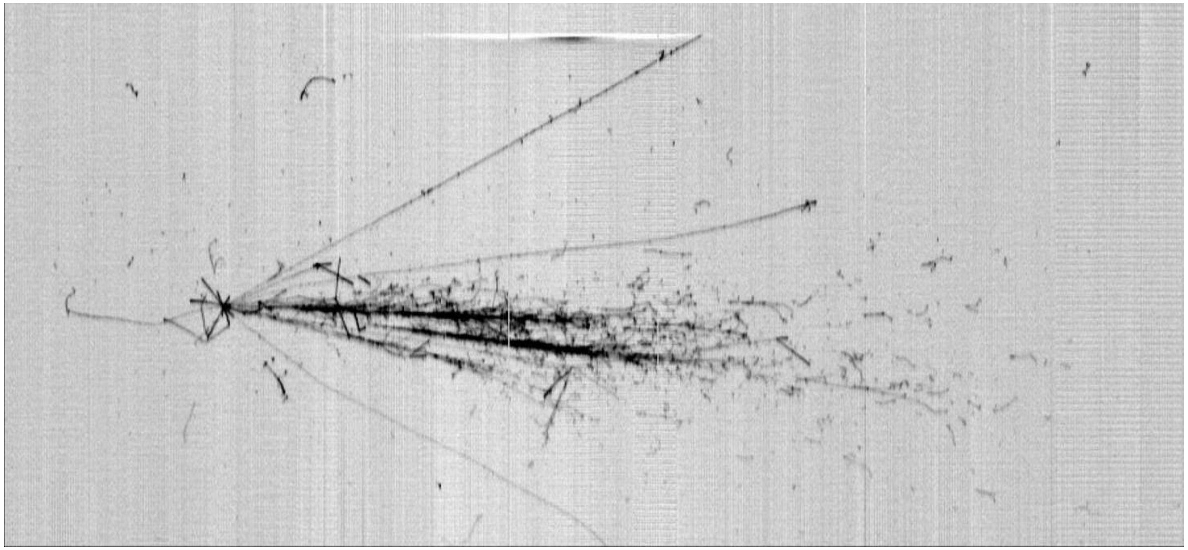
The ICARUS experiment



Christian Farnese
Università di Padova
and INFN

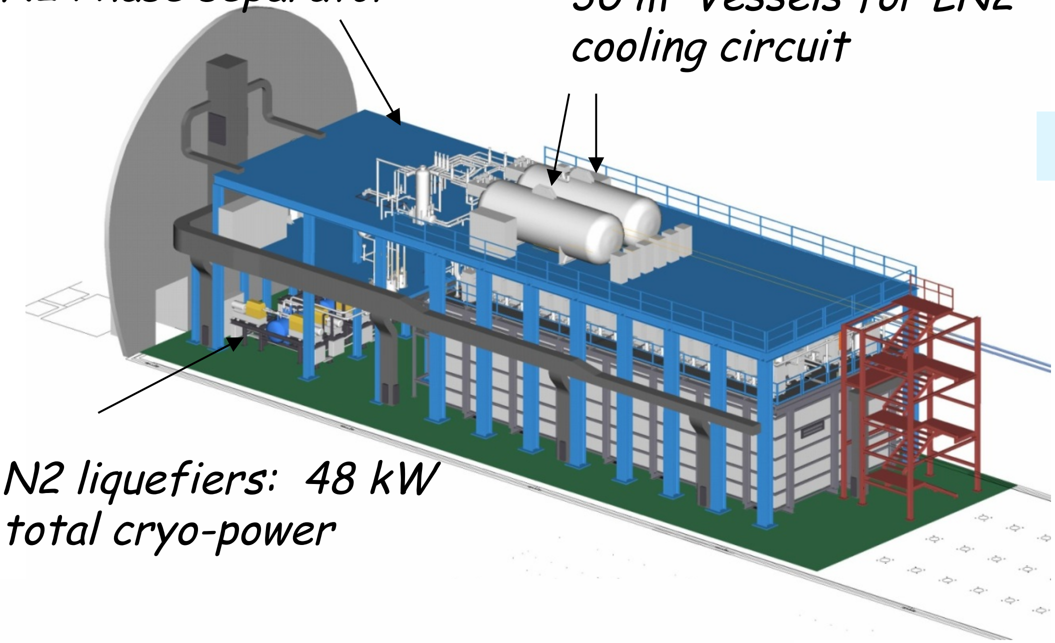
on behalf of the ICARUS
Collaboration

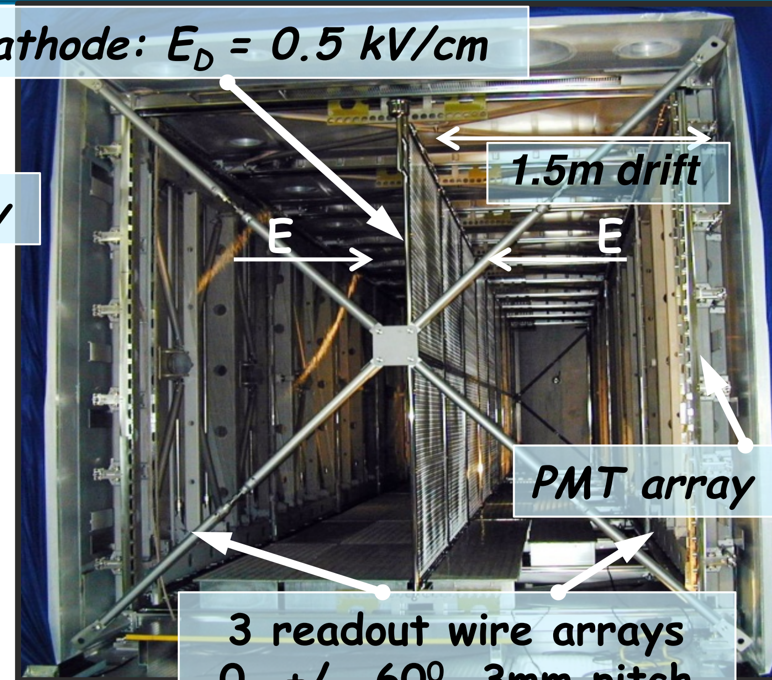
ICNFP 2017, Crete, August 22th

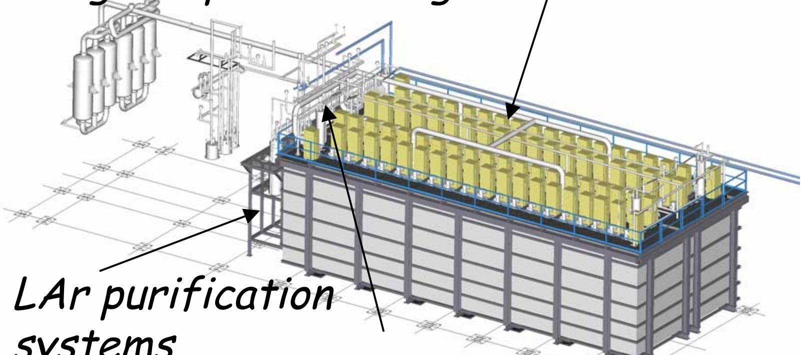
The LAr-TPC technology and ICARUS-T600

- *Exposed to CNGS ν beam ICARUS concluded in 2013 a very successful-3 years long run, collecting 8.6 x 10^{19} pot event statistics with detector live time > 93% recording also c-rays to study atmospheric νs (0.73 kt y exposure) .*
- Several physics/technical results has been achieved during the run at LNGS:
  - *An exceptionally low level ~20 p.p.t. [O_2] eq. of e-negative impurities in LAr;* the measured e- lifetime τ_{ele} >15 ms ensured few m long drift path of ionization e- signal without attenuation;
  - *Demonstrated the detector performance*, especially in νe identification and π^0 background rejection in νμ−νe study to unprecedented level;
  - *Performed a sensitive search for LSND-like anomaly with CNGS beam,* constraining the LSND window to a narrow region at Δm^2 <~ 1 eV^2.
- 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 νμ−νe oscillations in the framework of SBN program.

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







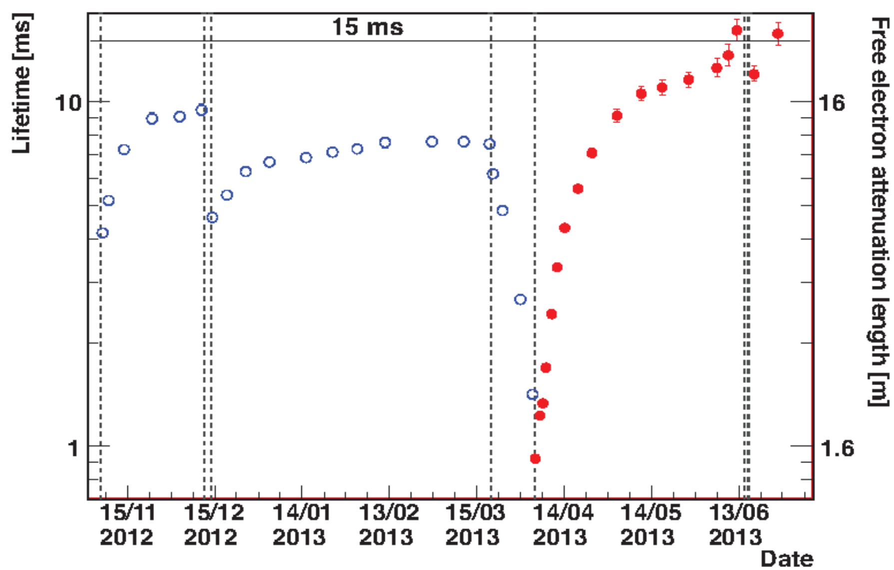
Two identical modules: 476 t active mass

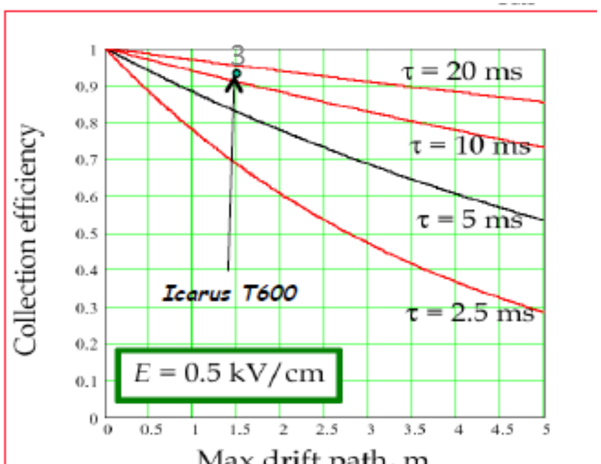
- 2 TPCs per module, common central cathode: E_D= 0.5 kV/cm, v_D=1.55 mm/μs, 1.5 m drift length;
- 3 "non-destructive" readout wire planes per TPC, ≈54000 wires at 0, ±60° wrt horizontal: Induct.1, Induct. 2 and Collect. views;
- Continuous TPC read-out, 0.4 μs sampling time;
- 74 8" PMTs +TPB wls, sensitive at 128 nm (VUV).

