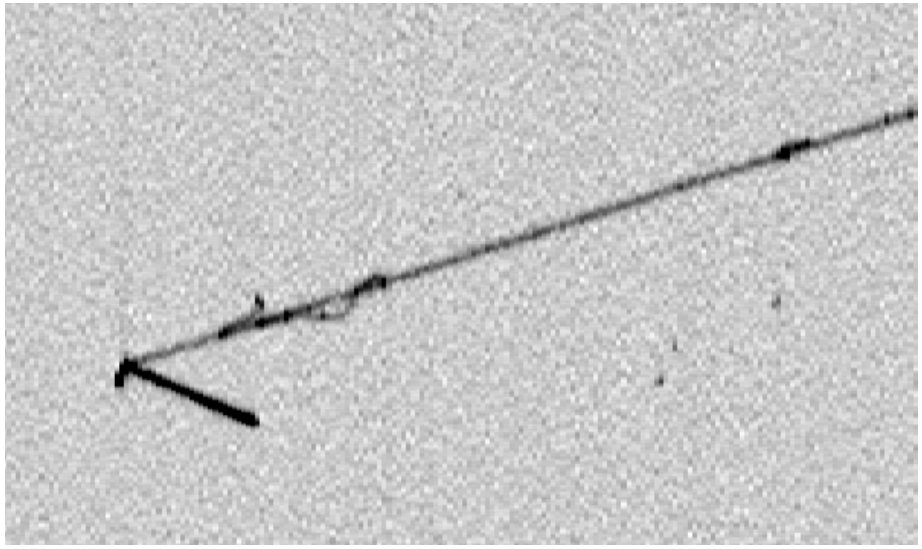
ICARUS and joint SBN data analysis



Intense MidTerm Review:
Particle Physics Experiments at the Intensity Frontier,
from New Physics to Spin-Offs

November 28th 2022

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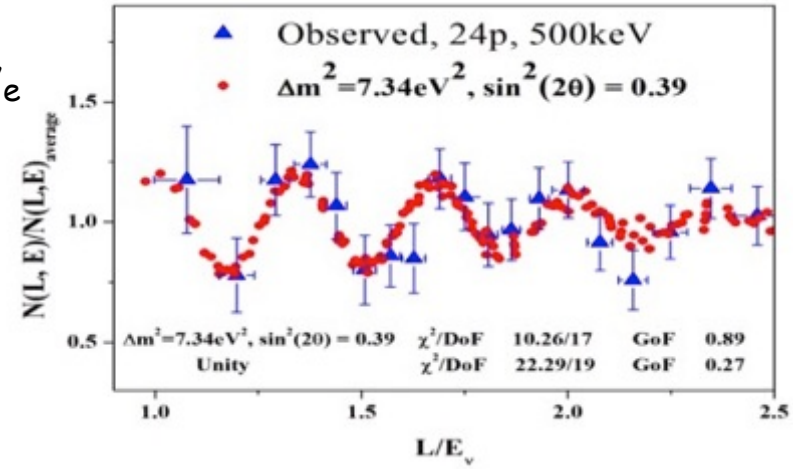
on behalf of the ICARUS collaboration

H2020, M. Sklodowska-Curie
R&I No. 822185

The sterile neutrino puzzle

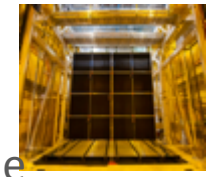
- Anomalies from accelerator experiments LSND, MiniBoone, reactors and radioactive sources GALLEX/SAGE have been collected in last 20 years hinting to a new "sterile" ν flavor at $\Delta m^2_{new} \sim eV^2$ and small mixing angle θ_{new}, driving oscillations at short distance.
- A recent result from Neutrino-4 (*Phys. Atom. Nuclei* **83,** 930–936 (2020)) points to reactor anti-ν_e disappearance with $\Delta m^2 \sim 7\ eV^2$ and $\sin^2 2\theta \sim 0.26$.
  - Further evidence (2022) suggesting sterile neutrinos as the candidate for Dark Matter with a dominant contribution due to the high density of relic sterile-νs with $m\nu_4 = 2.7$ eV



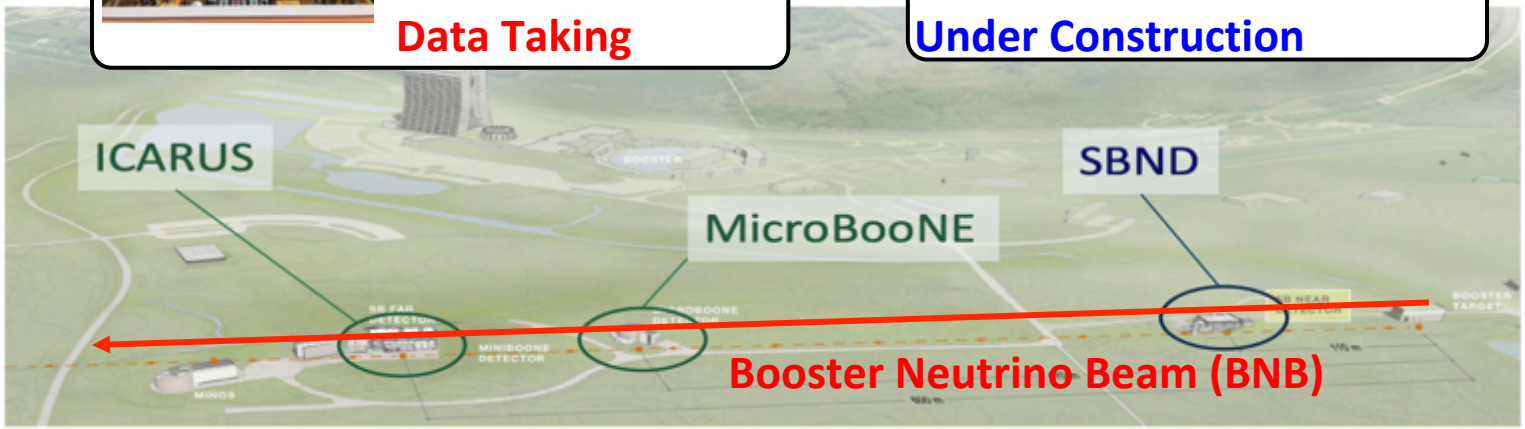
ICARUS

600m baseline
470t active volume
Data Taking

SBND



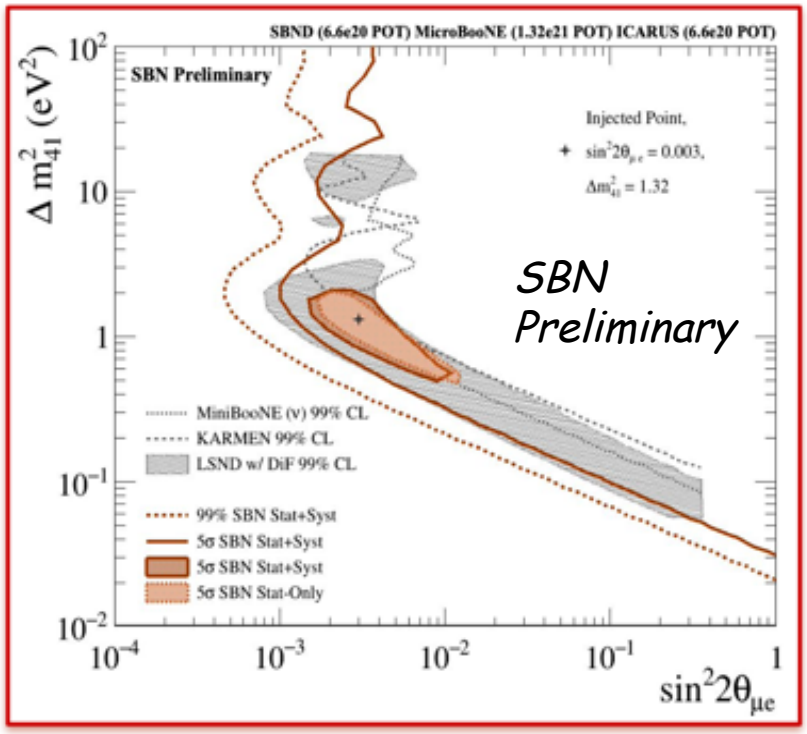
110m baseline
112t active volume
Under Construction



