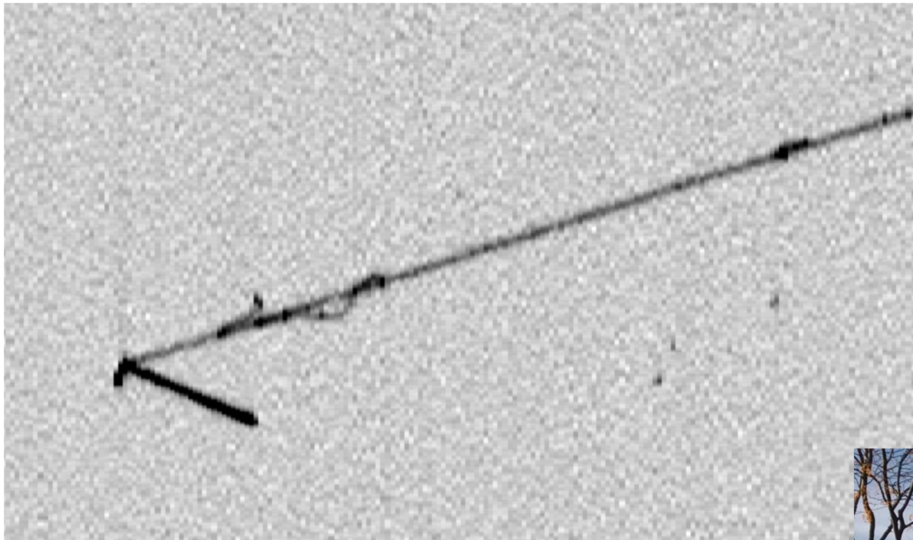
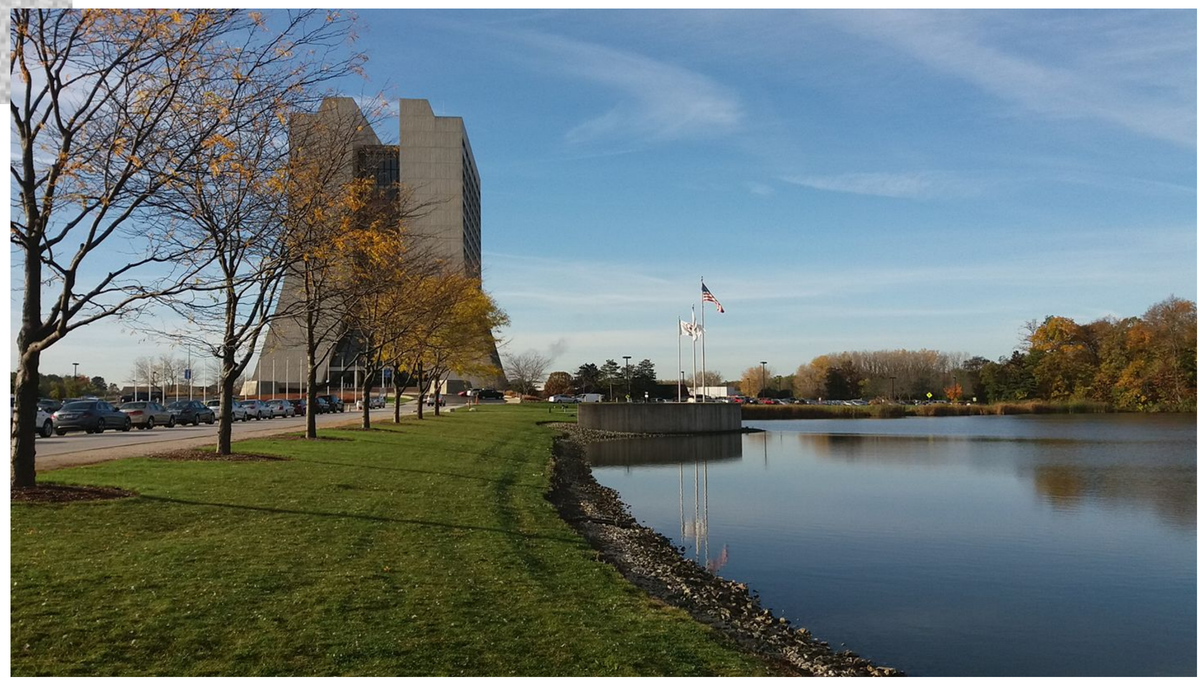
Neutrino search with the ICARUS T600 detector



FERMILAB 2021 SUMMER SCHOOL AT LNF

August 3rd 2021



Christian Farnese
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on behalf of the ICARUS collaboration

European Commission

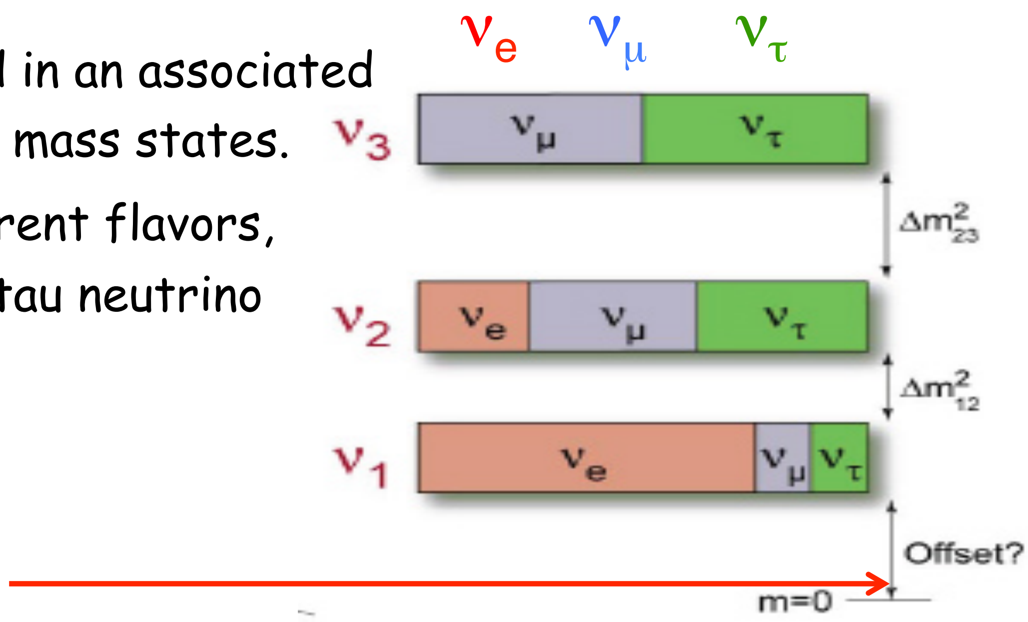
INFN

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.

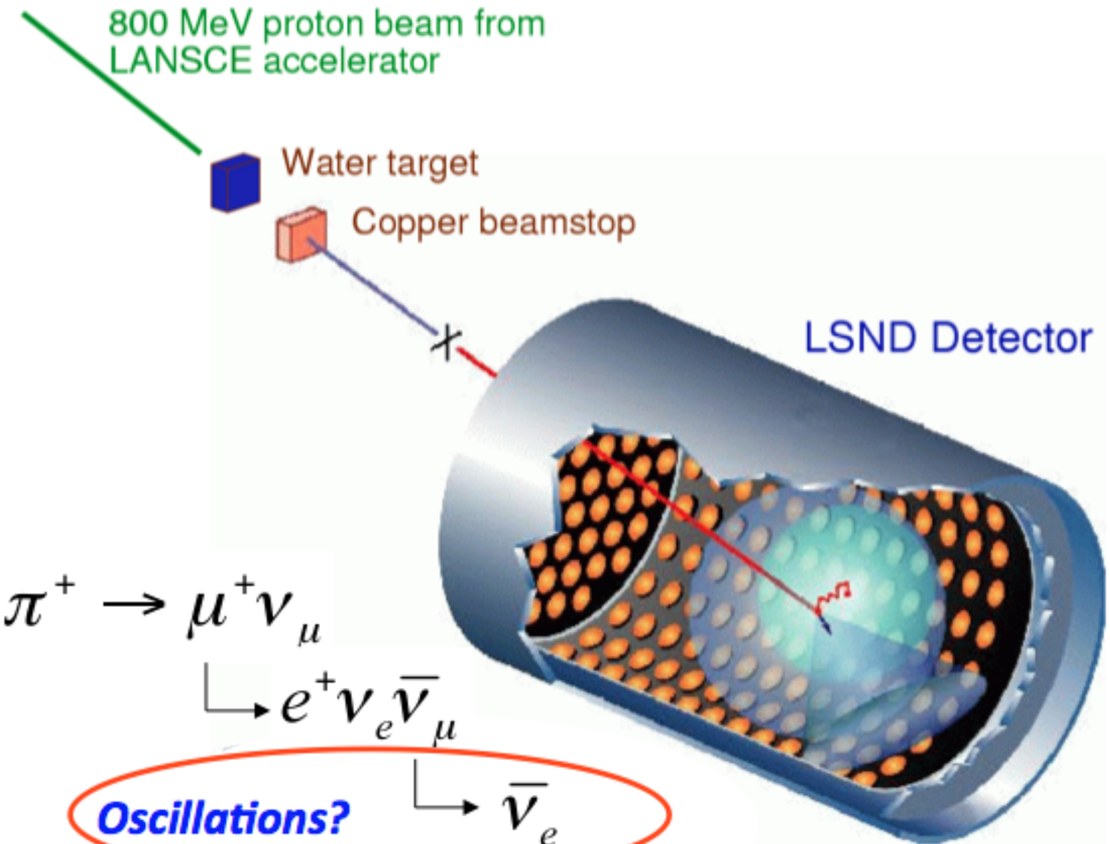
Neutrinos are the most abundant massive particles in Universe

- 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 experiment: evidence for a fourth neutrino?

