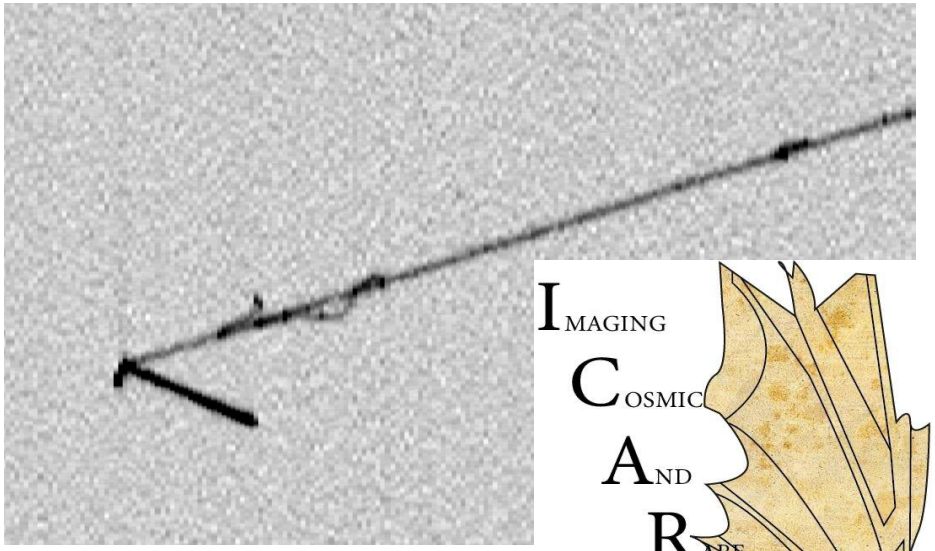
Latest Results from the ICARUS experiment at the Short-Baseline Neutrino Program



MAYORANA
International workshop
June 17th 2025

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ICARUS collaboration

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ICARUS Collaboration at SBN

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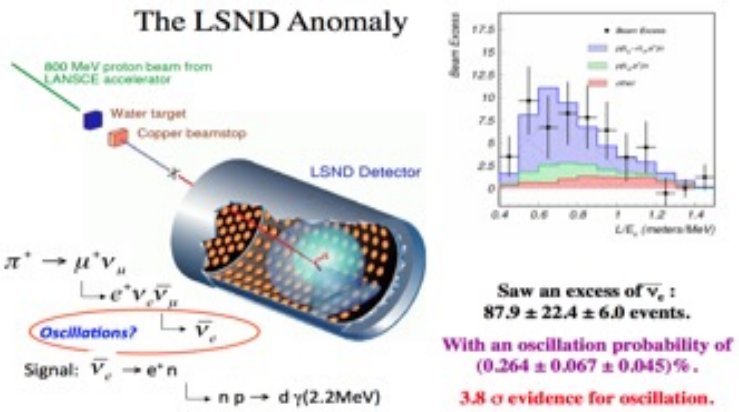
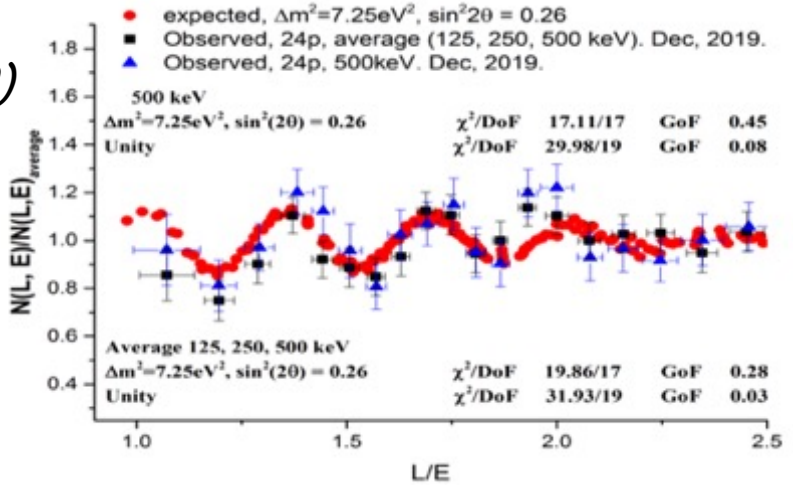
a On Leave of Absence from INFN Padova
b On Leave of Absence from INFN Pavia

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.





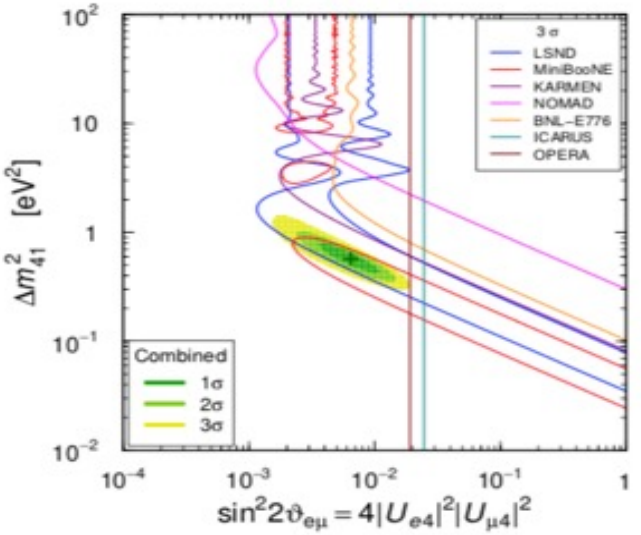
Combined analysis of Neutrino-4, GALLEX, SAGE, BEST data:
$\Delta m^2_{14} = 7.3\ eV^2$ $\sin^2(2\theta_{14}) = 0.36$ at 5.8 σ C.L. (A.P. Serebrov et al. arXiv:2302.09958)

The sterile neutrino puzzle

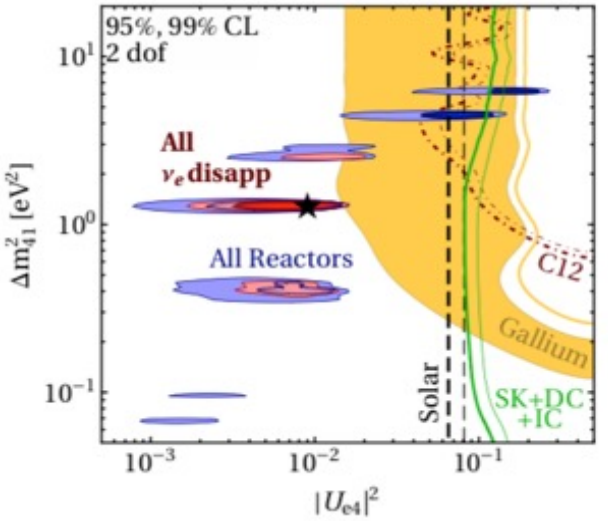
- Several experiments performed to study "ν anomalies" but:
  - No evidence in νμ disapp. exps (*IceCube, NOνA, MINOS/MINOS+, T2K*);
  - Clear tension between appearance and disappearance experiments, which are characterized by different ν energy range and detection technique, is evident.
    - ✓ *Measuring 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

