ICARUS

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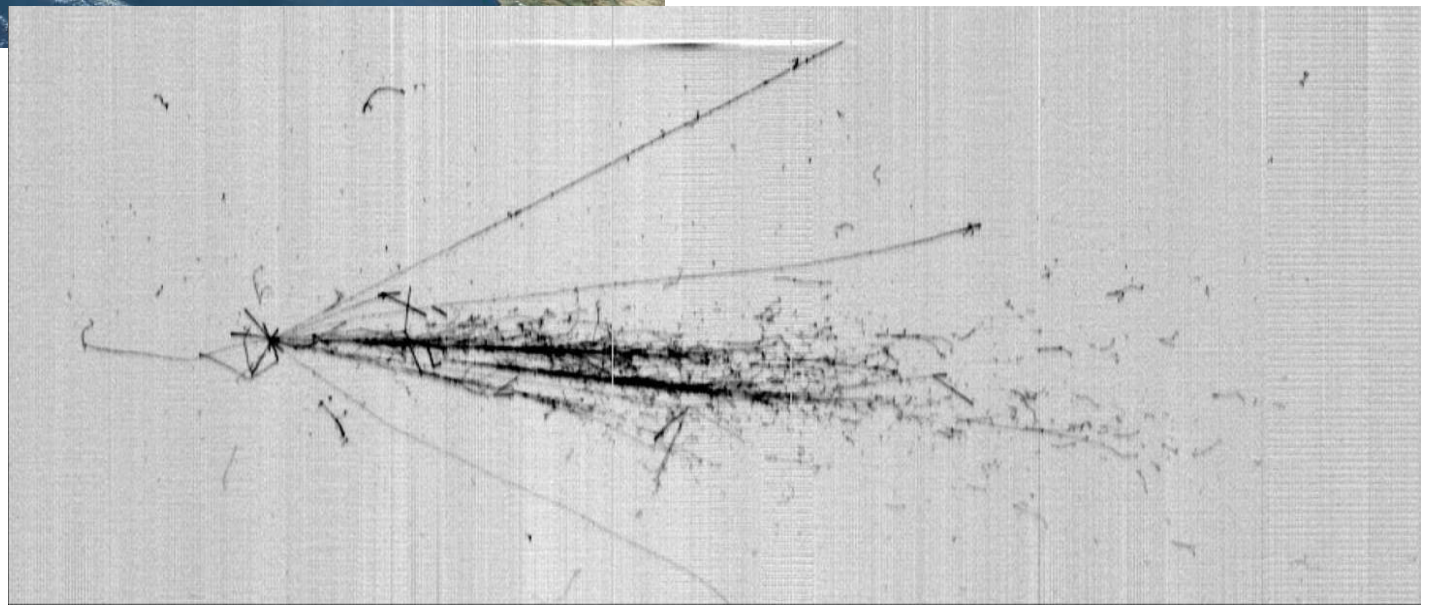
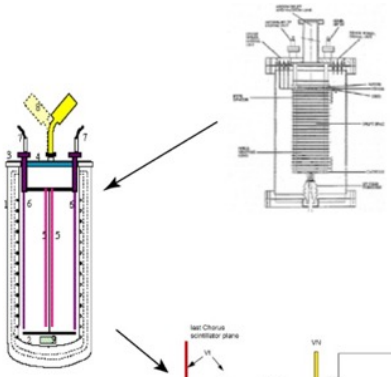
on behalf of
the ICARUS Collaboration



XLVII Meeting of LNGS S.C., April 3-4, 2017

The remarkable evolution of ν- experiments: the LAr-TPC

- Cherenkov radiation detection has been so-far one of the key choices for exploring neutrinos with k-ton water/ice detectors.
- *As an alternative, the Liquid Argon Imaging technology LAr-TPC, an "electronic bubble chamber" which permits to identify unambiguously each ionizing track in complex ν events, was originally proposed by C. Rubbia [CERN-EP/77-08].*
- With the continuing effort of ICARUS Collab. and INFN support, LAr-TPC technology has been taken to full maturity with T600, the largest LAr-TPC ever constructed, 0.76 kt of LAr mass.



1 — 24 cm drift wires chamber

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

2 — 3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

CERN

3 — 50 litres prototype 1.4 m drift chamber

CERN

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4 — 10 m³ industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

Pavia

T600 detector

ICARUS-T600 experiment

5 — Cooperation with industry: AirLiquide, Breme, Cinel, CAEN

6 — LNGS Hall-B

The path to larger LAr detectors

The ICARUS Collaboration at LNGS

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ICARUS: a summary

- T600 detector concluded in 2013 a successful three year long run at LNGS taking data both with CNGS ν beam and cosmic rays. *Several relevant physics and technical results have been achieved:*
  - ICARUS demonstrated its excellent performance as tracking device and homogeneous calorimeter with a remarkable P.id capabilities exploiting the measurement of dE/dx vs. range.
  - Reconstruction of ν interaction vertex and measurement of e.m. showers by primary electrons and invariant mass of γ pairs, allowed to reject background in the study of ν_μ–ν_e transitions to unprecedented level.
- ICARUS performed a sensitive search for LSND-like anomaly with CNGS beam reducing the LSND window to a narrow region at $\Delta m_s^2 \approx 1\ eV^2$, as confirmed by OPERA. Moreover ICARUS contributed to solve the superluminal ν claim.
- All these results have marked a milestone for the LAr-TPC technology with a large impact on the future neutrino and astro-particle physics projects, like the current SBN short base-line neutrino program at FNAL with three LAr-TPCs (SBND, MicroBooNE and ICARUS) and the multi-kt DUNE LAr-TPC detector.
- T600 detector is now at CERN for overhauling before to be exposed to ~0.8 GeV Booster ν beam at 600 m from target to definitely test the LSND claim with a highly sensitive search for $\nu\mu$–νe in the framework of SBN program.

Selected ICARUS papers - 1

1) F. Arneodo et al., "*Observation of long ionizing tracks with the ICARUS T600 first half-module*", Nucl. Instr. Meth. in Phys. Res., A508, 287 (2003).

2) S. Amoruso et al., "*Analysis of the liquid argon purity in the ICARUS T600 TPC*", Nucl. Instr. Meth. in Phys. Res. A516, 68 (2004).

3) S. Amoruso et al., "*Study of electron recombination in liquid Argon with the ICARUS TPC*", Nucl. Instr. Meth. in Phys. Res. A523, 275 (2004).

4) S. Amoruso et al., "*Measurement of the μ decay spectrum with the ICARUS liquid Argon TPC*" Eur. Phys. J. C33, 233 (2004).

5) S. Amerio et al., "*Design, construction and tests of the ICARUS T600 detector*", Nucl. Instr. Meth. in Phys. Res. A527, 329 (2004).

6) A. Ankowski et al., "*Characterization of ETL 9357FLA photomultiplier tubes for cryogenic temperature applications*", Nucl. Instr. Meth. in Phys. Res. A556, 146 (2006).

7) C. Vignoli et al., "*ICARUS: an innovative large LAr detector for neutrino physics*", Adv. in Cryog. Eng. 51, 1643 (2006).

Selected ICARUS papers - 2

8) A. Ankowski et al., "*Measurement of through-going particle momentum by means of multiple scattering with the ICARUS T600 TPC*", Eur. Phys. J. C 48, 667(2006).

9) F. Arneodo et al., (ICARUS and Milano Coll.s), "*Performance of a liquid argon time projection chamber exposed to the CERN West Area Neutrino Facility neutrino beam*", Phys. Rev. D74, 112001 (2006).

10) Ankowski et al., "*Energy reconstruction of electromagnetic showers from $\pi 0$ decays with the ICARUS T600 liquid argon TPC*", Acta Phys. Pol. B41, 103 (2010).

11) C. Rubbia et al., "*Underground operation of the ICARUS T600 LAr-TPC: First results*", J. Instr.6, P07011 (2011).

12) M. Antonello et al., "*A search for the analogue to Cherenkov radiation by high energy neutrinos at superluminal speeds in ICARUS*", Phys. Lett. B 711, 270 (2012).

13) M. Antonello et al., "*Measurement of the neutrino velocity with the ICARUS detector at the CNGS beam*", Phys. Lett. B713, 17 (2012).

14) M. Antonello et al., "*Precision measurement of the neutrino velocity with the ICARUS detector in the CNGS beam*", J. H.E.P., 2012 (11), art. no. 049 (2012).

Selected ICARUS papers- 3

15) M. Antonello et al., "*Experimental search for the "LSND anomaly" with the ICARUS detector in the CNGS neutrino beam*", Eur. Phys. J. C,73 , art. no. 2345, 1 (2013).

16) M. Antonello et al., "*Search for anomalies in the ν_e appearance from a ν_μ beam*", Eur. Phys. J. C73, art. no. 2599, 1 (2013).

17) M. Antonello et al., "*Precise 3D track reconstruction algorithm for the ICARUS T600 liquid argon time projection chamber detector*", Adv. in H.E.P. 260820 (2013).

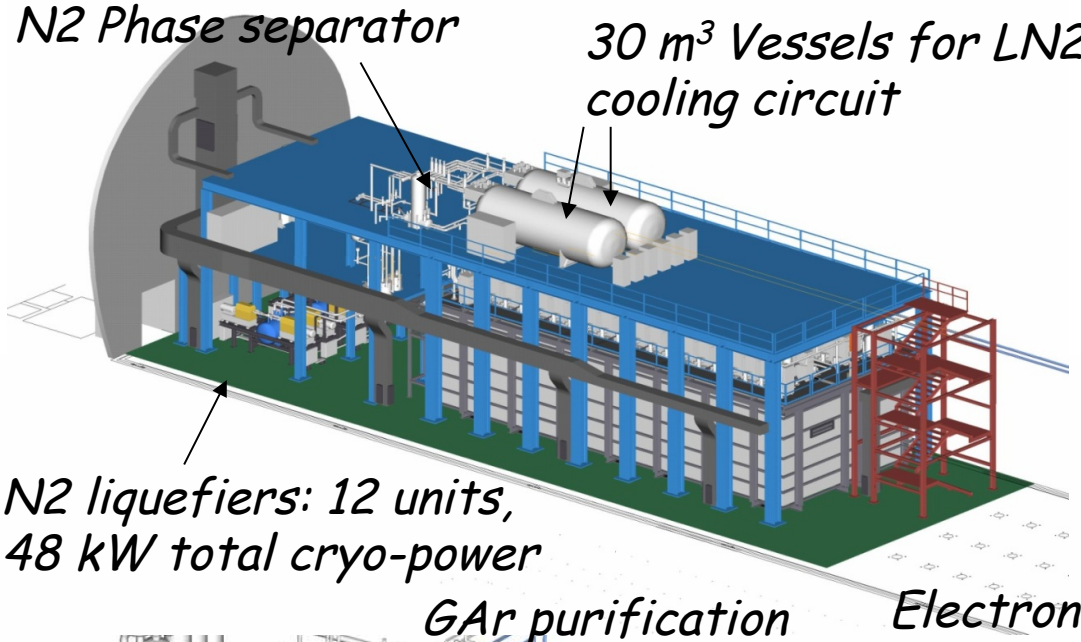
18) M. Antonello et al., "*The trigger system of the ICARUS experiment for the CNGS beam*", J. Inst. 9, P08003 (2014).

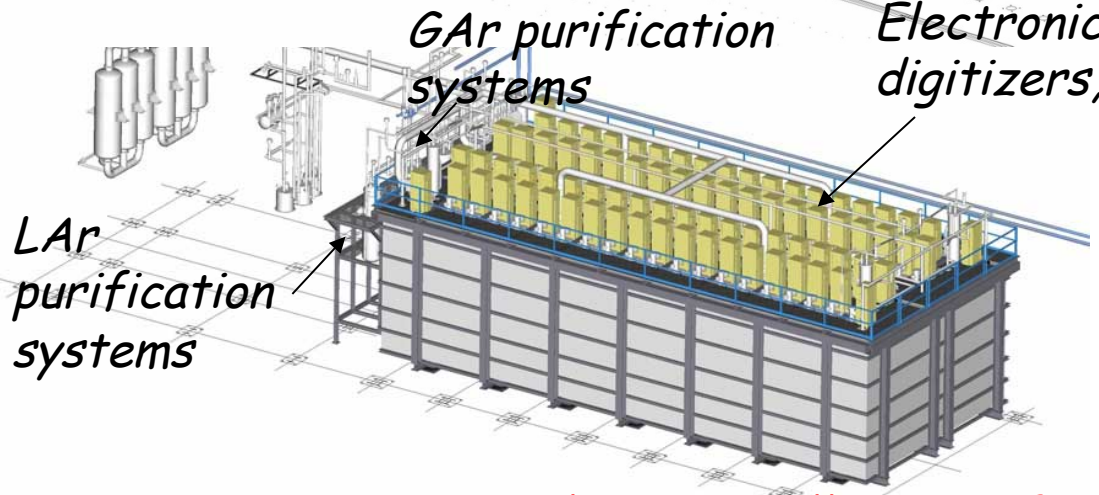
19) M. Antonello et al., "*Experimental observation of an extremely high electron lifetime with the ICARUS-T600 LAr-TPC*", J. Inst. 9, P12006 (2014).

