The ICARUS experiment

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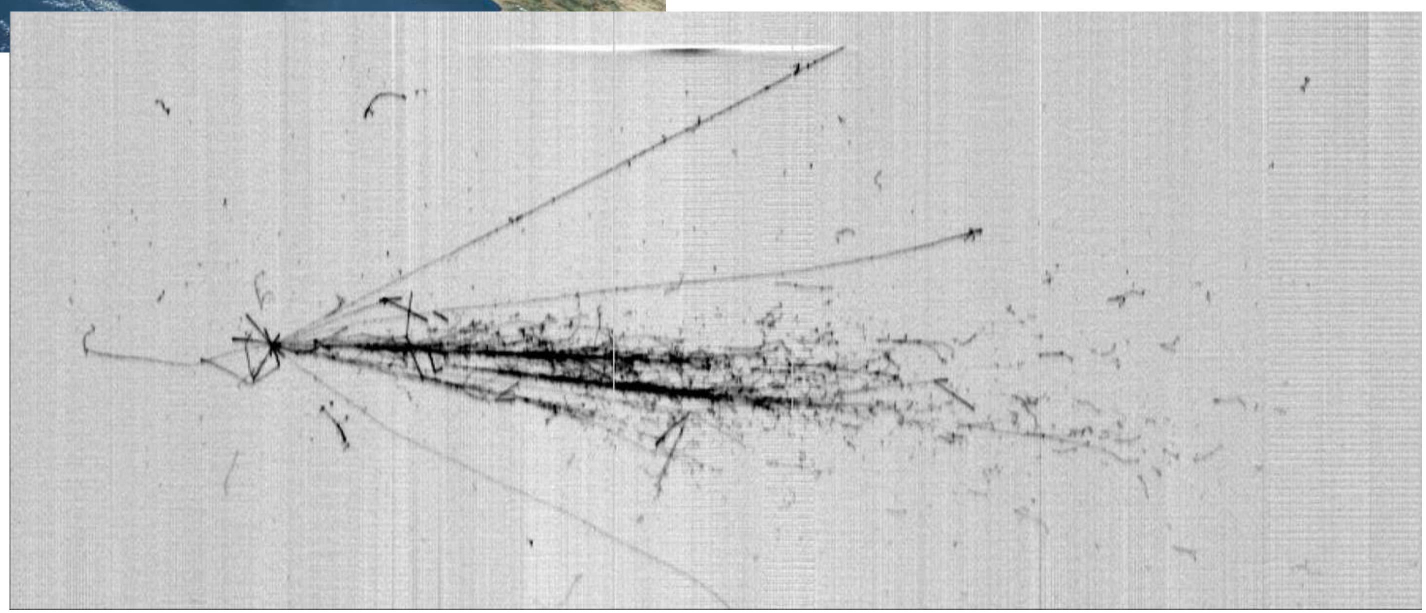
on behalf of the ICARUS Collaboration



EPS-HEP 2017, July 7th, 2017

The LAr-TPC technology and ICARUS-T600

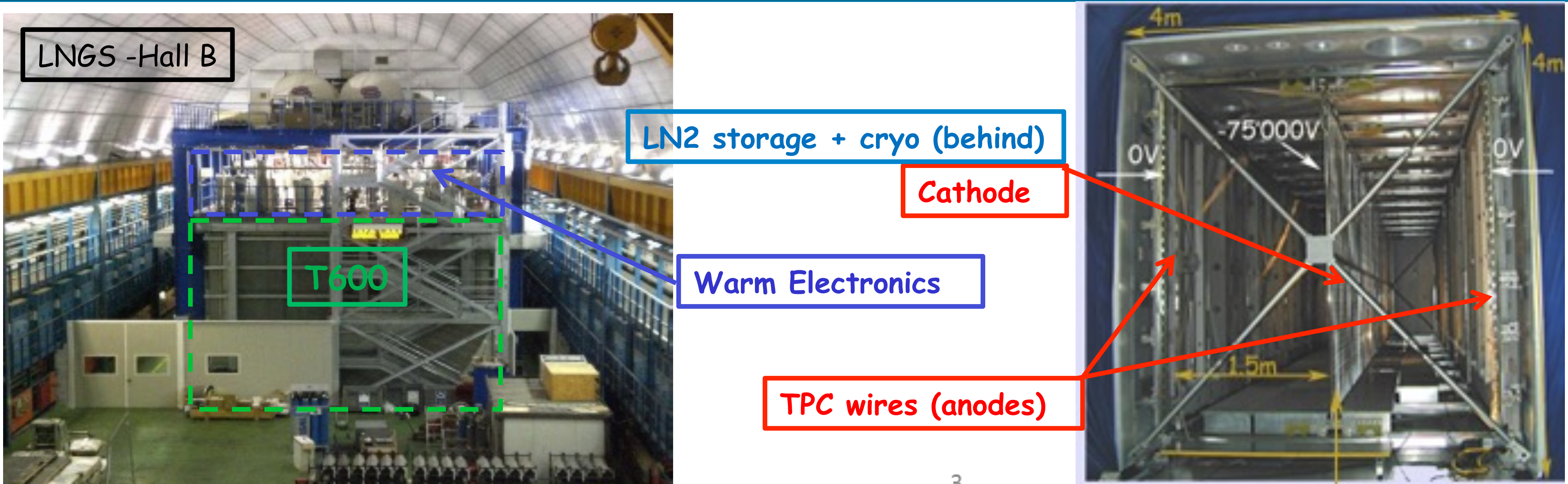
- ICARUS-T600 is the first large-scale liquid Argon TPC (760 tons of LAr). It is a uniform, self-triggering detector, with high granularity (~mm), 3D imaging capability, and good calorimetry. It is capable of accurately reconstructing a wide variety of ionizing events with complex topologies.

- ICARUS concluded in 2013 a successful 3-year run at LNGS, with CNGS beam and cosmic neutrinos. *Several relevant physics and technical results have been achieved:*
  - Demonstrated the detector performances, especially in ν_e identification and background rejection
  - Search for LSND-like anomaly with CNGS beam, constraining the LSND window to a narrow region at $\Delta m_s^2 <\sim 1\ eV^2$.
  - Verification and rejection of the superluminal neutrino claim.

- 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 underwent an overhauling at CERN before being exposed to ~0.8 GeV Booster ν beam at 600 m from target to definitely test the LSND claim searching for $\nu\mu-\nu e$ oscillations in the framework of SBN program.

