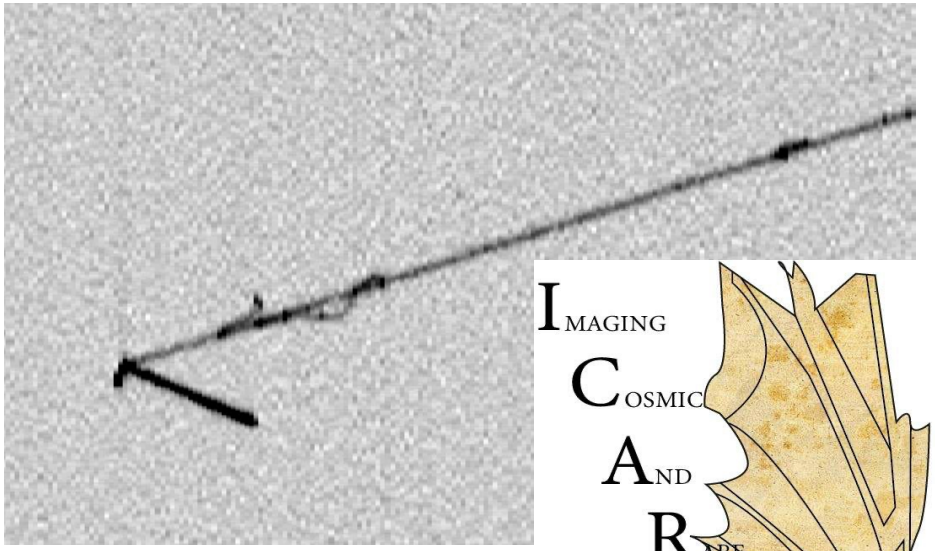
Latest Results from the ICARUS experiment at the Short-Baseline Neutrino Program



MAYORANA
International workshop
June 17th 2025

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ICARUS collaboration

ICARUS Collaboration at SBN

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Spokesperson: C. Rubbia, GSSI

1. Brookhaven National Lab., USA
2. CERN, Switzerland
3. CINVESTAV, Mexico,
4. Colorado State University, USA
5. Fermi National Accelerator Lab., USA
6. INFN Bologna and University, Italy
7. INFN Catania and University, Italy
8. INFN Genova and University, Italy
9. INFN GSSI, L'Aquila, Italy
10. INFN LNGS, Assergi, Italy
11. INFN LNS, Catania, Italy
12. INFN Milano, Milano, Italy
13. INFN Milano Bic. and University, Italy
14. INFN Napoli, Napoli, Italy
15. INFN Padova and University, Italy
16. INFN Pavia and University, Italy
17. SLAC National Accelerator Lab., USA
18. Southern Methodist University, USA
19. Tufts University, USA
20. University of Chicago, USA
21. University of Houston, USA
22. University of Pittsburgh, USA
23. University of Rochester, USA
24. University of Texas (Arlington),USA
25. INFN Pisa and University, Italy
26. Ramanujan Faculty Phys. Res. India
27. Virginia Tech Institute

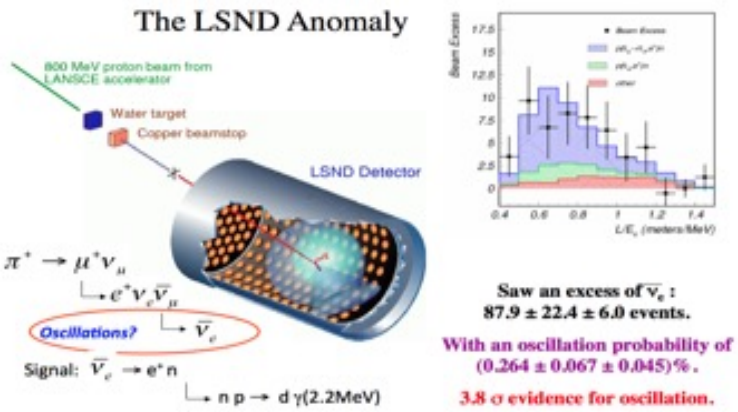
12 INFN groups, 12 US institutions, CERN, 1 Mexican institution, 1 Indian Institution

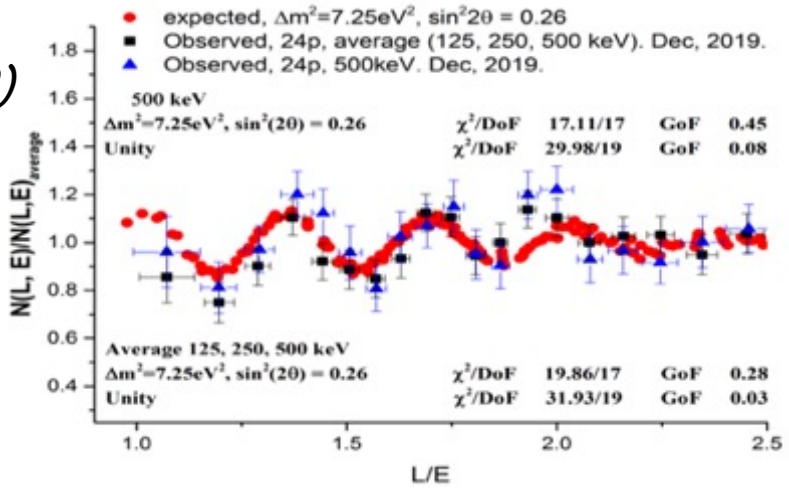
a On Leave of Absence from INFN Padova
b On Leave of Absence from INFN Pavia

The sterile neutrino puzzle

- Despite the well-established 3-flavour ν mixing, several anomalies collected so far hinting to additional ν states driving oscillations at small distance with $\Delta m^2_{new} \sim 1$ eV^2, small $\sin^2 2\theta_{new}$:

  - anti–νe appearance: in anti-$\nu\mu$ accelerator LSND experiment;
  - νe disappearance: SAGE, GALLEX experiments with Mega-Curie radioactive sources showing an observed/predicted rate R = 0.84±0.05, recently confirmed at 4σ by BEST exp.
  - anti-νe disappearance of near-by nuclear reactor experiment, initially R = 0.934±0.024, *but* recent anti-ν_e measurement at reactors (*Daya Bay, RENO, STEREO*) reduced the significance of the initial evidence;
  - anti-νe disappearance signal with a clear L/Eν ~ 1-3 m/MeV modulation detected by Neutrino-4 experiment (A.P. Serebrov et al.) at Dimitrovgrad SM-3 reactor.





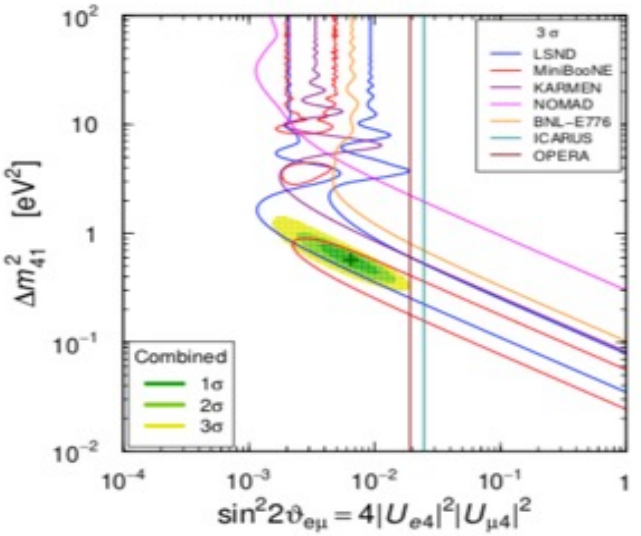
Combined analysis of Neutrino-4, GALLEX, SAGE, BEST data:
Δm^2_{14} =7.3 eV^2 $\sin^2(2\theta_{14})$ =0.36 at 5.8 σ C.L. (A.P. Serebrov et al. arXiv:2302.09958)

The sterile neutrino puzzle

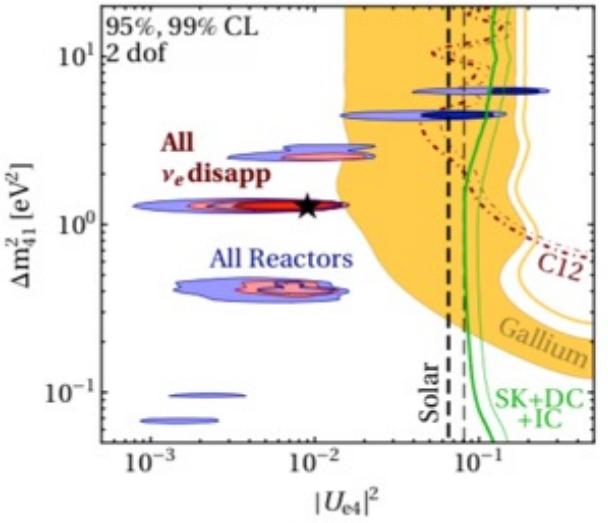
- Several experiments performed to study "ν anomalies" but:
  - No evidence in νμ disapp. exps (*IceCube, NOνA, MINOS/MINOS+, T2K*);
  - Clear tension between appearance and disappearance experiments, which are characterized by different ν energy range and detection technique, is evident.
    - ✓ *Measuring both appearance /disappearance in the same experiment using a detector with optimal ν id. and backgr. rejection is mandatory to disentangle physics scenario;*
    - ✓ *Far to near detector neutrino spectra comparison is crucial for the control of backgr. and beam/detector systematics.*

The Short Baseline Neutrino (SBN) program at Fermilab satisfies these requirements: it could have a crucial role in solving the sterile neutrino puzzle!

