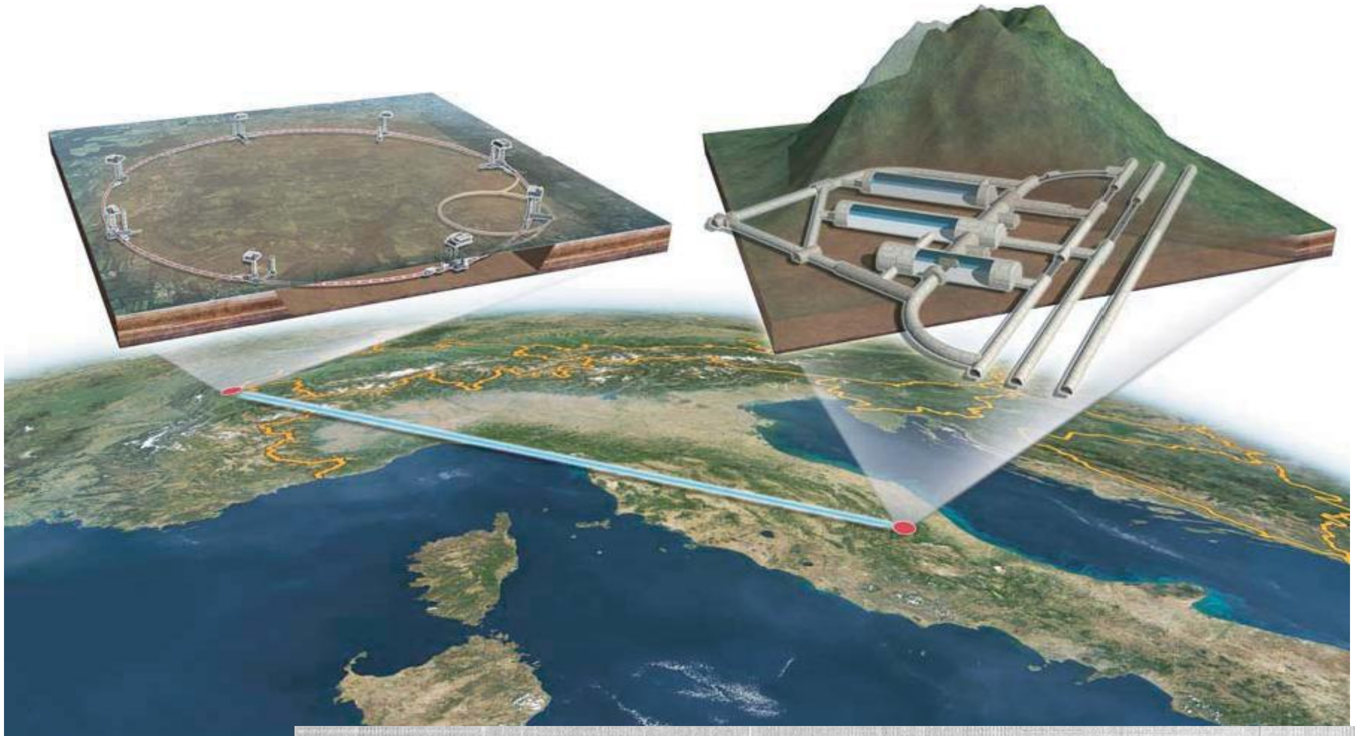
ICARUS Status and Plans



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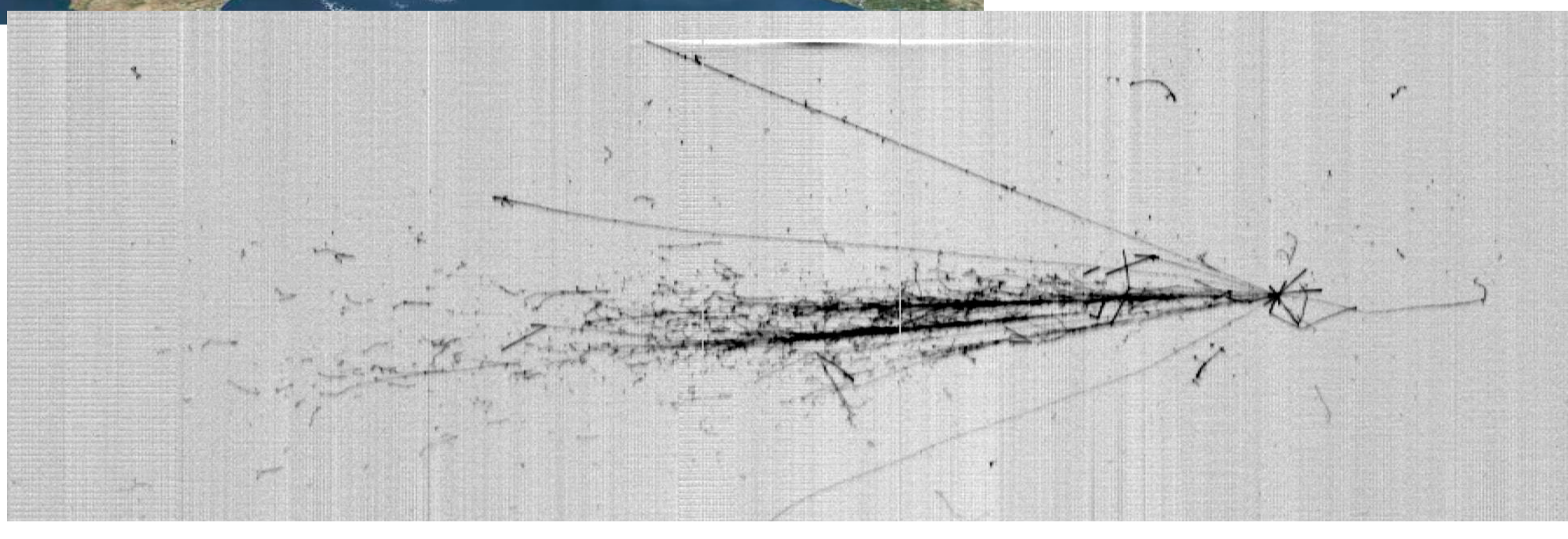
INFN Milano
For the ICARUS Collaboration

Nufact
2013



The ICARUS Collaboration

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The ICARUS detector at LNGS Laboratory

- ICARUS T600 is the first large mass LAr-TPC (760 tons) operated underground (in Hall B of LNGS Laboratory).
- Exposed to CNGS ν beam, taking data also with cosmic rays to study the detector capability for atmospheric ν and proton decay search.

In operation since May 2010

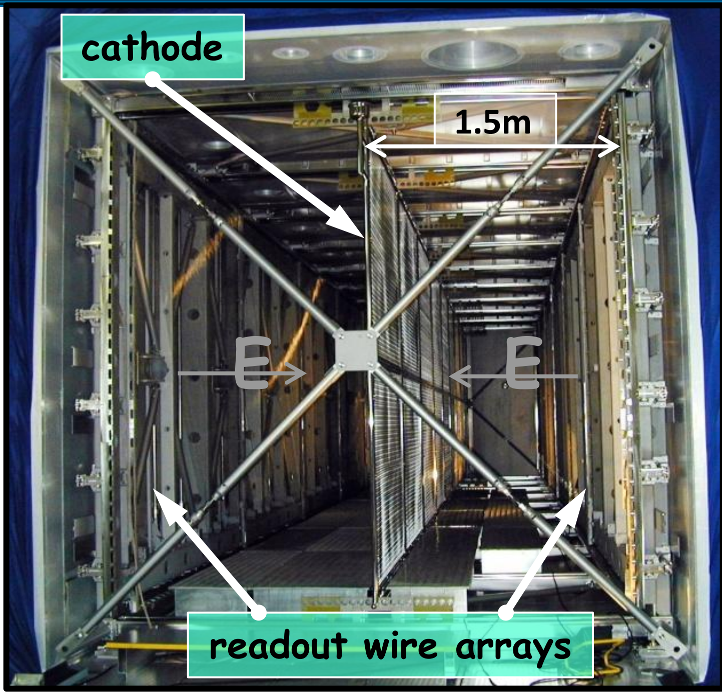
ICARUS decommissioning started on June 27th, cryo empty on July 25th

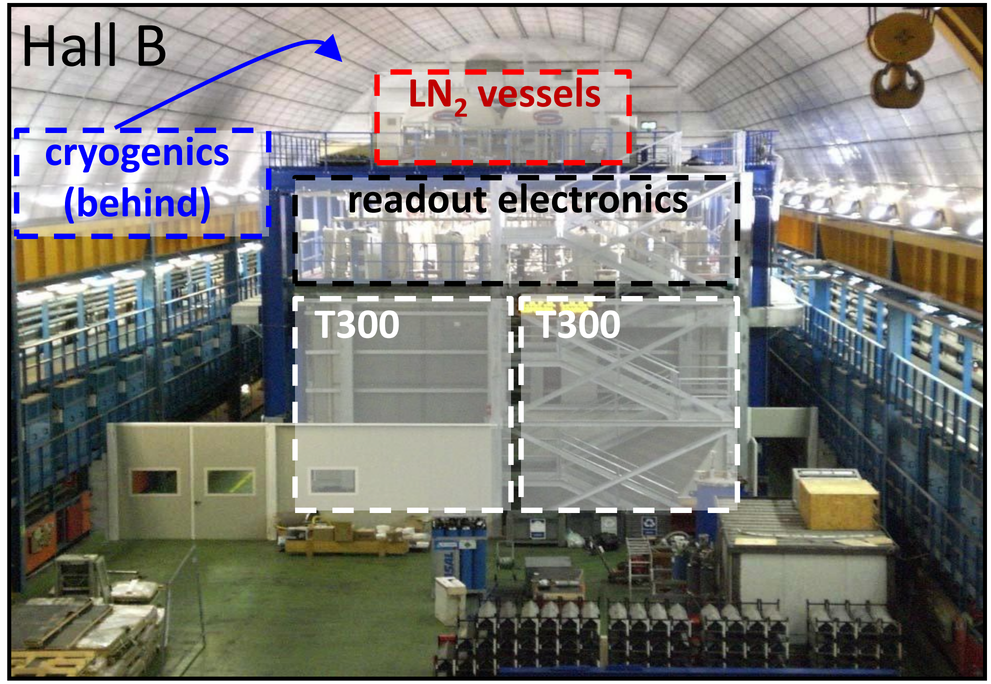
740 tons of LAr recovered

Outline

- Plenty of high quality data from CNGS and cosmic rays allows for physics studies, for deep investigation of all the detector technical aspects and for development of advanced reconstruction algorithms
- In this talk, focus will be on
  - Validation of the muon momentum measurement with the Multiple Scattering technique
  - Search for $\nu_\mu \rightarrow \nu_e$ oscillations in the framework the "LSND/MiniBooNE" anomaly

ICARUS @ LNGS: the first LARGE LAr-TPC



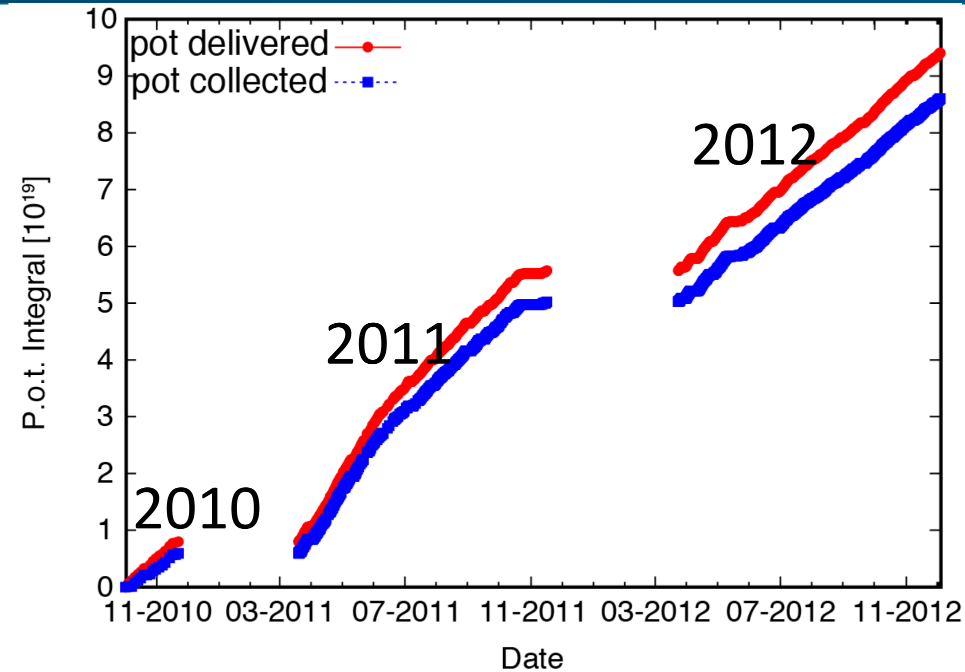


- Two identical T300 modules (2 TPC chambers per module)
- LAr active mass 476 t:;
  - drift length = 1.5 m;
  - E_{drift} = 0.5 kV/cm; v_{drift} = 1.6 mm/μs
- 3 readout wire planes at 0°, ±60
  - ≈ 53000 wires, 3 mm pitch
  - **2 Induction** planes, **1 Collection**
- PMT for scintillation light (128 nm):
  - (20+54) PMTs
  - **trigger** and **t_0**

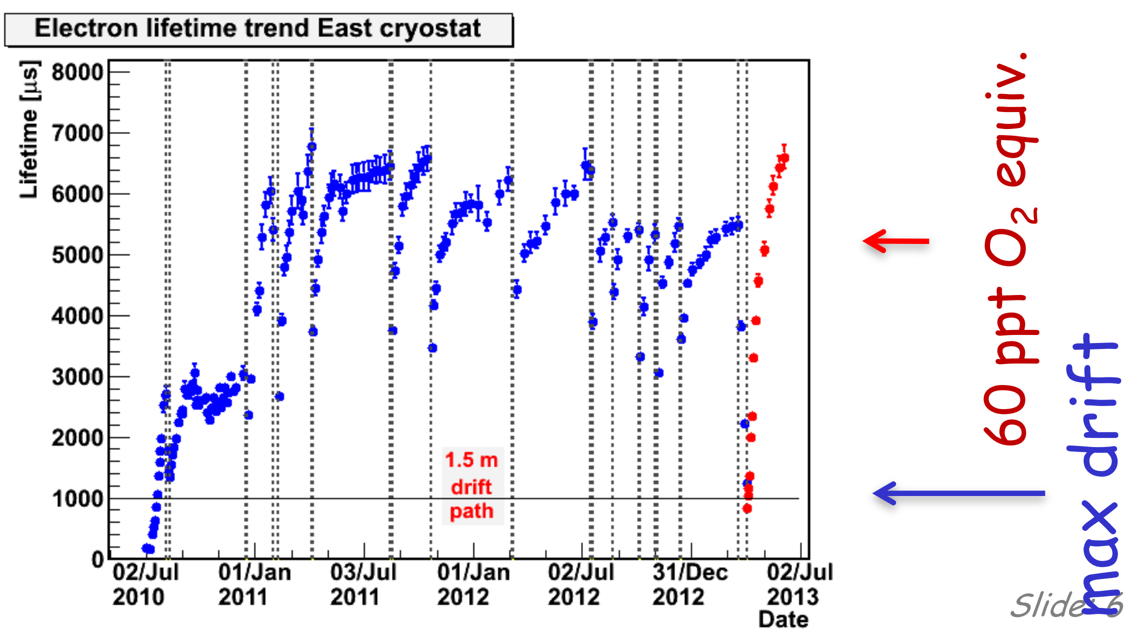
- Total energy reconstruction of events from charge integration.
- Full sampling, homogeneous calorimeter; excellent accuracy for contained events.