ICARUS-T600 at LNGS



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)

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

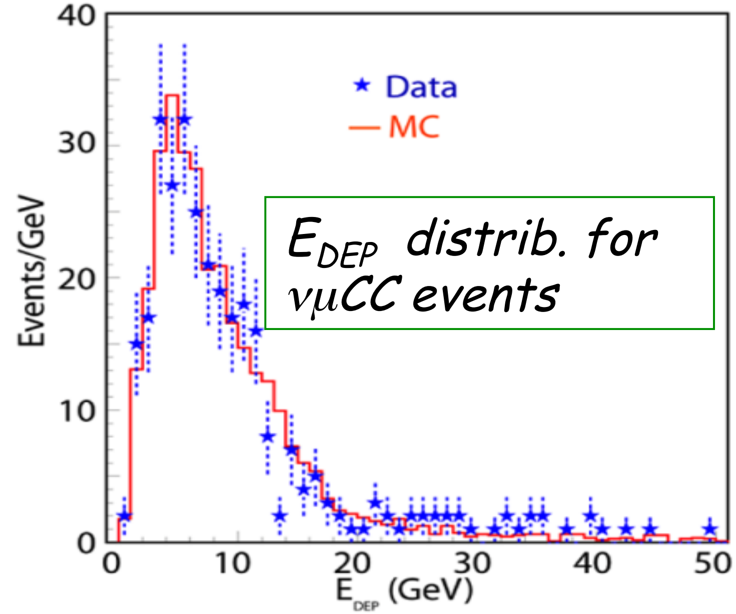
Charge and light detectors
- 3 "non-destructive" readout wire planes per TPC, wires at 0°, ±60° (Ind1, Ind2, Coll. View)
- ≈54000 wires (150 μm Ø, 3 mm pitch)
- 54+20 photomultipliers (8" Ø) + wls (TPB), sensitive at 128 nm (VUV)

Cryogenics
- Liquid and gas Ar recirculation;
- Passive insulation + dual phase N_2 shield
- High purity <~ 40 ppt O_2 equiv. (τ_e > 7 ms).

Live Time > 93%

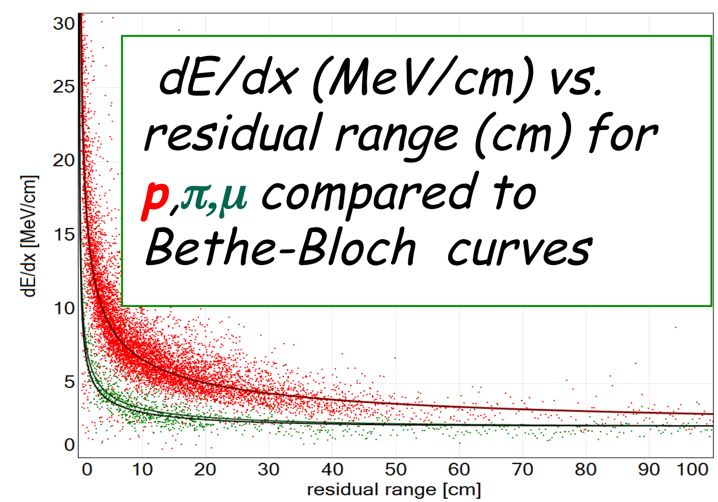
ICARUS LAr-TPC performance

- From the analysis of CNGS neutrinos and cosmic ray 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 $\Delta p/p$ ~15% in 1-5 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):



E_{DEP} distrib. for $\nu\mu$CC events

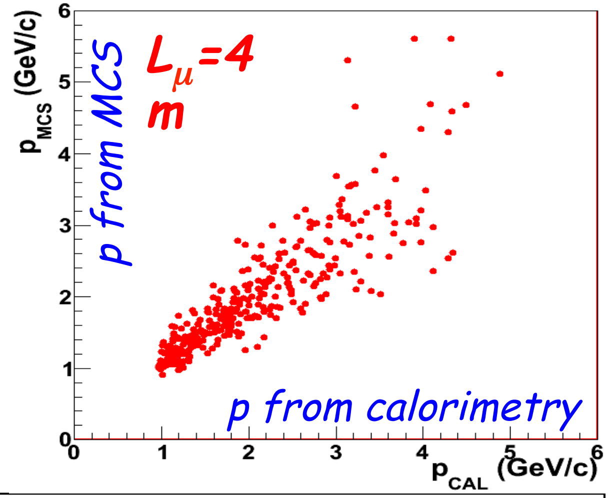
Low energy electrons:
$\sigma(E)/E = 11\%/\sqrt{E(MeV)}+2\%$
Electromagnetic showers:
$\sigma(E)/E = 3\%/\sqrt{E(GeV)}$
Hadron showers:
$\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$

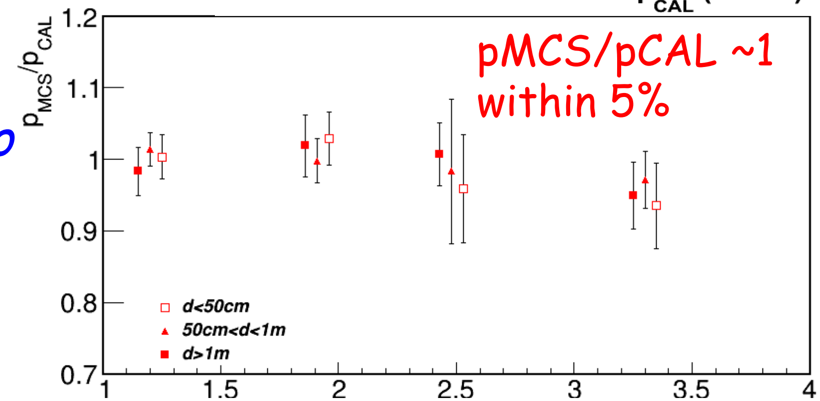


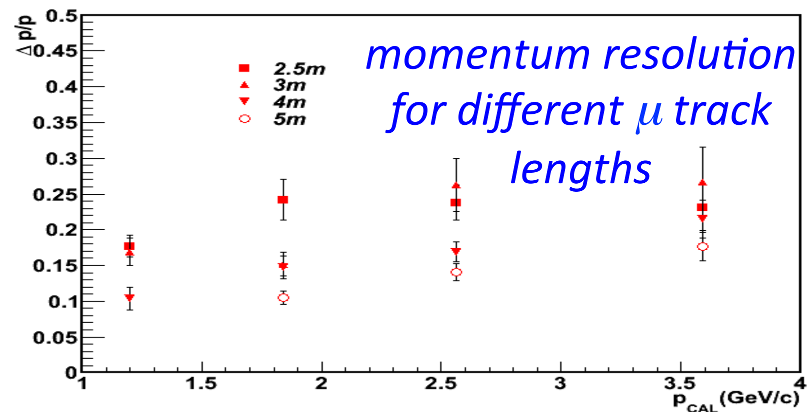
*dE/dx (MeV/cm) vs. residual range (cm) for **p**,π,μ compared to Bethe-Bloch curves*

Muon momentum measurement via multiple Coulomb scattering

- Measurement has been validated comparing p_{MCS} with calorimetric measurement p_{CAL} for ~500 *stopping muons* produced by CNGS ν_μ interactions in upstream rock;
- Small p_{MCS} under-estimation detected at p >3 GeV/c, due to non-perfect cathode planarity (up to ~25 mm) which affects electron drift velocity (*~% field 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 muon momentum and distance from cathode.*
- The resolution varies with muon length/energy: for 4 m length it's on average ~15% in the 1-5 GeV/c range (~10% at ~1 GeV/c)
- This method is well-suited to measure non-contained muon momentum. This is particularly important at SBN (<E_ν>~0.8 GeV) where a large fraction of muons will escape the detector

