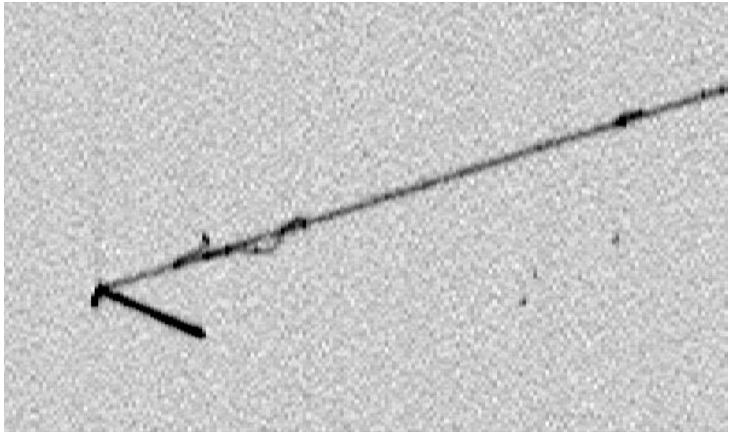
First Results of the ICARUS Experiment at the Short-Baseline Neutrino Program



59th Rencontres de Moriond
Electroweak Interactions & Unified Theories

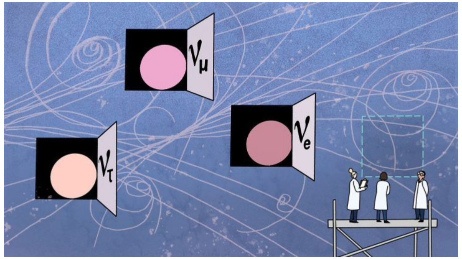
La Thuile, March 26th, 2025

Alessandro Menegolli
University of Pavia and INFN Pavia (Italy)
on behalf of the ICARUS Collaboration

H2020, M. Sklodowska-Curie RI No. 822185, 858199, 101003460, 101081478

A long-standing puzzle in neutrino oscillation sector

Anomalous results, over the past 25 years, in neutrino oscillations at short distances may be explained by the existence of a new sterile neutrino state ($\Delta m^2 \sim 1\ eV^2$).



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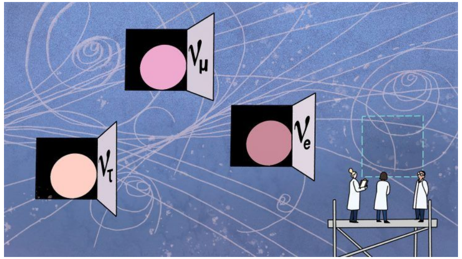

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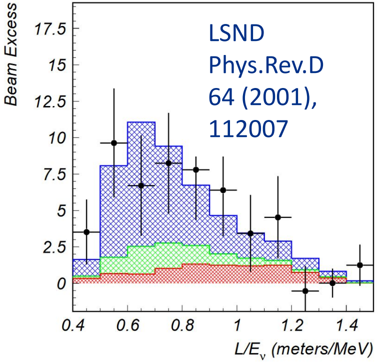
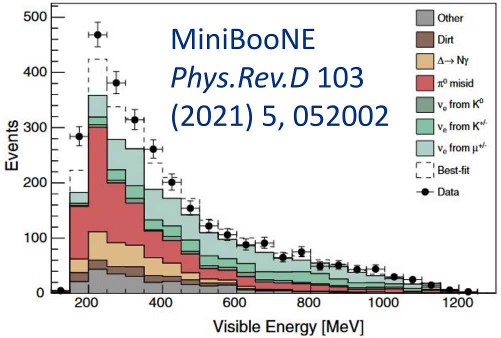
Accelerator experiment anomalies: ν_e excess in a ν_μ beam





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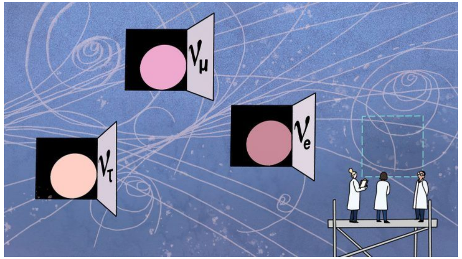

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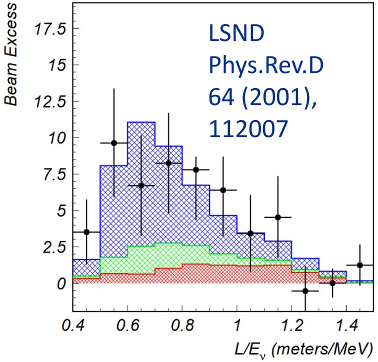
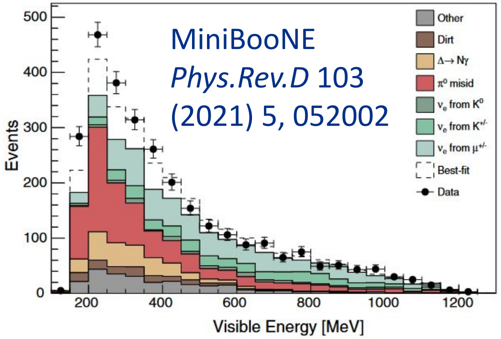
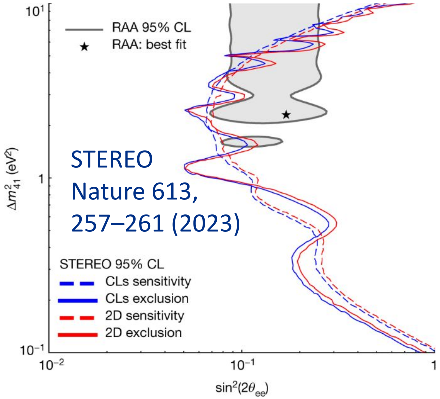
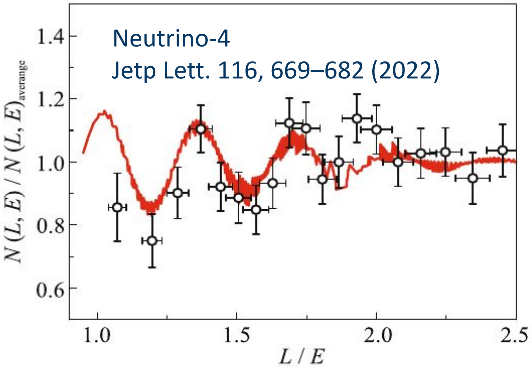




