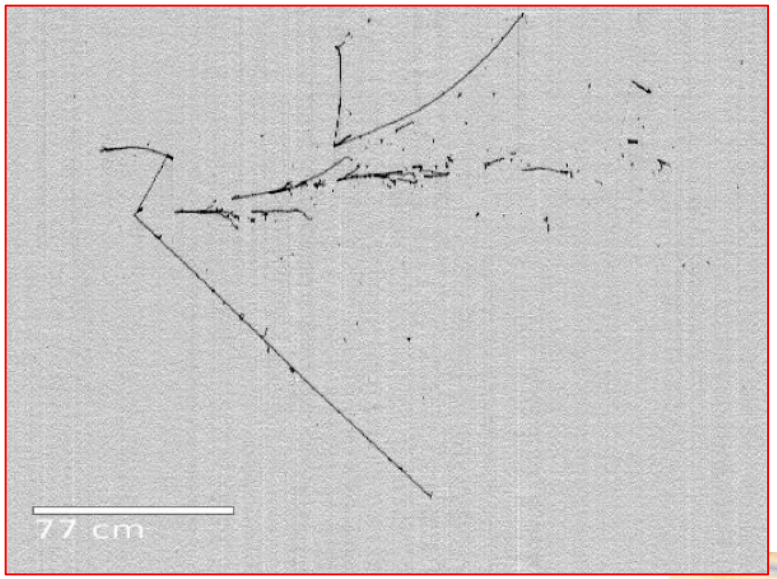
Latest Results from the ICARUS Experiment at the Short-Baseline Neutrino Program



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on behalf of the ICARUS collaboration

EPS-HEP 2025, Marseille, July 9th 2025

ICARUS Collaboration at SBN

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

Spokesman: C. Rubbia, GSSI

Neutrino related anomalies ?

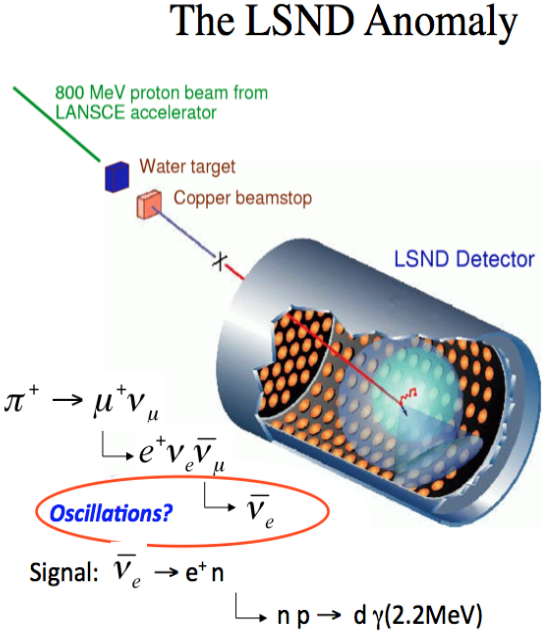
- Despite the well-established 3-flavour ν mixing picture, several anomalies have been collected far hinting to existence of additional ν states:

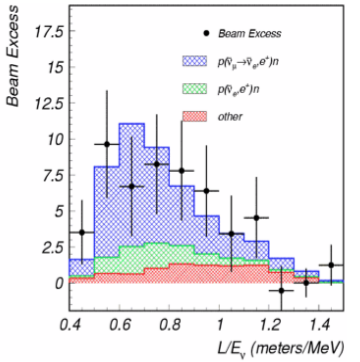
➢ anti–νe appearance: in anti-νμ accelerator LSND experiment where anti-νe -> e+ + n with neutron resulting n + p into d + γ.

➢ νe disappearance: SAGE, GALLEX experiments with Mega-Curie radioactive sources showing observed/predicted rate R = 0.84±0.05, recently confirmed at 4σ by BEST experiment

➢ anti-νe disappearance in nuclear reactor experiments, initially R = 0.934±0.024 but recently mitigated by Daya Bay, RENO, STEREO…

➢ anti-νe disappearance at reactor with clear L/Eν ~ 1-3 m/MeV modulation (Neutrino-4 experiment)

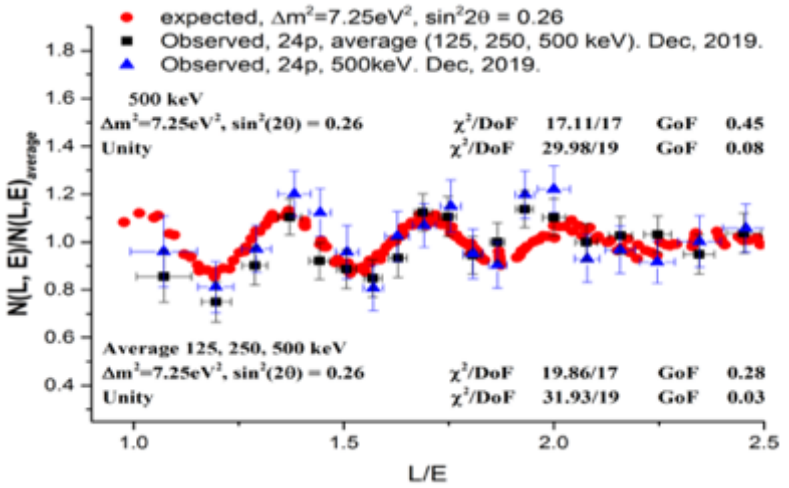




Saw an excess of $\bar{\nu}_e$: 87.9 ± 22.4 ± 6.0 events.

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

3.8 σ evidence for oscillation.



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

The sterile neutrino puzzle

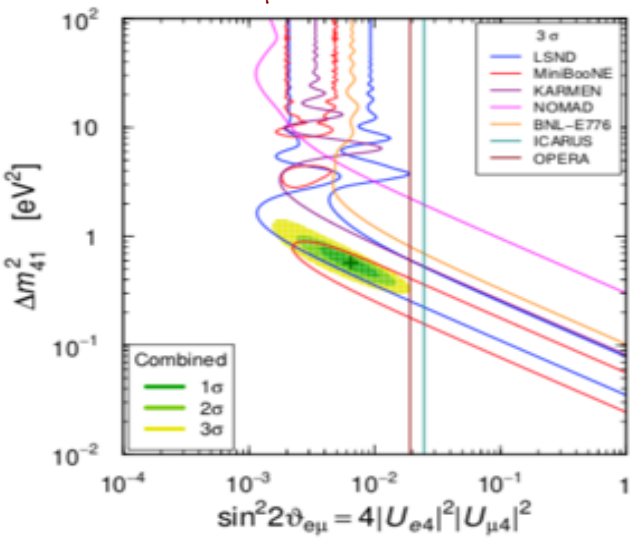
- Several experiments performed at reactors and accelerators to study neutrino anomalies, But:
  - ➢ No evidence in νμ disapp. exps (IceCube, NOνA, MINOS/MINOS+,T2K);
  - ➢ A clear tension between (anti-)νe appearance and (anti-)νμ disappearance experiments, with different neutrino energy ranges and detection techniques

✓ Measuring both νe appearance and νμ disappearance in the same experiment using a detector with optimal neutrino identification and background rejection is mandatory to disentangle the physics scenario;

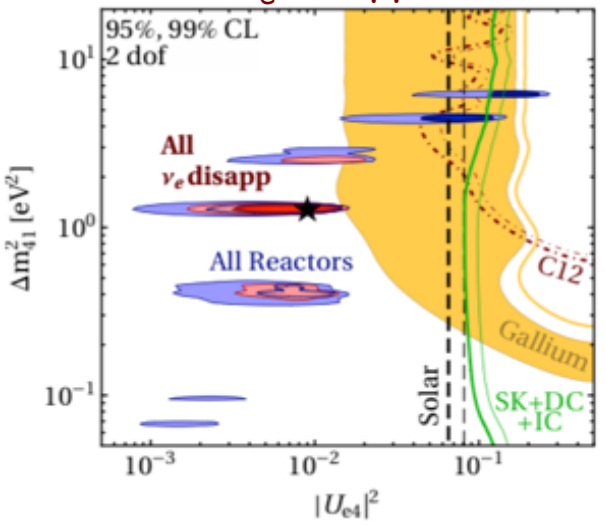
✓ Far to near detector neutrino spectra comparison is crucial for the control of background and beam/detector systematics.

