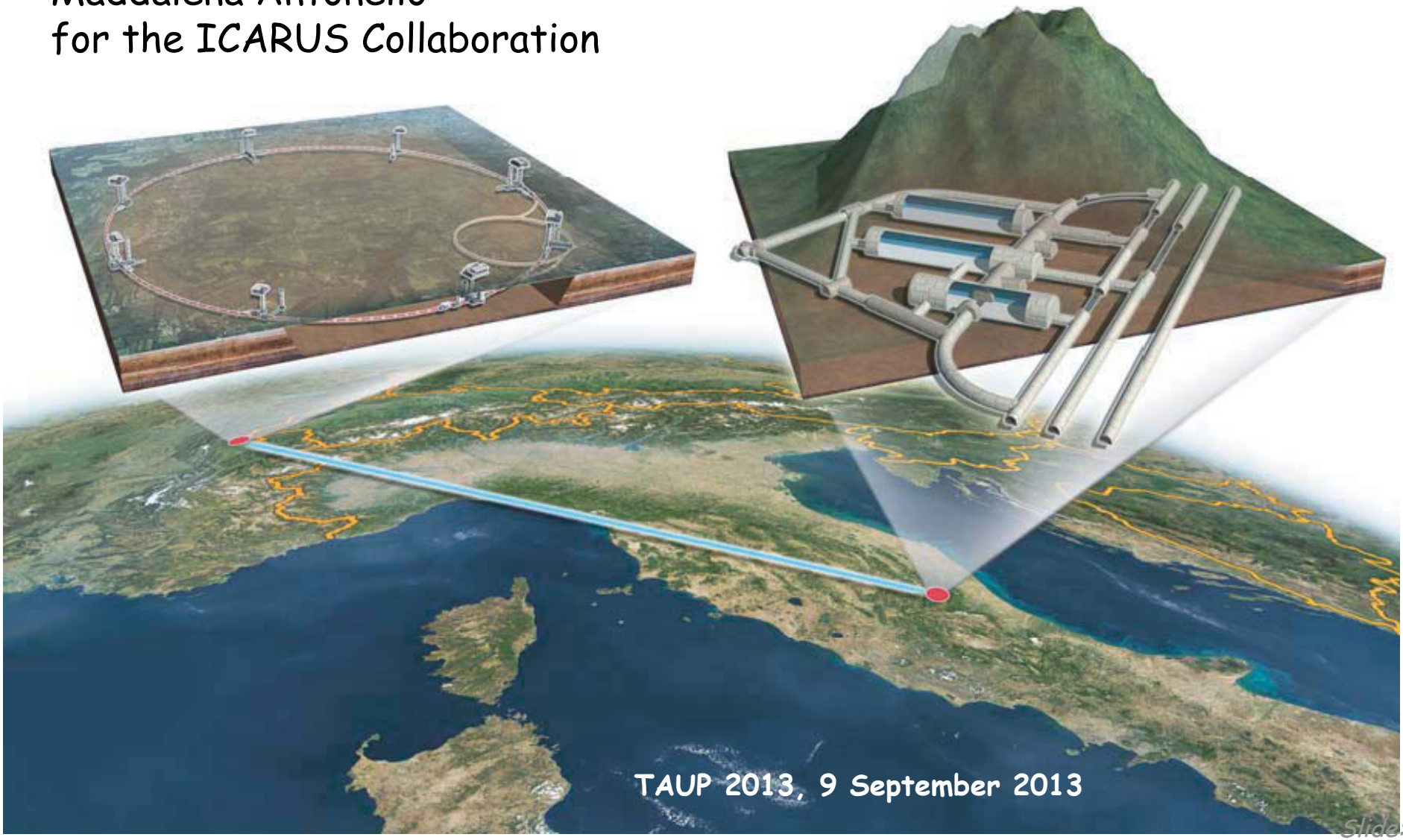
The ICARUS Experiment: latest results

Maddalena Antonello
for the ICARUS Collaboration



The ICARUS Collaboration

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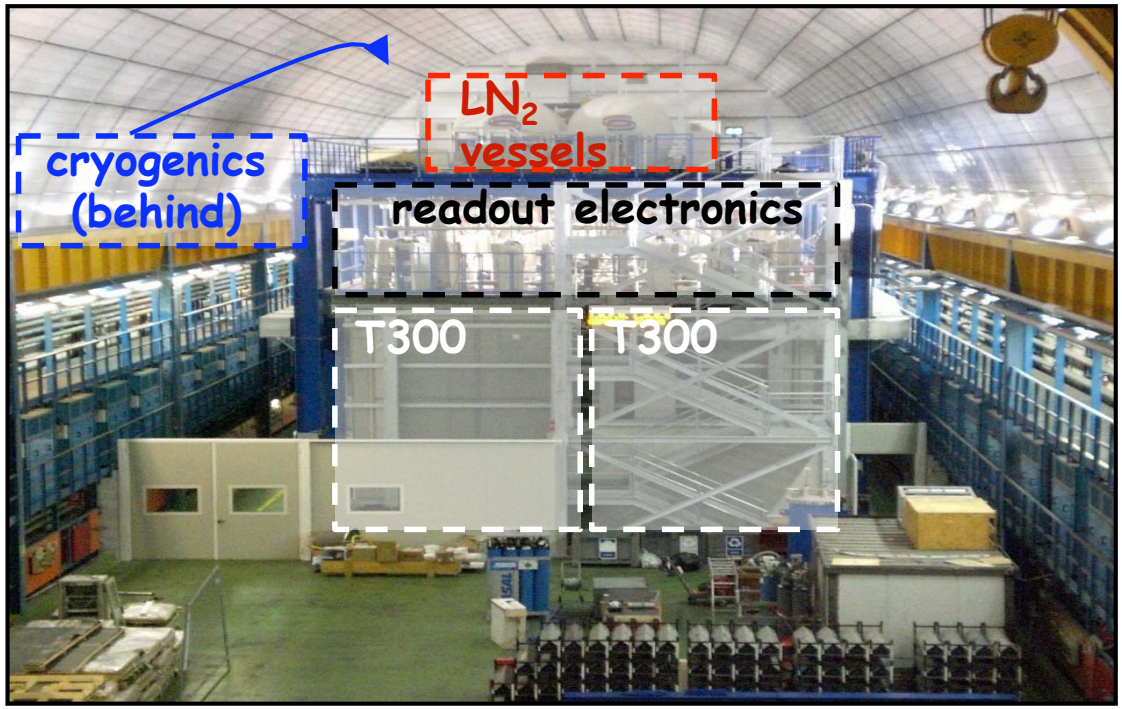
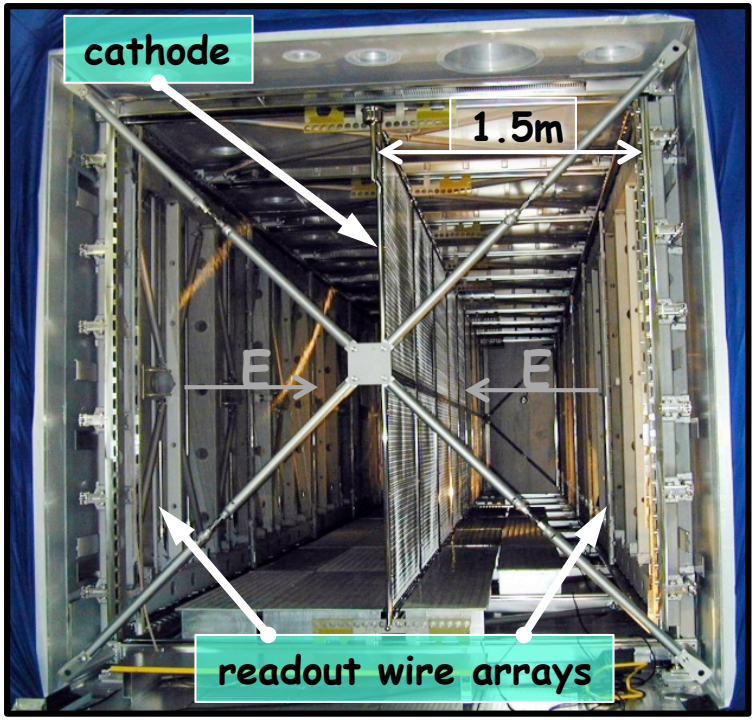
The ICARUS detector at LNGS Laboratory

- First large mass LAr-TPC (760 tons) operated underground (3600 m.w.e.), on-axis to CNGS ν beam
- May 2010 – June 2013: 3 years of non-stop smooth operation collecting CNGS neutrinos, but also cosmic rays to study the detector capability for atmospheric ν and proton decay searches
- June 27th 2013: Decommissioning started
  - cryo empty on July 25th; detector @ room temperature on Sept 1st
- T600 will soon be moved to CERN for refurbishing and further R&D activity with test beams

740 tons of LAr recovered

The ICARUS T600 detector



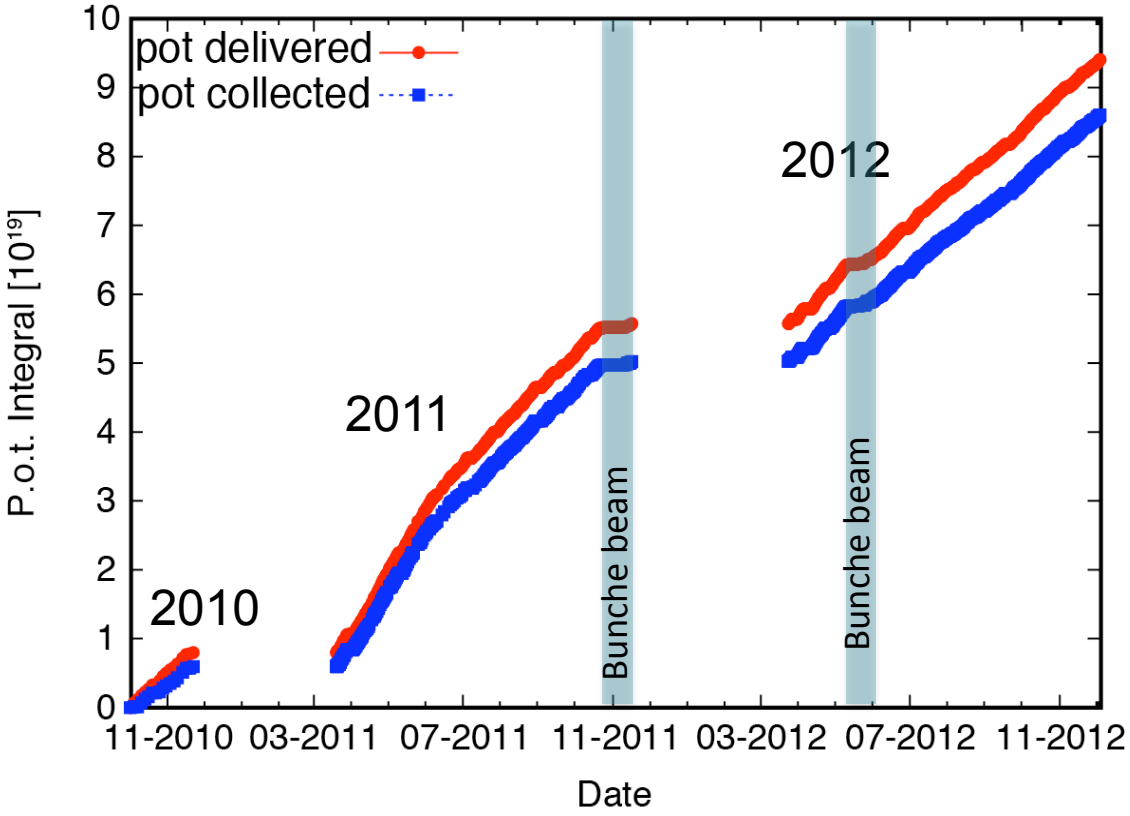


- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs

- 4 wire chambers (TPC):
  - 2 chambers per module
  - 3 readout wire planes/chamber, @ 0,±60°
  - ~54000 wires, 3mm pitch,3mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV light (128nm) with wave shifter (TPB)

Run with CNGS beam

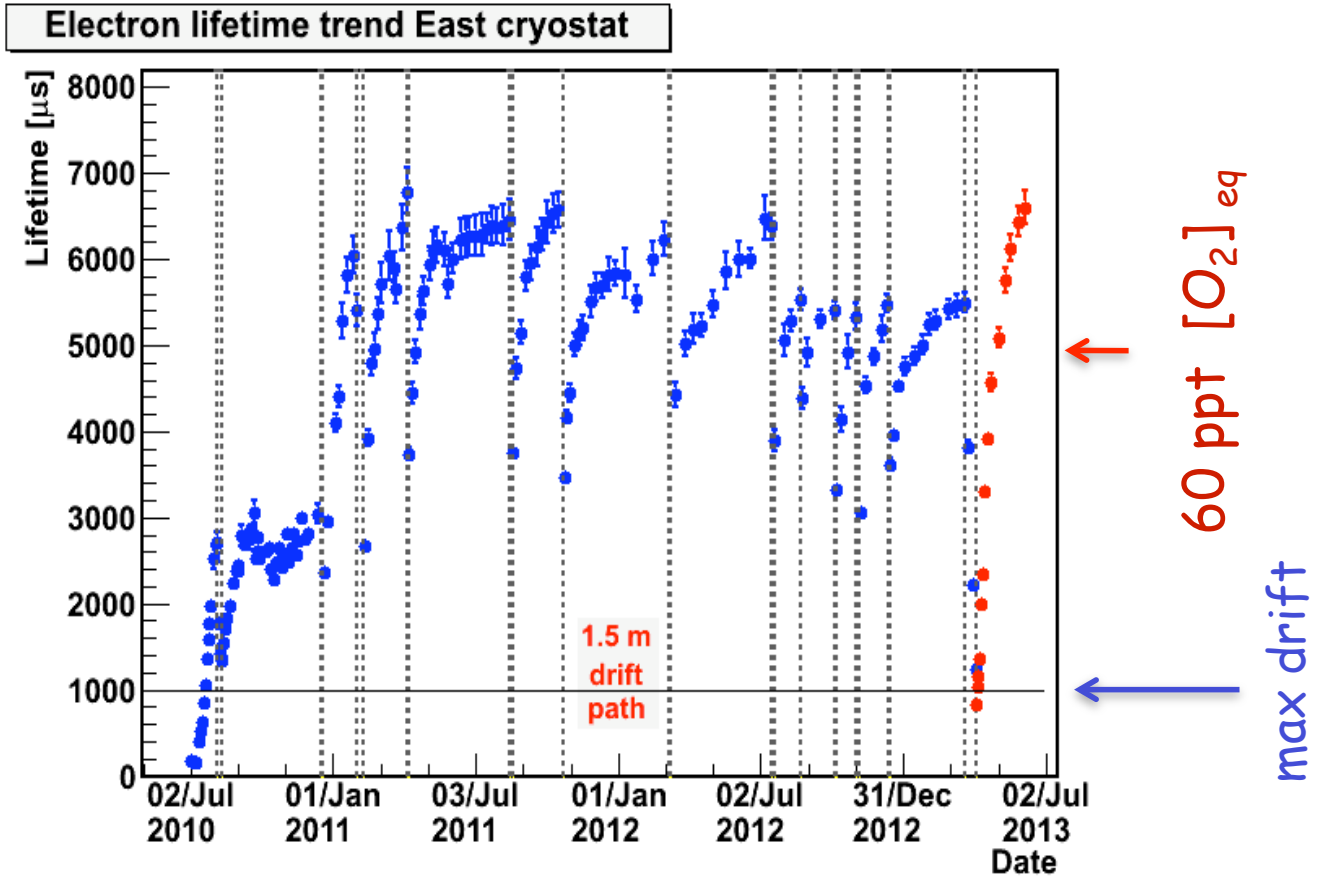
- Exposed to CNGS ν beam since 2010 October 1st up to 2012 December 3rd
- CNGS trigger: coincidence of PMT sum signals with beam spill
- Total collected event statistics: 8.6 10^{19} pot with a remarkable detector live-time > 93 %



