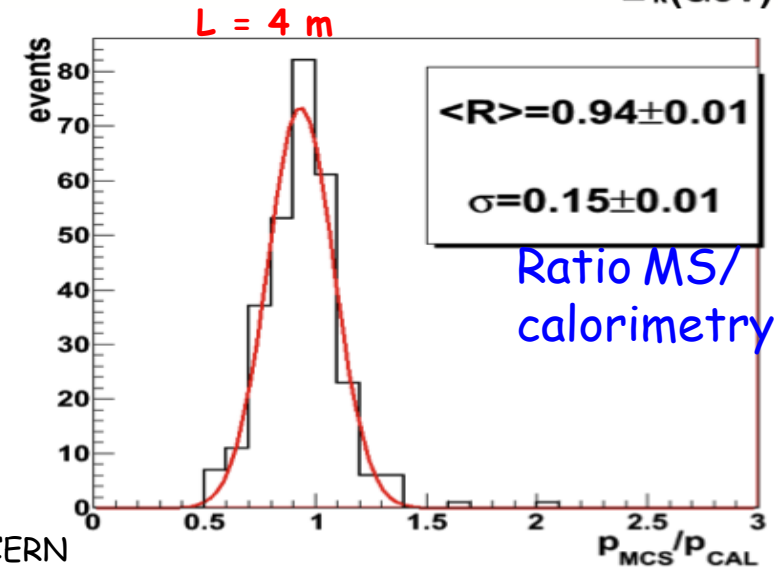
- However, important differences due to large number of cosmics overlapping beam events, resulting from the operation at shallow depth at FNAL, have to be accounted for.

- For all these reasons ICARUS installation at FNAL will be protected by 3 m concrete overburden to reduce background from neutrals, and by an active cosmic ray tagger.

Measurement of muon momentum via multiple scattering

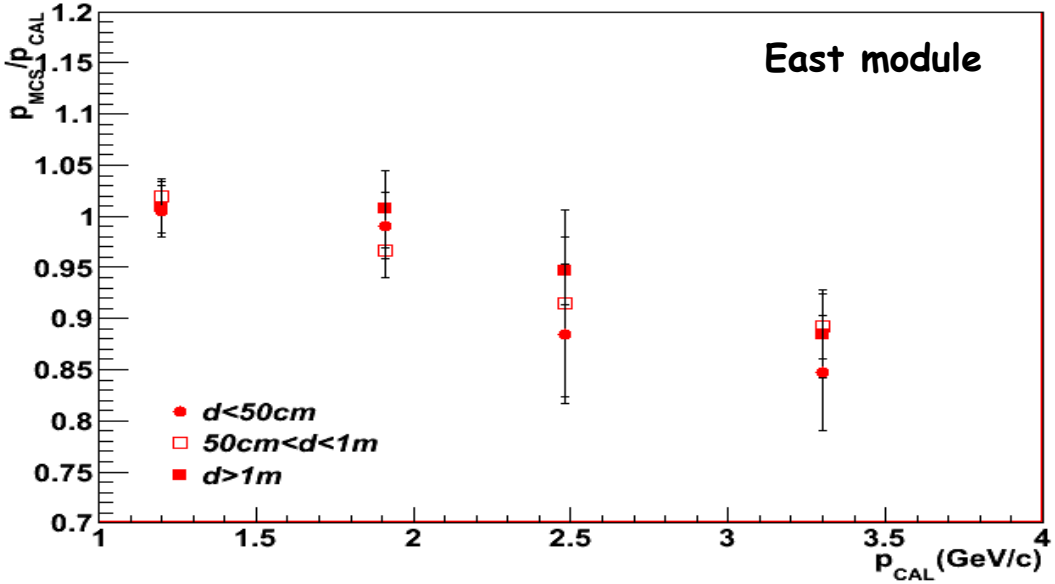
- Multiple Coulomb Scattering (MCS) is the only way to measure momentum of non-contained muons.
- Algorithm has been validated on ~400 *stopping muons* (track length min. 2.5 m, ~3 interaction lengths in LAr): produced in interactions of CNGS neutrinos upstream of T600, and stopping/decaying inside the detector.
- Average resolution of ~15% on the stopping muon sample (in a few-GeV energy range).
- Resolution depends both on momentum and muon track length used for measurement.