The LSND Anomaly



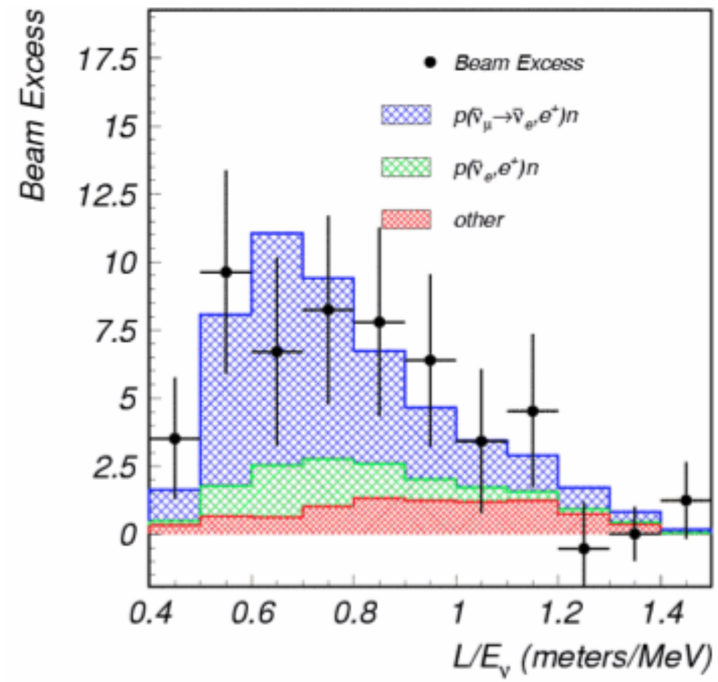
$\pi^+ \rightarrow \mu^+ \nu_\mu$

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

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

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

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



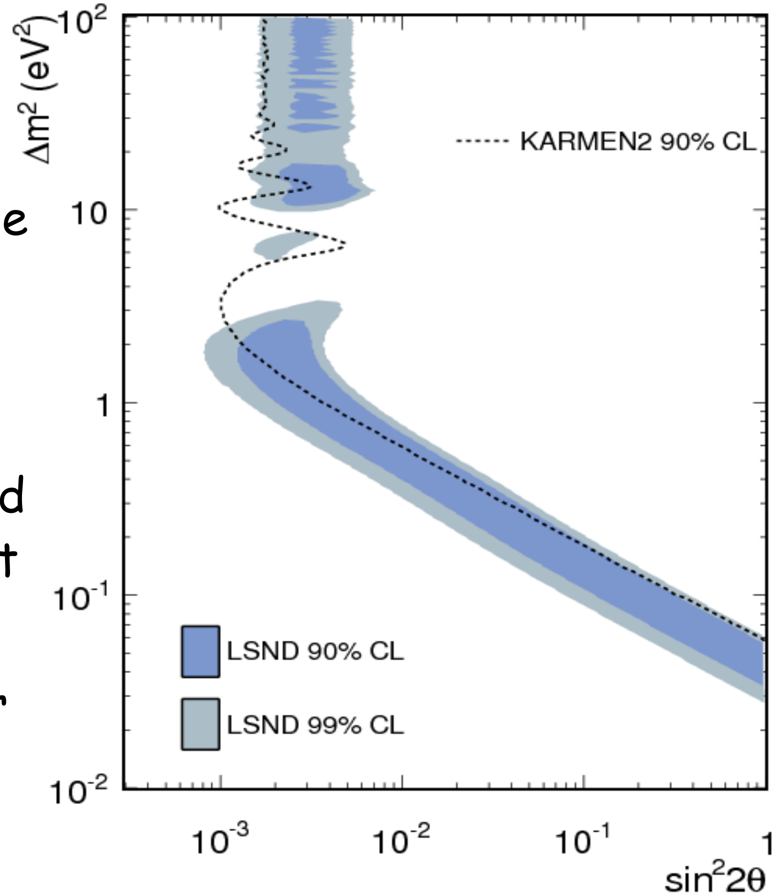
Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

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

3.8 σ evidence for oscillation.

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

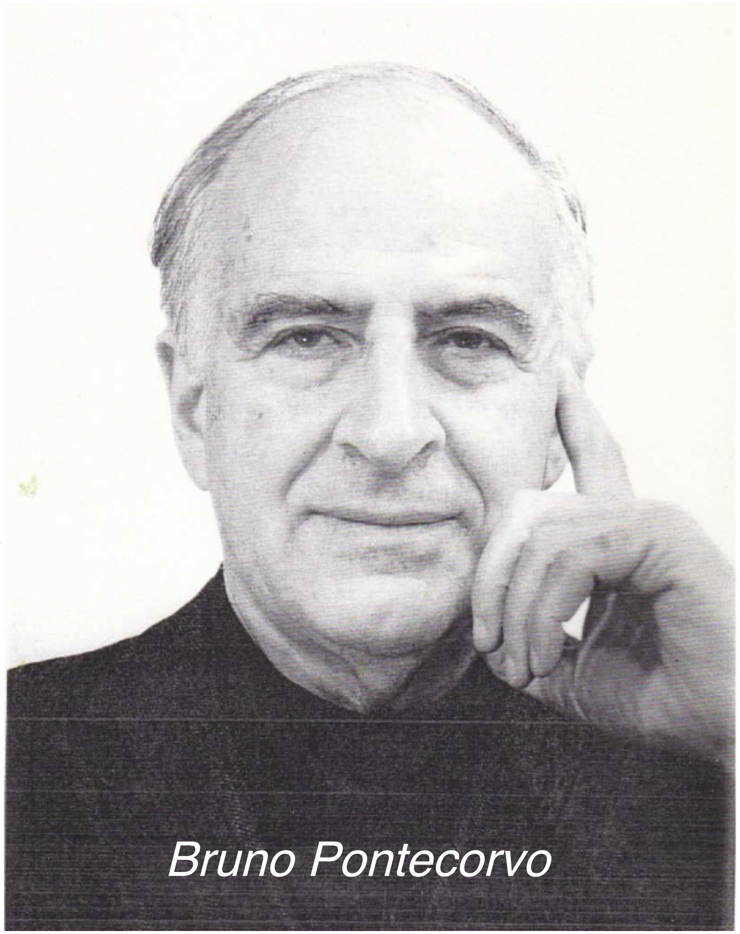


- Additional anomalous signals has been then observed and seems to indicate an evidence of oscillation that can be described considering a $\Delta m^2 \sim 1\ eV^2$:
  - ➢ appearance of νe from νμ beams in accelerator experiments, not only at LSND, but also at MiniBooNE, that studied the Booster neutrino 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 $\Delta m^2 = m^2_4 - m^2_1$???

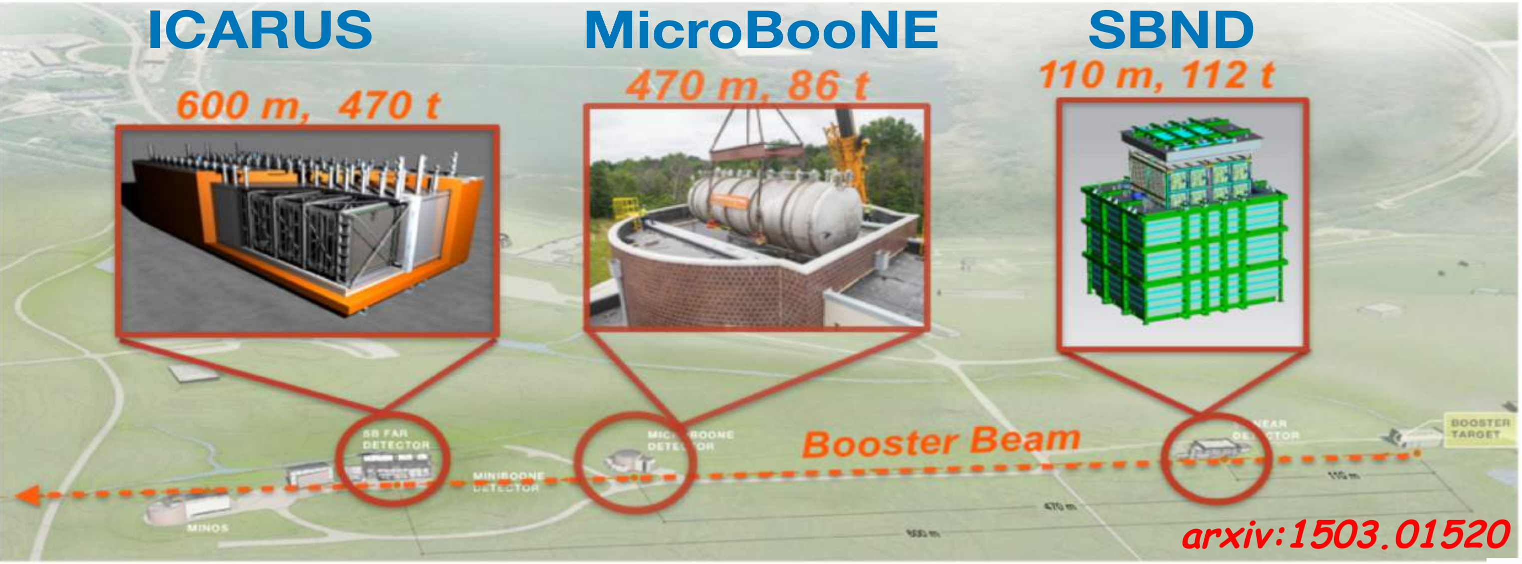
"Sterile" neutrinos?

