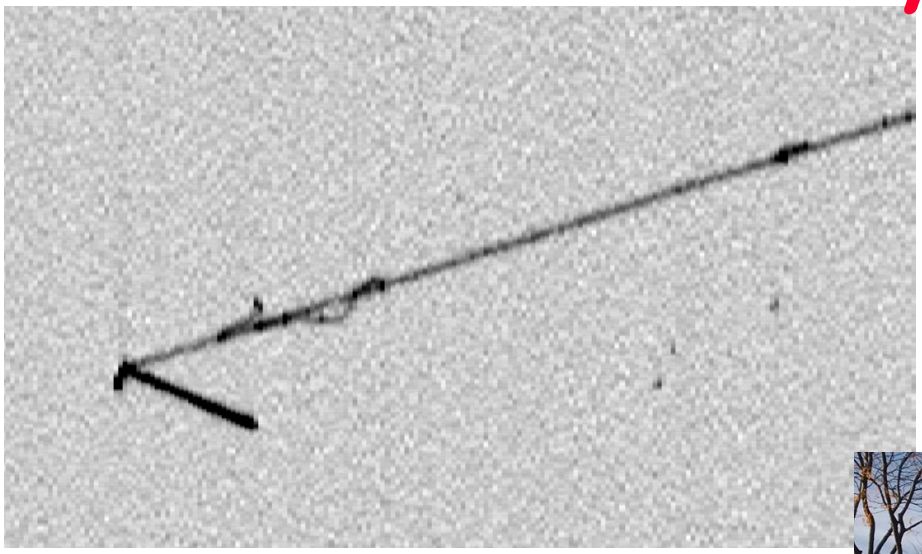
First results of ICARUS at the SBN program



SENSE
General meeting

April 1st 2025

IMAGING COSMIC AND RARE UNDERGROUND SIGNALS

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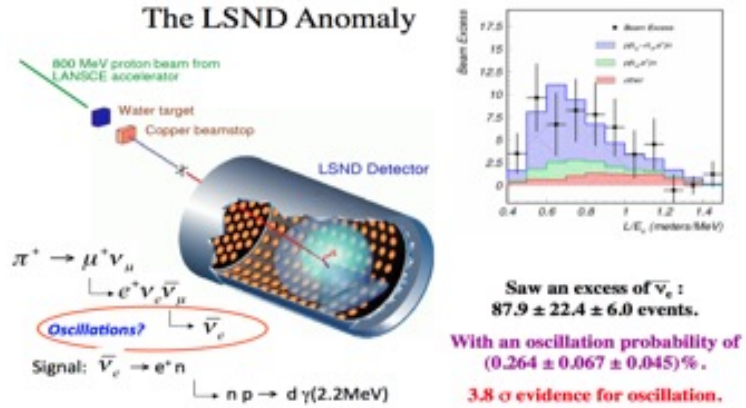
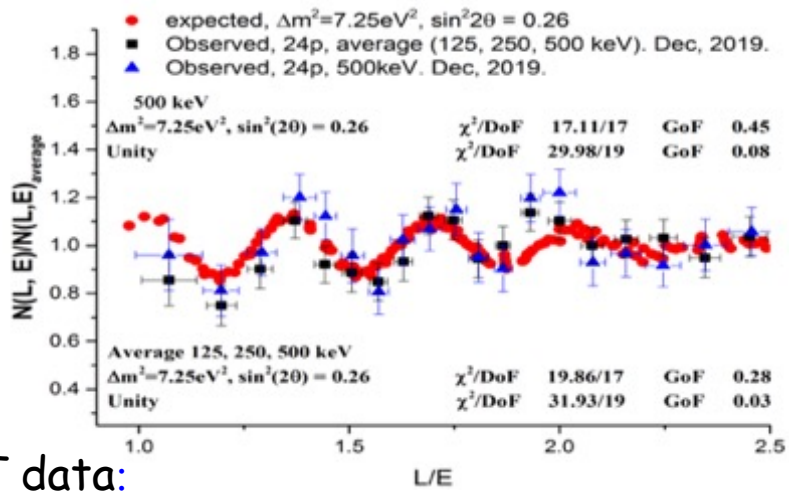
ICARUS collaboration

The sterile neutrino puzzle

- Different anomalies have been collected in last 20 years hinting to a new "sterile" ν flavor at Δm^2_{new}~ eV^2 and small mixing angle θ_{new}, driving oscillations at short distance.

  - 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 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 not easy…
  - 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.



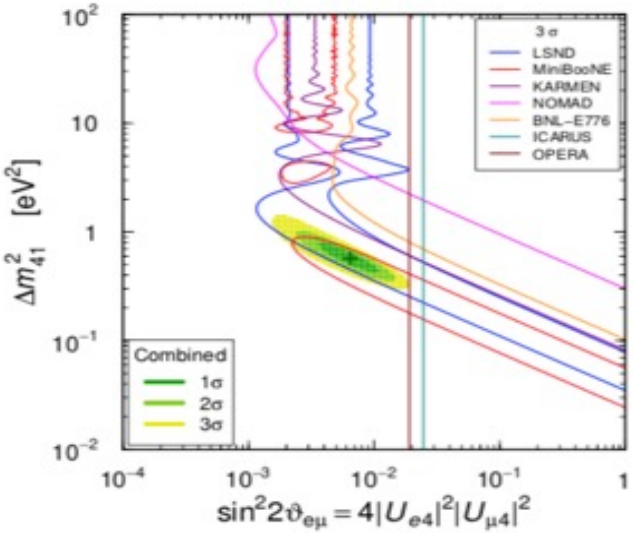


Combined analysis of Neutrino-4, GALLEX, SAGE, BEST data:
Δm^2_{14} =7.3 eV^2 sin^2 (2θ_{14}) =0.36 at 5.8 σ C.L. (A.P. Serebrov et al. arXiv:2302.09958)

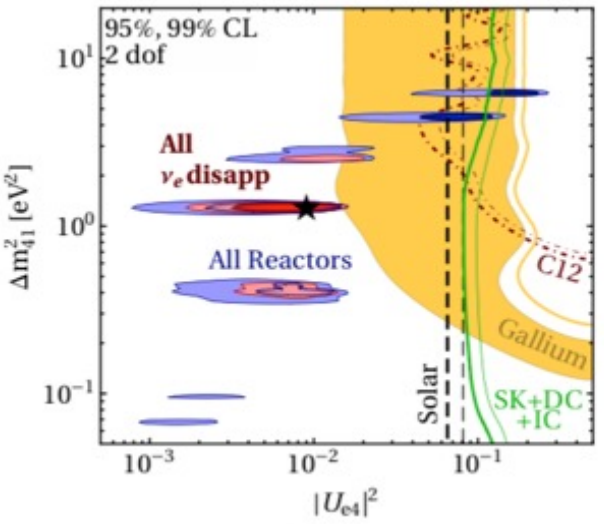
The sterile neutrino puzzle

- Several experiments performed at reactors and accelerators to study "ν anomalies", e.g. the recent result of MicroBooNE (arXiv:2210.10216), but:
  - A clear tension between appearance and disappearance experiments, which are characterized by different neutrino energy range and detection technique, is evident.

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



(anti-)ν_e Disappearance



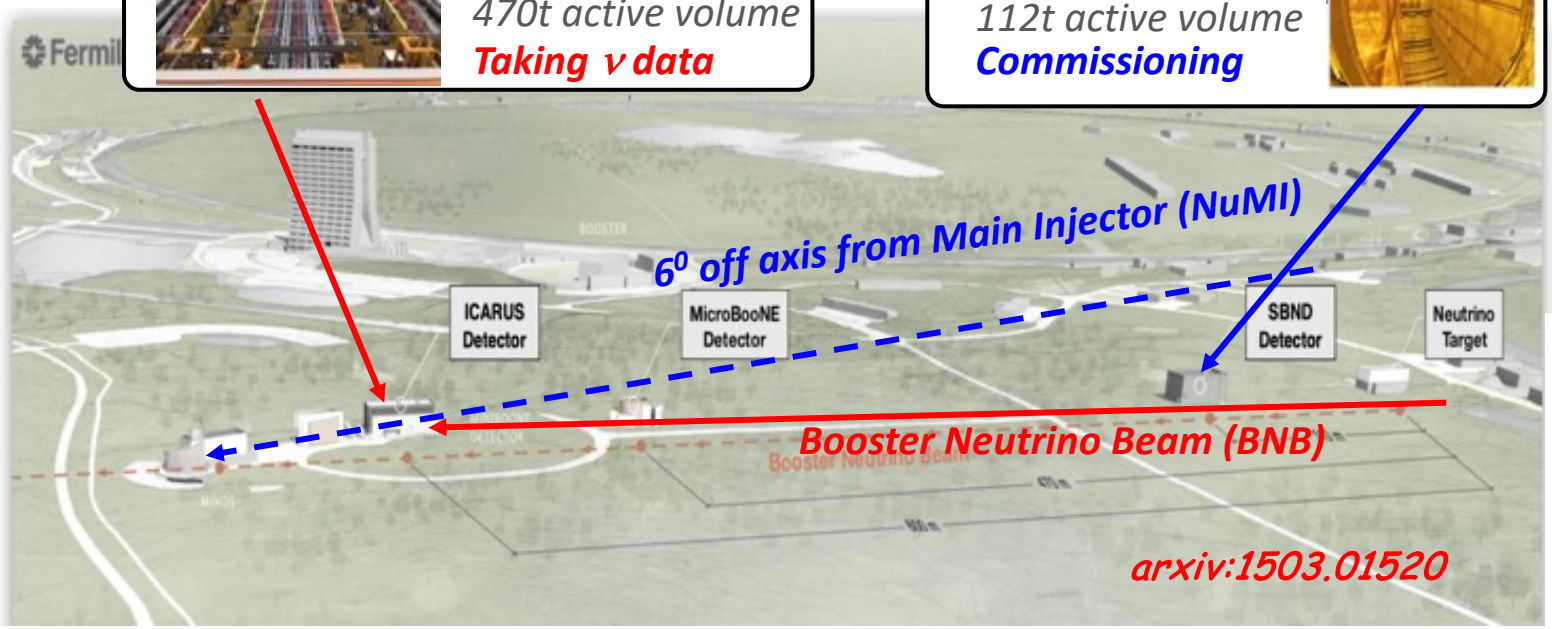
(arXiv:2106.05913)

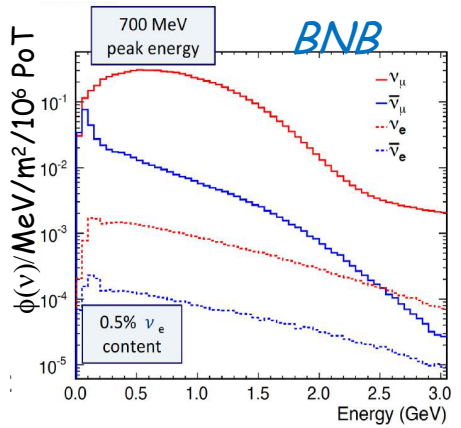
- ✓ *Measuring both appearance /disappearance in the same experiment using a detector with optimal ν id. and backgr. rejection is mandatory to disentangle physics scenario;*
- ✓ *Far to near detector neutrino spectra comparison is crucial for the control of backgr. and beam/detector systematics.*