Measurement of muon momentum via multiple scattering

- The EAST module inspection during its overhauling at CERN showed up to ~3 cm **deviation from planarity of TPC cathode.**
- This **mechanical distortions** - mainly located at the center of the 2 m long and ~1.6 m height cathode panels - produce a non-uniformity of the electric drift field ΔE at ~1% level.
- As a result **fake track scatterings** can occur, which could explain the observed p_{MCS} underestimation for p > 3.5 GeV/c

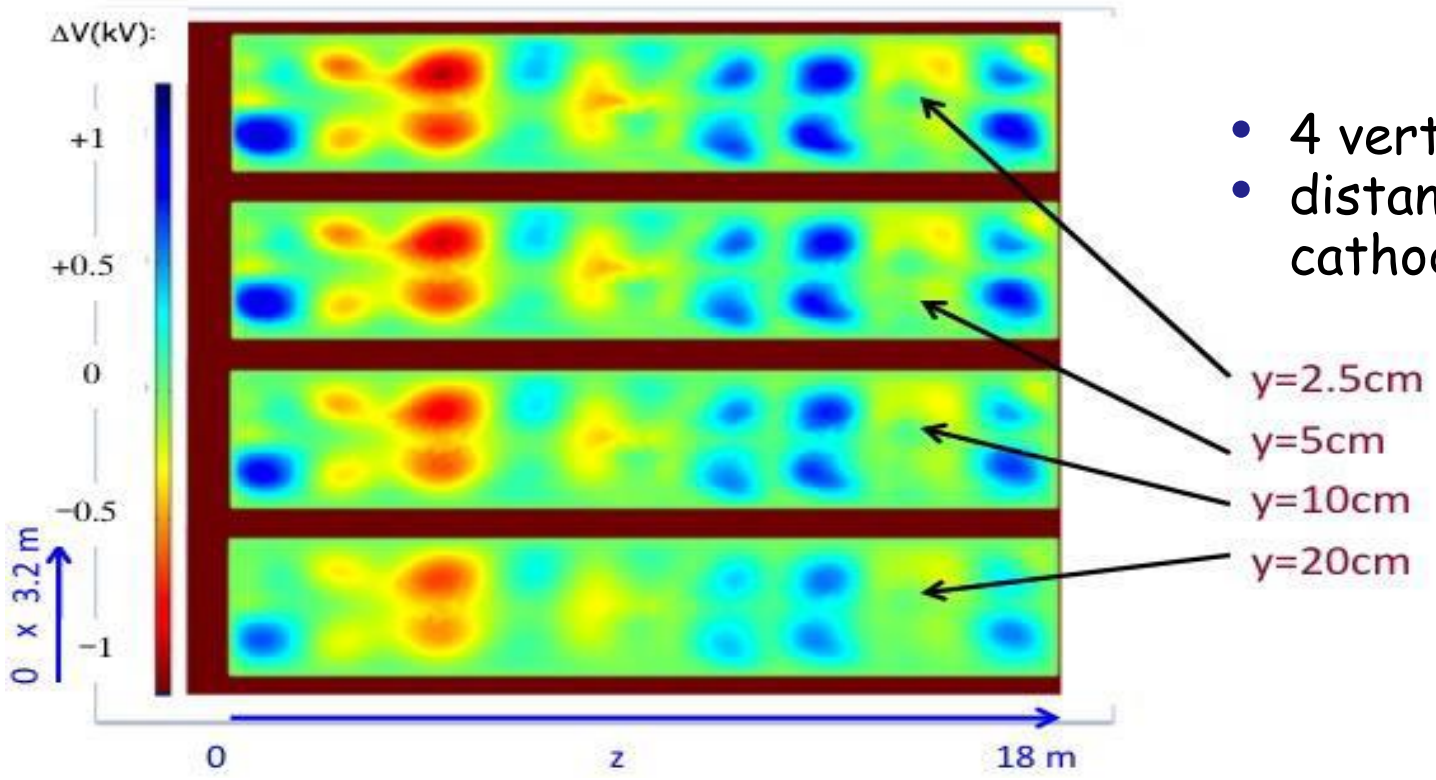


