Fermilab

June 10th, 2025

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

Harry Hausner
CIPANP 2025

U.S. DEPARTMENT of ENERGY
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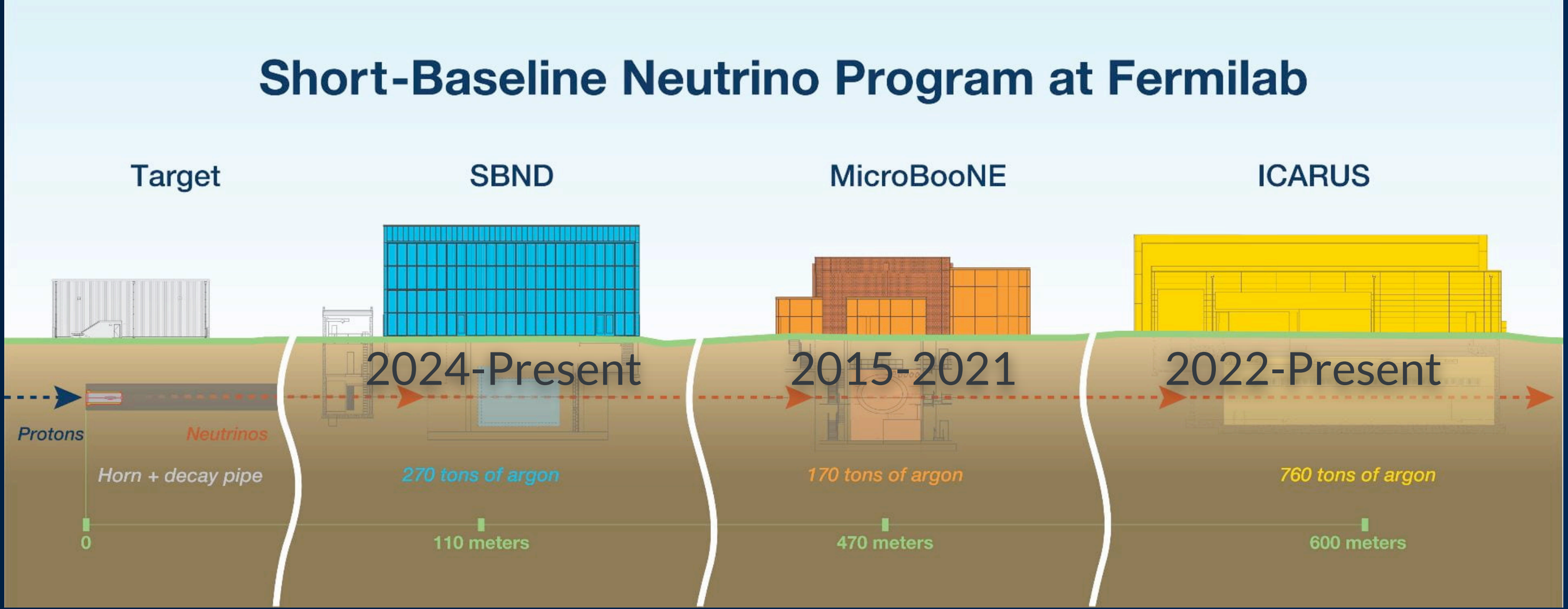
ICARUS @ SBN

Multiple Detector Program

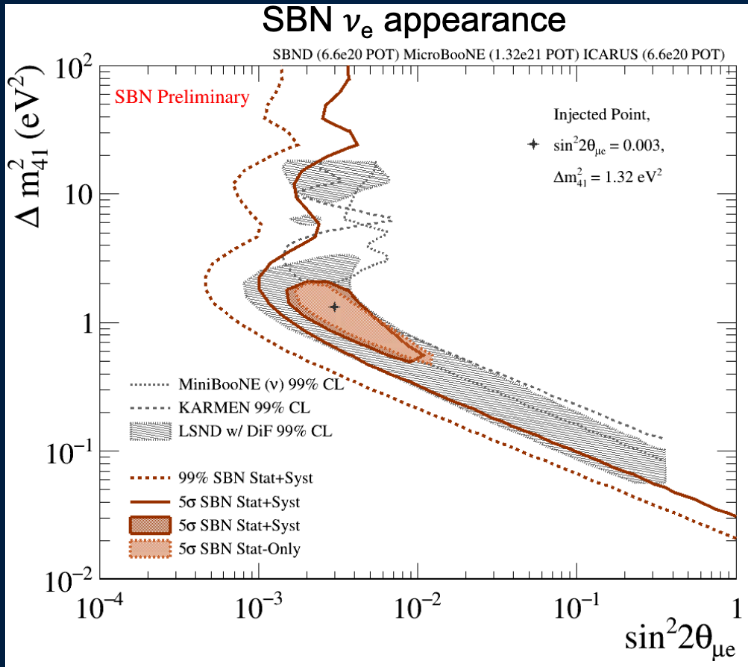
- The ICARUS T600 detector was first commissioned in Gran Sasso
- ICARUS T600 was refurbished and shipped from Gran Sasso to Fermilab to be part of the SBN program in 2017

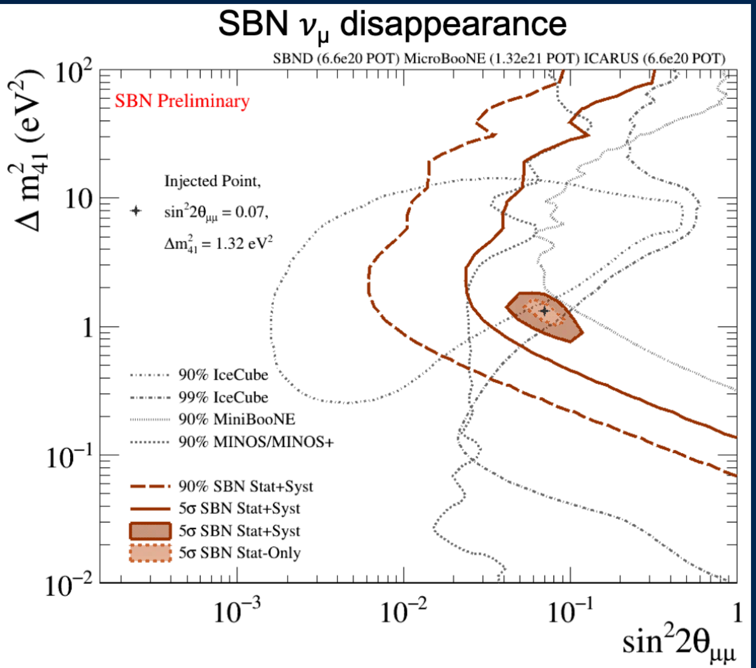


ICARUS @ SBN

Neutrino Disappearance

- Together the SBN program can provide world leading sensitivity to short baseline neutrino oscillations
- With proposed statistic and systematic constraints, LSND & MiniBooNE signals could be decisively located