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

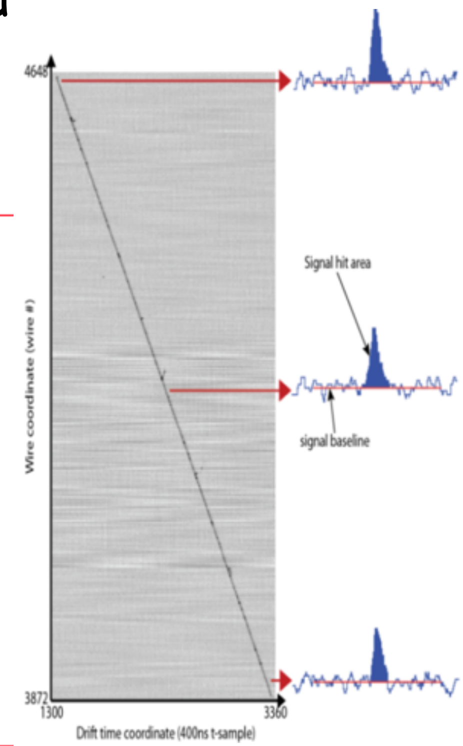
- Level of electronegative impurities in LAr must be kept exceptionally low to ensure ~m long drift path of ionization e^- signal without attenuation;
- New industrial/lab purification methods have been developed to continuously filter and re-circulate both liquid (2.5 m^3/hour) and gas (100 Nm^3/day)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

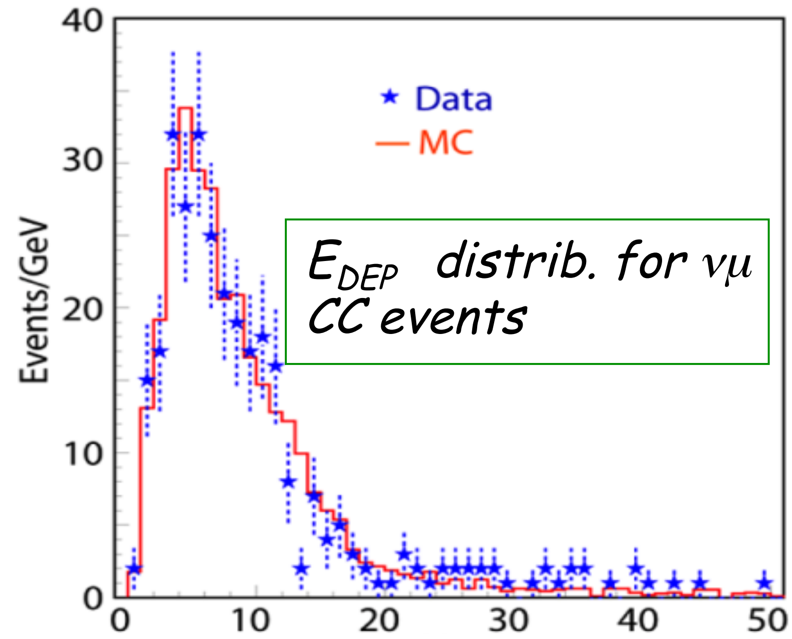


ICARUS demonstrated the effectiveness of single phase LAr-TPC technique paving the way to huge detectors with longer drift distances as required for LBNF/DUNE project.

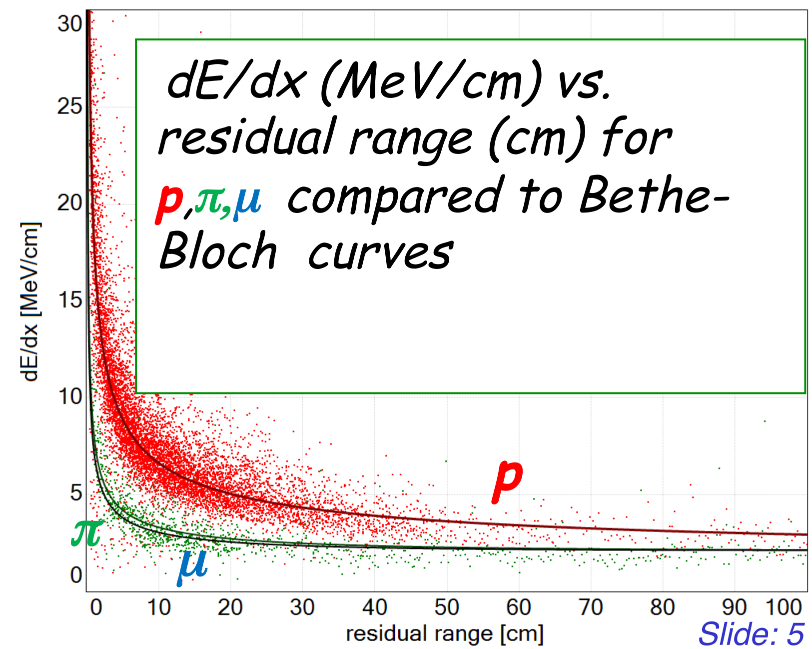
ICARUS LAr-TPC performance (CNGS ν's and cosmics)

- *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 Scattering with $\Delta p/p$ ~15%.
- *Measurement of local energy deposition dE/dx:* remarkable e/γ separation (0.02 X_0 sampling, X_0 =14 cm, and a powerful particle identification by dE/dx vs range):

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

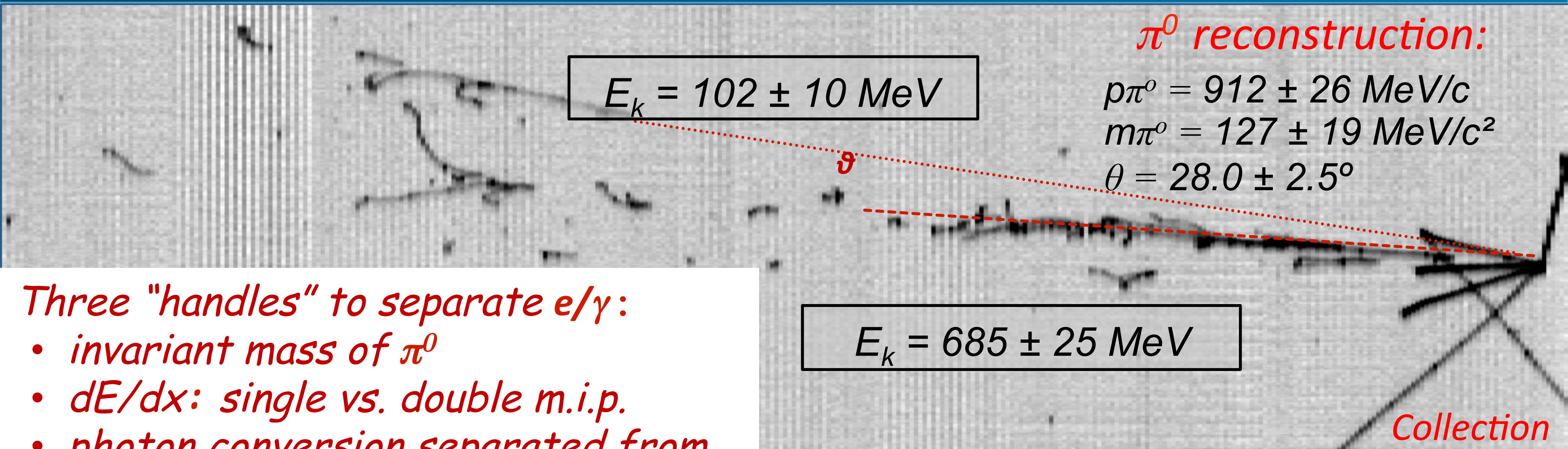


E_{DEP} distrib. for $\nu\mu$ CC events



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

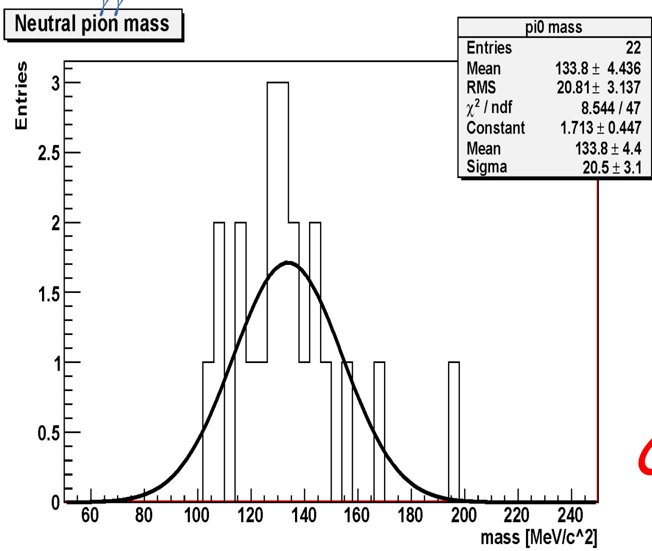
Unique feature of ICARUS: e/γ separation, π^0 reconstruction

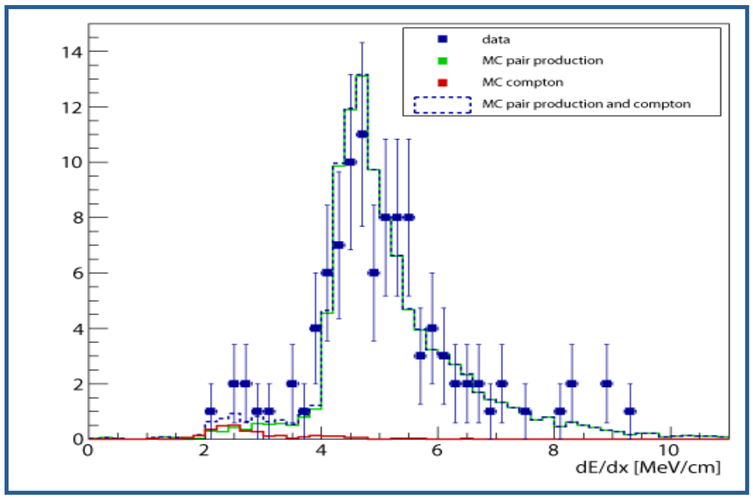


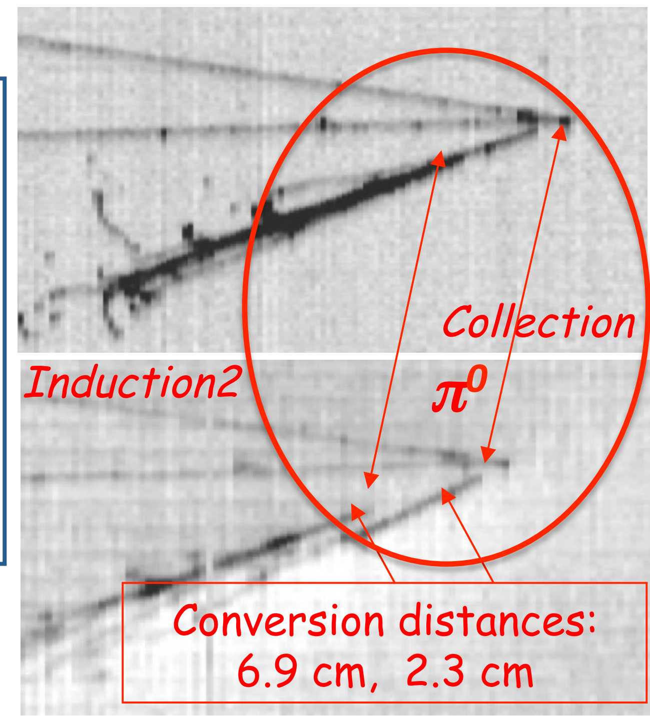
Three "handles" to separate e/γ :