Possible hint of larger effect near the cathode

The cathode planarity was restored within a few mm by a mechanical and thermal treatment of the panels (April 2016 SPSC meeting)

MCS: on the road to momentum improvement (1/4)

Full 3D numerical calculation of the electric field on a grid of 2.5 cm mesh was performed (starting from the planarity measurements):



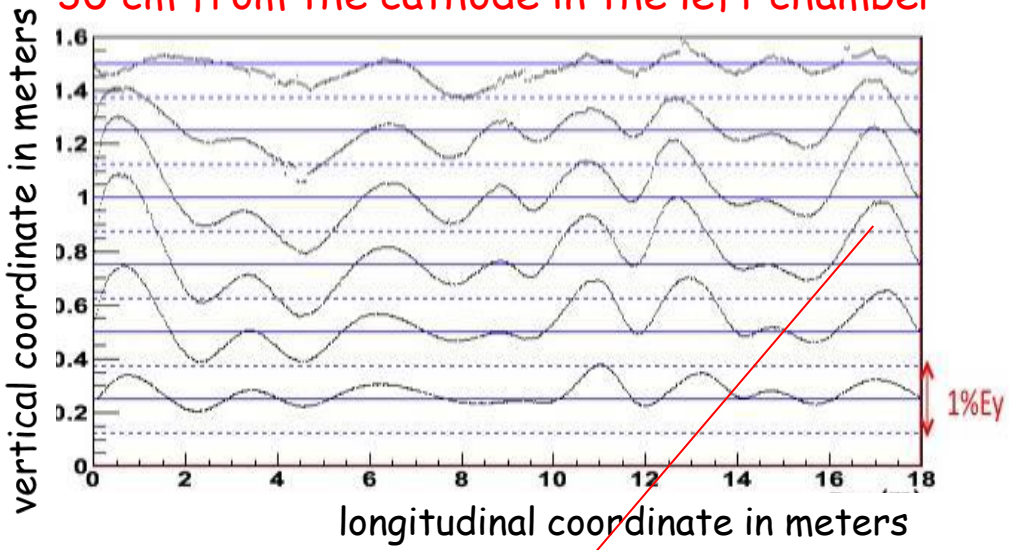
- 4 vertical slices
- distance from the cathode :

Electric potential distortions from the nominal value exhibit the observed mechanical features of the cathode.