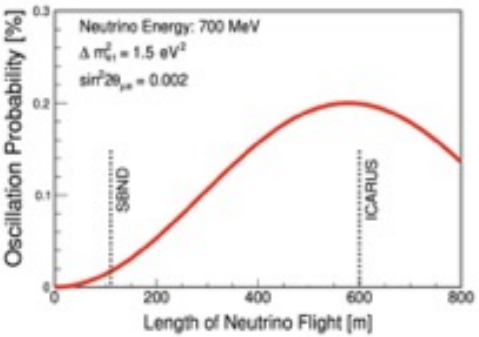
Short Baseline Neutrino (SBN) at FNAL BNB and NuMi beams: *a definitive answer to sterile neutrinos*

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

SBND LAr-TPC
110 m baseline
112t active volume
Commissioning





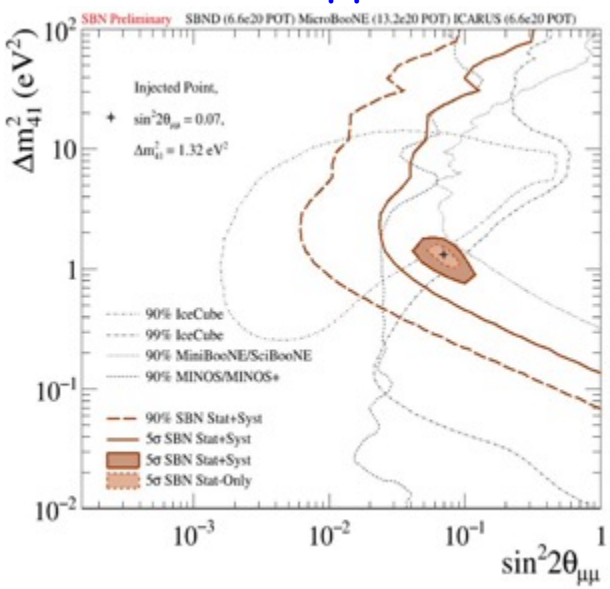


- ICARUS, SBND Liquid Argon TPCs (LAr-TPC) are installed at 600 and 110 m from Booster target, searching for sterile-ν oscillations both in appearance and disappearance channels
- In addition: high-statistics ν-Ar cross-section measurements and event identification/ reconstruction studies in view of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

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

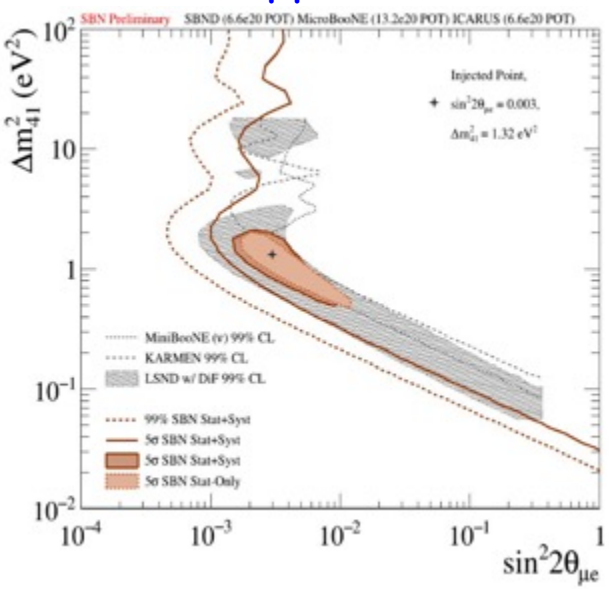
- Combined analysis of events collected far by ICARUS at far site and by SBND at near using the same LAr-TPC event imaging technology greatly reduces the expected systematics:
  - High νe identification capability of LAr-TPCs rejecting NC event background;
  - "Initial" BNB beam composition and spectrum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

νμ disappearance



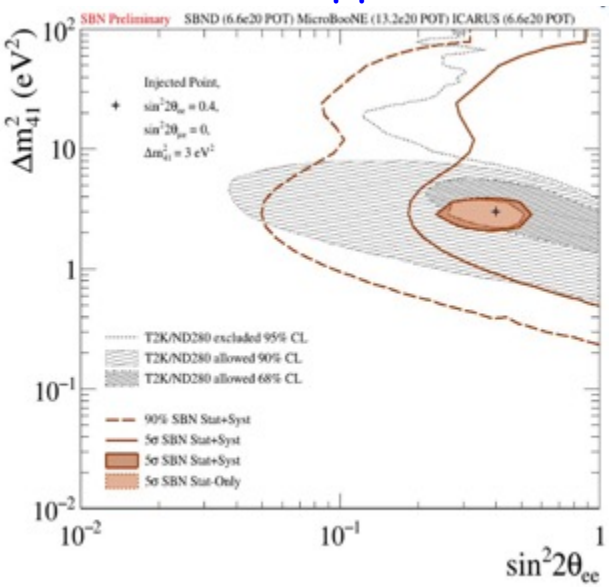
5σ coverage of the parameter area relevant to LSND anomaly

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 LAr-TPC detector

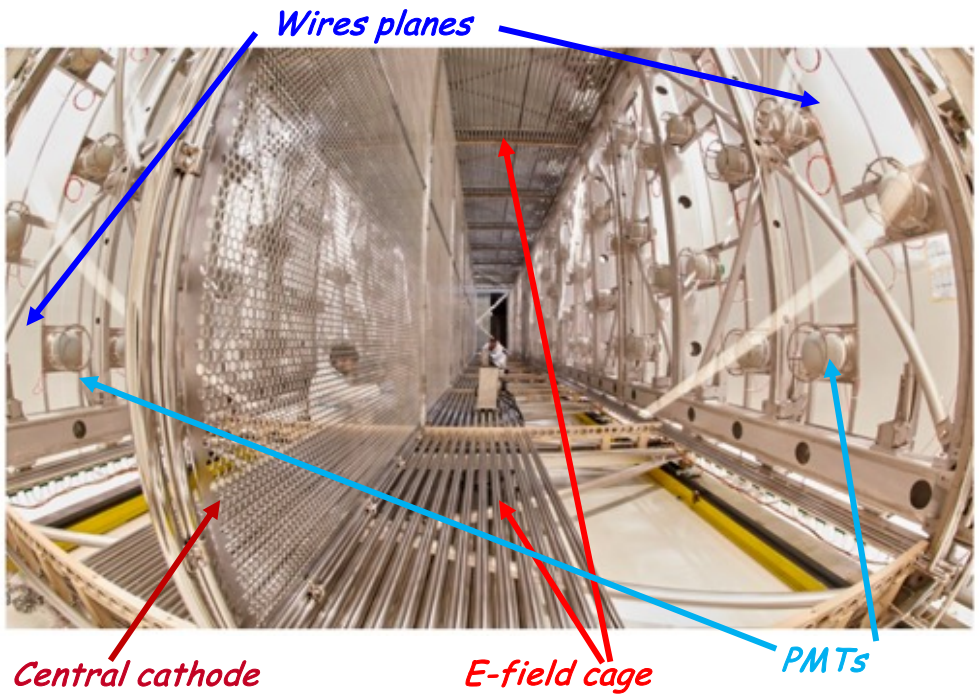
- First proposed by C. Rubbia in 1977, LAr TPCs are high granularity uniform self-triggering detectors with 3D imaging and calorimetric capabilities, allowing to accurately reconstruct a wide variety of ionizing events with complex topology: ideal detector for ν physics!

  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

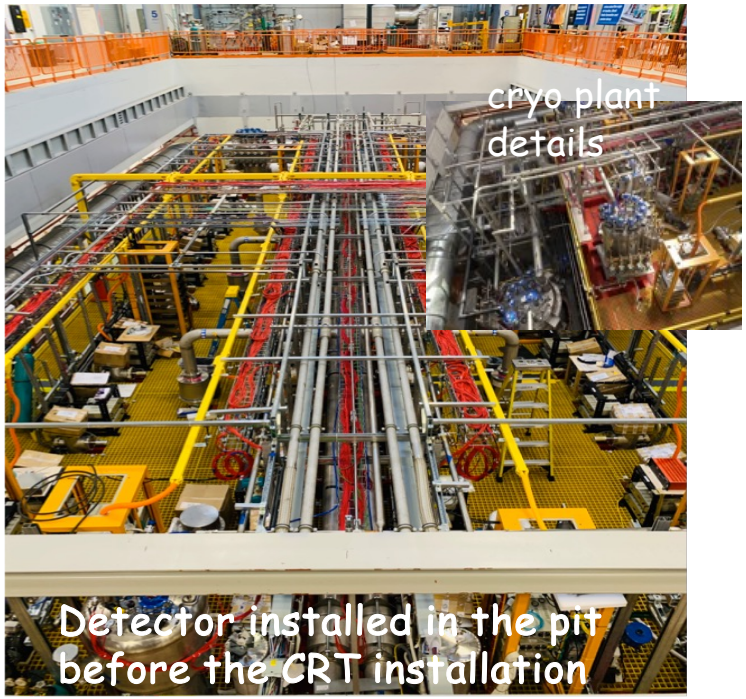
- ICARUS-T600 overhauled in 2014-18 in view of shallow depth operation at Fermilab:

  - 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;
  - LAr /GAr purified by copper filters and molecular sieves for water absorption;



Inner view of a TPC

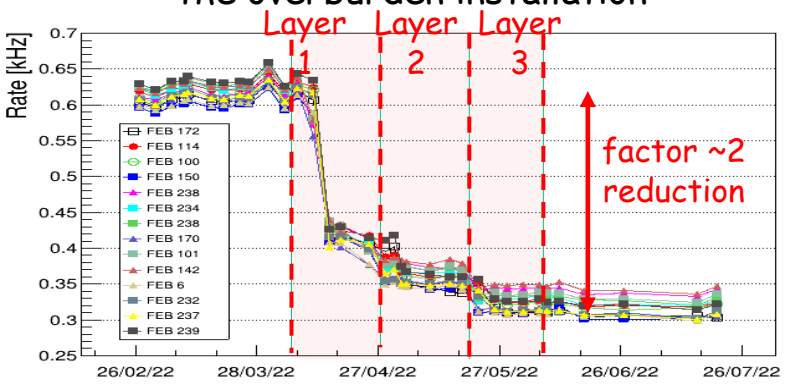
ICARUS T600 installation and activation



- The Cosmic Ray Tagger system (CRT) encloses the detector: a double layer of scintillator bars (~1000 m²) tagging incoming cosmics with ~95% efficiency.
  - Completion of the CRT installation in Dec 2021