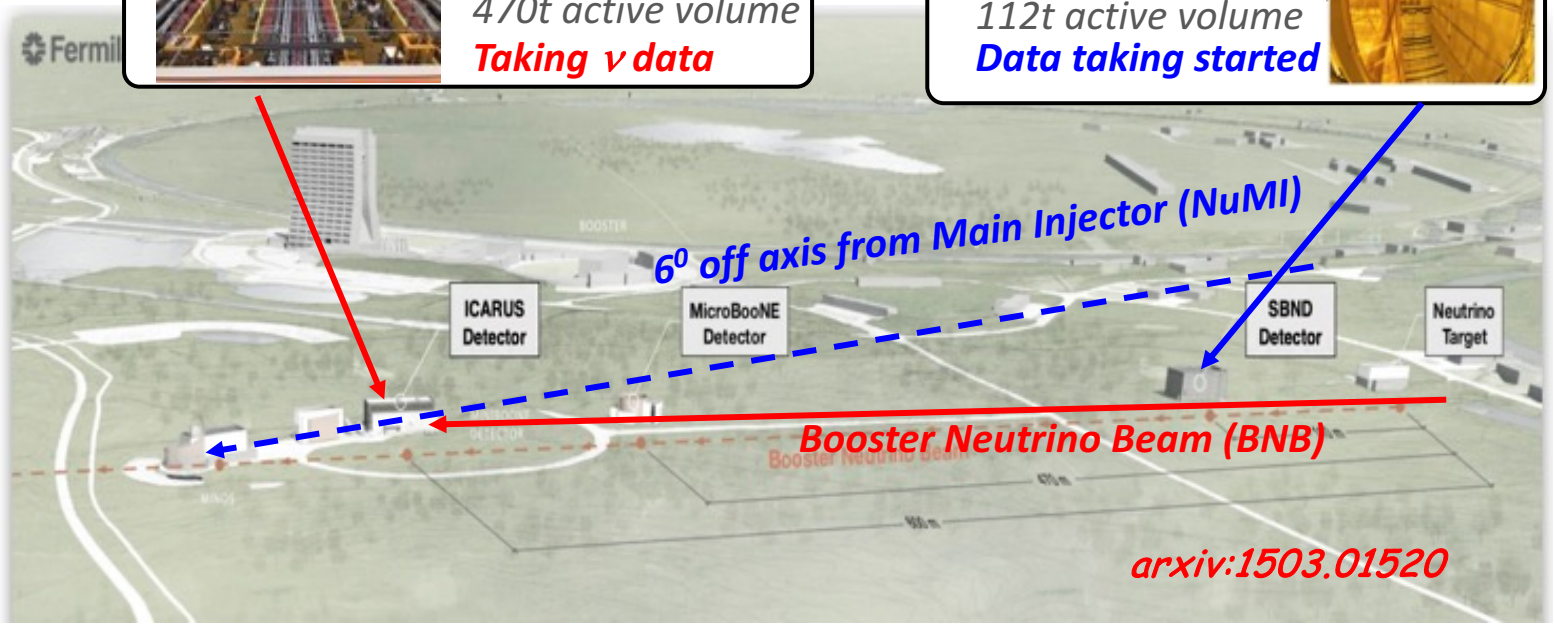


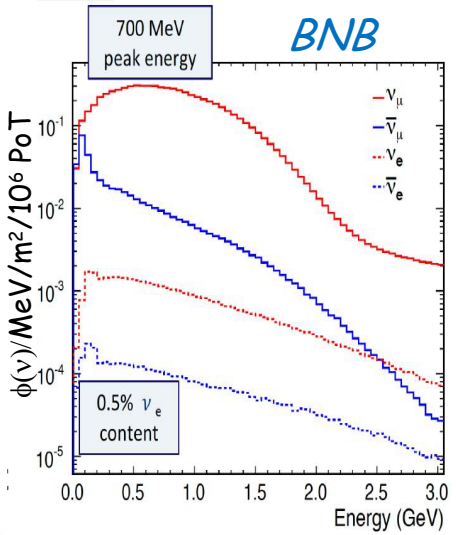
(arXiv:2106.05913)

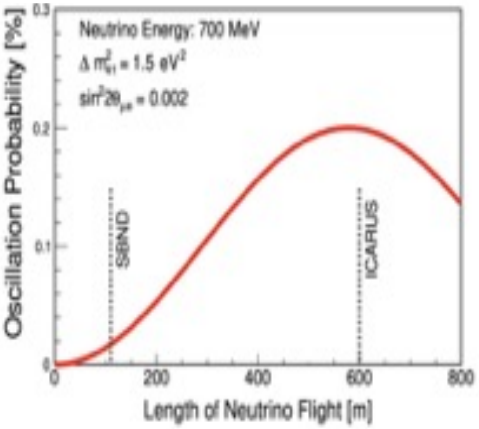
Short Baseline Neutrino (SBN) at FNAL BNB and NuMi beams

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

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





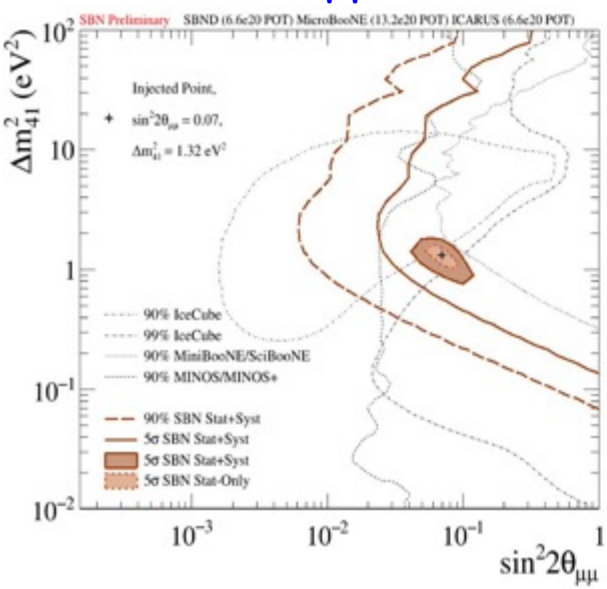


- ICARUS, SBND Liquid Argon TPCs (LAr-TPC) are installed at 600 and 110 m from Booster target, searching for sterile-ν oscillations both in appearance and disappearance channels;
- In addition: high-statistics ν-Ar cross-section measurements and event identification/ reconstruction studies in view of 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.

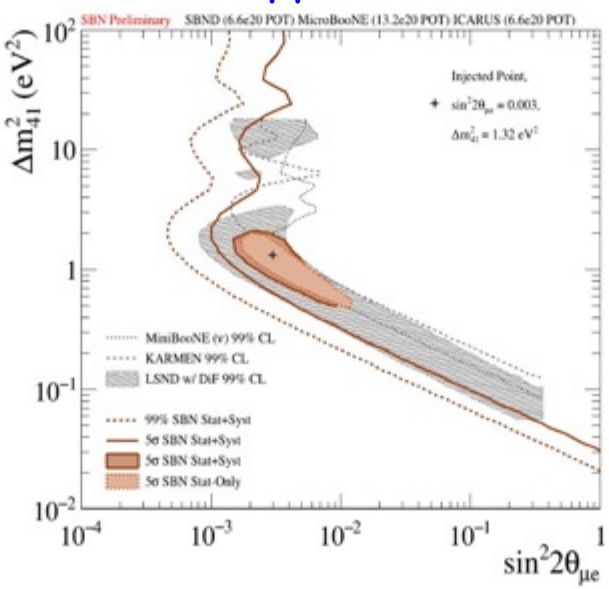
SBN Program: sterile neutrino sensitivity, 3 years (6.6 x10^{20} pot)

- 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;

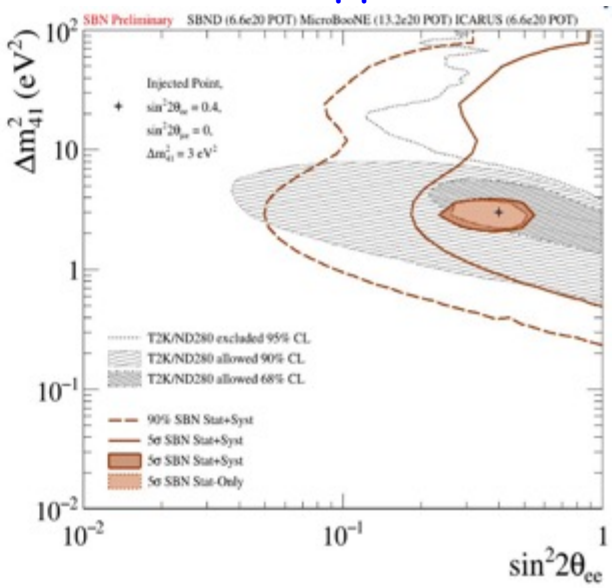
νμ disappearance



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.

