Upgrade of LAr-TPC ICARUS T600

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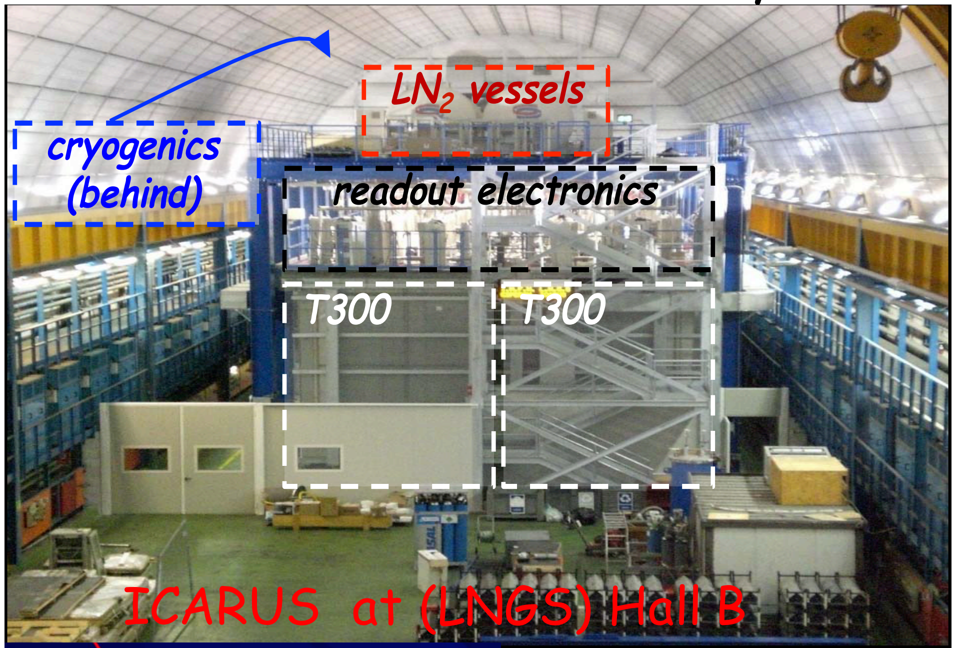
Outline

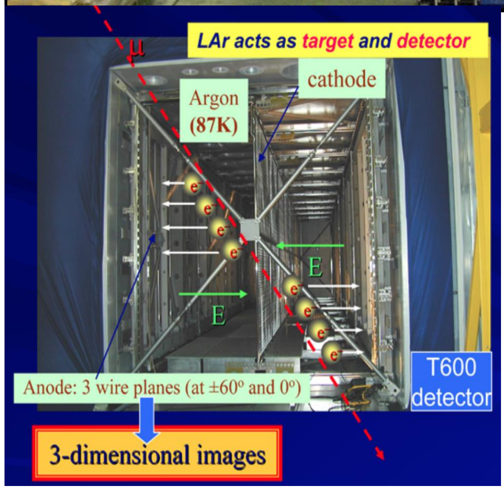
- ✓ ICARUS LAr-TPC technology: ICARUS T600 performance and results
- ✓ Generalities on the ICARUS T600 overhauling
- ✓ Search for sterile neutrinos at FNAL: the Short Baseline Neutrino Experiment
- ✓ Conclusions

CNNP 2017, Catania, October 15-21th, 2017

ICARUS T600: the first large liquid Argon TPC (760 t of LAr)

- ICARUS-T600 is an ideal detector for ν physics and search for rare events. It is a uniform, self-triggering detector, with high granularity (~mm), 3D imaging and calorimetric capabilities. It allows to accurately reconstruct a wide variety of ionizing events with complex topologies.





≈2 10^4 ionization electrons per MeV

Abundant λ=128 nm light (~10^4 γ/ MeV): 6 ns and 1.5 μs fast and slow component

Two identical modules: 476 t active mass:

- 2 TPCs per module, with a common central cathode: E_D= 0.5 kV/cm, v_D~1.6 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
- Ionization charge continuously read (0.4 μs sampling time);
- 8" PMTs arrays, sensitive at 128 nm via TPB wls on glass window, are used for t_0 signal, timing and triggering of events.

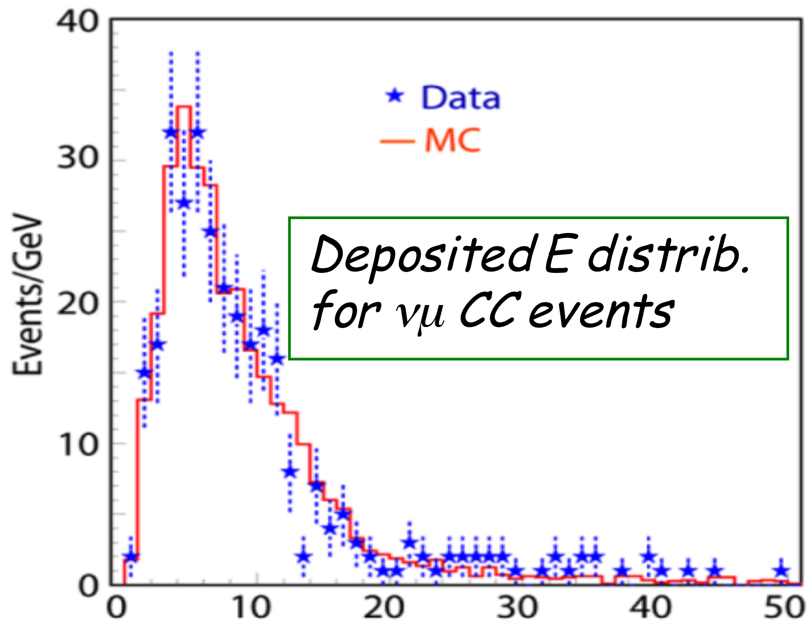
The LAr-TPC technology and ICARUS-T600

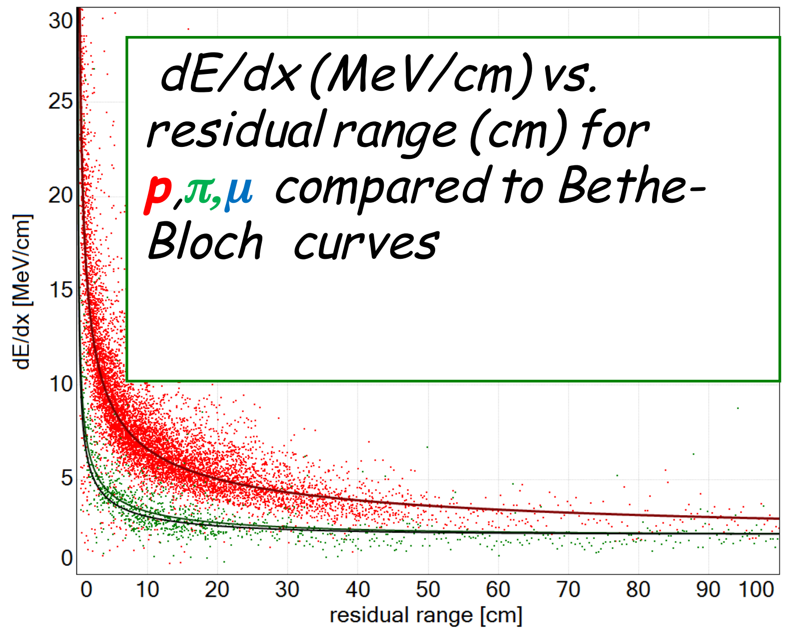
- Exposed to CNGS beam, ICARUS concluded in 2013 a very successful 3 years run at Gran Sasso INFN underground lab,collecting 8.6×10^{19} pot event statistics with a detector live time >93% and c-rays to study atmospheric ν's (0.73 kt y exposure).
- Several physics/technical results achieved during the run at LNGS:
  - *An exceptionally low level ~20 p.p.t. [O_2] eq. of electronegative 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 ν_e identification and π^o background rejection in $\nu_\mu - \nu_e$ study to unprecedented level;
  - *Performed a sensitive search for LSND-like anomaly with CNGS beam,* constraining the LSND window to a narrow region at $\Delta m^2 < 1$ eV^2.
- These results marked a milestone for LAr-TPC technology with a large impact on future neutrino and astro-particle physics projects, i.e. the current SBN short base-line neutrino program at FNAL with 3 LAr-TPC's (SBND, MicroBooNE and ICARUS) and the multi-kt DUNE LAr-TPC.
- T600 detector underwent an overhauling at CERN before being exposed to ~0.8 GeV Booster ν beam, 600 m from target to definitely test the LSND claim searching for $\nu_\mu - \nu_e$ oscillations in the framework of SBN program.

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:
$\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$

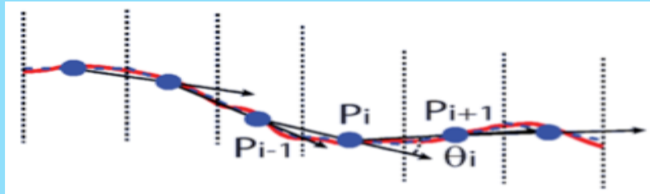




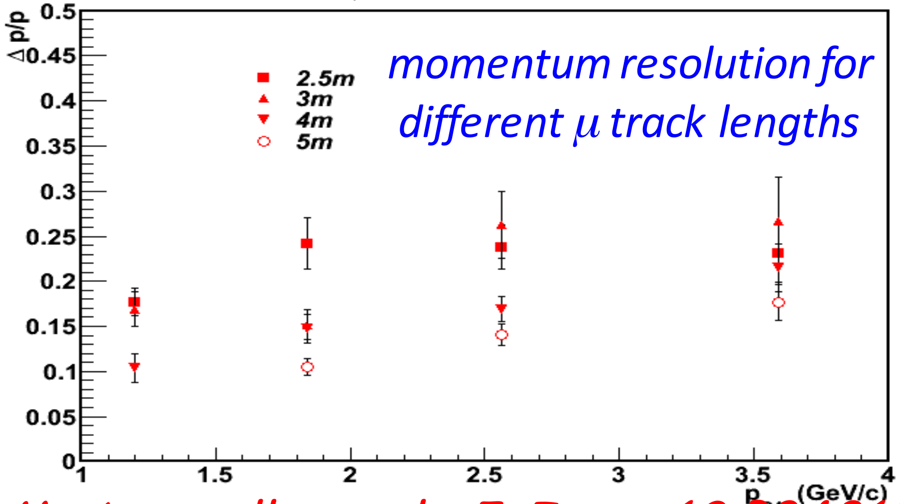
μ momentum measurement by multiple scattering (MCS)

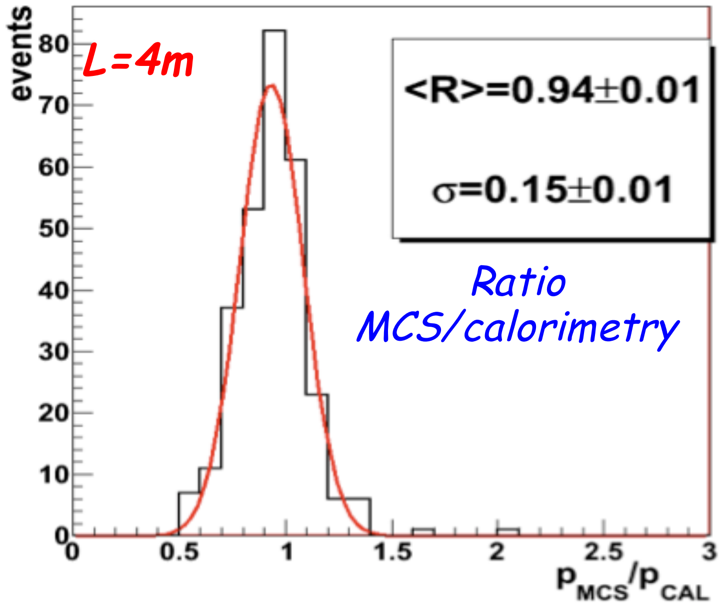
- Essential for escaping μ's, MCS also used to complement the range measurement for stopping μ's;
- RMS of μ deflection angle θ_{RMS}, depends on p, spatial resolution and segmentation;
- Method validated comparing p_{MCS} with corresponding calorimetric measured p_{CAL} for ~10^3 stopping μs (track length > 5 m, used 4 m, ~4-5 int. lengths in LAr) from CNGS ν_μ interacting in upstream rock;
- A Δp/p ~ 15% resolution on average has been determined in 0.4 - 4 GeV /c range

$$\theta_{MCS} = \frac{13.6 MeV/c}{\beta p_i}\sqrt{\frac{L_{seg}}{X_0 \cos\delta}}\,\frac{w_0}{\cos\delta}$$



