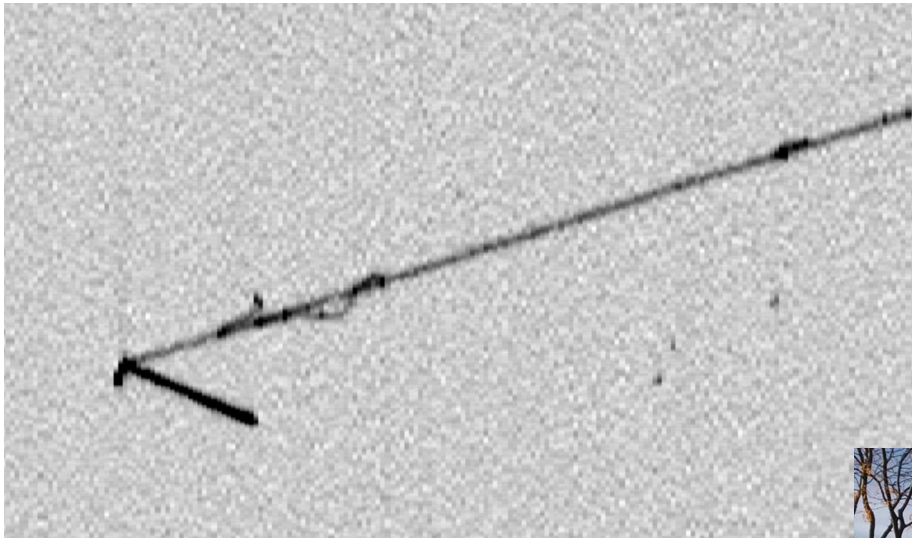
The Icarus Experiment at Fermilab

Imaging Cosmic And Rare Underground Signals

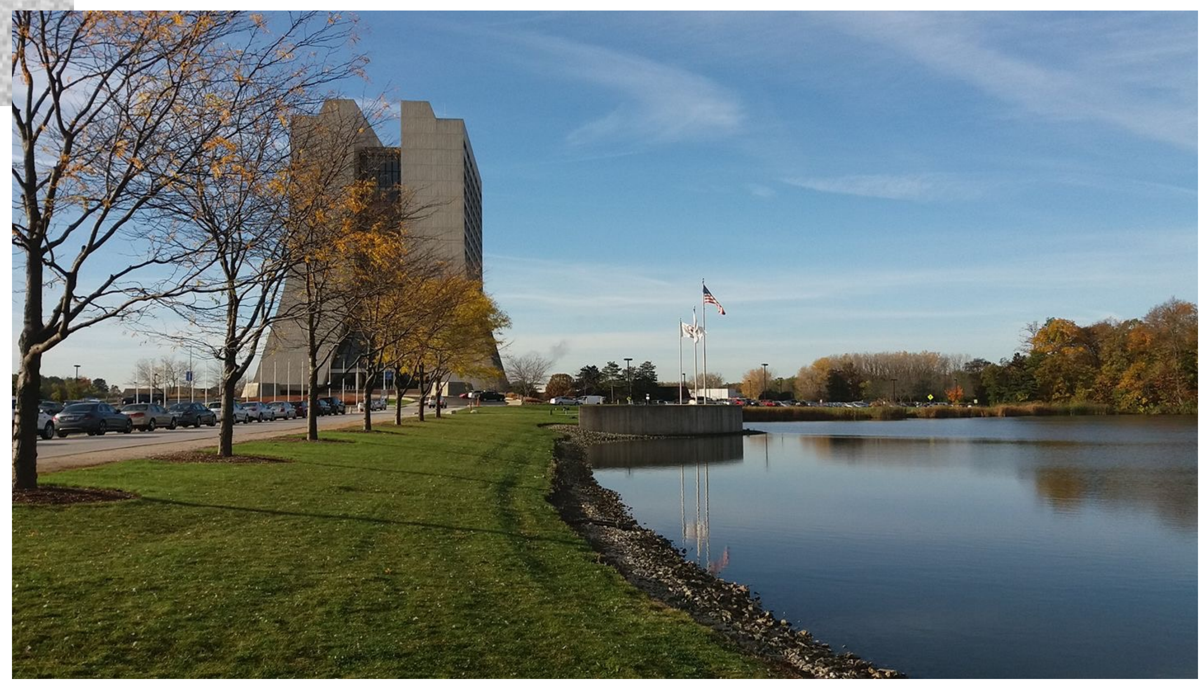


FERMILAB 2024
SUMMER STUDENTS
SCHOOL

Pisa, July 22th-24th 2024

Christian Farnese
INFN Padova
farnese@pd.infn.it

ICARUS collaboration



European Commission

INFN

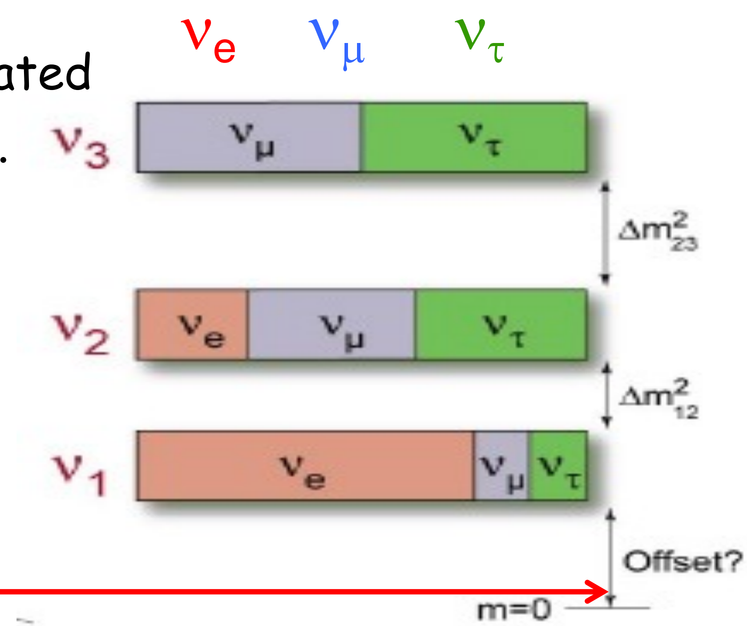
Neutrinos

- 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

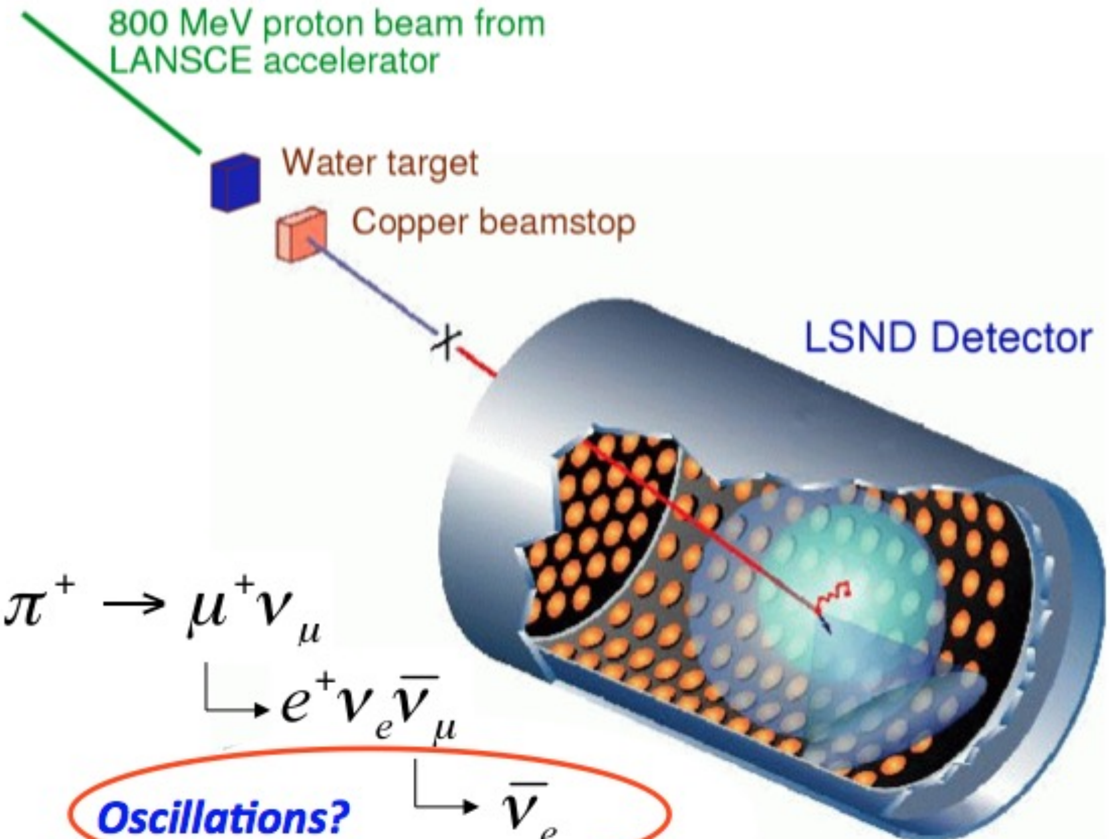
- Neutrino oscillations have established a picture consistent with the mixing of three physical neutrino νe, $\nu \mu$ and $\nu \tau$ with the help of three mass eigenstates $\nu 1$, $\nu 2$ and $\nu 3$.

- 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 ($\Delta m^2{}_{12}$, $\Delta m^2{}_{23}$)*
  - *One unkown offset from m = 0*



The LSND experiment: evidence for a fourth neutrino?

The LSND Anomaly

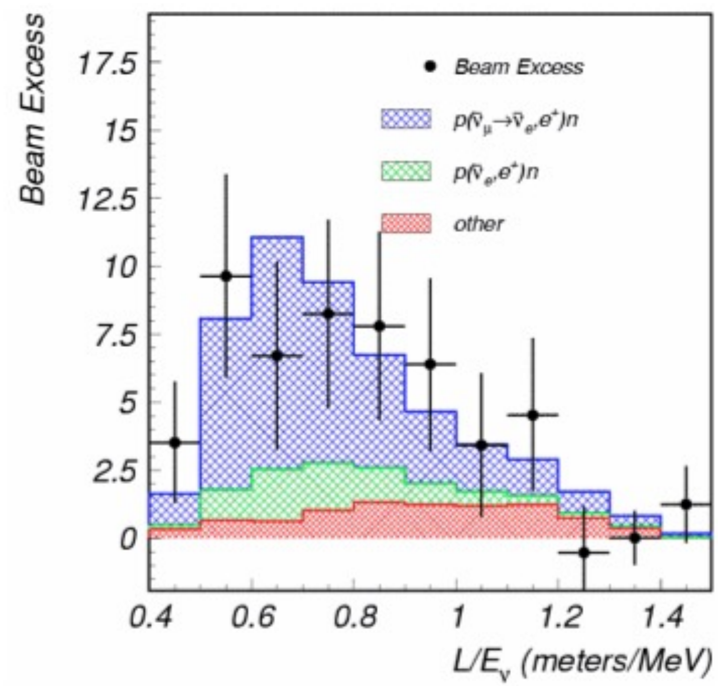


$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\qquad \hookrightarrow \bar{\nu}_e$$

Oscillations?

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

$\hookrightarrow$ n p $\rightarrow$ d γ(2.2MeV)



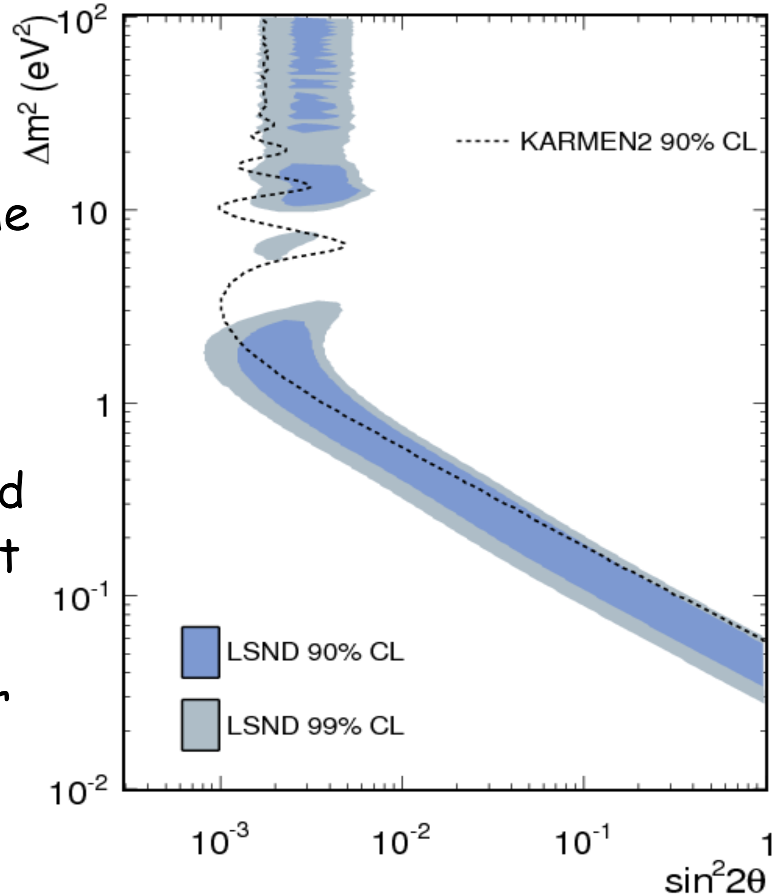
Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

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

3.8 σ evidence for oscillation.