Reactor experiments: ν_e disappearance at O(10m) from the core





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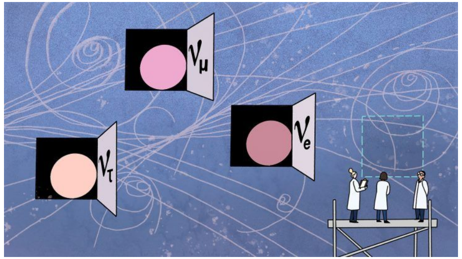

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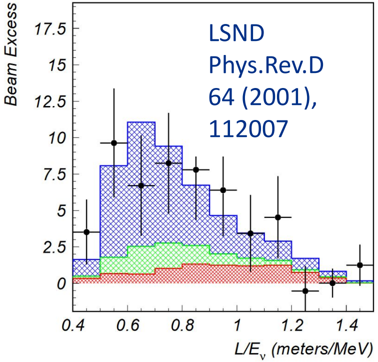

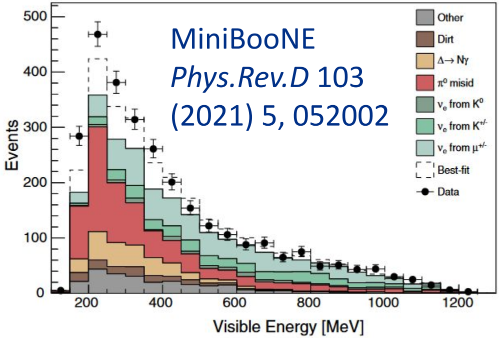

IceCube

Phys.Rev.Lett. 125 (2020) 14, 141801

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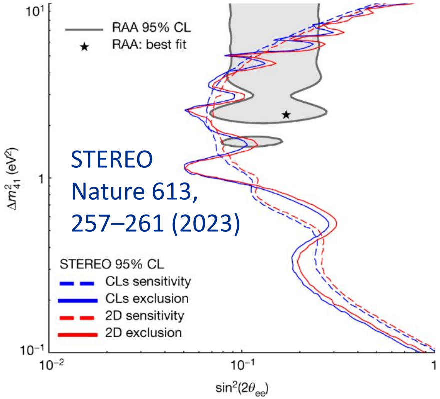

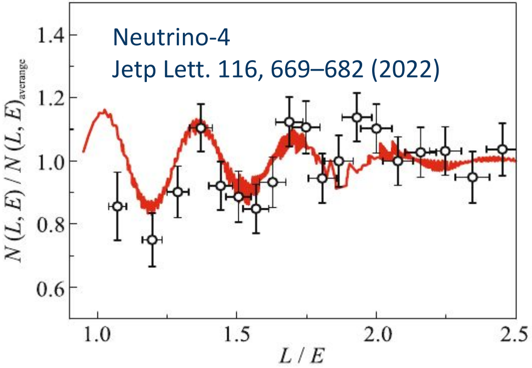

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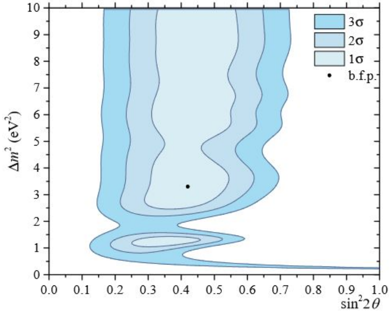
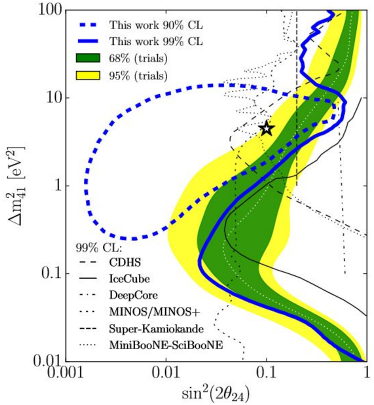
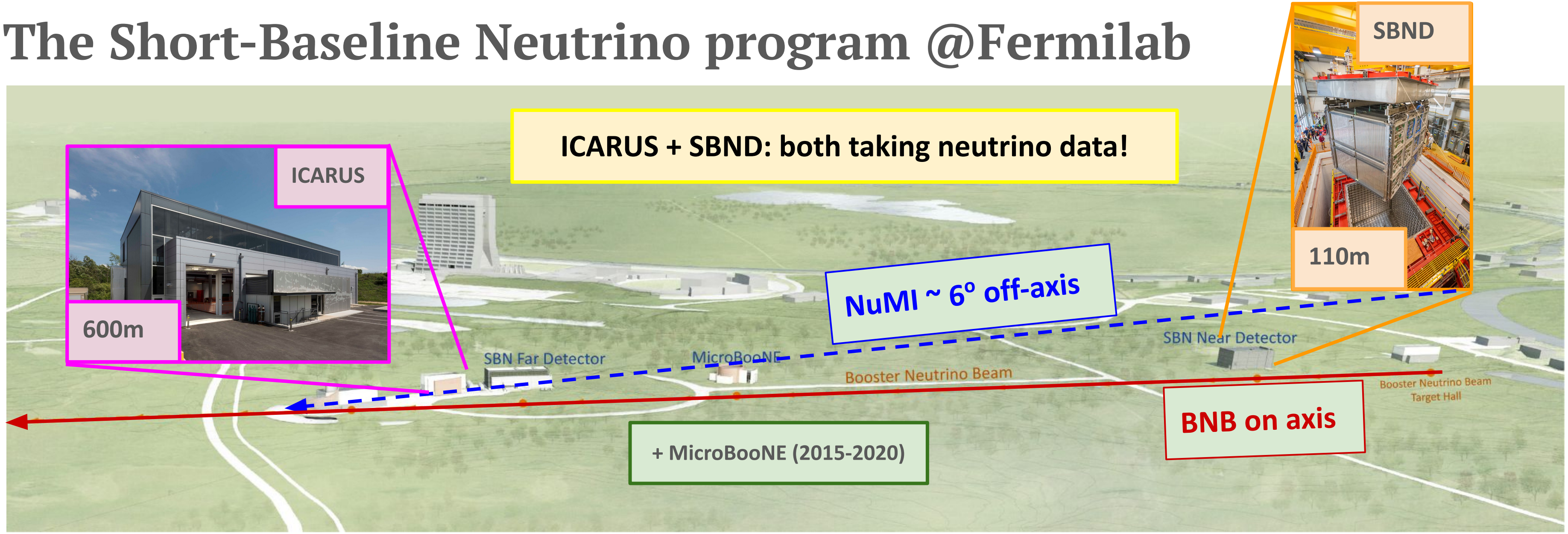
Phys.Rev.Lett. 128 (2022) 23, 232501