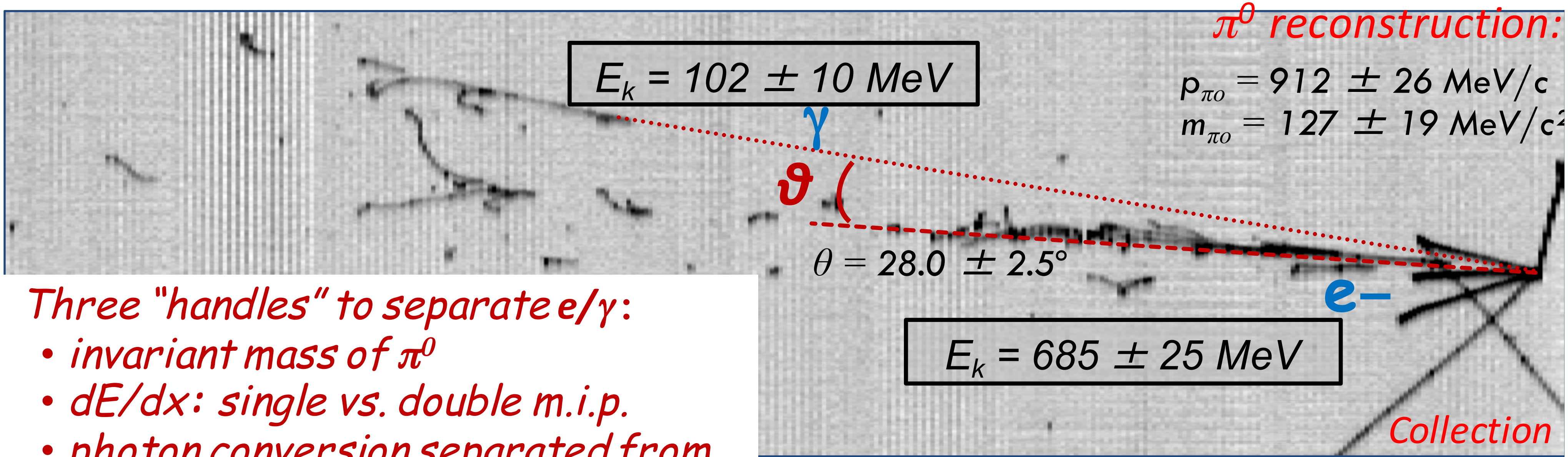
X_0 =14 cm radiation length in LAr
L_{seg}: segment length
P_i : momentum in the i^{th} -segment
δ : projection angle from 3D to2D
w_0 "averaging" factor ~ 0.74 ± 1%





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

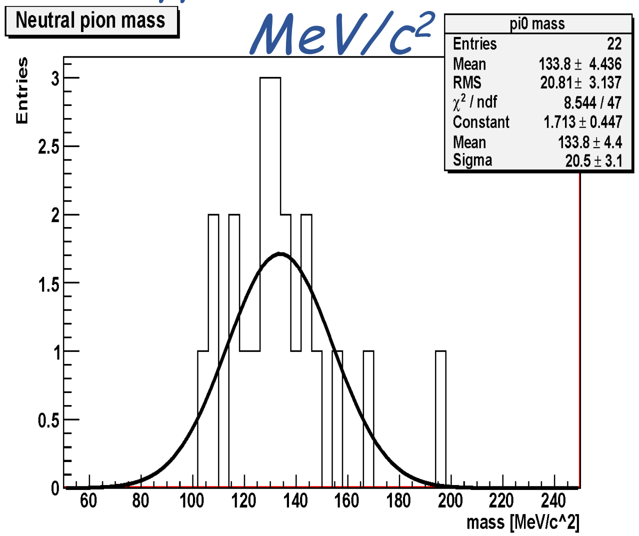
Unique feature of ICARUS: e/γ separation, π^0 reconstruction

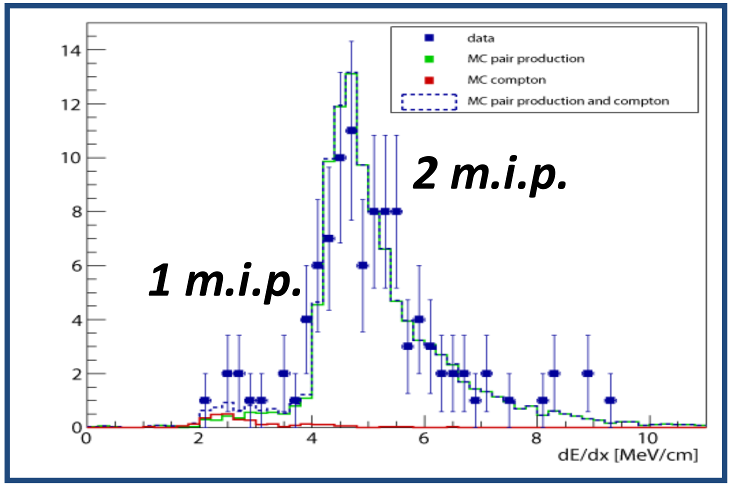


Three "handles" to separate e/γ:

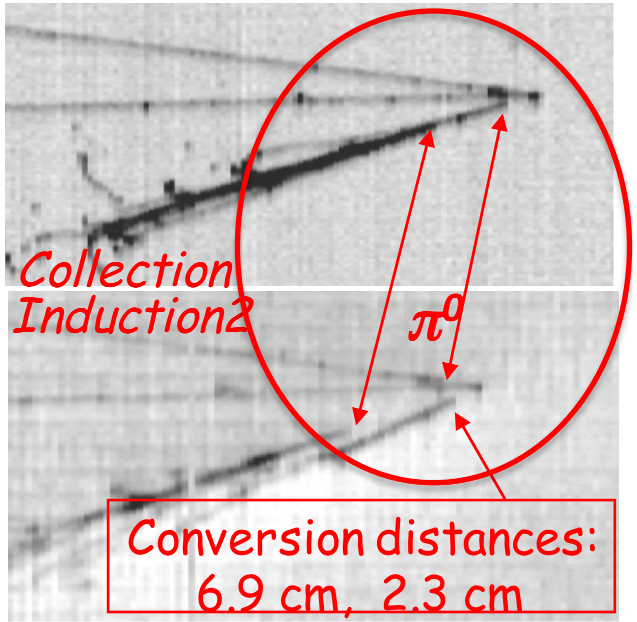
- invariant mass of π^0
- dE/dx: single vs. double m.i.p.
- photon conversion separated from primary vertex

$M_{\gamma\gamma}$: 133.8±4.4±4 MeV/c²



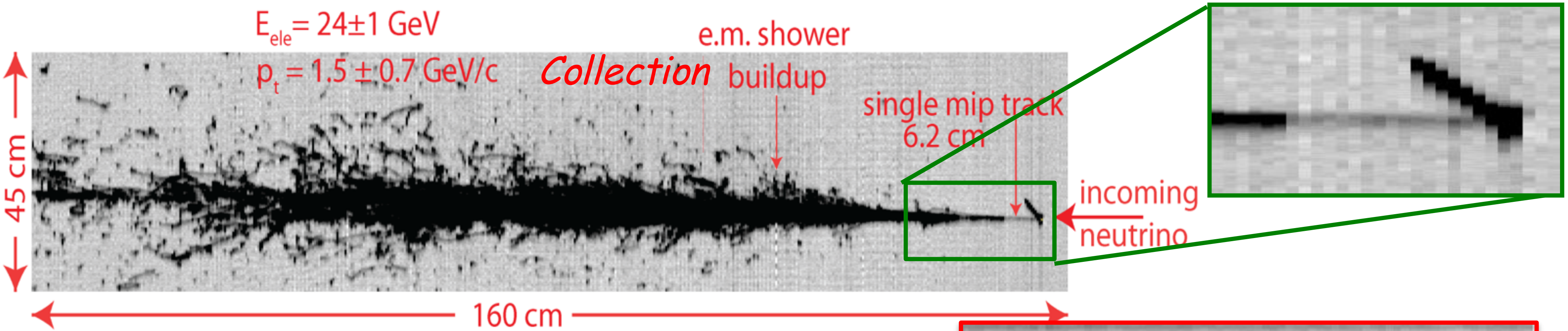


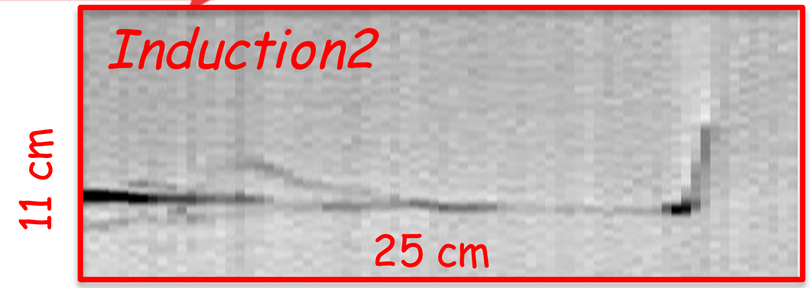
Crucial for NC rejection in ν_e-physics



ν_e CC 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

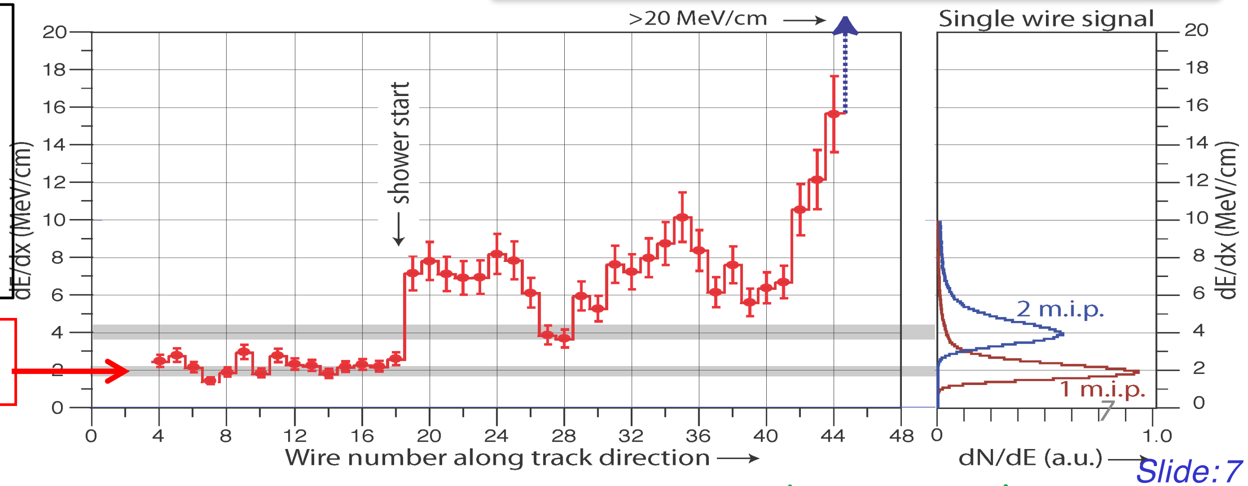




Single electron at interaction vertex well identified also in Induction view

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

Single M.I.P.