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

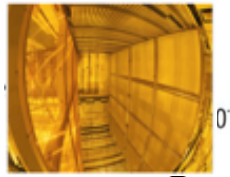


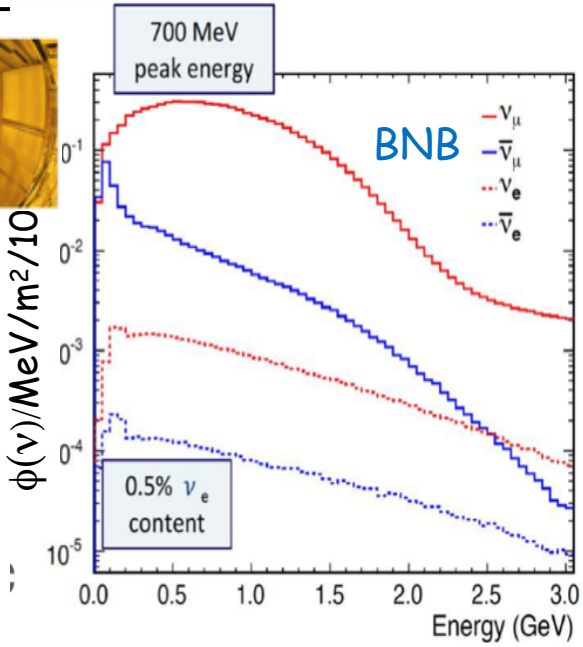
(arXiv:2106.05913)

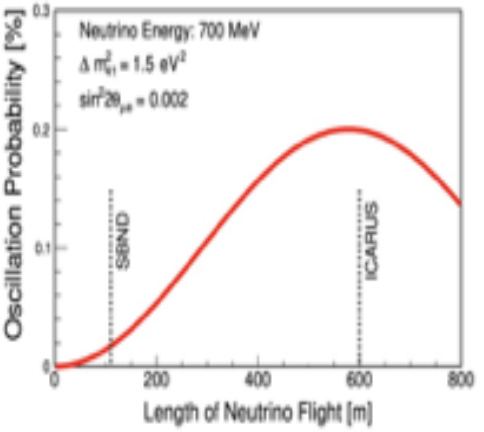
SBN program at FNAL: a definitive answer to sterile neutrinos?

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

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





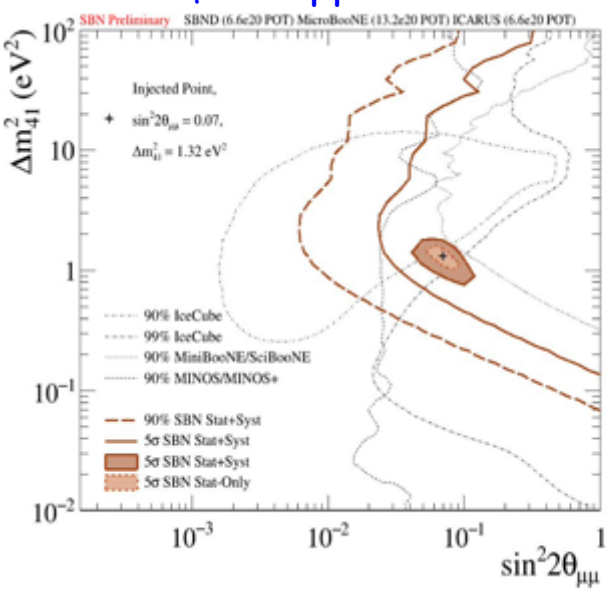


- ICARUS and SBND LAr-TPC's installed at 600 and 110 m from Booster target, searching for sterile-ν oscillations both in appearance and disappearance channels.
- Furthermore, high-statistics ν-Ar cross-section measurements and event identification/reconstruction studies for DUNE:
  - ~10^6 events/y in SBND < 1 GeV from Booster
  - ~10^5 events/y in ICARUS > 1 GeV from off-axis NuMI beam.
- Rich program of beyond standard model searches at both detectors

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

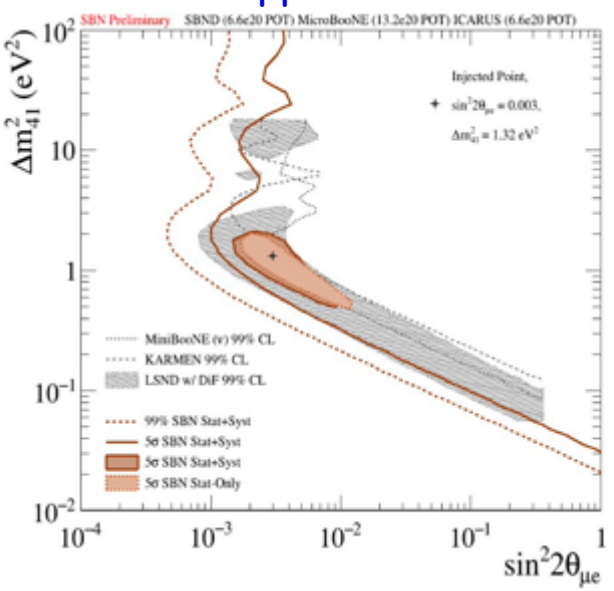
- Combined analysis of events collected ICARUS (far detector) and SBND (near detector) using the same LAr-TPC event imaging technology greatly reduces the expected systematics:
  - ➢ High νe identification capability of LAr-TPCs rejecting NC event background;
  - ➢ "Initial" BNB beam composition and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

νμ disappearance



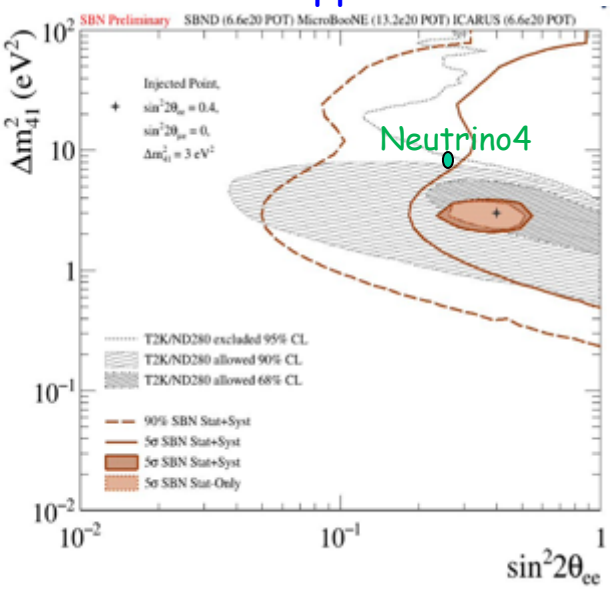
5σ coverage of the parameter area relevant to LSND anomaly

νe appearance



Probing the parameter area relevant to reactor and gallium anomalies.