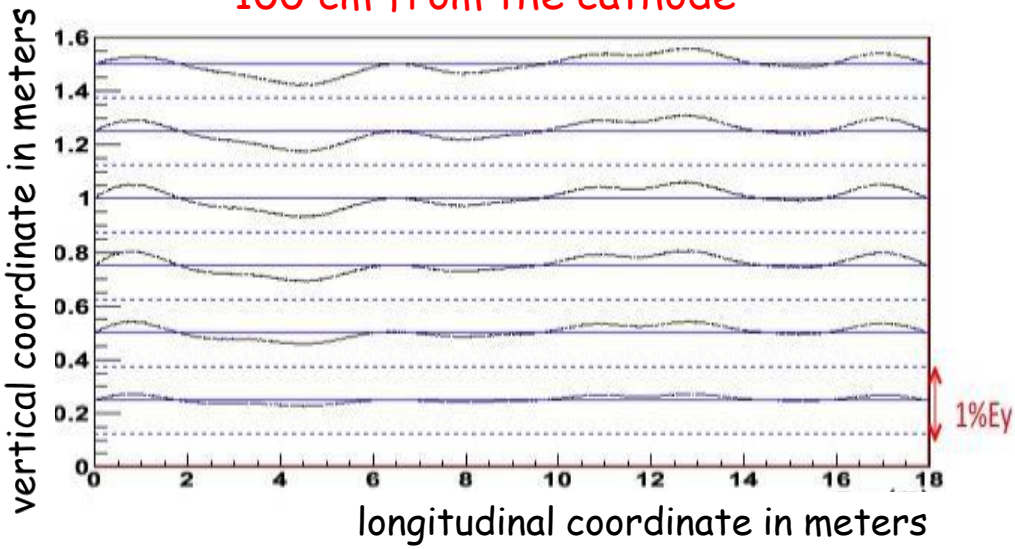
MCS: on the road to momentum improvement (2/4)

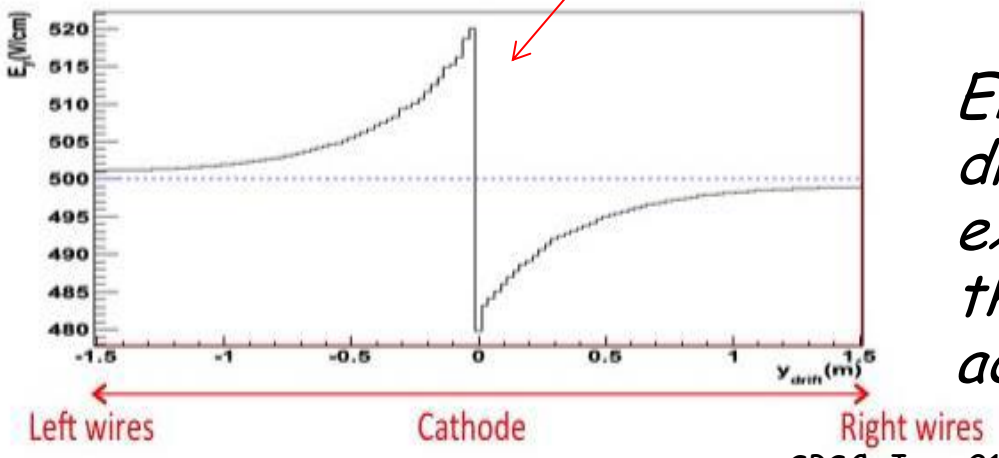
The corresponding electric field distortion from 500 V/cm nominal value (solid lines) is shown for the lower half of cathode as a function of vertical and longitudinal coordinates