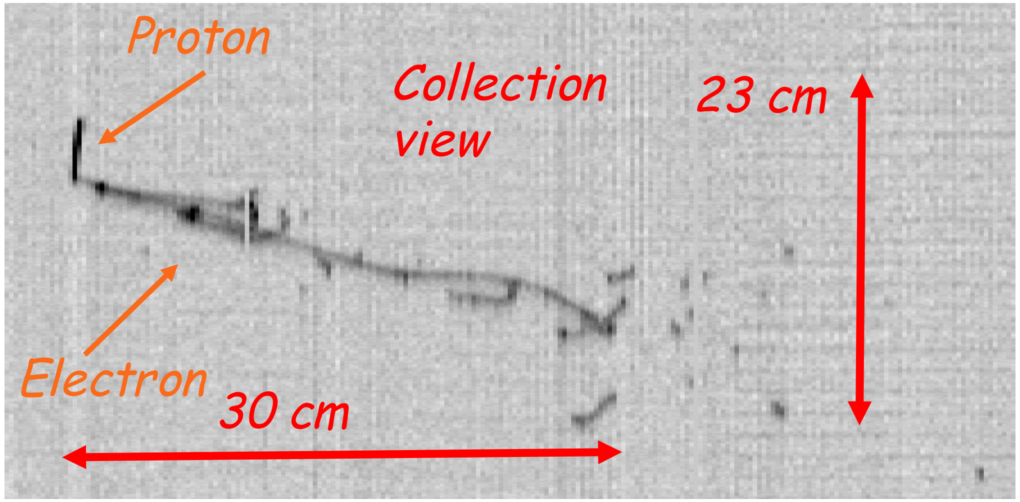


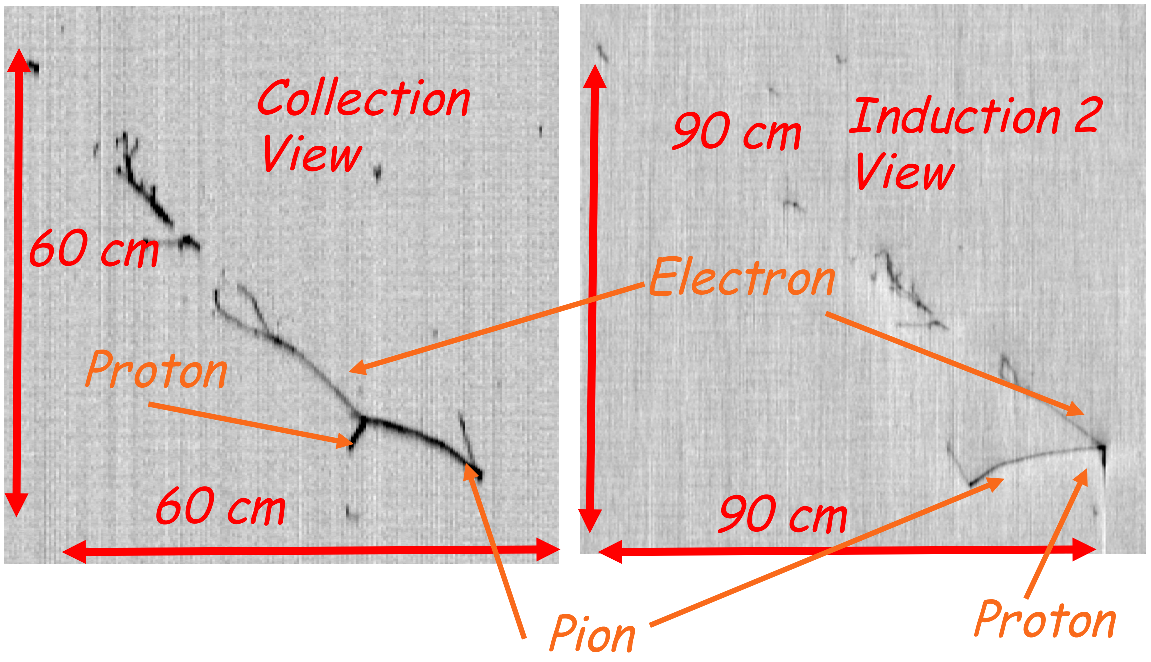
Beware, horizontal wire-coordinate axes are going into opposite directions!

Atmospheric ν_e CC: low energy events

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

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



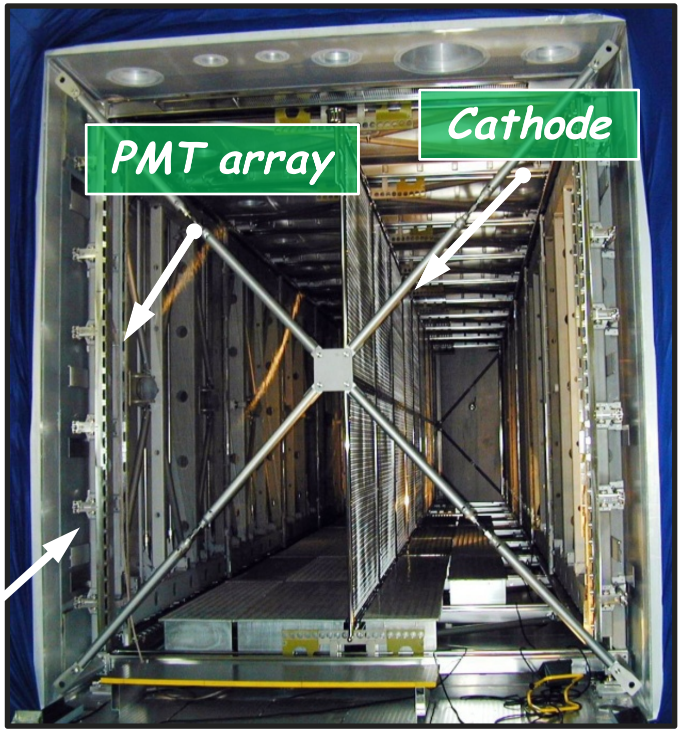


Downward-going ν_e CC interaction

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

ICARUS T600 Overhauling at CERN (WA104/NP01)

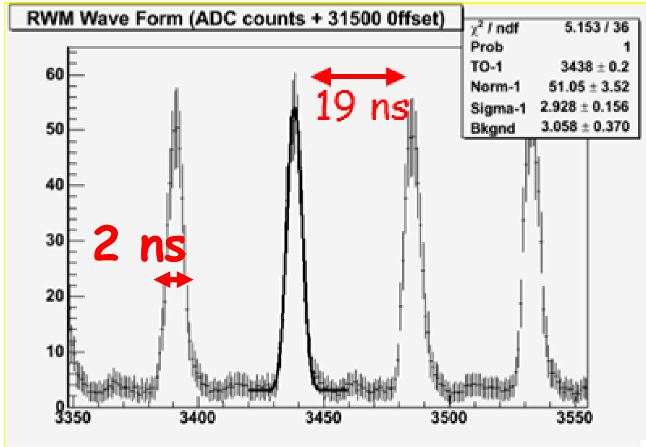
- To face the new experimental situation at FNAL ICARUS T600 underwent an intensive overhauling at CERN in the framework of CERN Neutrino Platform (WA104/NP01 project) before being shipped to FNAL
- In 2015, T600 detector was moved from LNGS to CERN to introduce some technology developments *while maintaining the already achieved performance:*
  - *New cold vessels,* purely passive insulation;
  - *Renovated cryogenic/ LAr purification* equipment;
  - *Flattening of TPC cathode*: the punched stainless-steel panels, 58% transparency, underwent a thermal treatment improving planarity to few mm;
  - Upgrade of light collection system;
  - New higher performance TPC read-out electronics



The light collection system 1/2

Currently, in ICARUS, light has simply been integrated over all the PMT's. Fine, but light collection can do more than just the generation of a trigger signal. It can also be used to:

- Identify the time of occurrence (T_0) of each interaction with high temporal precision;
- Identify the event topology for fast selection purposes.

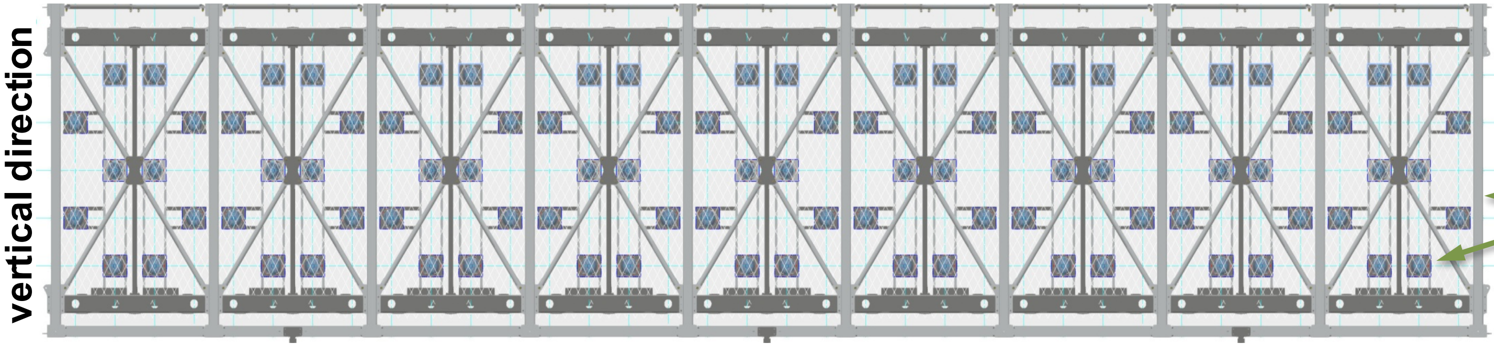


In order to achieve these goals, there are some requirements to fulfil:

1. High detection coverage, in order to be sensitive to the lowest-expected neutrino energy deposition in the TPC (approximately 100 MeV), also using the light fast-component only;
2. High detection granularity in order to localize the events with sufficient precision to associate unambiguously the collected light to the deposited charge;
3. Fast response time/ high time resolution (≈1 ns), to be sensitive to the time of occurrence and evolution of each event in the T600 acquisition windows (order of ms), and to exploit bunched beam structure.

The light collection system 2/2

- Different geometries and cathode coverage area (fraction of the wire plane surface covered by PMT windows) have been tested.
- The following 90 PMT's per TPC layout (with 5% cathode coverage area) configuration has been chosen. Gray blocks represent PMT's positions.



PMT: H R5912-MOD

- Longitudinal resolution is better than 0.5 m (effective Q.E. = 5%). A total of 4 modules (so 400 PMT's including 10% of spares) has been used for ICARUS.
- This geometry addresses main requirements 1 and 2.