- First published physics results
  - Superluminal ν searches:
    1. Cherenkov-like e^+e^- emission: PL B711 (2012) 270
    2. ν–tof measurement PL B713 (2012), 17
    3. ν–tof precision measurement: JHEP 11 (2012) 049
  - Search for $\nu_\mu \rightarrow \nu_e$ "LSND/MiniBooNE" anomaly:
    1. Eur. Phys. J. C 73 (2013)
    2. New improved results: arXiv:1307.4699, submitted to EPJC
- Technical run with cosmics from Dec. 2012 to June 2013

LAr High Purity

- Excellent results on LAr purification: τ_{ele} > 5ms (~60 ppt $[O_2]_{eq}$), maximum charge attenuation at 1.5 m: 17%
  - Ultra High Vacuum techniques
  - Continuous purification by gas and liquid recirculation
  - Highly efficient filters for O_2 and H_2O
- New non-immersed motor re-circulating pump tested (Apr 2013): τ_{ele} > 7ms



LAr-TPC reconstruction performance

- *Tracking:*
  - Automatic vertex and track identification
  - Precise (1 mm) 3D track reconstruction
  - Muon momentum via multiple scattering

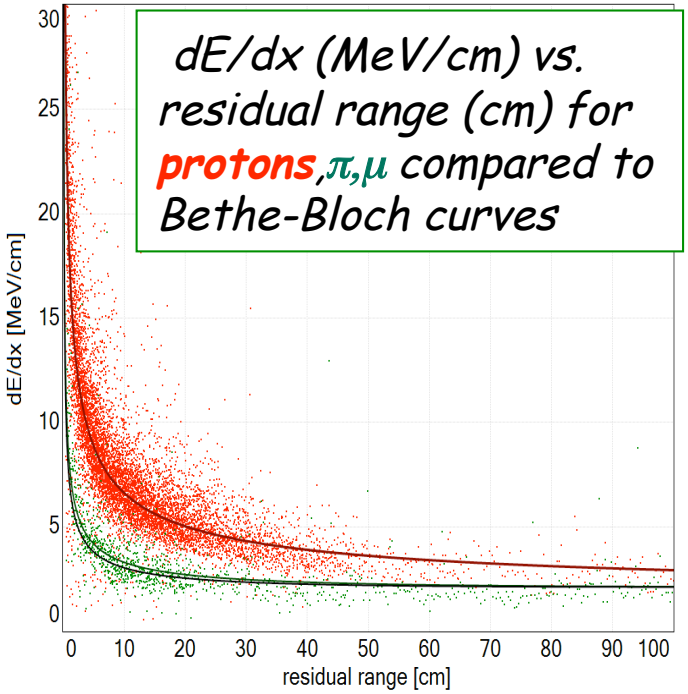
- *Measurement of energy deposition dE/dx:*
  - Good e/γ separation
  - Particle ID (dE/dx vs. res. range)

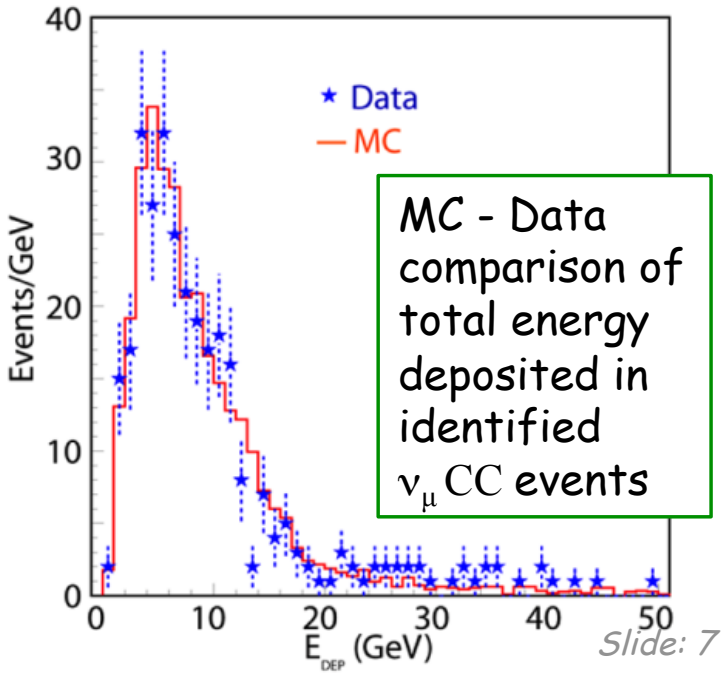
- *Total energy reconstruction of events from charge integration:*
  - Full sampling, homogeneous calorimetry with excellent accuracy for contained events

Low energy e-: σ(E)/E = 11% / √ E(MeV)+2%

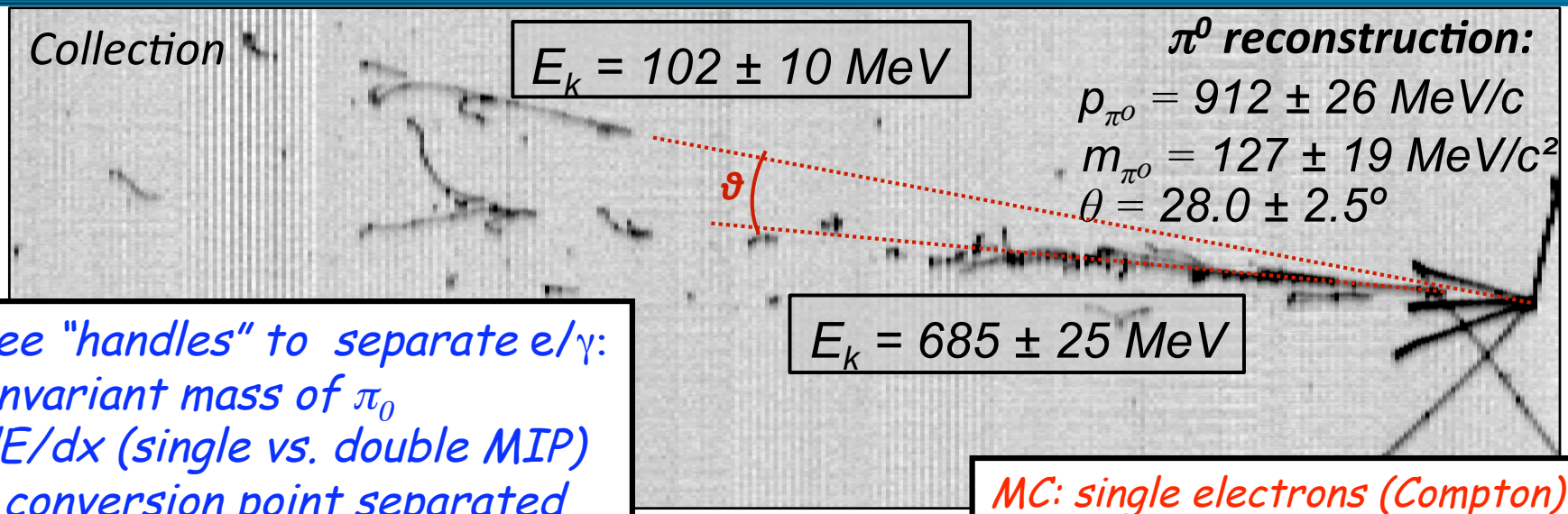
e.m. Showers: σ(E)/E = 3% / √ E(GeV)

Hadron showers: σ(E)/E ≈ 30% / √ E(GeV)





e/γ separation and π^0 reconstruction



π^0 reconstruction:

$p_{\pi o}$ = 912 ± 26 MeV/c

$m_{\pi o}$ = 127 ± 19 MeV/c²

θ = 28.0 ± 2.5°

Three "handles" to separate e/γ:

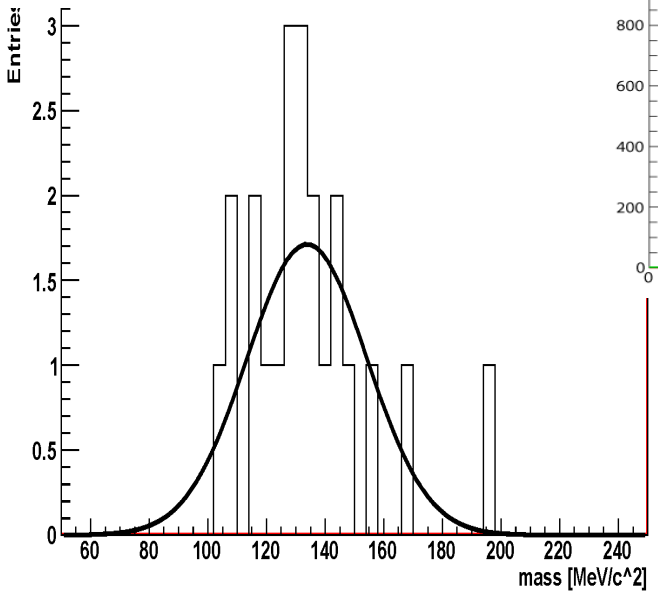
- *invariant mass of π_0*
- *dE/dx (single vs. double MIP)*
- *γ conversion point separated from primary vertex*

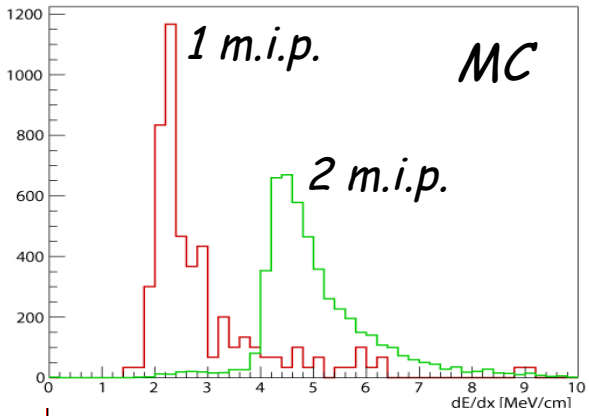
MC: single electrons (Compton)

MC: e^+ e^- pairs (γ conversions)

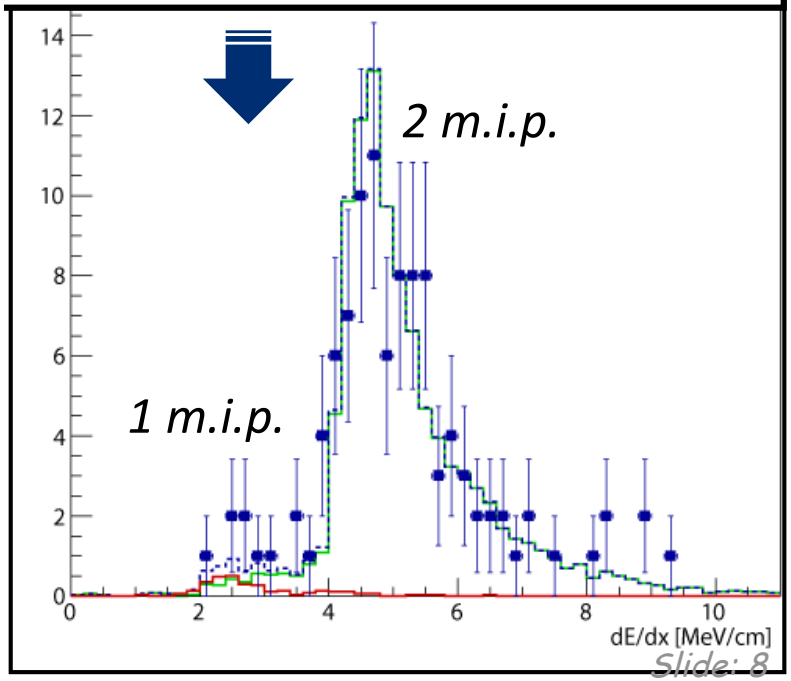
data: EM cascades (from π^0 decays)

Mγγ:133.8 ± 4.4 ± 4 MeV/c²



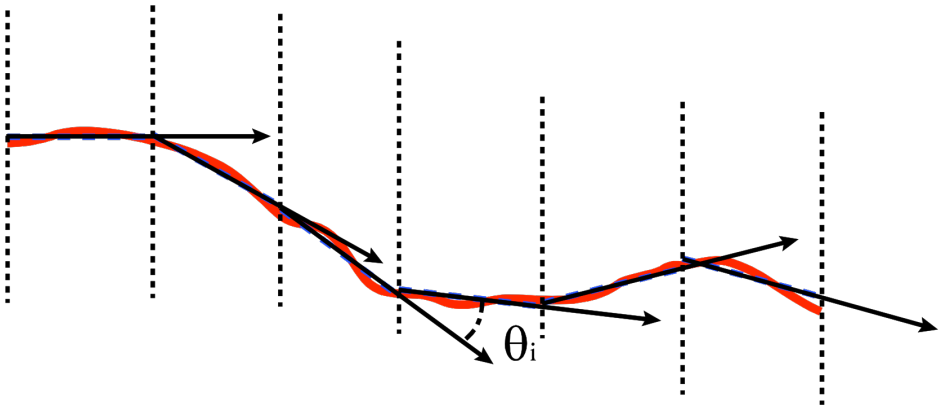


Unique feature of LAr Crucial for ν_e physics



Measurement of muon momentum via multiple scattering

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

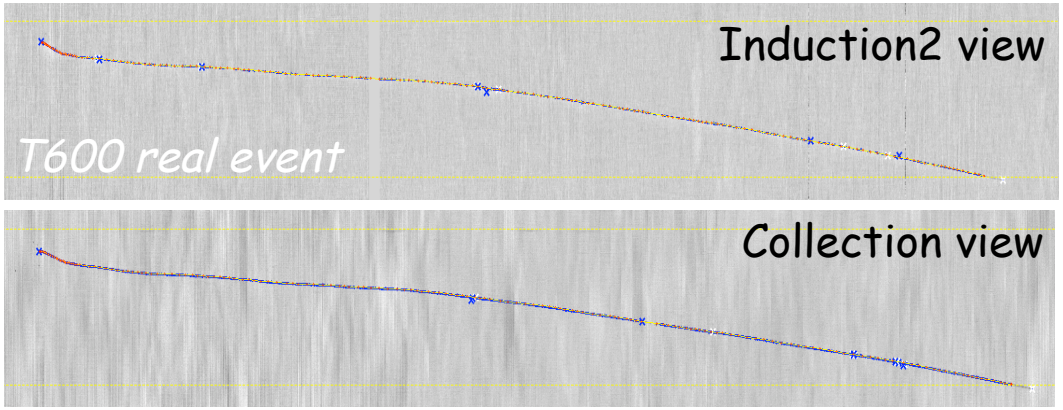


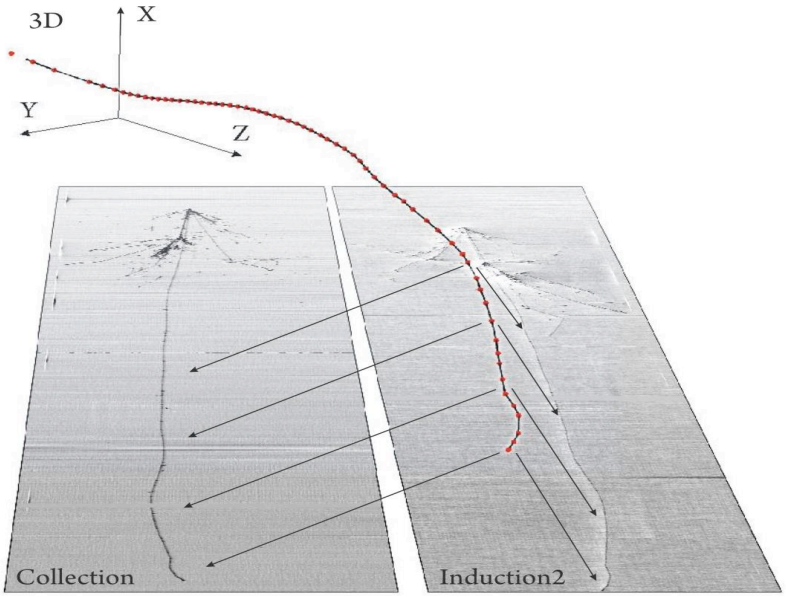
$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$