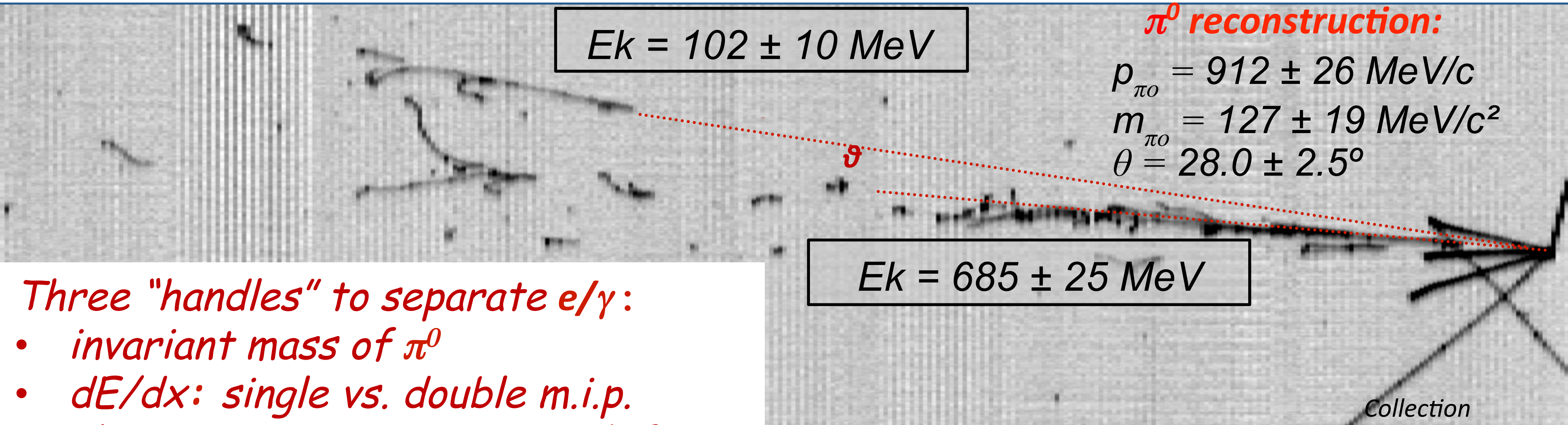






M. Antonello et al., J. Inst., 12 P04010 (2017)

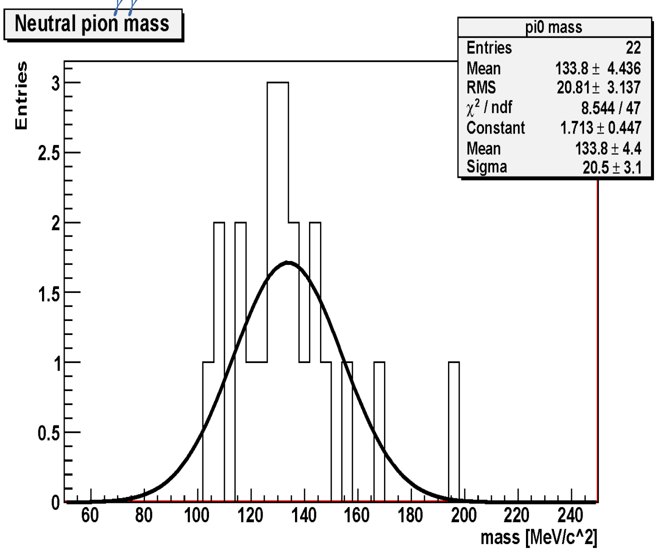
Unique feature of ICARUS: e/γ separation, π^0 reconstruction

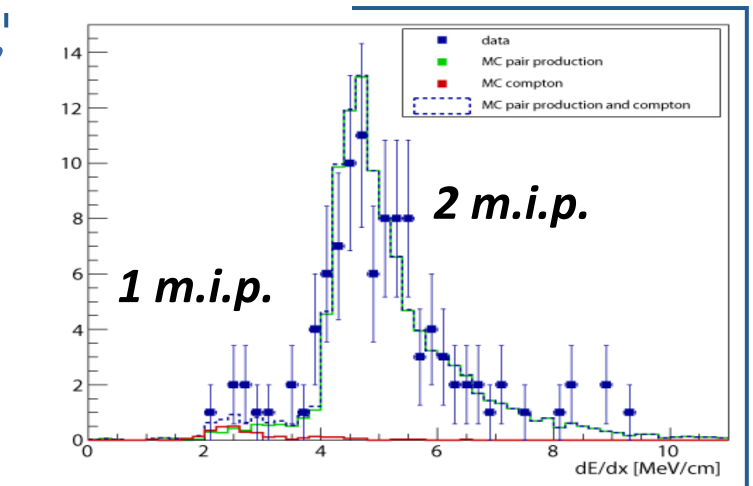


Three "handles" to separate e/γ:

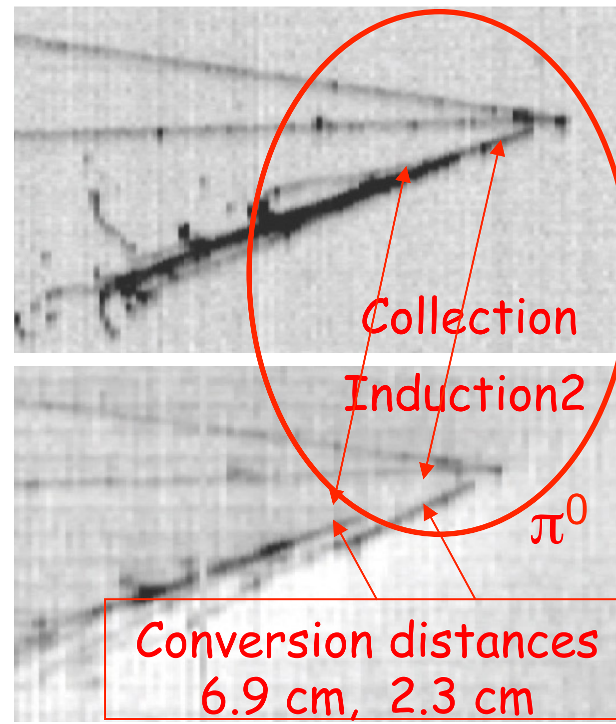
- *invariant mass of π^0*
- *dE/dx: single vs. double m.i.p.*
- *photon conversion separated from primary vertex*

