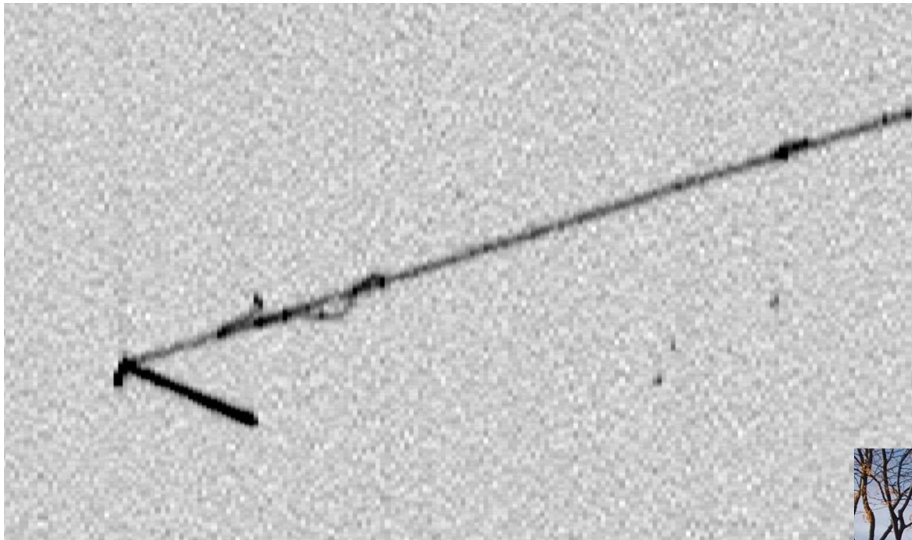
The Icarus Experiment at Fermilab



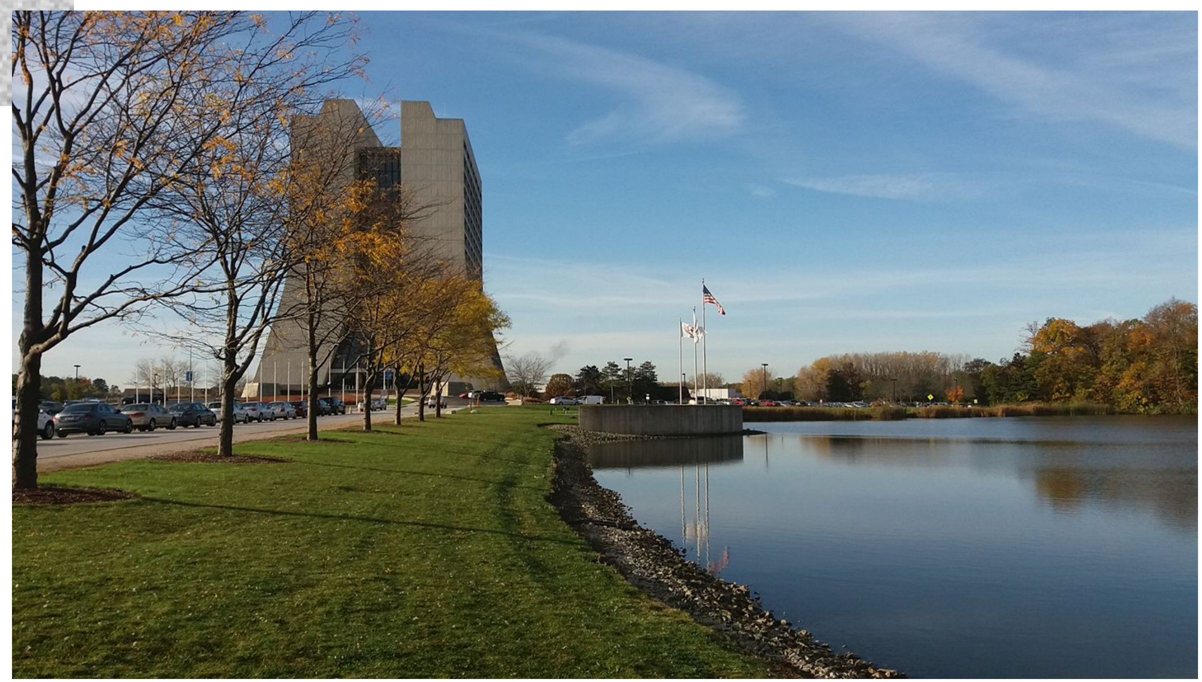
IMAGING COSMIC AND RARE UNDERGROUND SIGNALS

FERMILAB 2023
SUMMER STUDENTS
SCHOOL

Pisa, July 24th 2023

Christian Farnese
INFN Padova
farnese@pd.infn.it

ICARUS collaboration



European Commission

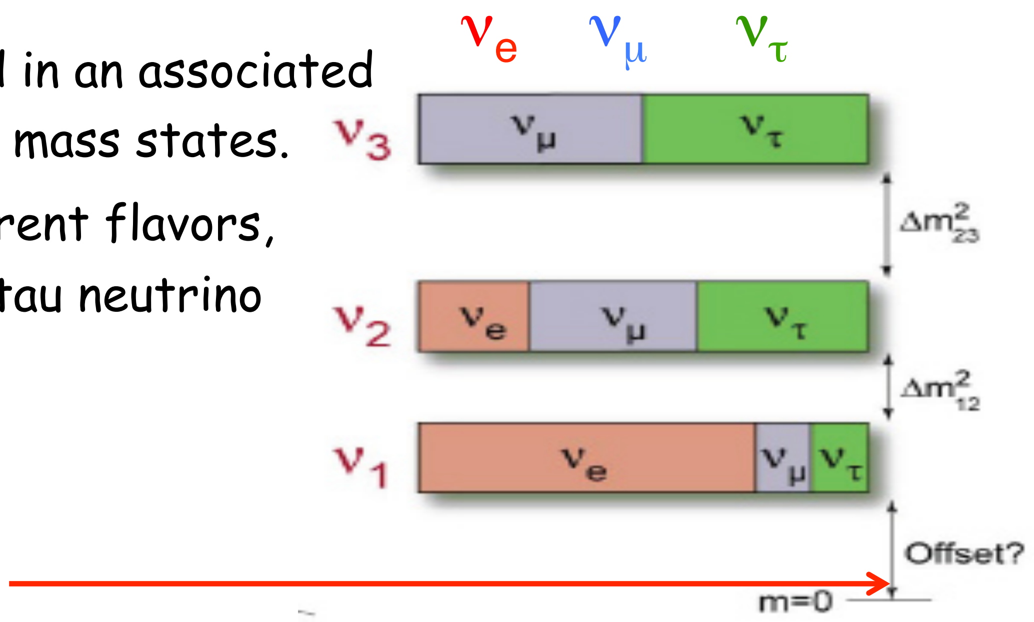
INFN

Neutrinos

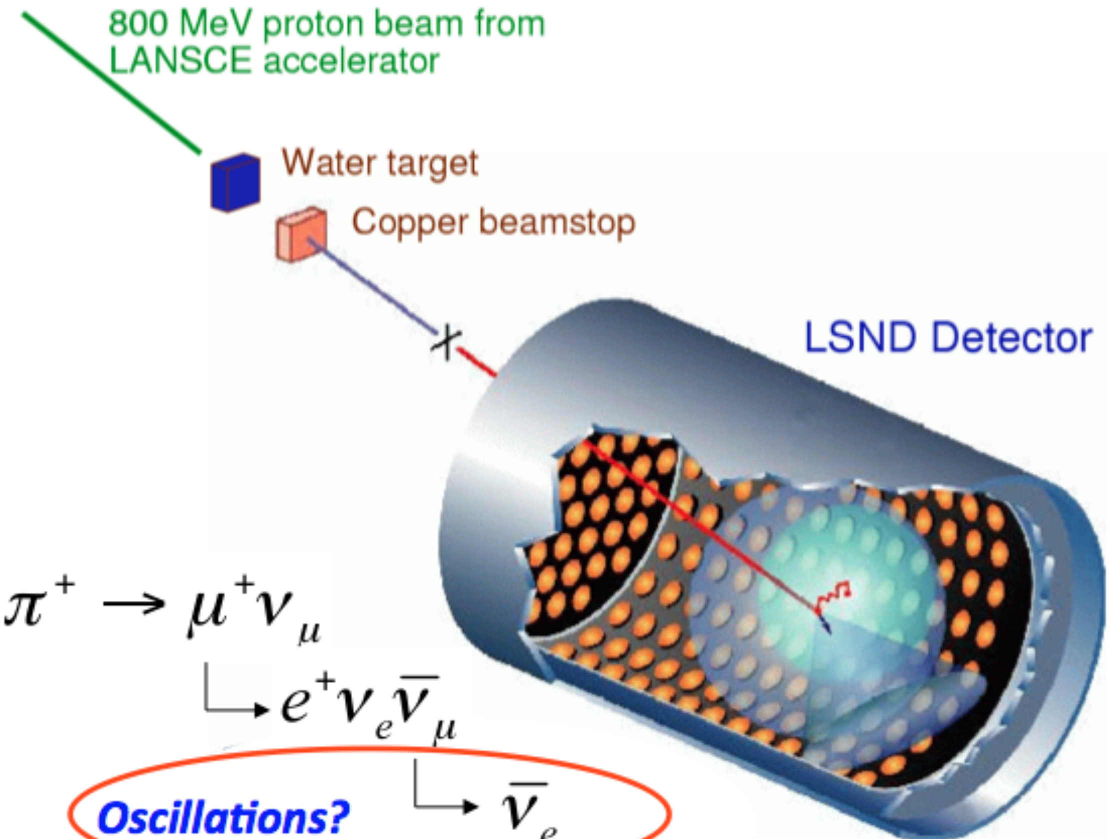
- Being fermions whose basic properties are still largely unknown, neutrinos are one of the main experimental potentials for novel physics beyond the Standard Model.
- Neutrinos can be created in several ways, like for instance
  - nuclear reactions such as the core of a star, a supernova + etc
  - accelerated particle beams or cosmic rays hitting atoms,
  - beta decay of atomic nuclei or hadrons.

Neutrinos are the most abundant massive particles in Universe

- Neutrino oscillations have established a picture consistent with the mixing of three physical neutrino νe, $\nu \mu$ and $\nu \tau$ with the help of three mass eigenstates $\nu 1$, $\nu 2$ and $\nu 3$.
- A neutrino with a specific flavor is created in an associated specific quantum superposition of all three mass states.
- Neutrinos oscillate in flight between different flavors, f.i., a $\nu \mu$ may be observed as a electron or tau neutrino
  - *Three angles (θ_{12}, θ_{13}, θ_{23})*
  - *Two mass differences (Δm^2_{12}, Δm^2_{23})*
  - *One unkown offset from m = 0*



The LSND Anomaly



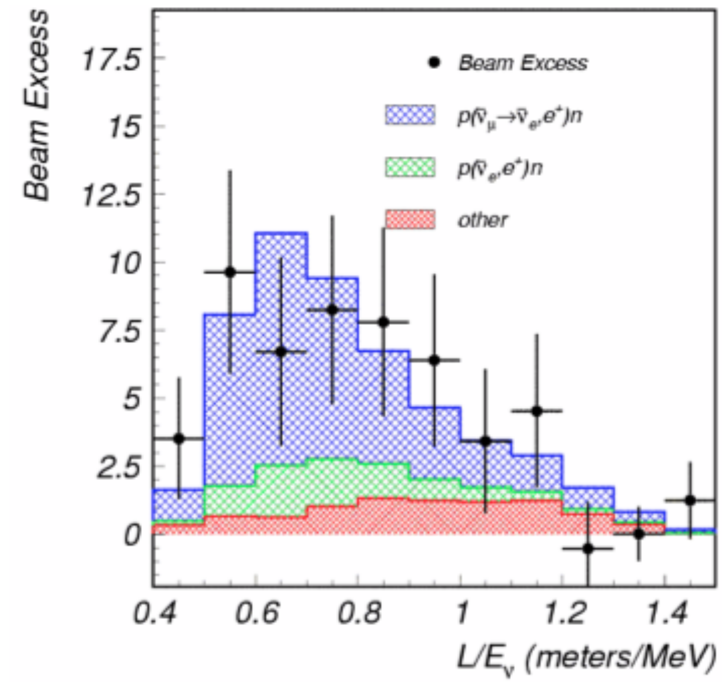
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

Oscillations? $\hookrightarrow \bar{\nu}_e$

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

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



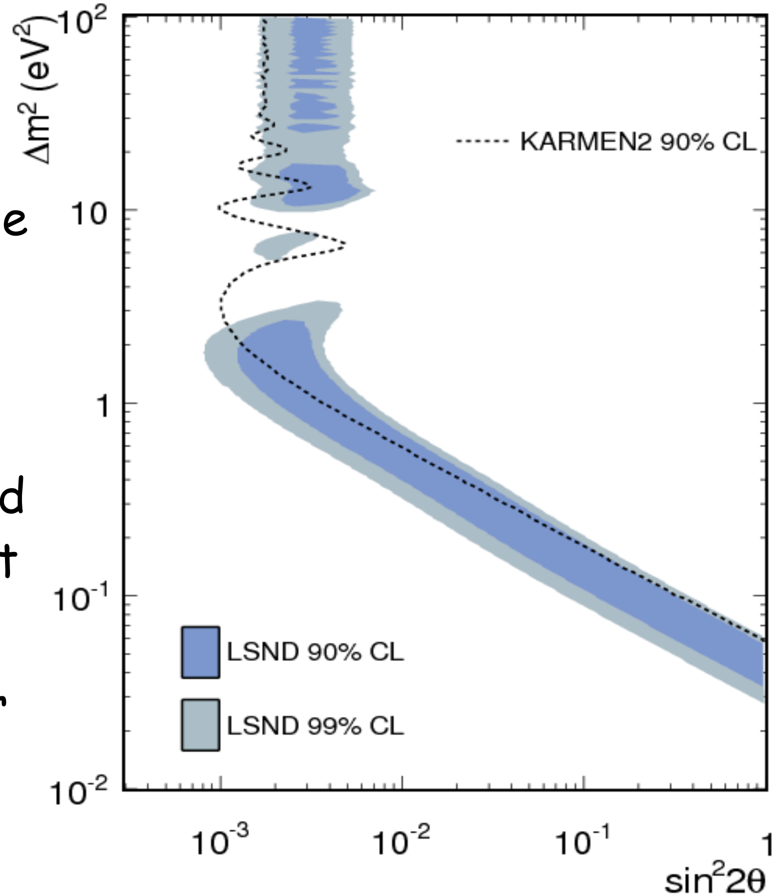
Saw an excess of $\bar{\nu}_e$:
$87.9 \pm 22.4 \pm 6.0$ events.

With an oscillation probability of $(0.264 \pm 0.067 \pm 0.045)\%$.

3.8 σ evidence for oscillation.

“Sterile neutrino puzzle”

- The oscillation signal observed by the LSND experiment (evidence of an anti-νe appearance) allows to define an allowed region in the Δm^2 and $\sin^2 2\theta$ parameter space that is incompatible with the Δm^2 previously observed ($\Delta m^2_{21} \sim 7.5\ 10^{-5}\ eV^2$; $\Delta m^2_{31} \sim 2.5\ 10^{-3}\ eV^2$):
  - ➢ $\Delta m^2 \sim 1\ eV^2$

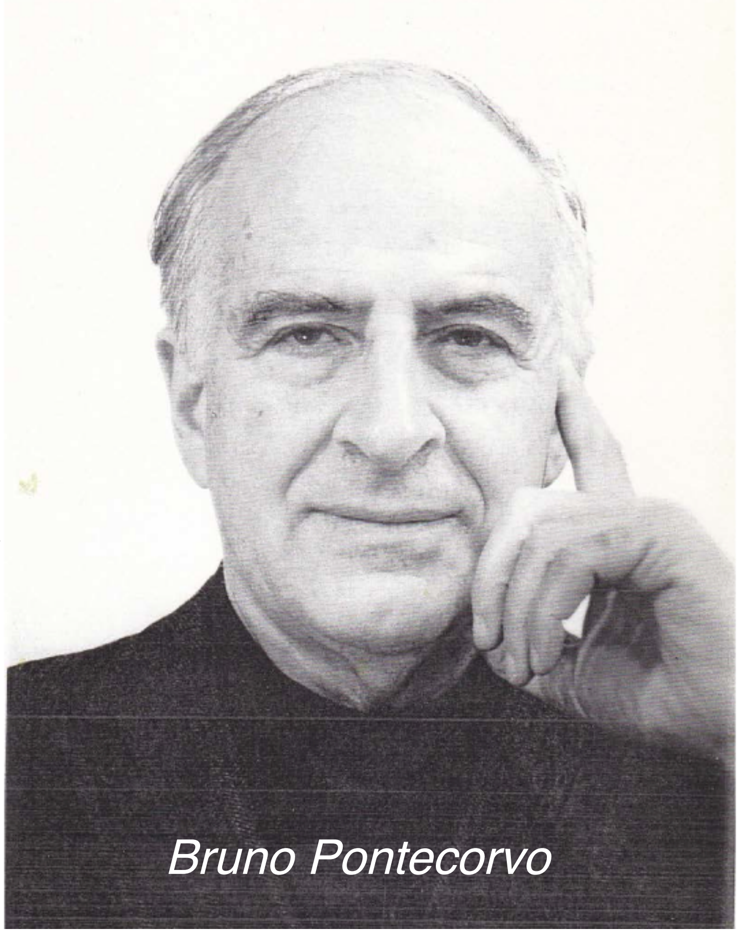


- Additional anomalous signals has been then observed and seems to indicate an evidence of oscillation that can be described considering a $\Delta m^2 \sim 1\ eV^2$:
  - ➢ appearance of νe from νμ beams in accelerator experiments, not only at LSND, but also at MiniBooNE, that studied the Booster neutrino beam at FNAL (L~540 m, Eν~700 MeV);
  - ➢ disappearance of anti-νe, hinted by near-by nuclear reactor experiments, that study the neutrinos in proximity of the reactor;
  - ➢ disappearance of νe, hinted by solar ν experiments during their calibration with Mega-Curie sources (SAGE, GALLEX).

… is this $\Delta m^2 = m^2_4 - m^2_1$???

“Sterile” neutrinos?

- Sterile neutrinos are an hypothetical type of neutrinos that do no interact via any of the fundamental interactions of the Standard Model except gravity.
- The name was conied in 1957 by Bruno Pontecorvo.
- If they are heavy enough, they may also contribute to cold or warm dark matter.
- Sterile neutrino may mix with ordinary neutrinos via a mass term. So if this fourth state of neutrinos exists, it is necessary to extend the “standard neutrino model” based on 3 neutrinos a least to a minimal 3+1 model with a new 4x4 neutrino mixing matrix
- Since they would not interact electromagnetically, weakly or strongly they are extremely difficult to detect and they can be recognized only “indirectly”:

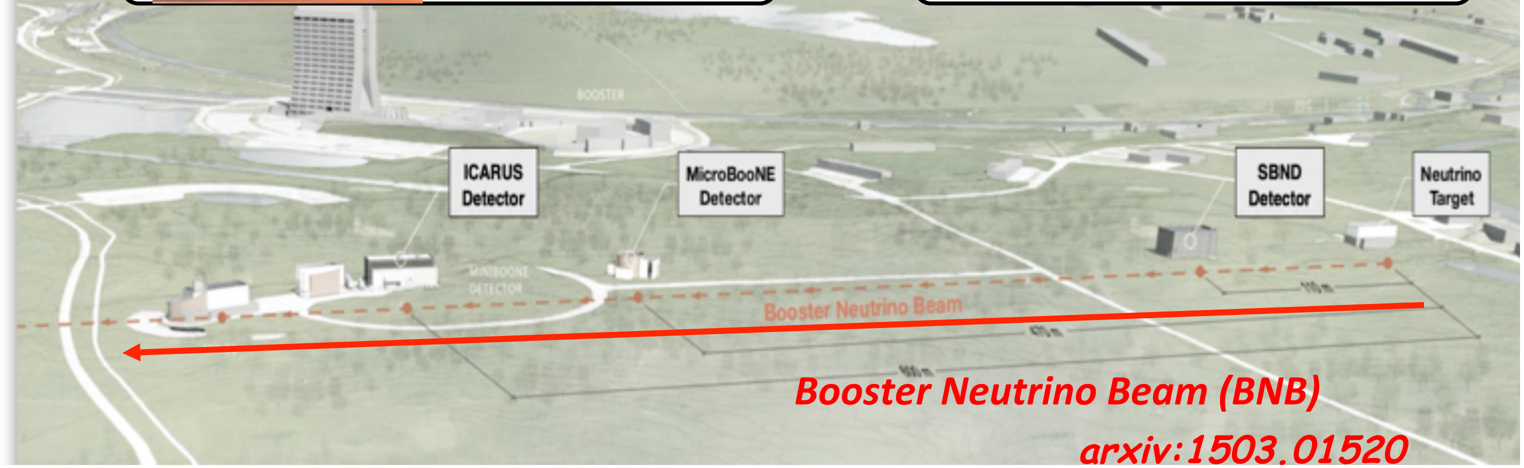

Bruno Pontecorvo

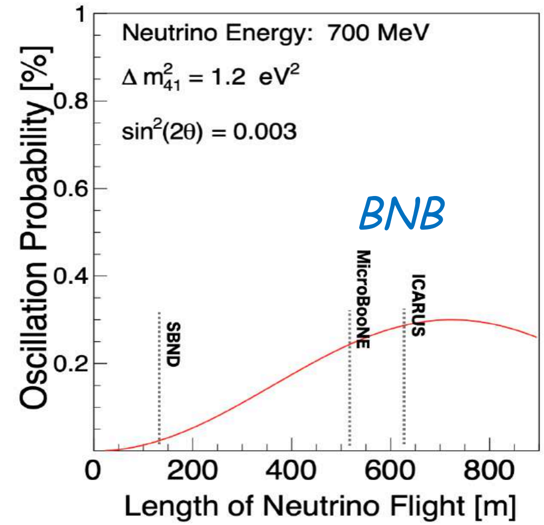
  - Search for anomalous neutrino appearance/disappearance signals using dedicated neutrino sources/beams