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

- Momentum reconstruction in ICARUS:
  - Accurate, automatic track cleaning from Bremsstrahlung, δ rays and crossing tracks
  - Track splitting into "segments", optimized to enhance MS contribution w.r.t. errors (estimated event-by-event)
  - "$\chi^2(p)$" built on the base of angles between consecutive segments permits to estimate muon momentum and errors

3D reconstruction



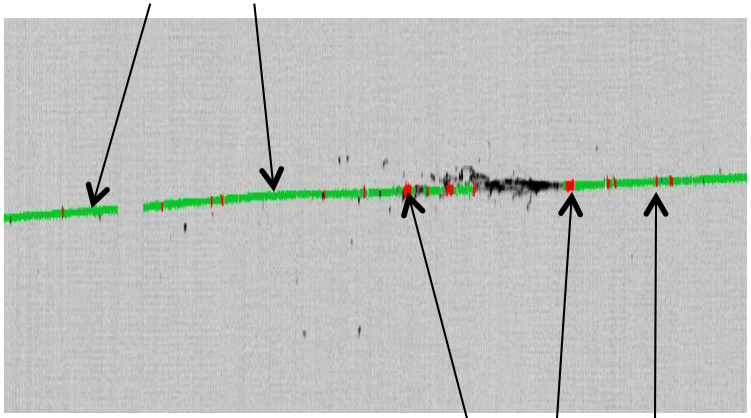


Simultaneous **3D** polygonal fit →**2D**
hit-to-hit associations no longer needed

Adv.High Energy Phys. 2013 (2013) 260820

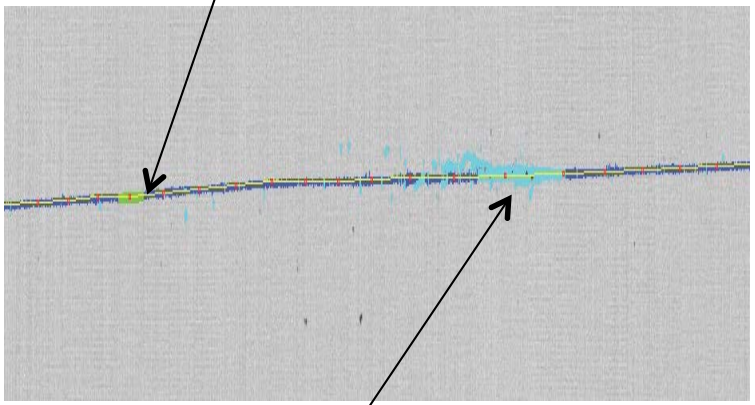
Track cleaning

Muon hits used for MS



Identified δ rays

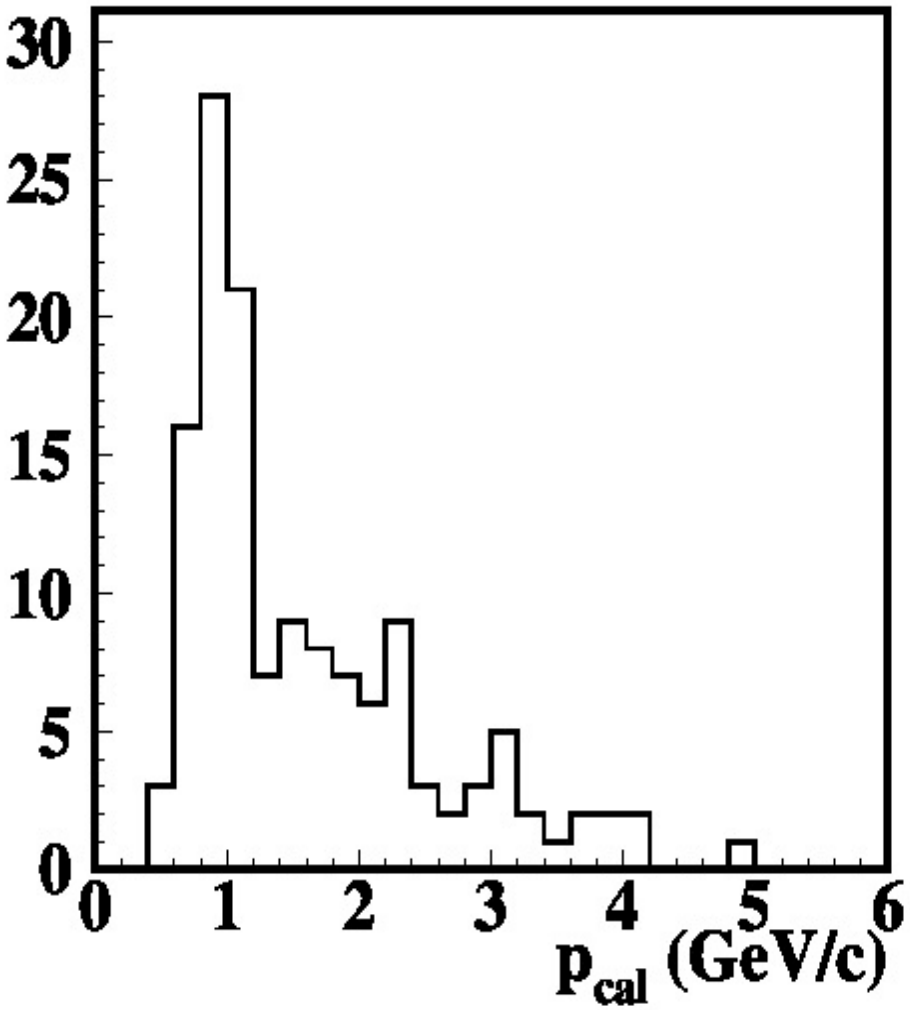
Filling missing wires for dE/dx estimate



Bremsstrahlung

Measurement of μ-stop momentum via multiple scattering

- Horizontal μ-stop in the T600 are an excellent benchmark

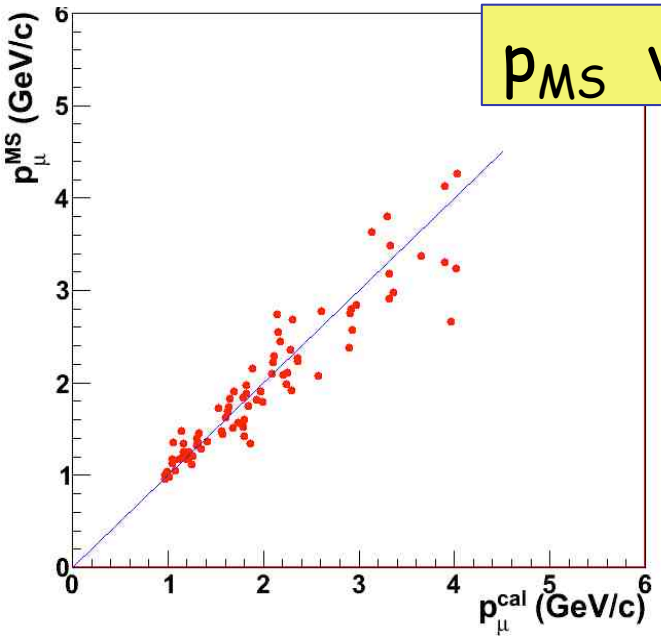


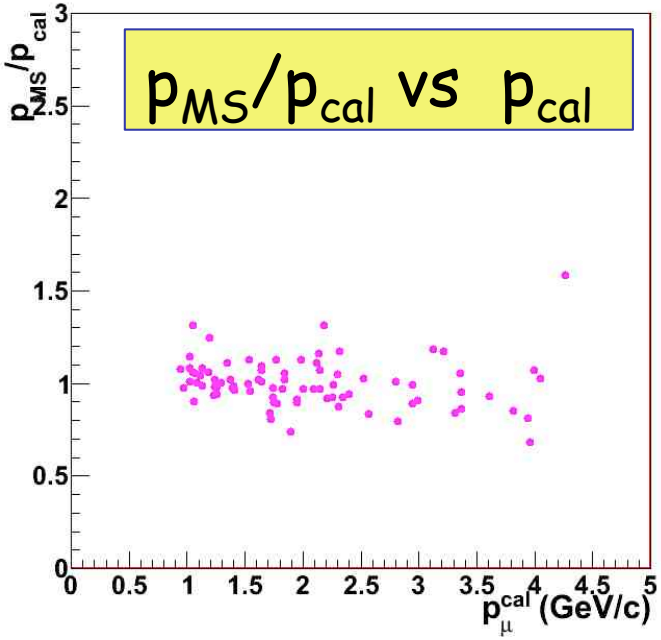
- Calorimetric measurement is possible with resolution and bias < 1%
- The energy range (0.5-4 GeV) is perfectly matched to those of future short and long baseline experiments

- A sample of 130 stopping muons from CNGS ν interactions in the upstream rock has been selected and analyzed (length > 2.5 m)

Muon momentum reconstructed by calorimetric measurement for the stopping muon sample

MS vs. calorimetry comparison

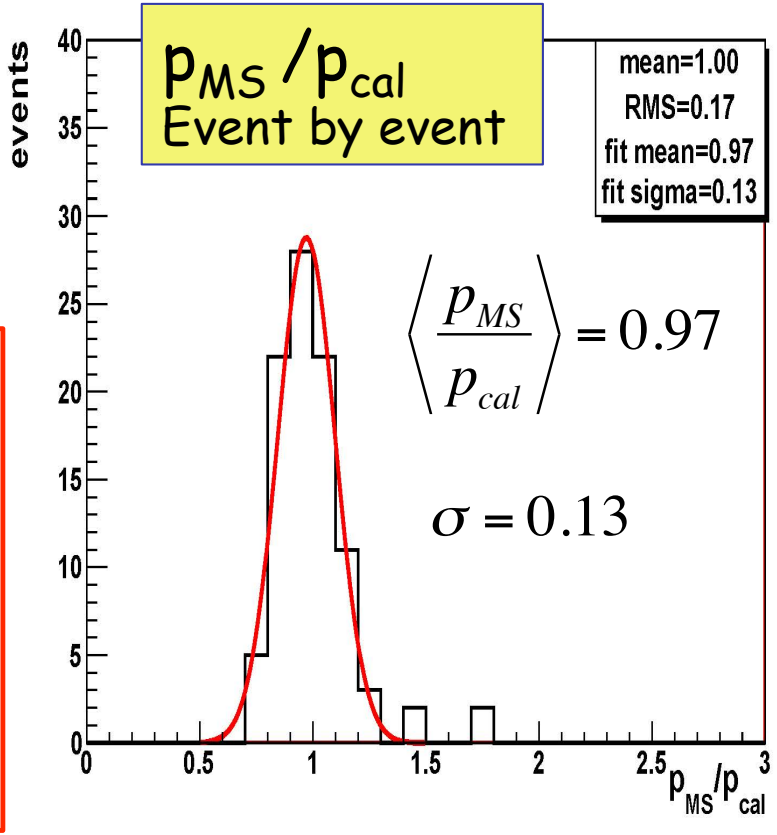




Excluding the last 1.5 m of track, to really mimic escaping muons

More statistics coming

Muon p determination by MS is possible with a resolution ≈ 13% in the momentum range of interest for future LAr TPCs



Extension to much higher energies /complex CNGS ν_μCC events: ongoing

evaluation/correction of possible detector effects

ICARUS and the sterile neutrino puzzle

- Significant evidence of $\nu_\mu \rightarrow \nu_e$ transitions from LSND experiment, with L/E~ 1 m/MeV. MiniBooNE results do not fully confirm or rule out LSND.

- In recent years, many hints to (anti-)neutrino oscillations in a similar L/E range

- LSND's most likely interpretation, if confirmed, is the existence of at least a 4th sterile neutrino flavor, mixing with $\Delta m^2 \approx 10^{-2} \div 1$ eV^2

Anomaly	*Source*	*Type*	*Channel*	*Significance*
LSND	*Short baseline*	*Decay at rest*	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ *appear.*	3.8 σ
MiniBooNE	*Short baseline*	*Neutrino beam*	$\nu_\mu \rightarrow \nu_e$ *appear.*	3.0 σ → 3.4 σ
MiniBooNE	*Short baseline*	*Anti-neutrino beam*	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ *appear.*	1.7 σ → 2.8 σ
Gallium	*Electron capture*	*Source*	ν_e *disapp.*	2.7 σ
Reactors	*Fission*	*Beta decay*	$\bar{\nu}_e$ *disapp.*	3.0 σ → 1.4 σ

Recent MiniBooNE results PRL 110, 161801 → improve anomaly significance
C. Zhang et al. arXiv 1303.0900 → reduce reactor anomaly significance

ICARUS-T600 is addressing the LSND claim for a large fraction of parameter space

A search for LSND effects with ICARUS at CNGS

$\nu_\mu \rightarrow \nu_e$ signal from the CNGS ν_μ beam at: L = 730 km, $10 \leq E_\nu \leq 30$ GeV

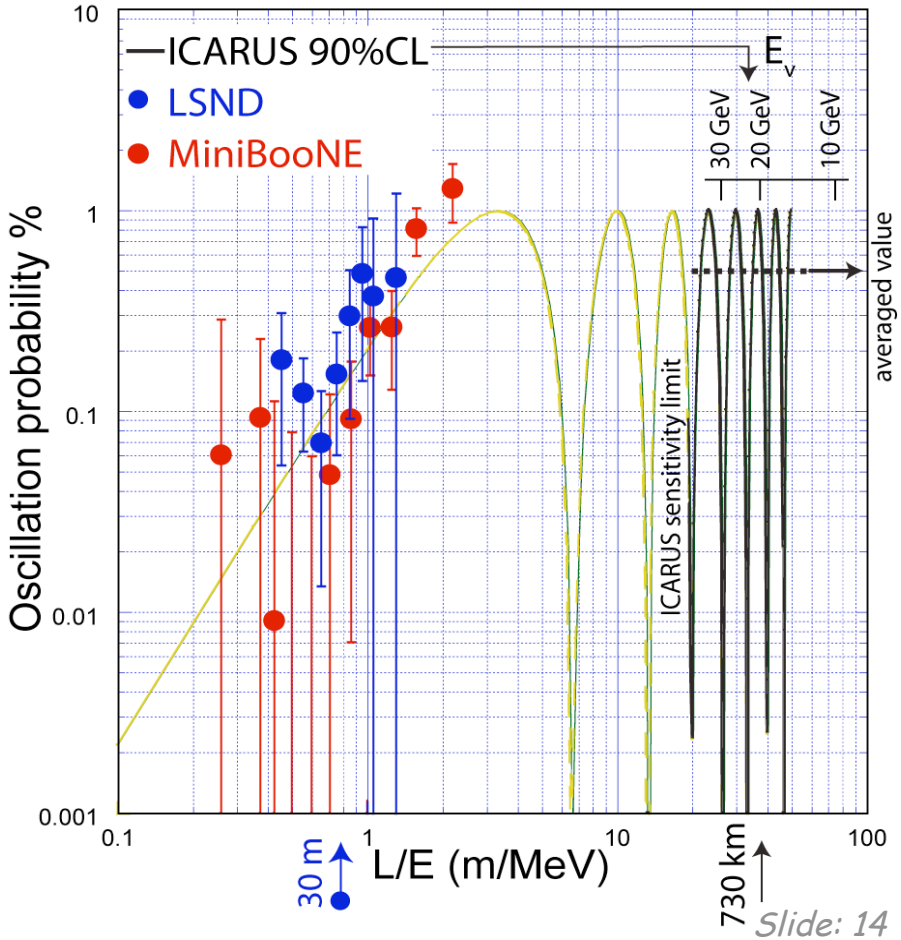
- Differences w.r.t. the LSND experiment:
  - $L/E_\nu \approx$ **1 m/MeV at LSND**, but $L/E_\nu \approx$ **36.5 m/MeV at CNGS**

- LSND-like short distance oscillation signal averages to: $\sin^2(1.27\Delta m^2_{new} L/E) \approx 1/2$ and: $\langle P \rangle_{\nu\mu\rightarrow\nu e} \approx 1/2 \sin^2(2\theta_{new})$

- In the ICARUS L/E region, contributions from standard neutrino oscillations are not too relevant, unlike other LBL experiments i.e. MINOS, T2K.