- 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/c²



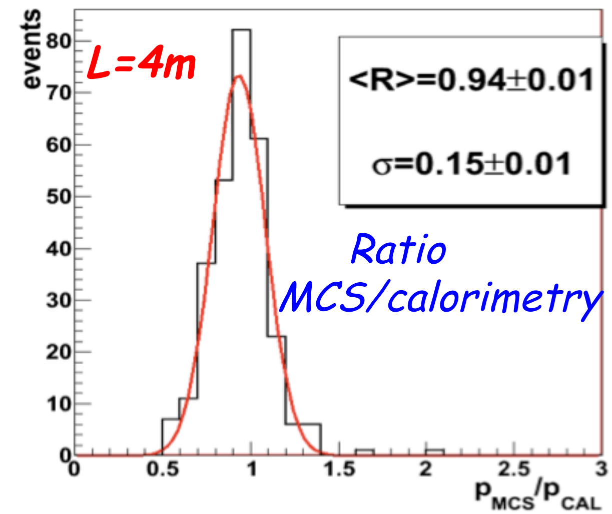


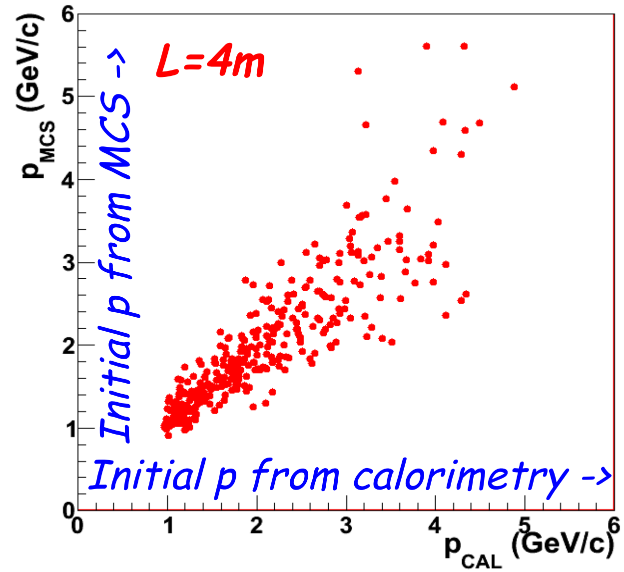


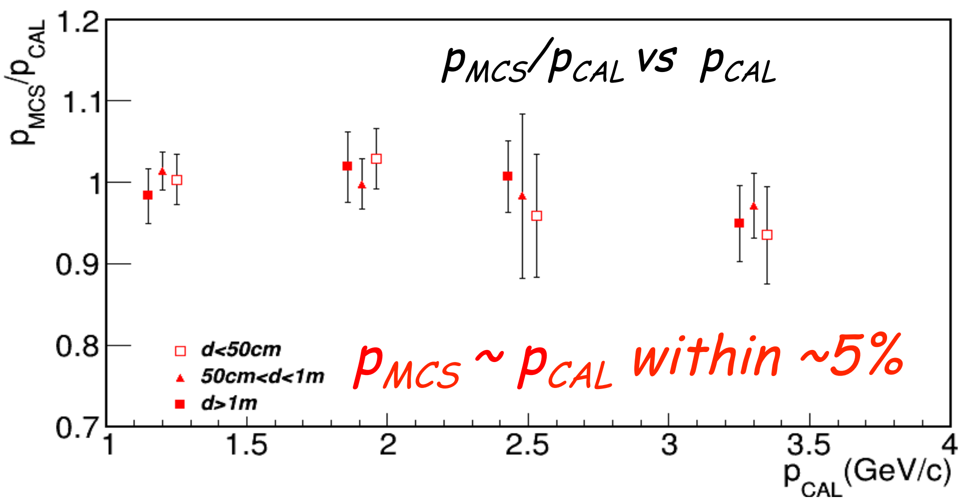
Crucial for NC rejection in νe-physics

Muon momentum measurement via multiple scattering (MCS)

- Essential for escaping μ, MCS can be also used to complement the range measurement for stoppings;
- MCS method has been validated comparing p_{MCS} with corresponding calorimetric measurement p_{CAL} for ~ 500 *stopping μs* from CNGS νμ interacting in upstream rock;
- *p_{MCS} well correlated with p_{CAL} (L= 4m track).*
  Small p_{MCS} under-estimation detected above 3 GeV/c, are due to non-perfect cathode planarity (up to ~25 mm) which affects e^- drift velocity (~% E_D *field distortion).*
- *The effects have been modeled computing actual E_D in MC events to extract a correction to p_{MCS} as a function of p and track distance from cathode.*

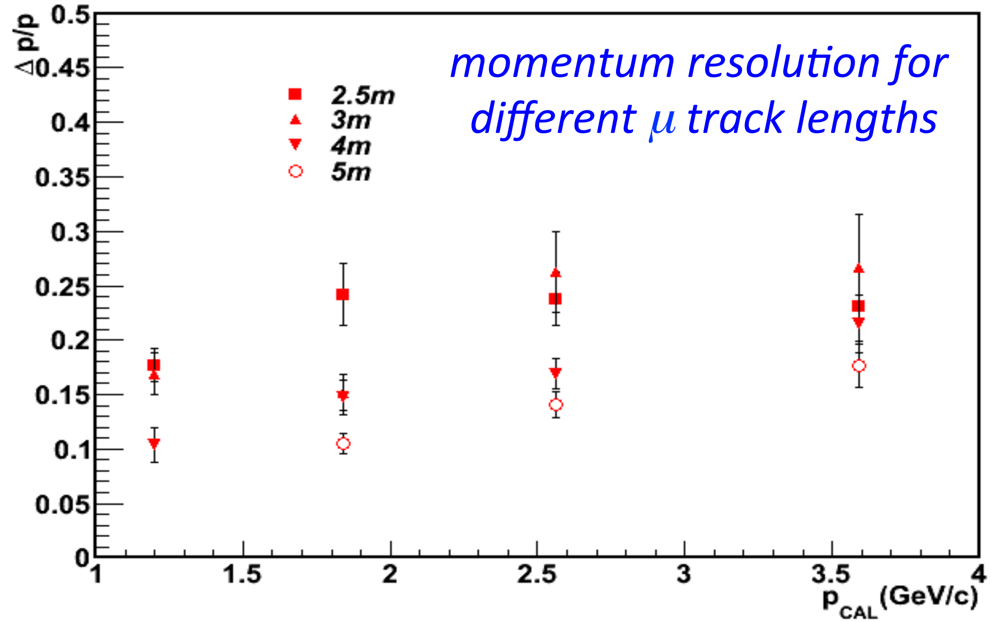






Resolution of muon momentum measurement via MCS

- The Δp/p resolution depends from the muon momentum and the track length used for MCS measurement:
  - Δp/p ~ 15% on average in the full 0.4 - 4 GeV /c momentum range (~10% at ~ 1 GeV/c) for 4 m μ track length;
- A slightly better resolution expected after the T600 overhauling at CERN:
  - Cathode panels have been flattened within few mm residual non-planarity;
  - New TPC read-out electronics will provide a fully synchronized digitization of the wire signals.



The method apply to momentum range of interest of next short/long baseline expts.

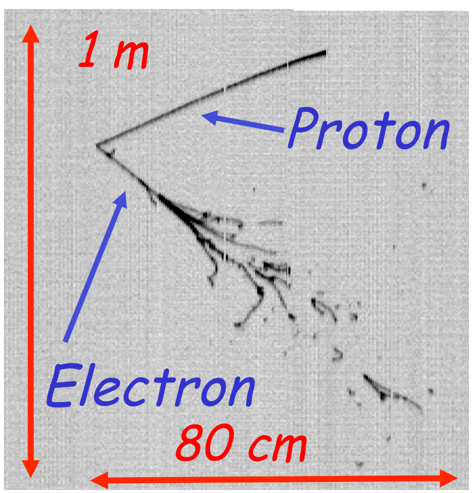
In particular well suited to measure initial momentum of non-contained μ's at SBN experiment at FNAL Booster Eν~0.8 GeV where ~50% of μ's will escape the detector

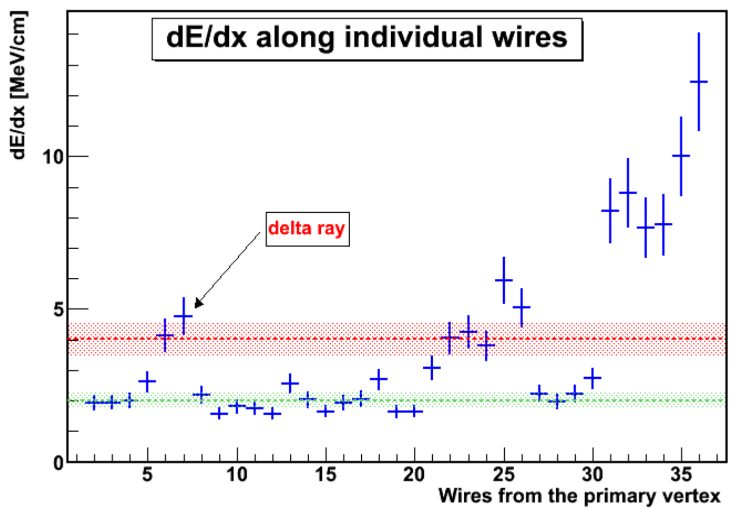
M. Antonello et al., J. Inst., 12 P04010 (2017)

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 νe), then validated by visual scanning;
- About ~50% of exposure analyzed so far: 7 νμCC and 8 νeCC atmospheric neutrino events have been identified
- Can also address a sensitive search for nucleon decay in channels involving kaons, based on a single event study with zero background - competitive with present limits for $n \to K^+ e^-$. Preliminary selection/id. event efficiency: ~80%.

TYPICAL νe ATMOSPHERIC EVENT:



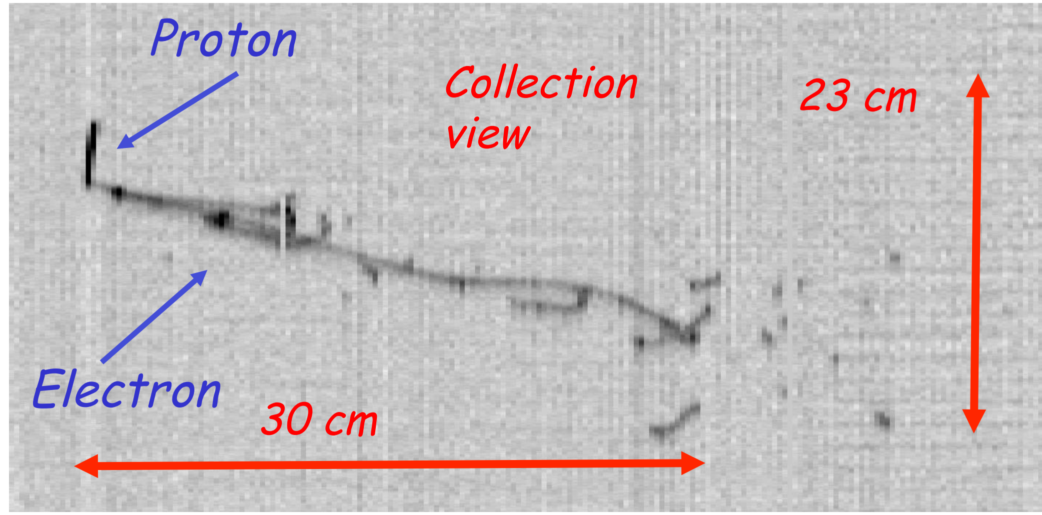


- Quasi-elastic νeCC with E_{Dep}= 0.9 GeV.
- Proton identified by dE/dx.
- Electron identified by single m.i.p. deposition before showering