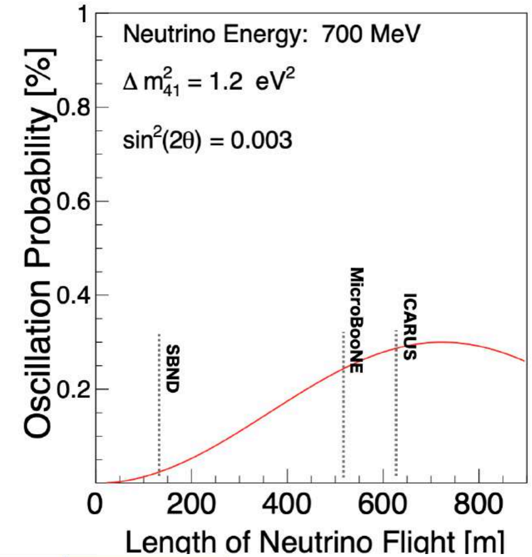
- Sterile neutrinos are an hypothetical type of neutrinos that do no interact via any of the fundamental interactions of the Standard Model except gravity.
- The name was conied in 1957 by Bruno Pontecorvo.
- If they are heavy enough, they may also contribute to cold or warm dark matter.
- Sterile neutrino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

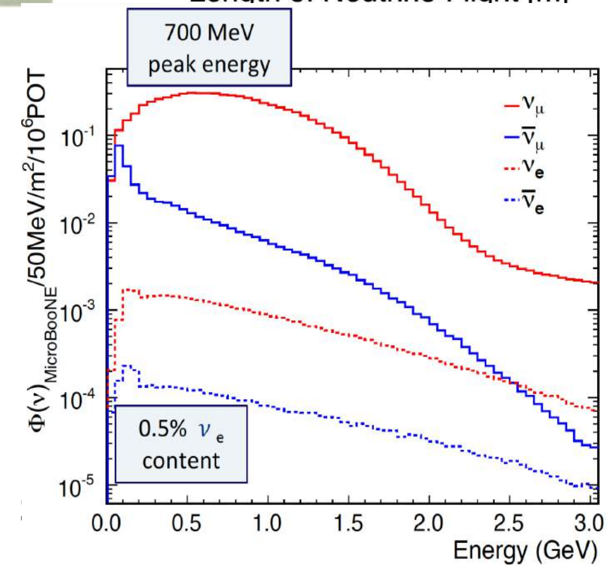

Bruno Pontecorvo

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

The SBN project





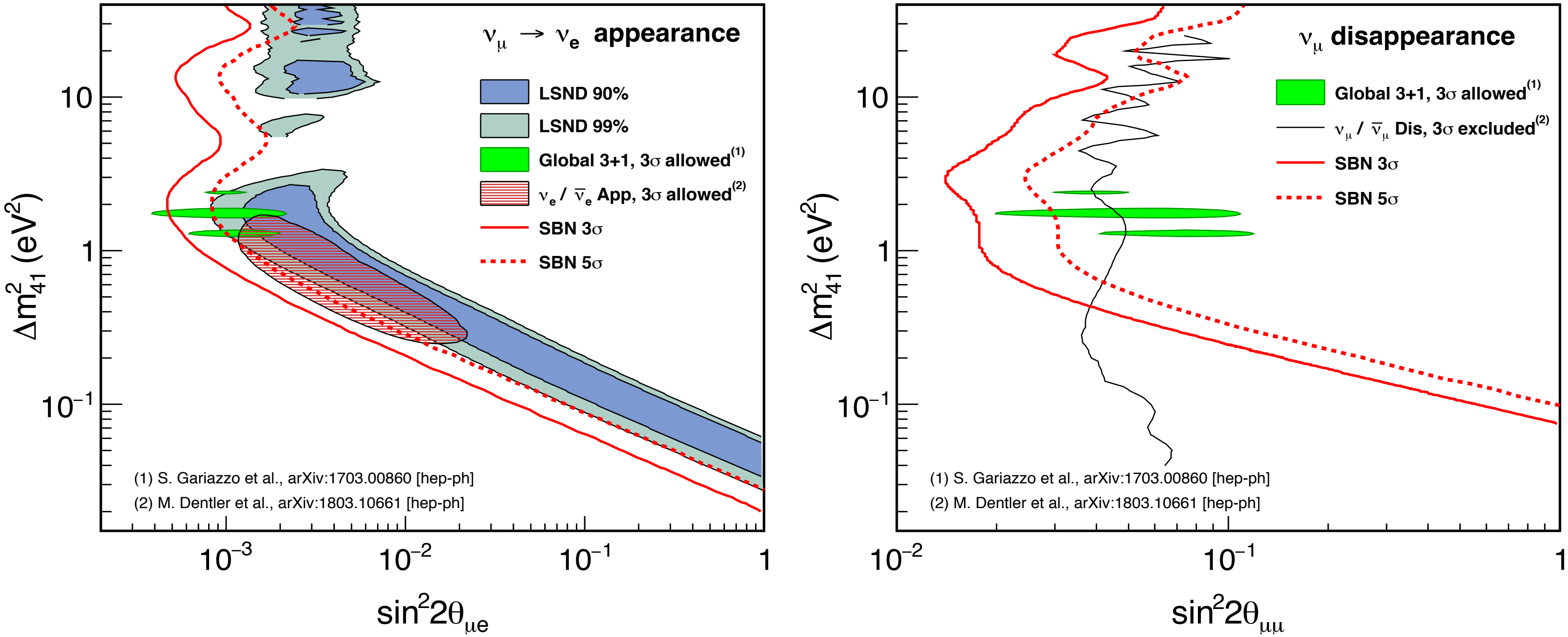


- Three LArTPC detectors at different baselines from Booster neutrino beam searching for sterile ν oscillations measuring both appearance and disappearance channels
- During SBN operations, ICARUS, as far detector, will also collect neutrinos from NuMI Off-Axis beam with a large νe component with ~3 GeV energy, providing ν interaction cross-section measurements in LAr and identification/reconstruction studies for the future long-baseline project DUNE.
- Expected events Rates (Hz) at ICARUS:

	neutrinos	cosmics
from Booster	0.03	0.11
from NuMI	0.014	0.08

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



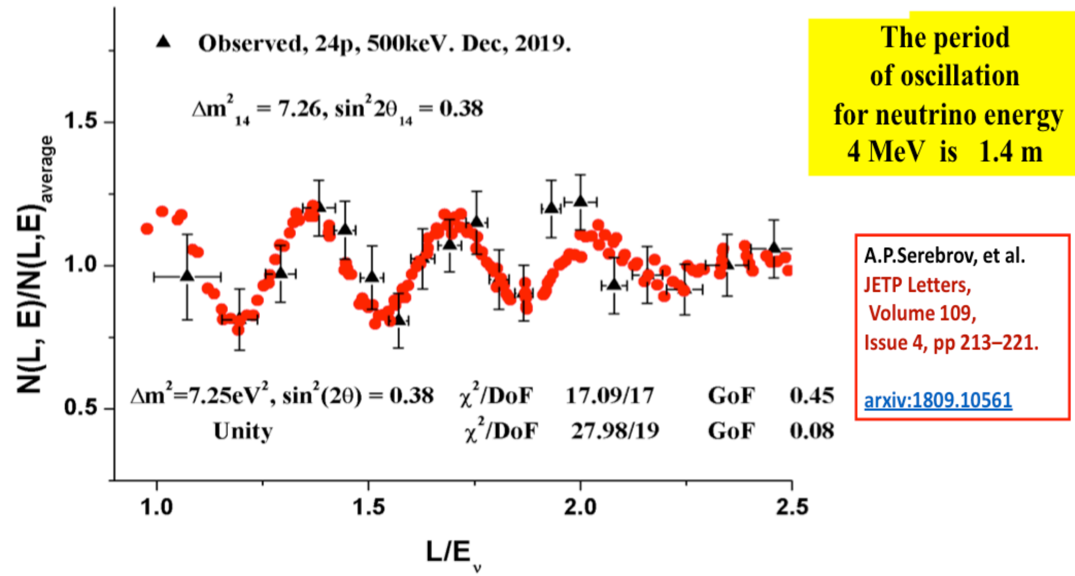
https://arxiv.org/pdf/1903.04608.pdf

- 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

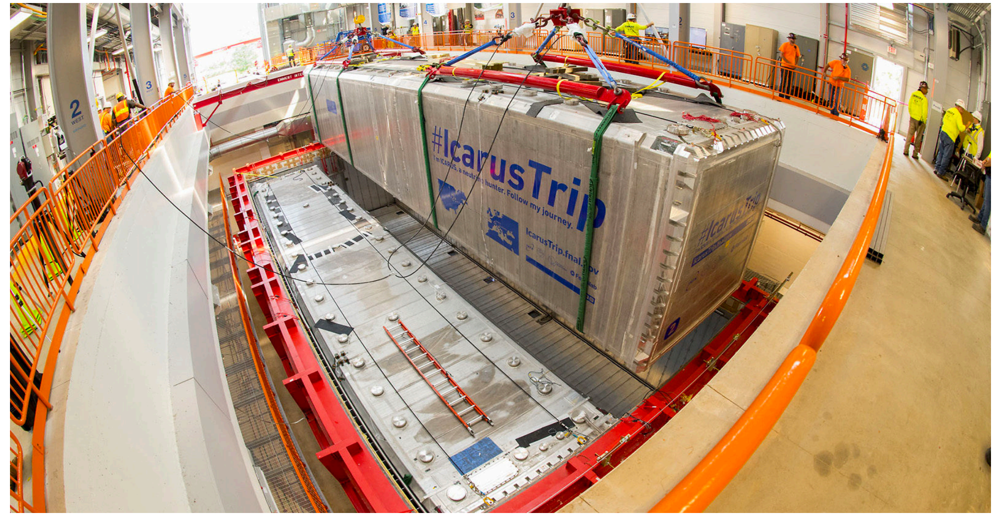


- ICARUS will be able to test this oscillation hypothesis in the same L/E range in two independent channels, with different beams:
  - Disappearance of $\nu\mu$ from the BNB beam, focusing the analysis on quasi-elastic $\nu\mu$CC interactions where the muon is contained and at least 50 cm long. ~11500 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 T600: the first large Liquid Argon TPC (760 t of LAr)

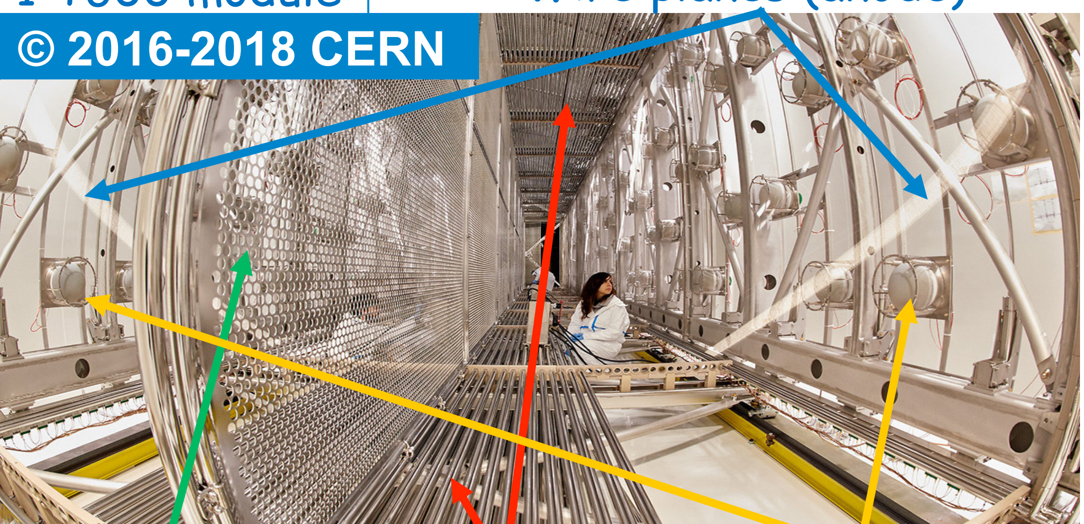
- ICARUS-T600 LAr TPC is a high granularity uniform self-triggering detector with 3D imaging and calorimetric capabilities, ideal for ν physics. It allows to accurately reconstruct a wide variety of ionizing events with complex topology.
- Its operation at the underground LNGS laboratory (2010-13) confirmed the maturity of this technique.