20) M. Antonello et al., "*Operation and performance of the ICARUS T600 cryogenic plant at Gran Sasso underground Laboratory*", J. Inst. 10, P12004 (2015).

21) M. Antonello et al., "*Muon momentum measurement in ICARUS-T600 LAr-TPC via multiple scattering in few-GeV range*", accepted for publication on J. Inst., arXiv: 1612.07715 (2017).

ICARUS-T600 plant @ LNGS Hall B: 0.77 kton LAr-TPC

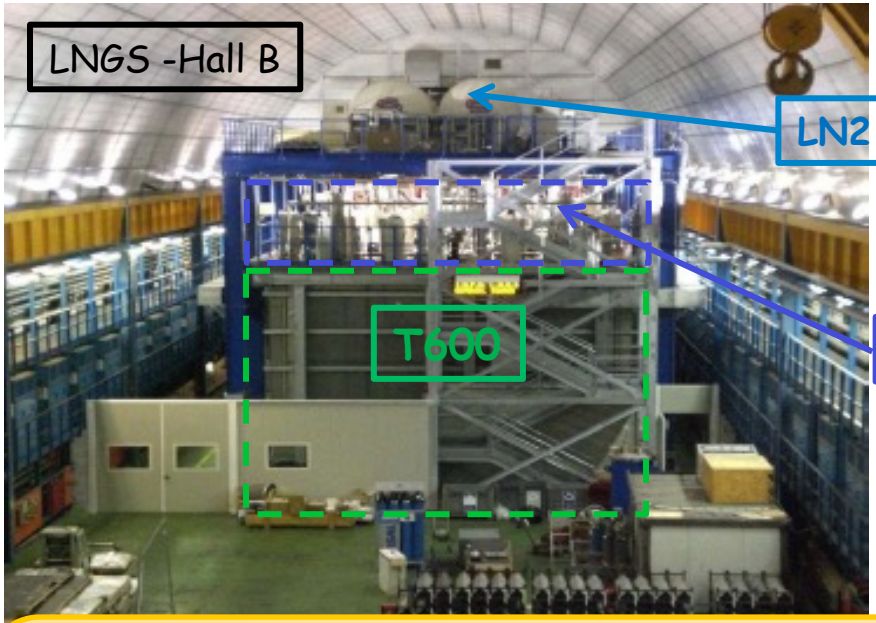




A superbe Cryogenic plant: excellent performance, smooth & safe operation guaranteed by the local group

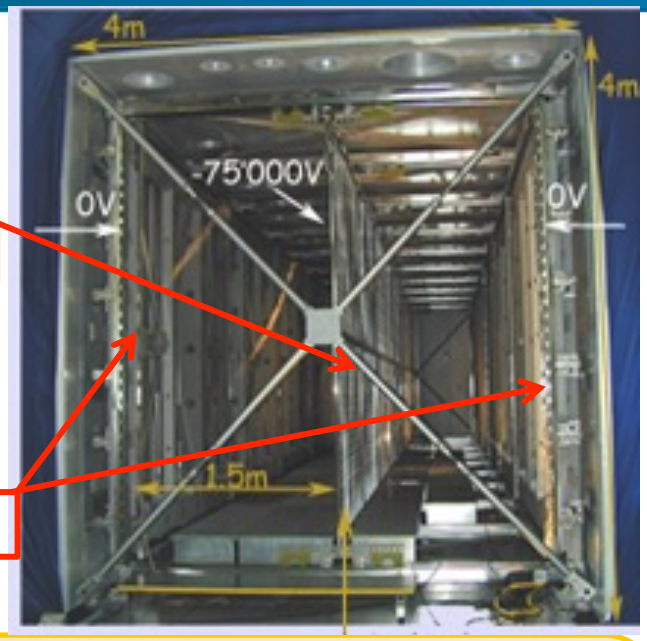
Remarkable detector live-time >93 % during operation with CNGS

The ICARUS T600 detector



LN2 storage + cryo (behind)

Warm Electronics



Cathode

TPC wires (anodes)

Two identical modules, 4 wire chambers

- 3.6 x 3.9 x 19.6 m ≈ 275 m^3
- Total active mass ≈ 476 ton
- 2 TPCs per module, with common central cathode -> 1.5 m drift length
- E_{drift}= 0.5 kV/cm, v_{drift} = 1.55 mm/μs) (sub-mm resolution in drift direction).

TPC Warm Electronics

- Continuous read-out, digitization, waveform recording, 0.4 μs sampling time (sub-mm resolution in drift direction).

Charge and light detectors

- 3 "non-distructive" readout wire planes per TPC, wires at 0°, ±60° (Ind1, Ind2, Coll. View)
- ≈54000 wires (150 μm Ø, 3 mm pitch)
- 54+20 photomultipliers (8" Ø) + wls (TPB), sensitive at 128 nm (VUV)

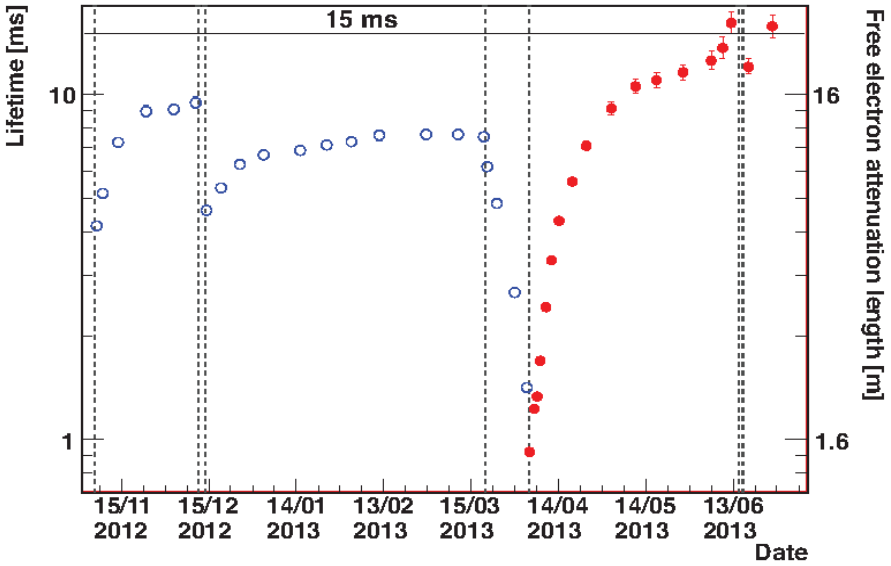
Cryogenics

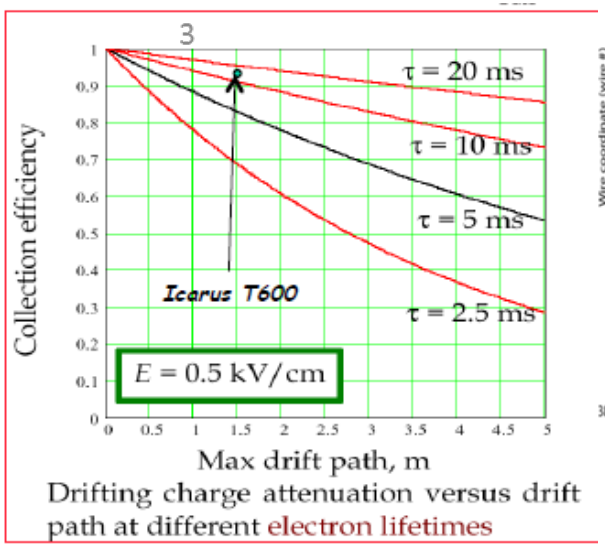
- Liquid and gas Ar recirculation;
- Passive insulation + dual phase N_2 shield
- High purity ~ 20 ppt O_2 equiv. (τ_e > 16 ms).

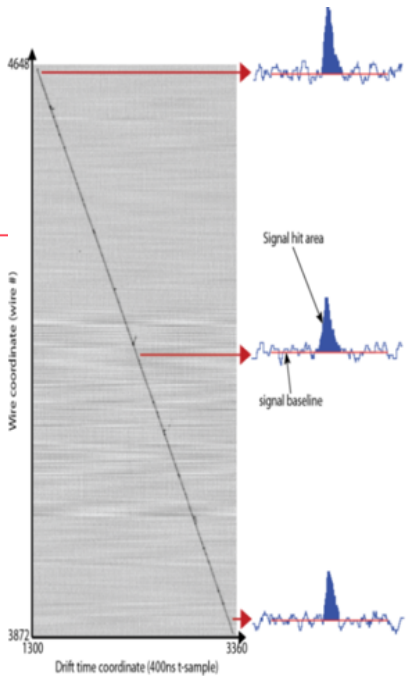
A key feature of LAr imaging: very long e^- mobility

- Level of electronegative impurities in LAr must be kept exceptionally low to ensure ~m long drift path of ionization e^- signal without attenuation;
- New industrial/lab purification methods have been developed to continuously filter and re-circulate both liquid (100 m^3 /day) and gas (2.5 m^3/hour) phases;
- e^- lifetime τ_{ele} > 7 ms (<40 p.p.t [O2] eq. impurities) measured with cosmic μ's : 12% max. charge attenuation on 1.5 m drift.

With a new not-immersed pump on East cryostat: τ_{ele}>15 ms !







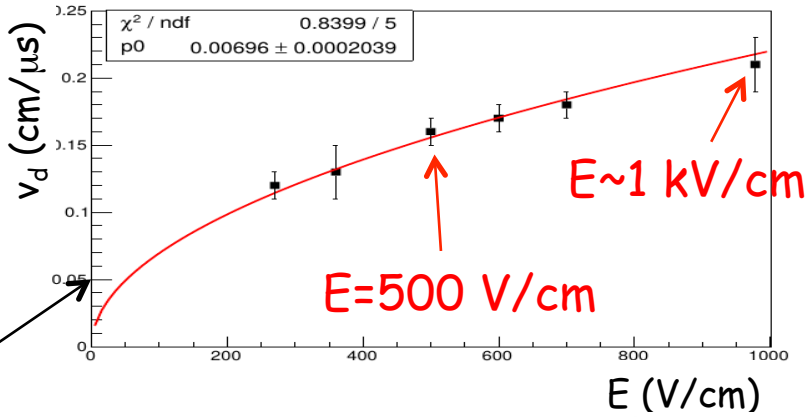
ICARUS demonstrated the effectiveness of single phase LAr-TPC technique paving the way to huge detectors with longer drift distances as required for LBNF/DUNE project.

ICARUS experiment at LNGS

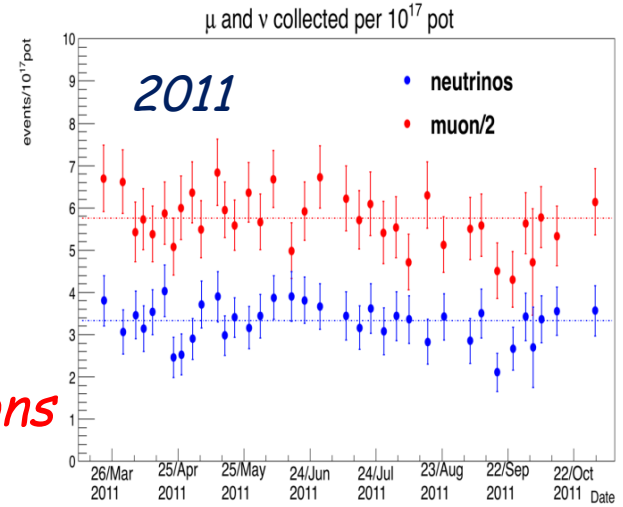
- Exposed to CNGS ν beam ICARUS concluded in 2013 a successful-3 years long run, collecting 8.6 x 10^{19} pot statistics with a remarkable detector live time > 93%, recording also c-rays induced events (0.73 kt y effective exposure).
- Several physics and technical results were achieved, including detailed studies of all technical aspects of LAr-TPC detection technique and the development of advanced reconstruction algorithms.

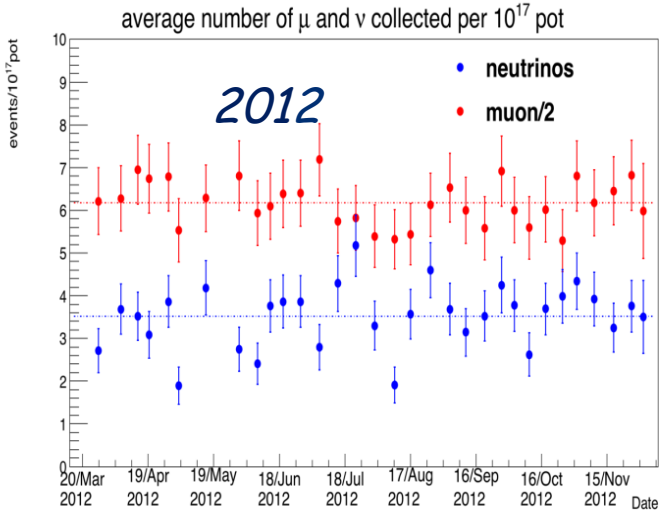
Different operating conditions have been successfully tested in last months of run proving that ICARUS can safely stand up to ~1 kV/cm drift field without any discharges.