νe disappearance

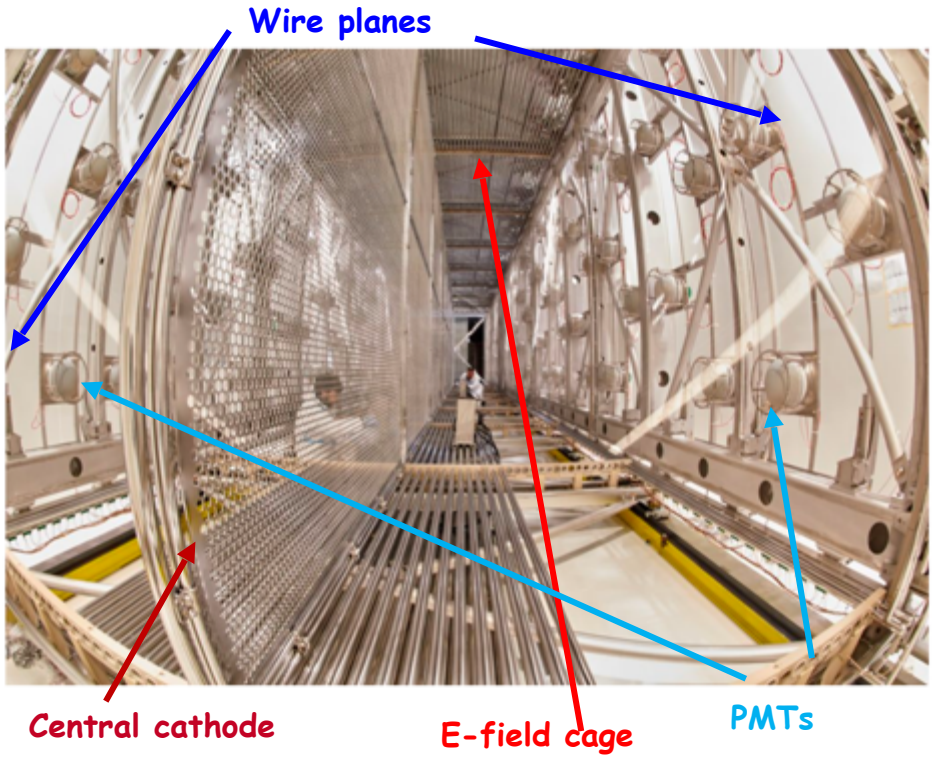


Unique capability to study neutrino appearance and disappearance simultaneously

The ICARUS detector

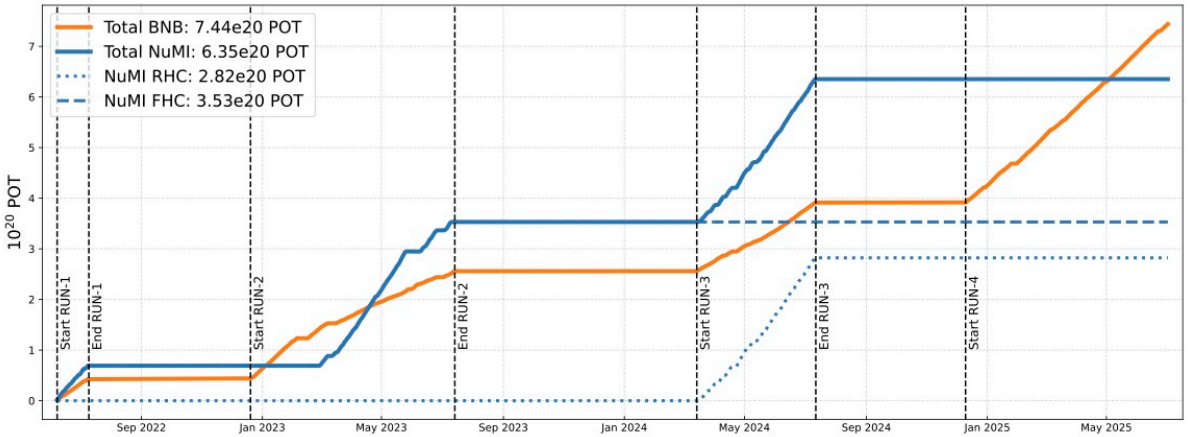
- LAr TPCs combine high-resolution (few mm) 3D imaging and calorimetric capabilities, allowing to accurately reconstruct a wide variety of ionizing events with complex topology: ideal detector for ν physics!
- LAr scintillation properties allow to use light for triggering and timing
- First proposal by C.Rubbia in 1977. After a long R&D phase, ICARUS at LNGS (2010-13) proved the maturity of Lar-TPCs for large-scale neutrino experiments
- A crucial milestone for the development of DUNE!

- Total active mass of ~476 t
- 2 identical modules, 2 TPCs per module with central cathode (1.5 m drift, E_D= 0.5 kV/cm);
- 3 readout wire planes per TPC (2 Inductions+1 Collection). 54000 wires in total at 0, ± 60^0, 3 mm pitch;
- 360 photomultipliers, TPB coated, to detect the scintillation light produced in LAr;
- ~2.8 m (6 mwe) concrete overburden + 4π Cosmic Ray Tagger (CRT) to suppress/tag cosmics



ICARUS physics runs at FNAL

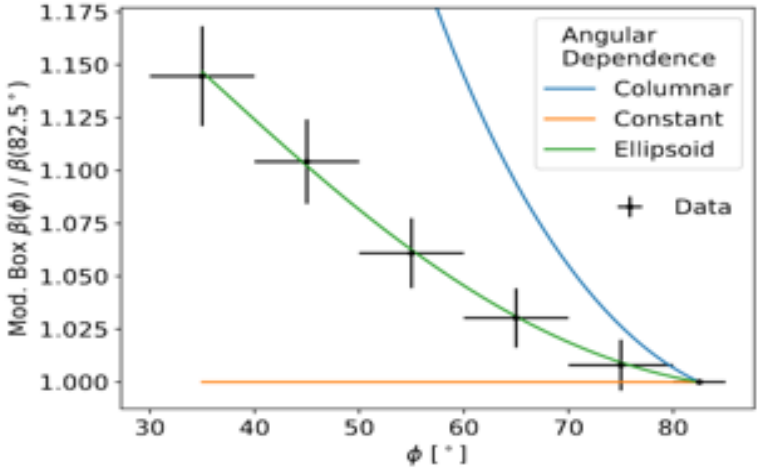
- ICARUS data taking for physics started on June 9th 2022, after the concrete overburden installation, with TPC, PMT and CRT systems fully operational;
- Events are triggered requiring at least 4 fired PMT pairs inside a 6 m longitudinal T600 slice in coincidence with BNB, NuMI beam spills, >90% efficiency for E_{dep} >200 MeV (arXiv:2506.20137)
- Steady data taking with excellent stability at BNB rate > 4 Hz, >95% lifetime: 3 physics runs completed + fourth run ongoing since December 2024
- Electron lifetime was stable and adequate for physics (>3 ms) for all runs. Currently ~8 ms



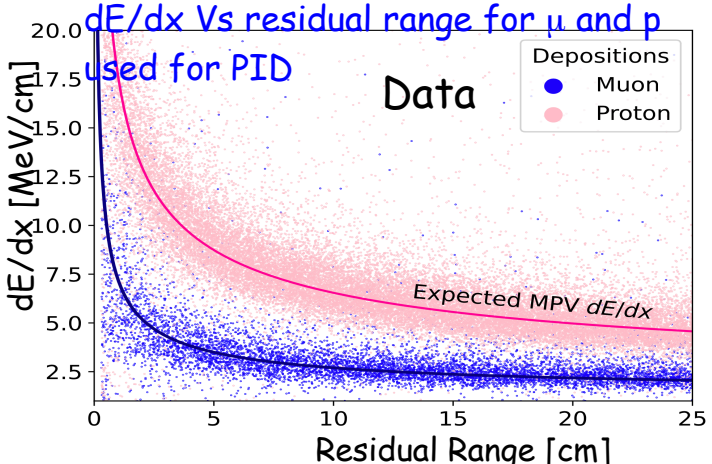
Collected Protons on target (PoT)	BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1 (Jun-Jul 22)	0.41 10^{20}	0.68 10^{20}	-
RUN-2 (Dec 22-Jul 23)	2.06 10^{20}	2.74 10^{20}	-
RUN-3 (Mar -July 24)	1.36 10^{20}	-	2.82 10^{20}
RUN-4 (no NuMI) (Dec 24 -ongoing)	3.55 10^{20}	-	-
TOTAL	7.38 10^{20}	3.42 10^{20}	2.82 10^{20}

Detector calibration measurements

- Two recent JINST papers on TPC calibration
- **JINST 20, P01032** summarizes the full simulation, equalization and tuning of the TPC signal and the corresponding noise modeling
  - **JINST 20, P01033** analyzes electron recombination in liquid Argon with the study of cosmic muons and protons
  - Observed dependence of electron recombination on track angle ϕ wrt drift coordinate for high dE/dx (proton tracks). Consistent with ArgoNeut
  - This results in improved capabilities in particle identification via dE/dx