(anti-)$\nu_\mu \rightarrow \nu_e$ Appearance



(anti-)ν_e Disappearance

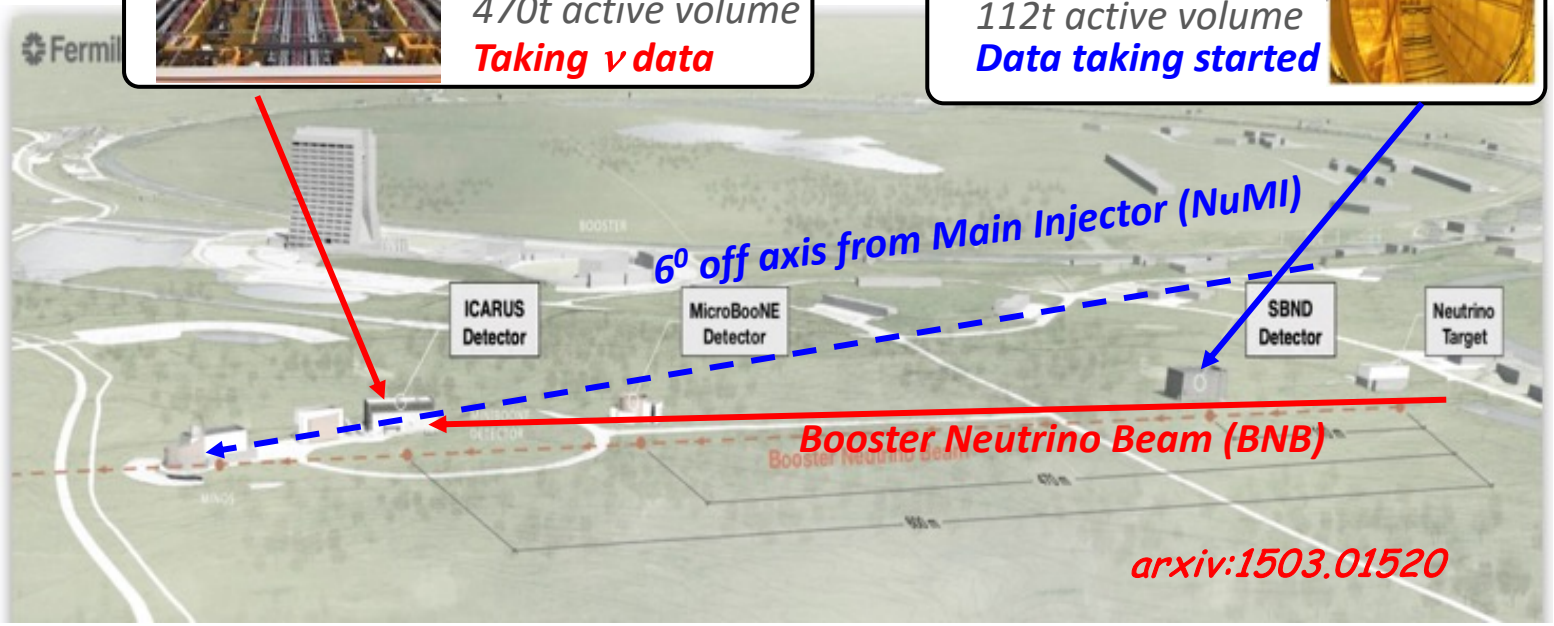


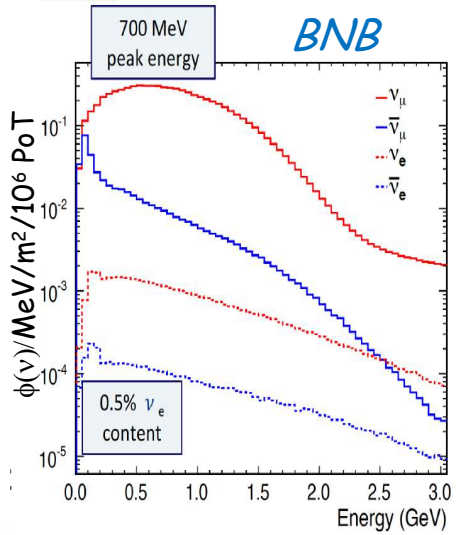
(arXiv:2106.05913)

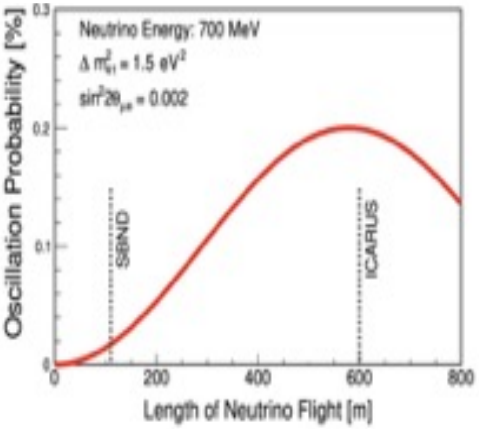
Short Baseline Neutrino (SBN) at FNAL BNB and NuMi beams

ICARUS LAr-TPC
600m baseline
470t active volume
Taking ν data

SBND LAr-TPC
110 m baseline
112t active volume
Data taking started





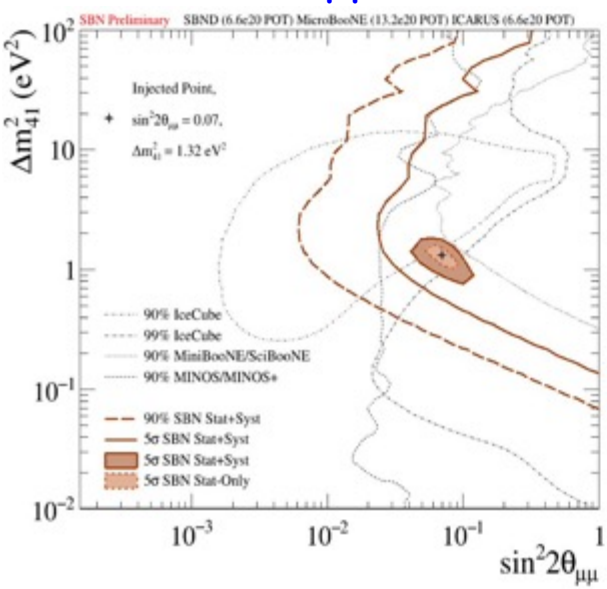


- ICARUS, SBND Liquid Argon TPCs (LAr-TPC) are installed at 600 and 110 m from Booster target, searching for sterile-ν oscillations both in appearance and disappearance channels;
- In addition: high-statistics ν-Ar cross-section measurements and event identification/ reconstruction studies in view of DUNE
  - ~10^6 events/y in SBND <1 GeV from Booster
  - ~10^5 events/y in ICARUS > 1 GeV from off-axis NuMI beam, allowing also for a rich Beyond the Standard Model search program.

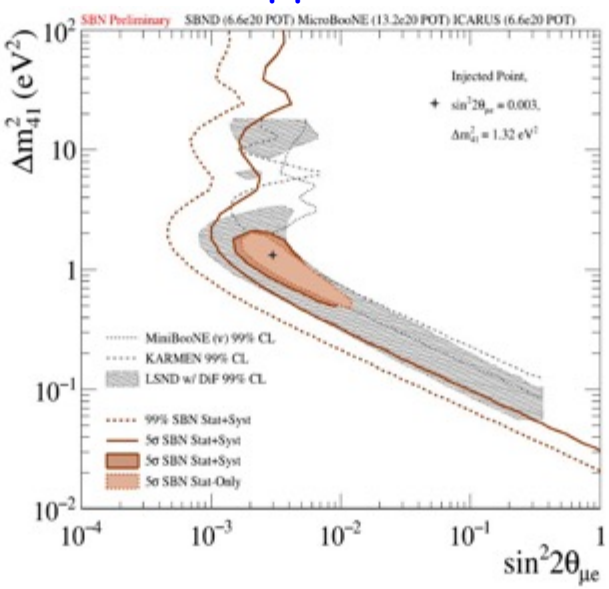
SBN Program: sterile neutrino sensitivity, 3 years (6.6 x10^{20} pot)

- 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:
  - "Initial" BNB beam composition and spectrum provided by SBND detector.
  - High νe identification capability of LAr-TPCs rejecting NC event background;

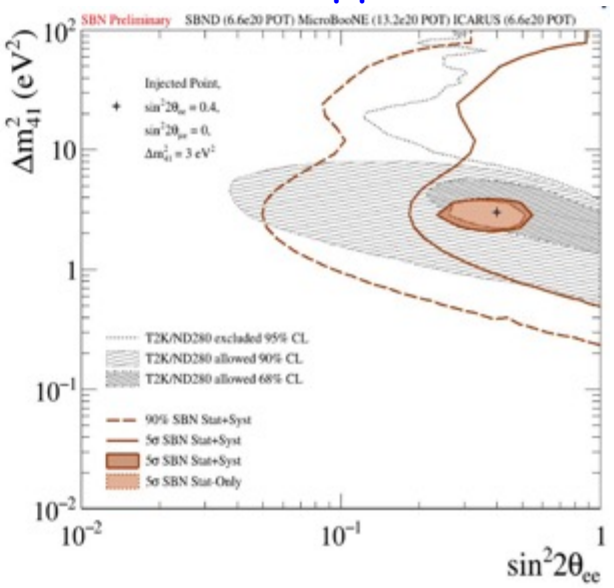
νμ disappearance



νe appearance



νe disappearance



Unique capability to study neutrino appearance and disappearance simultaneously

SBN is able to achieve a world-leading exclusion sensitivity

- 5σ coverage of the parameter area relevant to LSND anomaly
- Probing the parameter area relevant to reactor and gallium anomalies.