ICARUS CNGS RUN (Oct 2010 - Dec 2012)

- Exposed to CNGS ν beam since 2010 October 1st up to 2012 December 3rd
- CNGS trigger: coincidence of PMT sum signals with beam extraction
- Total collected event statistics: 8.6 10^{19} pot with a remarkable detector live-time > 93 %

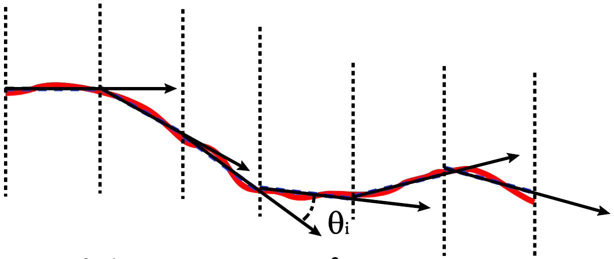


- Excellent results on Lar purification
- LAr continuously filtered
- τ_{ele} > 5ms (~60 ppt $[O_2]_{eq}$), maximum charge attenuation at 1.5 m: 17%.



Measurement of muon momentum via multiple scattering

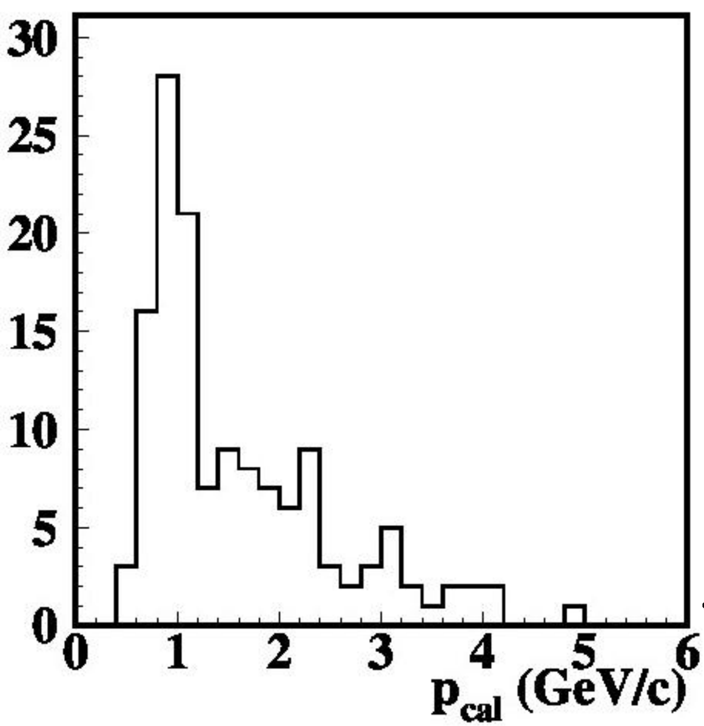
- In the T600 and in future LAr TPCs, a method to measure the momentum of escaping μ is needed in order to reconstruct ν_μ CC events
- Deflections due to Multiple Coulomb Scattering (MS) provide such a tool



The RMS of θ depends on p and on the meas. error σ

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

- **Horizontal μ stopping in the T600 are an excellent benchmark**

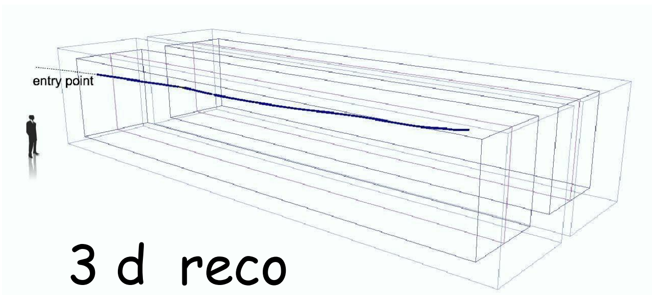


  - Calorimetric measurement is possible
  - The energy range (0.5-4 GeV) is perfectly matched to those of future short and long baseline experiments

- A sample of 130 stopping muons from CNGS ν interactions in the upstream rock has been selected and analyzed

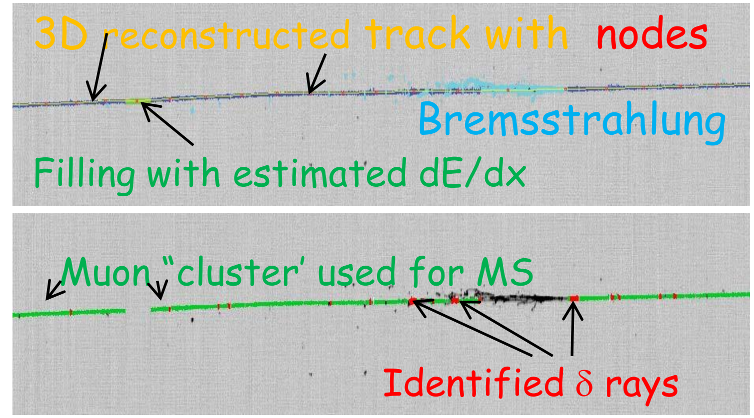
Muon momentum reconstructed by calorimetric measurement for the stopping muon sample

Results

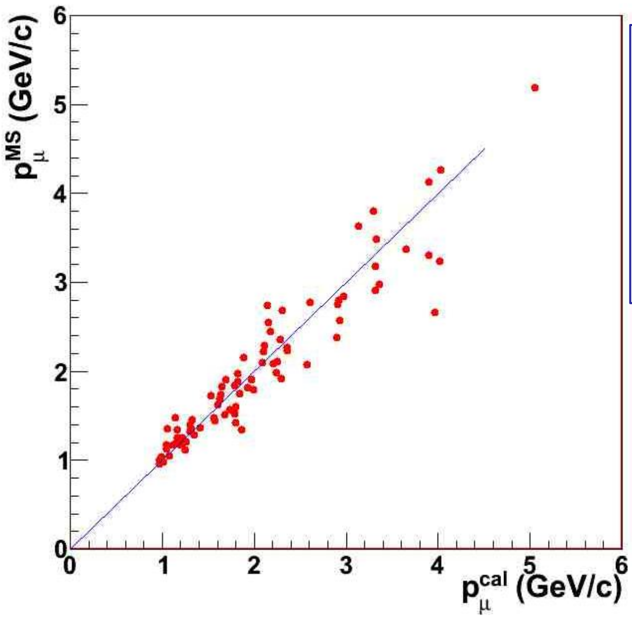


δ and brem excluded from MS

Calorimetric estimate σ <1%



Exluding the last 1.5 m of track, to really mimic escaping muons

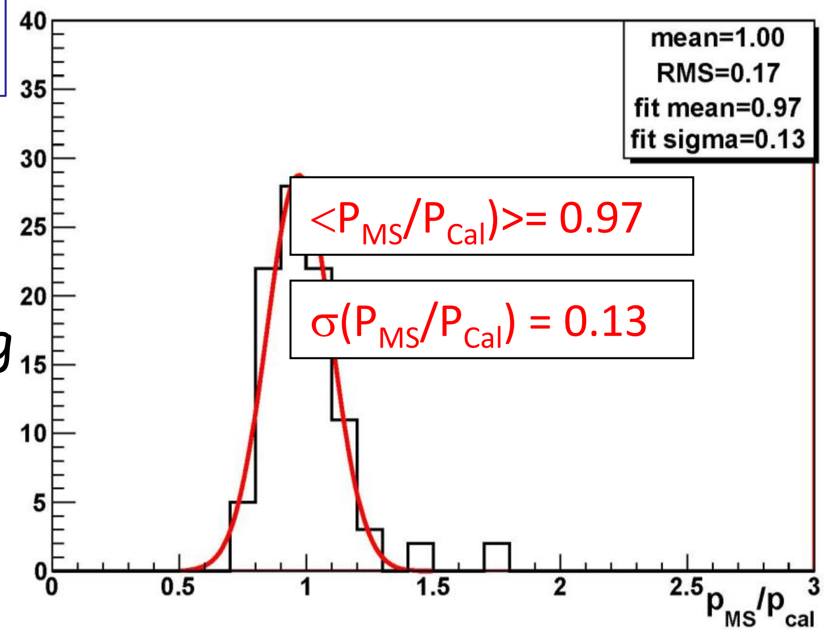


Distribution of momentum by MS p_{MS} vs momentum by calorimetry p_{cal}

More statistics coming

Extension to full CNGS sample ongoing

Event by event ratio p_{MS} / p_{cal}

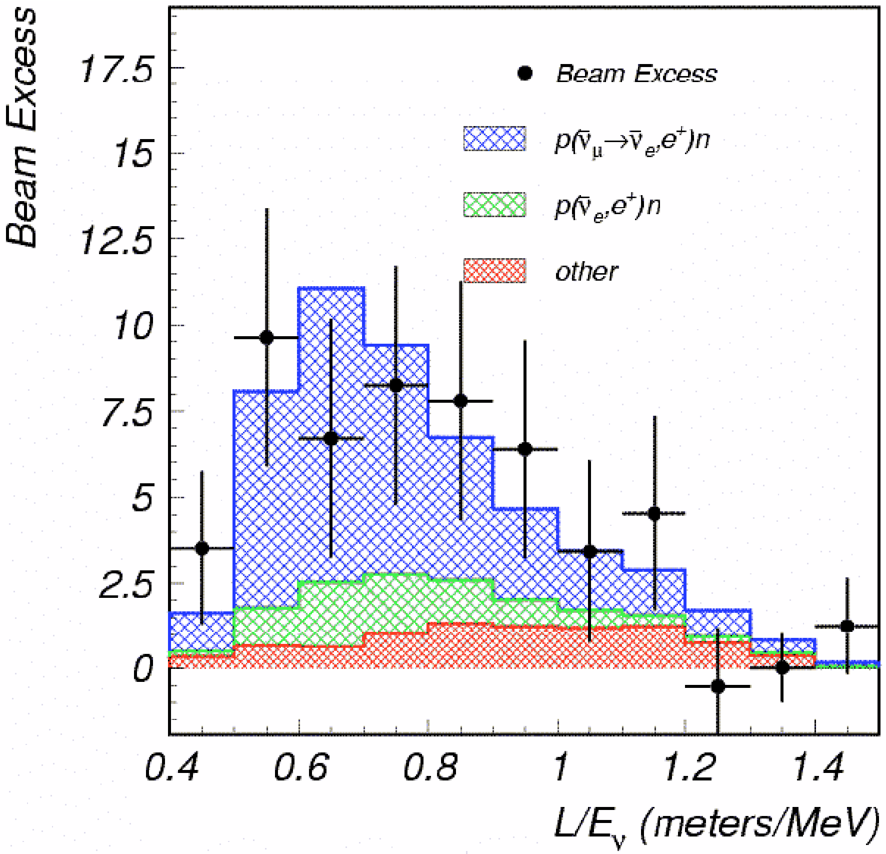


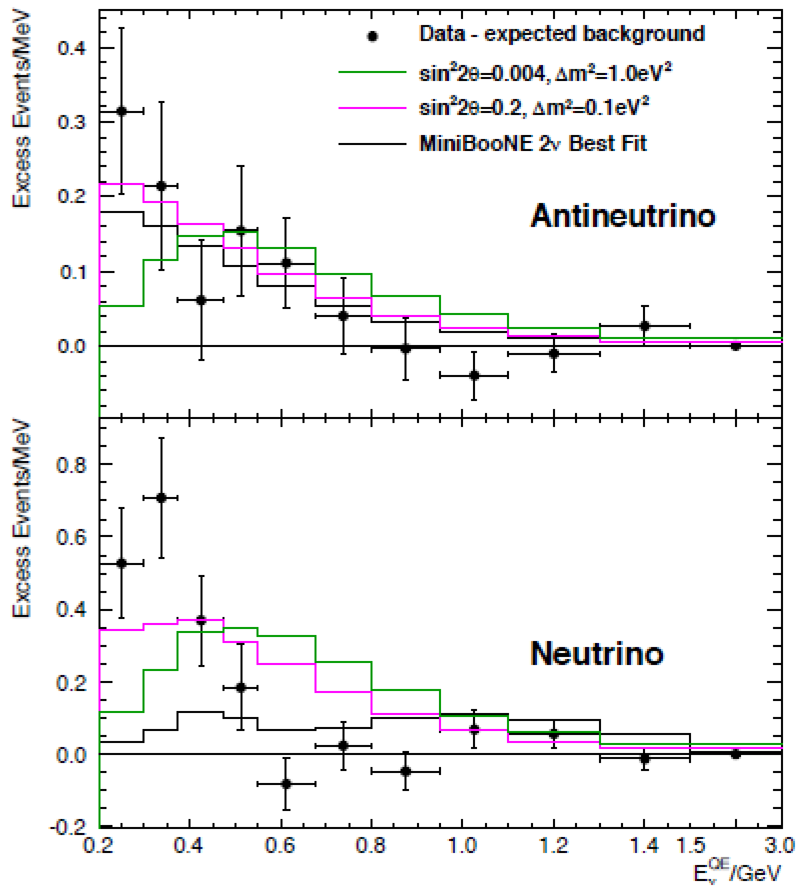
Muon p determination by MS is possible with a resolution ≈10% in the momentum range of interest for future LAr TPCs

$\nu_\mu \rightarrow \nu_e$ "anomalous" oscillations

See Carlo Giunti's talk on sterile ν

LSND has observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam,
87.9 ± 22.4 ± 6.0 ⇒ 3.8 σ





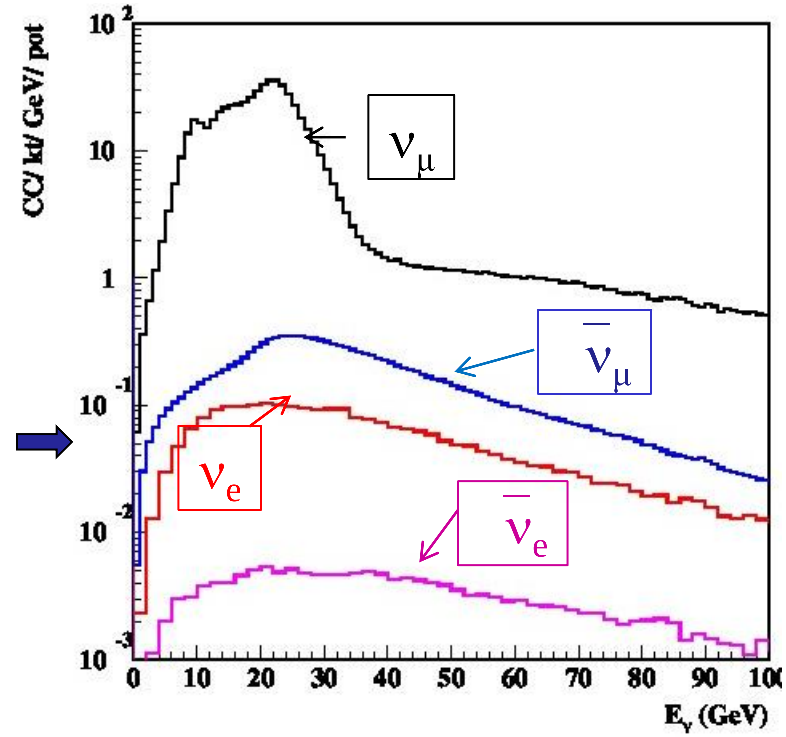
MiniBoone (PRL 110 (2013) 161801) event excess:

- antineutrino **78.4 ±28.5** events **(2.8σ)** for 200 < E_{QE} <1250 MeV.
- neutrino 162±47.8 events (3:4σ) but the energy distribution is marginally compatible with a two neutrino oscillation formalism.