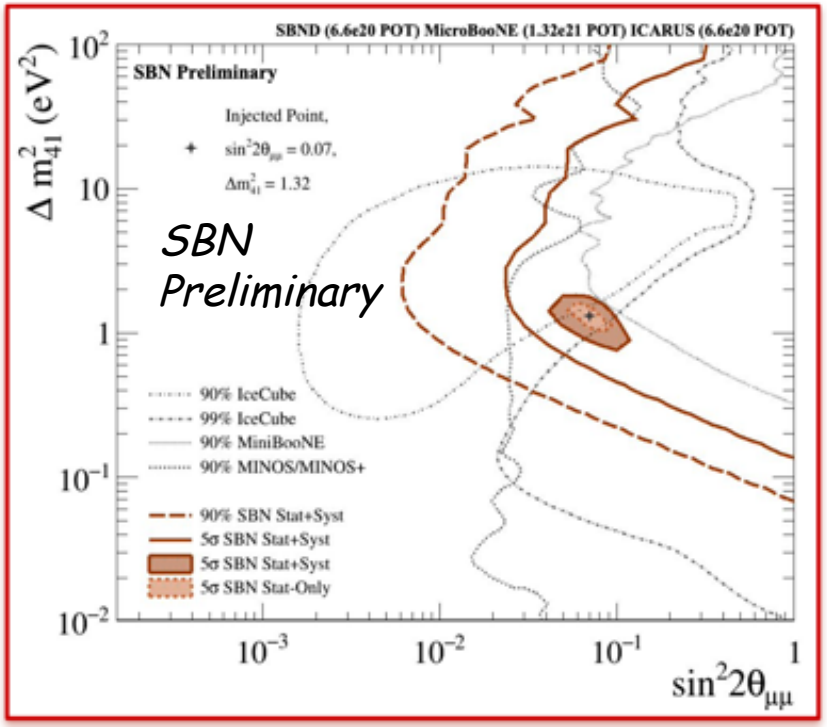
ICARUS and SBND LAr-TPC's at 600 m and 110 m from the Booster target are searching for sterile-ν oscillations both in appearance and disappearance channels.

SBN program: sterile ν sensitivities for 3 years (6.6 • 10^{20} pot)

- The combined analysis of near and far detector data will allow to cover the currently allowed parameter region with 5σ sensitivity both in appearance and disappearance channels, in 3 years of data-taking (6.6 • 10^{20} pot):
  - ✓ Using the same detector technology 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 backgrounds



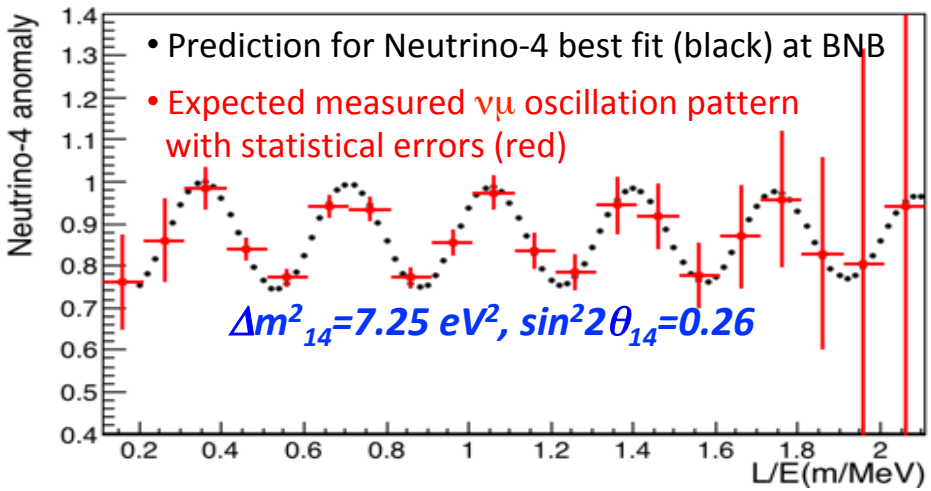
SBN appearance sensitivity

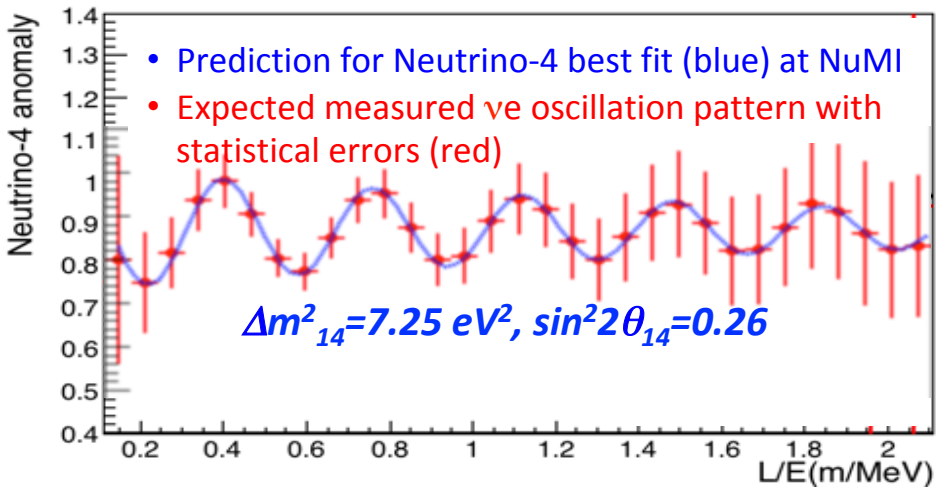


SBN disappearance sensitivity

Search for Neutrino-4 oscillation signal with ICARUS at FNAL

- The initial ICARUS-only phase should allow to settle the NEUTRINO-4 (~7 eV^2) sterile-ν claims:
  - Oscillations produce disappearance pattern of νμ in BNB and of νe in NuMI, in same L/E ~ 1-3 m/MeV of Neutrino-4 but with events collected with ~100 times the energy, focusing on contained quasi-elastic CC interactions.





νμ survival oscillation probability at Booster:
~8500 QE events with >50 cm contained μ track in ~ 3 months data taking, ~7 x 10^{19} pot, ΔE/E ~ 3 %.