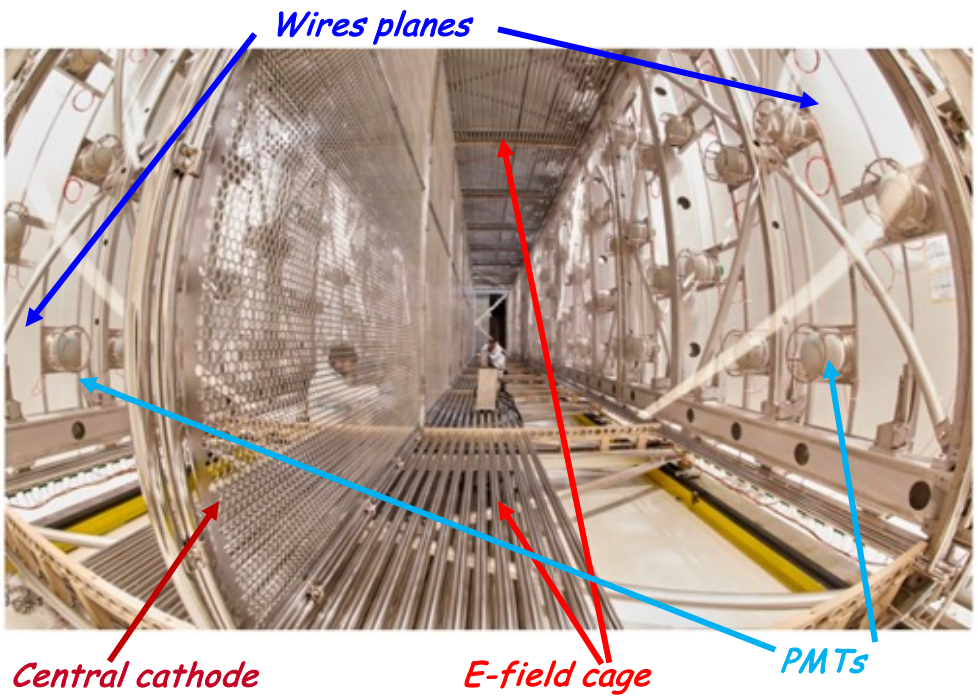
The ICARUS LAr-TPC detector

- First proposed by C. Rubbia in 1977, LAr TPCs are high granularity uniform self-triggering detectors with 3D imaging and calorimetric capabilities, allowing to accurately reconstruct a wide variety of ionizing events with complex topology: ideal detector for ν physics!

  After a long R&D by INFN/CERN, the successful operation in 2010-2013 of ICARUS T600 LAr-TPC at the G. Sasso underground lab, exposed to CNGS beam, demonstrated the full maturity of this detection technique:

  … paving the way for Long-Baseline experiments

- ICARUS-T600 overhauled 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);
  - Total active mass 476 ton;
  - 3 readout wire planes per TPC, in total 54000 wires at 0, ± 60^0, 3 mm pitch;
  - 360 8" PMTs, TPB coated detecting scintillation light by particles in LAr;
  - 2.85 m (~ 6 m.w.e.) concrete overburden + 4π Cosmic Ray Tagger (CRT) to suppress and tag cosmics.



Inner view of a TPC

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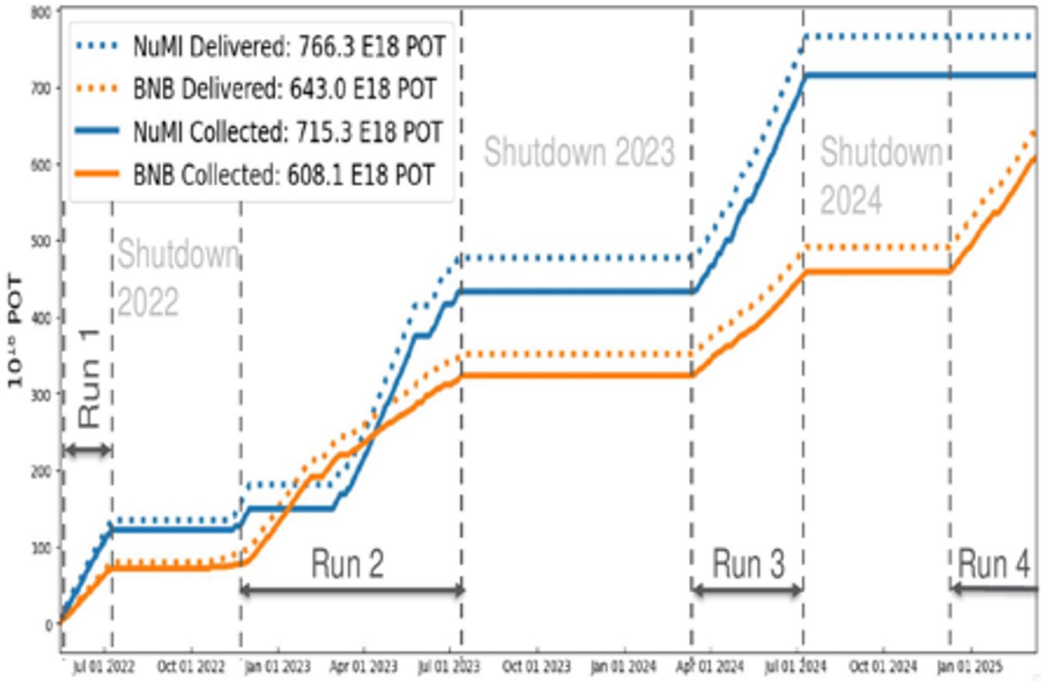
ICARUS FNAL operation

- ICARUS data taking for physics started on June 9th 2022, after the concrete overburden installation completion, with TPC, PMT and CRT systems 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;
- Steady data taking with excellent stability at BNB rate > 4 Hz, >90% lifetime: 3 physics runs completed + fourth run ongoing since December 2024.

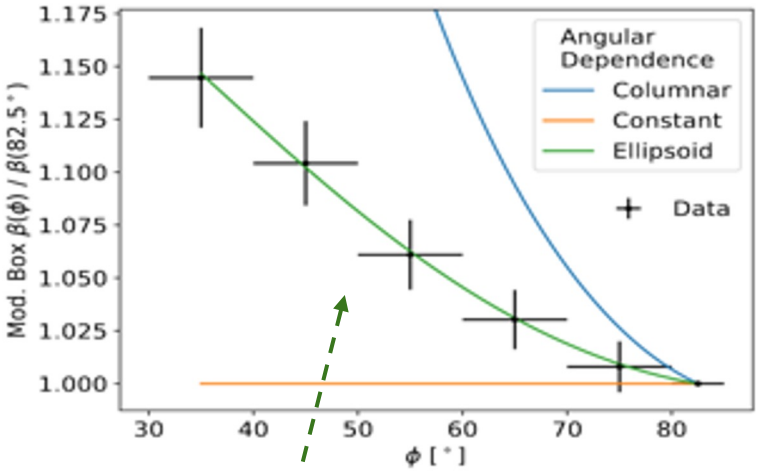


Collected Protons on target (PoT)	BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1 (Jun-Jul 22)	0.41 10^{20}	0.68 10^{20}	-
RUN-2 (Dec 22-Jul 23)	2.06 10^{20}	2.74 10^{20}	-
RUN-3 (Mar -July 24)	1.36 10^{20}	-	2.82 10^{20}
RUN-4* (Dec 24 -ongoing)	2.58 10^{20}	-	-
TOTAL	6.41 10^{20}	3.42 10^{20}	2.82 10^{20}

* No NUMI beam during RUN-4, table updated in mid May

ICARUS performance: calibration

- TPC wires signals have been accurately characterized and modeled in Monte Carlo
- Detector response is calibrated with cosmic μ and p from ν interactions including a new angular dependent ellipsoidal recombination model (EMB)



Angular dependence of recombination β parameter

Modified Birks' law taking into account the angle between the track and the drift direction (Modified Box Recombination)

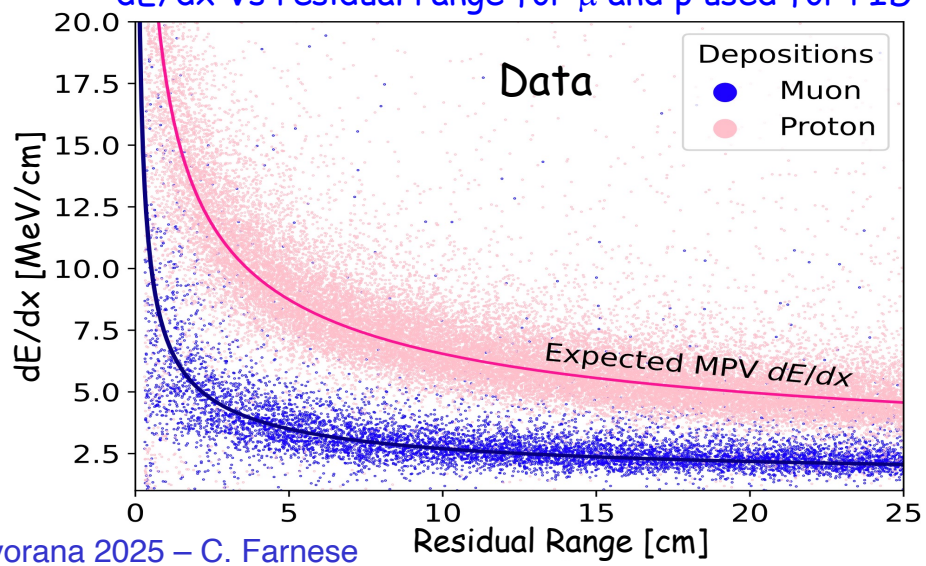
$$\frac{dx}{dQ} = \frac{1}{G}\frac{\log(\alpha+\beta(\phi))\frac{dE}{dx}}{\beta(\phi)W}$$