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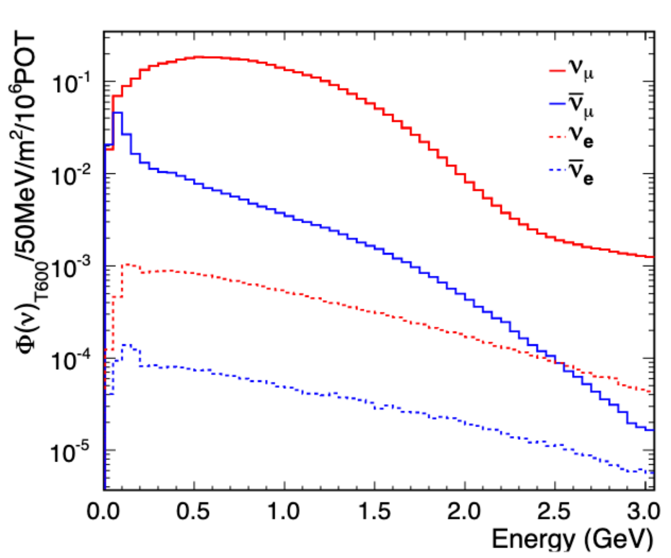
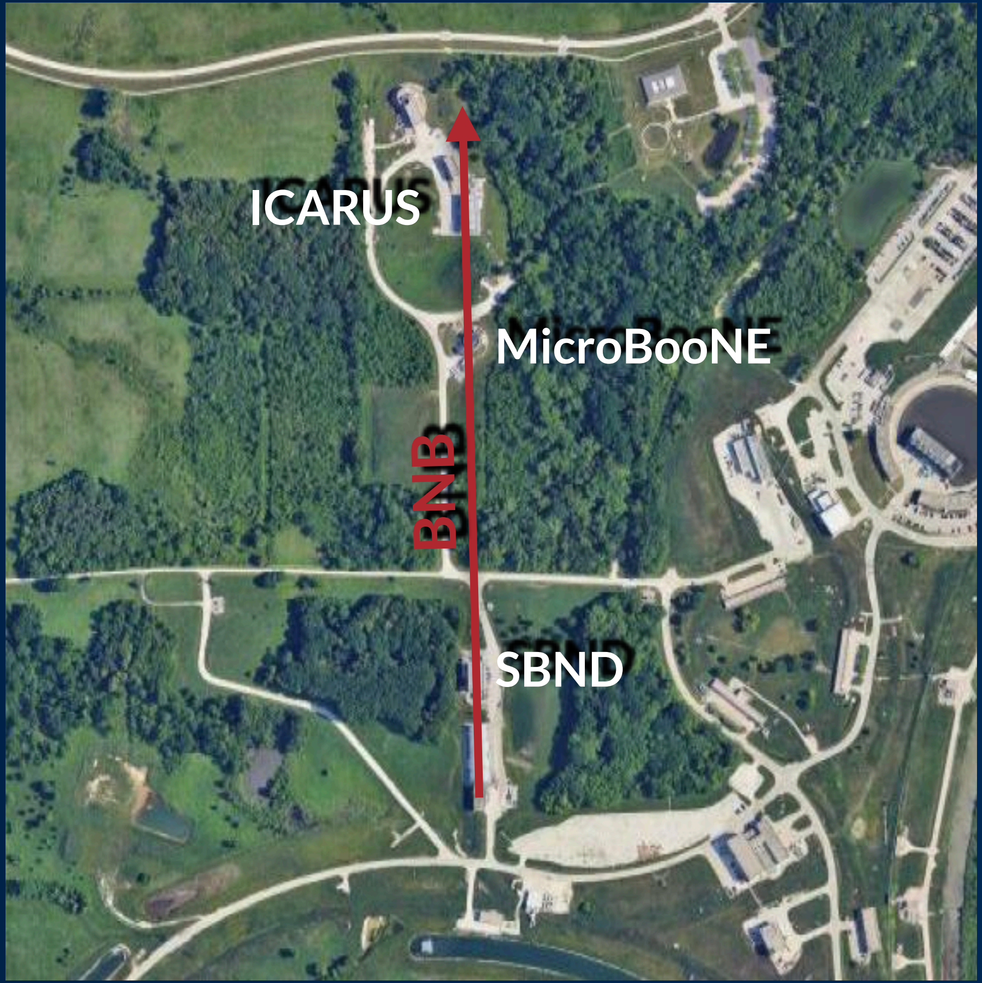
ICARUS @ SBN

BNB

- ICARUS is 600m from the Booster Neutrino Beam target
- The BNB is produced from 8 GeV protons on a beryllium target and focusing the decaying mesons
- Produces neutrinos peaked at ~0.7 GeV



doi:10.48550/arXiv.1503.01520



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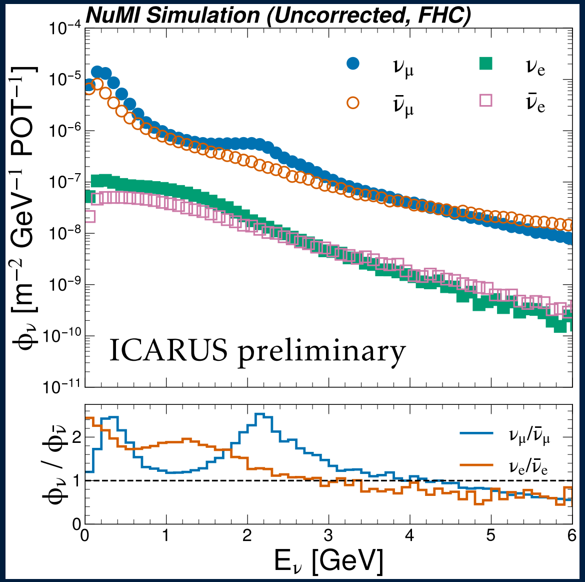
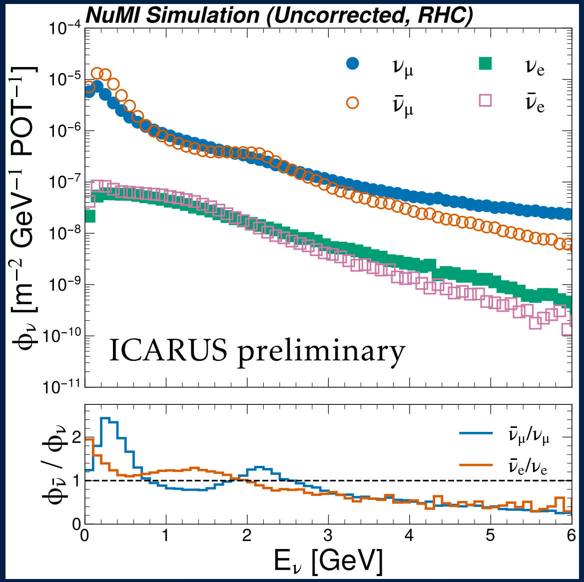
ICARUS @ SBN