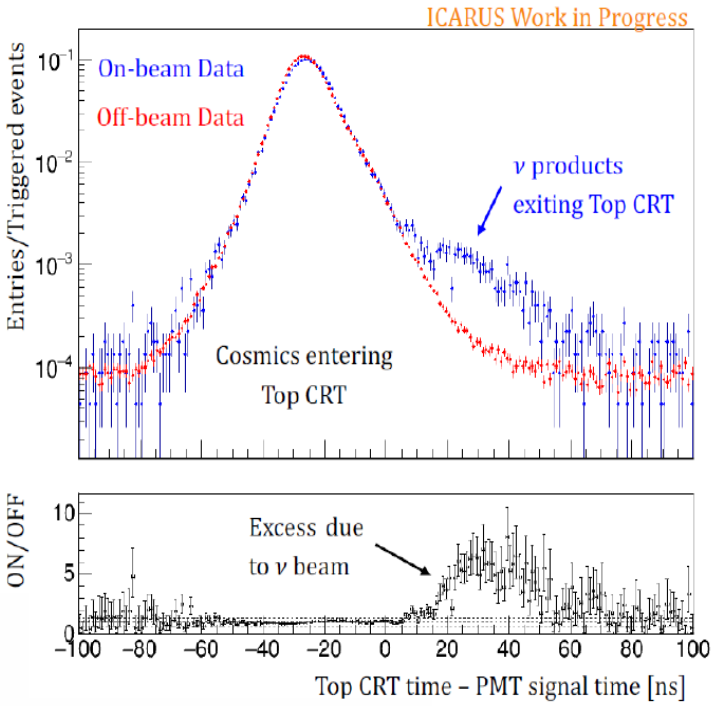


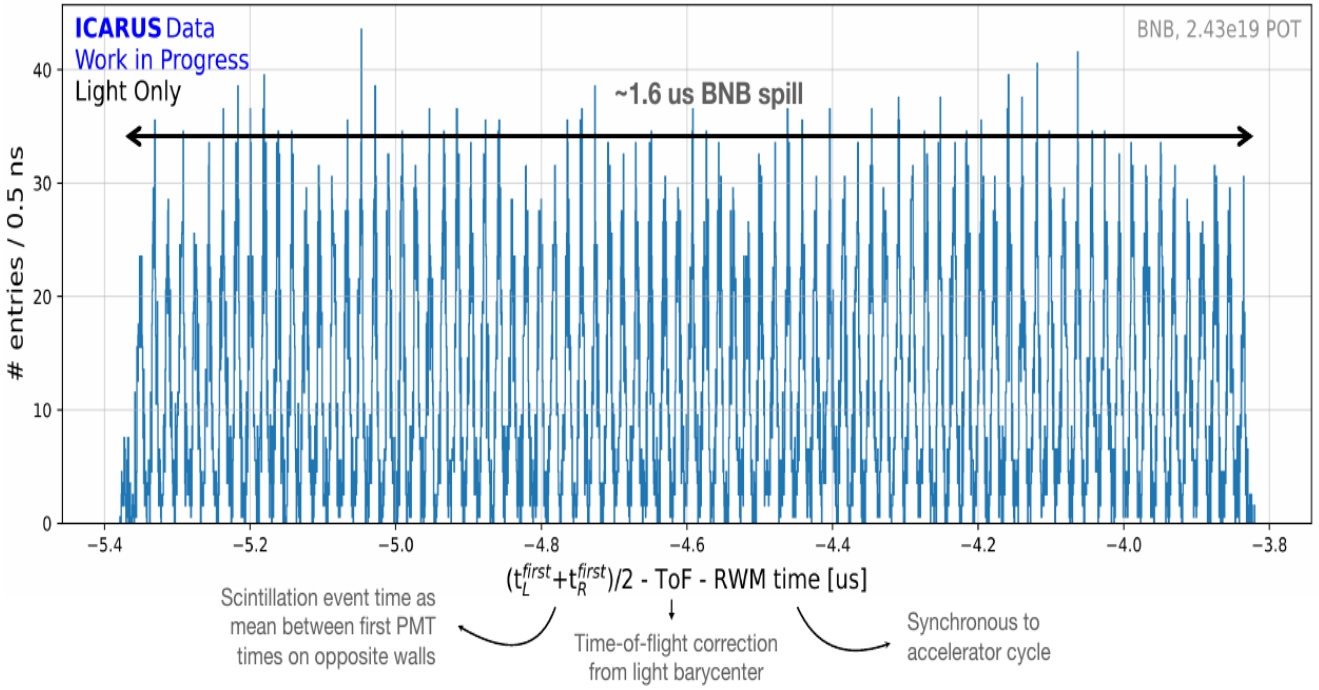
$$\frac{dx}{dQ} = \frac{1}{G}\frac{log(\alpha+\beta(\phi))\frac{dE}{dx}}{\beta(\phi)W_{ion}}$$

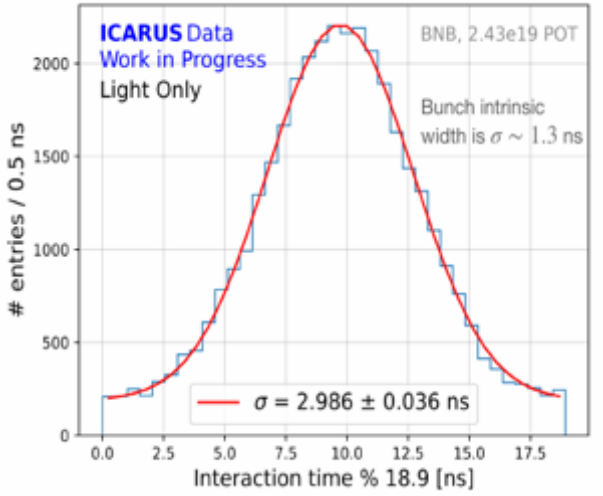


PMT and CRT timing performance

- Both external CRT and inner PMT systems can complement "slow" TPC signals by providing ns-level timing resolution
- This allows rejection of incoming cosmics based on time-of-flight (difference between CRT and PMT times)
- It also allows to reconstruct the bunched structure of both beams with respect to proton extraction time, improving cosmic rejection during beam window







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;

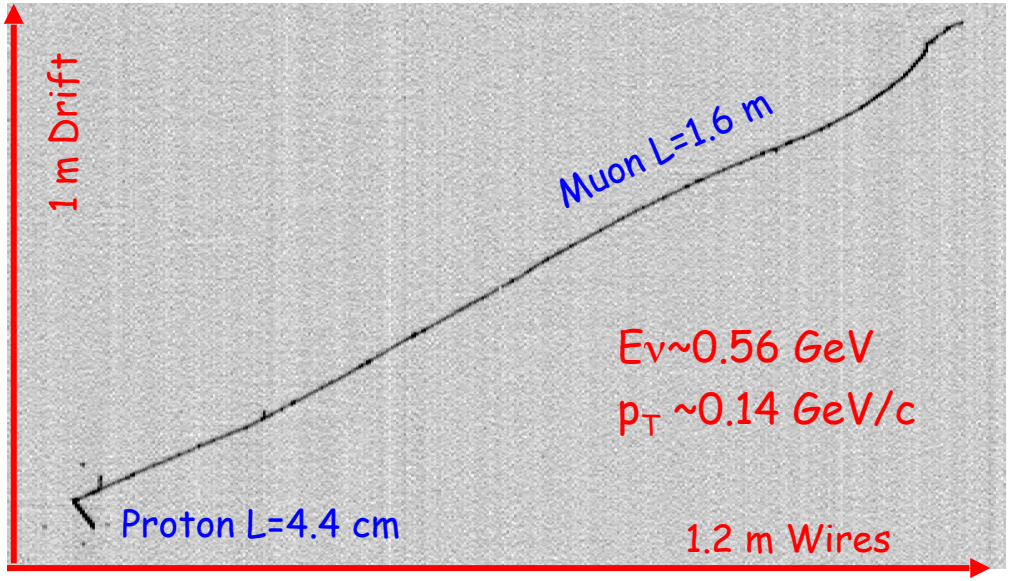
Study of ν_e, ν_μ events from off-axis NuMI beam, to measure ν-Ar interaction cross sections and optimize ν reconstruction identification in an energy range of interest for DUNE. Event selection ready, sidebands studied for a subset of data;

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.