JINST 20, P01032

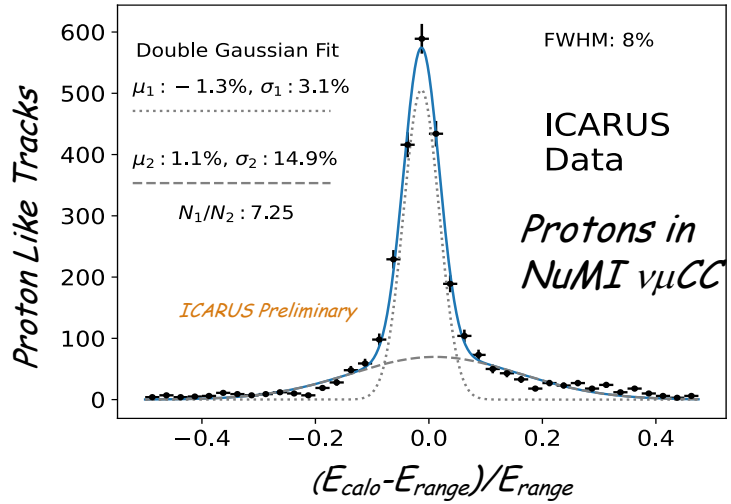
JINST 20, P01033

(2025)

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



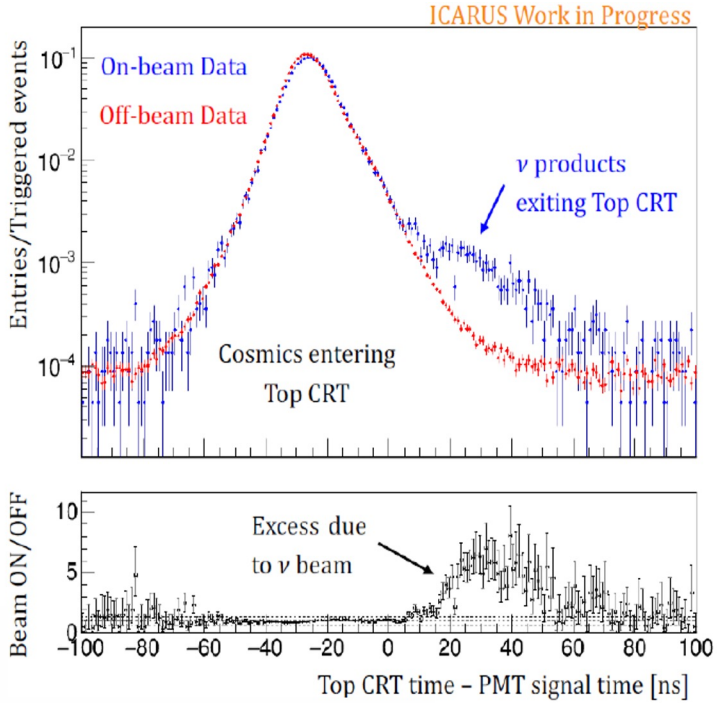
3% resolution

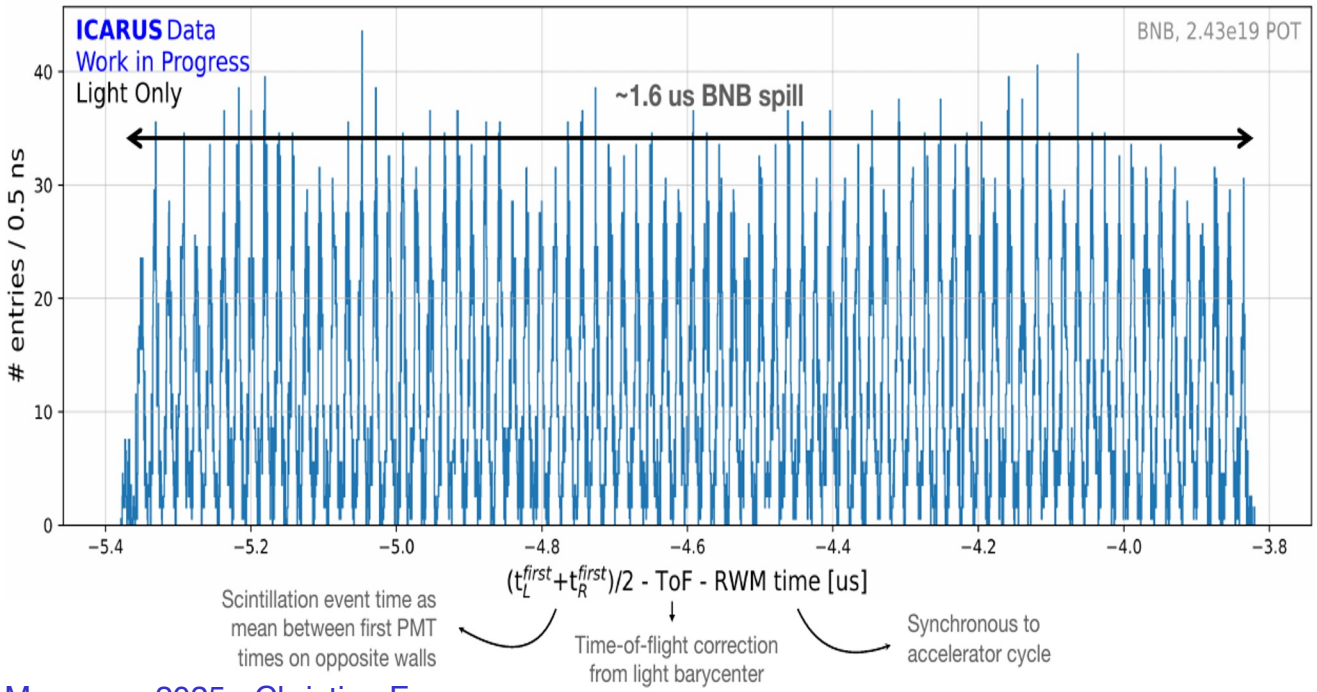


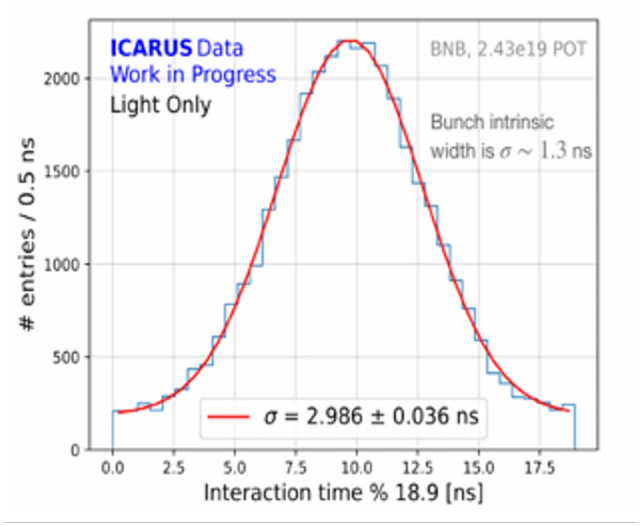
Difference between calorimetric and range measurement of the proton energy

ICARUS performance: timing

- Time-of-flight rejection of incoming cosmic rays using the external CRT and the inner PMT system.
- Reconstruction of bunched structure of beam spill – both BNB and NuMI:
  - Neutrino event time (PMTs only) with respect to the proton beam extraction time (RWM counters) after rejecting incoming cosmics (CRT) and correcting for ν flight distance.







ICARUS Research Program

- 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.
- Before the start of joint 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, later complemented by the investigation of ν_e disappearance with off-axis NuMI beam, addressing the Neutrino-4 claim. BNB ν_μ event selection: ready and validated;

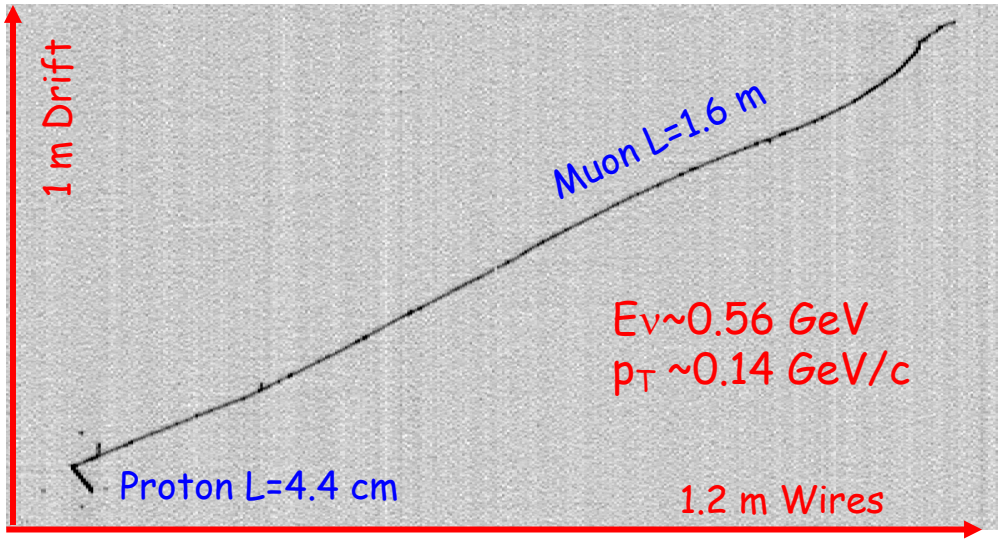
Study of ν_e, ν_μ events from off-axis NuMI beam, to measure ν-Ar interaction cross sections and optimize ν reconstruction identification in an energy range of interest for DUNE. Event selection ready, sidebands studied for a subset of data;

Exploit the off-axis NuMI beam to investigate sub-GeV Beyond Standard Model (BSM) signals: signal box opened for $\mu\mu$ decay channel;

- ICARUS established a blinding policy to ensure robust and unbiased interpretation of the collected data; analyses are initially validated with a subset of collected data.