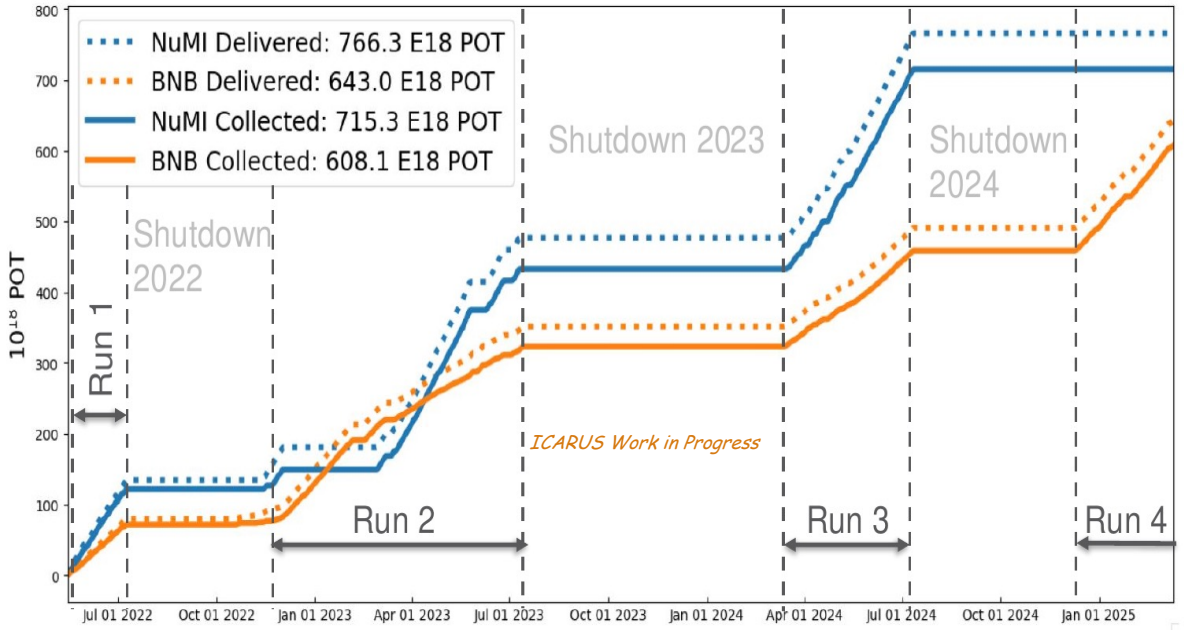
- Cosmic γ's and and neutrons are suppressed by ~2.85 m thick concrete overburden installed on top of the CRT,

Rate of cosmic rays measured during the overburden installation



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;
- The cryogenic/purification system performed smoothly keeping the free electron lifetime τ_{ELE} stable and adequate for physics runs: τ_{ELE} ≈7-8 ms, (residual impurities in LAr at ~40 p.p.t. of [O_2] equivalent): almost full track detection efficiency in the whole 1.5 m drift (t ~ 1 ms).
- 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



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- Steady data taking with excellent stability at BNB rate > 4 Hz, >90% lifetime

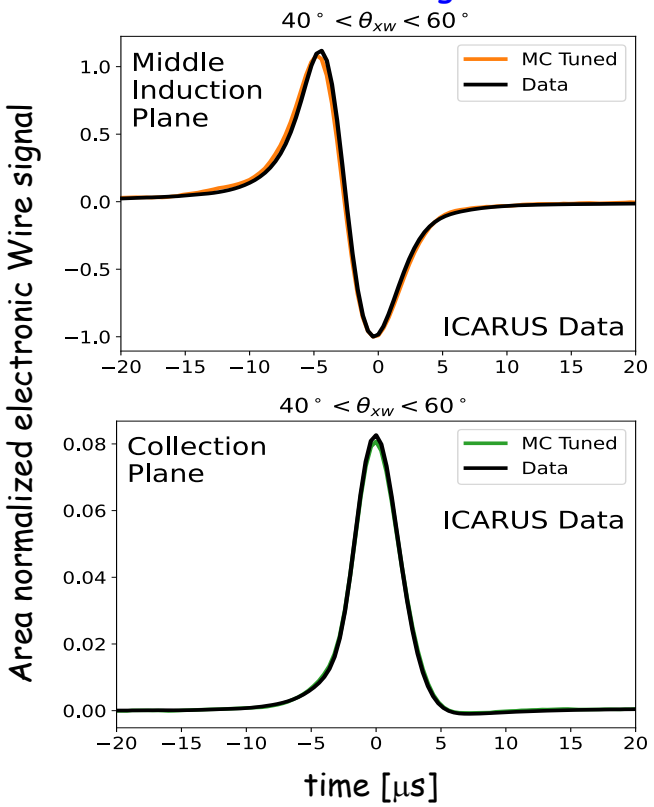
Collected Protons on target (PoT)	BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1 (Jun-Jul 22)	0.41 10^{20}	0.68 10^{20}	-
RUN-2 (Dec 22-Jul 23)	2.05 10^{20}	2.74 10^{20}	-
RUN-3 (Mar -July 24)	1.36 10^{20}	-	2.82 10^{20}
RUN-4* (Dec 24 -ongoing)	1.37 10^{20}	-	-
TOTAL	5.19 10^{20}	3.42 10^{20}	2.82 10^{20}

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

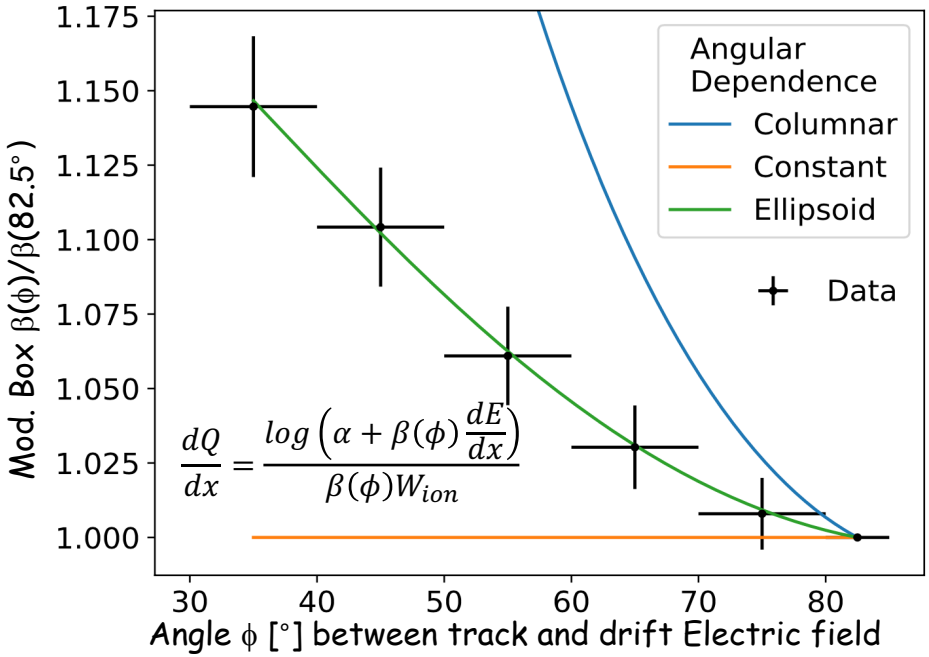
Detector calibration and modelling

- Signals from TPC wires have been accurately characterized and modeled in MC;
- Detector response is calibrated with cosmic muons and protons from ν interactions, including a new angular dependent-ellipsoidal recombination model;
- Improved reconstruction is expected from a new processing accounting for charge sharing amongst multiple wires.

Average signal response per plane (Data/tuned MC) for one track angular bin



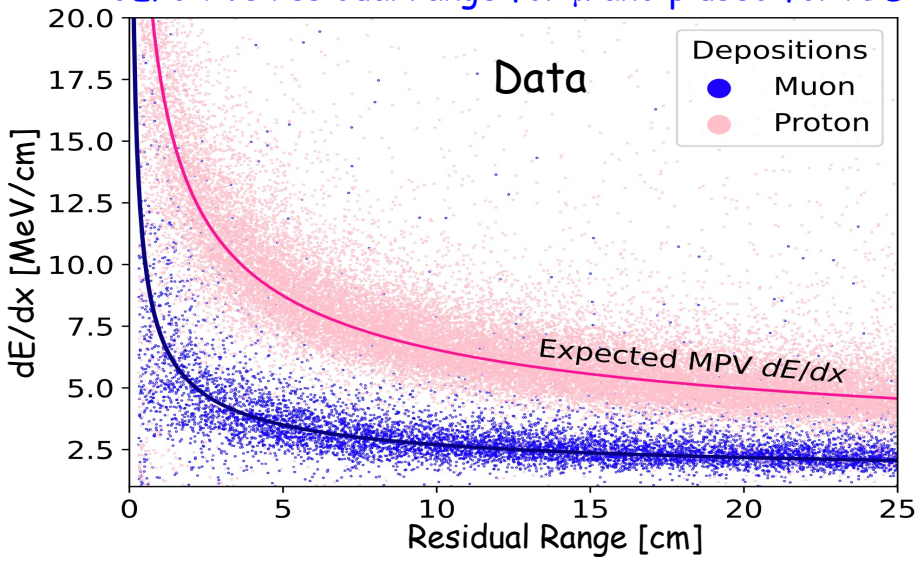
Angular dependence of recombination β parameter

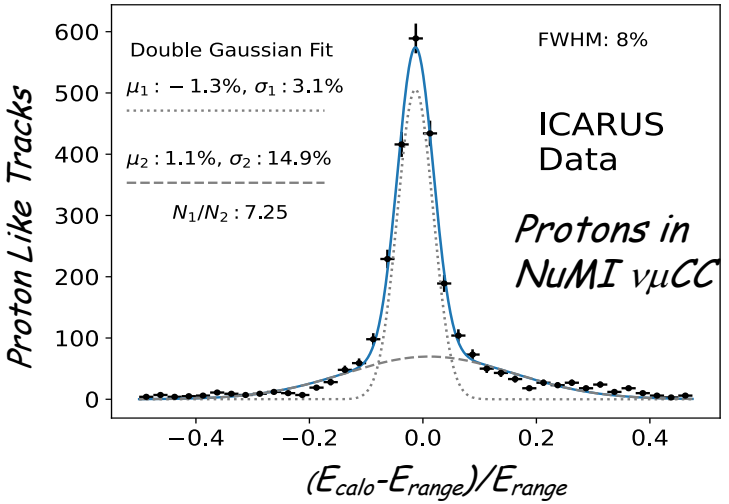


See JINST 20, P01032 (2025) and JINST 20, P01033 (2025)