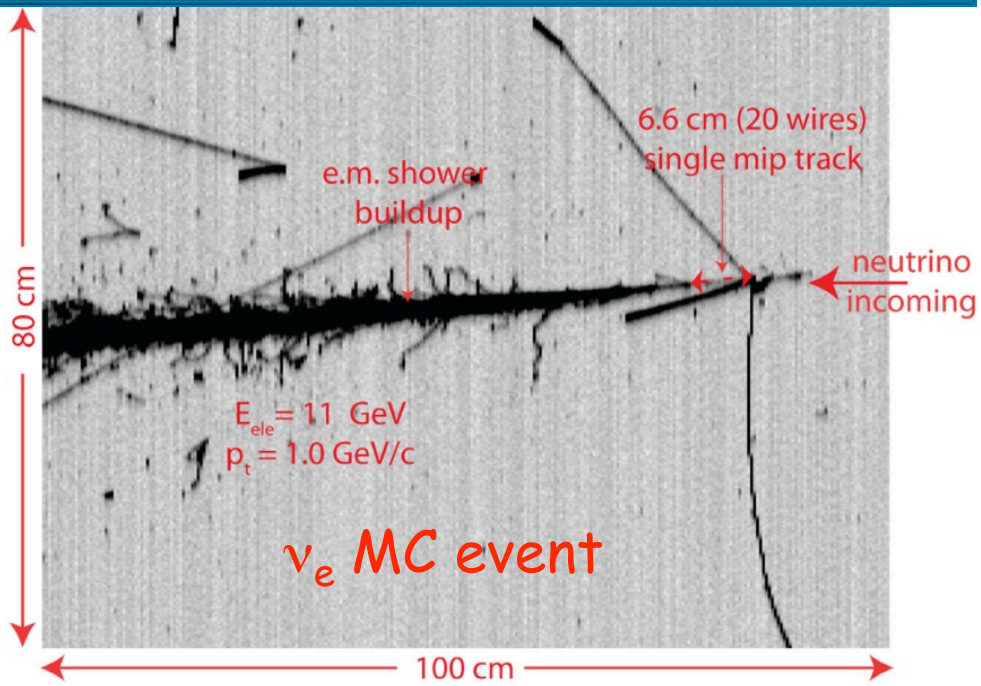
- LAr-TPC allows to identify individual ν_e events and to reject NC π^0 background events with high efficiency

Updated results presented here refer to 1995 ν interactions (6.0×10^{19} pot)



Selection of ν_e events

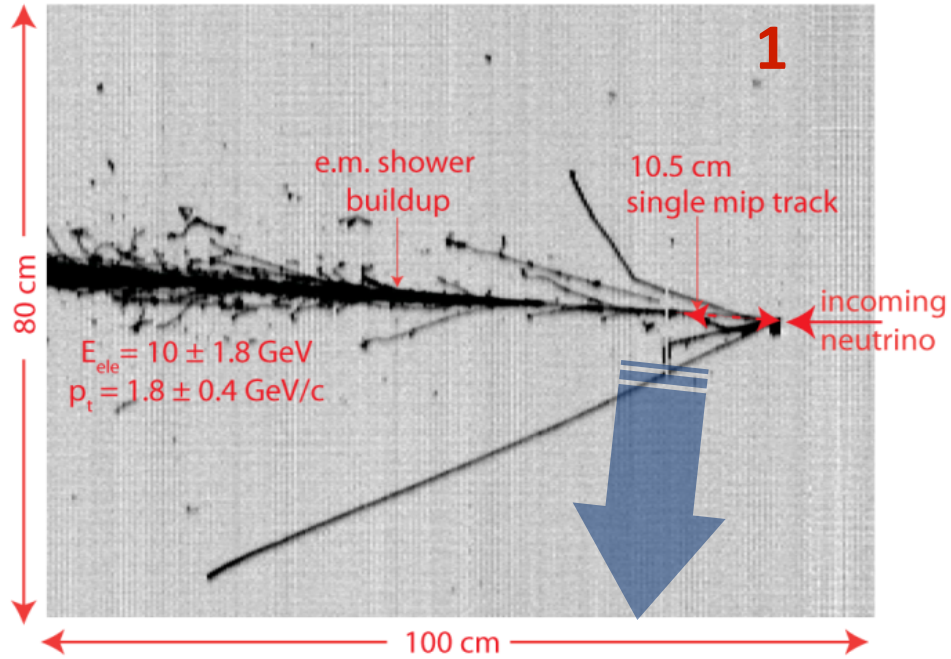
- POSITION AND ENERGY CUTS:
  - Primary vertex at > 5 cm from TPC walls (50 cm downstream) for shower identification
  - Visible energy <30 GeV (beam extends to higher E_ν), only 15% signal events rejected

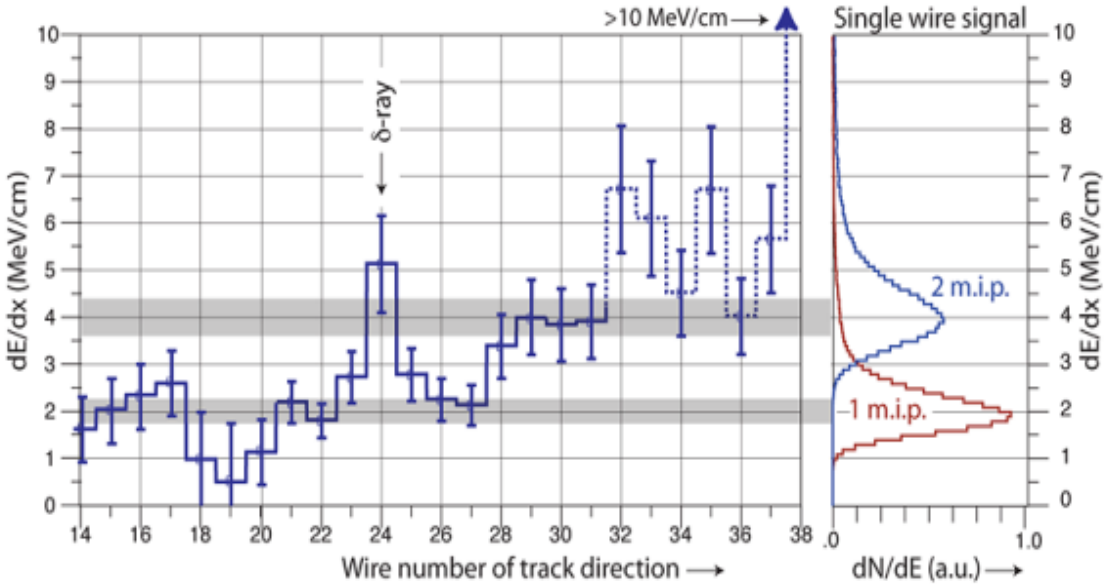


- ELECTRON SIGNATURE:
  - A charged track from primary vertex, m.i.p. on 8 wires, subsequently building up into a shower (very dense sampling: every 0.02 X_0)
  - Clear separation (150 mrad) from other ionizing tracks near the vertex in at least one of 2 transverse views
- ν_e selection efficiency studied with a sophisticated simulation: η=0.74±0.05
  (for intrinsic ν_e background, η' = 0.65±0.06 due to harder spectrum)

Background estimation from intrinsic ν_e beam, θ_{13}~9^0 and $\nu_\mu \rightarrow \nu_\tau$ oscillations is 6.4±0.9

4 ν_e events observed on 1995 neutrinos





Reconstruction:

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

(2) E_{tot} = 17 GeV,
p_t = 1.3 ±0.18 GeV/c

(3) E_{tot} = 27 ± 2.0 GeV,
p_t = 3.5 ± 0.9 GeV/c

(4) E_{tot} = 14 ± 1 GeV,
p_t = 1.2 ±0.2 GeV/c

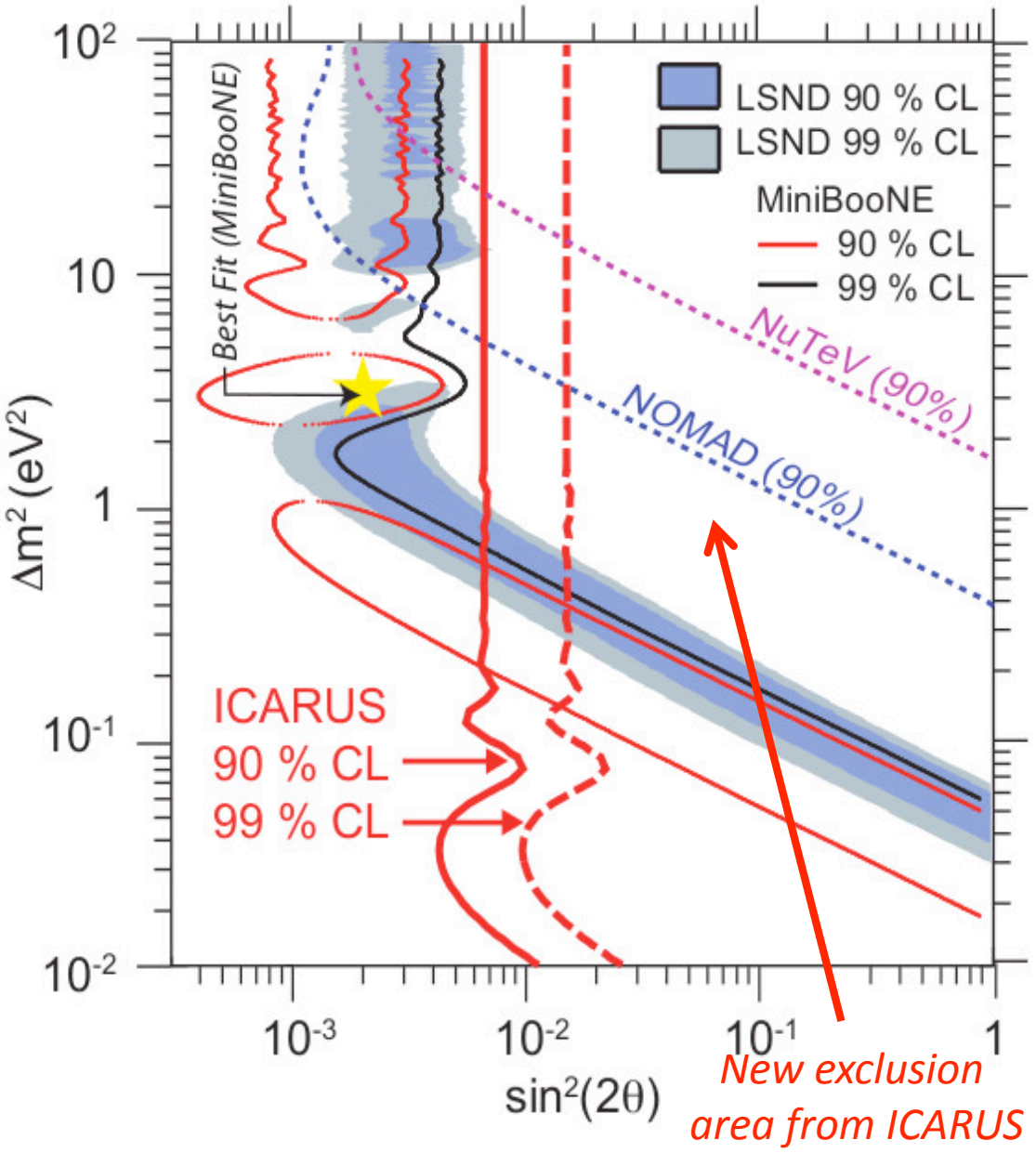
In all events: single electron shower clearly opposite to hadronic component in the transverse plane

Results on LSND-like anomaly

- The first ICARUS result (Eur. Phys. J. C 73) based on 1091 ν interactions ($3.3\ 10^{19}$ pot) ruled out most of LSND anomaly parameter region, indicating a narrow region around $(\Delta m^2 \sin^2 2\theta)=(0.5 eV^2\text{-}0.005)$ where all results are compatible.
- New updated analysis with almost doubled statistics $\Rightarrow$ in total 6.0×10^{19} pot and 1995 ν events
- Limits on number of events:

  3.7 (90% CL) 8.3 (99% CL)
- Limits on oscillation probability:

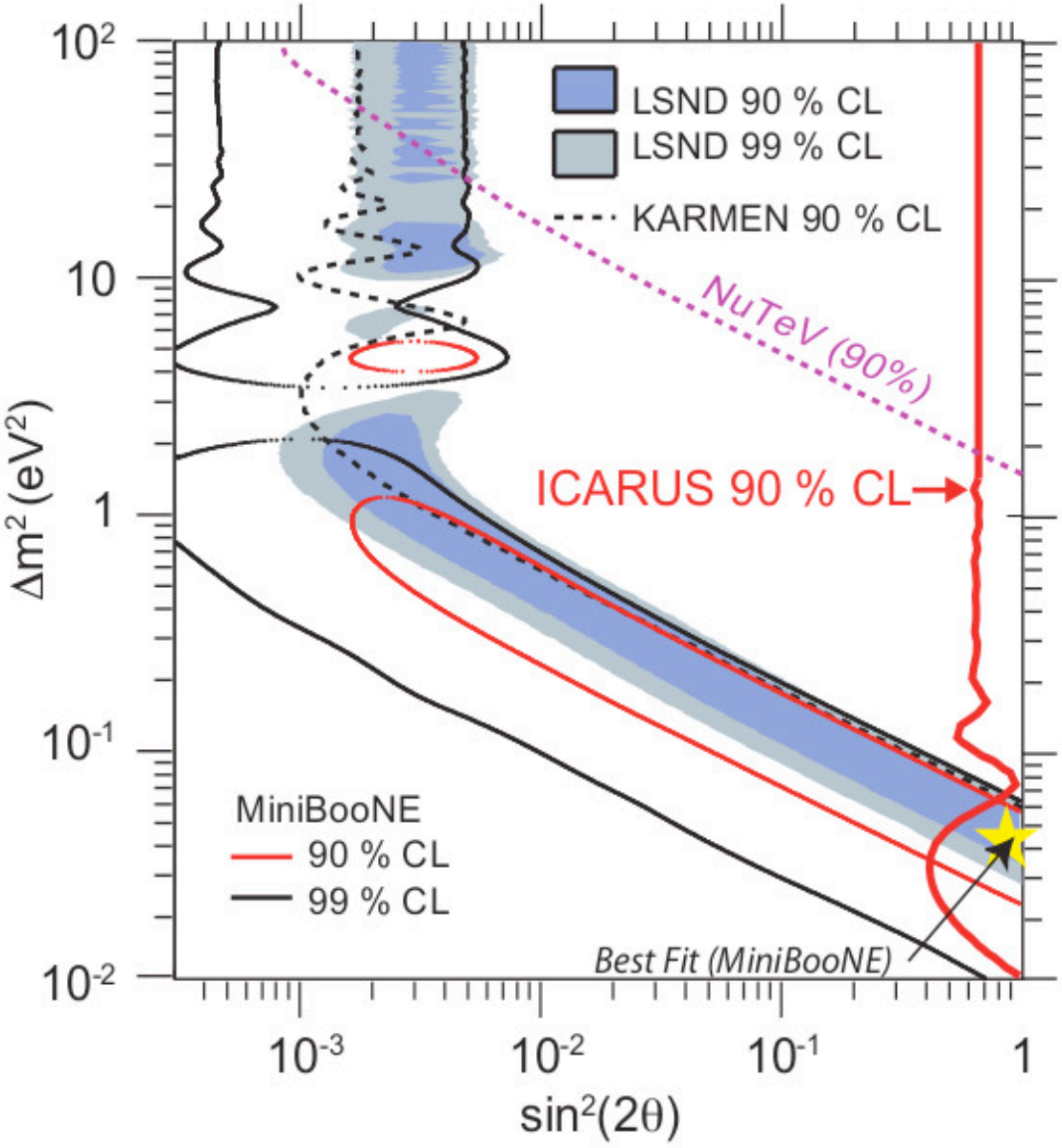
  $P_{\nu\mu\rightarrow\nu e} \leq 3.4\ 10^{-3}$ (90% CL)
  $P_{\nu\mu\rightarrow\nu e} \leq 7.6\ 10^{-3}$ (99% CL)



arXiv:1307.4699, submitted to EPJC

Search for antineutrino oscillation

- A test of "LSND-like" antineutrino oscillation can be performed using the anti-ν_μ contamination in the CNGS beam (2%); search for appearance of anti-ν_e (signature is identical to ν_e)
- The absence of an anomalous anti-ν_e excess gives a limit of 4.2 events @90% C.L.
- Large $\sin^2 2\theta$ solutions in LSND/MiniBooNE antineutrino parameter space are excluded.



arXiv:1307.4699, submitted to EPJC

Conclusions and outlooks

- ICARUS-T600 just ended 3-years of continuous, smooth & safe operation at LNGS collecting CNGS ν's and cosmics
- The successful long-term operation of a large LAr-TPC in an underground laboratory paved the way for a promising future of this detection technique
- Analysis of the full collected CNGS sample and cosmic data is ongoing
- First physics results were published on:
  - Neutrino velocity (high precision measurement)
  - LSND ν_e excess anomaly (most of the neutrino parameter region ruled out)
- Detector decommissioning/dismantling is ongoing; the T600 will soon be moved to CERN for refurbishing and further R&D activity with test beams
- Partnership with LBNE project ensures a long-term future for LAr-TPC technology


Thank you !

Backup Slides

ν_e CC events in the data

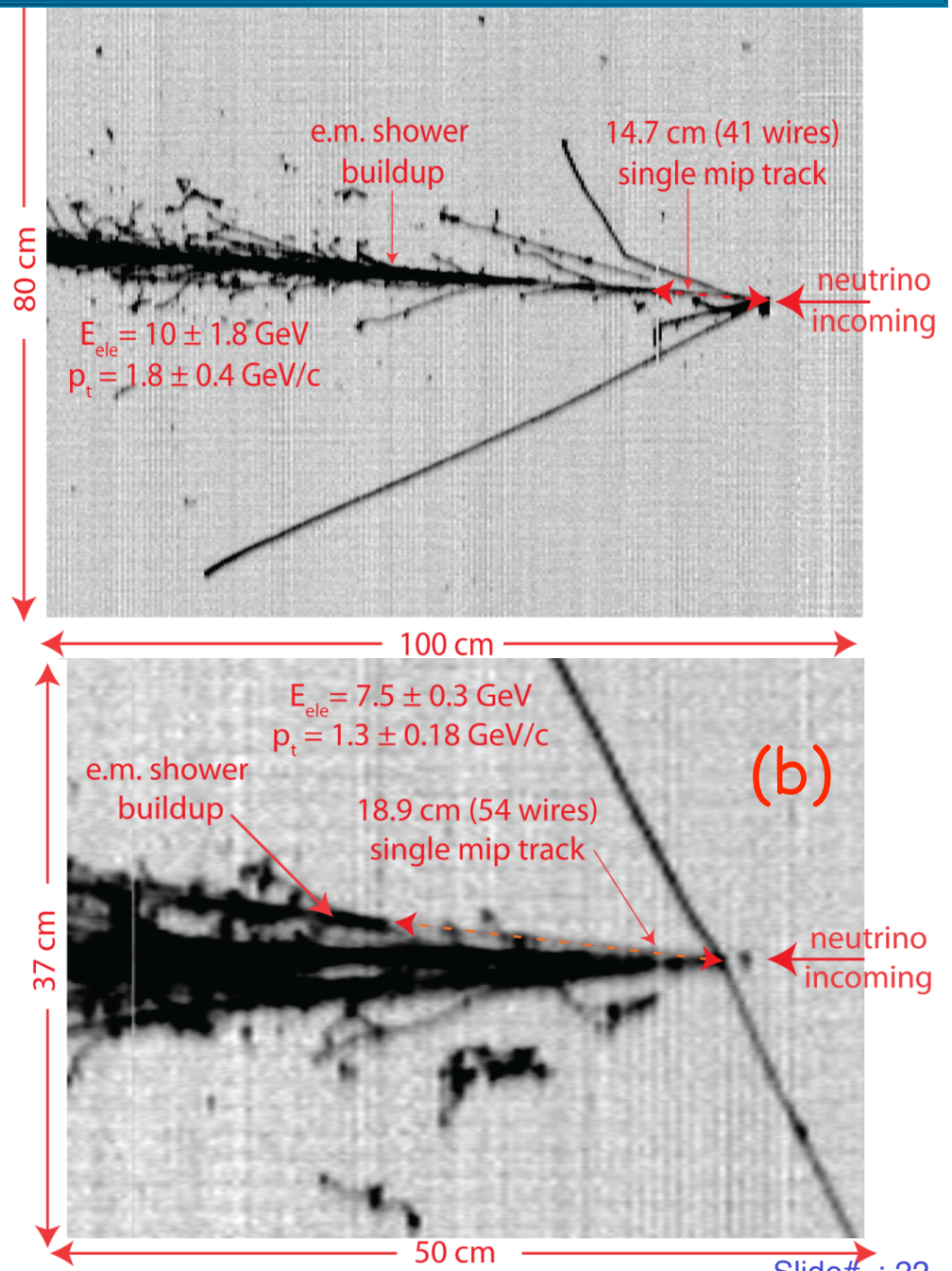
- Two T600 ν_e events (a) and (b) with E_{dep}<30 GeV with a clearly indentified electron signature from a total sample of 1091 neutrino interactions - 3.3 10^{19}pot

(a) total energy: 11.5 ± 1.8 GeV
P_t = 1.8 ± 0.4 GeV/c

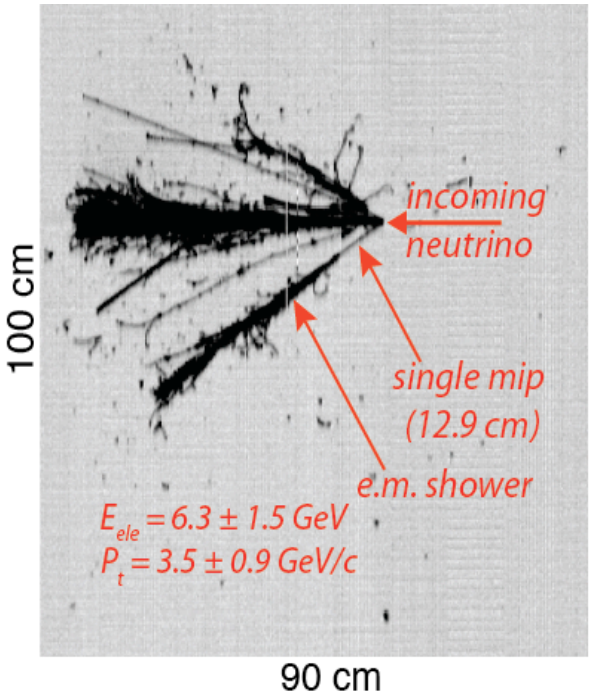
(b) total visible energy: 17 GeV
P_t = 1.3 ±0.18 GeV/c

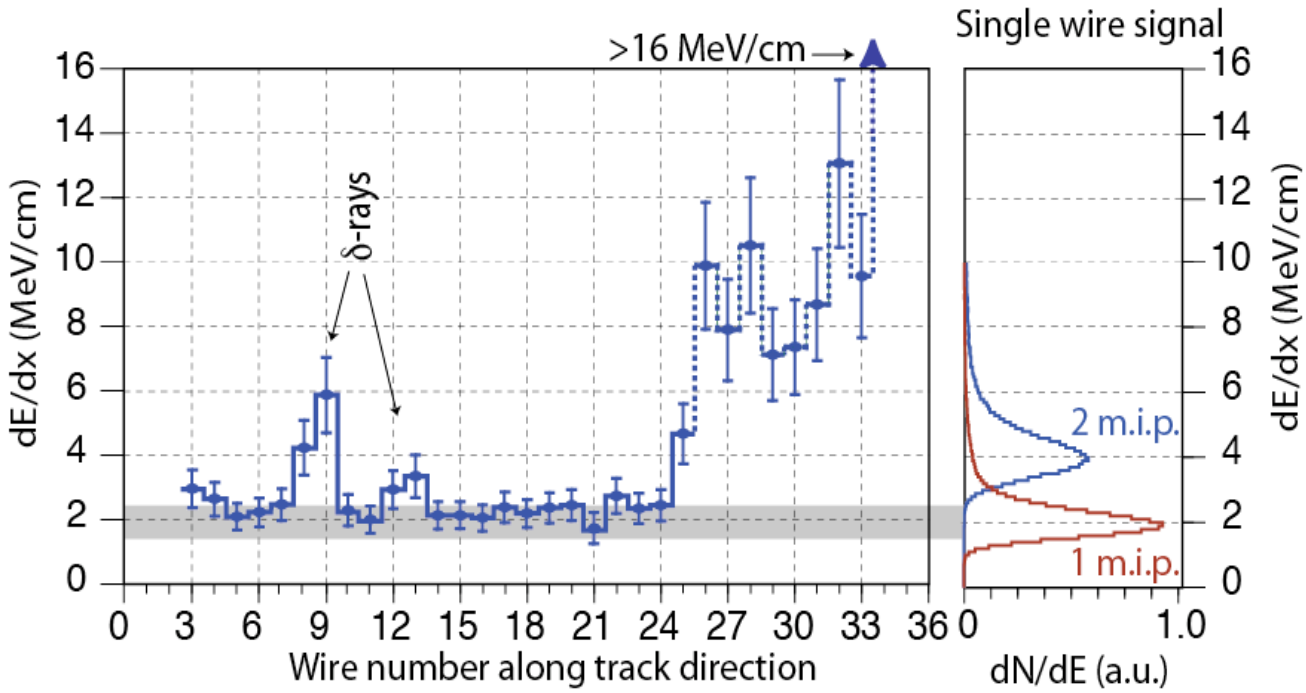
to be compared with 3.7 backg. expected events mainly from the intrinsic ν_e beam component.

- In both events the single electron shower in the transverse plane is clearly opposite to the remaining of the event.



Event n. 3



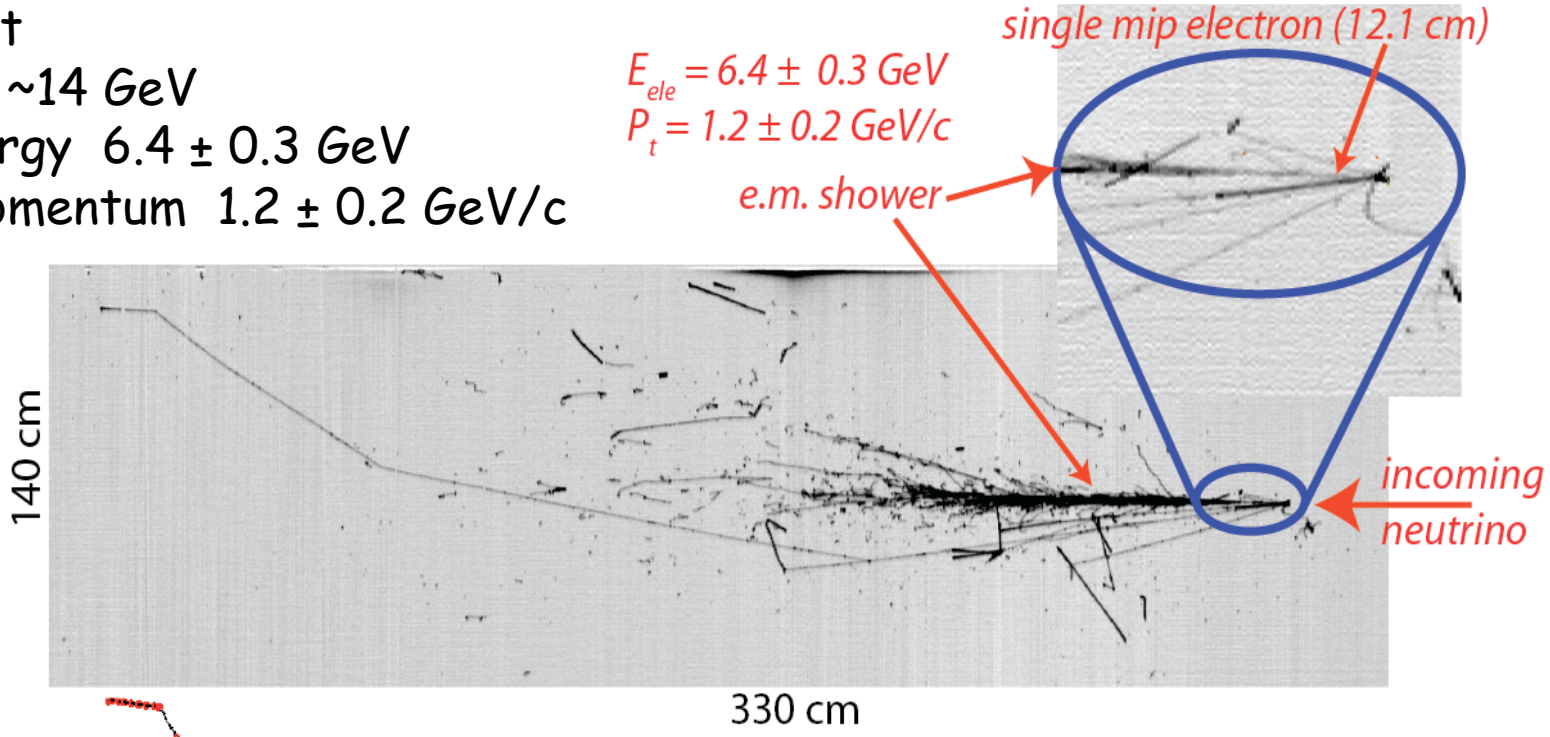


- Experimental pictures of the third event with a clear electron signature
- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is shown along the individual wires.
- The event has a total energy of ~27 GeV and an electron of 6.3 ± 1.5 GeV with a transverse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