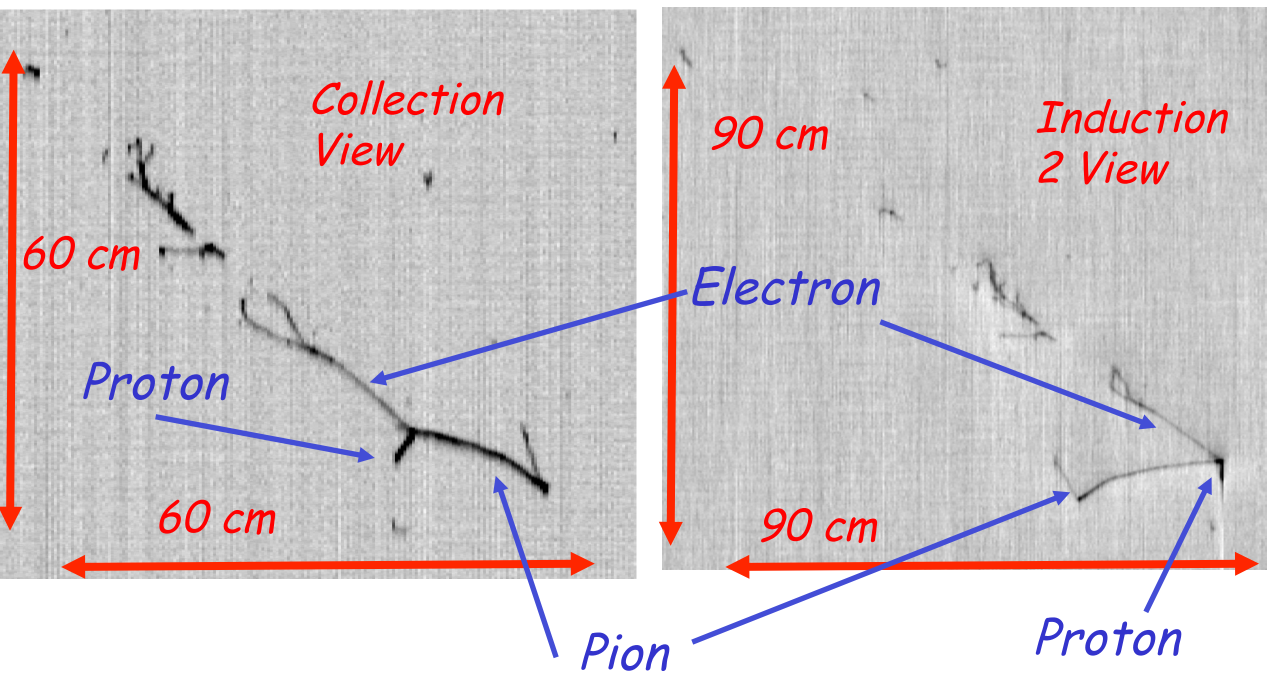
Atmospheric ν_e CC: low energy events

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

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

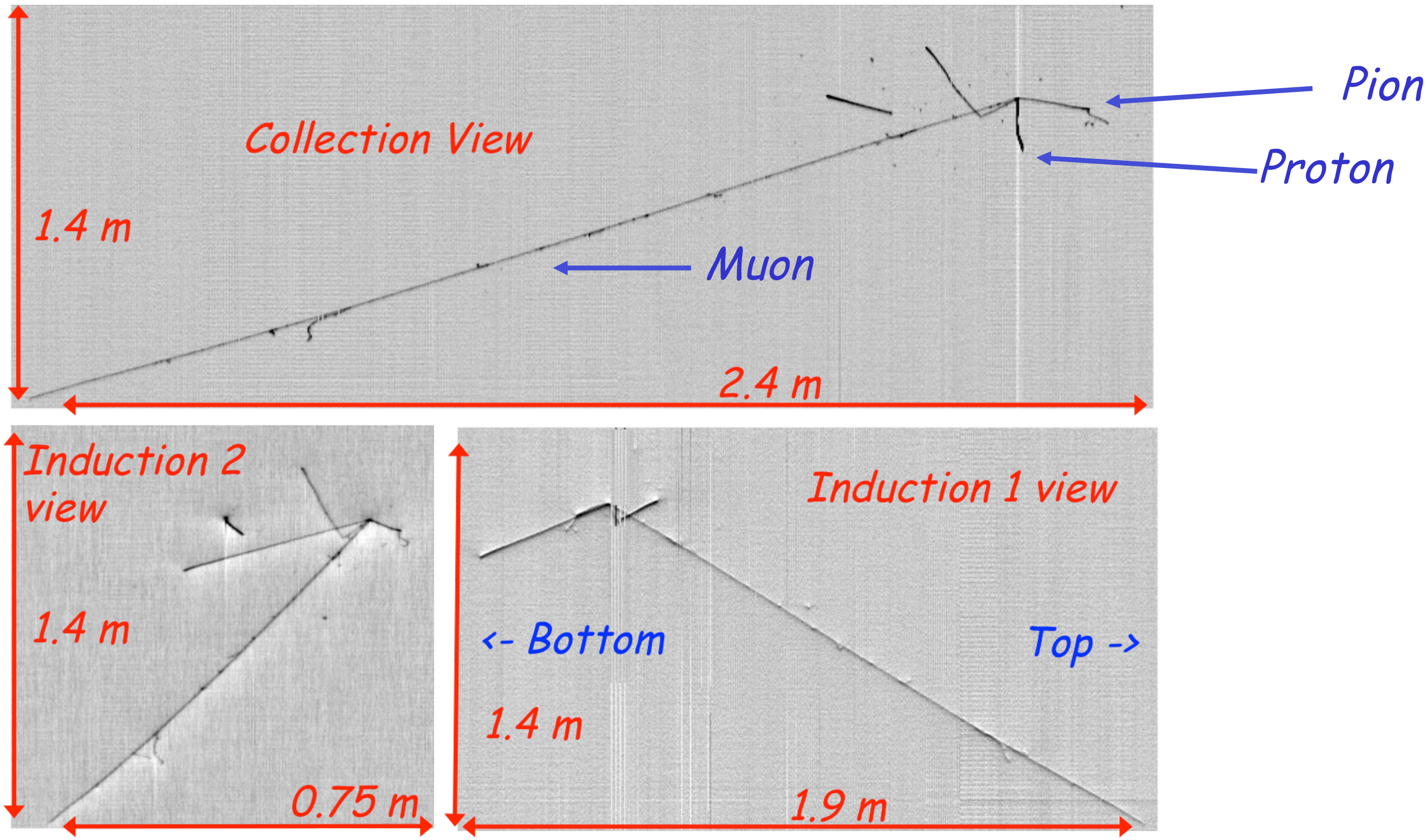


Downward-going ν_e CC interaction



- *Deposited energy ~420 MeV*
- *240 MeV electron, clearly visible also in Induction view; a pion (E_{dep}~120 MeV) and a short proton (E_{kep}~60 MeV) also produced at the interaction vertex*
- *Preliminary reconstruction of the ν direction: zenith angle ~108°.*

Atmospheric ν_μ CC event

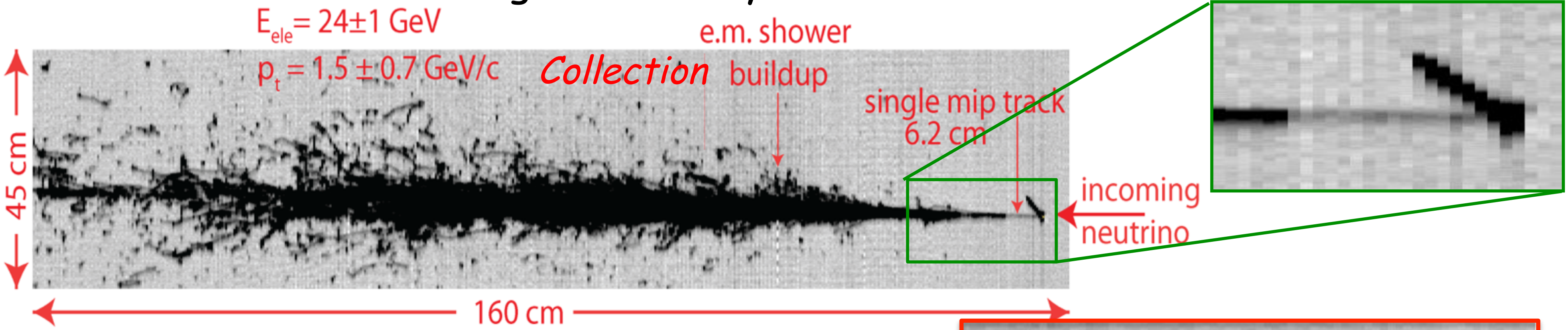


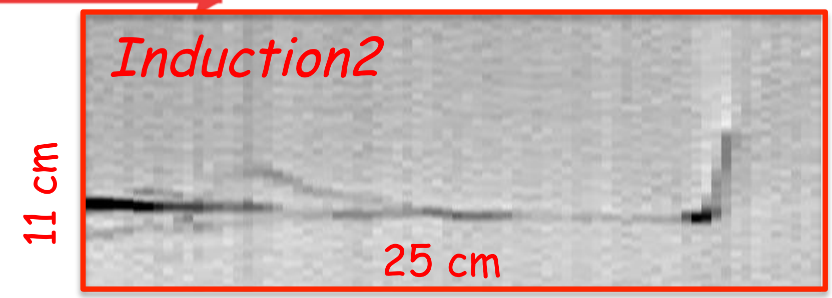
Upward-going νμ CC event with a deposited energy ~ 1.7 GeV:

- *4m escaping muon: p = 1.8 ± 0.3 GeV/c from multiple scattering;*
- *Three hadrons produced in the ν interaction vertex, two of which identified as a pion (Edep ~80 MeV) and a proton (Edep ~ 250 MeV).*
- *Preliminarly reconstructed ν energy ~2 GeV with a zenith angle ~78°.*