Nμ disappearance study: event selection

- Automatic procedure for selecting fully contained 1μNp νμCCQE interactions required:
  - PMT light signal inside 1.6μs p beam spill window correlated with TPC tracks, no CRT signal;
  - 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;
  - no additional π, γ.

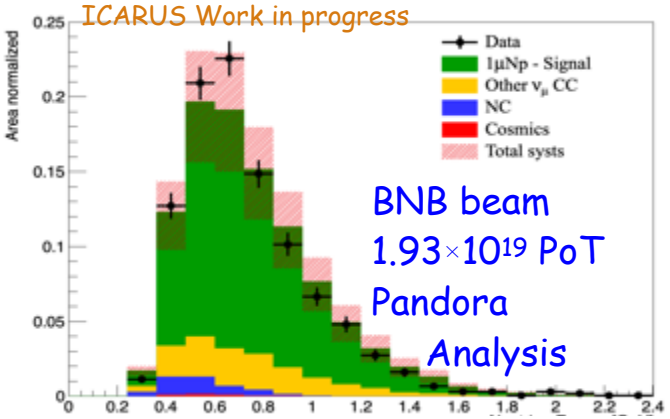


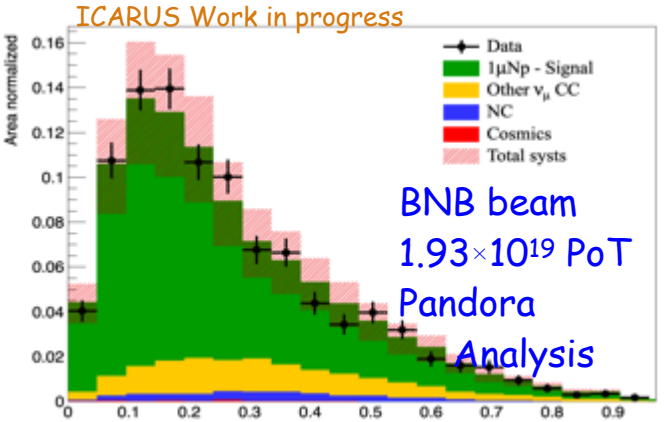
- The global event kinematics is obtained from range measurement of μ and p.
- Residual cosmic backgrounds < 1%.
- Flux, cross section and detector systematic uncertainties have been included:
  - Preliminarily, the impact of detector systematics is evaluated comparing calibrated and uncalibrated MC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

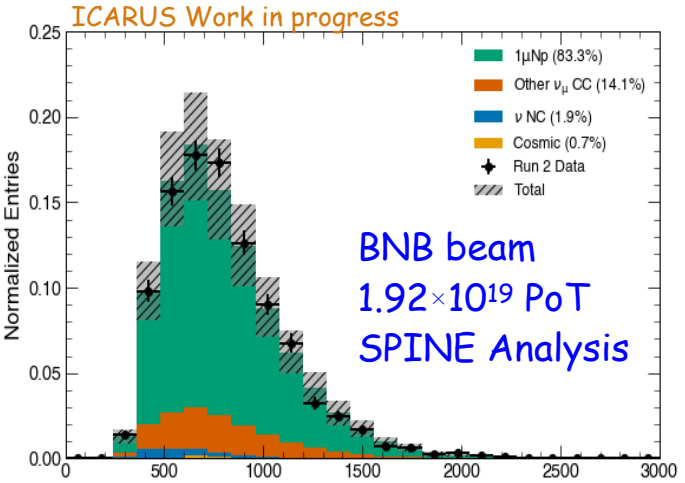
Event selection results

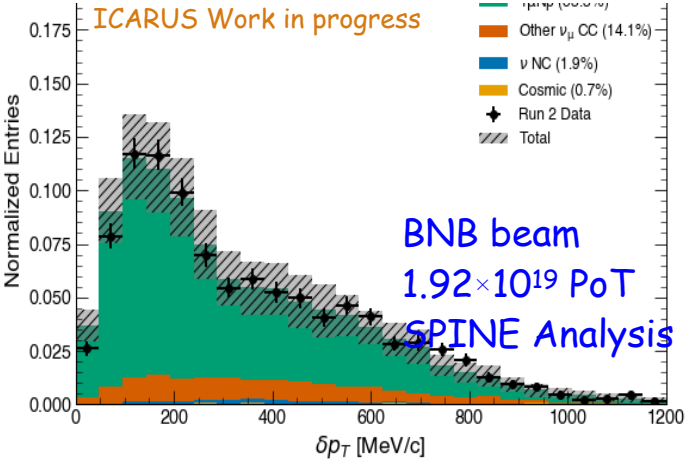
- Two independent analysis approaches are being considered:
  - Pandora pattern recognition: 50% signal identification efficiency
  - ML-based pattern recognition (SPINE): 75% signal efficiency

- 10% of run2 data unblinded and analyzed
- Data agree with MC for all variables within systematics
- Unblinding of full sample and oscillation fit will happen soon





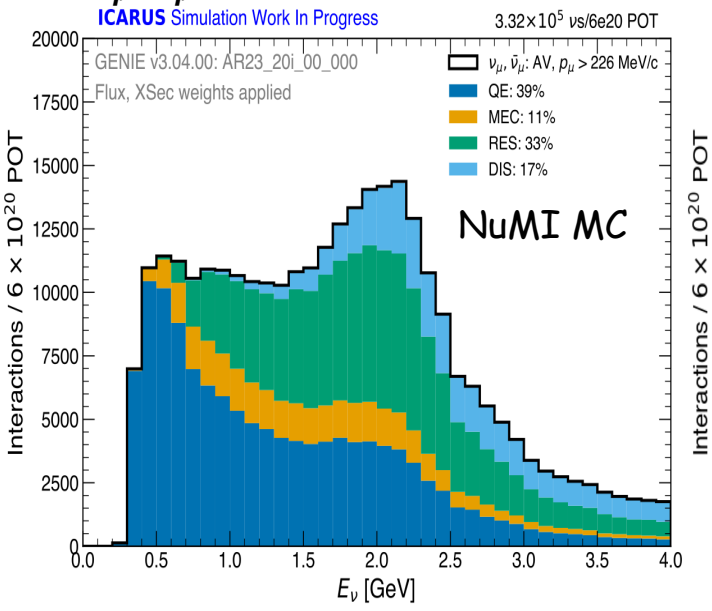




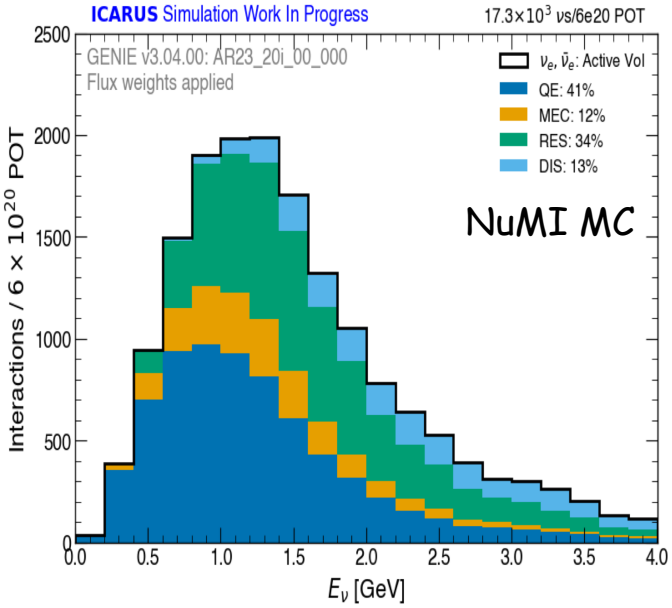
ICARUS physics searches with NuMI beam

- Further exploitation of the NuMI Off-Axis beam (6 degrees from ICARUS):
  - High statistics precision measurements of ν-Ar cross sections (~2 10^5 νμ, ~10^4 νe events/year) and tests of interaction models in the few hundred MeV to few GeV energy range
  - It covers the first DUNE oscillation maximum and most of its phase space
  - Rich Beyond Standard Model search program: Higgs portal scalar through di-muon final states (advanced analysis), ν tridents, light dark matter, heavy neutral leptons