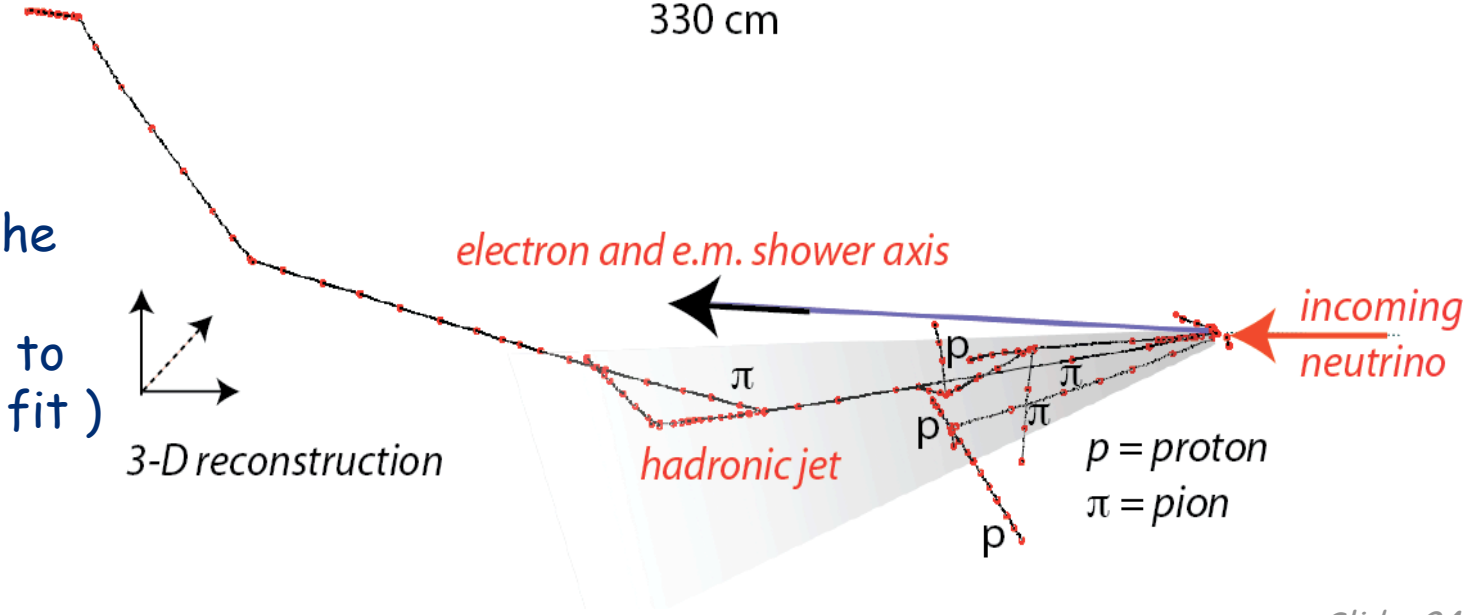
Event N.4

Fourth ν_e event

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

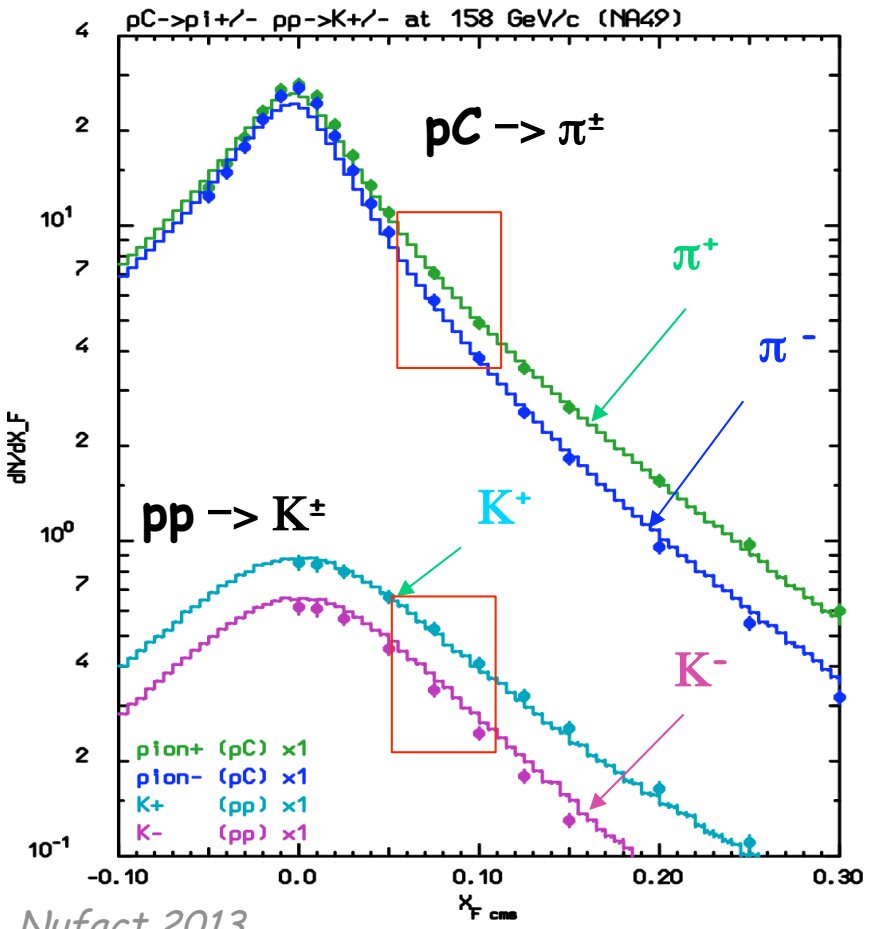


3D reconstruction of primary particles in the event
(red dots correspond to vertices of polygonal fit)



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 %.

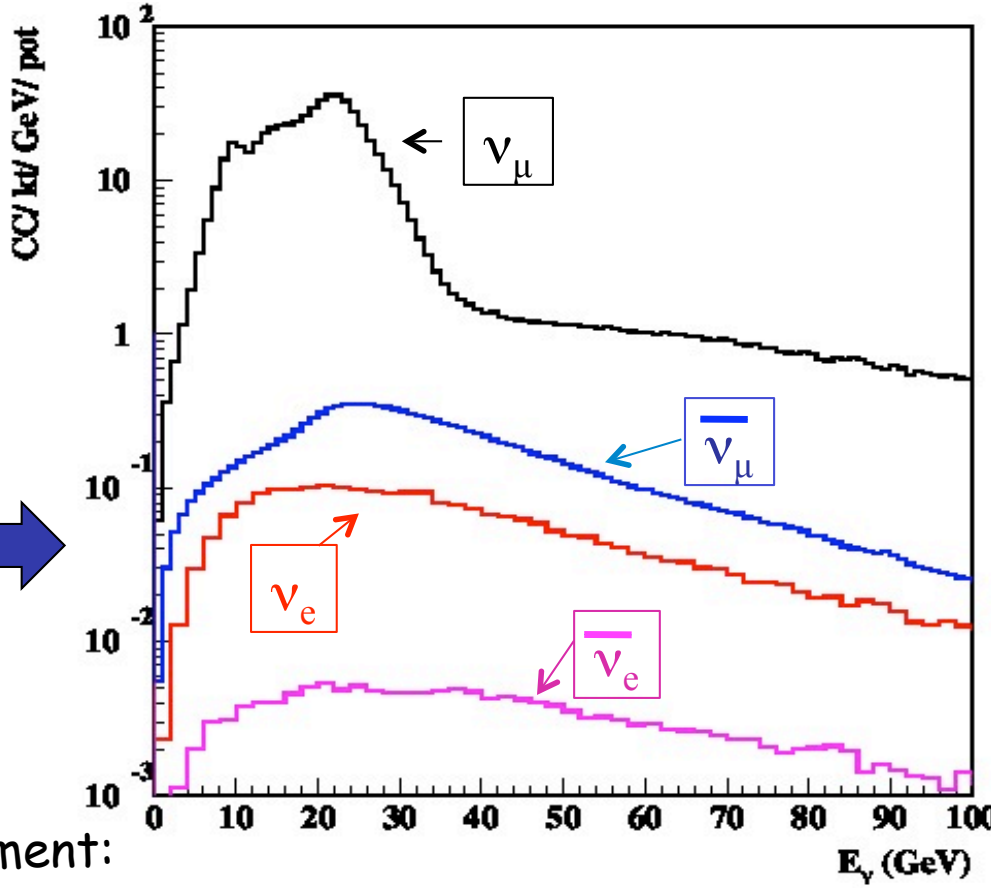
Conservative estimate on ν_e / ν_μ : 10%

Work in progress for next analyses

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

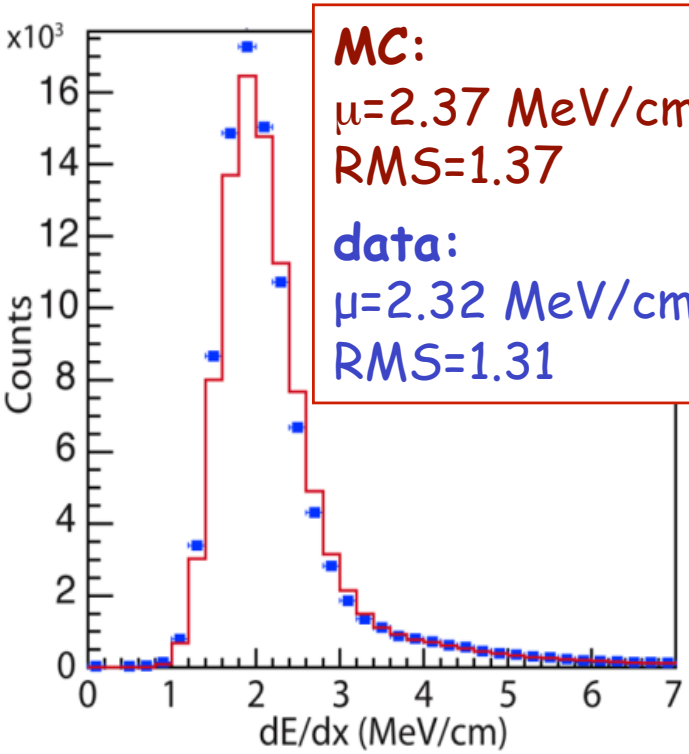
Expected CNGS neutrino CC spectra at LNGS



- 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 $\langle P \rangle \nu_\mu \rightarrow \nu_e \approx \frac{1}{2} \sin^2(2\theta_{new})$
- 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..

Sources of systematic errors : 2

Effect of 30 GeV energy cut on background estimate:



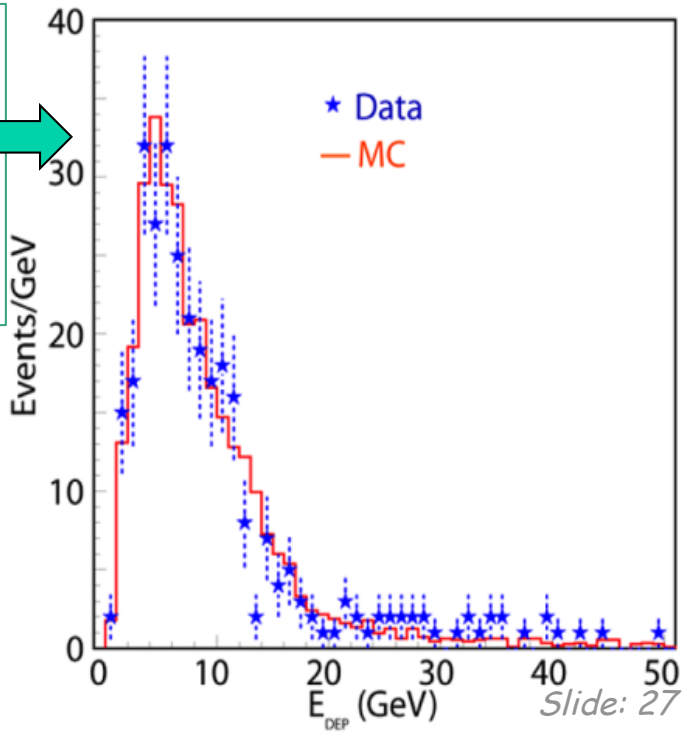
MC:
μ=2.37 MeV/cm
RMS=1.37

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%
S/N from Landau + gaussian ≈ 10

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



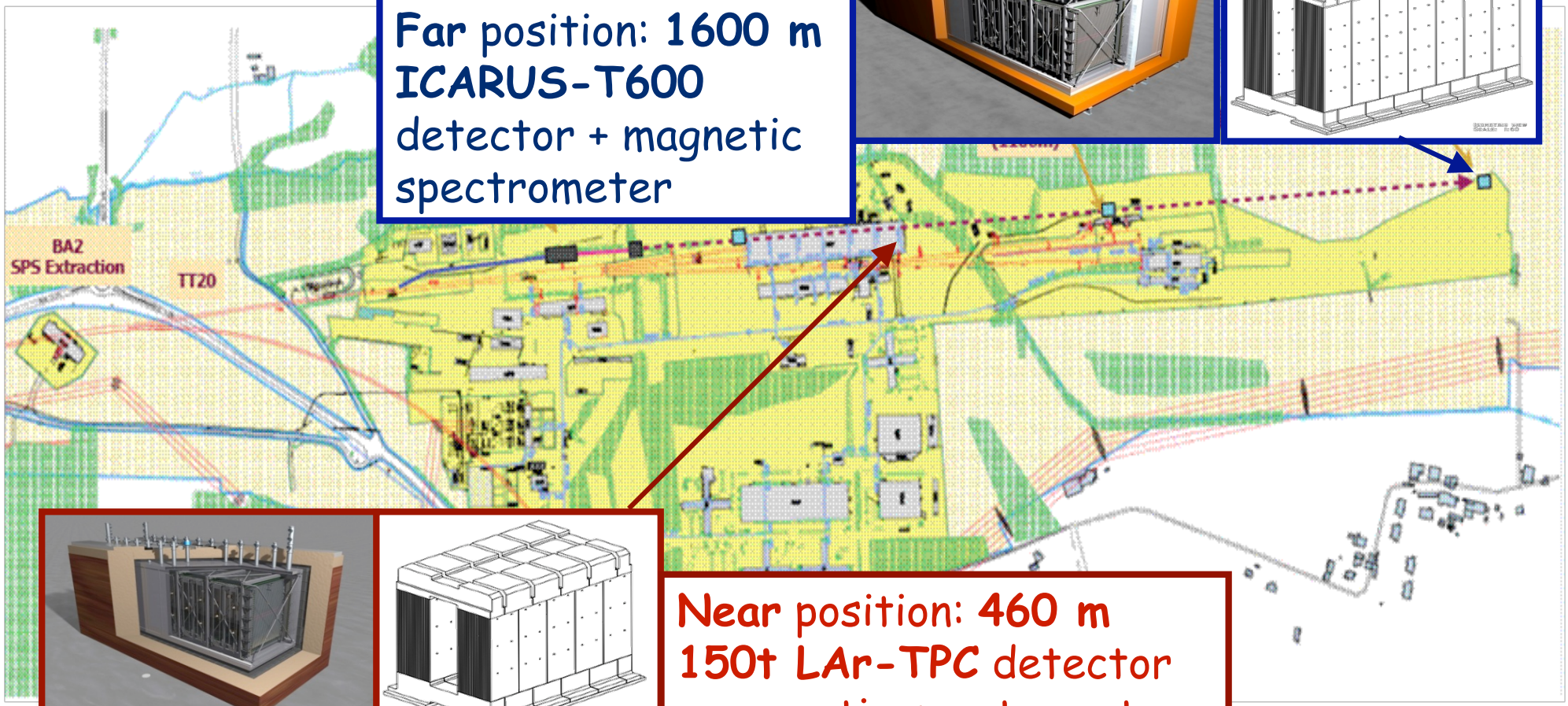
- Agreement data-MC on dE/dx and total energy better than 2.5%
- Applied to ν_e spectrum→ uncertainty < 10%