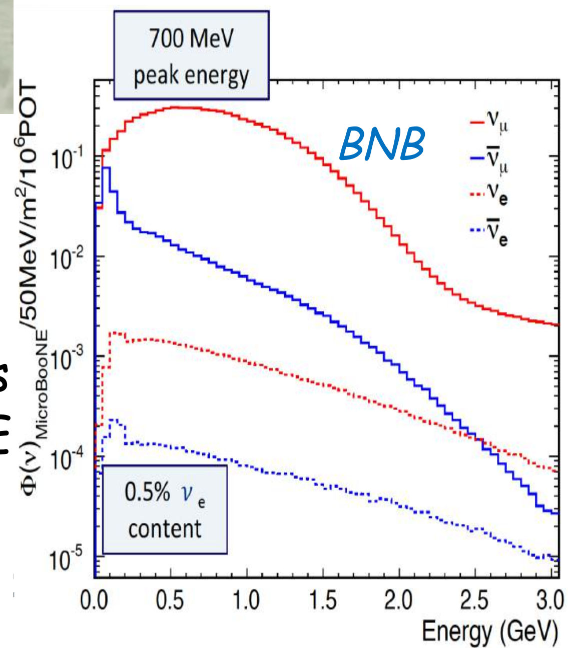
Short Baseline Neutrino (SBN) at FNAL BNB and NuMi beams: *a definitive answer to sterile neutrinos ?*

ICARUS
600m baseline
470t active volume
data taking

SBND
110 m baseline
112t active volume
under completion





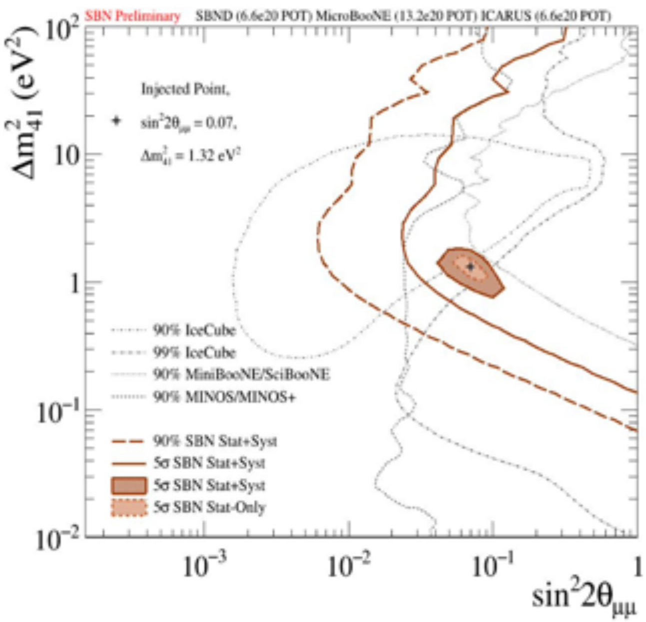


- ICARUS and SBND LAr-TPC's installed at 600 and 110 m from Booster target, searching for sterile-ν oscillations both in appearance and disappearance channels.
- Furthermore, high-statistics ν-Ar cross-sections measurements and event identification/reconstruction studies in view of DUNE
  - ~10^6 events/y in SBND <1 GeV from Booster
  - ~10^5 events/y in ICARUS >1 GeV from NuMI beam (700 m, 6^0 off-axis from target).

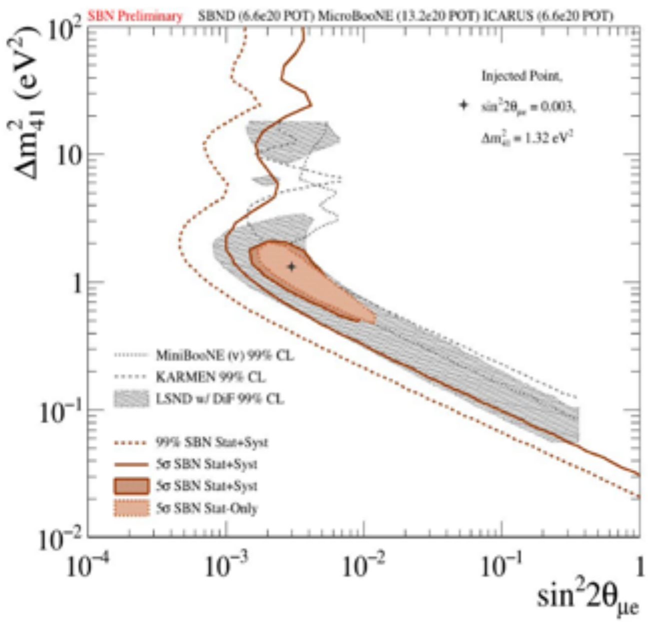
SBN expected sensitivities for 3 years (6.6 10^{20} pot)

- Using the same detector technology for all the 3 detectors will greatly reduce the systematic errors: SBND (near detector) will provide the "initial" beam composition and spectrum
- The great νe identification capability of LAr-TPC will help reduce the NC background

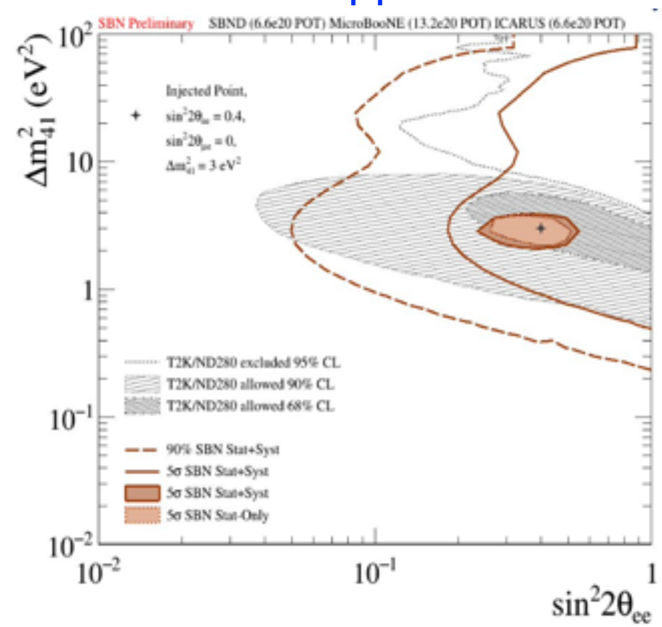
$\nu\mu$ disappearance



νe appearance



νe disappearance

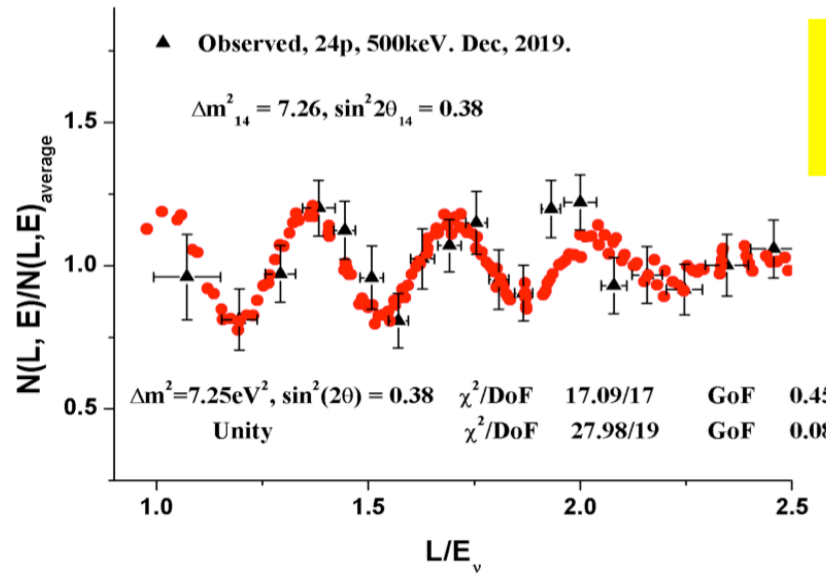


- Thanks to the simultaneous study of the electron neutrino appearance and of the muon neutrino disappearance channels, SBN will cover much of the parameters allowed by past anomalies at >5σ significance

Search for Neutrino-4 oscillation signal

- The Neutrino-4 collaboration claimed a reactor neutrino disappearance signal with a clear modulation with L/E ~ 1-3 m/MeV

NEUTRINO-4 reactor signals



A.P.Serebrov, et al. JETP Letters, Volume 109, Issue 4, pp 213–221.

arxiv:1809.10561

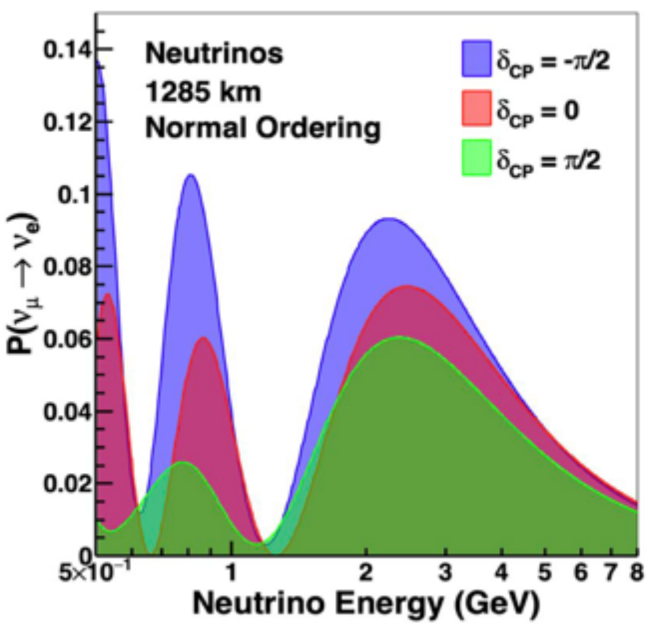
- ICARUS will be able to test this oscillation hypothesis in the same L/E range in two independent channels, with different beams:
  - Disappearance of νμ from the BNB beam, focusing the analysis on quasi-elastic νμCC interactions where the muon is contained and at least 50 cm long. ~11500 such events are expected in 3 months data taking
  - Disappearance of the νe component in the NuMI beam, selecting quasi-elastic νeCC events with contained EM showers. ~5200 events expected per year

- The study of these channels, complemented with a beam-off sample, would allow to observe or reject a modulation as observed by Neutrino-4

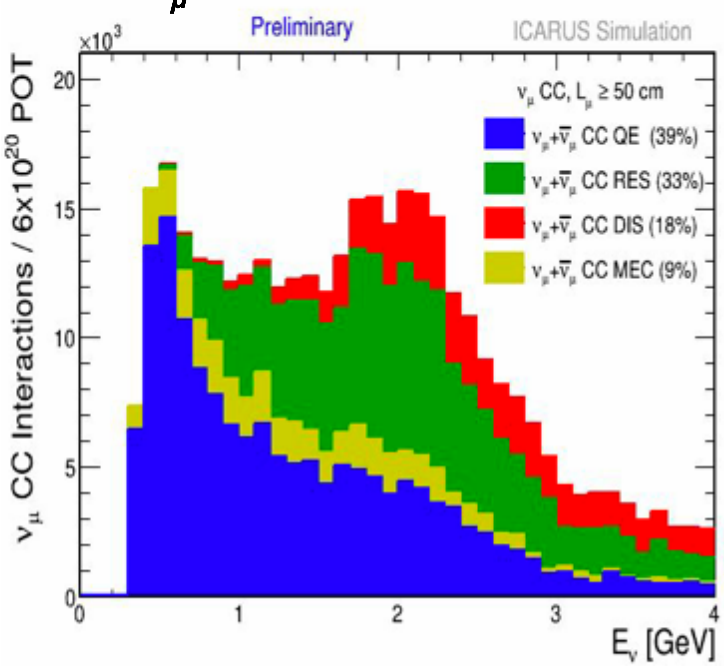
ICARUS physics searches with NuMI beam

- Further exploitation of the NuMI Off-Axis beam (6^0 from ICARUS):
  - High statistics precision measurements of ν-Ar cross sections (~10^5 νe events/year) and tests of interaction models in the few hundred MeV to few GeV energy range, of use to SBN oscillation studies and DUNE.
  - Develop a rich Beyond Standard Model search program: Higgs portal scalar, ν tridents, light dark matter, heavy neutral leptons …

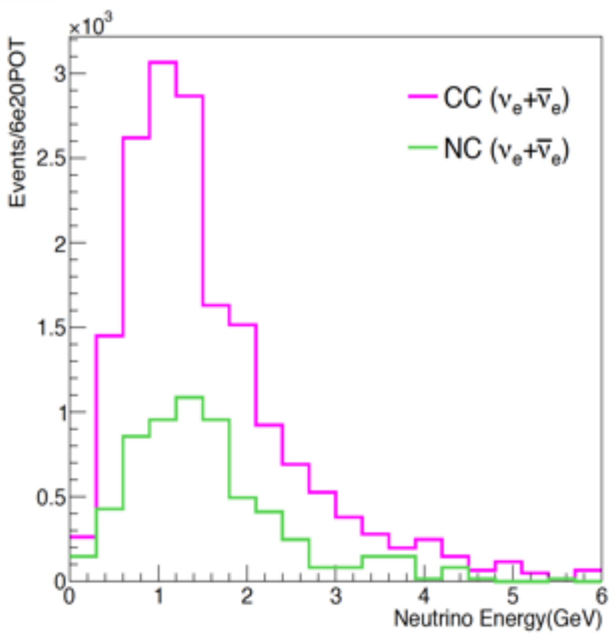
Oscillation probability at DUNE



ν_μ from NuMI at ICARUS

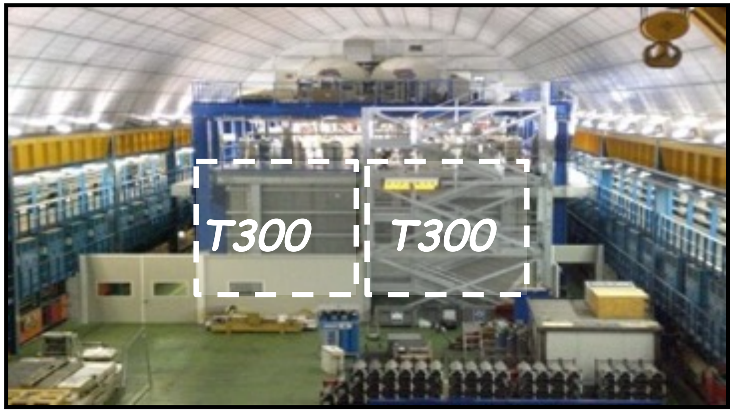


ν_e from NuMI at ICARUS



The remarkable evolution of ν-detectors: the ICARUS LAr-TPC

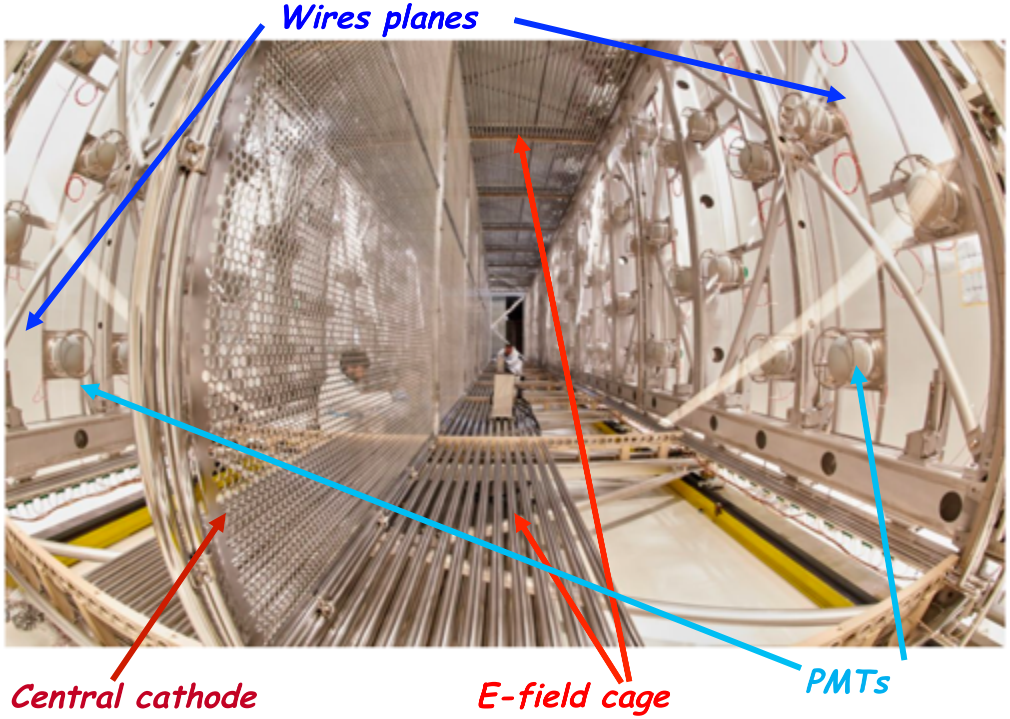
- Liquid Argon Imaging technology LAr-TPC, an "electronic bubble chamber" identifying unambiguously each ionizing track in complex neutrino events, was proposed by C. Rubbia [CERN-EP/77-08] as an alternative to Cherenkov detectors.



Long R&D by INFN/CERN culminated in the first large scale experiment ICARUS-T600, 0.76 kt ultra-pure LAr-TPC at G. Sasso underground lab:

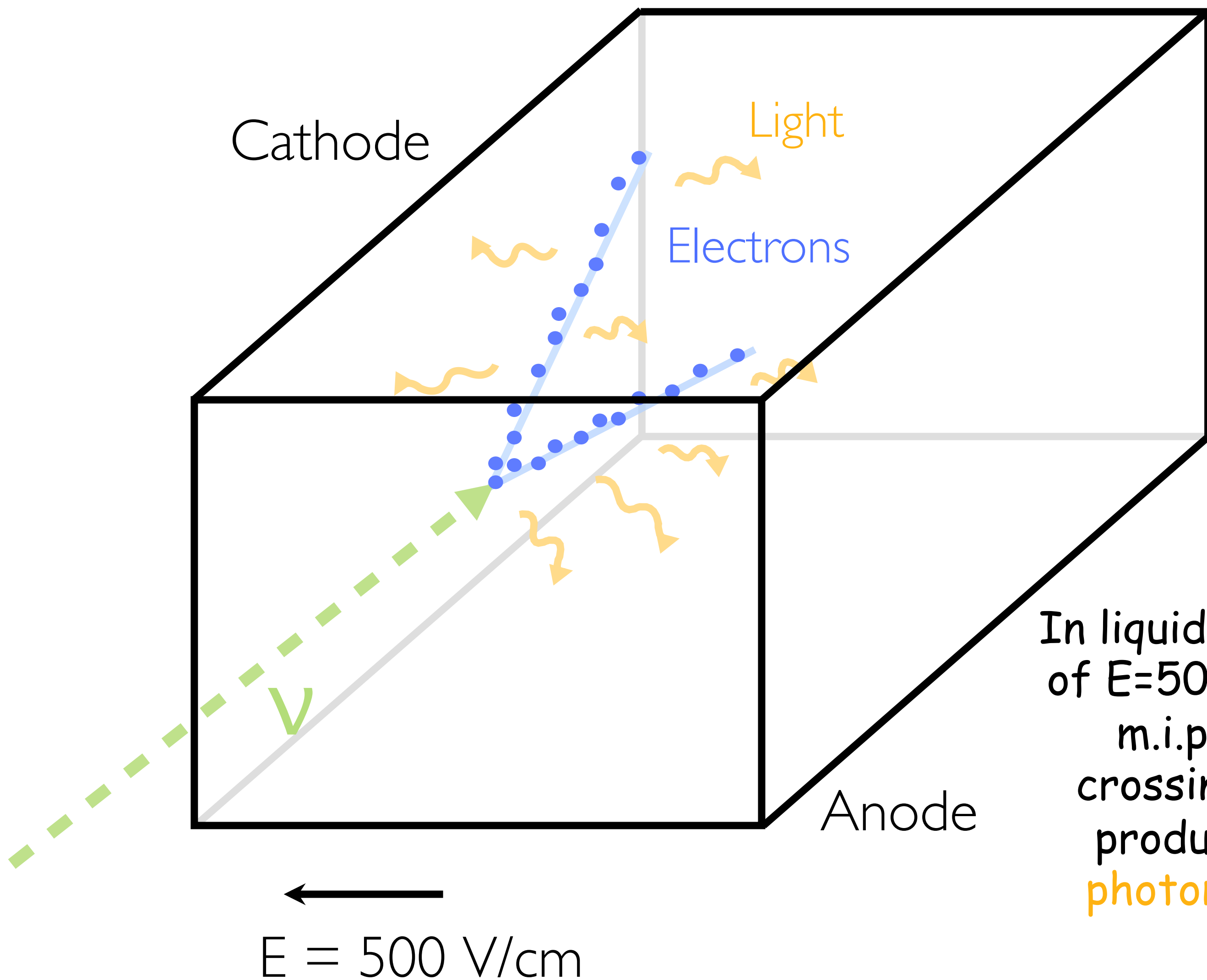
… paving the way for Long-Baseline experiments

- ICARUS-T600 overhauling in 2014-18 in view of shallow depth operation at Fermilab:
  - 2 modules, 2 TPCs per module with central cathode (1.5 m drift, E_D= 0.5 kV/cm);
  - 3 readout wire planes per TPC, 54000 wires at 0, ± 60^0, 3 mm pitch, in total;
  - 360 PMTs, TPB coated detecting scintill. light produced by particles in LAr
  - LAr /GAr purified by copper filters and molecular sieves for water absorption