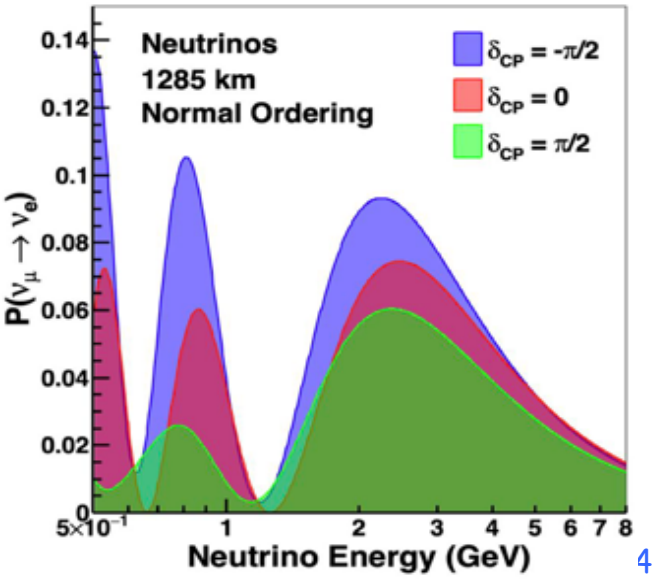
ν_μ, $\bar{\nu}_\mu$ from NuMI at ICARUS



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

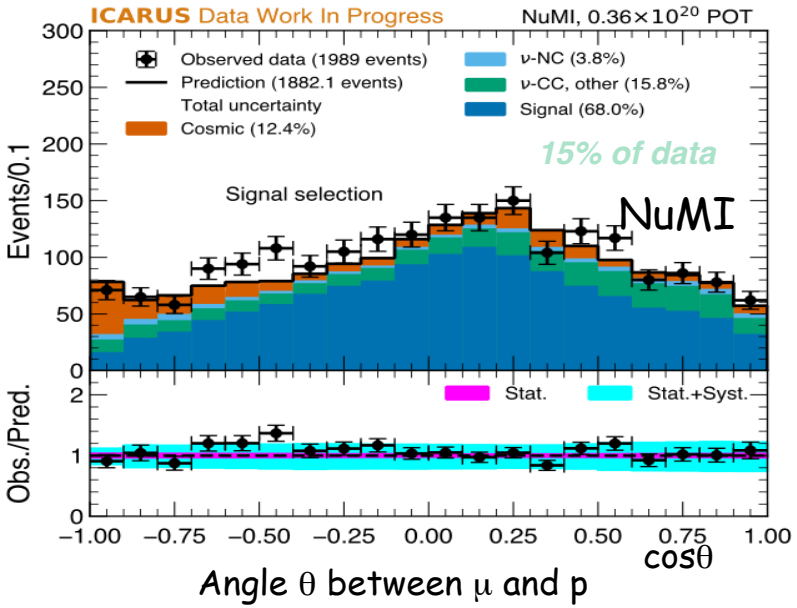


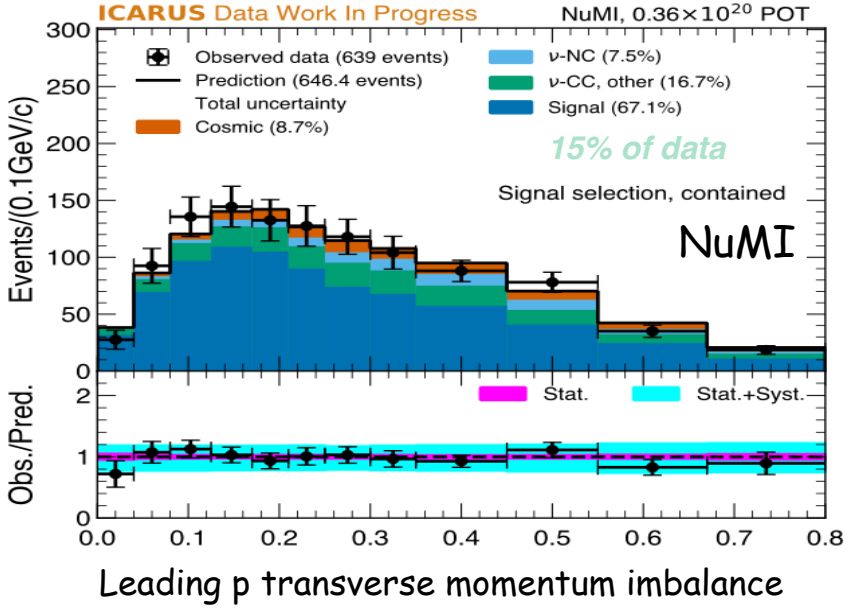
Oscillation probability at DUNE



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.

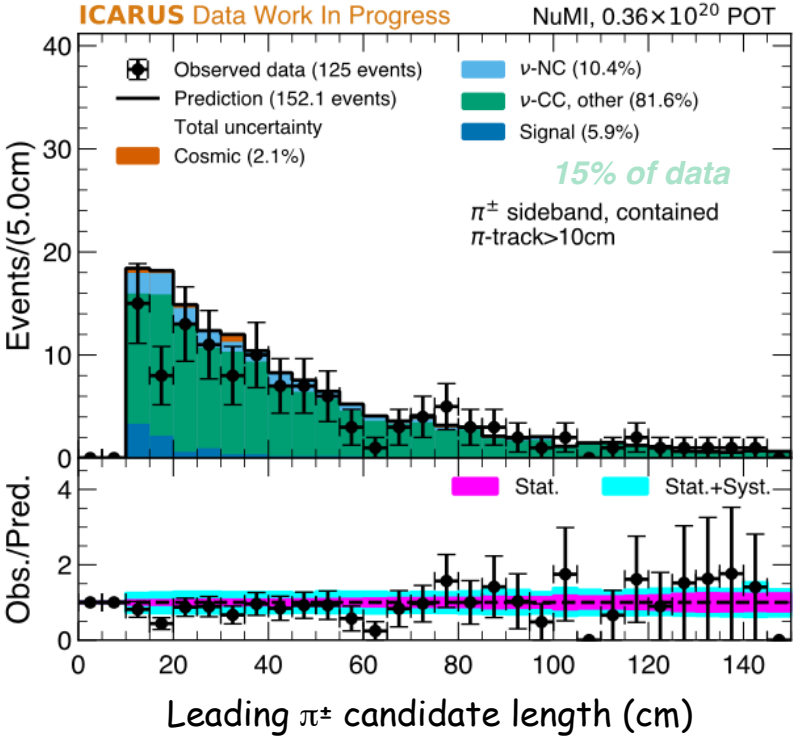


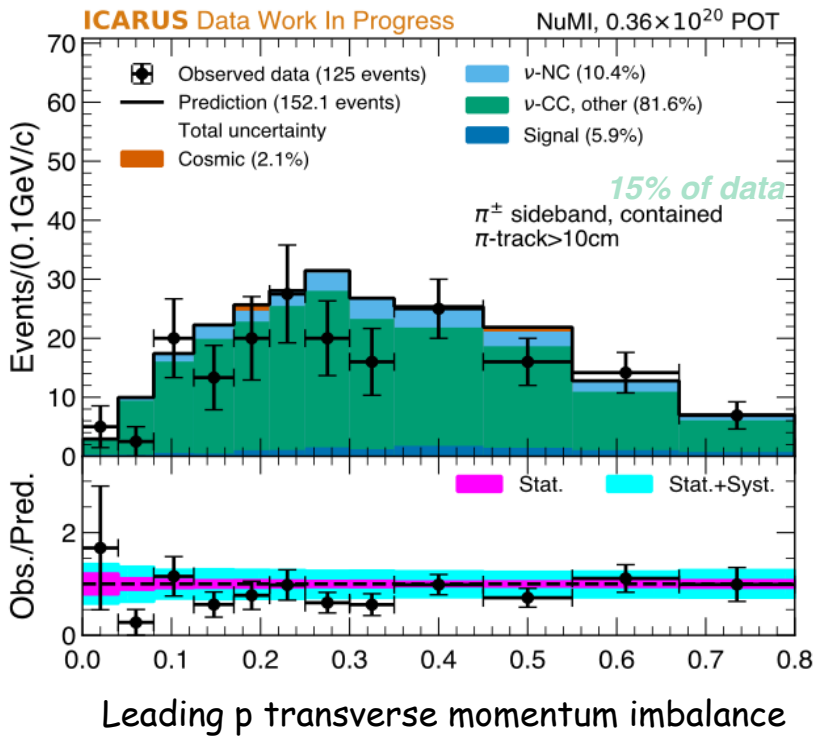


Initial study with 15% of data.