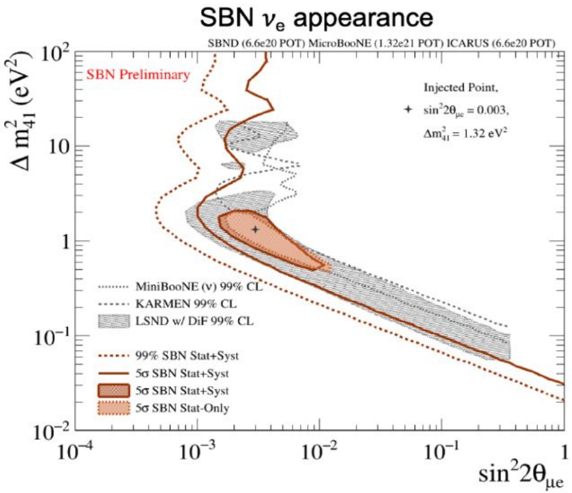
The Short-Baseline Neutrino program @Fermilab

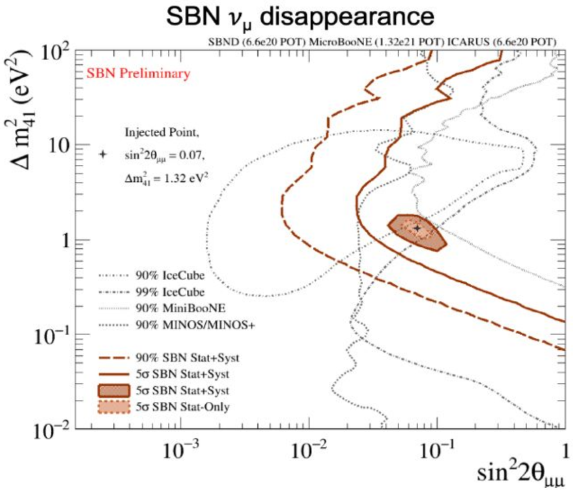


- ICARUS and SBND Liquid Argon Time Projection Chambers: same technology to minimize beam, background and detectors systematics.
- Two ν_μ beams: Booster Neutrino Beam (**BNB, E_ν ~ 0.8 GeV**) and (ICARUS only) Neutrino at the Main Injector (**NuMI, E_ν ~ 2 GeV**).
- Sensitive search of ν_e appearance and ν_μ disappearance to definitively clarify the sterile neutrino puzzle.
- ICARUS goals: first ν_μ disappearance analysis with BNB data; neutrino-Argon cross sections with NuMI data; Beyond Standard Model (BSM) searches with NuMI data.

The Short-Baseline Neutrino program

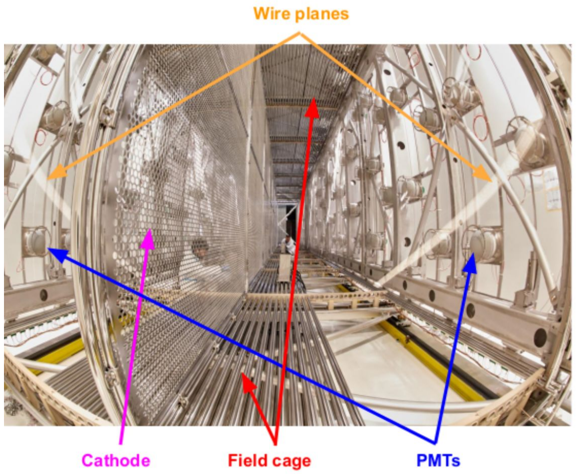
The combined analysis of near and far detector grants the unique capability to study appearance and disappearance channels simultaneously!

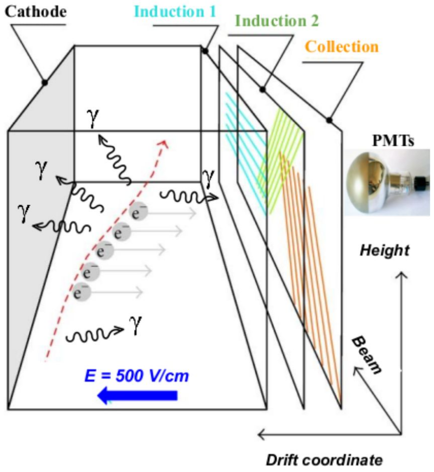




5σ sensitivity to LSND anomaly in three years of data taking - reactor and gallium anomalies will be also probed.

Why… ICARUS?





- Liquid Argon Time Projection Chambers (LArTPCs) [C. Rubbia, 1977]: high granularity, continuously sensitive, self-triggering detectors - 3D imaging, topological and calorimetric reconstruction: ideal for ν physics!

- ICARUS T600: first large scale LArTPC - 760 tons of pure LAr, 470 tons active mass.

- 2 Cryostats (~300 m^3) × 2 TPCs, each with common central cathode, 1.5 m drift.
- Three read-out wire planes per TPC (0^o, $\pm 60^o$), 3 mm pitch.
- 360 - 8” Photo-Multiplier Tubes for scintillation light detection (trigger and timing).
- 2.85 m (~ 6 m.w.e.) concrete overburden + 4π Cosmic Ray Tagger (CRT to suppress and tag cosmics.