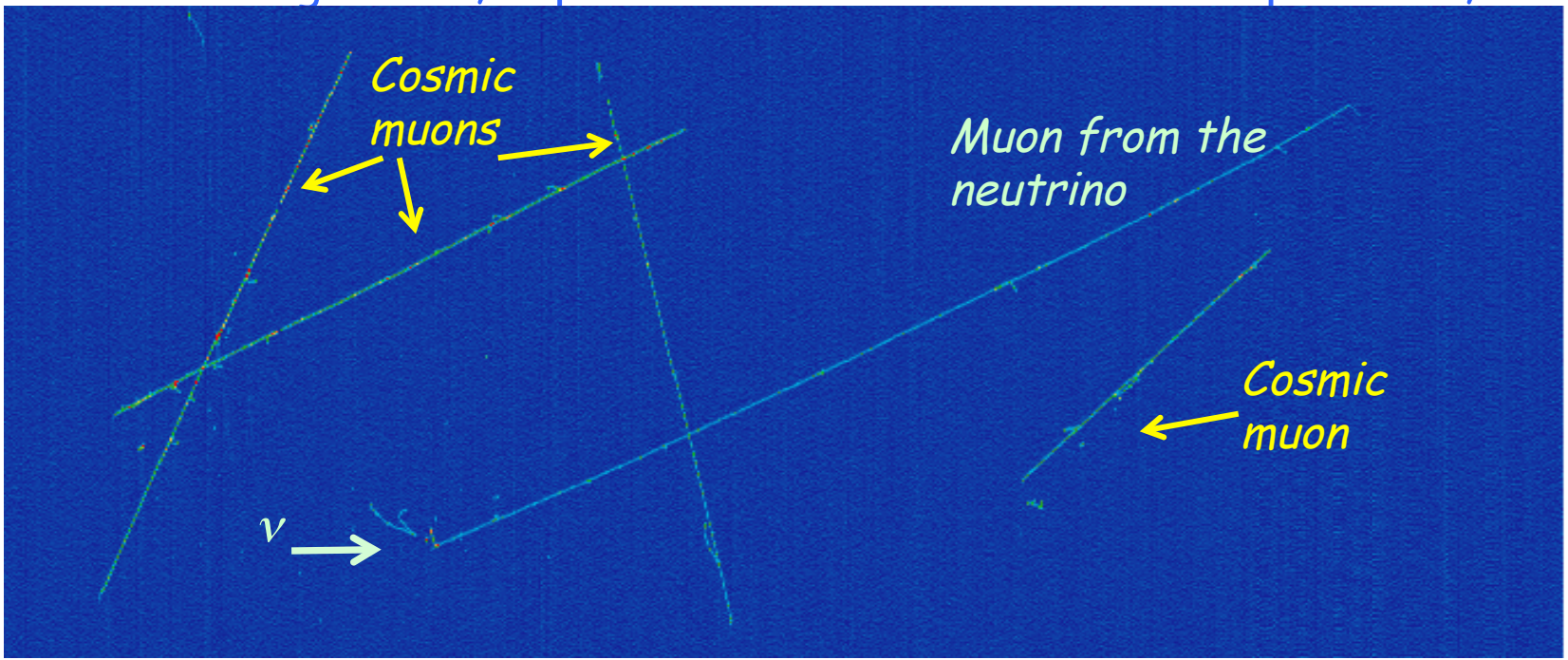
νe survival oscillation probability at NuMI:
~ 5200 QE events with contained E.M. shower in 1 year data taking (6 x 10^{20} pot).

- The analysis complemented with a beam-off event sample collected in parallel will allow to observe the Neutrino-4 modulation *in a short time!*

An experimental challenge: a LAr-TPC on surface

ICARUS at FNAL is facing a challenging experimental condition:

- The T600 is installed in a pit and exposed to cosmic rays: electrons produced by cosmic γ's via Compton Scatt./Pair Prod. can mimic a genuine ν_e CC interaction
  - A 2.85 m concrete overburden, 6 m water equivalent, above ICARUS removes all primary γ's and strongly reduces cosmic neutrons by a factor 200;
- $O(10^6)$ ν interactions will be recorded in 3 years data taking and should be recognized amongst the cosmic muon tracks entering ICARUS in the 1 ms TPC drift time
  - Automatic tools for the selection of the neutrino interactions and to reject the backgrounds, in particular associated to cosmic particles, are mandatory!



5m x 1.5m

ν event selection and cosmic rejection

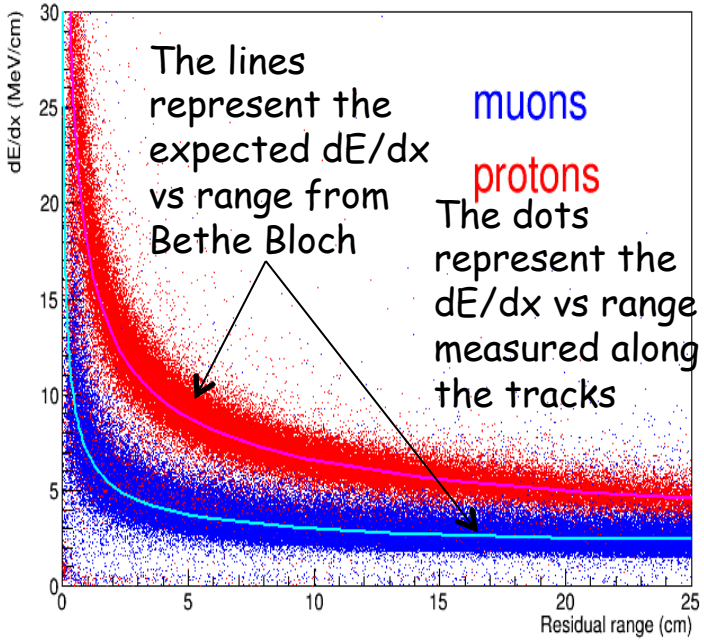
- The main "event selection" goal is the identification of the neutrino interactions, recognizing them among the background interactions, in particular from cosmics.
- The ν event selection will be performed exploiting the combination of the signals provided by the TPC, the PMTs and the CRT and using all the common reconstruction tools developed within ICARUS and in SBN analysis joint effort:
  - The Pandora pattern recognition tools to recognize the neutrino candidates in the TPCs and reject the clear through-going muons
  - The matching of the wire charge signals and the PMTs light signals to recognize the in spill events and reject the out-of-time cosmics
  - The CRT signals will allow to reject the incoming cosmic particles
  - The detailed study of the particles produced at the primary vertex, to identify the primary lepton (muon/electron) and the produced hadrons;
    - In particular the ν vertex should be located inside the fiducial volume, i.e. >25 cm from the lateral TPC walls and 30/50 cm from the upstream/ downstream walls;
- The exploitation of all these elements will be crucial to reject the backgrounds;

Neutrino identification

- The selected candidates should be studied in details to identify the neutrino interaction and to reconstruct the particle produced at the primary vertex:

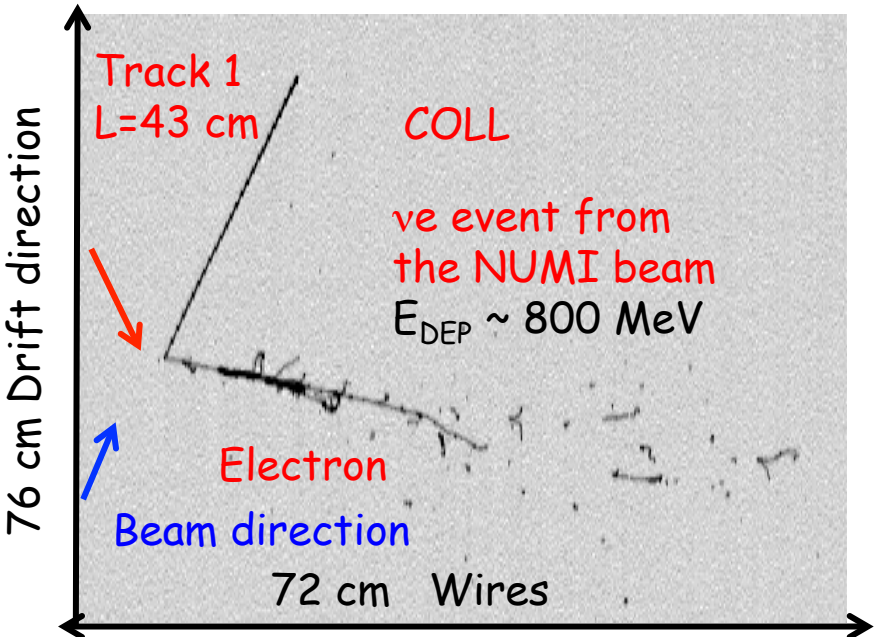
$\nu\mu$CC events are recognized requiring:

- A track longer than 50 cm if it stops inside the detector or longer than 1 m if it is not fully contained
- The dE/dx along the track should be compatible with a muon.

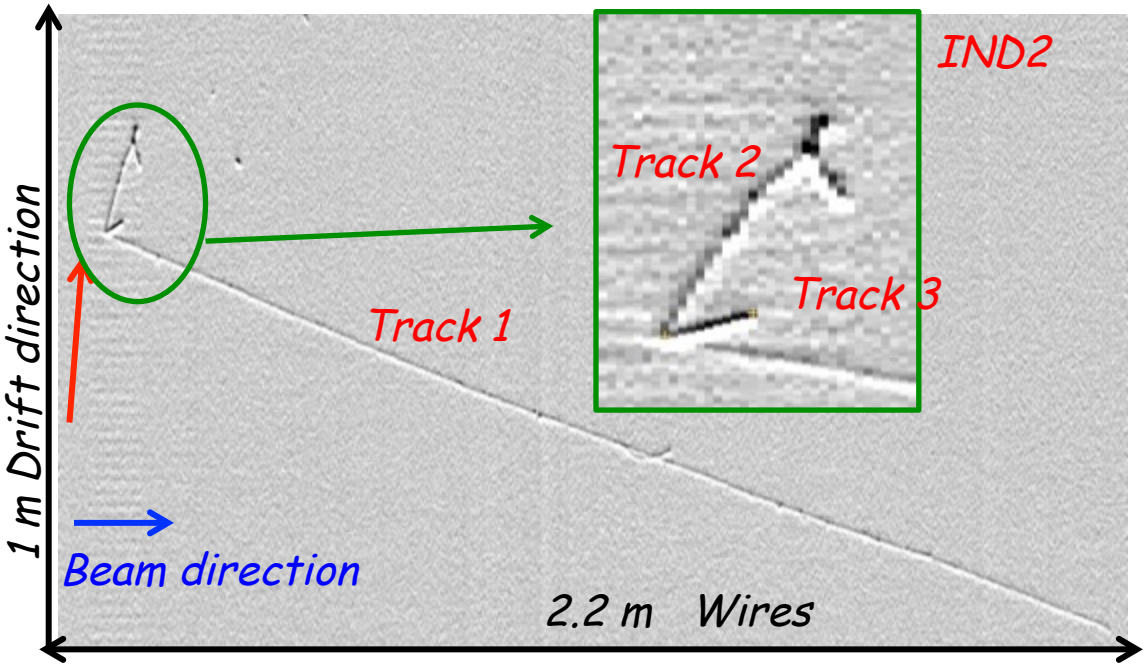


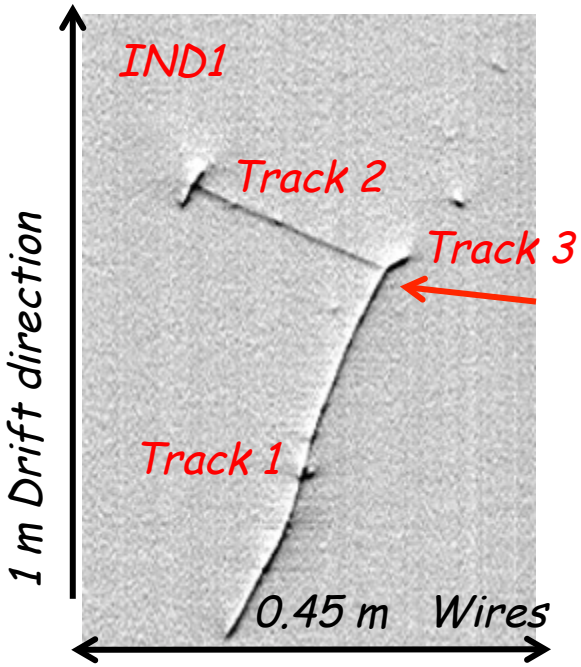
νe events are recognized requiring:

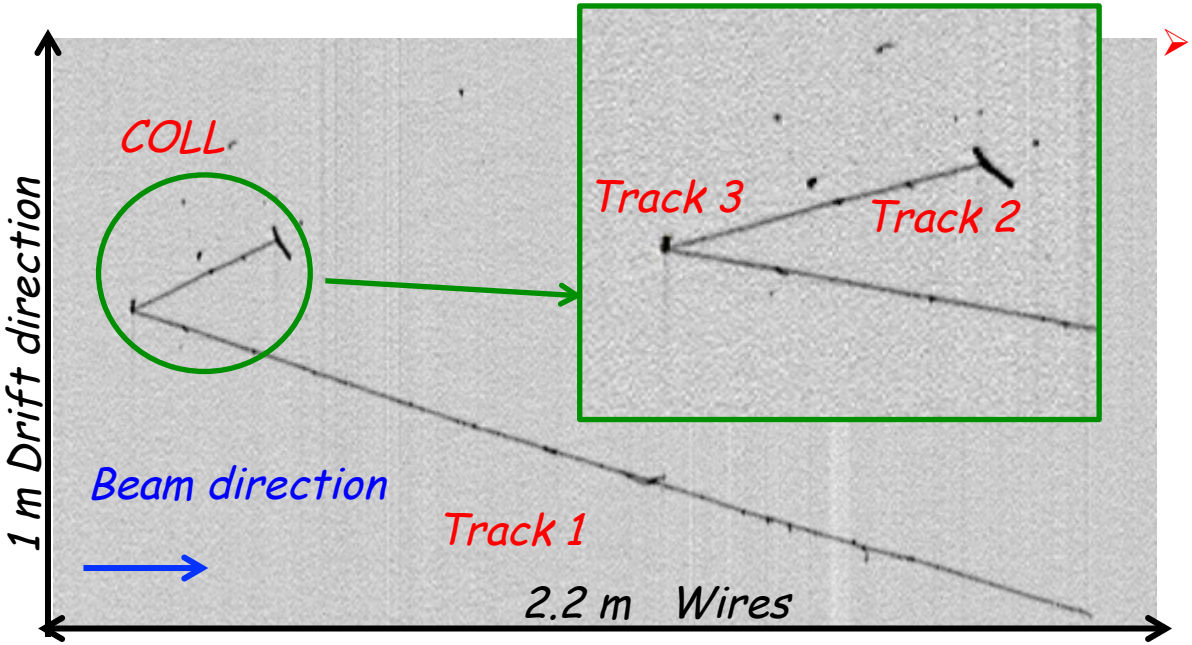
- An e.m. shower produced and clearly connected to the primary vertex and with energy > 200 MeV.
- The dE/dx at the beginning of the shower should be fully compatible with a m.i.p.



