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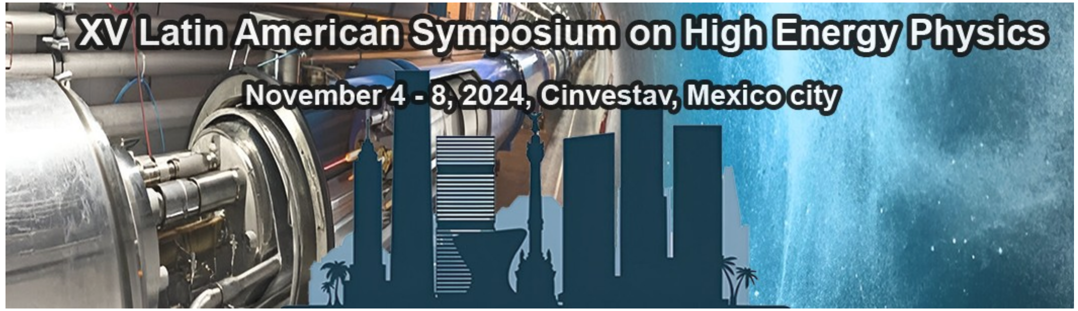


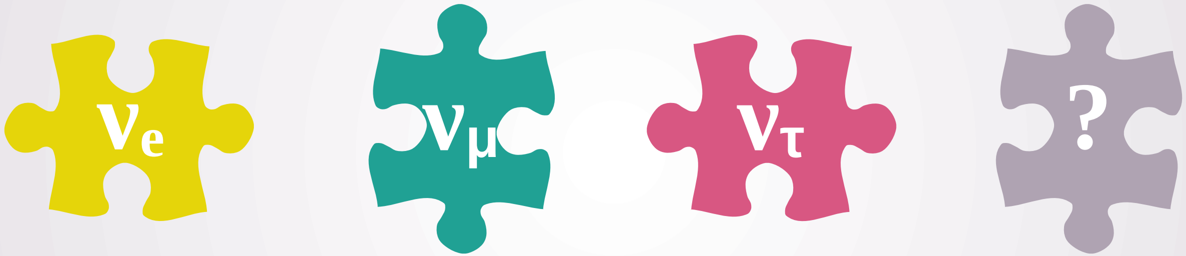
ICARUS at the Short-Baseline Neutrino program: First Results

Guadalupe Moreno Granados
Center for Neutrino Physics, Virginia Tech
On behalf of the ICARUS collaboration

XV Latin American Symposium on High Energy Physics (SILAFAE)
November 8^{th}, 2024

Outline

- The Sterile Neutrino Puzzle
- The SBN Program
- The ICARUS Detector
- ICARUS Physics Program
- Summary and Future



THE STERILE ν PUZZLE

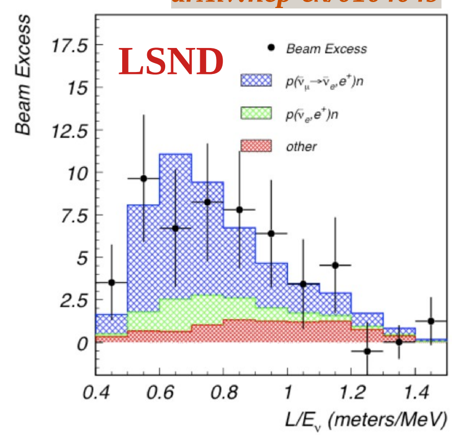
See Pedro Ochoa's talk!

The Sterile Neutrino Puzzle

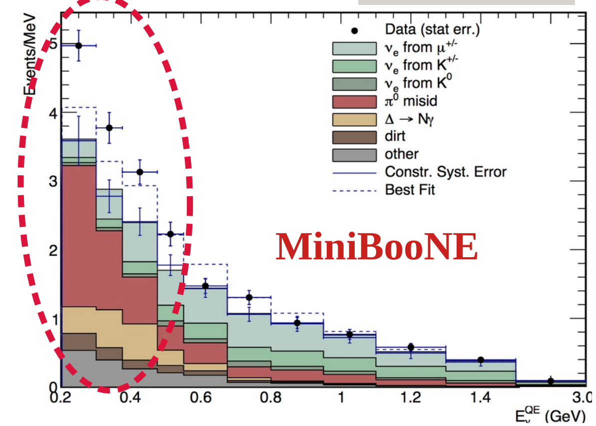
Though **the 3νSM model matches well many experiments, some anomalies have been observed in neutrino experiments at short baseline** hinting to a new sterile neutrino flavor at $\Delta m^2_{new} \sim 1$ eV^2:

- ***Accelerator Experiments***
  - LSND: Observed excess of $\bar{\nu}_e$ events
  - MiniBooNE: Electron-like excess observed in both ν and $\bar{\nu}$ modes.

arXiv:hep-ex/0104049



arXiv:2006.16883



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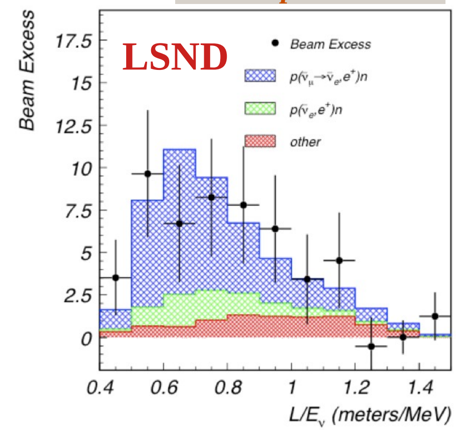

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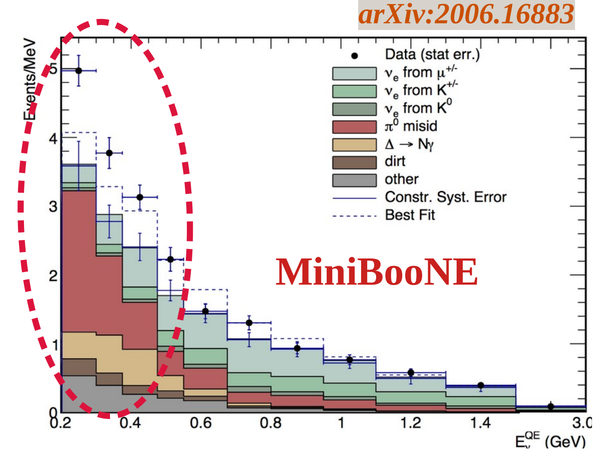
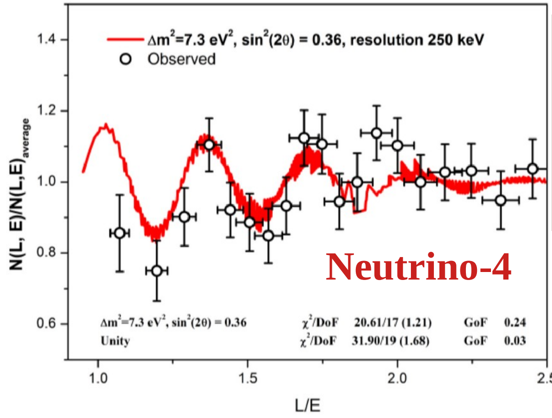


- ***Radiochemical Experiments***
  - SAGE, GALLEX, and BEST.

- ***Reactor Experiments***
  - Neutrino-4



arXiv:2302.09958

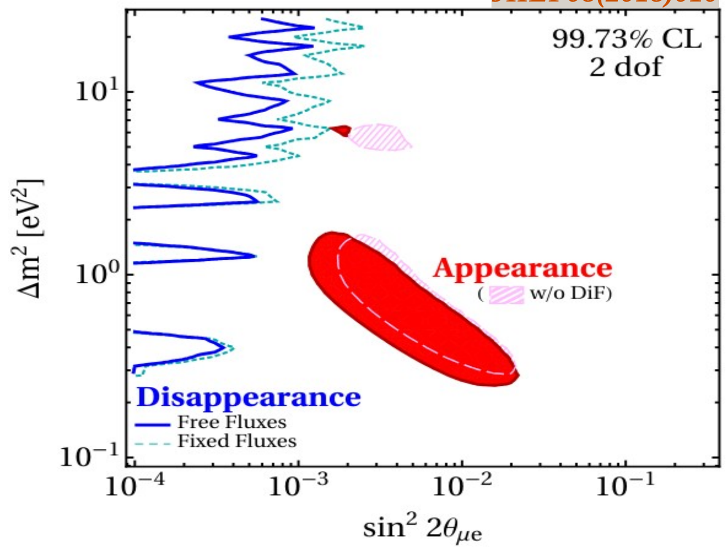
Combined analysis of Neutrino-4 with other experiments results in a best fit of ***Δm^2_{14}= 7.3 eV² and sin²(2θ₁₄)=0.36 at 5.8 σ***

The Sterile Neutrino Puzzle

Several experiments at reactors and accelerators, including the recent MicroBooNE result (arXiv:2210.10216), have been studied the 'neutrino anomalies.'

However, there remains a ***clear tension between appearance and disappearance*** experiments, ***which differ in both the neutrino energy ranges they explore and the detection techniques they use***.

JHEP08(2018)010



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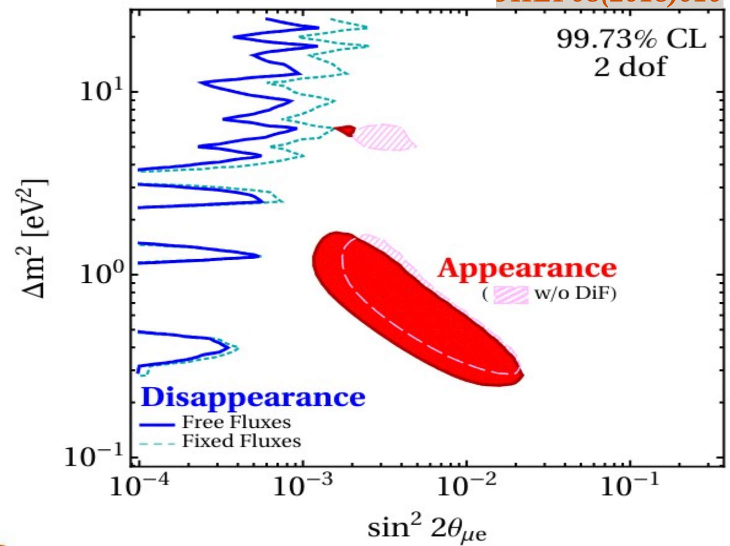
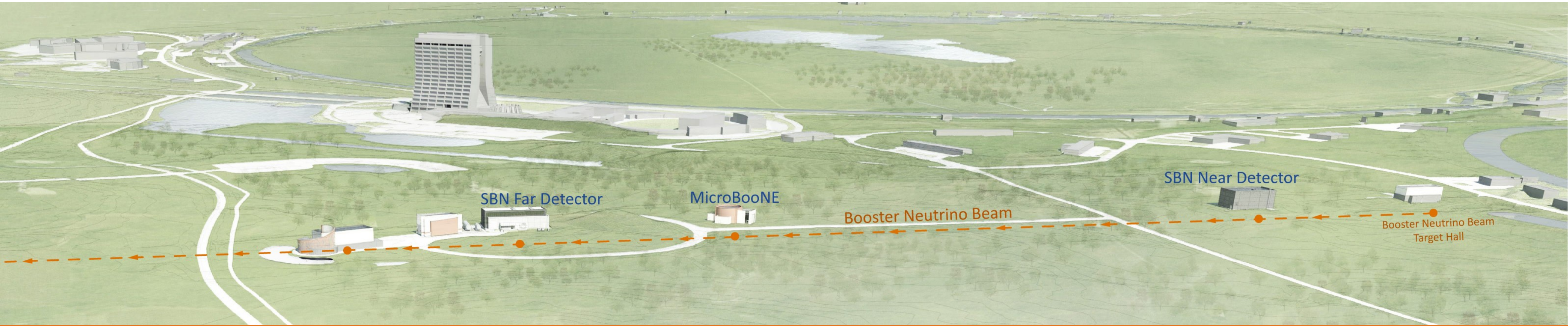


Untangling the current experimental scenario requires:

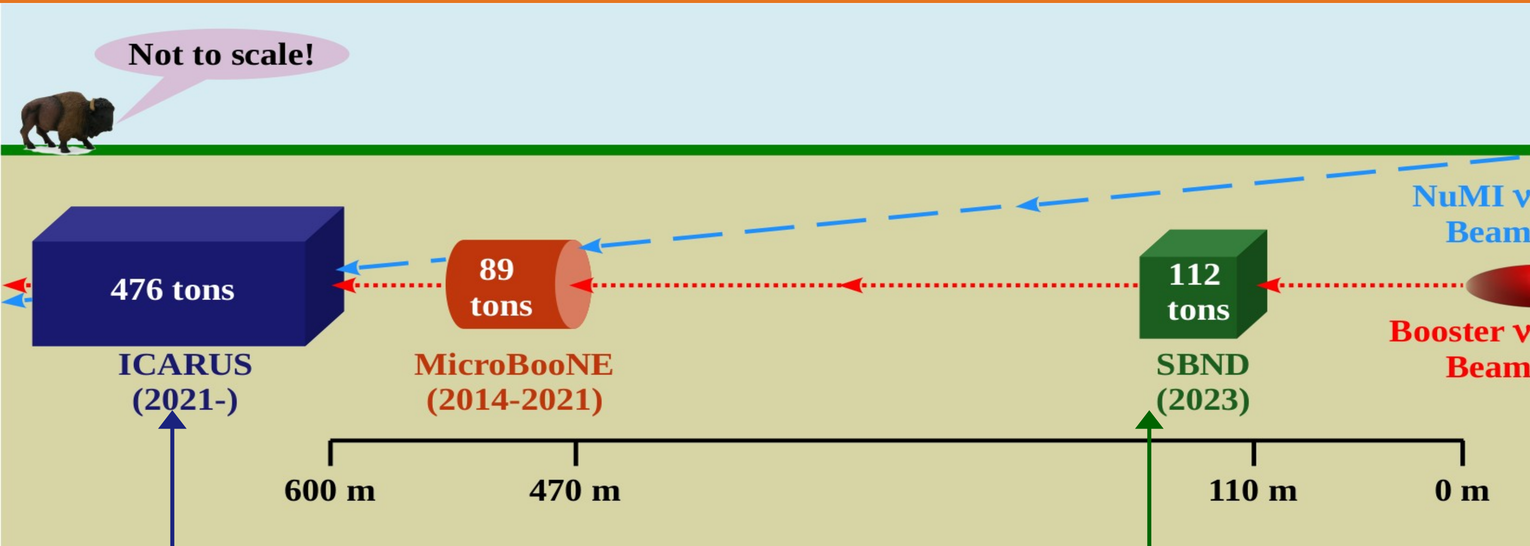
- ***Measure both appearance and disappearance channels in the same experiment***, using a detector that can precisely identify neutrinos and reject background.
- ***Compare Far and Near detector neutrino spectra*** to control systematic uncertainties.