Two identical modules: 476 t total active mass:

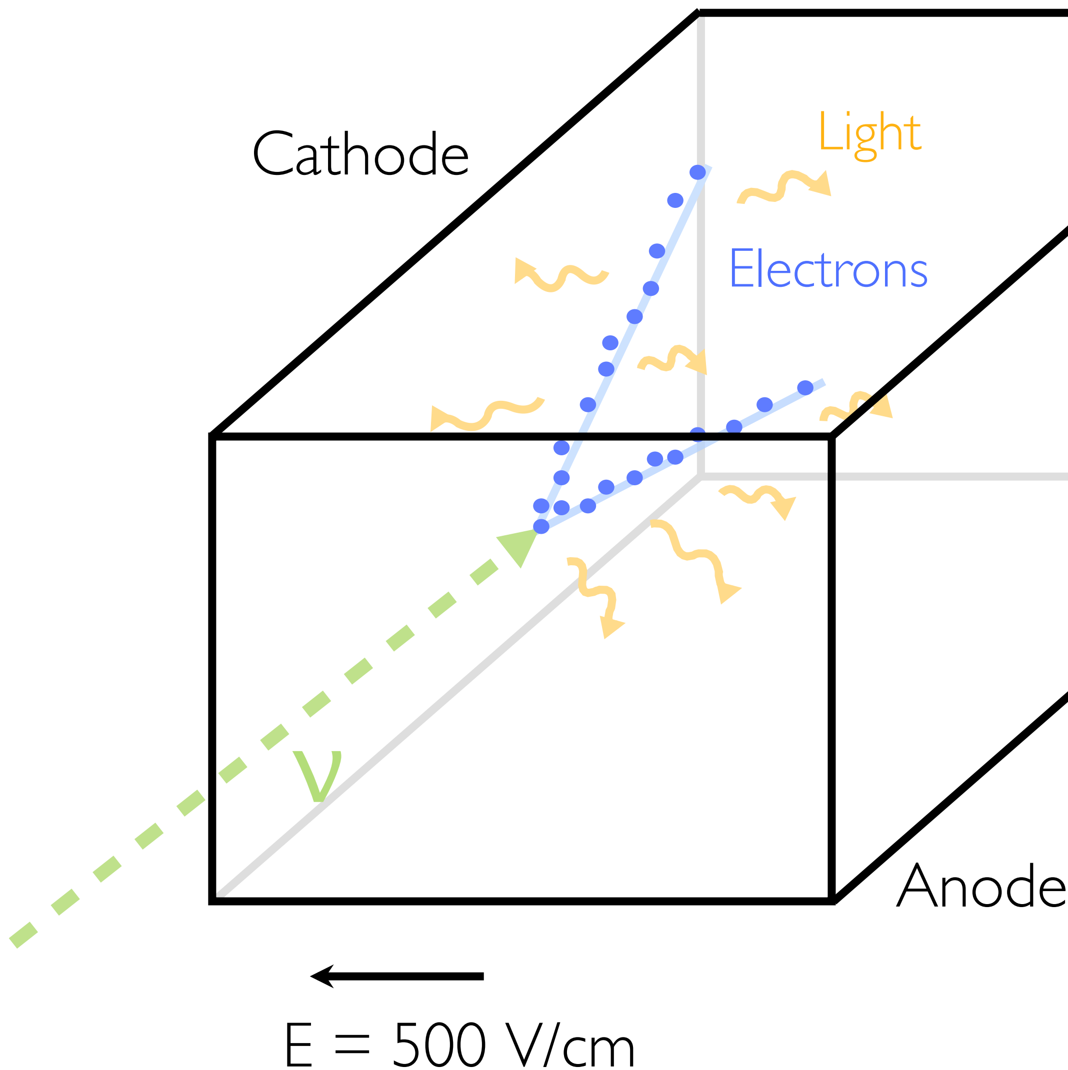
- 2 TPC's per module, with a common central cathode: E_{Drift}= 0.5 kV/cm, v_{Drift}~1.6 mm/μs, 1.5 m drift length;
- Ionization charge continuously read (0.4 μs sampling time) by 3 "non-destructive" readout wire planes per TPC, ≈54000 wires at 0°, ±60° w.r.t. horizontal: Induction 1, Induction 2 and Collection views;
- 8" PMT's, coated with TPB wls, for t_0, timing and triggering.