Measured e- drift velocity $v_{DRIFT} \propto \sqrt{E}$



Collected CNGS νs + μs normalized to 10^{17} pot: 3.4 νs + 12 μs on average. Data statistics consistent within 6% with MC predictions

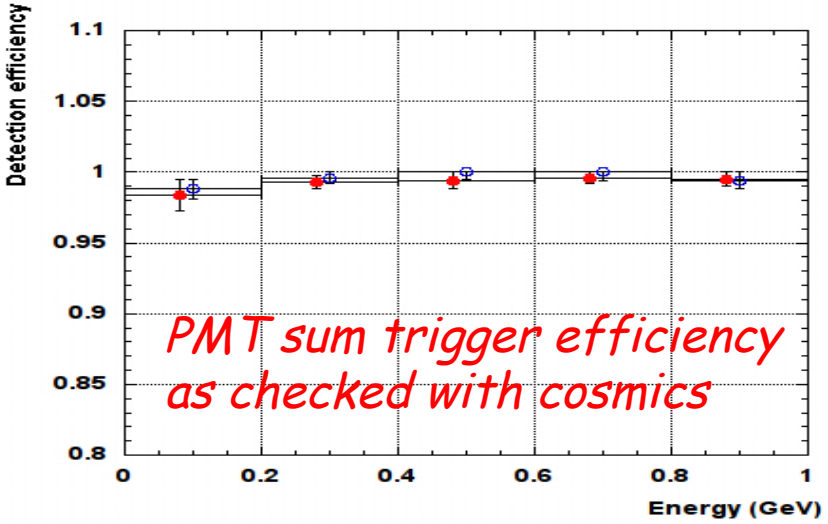


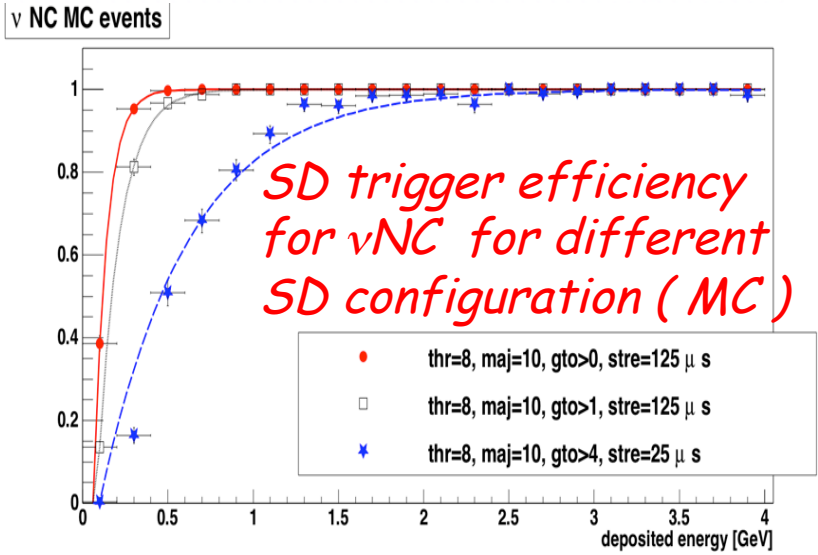


ICARUS-T600 trigger system - 1

- ICARUS-T600 relies on its self-triggering capability by both scintillation light and charge signals by ionizing particles in LAr to detect CNGS and c-ray events, spanning a wide range of E_{DEP} ~ 100MeV ÷ 10 GeV, with event topologies significantly different from each other.

- T600 exploited a GPS time-base shared at CERN & LNGS to open on-line a 60 ms gate at the ν bunch arrival time, as predicted by SPS "early warning" proton extraction (+ 2.44 ms CERN /LNGS ν tof):
  - Few mHz trigger for CNGS events by coincidence of PMT sum signal in at least one TPC with CNGS gate guaranteeing a ~ full detection eff. E_{DEP} >300 MeV;
  - Charge recognition on TPC wires by Super Daedalus chip (SD) to further increase efficiency at low E_{DEP} by detecting wire signals above threshold with a majority logic: 99% and 91% efficiency for νCC and νNC .

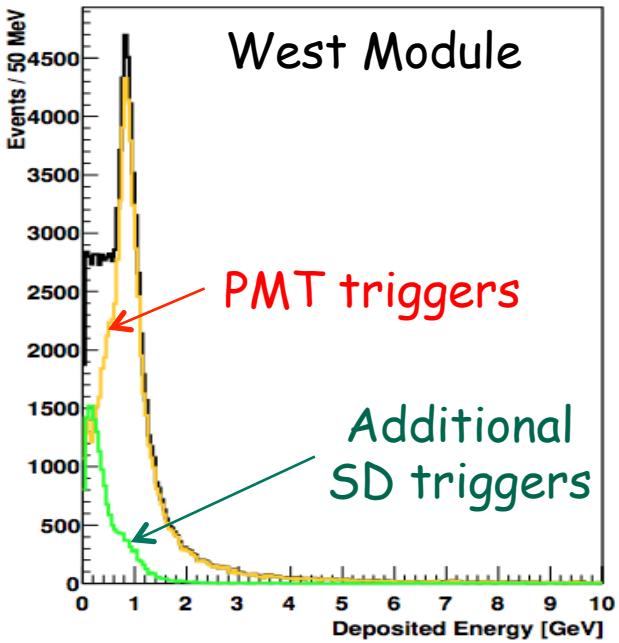


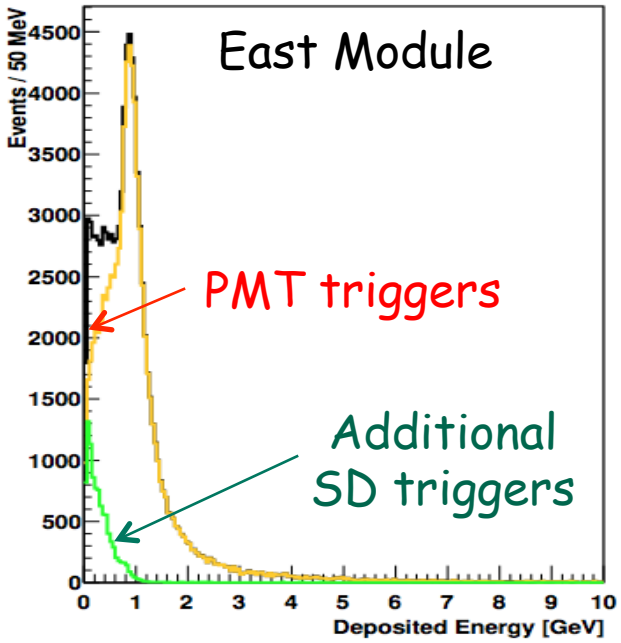


ICARUS-T600 trigger system - 2

- The SD trigger allowed also to directly qualify PMT trigger on the basis of a "minimum bias" request, i.e. the presence of a ~5 cm long track in the TPC.
- The analysis of ~ 2.5 10^{19} pot event statistics collected with the SD trigger proved the ~full PMT trigger efficiency for both ν interactions in the LAr active volume and crossing muon. The SD trigger allowed to significantly increase the detection efficiency below 500 MeV energy deposition.
- Cosmic-ray induced events have been triggered with > 90% efficiency for E_{DEP} >500 MeV requiring the coincidence of PMT sum signals in two adjacent chambers or a single SD minimum bias signal, out of CNGS spill.

J. Inst. 9, P08003 (2014)



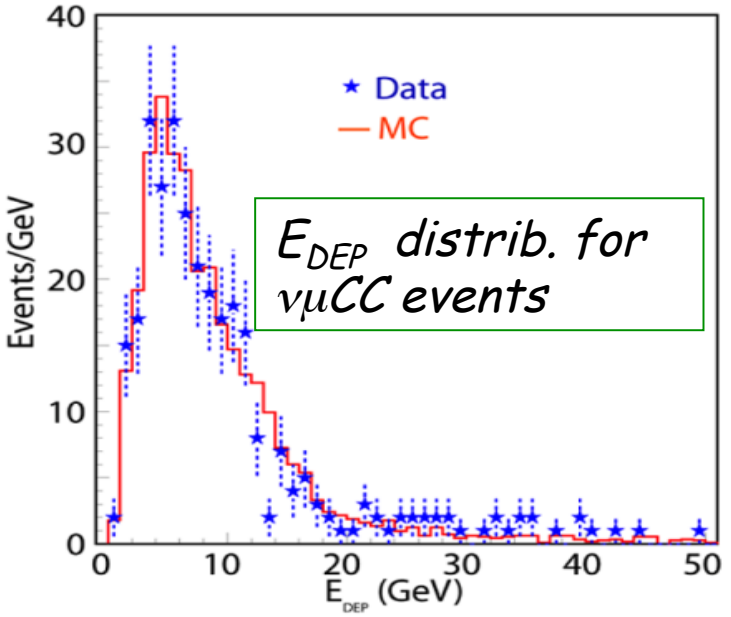


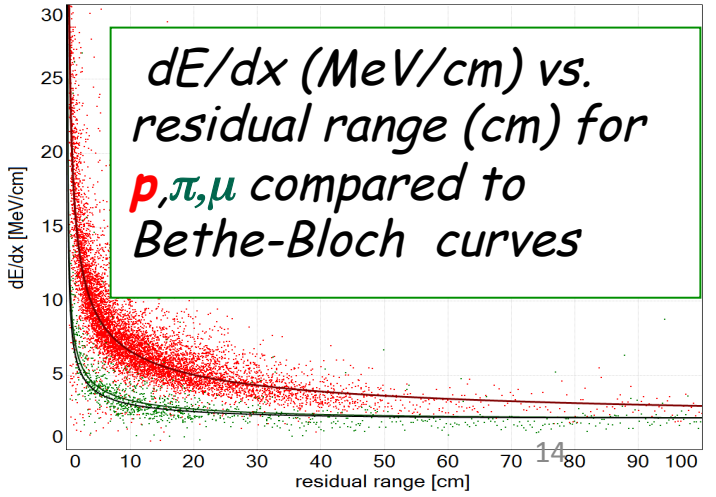
Successful operation of ICARUS T600 trigger system: high reliability, efficiency and live-time: a robust baseline for next ICARUS exp. at FNAL and future developments in multi-kt LAr-TPC

ICARUS LAr-TPC performance

- From the analysis of CNGS ν and of c-ray induced events:
  - *Tracking device:* precise 3D event topology with ~1 mm^3 resolution for any ionizing particle;
  - *Global calorimeter:* full sampling homogeneous calorimeter; total energy reconstructed by charge integration with excellent accuracy for contained events; momentum of non contained μ by Multiple Coulomb Scattering with Δp/p ~15% in 0.4-4 GeV/c range;
  - *Measurement of local energy deposition dE/dx:* remarkable e/γ separation (0.02X_0 sampling, X_0=14 cm, particle id. by dE/dx vs range):

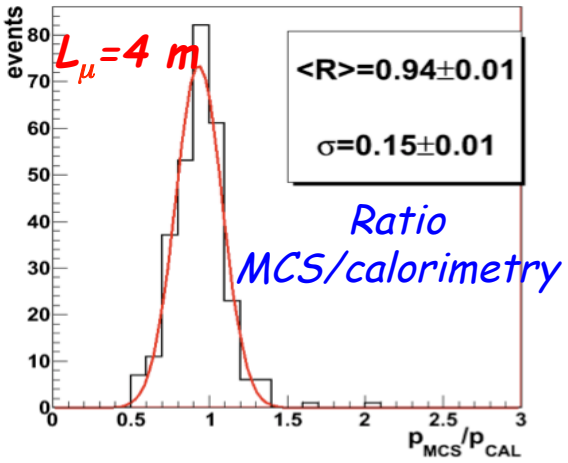
Low energy electrons:
σ(E)/E = 11%/√ E(MeV)+2%
Electromagnetic showers:
σ(E)/E = 3%/√ E(GeV)
Hadron showers:
σ(E)/E ≈ 30%/√ E(GeV)