ν_μ event selection for disappearance analysis at BNB

- Fully contained $\nu\mu$CC events with 1μ+N protons are studied, requiring:
  a) PMT light signal inside 1.6μs p beam spill window correlated with TPC tracks, no CRT signal;
  b) a muon with L_μ >50 cm and at least one proton track with E_K >50 MeV (L_p >2.3 cm) fully contained and identified by PID scores based on dE/dx;
  c) no additional π, γ.

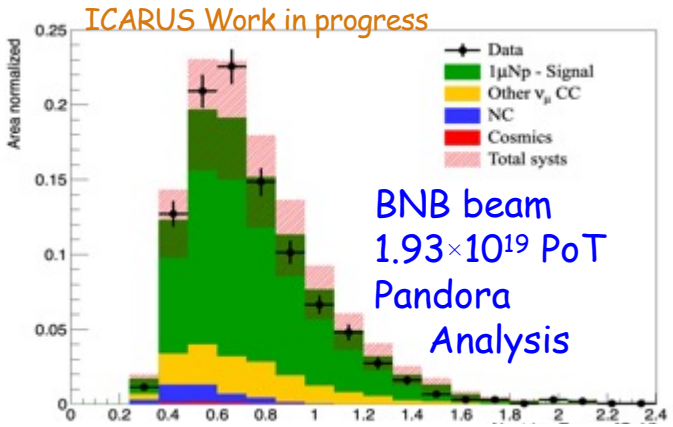


- The global event kinematics is obtained from range measurement of μ and p.
- Residual cosmic backgrounds < 1%.
- Flux, cross section and detector systematic uncertainties have been included:
  - Preliminarily, the impact of detector systematics is evaluated comparing calibrated and uncalibrated MC samples; the ongoing simulation improvements reducing residual Data/MC discrepancies are expected to reduce also detector systematics.
  - Substantial cancellation of cross section and flux uncertainties and of common detector systematics is expected in the joint SBN analysis;

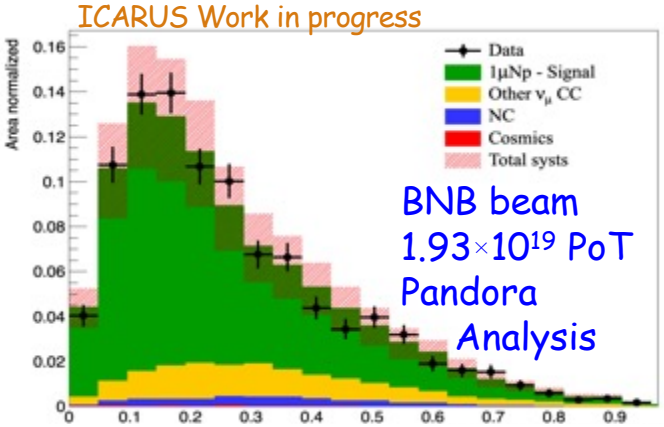
1μNp analysis – event selection results

- Two independent analysis streams considered, respectively based on:
  a) Pandora pattern recognition: ~50% efficiency for the signal
  b) Machine Learning (ML) SPINE reconstruction code: ~75% efficiency for the signal

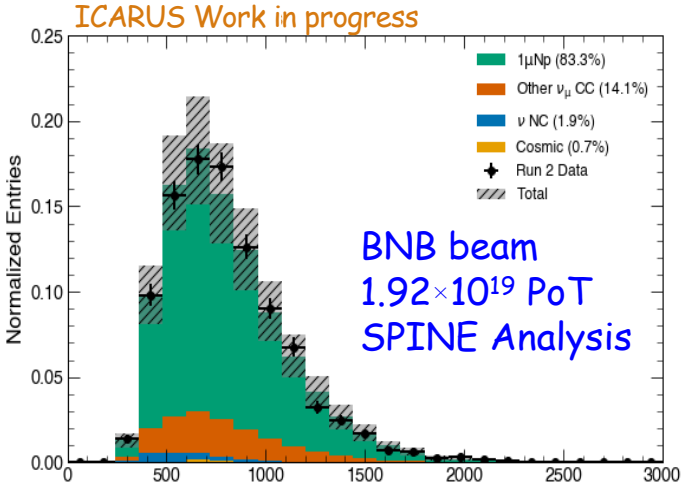
- 10% of RUN-2 data analyzed;
- Data-MC agreement for all studied event kinematic variables within systematics;
- Next analysis steps: full dataset unblinding and oscillation fit.



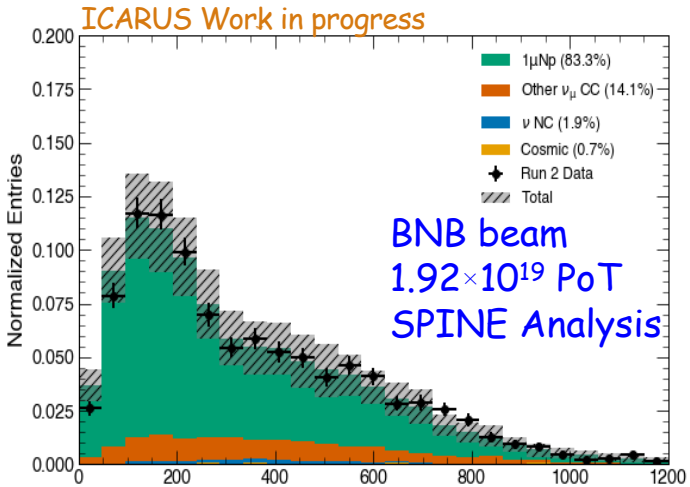
Reconstructed neutrino Energy [GeV]



Total transverse momentum p_T ([GeV]/c)



Reconstructed neutrino Energy [MeV]



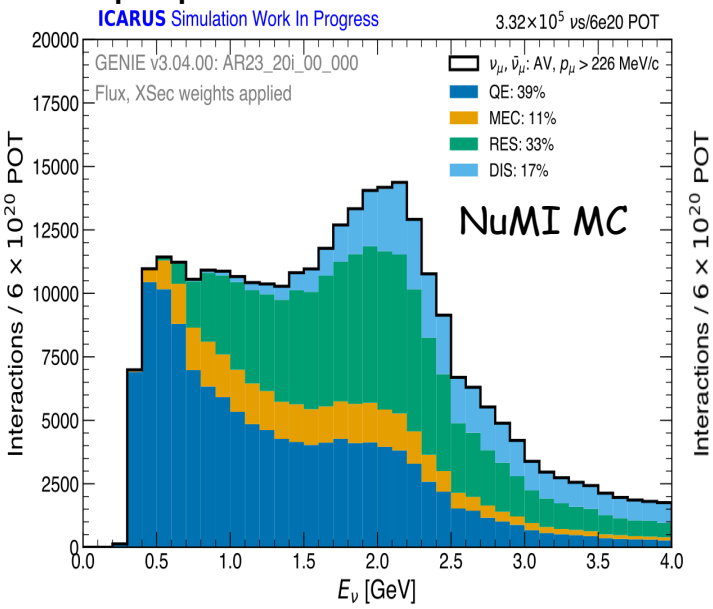
Total transverse momentum p_T ([MeV]/c)

Neutrino Interactions from NuMI off axis at ICARUS

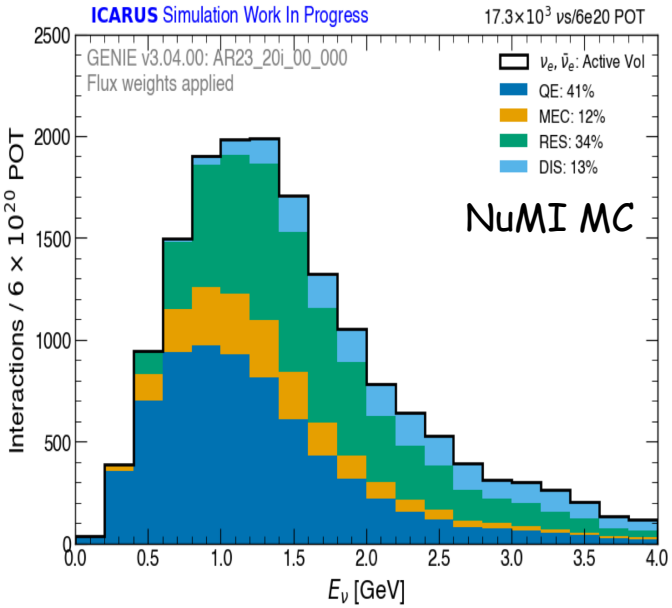
- Excellent statistics to measure cross section for quasi-elastic, resonance and deep inelastic scattering, for both electron and muon neutrinos;
- Available data ~3.42E20 POT for physics analysis now

  Expected CC events in the available statistics : ν_μ 188,000 and ν_e 9,600.
- Neutrino energy spectrum from NuMI at ICARUS covers the first oscillation peak and good coverage of the relevant phase space for DUNE experiment.