Detector calibration and energy measurement

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

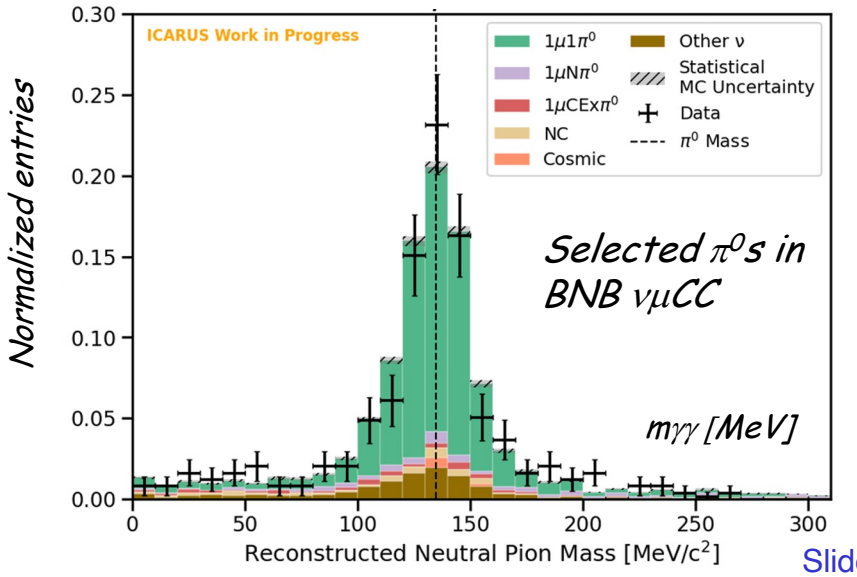




Difference between calorimetric and range measurement of the proton energy

- Calibration/calorimetric reconstruction of E_{DEP} are validated with
  - π^0 in ν interactions (~10% resolution on $m_{\gamma\gamma}$);
  - stopping protons recognized in NuMI νμCC interactions (~3% resolution).

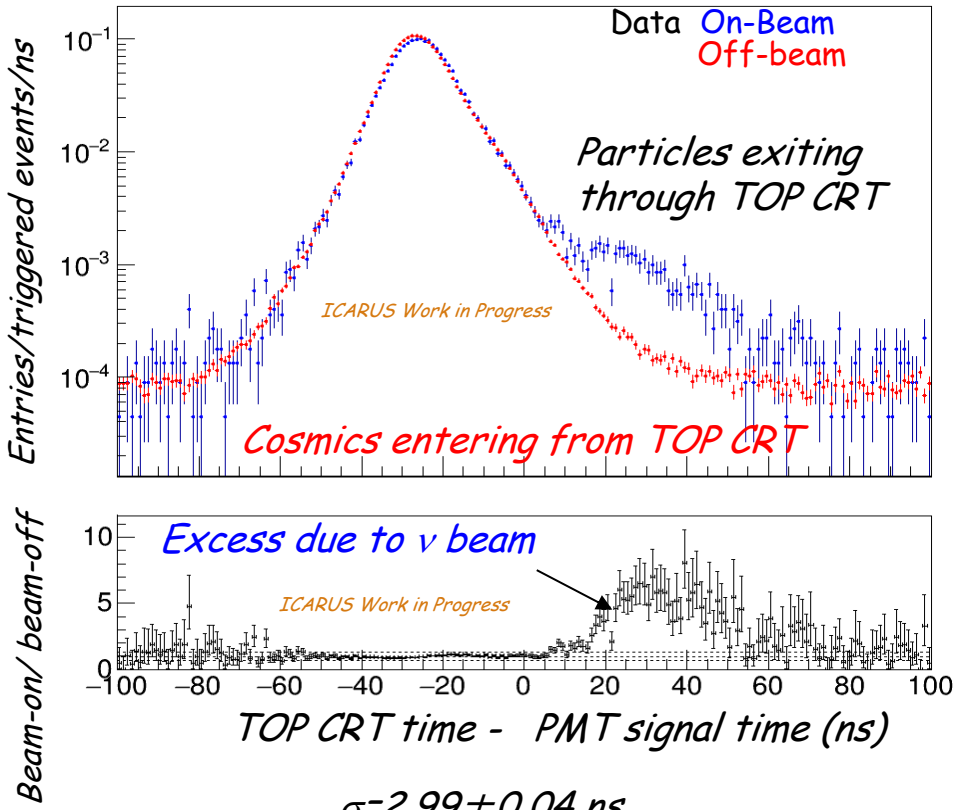
Reconstructed π^0 mass

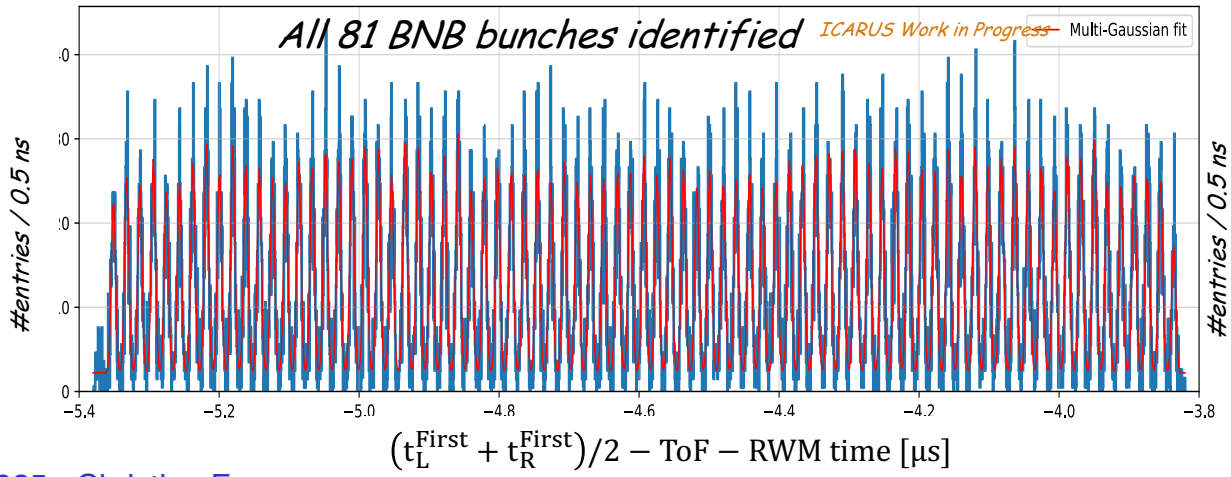


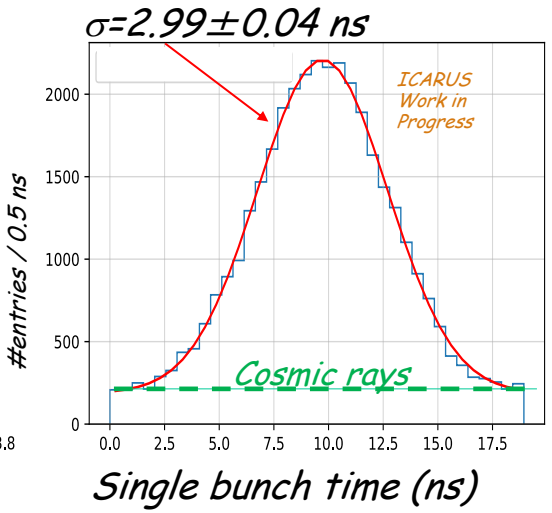
Detector performance: Cosmic ray Rejection and Precision Timing

- Time-of-flight rejection of incoming cosmic rays using the external CRT and the inner PMT system.

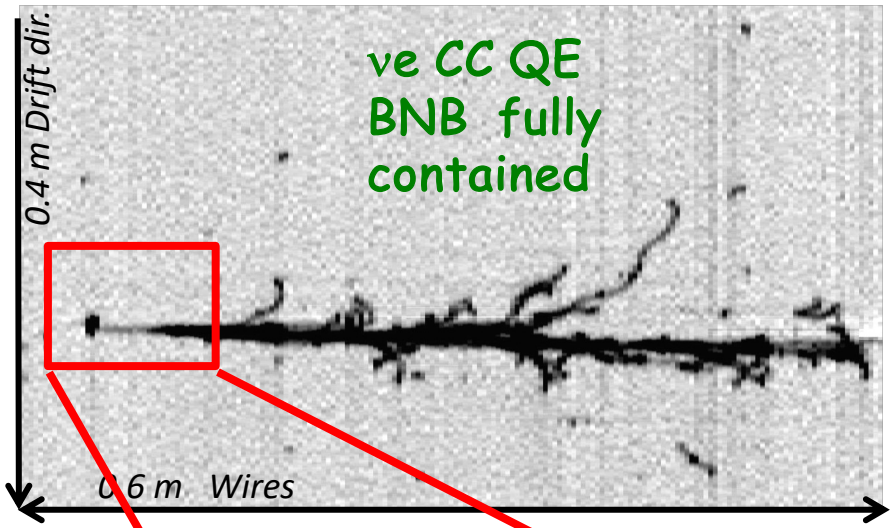
- Reconstruction of bunched structure of beam spill – both BNB and NuMI:
  - Neutrino event time (PMTs only) with respect to the proton beam extraction time (RWM counters) after rejecting incoming cosmics (CRT) and correcting for ν flight distance.