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

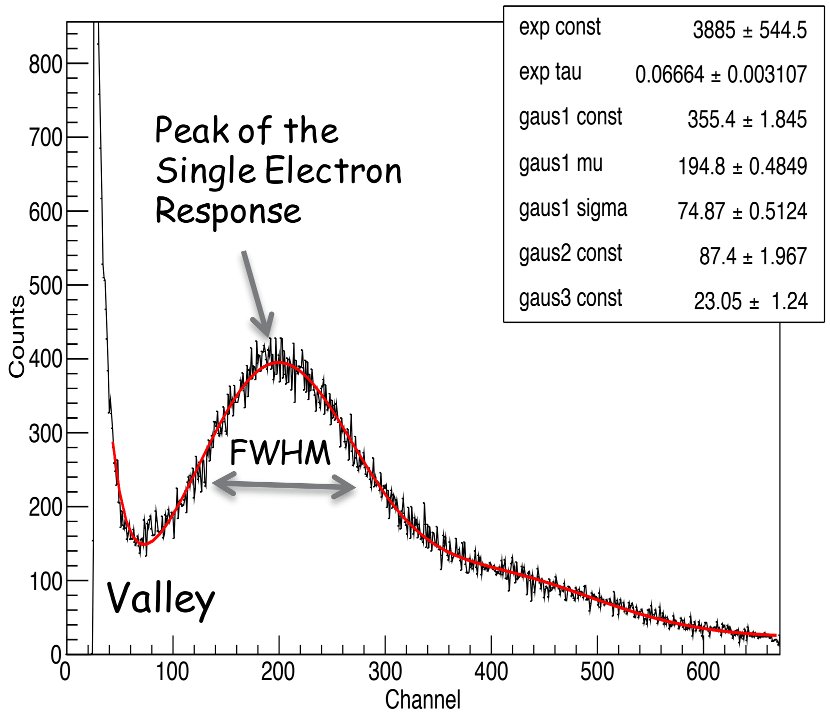
- The achievement of ~1 ns timing resolution (main requirement 3) implies a PMT timing calibration system to compensate individual channel delays and transit-time drifts.

Characterization of the PMT's

- Hamamatsu R5912-MOD series (8", 10 dynodes) are rated for cryogenic temperature, as they feature a cathode with platinum under-layer.
- PMT sand blasted glass windows coated by ~200 μg/cm² 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.

Characterization of all 400 such devices focused on these points:

- gain and linearity;
- effective Quantum Efficiency (i.e. with Tetra Phenyl Butadiene WLS on window);
- response uniformity on photocathode surface;
- peak-to-Valley ratio of SER distribution.

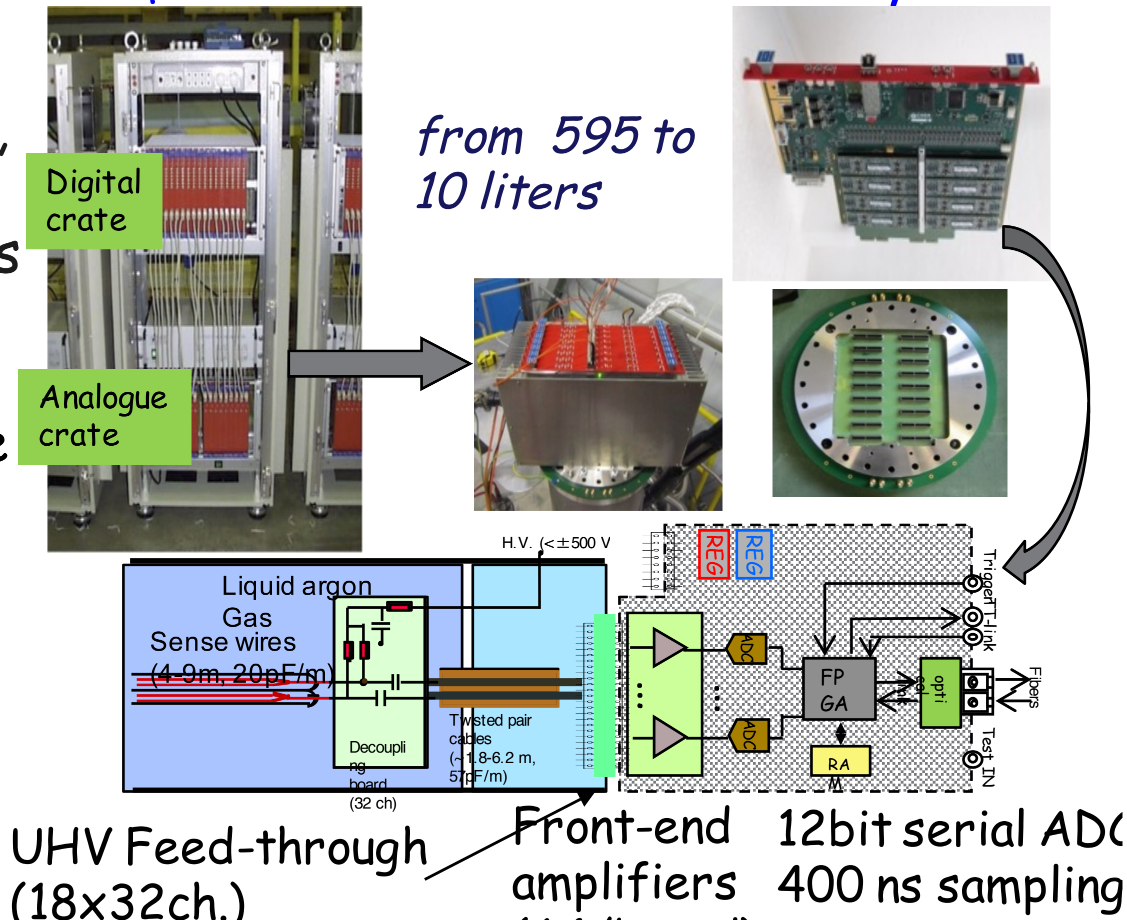


Measurements done both at room and cryogenic temperature.

360 PMTs installed in ICARUS T600

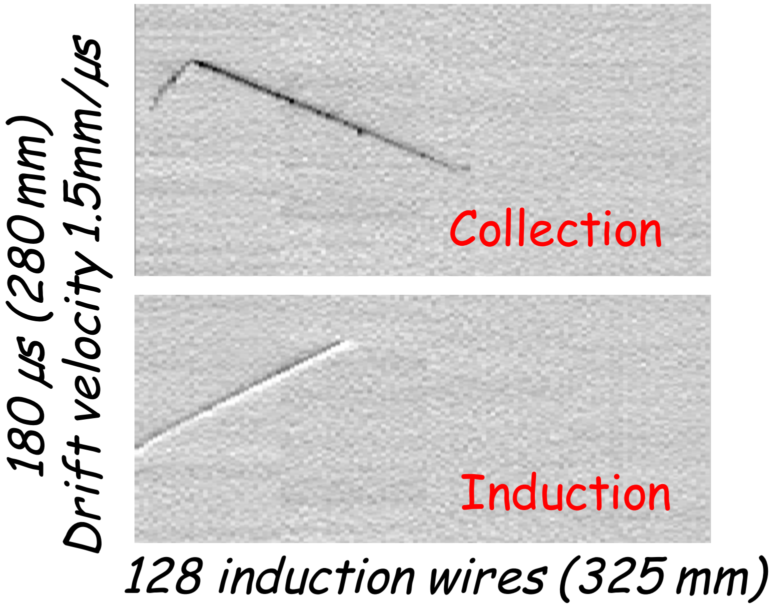
The new TPC read-out electronics

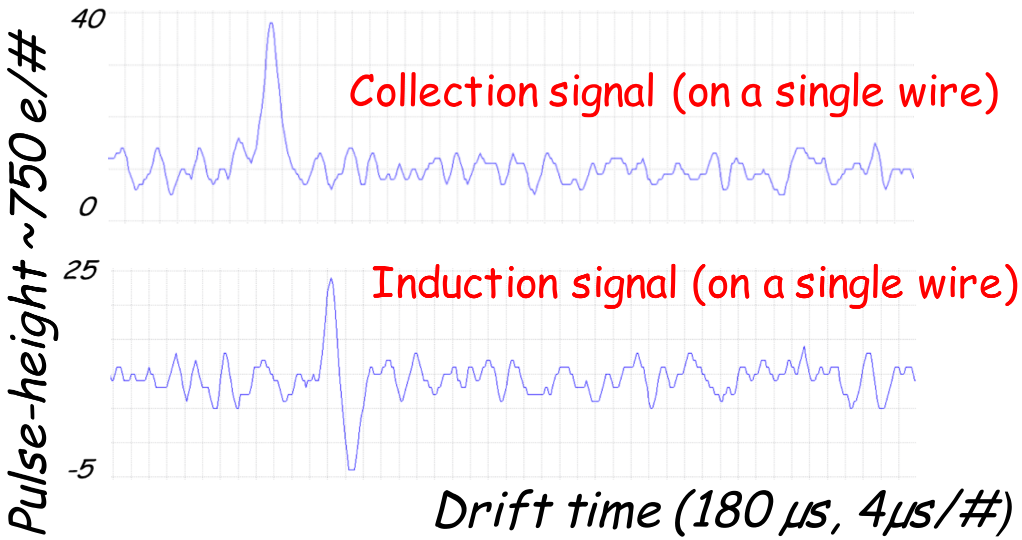
- Architecture of ICARUS electronics at LNGS based on analogue low noise "warm" front-end amplifier, a multiplexed 10-bit 2.5 MHz AD converter and a digital VME module for local storage, data compression, trigger information:
  - S/N ~9 in Collection, ~0.7 mm single hit resolution, resulting in a precise spatial event reconstr. 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 MHz);
  - *New compact design* to host both analogue/digital electronics (single high performance FPGA) directly on ad-hoc signal feedthrough flanges acting as electronics backplane.



Improved front-end electronics for T600

- Adopted improvements in the analogue front-end for a better event reconstruction 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 to slightly improving the resolution on μ momentum by MCS.

From CERN to FNAL: the ICARUS journey

- *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*

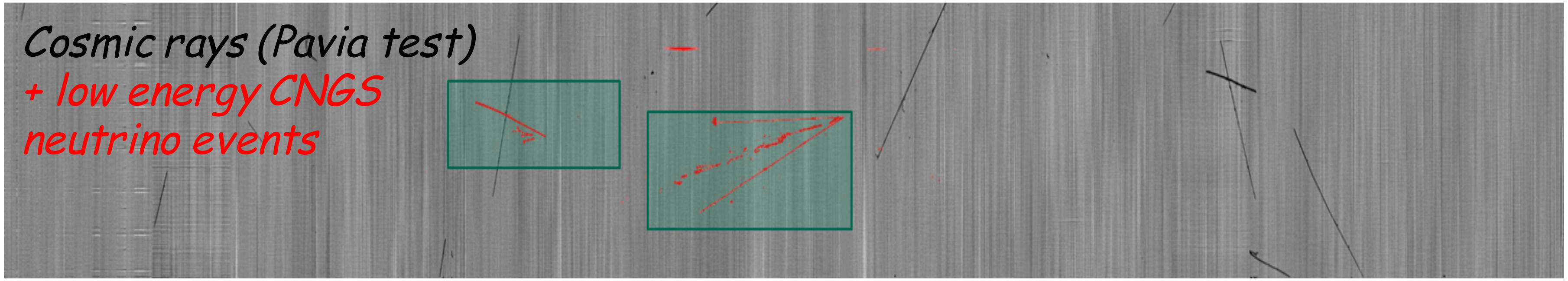
SBN 0.8 GeV ν FNAL Booster: 3 shallow-depth LAr-TPCs as definitive answer to sterileν puzzle

L/Eν ~ 600 m / 800 MeV ~ 1m/MeV

ICARUS T600 will collect also ~2 GeV νe NuMI Off-Axis: an asset for next LBL LBNF-DUNE (ν cross-section in LAr)

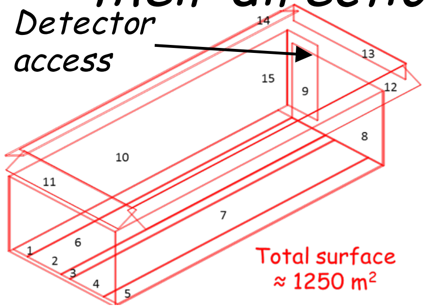
Taking data @ shallow depth: Cosmic Ray Tagger is mandatory

- ICARUS at FNAL will face a more challenging experimental condition than at LNGS, requiring the recognition of ν interactions amongst 11 KHz of cosmic's.
- *A 3 m concrete overburden* will remove contribution from charged hadrons/γ's.
- *Moreover ~11 μ tracks will occur per triggering event in 1 ms TPC drift readout: associated γ's represent a serious background source for ν_e search since e's produced via Compton scatt./ pair prod. can mimic a genuine ν_e CC.*



- Rejecting cosmic background, i.e. reconstructing the triggering event, would require to precisely know timing of each track in the TPC image, exploiting:
  - *A much improved light detection system, high granularity/~ns time resolution;*
  - *An external cosmic ray tagger (CRT) to detect incoming particles and their direction of propagation by time-of-flight measurements:*

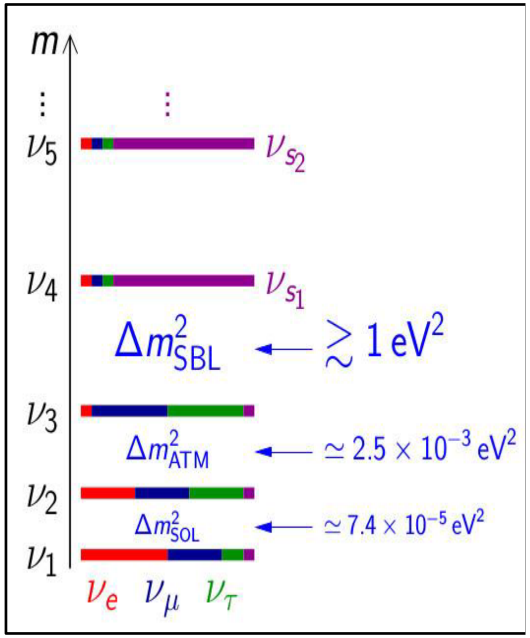
Mandatory !