"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 ($\Delta m^2_{21} \sim 7.5\ 10^{-5}\ eV^2$; $\Delta m^2_{31} \sim 2.5\ 10^{-3}\ eV^2$):
  - ➢ $\Delta m^2 \sim 1\ eV^2$

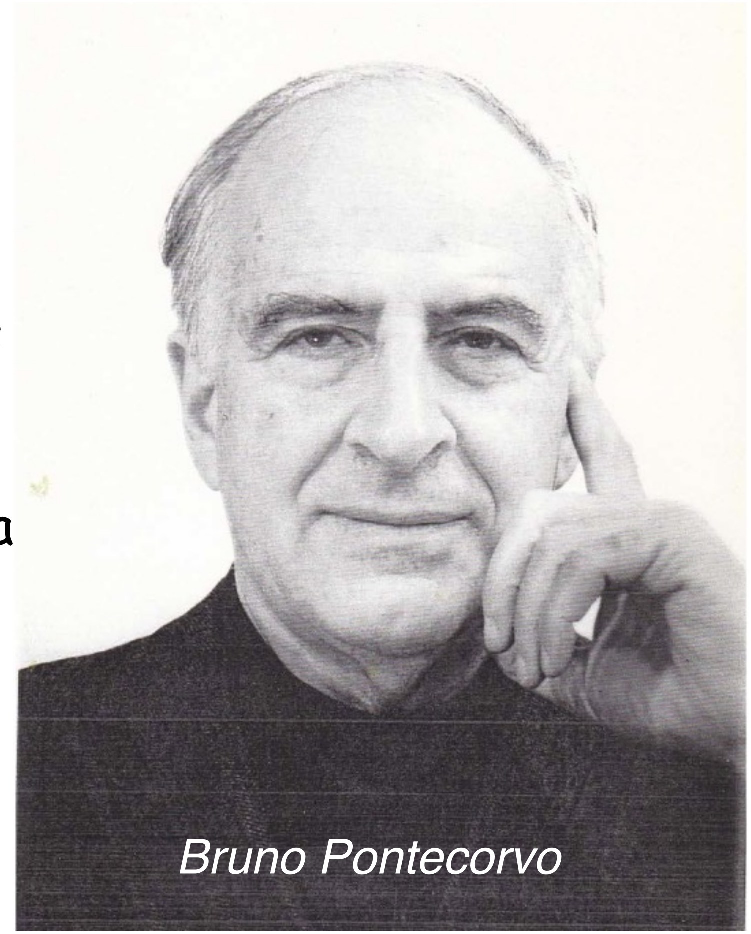


- Additional anomalous signals has been then observed and seems to indicate an evidence of oscillation that can be described considering a $\Delta m^2 \sim 1\ eV^2$:
  - ➢ appearance of νe from νμ beams in accelerator experiments, not only at LSND, but also at MiniBooNE, that studied the Booster neutrino 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?

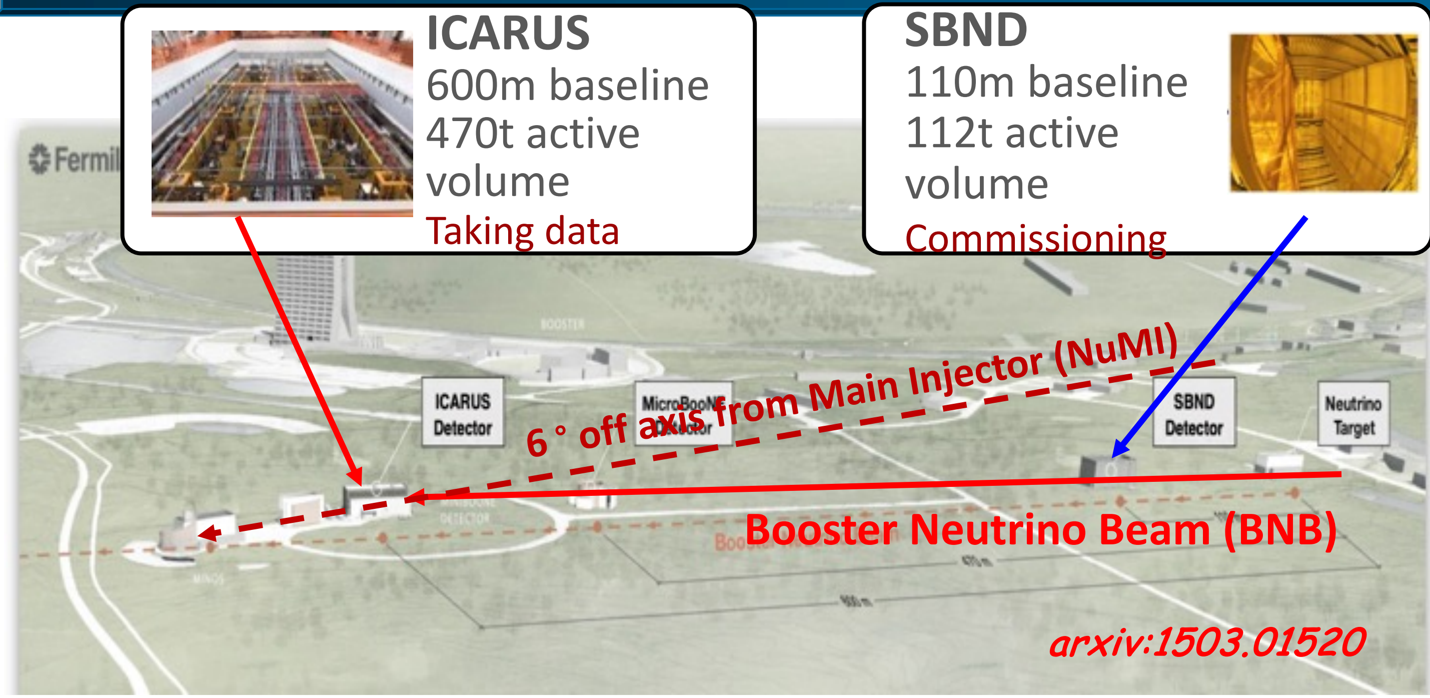
- Sterile neutrinos are an hypothetical type of neutrinos that do no interact via any of the fundamental interactions of the Standard Model except gravity.
- The name was conied in 1957 by Bruno Pontecorvo.
- If they are heavy enough, they may also contribute to cold or warm dark matter.
- Sterile neutrino 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":

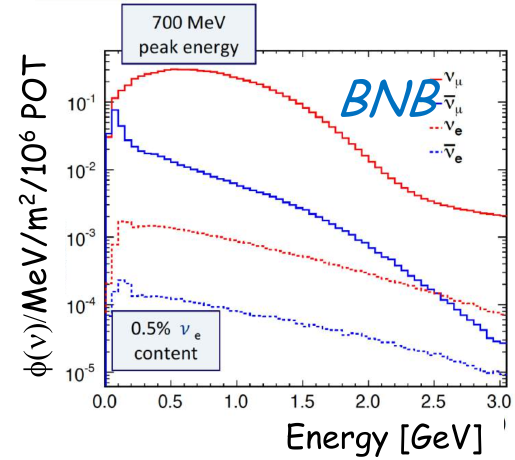


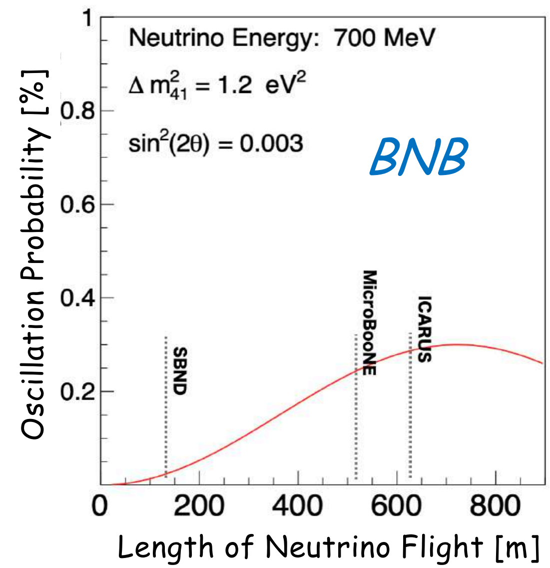
Bruno Pontecorvo

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

ICARUS and the Short Baseline Neutrino (SBN) at FNAL: *a definitive answer to sterile neutrinos ?*





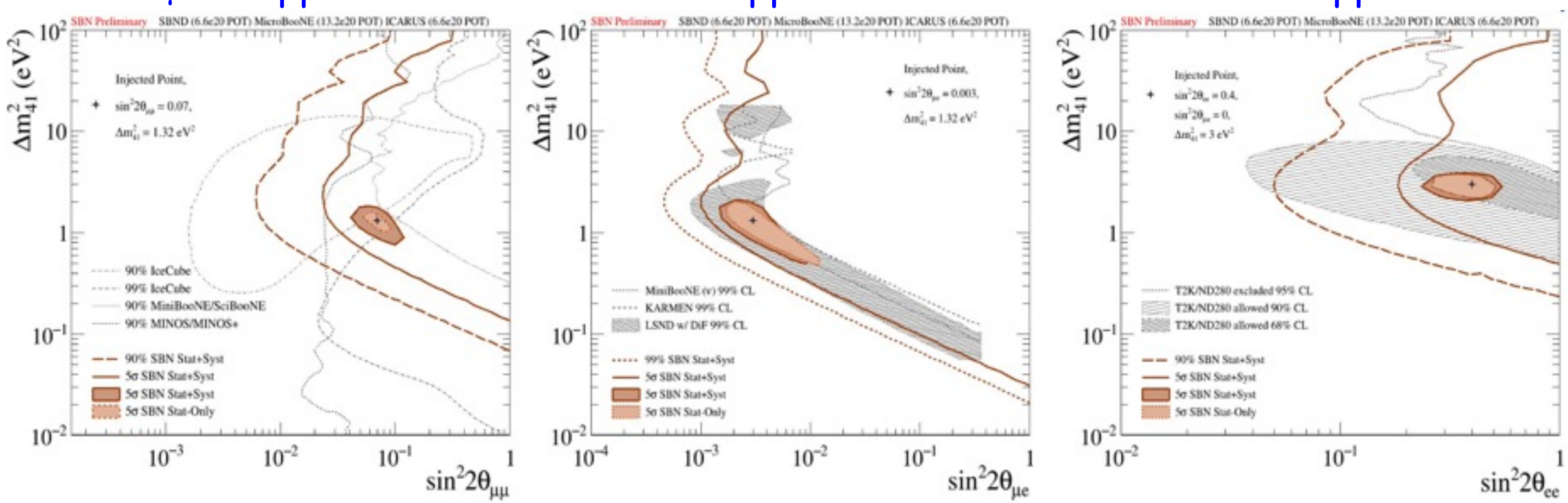


- ICARUS LAr-TPC is presently taking data at shallow depth installed at 600 m from the Booster target within the SBN experiment
  - The SBN program is addressing the question of sterile neutrinos with the BNB beam comparing ν_e and ν_μ interactions at different distances from target as measured by ICARUS and SBND LAr-TPCs.
  - In addition, ICARUS is exposed to the NuMI beam at ~6° off-axis (ν cross-section and BSM searches).

SBN Program: sterile neutrino sensitivity, 3 years (6.6 x10^{20} pot)

- Combined analysis of events collected far by ICARUS at far site and by SBND at near using the same LAr-TPC event imaging technology greatly reduces the expected systematics:
  - High νe identification capability of LAr-TPCs rejecting NC event background;
  - "Initial" BNB beam composition and spectrum provided by SBND detector.

νμ disappearance — νe appearance — νe disappearance



5σ coverage of the parameter area relevant to LSND anomaly

Probing the parameter area relevant to reactor and gallium anomalies.

Unique capability to study neutrino appearance and disappearance simultaneously

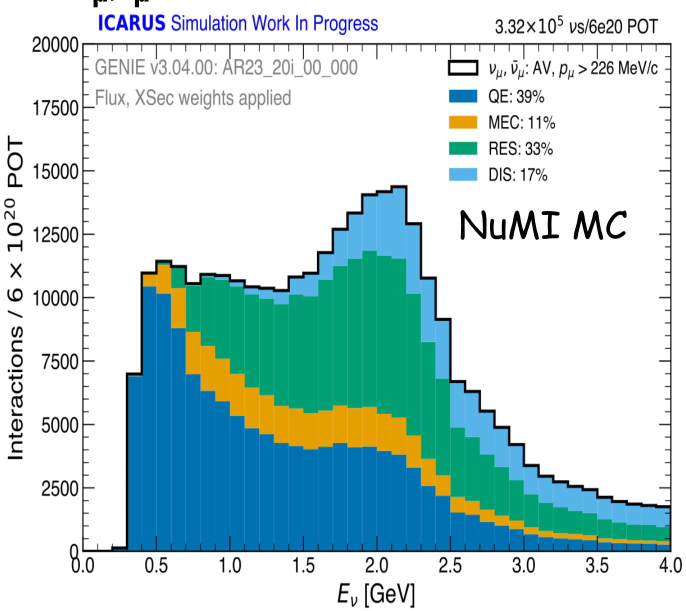
Neutrino Interactions from NuMI off axis at ICARUS

- Excellent statistics to measure cross section for quasi-elastic, resonance and deep inelastic scattering, for both electron and muon neutrinos:

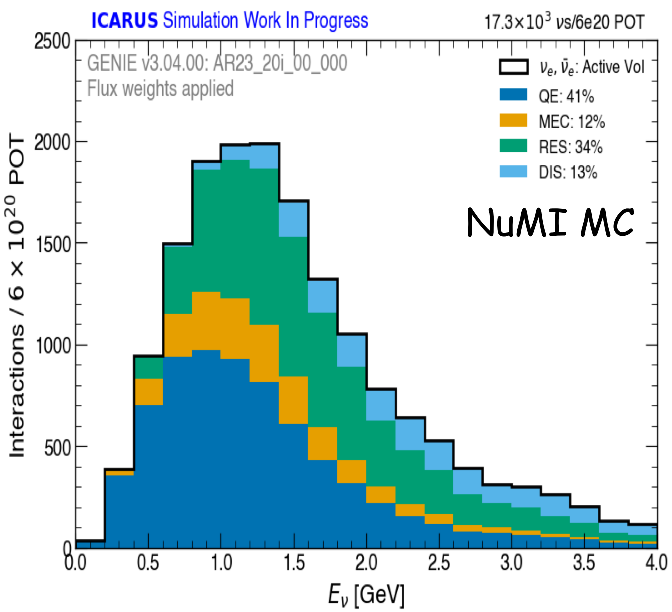
  CC events/6E20 pot : ν_μ 332,000 and ν_e 17,000.

- Neutrino energy spectrum from NuMI at ICARUS covers the first oscillation peak and good coverage of the relevant phase space for DUNE experiment.