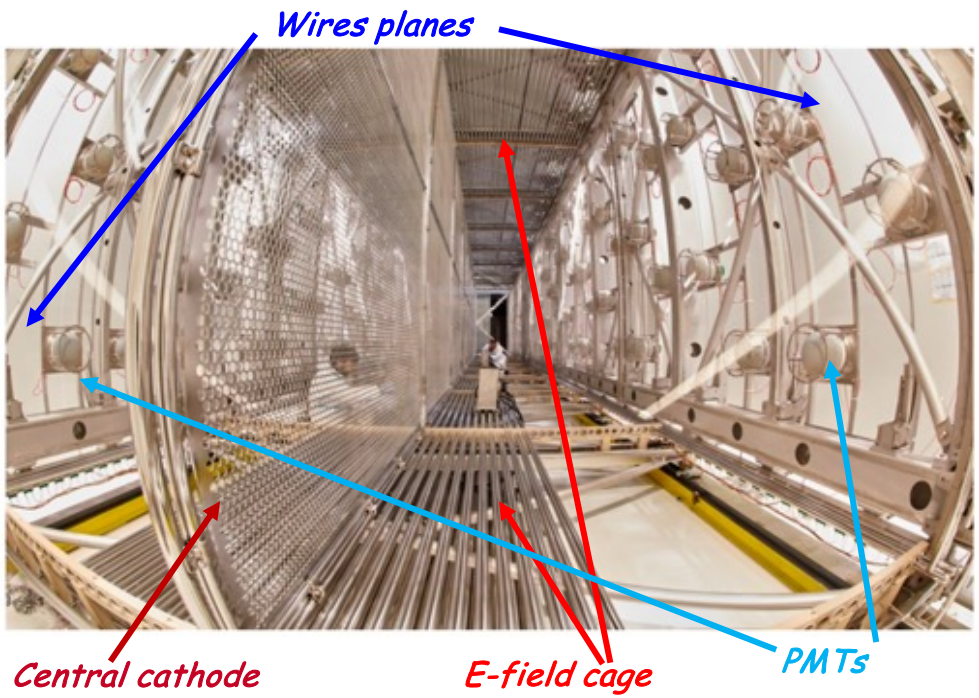
The ICARUS LAr-TPC detector

- 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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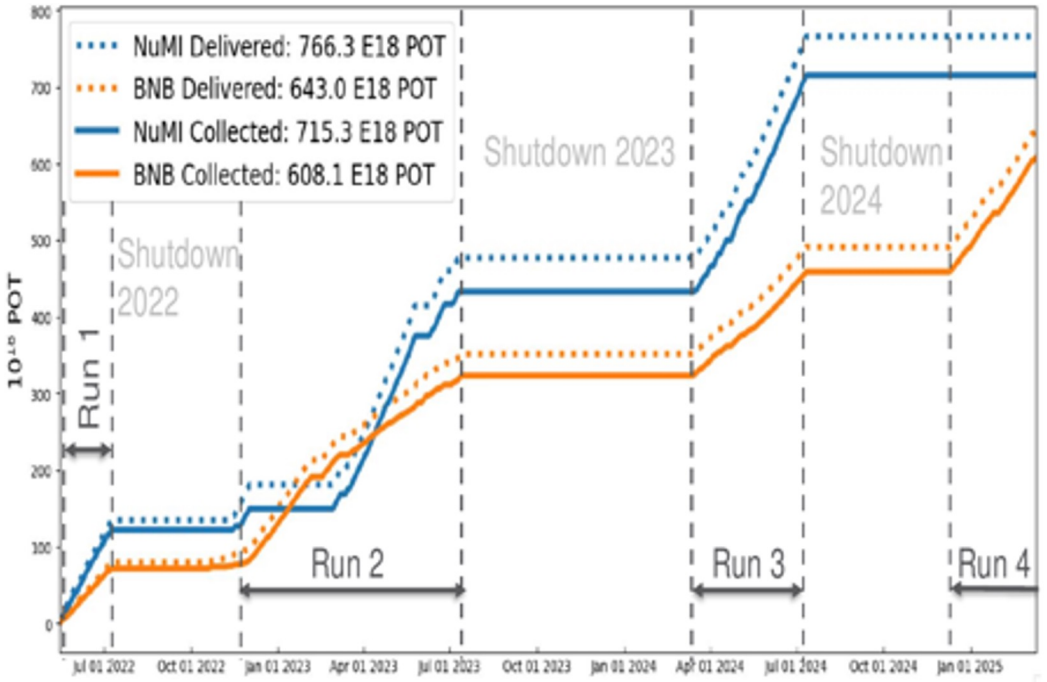
ICARUS FNAL operation

- 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.

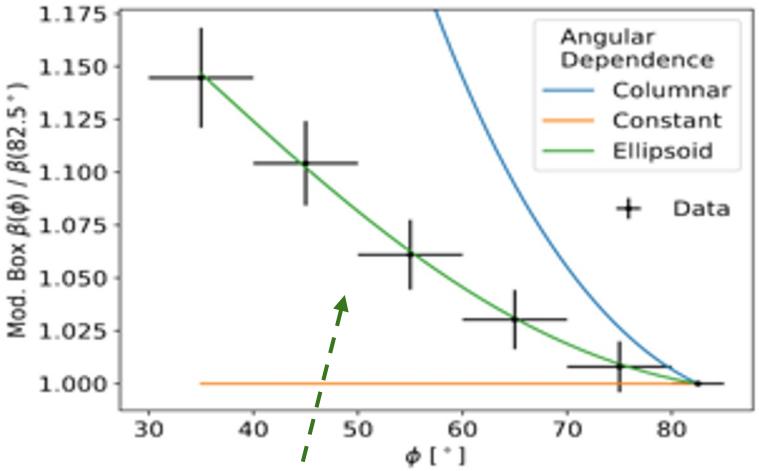


Collected Protons on target (PoT)	BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1 (Jun-Jul 22)	0.41 10^{20}	0.68 10^{20}	-
RUN-2 (Dec 22-Jul 23)	2.06 10^{20}	2.74 10^{20}	-
RUN-3 (Mar -July 24)	1.36 10^{20}	-	2.82 10^{20}
RUN-4* (Dec 24 -ongoing)	2.58 10^{20}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

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

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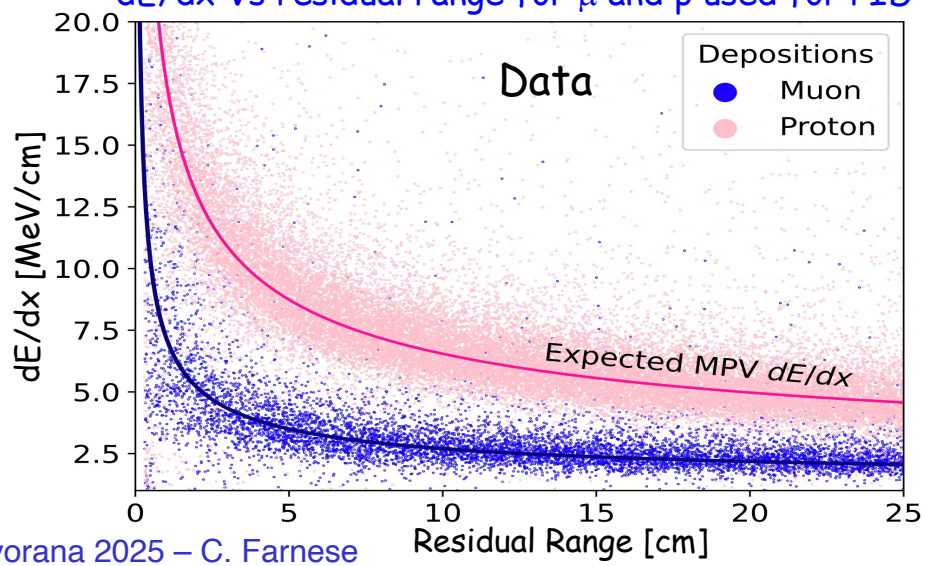
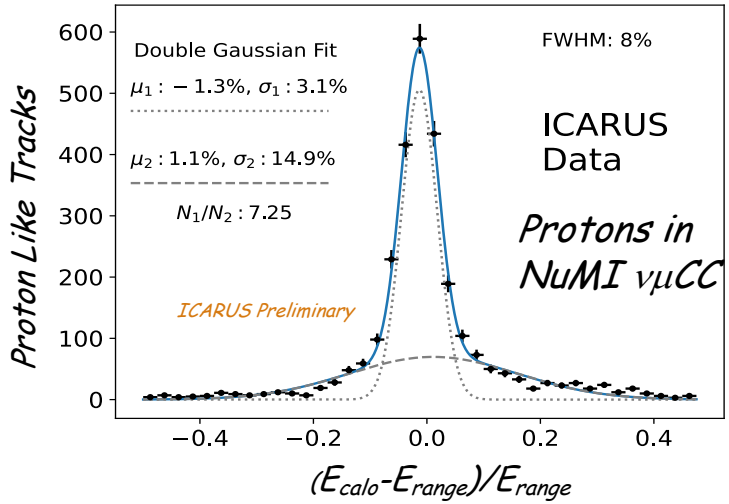
dE/dx Vs residual range for μ and p used for PID