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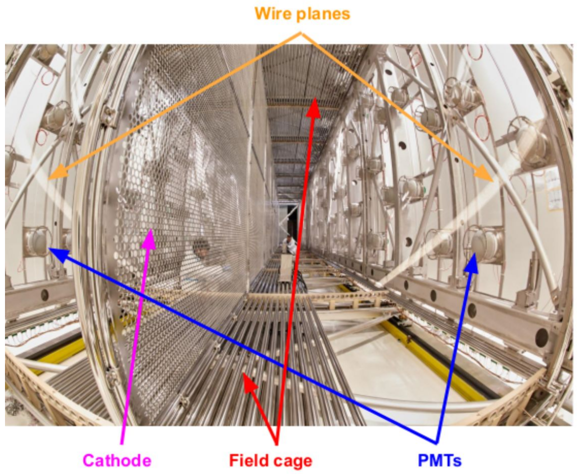

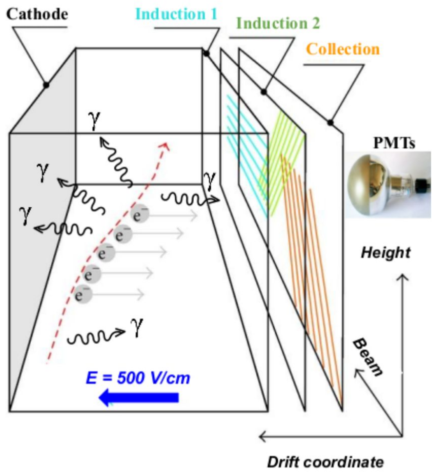

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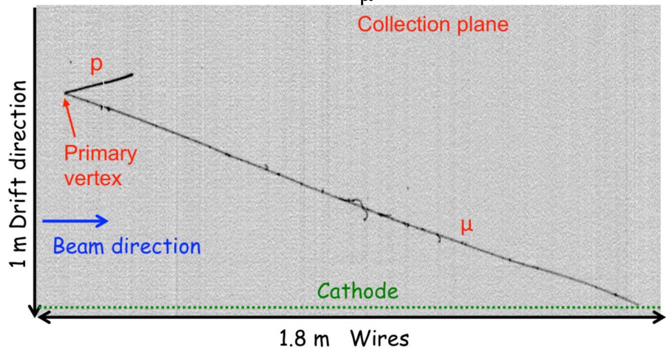
BNB QE ν_μ CC event



Eur. Phys. J. C 83:467 (2023)

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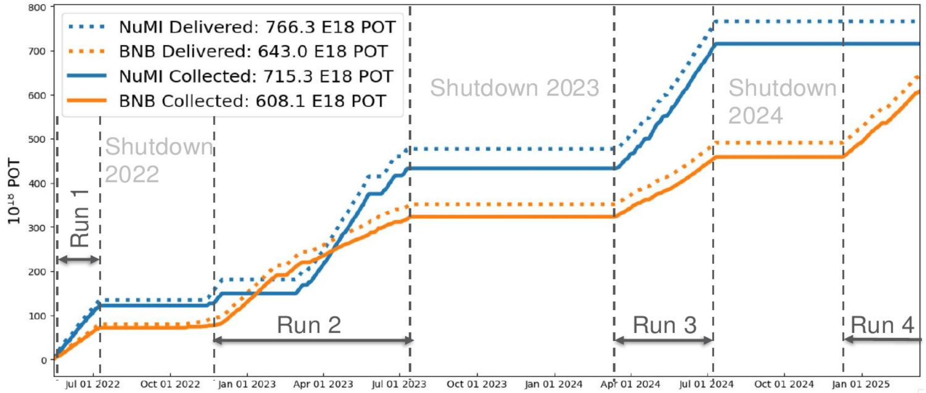
Successful three-year physics run at LNGS (2010-2012) → Intensive overhaul at CERN (2014-2017) → Installation at FNAL completed in 2021 → Commissioning → taking data for physics since June 2022.

ICARUS operations and data collection @FNAL

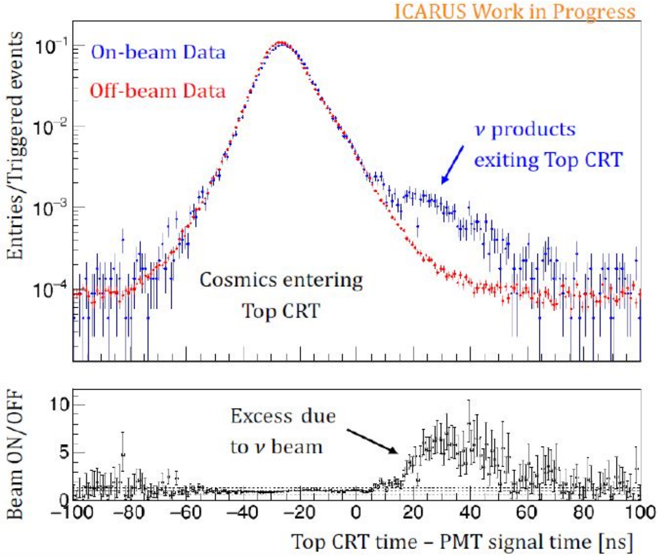
- ICARUS data taking for physics started in June 2022 with TPC, PMT and CRT systems fully operational.
- Three physics runs completed since then + fourth run ongoing since December 2024.
- Steady data taking with excellent stability at BNB rates > 4Hz, >90% live time.
- Free electron lifetime $\tau_e \approx$ 7-8 ms $\rightarrow$ full track detection efficiency in the 1.5 m drift.
- Trigger: light signal registered by 4 PMT pairs in a 6 m detector slice in coincidence with BNB (1.6 μs), NuMI (9.5 μs) beam spills.