νeCC 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

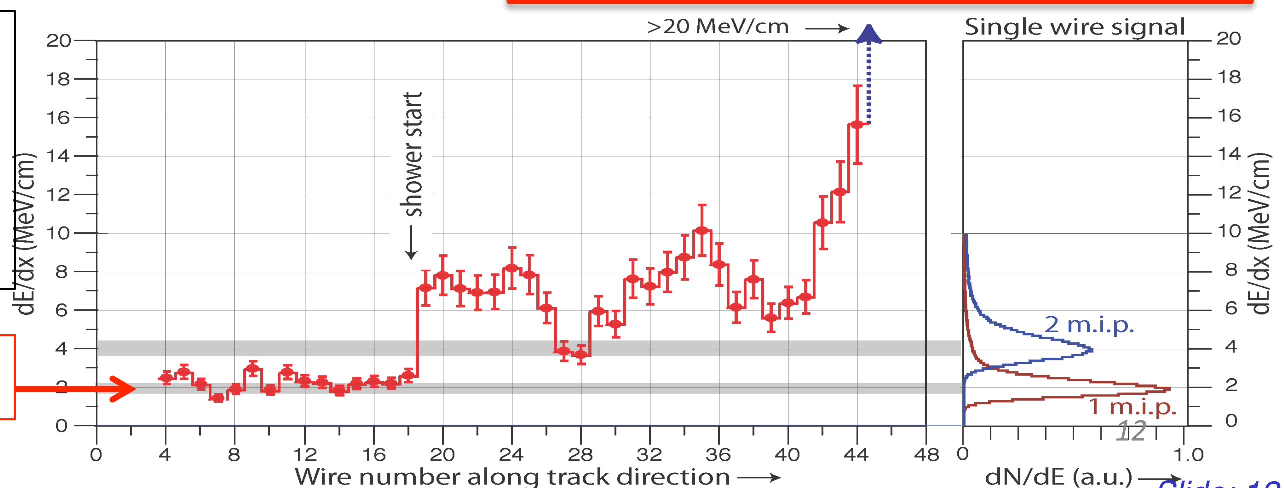




Single electron at interaction vertex well identified also in Induction view

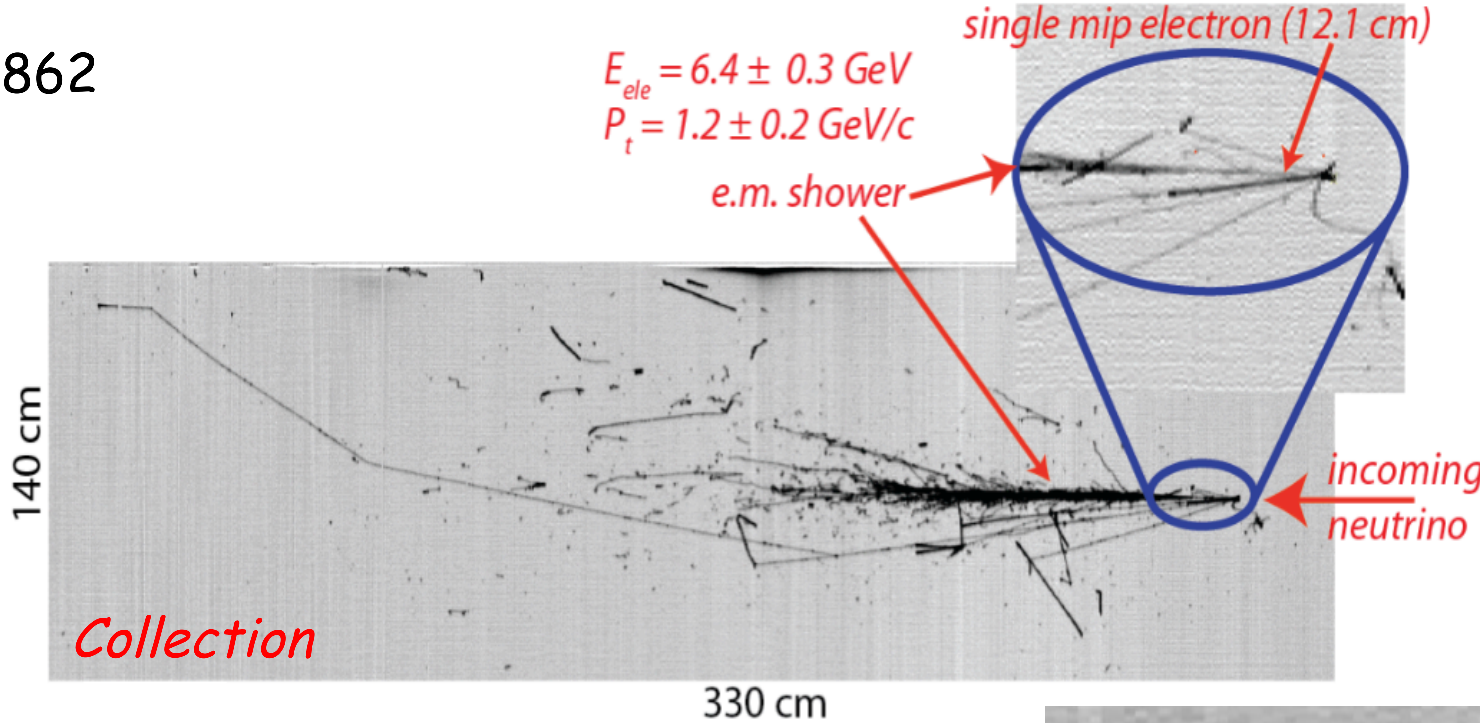
Evolution in Collection view from single m.i.p. to e.m. shower evident from dE/dx on individual wires.

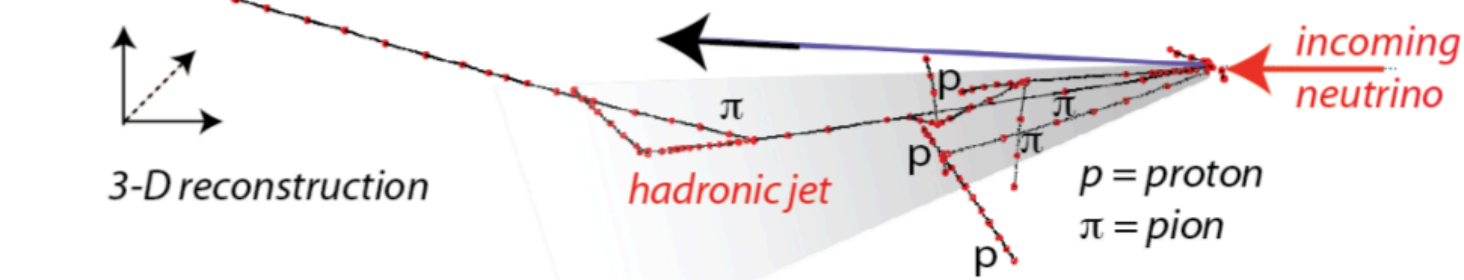
Single M.I.P.

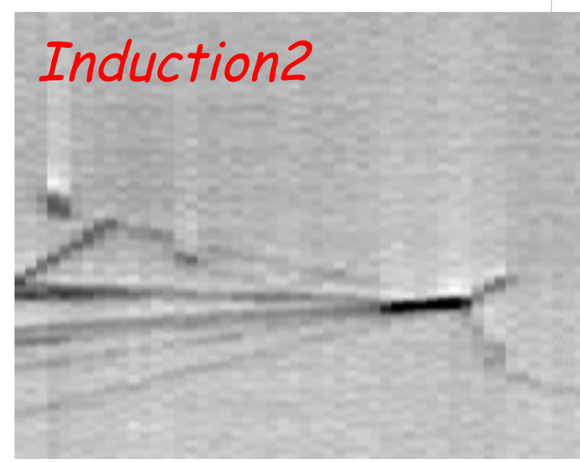


νeCC identification/ 3D- reconstruction in CNGS beam

Run 11319 Ev. 2862







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

Induction2 view: essential to solve complex /crowded events

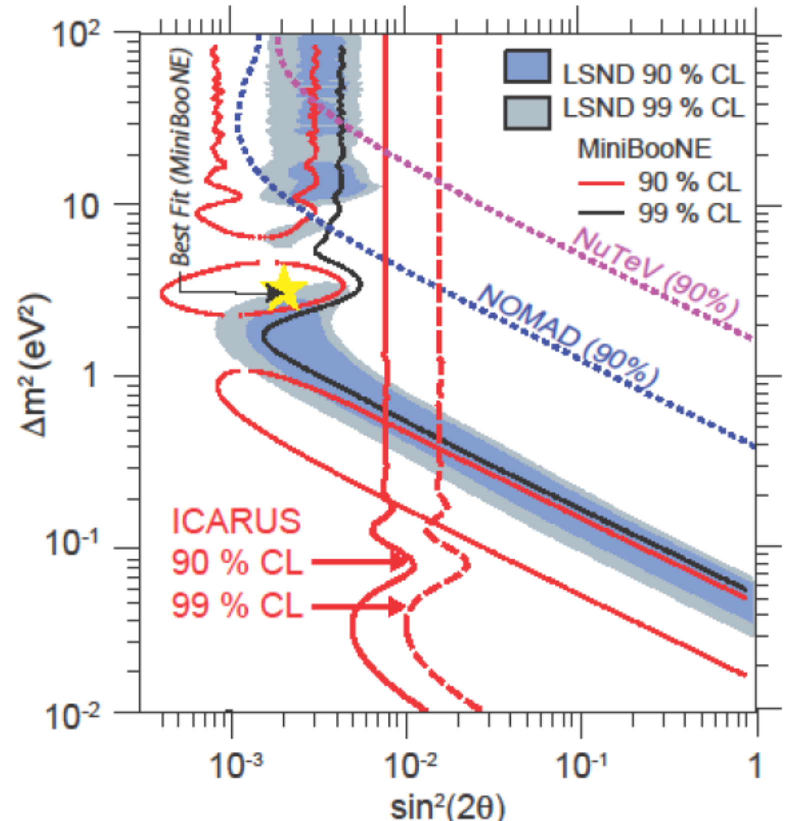
ICARUS search for an LSND-like effect with CNGS beam

- ICARUS searched for a νe-excess related to a LSND-like anomaly with the CNGS ν beam (~ 1% intrinsic νe contamination) despite the larger L/Eν ~36.5 m/MeV when compared to L/Eν ~ 1 m/MeV for LSND/ MiniBooNE:
  - LSND-like oscillation signal would average to $\sin^2(1.27\Delta m^2_{new} L/E) \sim 1/2$; compared to MINOS and T2K, ICARUS operated in a L/Eν range where contributions from standard oscillations not yet too relevant.

- *No excess observed in 7.93 x 10^{19} pot sample:* 7 νe CC events compared to 8.5±1.1 expected in absence of effect providing the limits:

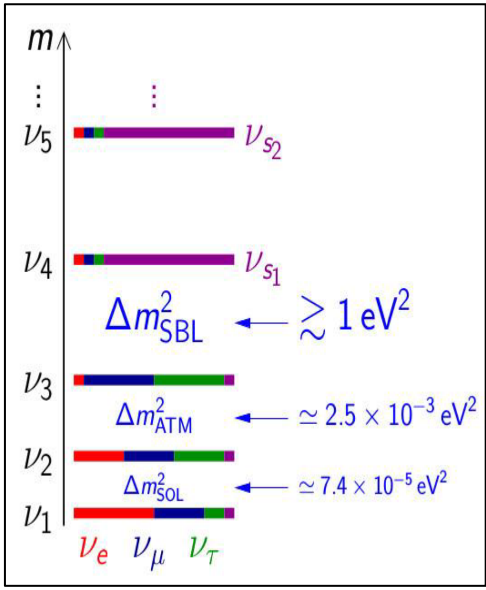
$$P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3}\ (90\%\ C.L.)$$
$$P(\nu_\mu \rightarrow \nu_e) \leq 7.60 \times 10^{-3}\ (99\%\ C.L.)$$

- *ICARUS and OPERA restrict the allowed parameter to a narrow region $\Delta m^2 \sim< 1\ eV^2$, $\sin^2 2\theta \sim< 0.005$ where all positive/negative experimental results can be coherently accommodated at 90% C.L.*