νμ CC candidate: 1 event, 3 pictures

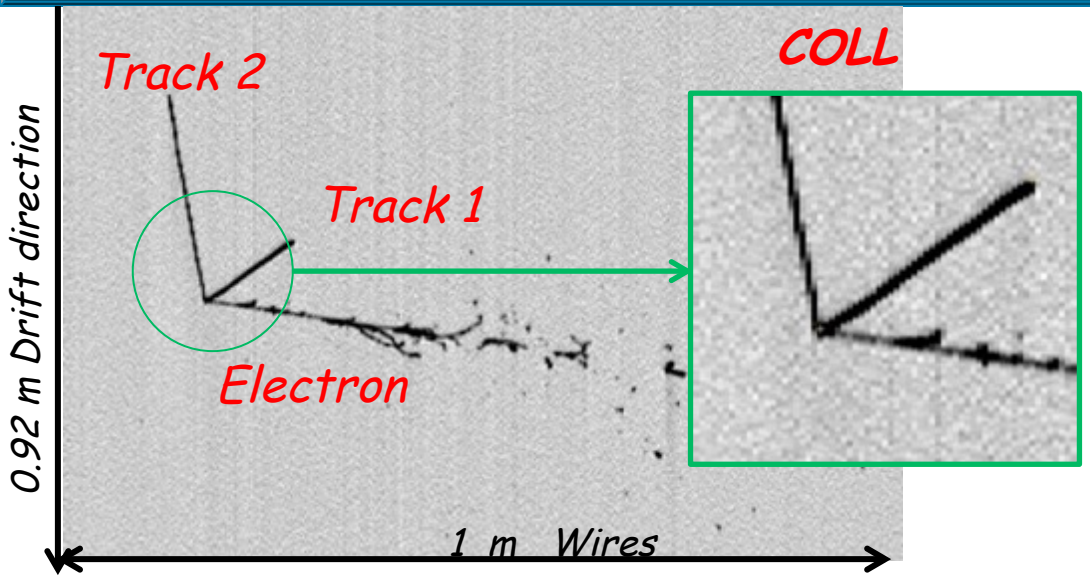






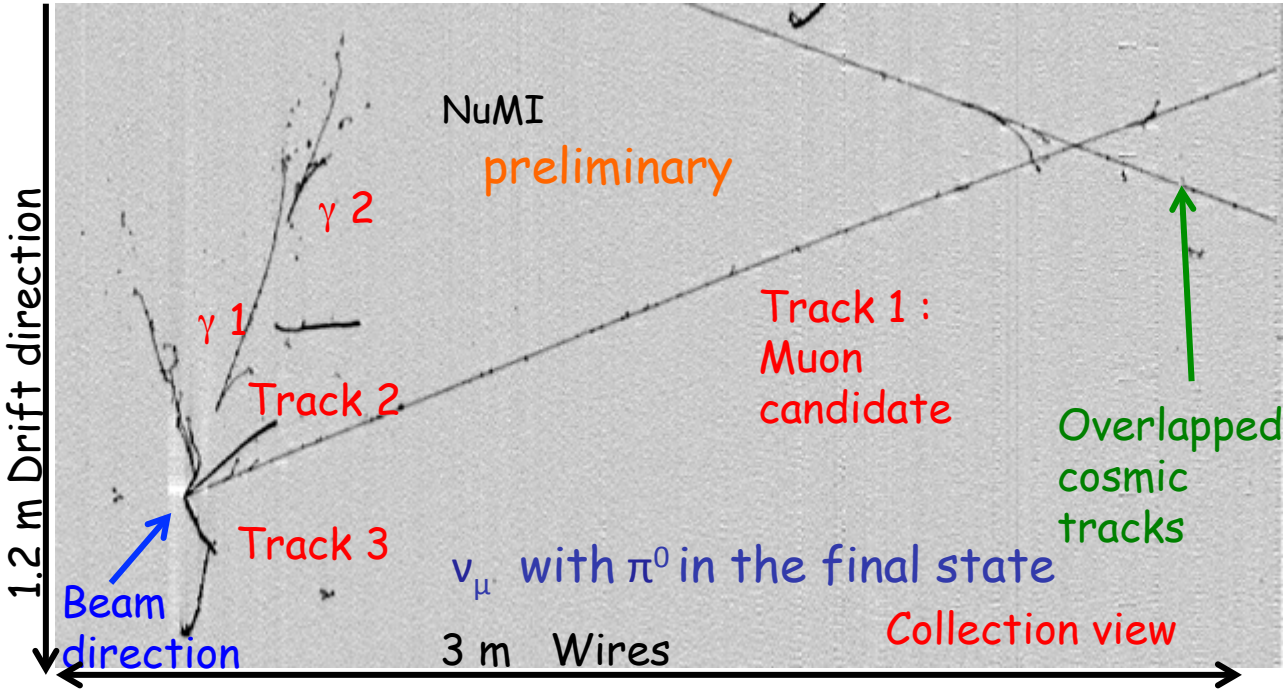
- Three tracks at the primary vertex:
  - ✓ Track 1 (muon) is downward going, crossing the cathode and stopping in the detector L= 6.4 m;
  - ✓ Track 2 (hadron) is downward going and interacting in the detector and producing two short protons;
  - ✓ Track 3 (proton) is upward going L=3.4 cm

Neutrino Candidates from NuMI beam



ν_e CC event candidate fully contained in active LAr, Edep~830 MeV:

- ✓ The electron shower, Edep~570 MeV is downward going;
- ✓ Track 1: upward going stopping proton candidate, L = 23.7 cm; Track 2: stopping hadron, L = 33.4 cm.

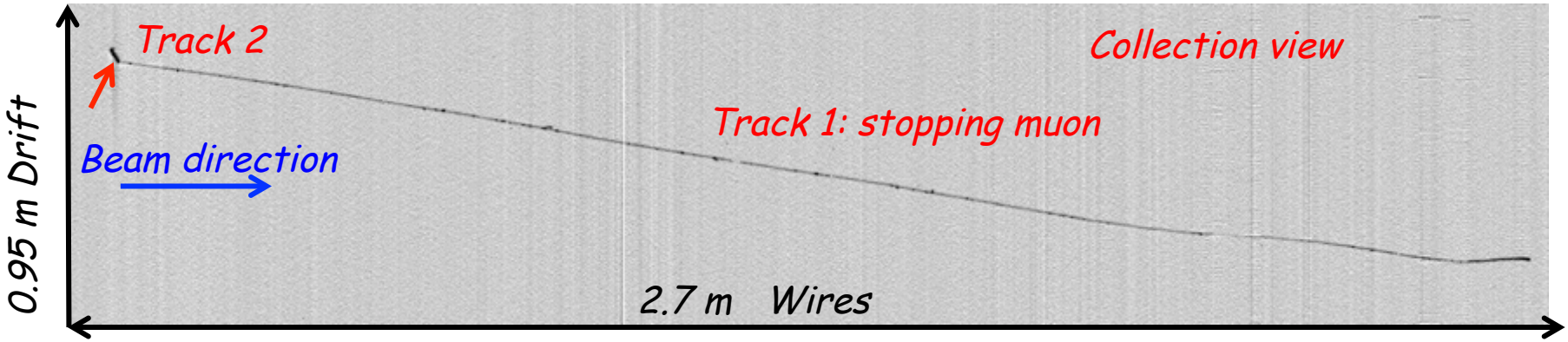


Muon neutrino candidate:

- Track 1: muon candidate crossing the cathode and exiting downstream (L~4.2m, p~1.3 GeV/c from MCS)
- Track 2: upward-going proton candidate, L~31 cm
- γ1,γ2: π_0 candidate with photons of 200 and 240 MeV respectively, converting at 18 and 58 cm from neutrino interaction vertex.