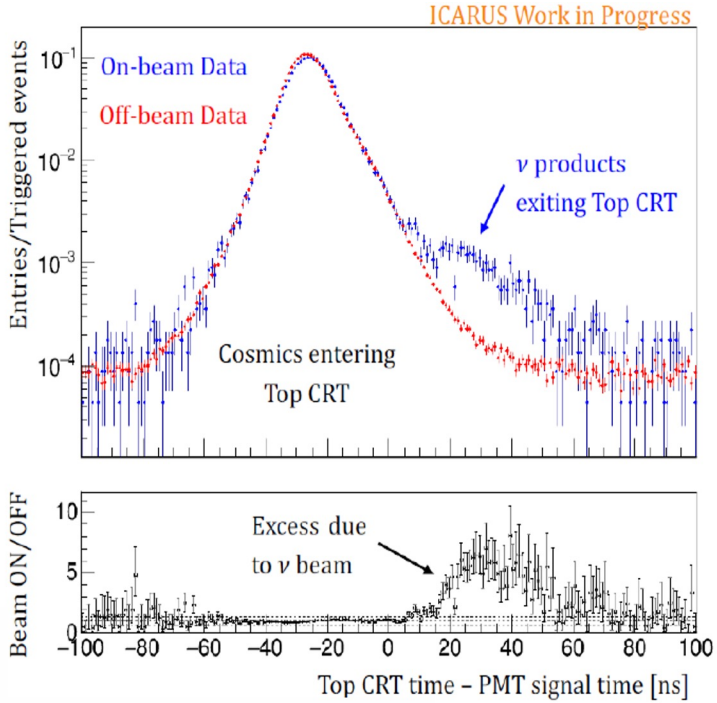
3% resolution

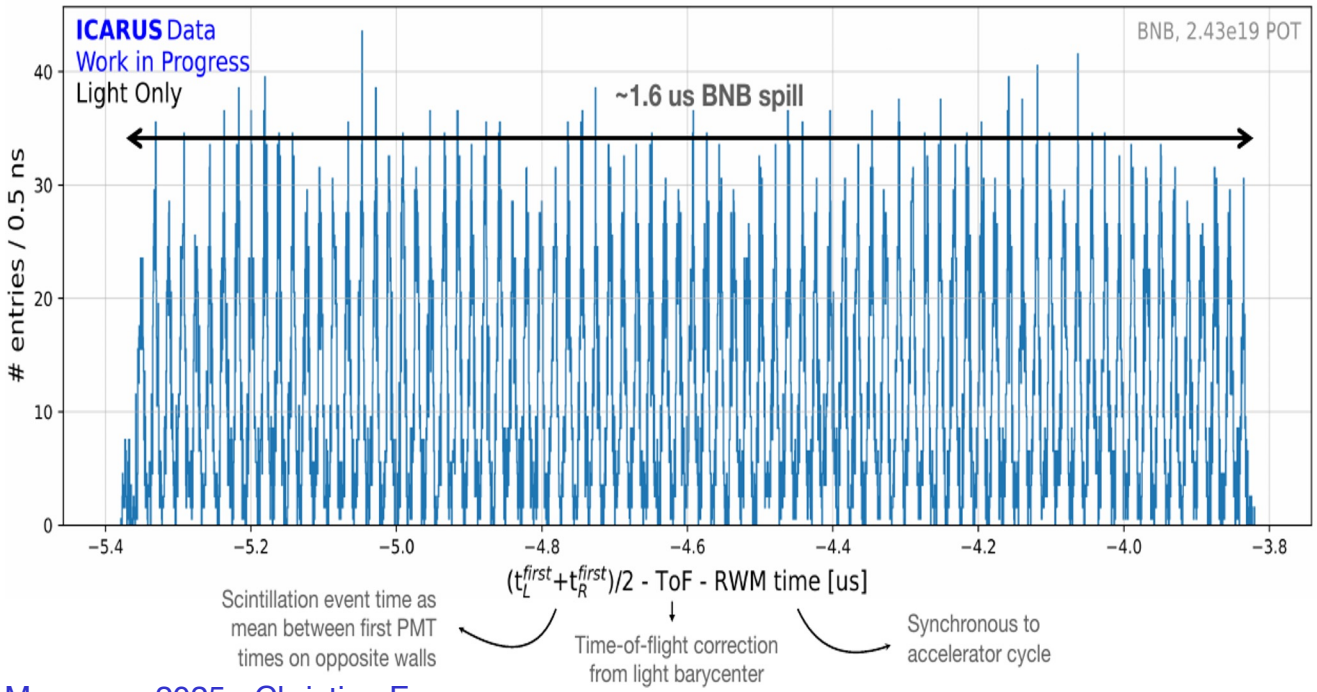


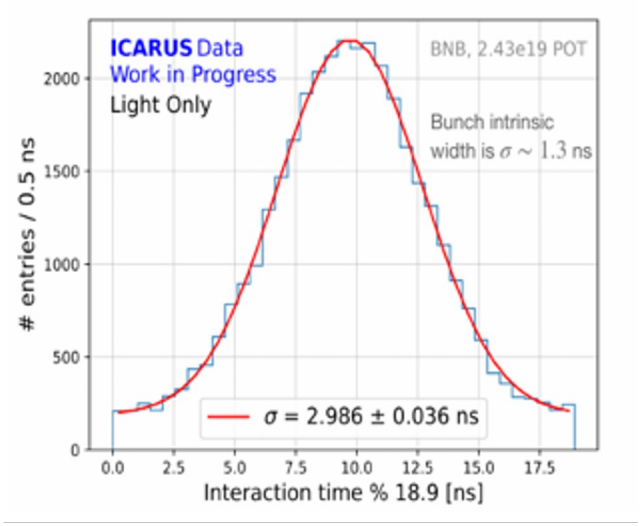
Difference between calorimetric and range measurement of the proton energy

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;

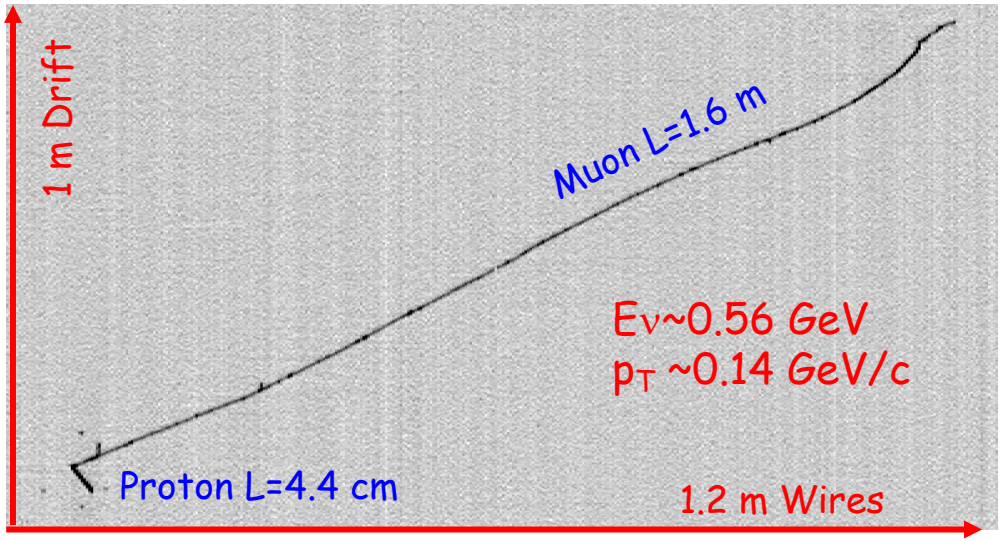
Study of ν_e, ν_μ events from off-axis NuMI beam, to measure ν-Ar interaction cross sections and optimize ν reconstruction identification in an energy range of interest for DUNE. Event selection ready, sidebands studied for a subset of data;

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.