A search for LSND effects

- The CNGS facility delivered an almost pure ν_μ beam peaked in 10-30 GeV energy range (beam associated ν_e ~1%) at a distance L=732 km from target

Expected CNGS neutrino CC spectra at LNGS

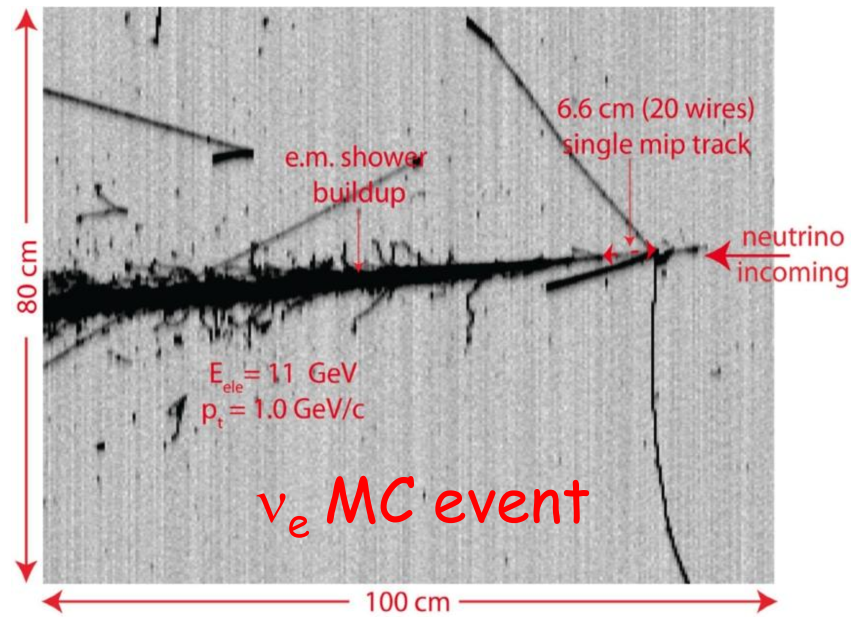


- Differences w.r.t. the LSND experiment:
  - $L/E_\nu \approx 1$ m/MeV at LSND, but $L/E_\nu \approx 36.5$ m/MeV at CNGS
  - LSND-like short distance oscillation signal averages to: $\sin^2(1.27\Delta m^2_{new} L/E) \approx \frac{1}{2}$ and $\langle P \rangle_{\nu_\mu \to \nu_e} \approx \frac{1}{2}\sin^2(2\theta_{new})$

- When compared to other long baseline results (MINOS,T2K) ICARUS operates in a L/E_ν region in which contributions from standard neutrino oscillations are not yet too relevant..

Event Selection

- ν_e CC eventcandidates are selected visually
- Fiducial volume (for shower id.) : > 5 cm from TPC walls and 50 cm downstream
- Energy cut: < 30 GeV
  - $\approx$ 50% reduction on beam ν_e
  - only 15% signal events rejected
- ν_μ CC events identified by L > 250 cm primary track without had. int.



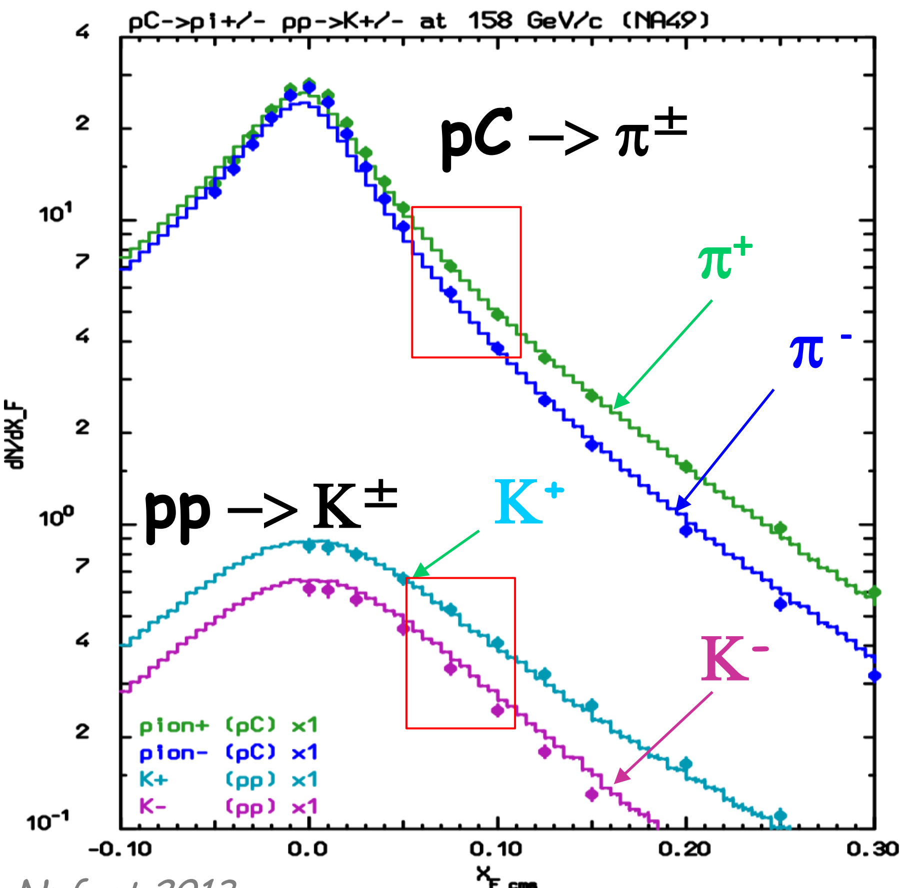
- The "Electron signature" requires:
  - A charged track from primary vertex, m.i.p. on 8 wires, subsequently building up into a shower; very dense sampling: every 0.02 X_0 !!!
  - Clearly separated (150 mrad) from other ionizing tracks near the vertex in at least one of 2 transverse views.
- Electron efficiency studied with events from a MC (FLUKA) reproducing in every detail the signals from wire planes: η = 0.74 $\pm$ 0.05 (η' = 0.65 $\pm$ 0.06 for intrinsic ν_e beam due to its harder spectrum).

Event rates

- First results published in Eur. Phys. J. C 73 (2013).
- New analysis presented here refers to 1995 ν interactions (6.0 10^{19} pot statistics).
- The expected number of ν_e events due to conventional sources in the energy range and fiducial volume are:
  - 5.7 $\pm$ 0.8 events due to the estimated ν_e beam contamination;
  - 2.3 $\pm$ 0.5 ν_e events due to the oscillations from $\sin^2(\theta_{13})$ = 0.0242 $\pm$ 0.0026;
  - 1.3 $\pm$ 0.1 ν_τ with $\tau \rightarrow e$ events from the three neutrino mixing standard model predictions,
  - Giving a total of 9.3 $\pm$ 0.9 expected events
- Taking into account the selection efficiency, the expected number of e- events from intrinsic ν_e beam, θ_{13}~9^0 and $\nu_\mu - \nu_\tau$ oscillations is then **6.4±0.9 (syst. only)**.
- The measurement error is dominated by statistics

Sources of systematic errors : 1

- ν_e component in the CNGS beam: from MC predictions on particle production and transport
- Normalization errors cancel out in the ν_e/ ν_μ ratio



Comparison of FLUKA predictions with NA49 data for primary $\pi^\pm$ (on C) and $K^\pm$ production (on free proton).

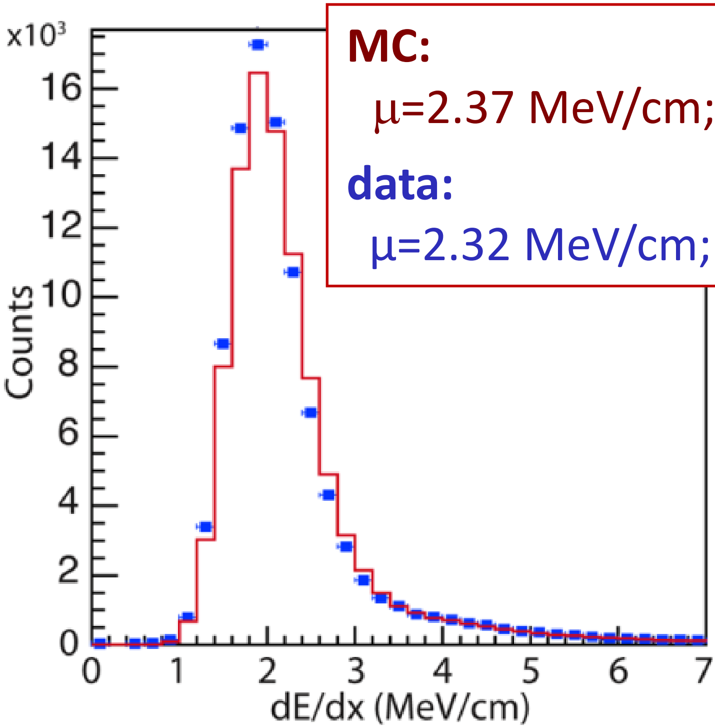
~5% extimated uncertainty on particle production mostly based on NA49 angle integrated data at 158 GeV (3.8% exp. systematics), assuming the X_F scaling between reality and MC is the same within few %.

Conservative estimate on ν_e/ ν_μ : 10%

Work in progress for next analyses

Sources of systematic errors : 2

Effect of 30 GeV energy cut on background estimate:



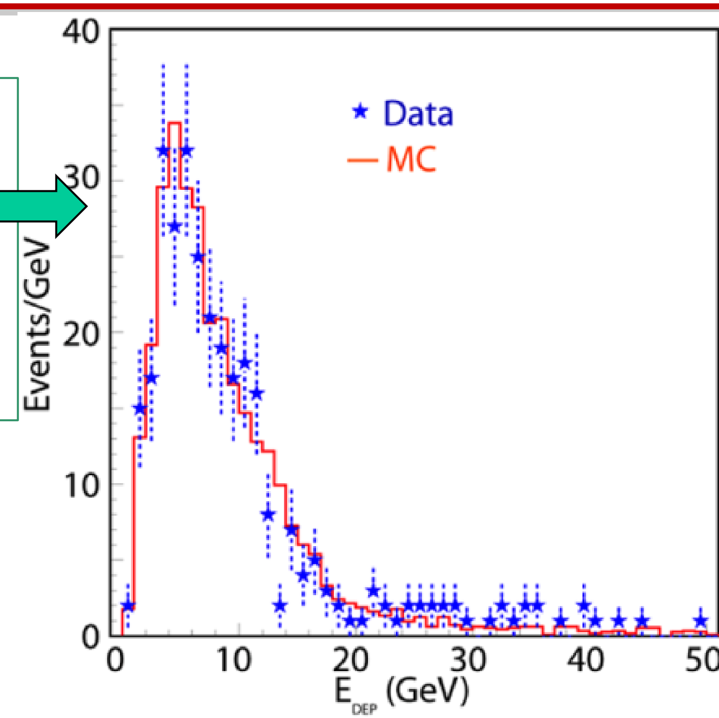
MC:
μ=2.37 MeV/cm; RMS=1.37

data:
μ=2.32 MeV/cm; RMS=1.31

Test of MC/data agreement on dE/dx from long muon tracks

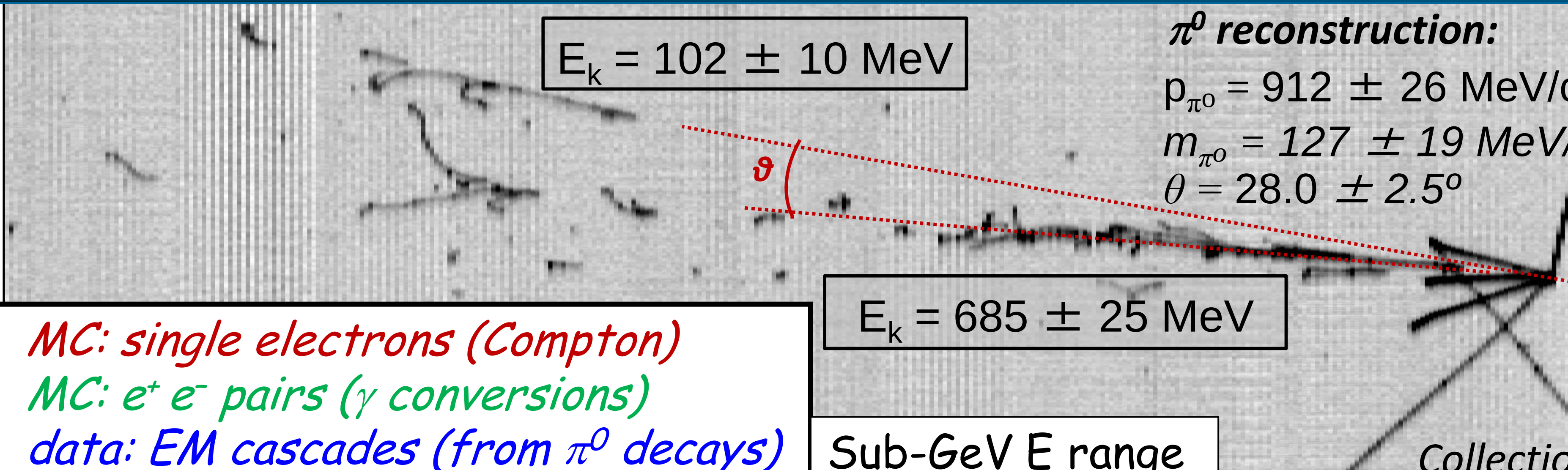
dE/dx in 3 mm track segments (3D), after removing δ rays and e.m. cascades
MC – data agreement on the level of 2%
signal/noise from Landau + gaussian ≈ 10