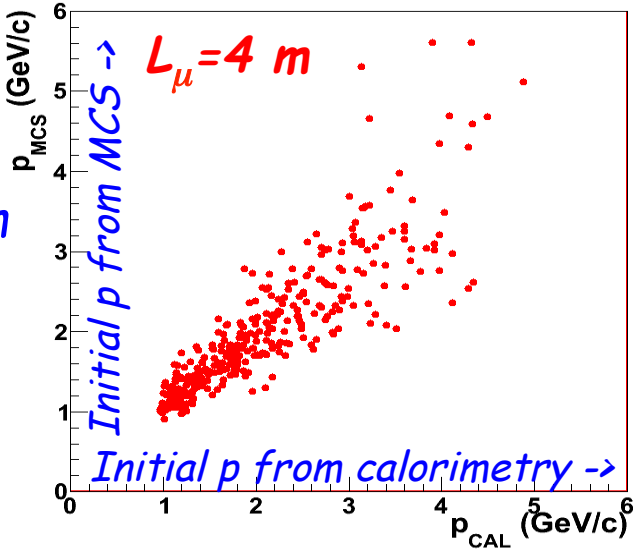


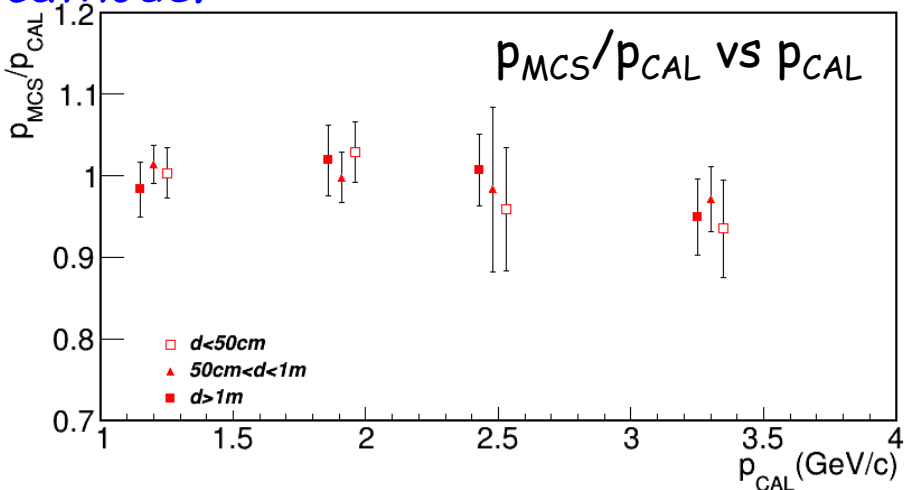


Muon momentum measurement via multiple Coulomb scattering

- Muon momentum measurement by *Multiple Coulomb Scatt.* has been validated comparing p_{MCS} with corresponding calorimetric measurement p_{CAL} for ~500 *stopping* μ*s* produced by CNGS ν_μ interactions in upstream rock;
- *p_{MCS} is well correlated with p_{CAL}.*
  Unexpected *p_{MCS}* under-estimation is detected at p >3 GeV/c for μs travelling close to TPC cathode, due to its $\Delta x \sim \pm 15$ mm non-perfect planarity which affect electron drift velocity (*percent E_D distortions)*
- *These effects have been accounted for applying the actual computed electric field to MC events to extract average corrections to p_{MCS} as a function of μ momentum and distance from cathode.*



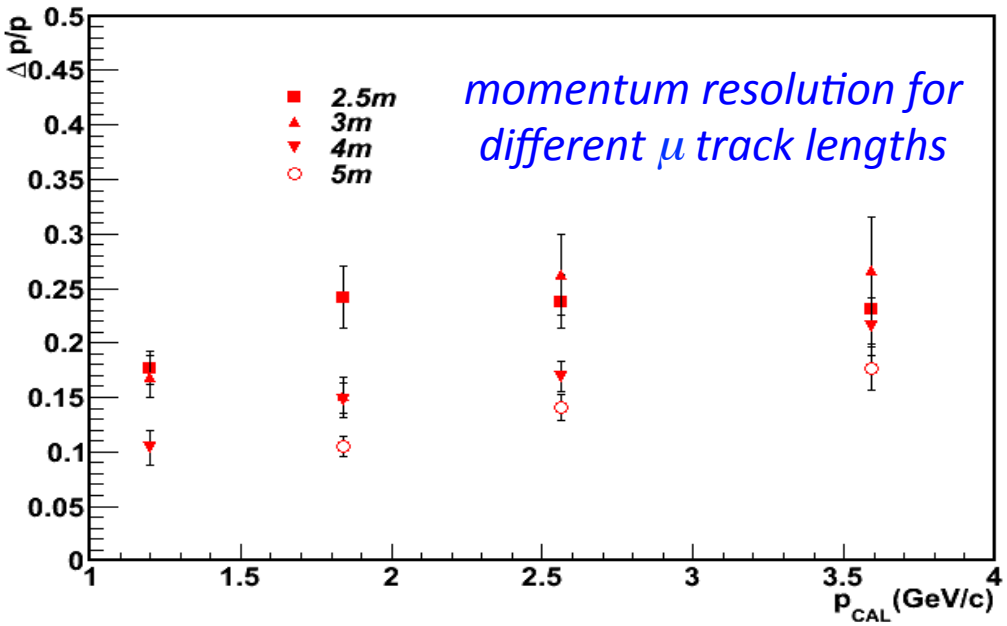




$p_{MCS} \sim p_{CAL}$ data within ~5%.

Resolution of muon momentum measurement via MCS

- The resolution on p_{MCS} measurement depends from the muon momentum and from the track length used for the MCS measurement.
- For 4 m muon track length, the resolution of the method is ~15% in 0.4-4 GeV /c momentum range.
- Moreover a better resolution on μ momentum measurement by MCS is expected after the T600 overhauling at CERN:
  - the cathode has been flattened with a less than ~ 1 mm residual non planarity.
  - the new TPC read-out electronics will provide a fully synchronized digitization of the wire signals.

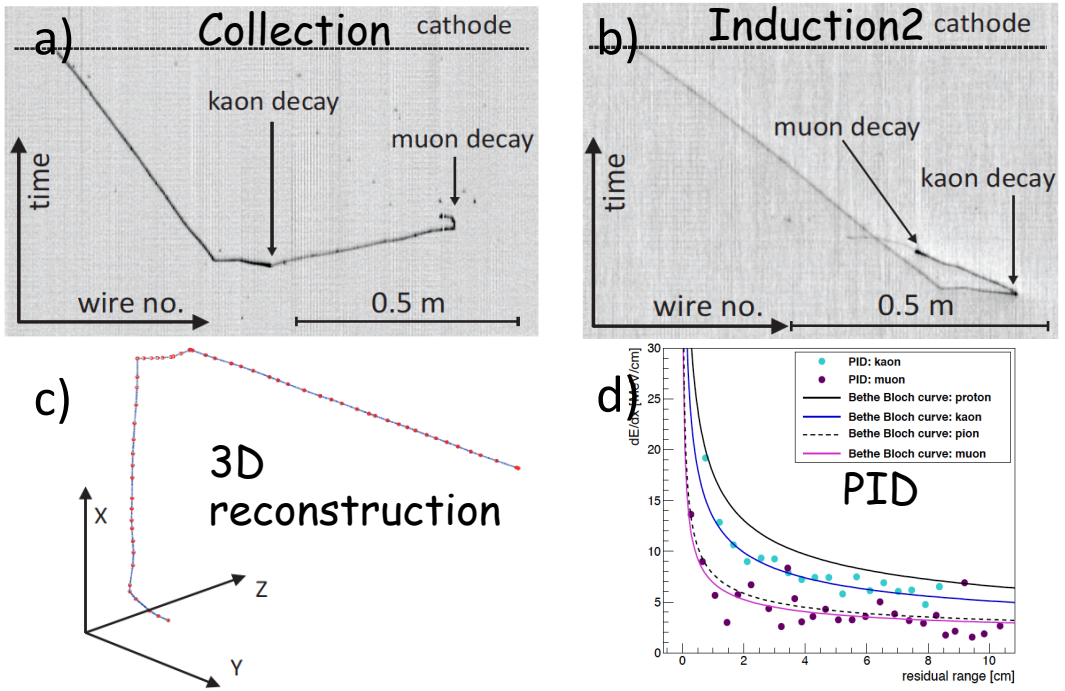


The method is applicable to momentum range of interest of the proposed short/ long baseline experiments.

Paper in print on JINST, arxiv.org/abs/1612.07715

Tools for event reconstruction in LAr

- Bubble chamber like reconstruction of the event topology in conjunction with calorimetric measurement of global and local energy deposits perfectly suitable for detailed visual analysis of the event.
- The large amount of data collected with CNGS-νs and cosmic rays required the use of automatic tools, to assist and complement the visual scanning.
- Innovative approach:
  direct 3D reconstruction with simultaneous optimization and matching of hits identified in the different 2D views.
  - All available information is used
  - Applied to reconstruction of tracks, shower objects, interaction vertices and to global event analysis
  - Improves the PID

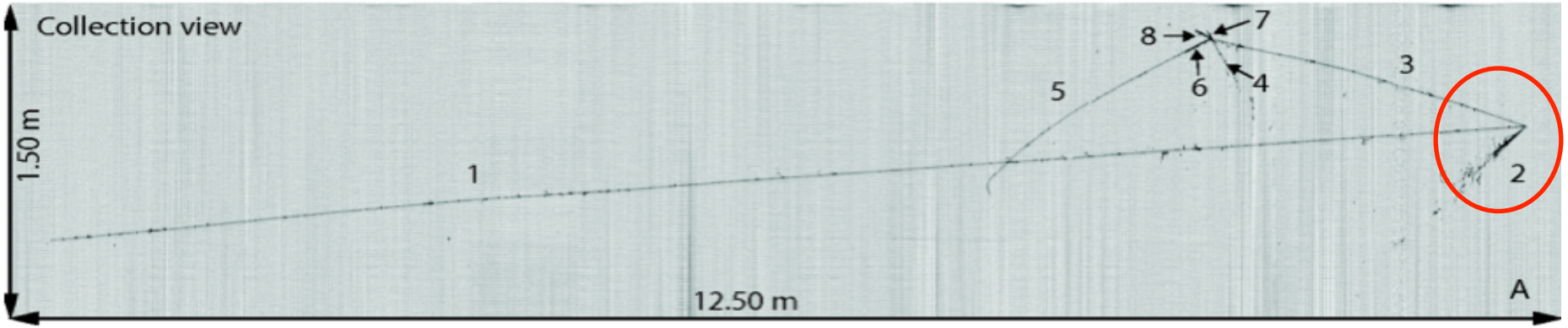


Example of a K→μ→e decay in CNGS data:
a) Collection & b) Induction2 views;
c) 3D reconstruction; d). PID

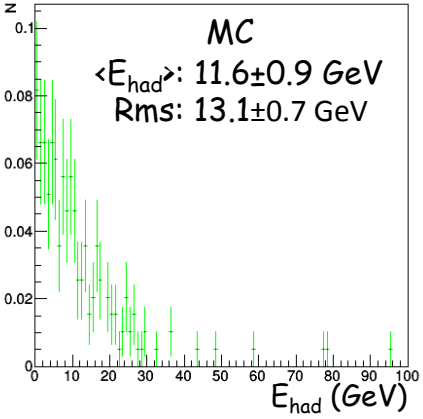
Advances in High Energy Physics,260820(2013)

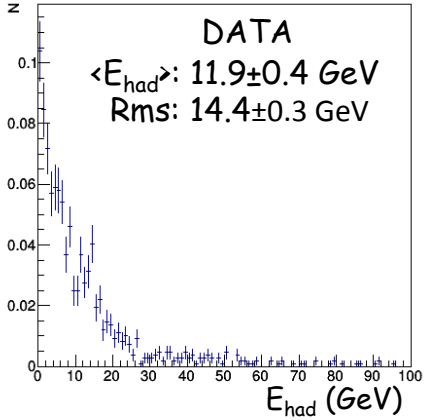
ν_μCC events in CNGS neutrino beam

- ν_μ CC/anti-ν_μCC were selected, with a ~70% efficiency and a rejection factor ~60 for NC events, requiring the μ track to be longer than 2.5 m.
- Globally 1285 ν_μ and anti-ν_μ CC events have been selected in a 6.7 x 10^{19} pot event statistics (2011 and 2012 runs). All these events have been visually measured and reconstructed in detail separating μ tracks from hadronic jet.