ICARUS first phase analysis: NEUTRNO-4 search

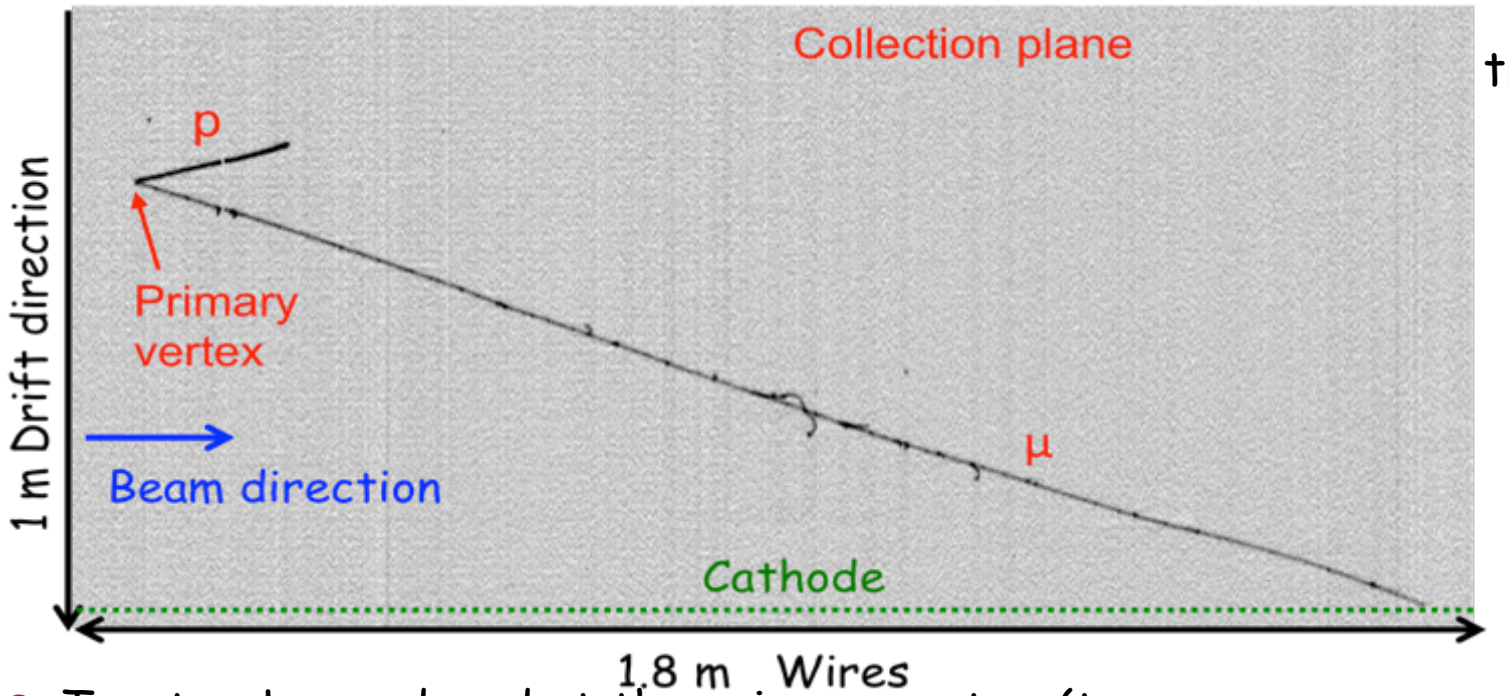
- The goal of the first phase of the experiment is to select $\nu\mu$CC Quasi Elastic (QE) events from Booster beam fully contained in the detector, golden sample for the Neutrino-4 ICARUS-only analysis.
- This analysis could be performed with the events collected in three months exposure to BNB beam, for which we expect:
  - 47000 $\nu\mu$CC interactions in the active volume;
  - On this sample, 9500 are QE contained events, corresponding to 8600 events with a muon track longer than 50 cm;
  - In the same period ~200k in spill cosmic ray events are also expected.
- Events should be automatically recognized and reconstructed to evaluate the corresponding neutrino energy E and the travelled distance L, in order to search for on oscillatory pattern depending on L/E.



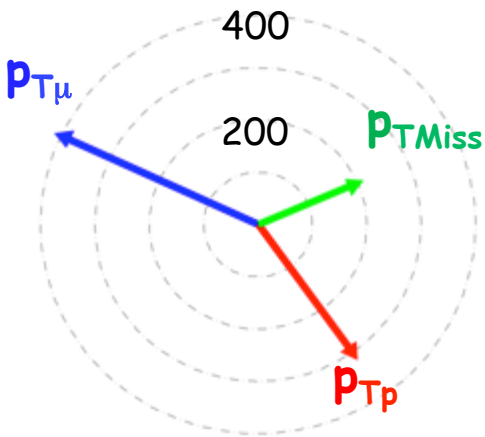
A dedicated selection workflow for the CCQE contained events

- A dedicated workflow to select the $\nu\mu$CC Quasi Elastic (QE) events from BNB beam fully contained in the detector is under preparation and will be based on:
  - Application of a CRT veto, to strongly remove events whose trigger is produced by in-spill cosmics, to remove ν interactions not contained and ν interactions with the primary vertex outside the active volume;
  - Identification of the detector "Region of Interest" containing the ν interaction, based on PMT signals and using the matching of the barycenter of the light and of the TPC signals;
  - Selection of the interactions contained in the TPC, requiring no signal in the last 5 cm of the LAr active volume;
  - Identification of the muon and of at least a proton track with L_p>1 cm produced at the primary vertex using the available PID tools;
  - Measurement of the μ and p momentum to provide the global event kinematics;
- This event selection procedure will also benefit from reconstruction tools developed within the SBN joint analysis framework.
- The performance of the selection/reconstruction procedure are verified on a sizeable sample of neutrino candidates visually selected.