MC - Data comparison of total energy deposited in identified ν_μ CC events



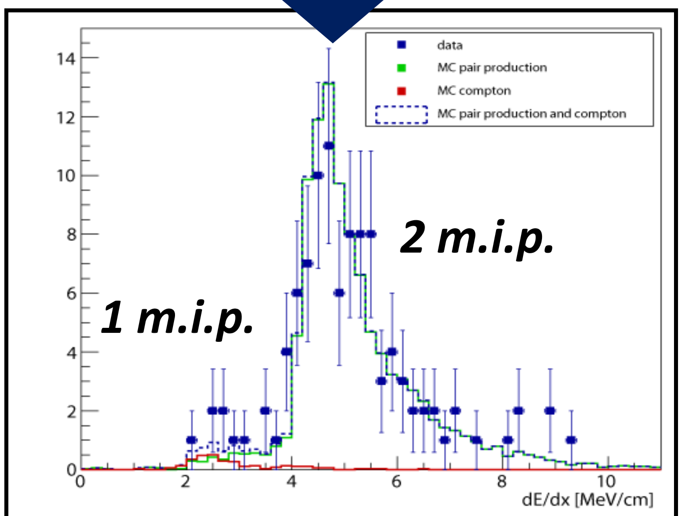
- Agreement data-MC on dE/dx and total energy better than 2.5%
- Applied to ν_e spectrum→ uncertainty < 10%

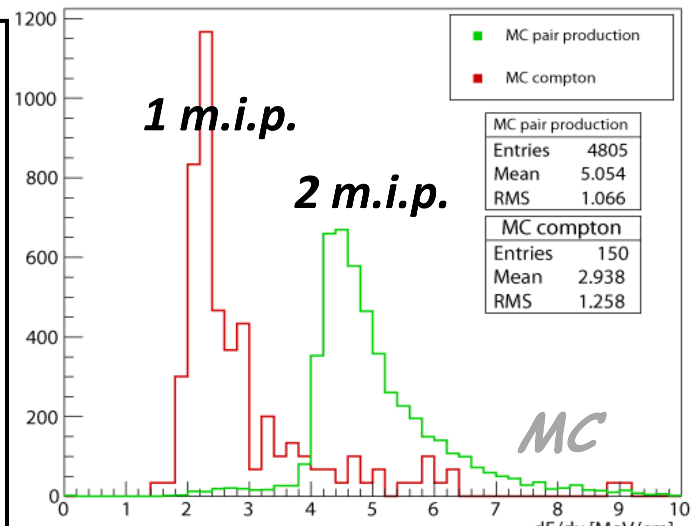
e/γ separation and π^0 reconstruction in ICARUS



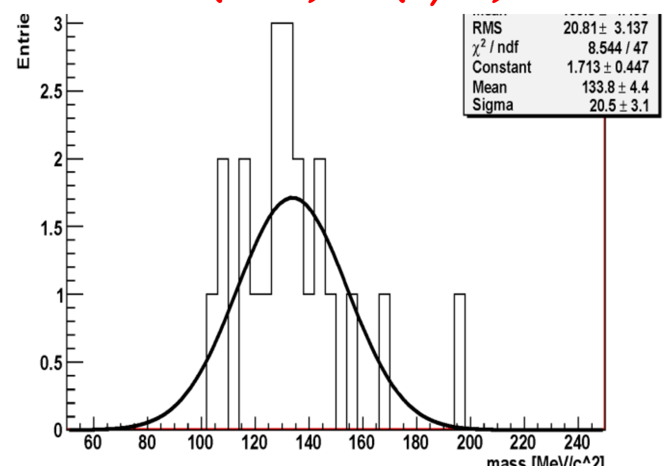
- *MC: single electrons (Compton)*
- *MC: $e^+ e^-$ pairs (γ conversions)*
- *data: EM cascades (from π^0 decays)*

Sub-GeV E range





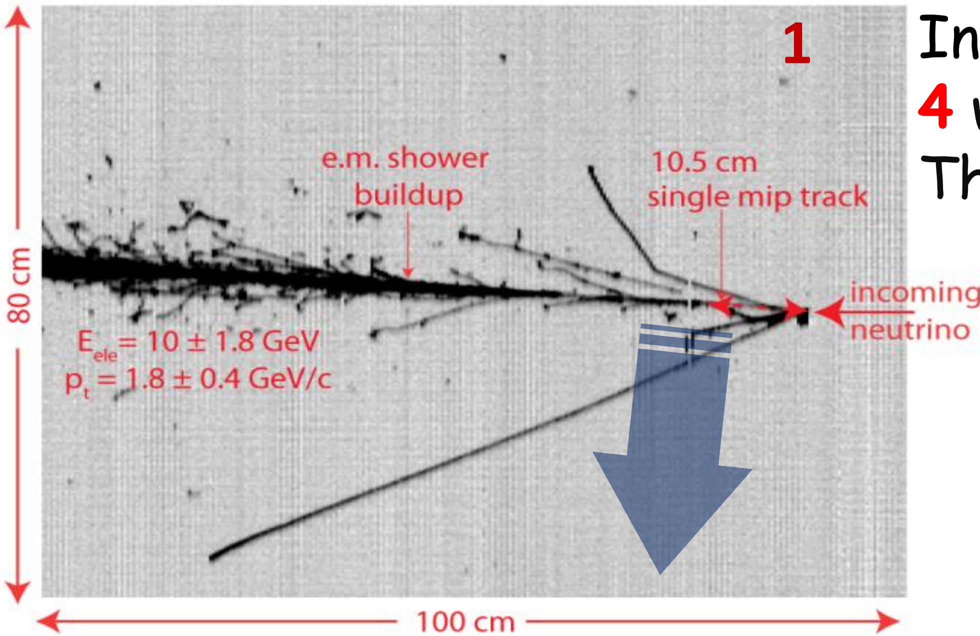
Mγγ:
133.8±4.4(stat)±4(syst) MeV/c²



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 (from MC and scanning)

ν_e events



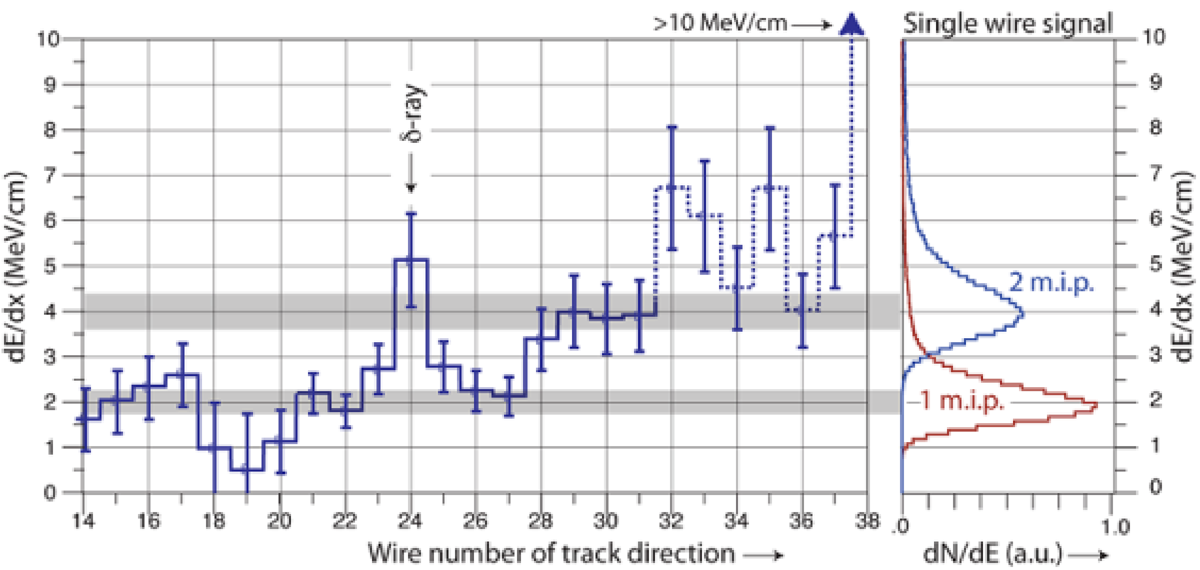
In the sample of 1995 ν events,
4 were identified as ν_e CC
The expected backgr. being 6.4 ± 0.9

(1) $E_{tot} = 11.5 \pm 1.8$ GeV,
$p_t = 1.8 \pm 0.4$ GeV/c

(2) $E_{tot}vis = 17$ GeV,
$p_t = 1.3 \pm 0.18$ GeV/c

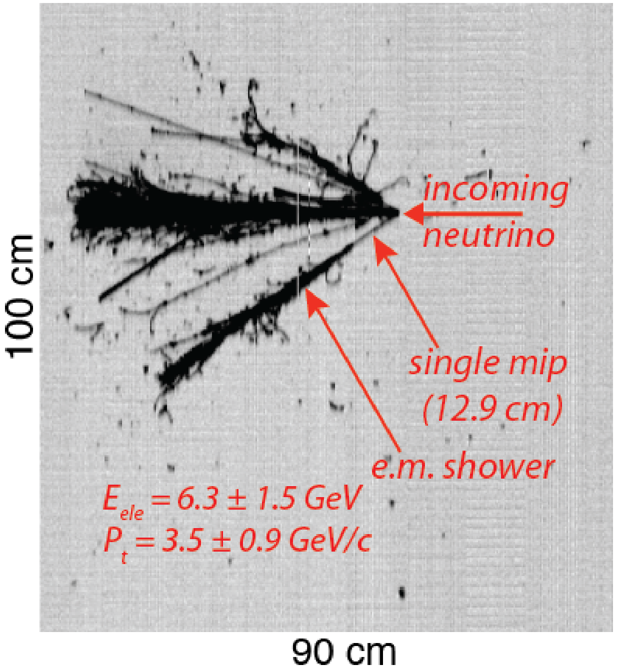
(3) $E_{tot} = 27 \pm 2.0$ GeV,
$p_t = 3.5 \pm 0.8$ GeV/c

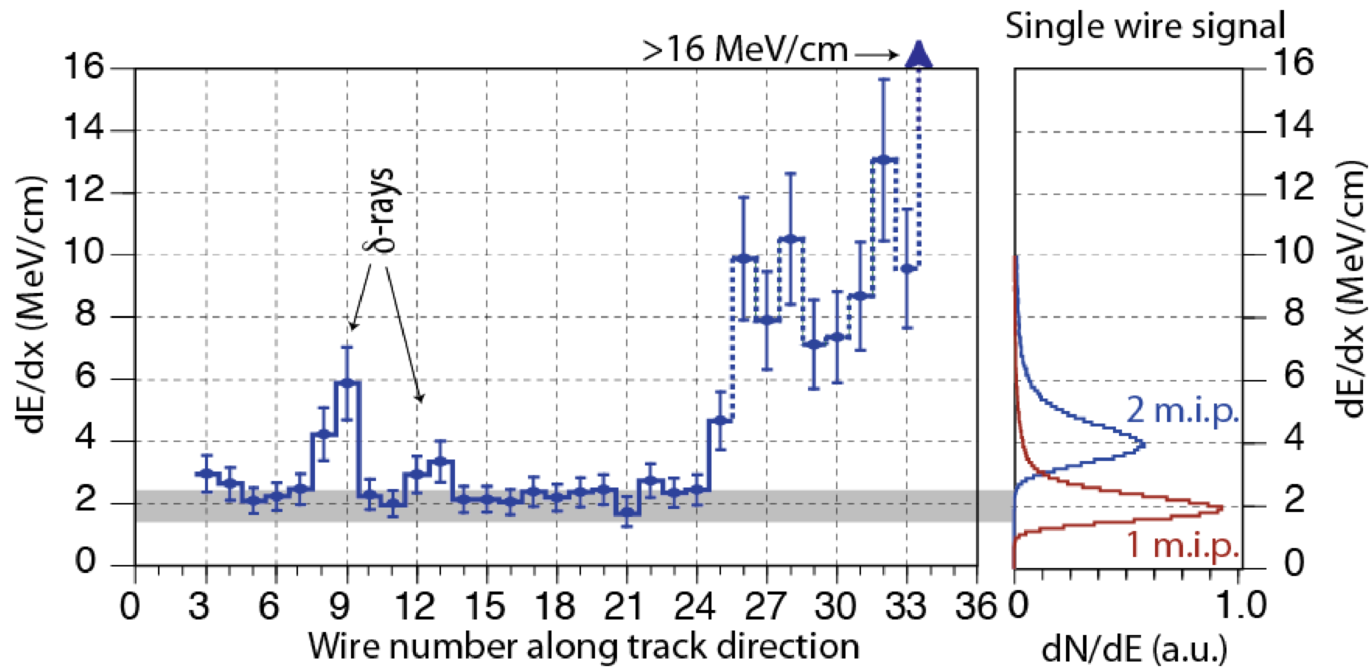
(4) $E_{tot} = 14 \pm 1$ GeV,
$p_t = 1.5 \pm 0.1$ GeV/c



In all events: single electron shower opposite to had. component in the transverse plane