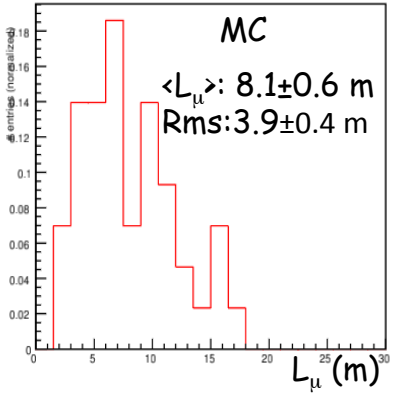


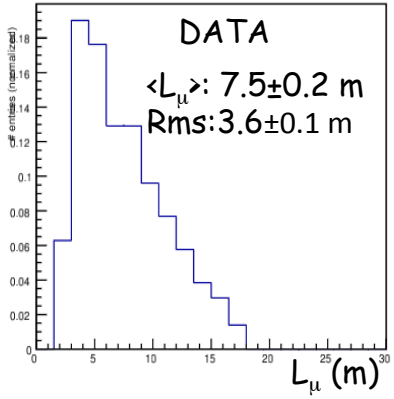
- The reconstructed hadronic energy in agreement with expectations



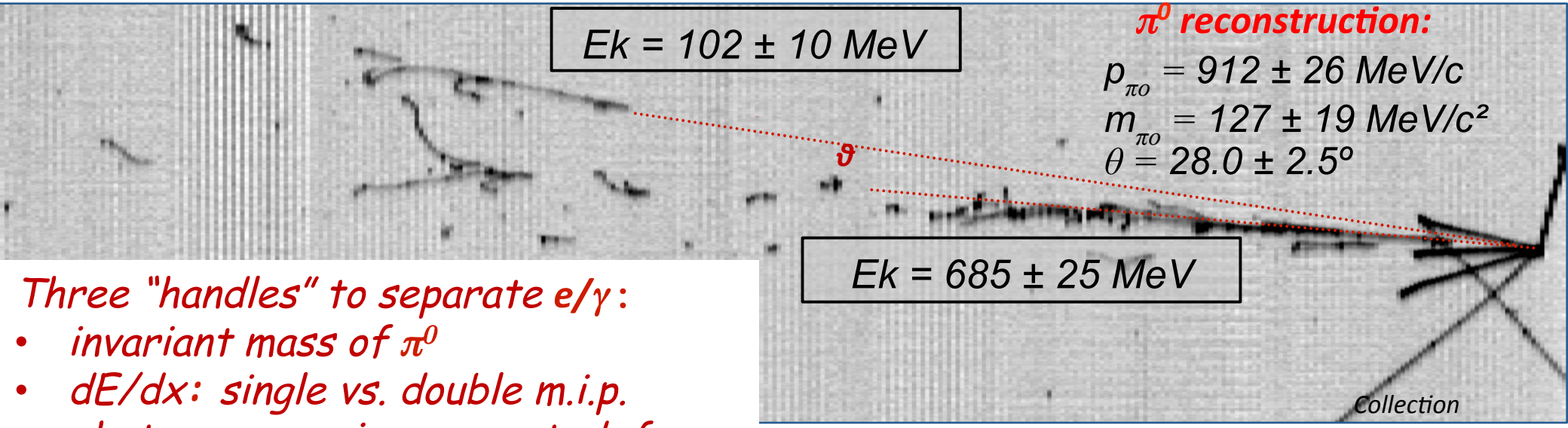


- The μ length matches its expected distribution





Unique feature of ICARUS: e/γ separation, π^0 reconstruction



π^0 reconstruction:

$p_{\pi o} = 912 \pm 26$ MeV/c

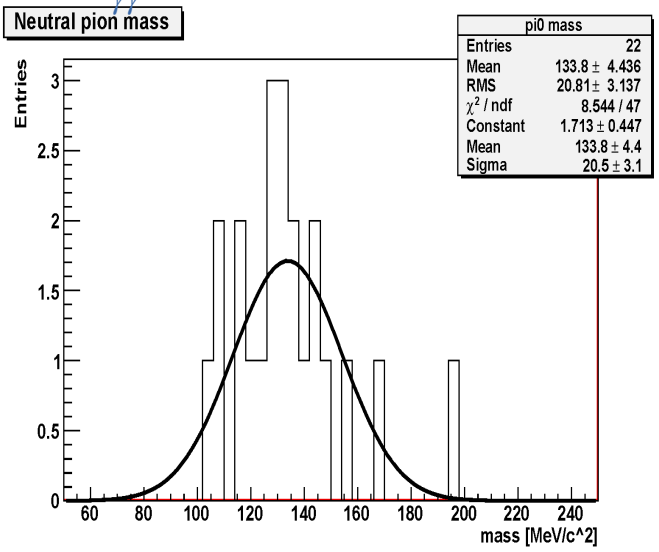
$m_{\pi o} = 127 \pm 19$ MeV/c²

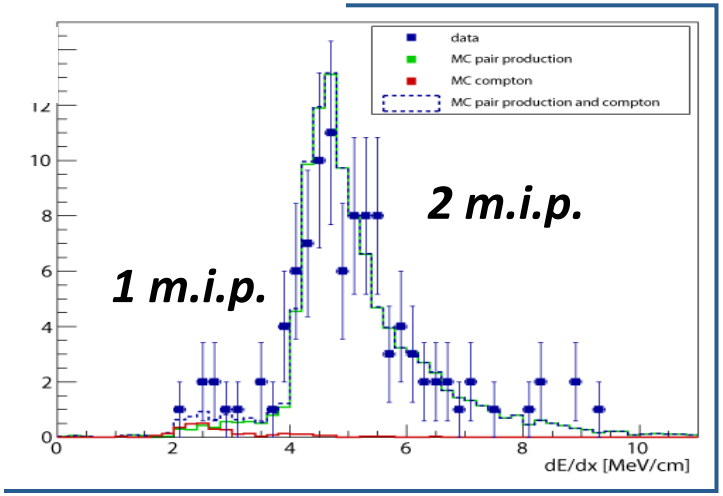
$\theta = 28.0 \pm 2.5°$

Three "handles" to separate e/γ:

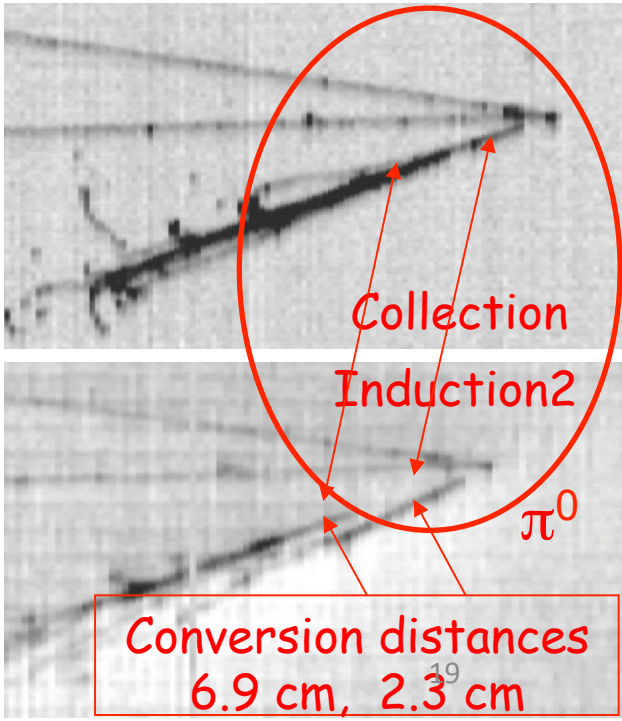
- *invariant mass of π^0*
- *dE/dx: single vs. double m.i.p.*
- *photon conversion separated from primary vertex*

$M_{\gamma\gamma}$:133.8±4.4±4 MeV/c²



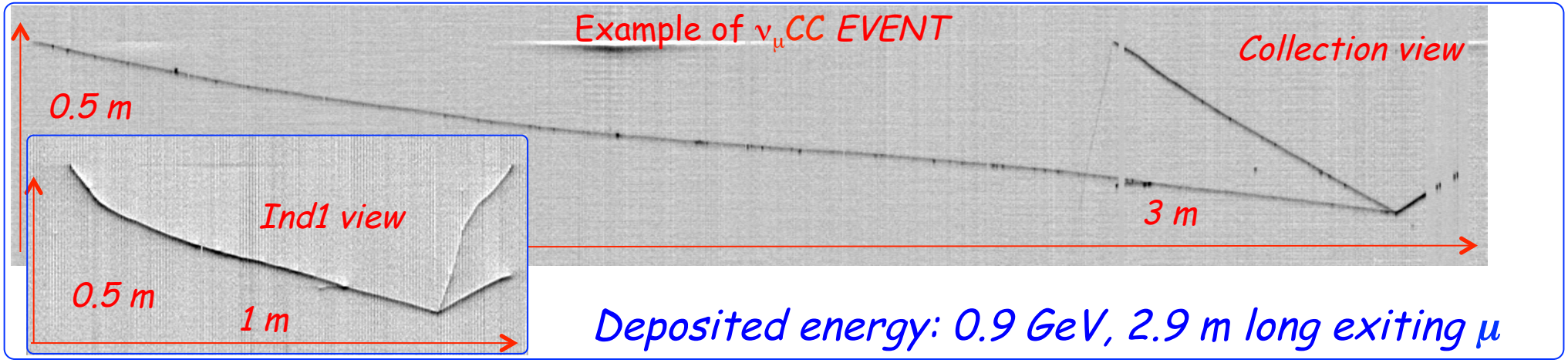


Crucial for NC rejection in ν_e-physics

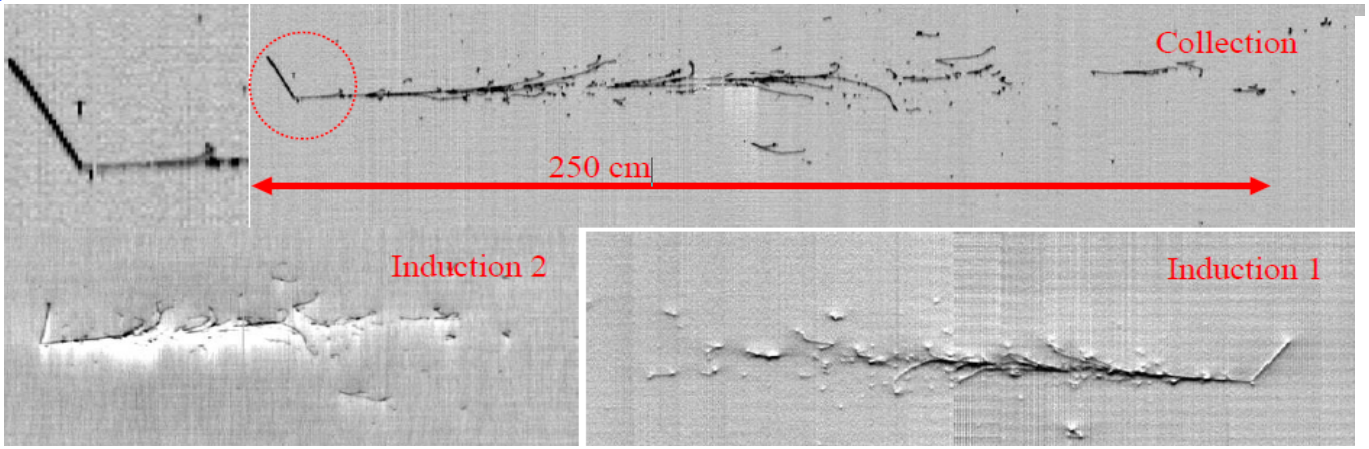


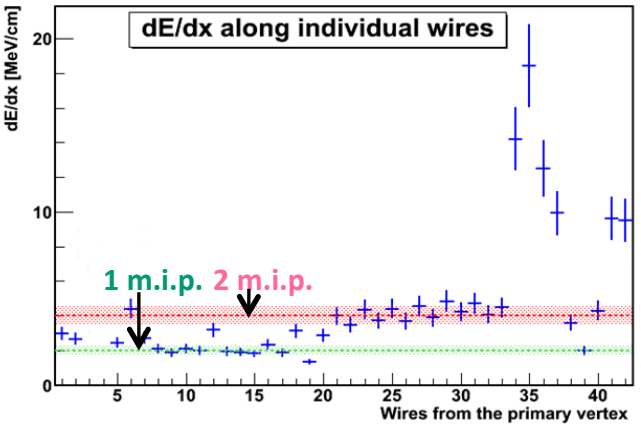
Towards automatic neutrino search: atmospheric ν

- Cosmic ray events recorded in ~0.48 kton y exposure (2012-2013 run), are being analyzed to identify and study atmospheric ν events, of interest since they cover the energy range expected for the SBN experiment at FNAL.
- Incoming c-rays are rejected (by factor ~100) and ν candidates pre-selected by two automatic procedures, then validated by visual scanning:
  a) reconstruction of vertex and multi-prong candidates (~30% efficiency for ν_eCC & ν_μCC); ~42% of the exposure analyzed;
  b) selection optimized for ν_eCC, rejecting straight incoming tracks (~70%, ~18% eff. for ν_eCC and ν_μCC respectively); ~65% of sample analyzed;
- In total 7 ν_μCC and 7 ν_eCC atmospheric neutrino events have been identified in the sample analyzed so far.