- ✓ Scintillating bars surrounding 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/Double Chooz for side/bottom.

"Sterile neutrino puzzle" 1/2

- Anomalies have been collected in last years in neutrino sector despite the well-established 3-flavour mixing picture within Standard Model:
  - appearance of ν_e from ν_μ beams in accelerator experiments (LSND + MiniBooNE, combined evidence > 3σ);
  - disappearance of anti-ν_e, hinted by near-by nuclear reactor experiments (ratio observed/predicted event rates R = 0.9384 ± 0.024);
  - disappearance of ν_e, hinted by solar ν experiments during their calibration with Mega-Curie sources (SAGE, GALLEX, R = 0.84 ± 0.05).
- Results hint to a new "sterile" flavor, described by $\Delta m^2 \sim eV^2$ and small mixing angle, driving oscillations at short distance:
  - ICARUS constrained $\Delta m^2_{new} \leq 1\ eV^2$, and small mixing;
  - Planck data and Big Bang cosmology point to at most one further flavor with $m_{new} < 0.27$ eV;
  - No evidence of ν_μ disappearance in MINOS and IceCube in 0.32-20 TeV;
  - Recent reactor data (especially NEOS) are intriguing but inconclusive… New results are expected from ongoing/new experiments at reactor/radioactive source,…SOX at LNGS.



THE EXPERIMENTAL SCENARIO CALLS FOR A DEFINITIVE CLARIFICATION!

"Sterile neutrino puzzle" 2/2

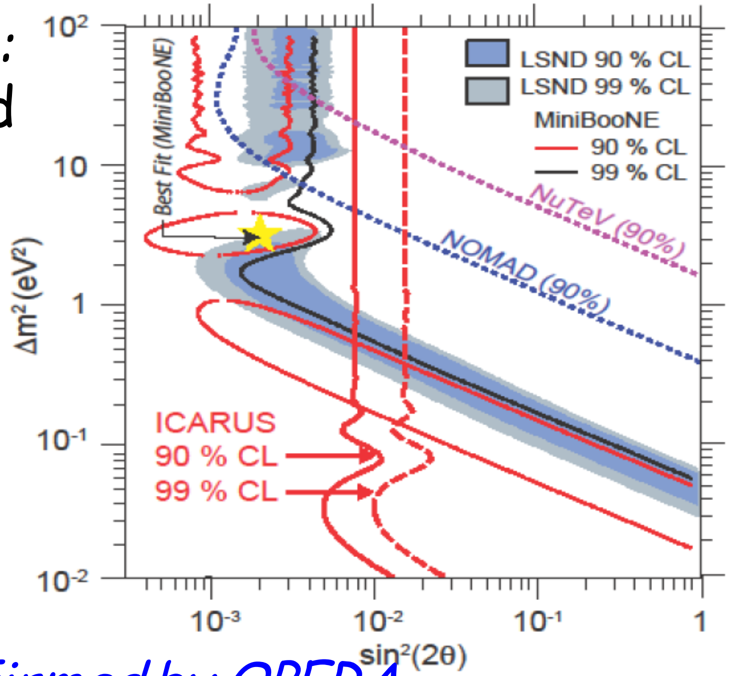
- ICARUS searched for ν_e-excess related to LSND-like anomaly with CNGS ν beam (~ 1% intrinsic ν_e contamination) despite the larger L/E_ν ~36.5 m/MeV when compared to L/E_ν ~ 1 m/MeV for LSND/ MiniBooNE:
  - ➢LSND-like oscillation signal would average to $\sin^2(1.27\Delta m^2 L/E) \sim 1/2$; compared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

- *No excess observed in 7.93×10^{19} pot sample:* 7 ν_e 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.)

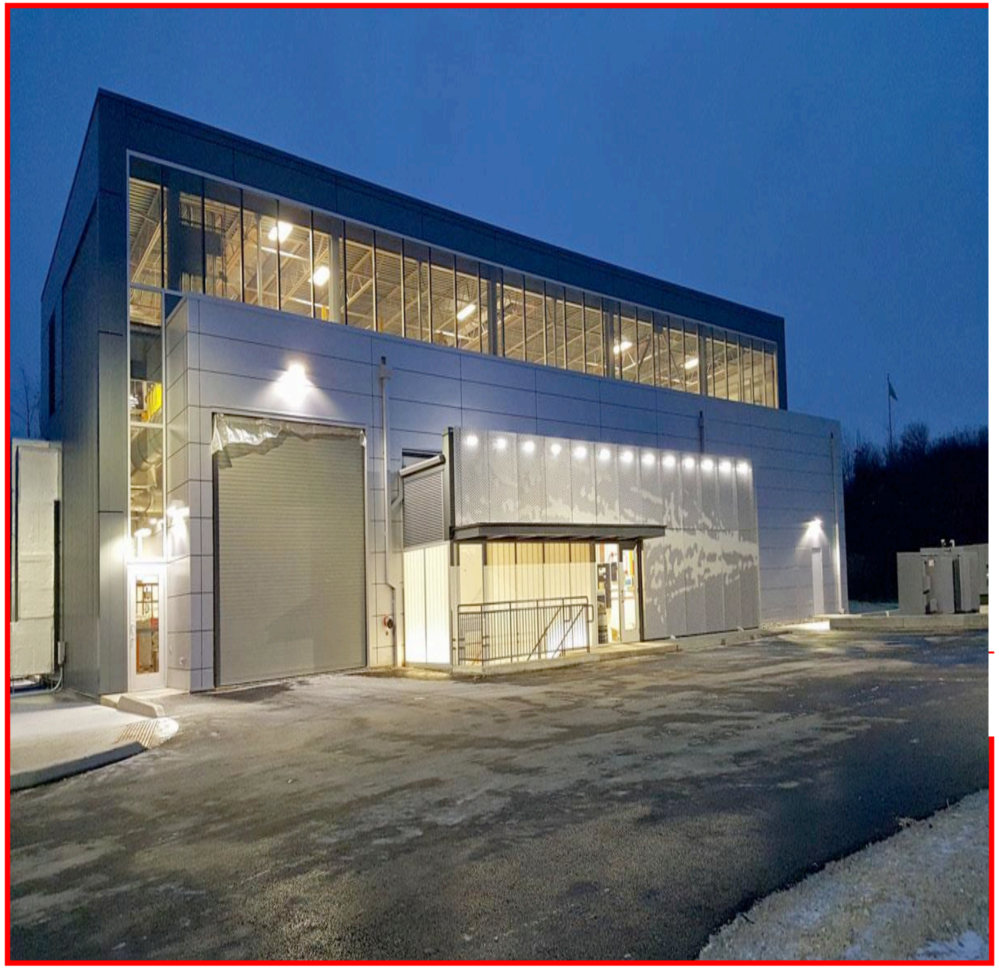
- *ICARUS restricted the allowed LSND parameters to a narrow region $\Delta m^2 < 1$ eV^2, $\sin^2 2\theta \sim 0.005$ where all positive/ negative experimental results can be coherently accommodated at 90% C.L.*



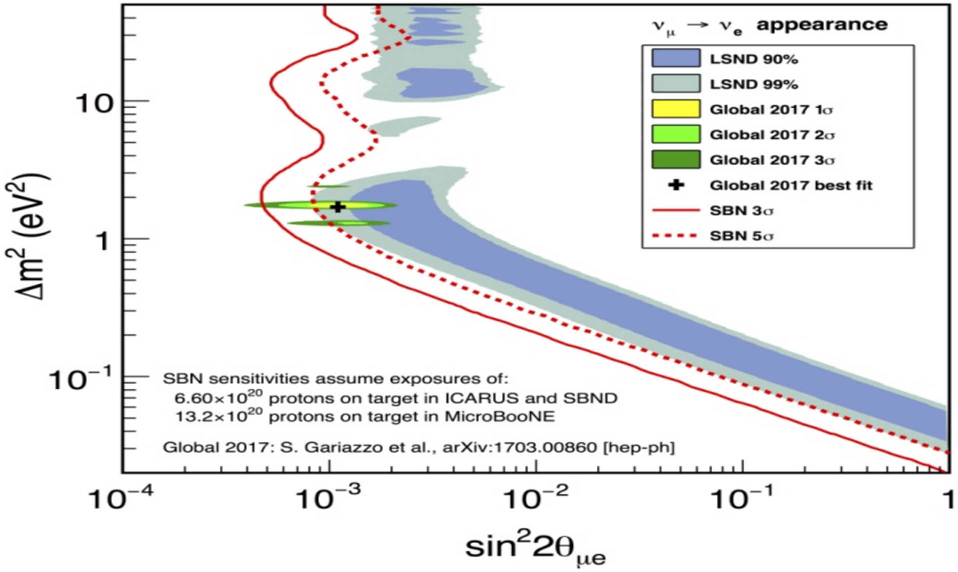
Confirmed by OPERA

- SBN experiment will likely clarify both LSND and reactor anomalies by precisely and independently measuring both ν_e appearance and ν_μ disappearance, mutually related through $\sin^2(2\vartheta_{\mu e}) \leq \frac{1}{4}\sin^2(2\vartheta_{\mu x})\sin^2(2\vartheta_{ex})$