Event n. 3

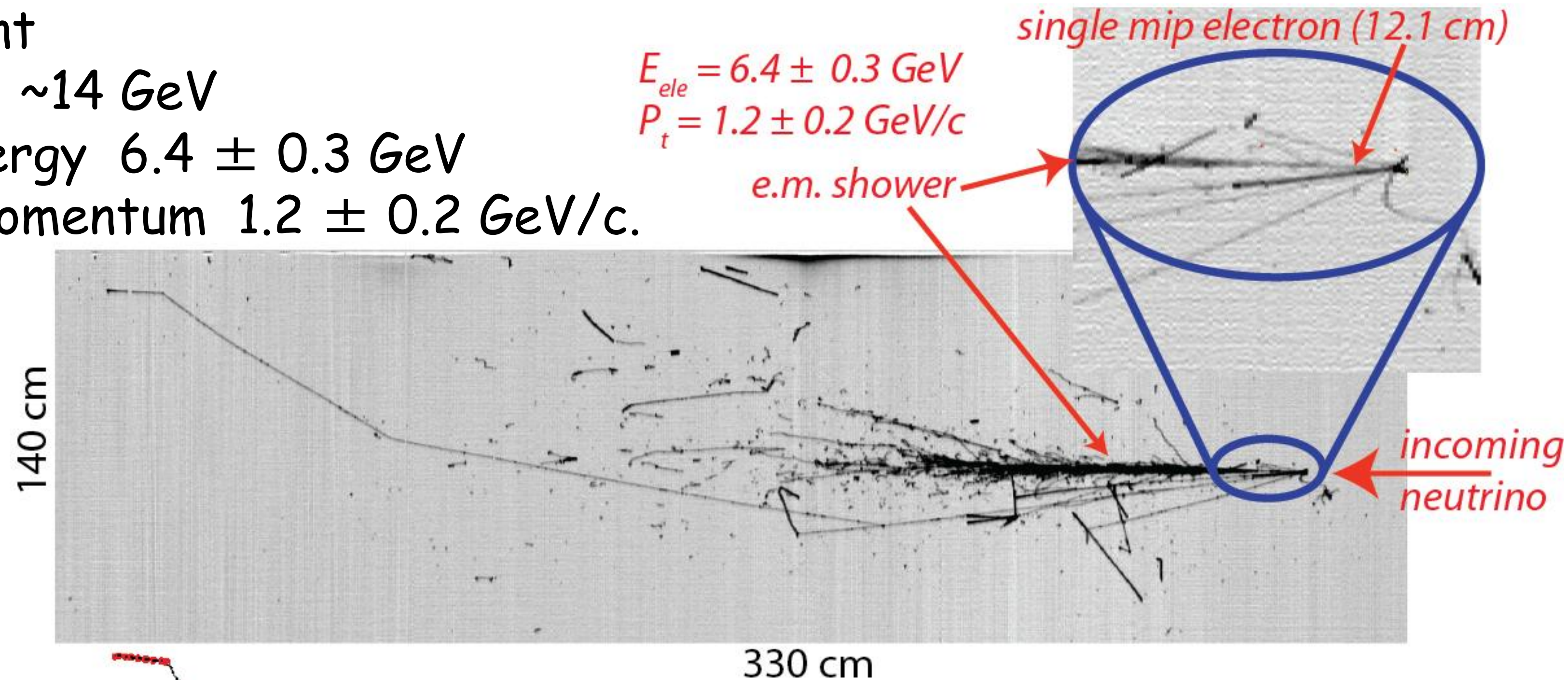




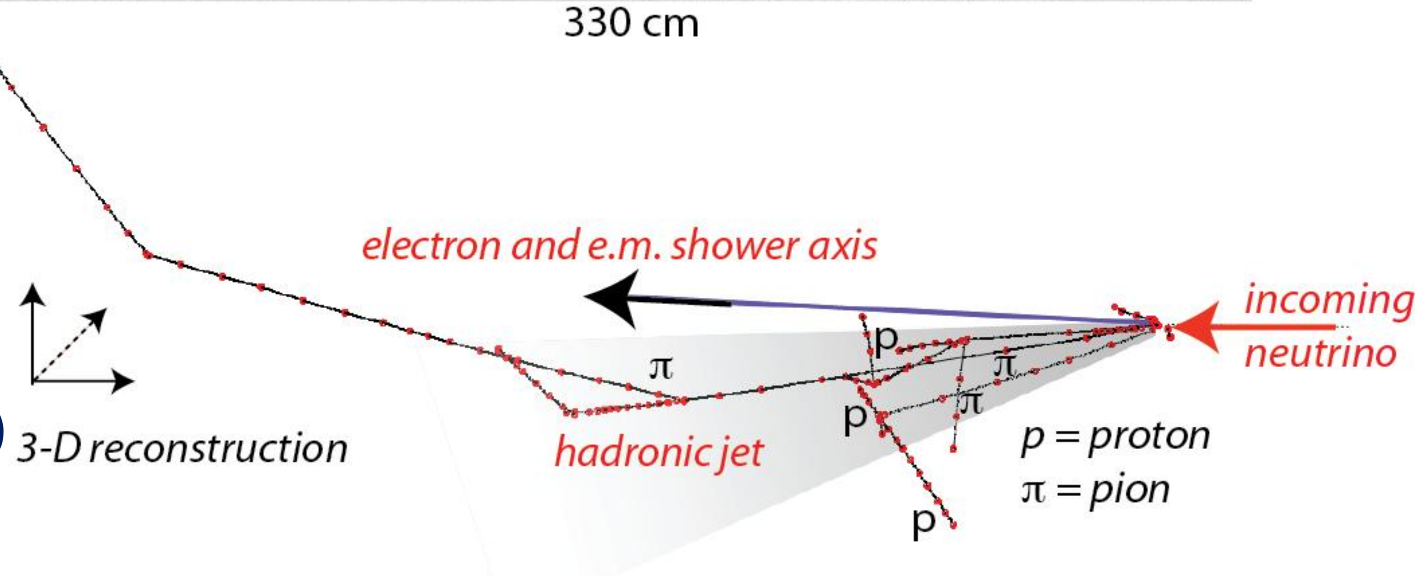
- Experimental pictures of the third event with a clear electron signature
- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is shown along the individual wires.
- The event has a total energy of ~27 GeV and an electron of 6.3 ± 1.5 GeV with a transverse momentum of 3.5 ± 0.9 GeV/c.

Event N.4

Fourth ν_e event
- total energy ~14 GeV
- electron energy 6.4 ± 0.3 GeV
- transverse momentum 1.2 ± 0.2 GeV/c.



3D reconstruction of primary particles in the event
(red dots correspond to vertices of polygonal fit)



ICARUS results on the LSND-like anomaly

- The first ICARUS result (Eur. Phys. J. C 73 2013) limits the window of possible parameters for LSND anomaly to a narrow region around $(\Delta m^2 - \sin^2 2\theta) = (0.5\ eV^2 - 0.005)$, where all experiments are compatible.

- This analysis is based on a doubled statistics ⇒ in total 6.0 x 10^{19} pot and 1995 ν events
- 4 evt observed , 6.4±0.9 expected background
- Limits on number of events due to LSND anomaly:

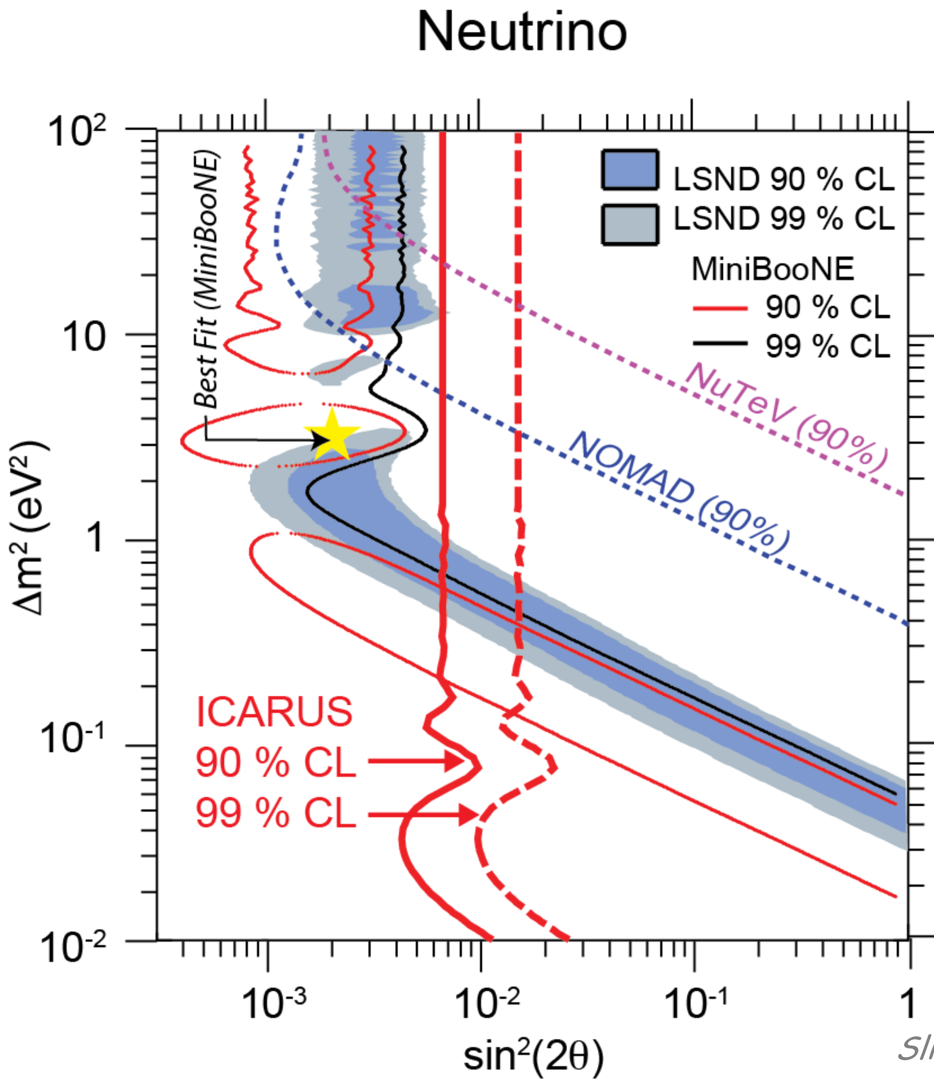
  3.68 (90% CL)

  8.34 (99% CL)

  the corresponding limits on oscillation probability are:

  $P_{\nu\mu\rightarrow\nu e} \leq 3.4\ 10^{-3}$ (90% CL)

  $P_{\nu\mu\rightarrow\nu e} \leq 7.6\ 10^{-2}$ (99% CL)



Antineutrino

The LSND result was based on anti-neutrino events. A small ~2% anti-neutrino event contamination is also present in the CNGS beam

According to simulations, the $\bar{\nu}_\mu$ CC event rate is (1.2 ± 0.25) % of ν_μ CC for $E_\nu < 30$ GeV

In the limiting case in which the whole effect is due to $\bar{\nu}_\mu$, the absence of an anomalous signal gives a limit of

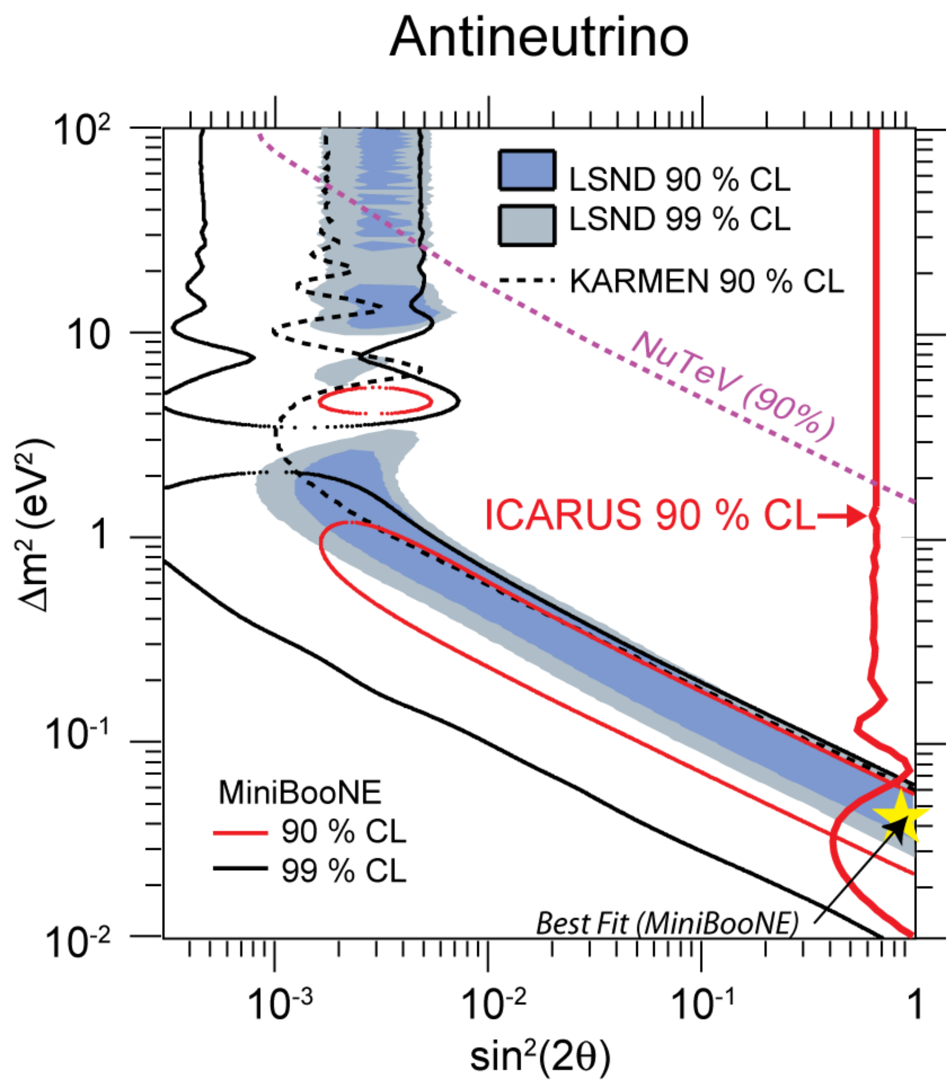
4.2 events at 90% CL.