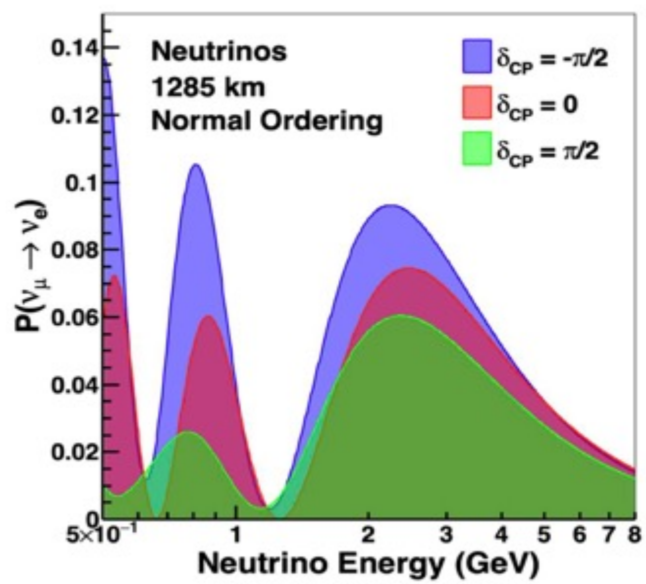
μ, μ from NuMI at ICARUS



e, e from NuMI at ICARUS



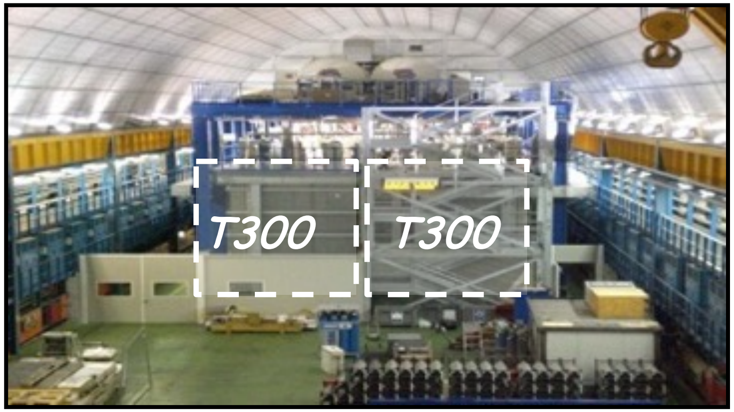
Oscillation probability at DUNE



- Further exploitation of NuMI: rich Beyond Standard Model search program: Higgs portal scalar, ν tridents, light dark matter, heavy neutral leptons …

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

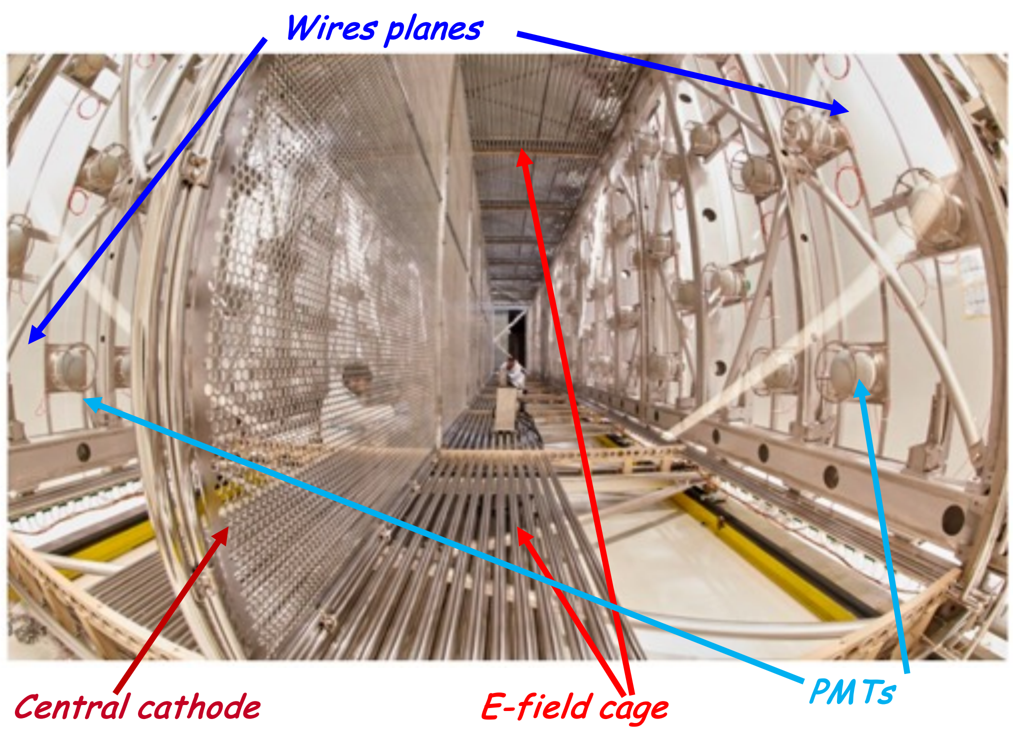
- Liquid Argon Imaging technology LAr-TPC, an "electronic bubble chamber" identifying unambiguously each ionizing track in complex neutrino events, was proposed by C. Rubbia [CERN-EP/77-08] as an alternative to Cherenkov detectors.



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:

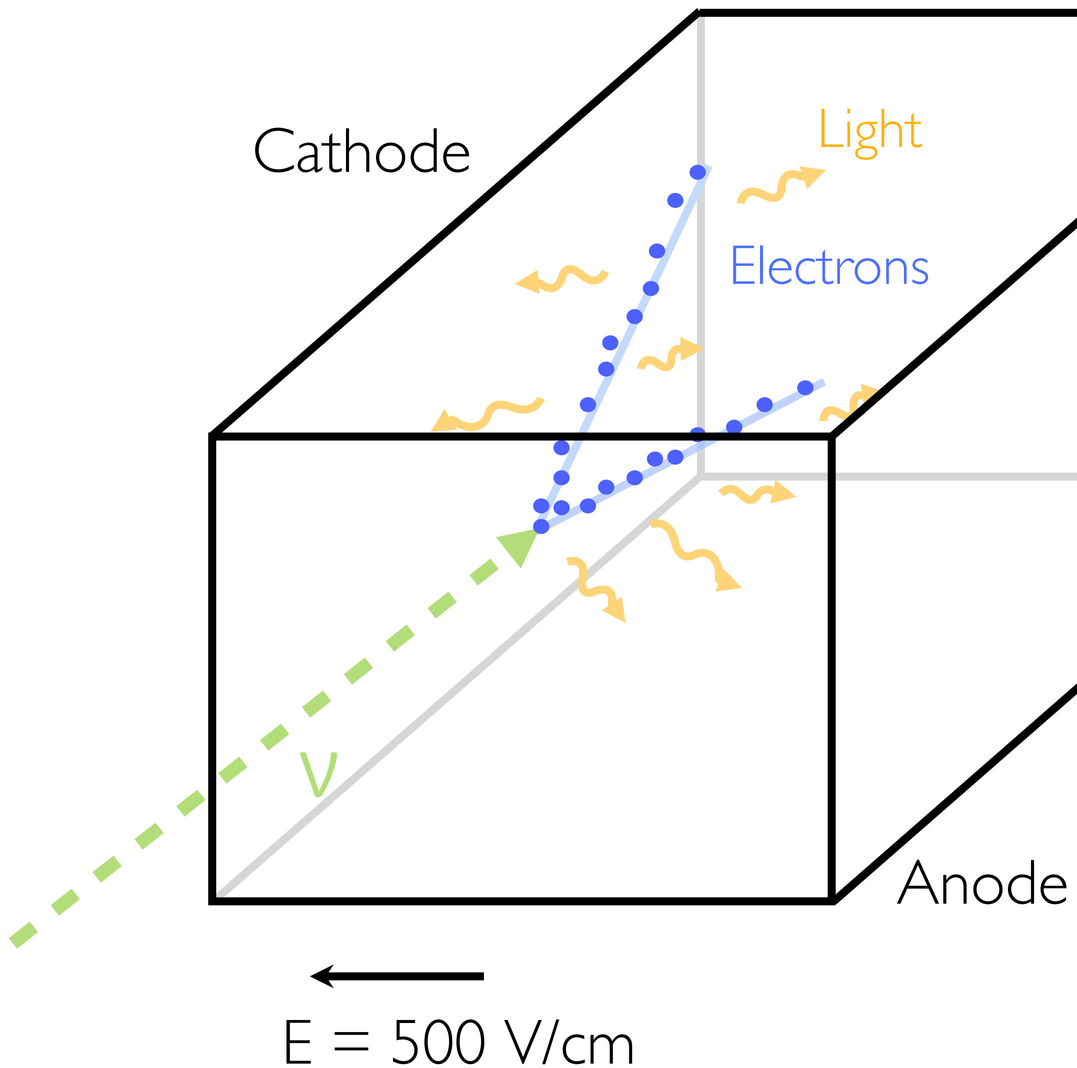
... paving the way for Long-Baseline experiments

- 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



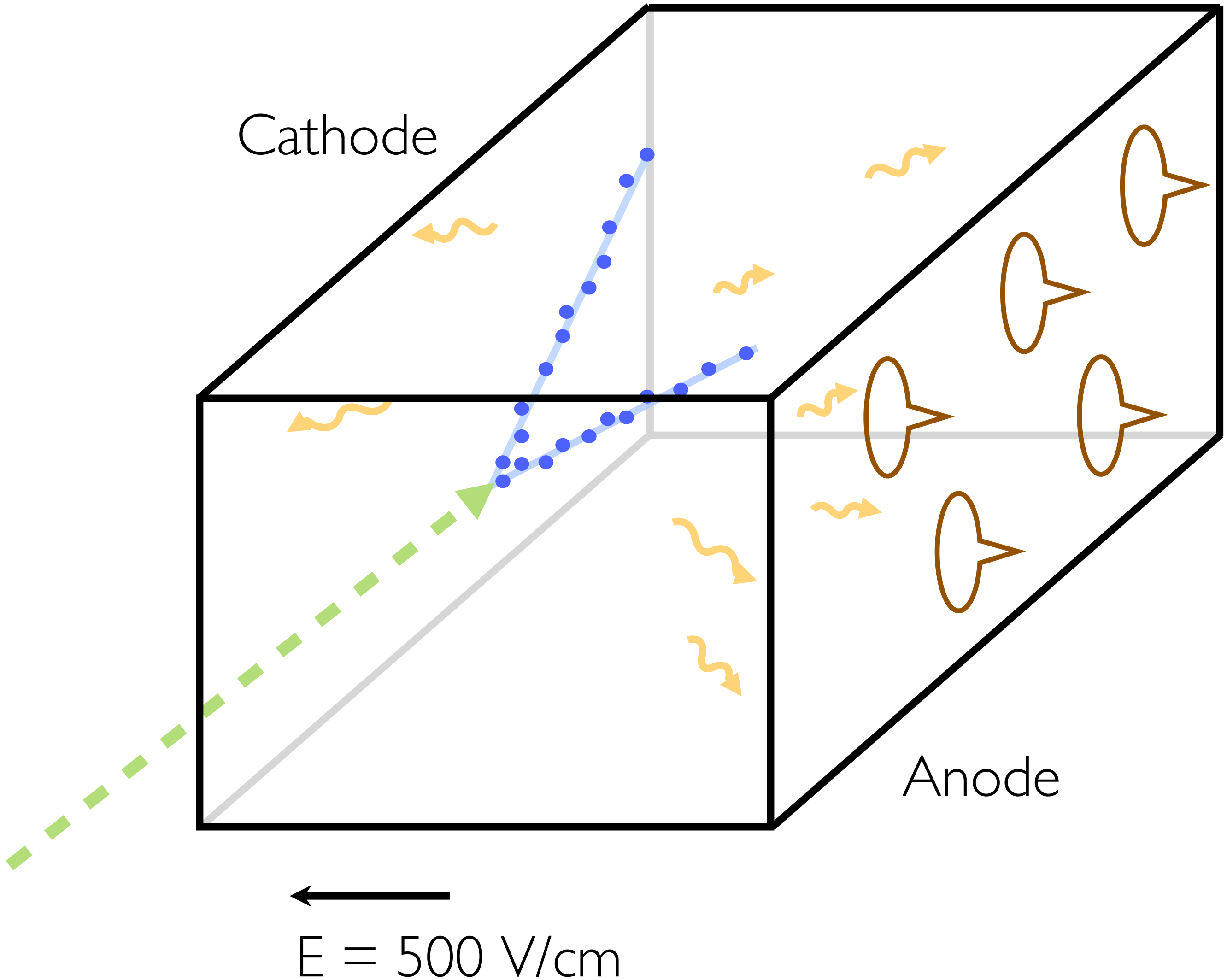
Lar-TPC working principle

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



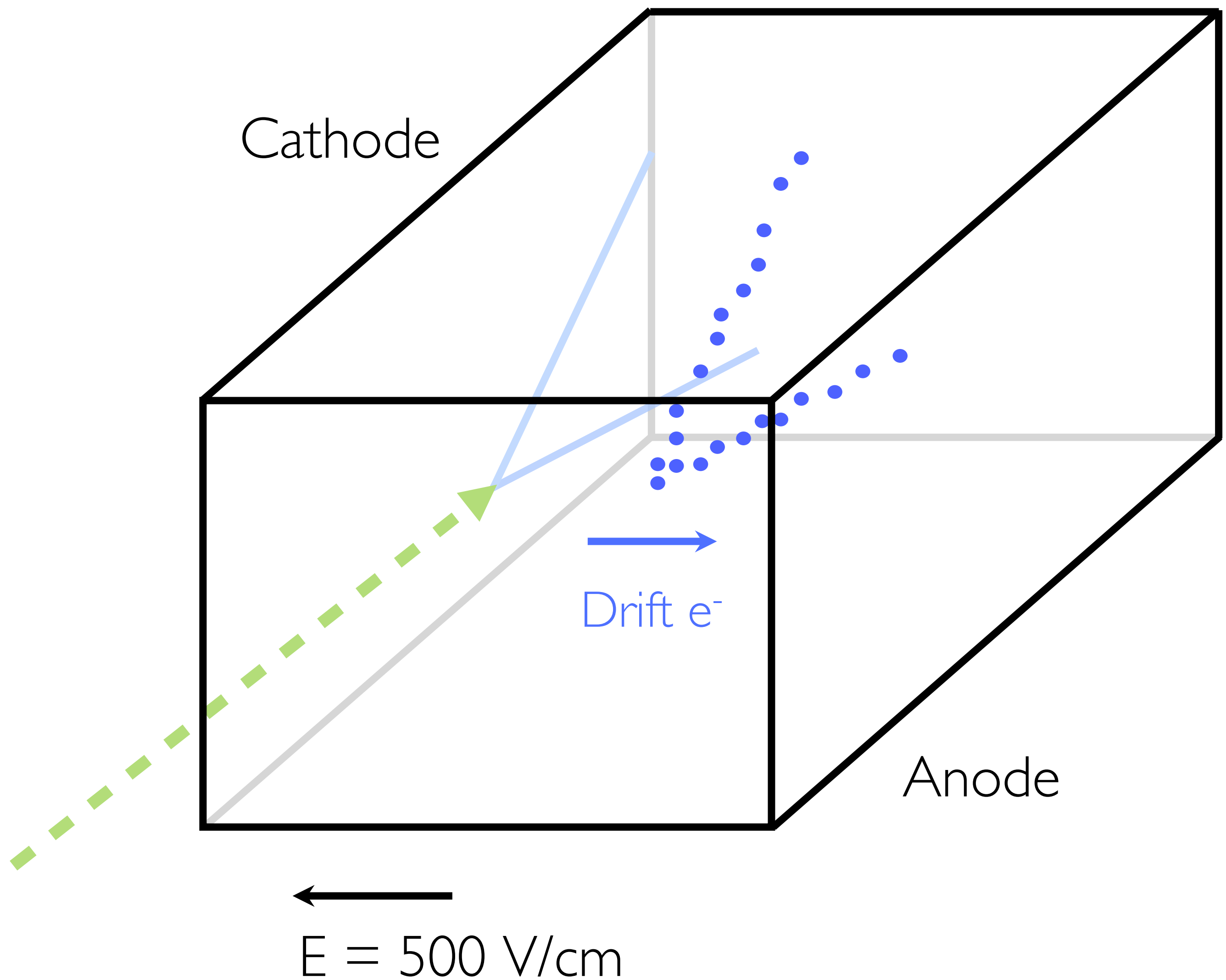
In liquid Argon, if an electric field of E=500 V/cm is applied, a muon m.i.p. (dE/dx ~ 2 MeV/cm) crossing 1 mm of the detector produces ~4000 scintillation photons and ~5000 ionization electrons