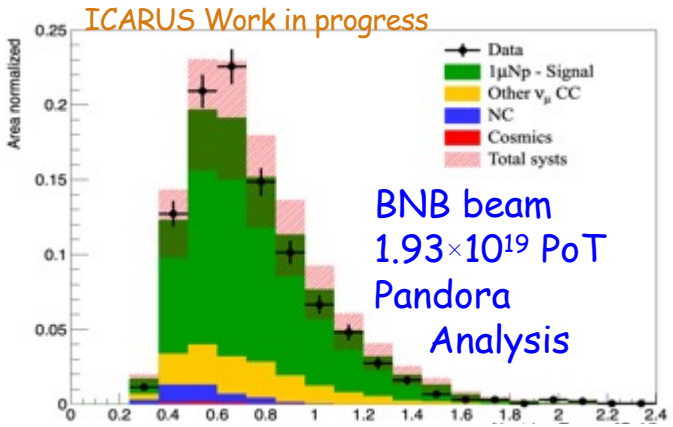


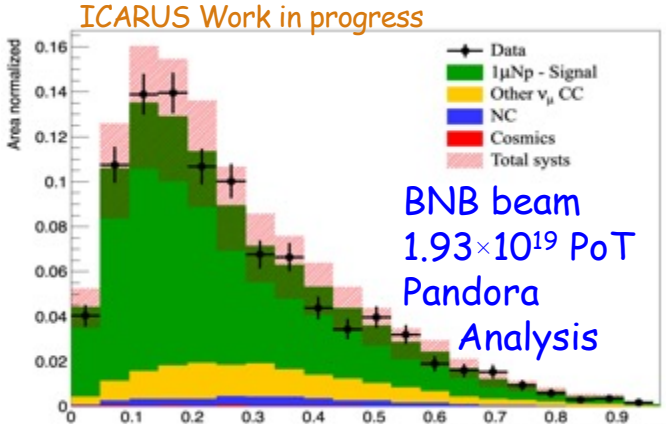
- The global event kinematics is obtained from range measurement of μ and p.
- Residual cosmic backgrounds < 1%.
- Flux, cross section and detector systematic uncertainties have been included:
  - Preliminarily, the impact of detector systematics is evaluated comparing calibrated and uncalibrated MC 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;

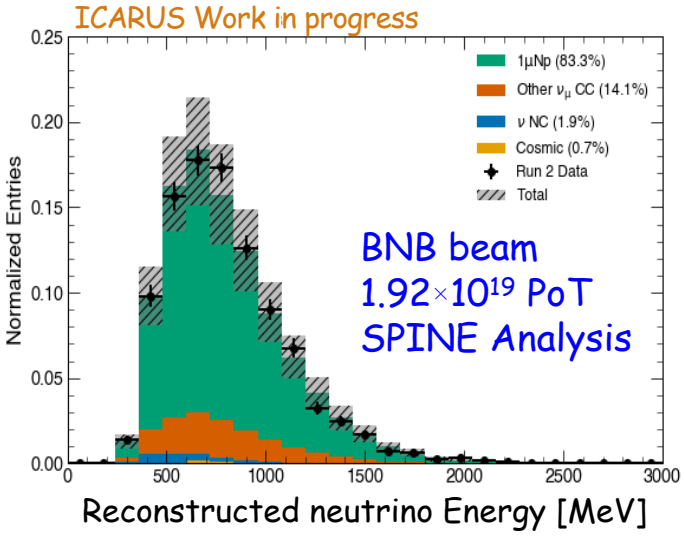
1μNp analysis – event selection results

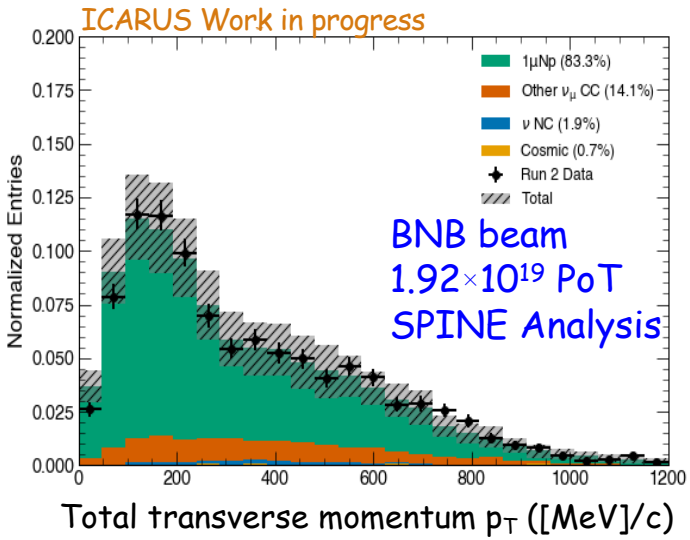
- Two independent analysis streams considered, respectively based on:
  a) Pandora pattern recognition: ~50% efficiency for the signal
  b) Machine Learning (ML) SPINE reconstruction code: ~75% efficiency for the signal

- 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.







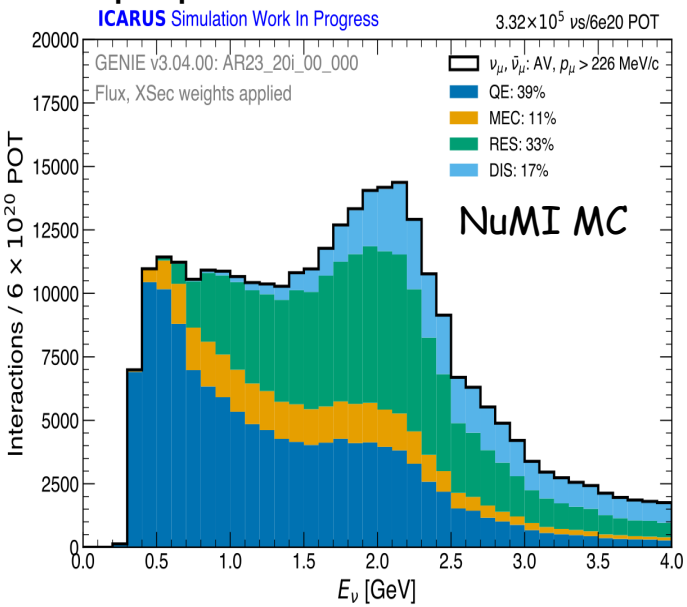


Neutrino Interactions from NuMI off axis at ICARUS

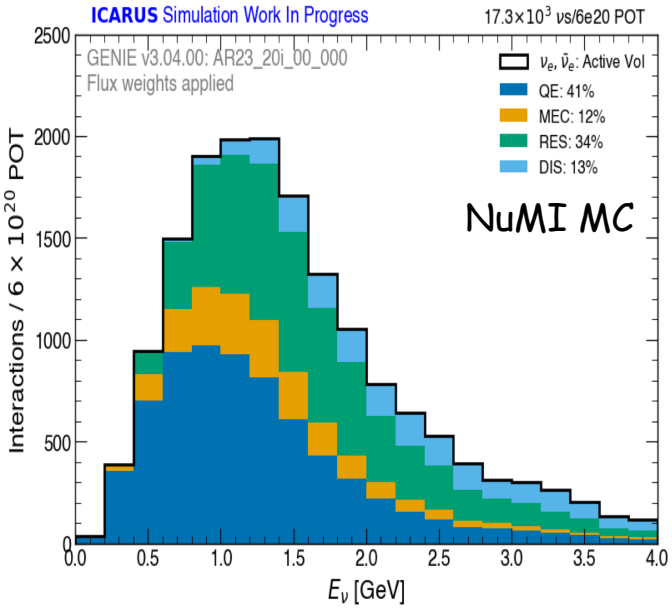
- Excellent statistics to measure cross section for quasi-elastic, resonance and deep inelastic scattering, for both electron and muon neutrinos;
- Available data ~3.42E20 POT for physics analysis now

  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.

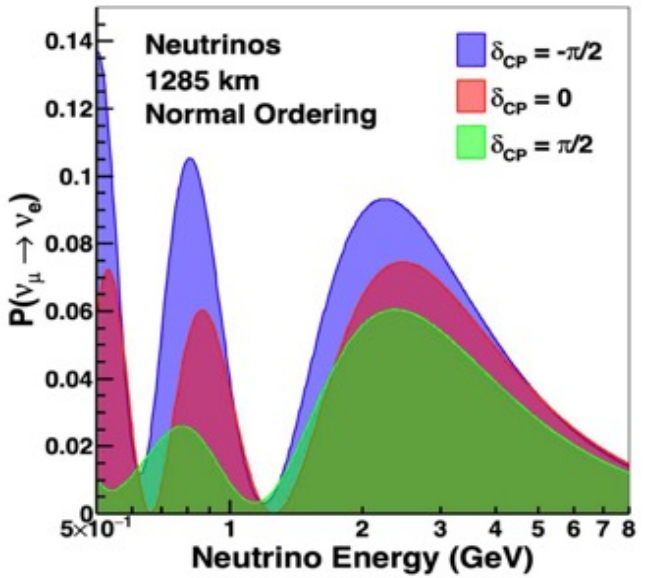
ν_μ, $\bar{\nu}_\mu$ from NuMI at ICARUS