NuMI

- ICARUS also lays approximately 6° off-axis of the NuMI beam, approx. 800m from the target
- 120 GeV protons on a carbon target
- Multi-GeV neutrinos similar to DUNE

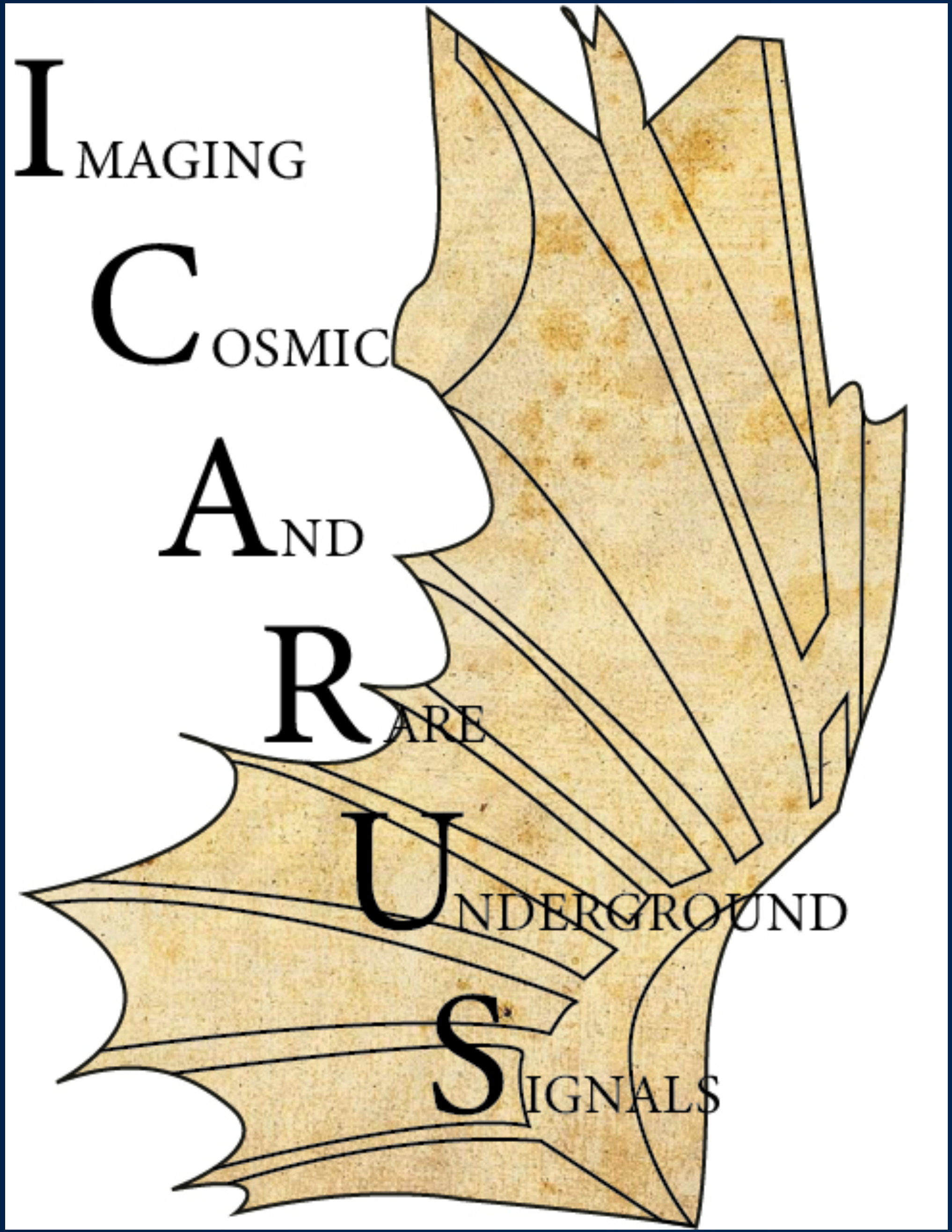




ICARUS @ SBN

SBN Goals

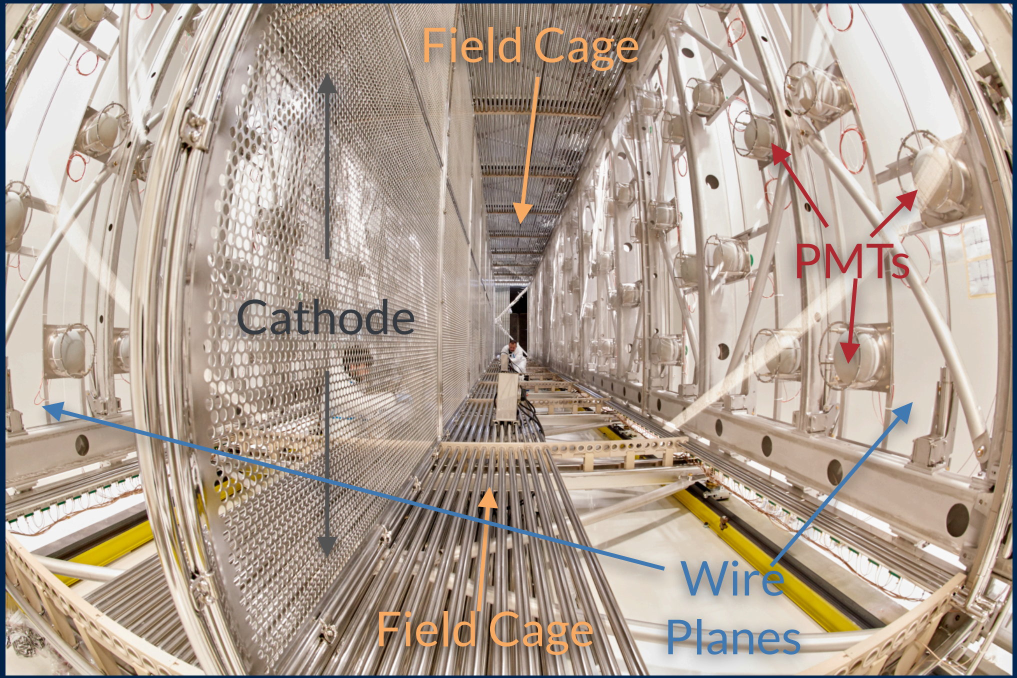
- Refine our understanding of Liquid Argon Time Projection Chambers (LArTPC) in preparation for DUNE
- Definitive search for $\Delta m^2 \sim 1\text{eV}^2$ neutrino oscillations
- Study neutrino-argon interactions in the regime applicable to DUNE
- Search for/provide limits on BSM physics