SBN Program



THE SBN PROGRAM

The Short-Baseline Neutrino Program



Near and Far **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber (**LArTPC**) detectors at different baselines from the **B**ooster **N**eutrino **B**eam (**BNB**) at Fermilab.

The **Far Detector** measures the oscillated neutrino spectrum.
It's taking ν data

The **Near Detector** provides constraints on flux and ν-Ar cross sections.
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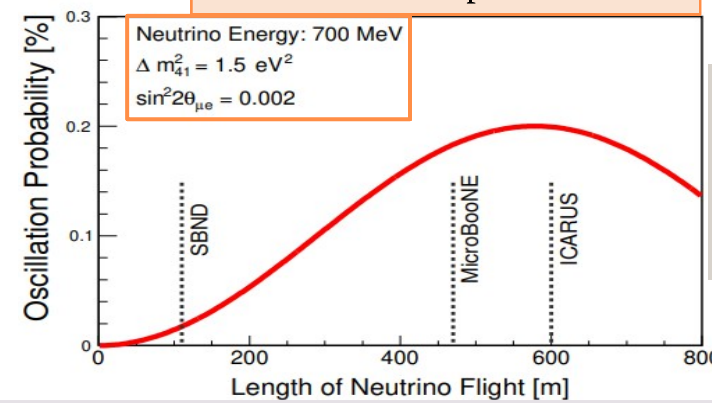
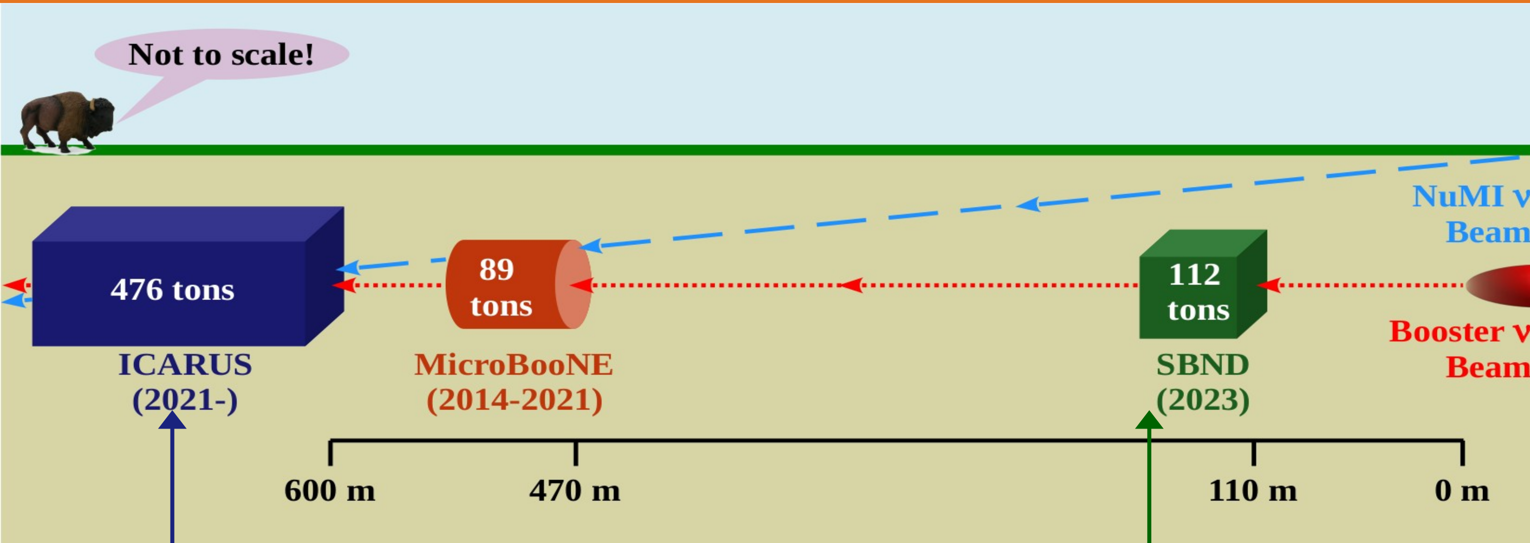
Possible oscillation signature under a set of parameters.



arXiv:1903.04608

The Short-Baseline Neutrino Program



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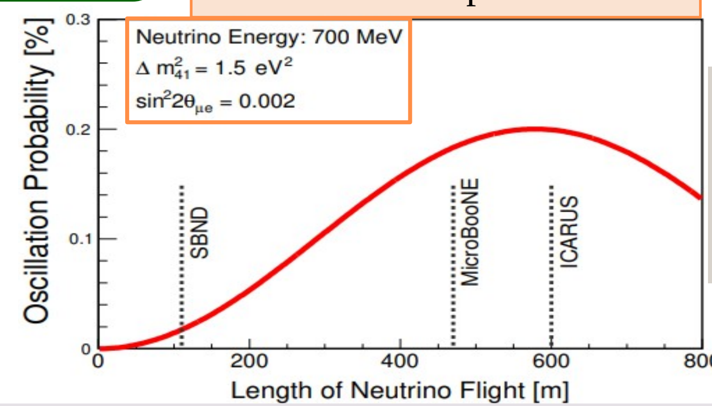
It's taking ν data

- SBN has been designed to ***address the sterile neutrino interpretation*** of the experimental at short-baseline anomalies.
- The SBN physics program includes ***the study of ν–Ar cross sections with unprecedented precision.***
- The high sensitivity leads to ***invaluable opportunities for New Physics searches.***

Possible oscillation signature under a set of parameters.



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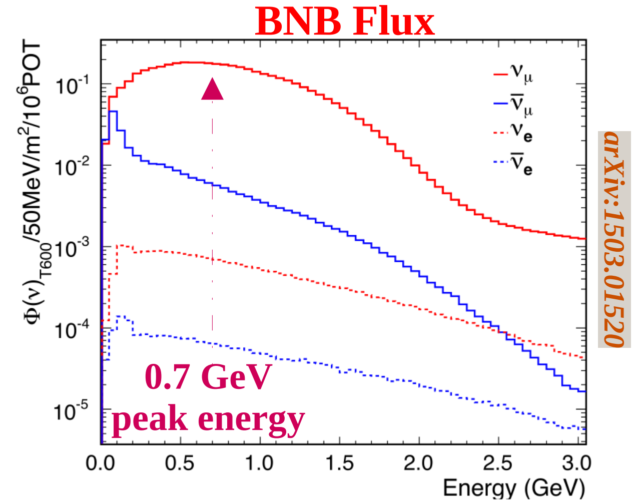
The Short-Baseline Neutrino Program

The **BNB** is a well-characterized **ν_μ ($\bar{\nu}_\mu$) - beam**, with minimal ν_e contamination.



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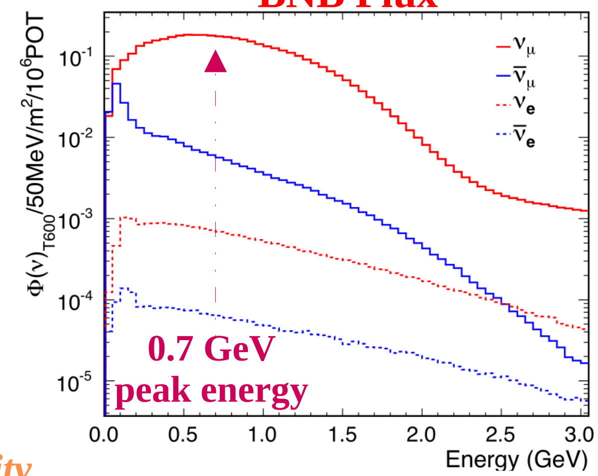
A **combined analysis** of events collected by **Far Detector** and Near Detector over 3 years (6.6×10^{20} POT) will allow:

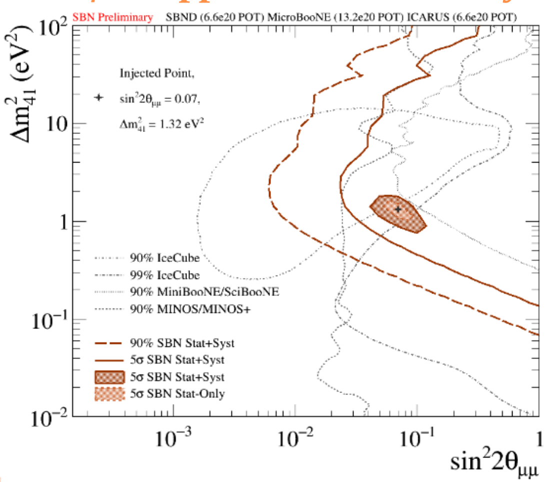
- 5σ coverage of the parameter space *relevant to the accelerator anomaly*
- Prove of the parameter space associated with reactor and radiochemical anomalies

BNB Flux

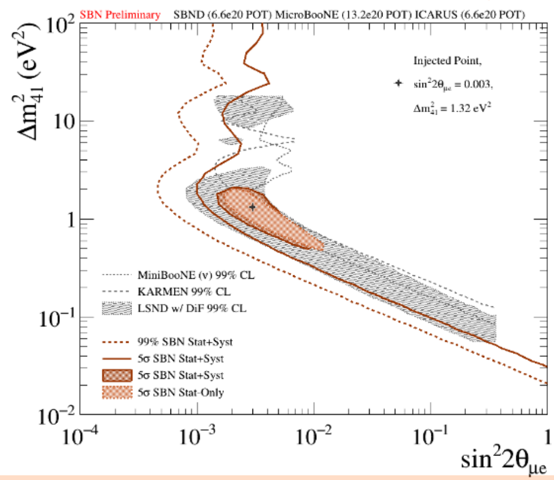


arXiv:1503.01520

ν_μ disappearance sensitivity



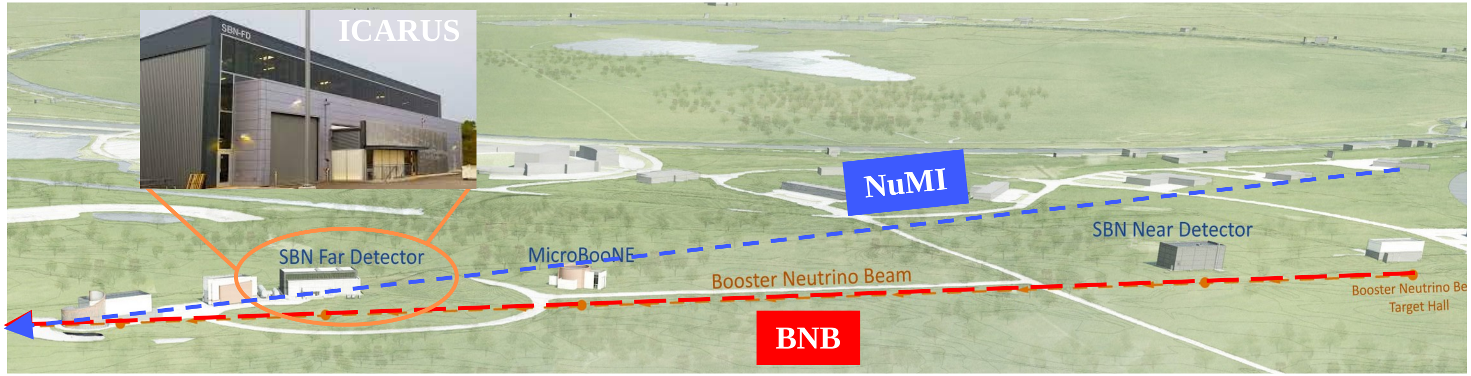
ν_e appearance sensitivity



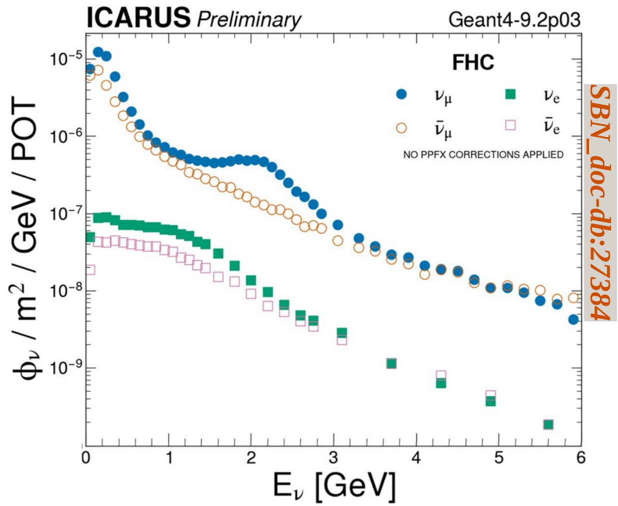
A ***unique capability to simultaneously study both ν appearance and disappearance*** sensitivities.

Exclusive ICARUS Physics Program

The Far Detector, ***ICARUS*, *is also located ~6° off-axis to the NuMI beam,*** allowing it to access the ν_e-rich portion of the spectrum.