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)

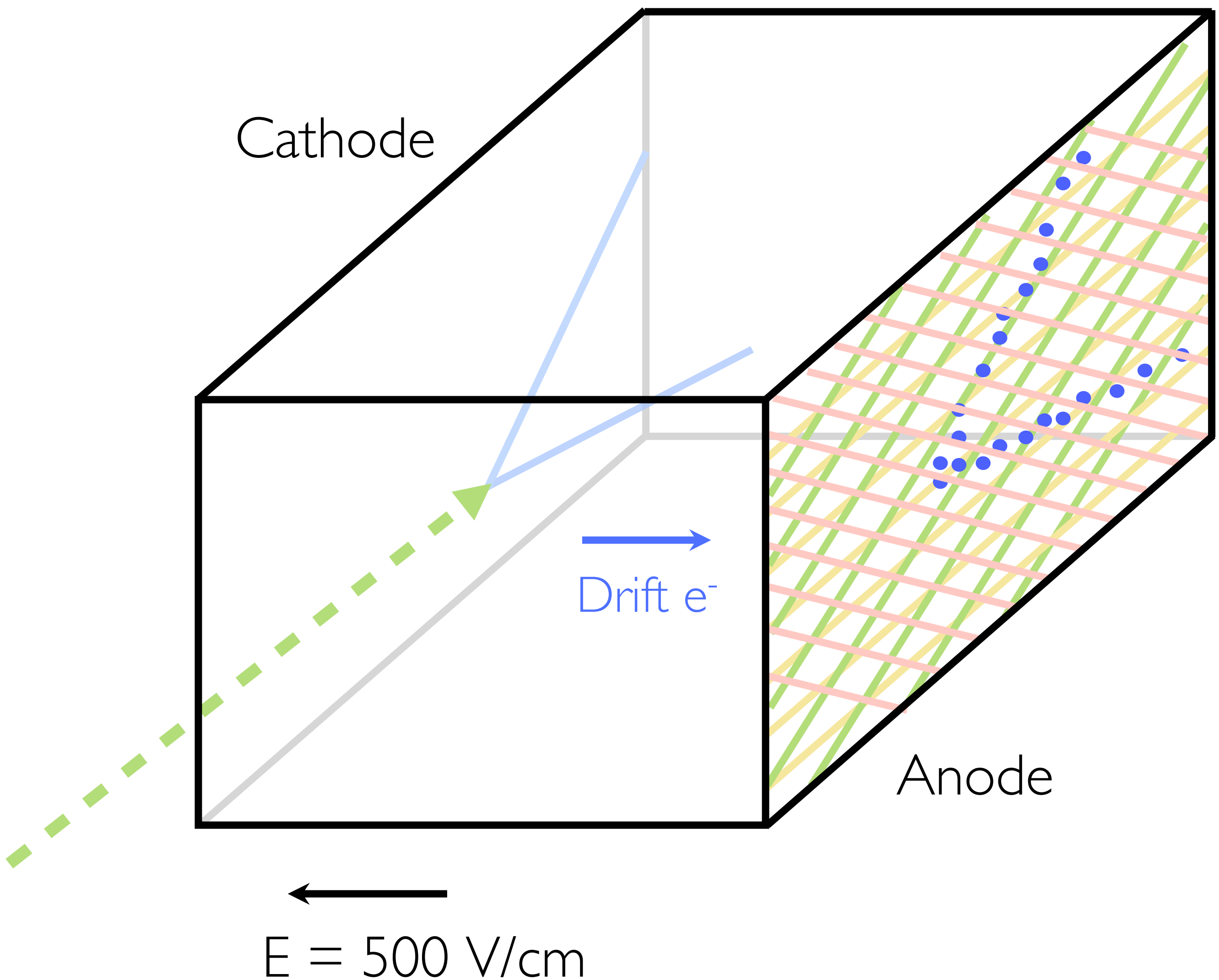
Lar-TPC working principle



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)

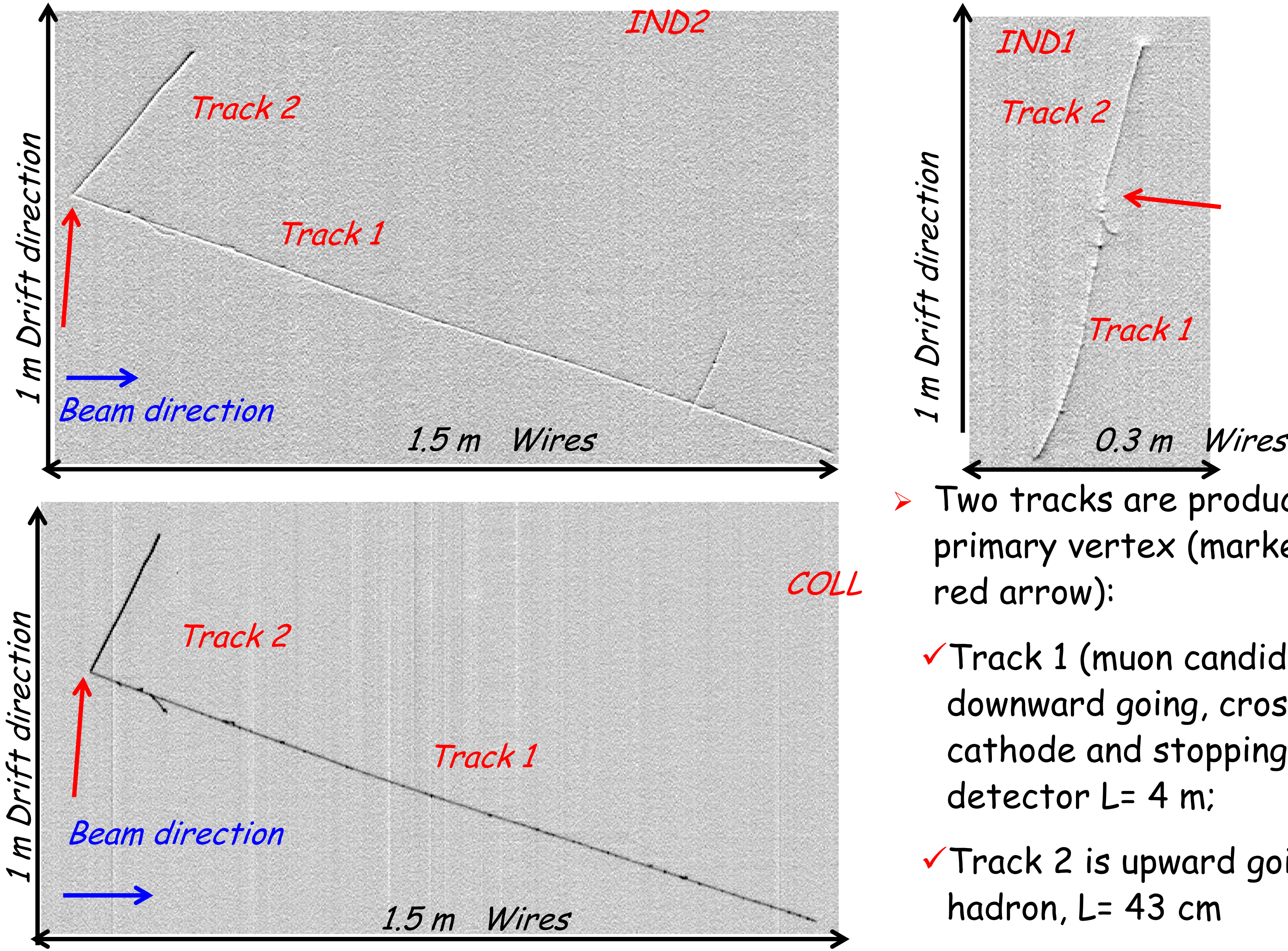
The presence of electronegative impurities, most of all O_2, in the LAr produces an exponential attenuation of the ionization signal along the drift coordinate: to reduce this effect, that can make the signals too low to be identified, the Argon must be continuously filtered and the purity level should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

Lar-TPC working principle



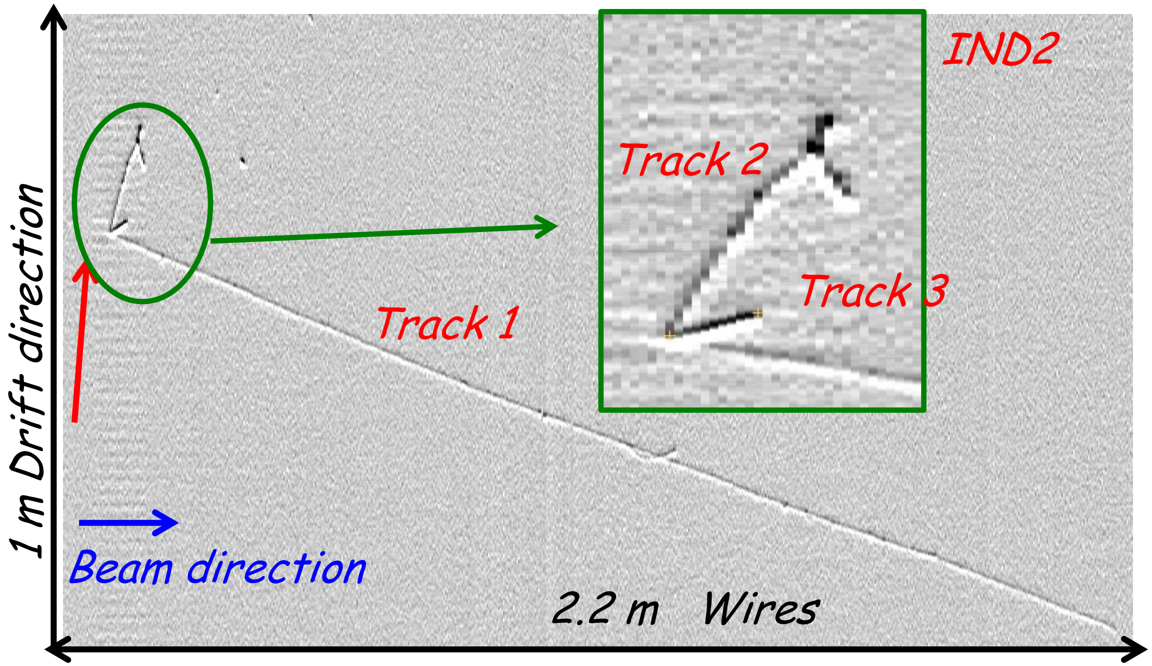
The ionization electrons are then detected by the 3 anodic wire planes providing simultaneous different projections of the same event. The information from these three projections allow a precise reconstruction of the recorded particle trajectories and a precise calorimetric measurement.