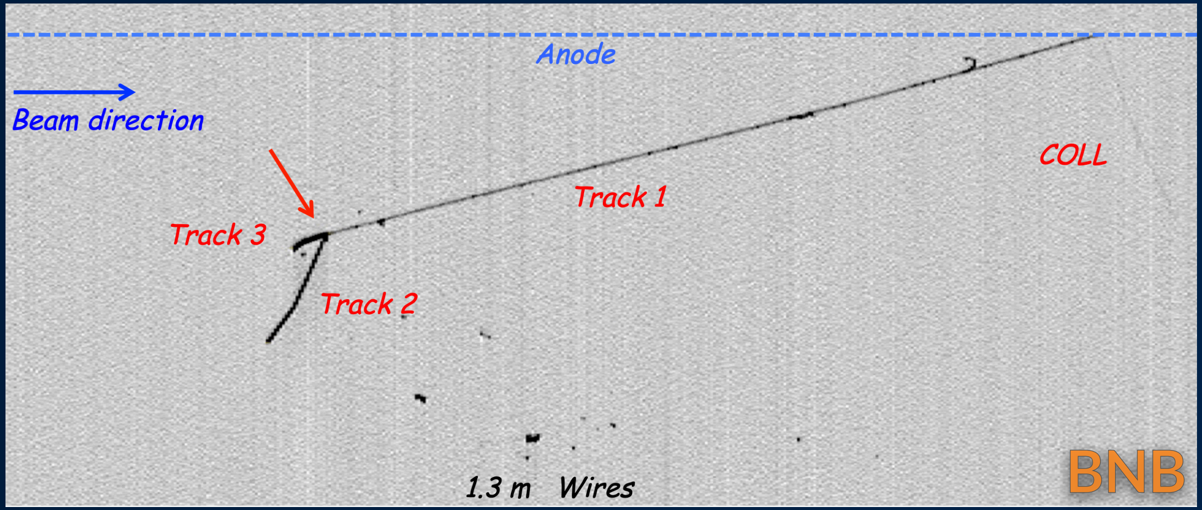


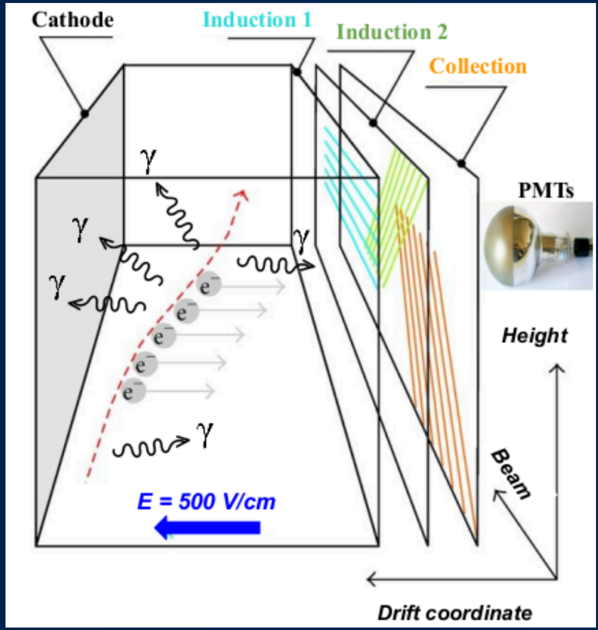
ICARUS T600

What is in a Neutrino Detector?

- 760 tons (476 ton active mass)
- 360 photomultiplier tubes (PMT)
- Cosmic Ray Tagger (CRT) system surrounds the cryostats to remove cosmogenic backgrounds
- 3m concrete overburden
- Two cryostats. each with two LArTPCs
    - 3 Wire Planes per LArTPC
        - Wires 0º, ±60º from vertical
    - 500 V/cm drift electric field
    - Shared cathode between LArTPCs







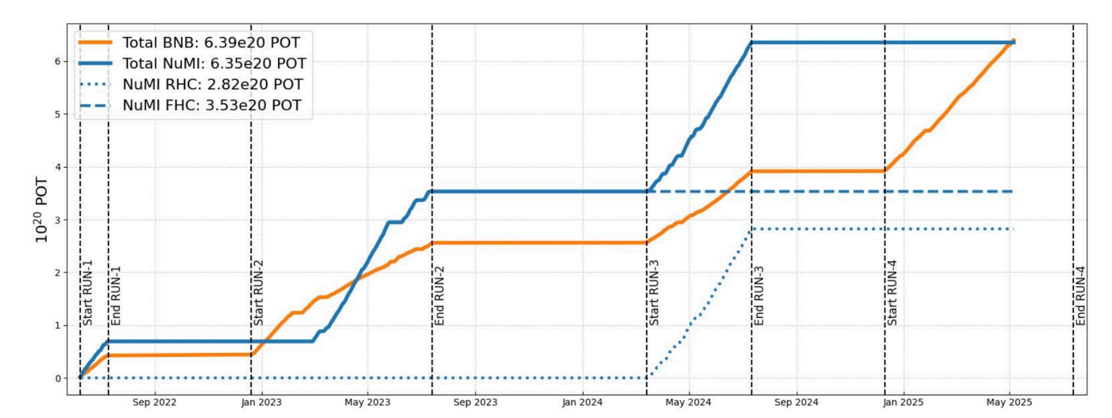
doi:10.1140/epjc/s10052-023-11610-y

ICARUS Operations

Protons, Protons, Protons

- ICARUS has been collecting data from the BNB and NuMI beam since June of 2022
- Large data sets from NuMI in neutrino and anti-neutrino mode
- Collected ~13 x 10^{20} protons on target (POT) and counting