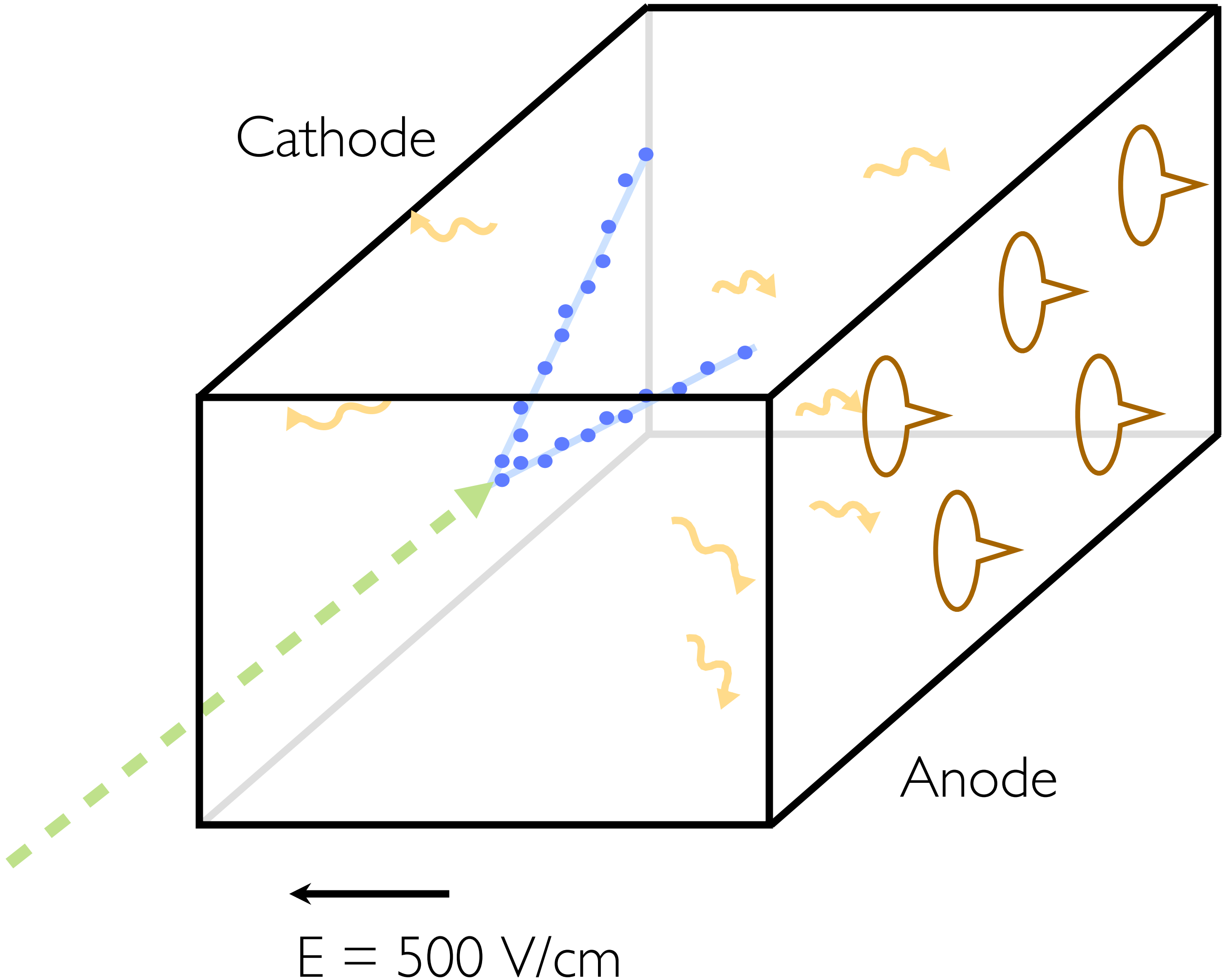
Lar-TPC working principle

When a neutrino interacts in the Liquid Argon, it produced charged particles that deposite their energy, producing ionization electrons and scintillation light



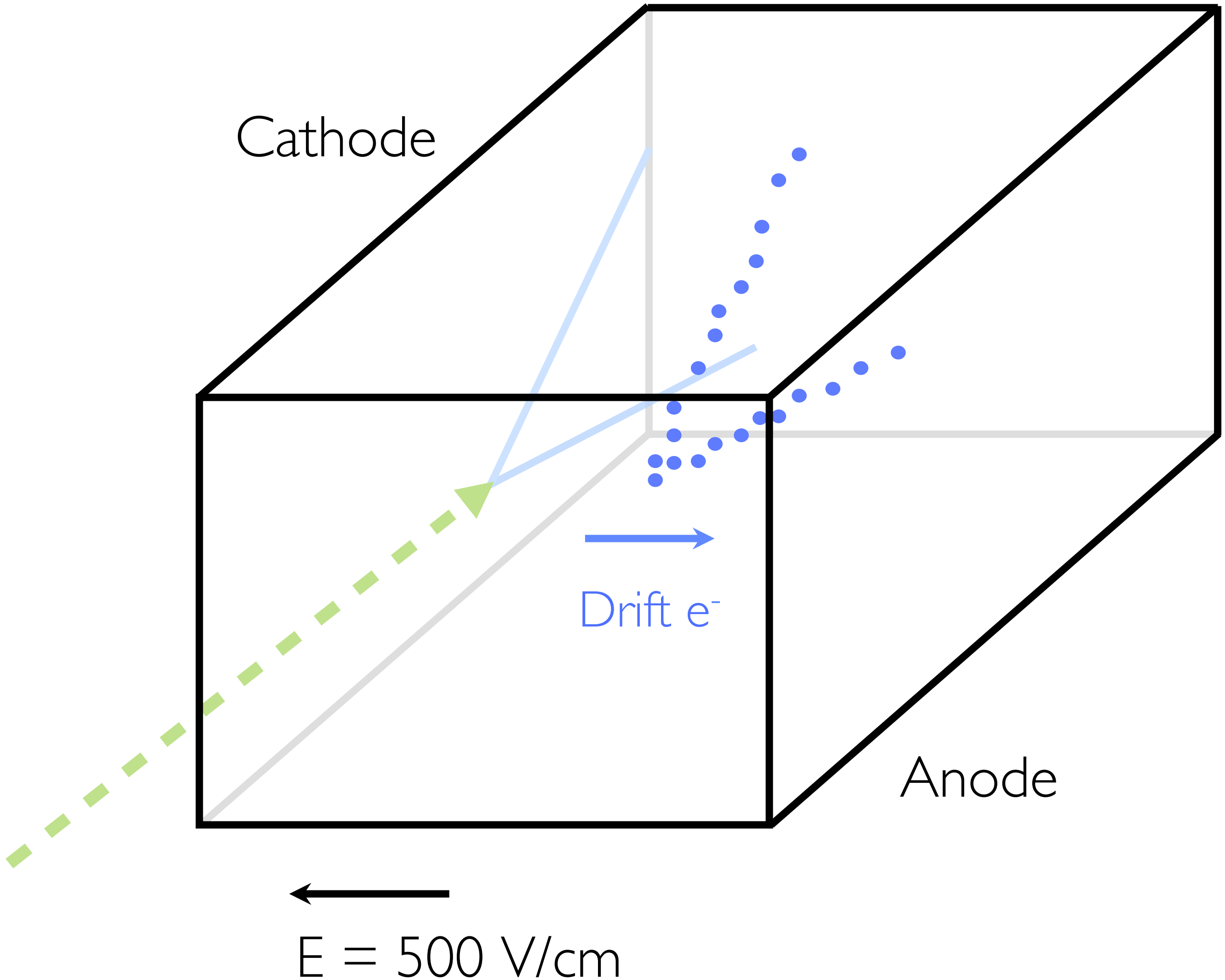
In liquid Argon, if an electric field of E=500 V/cm is applied, a muon m.i.p. (dE/dx ~ 2 MeV/cm) crossing 1 mm of the detector produces ~4000 scintillation photons and ~5000 ionization electrons

Lar-TPC working principle



Since the liquid Argon is transparent to its own scintillation light, this light propagate inside the detector and can be collected by PMTs: this signal is the basis to recognize that there has been a particle interaction in the detector (TRIGGER)

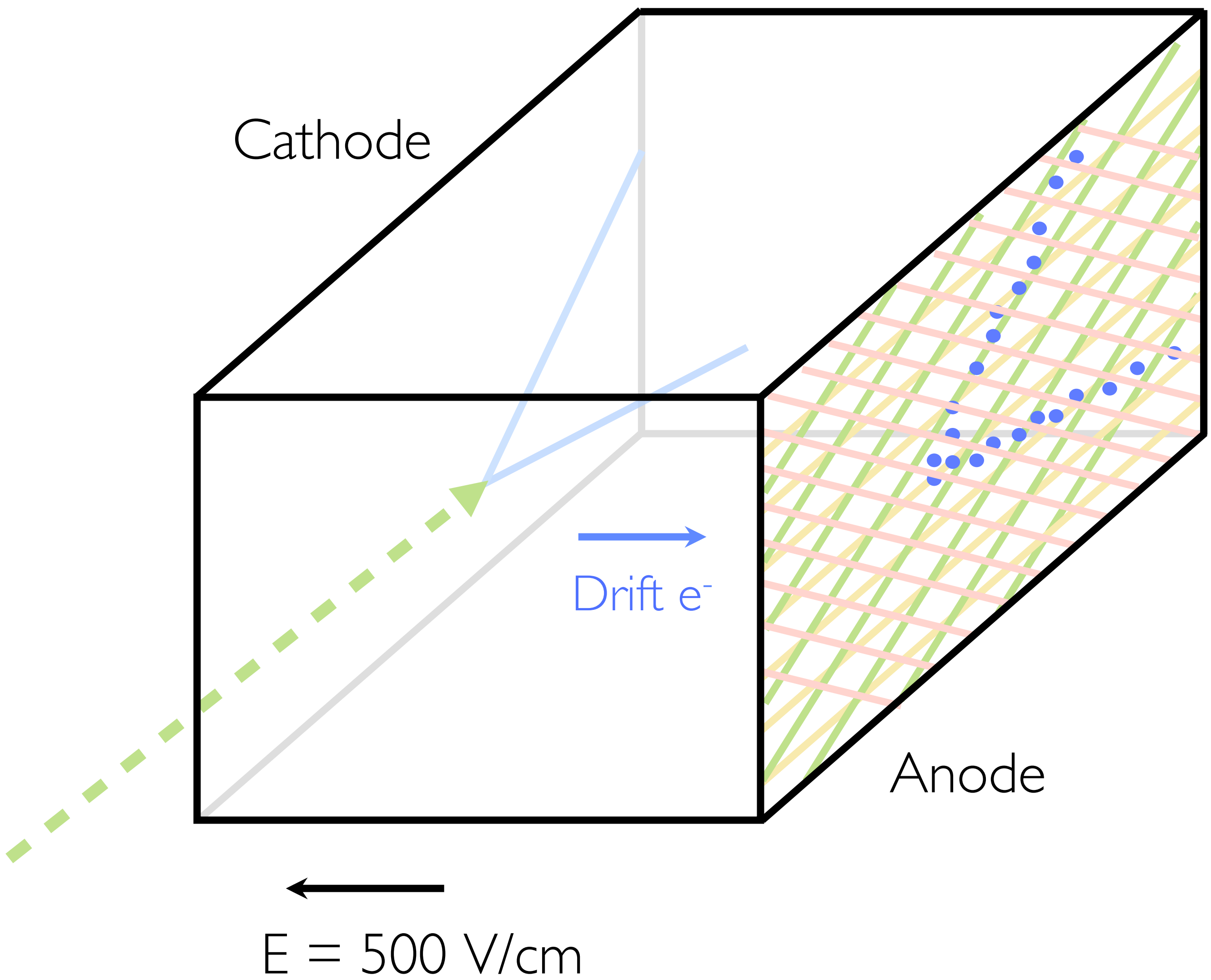
Lar-TPC working principle



The ionization electrons produced by each ionizing particle are transported by the uniform electric field and can be detected in the anodic plane placed at the end of the drift path (maximum drift time 1 ms)

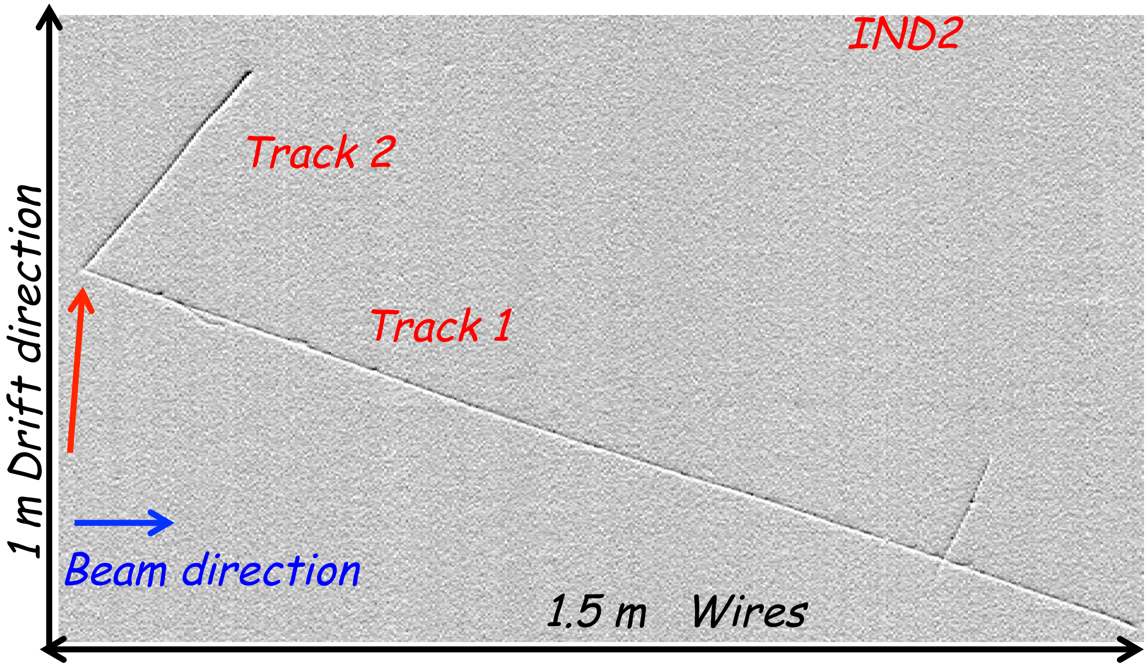
The presence of electronegative impurities, most of all O_2, in the LAr produces an exponential attenuation of the ionization signal along the drift coordinate: to reduce this effect, that can make the signals too low to be identified, the Argon must be continuously filtered and the purity level should be monitored online.

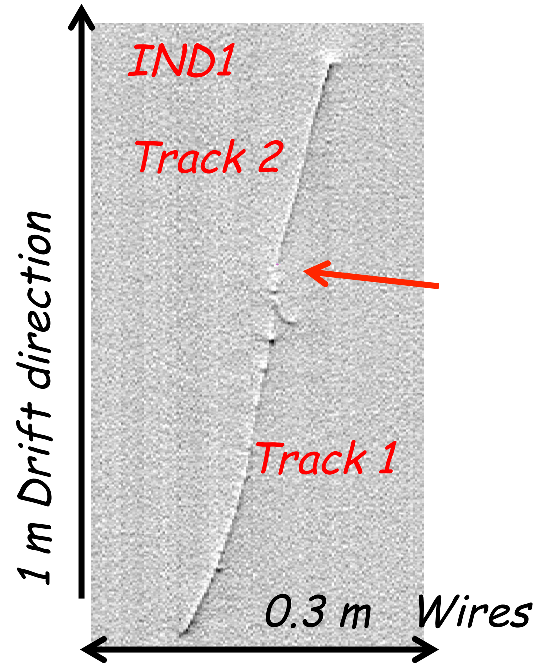
Lar-TPC working principle

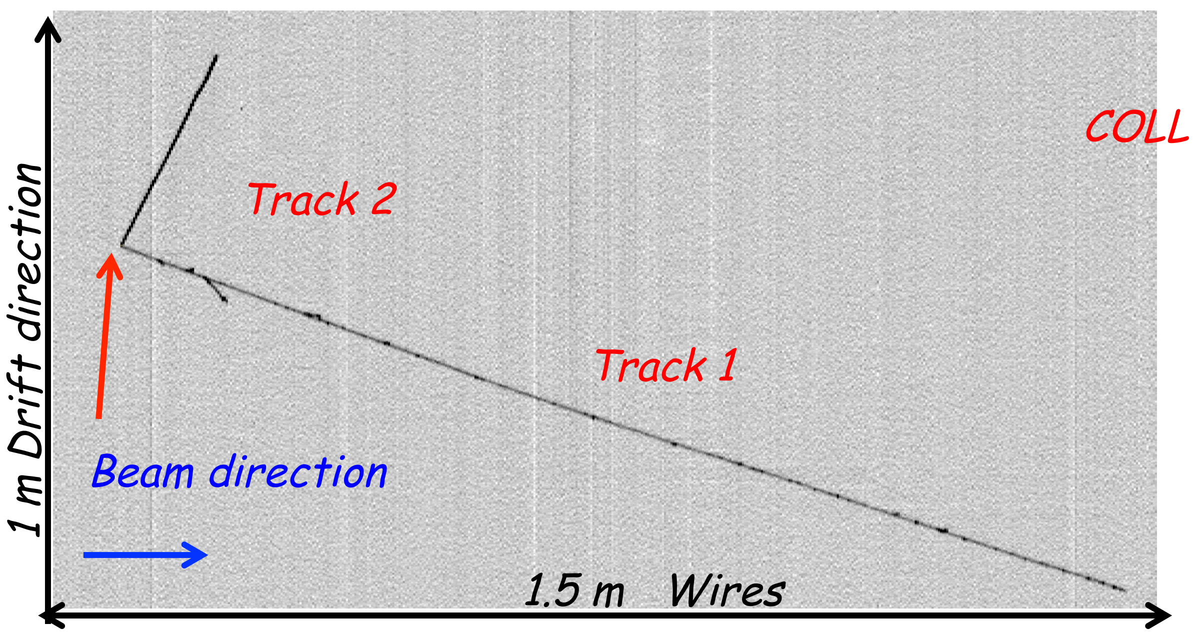


The ionization electrons are then detected by the 3 anodic wire planes providing simultaneous different projections of the same event. The information from these three projections allow a precise reconstruction of the recorded particle trajectories and a precise calorimetric measurement.

νμ CC candidate: 1 event, 3 pictures

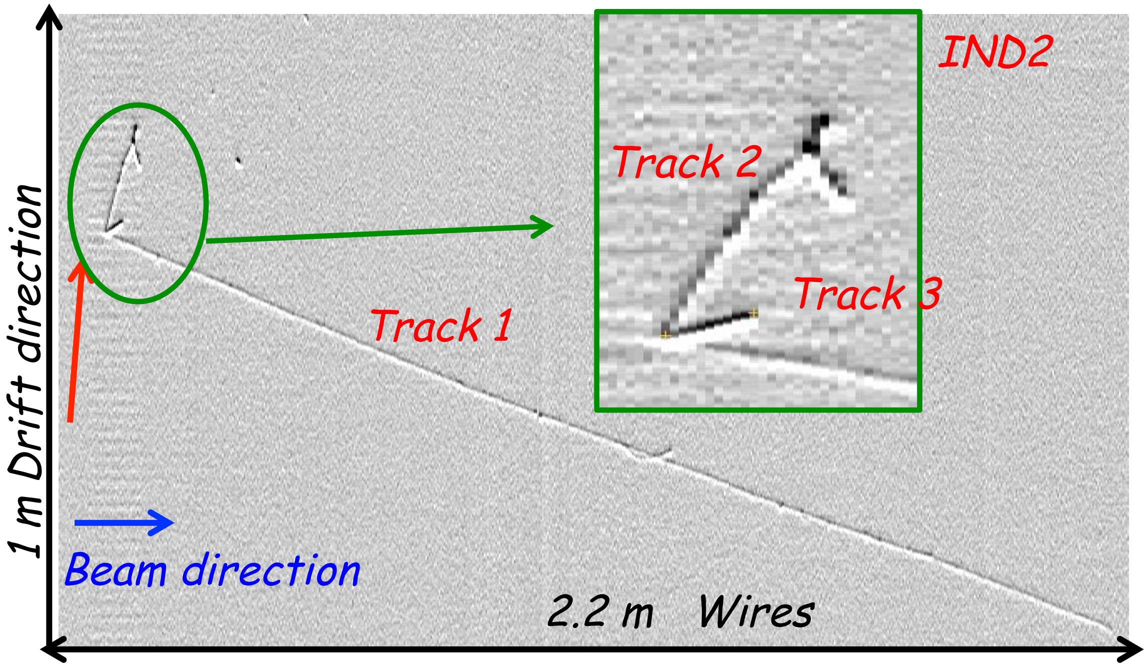


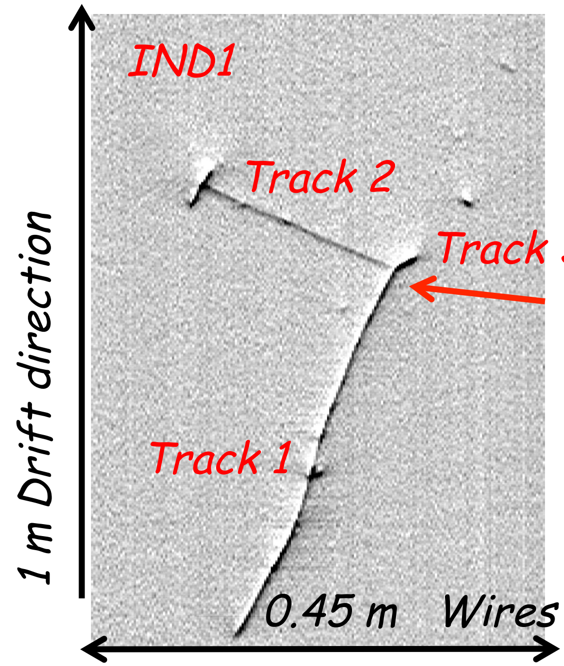


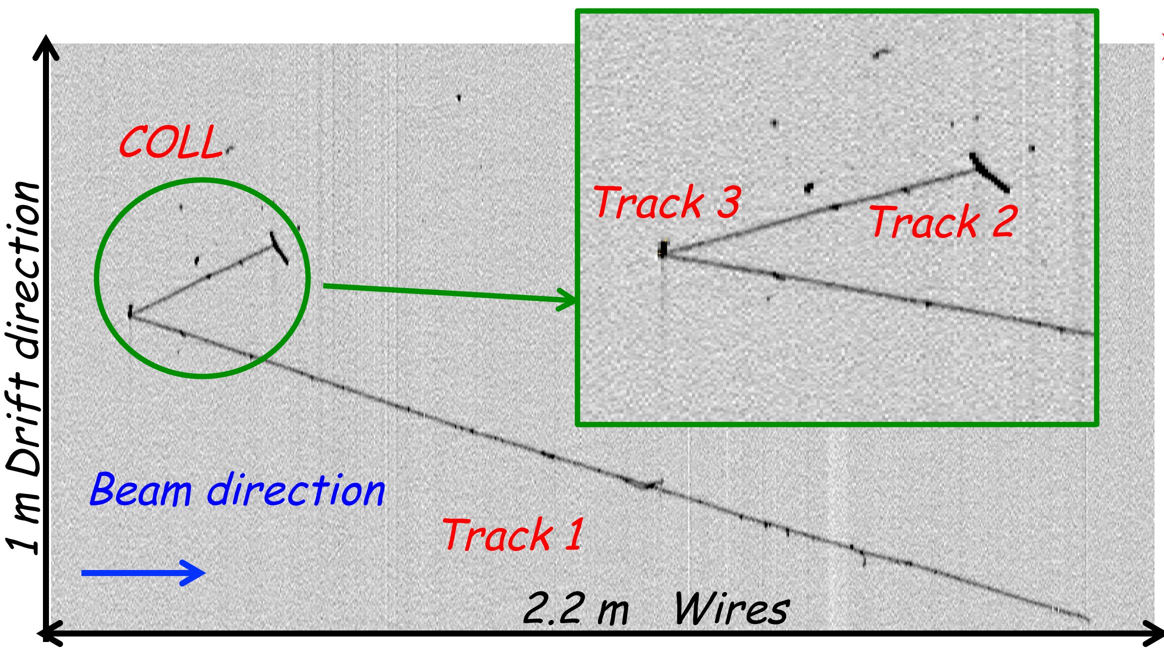


- Two tracks are produced at the primary vertex (marked by the red arrow):
  - ✓Track 1 (muon candidate) is downward going, crossing the cathode and stopping in the detector L= 4 m;
  - ✓Track 2 is upward going, stopping hadron, L= 43 cm