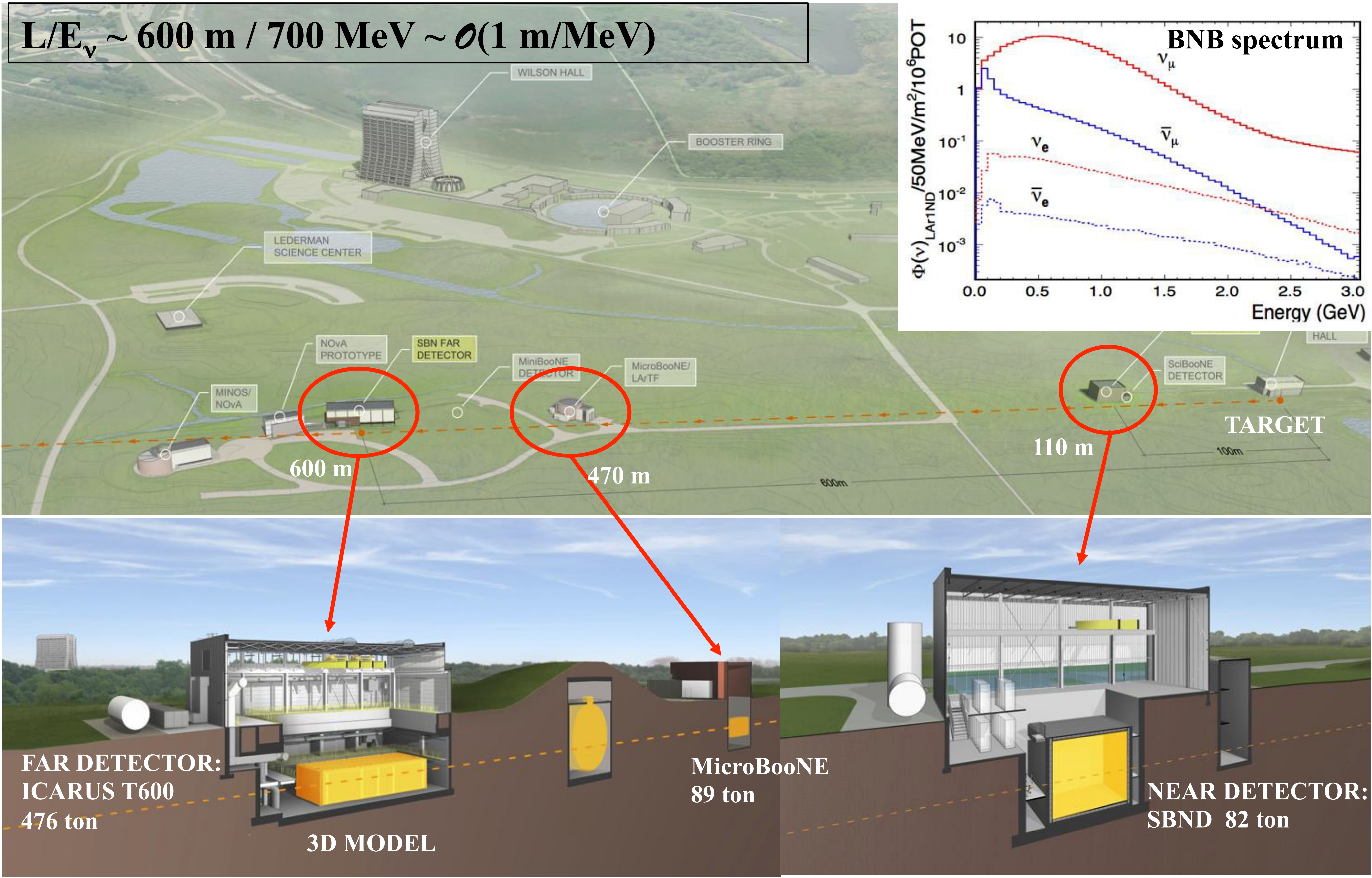
Sterile neutrinos?

- Different anomalies have been collected in last years in neutrino sector despite the well-established 3-flavour mixing picture within Standard Model:
  - appearance of νe from $\nu\mu$ beams in accelerator experiments (LSND + MiniBooNE, combined evidence > 3σ);
  - disappearance of anti-νe, hinted by near-by nuclear reactor experiments (ratio observed/predicted event rates R = 0.934 ± 0.024);
  - disappearance of νe, hinted by solar ν experiments during their calibration with Mega-Curie k-capture ν sources (SAGE, GALLEX, R = 0.84 ± 0.05).
- Results hint to a new "sterile" flavour, described by large $\Delta m^2_{new} \sim eV^2$ and small mixing angle θ_{new}, driving oscillations at short distance.
  - ICARUS constrained $\Delta m^2_{new} < eV^2$ with a small mixing
  - Constraints from Planck data and Big Bang cosmology remain far away from the oscillation preferred region, pointing to at most one further flavor with $m_{new} < 0.27$ eV.
  - No evidence of $\nu\mu$ disappearance in IceCube in 0.32-20 TeV
  - Recent reactor data (especially NEOS) are intriguing but inconclusive…



THE EXPERIMENTAL SCENARIO CALLS FOR A DEFINITIVE CLARIFICATION!

The *Short Baseline Neutrino* program

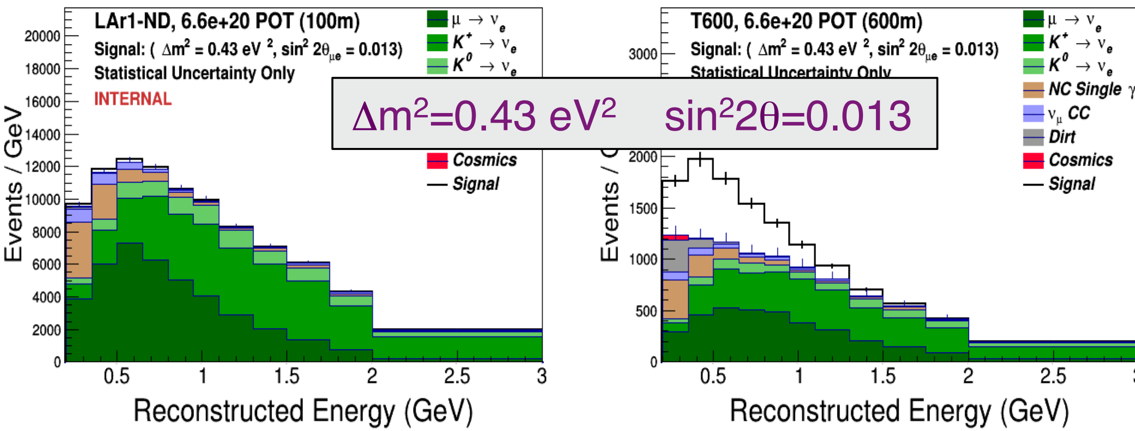


The *Short Baseline Neutrino* program

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

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

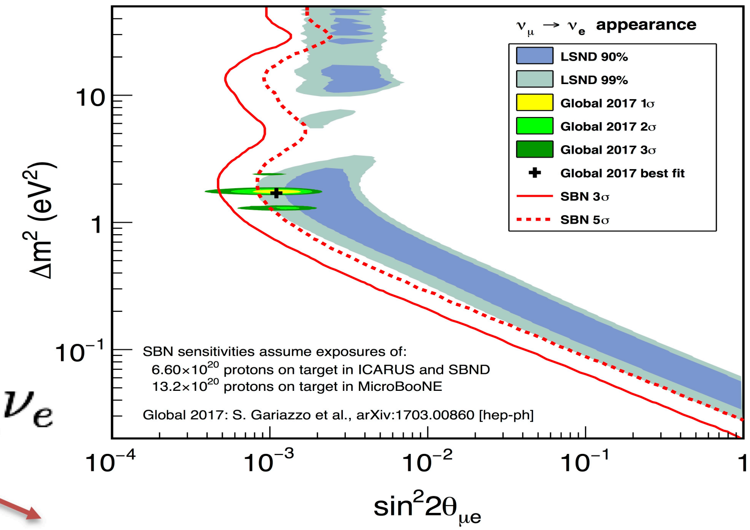
LSND 99% CL region covered at 5 σ level

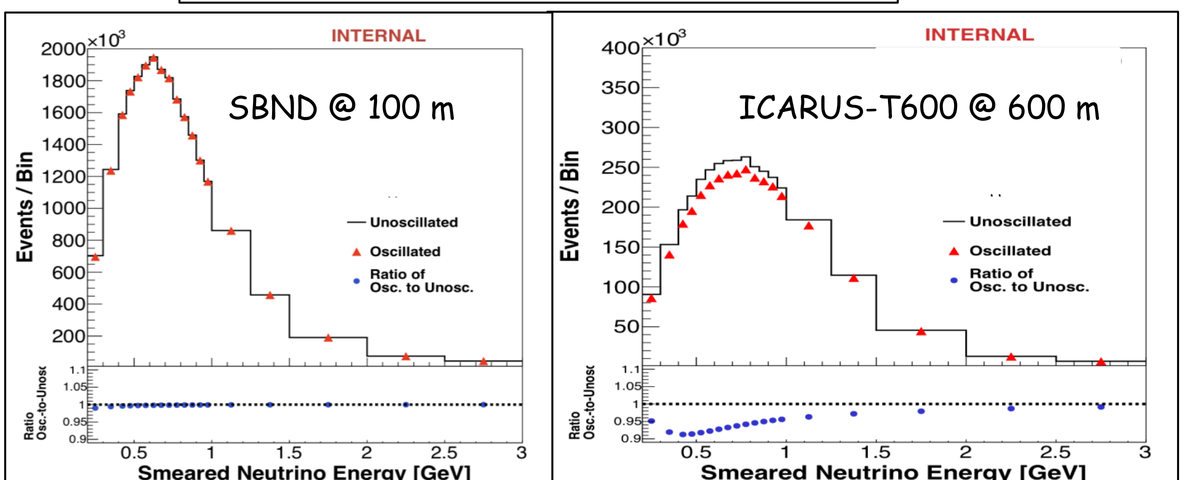


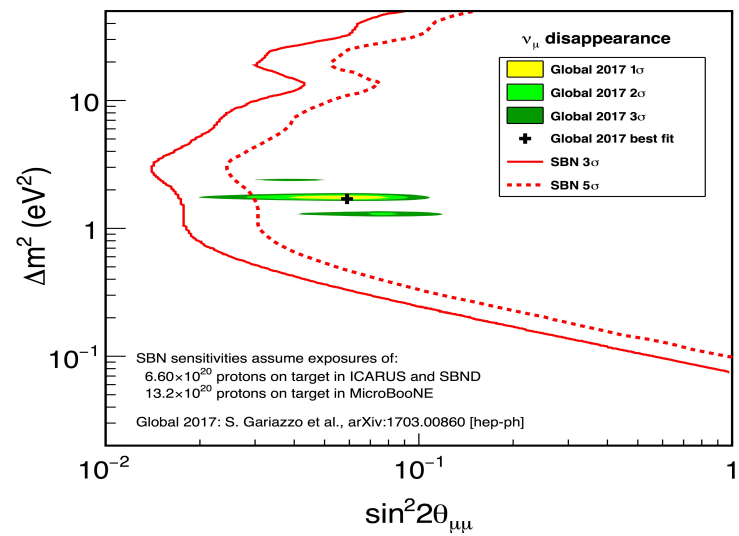
Δm^2=0.43 eV^2 $\sin^2 2\theta$=0.013

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

$\nu_\mu \to \nu_s \to \nu_e$







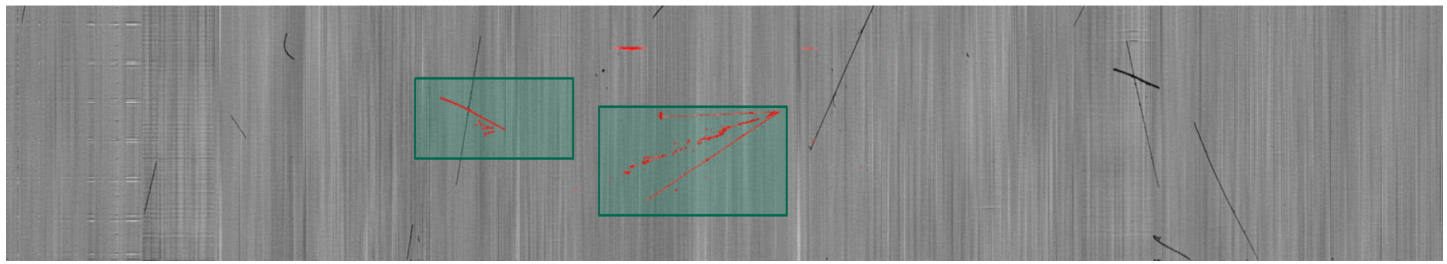
Δm^2=1.1 eV^2 $\sin^2 2\theta$=0.1

SBN will clarify the issue with a single experiment, exploiting similar LAr-TPCs at different distances from the target.