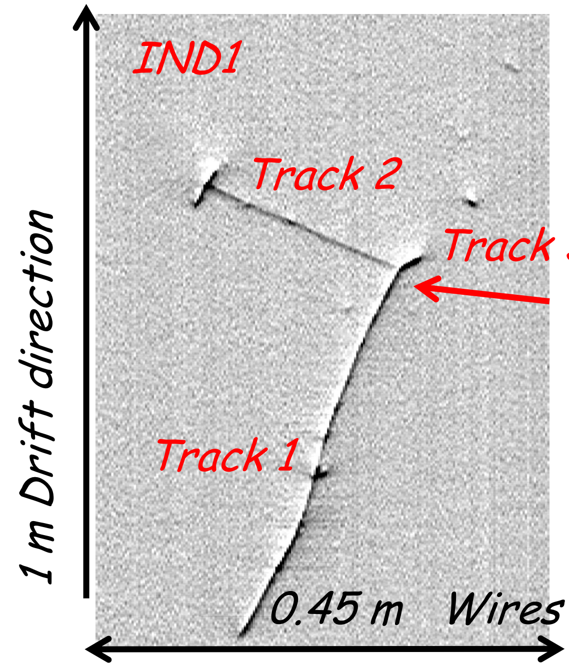
νμ CC candidate: 1 event, 3 pictures

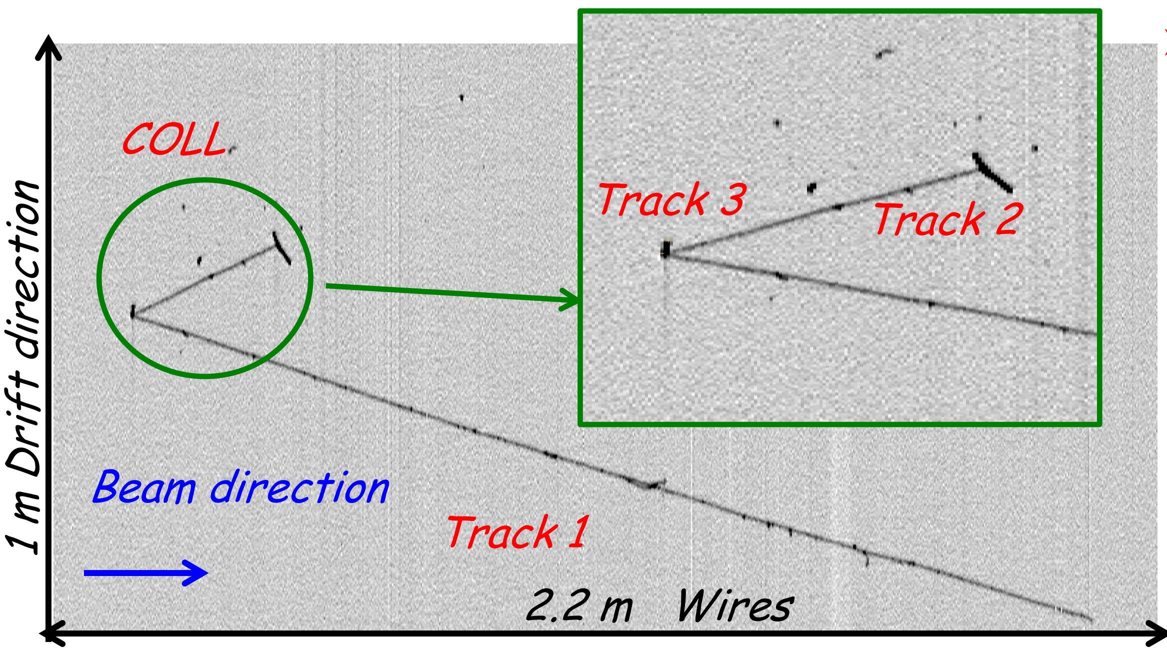


- Two tracks are produced at the primary vertex (marked by the red arrow):
  - ✓ Track 1 (muon candidate) is downward going, crossing the cathode and stopping in the detector L= 4 m;
  - ✓ Track 2 is upward going, stopping hadron, L= 43 cm

νμ CC candidate: 1 event, 3 pictures

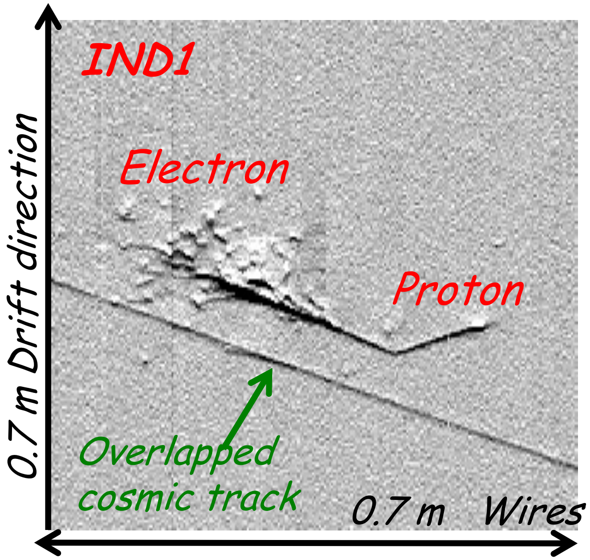


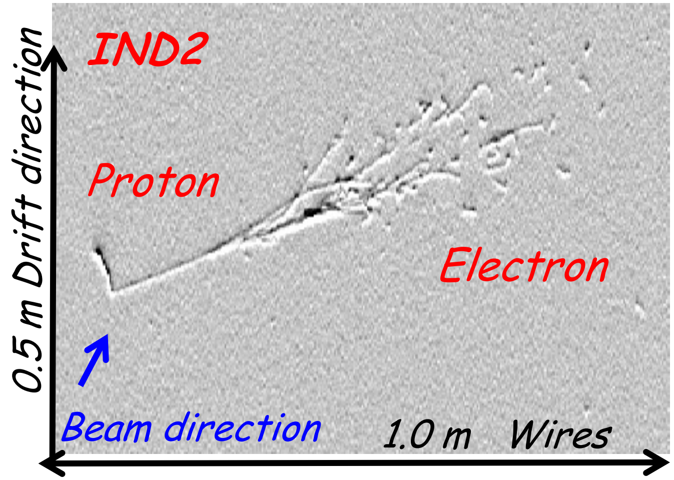




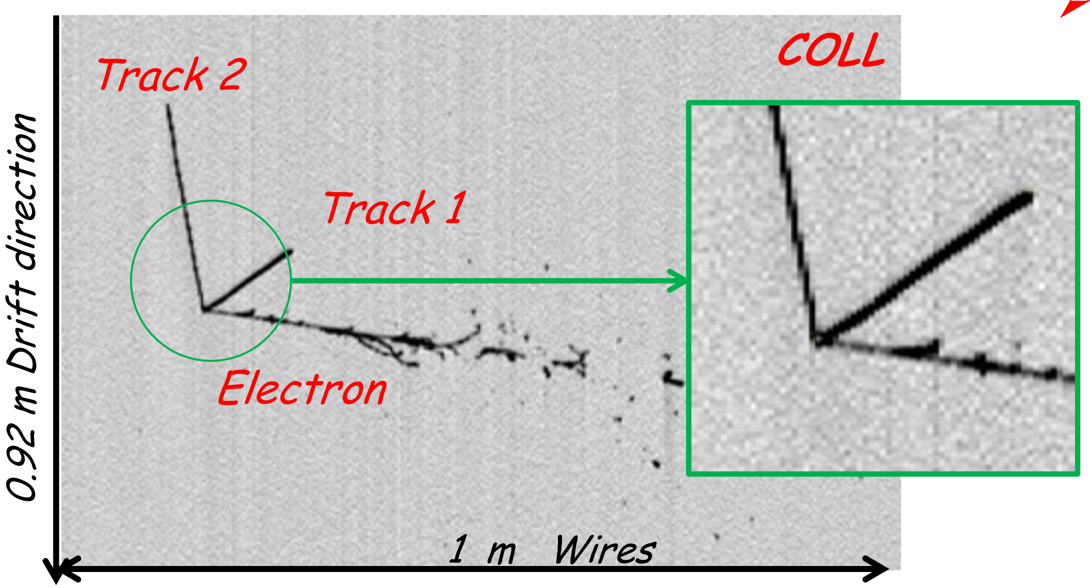
- Three tracks at the primary vertex:
  - ✓Track 1 (muon) is downward going, crossing the cathode and stopping in the detector L= 6.4 m;
  - ✓Track 2 (hadron) is downward going and interacting in the detector and producing two short protons;
  - ✓Track 3 (proton) is upward going L=3.4 cm

NuMI νe CC candidates





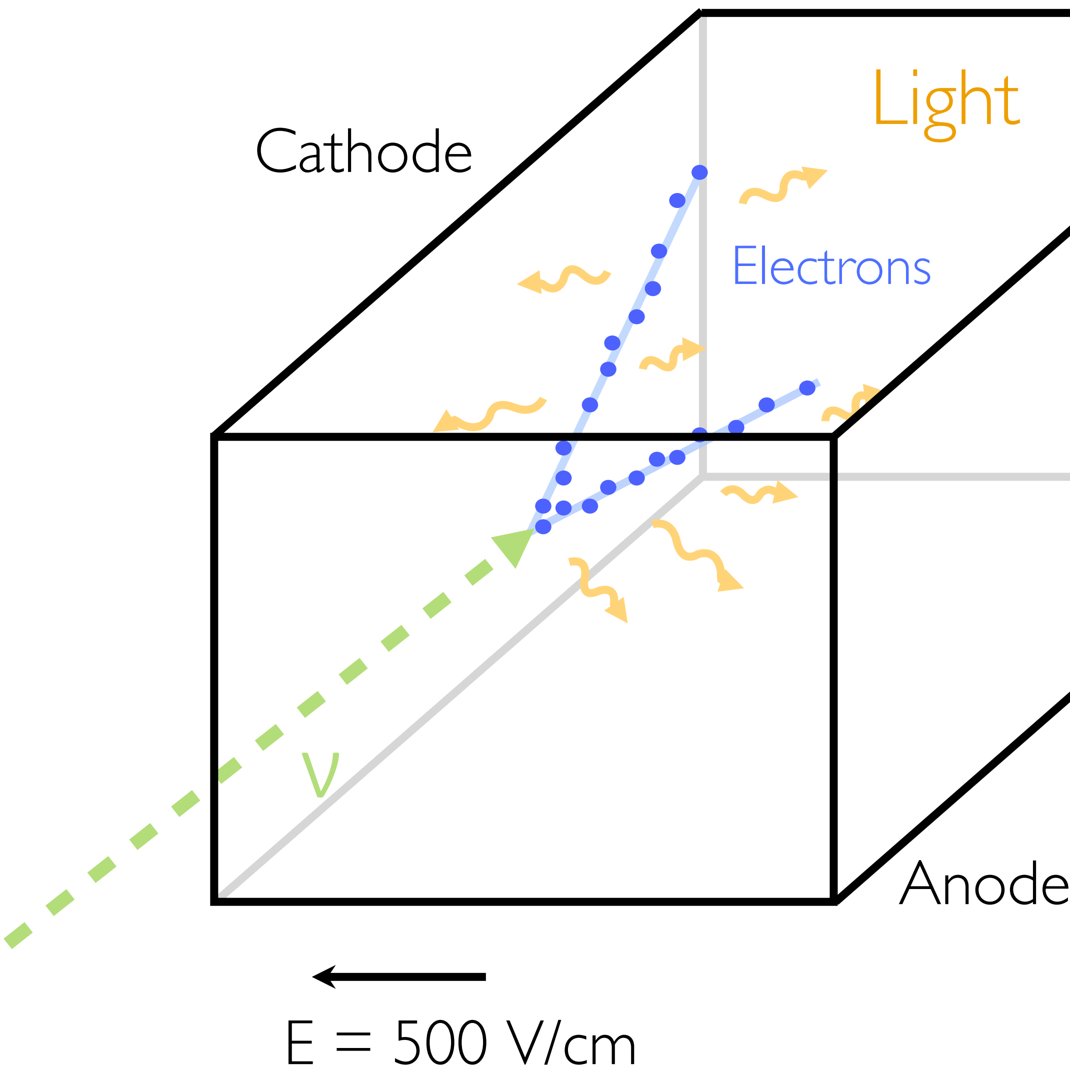
- QE νe CC event candidate, E_{DEP}~870 MeV:
  - ✓ proton candidate is upward going/stopping L= 13 cm;
  - ✓ e-shower is downward going.



- 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.

A new experimental challenge: a LAr-TPC on surface

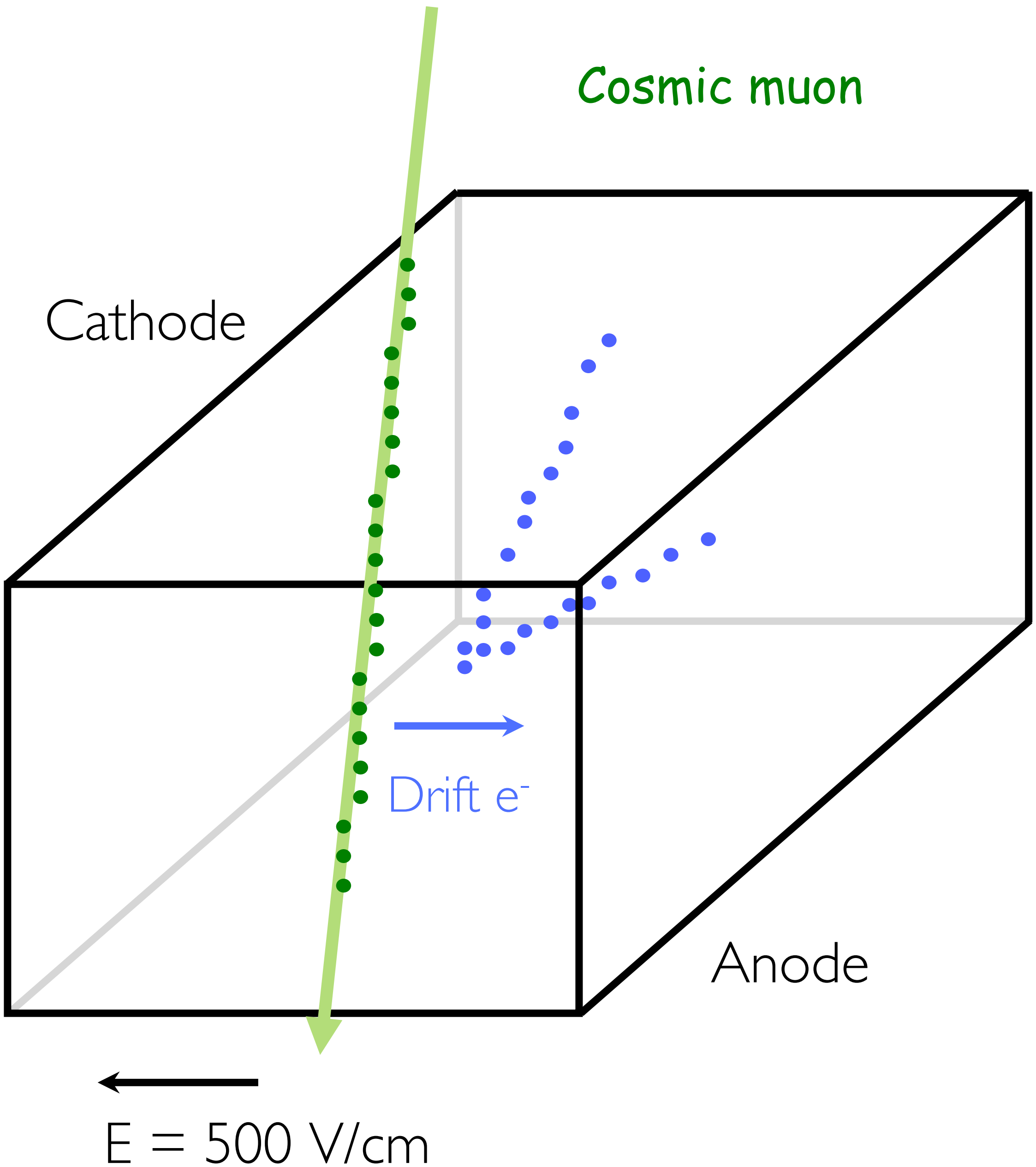
- ICARUS at FNAL is taking data on the Earth surface, facing a more challenging conditions than at LNGS (where cosmic rays are suppressed by a factor ~10^6):