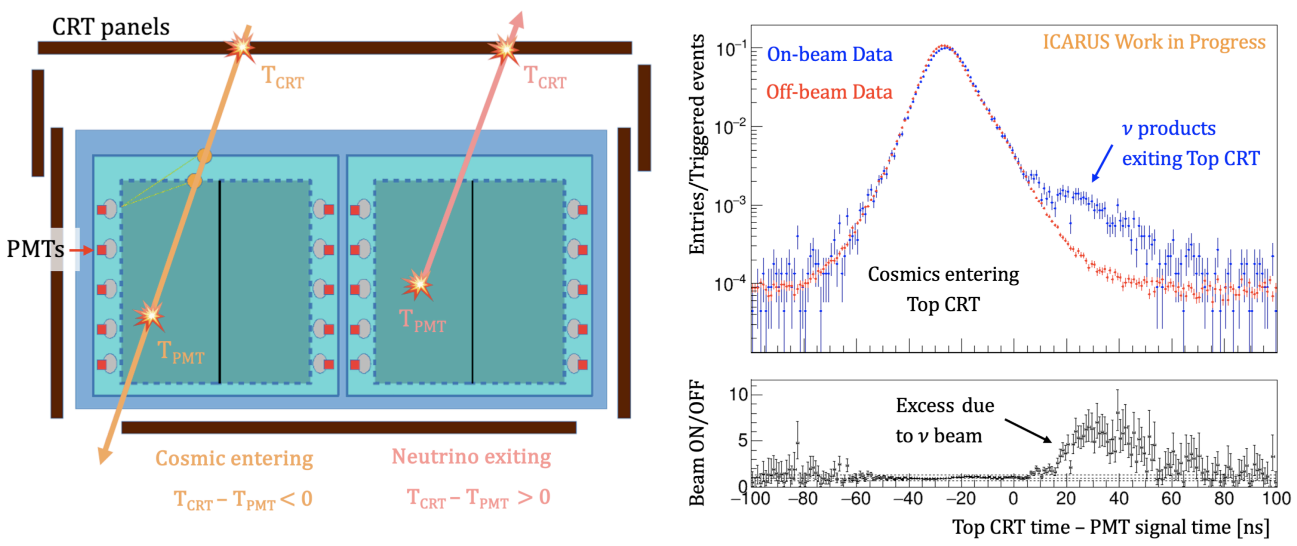
Collected POT (x10^{20})	BNB	NuMI (ν)	NuMI ($\bar{\nu}$)
Run 1	0.41	0.68	–
Run 2	2.06	2.74	–
Run 3	1.36	–	2.82
Run 4 (Ongoing)	2.98	–	–
Total	6.81	3.42	2.82

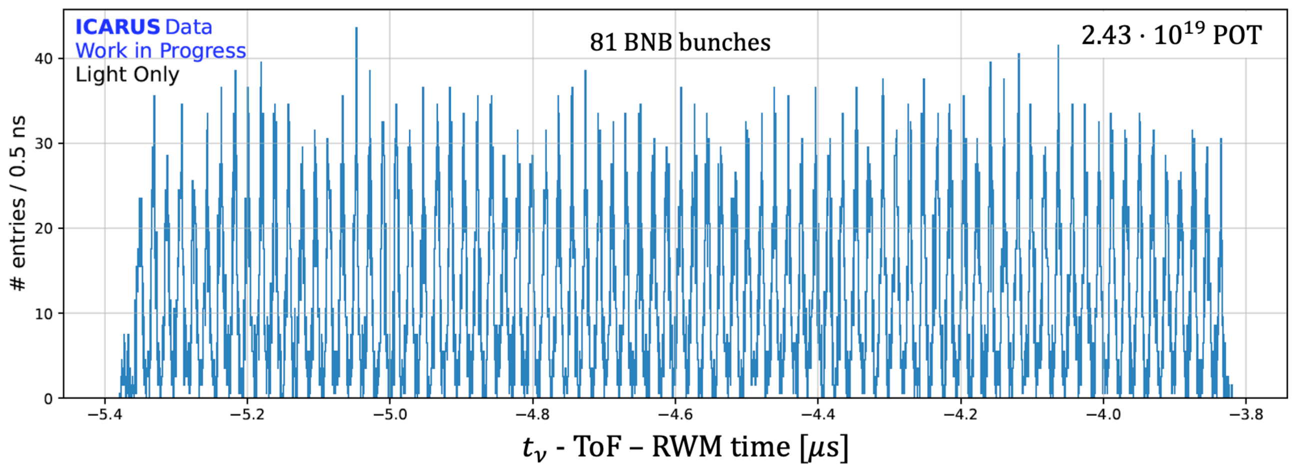


ICARUS Performance

Beam Structure

- Using the CRT and PMT systems we can distinguish cosmic ray activity from beam neutrinos
- Light barycenter can locate the position of the interaction in the TPC
- Combining this information we can recover the bunch structure of the BNB
    - ~19 ns between 81 bunches of protons hitting the BNB target
    - Meson decays preserve these timing peaks with 3 ns resolution
- Can do the same for NuMI as well





doi:10.3390/particles8010018

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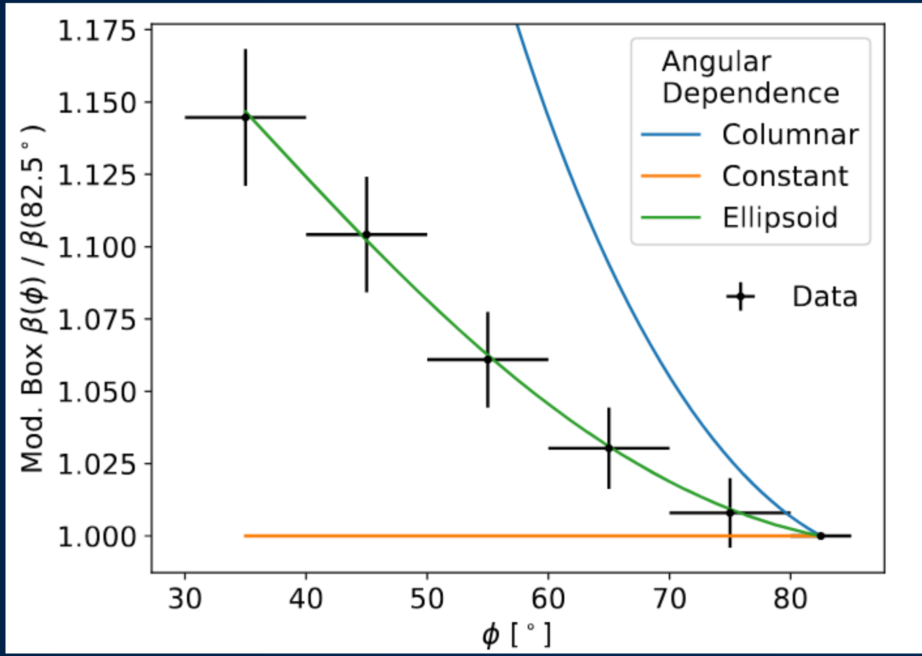
ICARUS Performance

Detector Physics

- We have measured the angular dependance of election-ion recombination in liquid argon
- Understanding this angular dependence is critical for calibrating track energy in ICARUS