$M_{\gamma\gamma}$:133.8±4.4±4 MeV/c^2



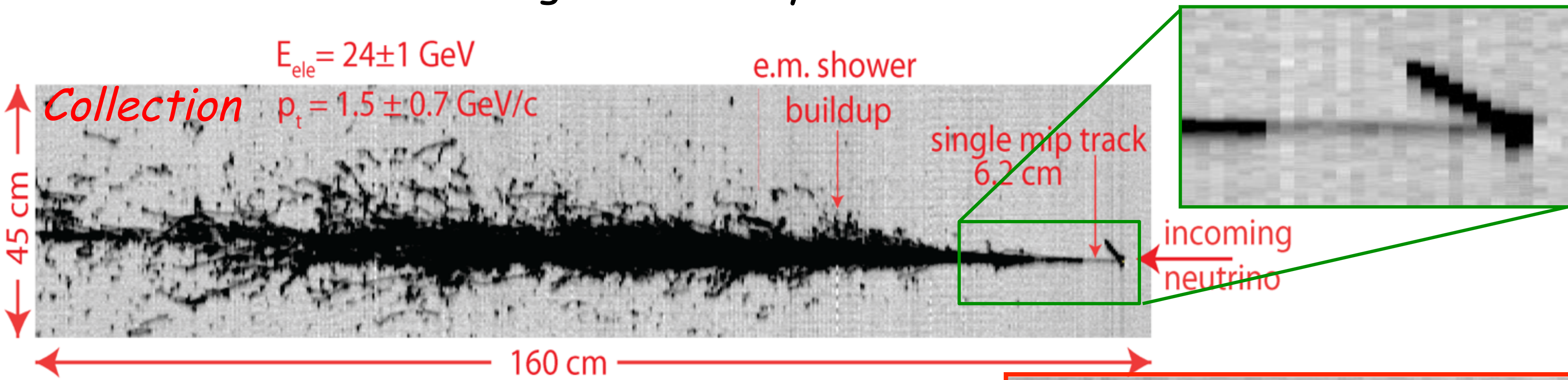


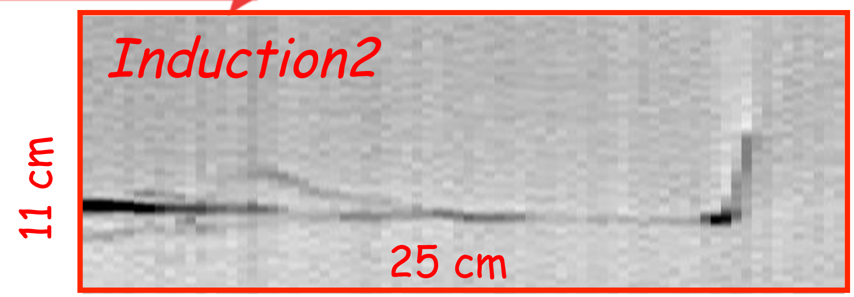
Crucial for NC rejection in ν_e-physics



ν_eCC identification in CNGS beam

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

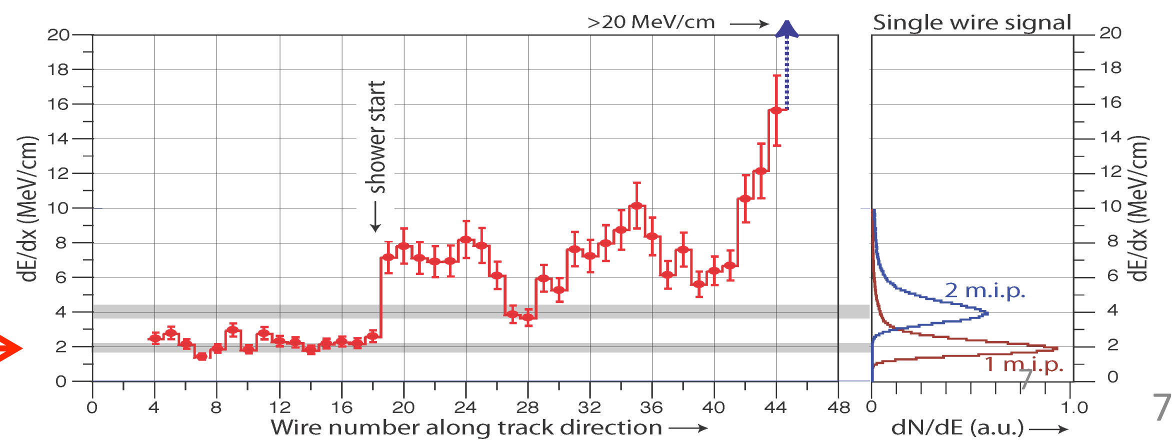




Single electron at interaction vertex well identified also in Induction view

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

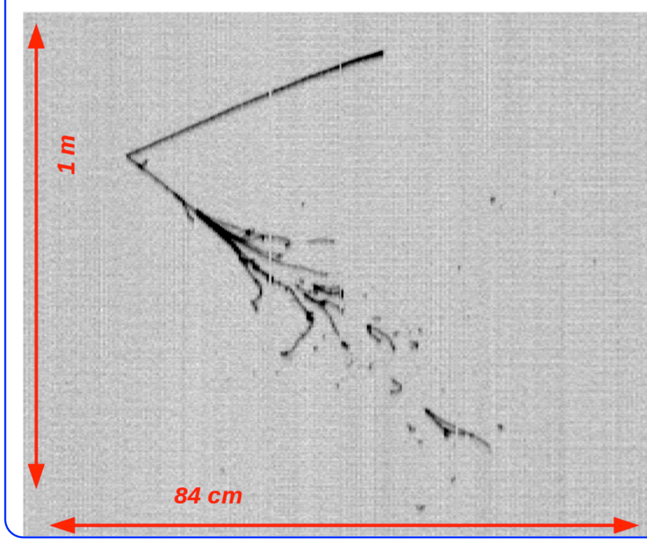
Single M.I.P.

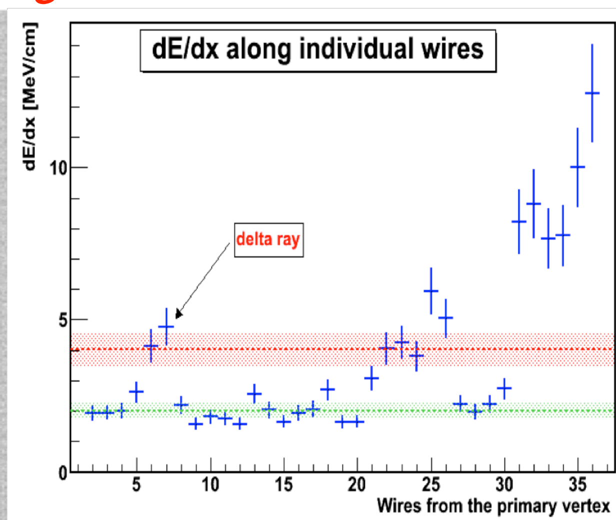


Towards automatic neutrino search: atmospheric ν

- 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 automatically (~70% efficiency for ν_e), then validated by visual scanning;
- About ~50% of exposure analyzed so far: 7 ν_μCC and 8 ν_eCC atmospheric neutrino events have been identified
- Can also address nucleon decay search in channels involving kaons (competitive with present limits): single event studies with zero background. Preliminary efficiency ~80%

TYPICAL ν_e ATMOSPHERIC EVENT:





- Quasi-elastic ν_eCC with E_{Dep}= 0.9 GeV.
- Proton identified by dE/dx.
- Electron identified by single m.i.p. deposition before shower

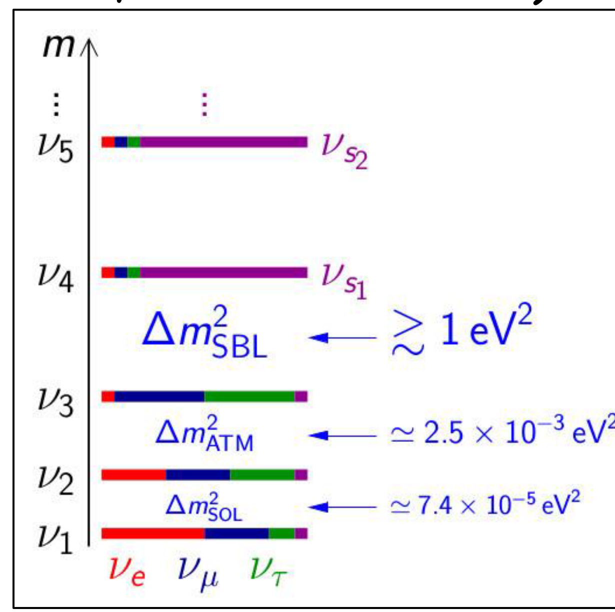
The sterile neutrino hypothesis

Different anomalies have been collected in the last years in the neutrino sector, despite the well-established 3-flavour mixing picture within the Standard Model:

- appearance of ν_e/ν_e(excess) from muon neutrino beams in accelerator experiments (LSND + MiniBooNE, combined evidence > 3σ);
- disappearance of ν_e, hinted by near-by nuclear reactor experiments (ratio observed/predicted event rates R = 0.938 ± 0.023);
- disappearance of ν_e, hinted by solar ν experiments during calibration with Mega-Curie k-capture neutrino sources (SAGE, GALLEX, R = 0.86 ± 0.05).