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)

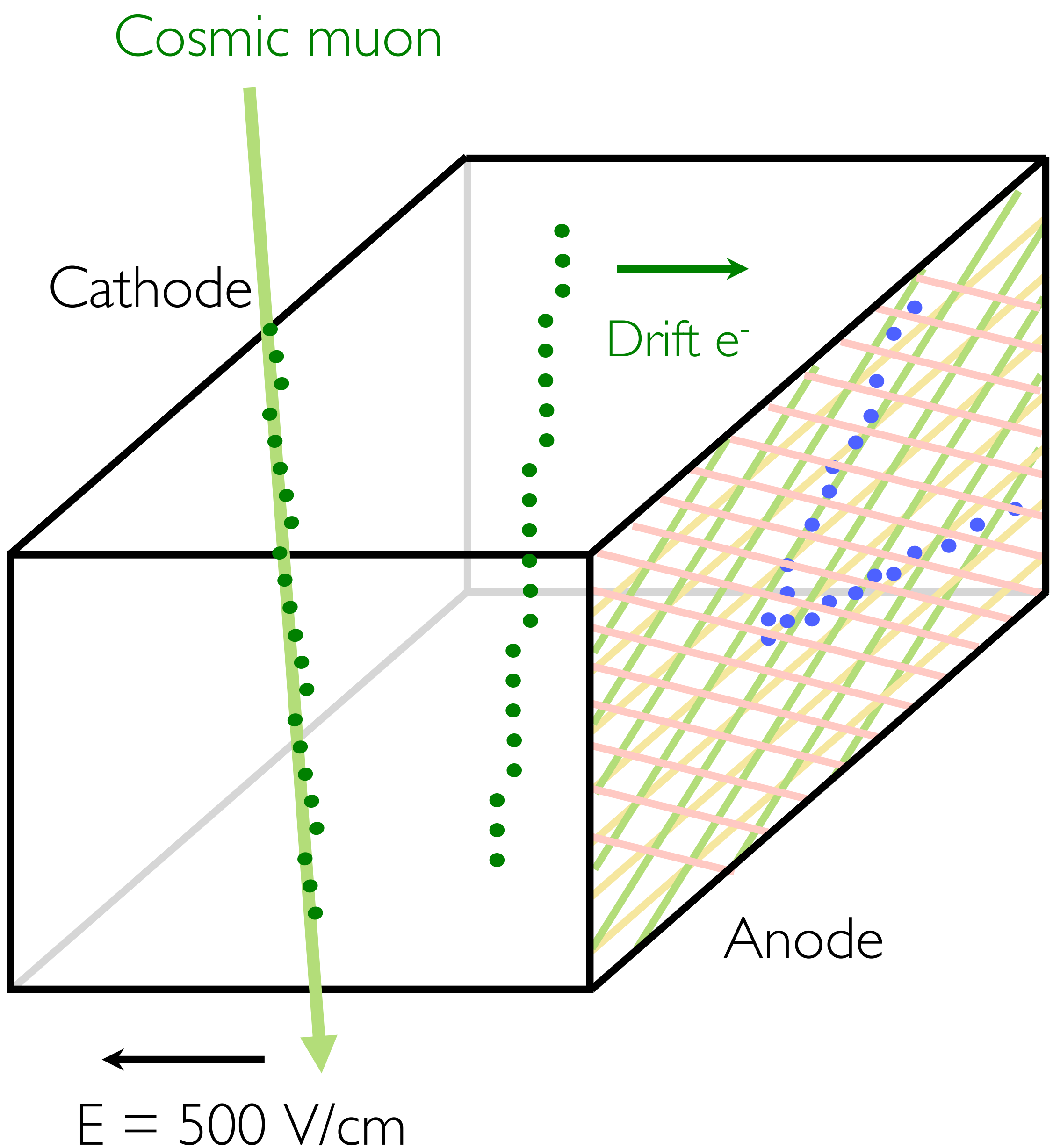
In this time interval all the ionization signals produced in the detector are recorded

A new experimental challenge: a LAr-TPC on surface



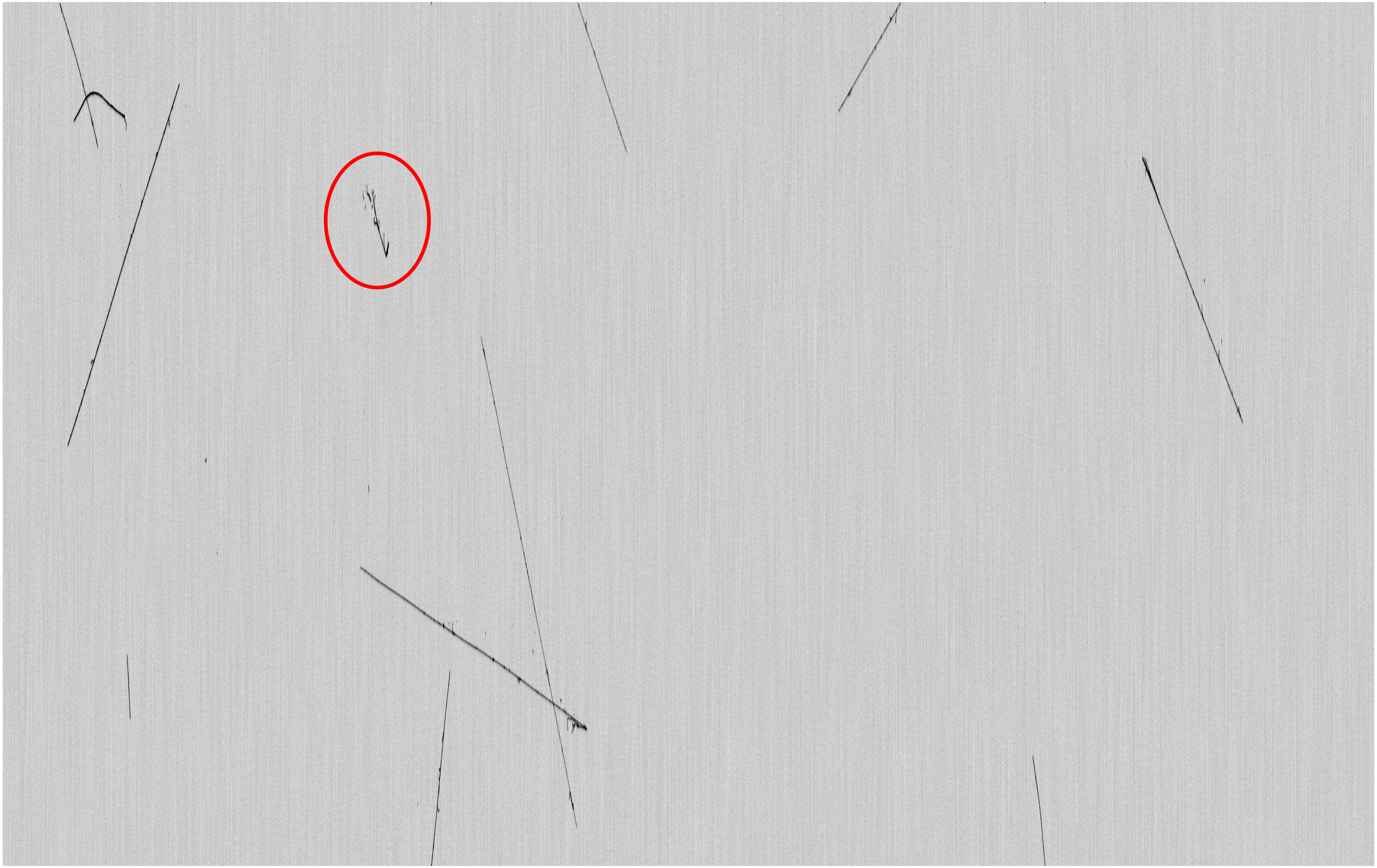
If a charged cosmic particle crosses the detector in a time near the neutrino interaction, also the signal from the cosmic particle will be saved

A new experimental challenge: a LAr-TPC on surface

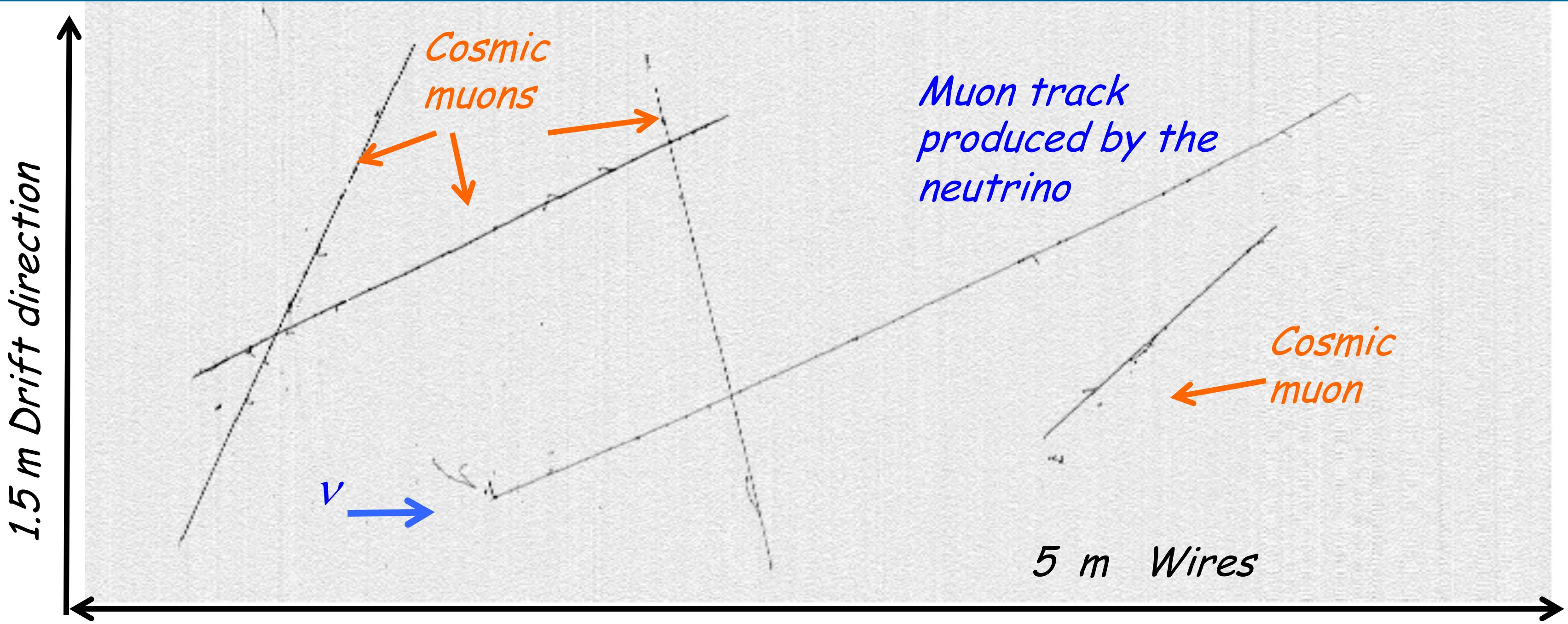


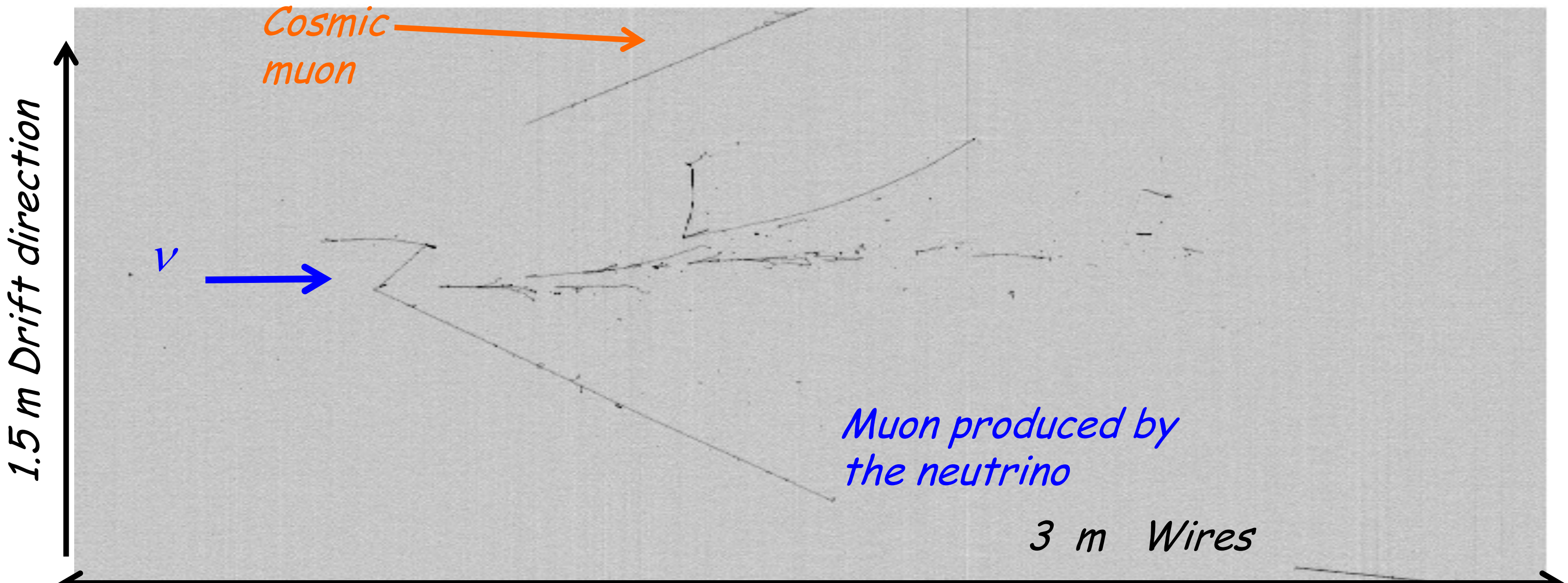
The particle generating the trigger is defined the "in time" particle while the other cosmic particles are defined "out of time" and for them usually the time of the passage in the detector is unknown