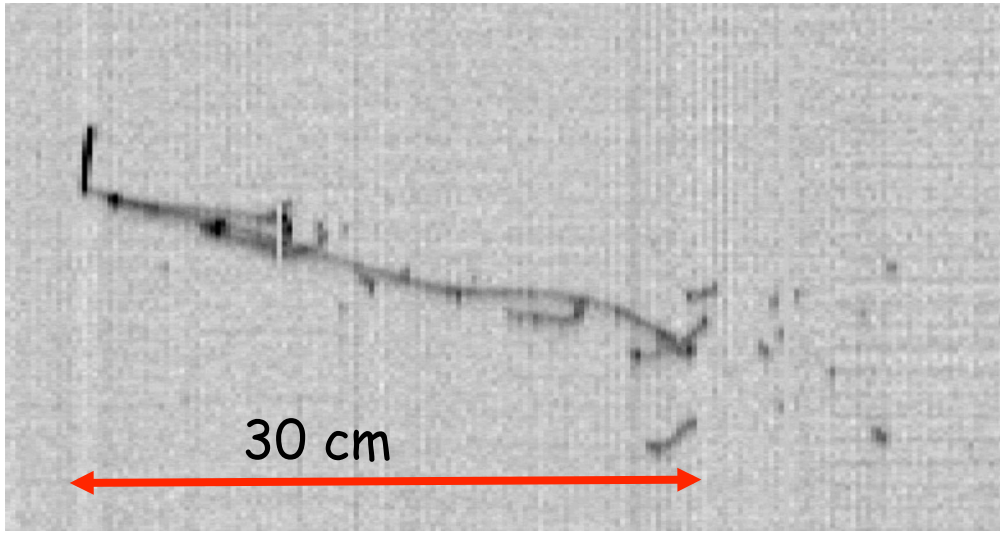


First atmospheric ν_e CC events observed in LAr TPC





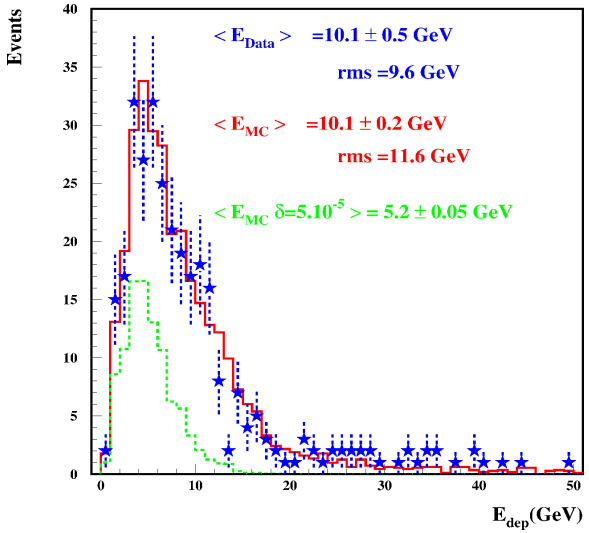
- Quasi-elastic ν_eCC with E_{Dep}=2.12 GeV
- Clear primary electron initiated (single m.i.p.) shower (2 GeV);
- 115 MeV proton identified by dE/dx



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

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

Search for superluminal neutrino

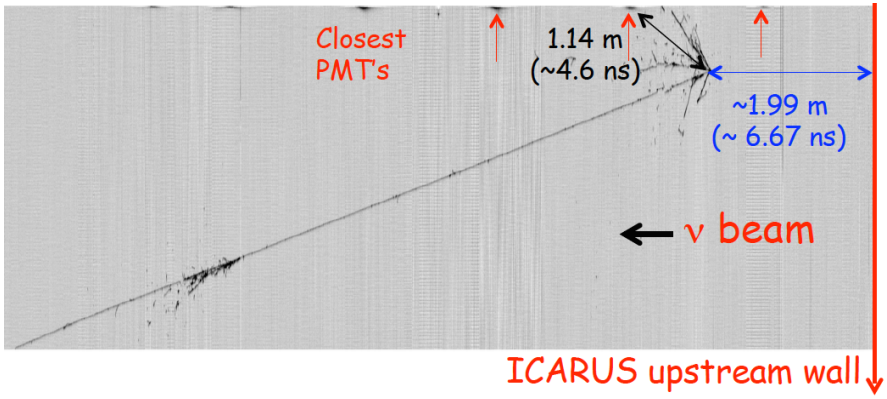


- Indirect search of effects of ν energy loss by analogous to Cherenkov radiation emission (Cohen and Glashow [Phys. Rev. Lett., 107 (2011) 181803])
- No distortion in the measured deposited ν energy no observed e^+e^- pair ➔ $\delta = (v_n^2 - c^2)/c^2 < 2.5\ 10^{-8}$ @90% CL

  [$\delta < 1.4\ 10^{-8}$ (SK atmosph. ν) ; $\delta < 4\ 10^{-9}$ (SN1987A)]

Phys. Lett. B., 711, 270-275 (2012)

- Direct measurement of CERN to T600 ν t.o.f. with special bunched beam



JHEP 049 (2012)

- First measurement (2011): 7 ν events
  → $\delta t = tof_c - tof_\nu = 0.3 \pm 4.9_{stat} \pm 9.0_{syst}$ ns

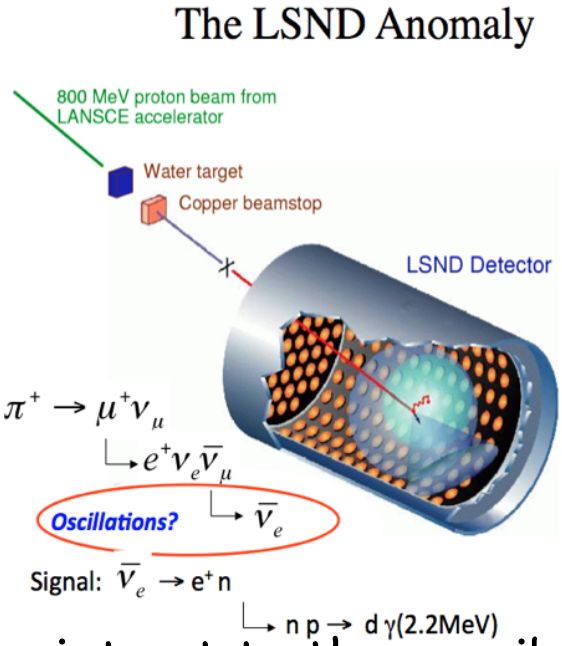
  Phys. Lett. B., 713, 17-22 (2012)
- Precision measurement (2012): 25 ν events (4 timing systems, special PMT DAQ better granularity, new precision geodesy)

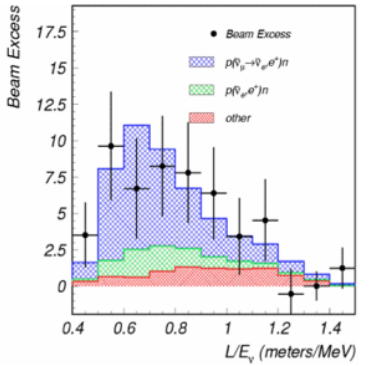
  $\delta t = +0.10 \pm 0.67_{stat} \pm 2.39_{syst}$ ns

Demonstration of the capability to measure the event absolute time with ns resolution, key feature for the next shallow depth operation

Persisting anomalies in the neutrino sector

- Neutrino oscillations established a coherent picture with the mixing of physical ν_e, ν_μ, ν_τ with small mass difference. However three main classes of anomalies have been reported, namely the observation of:
  - Electron-ν excess signals from muon-ν at accelerators by LSND (3.8σ)+ MiniBooNE
  - Disappearance of anti-ν_e by near-by nuclear reactor experiments (event rate R =0.938±0.023).
  - Disappearance of ν_e hinted by solar ν experiments in the calibration with Mega-Curie ν sources (R=0.86±0.05).





Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

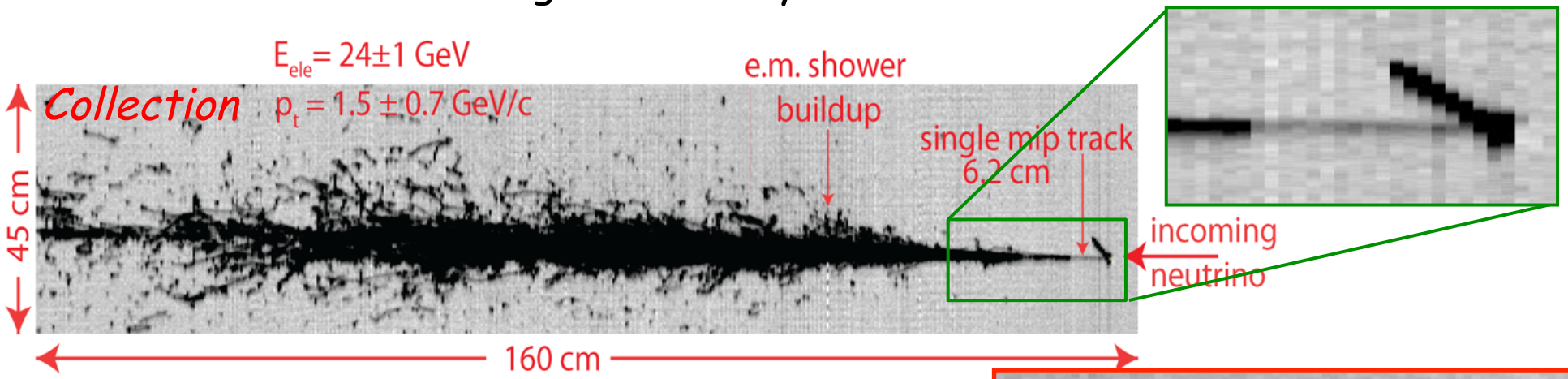
With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

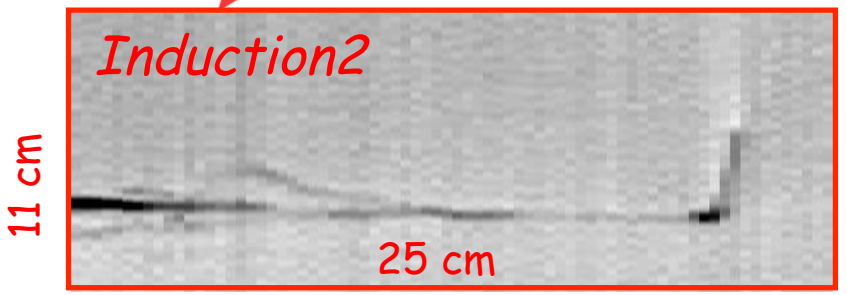
- These three independent signals may all point out to the possible existence of at least a fourth non standard and heavier "sterile" neutrino state driving oscillations at small distances, with Δm^2_{new} of the order of ≈ 1 eV^2 and relatively small $\sin^2(2\theta_{new})$ mixing angles.
- ICARUS addressed the LSND anomaly with the CNGS beam performing a sensitive search for a possible LSND-like $\nu_\mu \rightarrow \nu_e$ oscillations.

ν_eCC identification in CNGS beam: Run 11580 event 7943

- The unique detection properties of the LAr-TPC allow to identify unambiguously individual e-events with high efficiency in Collection and Induction2