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);



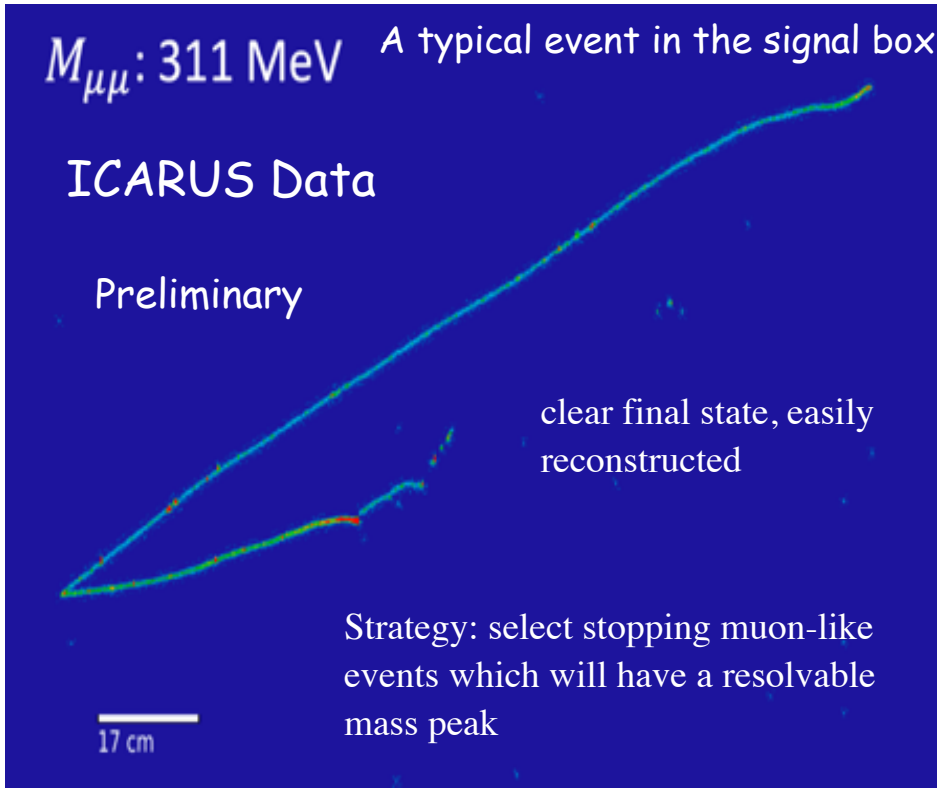


Results for the full 1μ+Np+0π dataset soon !

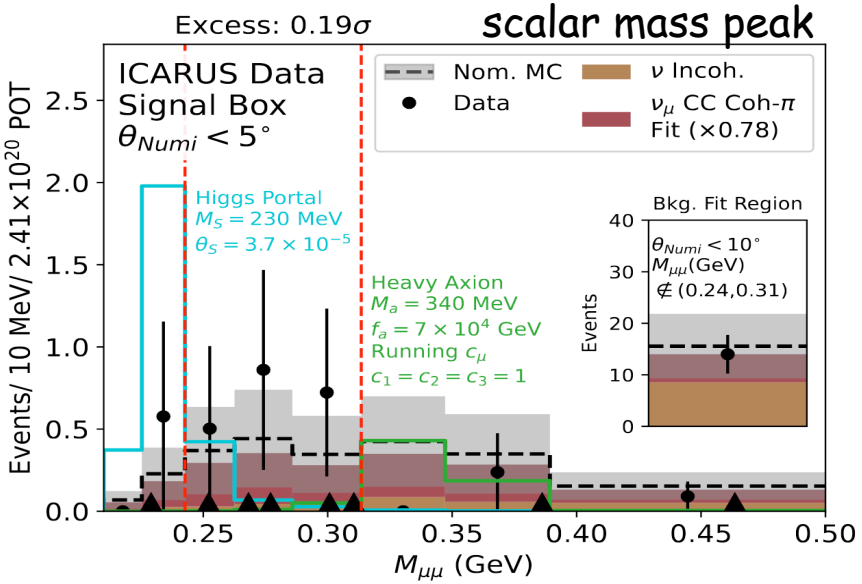
Dark sector models investigation by ICARUS