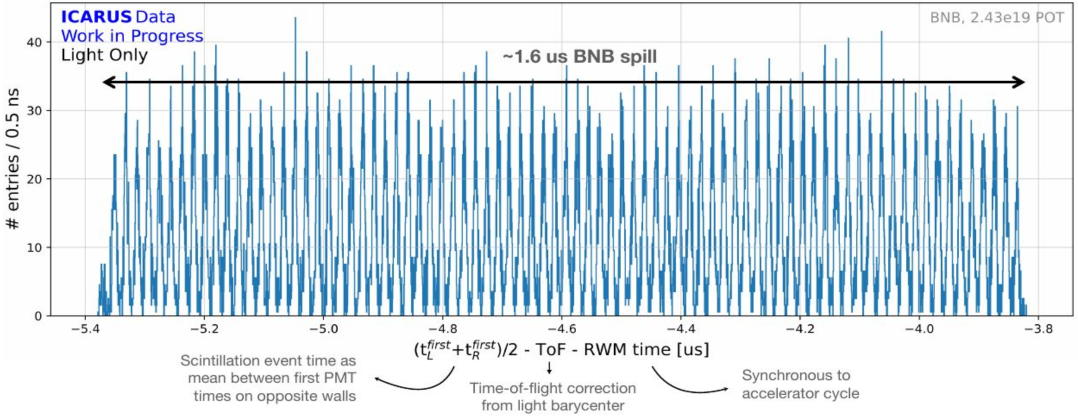


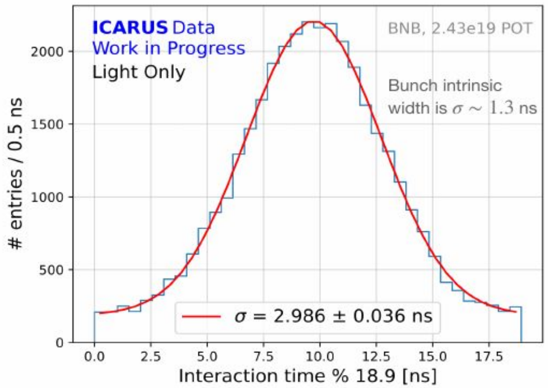
Collected POT	BNB FHC (pos. focusing)	NuMI FHC (pos. focusing)	NuMI RHC (neg. focusing)
Run1 (Jun – Jul 22)	$0.41 \cdot 10^{20}$	$0.68 \cdot 10^{20}$	-
Run2 (Dec 22 – Jul 23)	$2.06 \cdot 10^{20}$	$2.74 \cdot 10^{20}$	-
Run3 (Mar – Jul 24)	$1.36 \cdot 10^{20}$	-	$2.82 \cdot 10^{20}$
Run4 (Dec 24 – ongoing)	$1.37 \cdot 10^{20}$	-	-
Total	$5.19 \cdot 10^{20}$	$3.42 \cdot 10^{20}$	$2.82 \cdot 10^{20}$

ICARUS performance: timing

- Rejection of incoming cosmic rays by means of time-of-flight between the external CRT and the inner PMT system.
- Reconstruction of BNB and NuMI beam bunch structures: neutrino event time (PMTs only) with respect to the proton beam extraction time (RWM counters) after rejecting incoming cosmics (CRT) and correcting for neutrino flight distance.



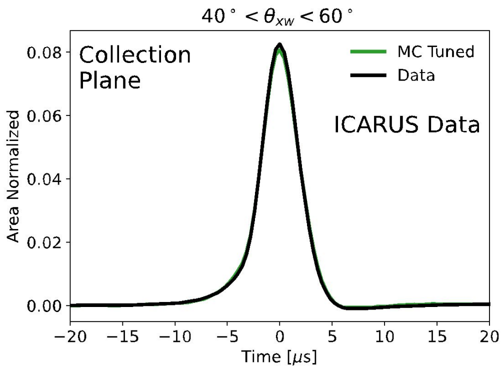




ICARUS performance: calibration

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

Average signal response per plane (Data/tuned MC) in a track angular bin

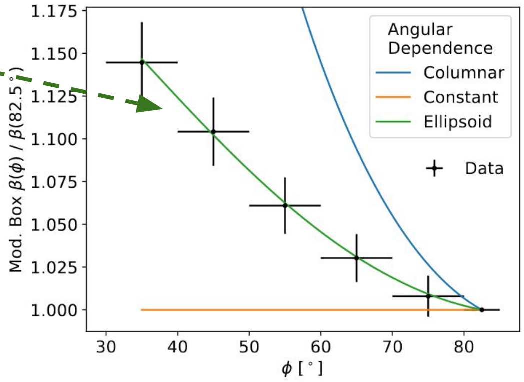


JINST 20 P01032 (2025)

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

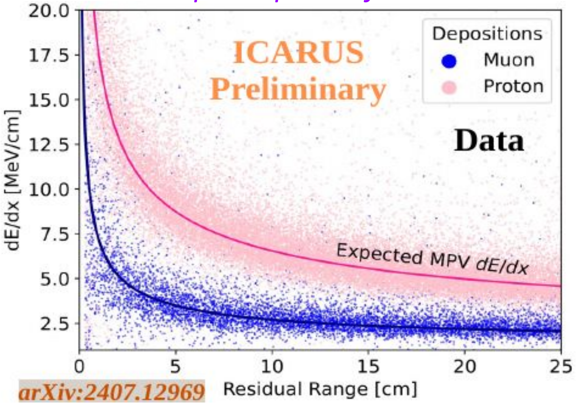
$$\frac{dx}{dQ} = \frac{1}{G}\,\frac{\log\left(\alpha+\beta(\phi)\frac{dE}{dx}\right)}{\beta(\phi)W_{ion}}$$

Angular dependence of recombination β parameter



JINST 20 P01033 (2025)

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



ICARUS physics program

- Before the start of joint analysis with the Near Detector SBND, ICARUS is facing a standalone physics program:

- *Blinding policy* defined to ensure robust and unbiased interpretation of the collected data: analysis are validated using sidebands, a subset of the full dataset and variables insensitive to oscillations

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→ BNB ν_μ event selection ready and validated

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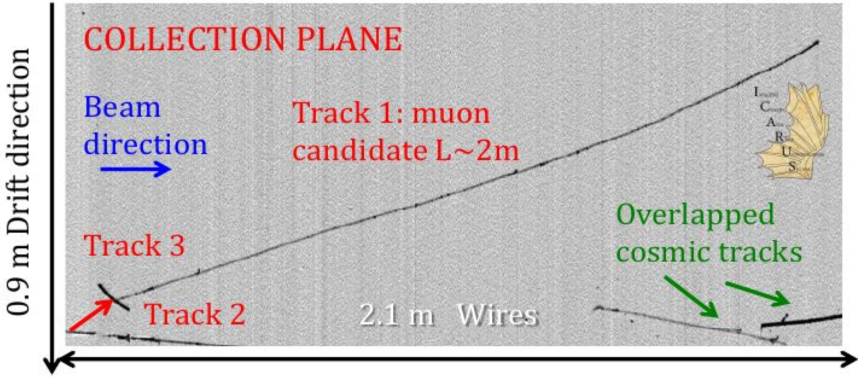
- Search for sub-GeV Beyond the Standard Model (BSM) Physics with the NuMI beam
  → Signal box opened for μμ decay channel

ν_μ Event selection for disappearance with BNB

*Study of Fully Contained ν_μ CC Events (**1μNp**)*

- Event Selection Criteria:
  - TPC track linked with PMT light and no CRT signal within beam spill window.
  - Muon track with length $L_\mu > 50$ cm.
  - At least 1 proton with $L_p > 2.3$ cm (corresponding to $E_k > 50$ MeV)
  - Particles correctly identified by PID tool (based on dE/dx).
  - Events contain fully contained particles (no additional π or γ).