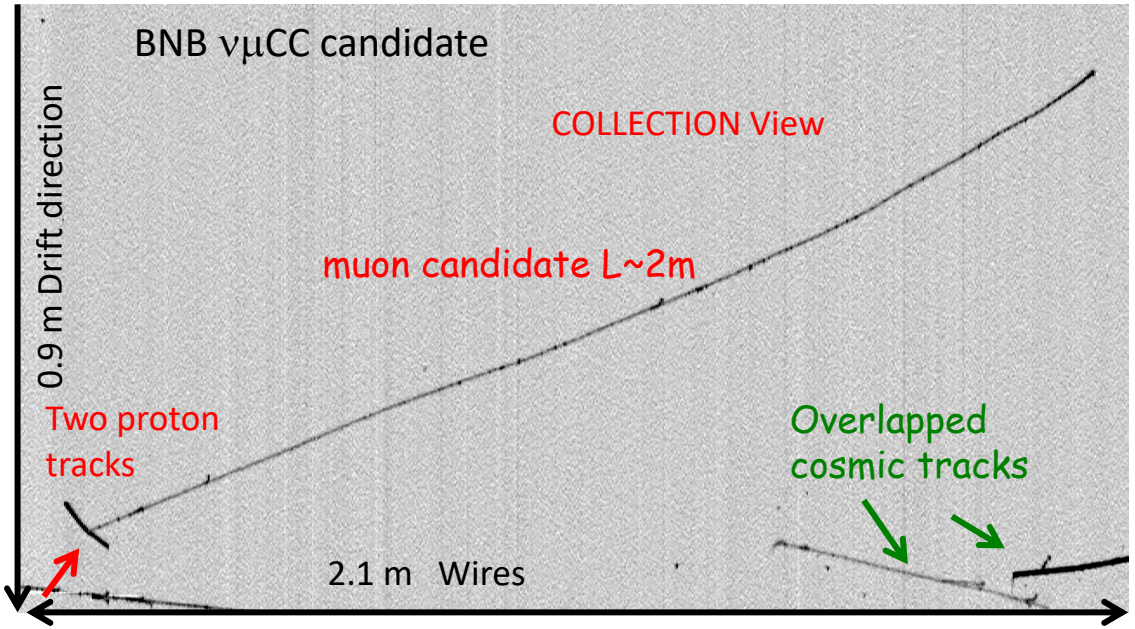


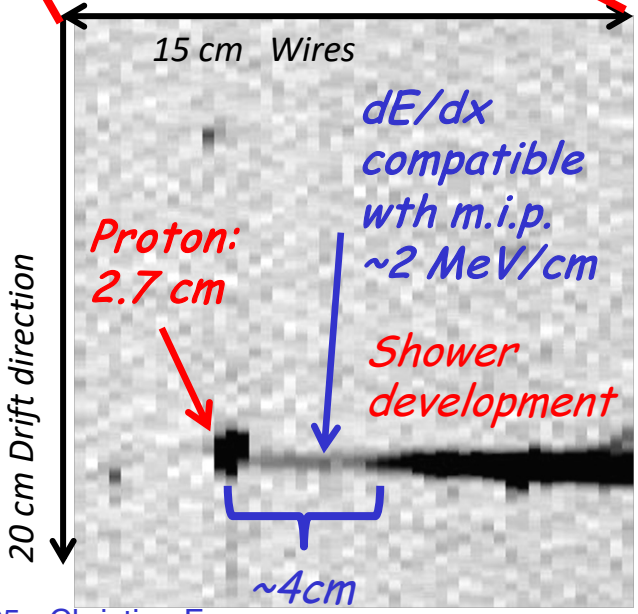


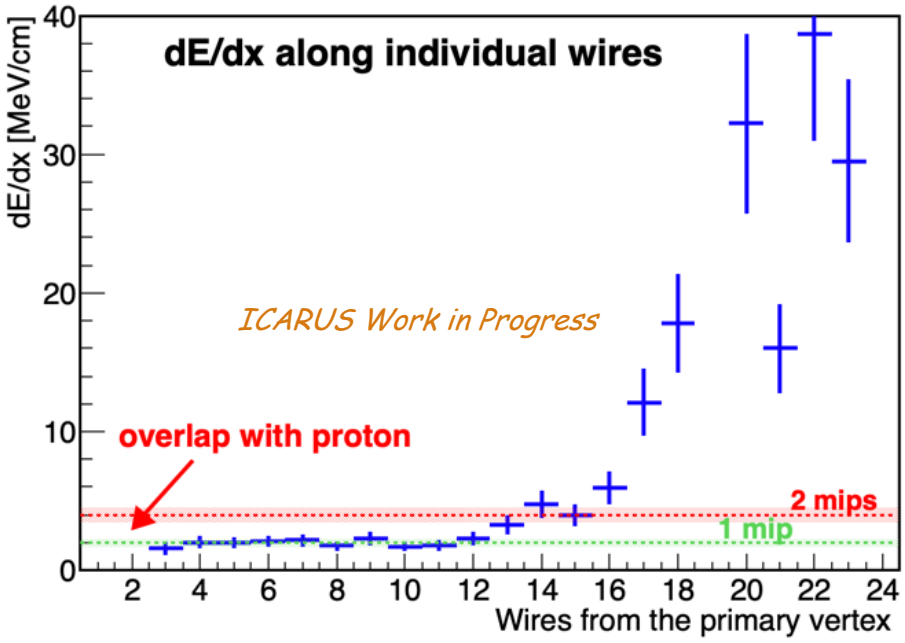


Neutrino events collected in the BNB beam





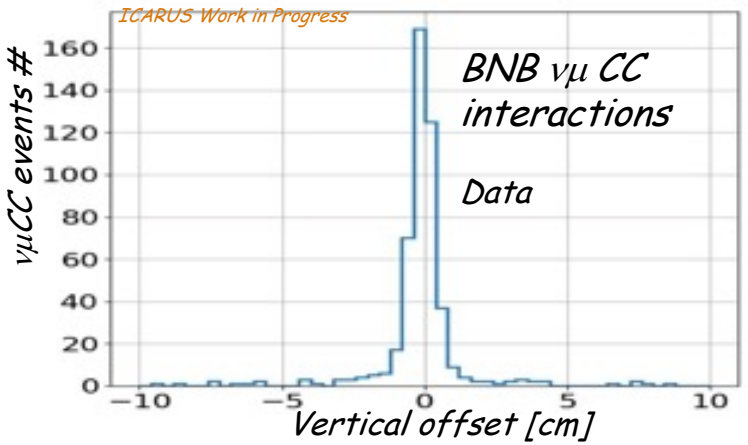




A powerful tool: the visual study of the events

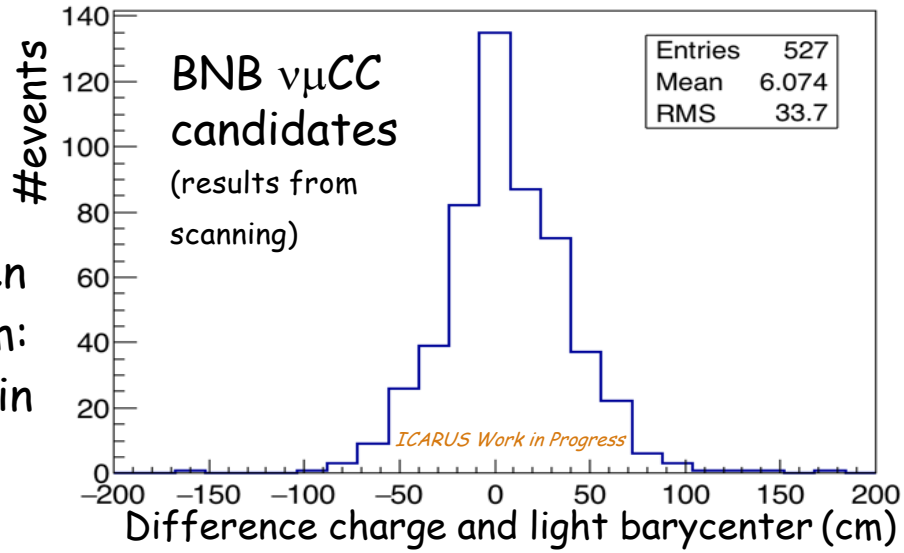
Neutrino events found from visual scanning of collected data are used to investigate/test automated software tools and compare MC/data performance.

Neutrino vertex reconstruction



Difference between automatic and visual reconstruction of ν interaction vertex

- Automatic reconstruction of ν vertex with few mm resolution was validated using a sample of νμCC candidates visually selected and measured.



- The association of light and charge signals has been validated on visually selected νμ CC with Lμ > 50 cm: charge and light barycenter are in agreement within 1 m along the longitudinal beam direction.

- A visual selection of ν candidates is also used to validate the performance of selection/ reconstruction procedures in the ongoing analyses;

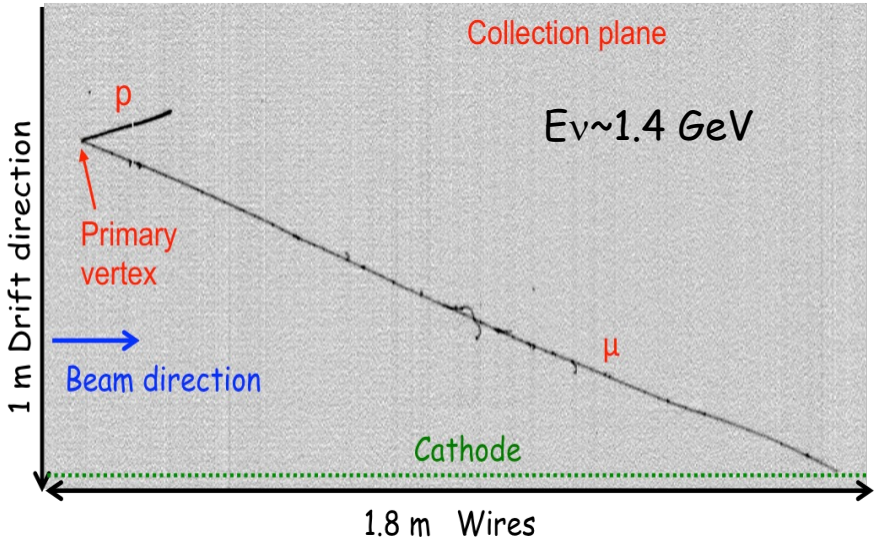
ICARUS Research Program

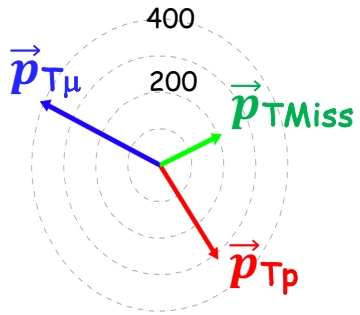
- The SBN program is addressing the question of sterile neutrinos with the BNB beam comparing ν_e and ν_μ interactions at different distances from target as measured by ICARUS and SBND LAr-TPCs.
- Before the start of joint operation ICARUS is focusing on standalone physics program, also in preparation 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%.