NuMI Flux



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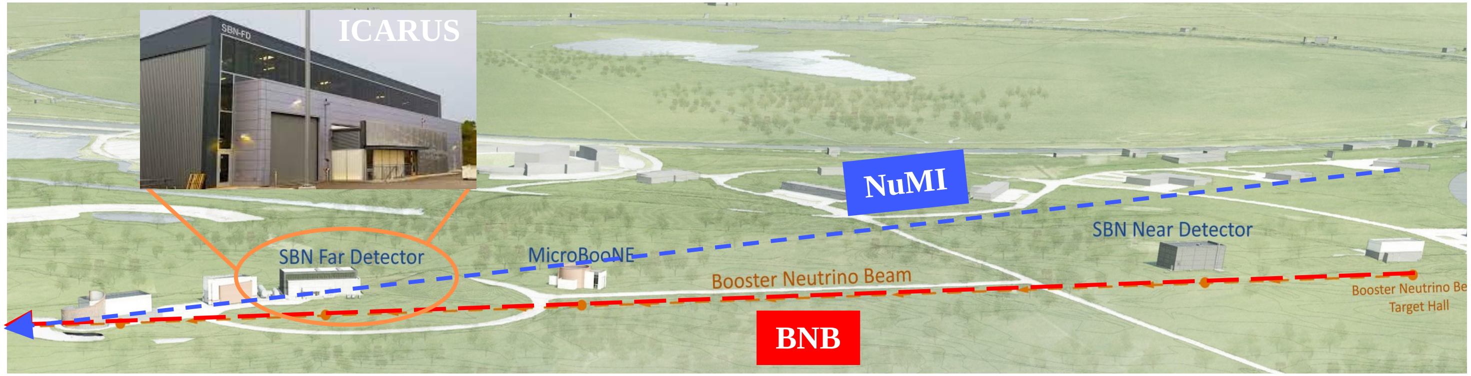
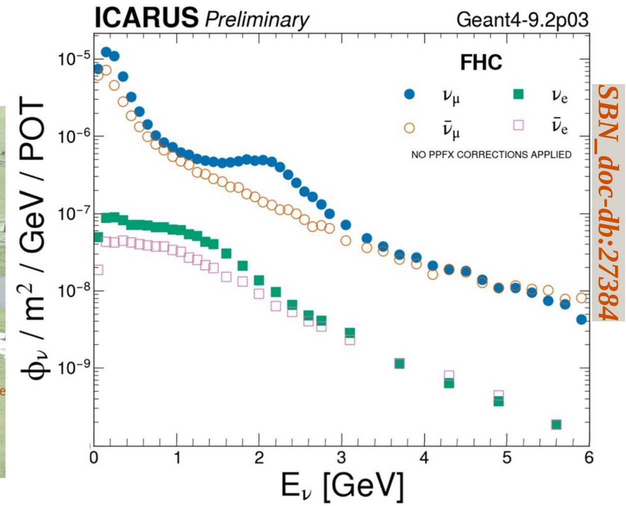


NuMI Flux



Before starting joint analysis with the Near Detector, ***ICARUS is pursuing its own physics program, which includes***:

- Searching for ***ν_μ disappearance using the BNB beam***, followed by searches for ν_e disappearance with the off-axis NuMI beam.
- Measuring ***ν-Ar cross sections*** with hight statistics (***332k ν_μ CC and 17k ν_e CC interactions*** in 6×10^{20} POT) and improving reconstruction and identification techniques ***with the NuMI beam***, focusing on the energy ***range relevant to DUNE***.
- Searching for sub-GeV Beyond the Standard Model ***(BSM) physics using the NuMI beam***.

THE ICARUS DETECTOR

The ICARUS Detector

The first ***LAr TPC*** was proposed by C. Rubbia in 1977.

These detectors ***are high-granularity, uniform, and self-triggering, with 3D imaging and calorimetric*** capabilities, making them ideal for neutrino physics.

ICARUS operated at LNGS and refurbished at CERN

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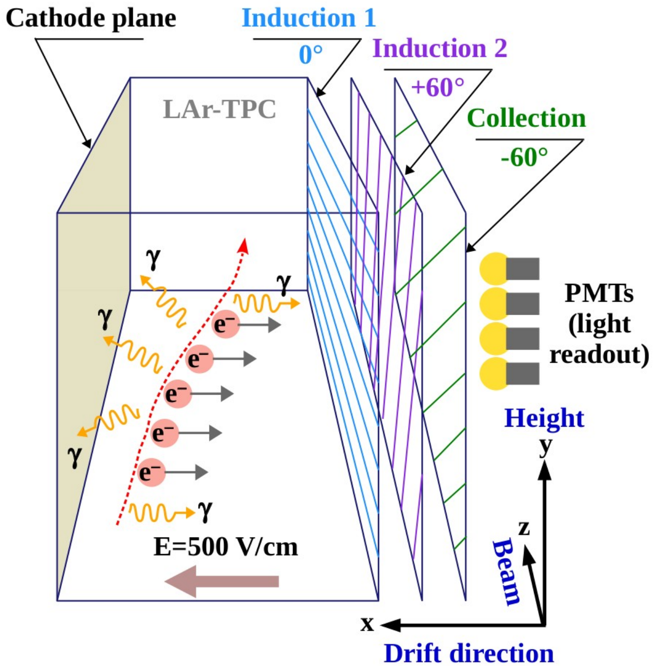

ICARUS operated at LNGS and refurbished at CERN

How LArTPCs work

- The ***ν-Ar interactions produce tracks, with ions and photons along those***.
- ***Photons propagate inside the detector*** [the scintillation light is collected by the photomultiplier tubes (PMTs) for precise event timing and event calorimetry].
- ***The ionized electrons will slowly drift towards the anode*** by an applied electric field.
- ***The ionized electrons produce induction signals*** as they pass the first two wire planes and are collected on the last wire plane.

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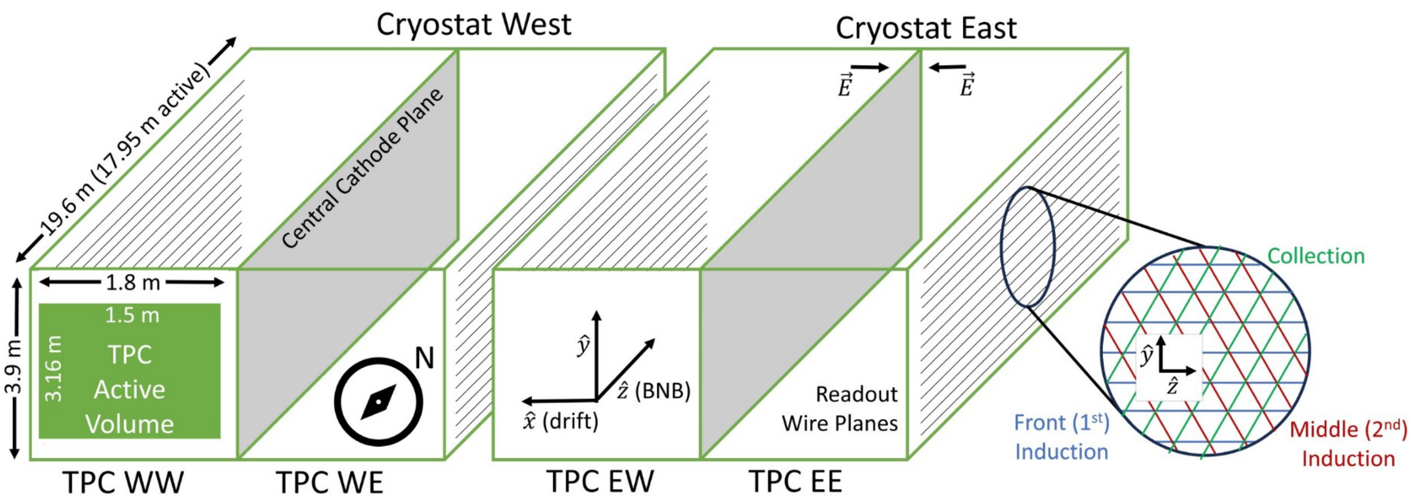
The ICARUS Detector

- ***2 identical cryostats*** with 2 TPCs per cryo with central cathode.
- ***500 V/cm Ē field*** in 1.5 m drift lengths.
- ***3 readout wire planes per anode***, oriented at 0° and ±60° w.r.t. horizontal.

ICARUS operated at LNGS and refurbished at CERN



The ICARUS Detector Subsystems

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

Time Projection Chambers (TPC)

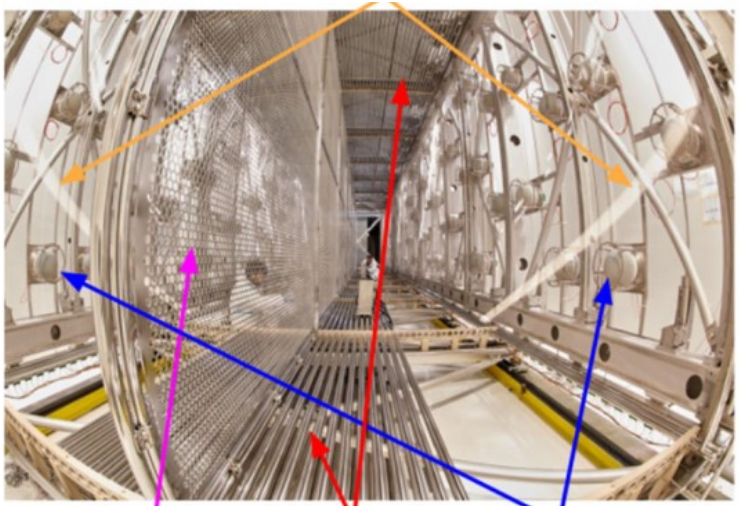
- ~54k channels at different orientations and 3 mm pitch.

Photon Detection System (PDS)

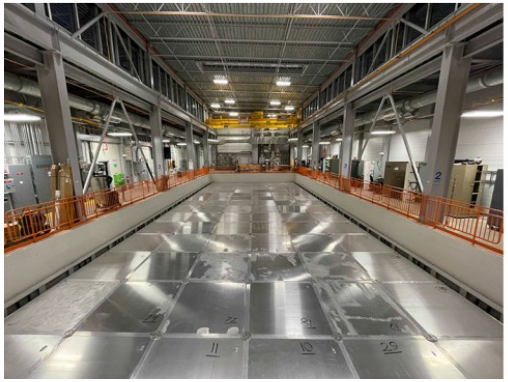
- 360 TPB-coated PMTs to detect scintillation light.
- Used for event timing and triggering.

Cosmic Ray Tagger (CRT)

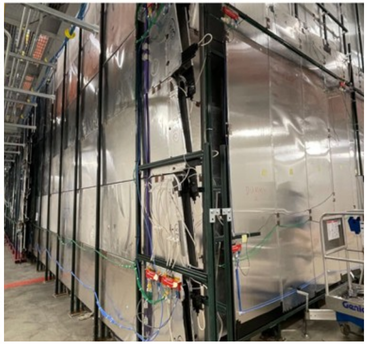
- Nearly 4π coverage with scintillator panels and SiPM readout for cosmic tagging.
- Shielded by ~2.85 m thick concrete layer for external γ/n suppression.



Top CRT



Side CRT

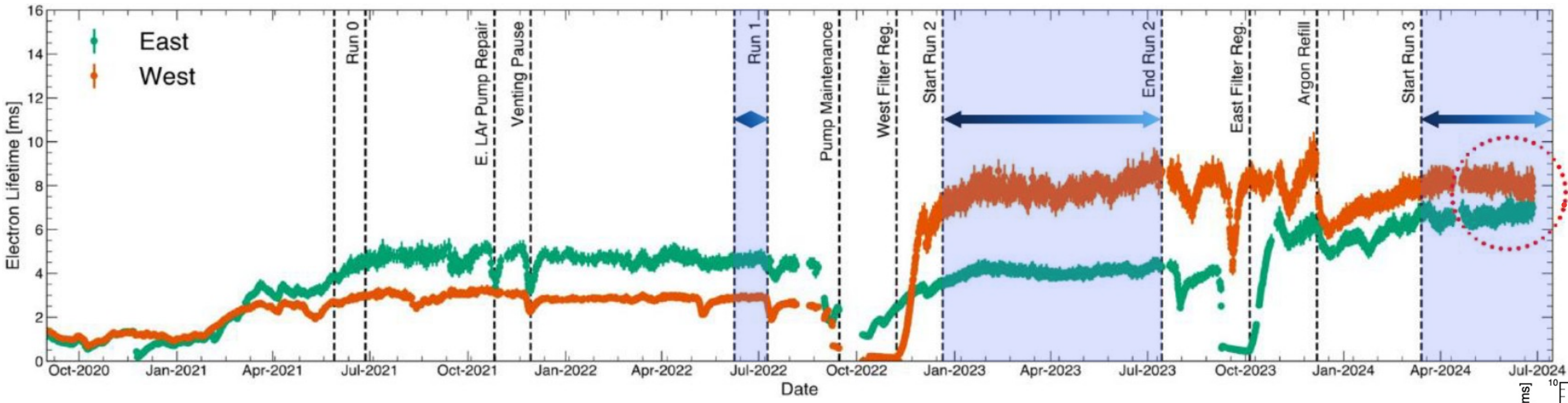


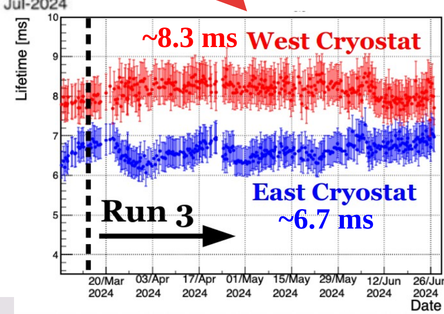
Overburden

ICARUS Data Collection

- ICARUS ***began collecting data for physics on June 9th, 2022***, with ***the TPC, PMT, and CRT systems fully operational***.
- The cryogenic and purification systems performed smoothly*, ***maintaining a stable free electron lifetime of 7-8 ms***, enabling nearly full track detection efficiency over the 1.5 m drift distance (~1 ms).