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 ν and anti-ν focussing



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

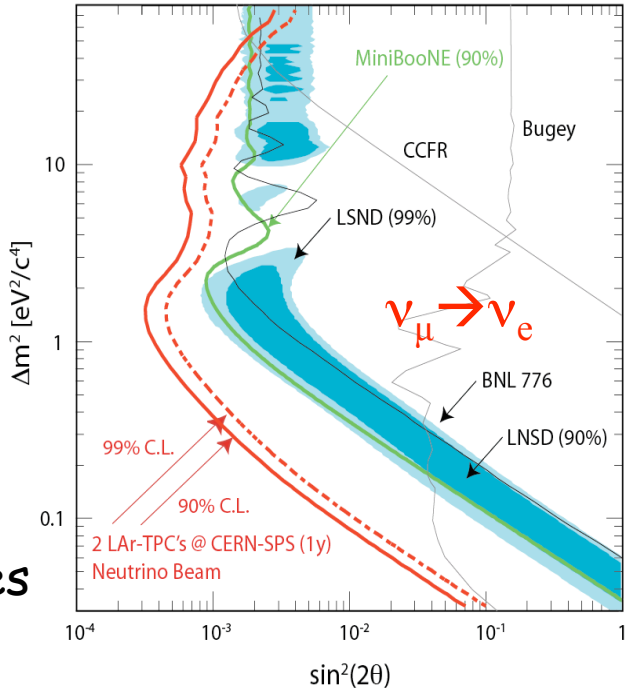
Near position: **460 m**
150t LAr-TPC detector
+ magnetic spectrometer

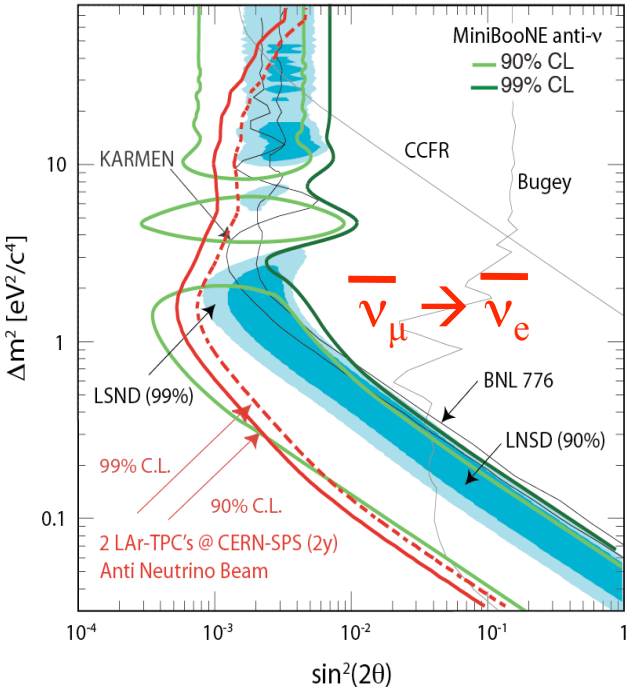
Exploring all channels: expected sensitivity

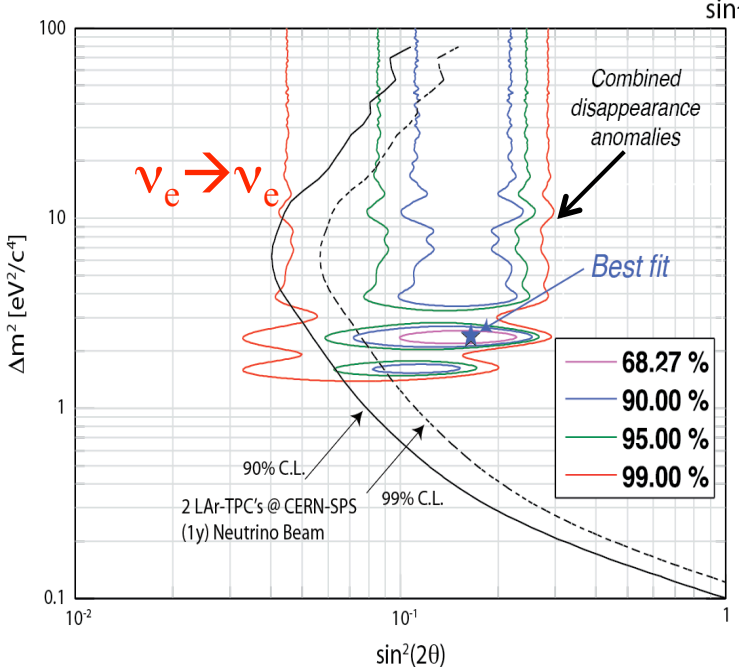
e-appearance

1 year ν_μ beam (left)
2 year anti-ν_μ beam (right)
for 4.5 10^{19} pot/year,
3% syst. uncertainty
on ν energy spectrum.

LSND allowed region is
fully explored in both cases





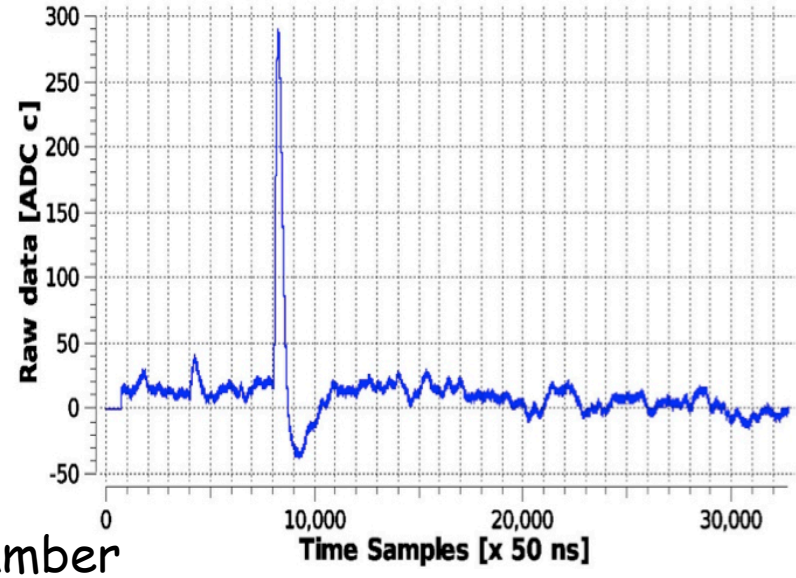


e/μ-disappearance:
1 year ν_μ beam (left)
1 year ν_μ + 2 years anti-ν_μ
beams (right)

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

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



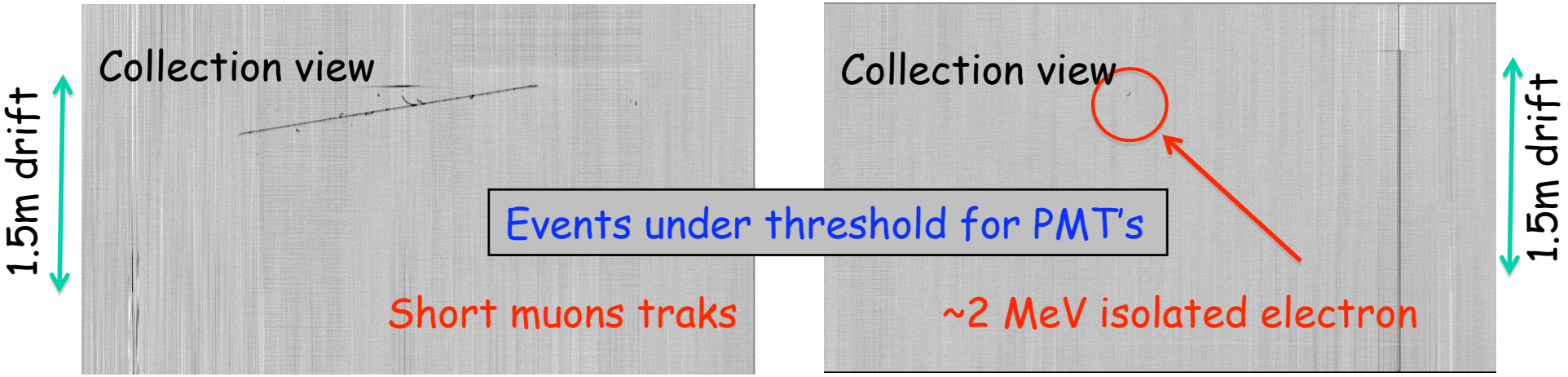
- CNGS neutrino trigger:
  - PMT-Sum signal (thr. ~100 phe) for each chamber in coincidence with CNGS "Early Warning" beam gate (60 μs)
  - ~80 triggers/day (few tens events expected).
- Cosmic Rays trigger:
  - PMT-Sum signal coincidence of two adjacent chambers (50% central cathode transparency)
  - ~130 events/h (~160 expected)

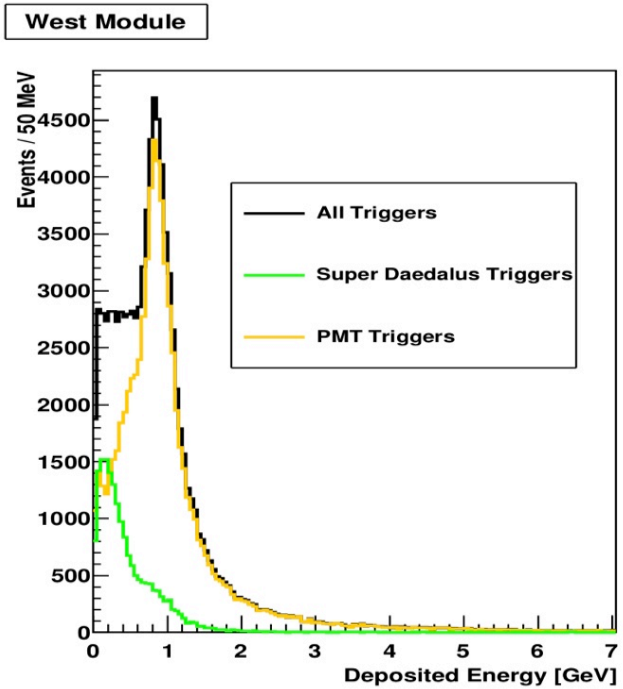
Preliminary analysis done, needing a more detailed study of the collected data and comparison with MC simulation.

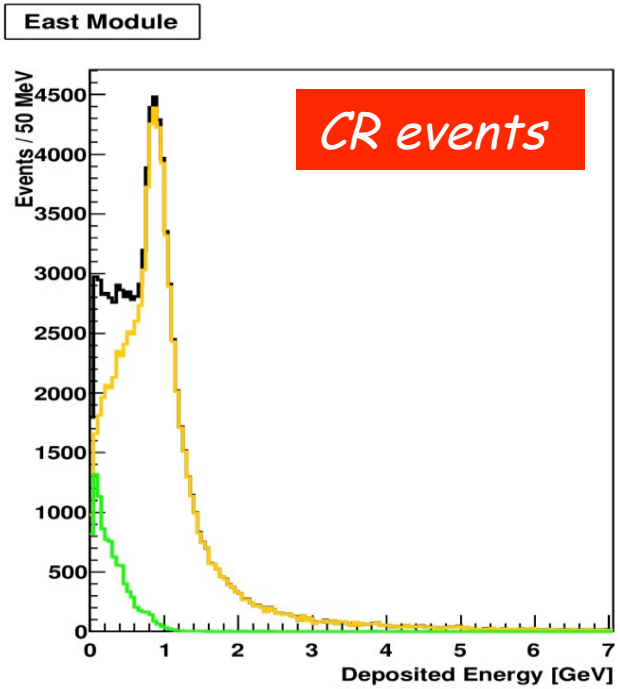
Slide 30

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







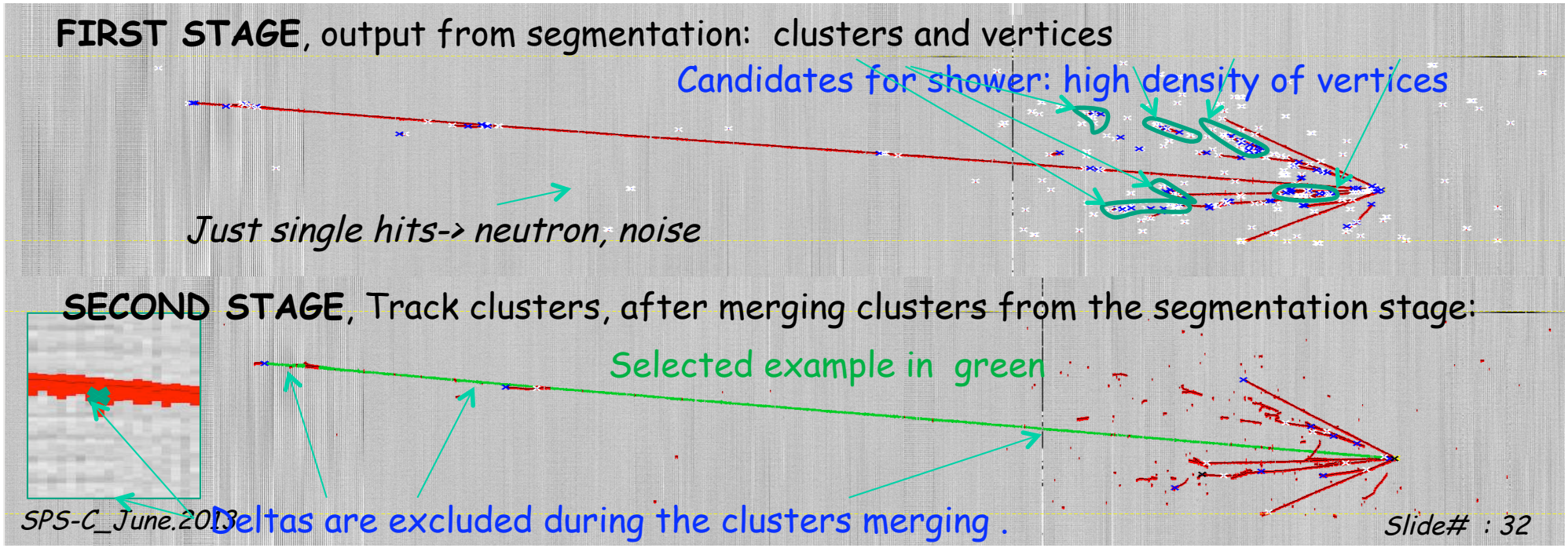
Used to improve the cosmic ray/CNGS trigger efficiency in 0.1 – 1 GeV range