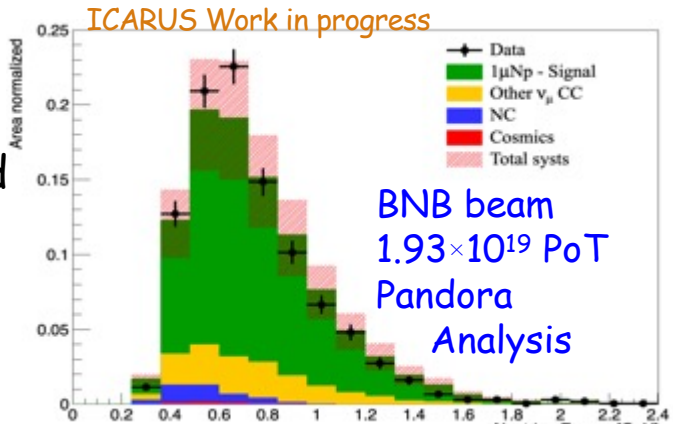
Momentum in the transverse plane (MeV/c)

- 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;

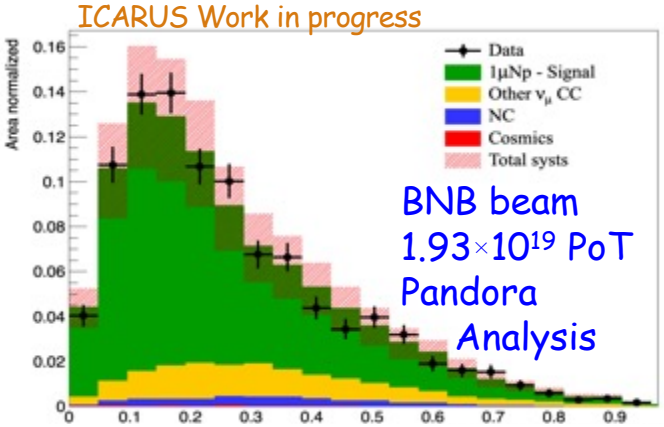
1μNp analysis – event selection results

- 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

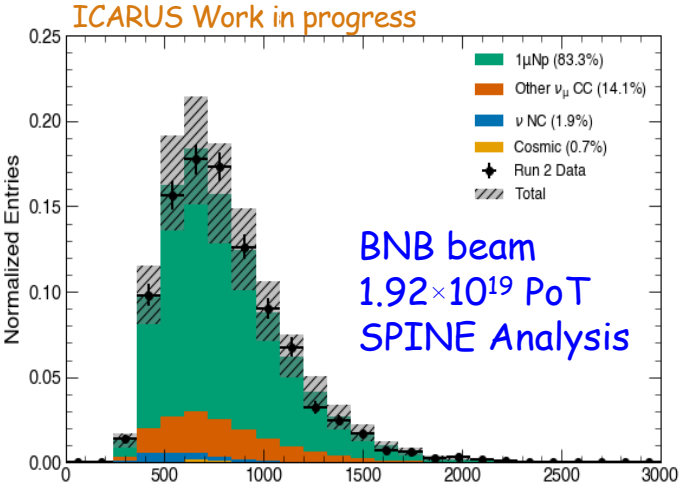
- 10% of RUN-2 data analyzed
  20 time more data available
- Data-MC agreement for all studied event kinematic variables within systematics;
- Ready for the next analysis steps: enlarge the control sample to confirm the analysis robustness and proceed to full dataset unblinding and oscillation fit.



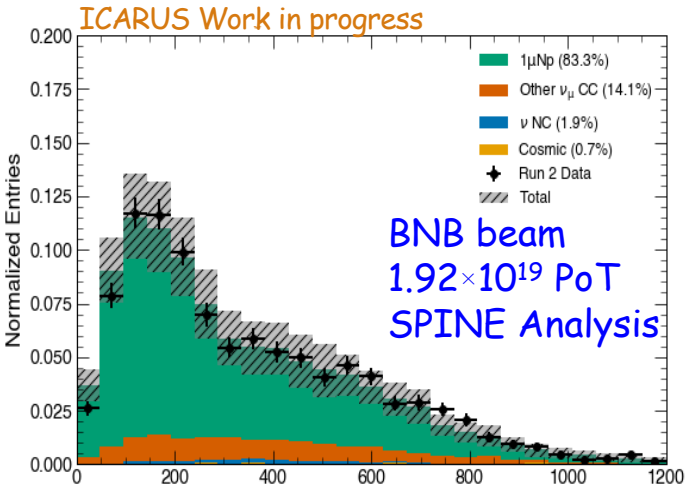
Reconstructed neutrino Energy [GeV]



Total transverse momentum p_T ([GeV]/c)



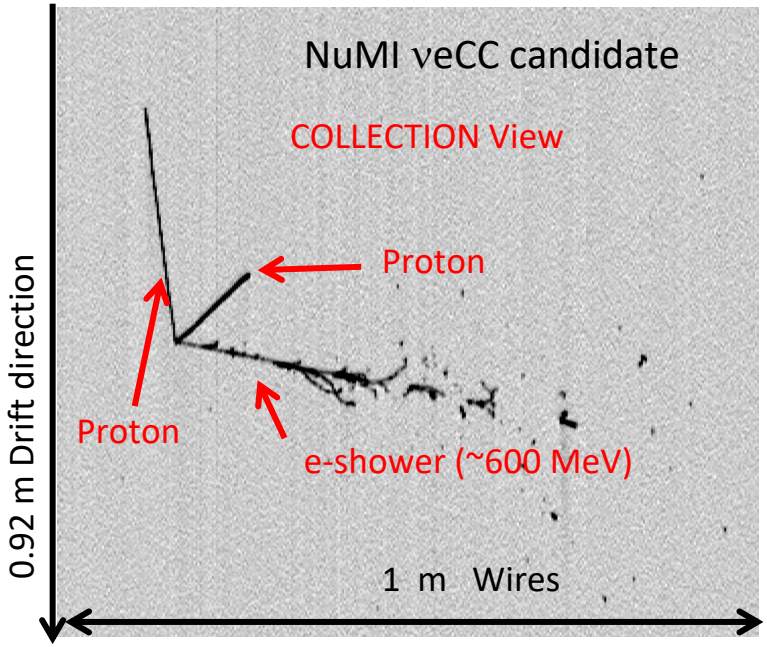
Reconstructed neutrino Energy [MeV]

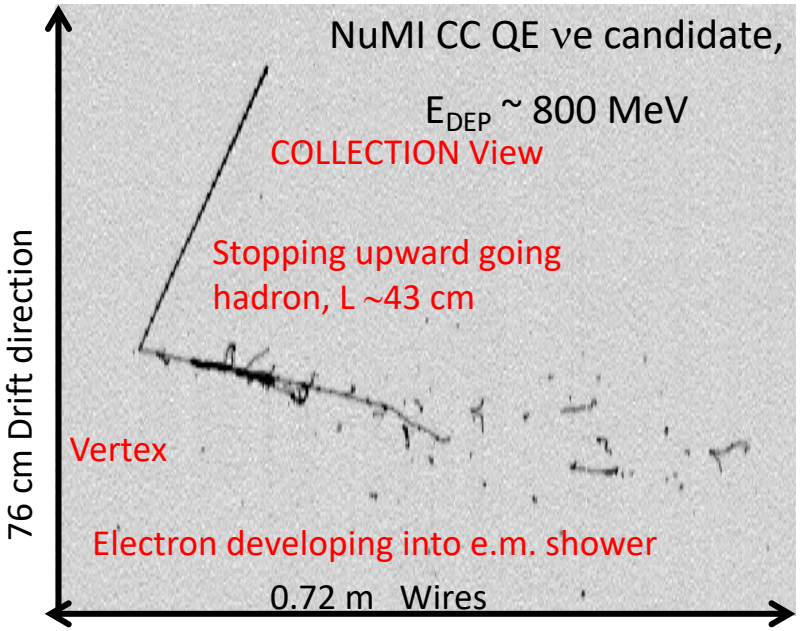


Total transverse momentum p_T ([MeV]/c)

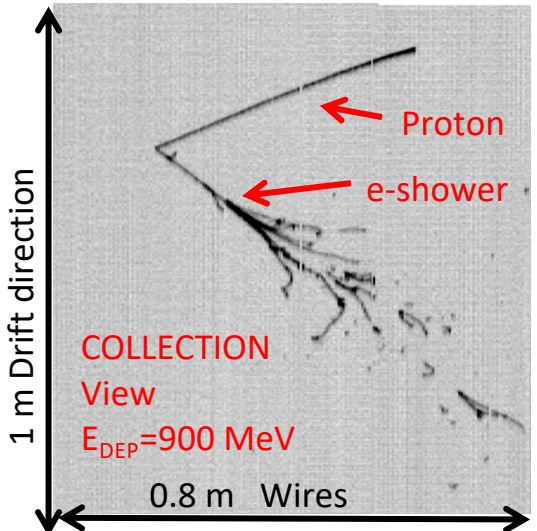
Search for the electron neutrino events

- ICARUS will also search for a possible ν_e disappearance with off-axis NuMI beam to address the Neutrino-4 claim. The focus will be on QE-like events fully contained in the active volume;





- The development of the tools for the selection and reconstruction of the ν_e events is ongoing:
  - The search for the atmospheric νs recorded in the T600 during the LNGS run demonstrated that an efficiency ~ 80% can be reached for νe events in the same energy range;



Atmospheric νeCC QE candidate recorded at LNGS

See 2019 Universe, 5, 17

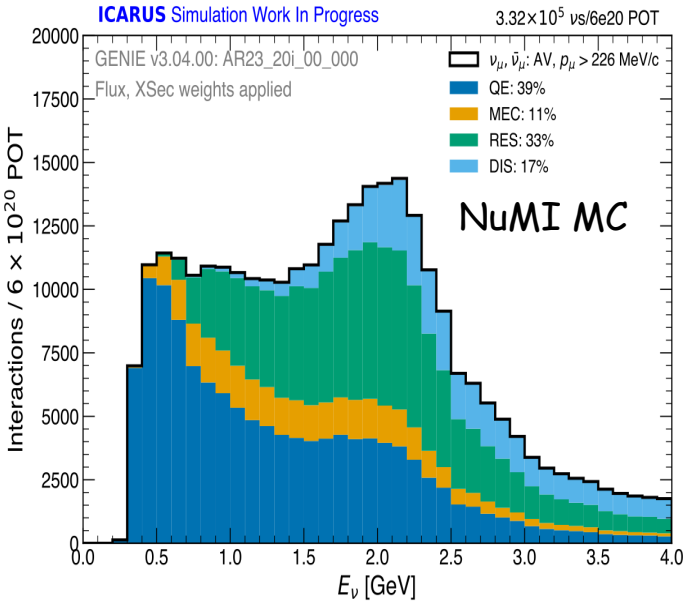
Neutrino Interactions from NuMI off axis at ICARUS

- Excellent statistics to measure cross section for quasi-elastic, resonance and deep inelastic scattering, for both electron and muon neutrinos:

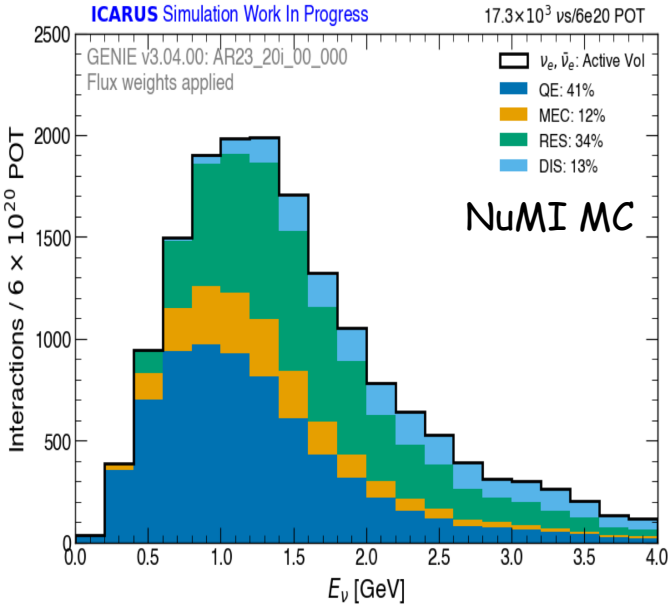
  CC events/6E20 pot : ν_μ 332,000 and ν_e 17,000.