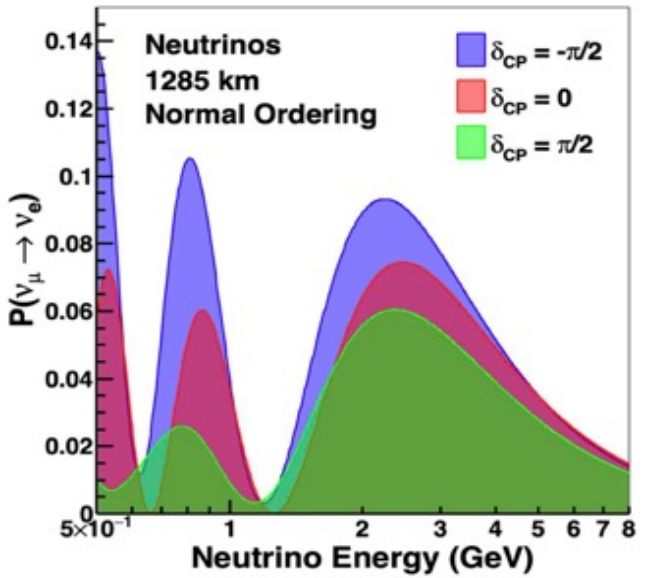
ν_μ, $\bar{\nu}_\mu$ from NuMI at ICARUS



ν_e, $\bar{\nu}_e$ from NuMI at ICARUS

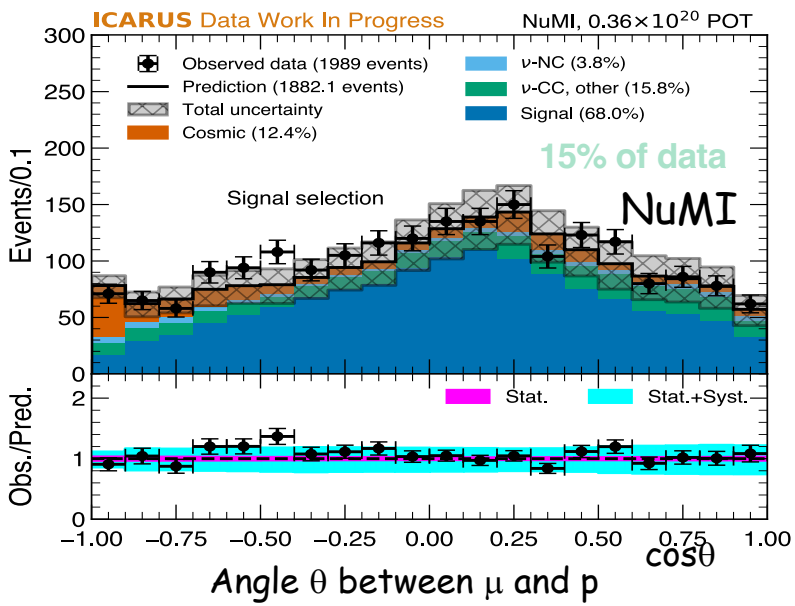


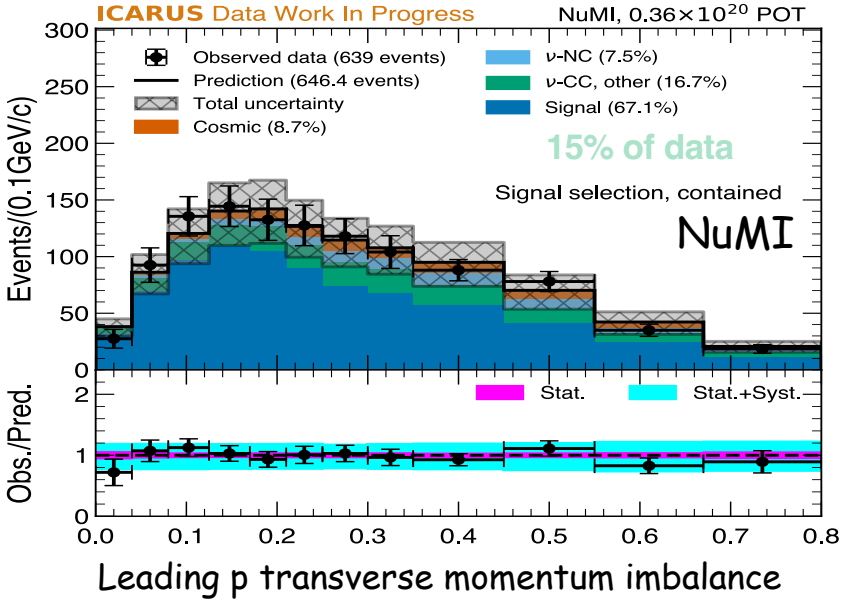
Oscillation probability at DUNE



CC 0π analysis – results for the selected sample

- First analysis targets 1μ+Np+0π enhanced in quasi elastic and 2p2h interactions :
  - Signal definition: one μ with momentum > 226 MeV/c, any proton with momentum between 400 MeV/c and 1 GeV/c, no $\pi^{\pm}$ or π^0 in the final state;
  - Flux, interaction model and detector systematic uncertainties have been included.
  - The angle between μ and leading p candidates populates broadly the phase space and is expected to encode information about Final State Interactions for all events;
  - Transverse kinematic observables are sensitive to Initial and Final State effects.

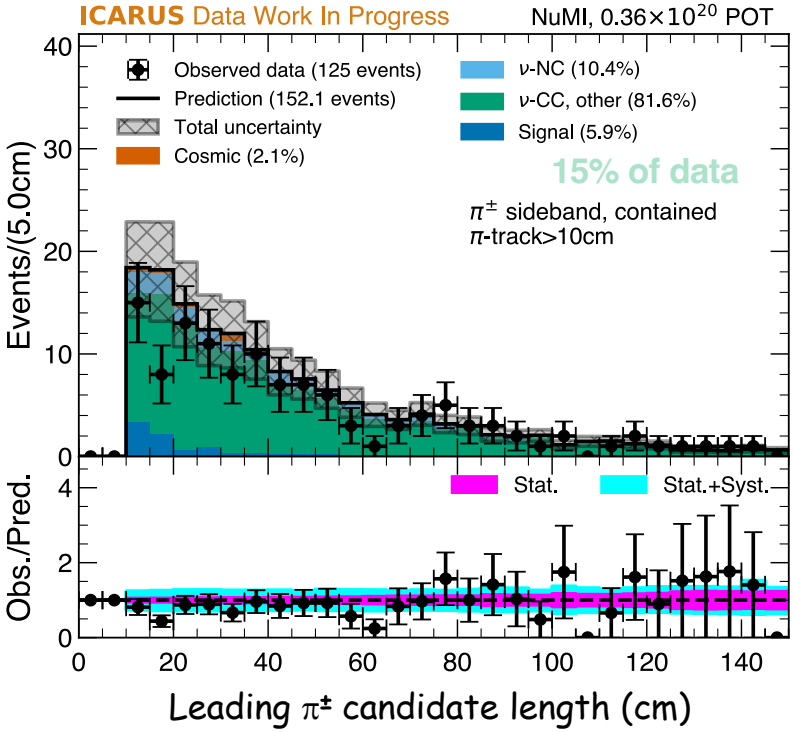


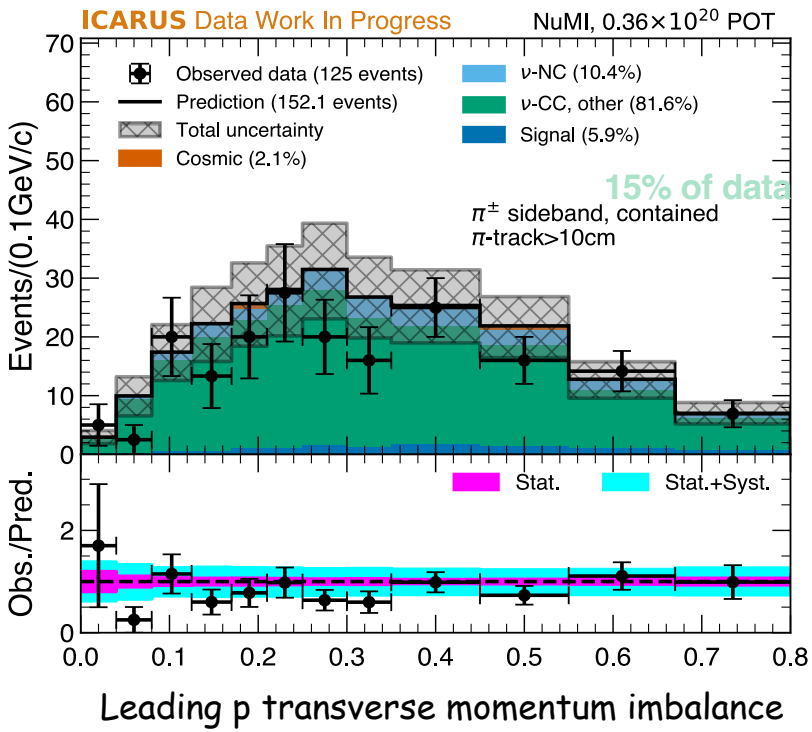


Initial study with 15% of data.