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

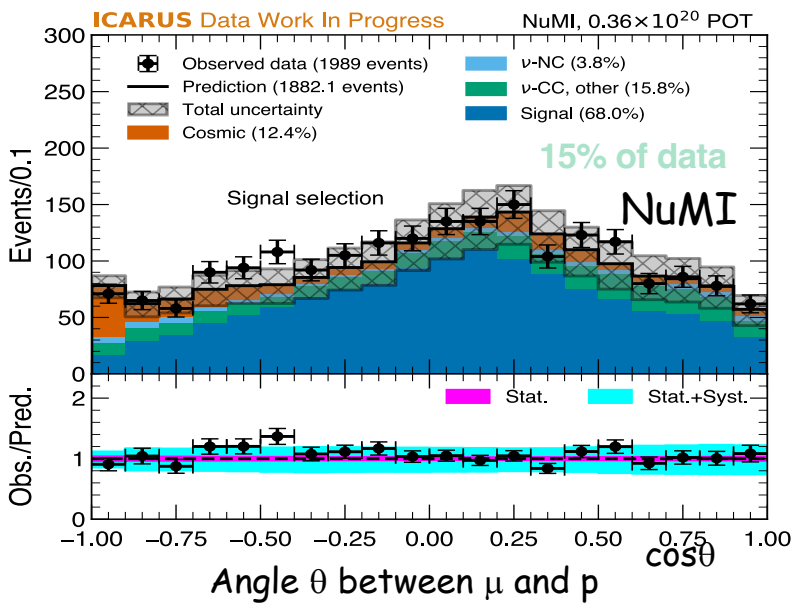


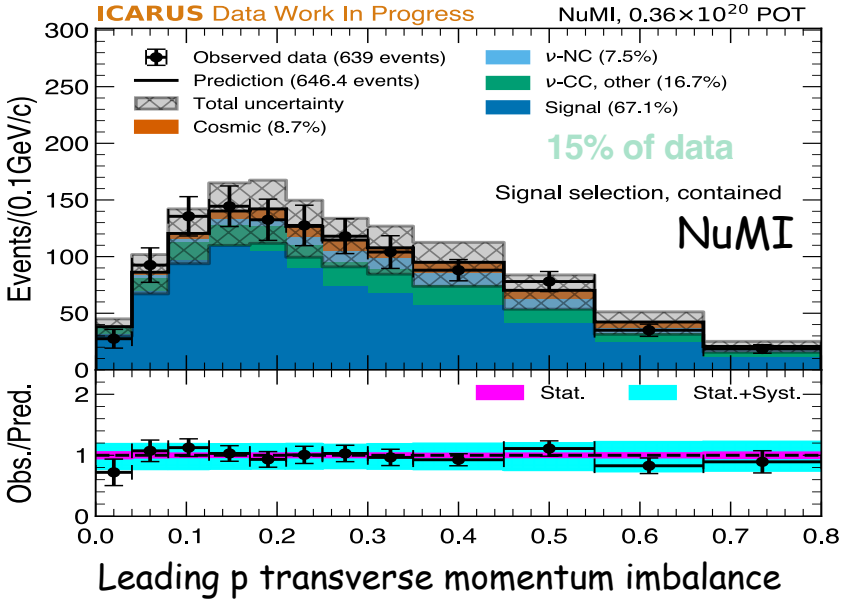
Oscillation probability at DUNE



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.

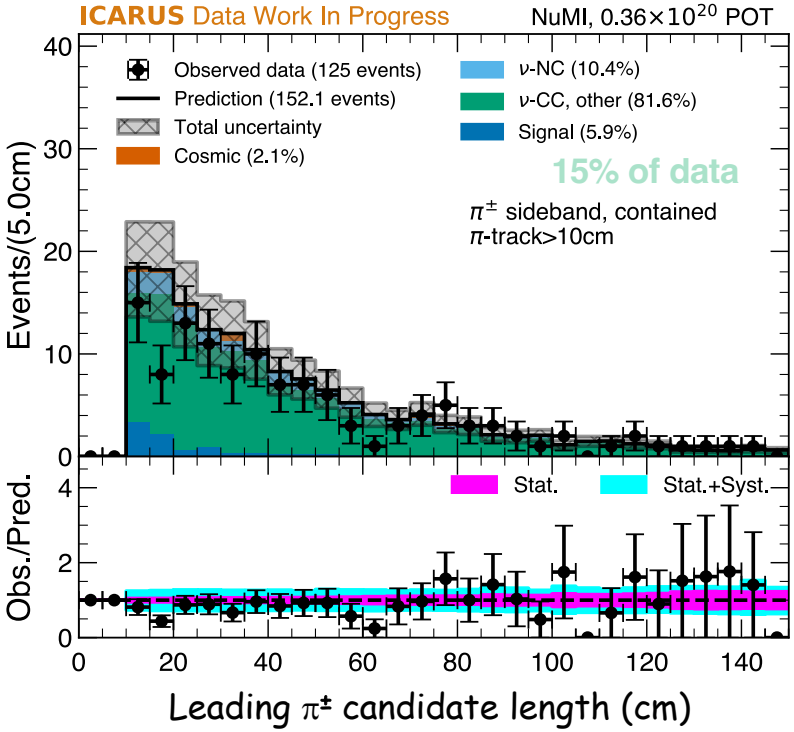


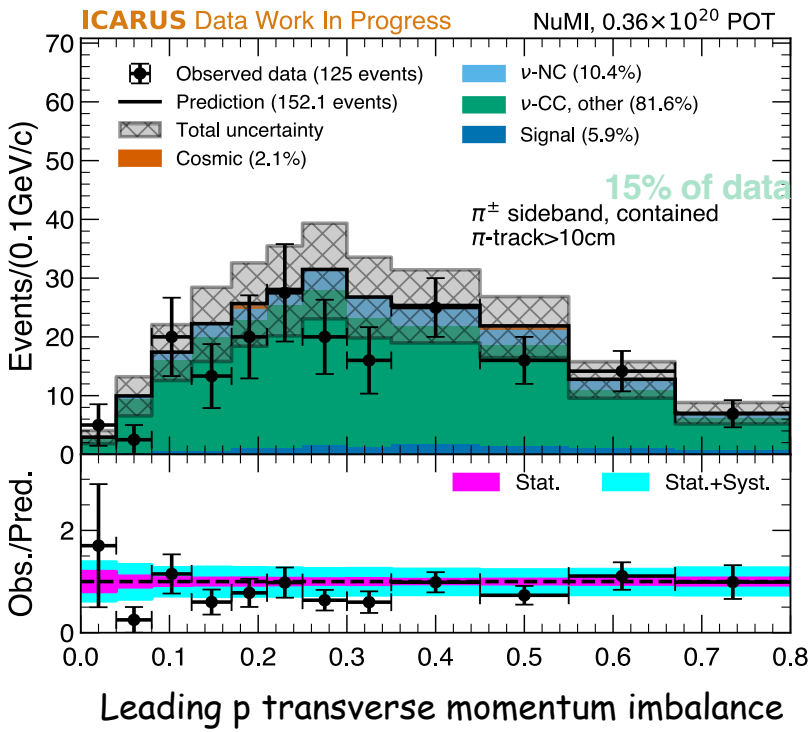


Initial study with 15% of data.

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);



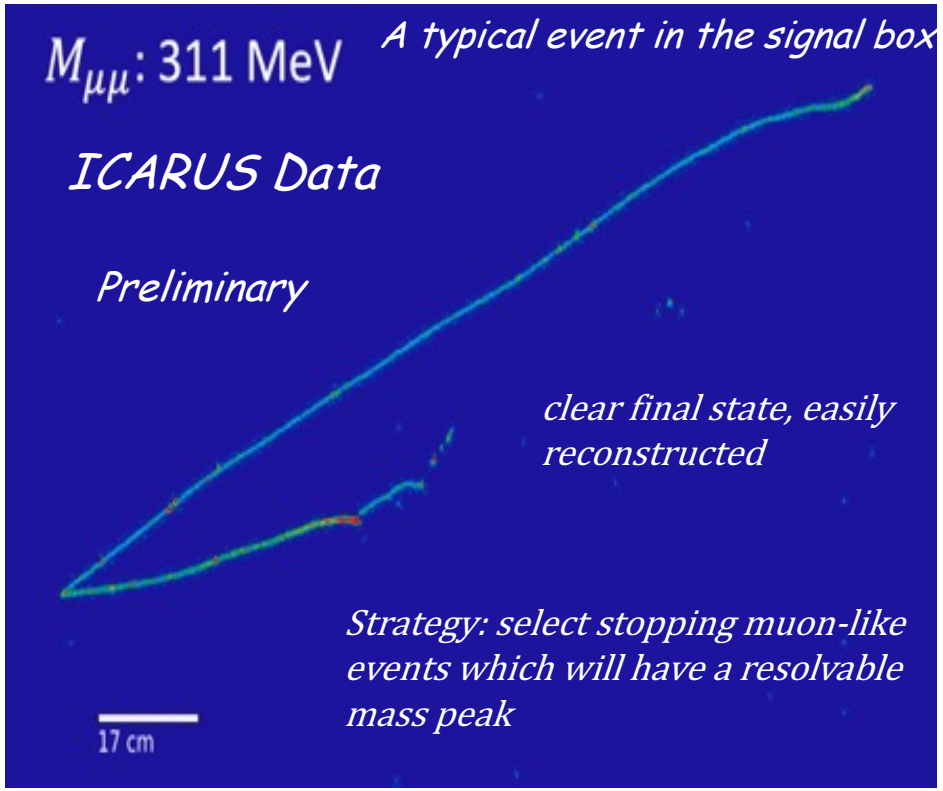


Results for the full 1μ+Np+0π dataset soon !