- Neutrino energy spectrum from NuMI at ICARUS covers the first oscillation peak and good coverage of the relevant phase space for DUNE experiment.

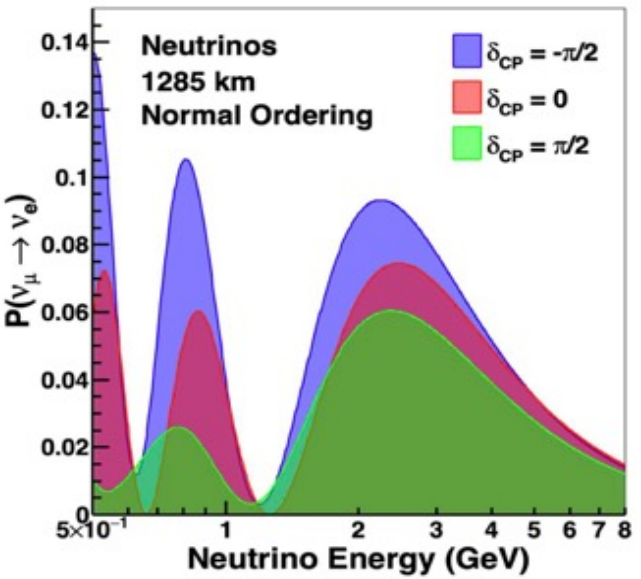
ν_μ, $\bar{\nu}_\mu$ from NuMI at ICARUS



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



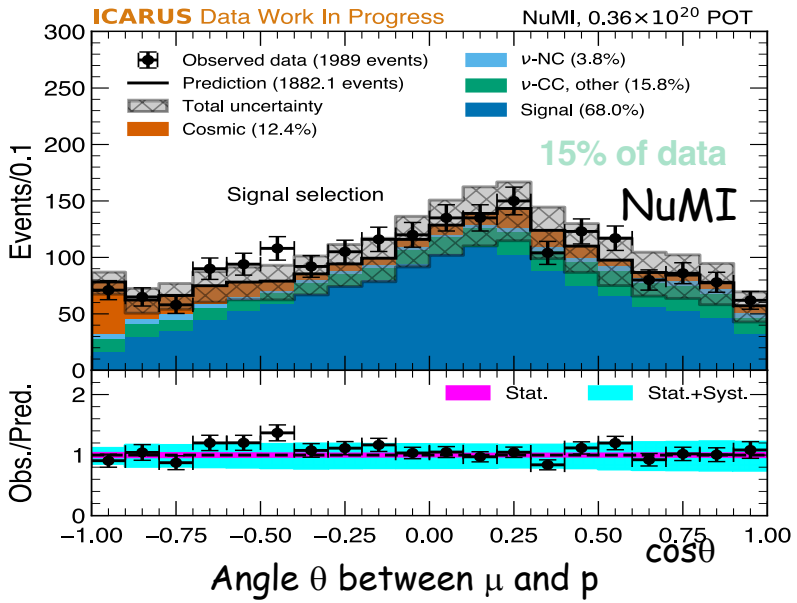
Oscillation probability at DUNE

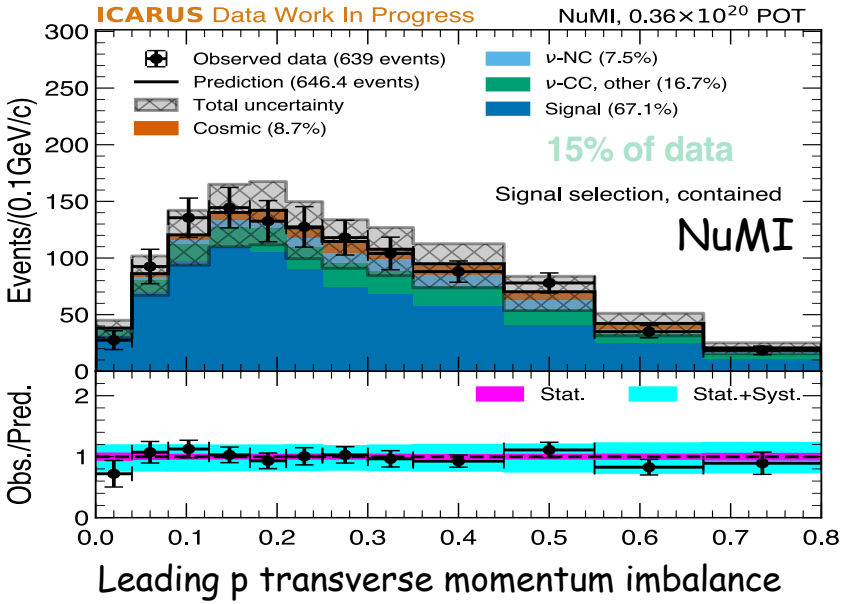


- Available data ~3.42E20 POT for physics analysis now

CC 0π analysis – results for the selected sample

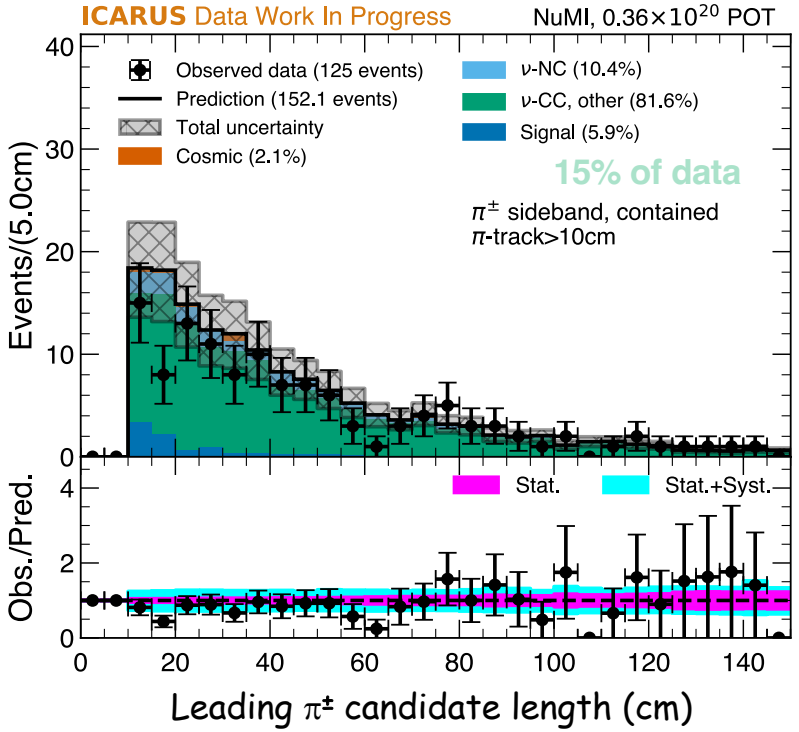
- First analysis targets 1μ+Np+0π enhanced in quasi elastic and 2p2h interactions :
  - Signal definition: one μ with momentum > 226 MeV/c, any proton with momentum between 400 MeV/c and 1 GeV/c, no $\pi^{\pm}$ or π^0 in the final state;
  - Selection: at least two primary tracks, a μ and proton candidates, identified by PID;
  - 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.

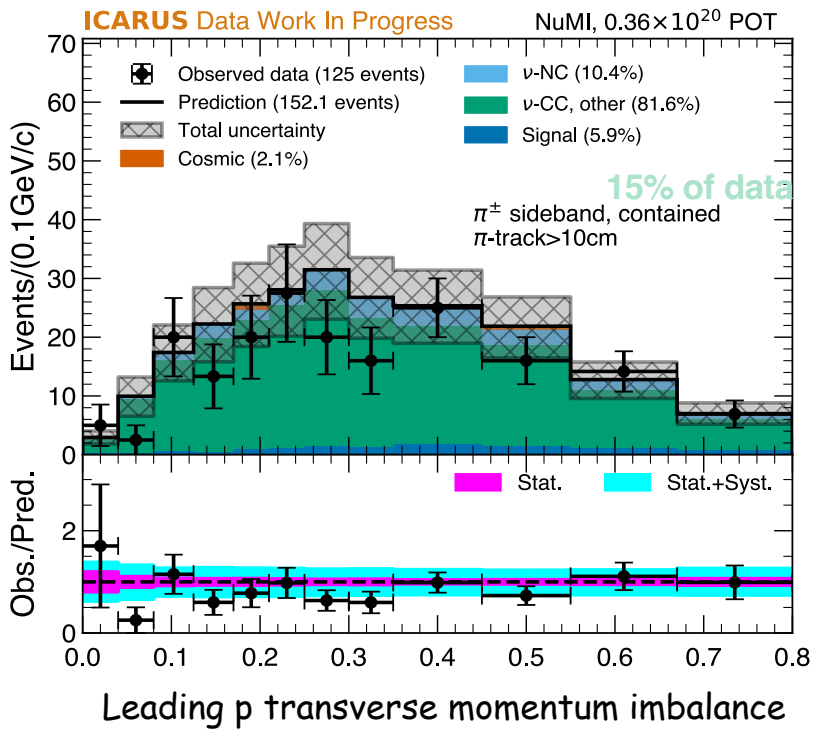




Charged Current Pion Control Sample

- 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);
- The kinematic of this control sample is initially studied with 15% of data. Ready to study sidebands with the full Run-1 + Run-2 event statistics.