Charged Current Pion Control Sample

- The major background for the selected sample is represented by events with undetected/misidentified pions;
- To directly characterize this background an event control sample has been selected with charged pion candidates (requiring the presence of a secondary muon-like track);



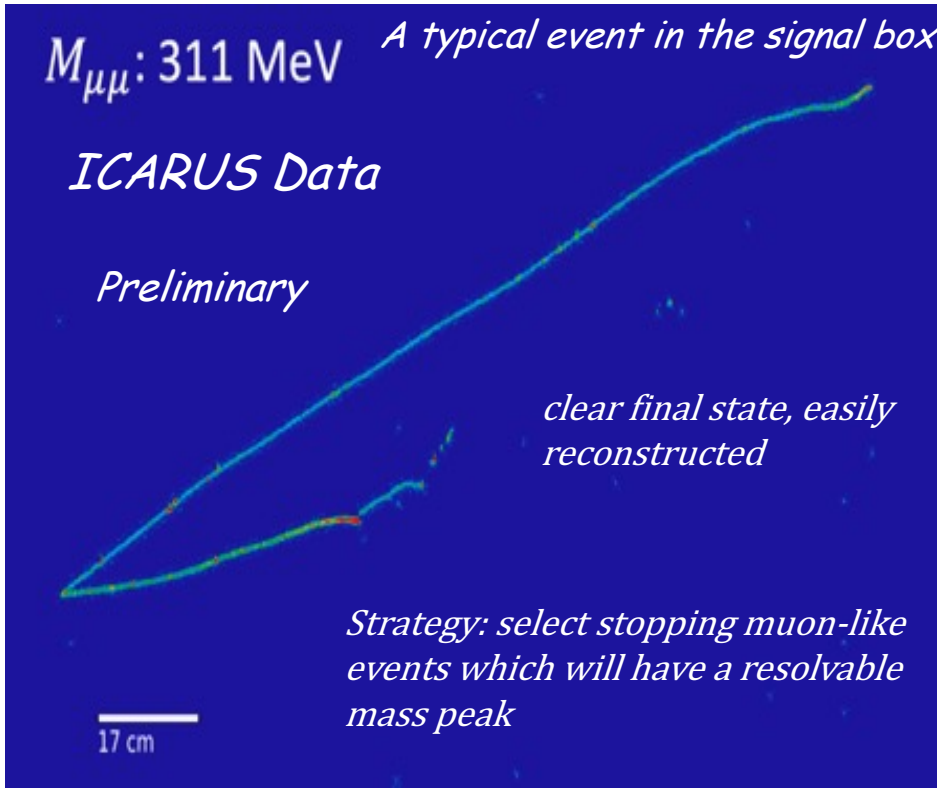


Results for the full 1μ+Np+0π dataset soon !

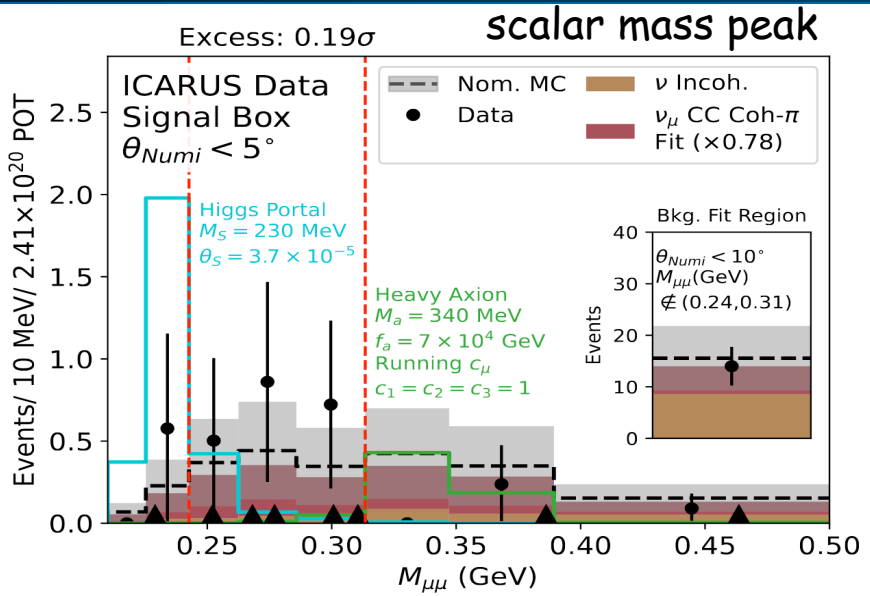
Dark sector models investigation by ICARUS

- A rich Beyond Standard Model search program (DM, heavy neutral leptons,…) has been pursued exploiting the off-axis NuMI beam;
- Models considered so far involve dark particles coupling to Standard Model particles via Scalar Portal Interactions:
  - Higgs portal Scalar: Scalar dark sector particles, interactions by mixing with Higgs boson;
  - Heavy QCD axion: Pseudo-scalar particles, interactions by mixing with pseudo-scalar mesons.

- A first search for new particle decaying into di-muon has been completed.
- Events with 2 stopping μs are selected, to reconstruct the scalar mass peak;
  - Signal expected at small angle to beam (θ_{NuMI} <5^0);
- Flux, interaction model and detector systematic uncertainties have been included.



Search for BSM scalar decays in $\mu^+\mu^-$ with NuMI - results



- Open box result: 8 events observed, compared to MC expectations of 8 events, mostly from $\nu\mu$CC coherent π production;
- No new physics signal was observed, the maximum excess being 0.19 σ;

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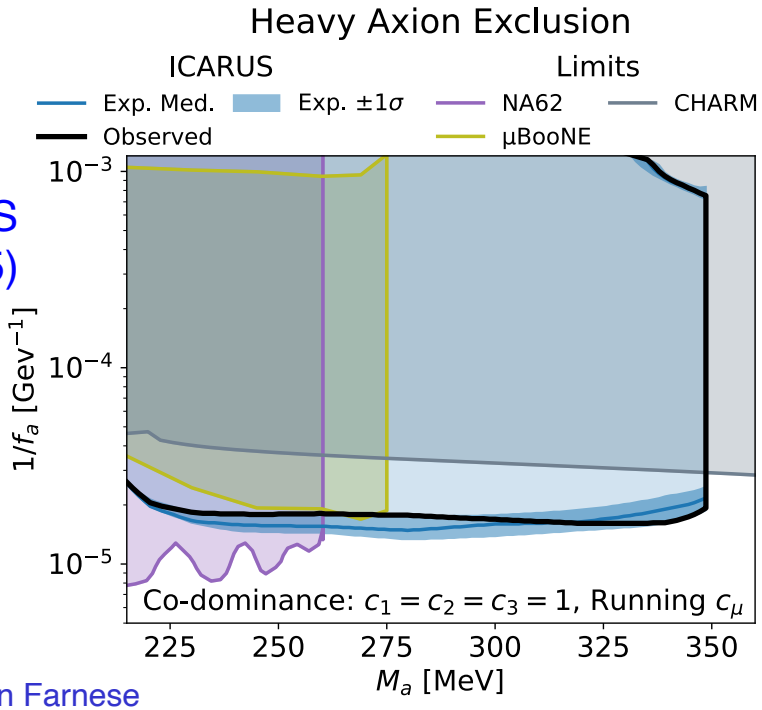
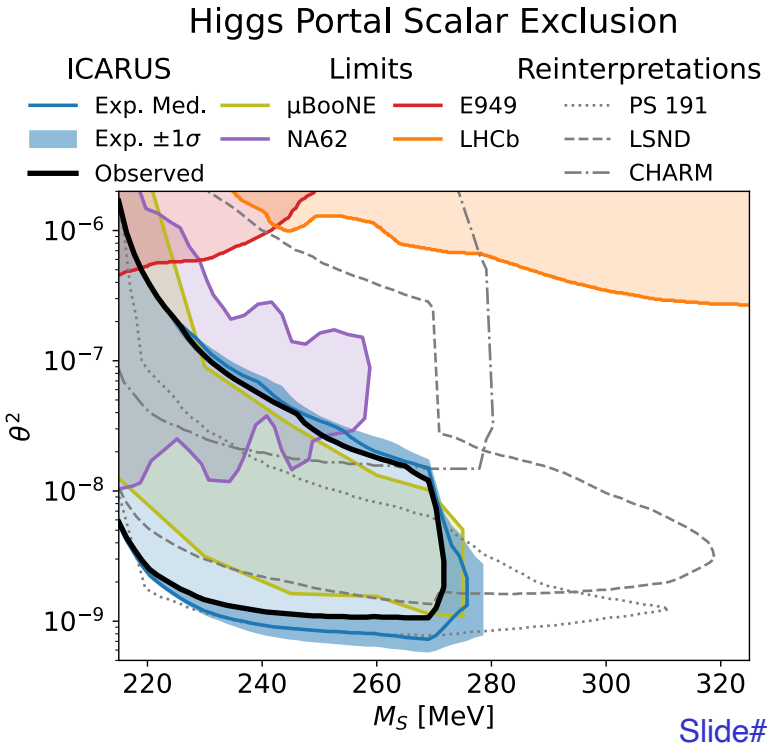
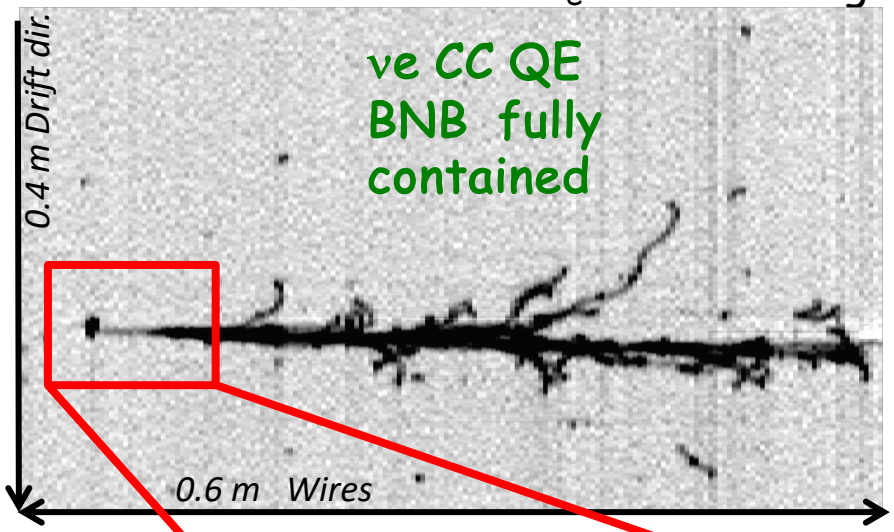
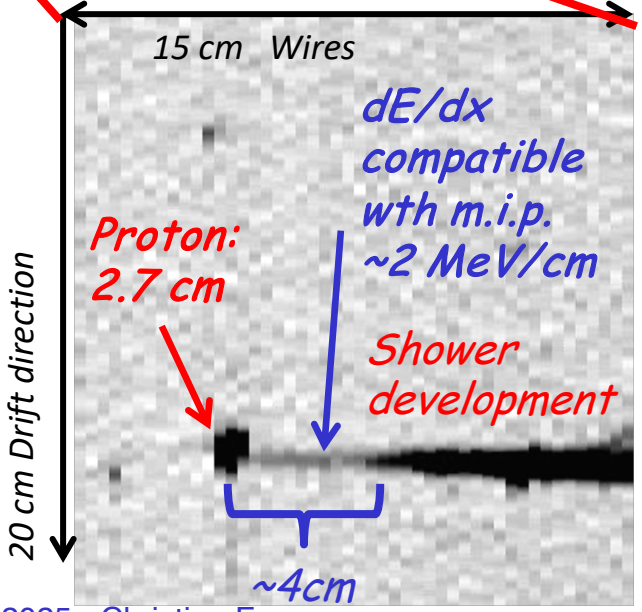