1 T600 module



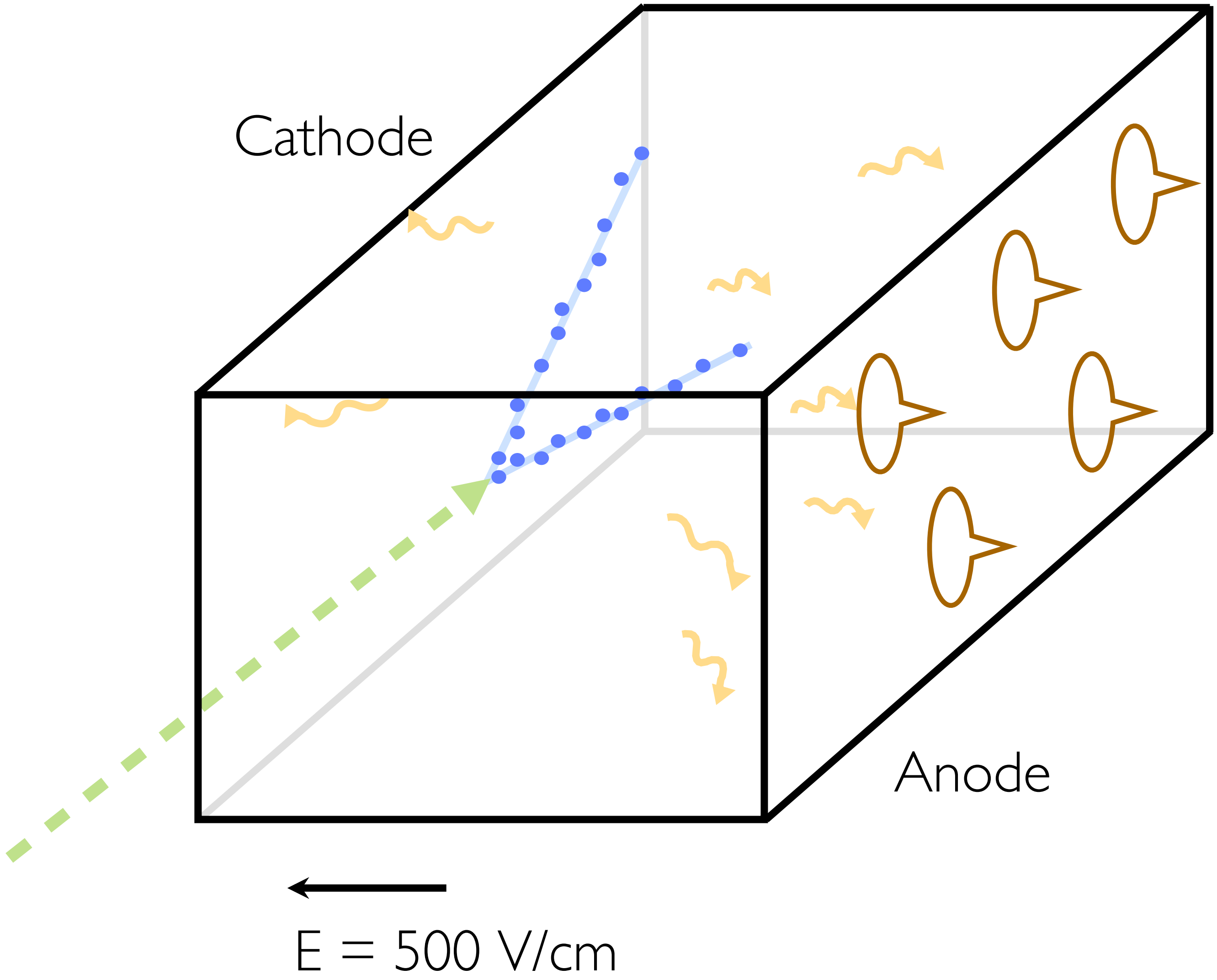
Lar-TPC working principle

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



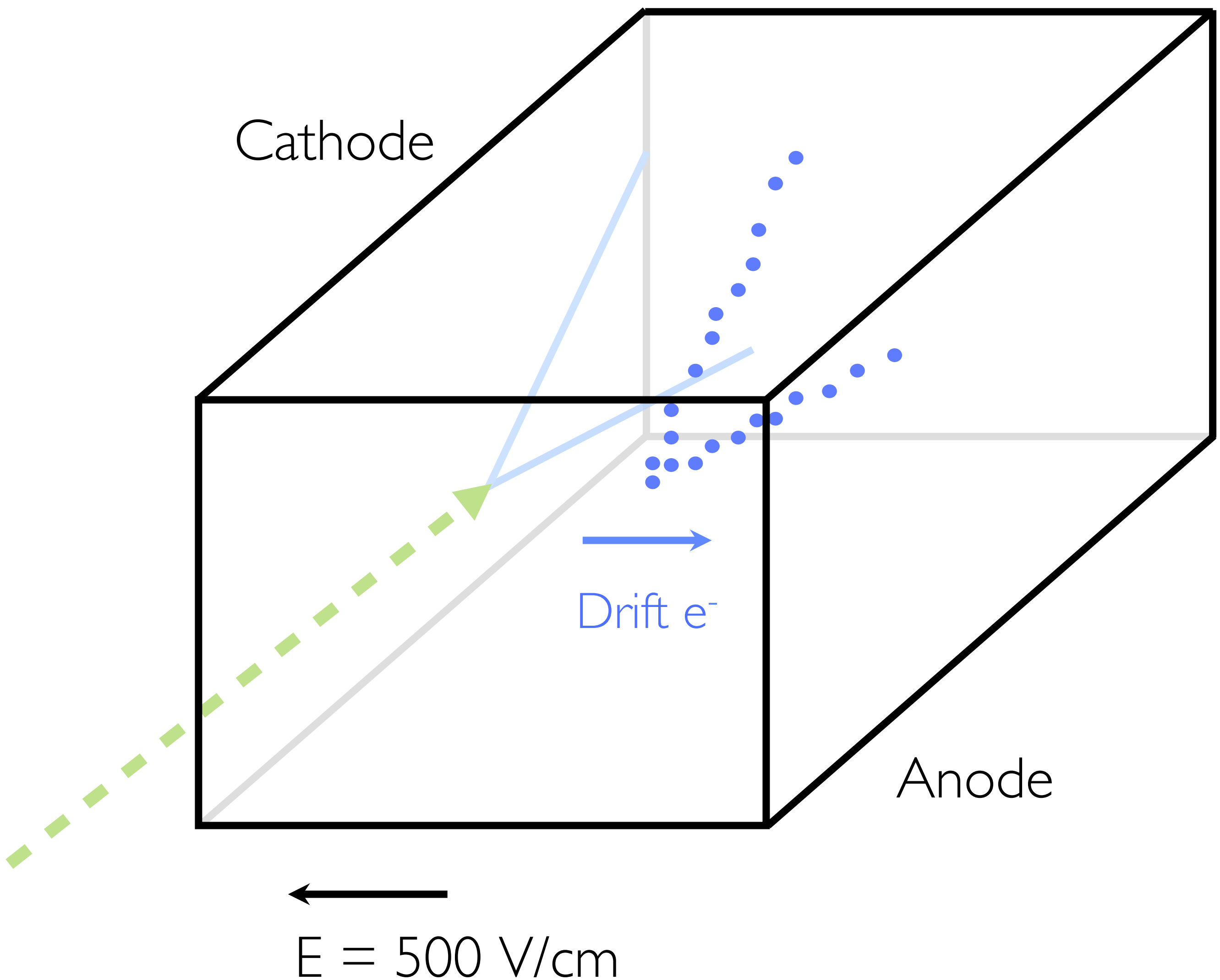
In liquid Argon, if an electric field of E=500 V/cm is applied, a muon m.i.p. (dE/dx ~ 2 MeV/cm) crossing 1 mm of the detector produces ~4000 scintillation photons and ~5000 ionization electrons

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)

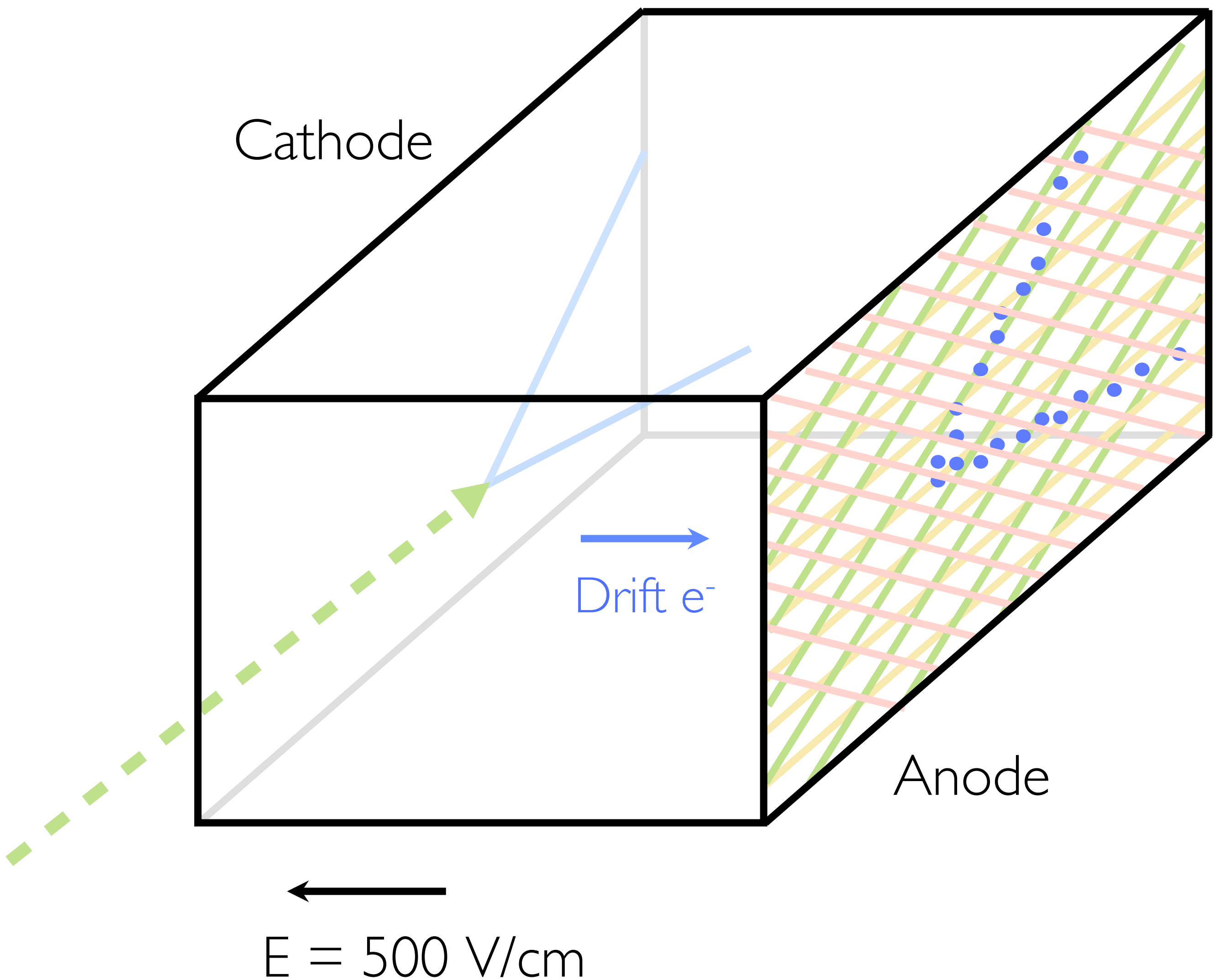
Lar-TPC working principle



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)

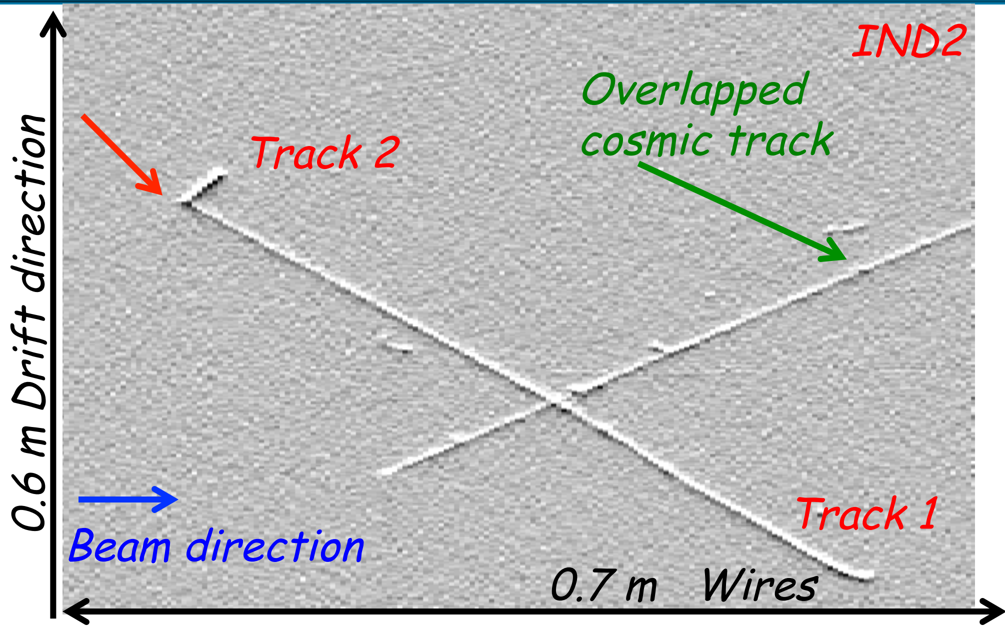
The presence of electronegative impurities, most of all O_2, in the LAr produces an exponential attenuation of the ionization signal along the drift coordinate: to reduce this effect, that can make the signals too low to be identified, the Argon must be continuously filtered and the purity level should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