Results hint to a new "sterile" flavour, described by large $\Delta m^2_{new} \approx 1$ eV^2 and small mixing angle θ_{new} , driving oscillations at short distance.

- Planck data and Big Bang cosmology point to at most one further flavor, with mass $m_{new} < 0.4$ eV.
- No evidence of ν_μ disappearance is found in IceCube results in the 320 GeV-20 TeV E_ν range.
- Recent reactor neutrino data (especially NEOS) are intriguing but inconclusive



THE EXPERIMENTAL SCENARIO CALLS FOR A DEFINITIVE CLARIFICATION!

ICARUS search for an LSND-like effect with CNGS beam

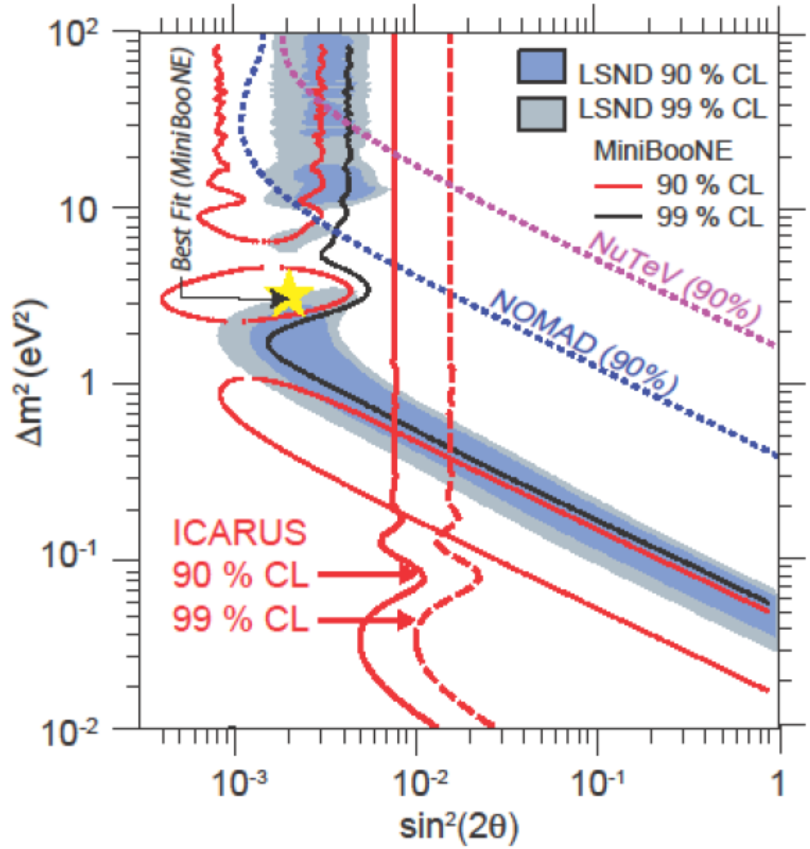
- ICARUS searched for a ν_e-excess, related to a LSND-like anomaly, with the CNGS ν beam (~ 1% intrinsic ν_e contamination), despite the larger L/E_ν ~36.5 m/MeV [L/E_ν ~ 1 m/MeV for LSND and MiniBooNE].
- The search found no ν_e-excess: the derived limits on events due to LSND anomaly are: 5.2 (90% C.L.), or 10.3 (99% C.L.), the corresponding oscillation probability being:

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

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

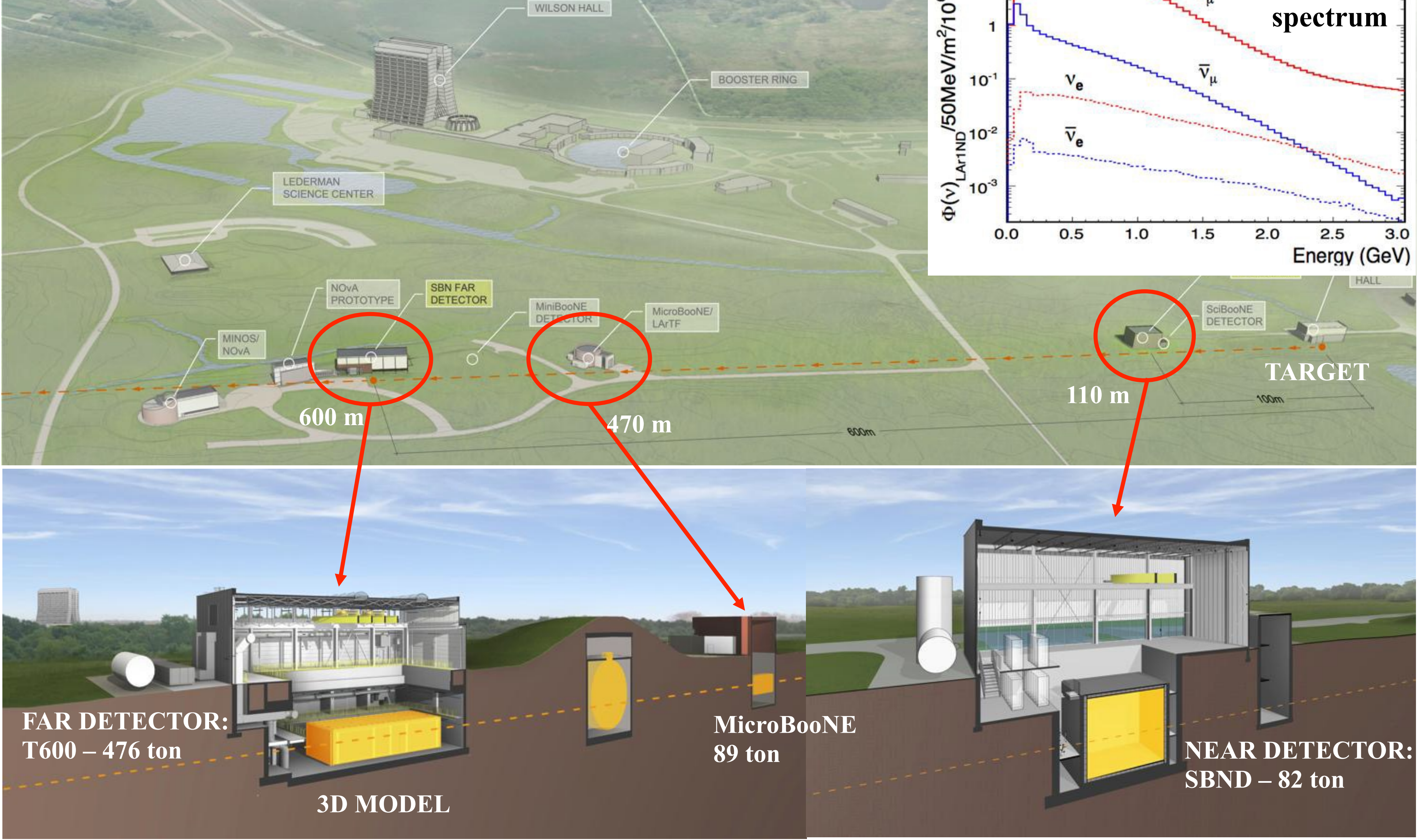
- Similar results were obtained by the Opera experiment. Combining all positive and negative world results, the possible evidence for sterile neutrinos concentrates in a narrow region, centered around:

  $\Delta m^2_{new} \sim 1 \text{ eV}^2$

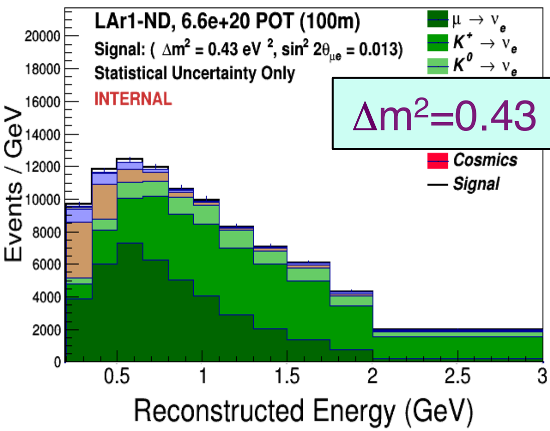


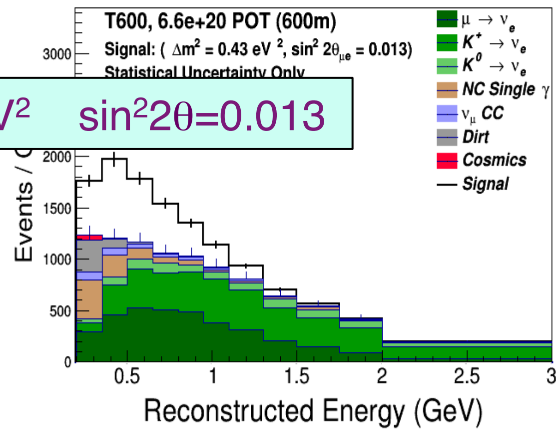
The *Short Baseline Neutrino* program

$L/E_\nu \sim 600$ m / 700 MeV $\sim \mathcal{O}$(1 m/MeV)

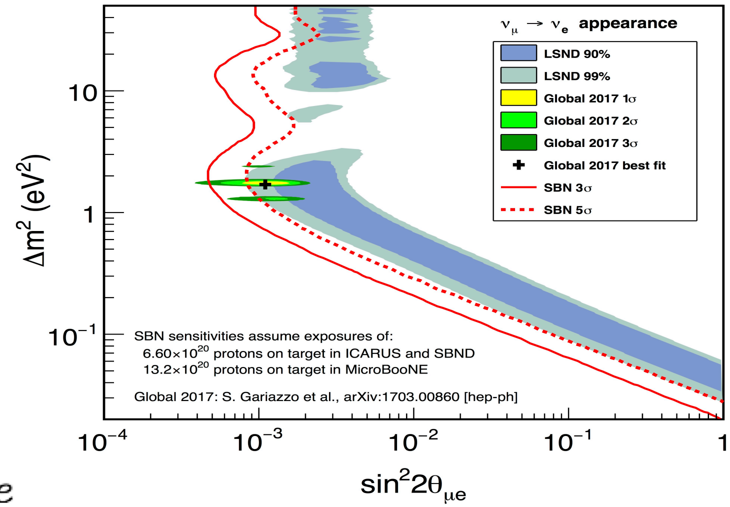


SBN sensitivity (3 yr, 6.6 10^{20} pot)



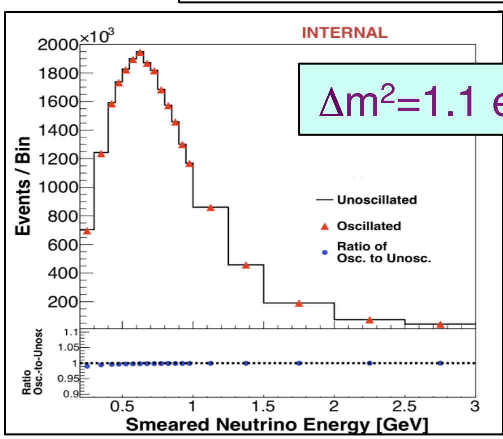


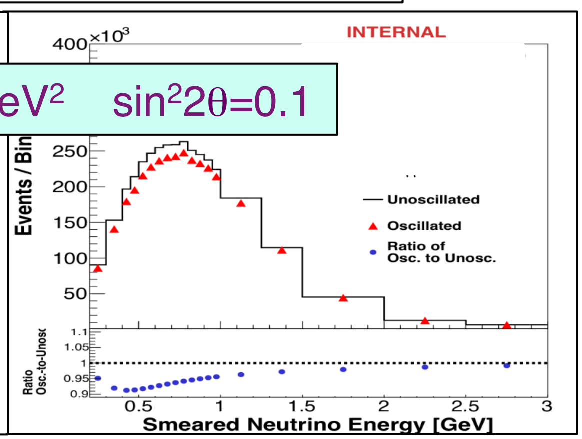
Δm^2=0.43 eV^2 $\sin^2 2\theta$=0.013



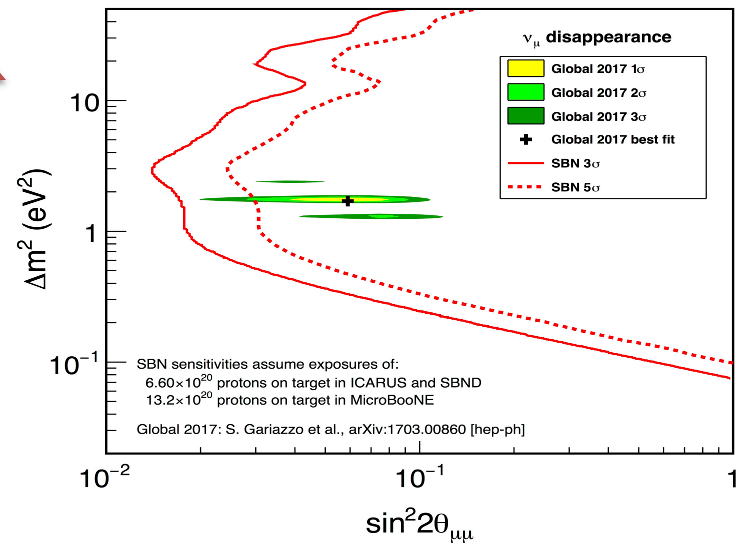
$$\sin^2(2\vartheta_{\mu e}) \leq \frac{1}{4}\sin^2(2\vartheta_{\mu x})\sin^2(2\vartheta_{ex})$$