Example of an automatically selected νμCCQE candidate

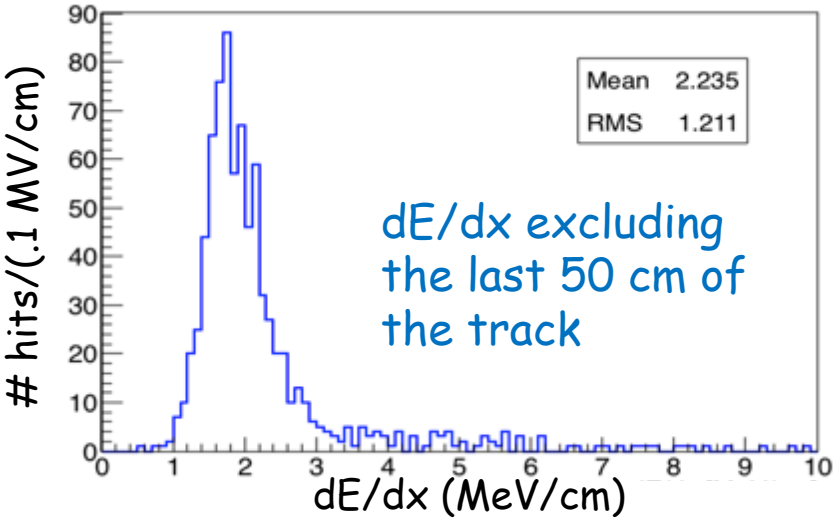


Momentum in the transverse plane (MeV/c)

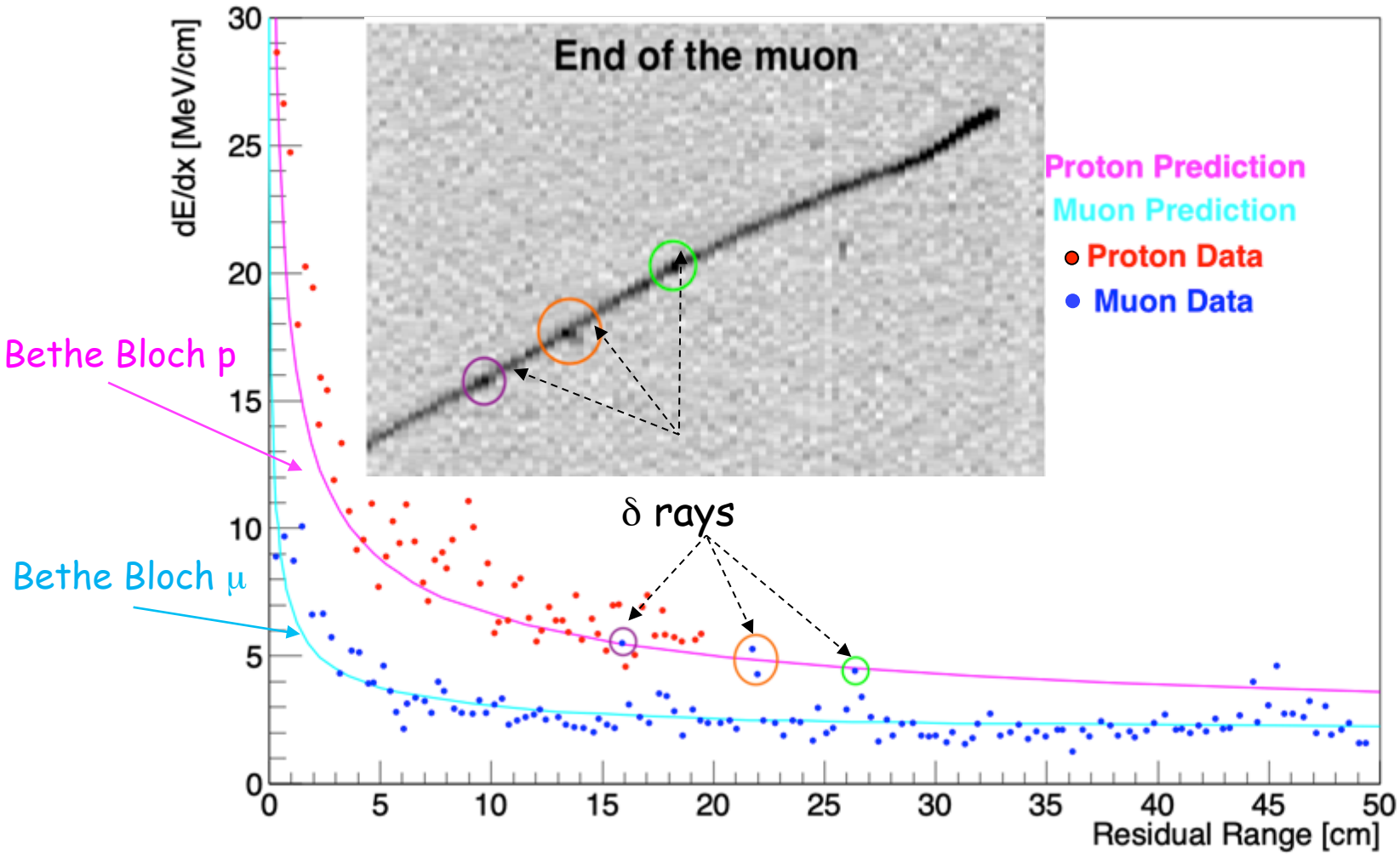


- Two tracks produced at the primary vertex (top left picture): the muon candidate is crossing the cathode and stopping after = 3.8 m while the proton candidate is stopping after 20 cm;
- The total deposited energy is ~1.1 GeV;
- The total momentum $\boldsymbol{p}_{tot} = \boldsymbol{p}_{\mu} + \boldsymbol{p}_{p}$ is at 8° from the beam axis; the total transverse momentum is ~200 MeV/c (top picture right).

Credit M. Artero Pons



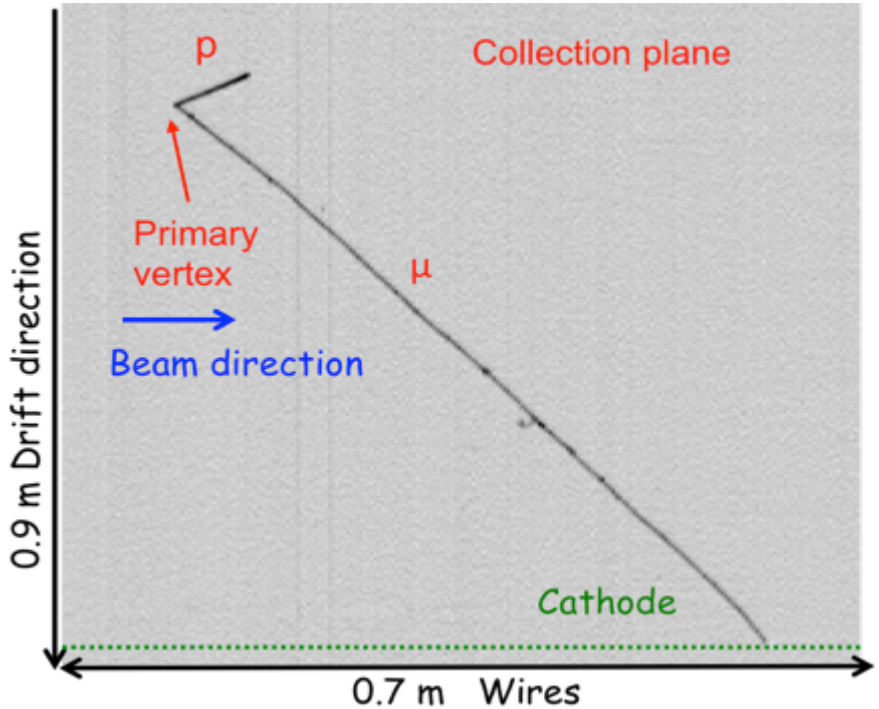
Example of an automatically selected νμCCQE candidate: PID



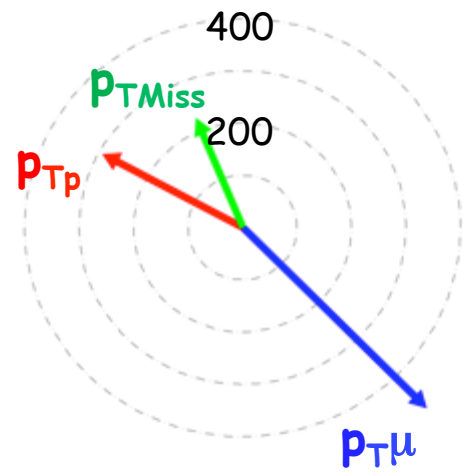
- The present calibration allows to correctly reconstruct the different dE/dx and the Bragg peaks for the stopping muon and proton.