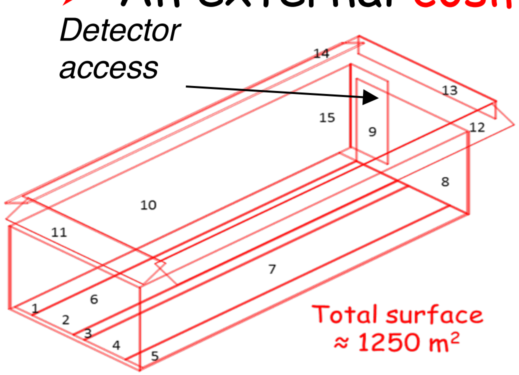
Event finding at shallow depth and Cosmic Ray Tagger

- ICARUS at FNAL will take data at shallow depth, facing more challenging experimental conditions than at LNGS, requiring a cosmic's background mitigation.
- A 3 m concrete overburden will remove contribution from cosmic hadrons and γ's. Moreover ~11 μ tracks will occur per triggering event in 1 ms drift readout.
- The γ's associated to muons represent a serious background for νe search since e's produced via Compton scattering/ pair production can mimic a genuine νe CC.

Cosmic rays (Pavia test)
+ low energy CNGS neutrino events



- To reconstruct 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, ~1 ns PMT's time resolution.
  - An external cosmic ray tagger (CRT) to detect incoming particles:

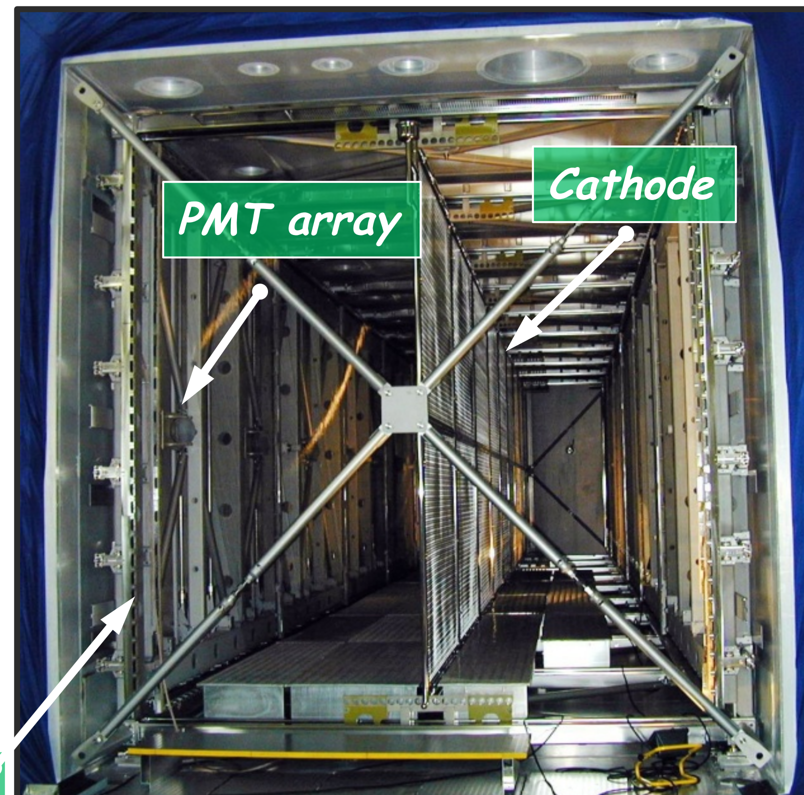


✓ Scintillating bars surrounding the T600 (aim: 98% coverage) equipped with optical fibers to convey light to SiPM arrays.

✓ Top coverage under INFN/ CERN responsibility. FNAL is recovering modules by MINOS and Double Chooz

T600 Overhauling at CERN (WA104/NP01)

- To face the new experimental situation at FNAL - shallow depth data taking with higher beam rate- the T600 detector underwent an intensive overhauling at CERN before being shipped to FNAL.
- In 2015, T600 detector was moved from LNGS to CERN for overhauling in the framework of CERN Neutrino Platform (WA104 project) to introduce some technology developments *while maintaining the already achieved performance:*
  - New cold vessels made of extruded aluminum profiles welded together, with a purely passive insulation;
  - renovated cryogenic/ LAr purification equipments;
  - Flattening of TPC cathode: the punched stainless-steal panels underwent thermal treatment improving planarity to few mm;
  - Upgrade of light collection system with high granularity/sensitivity, ~1 ns time resolution;
  - New higher performance read-out electronics



3 Wire Planes: Induction1, Induction2 and Collection

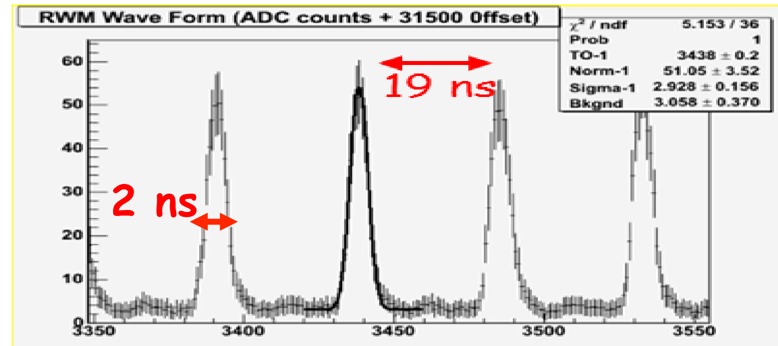
The ICARUS/WA104 Collaboration*

Argonne National Laboratory (ANL), USA
Brookhaven National Laboratory (BNL), USA
CERN, Geneva, Switzerland
Colorado State University, USA
Fermi National Laboratory (FNAL), USA
INFN Sez. di Catania and University, Catania, Italy
INFN GSSI, L'Aquila, Italy
INFN LNGS, Assergi (AQ), Italy
INFN Sez. di Milano Bicocca, Milano, Italy
INFN Sez. di Napoli, Napoli, Italy
INFN Sez. di Padova and University, Padova, Italy
INFN Sez. di Pavia and University, Pavia, Italy
Los Alamos National Laboratory (LANL), USA
Pittsburgh University, USA
SLAC, Stanford, CA, USA
Texas University, Arlington, USA

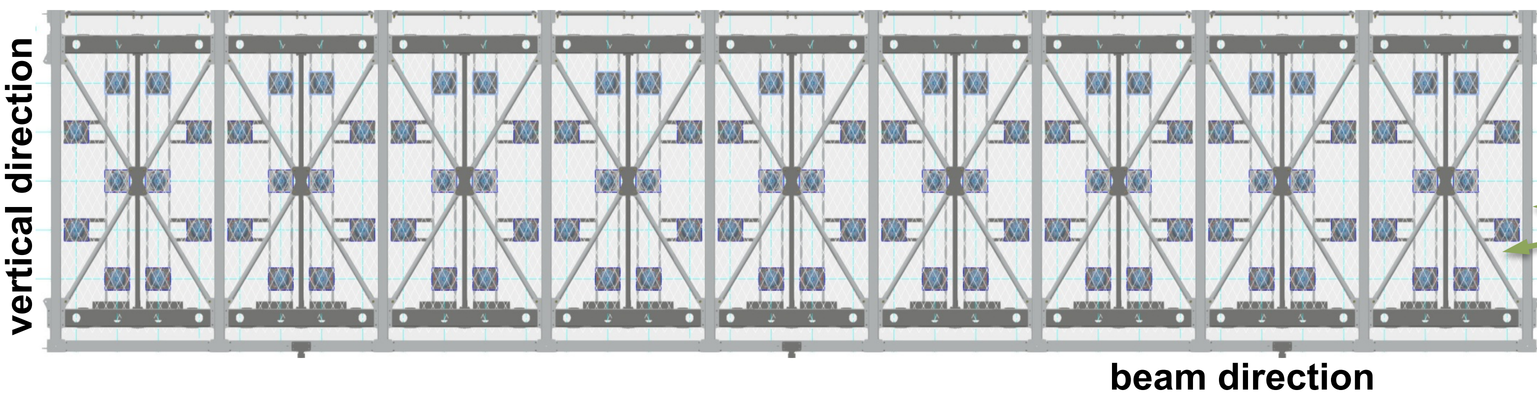
**Spokesman: C. Rubbia , GSSI*

Upgrade of the light collection system

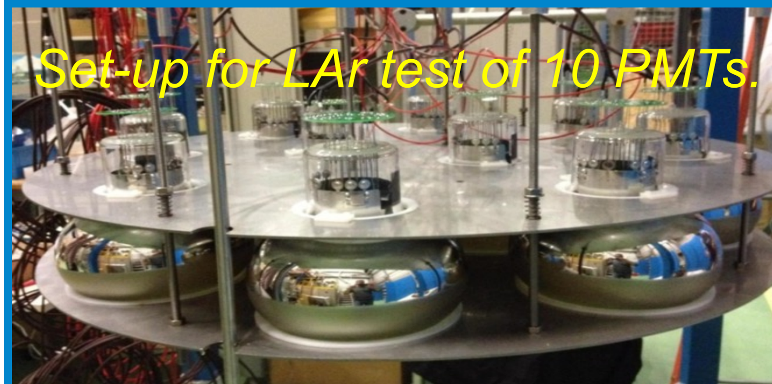
- Comparing to LNGS, major improvements in space/time event localization capabilities are required *to reject the expected huge cosmic's background due to shallow depths operations:*
  - *High detection coverage*, to be sensitive to low Eν deposition in the TPC (~ 100 MeV) and to reject ^{39}Ar background;
  - *High detection granularity*, to localize events/unambiguously associate the collected light to deposited charge;
  - *Fast response - high time resolution*, to be sensitive to time and evolution of each event in ~1.5 ms DAQ windows ; ~1 ns precision is advisable to exploit bunched beam structure.



- The system consists of 90 PMT 8" HAMAMATSU R5912-MOD installed behind TPC wires (360 PMT in whole T600) for a 5% total coverage of TPC wire planes.