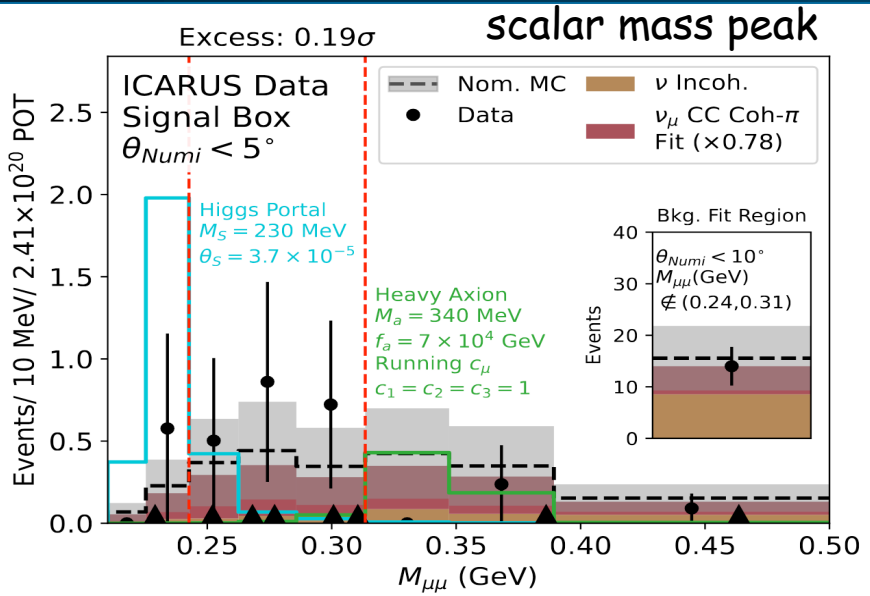
Dark sector models investigation by ICARUS

- 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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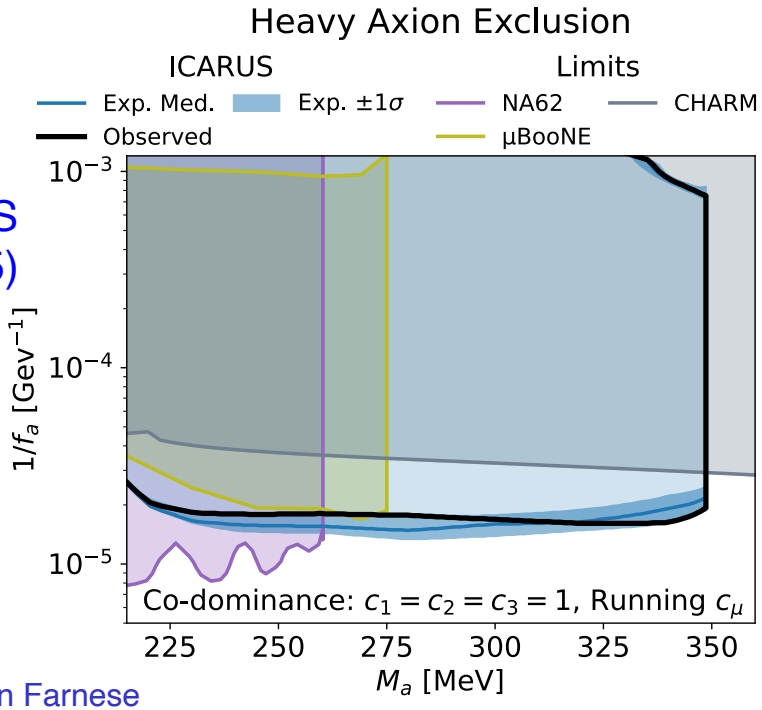
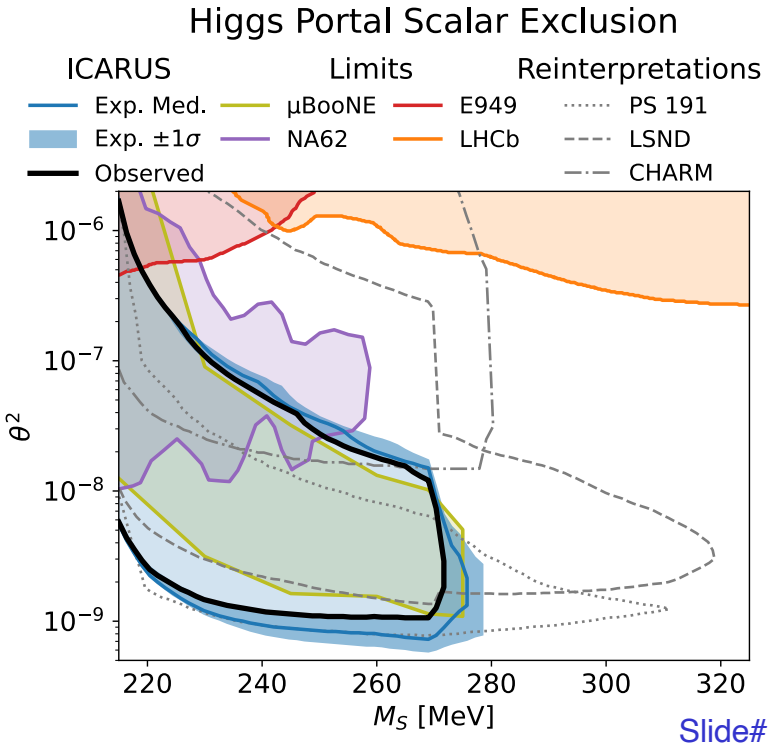
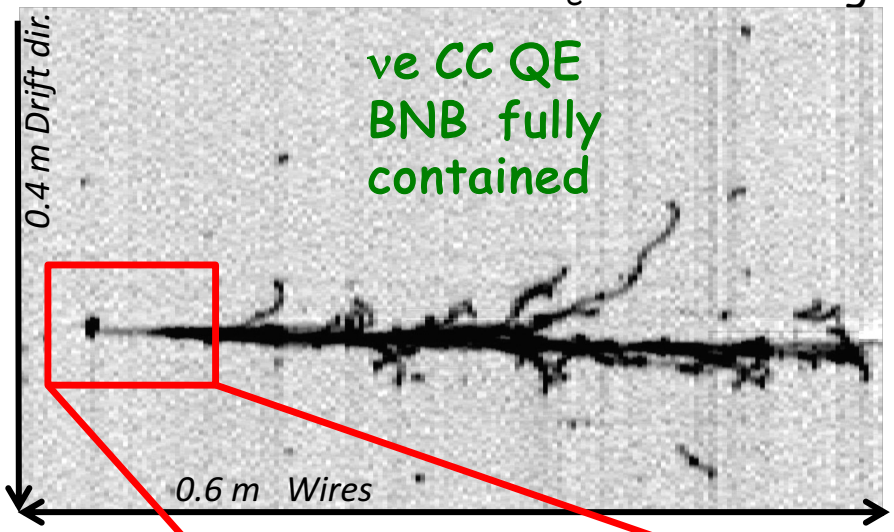
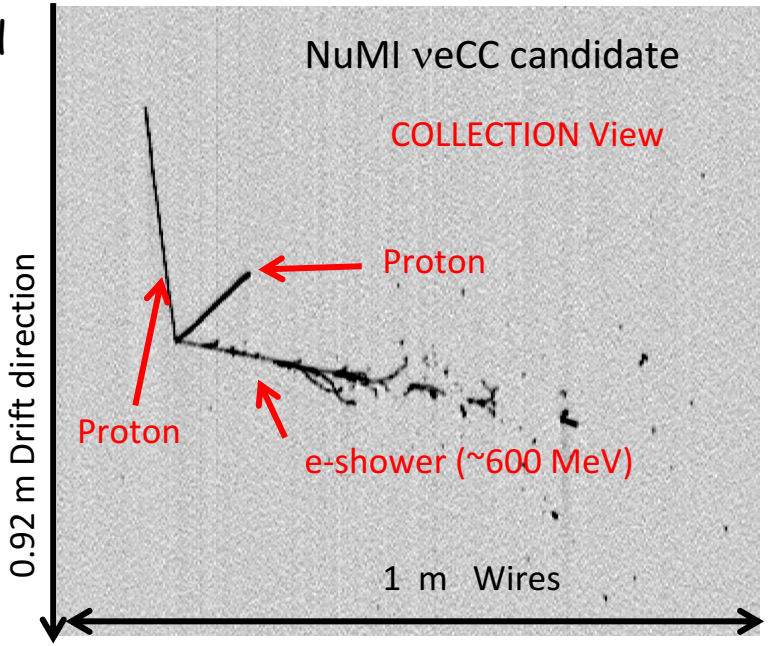