A new experimental challenge: a LAr-TPC on surface

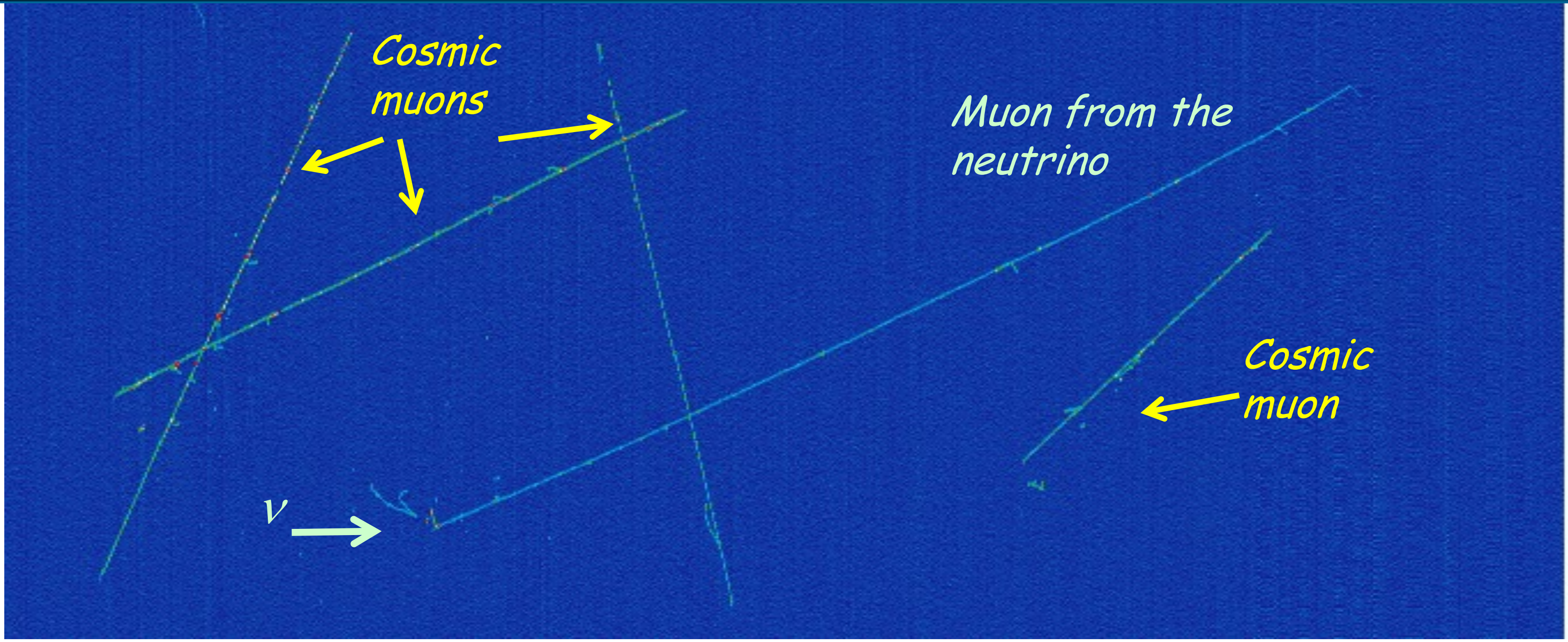


Neutrinos collected by ICARUS at FNAL

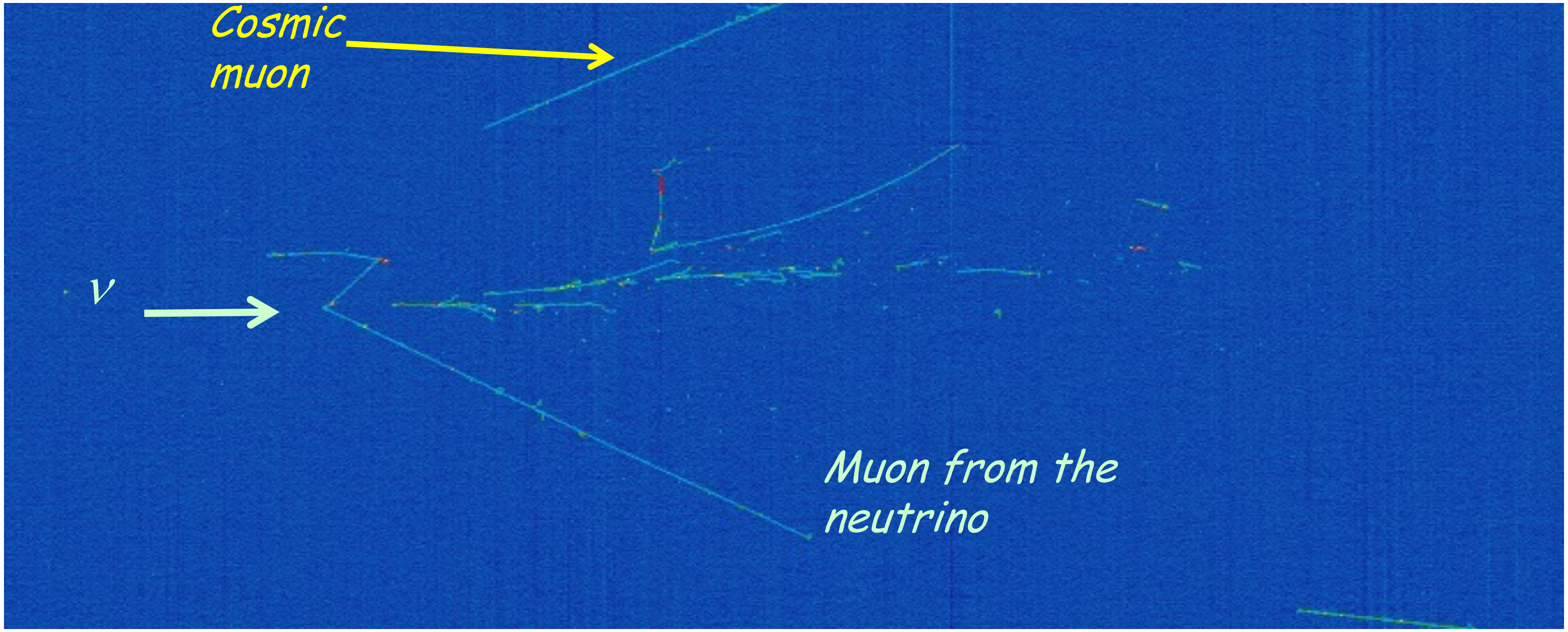




Neutrinos collected by ICARUS at FNAL



5m x 1.5m

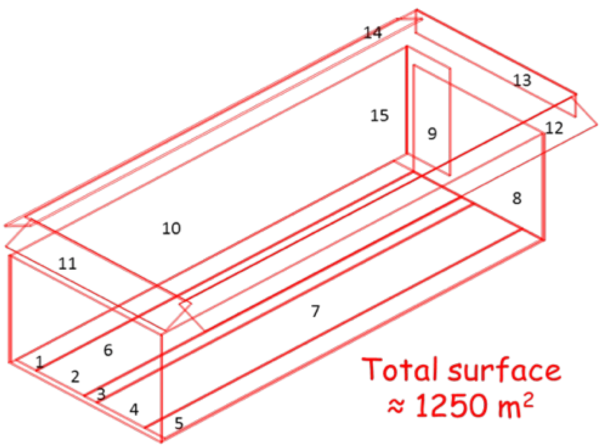


3m x 1.5m

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.

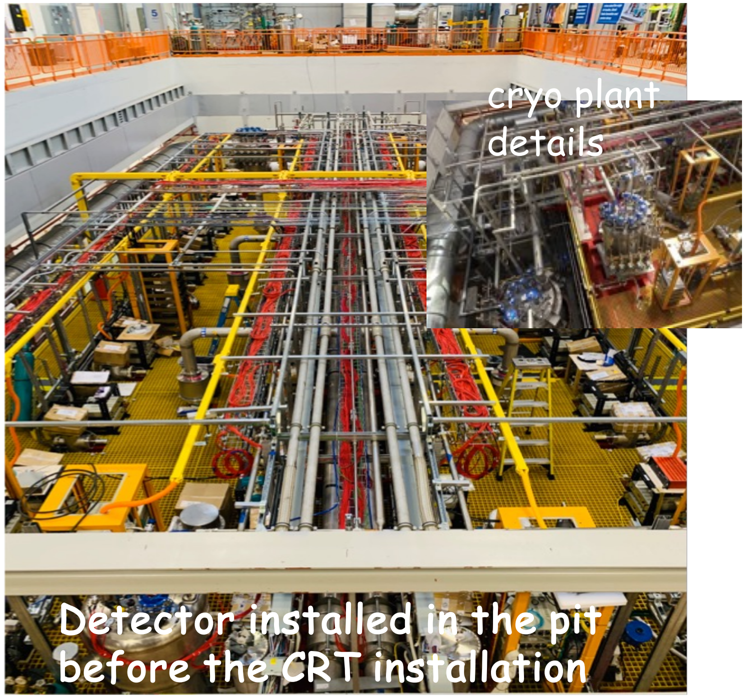
- A 3 m concrete overburden will remove contribution from charged hadrons/γ's.
- ~11 μ tracks will hit the T600 in 1 ms TPC drift window:
  - Automatic tools for the selection of the neutrino interactions and to reject the backgrounds, in particular associated to cosmic particles, are mandatory!
  -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



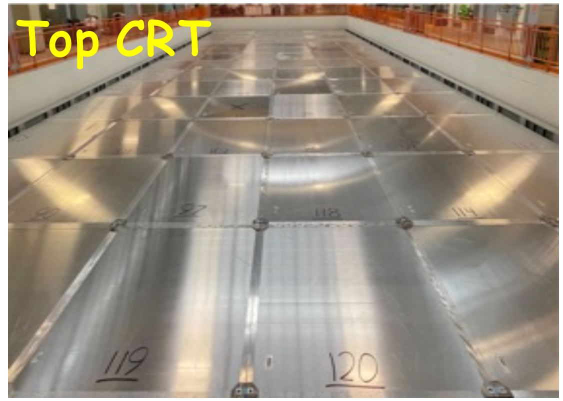
Cosmic Ray Tagging System surrounding the T600 to reject incoming cosmic particles

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

ICARUS T600 installation and activation

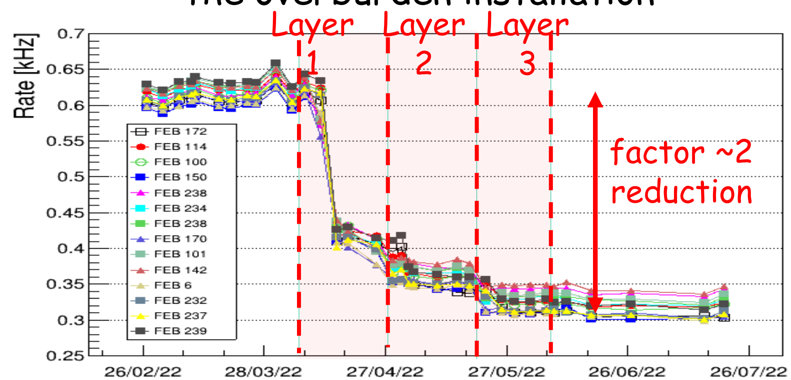


- The Cosmic Ray Tagger system (CRT) encloses the detector: a double layer of scintillator bars (~1000 m^2) tagging incoming cosmics with ~95% efficiency.



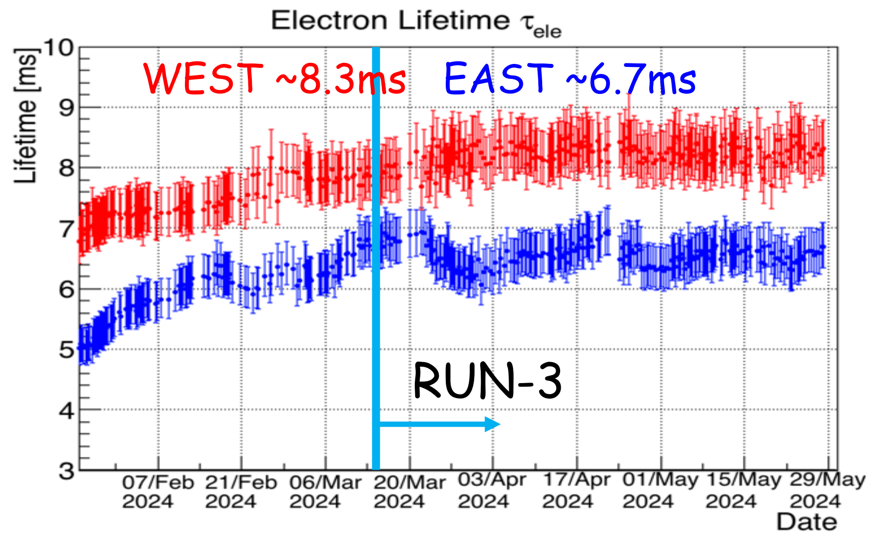
- Cosmic γ's and and neutrons are suppressed by ~2.85 m thick concrete overburden installed on top of the CRT,

Rate of cosmic rays measured during the overburden installation



FNAL operation, runs, collected statistics

- June 2022: start of data taking for physics with TPCs, PMT light detection system and CRT fully operational;
- Events are triggered requiring at least 4 fired PMT pairs inside a 6 m longitudinal T600 slice in coincidence with BNB, NuMI beam spills, >90% efficiency for E_{dep} >200 MeV;
- Data acquisition is largely successful, currently with >97% collection efficiency;
- The cryogenic and purification system performed smoothly keeping residual impurities in LAr at ~40 p.p.t. of [O2] equivalent:
  - The free electron drift lifetime τ_{ELE} ≈7-8 ms, results in an almost full track detection efficiency in the whole 1.5 m drift (t ~ 1 ms).