ICARUS Electron Lifetime



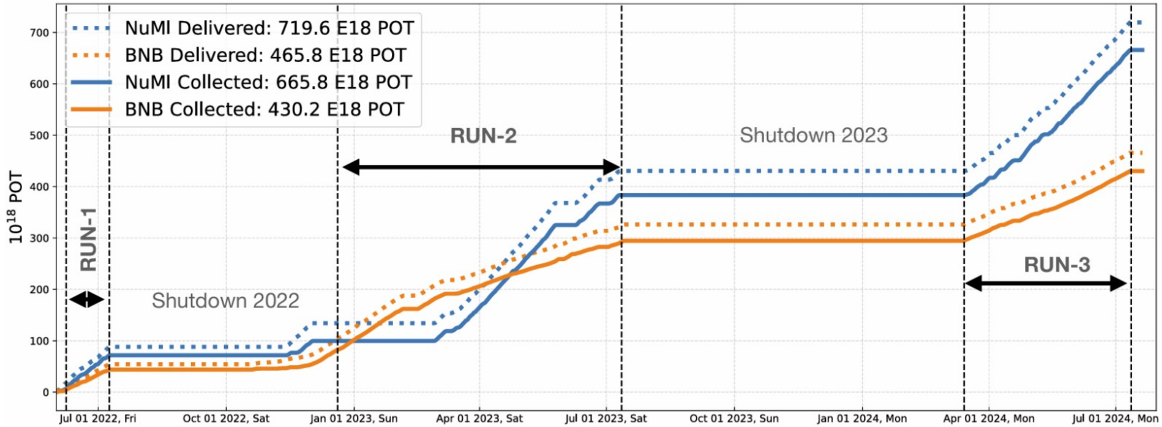


** Residual impurities in liquid argon at approximately 40 p.p.t. of [O_2] equivalent.*

ICARUS Data Collection

- Light signal registered simultaneously by ***4 PMT pairs inside a 6 m*** longitudinal slice in coincidence with BNB (1.6 μs), NuMI (9.5 μs) beam spills.

- ***> 90% efficiency*** for E_{dep} >200 MeV



Collected Protons on Target (POT)	BNB (FHC*) positive focusing	NuMI (FHC*) positive focusing	NuMI (RHC*) negative focusing
RUN-1 (Jun 9th – Jul 10th, 2022)	0.41×10^{20}	0.68×10^{20}	–
RUN-2 (Dec 20th, 2022 – Jul 14th, 2023)	2.05×10^{20}	2.74×10^{20}	–
RUN-3** (Mar 15th – Jul 12th, 2024)	1.36×10^{20}	–	2.82×10^{20}
TOTAL	$\mathbf{3.82\times10^{20}}$	$\mathbf{3.42\times10^{20}}$	$\mathbf{2.82\times10^{20}}$

** FHC: Forward Horn Current (neutrino) and RHC: Reverse Horn Current (antineutrino).*
*** Reduced exposure for RUN-3 due to the prolonged accelerator shutdown.*

ICARUS Detector Calibration

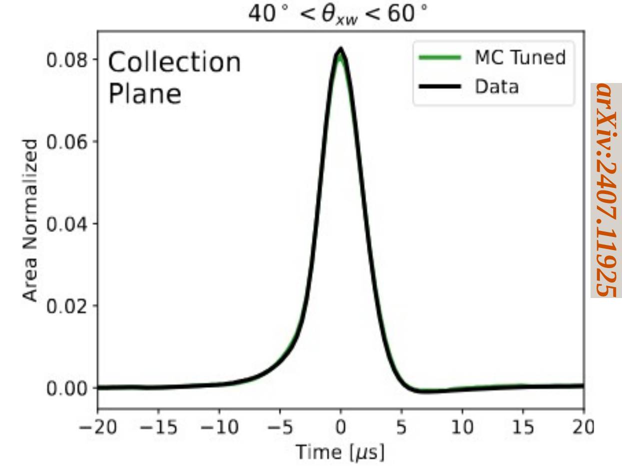
- ***TPC wire signals*** are accurately ***characterized and modeled in MC*** simulations.
- ***Detector response is calibrated using cosmic muons and protons from ν interactions***, with a new angular-dependent ellipsoidal recombination model (***EMB***).

Observed ionization charge per length: $$\frac{dQ}{dx} = \frac{\log\left(\alpha + \mathcal{B}(\phi)\frac{dE}{dx}\right)}{\mathcal{B}(\phi)W_{\text{ion}}}$$

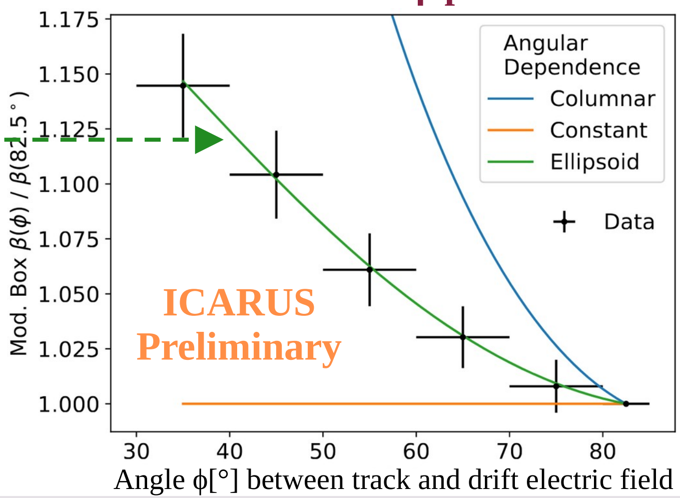
$$\mathcal{B}(\phi) = \frac{\beta_{90}}{\mathcal{E}\rho\sqrt{\sin^2\phi + \cos^2\phi/R^2}}$$

- ***Reconstruction has improved with new processing*** that accounts for shared charge between multiple wires.

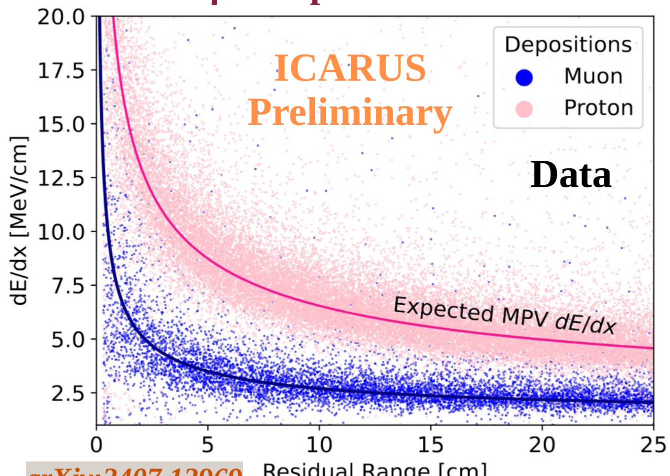
Average signal response per plane (Data/tuned MC) in a track angular bin



Angular dependence of recombination β parameter



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



arXiv:2407.12969

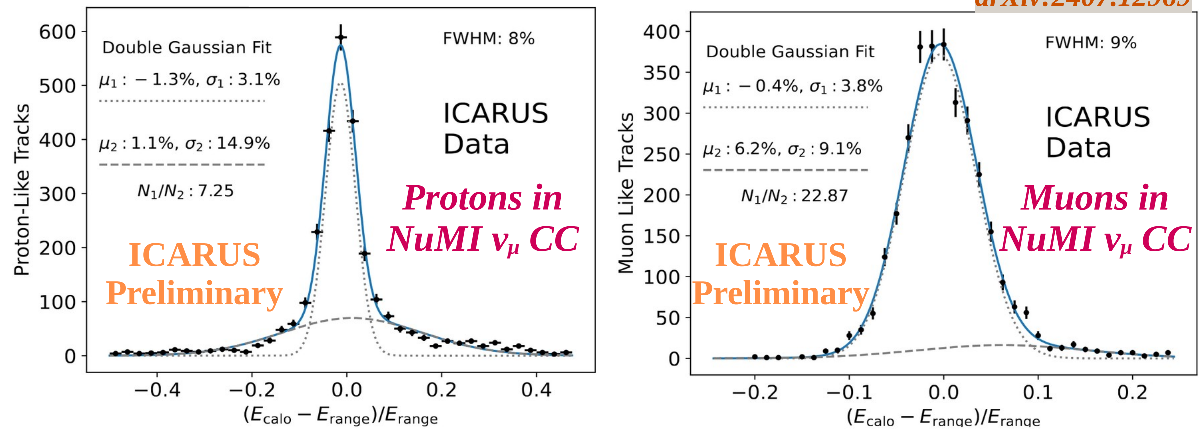
ICARUS Detector Validation

Deposited energy is used to *validate calibration and improve calorimetric reconstruction.*

- ***Difference between calorimetric energy reconstruction and the range measurement of the proton and stopping muon energy*.**

EMB-based calibration is applied

arXiv:2407.12969



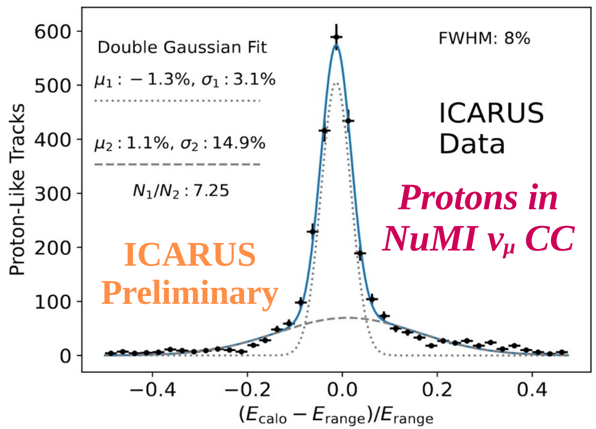
ICARUS Detector Validation

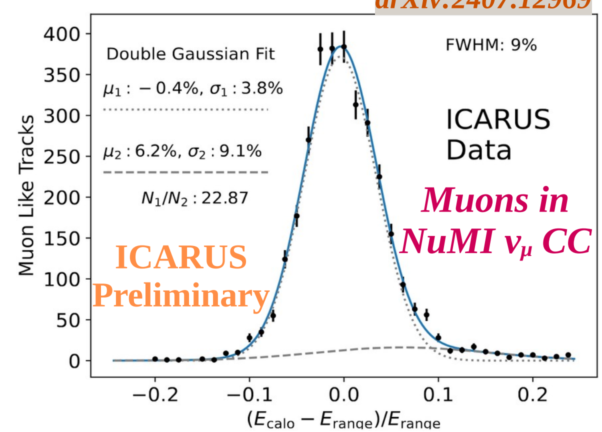
Deposited energy is used to *validate calibration and improve calorimetric reconstruction.*

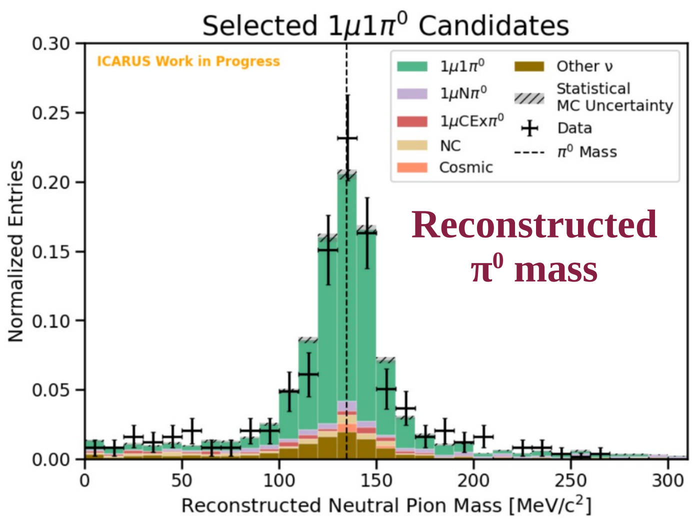
- ***Difference between calorimetric energy reconstruction and the range measurement of the proton and stopping muon energy***.
- π^0 from neutrino interactions, achieving ~10% resolution on $m_{\gamma\gamma}$

EMB-based calibration is applied

arXiv:2407.12969

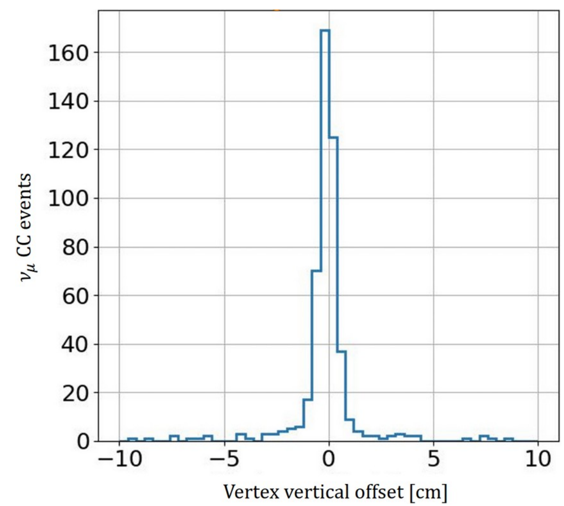


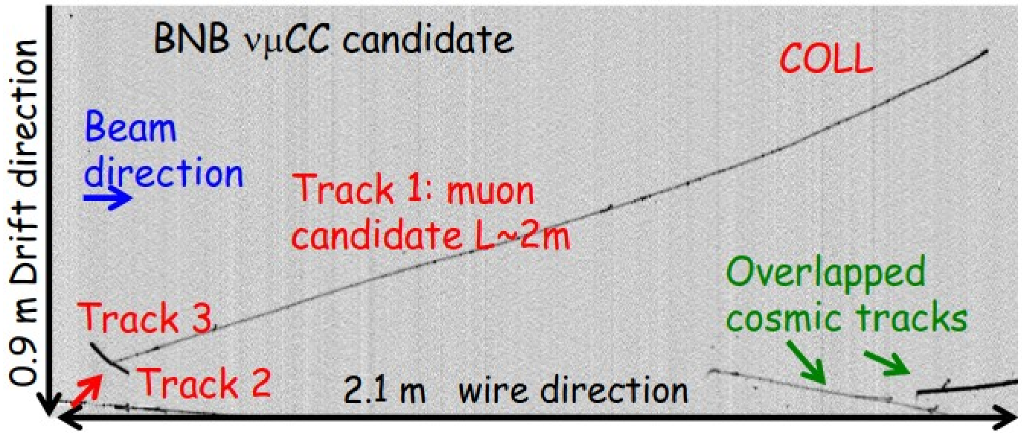


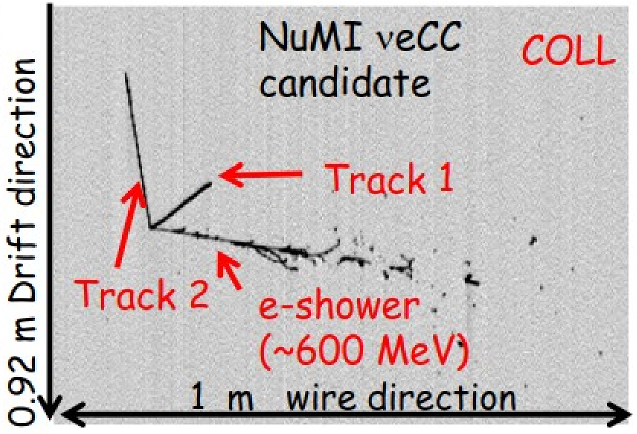


ν events identified through ***visual scanning of collected data are used to test automated software tools***:

- The difference between automatic and visually reconstructed vertex positions for ~500 visually selected ν_μ CC candidates shows a resolution of a few millimeters.