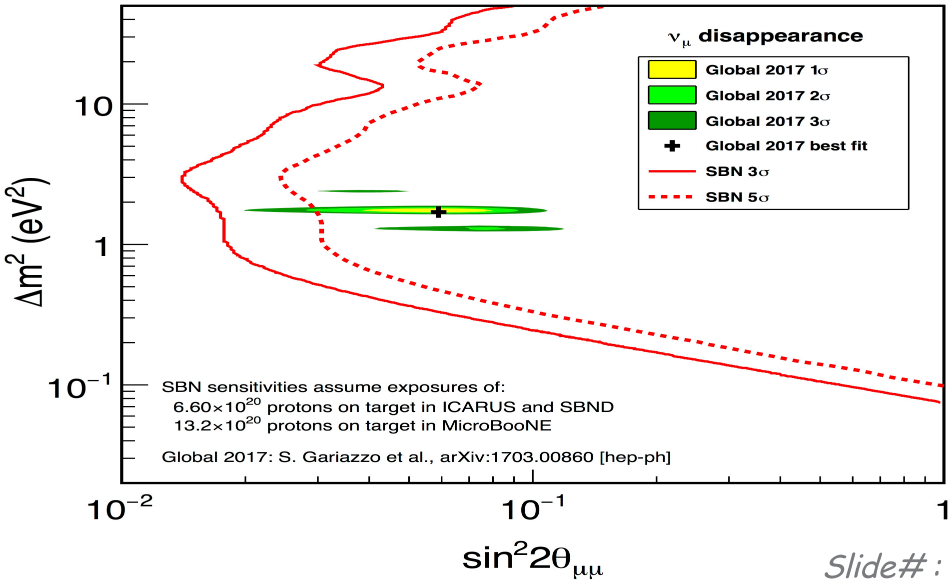
SBN sensitivity



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



3-5 σ νμ disappearance SBN sensitivity



ICARUS will operate beneath SBN Far Site Building @ FNAL

Conclusions

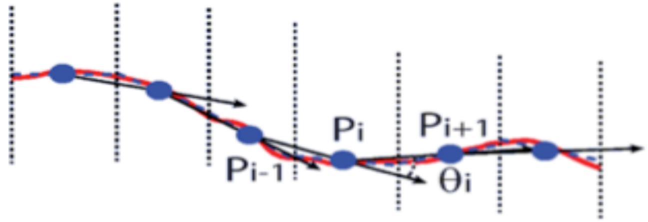
- LAr-TPC detection technique taken to full maturity with ICARUS-T600, a result of many years of R&D with continuous support of INFN.
- ICARUS completed in 2013 a successful continuous 3- year run at LNGS exposed to CNGS neutrinos and cosmic rays, obtaining remarkable physics and technical achievements, proving the effectiveness of the single phase LAr-TPC technology for ν physics.
- The ability in reconstructing ν ιnteractions 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 the LSND–like anomaly with CNGS beam defining a narrow region at $(\Delta m^2, \sin^2 2\theta) \sim (1\ eV^2, 0.005)$ 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 underwent a major overhauling at CERN and has been transported to FNAL to be exposed to Booster and NuMi neutrinos.
- The SBN experiment will provide a clarification of the sterile neutrino issue, both in appearance and disappearance modes.


Thank you !

Algorithm of angle of deflection measurement via MCS

- A track-by-track estimation of the muon momentum *p* can be provided by measuring genuine RMS multiple scattering angle ψ_{MCS} over a length *L*, roughly described in LAr within ~ 1% percent accuracy at L ~ X_0 by (G.R.Lynch and O.I.Dahl, 1991). Approximates gaussian part of scattering distribution
- Muon track divided into segments, grouping hits belonging to two consecutive electronic boards
  - Compromise: longer segments allow enhancing physical MCS deflections, that grow as $L^{1/2}$, while reducing impact of measurement errors on single wires. On the other hand, adequate segment statistics (> 10) is required to correctly estimate average deflections, even for shortest muon lengths (2.5 m).
- Muon trajectory within a segment described by position of hits barycenter and by its slope defined on the 2D Collection plane. Deflection angle θ_{MCS} between consecutive segments defined as angle between two consecutive pieces of polygonal line connecting consecutive barycenters.
- ψ_{MCS} expresses local deflection at a point along the muon track, in θ_{MCS} the deflection is averaged over the finite segment length, resulting in a reduction of the MCS effect quantified by the factor $w_0 \sim 0.74 \pm 1\%$

$$\psi_{MCS} = \frac{13.6\ MeV/c}{\beta p}\sqrt{\frac{L}{X_0}}\left(1+\ln\frac{L}{X_0}\right)$$



$$\theta_{MCS} = \frac{13.6\ MeV/c}{\beta p_i}\sqrt{\frac{L}{X_0\cos\delta}\frac{w_0}{\cos\delta}}$$

X_0 =14 cm radiation length in Lar

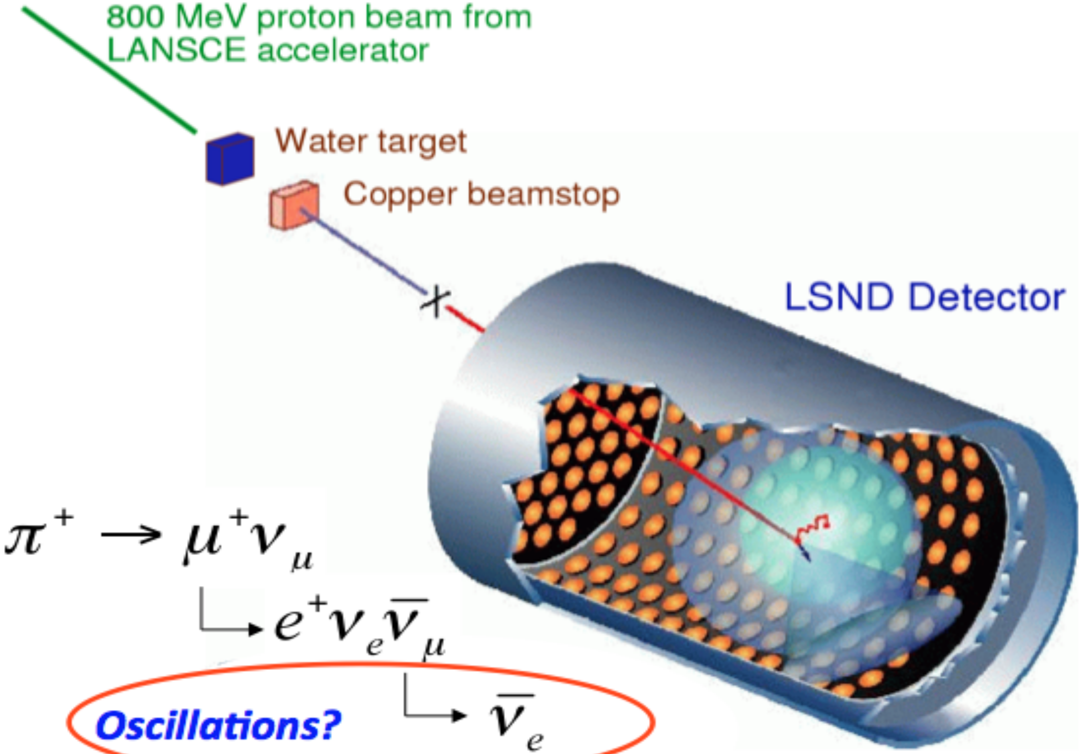
L: segment length ~ 19.2 cm (about 57 hits)

$\beta = v_\mu / c$

P_i : momentum in the i^{th} -segment

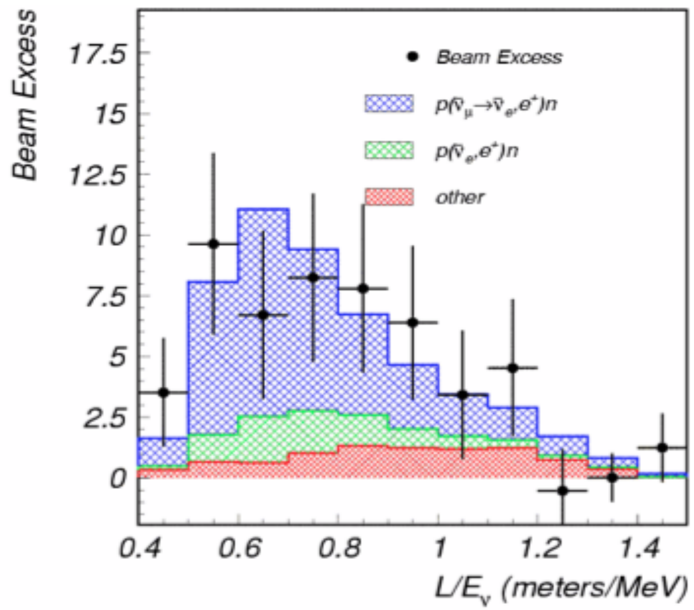
δ : projection angle from 3D to 2D

The LSND anomaly (appearance of νμ -> νe events)



Signal: $\bar{\nu}_e \rightarrow e^+ n$

$\hookrightarrow n\, p \rightarrow d\, \gamma(2.2\text{MeV})$



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)%.

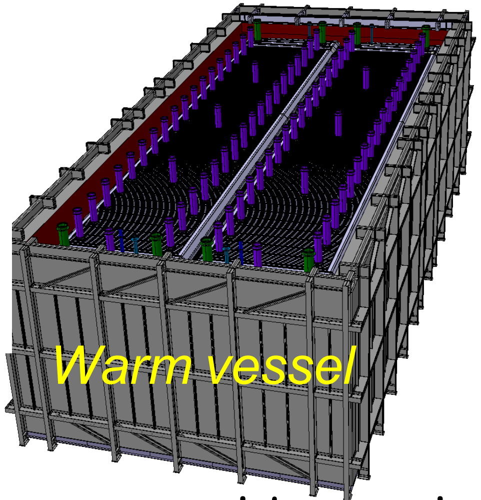
3.8 σ evidence for oscillation.

Cryogenic Upgrades

- A purely passive insulation coupled to standard two-phase N2 cooling shield, redesigned/ tested at CERN.
  - New cold vessels, made of extruded aluminum profiles welded together at CERN containing TPC's and PMT's.

Leak tightness checked to <10^{-7} mbar l/s. Structural test on the vessel by pumping down to 20 mbar. All measurements agree with calculation: 11 mm max. deformation.

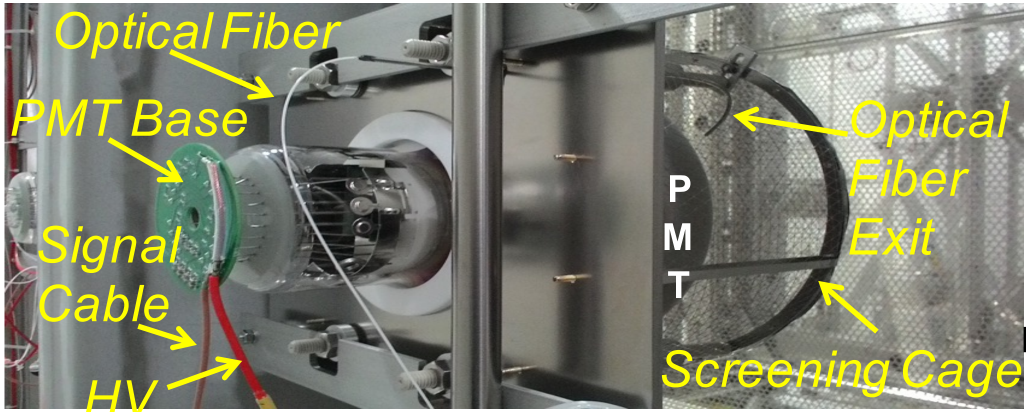
Expected heat loss through insulation: 6.6 kW (~10 W/m^2)



  - Warm vessel will host two cold vessels, N2 cooling shield and the plywood + thermal insulating foam panels produced in Europe/assembled at FNAL