νμ CC candidate: 1 event, 3 pictures

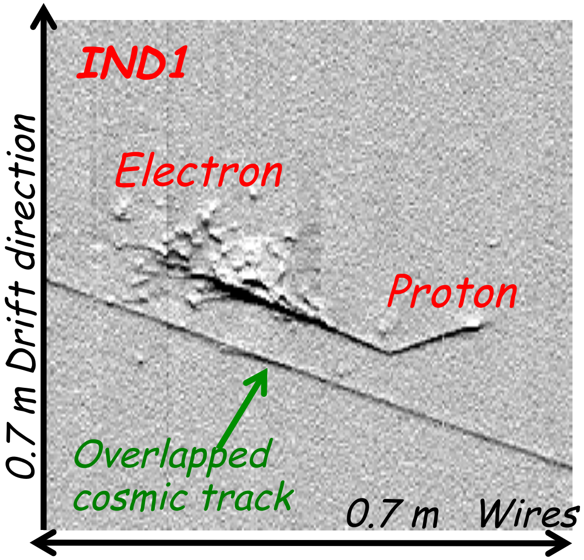


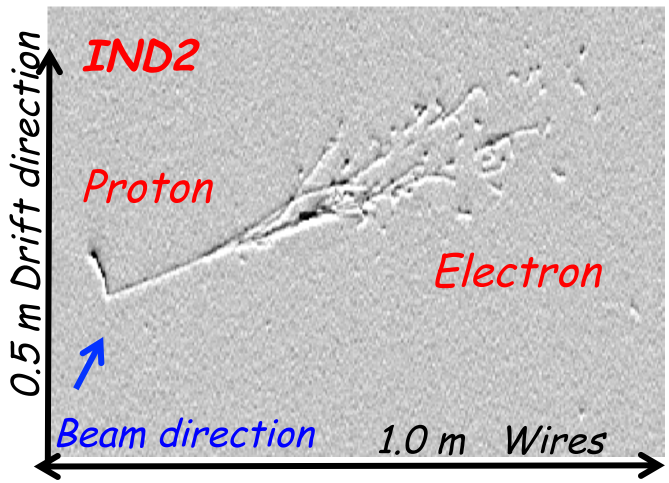




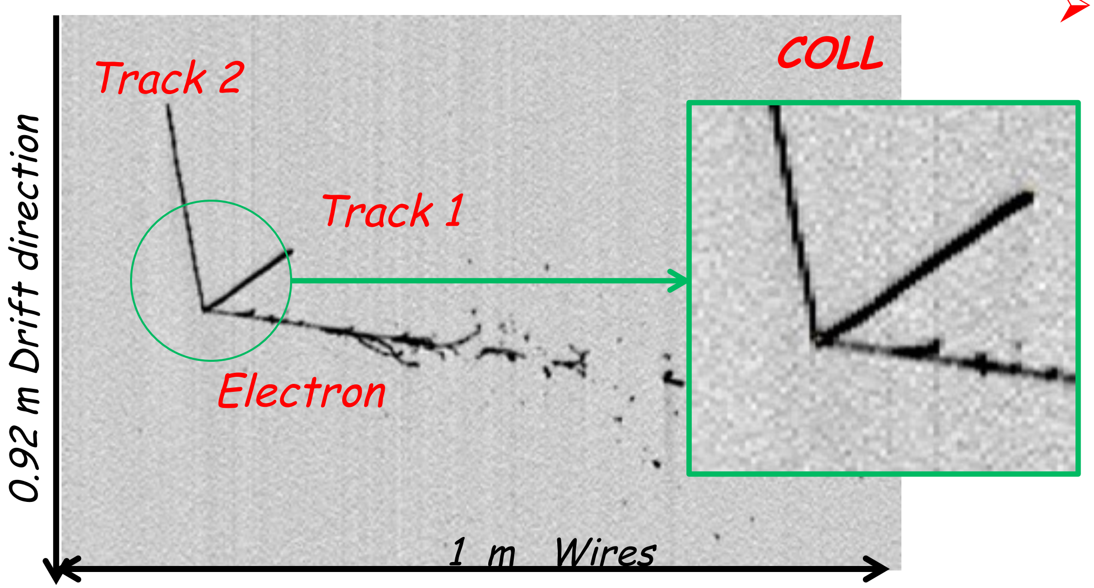
- Three tracks at the primary vertex:
  - ✓Track 1 (muon) is downward going, crossing the cathode and stopping in the detector L= 6.4 m;
  - ✓Track 2 (hadron) is downward going and interacting in the detector and producing two short protons;
  - ✓Track 3 (proton) is upward going L=3.4 cm

NuMI νe CC candidates





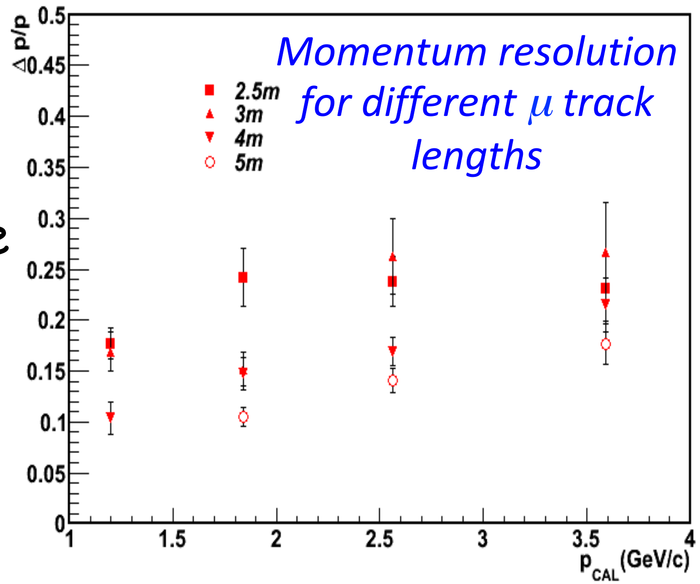
- QE νe CC event candidate, E_{DEP}~870 MeV:
  - ✓ proton candidate is upward going/stopping L= 13 cm;
  - ✓ e-shower is downward going.



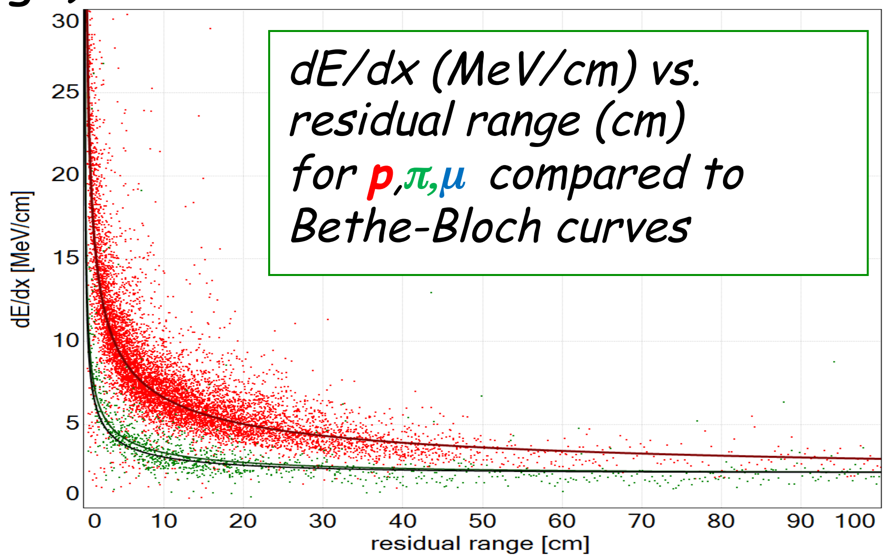
- νe CC event candidate fully contained in active LAr, E_{dep}~830 MeV:
  - ✓ The electron shower, E_{DEP}~570 MeV is downward going;
  - ✓ Track 1: upward going, stopping proton candidate, L = 23.7 cm;
    Track 2: stopping hadron, L = 33.4 cm.

ICARUS LAr-TPC performance

- Tracking device: precise 3D event topology, ~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 (MCS) with Δp/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):



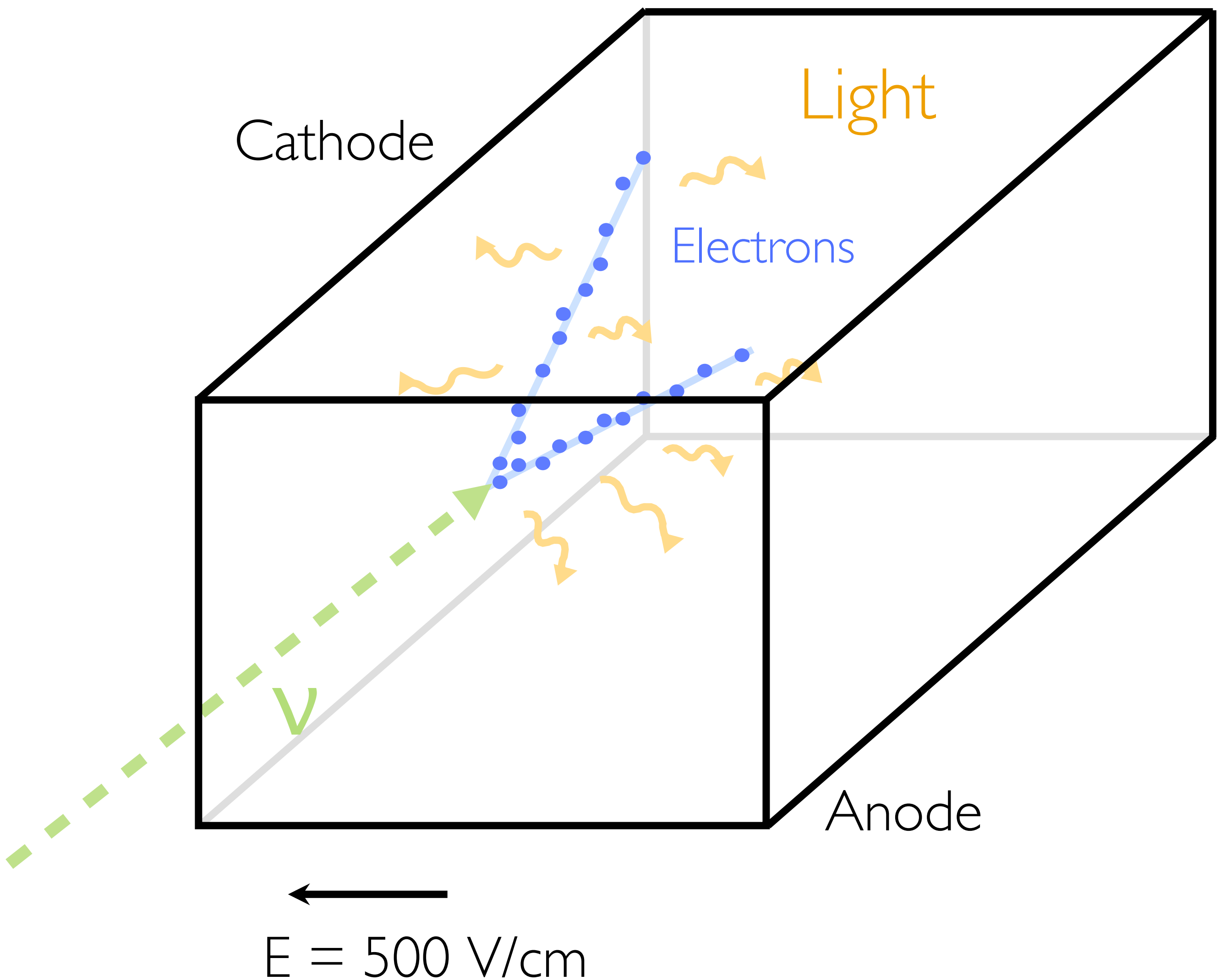
Validation on p_{MCS} of stopping μ's, compared with calo estimate.



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)

A new experimental challenge: a LAr-TPC on surface

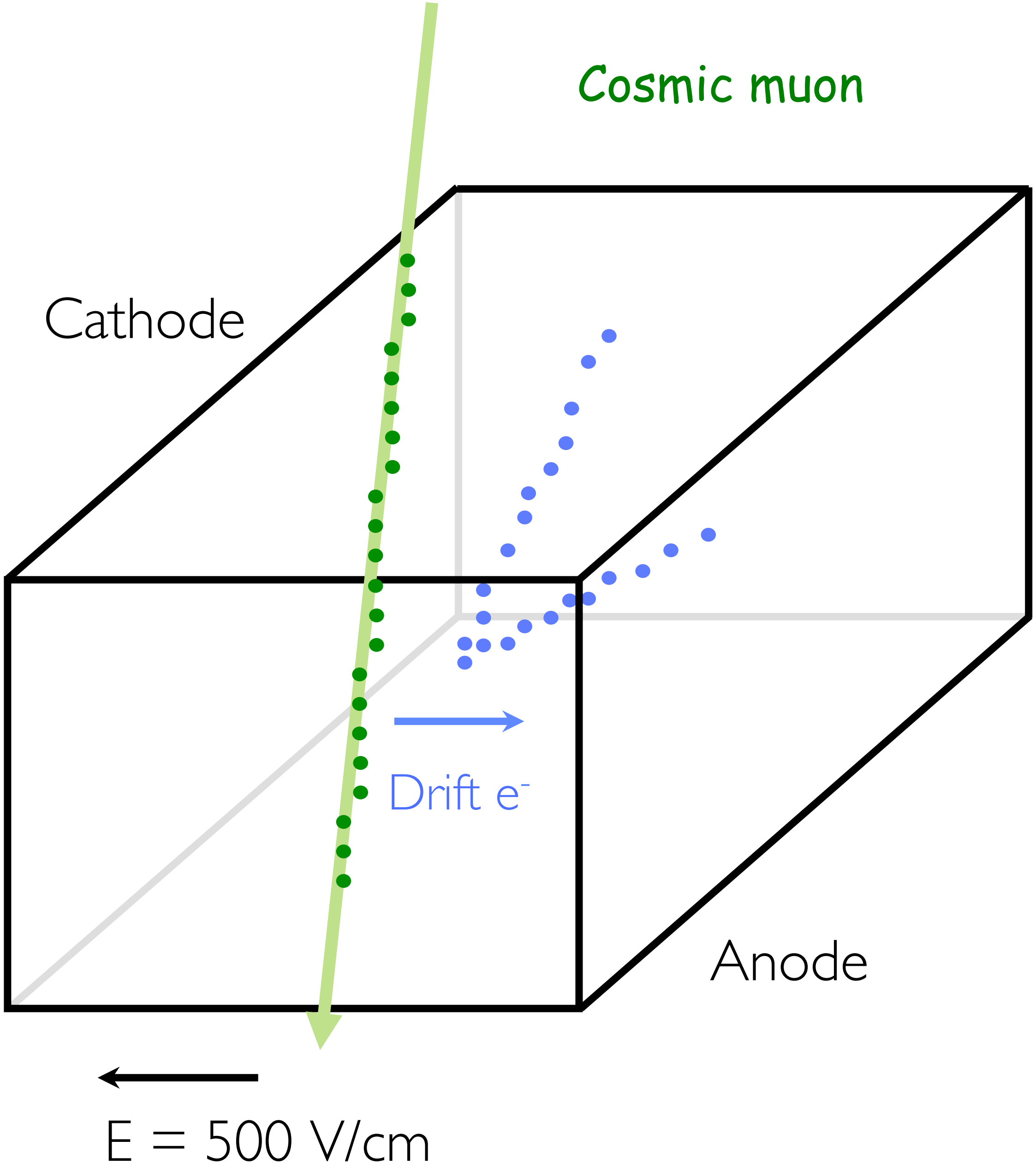
- ICARUS at FNAL is taking data on the Earth surface, facing a more challenging conditions than at LNGS (where cosmic rays are suppressed by a factor ~10^6):



The ionization electrons produced by each ionizing particle are transported by the uniform electric field and can be detected in the anodic plane placed at the end of the drift path (maximum drift time 1 ms)

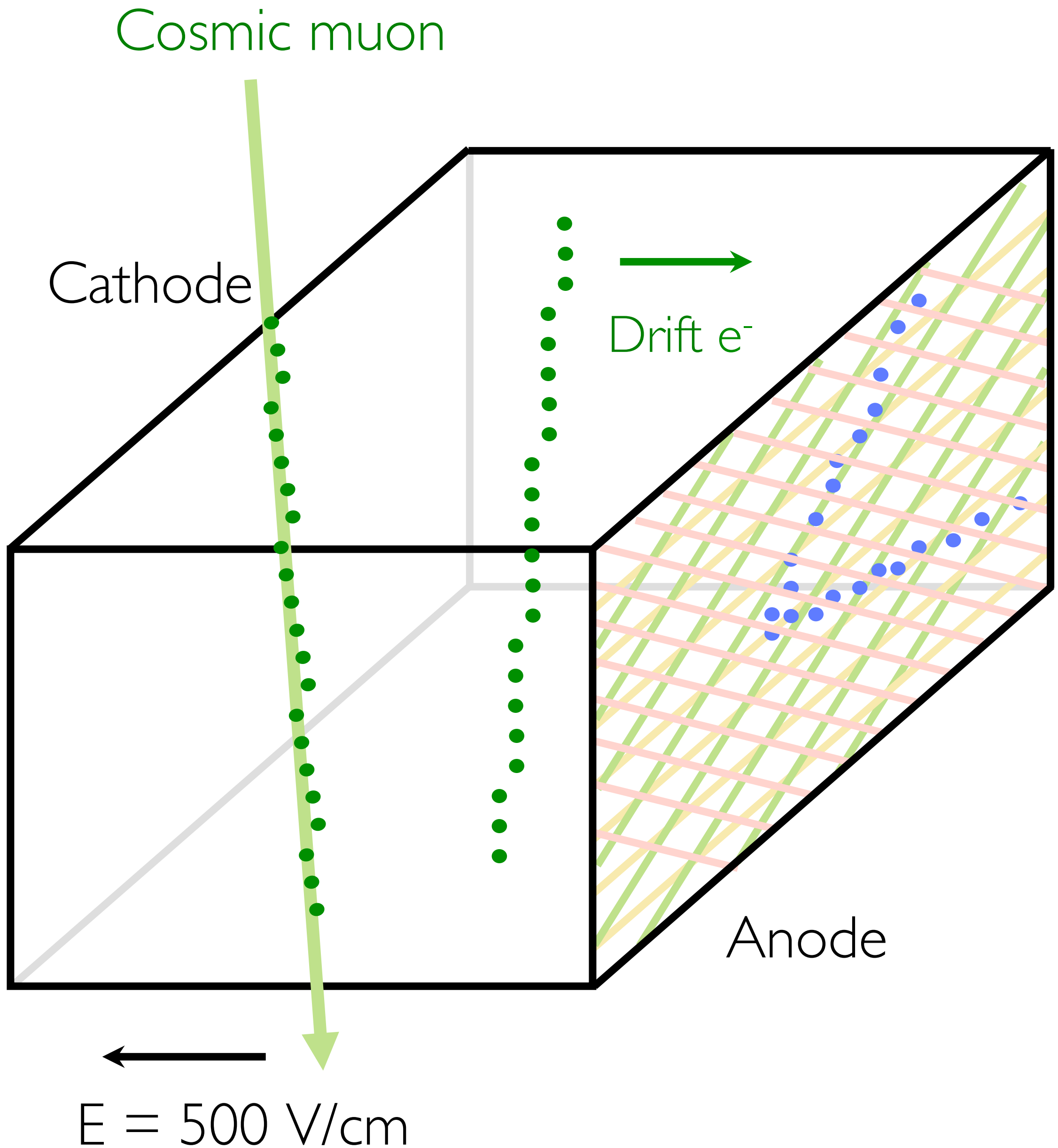
In this time interval all the ionization signals produced in the detecotr are recorded