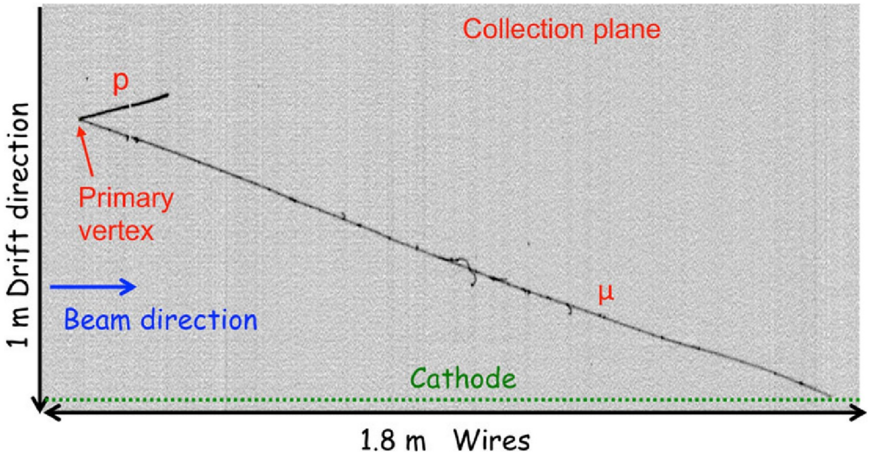


ICARUS PHYSICS PROGRAM

ν_μ Event Selection for disappearance with BNB

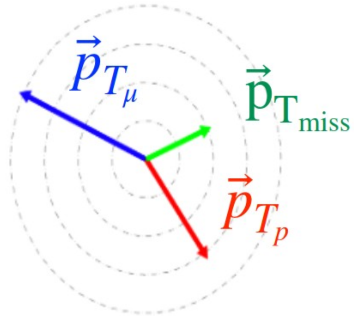
Study of Fully Contained νμ CC Events (1μ+ Np)

- ***Event Selection Criteria***
  - TPC track linked with PMT light and no CRT signal within beam spill window.
  - Muon track with length L_μ>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).



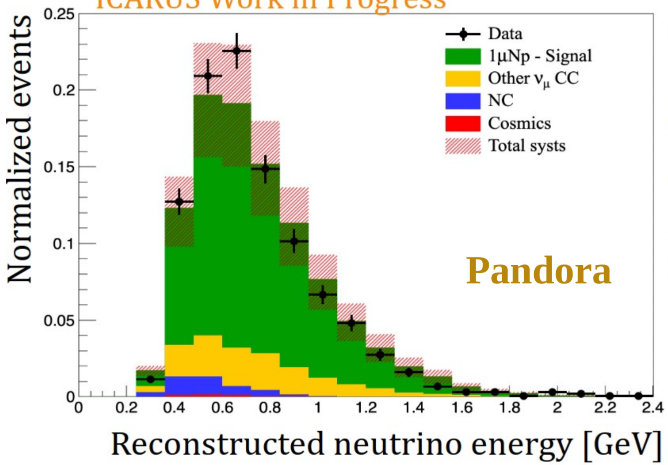
- ***Reconstruction Approaches***
  - Pandora Pattern Recognition Algorithm
  - Machine Learning-based SPINE

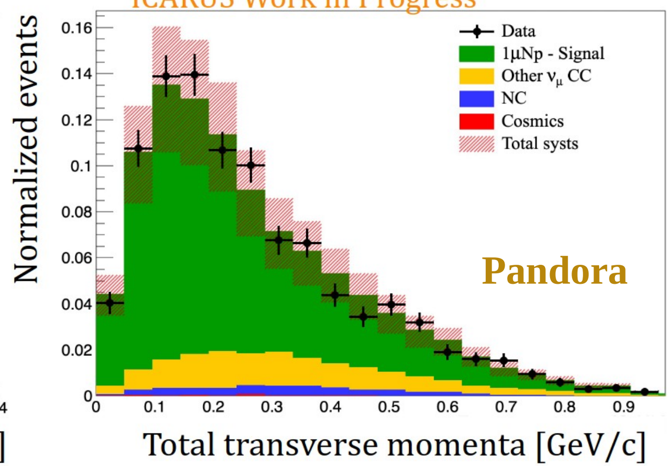
- ***Background Rejection & Validation***
  - Cosmic backgrounds are kept below 1%.
  - Event kinematics validated through visual studies and range measurements.

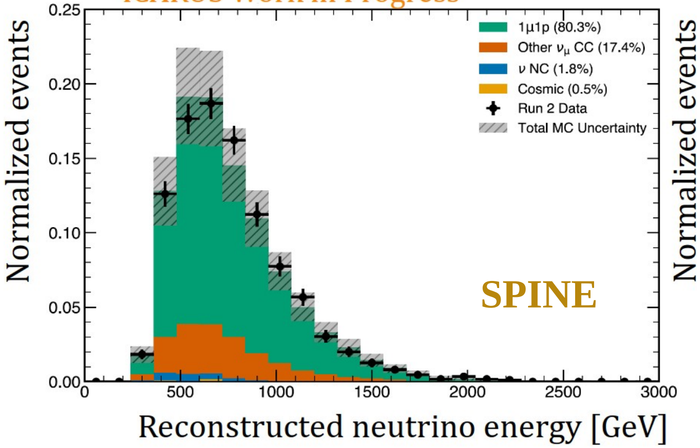


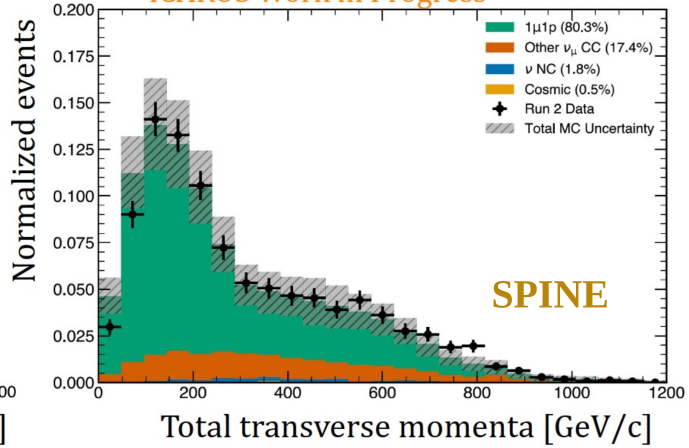
1μNp Analysis from BNB

- ***10% of RUN-2 data analyzed***; 20x more data available, showing ***Data-MC agreement*** within systematics.









Use two independent reconstruction approaches:

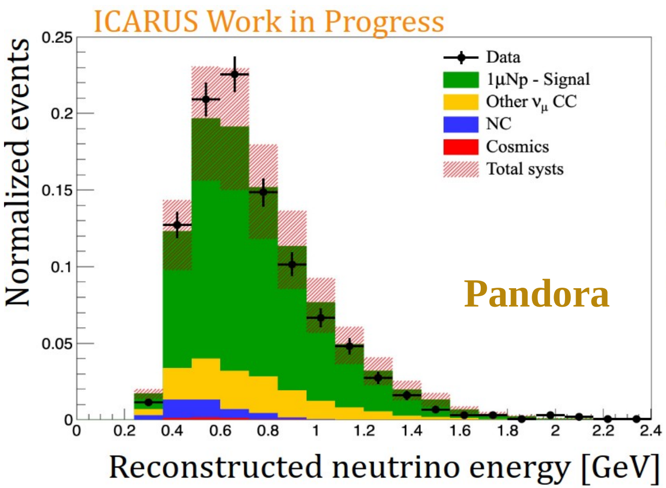
- ***Pandora*** pattern recognition algorithm
- ***SPINE***, a Machine Learning reconstruction

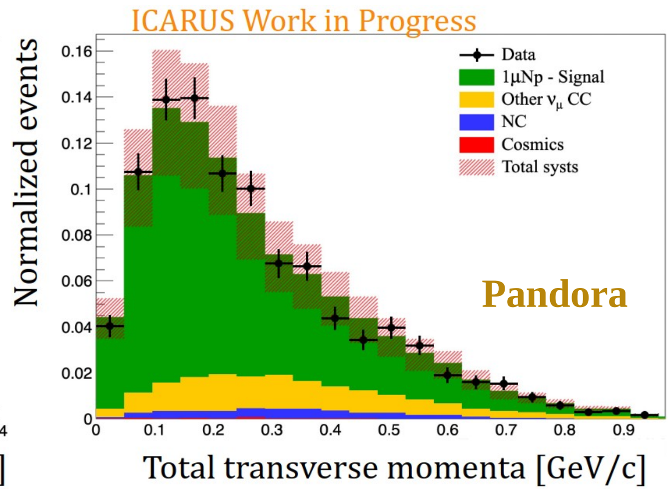
	Pandora	**SPINE**
Efficiency	50 %	75 %
Purity	80 %	80 %
POT	1.93 x 10^{19}	1.92 x 10^{19}
Total Events*	**34 k**	**47 k**

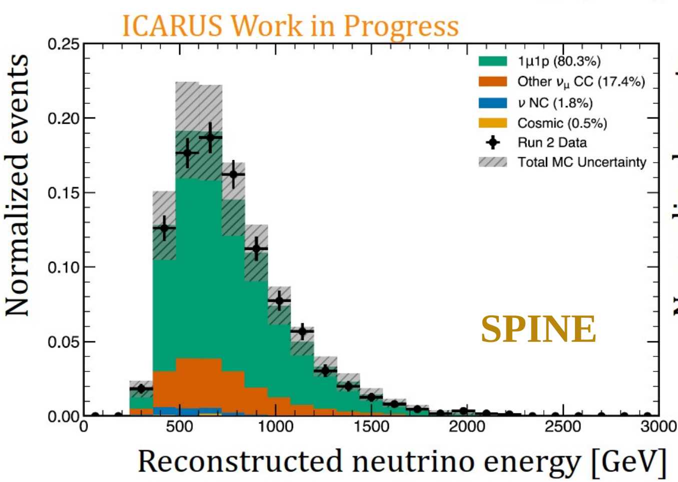
** Using the Run 1, 2, and 3 POT*

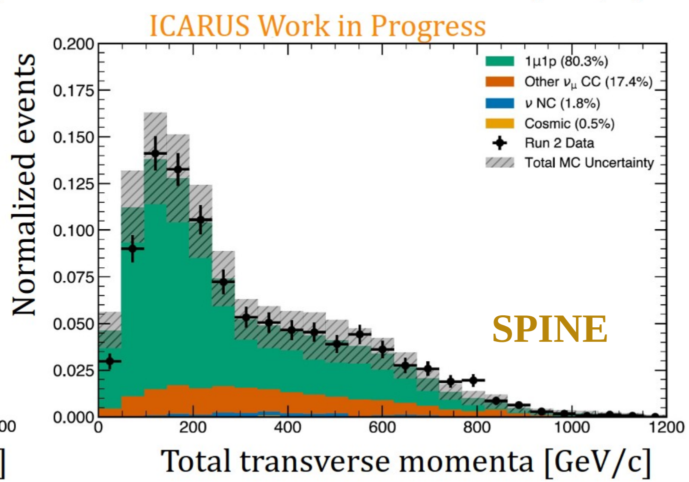
1μNp Analysis from BNB

- ***10% of RUN-2 data analyzed***; 20x more data available, showing ***Data-MC agreement*** within systematics.









Use two independent reconstruction approaches:

- ***Pandora*** pattern recognition algorithm
- ***SPINE***, a Machine Learning reconstruction

	Pandora	**SPINE**
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POT	1.93×10^{19}	1.92×10^{19}
Total Events*	**34 k**	**47 k**

Ready for the next steps:

- ***Enlarge the control sample*** to confirm analysis robustness.
- ***Unblind the full dataset***.
- ***Perform an oscillation fit*** using ICARUS data only.