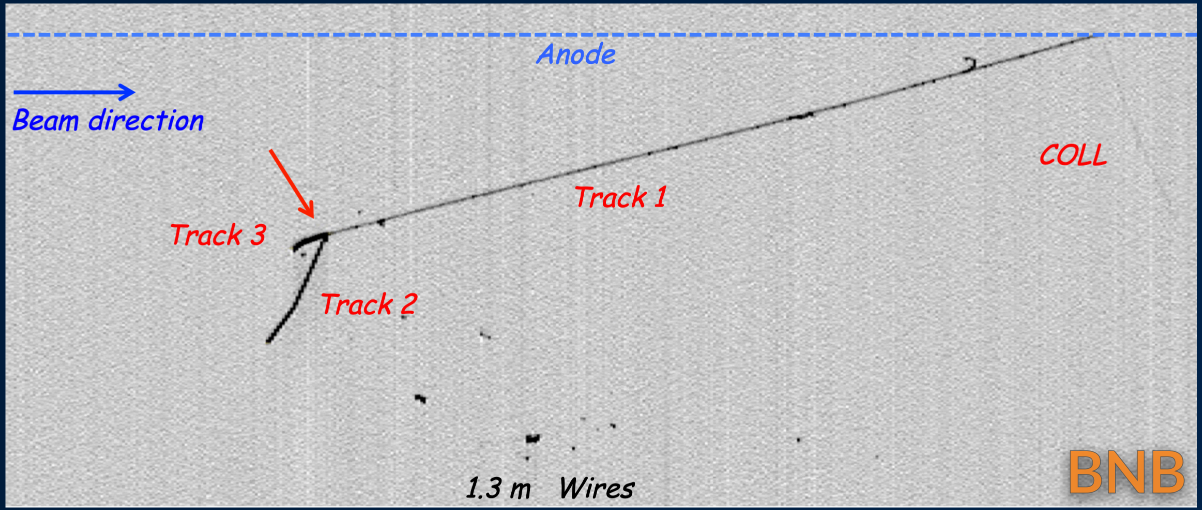


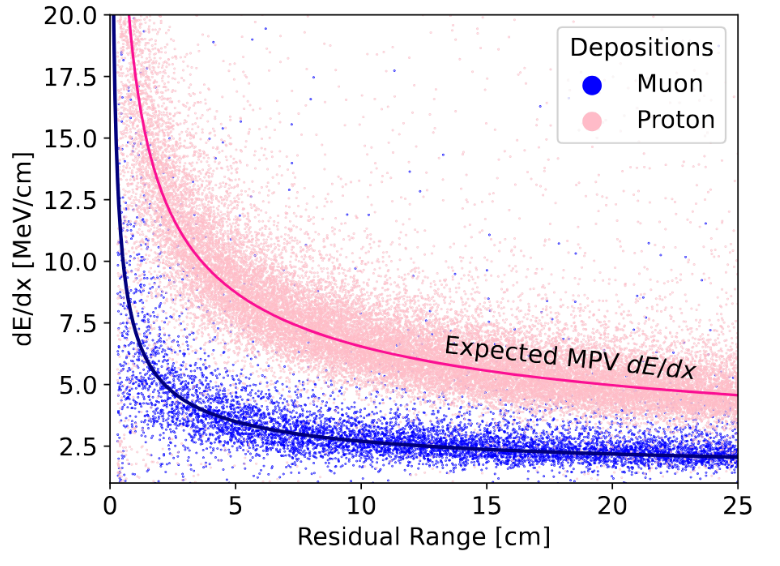
doi:10.1088/1748-0221/20/01/P01033

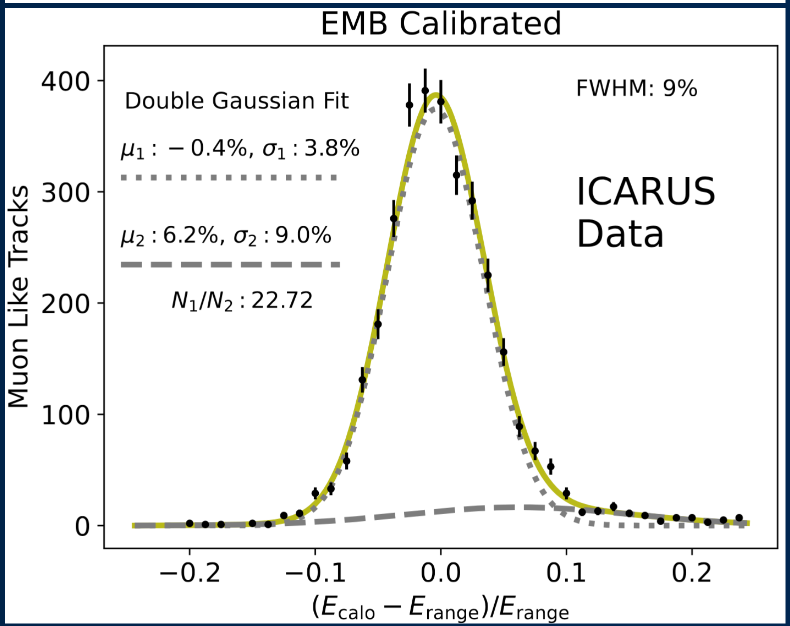
ICARUS Performance

Track Reconstruction

- Track in ICARUS are well reconstructed
- With our detector energy scale well calibrated we can distinguish muons and protons by their stopping power profiles
- Energy estimation from stopping power profile is in good agreement with range based approaches