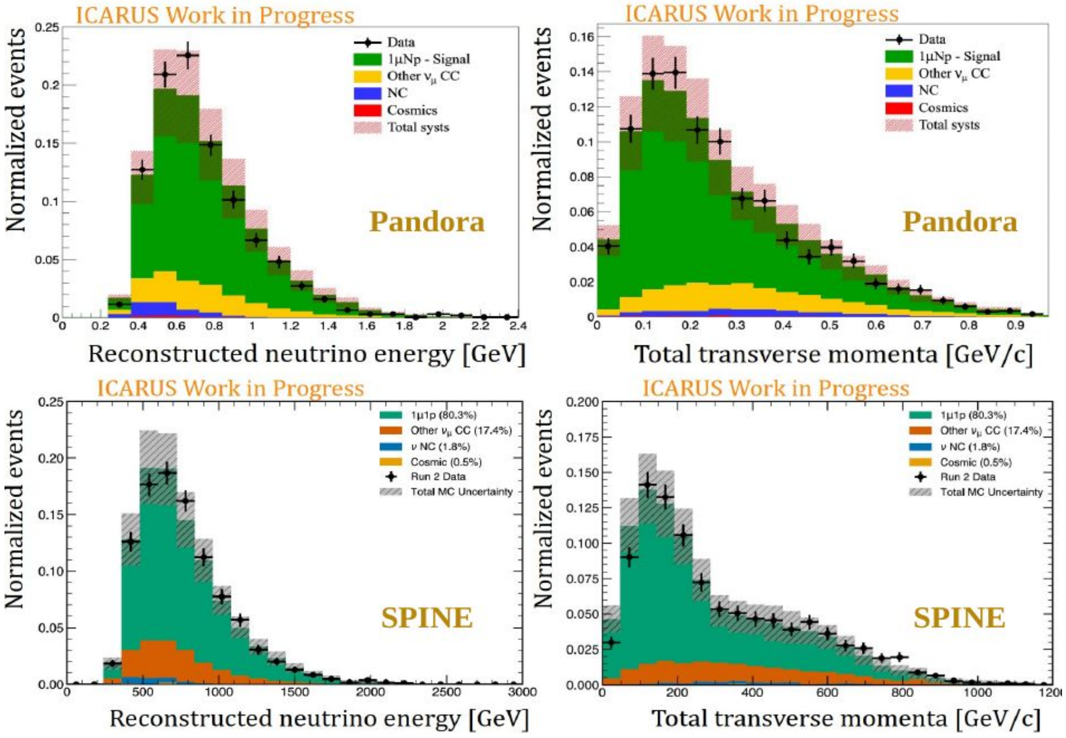
- The event kinematics is obtained by range measurements.
- Residual cosmic background < 1%.
- Flux, cross section and detector systematics are evaluated comparing calibrated vs uncalibrated MC samples:

flux / cross section / detector ~ 10% / 15% / 15%

- Improved simulations → reduce detector sistematics.
- Joint SBN analysis → cancellation of cross section and flux uncertainties and common detector systematics.

1μNp analysis: first results at BNB

- 10% of RUN-2 data analyzed: ~$2 \cdot 10^{19}$ (**20x more data available from RUN2**), showing Data-MC agreement within systematics.



Two independent reconstruction approaches:

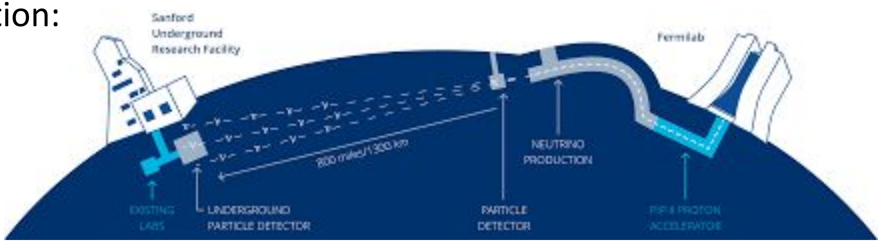
- Pandora: pattern recognition algorithm.
- SPINE: Machine Learning-based reconstruction.

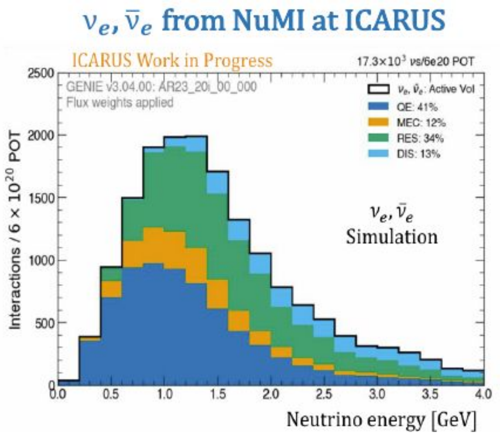
Ongoing:

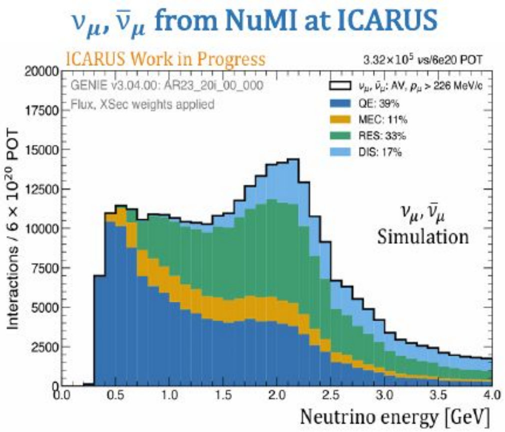
- increase the studied data sample.
- dataset unblind foreseen soon.