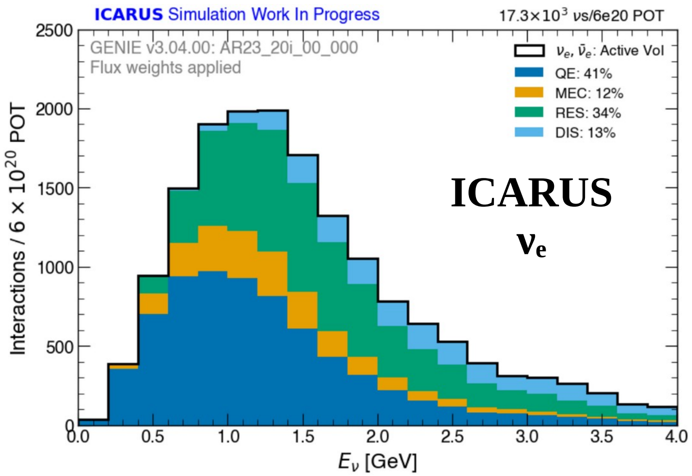
** Using the Run 1, 2, and 3 POT*

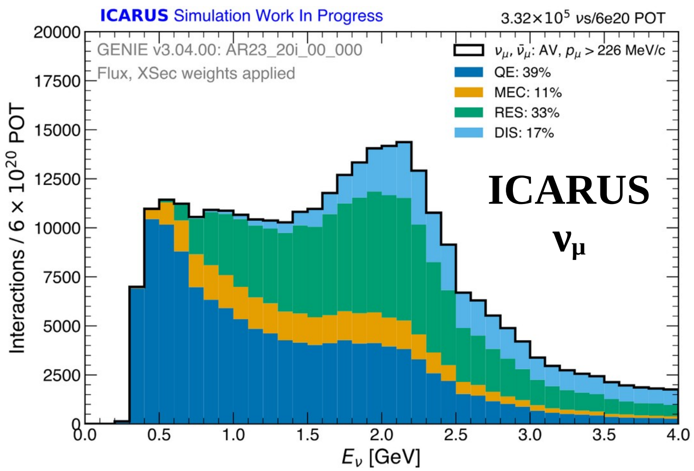
ν-Ar Interactions from NuMI

- ICARUS has a large NuMI dataset for ν-Ar cross-section measurements:
  - ***332k ν_μ CC and 17k ν_e CC interactions*** in 6×10^{20} POT.

- Currently ***available data: ~3.42×10^{20} POT.***

Expect to have **larger statistics of ν_e interactions with Ar** in comparison with previous experiments.





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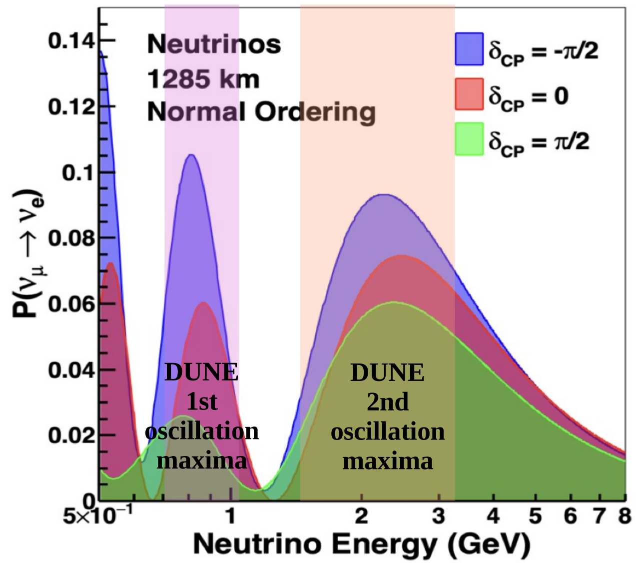
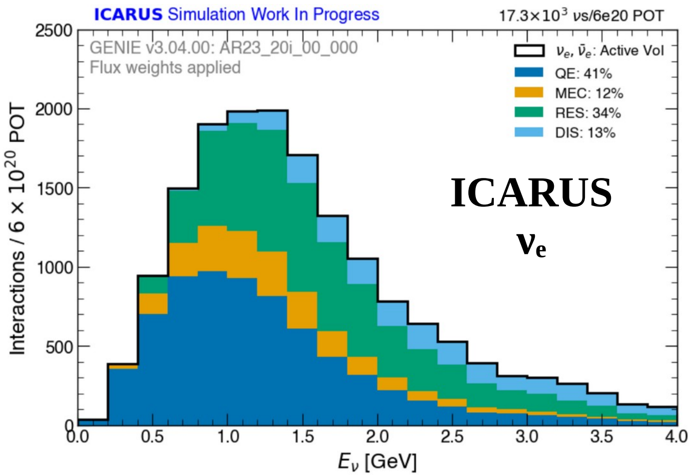
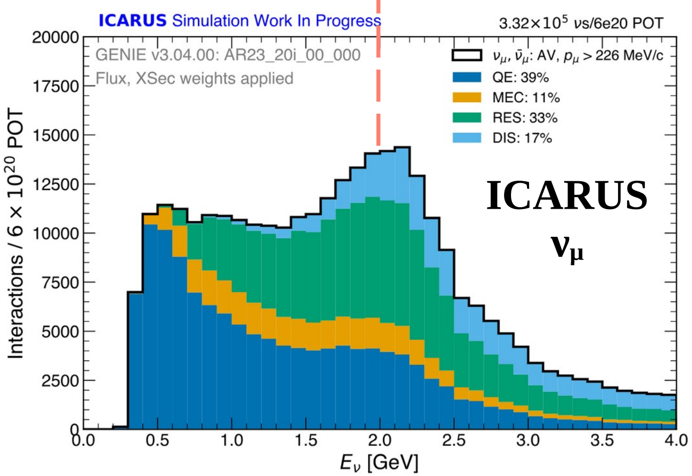
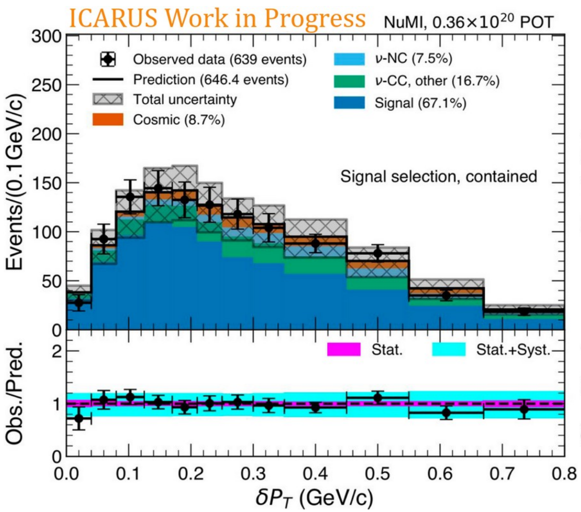
expected probability of oscillation in DUNE

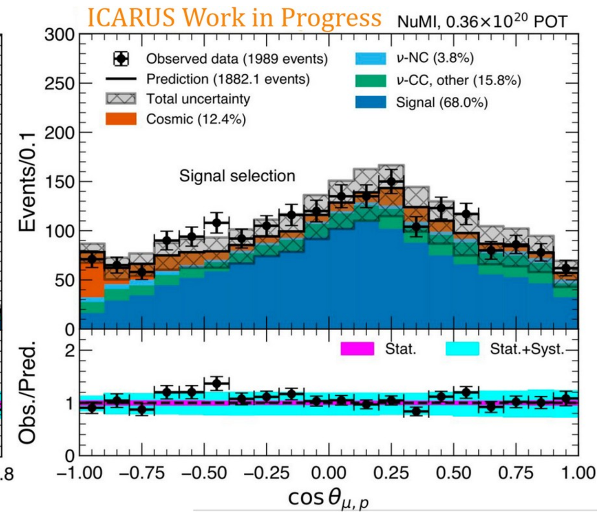






1μNp0π Analysis from NuMI





First Analysis Target, 1μNp0π Events

- ***Signal Definition***
  - 1 muon with p_μ>0.226 GeV/c
  - At least 1proton with 0.4<p_p<1 GeV/c
  - No pions ($\pi^\pm$ or π^0) in final state
- ***Systematics & Modeling***
  - Includes neutrino flux, interaction model, and detector systematics.
  - Angular and transverse kinematic observables are used to capture initial and final state effects.

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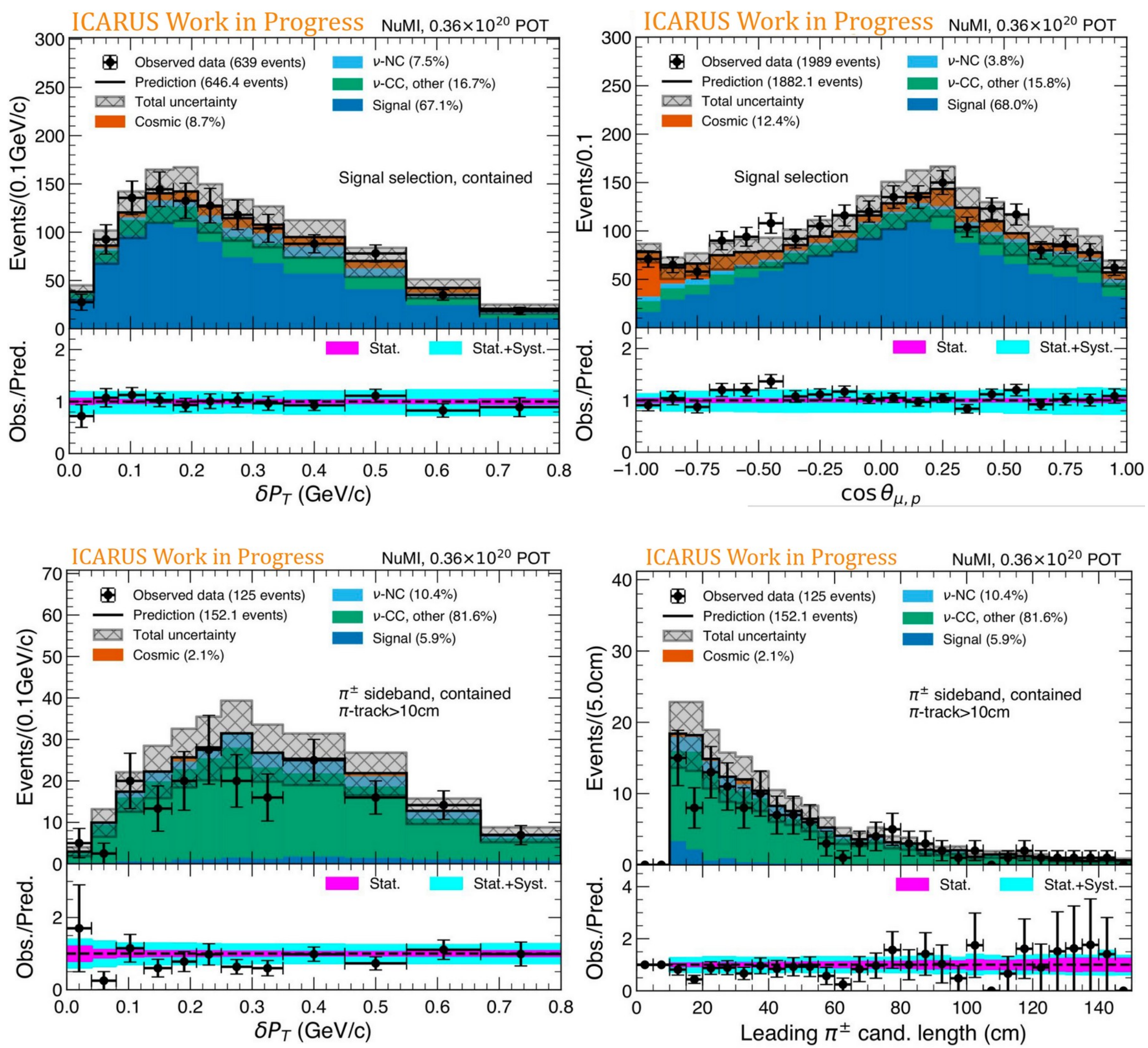

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  - Angular and transverse kinematic observables are used to capture initial and final state effects.

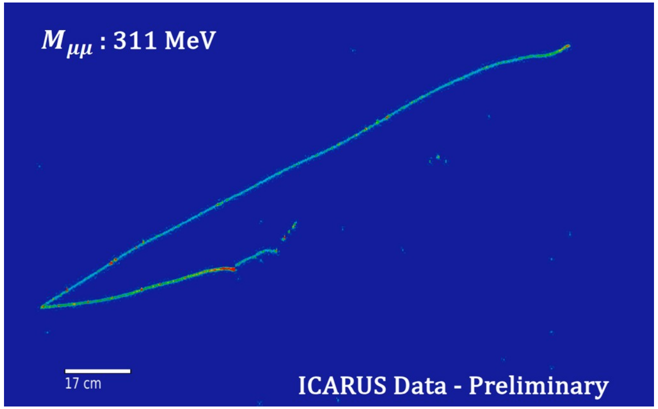
- ***Major Backgrounds*** (Events with undetected or misidentified pions)
  - Control sample with $\pi^\pm$ candidates selected to characterize this background (requires secondary μ-like track).
  - Data/MC shows good agreement within ~15%.

BSM Physics from NuMI

BSM Searches with NuMI Data

Models involving dark particles coupling to Standard Model particles through Scalar Portal.

- ***Higgs Portal Scalar (HPS):*** Scalar dark particles mix with the Higgs boson.
- ***Heavy QCD Axion (ALP):*** Pseudoscalar particles mix with pseudoscalar mesons.