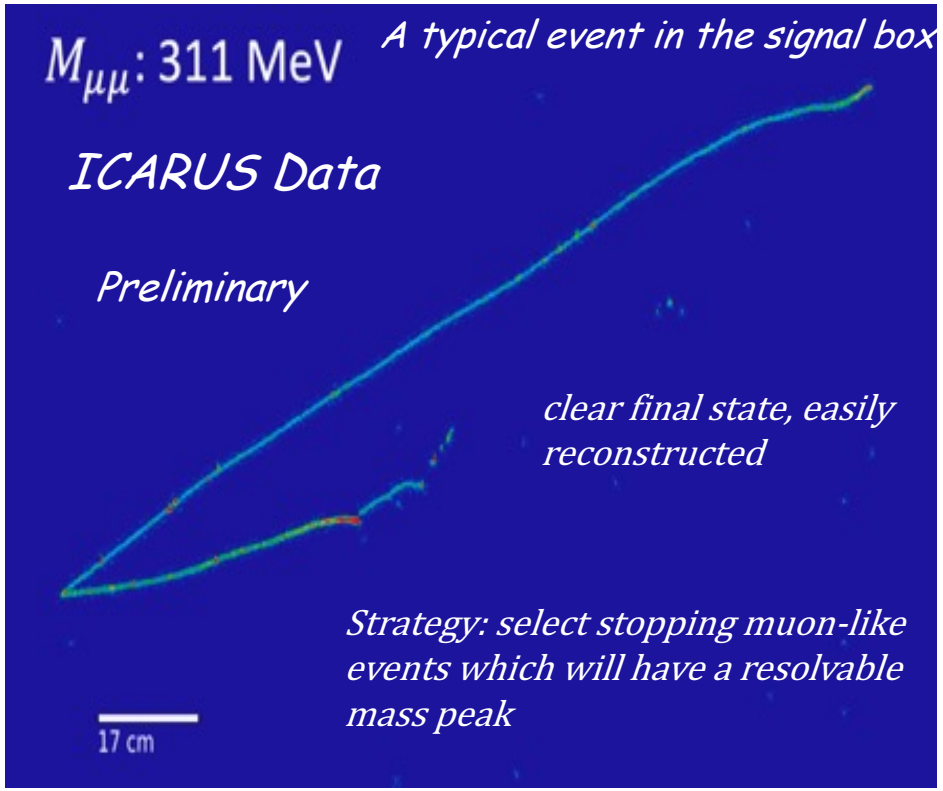




Dark sector models investigation by ICARUS

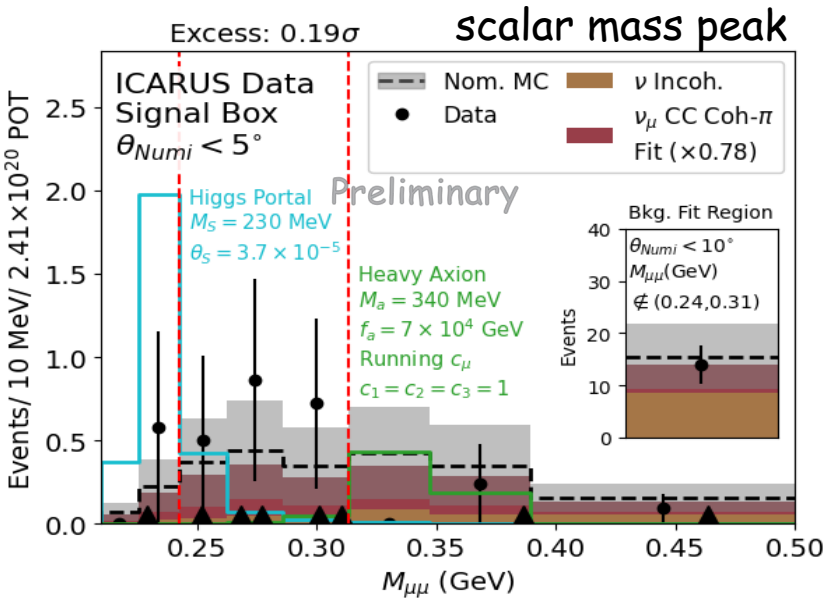
- A rich Beyond Standard Model search program, DM, heavy neutral leptons,…
  The experimental search has been pursued exploiting the off-axis NuMI beam;
- Models considered so far involve dark particles coupling to Standard Model particles via Scalar Portal Interactions:
  - Higgs portal Scalar: Scalar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

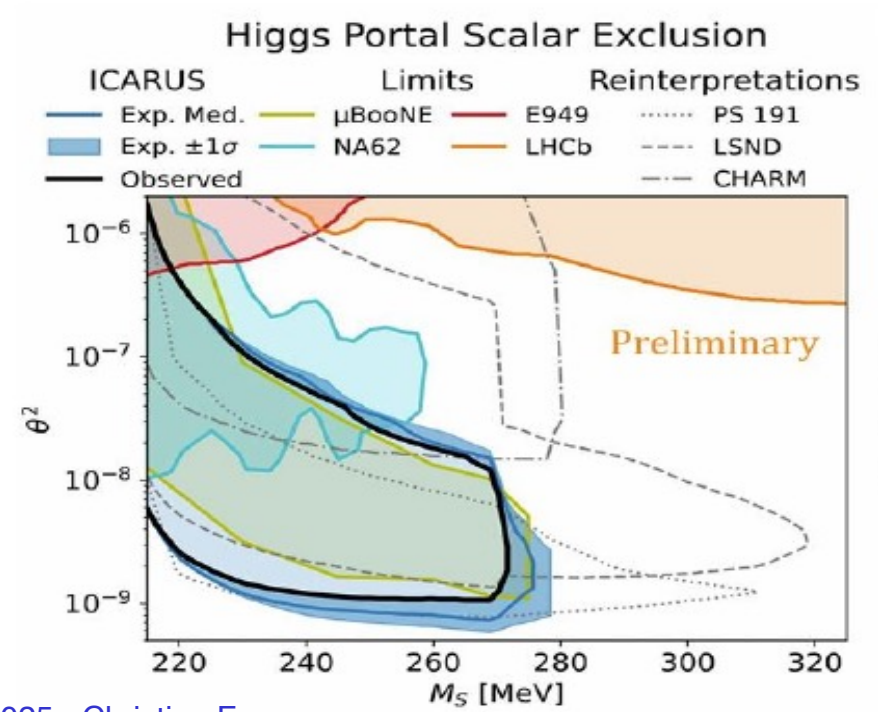
- A first search for new particle decaying into di-muon has been completed.
- Events with 2 stopping μs are selected, to reconstruct the scalar mass peak;
  - Signal expected at small angle to beam (θ_{NuMI} <5^0);
- Flux, interaction model and detector systematic uncertainties have been included.

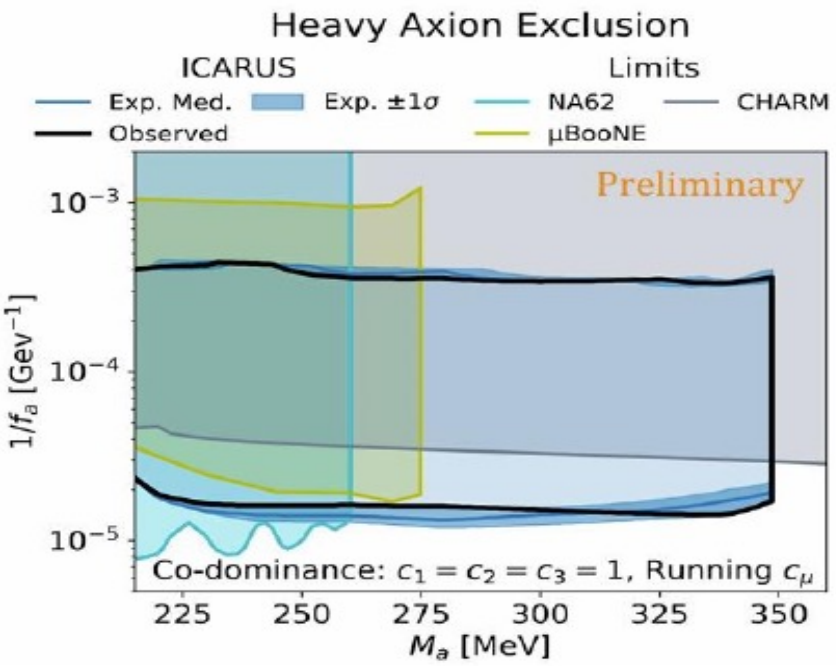


Search for BSM scalar decays in $\mu^+\mu^-$ with NuMI - results

- 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;
- Paper accepted in PRL (see arxiv:2411.02727)



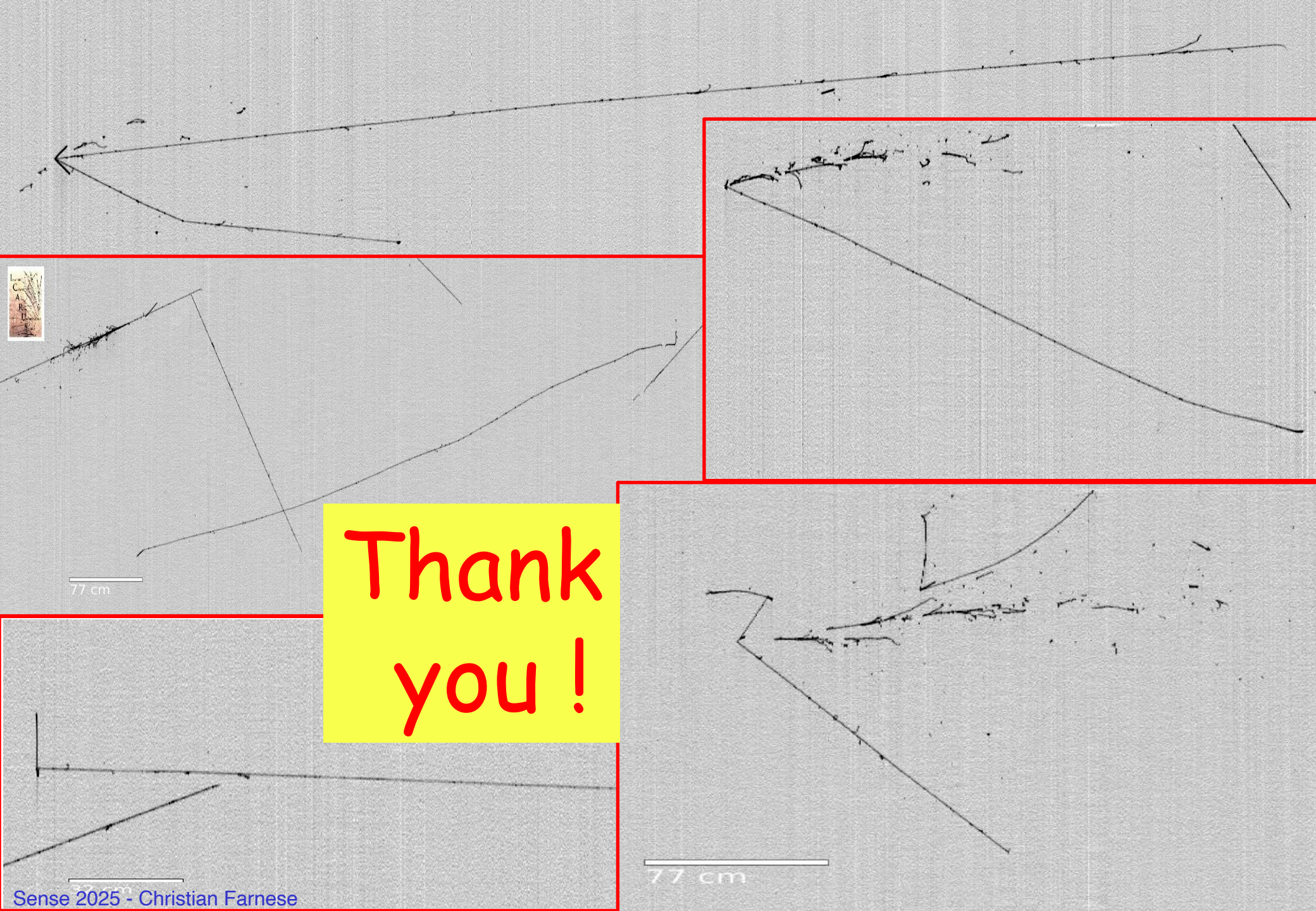




Conclusions

- 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 !



Thank you !