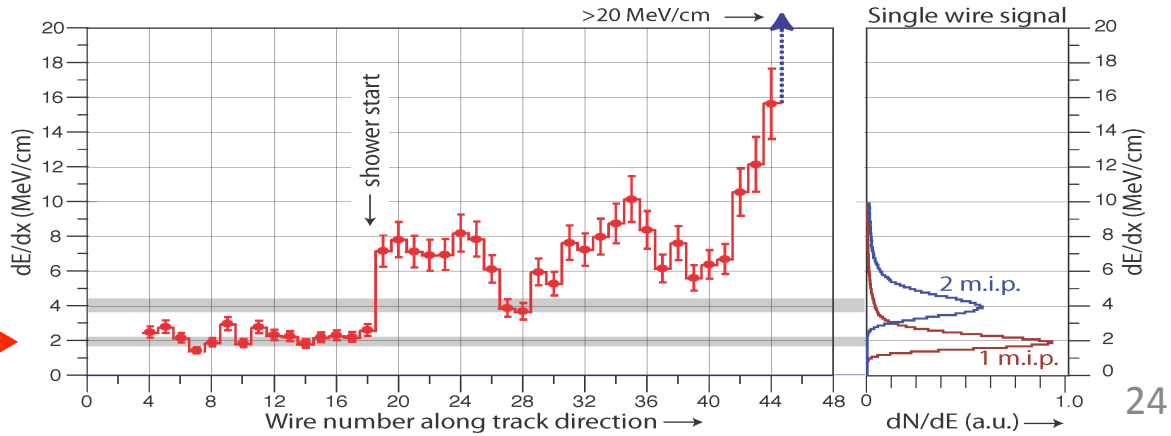


Single electron at interaction vertex well identified in Induction view

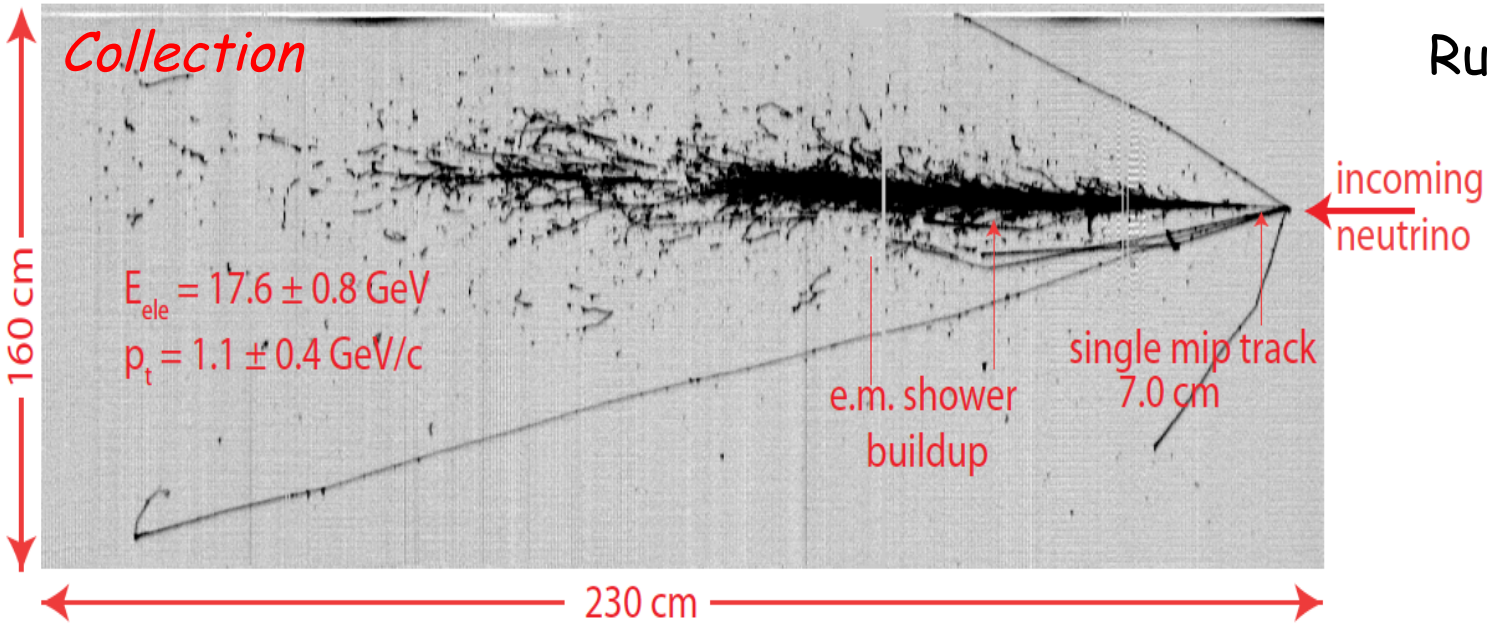


Evolution in Collection view from single m.i.p. to e.m. shower evident from dE/dx on individual wires.

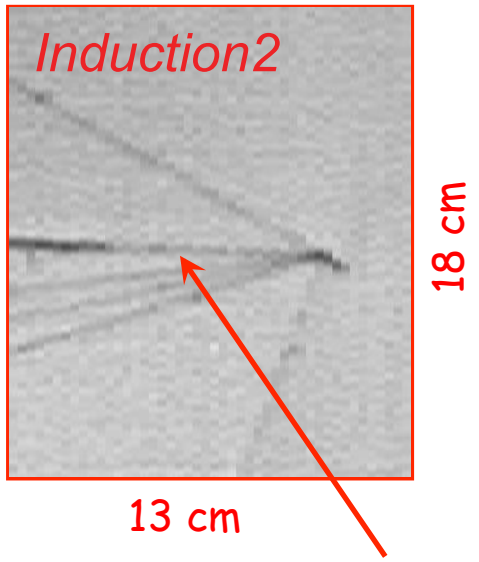
Single M.I.P →



ν_eCC events in CNGS beam

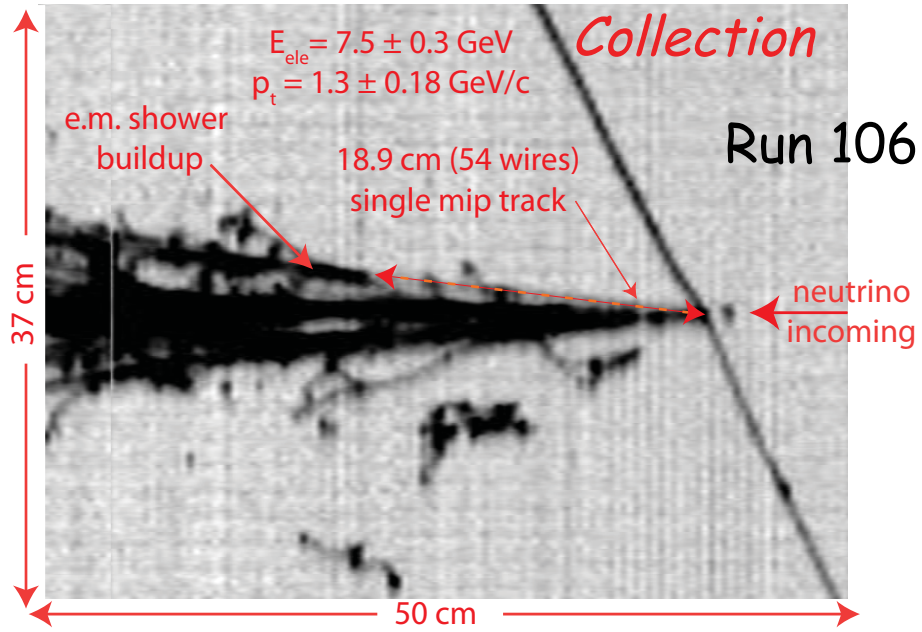


Run 11845 Ev 12764

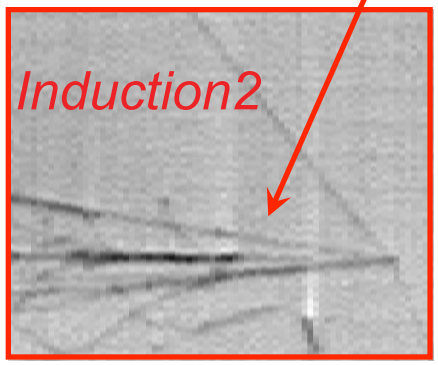


Single m.i.p. electron

Induction2 view is essential to solve complex and crowded events

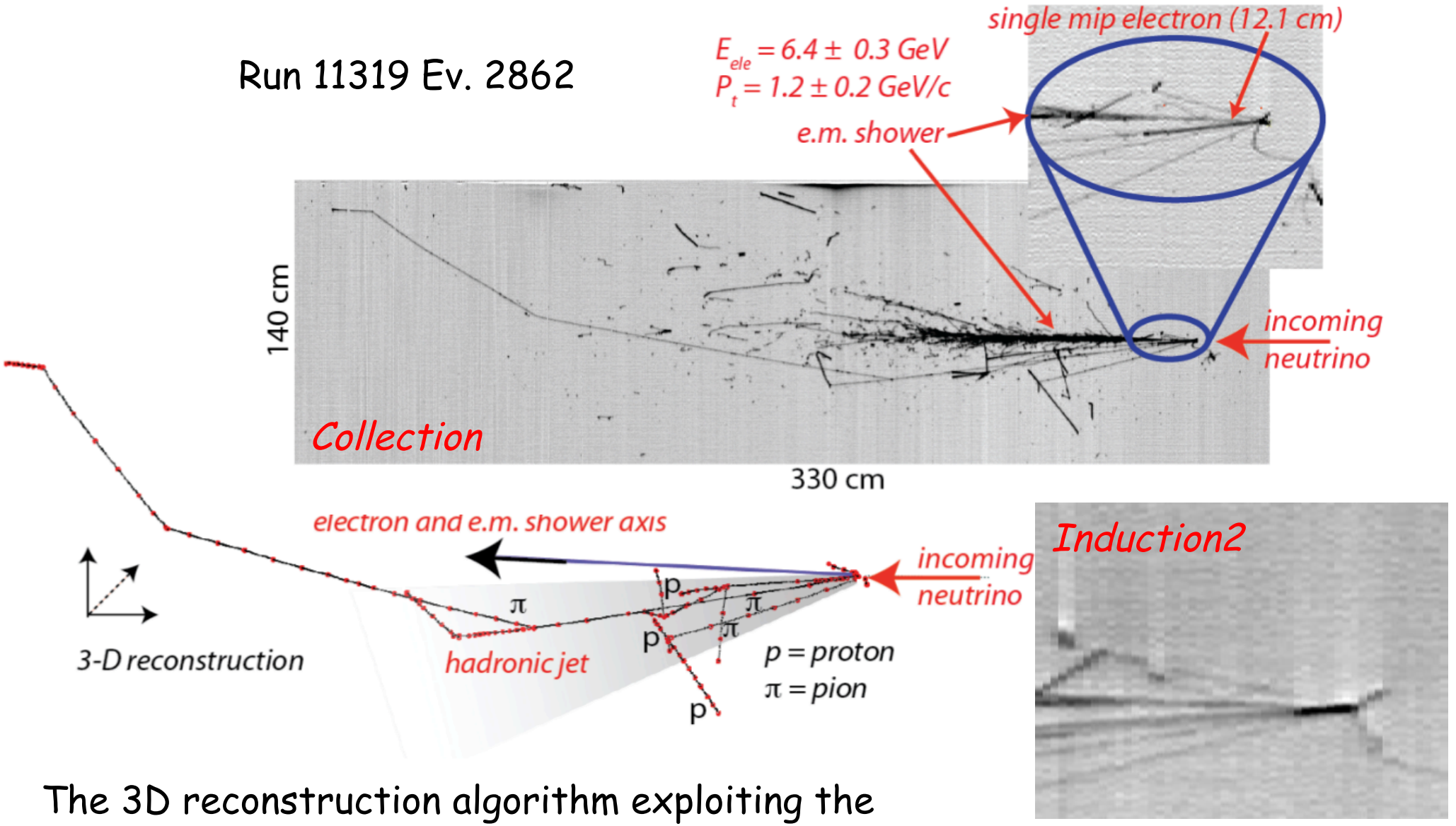


Run 10684 Ev. 296



ν_eCC identification in CNGS beam

Run 11319 Ev. 2862



The 3D reconstruction algorithm exploiting the Collection and Induction 1,2 views allows to fully reconstruct the events and to identify the involved particles

ν_eCC identification in CNGS beam

Single m.i.p. electron (11 cm)