An efficient data reduction system 0-skipping

Slide 31

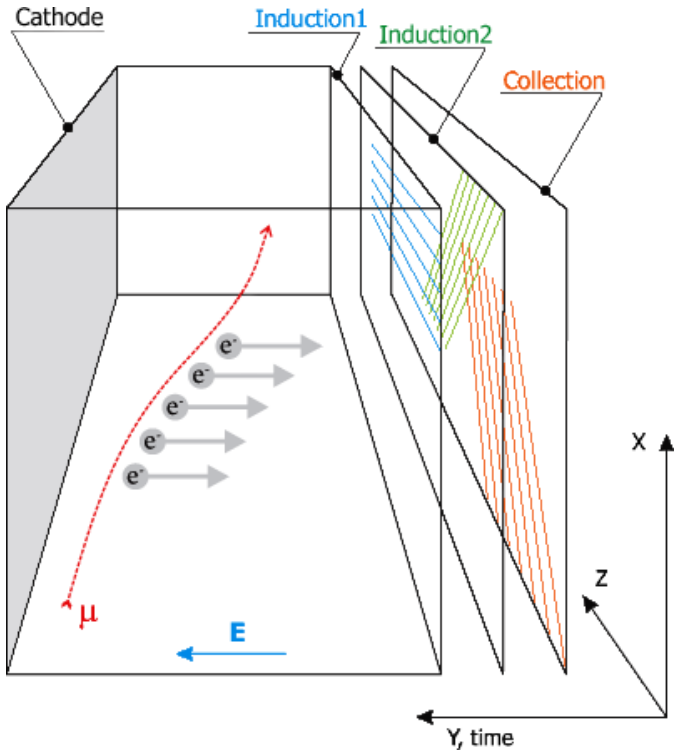
Automation of reconstruction

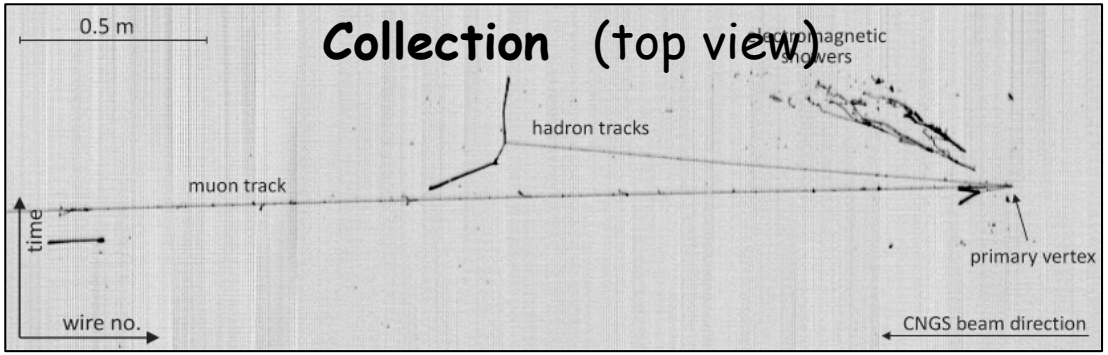
- CNGS ν event primary vertex: automatic reconstruction
  - Validation with visually identified CNGS vertices
  - algorithm efficiency ~ 97%
- automatic event segmentation algorithm
  - Track identification
  - Shower identification
  - Ready in 2D, to be extended in 3D

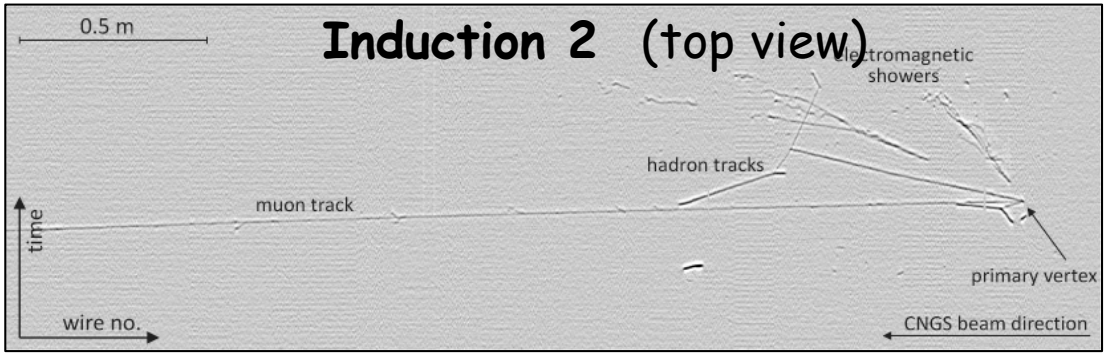


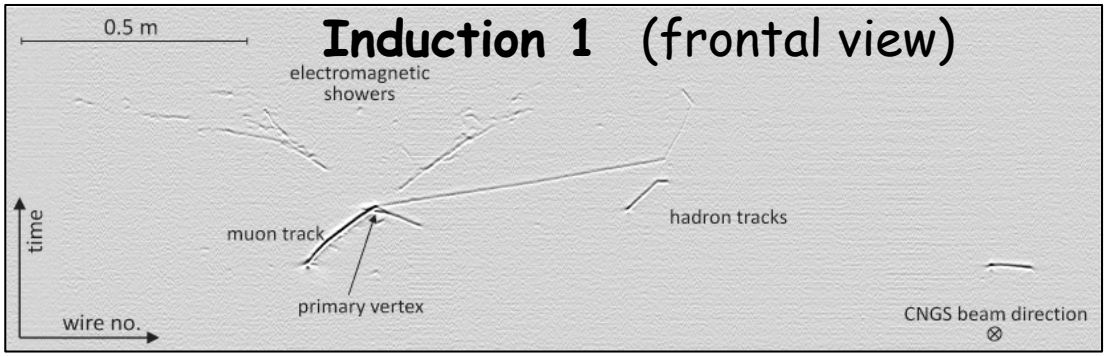
ICARUS LAr-TPC detection technique

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



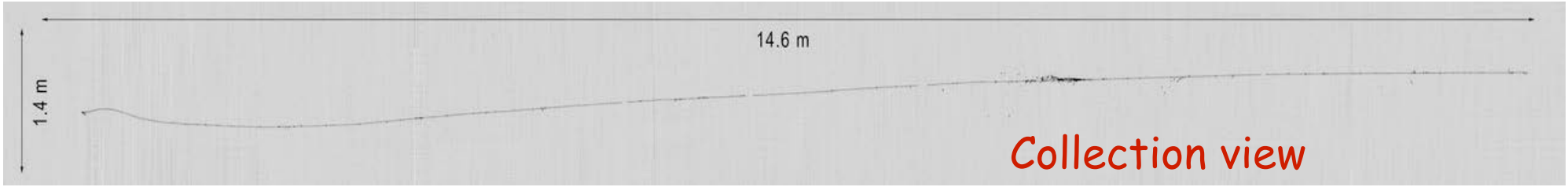


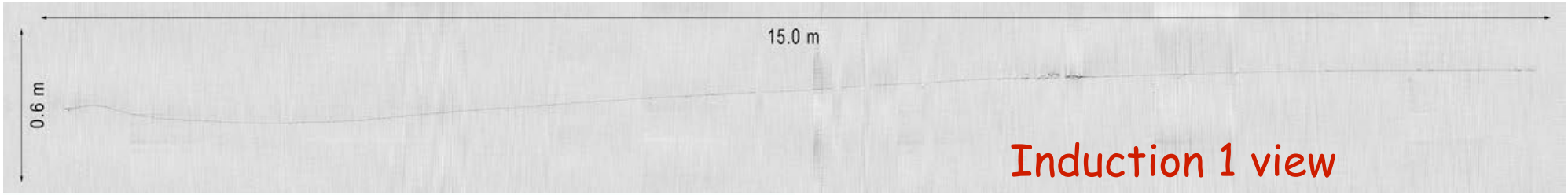


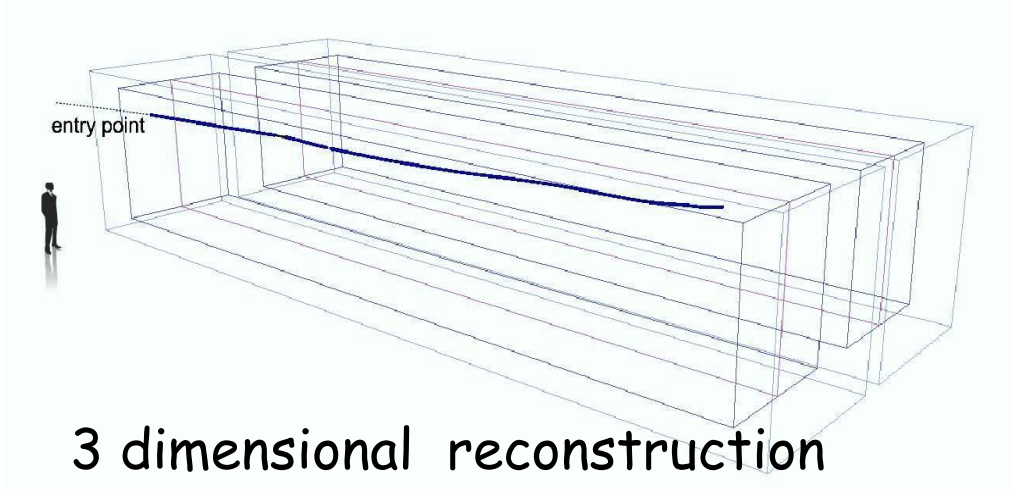


CNGS ν_μ charged current interaction

The method







3 dimensional reconstruction

Two method developed for ICARUS:

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

- 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

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

Signal selection efficiency check in MC simulation

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

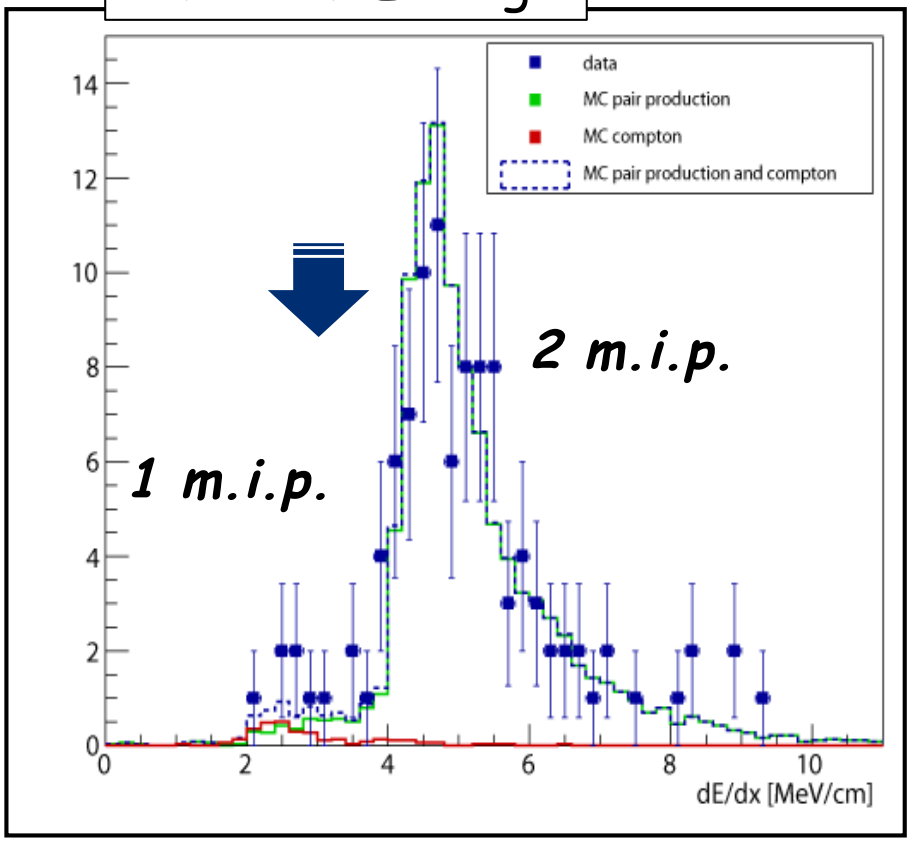
C1: inside fiducial volume and E_{dep} < 30 GeV;
C2: no identified muon, at least one shower;
C3: one shower: initial point (or γ conversion point) < 1 cm from vtx, separated from other tracks;
C4: ionisation signal from single mip in the first 8 wires.

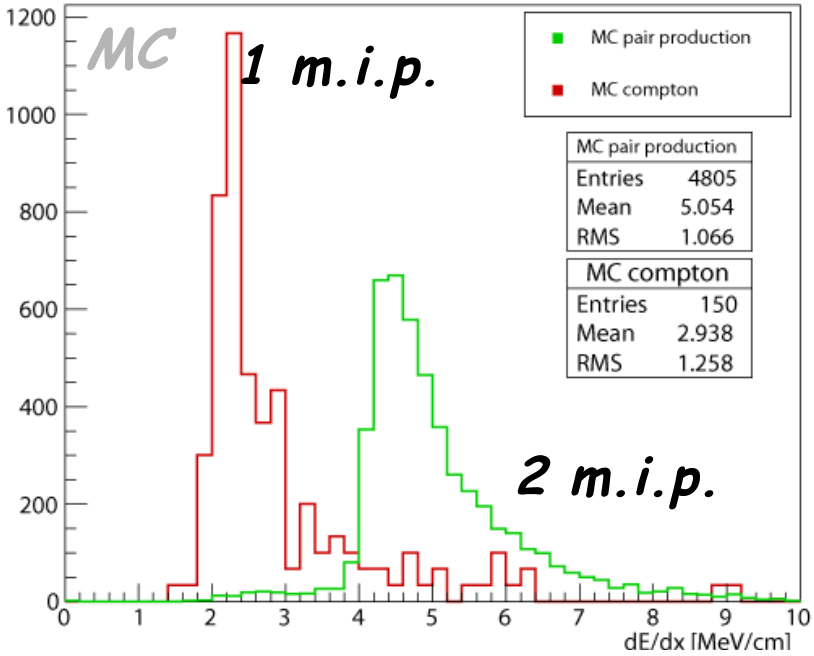
Sel. cut	ν_e CC beam	ν_e CC θ_{13}	ν_τ CC	NC	ν_μ CC	ν_e CC signal
C1	0.47	0.92	0.93	0.89	0.89	0.81
C2	0.47	0.92	0.17	0.66	0.19	0.81
C3	0.33	0.79	0.14	0.10	0.03	0.66
C4	0.30	0.71	0.13	0.0002	0.00005	0.60

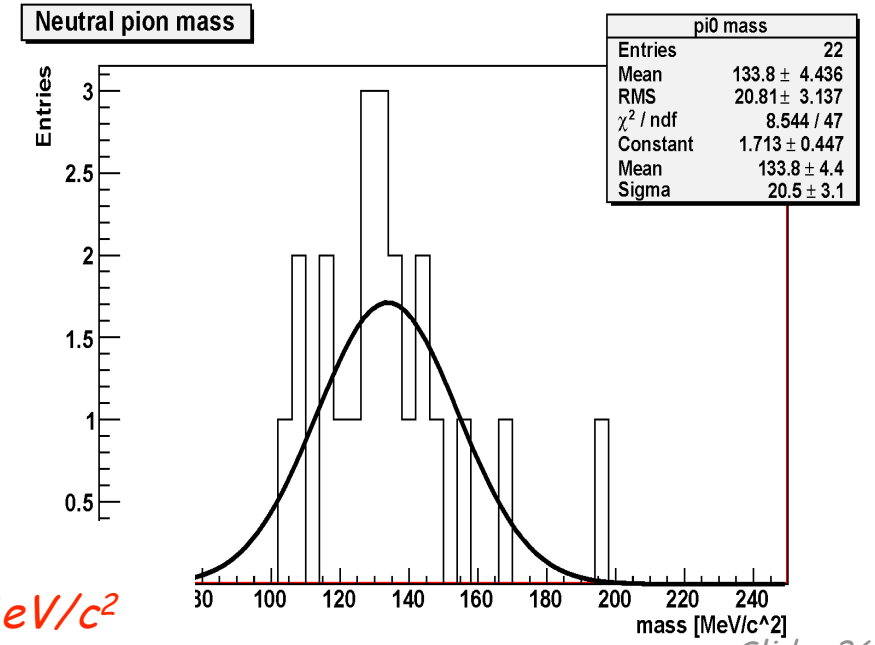
Signal selection efficiency (after the fiducial and energy cuts):
0.6/0.81 = 0.74, in agreement with the visual scanning method.

- *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