Credit M. Artero Pons

Another example of an automatically selected νμCCQE candidate

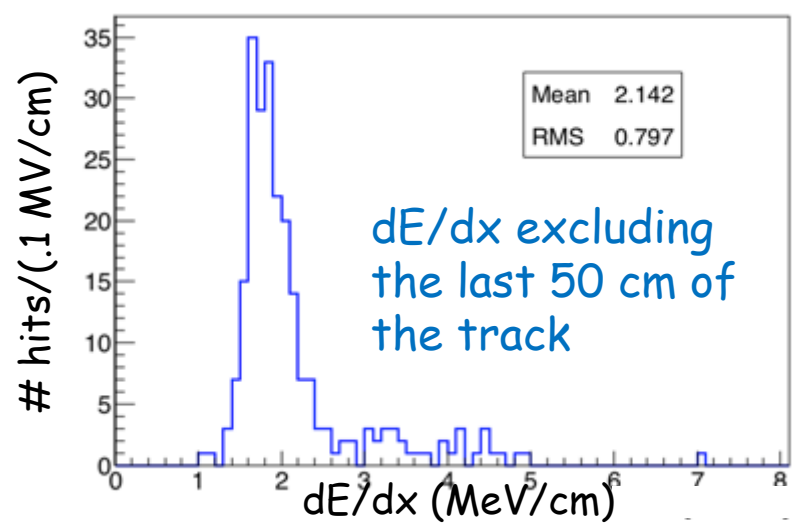


Momentum in the transverse plane (MeV/c)

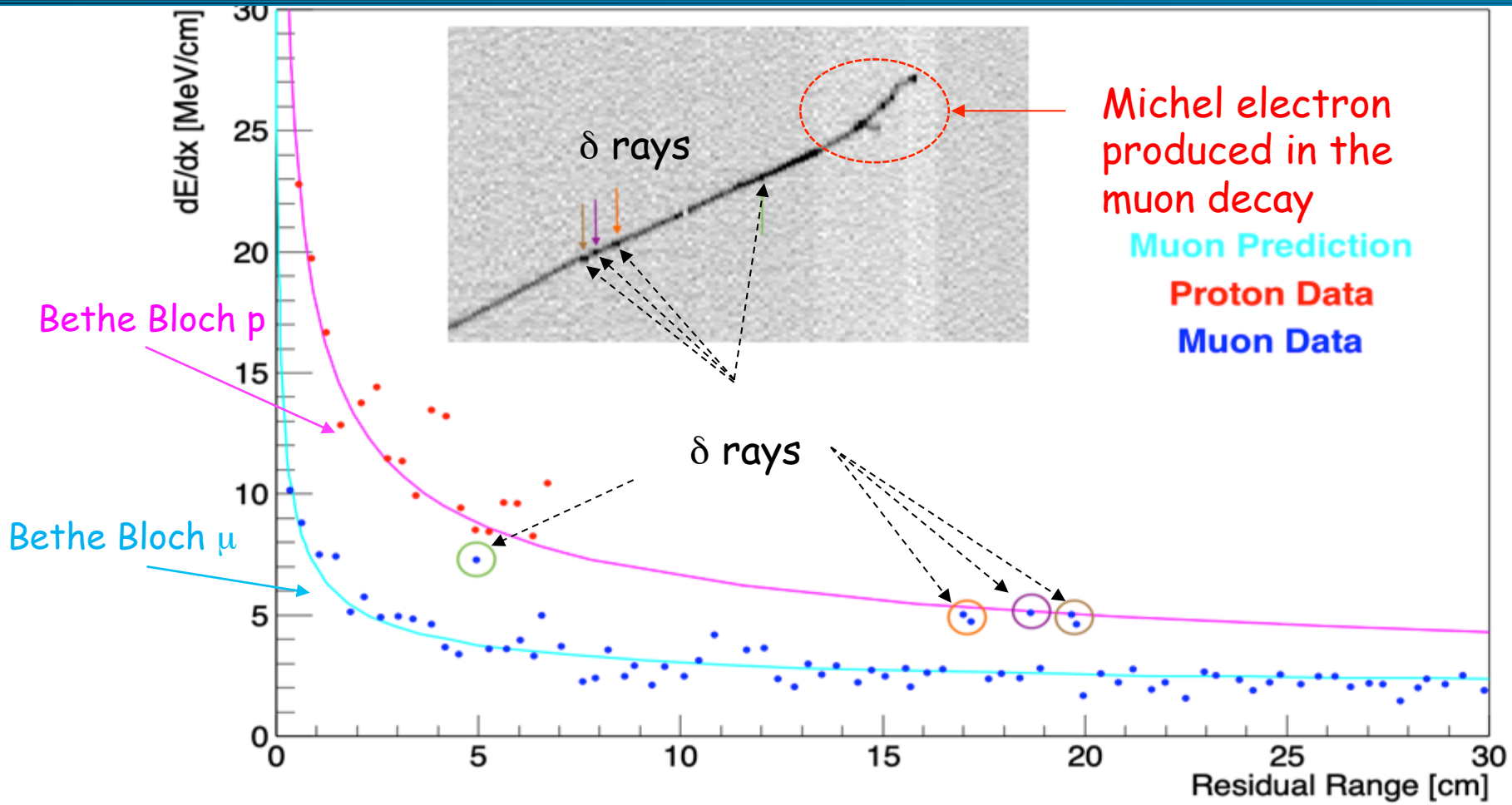


- Two tracks produced at the primary vertex (top left picture): the muon candidate is crossing the cathode and stopping after = 2.3 m while the proton candidate is stopping after 7.5 cm;
- The total deposited energy is ~620 MeV;
- The total momentum $p_{tot} = p_\mu + p_p$ is at 16° from the beam axis and the total transverse momentum is ~200 MeV/c (top picture right).

Credit M. Artero Pons



Example of an automatically selected νμCCQE candidate: PID



- The reconstructed dE/dx VS residual range agrees with expectations for both proton and the muon.

Credit M. Artero Pons

Conclusions

- The events collected during the commissioning phase of the ICARUS T600 detector are being used to further develop and tune the event simulation and reconstruction software and for the calibration of the detector.
- The full-time neutrino beam run started on June 9th 2022 exploiting both BNB and NuMI beam.
- Early phase of ICARUS data taking is started, primarily dedicated to the study of the Neutrino-4 claims looking for the $\nu\mu$ disappearance in the Booster beam and ve disappearance in the NUMI off-axis beam.
- The data analysis 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 developed within ICARUS and in SBN analysis joint effort
- 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!

Thank you !