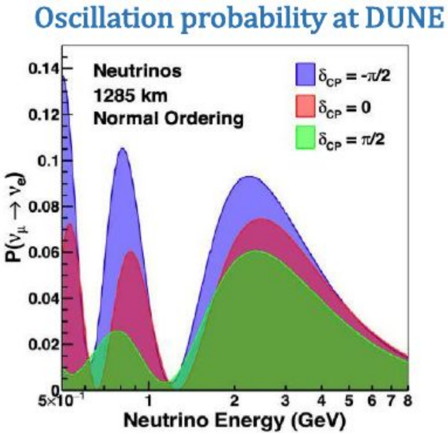
Neutrino cross-section measurements with NuMI

- **High statistics from NuMI** beam to measure ν-Ar cross section: 332k ν_μCC and 17k ν_eCC interactions in $6 \cdot 10^{20}$ POT.
- Current available data ~ $3.42 \cdot 10^{20}$ POT.
- Neutrino energy spectrum from NuMI covers the few hundred MeV to few GeV energy range relevant for DUNE experiment.



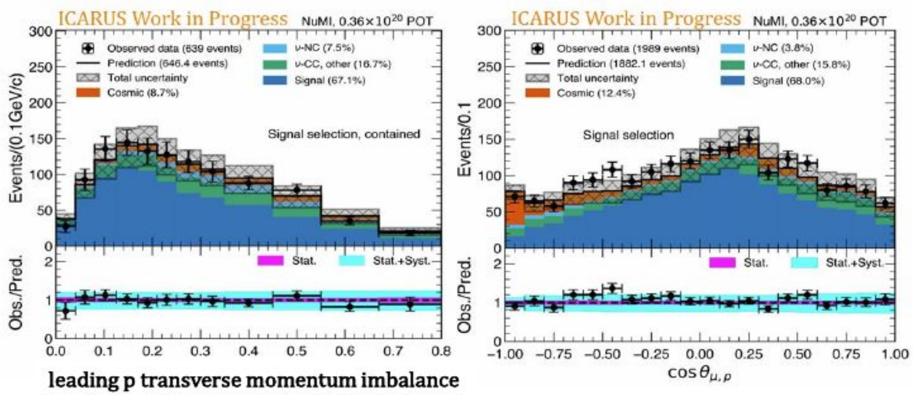






Neutrino CC 0π cross section analysis results

- First analysis targets 1μ Np 0π events:
  - Signal definition: 1μ with p_{μ} > 0.226 GeV/c + at least 1 proton with 0.4 < p_{μ} < 1 GeV/c, no $\pi^{\pm}$ or π^{0} in the final state.
  - Flux, interaction model and detector systematics have been included.
  - Angles and transverse kinematics observables are expected to encode to Initial and Final State effects



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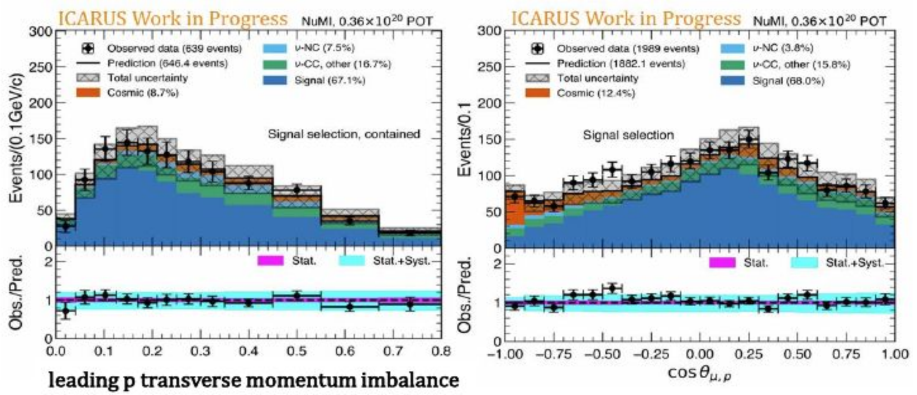
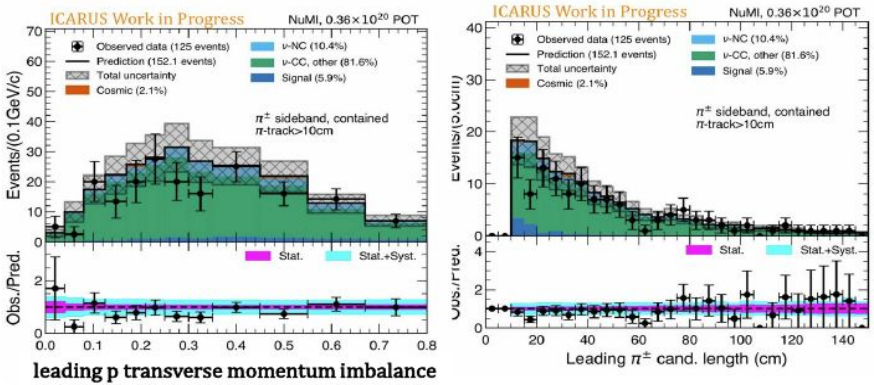


- Major background are events with undetected/misidentified pions:
  - Event control sample with $\pi^\pm$ candidates has been selected to characterize this background (requiring secondary μ-like track): good agreement between 15% data/MC.



- Results for the full dataset in mid 2025.

BSM searches with NuMI

- Models involving dark particles coupling to Standard Model particles through Scalar Portal Interactions:

    - **Higgs Portal Scalar (HPS)** → scalar dark sector particles, undergo mixing with Higgs boson
    - **Heavy QCD axion (ALP)** → Pseudoscalar particles, undergo mixing with pseudoscalar mesons

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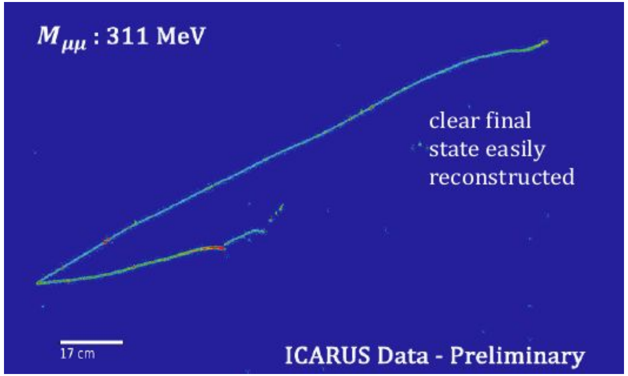