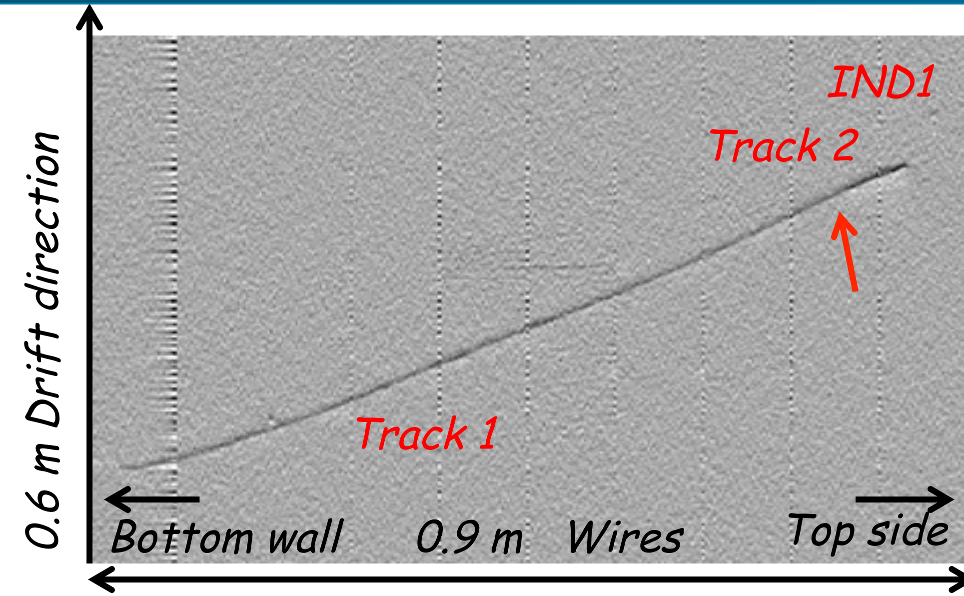
Lar-TPC working principle

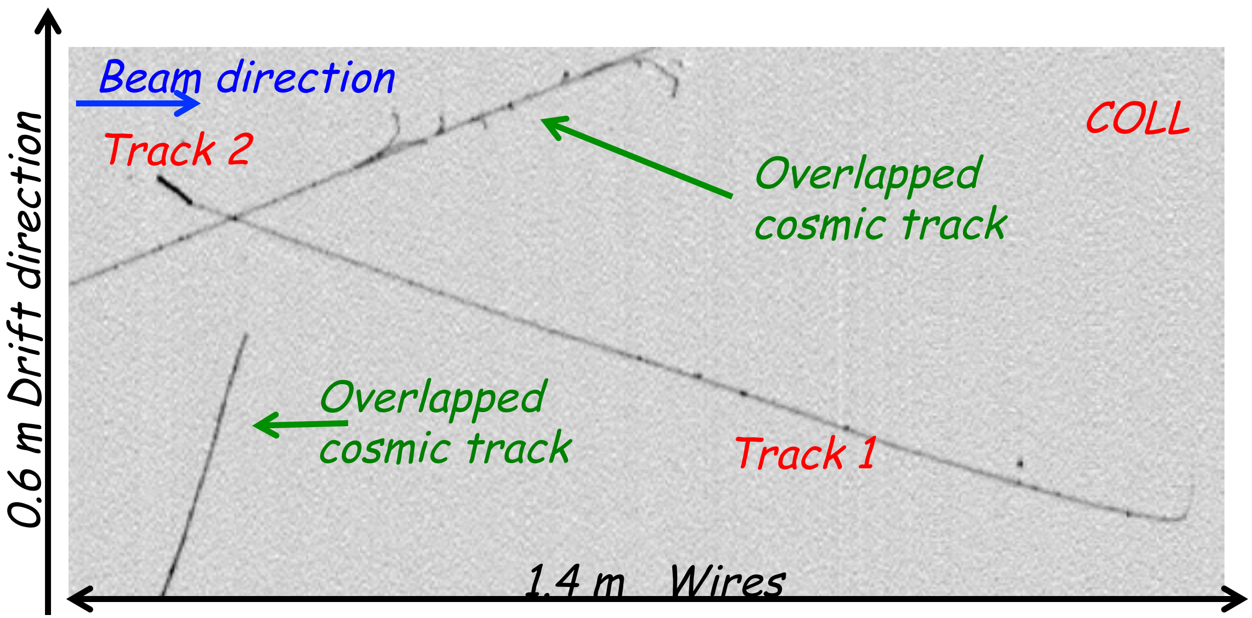


The ionization electrons are then detected by the 3 anodic wire planes providing simultaneous different projections of the same event. The information from these three projections allow a precise reconstruction of the recorded particle trajectories and a precise calorimetric measurement.

QE νμ CC candidate collected during the commissioning



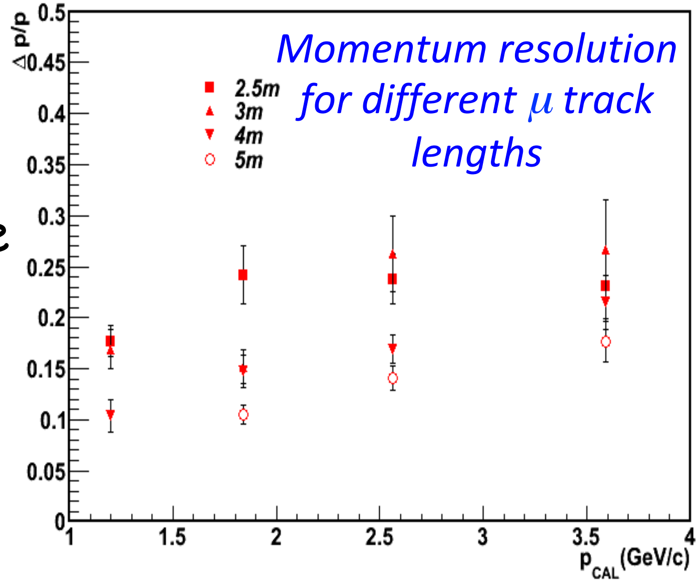




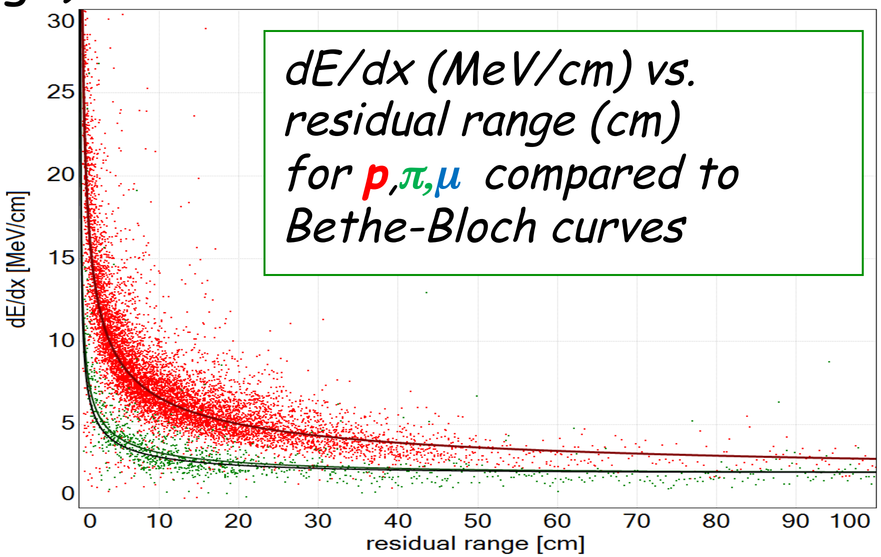
- The vertex is at ~ 0.8 m from the bottom wall (red arrows). Two tracks are produced, E_{DEP} ~ 370 MeV):
  - ✓ Track 1 (muon candidate) is downward going and exiting from the bottom wall L= 1.3 m;
  - ✓ Track 2 is upward going, stopping: proton candidate, L= 7.5 cm, E_K ~ 95 MeV from range.

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 $\Delta p/p$ ~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):



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



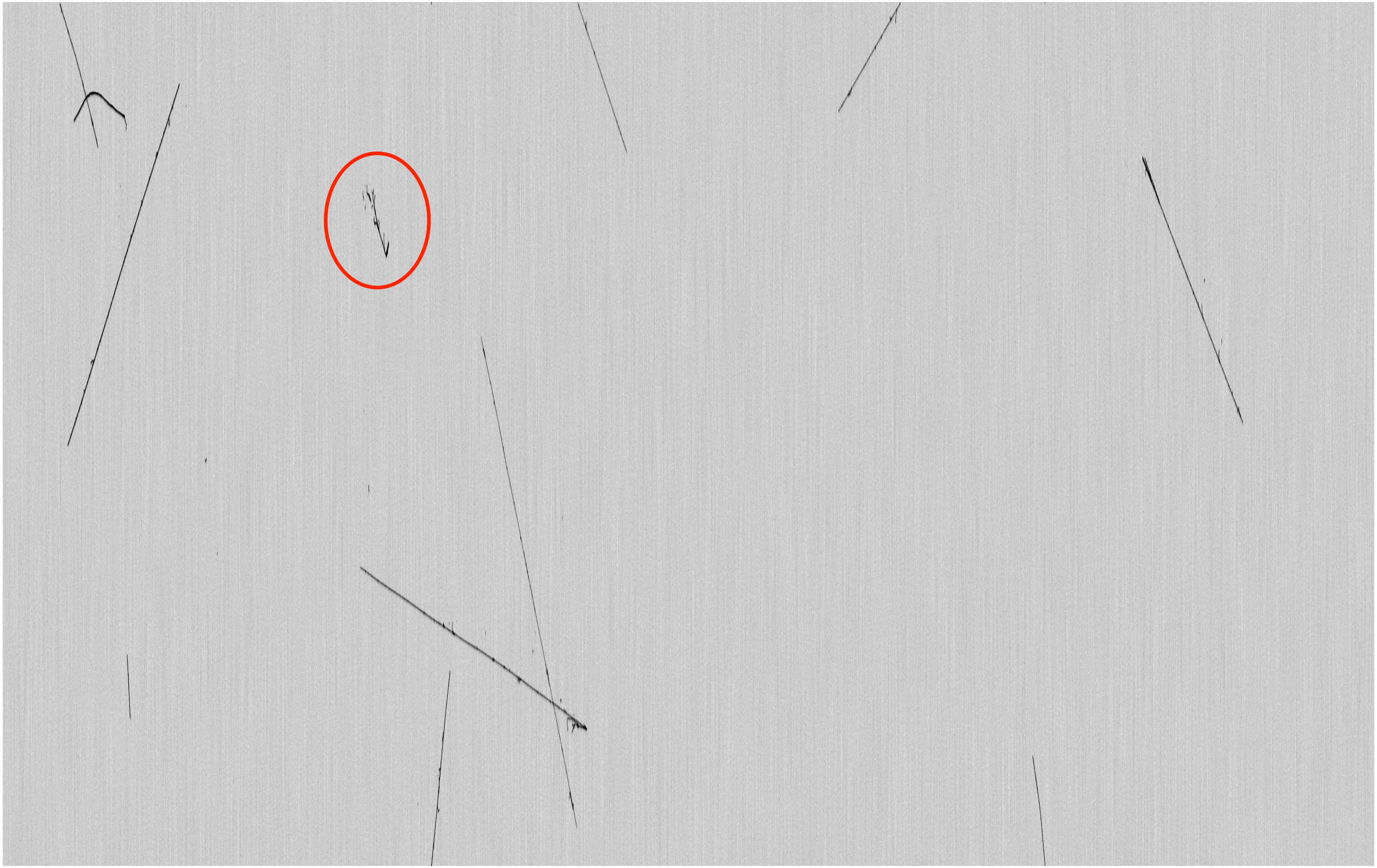
Low energy electrons:
$\sigma(E)/E = 11\%/\sqrt{E(MeV)} + 2\%$
Electromagnetic showers:
$\sigma(E)/E = 3\%/\sqrt{E(GeV)}$
Hadron showers:
$\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$