30 cm from the cathode in the left chamber



100 cm from the cathode



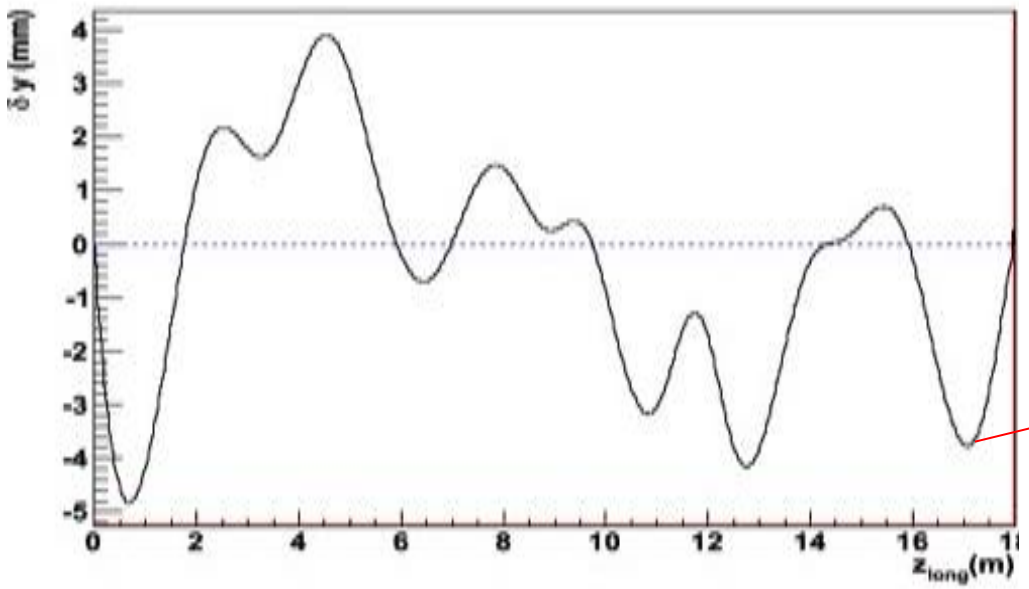


Electric field distortion along the drift coordinate decreases roughly exponentially with the distance from the cathode (opposite sign in the 2 adjacent chambers).

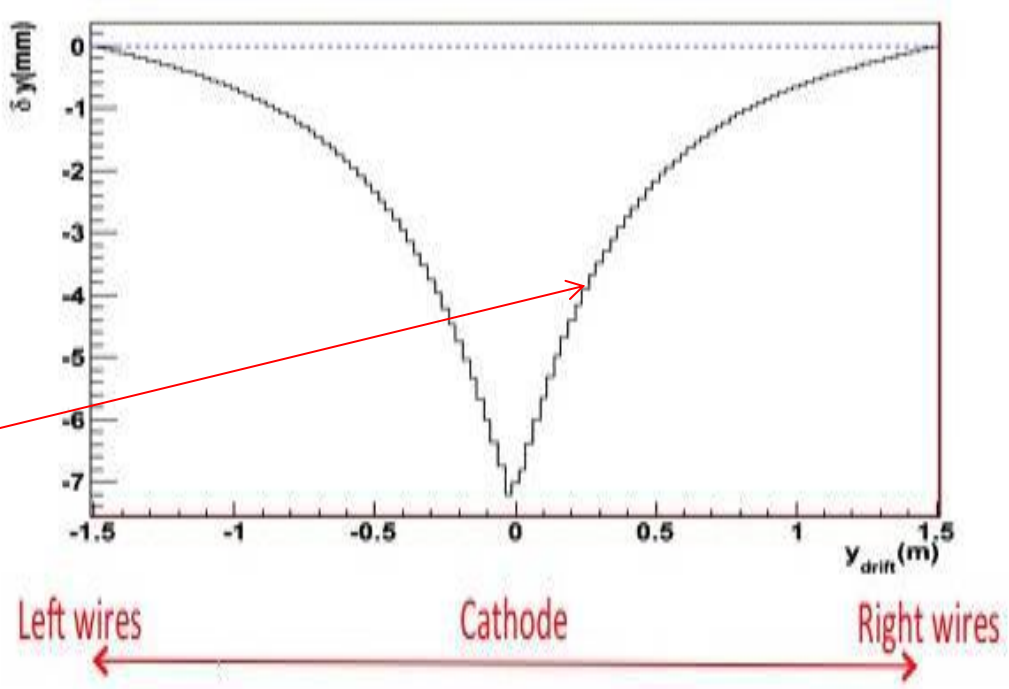
MCS: on the road to momentum improvement (3/4)

- The **distortion δy in the reconstructed drift coordinate** was computed by a numerical integration of the local effective electron drift velocity $v_D \propto E^{\frac{1}{2}}$ along the drift path → several mm spatial distortion has been determined

δy along the longitudinal coordinate
(middle of lower panels, 30 cm from cathode)