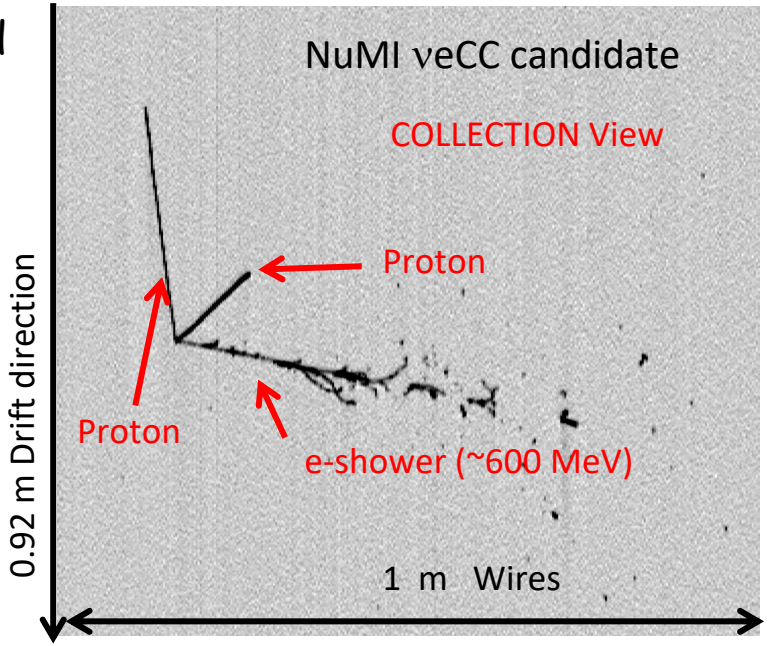


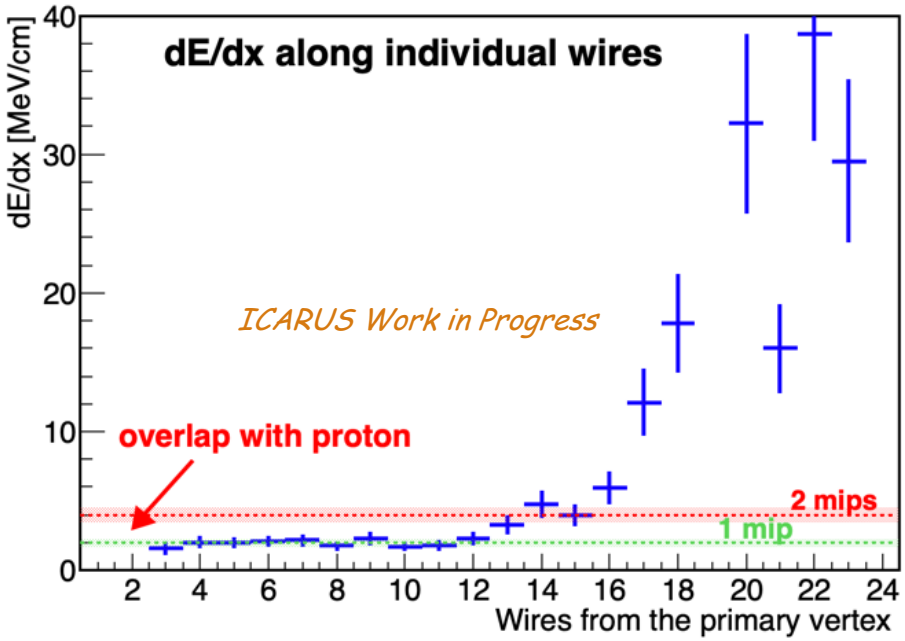
Search for electron neutrino events

- The development of tools for the selection and reconstruction of the ν_e events is ongoing;





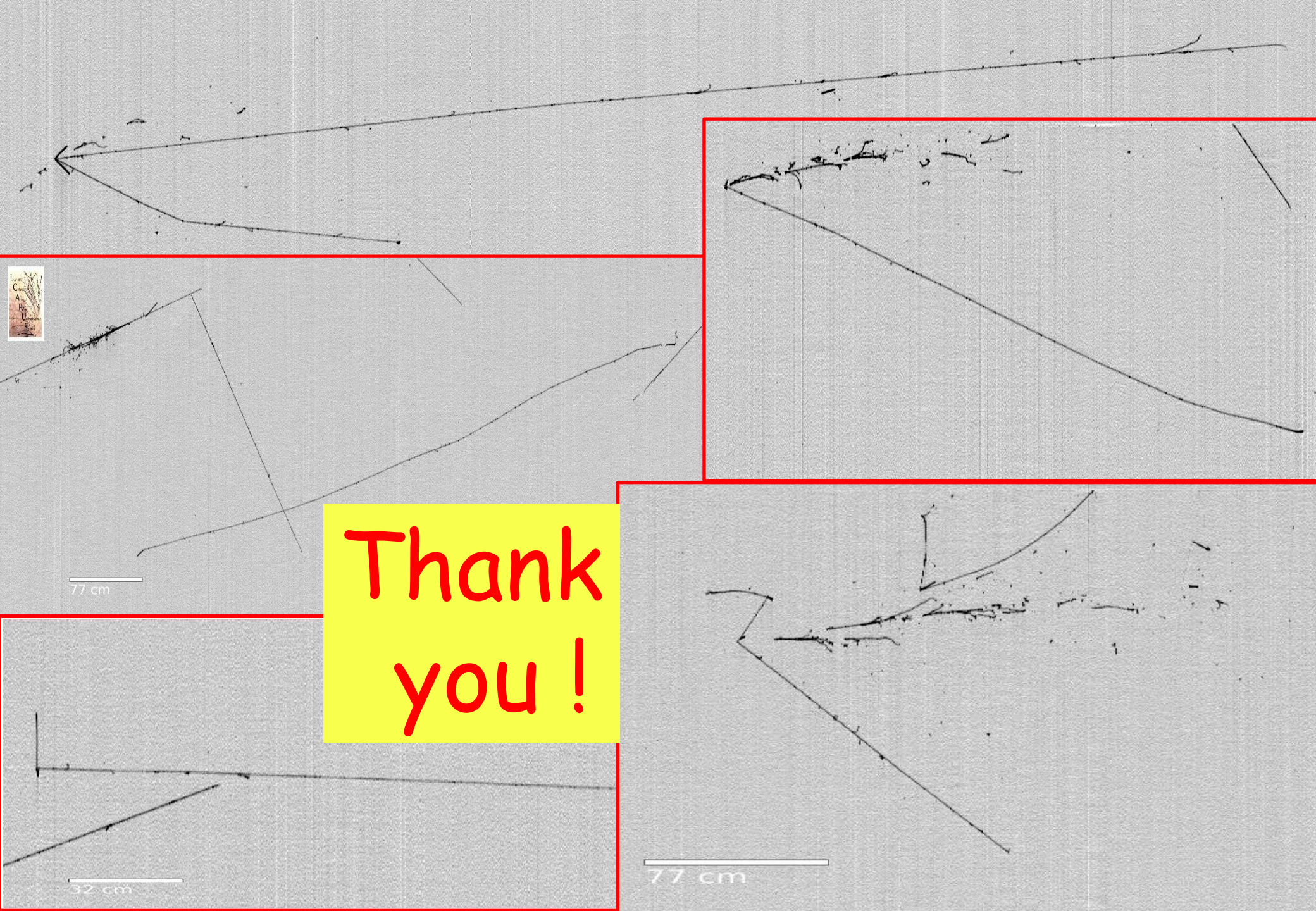




Conclusions

- ICARUS is smoothly running in physics mode since June 2022, exposed to the Booster and to the NuMI neutrino beams;
- The detector is calibrated with cosmic muons and protons from neutrino interactions, electronic response and physical properties have been accurately qualified and are being fully modeled in simulation.
- 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 analysis with di-muon final state topology has been completed.
- Analyses ready to proceed to validation with larger control samples in view of the full signal unblinding.

STAY TUNED !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Thank you !
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77 cm