- 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°);
- 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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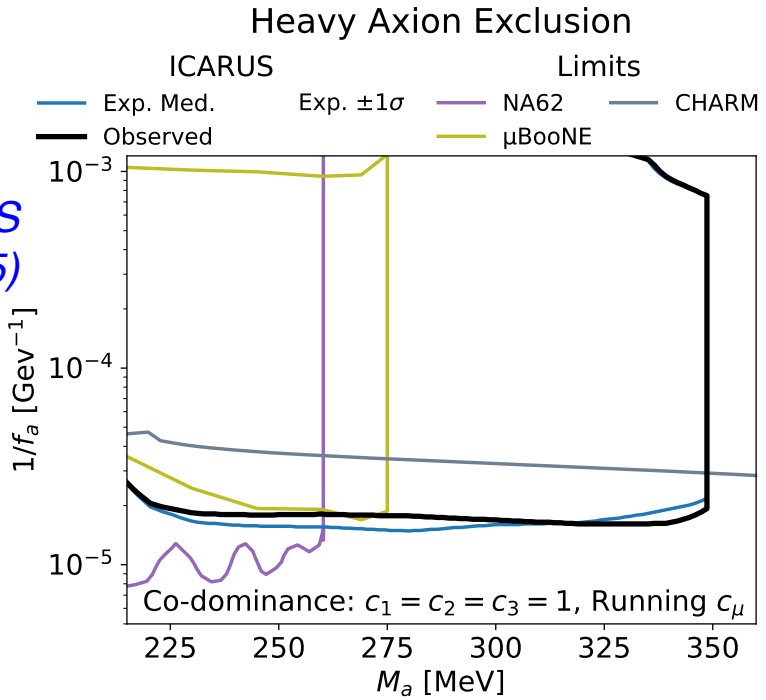
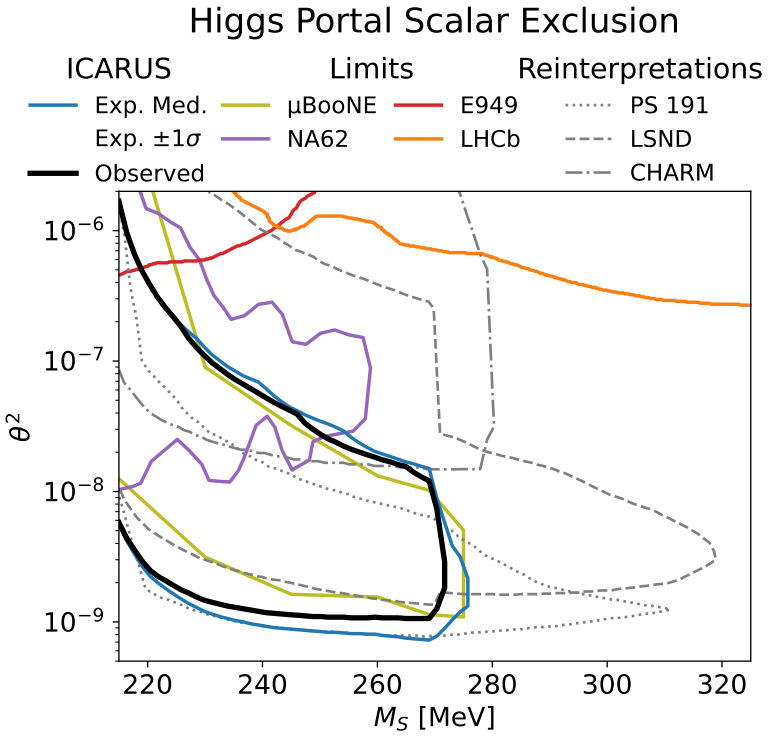
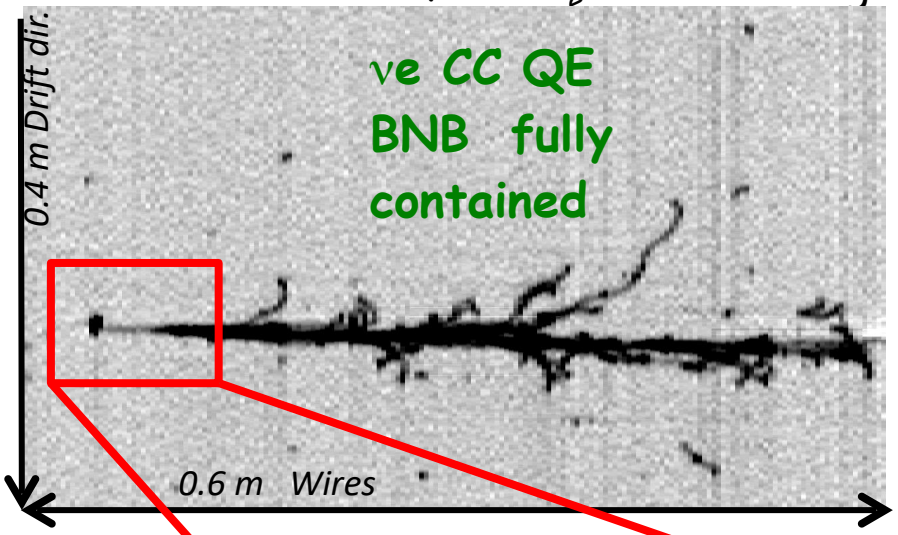
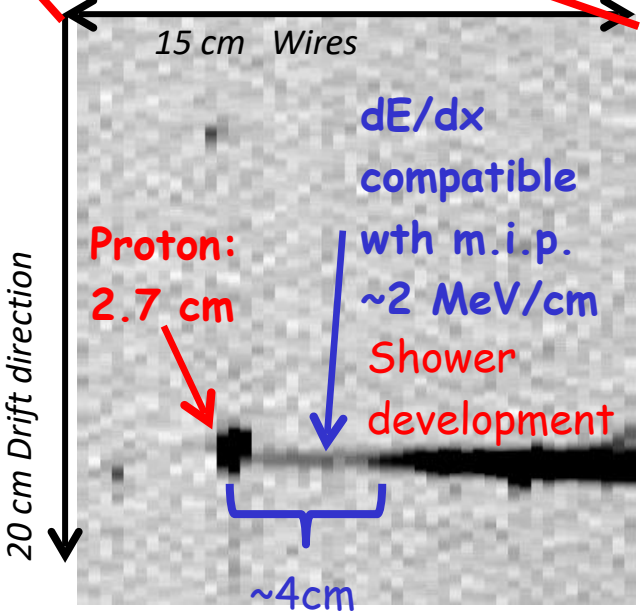


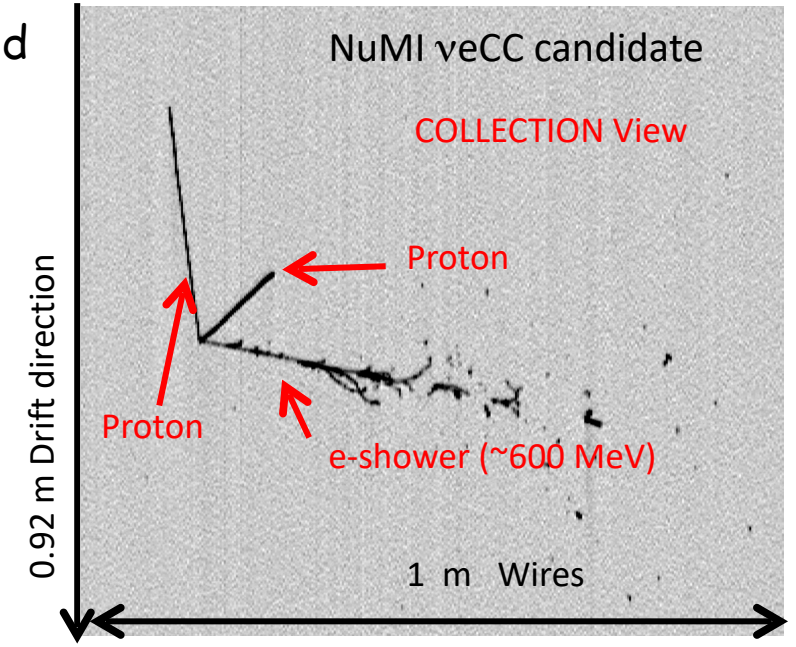


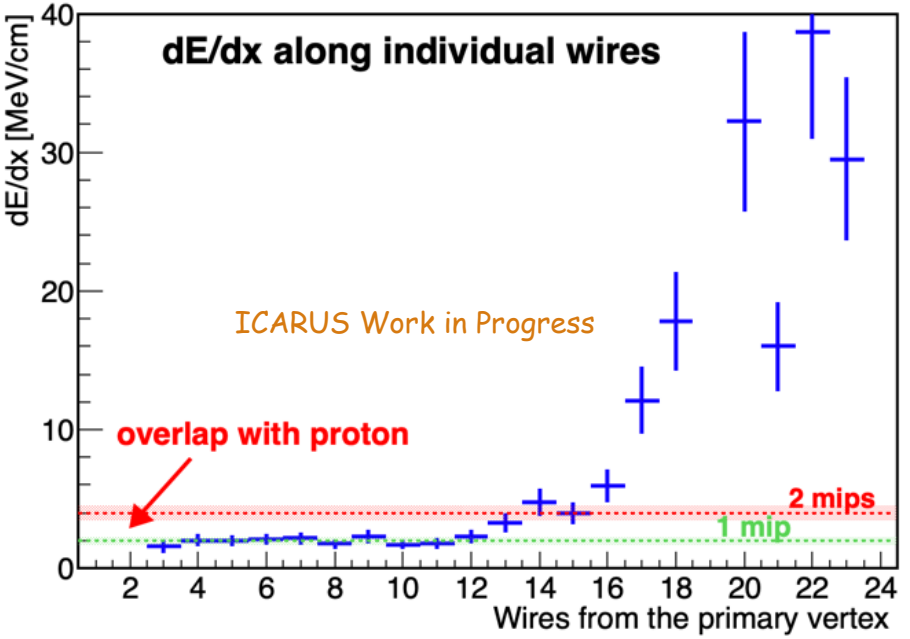
Search for electron neutrino events

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









Conclusions

- ICARUS has been taking high-quality physics data in stable conditions, with both Booster and NuMI beams, since June 2022
- The detector calibration with cosmic muons and protons from nmCC interactions allowed to qualify and characterize detector response, model detector effects and disuniformities and produce detector physics results
- The stand-alone ICARUS physics analysis program is progressing well:
  - 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 are being validated with control samples before full unblinding
- SBND running in physics mode since early 2025. Joint analyses between near and far detector will fully exploit the SBN program potential towards sterile neutrino searches

STAY TUNED !