PMT coating with TPB and installation in T600

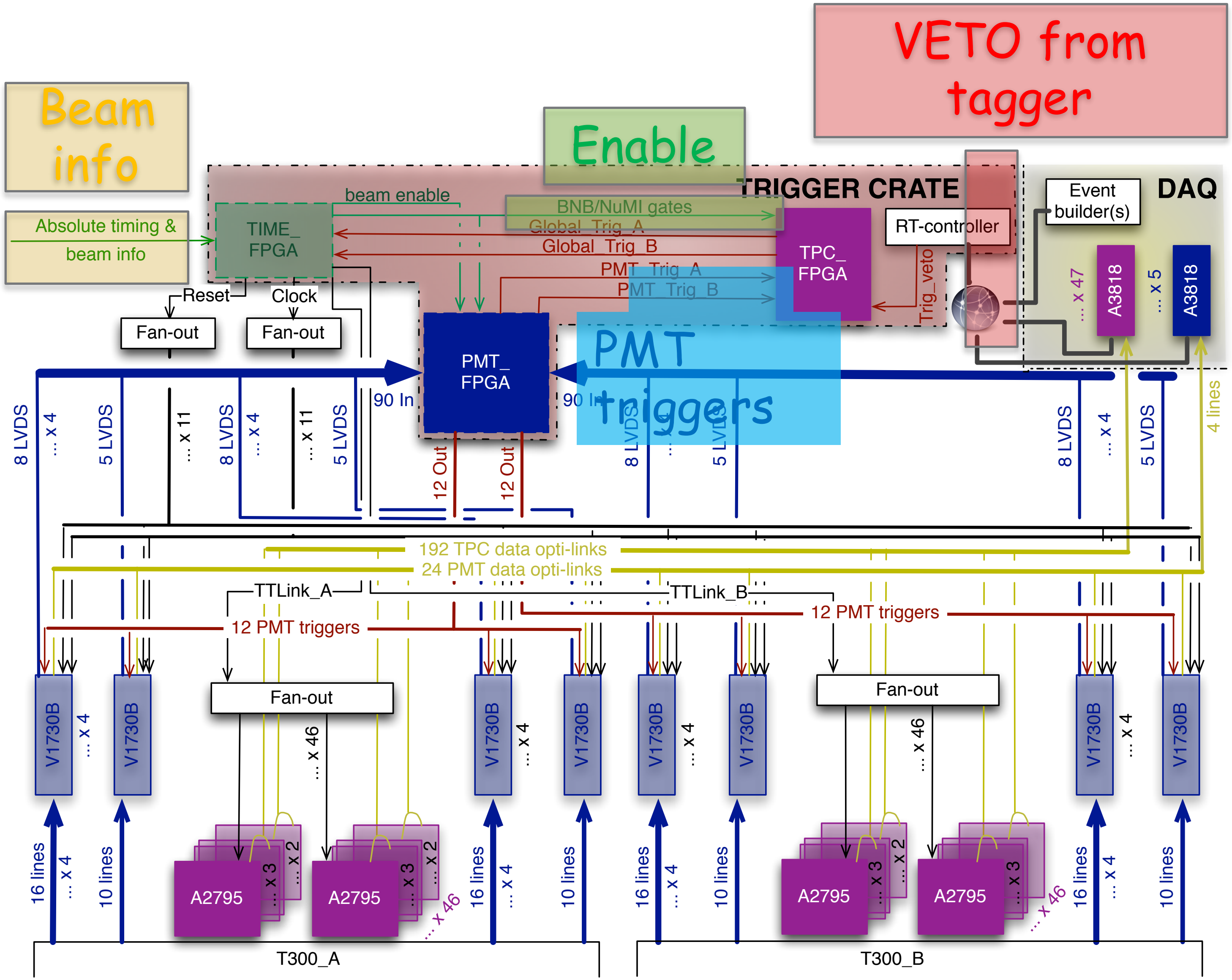
- PMT glass windows coated by ~200μg/cm^2 of Tetra-Phenyl-Butadiene (TPB) wls to detect λ = 128 nm scintillation light in LAr;
- Each PMT is enclosed in a wire screening cage to prevent induction of PMT pulses on facing TPC wires. PMT timing/calibration will be provided with Hamamatsu PLP10 LASER (405 nm).



<0.5 m event localization & an initial classification of different topologies, μ-tracks vs. e.m. showers, exploiting arrival time of prompt γs and light intensity

A clear cosmic μs identification will be provided by the combined use of different Neural Nets (~2% expected residual misidentification).

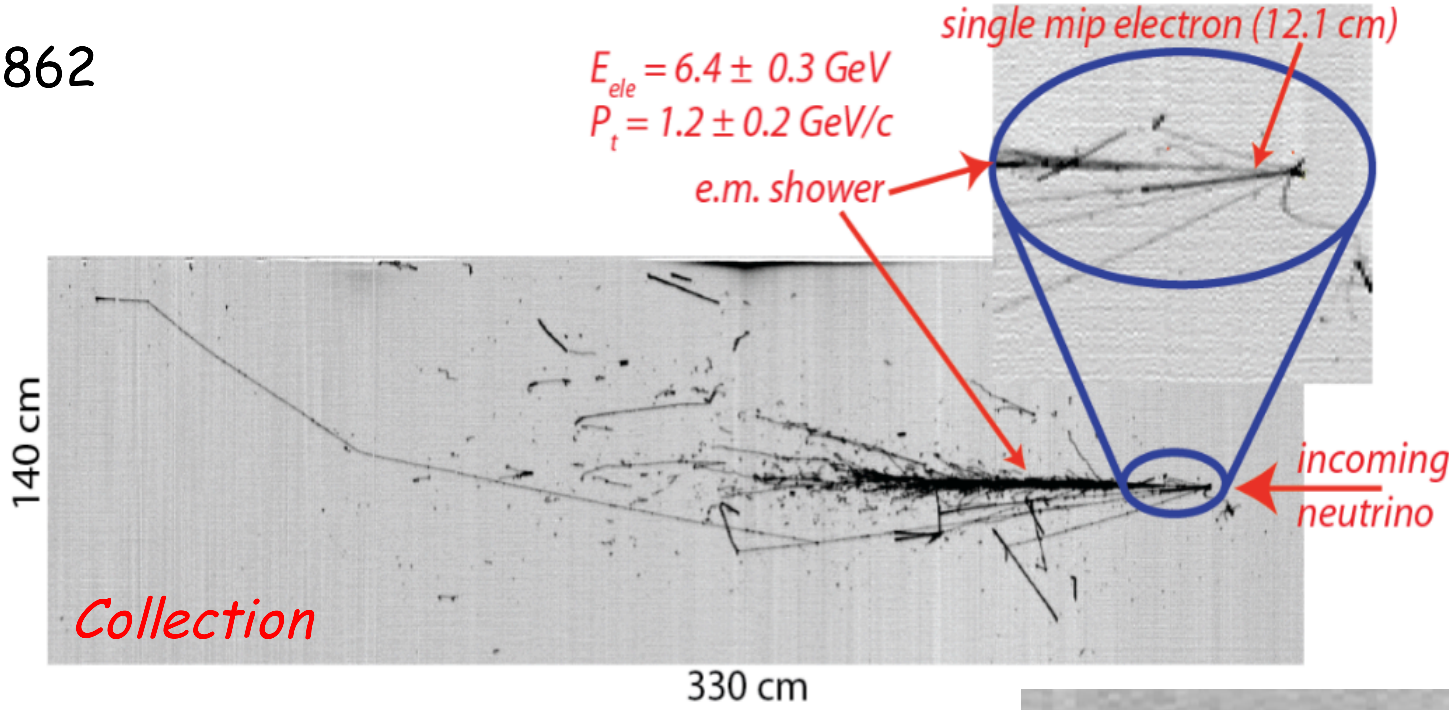
Trigger system layout

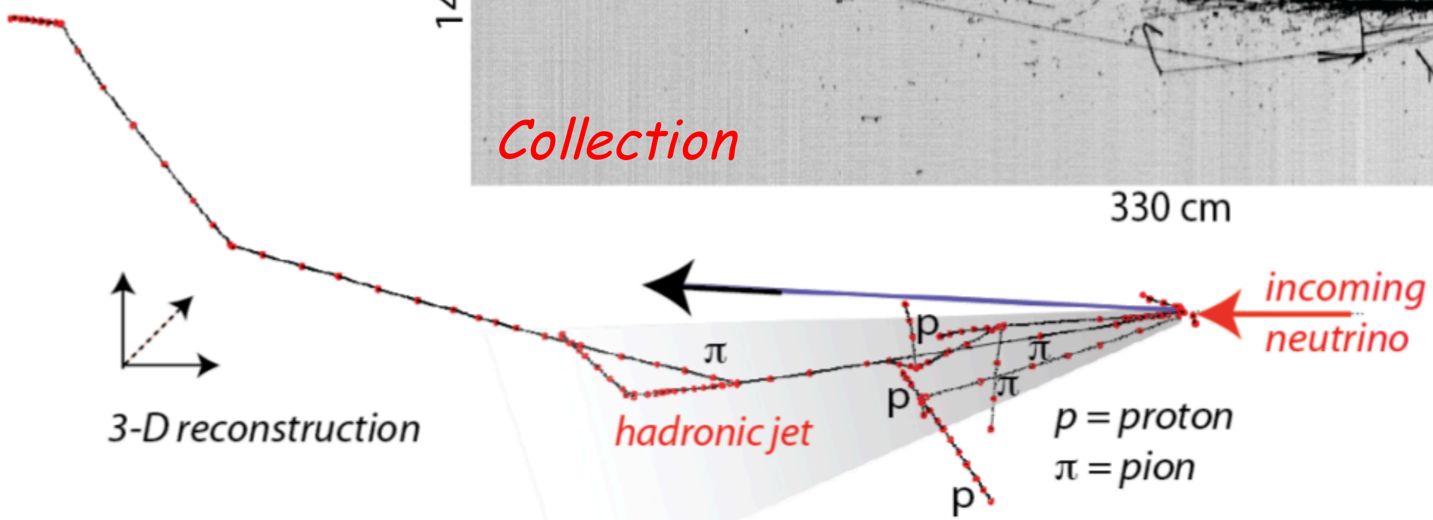


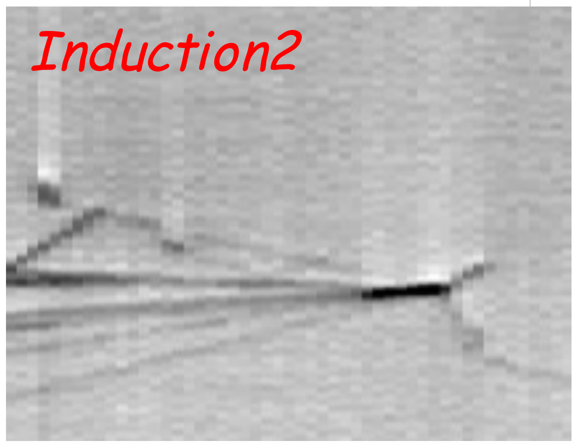
The majority signals from each half chamber (PMT triggers) are combined by the violet TPC_FPGA with a veto signal from a cosmic muon tagger, and an enable signal. The latter comes from the green TIME_FPGA, which checks whether there is beam from the FNAL Booster or from NuMI.