A new experimental challenge: a LAr-TPC on surface



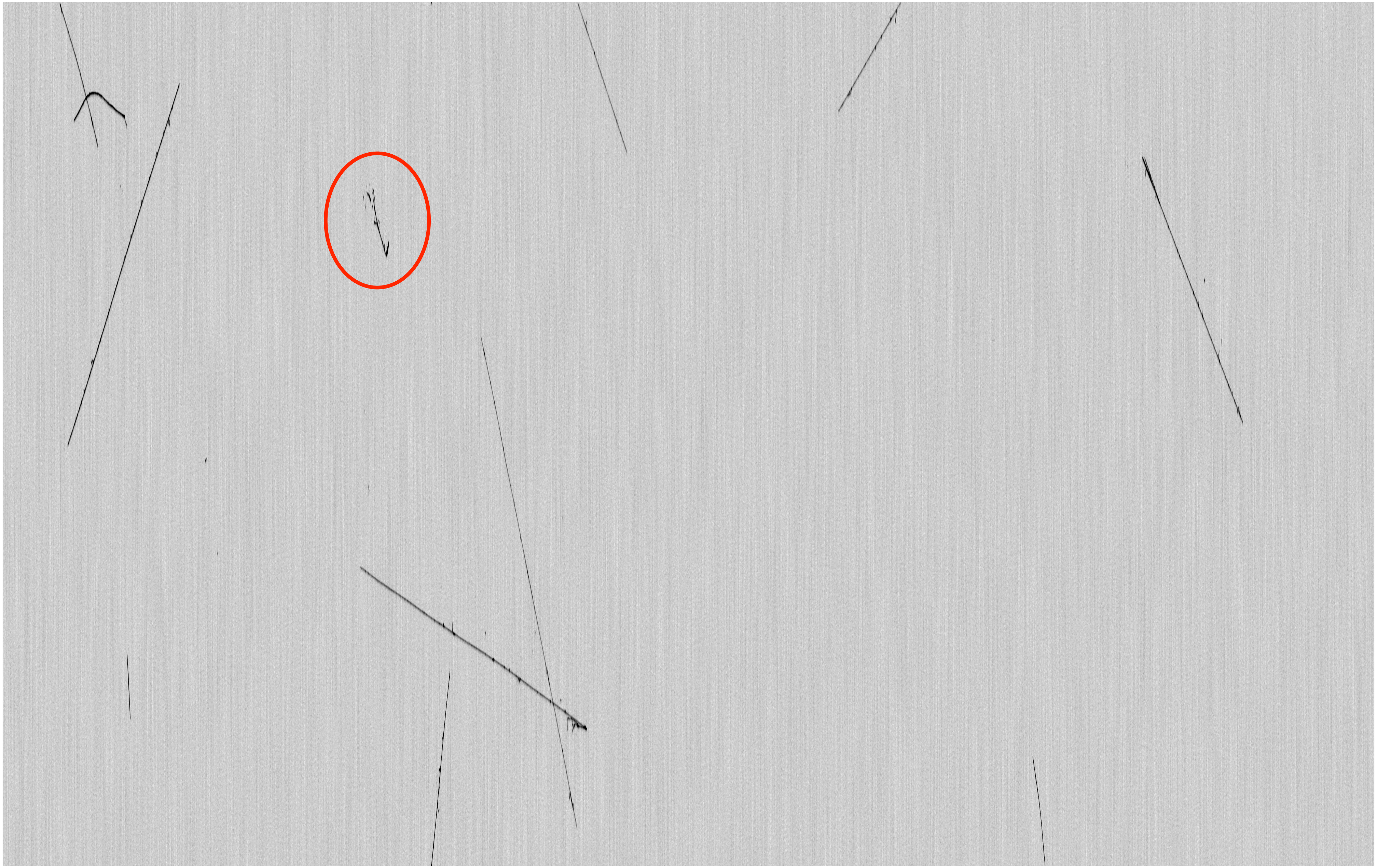
If a charged cosmic particle crosses the detector in a time near the neutrino interaction, also the signal from the cosmic particle will be saved

A new experimental challenge: a LAr-TPC on surface

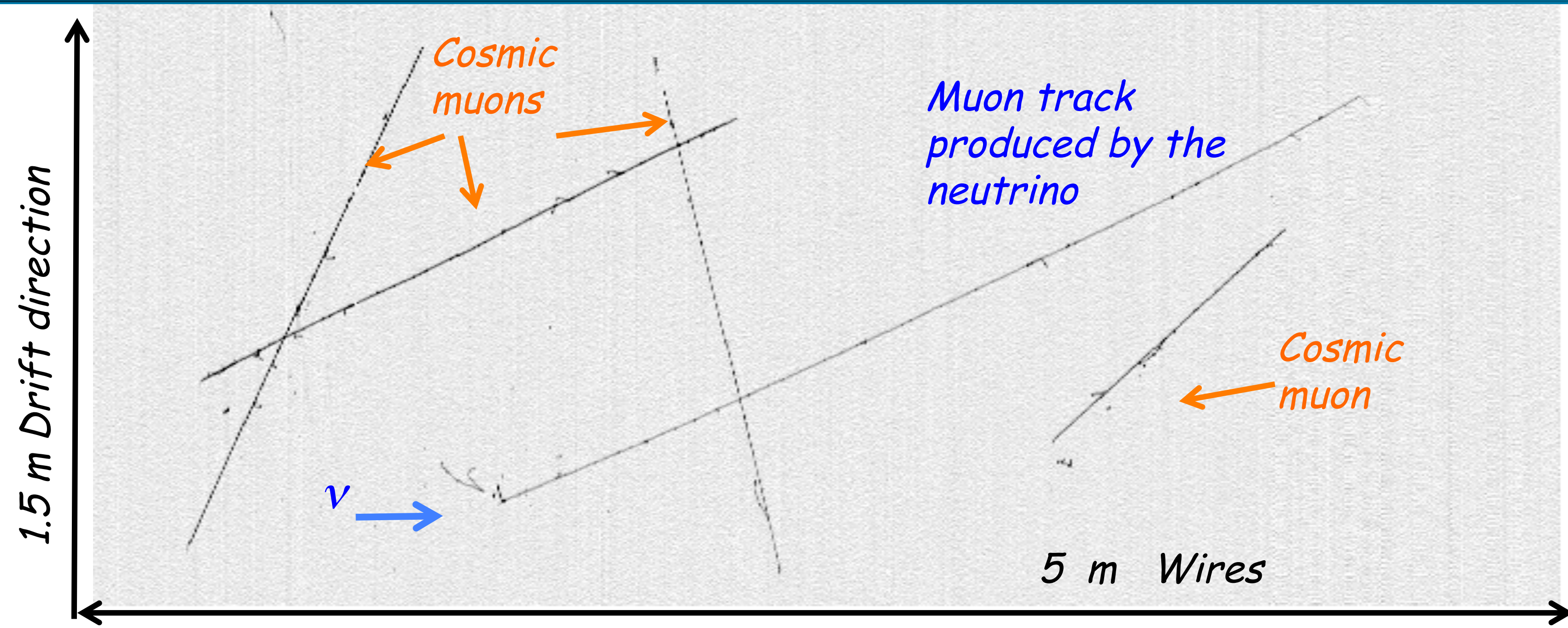


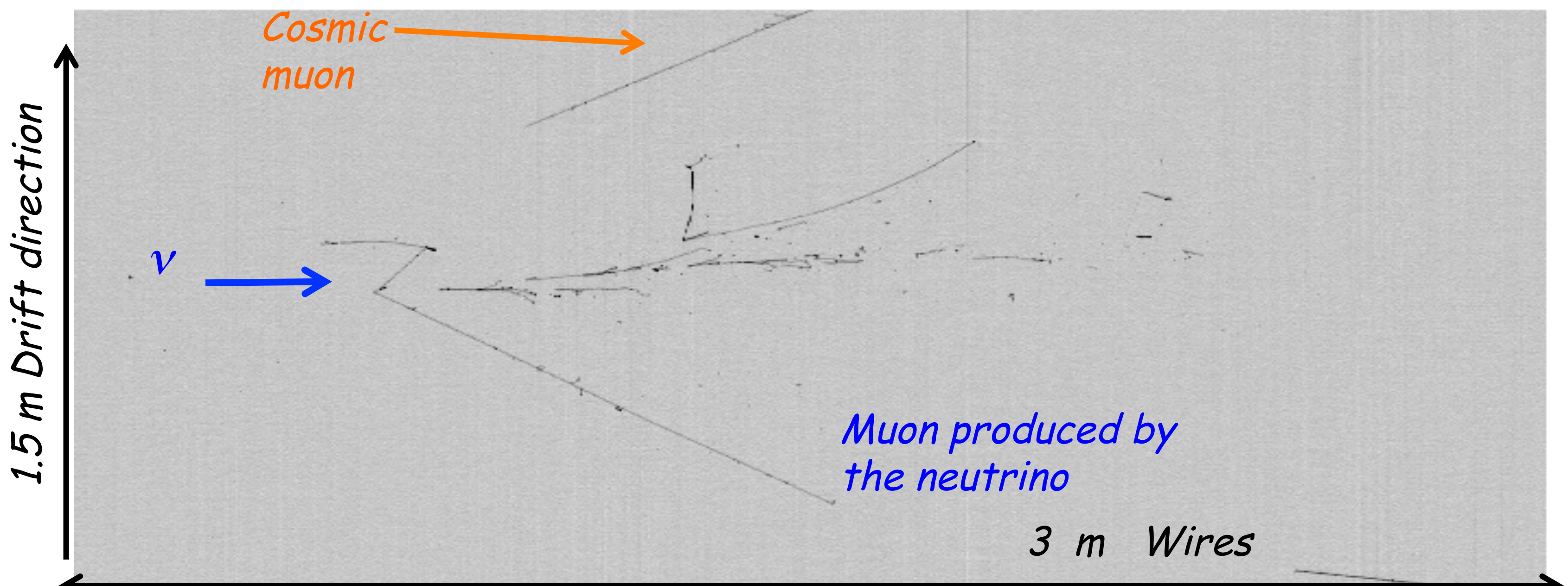
The particle generating the trigger is defined the "in time" particle while the other cosmic particles are defined "out of time" and for them usually the time of the passage in the detector is unknown

A new experimental challenge: a LAr-TPC on surface

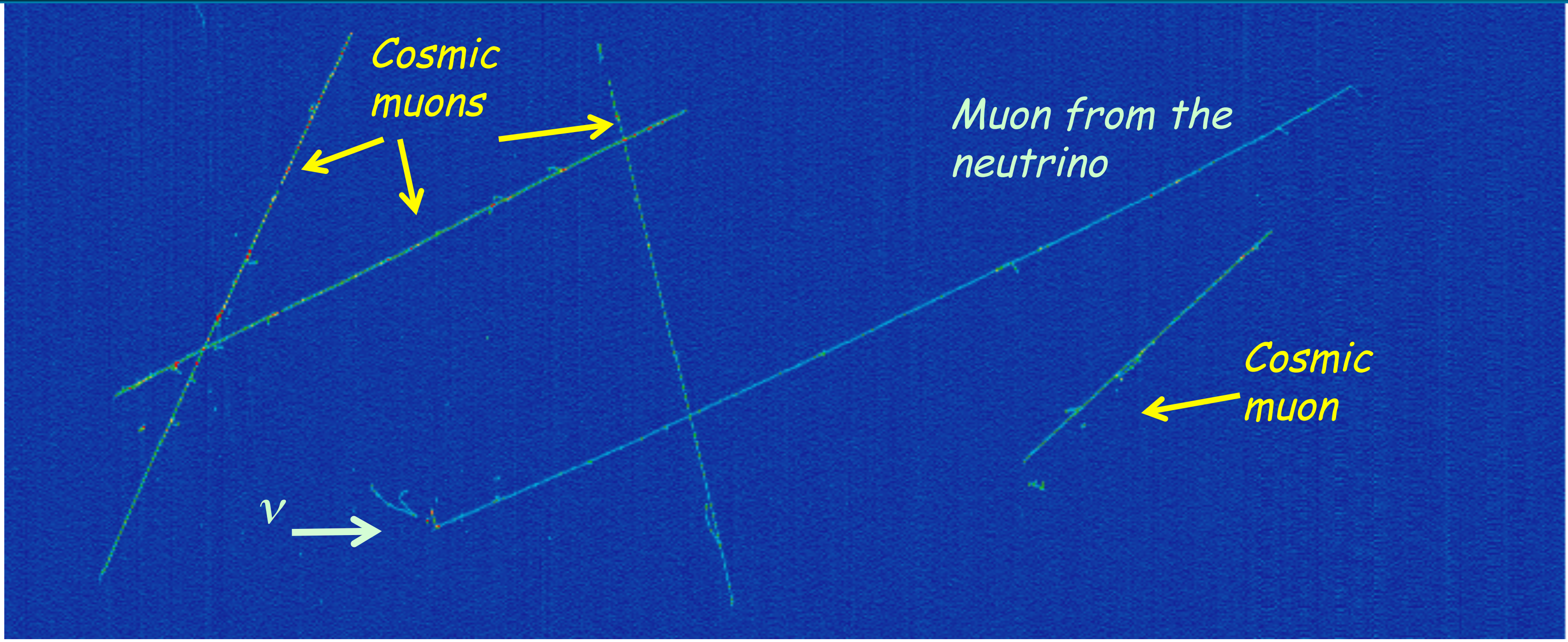


Neutrinos collected by ICARUS at FNAL

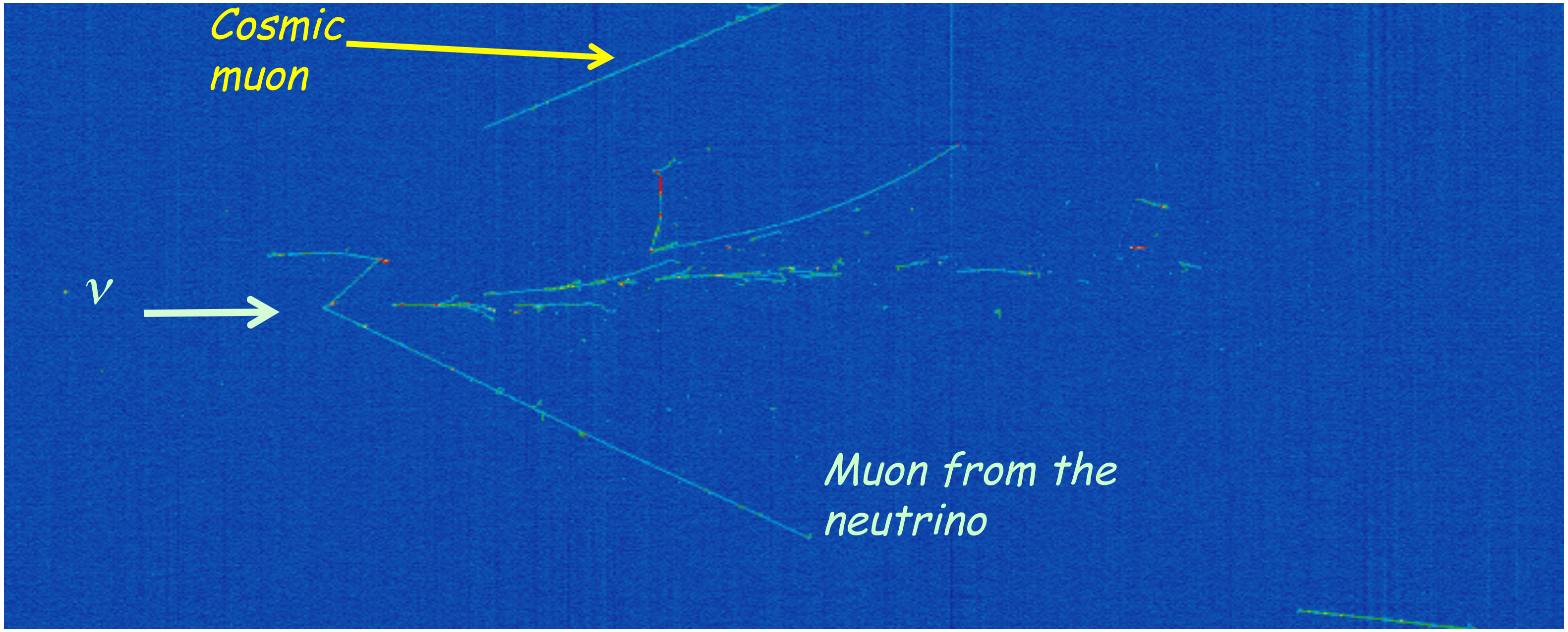




Neutrinos collected by ICARUS at FNAL



5m x 1.5m

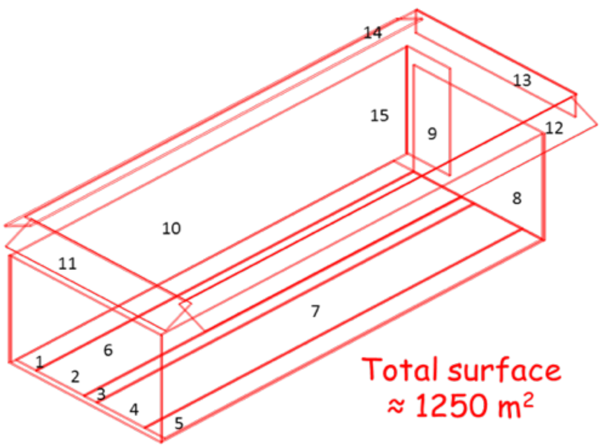


3m x 1.5m

A new experimental challenge: a LAr-TPC on surface

ICARUS at FNAL is facing a challenging experimental condition, requiring the recognition of $O(10^6)$ ν interactions amongst 11 KHz of cosmic rays.

- A 3 m concrete overburden will remove contribution from charged hadrons/γ's.
- ~11 μ tracks will hit the T600 in 1 ms TPC drift window:
  - Automatic tools for the selection of the neutrino interactions and to reject the backgrounds, in particular associated to cosmic particles, are mandatory!
  - The event selection should use all the available information

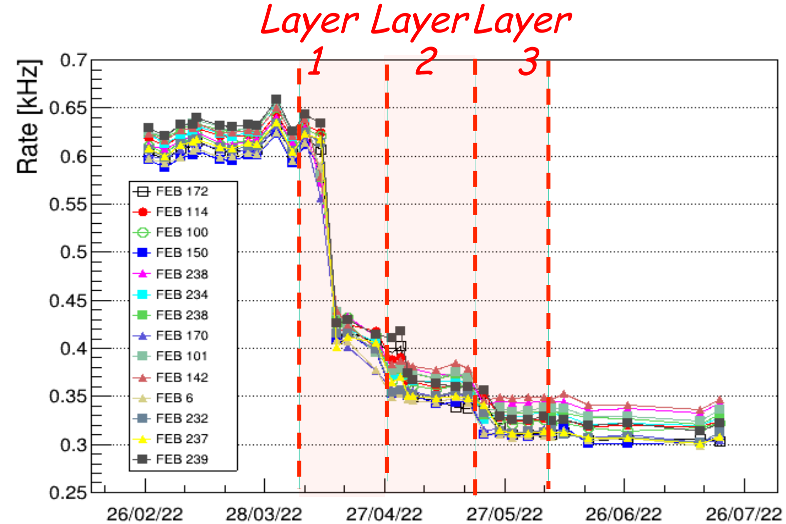


Cosmic Ray Tagging System surrounding the T600 to reject incoming cosmic particles

360 PMTs behind the wire planes provides the t_0 time of each particle with a time resolution ~ ns and the event localization

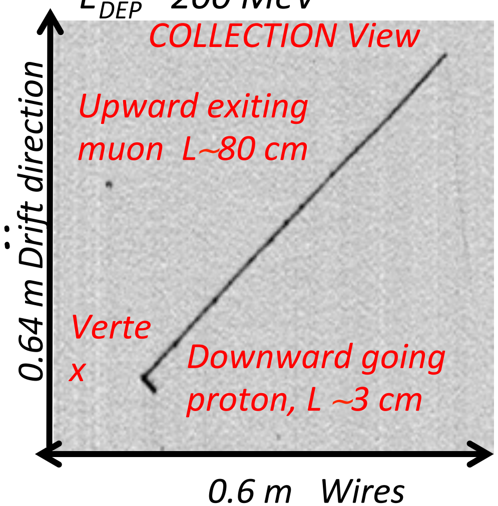
Run 1: first ICARUS physics run, June 9th – July 10th 2022

June 7th '22: overburden installed over the CRT

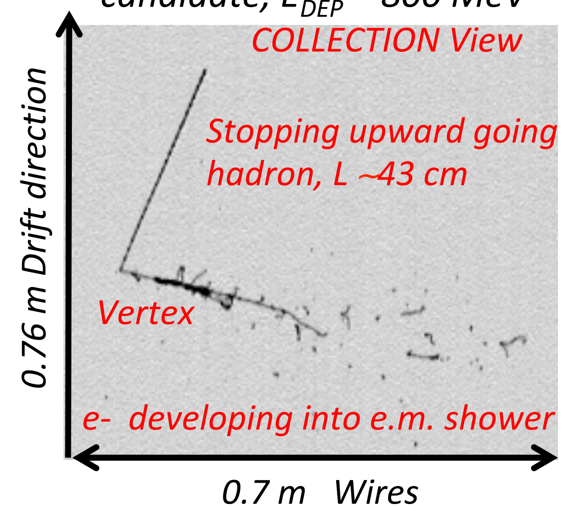


- Overburden installation lasted to June 7th completing the detector plant: *cosmics' rates reduced by ~2;*
- ICARUS started June 9th operating in physics mode as triggered by PMT signals in coincidence with BNB, NuMi spill.
- Data acquisition largely successful, ~93% collection efficiency for both BNB/NuMI:
  - *Total collected beam amounts to ~6.8 10^{19} POT for NuMI and ~4.1 10^{19} POT for BNB.*