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

A new experimental challenge: a LAr-TPC on surface



A new experimental challenge: a LAr-TPC on surface

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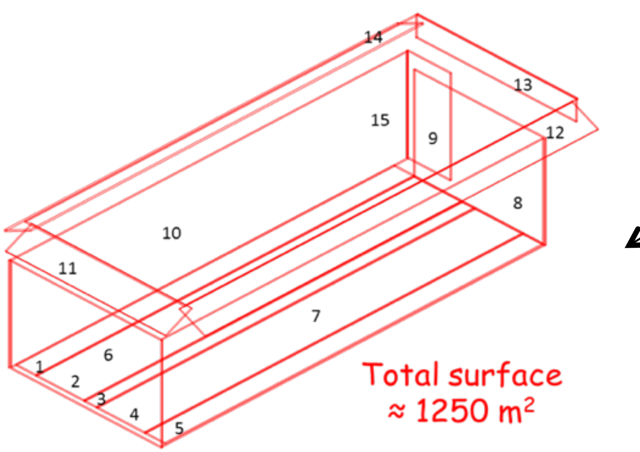
- A 3 m concrete overburden will remove contribution from charged hadrons/γ's.
- ~11 μ tracks will hit the T600 in 1 ms TPC drift window:
- γ's associated to cosmics represent a serious background source for νe search since e's produced via Compton scatt./ pair prod. can mimic a genuine νe CC.
  - Automatic 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

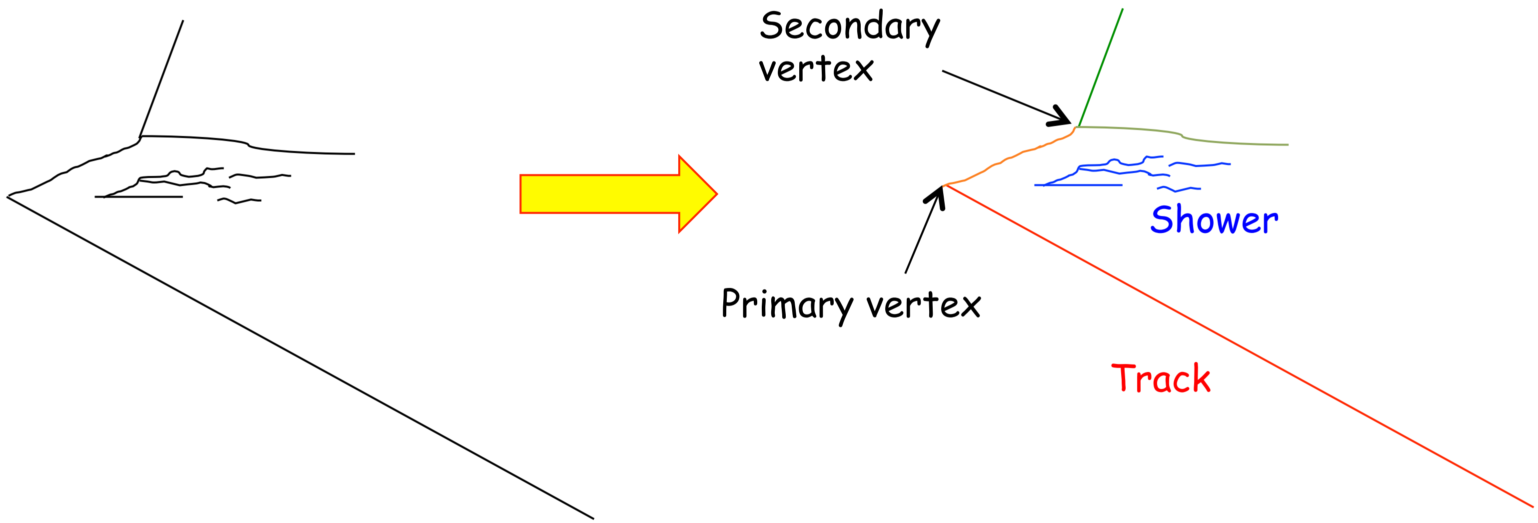


Cosmic Ray Tagging System surrounding the T600 to reject incoming cosmic particles

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

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.

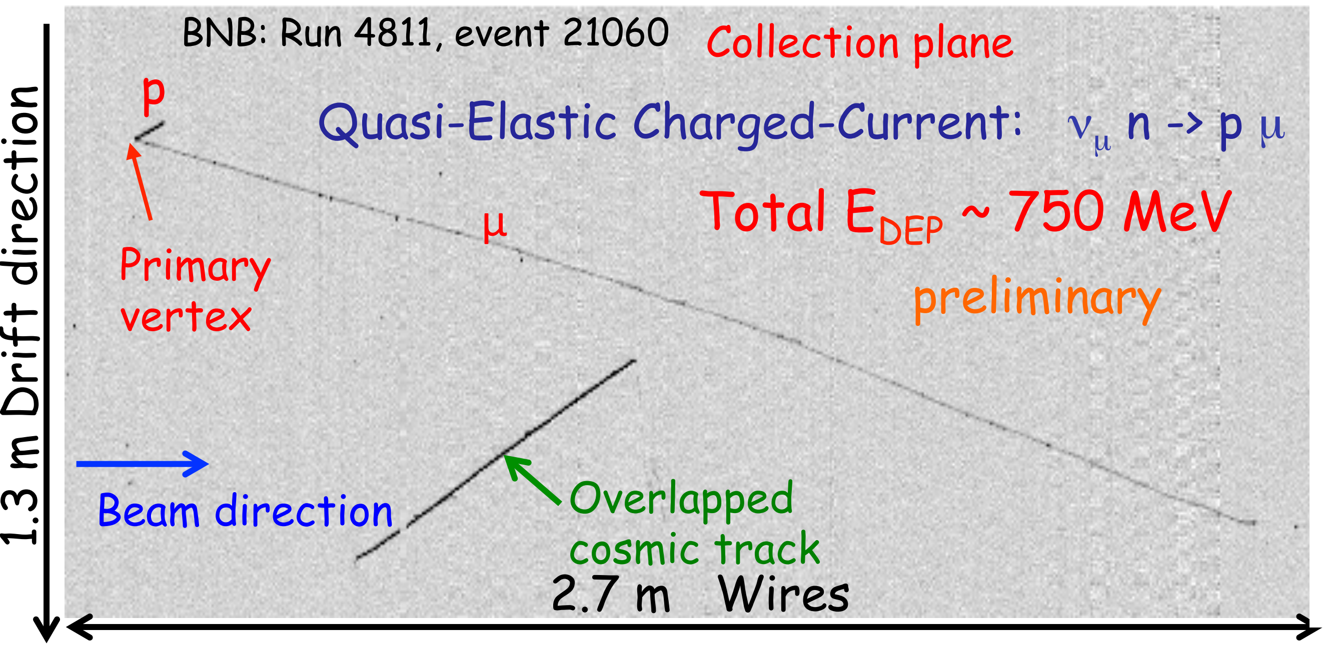


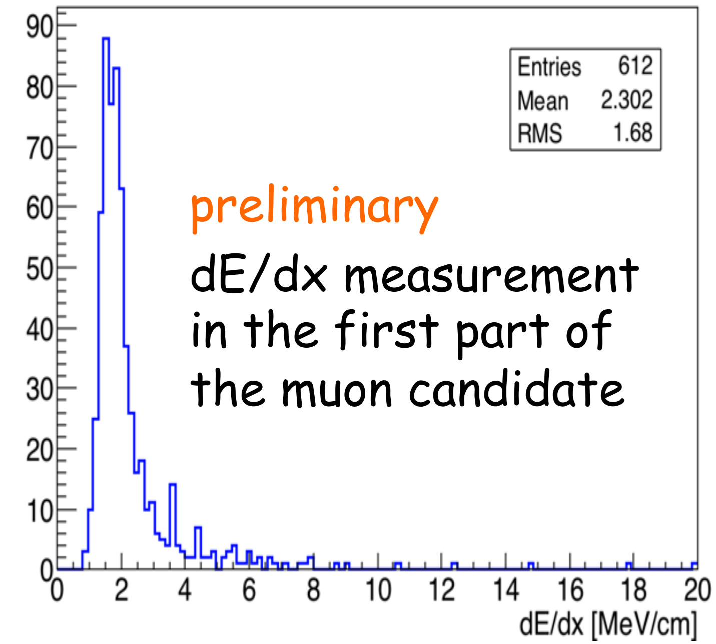
  - The track/shower and then reconstructed in detail to obtain the measurement of the deposited energy, the dE/dx along the track and the P.I.D.