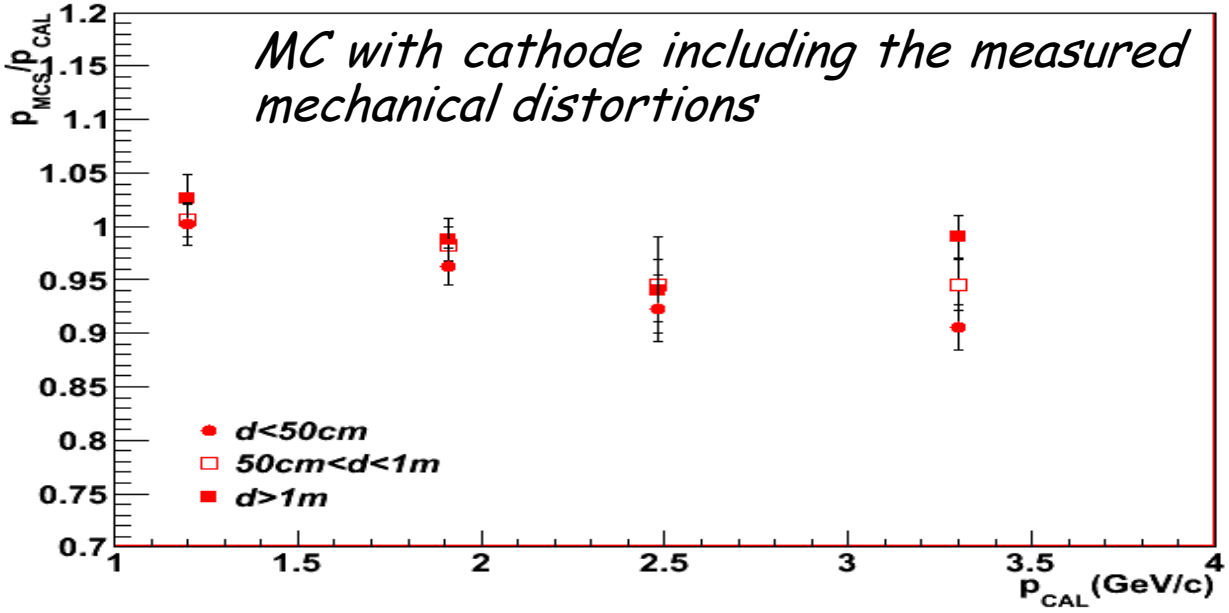
δy along the drift coordinate
(middle of 1st upstream panel)



MCS: on the road to momentum improvement (4/4)

New MC stopping muon simulation (T600 EAST module):

- with 3D map of the δy variation on the reconstructed drift coordinates
- 1000 stopping muon events for each of the three 50 cm width detector regions of the drift path to evaluate the impact on p_μ measurement by MCS at different distances from cathode.



- The completion of this analysis will validate the P_μ measurement by MCS to several GeV/c improving the reconstruction of neutrino events.
- Relevant to the SBN program due to similar muon momentum range.

Concluding remarks (1)

- ICARUS is the largest LAr TPC operated underground, acquiring data, without interruption, with both CNGS beam and cosmics.

- 3 years of continuous and safe operation at LNGS resulted in high quality data producing new constrains on sterile neutrinos searches, and allowed for detailed studies of all technical aspects of this detection technique (LAr purity resulted in a very long electron lifetime).

- *ICARUS proved the maturity of single phase LAr TPC detection technique → a milestone for next generation experiments.*

Concluding remarks (2)

- Ongoing analyses:
  - Study of CNGS neutrino interactions for the search of a possible disappearance signal;
  - Search for atmospheric neutrino events with unambiguous identification of primary electron from atmospheric ν_e events (observed for the first time in a LAr TPC);
  - Validation of the Coulomb multiple scattering algorithm for measuring muon momentum, including non-uniform electric field and its effect on the muon track reconstruction.

- *These analysis are extremely relevant for the realization of the SBN experiment at FNAL, and for next generation LAr-TPC detectors.*


Thank you