BNB CCQE $\nu\mu$ candidate, E_{DEP} ~200 MeV

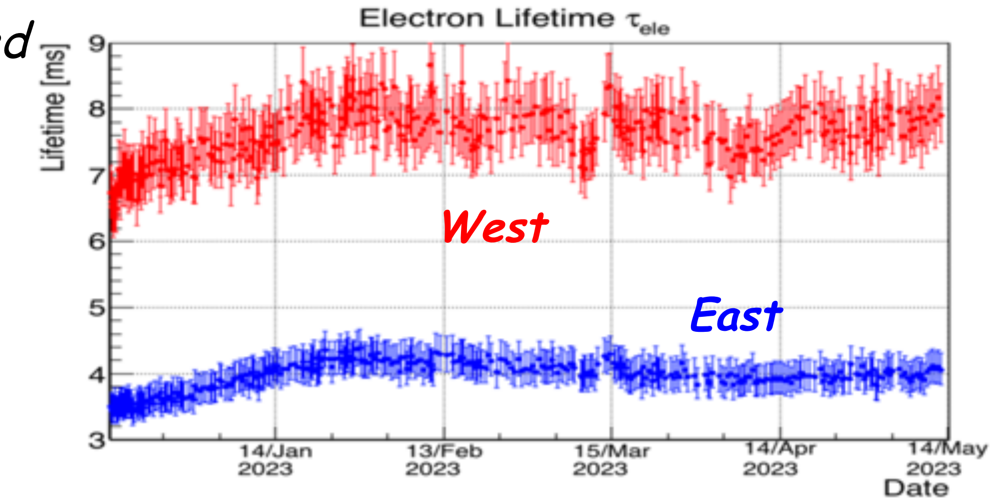


Contained NuMI CCQE νe candidate, E_{DEP} ~ 800 MeV

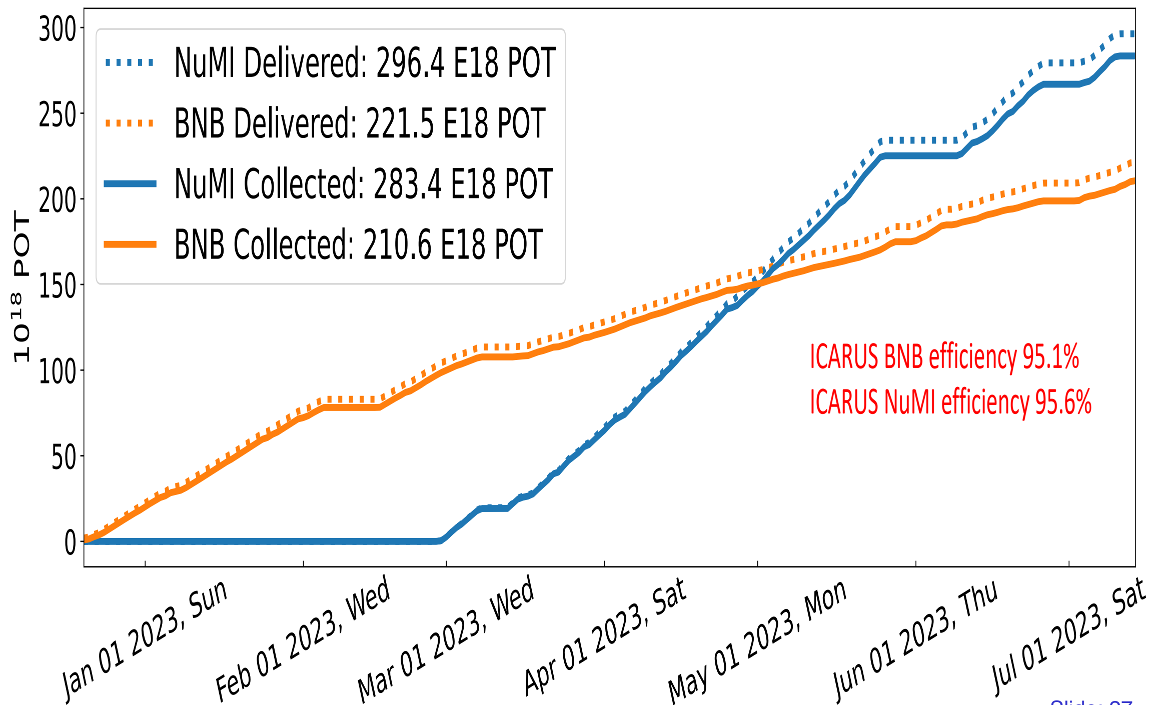


Run 2 Data taking: from December 2022 to July 14th 2023

- The 2nd ICARUS Physics Run started December 20th taking data with both BNB and NuMI beams after an intensive detector improvement during the beam shootdown:
  - *The free e-lifetime in West cryo increased to 8 ms in allowing for ~ optimal track detection;*
  - TPC, PMT and CRT adjustment and tuning from extensive cosmic rays calibration campaign
  - Trigger upgrade, increase of DAQ and data flow stability and throughput with a better Slow control.



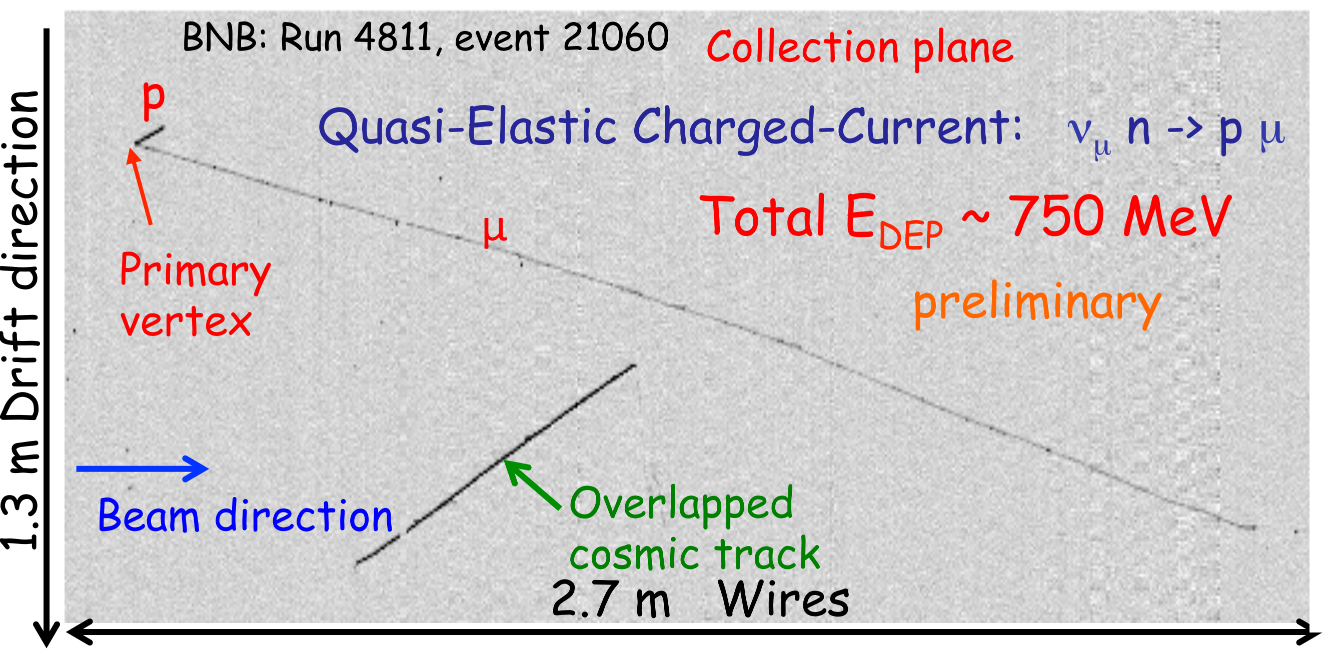
- Run 2 data taking started December '22 with an acquisition efficiency > 95 %;
- Collected events statistics: 2.1 10^{20} POT BNB and ~2.8 10^{20} POT NuMI.

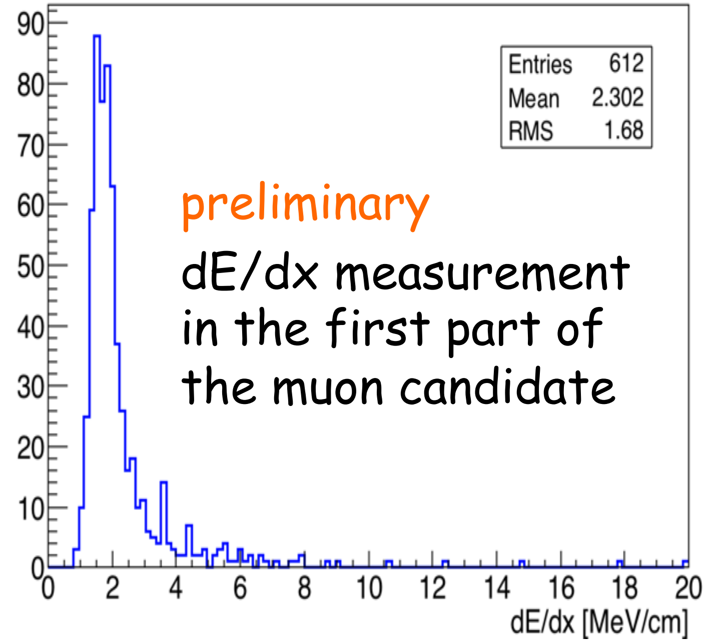


Event selection in ICARUS: finding and reconstructing neutrinos

- The neutrino event selection will be performed exploiting the combination of the signals provided by the TPC, the PMTs and the CRT and using all the common reconstruction tools available in **SBN**; the exploitation of all these elements will be crucial in particular to reject the backgrounds from cosmics:
  - The Pandora patter recognition tools will allow to recognize the neutrino candidates in the TPCs, providing the vertex identification and rejecting the clear through-going cosmic muons.
  - The matching of the charge signals on the wires and the light signals from the PMTs ("flash matching algorithm") will allow to recognize the particles generating the trigger and to reject the out-of-time cosmics
  - The CRT signals will allow to reject the incoming cosmic particles
- The selection of the $\nu\mu$CC interaction is performed requiring in particular the presence of a track longer than 50 cm if it stops inside the detector or longer than 1 m if it is not fully contained and whose dE/dx is compatible with a muon;
- The identification of the νeCC interactions requires the presence of an electromagnetic shower connected to the primary vertex, with E>200 MeV and with a dE/dx at the beginning of the shower compatible with a m.i.p.;
- A dedicated focus will be on the selection of the fully contained neutrino events, in particular for the study related to the NEUTINO-4 analysis

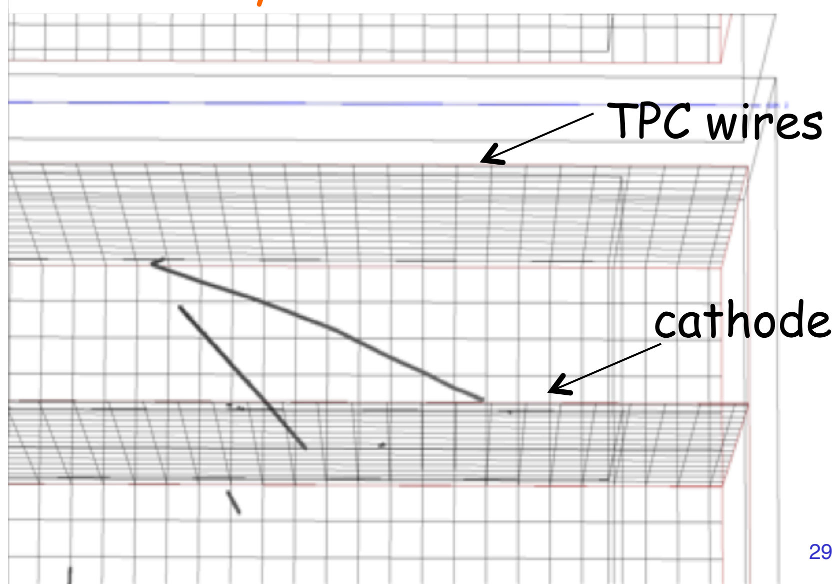
First neutrino candidates (BNB): CCQE





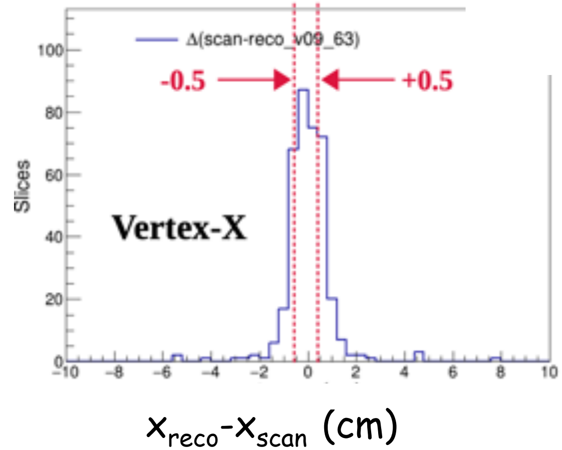
- Two tracks produced at the primary vertex, both stopping (top left picture): the muon candidate is stopping after = 2.8 m with E_{dep} ~ 650 MeV while the proton candidate is stopping after 10.9 cm with E_{dep} ~ 100 MeV
- The dE/dx measurement in the first 2 m for the muon candidate (top right picture) results in agreement with the expectations of the Landau distribution for a minimum ionizing particle.

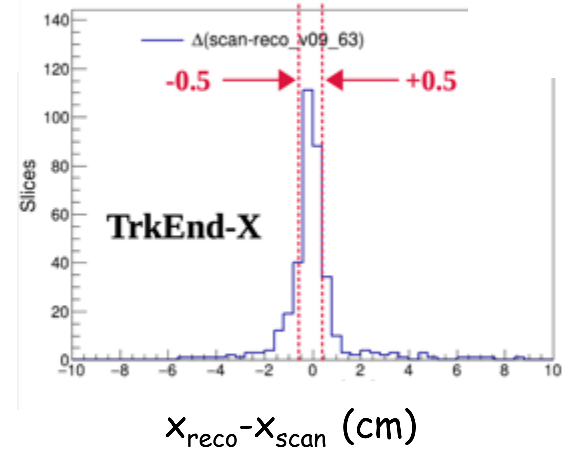
Preliminary 3D event reconstruction

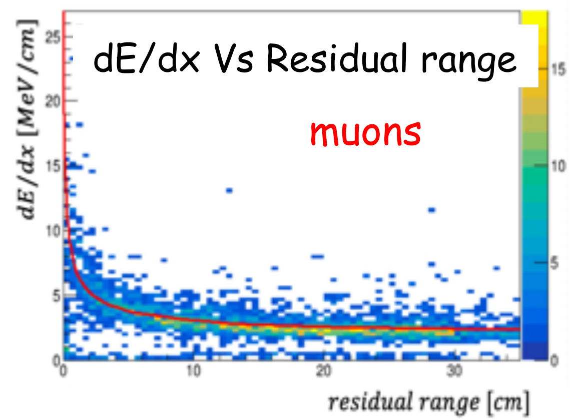


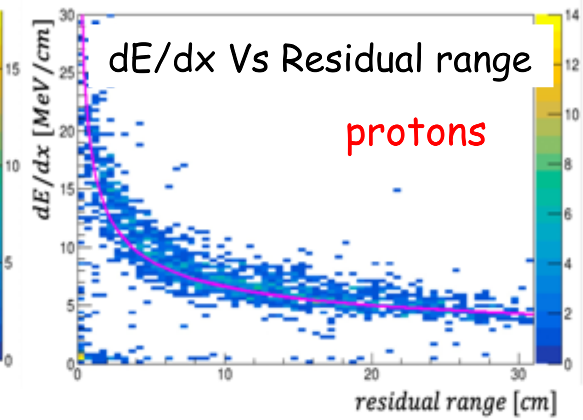
Check of event reconstruction with visually selected νμCC events

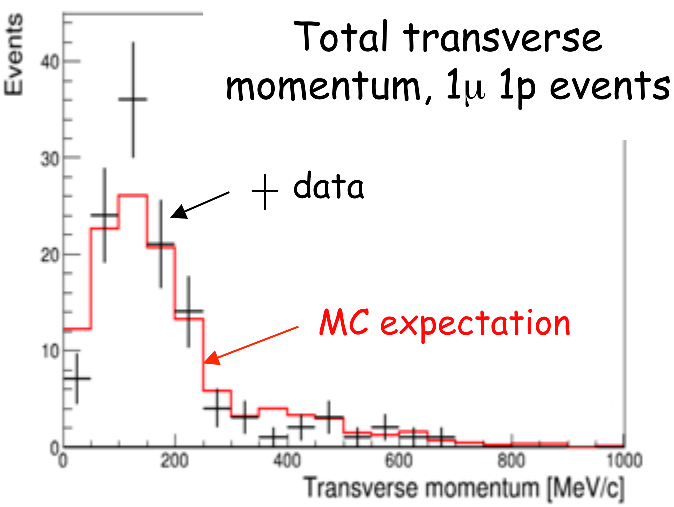
- Automatic procedure for selecting 1μ 1p νμCCQE interactions fully contained in the active volume is under tuning/validation:
  - 1μ 1p fully contained ν candidates: demonstrating PID and kinematic reconstruction capabilities in the transverse plane
  - Reconstructed ν interaction vertex and μ end-point within ~2 cm from the measured one;

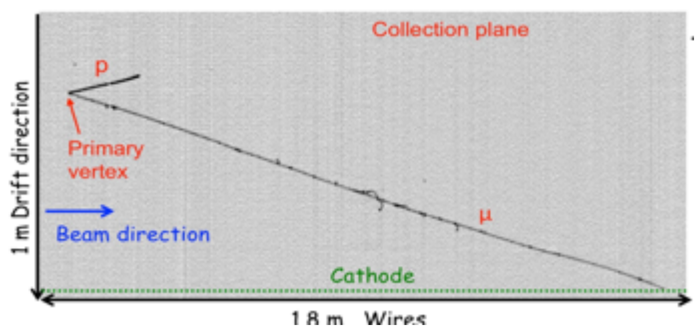


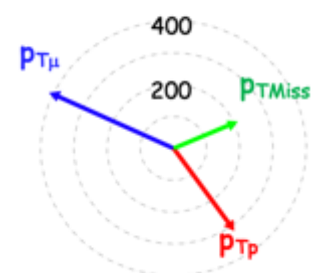








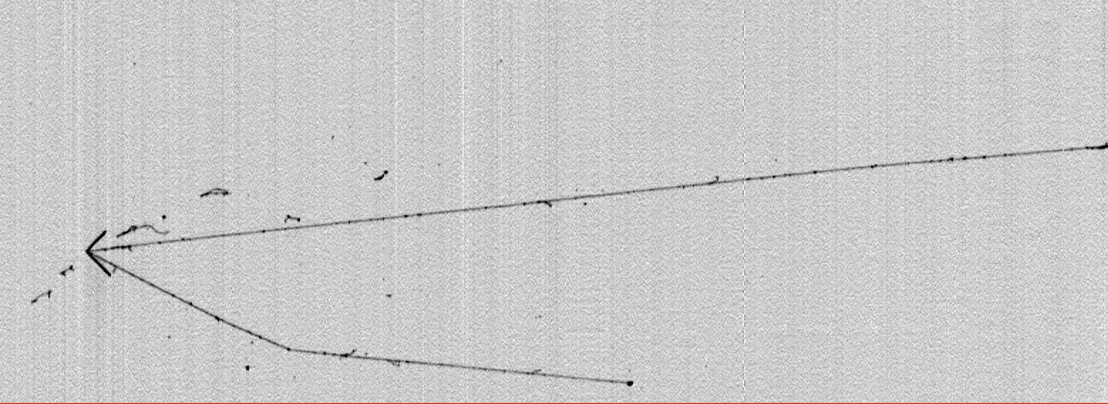


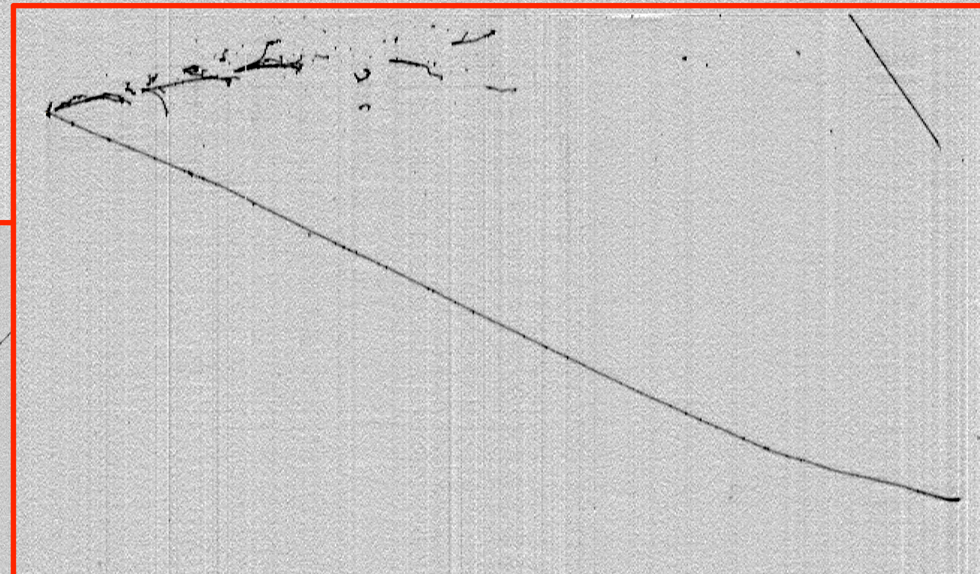


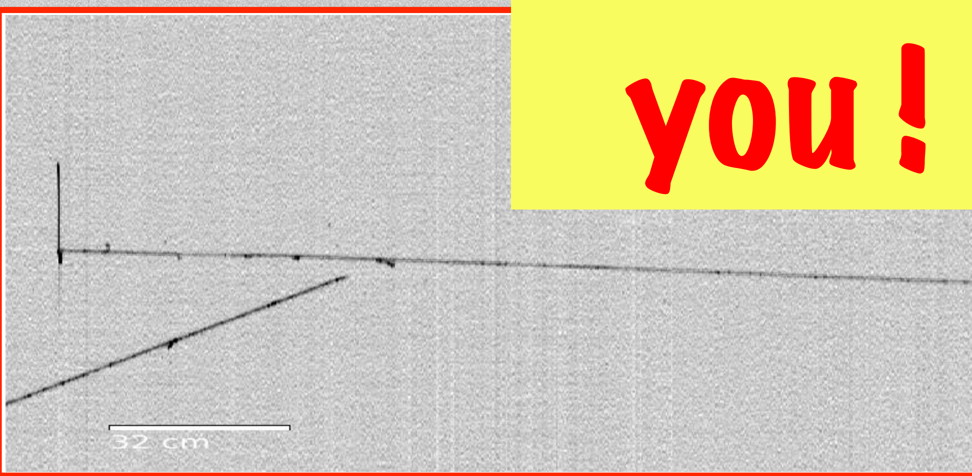
Conclusions

- ICARUS detector installation and commissioning has been completed: full time neutrino beam run started on June 9th 2022 and resumed last December exploiting regularly both Booster and NuMI beams with very high live-time;
- Neutrino events have been successfully collected and are being used to further develop and tune the event filter and the reconstruction software. The analysis of all the ICARUS cosmic events collected is also providing a better and better understanding of the detector response and systematics
- Early phase of ICARUS data taking has started, primarily dedicated to the study of the Neutrino-4 claims looking for the $\nu\mu$ *disappearance* in the Booster beam and then *νe disappearance* in the NUMI off-axis beam.
  Data collected are being actively analyzed, first results expected by this year.
- Other relevant physics goals with data collected in standalone mode from BNB and NuMI beams including ν-Ar interaction cross-sections measurement in a range of interest for DUNE;
- After the first year ICARUS-only operations, the SBND LAr-TPC detector will be added at shorter distance from the Booster target to perform with ICARUS a definitive 5 σ analysis of sterile neutrinos.