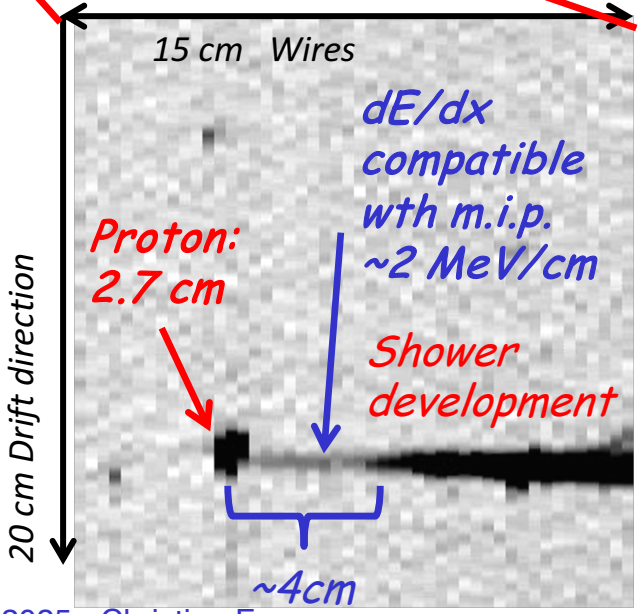


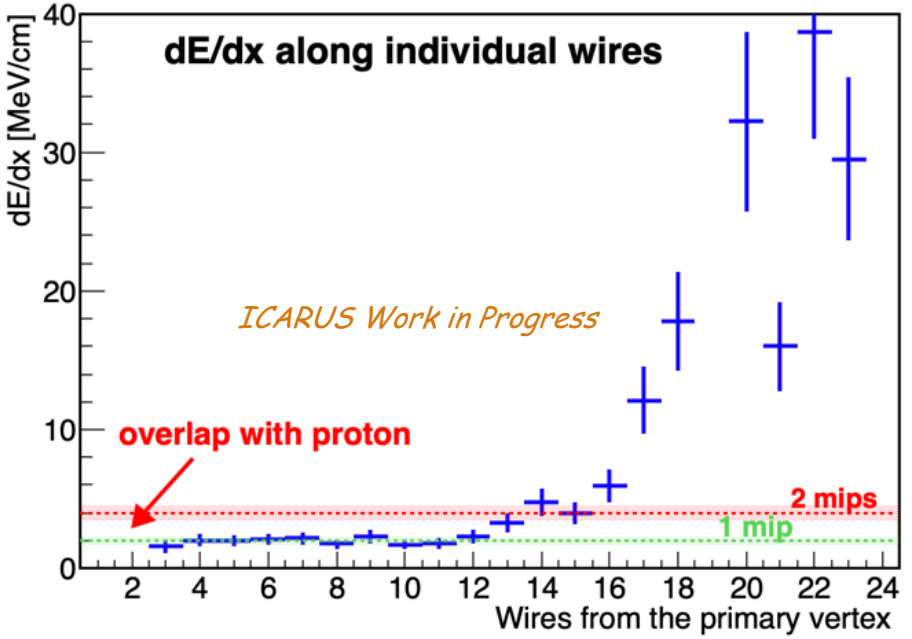
Search for electron neutrino events

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





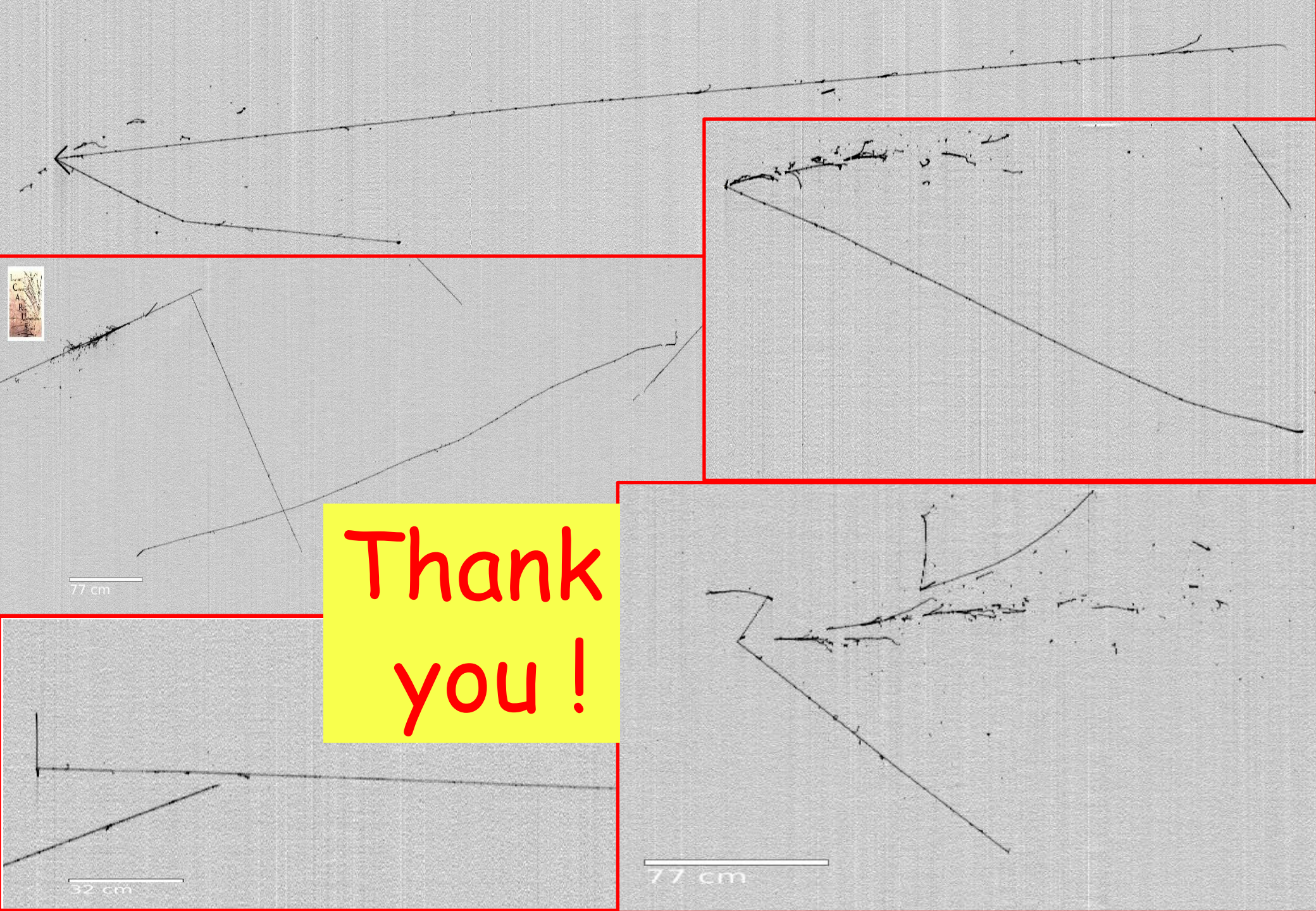




Conclusions

- 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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