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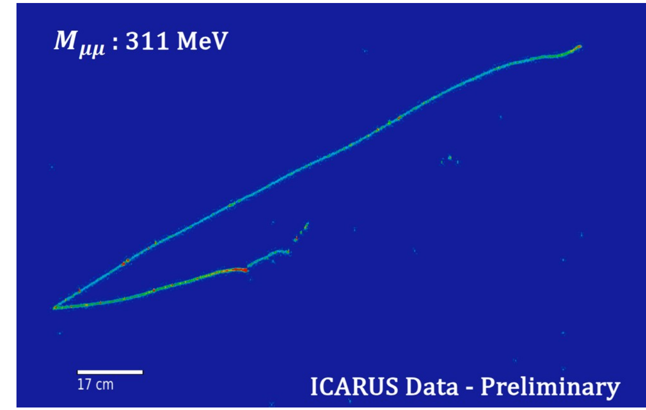

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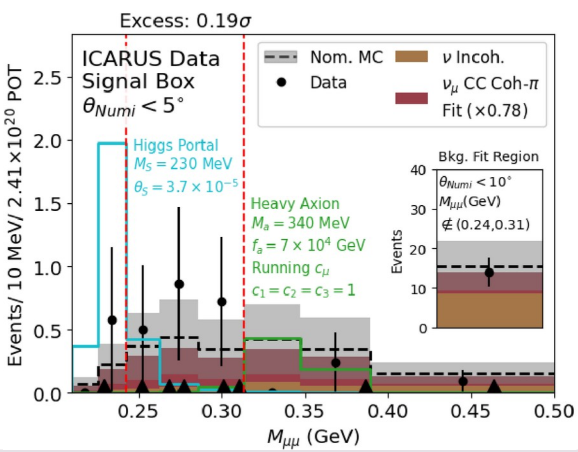
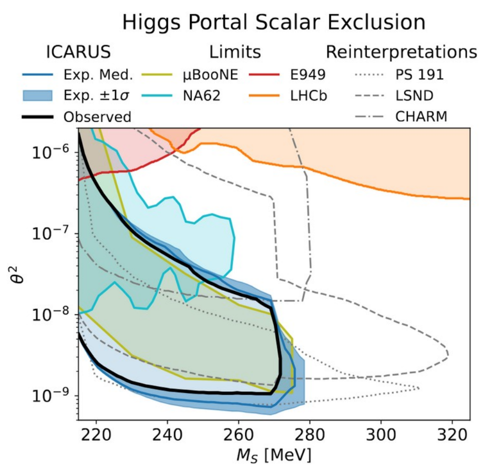
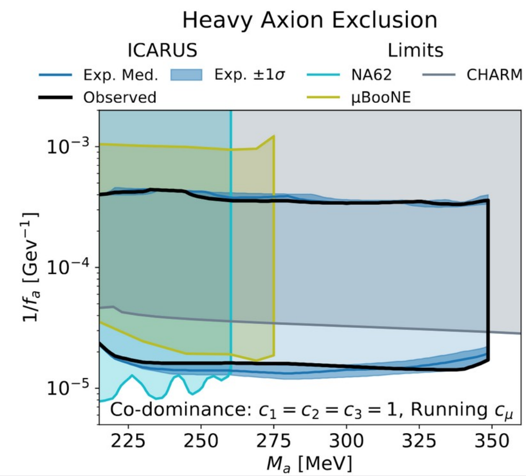
Scalar Decays in μ+μ- with Run2 NuMI, Results:

- 9 candidate events found, matching MC background expectation of 8 events (from ν_μ CC coherent pion production).
- Results show ***no significant new physics signal*** (0.19 σ).







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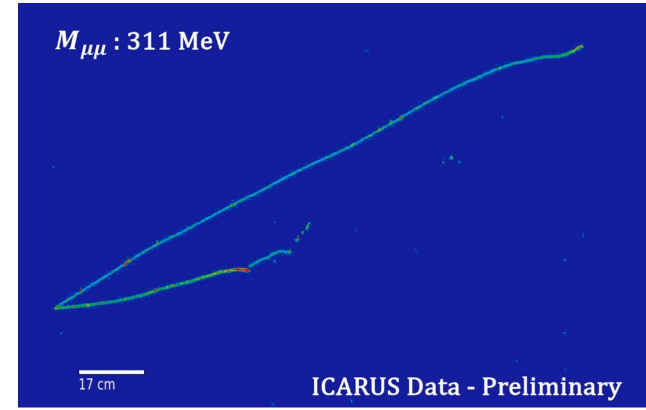

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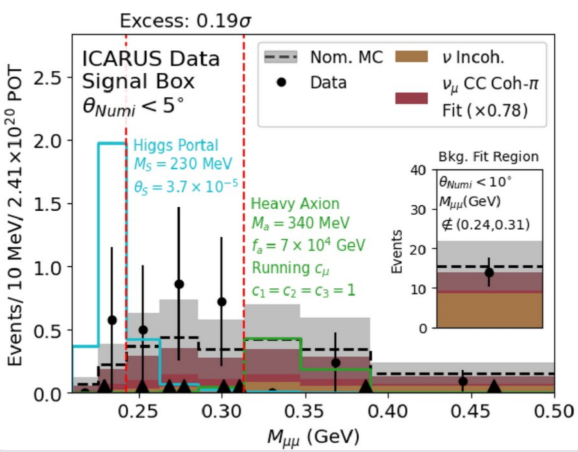
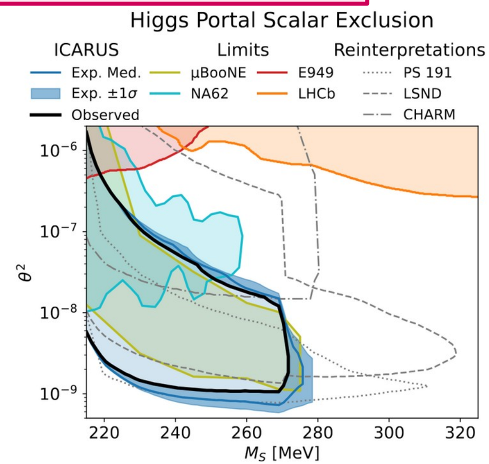
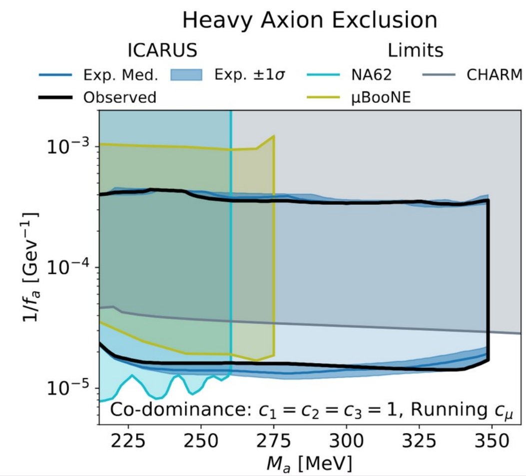
Submitted to publication!

arXiv:2411.02727







Imaging Cosmic And Rare Underground Signals

SUMMARY AND FUTURE

Summary

- ICARUS has been operating smoothly in physics mode since June 2022.

- The detector response is calibrated with cosmic muons and neutrino-induced protons, with TPC signals and main detector parameters accurately characterized and modeled in simulation.

- Before the start of the joint operation within SBN, ICARUS is on the way to first physics results:

  - ***ν_μ Disappearance Studies with BNB: Ready to expand control samples***.

  - ***ν-Ar Cross Section Measurements using NuMI data***.

  - Sub-GeV Dark Matter Search with NuMI beam: ***Analysis of scalar decays to $\mu^+\mu^-$ completed***.

Summary

Exciting prospects ahead as we gear up for the SBN joint analysis!


Muchas Gracias

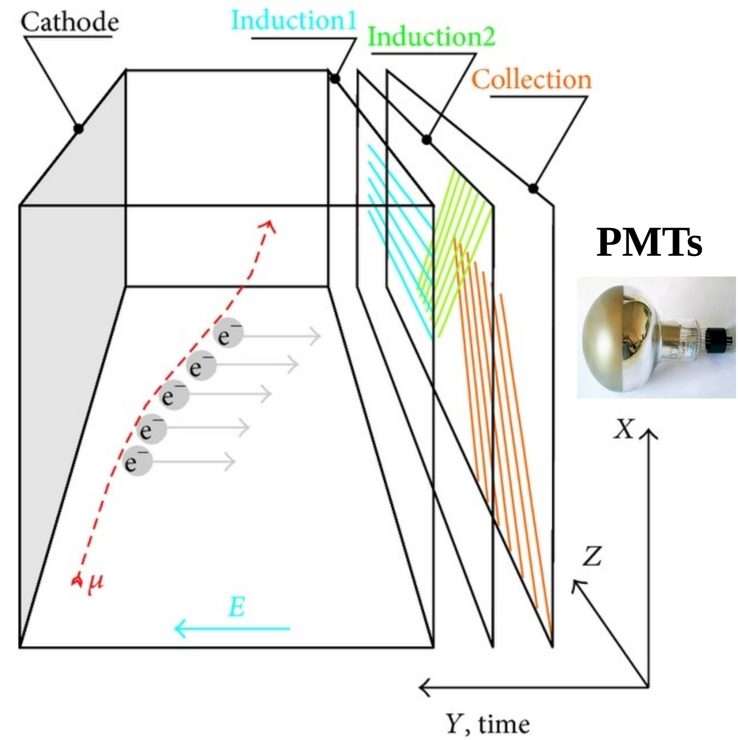
BACKUP

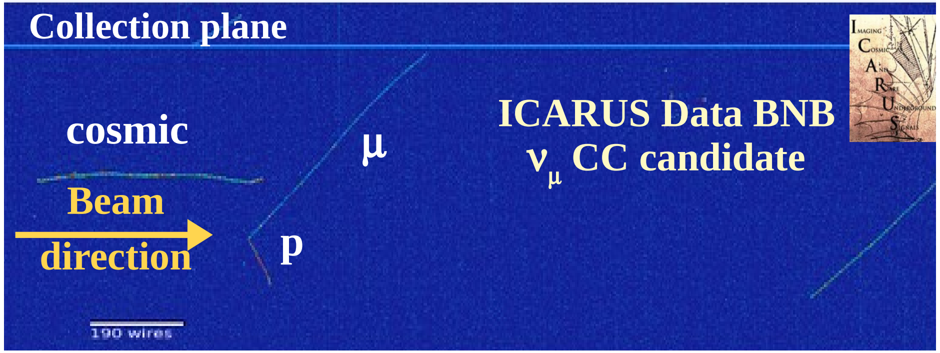
ICARUS: Abratenko, P. et al.
Eur. Phys. J. C 83, 467 (2023)

LAr TPCs

Why LAr TPCs?

- The ***ν-Ar interactions produce tracks, with ions and photons along those***.
- ***Photons propagate inside the detector*** [the scintillation light is collected by the photomultiplier tubes (PMTs) for precise event timing and event calorimetry].
- ***The ionized electrons will slowly drift towards the anode*** by an applied electric field.
- ***The ionized electrons produce induction signals*** as they pass the first two wire planes and are collected on the last wire plane.





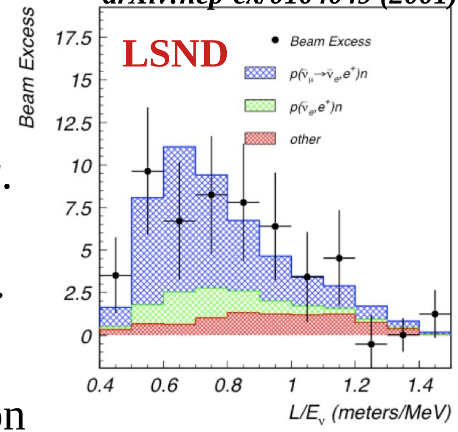
LAr TPC detectors, provide **full 3D imaging, precise calorimetric energy reconstruction**, and efficient **particle identification**. The detailed images of particle trajectories provide **significant information about final states**. The **high spatial resolution** allows for tracking. Thus, ***using the LArTPC technology we will be able to study ν_μ and ν_e with high precision.***

The Sterile Neutrino Puzzle

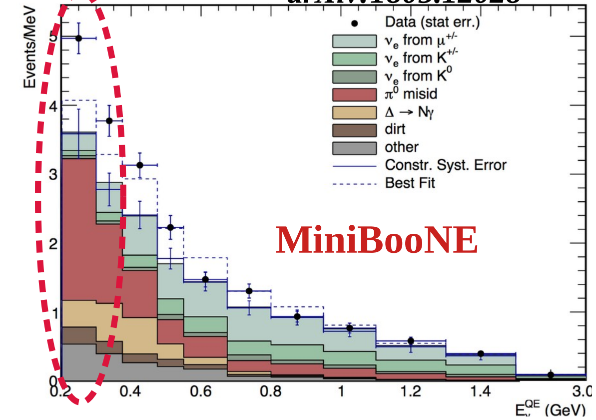
Even though **the 3vSM model has shown good agreement in many experiments, some anomalies have been observed in neutrino experiments at short baseline** hinting to a new sterile neutrino flavor at $\Delta m^2_{new} \sim 1\ eV^2$:

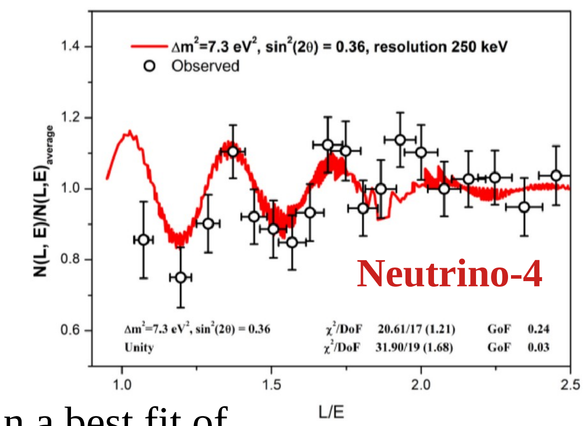
- ***Accelerator Experiments***
  - LSND: Observed excess of $\bar{\nu}_e$ events in the channel $\bar{\nu}_e + p \rightarrow e^+ + n$ at a significance of 3.8σ.
  - MiniBooNE: Electron-like excess observed in both ν and $\bar{\nu}$ modes, with a significance of 4.7σ.
- ***Radiochemical Experiments***
  - SAGE and GALLEX: Measured ^{71}Ge production rate at R = 0.84 ± 0.05, recently confirmed by BEST experiment at 4σ.
- ***Reactor Experiments***
  - Neutrino-4: Observed a $\bar{\nu}_e$ disappearance signal with L/E$_\nu$ modulation (~1–3 m/MeV) at the SM-3 reactor (Dimitrovgrad).