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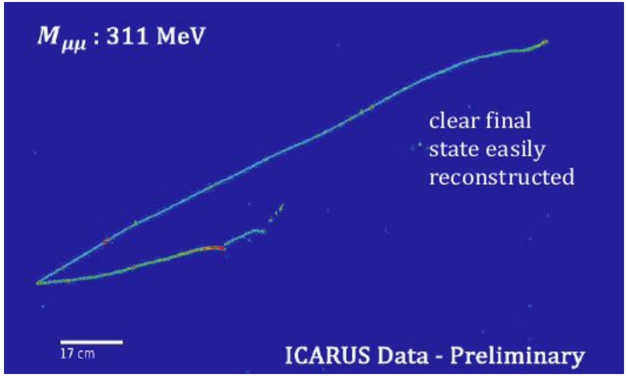
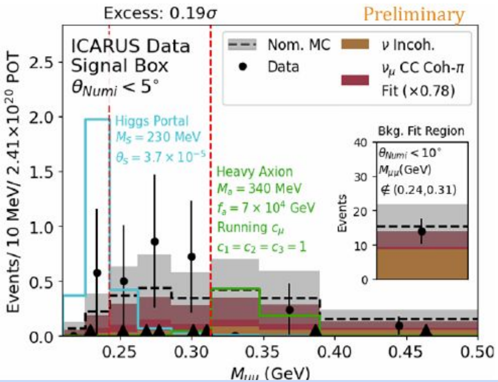
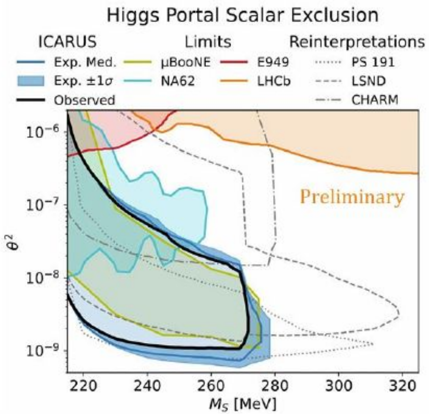
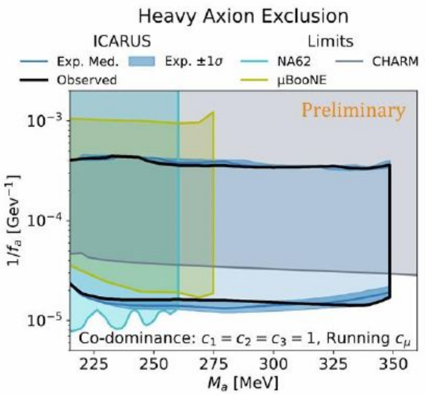
- Scalar Decays in $\mu^+\mu^-$ with RUN2 NuMI. Results:
  - Scalar mass $M_{\mu\mu}$ peak reconstructed using two stopping muons; signal expected at small angle w.r.t. beam direction $\theta_s < 5°$
  - 9 candidate events found, matching MC background expectation of 8 events (from $\nu\mu$ CC coherent pion production). Results show no significant new physics signal (0.19 σ).





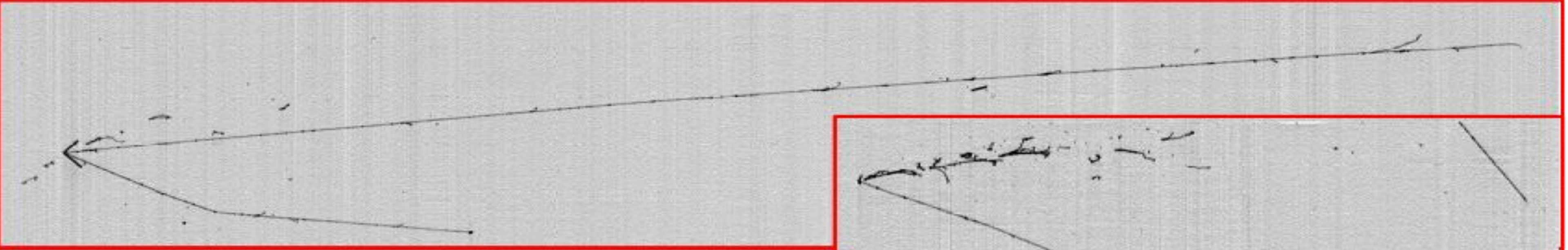
arXiv:2411.02727
(accepted by PRL)

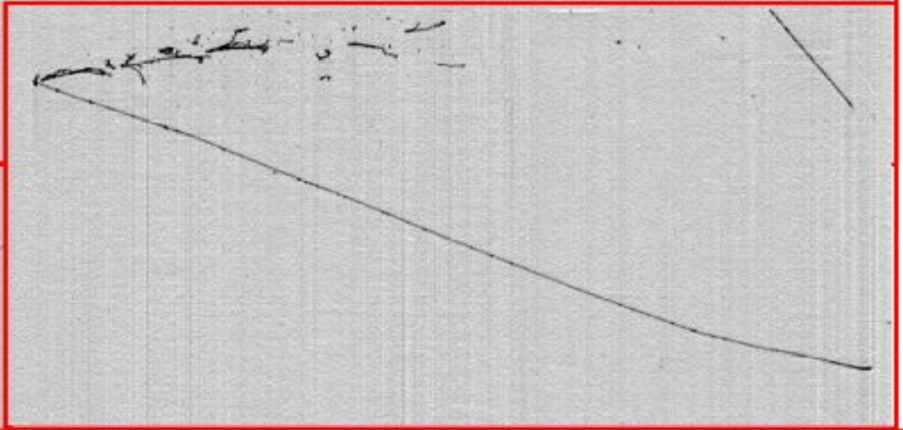




Conclusions

- ICARUS is smoothly running in Physics mode since June 2022, exposed to BNB and NuMI beams.
- The detector response is calibrated with cosmic muons and protons from neutrino interactions; TPC signals and main detector parameters have been accurately characterized and modeled in the simulation.
- Before the start of the joint operation within SBN, ICARUS only is carrying on several analysis:
  - Study of ν_μ disappearance with BNB → ready to enlarge the control samples and evaluate the systematics.
  - ν-Ar cross section measurements with NuMI → ready to study the sidebands with the full statistics available
  - Search for sub-GeV dark matter candidates with NuMI → completed analysis on scalar decays in $\mu^+\mu^-$
- Interesting results are expected soon as ν_e analysis on BNB and NuMI data is starting.
- ICARUS-only analyses with BNB and NuMI data are fundamental to study the analysis performance and the systematics before the joint analysis with SBND starts!
- In 2024 SBND data taking began too → full SBN program ready to definitively clarify the sterile neutrino puzzle!





Thank you !