$\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$





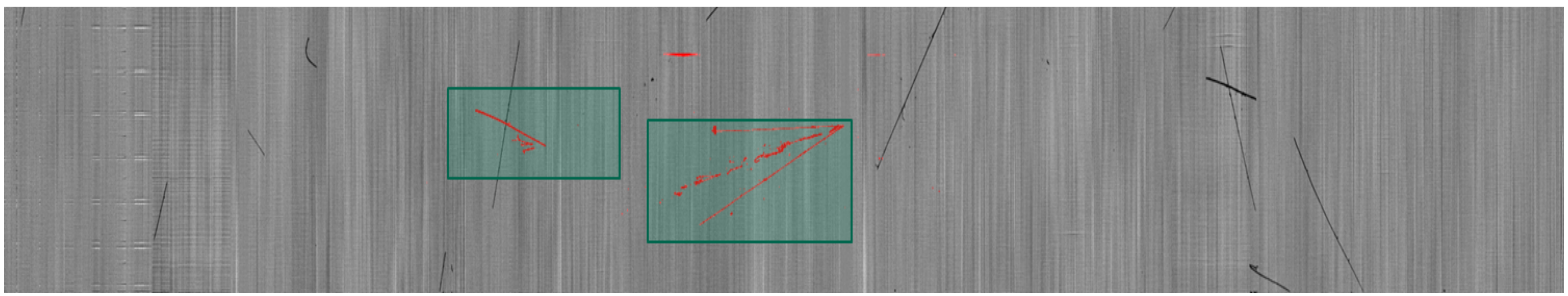
Δm^2=1.1 eV^2 $\sin^2 2\theta$=0.1



SBN can clarify the issue with a single experiment, exploiting similar LAr-TPCs at different distances from the target.
It will confirm or reject the LSND signal at the 5σ level, both in the appearance and disappearance channels.

T600 shallow depth operation

- ICARUS at FNAL will take data at shallow depth, facing more challenging experimental conditions than at LNGS: new strategies will be needed to mitigate the cosmic ray (CR) backgrounds
- A 3 meter concrete overburden over ICARUS-T600 will almost completely remove the contribution from cosmic hadrons and γ's
- Several uncorrelated CR muons will still hit the T600 during the ~1 ms drift window : ~ 11 tracks per drift, as measured in a surface test run (2001).



- To discern the true 3D position of the triggering event, it is necessary to precisely determine the timing of each track in the TPC image, exploiting:
  - A much improved light detection system (90 PMTs per chamber, with ~2 ns time resolution)
  - A cosmic ray tagger (CRT) surrounding the T600. Scintillating bars equipped with optical fibers driving light to SiPM arrays for readout.

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 neutrinos and cosmic 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 neutrino interactions with complex topologies in a broad energy range, combined with an efficient identification of primary electrons and a 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 $(\Delta m^2, \sin^2 2\theta) = (\sim 1\ \mathrm{eV}^2, 0.002)$ 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 underwent a major overhauling at CERN and is now being transported to FNAL (***see G. Raselli's talk tomorrow!***) to be exposed to Booster neutrinos,
- The SBN experiment will provide a clarification of the sterile neutrino issue, both in appearance and disappearance modes.

THANK YOU!

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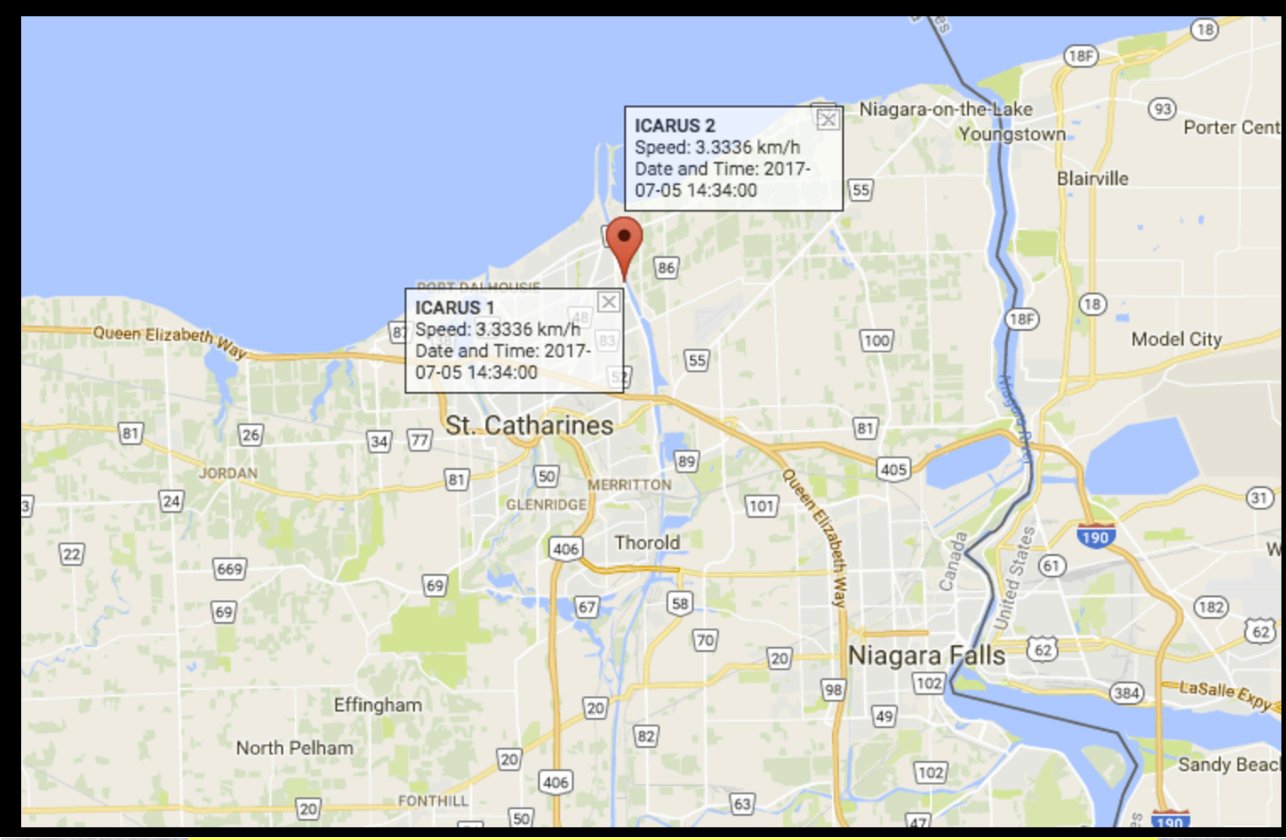