Corresponding to

$\langle P(\bar{\nu}_\mu \to \bar{\nu}_e) \rangle \leq 0.32$

Or

$\sin^2(2\theta_{new}) \leq 0.64.$



Conclusions on ν_e search

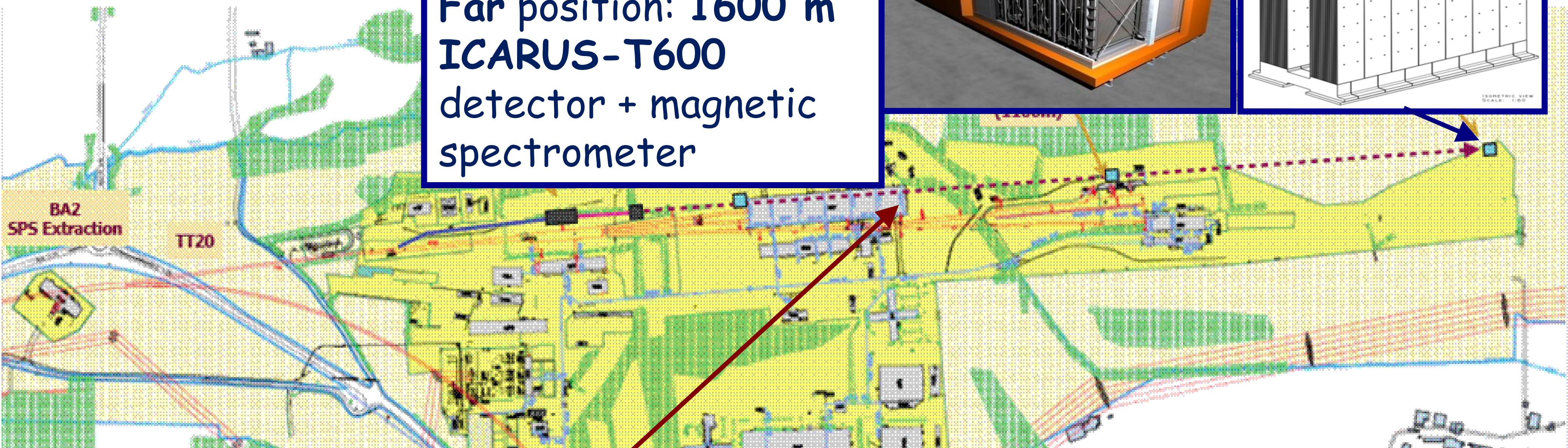
- A major fraction of the two dimensional plot $[\Delta m^2, \sin^2(2\theta)]_{new}$ from the experiments sensitive to the LSND anomaly is excluded by ICARUS
- The ICARUS result allows to define a small region around $(\Delta m^2, \sin^2(2\theta)) = (0.5\ eV^2, 0.005)$ in which there is 90 % CL agreement among all experiments
- A similar search performed at the CNGS beam by the OPERA exp. has confirmed our finding with an independent limit $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$
- There is tension between the limit $\sin^2(2\theta_{new}) < 6.8 \times 10^{-3}$ at 90% CL and $< 1.52 \times 10^{-2}$ at 99% CL of ICARUS and the neutrino lowest energy points of MiniBooNE (see also Giunti's talk)
- As a conclusion, the LSND anomaly appears to be still alive and further experimental efforts are required to prove the possible existence of sterile neutrinos. The recently proposed ICARUS/NESSiE experiment at the CERN-SPS neutrino beam , based on two identical LAr-TPC detectors, complemented with magnetized muon spectrometers and placed at two ("near" and "far") distances from proton target, has been designed to definitely settle the origin of these ν-related anomalies.

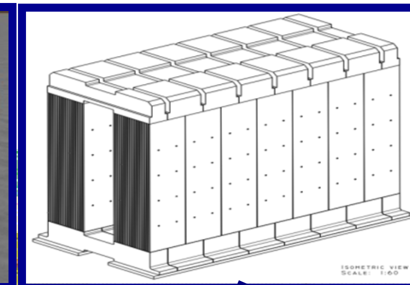
ICARUS at the (proposed) CERN North Area Neutrino Facility

New CERN SPS 2 GeV neutrino facility in North Area

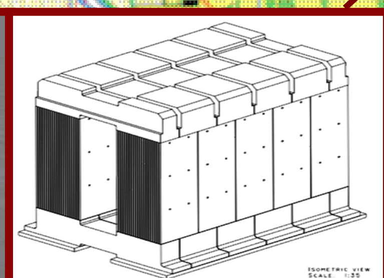
100 GeV primary proton beam fast extracted from SPS in North Area: C-target station + two magnetic horns, ≈100 m decay pipe, Fe/graphite dump, followed by μ stations.

Interchangeable n and anti n focussing.





Far position: 1600 m
ICARUS-T600
detector + magnetic spectrometer



Near position: 460 m
150t LAr-TPC detector
+ magnetic spectrometer

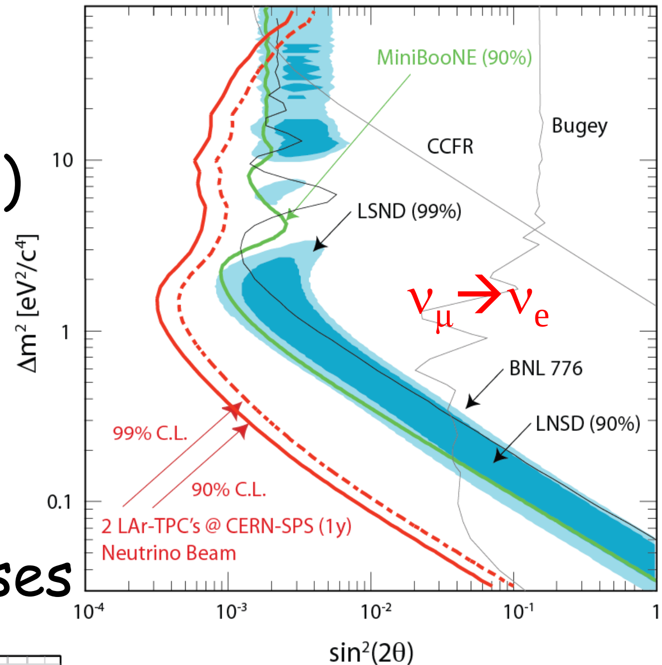
SPSC-P347

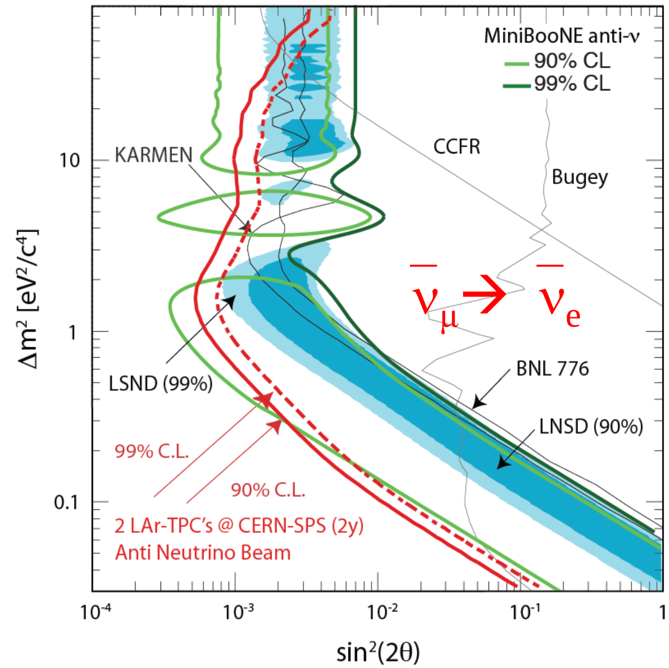
Exploring all channels: expected sensitivity

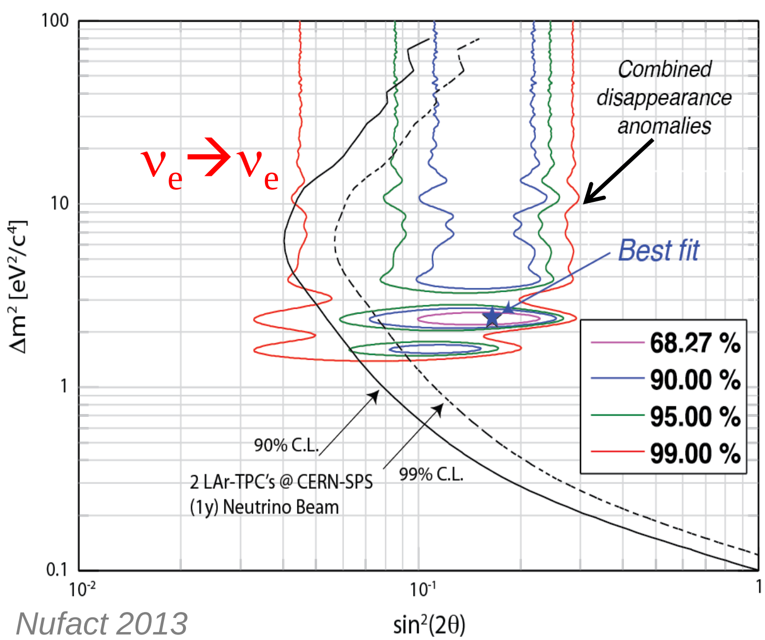
e-appearance:

1 year ν_μ beam (left)
2 year antiν_μ beam (right)
for 4.5 1019 pot/year,
3% syst. uncertainty

LSND allowed region is fully explored in both cases







e/μ-disappearance:

1 year ν_μ beam (left)
1 year ν_μ + 2 years anti-ν_μ beams (right)

combined "anomalies": from reactor νs, Gallex and Sage experiments.

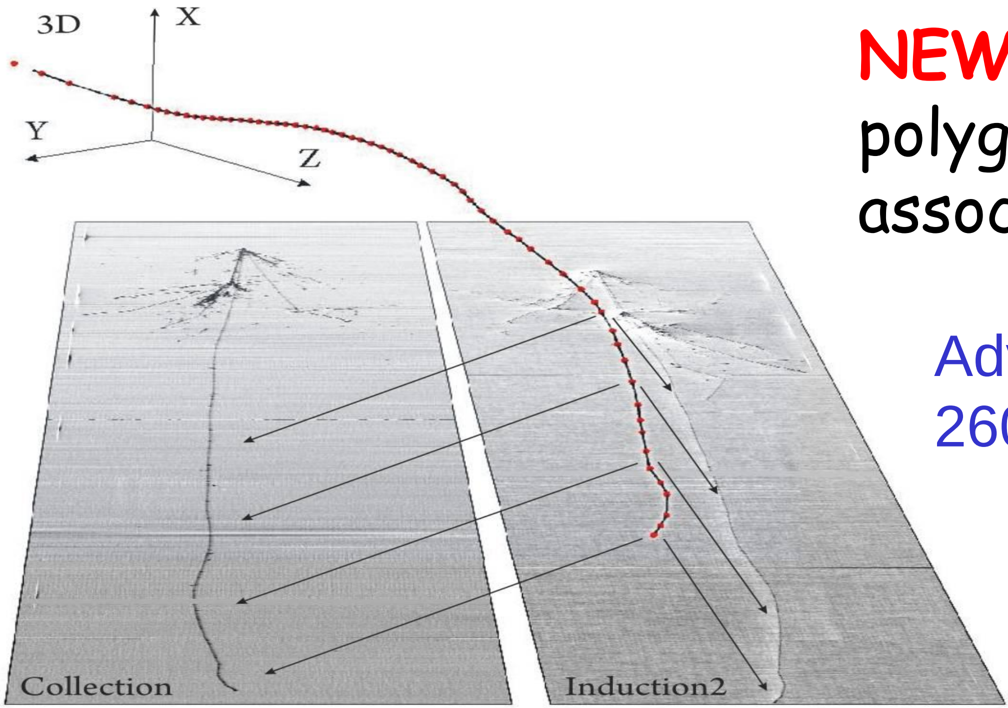
In addition:
Detector R&D (T150)
Neutrino cross sections (huge statistcs of ν_e)
Event reconstruction
"*pave the way for future LBL experiments*"


Thank you !

- Minutes of the 108th SPSC meeting – Jan 2013:
  - *The SPSC* ***recommends moving the ICARUS detector from LNGS to CERN*** *during LHC LS1, to a position suitable for use as the far detector of a* ***short baseline experiment*** *for search for sterile neutrinos.*
  - The SPSC **supports the physics cases**
  - The SPSC **supports the focus of the European neutrino community on the LAr TPC** technology,
  - The SPSC **recommends that future European R&D for neutrino beam physics at** CERN should be made in close contact with the US groups in anticipation of cooperation on future projects.

Backup slides

3D reconstruction (example of stopping μ)



NEW: Simultaneous **3D** polygonal fit →**2D** hit-to-hit associations no longer needed

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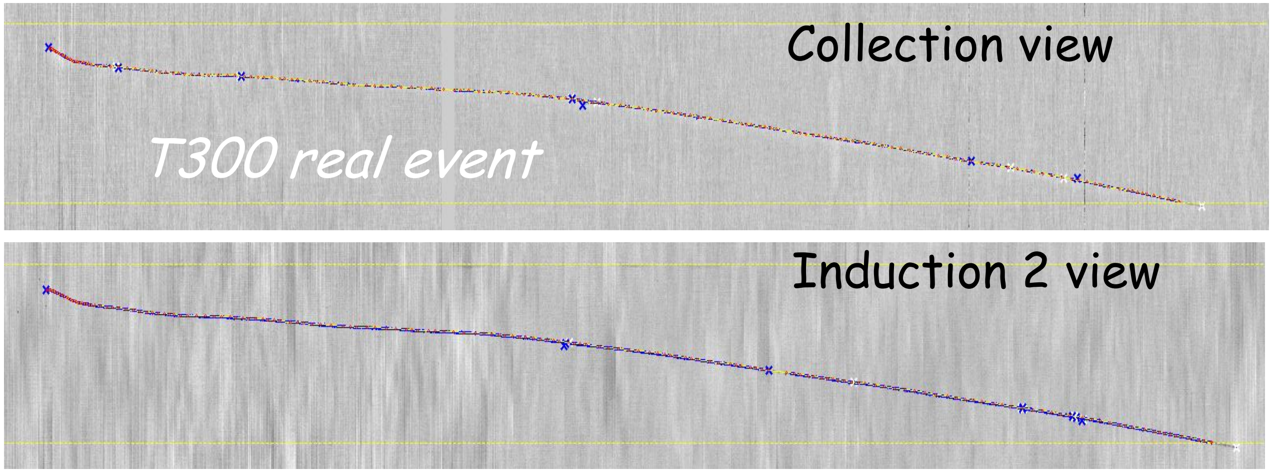
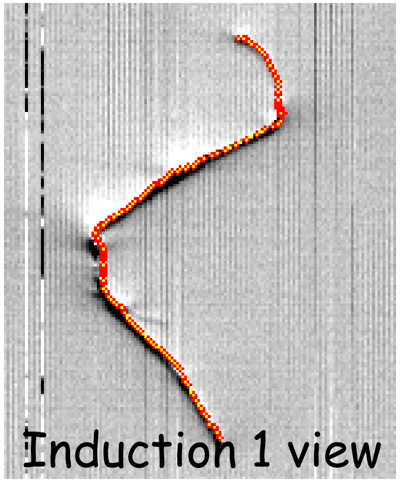
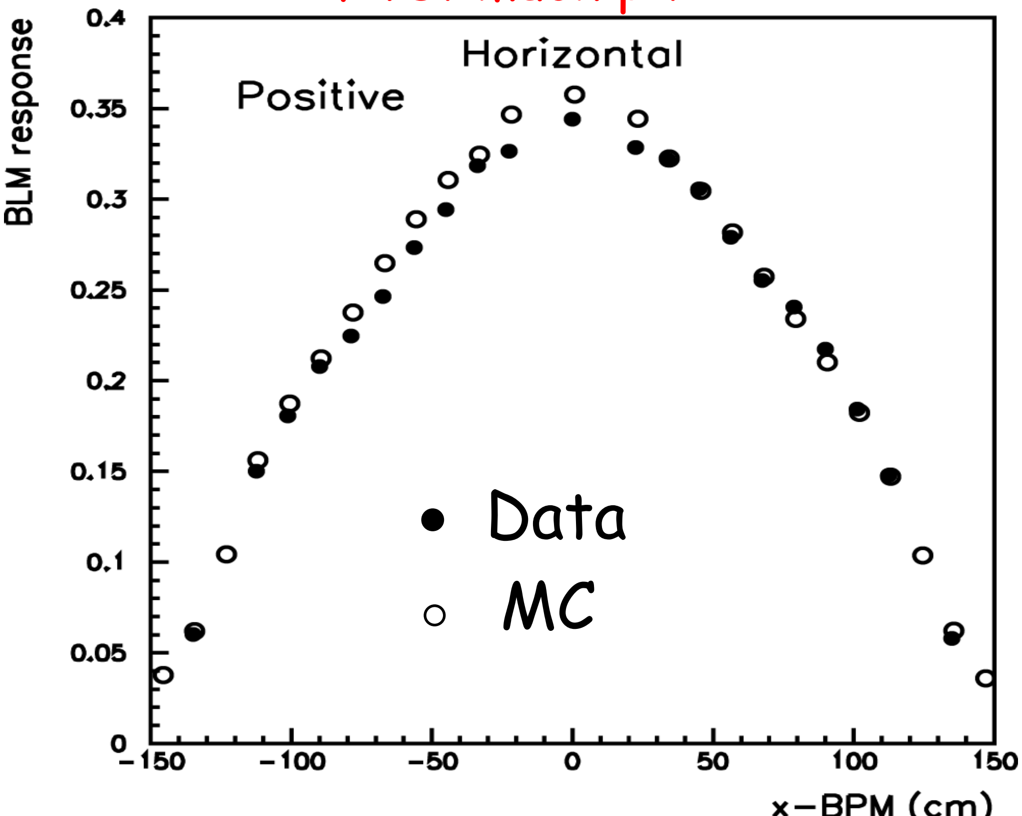