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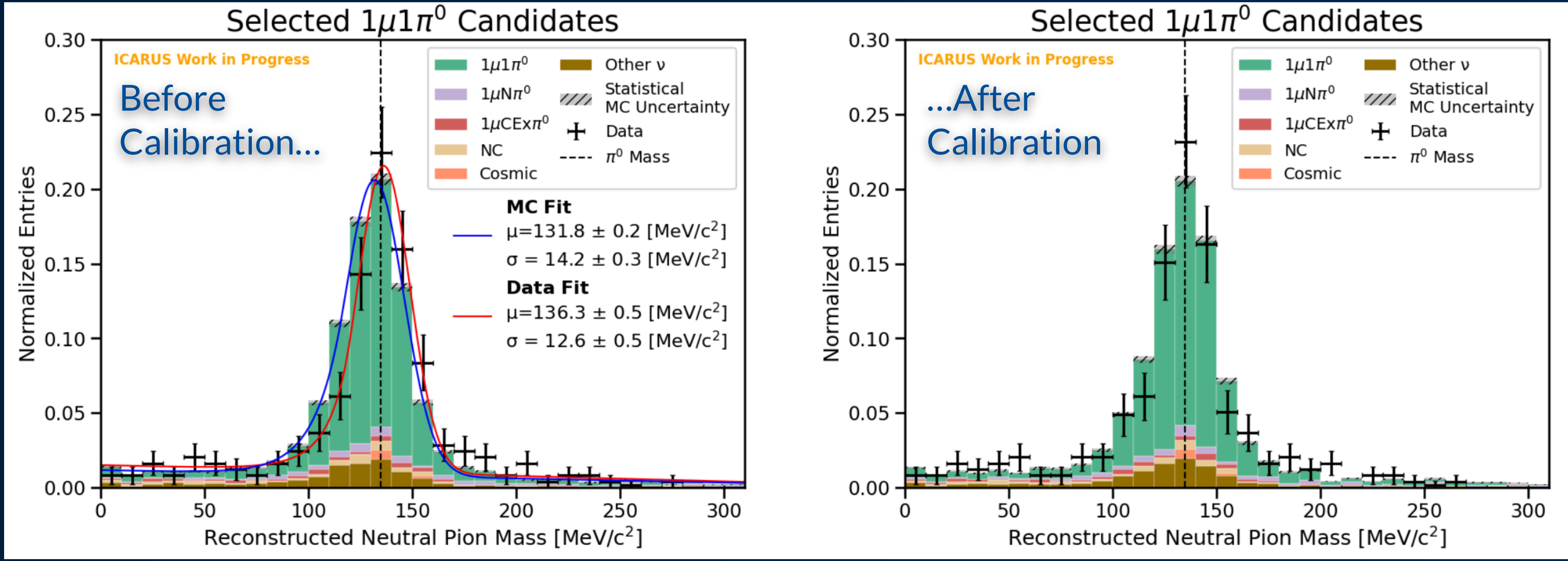
ICARUS Performance

Shower Reconstruction



Kashur, L.; Mueller, J.; Muon Neutrino Reconstruction at ICARUS with Machine Learning. June 2024

- Shower reconstruction is progressing well
- Preliminary results using the neutral pion mass peak we are able to calibrate our showers to ~10%

Physics ICARUS

How We Proceed

- In preparation for the joint SBN oscillation analysis ICARUS is first pursuing single detector searches
  - These help ICARUS understand and reduce our detector systematic uncertainty
- We have a blinding policy in place to ensure our initial studies are unbiased
  - Typically 10~15% of data is unblinded for development

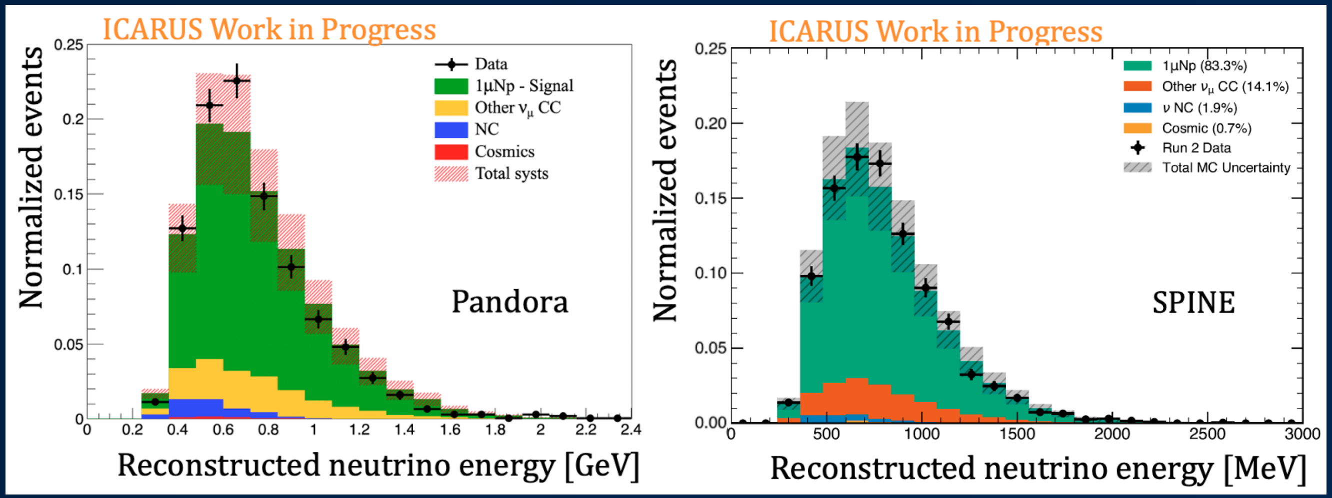
- Several analyses are in mature stages
  - BNB ν_μ Disappearance
    - Event selection ready & validated
  - Neutrino-argon cross sections with NuMI
    - Event selection validated and sidebands open
  - Beyond the Standard Model Physics with NuMI
    - Signal box opened for dimuon decay channel

ICARUS Results

BNB 1μNp Selection

- Selection criteria
  - TPC tracks matched to PMT signal and no CRT signal
  - Muon track longer than 50 cm
  - At least one proton track longer than 2.3 cm
  - No pions or photons

- Two independent reconstruction techniques for identifying 1μNp events
  - Pandora – pattern recognition
  - SPINE – machine learning
- Good data/MC agreement for both methods with 10% of Run2 BNB data
- Will contribute to ICARUS and Joint SBN oscillation results



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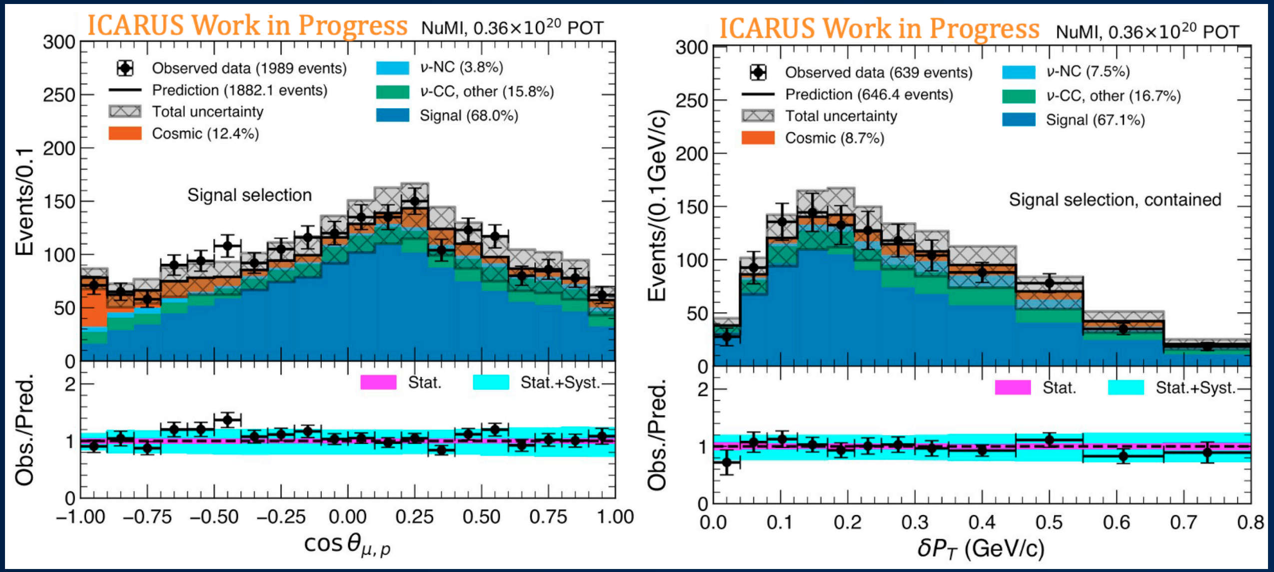
ICARUS Results