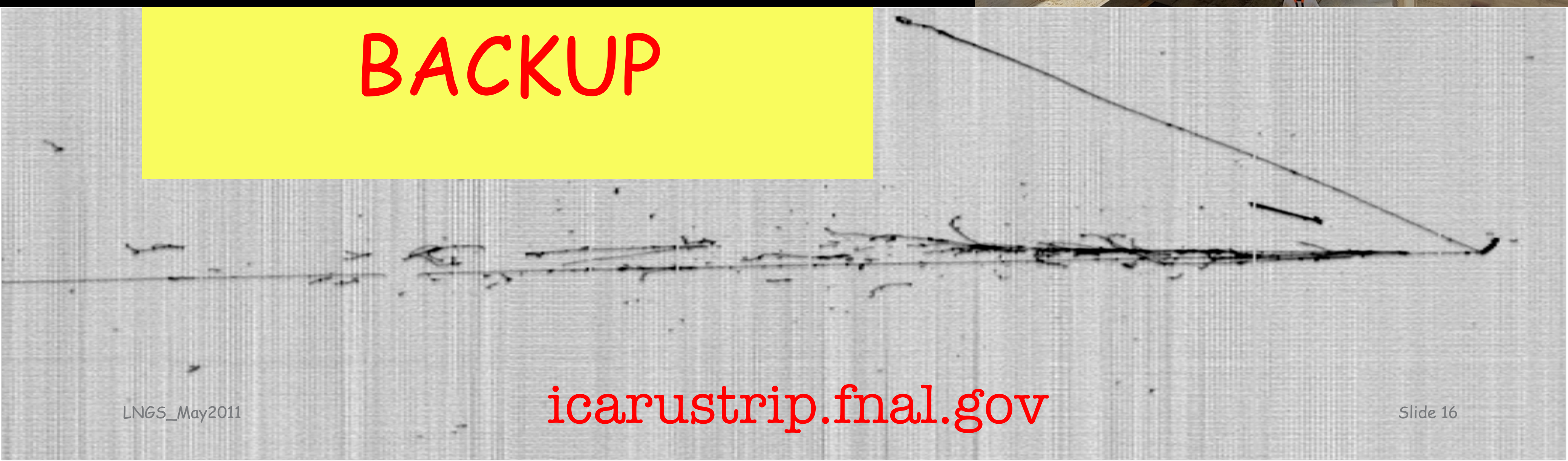

BACKUP

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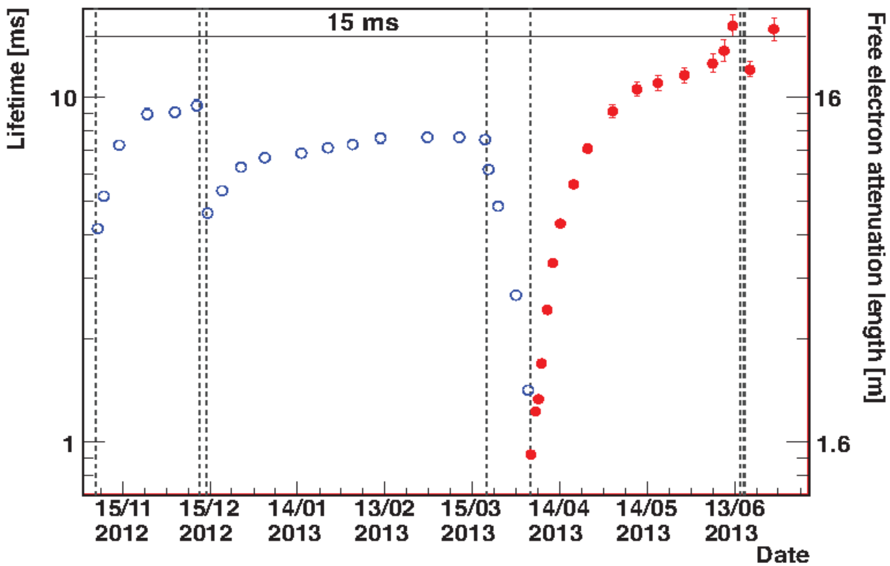
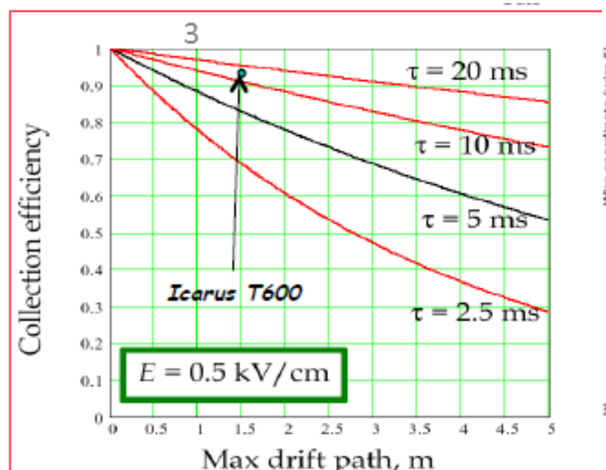
A key feature of LAr imaging: very long e$^-$ mobility

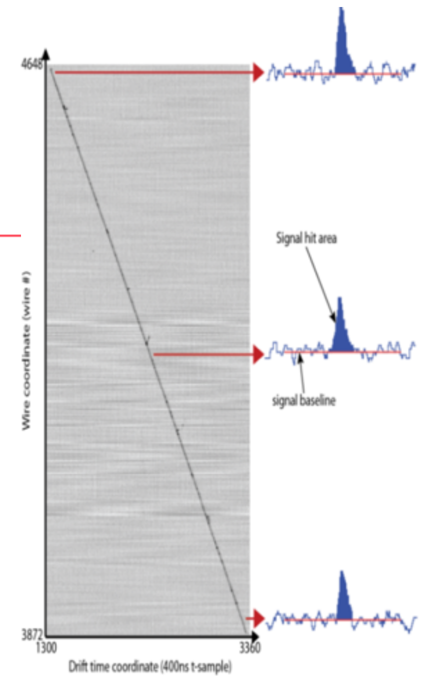
- Level of electronegative impurities in LAr must be kept exceptionally low to ensure ~m long drift path of ionization e$^-$ signal without attenuation;
- New industrial/lab purification methods have been developed to continuously filter and re-circulate both liquid (2.5 m^3/hour) and gas (100 Nm^3/day) 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 !





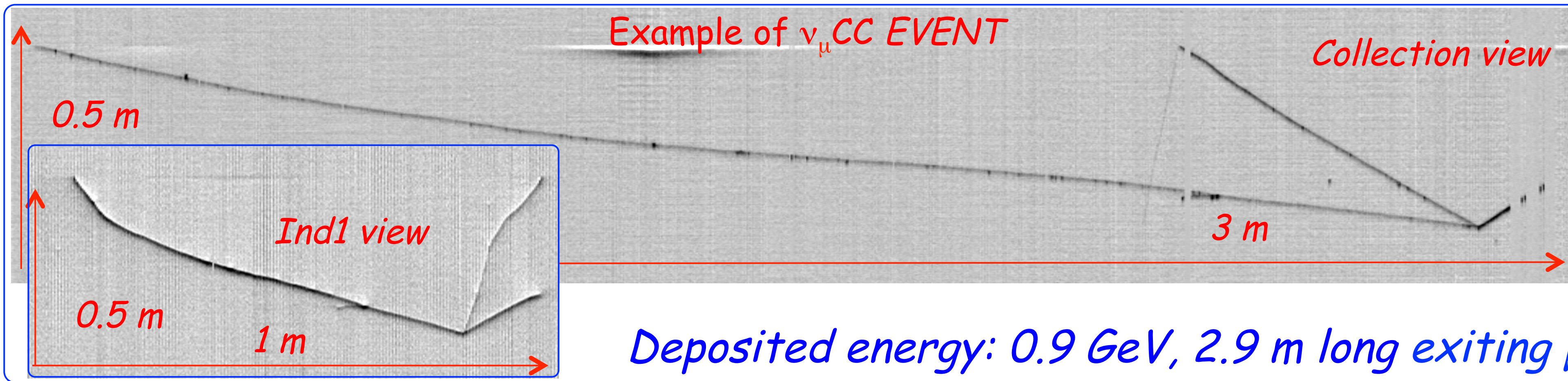
Drifting charge attenuation versus drift path at different electron lifetimes



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.

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 8 ν_eCC atmospheric neutrino events have been identified in the sample analyzed so far.



Deposited energy: 0.9 GeV, 2.9 m long exiting μ