Run 11319 Ev. 2862

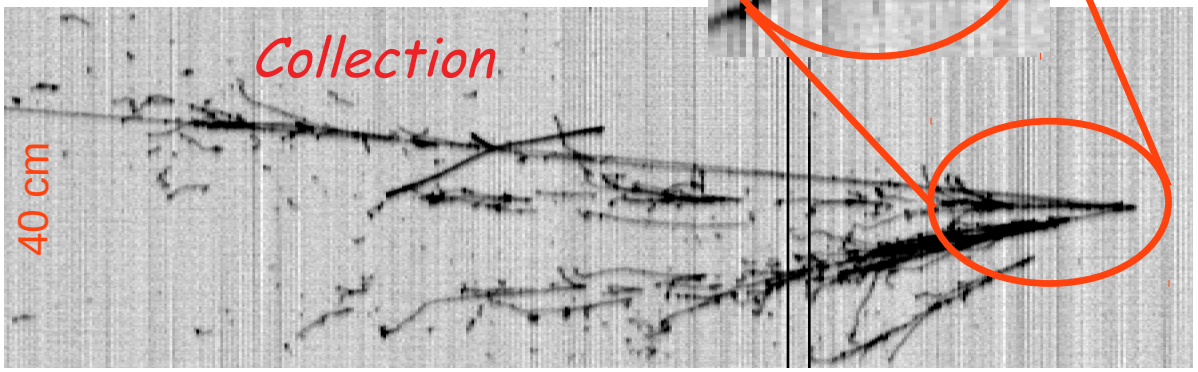
15 cm

15 cm

51 cm

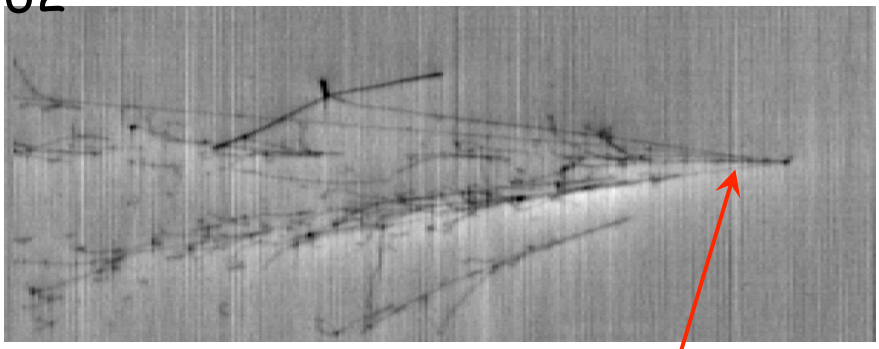
E_{ele} = 2.0 ± 0.1 GeV

p_T = 0.9 ± 0.3 GeV/c



135 cm

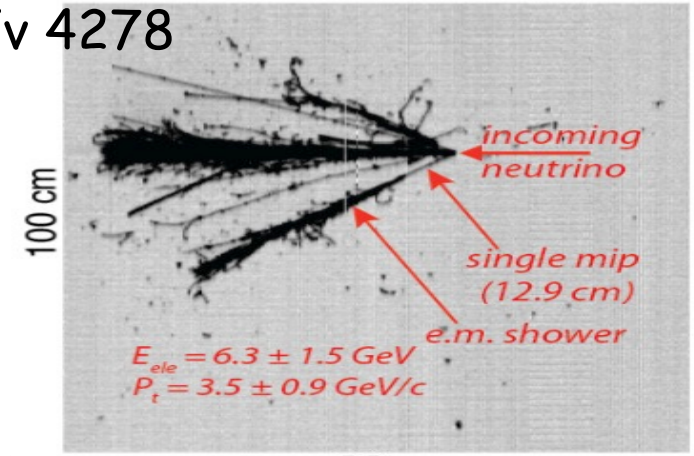
Induction2



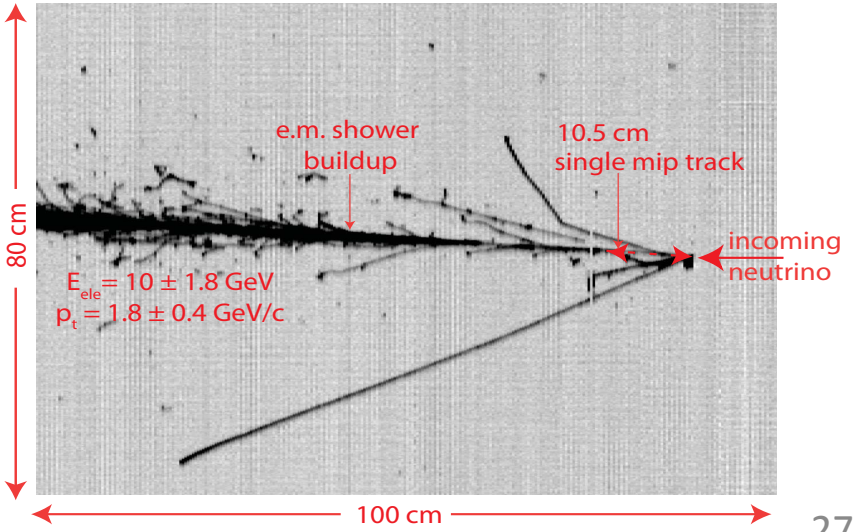
90 cm

Single m.i.p. electron

Run 11731 Ev 4278

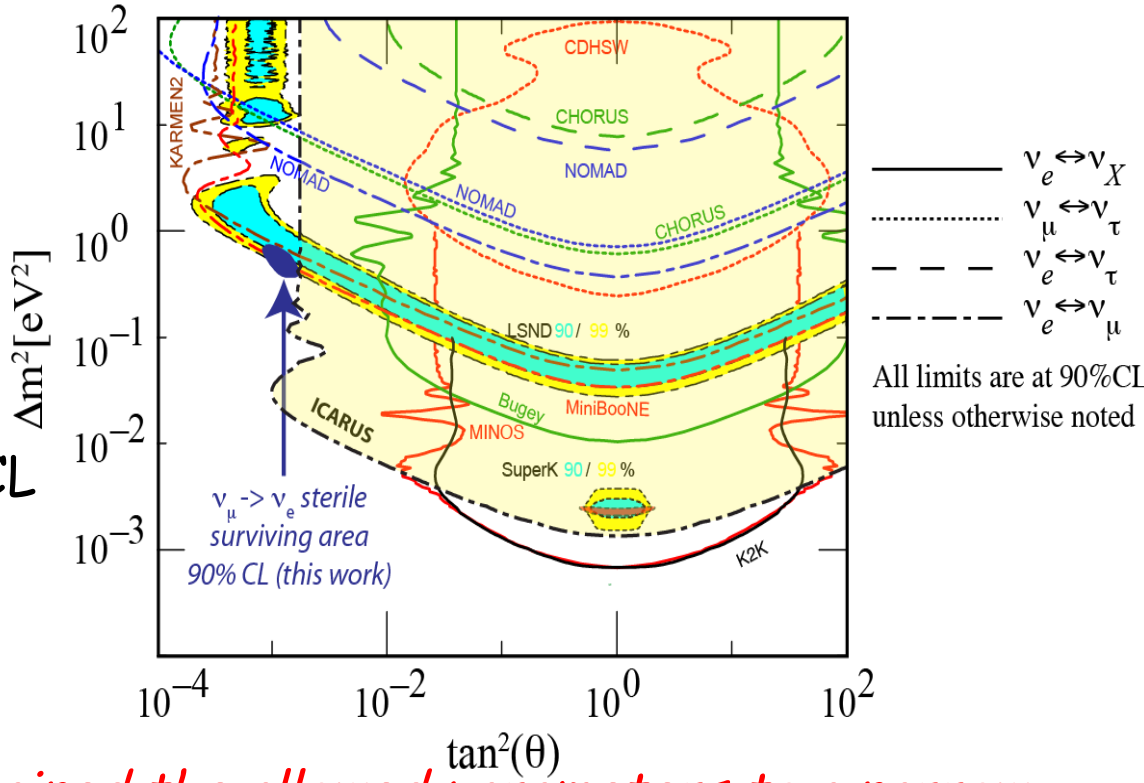


Run 10871 Ev 9185



LSND-like search by the ICARUS experiment at LNGS

- ICARUS searched for ν_e excess related to L/E_ν~1 m/MeV LSND anomaly on CNGS ν_μ beam (~1% intrinsic ν_e) in 10-30 GeV E_ν range at L=732 km;
- At CNGS L/E_ν ~36.5m/MeV: LSND-like oscillation signal averages to $\sin^2(1.27\Delta m^2_{new} L/E)\sim 1/2$. Compared to MINOS and T2K, ICARUS operated in L/E_ν range where contributions from standard oscillations not yet too relevant.
- Globally 7 e-like events were observed in the full 7.93×10^{19} pot event statistics, consistently with the 8.4 ± 1.1 expected from intrinsic νe component + standard oscillations providing the limit: $P(\nu\mu\rightarrow\nu e) \leq 3.92\times10^{-3}$ at 90 % C L and $P(\nu\mu\rightarrow\nu e) \leq 7.83\times10^{-3}$ at 99 % CL (in a two ν oscillation framework)



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

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

ICARUS, and OPERA, results constrained the allowed parameters to a narrow region at Δm^2~0.5 eV^2, $\sin^2 2\theta$~0.005 where all the experimental results can be coherently accommodated at 90% C.L, calling for a definitive experiment

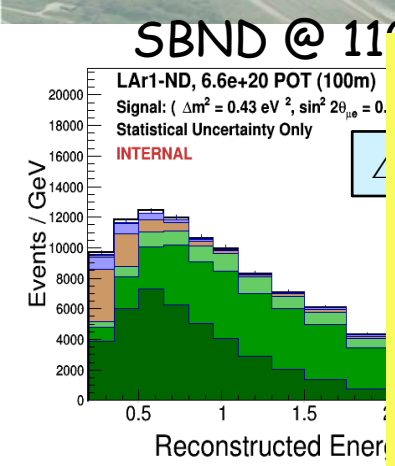
Conclusions

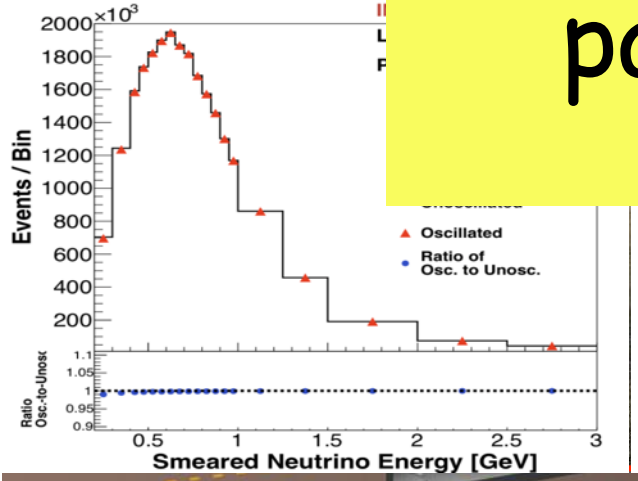
- The LAr-TPC detection technique has been taken to full maturity with ICARUS T600. It is a result of many years of R&D with continuous support of INFN.
- ICARUS completed in 2013 a successful continuous three year run at LNGS exposed to CNGS ν's and c-rays obtaining remarkable physics and technical achievements and proving the effectiveness of the single phase LAr-TPC technology for ν physics.
- The ability in reconstructing ν interactions with complex topologies in a broad energy range, combined with an efficient identification of primary electrons and an unique e/γ separation, allows rejecting backgrounds in the search for $\nu_\mu \rightarrow \nu_e$ transitions at an unprecedented level.
- ICARUS performed a sensitive search for a potential ν_e excess related to LSND-like anomaly with CNGS defining, with the other experimental results, a narrower region centered at $(\Delta m^2, \sin^2 2\theta) = (0.5\ eV^2, 0.005)$ which has to be investigated to definitively settle the LNSD hint of sterile ν.
  Atmospheric neutrinos have been identified in the ongoing data analysis.
- ICARUS is undergoing a major overhauling at CERN before to be exposed to FNAL Booster neutrinos aiming at a definitive experiment covering with 5 σ the LSND hint for sterile ν's.

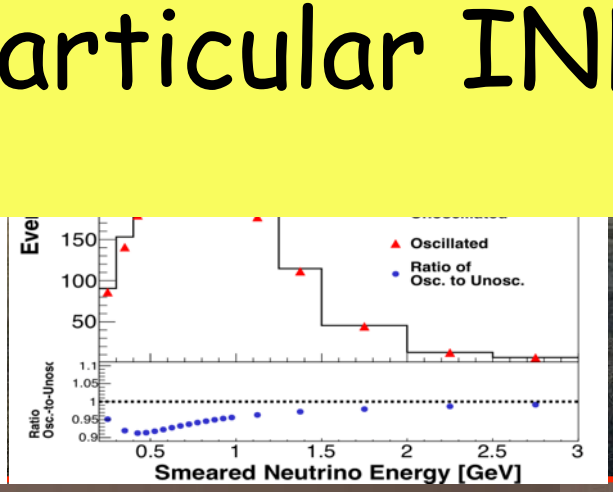
The *Short Baseline Neutrino* program

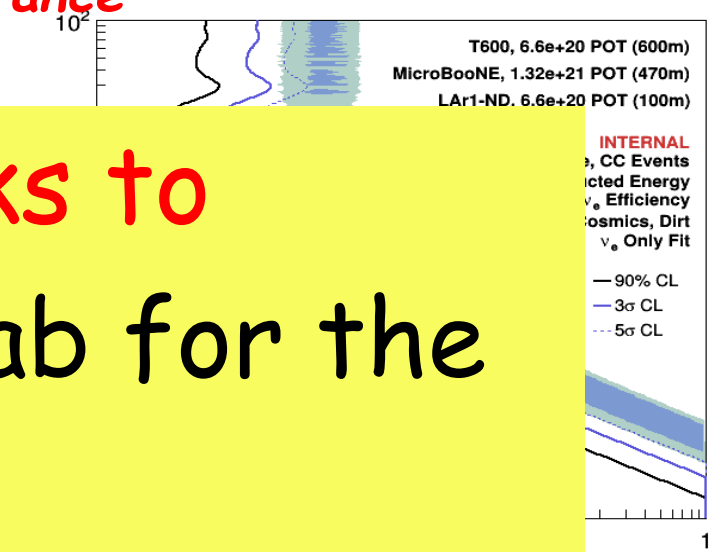
LSND 99%CL region: covered at ~5σ in νe appearance

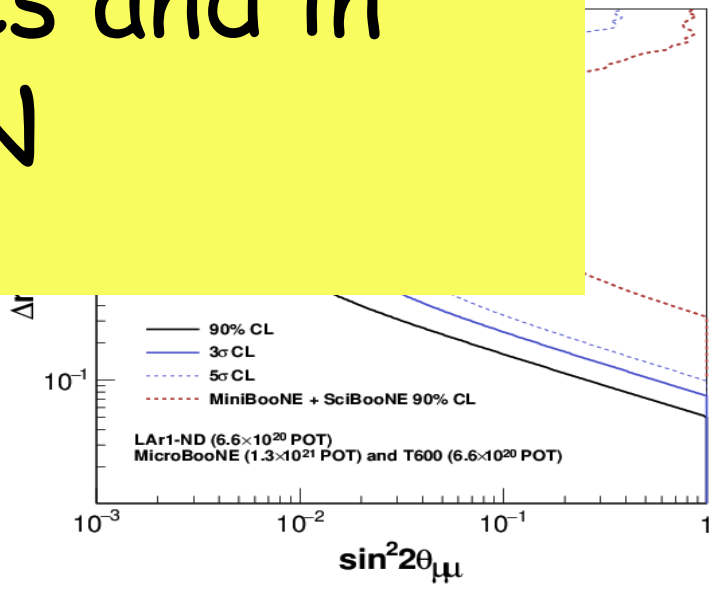
$L/E_\nu \sim 600\ \text{m} / 769\ \text{MeV} \sim \mathcal{O}(1\ \text{m/MeV})$











Many Thanks to

1) LNGS hosting lab for the superbe help
2) Funding agencies and in particular INFN

Sensitivity in ν_μ disappearance extended by 10 wrt present limits

3+1 MODEL