PMT tests and installation in the T600 detector



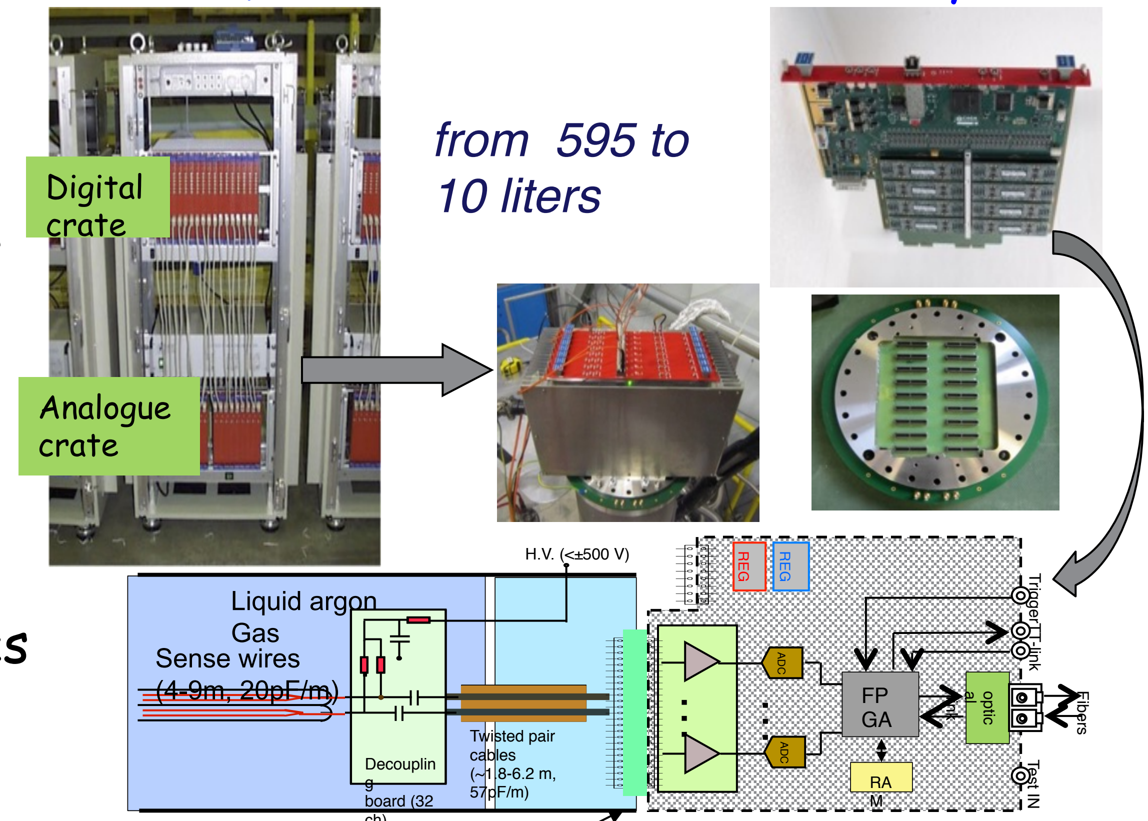
- All PMTs have been characterized at room temperature, gain set to 107 e^-/phe at ~1.5 KV.
- 60 PMTs directly tested in LAr bath to evaluate parameter variation at cryogenic temperature
- PMT glass windows coated by ~200μg/cm^2 of Tetra-Phenyl-Butadiene (TPB) wavelength shifter to detect the λ = 128 nm scintillation light in LAr;
- Each PMT is enclosed in a wire screening cage to prevent induction of PMT pulses on the facing TPC wires. PMT timing/calibration will be provided by LASER light system.

- The scintillation light collection system will allow for <0.5 m event localization and an initial classification of different topologies (μ-tracks vs. e.m. showers) exploiting arrival time of prompt photons and light intensity.

A clear cosmic μ's identification will be provided by Neural Nets (~2% expected residual misidentification).

The new TPC read-out electronics

- Architecture of ICARUS electronics at LNGS was based on analogue low noise "warm" front-end amplifier, a multiplexed 10-bit 2.5 MHz AD converter and a digital VME module for local storage, data compression, trigger information:
  - S/N ~8, in Collection view, ~0.7 mm single hit resolution, resulting in a precise spatial event reconstruction and μ momentum measurement by MCS.
- Improvements concern:
  - Serial 12 bits ADC, one per ch, 400 ns sampling synchronous on the whole detector (previous boards aligned within 400 ns);
  - Serial bus architecture with Gbit/s optical links to increase the bandwidth (10 Hz);
  - New compact design to host both analogue/digital electronics (single high performance FPGA) directly on ad-hoc signal feedthrough flanges acting as electronics backplane.



UHV Feed-through (18x32ch.)

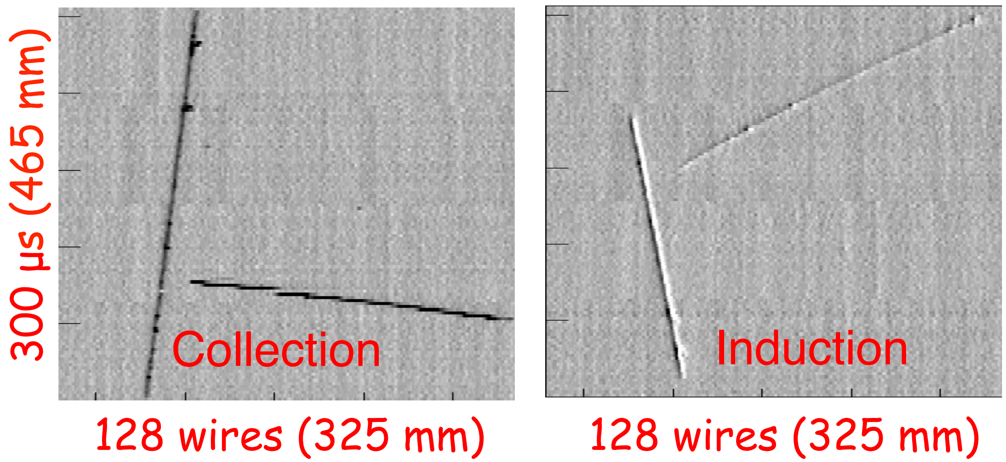
Front-end amplifiers (64/board)

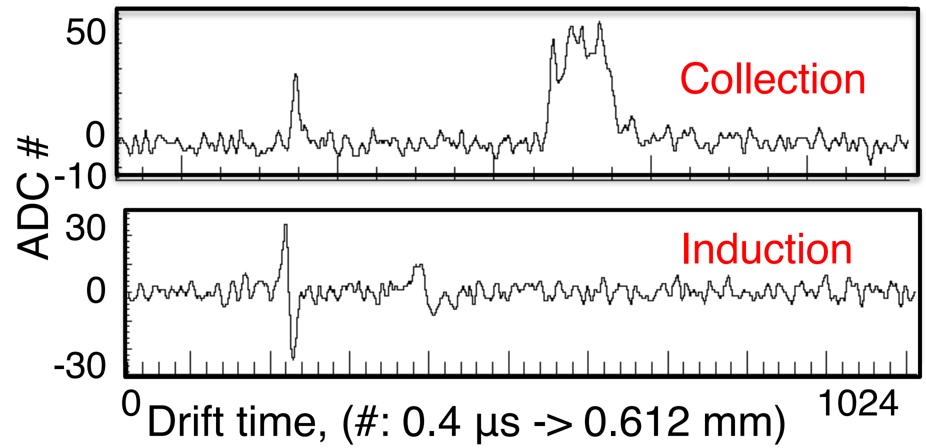
12bit serial ADC 400 ns sampling

Improved front-end electronics for T600

- In the newT600 analogue front-end the adopted improvements required for a better event reconstruction quality concern:
  - ➢ A faster shaping time ~1.5 μs of analogue signals to match electron transit time in wire plane spacing;
  - ➢ A drastic reduction of undershoot in the preamp response as well as of the low frequency noise while maintaining a same or better S/N;
  - ➢ A same preamp for both Induction and Collection wires.

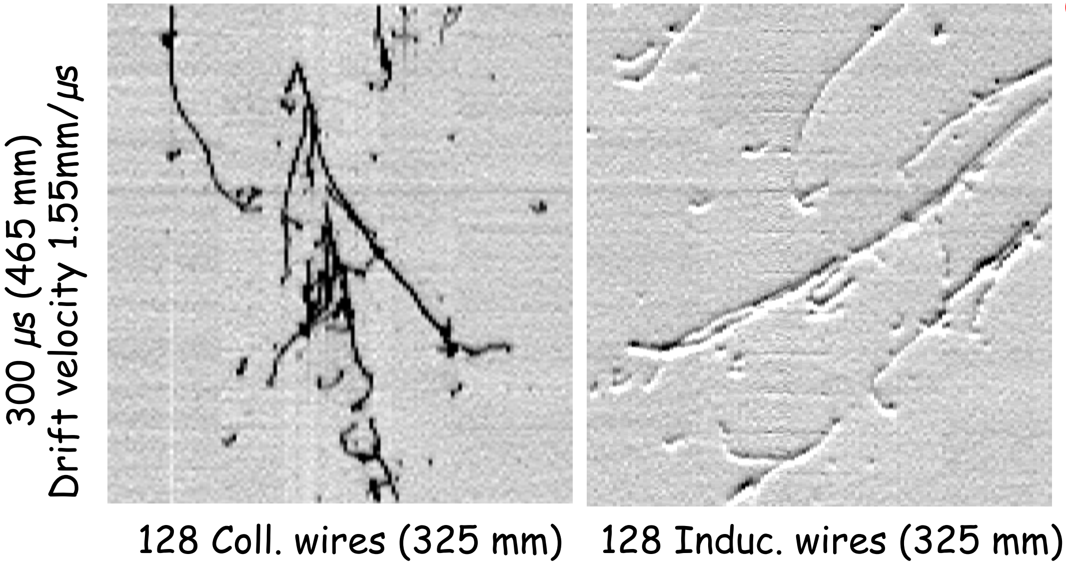
- In addition the full 400 ns synchronous signal sampling on the whole detector will allow slightly improving the resolution on μ momentum by MCS.

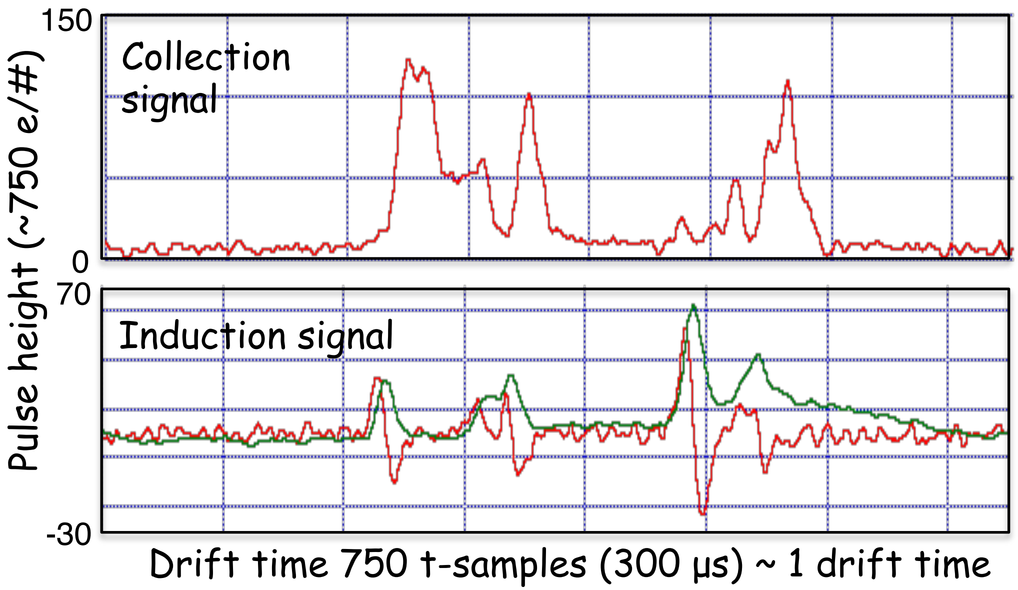




- Single m.i.p. track event collected in a mini LAr-TPC at CERN:
  - ➢ Same ~2ADC # (~1500 e^-) RMS noise for both Collect. & Induct. views;
  - ➢ Unipolar Coll. signal ~25 ADC # and symmetric bipolar Induction signal.

Induction and Collection signals from the new electronics





- The optimized preamp architecture results in:
  - No signal undershoot even for large signals;
  - A very stable baseline;
  - Unprecedented image sharpness also for complex shower events and better hit position separation due to faster shaping peak time.
- On Induct. wire planes, the deposited energy measurement with dedicated algorithms will allow for a better event reconstruction.
  - *Calorimetric measurement in Induction views, with ΔE/E ~27 % on the single wire hit;*
  - *This will result in the improvement by 10 % the νe identification efficiency at Booster neutrino energies.*

- T600 leaving from CERN June 12th

- T600 in Antwerp June21st : unloading from the barge from Basel and loading into ship to Burns Arbors, in the Michigan lake

- T600 arriving at SBN Far site building at FermiLab, July 26th