arXiv:hep-ex/0104049 (2001)



arXiv:1805.12028





Combined analysis of Neutrino-4 with other experiments results in a best fit of
Δm^2_{14}= 7.3 eV² and sin²(2θ$_{14}$)=0.36 at 5.8 σ

The ICARUS Detector Subsystems

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

Time Projection Chambers (TPC)

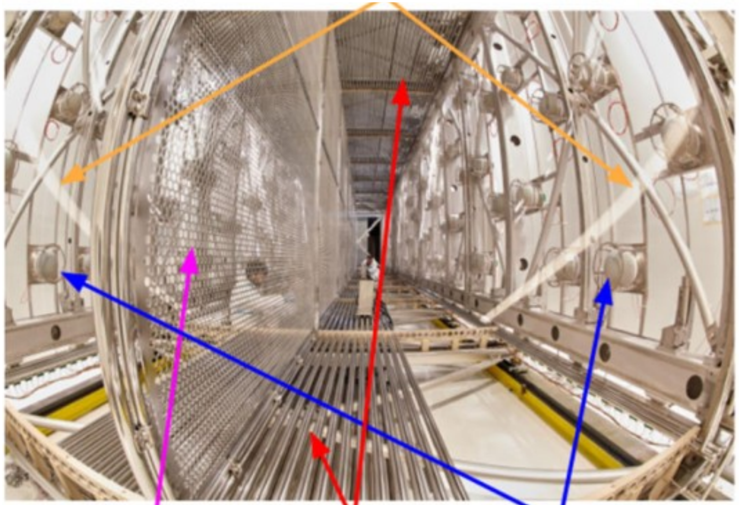
∼ 54k channels at different orientations and 3 mm pitch

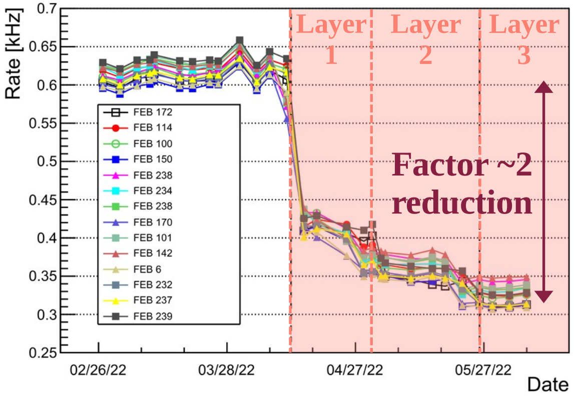
Photon Detection System (PDS)

- 360 PMTs, TPB coated to detect scintillation light
- Event timing and triggering purposes

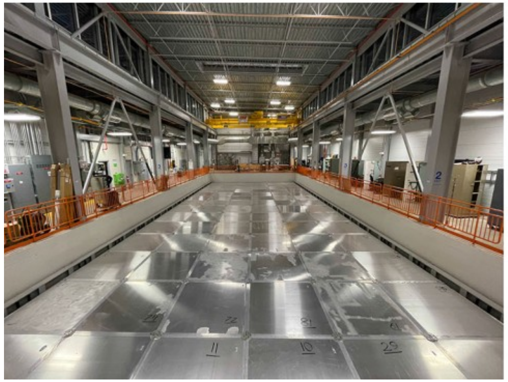
Cosmic Ray Tagger (CRT)

- ∼4π scintillator panels with SiPM readout for cosmic tagging
- Protected by ∼ 2.85 m thick concrete overburden for external γ/n suppression

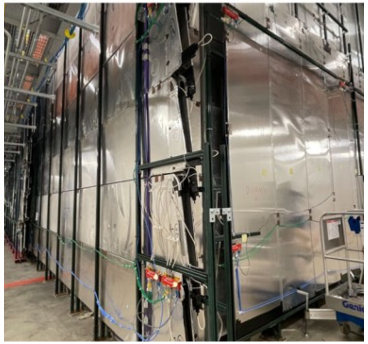




Top CRT



Side CRT



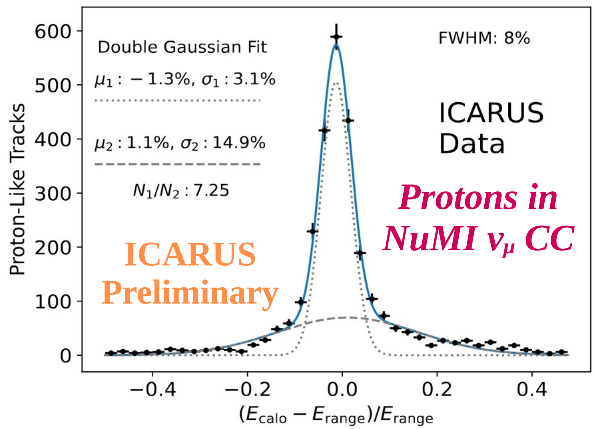
ICARUS Detector Validation

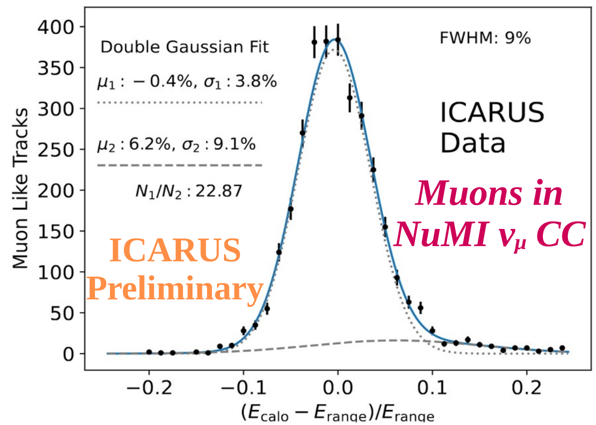
Deposited energy is used to ***validate calibration and improve calorimetric reconstruction***.

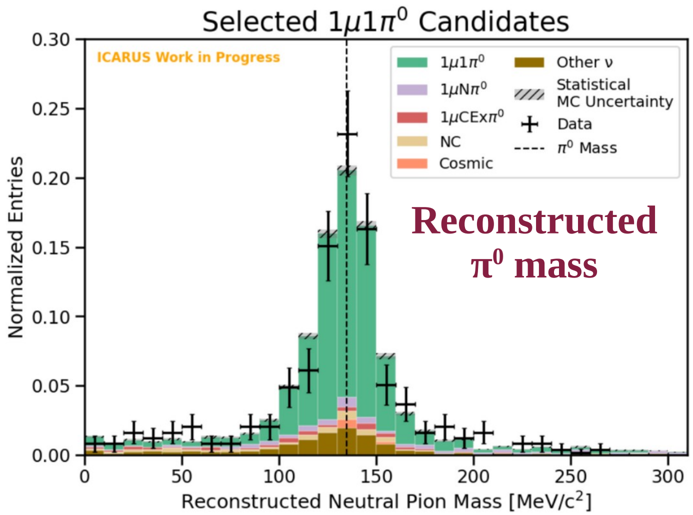
- Difference between calorimetric energy reconstruction and the range measurement of the proton and stopping muon energy.

- π^0 from neutrino interactions, achieving ~10% resolution on $m_{\gamma\gamma}$

EMB-based calibration is applied

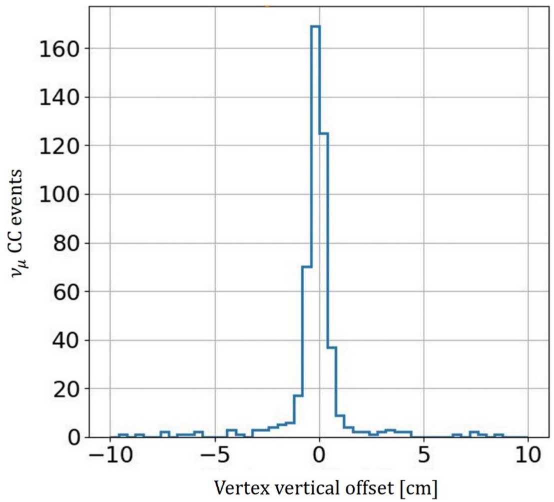






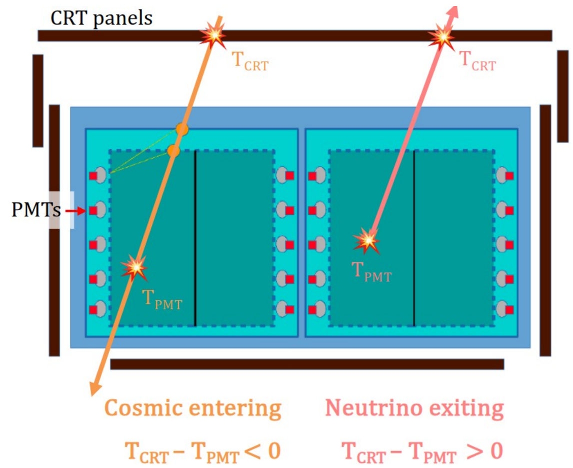
ν events identified through ***visual scanning of collected data are used to test automated software tools***:

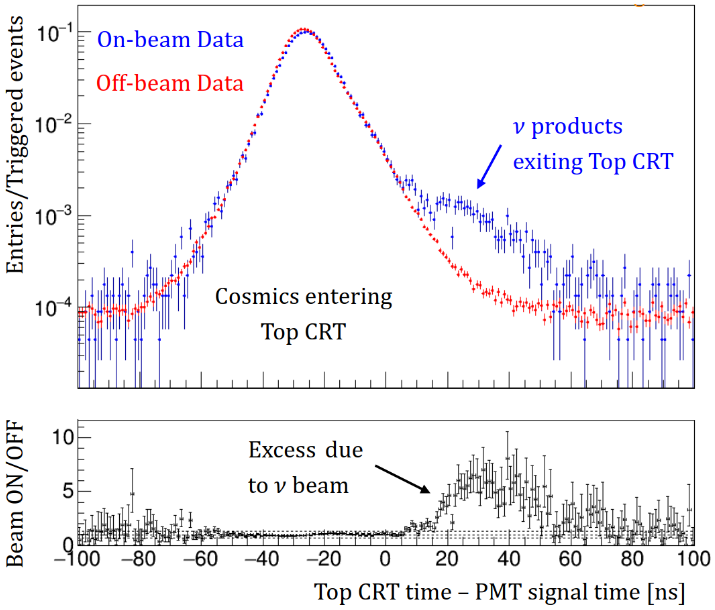
- The difference between automatic and visually reconstructed vertex positions for ~500 visually selected ν_μ CC candidates shows a resolution of a few millimeters.



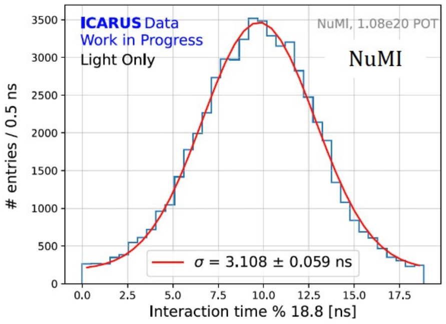
ICARUS Detector Performance

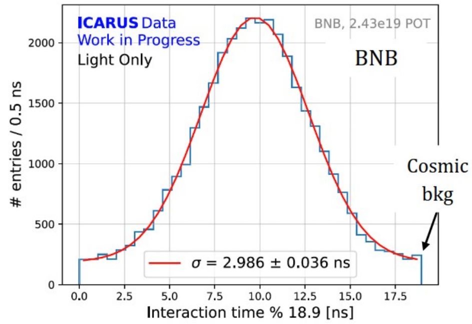
- Cosmic Ray Rejection and Neutrino Timing Reconstruction
  - Time-of-Flight Rejection: ***Use external CRT and inner PMT system to reject incoming cosmic rays***.

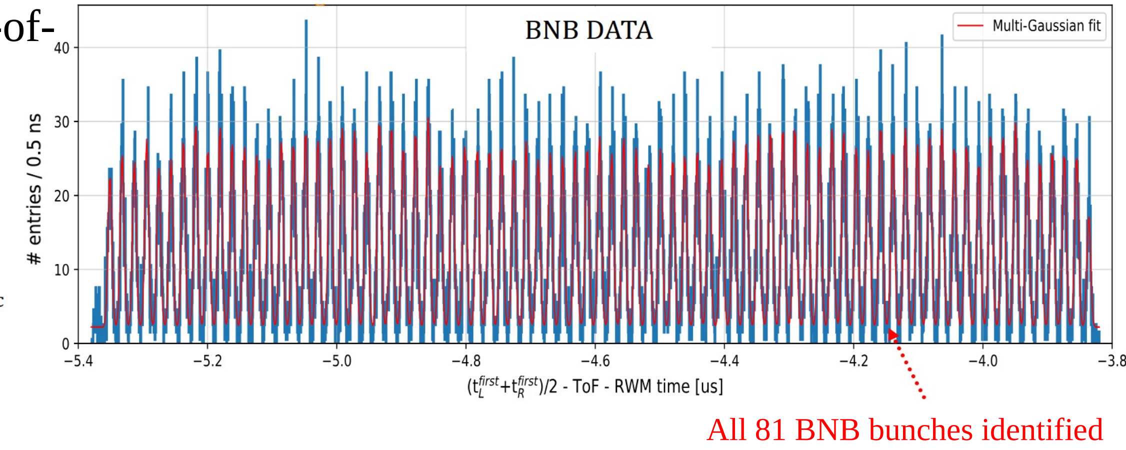




- Beam Spill Timing Reconstruction
  - Bunched structure of BNB and NuMI beam spill identified using neutrino interaction time (PMT) relative to proton beam extraction counters, with cosmic rejection (CRT) and neutrino time-of-flight (ToF) correction applied.







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