Beam and detector systematics on ν_μ disappearance

First muon pit



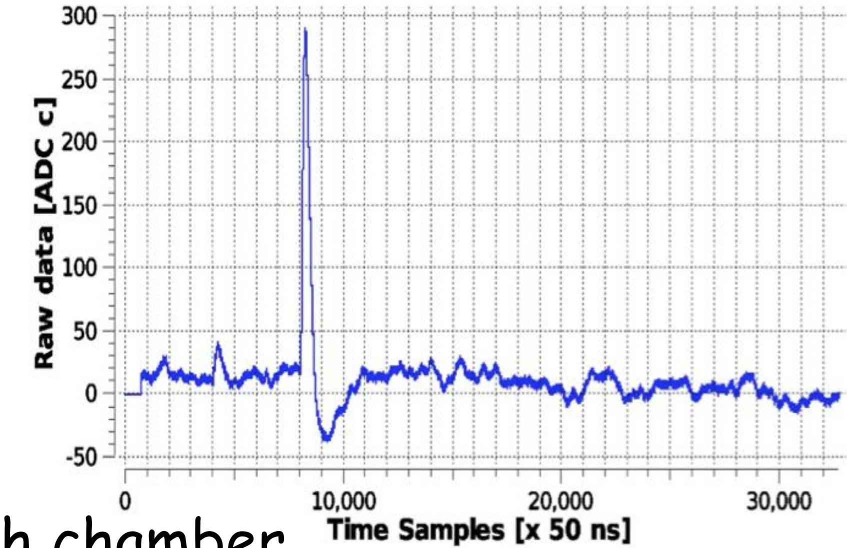
Results at Muon pits: data vs MC

Effect of Earth B field (in 1 km decay tunnel) included in MC.

Experimental uncertainties: muon detector calibration (work ongoing), density of rock in between the two pits (67 m).

- Spill by spill corrections for (small) horn/reflector instabilities
- ICARUS trigger system efficiency
- Selection efficiency & possible contamination from interactions in the materials around the active LAr: data and MC scanning ongoing
- Detector response uniformity/stability for interaction vertices.

Performance of the ICARUS T600 Trigger

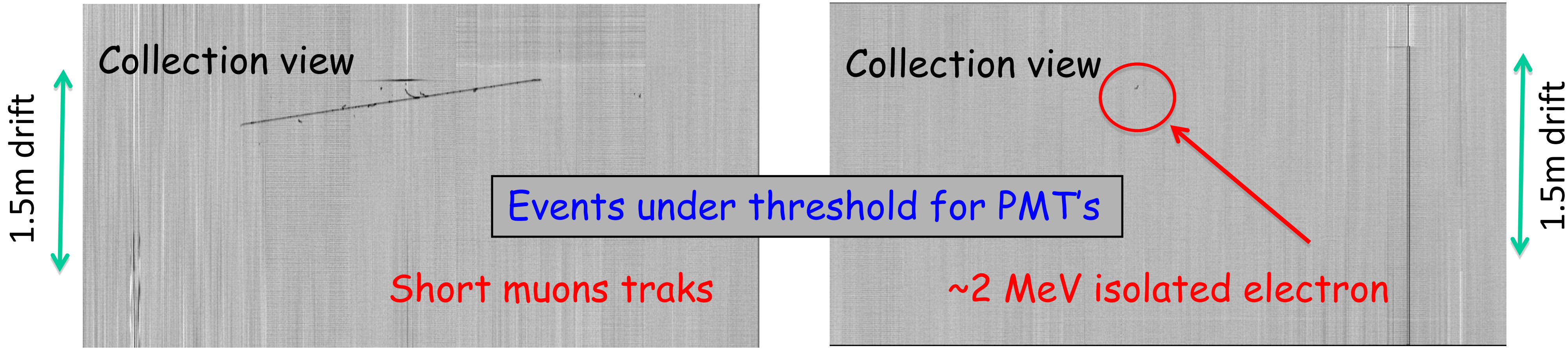


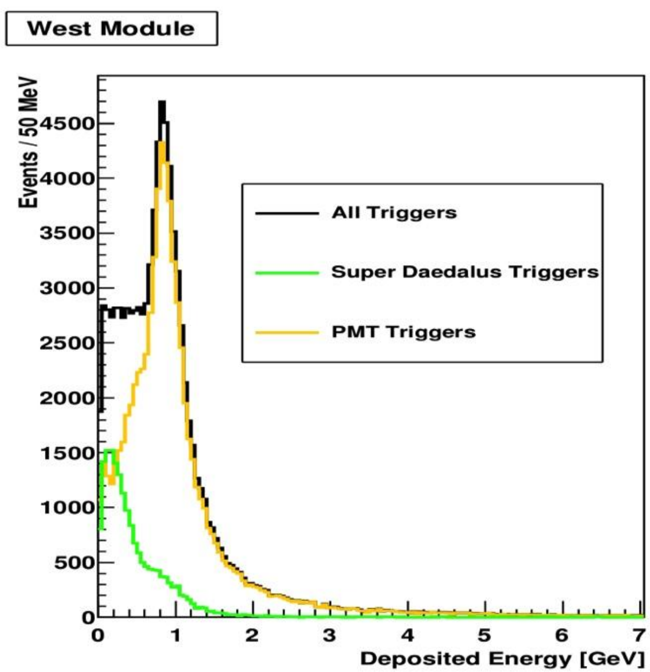
- Main trigger source: scintillation light signals from PMT system integrated with low noise (RC=10 μs) preamps to efficiently exploit the 6ns fast and 1.6 μs slow components
- CNGS neutrino trigger:
  - PMT-Sum signal (thr. ~100 phe) for each chamber in coincidence with CNGS "Early Warning" beam gate (60 μs)
  - ~80 triggers/day (few tens events expected).
- Cosmic Rays trigger:
  - PMT-Sum signal coincidence of two adjacent chambers (50% central cathode transparency)
  - ~130 events/h (~160 expected)

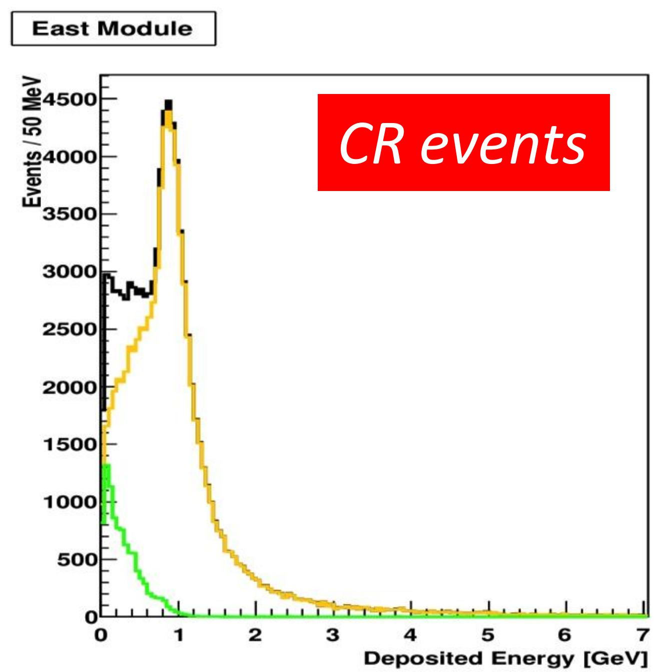
Preliminary analysis done, needing a more detailed study of the collected data and comparison with MC simulation.

Additional trigger on local charge deposition

- Dedicated algorithm implemented on FPGA on SuperDAEDALUS chip: on-line hit-finding of ionization charge signal from single TPC wires





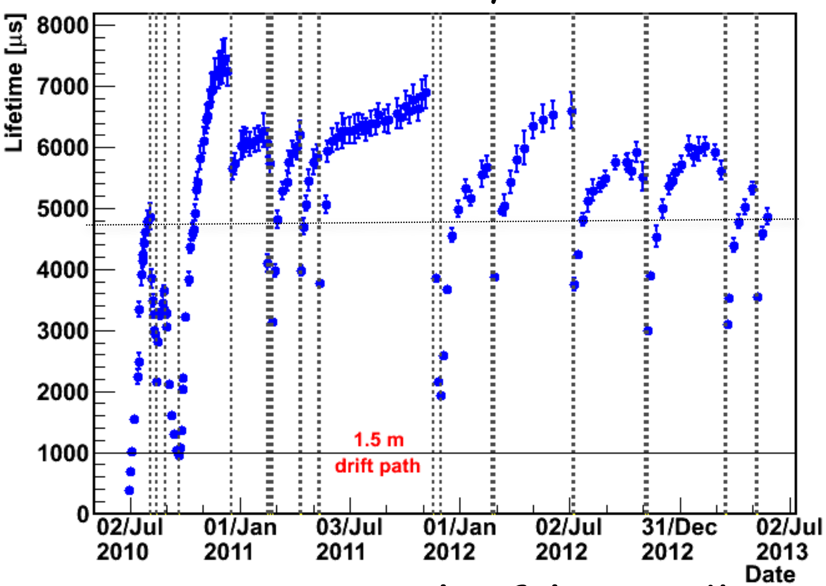


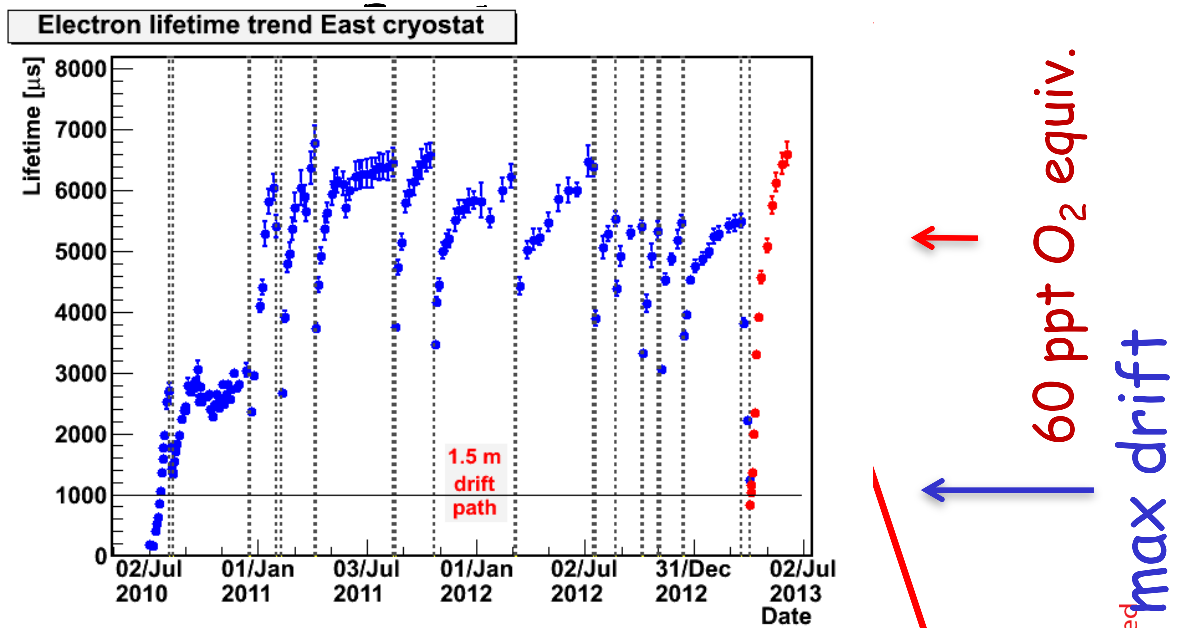
Used to improve the cosmic ray/CNGS trigger efficiency in 0.1 – 1 GeV range