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

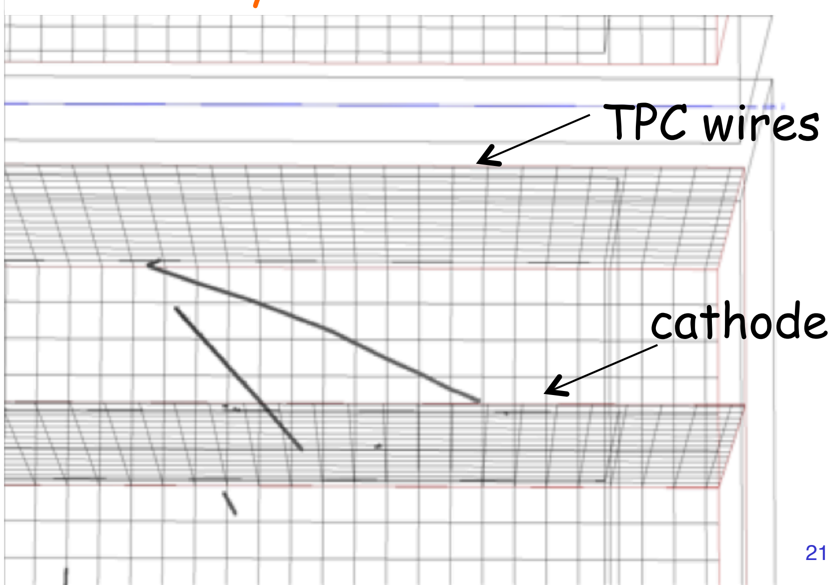
First neutrino candidates (BNB): CCQE





- 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



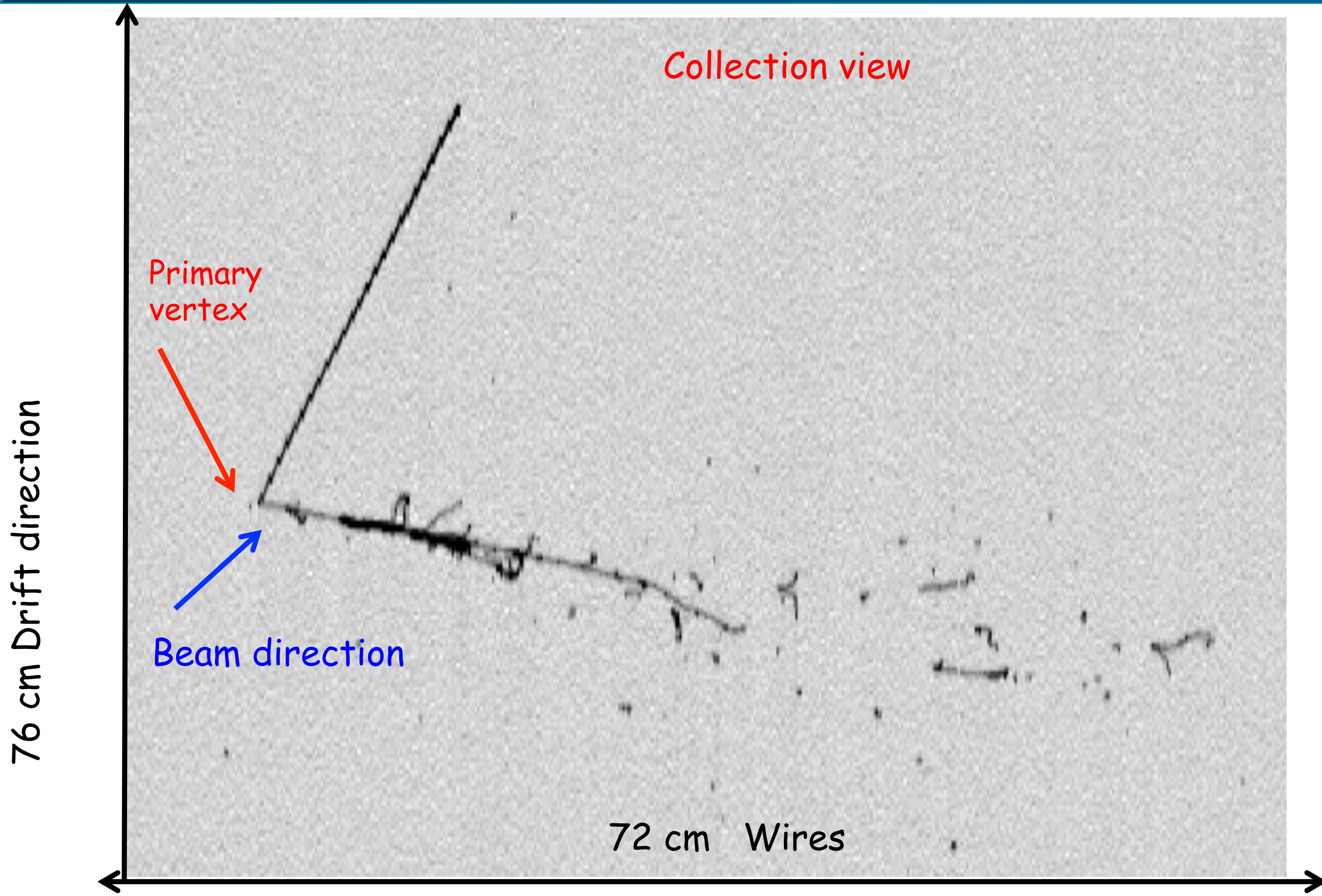
Ongoing activities

- A first "run 0" test has been performed in June: it confirmed that ICARUS is able to take physics data continuously with high live-time. The first neutrino events from both BNB and NuMI beams has been successfully collected.
- These collected neutrino events are being used to further develop and tune the event filter and the reconstruction software.
- The analysis of all the ICARUS cosmic events collected during the commissioning is also providing a better and better understanding of the detector response and systematics:
  - First absolute calibrations of wire signal response are being performed by looking at the relation between dQ/dx and residual range in stopping muons. Cathode-crossing tracks were selected in order to determine drift coordinate
  - Study of the space charge effects (SCE) measured using anode-cathode-crossing cosmic muon tracks. First results show rough agreement with previous ICARUS measurement (JINST 15 (2020) 07, P07001)
- First physics run is planned by October: new neutrino events will be recorded, selected and reconstructed;

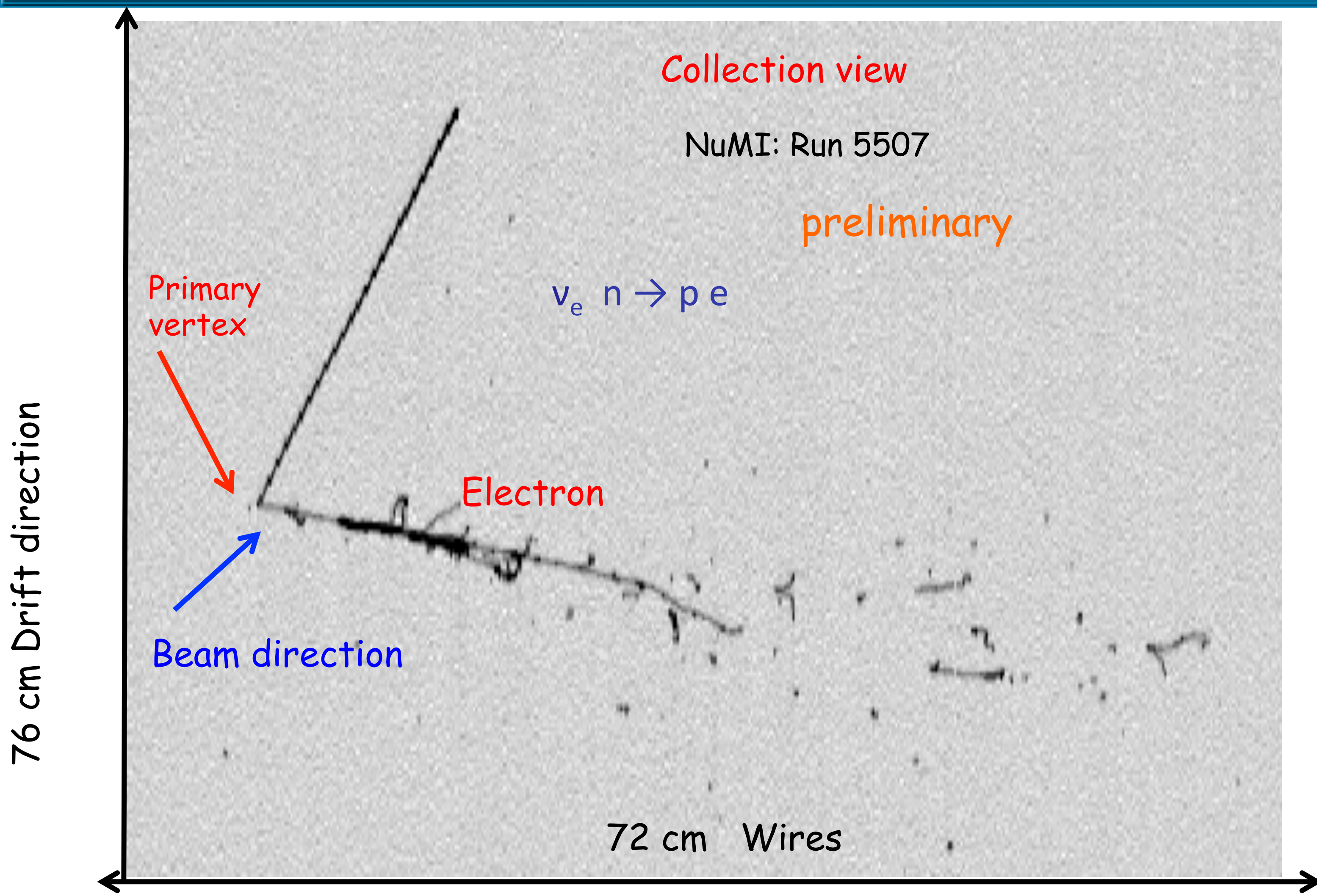
STAY TUNED !


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