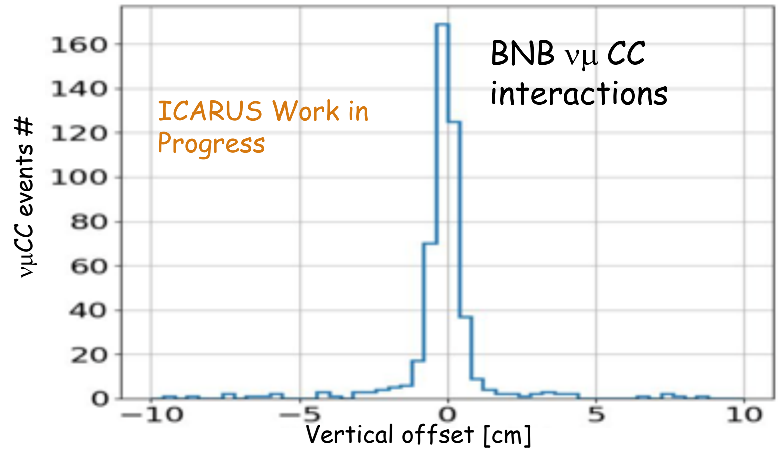


Collected Protons on target (PoT)	BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1 (Jun-Jul 22)	$0.41\ 10^{20}$	$0.68\ 10^{20}$	-
RUN-2 (Dec 22-Jul 23)	$2.05\ 10^{20}$	$2.74\ 10^{20}$	-
RUN-3* (Mar-July 24)	$1.36\ 10^{20}$	-	$2.82\ 10^{20}$
TOTAL (PoT)	$3.82\ 10^{20}$	$3.42\ 10^{20}$	$2.82\ 10^{20}$

* Reduced exposure for RUN-3 due to the prolonged accelerator shutdown

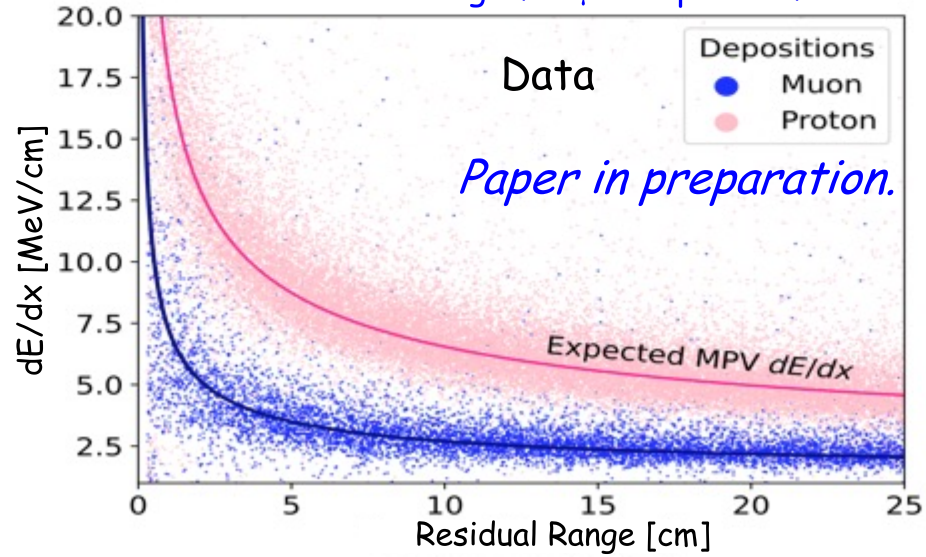
Calibration, detector performance and event reconstruction - highlights

Neutrino vertex reconstruction

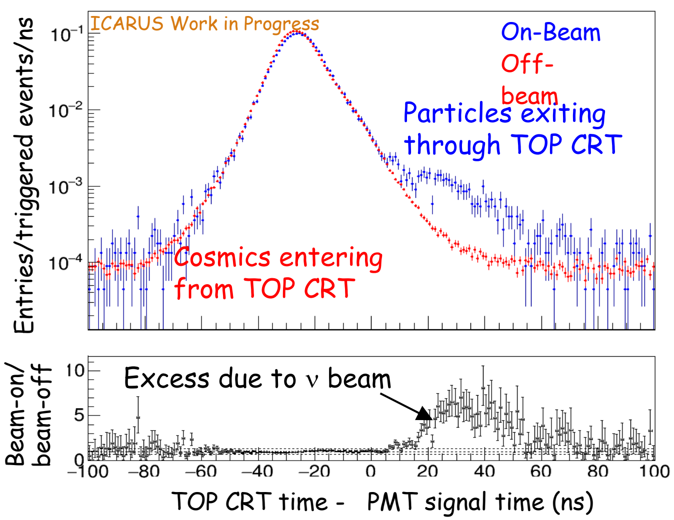


Offset between automatic and visual reconstruction of ν interaction vertex

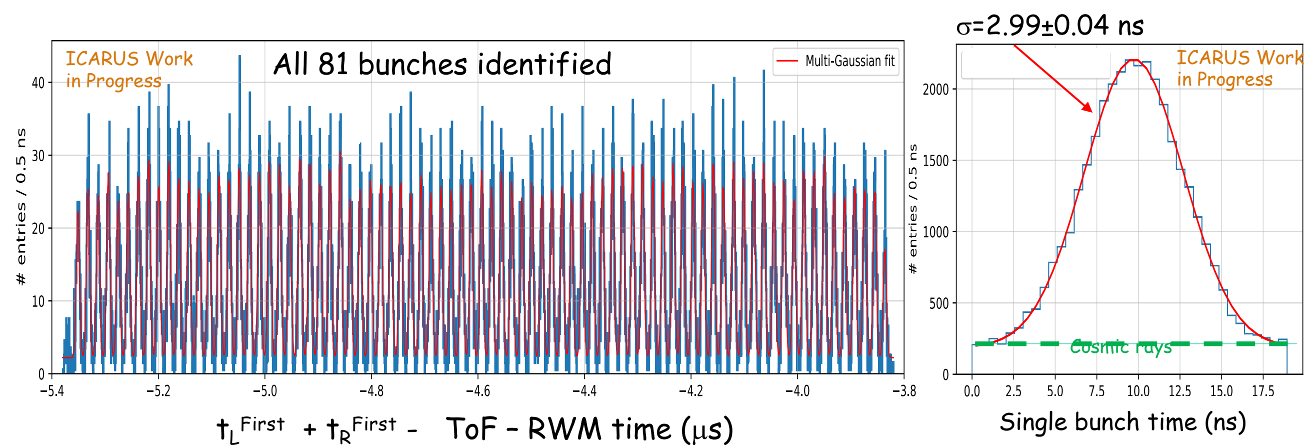
dE/dx Vs residual range for μ and p used for PID



Rejection of incoming cosmics by tof [2)]



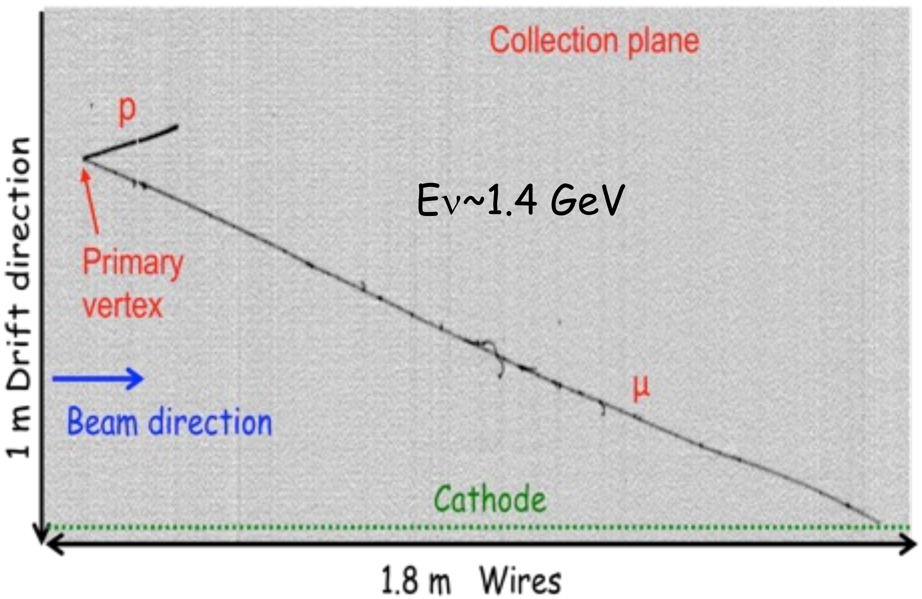
Reconstruction of bunched structure of beam spill

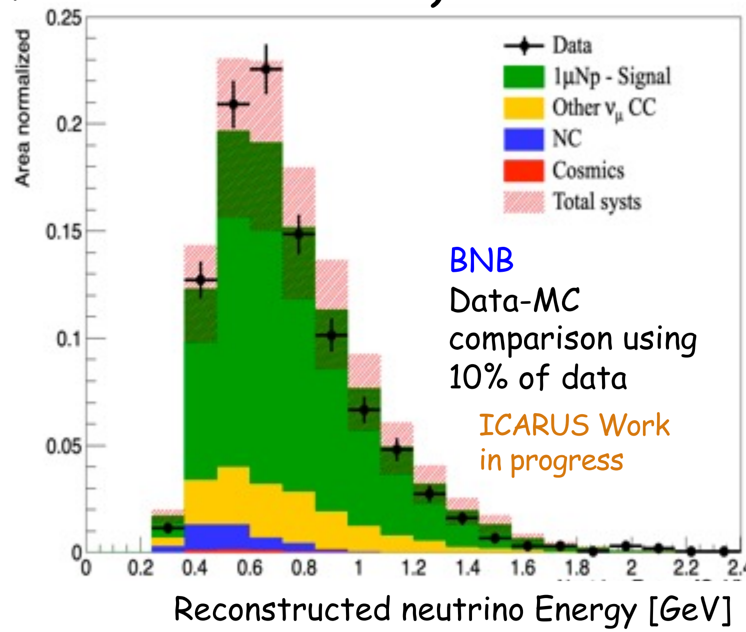


ν event time (PMTs only) wrt beam extraction time (RWM counters) after rejecting incoming cosmics (CRT) and correcting for ν flight

ICARUS Research Program

- Before the start of joint SBN operation, ICARUS is focusing on standalone physics program, also in preparation for the SBN oscillation analyses:
  - Investigation of ν_μ disappearance with BNB ν beam: focus on fully contained ν_μCC events with a muon L_μ>50 cm and at least one proton with E_K>50 MeV (L_p>2.3 cm);
    - ✓ Data-MC agreement within systematics for all studied event kinematic variables; (10% of RUN-2 data analyzed, 20 time more data available)



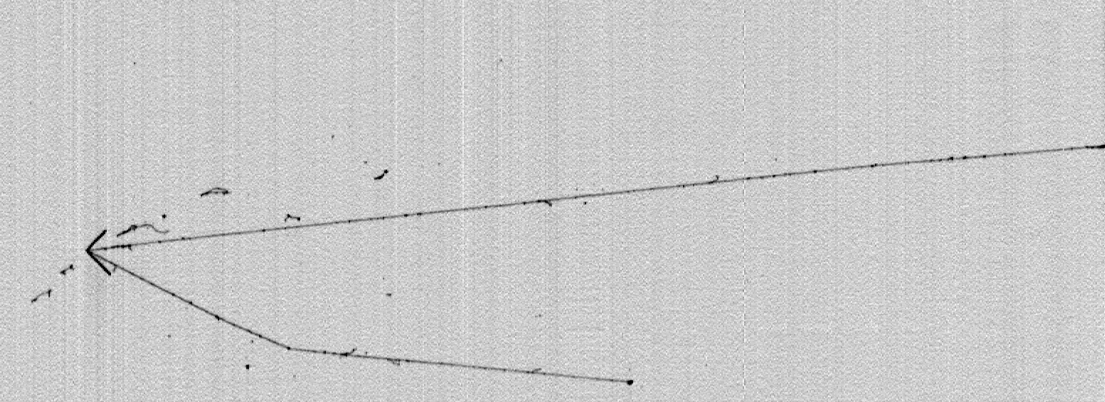


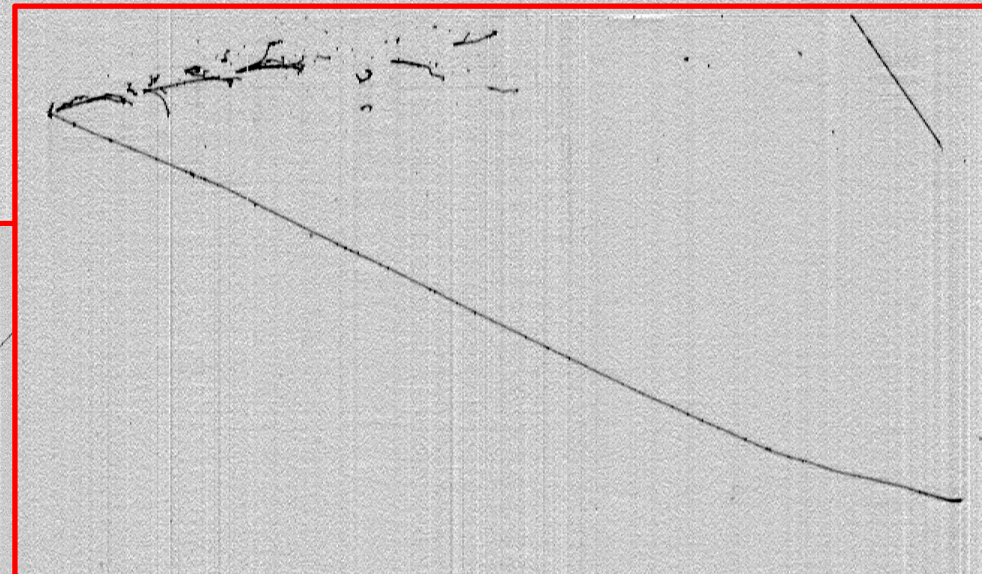
  - Study of ν_e, ν_μ events from NuMI beam, to measure ν-Ar interaction cross sections and optimize ν reconstruction/identification in an energy range of interest for DUNE.
  - Exploit the off-axis NuMI beam to investigate sub-GeV Beyond Standard Model (BSM) signals;

Conclusions

- ICARUS is smoothly running in physics mode since June 2022, exposed to the Booster and to the NuMI neutrino beams;
- The detector is calibrated, electronic response and physical properties have been accurately qualified and are being fully modeled in simulation. Papers are in preparation.
- While waiting for the joint operation within SBN, several single detector analyses are quite advanced:
  - Study of $\nu\mu$ disappearance with the BNB beam;
  - Measurement of $\nu\mu$ cross-sections with NuMI beam;
  - Search for Sub-GeV DM candidates in NuMI beam. A first search for new particle decaying into di-muon has been completed and now a paper is in preparation.
- Analyses ready to proceed to validation with larger control samples in view of the full signal unblinding.

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





Thank you!