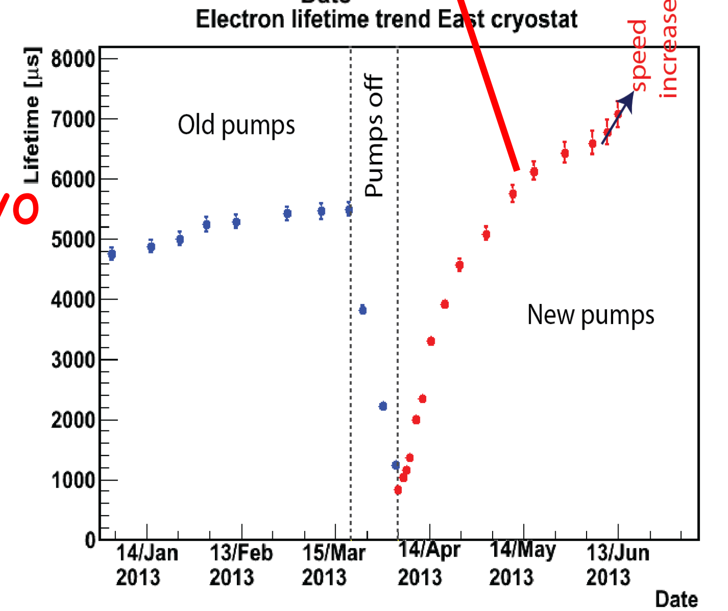
An efficient data reduction system 0-skipping

LAr purification (<60 parts per trillion O_2 equivalent)

West Cryostat



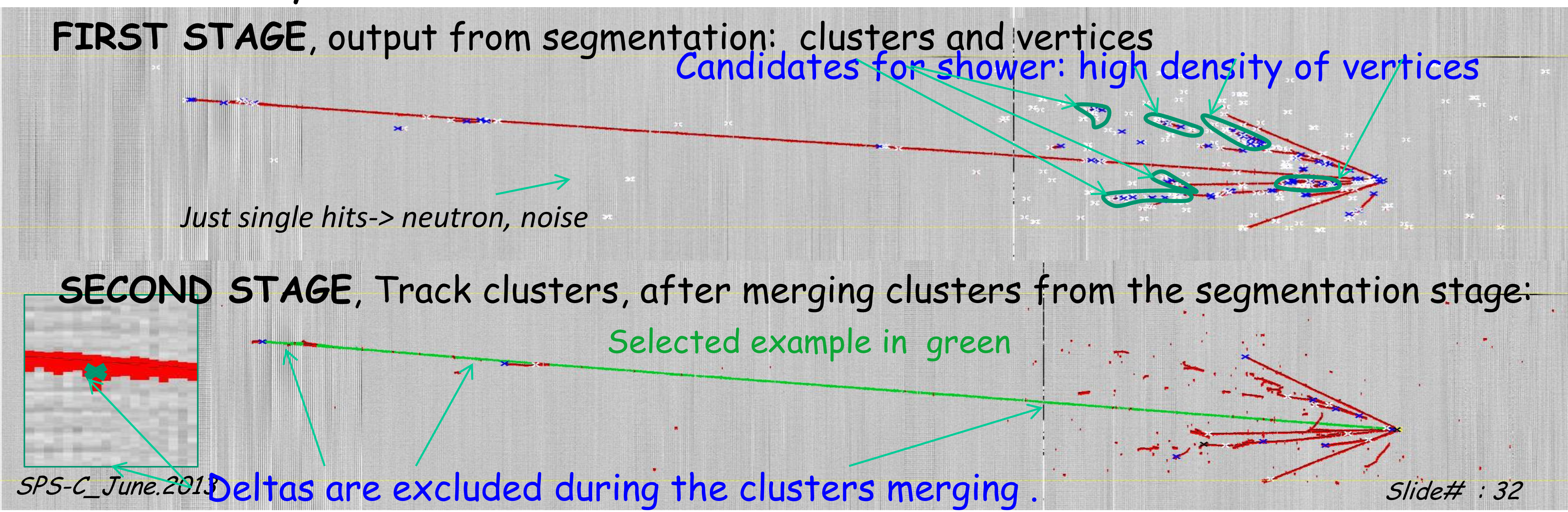




- LAr continuously filtered!
- LAr recirculation upgrade: new more efficient non-immersed motor pump installed in East-cryo
- τ_{ele} > 5ms (~60 ppt $[O_2]_{eq}$), maximum charge attenuation at 1.5 m: 17%.
- A paper in preparation on successful commissioning and three year underground operation of the cryogenic plant.

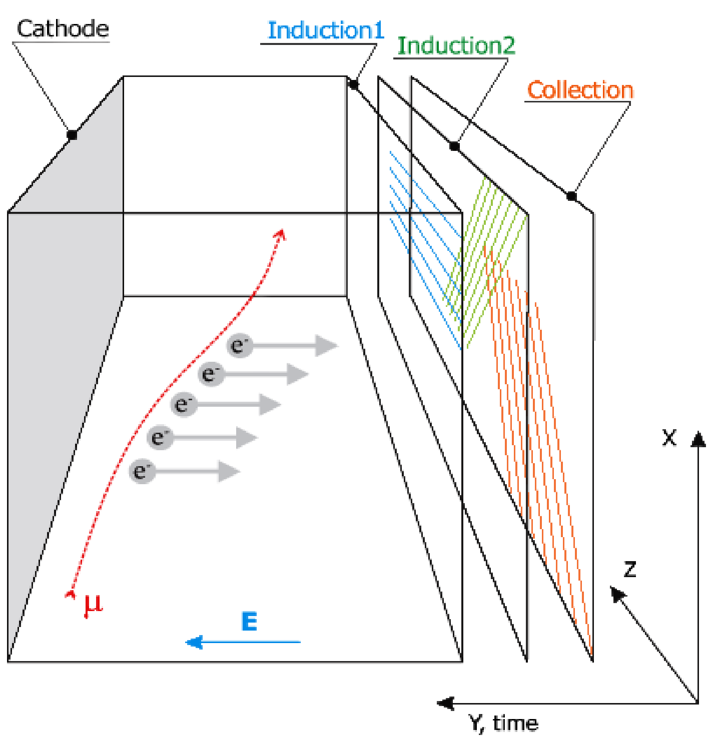
Automation of reconstruction

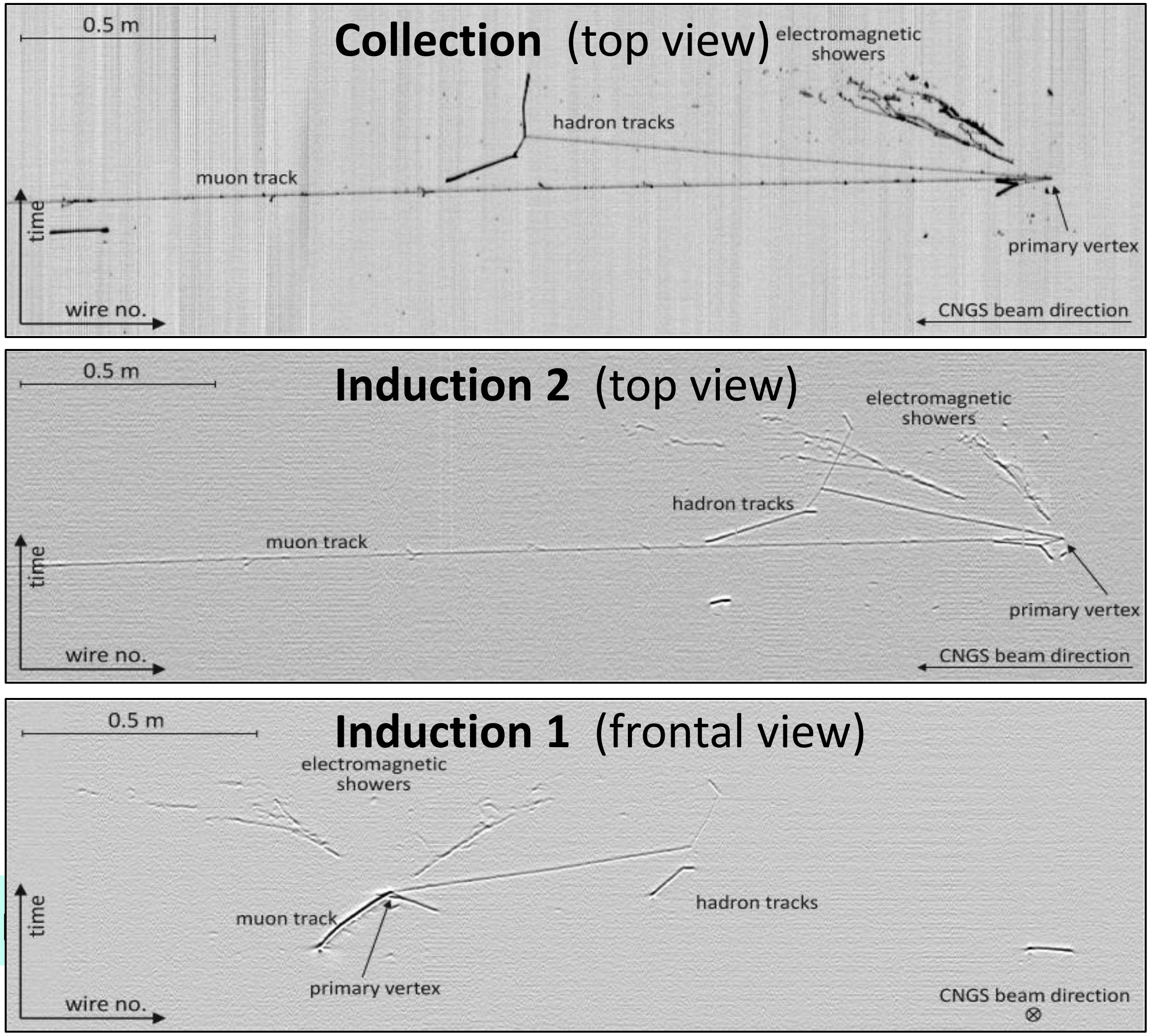
- CNGS ν event primary vertex: automatic reconstruction
  - Validation with visually identified CNGS vertices
  - algorithm efficiency ~ 97%
- automatic event segmentation algorithm
  - Track identification
  - Shower identification
  - Ready in 2D, to be extended in 3D



ICARUS LAr-TPC detection technique

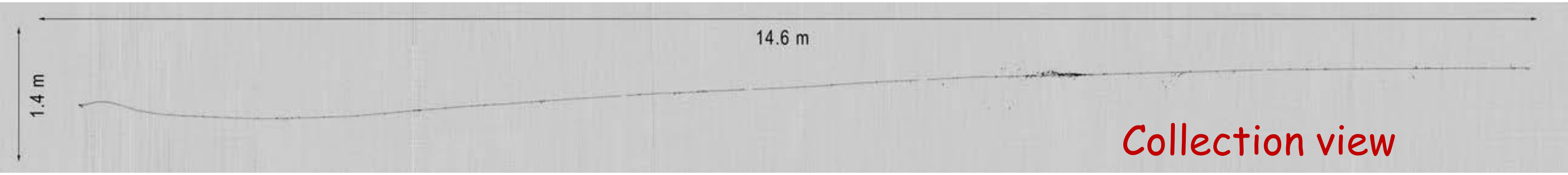
- 2D projection for each of 3 wire planes per TPC
- 3D spatial reconstruction from stereoscopic 2D projections
- charge measurement from Collection plane signals

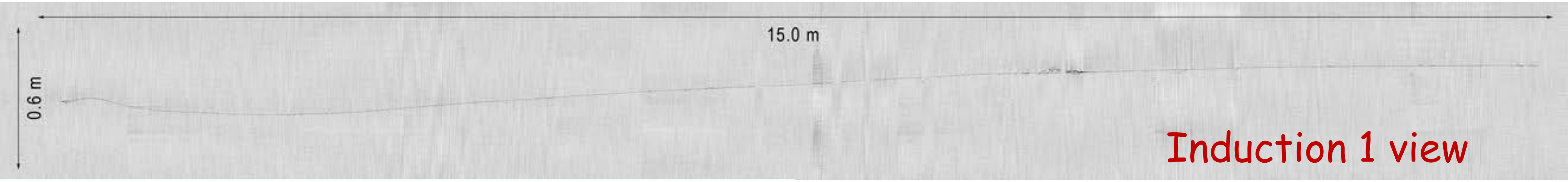


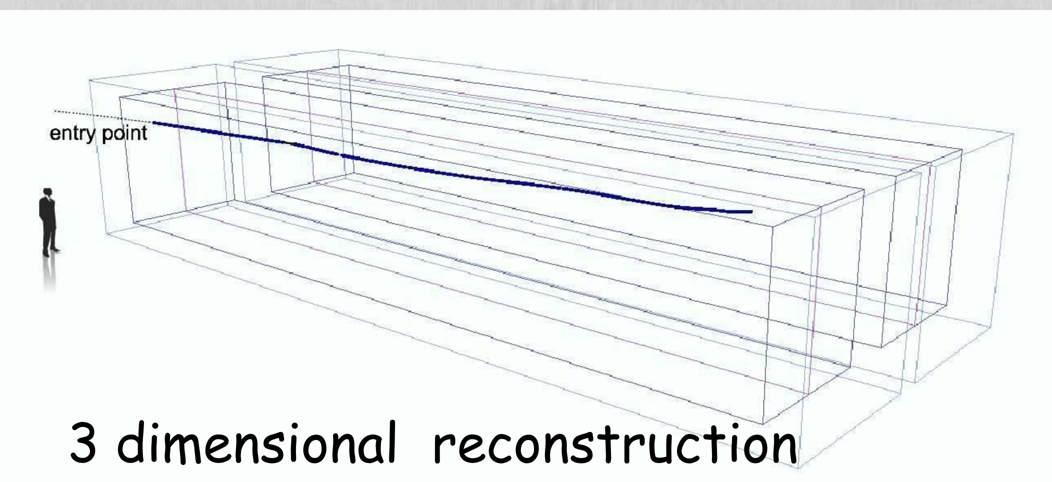


CNGS ν_μ charged current interactio

The method







- The projection of the track in the Collection plane is split in segments of length *l*
- Deflections between segments are calculated
- The RMS of deflection angles θ depends on the momentum *p* and on the measurement error σ

$$\theta \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma_{noise}}{l^{3/2}}$$

Two method developed for ICARUS:

- Variable track segmentation ("classical")
- Kalman filter

Signal selection efficiency check in MC simulation

- ***automatic cuts mimicking data selection, large sample of MC***

C1: inside fiducial volume and E_{dep} < 30 GeV;
C2: no identified muon, at least one shower;
C3: one shower: initial point (or γ conversion point) < 1 cm from vtx, separated from other tracks;
C4: ionisation signal from single mip in the first 8 wires.

Sel. cut	ν_e CC beam	ν_e CC θ_{13}	ν_τ CC	NC	ν_μ CC	ν_e CC signal
C1	0.47	0.92	0.93	0.89	0.89	0.81
C2	0.47	0.92	0.17	0.66	0.19	0.81
C3	0.33	0.79	0.14	0.10	0.03	0.66
C4	0.30	0.71	0.13	0.0002	0.00005	0.60

Signal selection efficiency (after the fiducial and energy cuts):
0.6/0.81 = 0.74, in agreement with the visual scanning method.