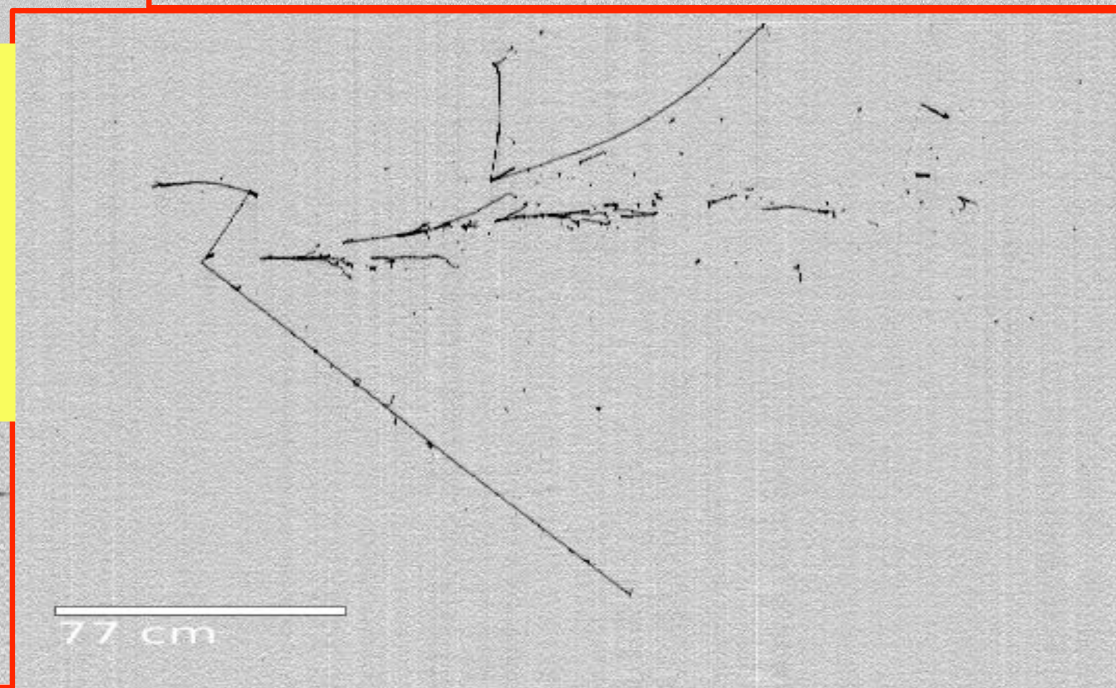
ICARUS is well on its way for intriguing physics searches with SBN and beyond!
STAY TUNED !



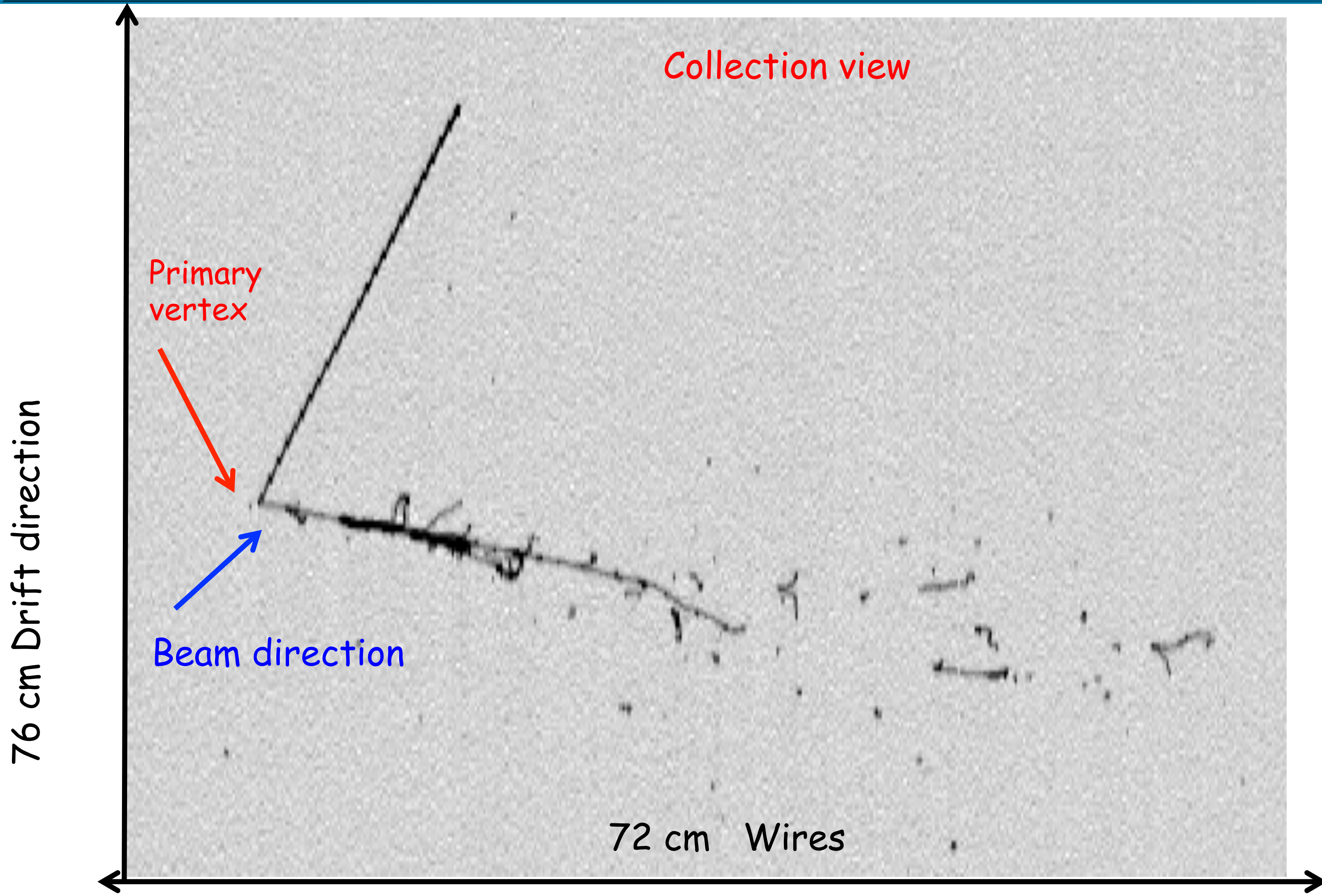




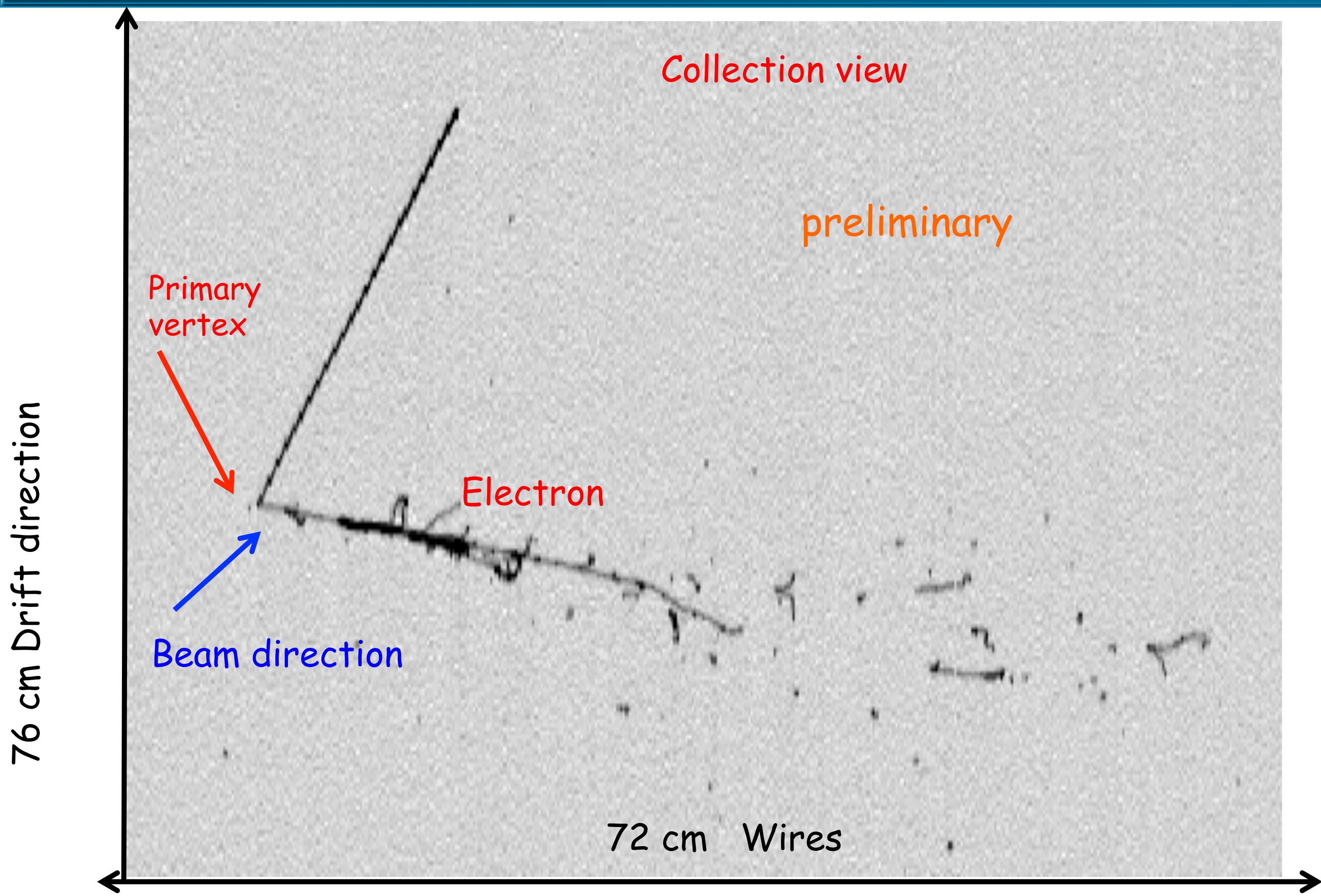
Thank you !



Guess, what is it?

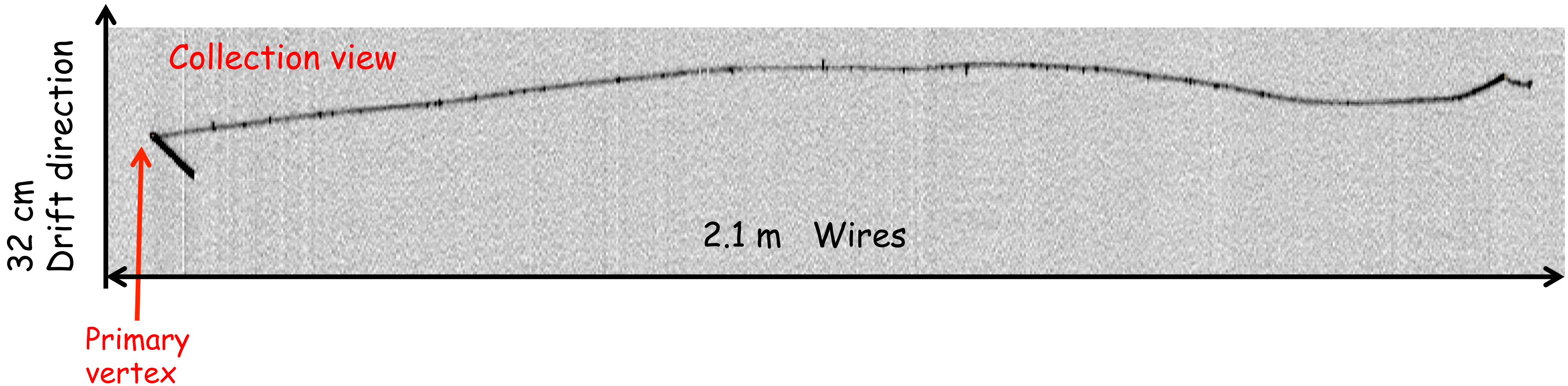


Neutrino Candidate from NuMI beam

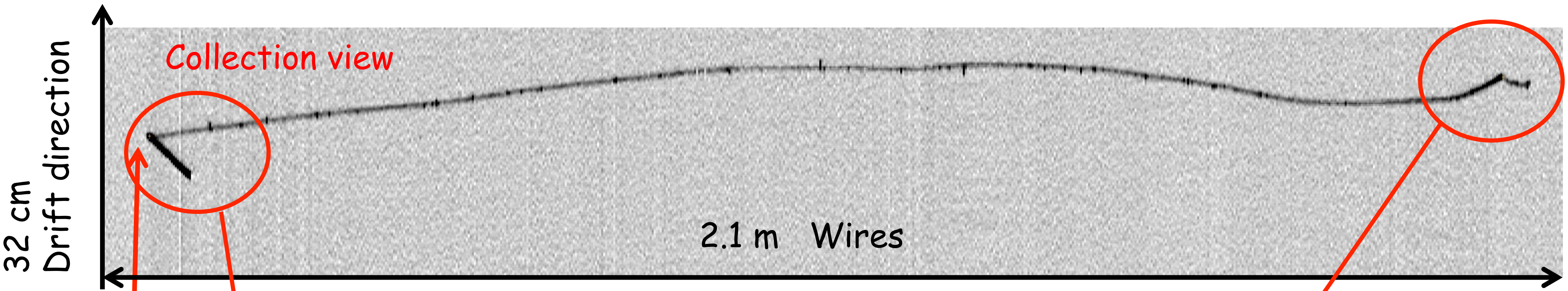


- Electron neutrino candidate:
  - Electromagnetic shower with E_{dep} ~ 600 MeV
  - Upward-going hadron (proton or pion candidate) with length ~ 43 cm

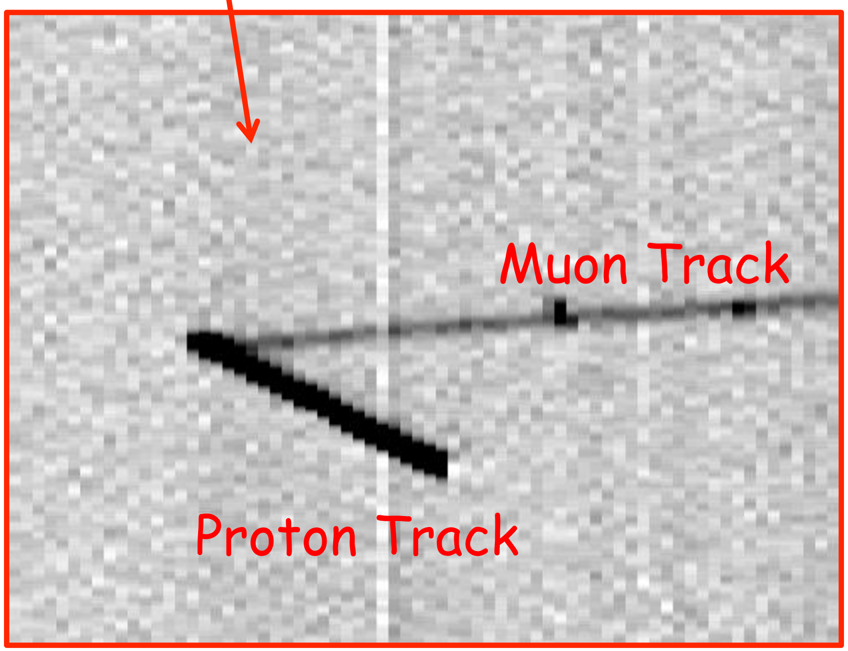
Guess, what is it?

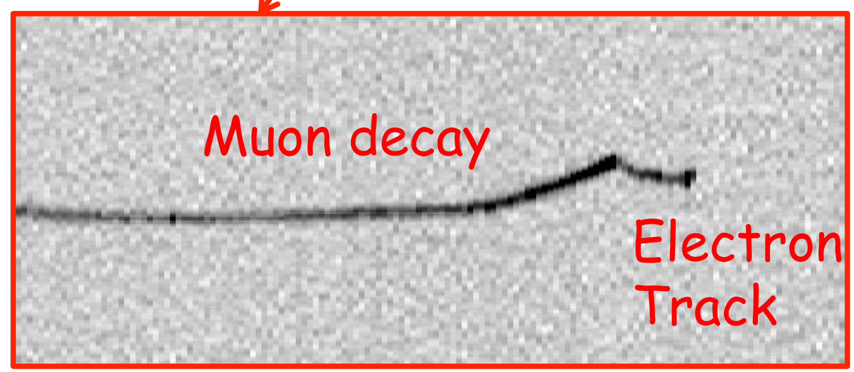


Muon neutrino candidate from BNB



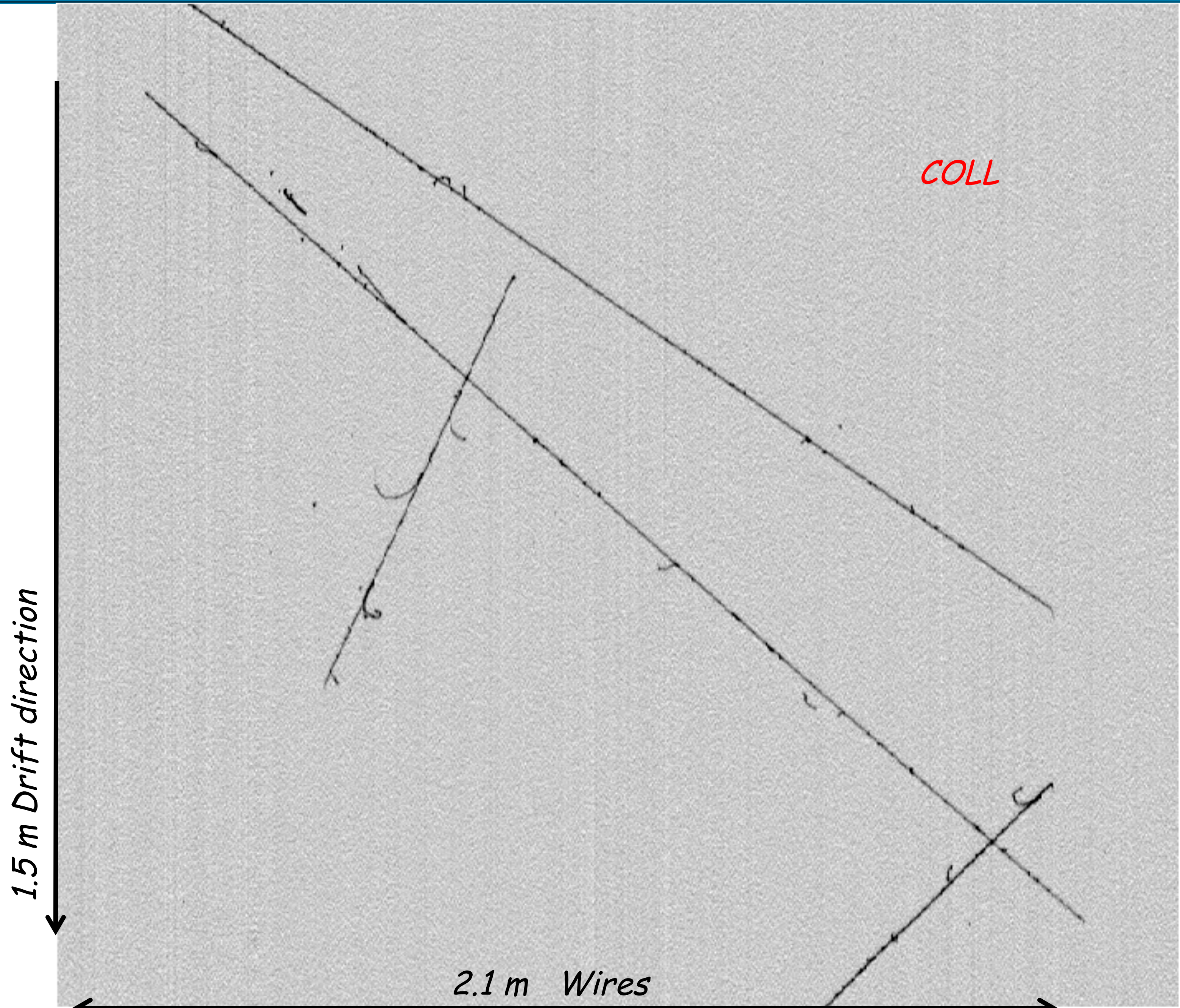
$\nu_\mu \; n \rightarrow p \; \mu$ Quasi-Elastic interaction