ν_e CC identification/ 3D- reconstruction in CNGS beam

Run 11319 Ev. 2862



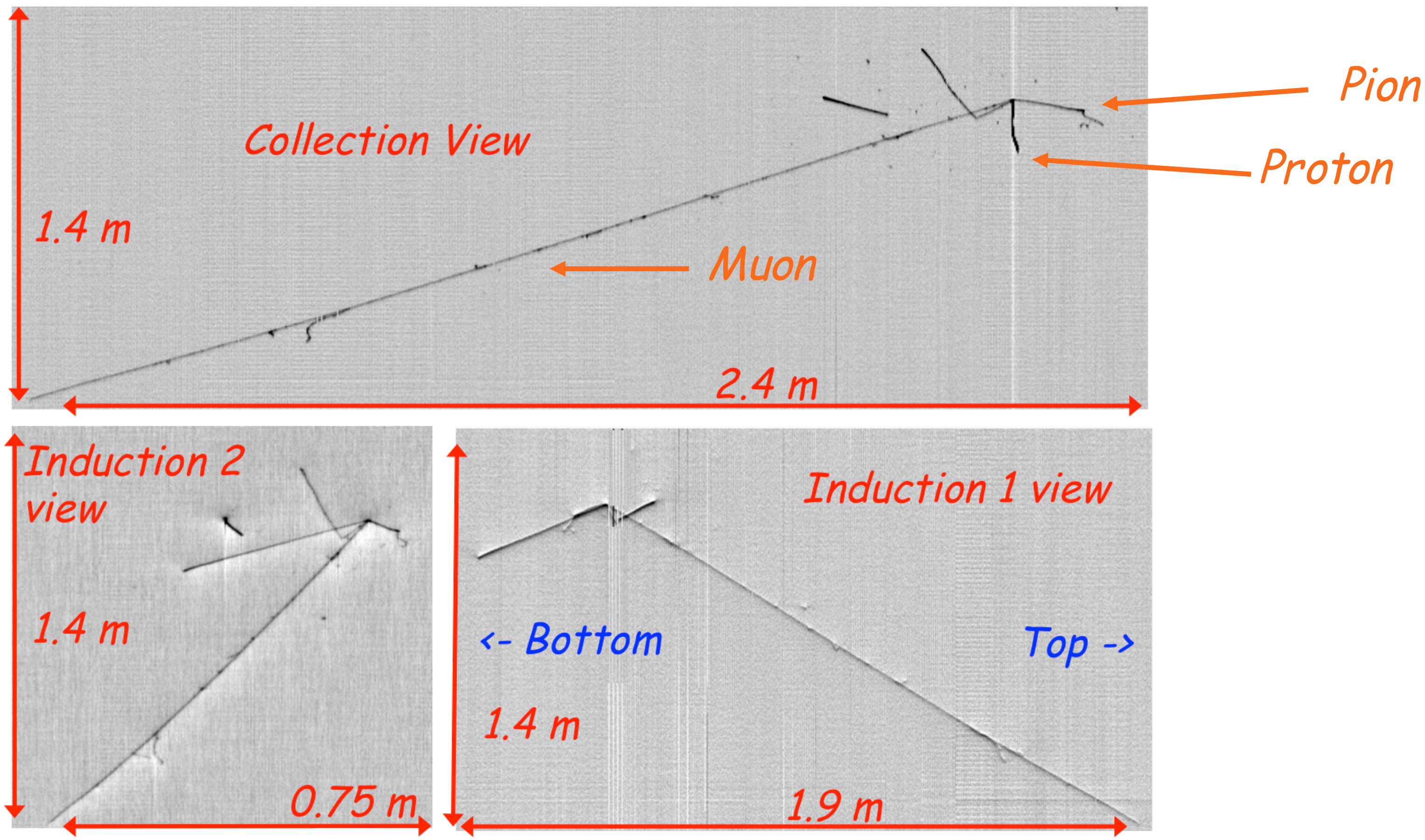




3D reconstruction algorithm exploiting the Collection and Induction 1,2 views allows to fully reconstruct events identifying the involved particles

Induction2 view: essential to solve complex /crowded events

Atmospheric n_{μ} CC event

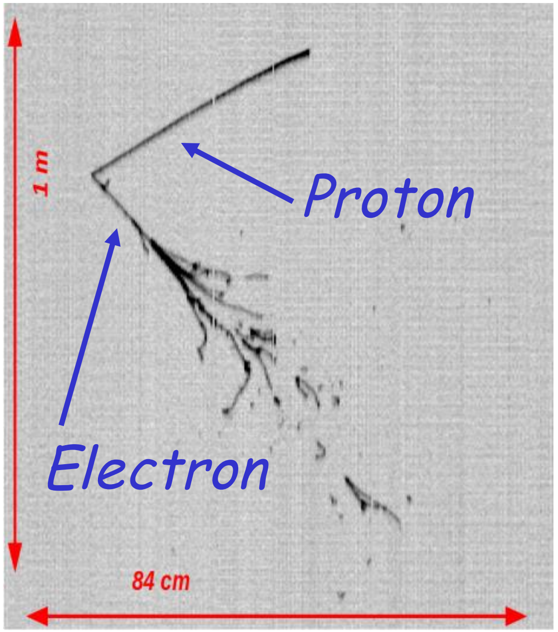


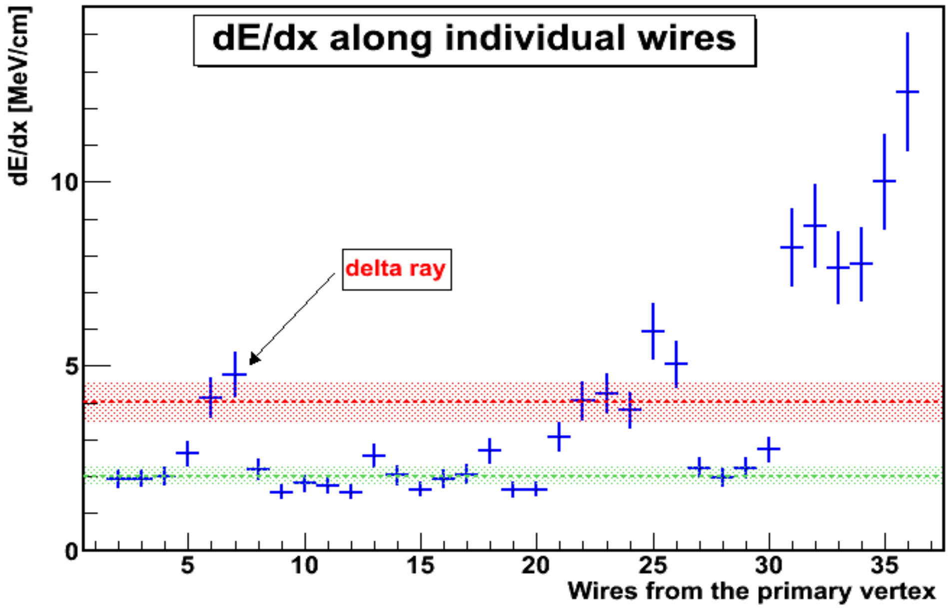
Upward-going νμ CC event with a deposited energy ~ 1.7 GeV:

- *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°.*

Atmospheric ν_e CC: "high" energy events

A quasi elastic electron-like atmospheric neutrino event candidate with deposited energy E_{dep} ~0.9 GeV (left, collection view). The hadronic track is identified as a proton by its dE/dx vs range. The plot on the right shows the evolution of the dE/dx from a single track to an e.m. shower for the primary electron: the green and red lines indicate the expected dE/dx for single m.i.p. and double m.i.p. respectively.





A beautiful muon neutrino interaction from CNGS run 11689, event 1486

Detailed description of next figure

To give you a feeling of what a neutrino event in ICARUS looks like, in the next slide I show a real event, not a MC.

This event is an interaction of a muon neutrino coming from the accelerator of the CNGS experiment at CERN, that was active in the period 2010-2014. How do we know for sure?

First, the trigger is tagged as coming from CNGS.

Second, the total moment 3D direction points in the direction of CERN, and points as coming from there.

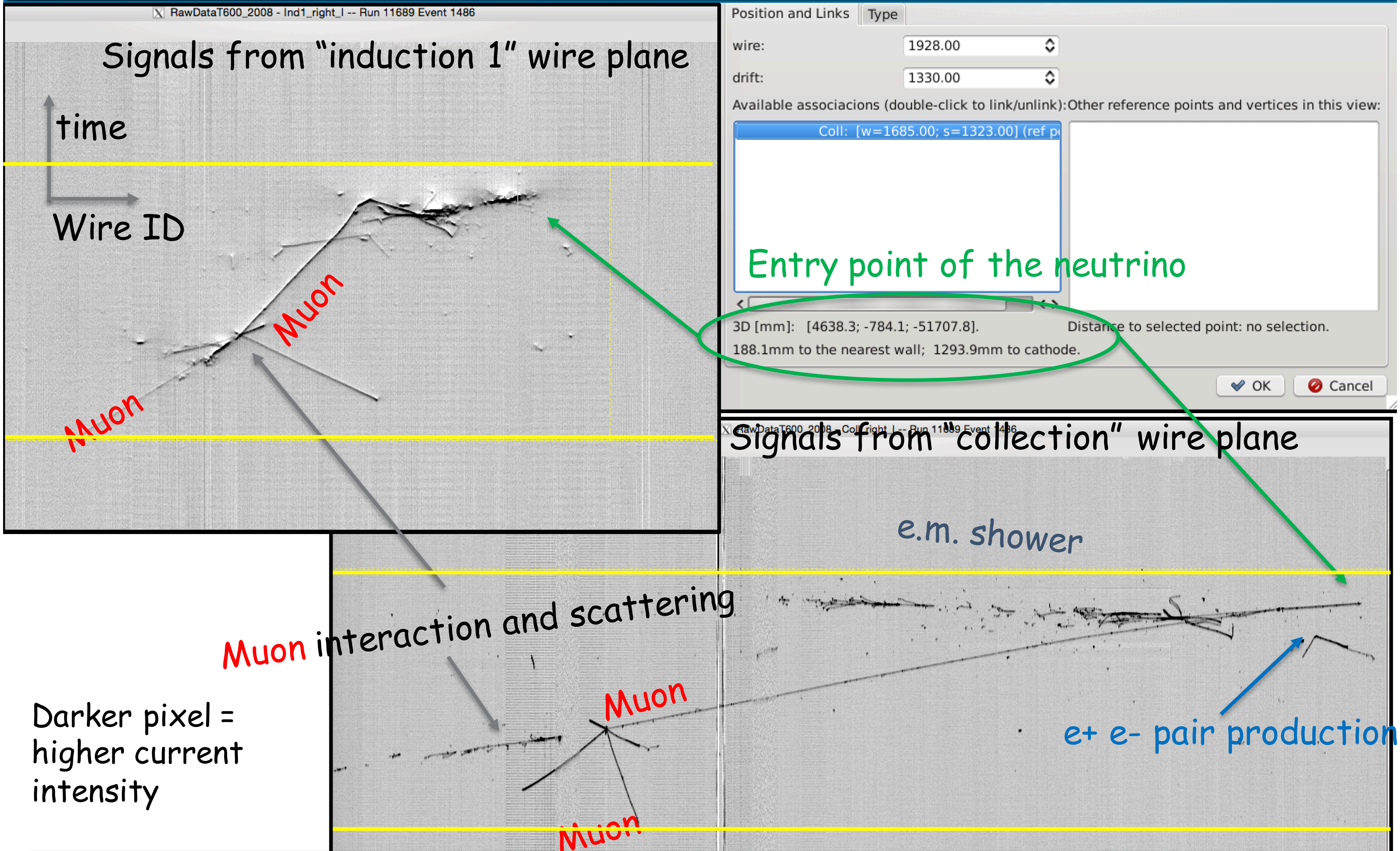
What about the nature of the primary particle? We see a long straight track, typical of a muon, that has been produced inside the fiducial volume. This means that the primary particle must be neutral, otherwise we would see the ionization it would produce.

The e.m. cascade start point is very near the entry point and fully contained in the fiducial volume (intuitively, look at the yellow horizontal lines as limits of such volume). A cascade coming from a muon would be superimposed on the muon track, so something else must have started it. In this case, detailed considerations tell us it was a positron.

Incidentally, we can also see a pair production, but the responsible photon does not come from the, let's say, main interaction vertex. We can ignore it for the identification of the primary particle.

Putting together all the clues, the primary particle is 1) neutral, 2) able to give leptons, in particular a muon, in the final state, and , 3) coming from the CNGS accelerator, so we can exclude many neutral particle candidates, leaving only a muon neutrino. I have chosen this particular event for illustration purposes because it is a very rare case of a well identified neutrino event where we can also see what many things look like: indeed, we can see a muon track (an extremely common occurrence), an e.m. cascade, a pair production, a muon interaction and scattering. That is, almost everything that could happen in the chamber is there

A beautiful muon neutrino interaction from CNGS run 11689, event 1486



Muon appearing inside the fiducial volume, event trigger tagged as originated from CNGS,
and
total momentum (3D) direction considerations tell us this is a muon neutrino interaction