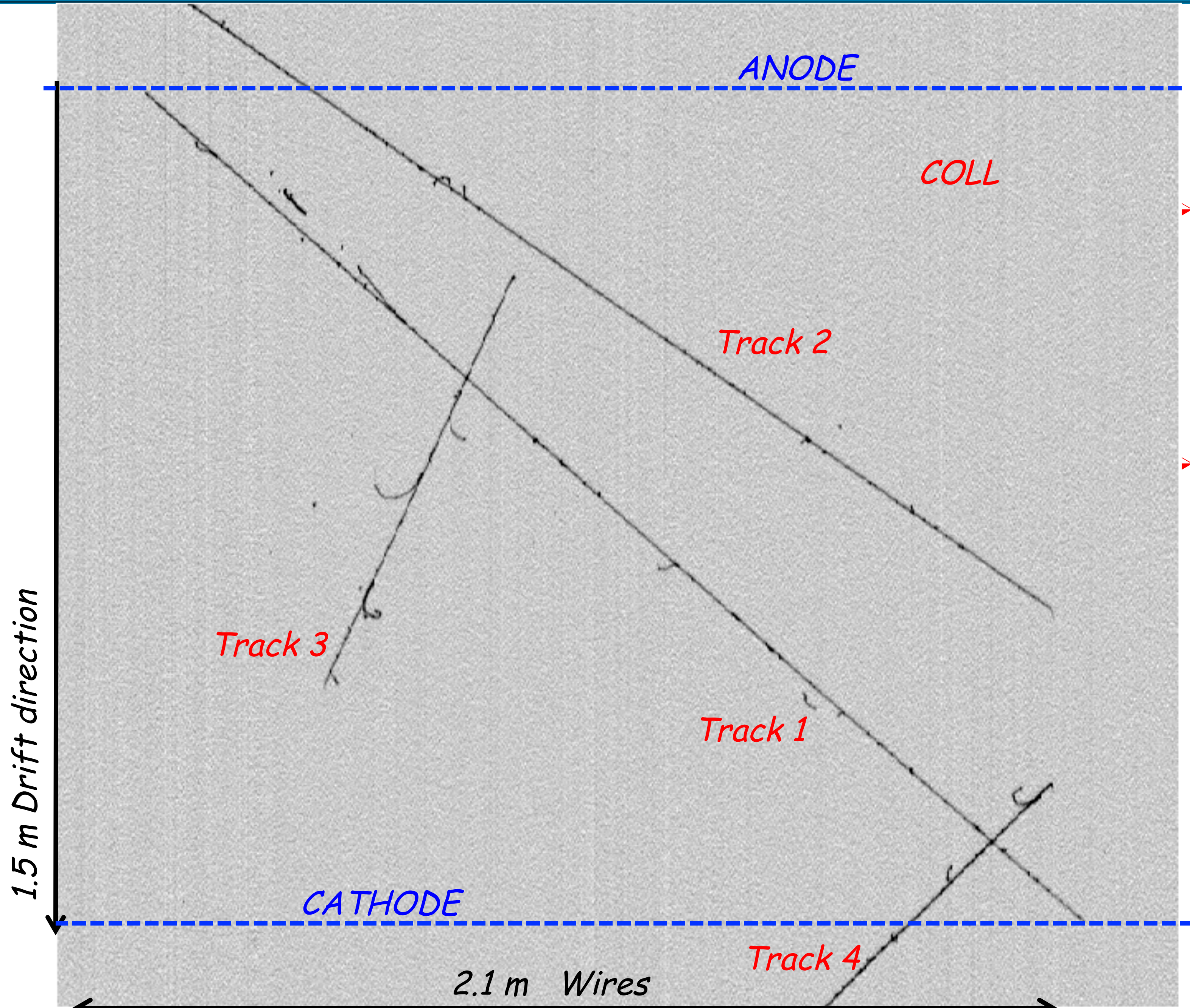


Muon Length: ~2.1 m
Proton Length: 15 cm

Guess, what is it?



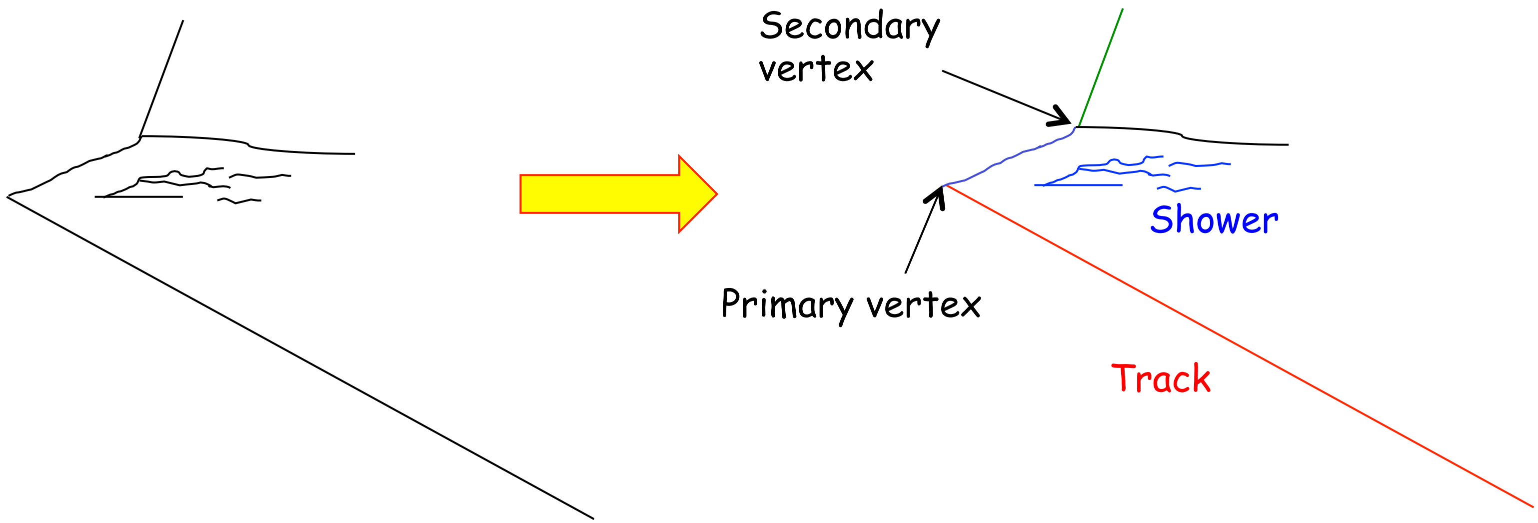
COSMIC EVENT



- Track 1 is an anode to cathode crossing cosmic muon track L=2.6 m
- Three additional tracks, crossing the detector at a different time with respect to track 1, are also visible

Searching for neutrinos: Pandora pattern recognition

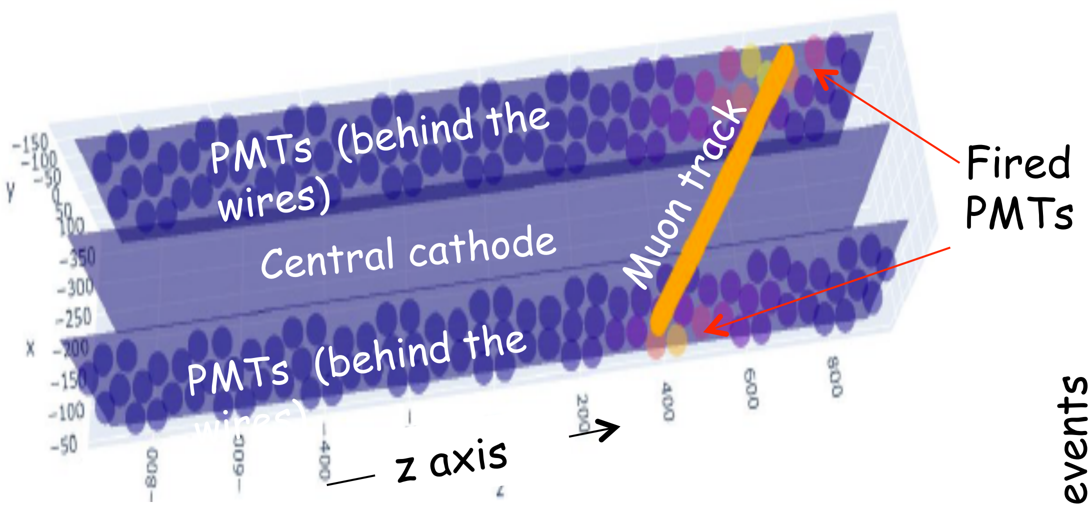
- Starting from the raw TPC images, the main steps of the TPC wire reconstruction are:
  - In each TPC wire, the physical signals (hits) are identified and organized into 2D clusters based on proximity/alignment;
  - The 2D clusters in the different wire plane projections are then associated on the basis of the drift time coincidence of the hits signals.
  - The Pandora pattern recognition tools allow then to discriminate signals associated to clear cosmic muon tracks crossing the detector from possible neutrino interactions; it identifies the individual particles, discriminating also between tracks/showers and it determines their 3D trajectories and arrange them into hierarchies.

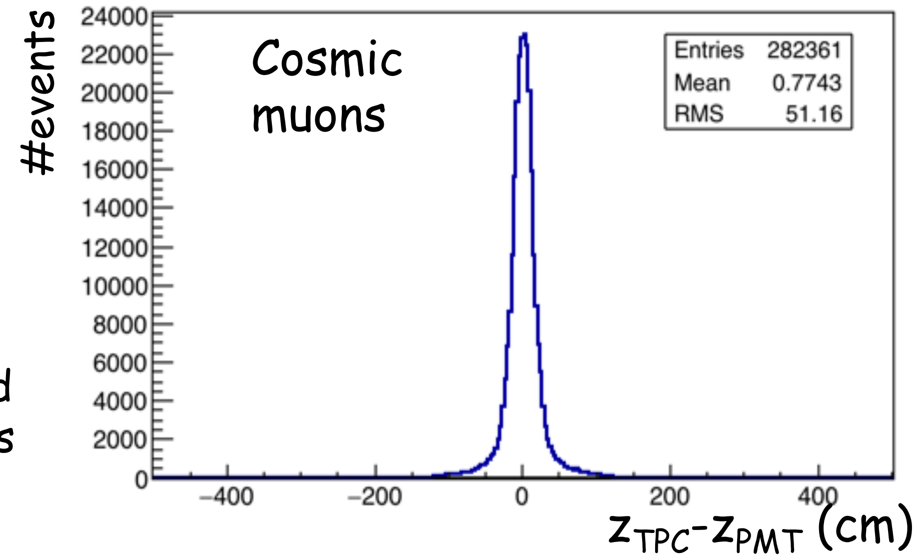


  - The track/shower and then reconstructed in detail to obtain the measurement of the deposited energy, the dE/dx along the track and the P.I.D.

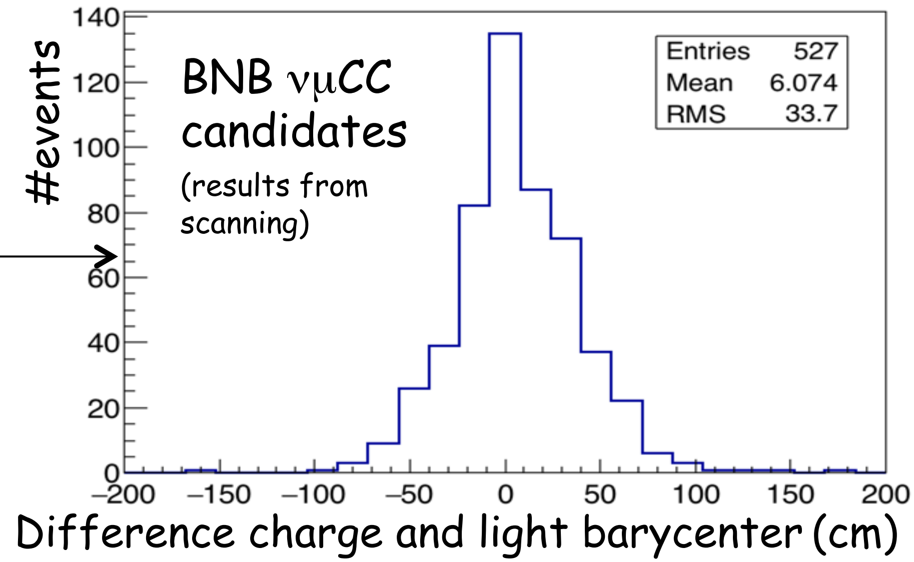
Exploiting the light to localize the event along the longitudinal axis

- The association of the light recorded in the PMTs to the track in the TPC that produced it is a powerful tool to localize the event that generate the trigger and, at the same time, to associate the proper time to each “out of time” track;
- A simple algorithm that compares the track and the light barycenter (z_{TPC}, z_{PMT}) has been prepared and tested on cosmic muons.



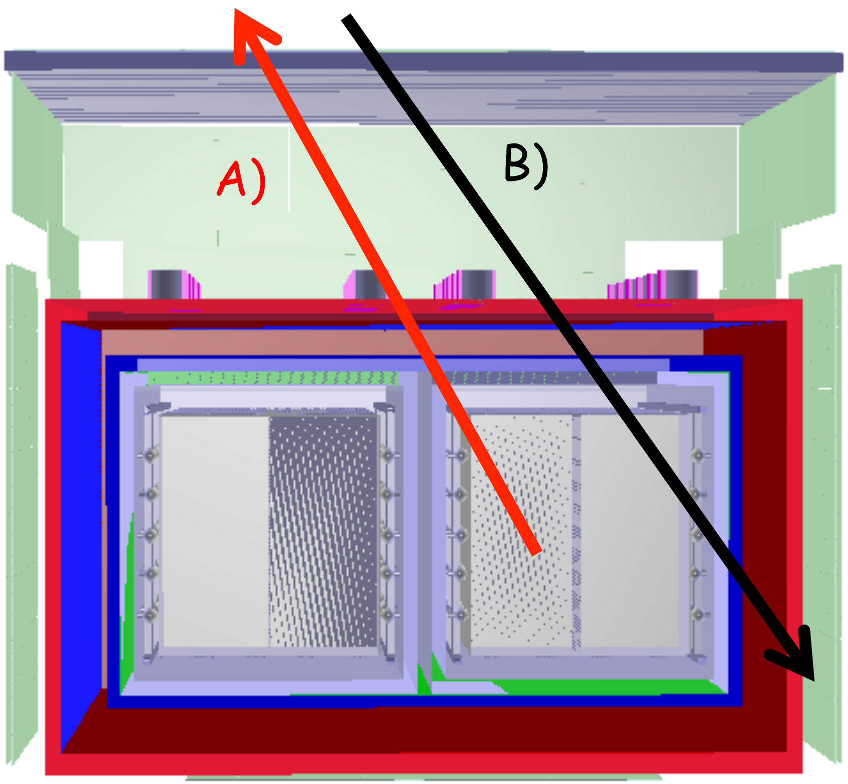


- A similar study has been performed on a set of BNB νμCC candidates with Lμ>50 cm identified by scanning: the average z coordinate of the muon z_{μ} agrees with the light barycenter within ~1 m.



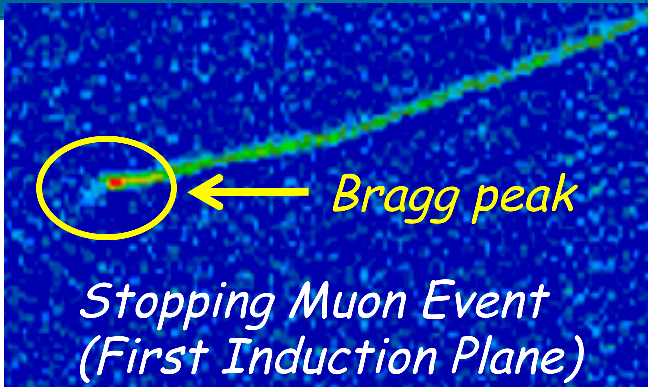
CRT exploitation for the event selection purposes

- The CRT will be a powerful element to strongly reduce the background from cosmics:
  - The presence of a CRT hit signal in coincidence with the beam spill can help to identify events with cosmic particles in time with the beam spill:
    - It will be the first request in order to select the contained ν interactions;

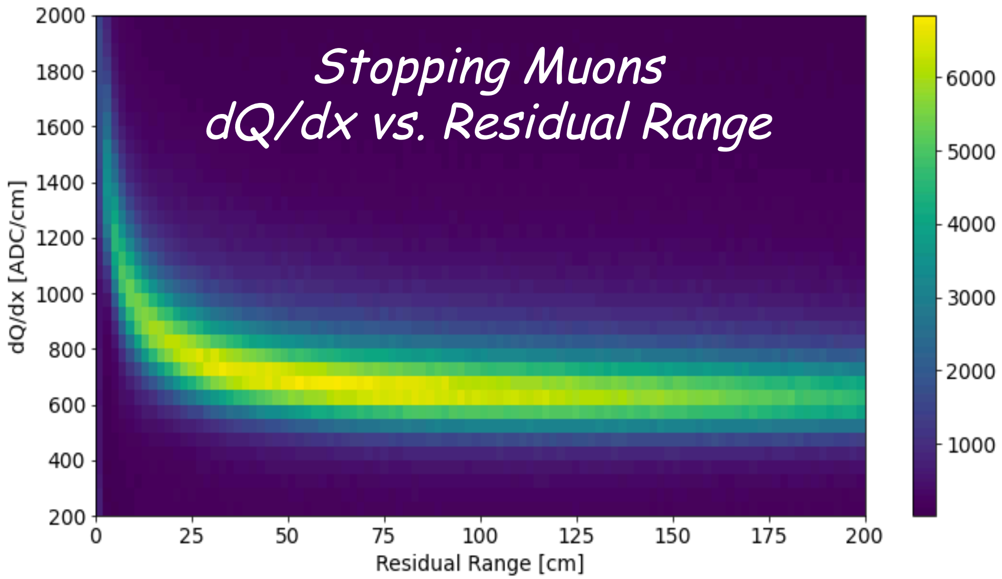


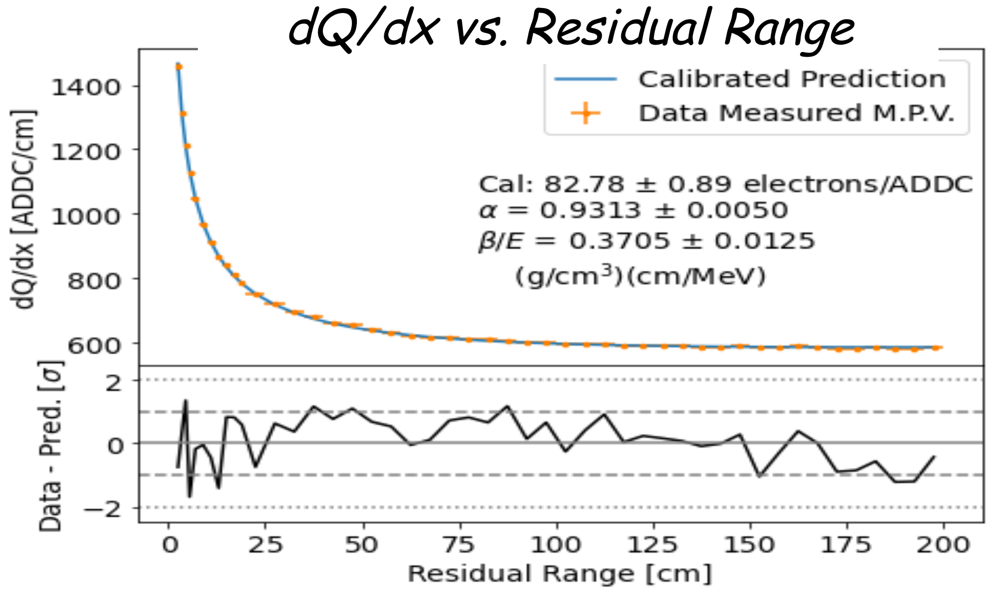
- The capability to match the tracks recorded in the TPCs with the signals recorded in the CRT will help to recognize also the "out-of-spill" cosmic particles;
- The PMT-CRT signal "matching", with a "time of flight" measurement, can help to disentangle particles generated in the detector and exiting (case A) from particle coming from outside (case B), reducing the autoveto on the neutrino events;

TPC wire signal reconstruction



- A full calibration chain has been developed. It is based on the study of the ionization vs residual range for cosmic μs crossing the cathode stopping/decaying in the active LAr and identified by the reconstruction program;
- Goals: a) calibrate the absolute energy scale,
  b) equalize the individual wire electronic response,
  c) improve the modeling of e- recombination, e- diffusion, space charge effects, and d) measure detector properties like drift velocity and the detailed wire response.





- This study is meant to tune and quantify the performance of the PID algorithm based on the measurement of dQ/dx Vs residual range for stopping particles.