NuMI Neutrino-Argon Cross Sections

- Selection Criteria
  - Single muon longer than 50 cm
  - leading proton momentum between 0.4 and 1 GeV/c
  - No charged or neutral hadrons
- Studies with 15% of our Run1/Run2 NuMI data shows good data/MC agreement



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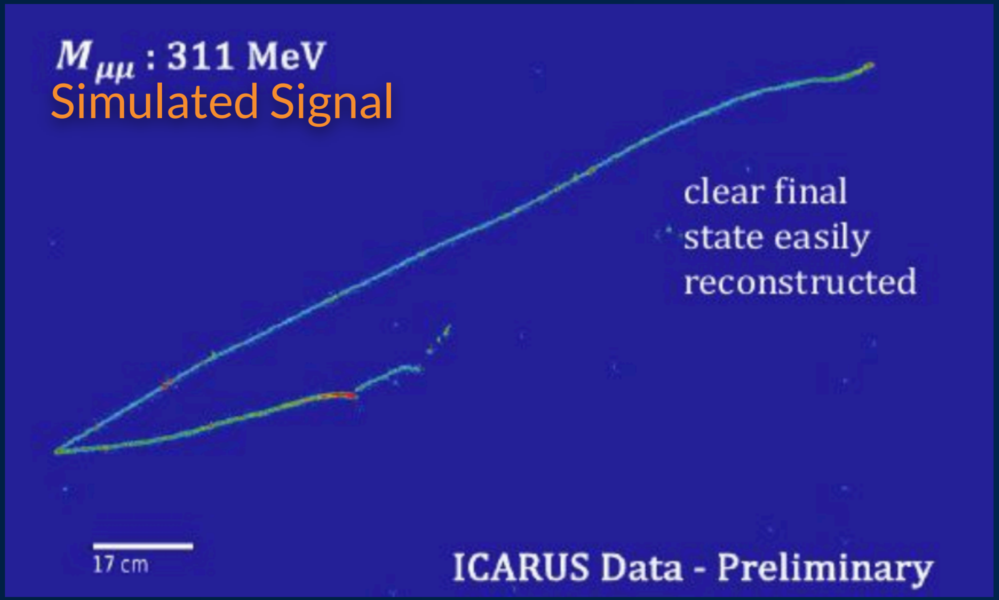
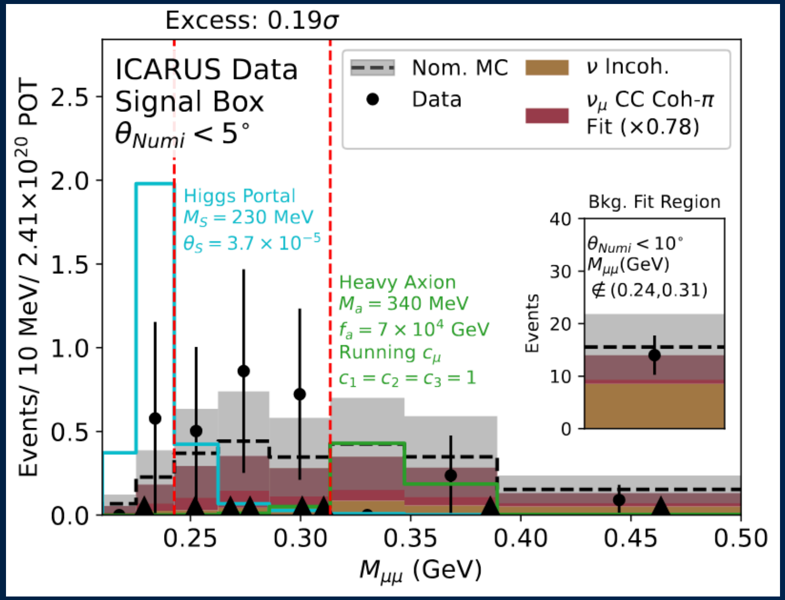
- Our NuMI data are critical for measuring neutrino-argon cross sections are energies applicable for DUNE
- Work in progress on a 1μNp0π cross section result

ICARUS Results

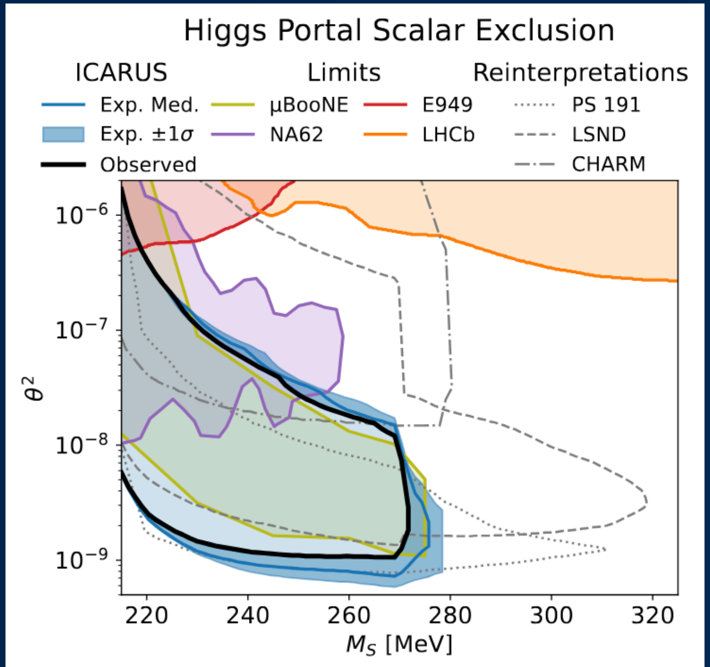
Dimuon BSM Search

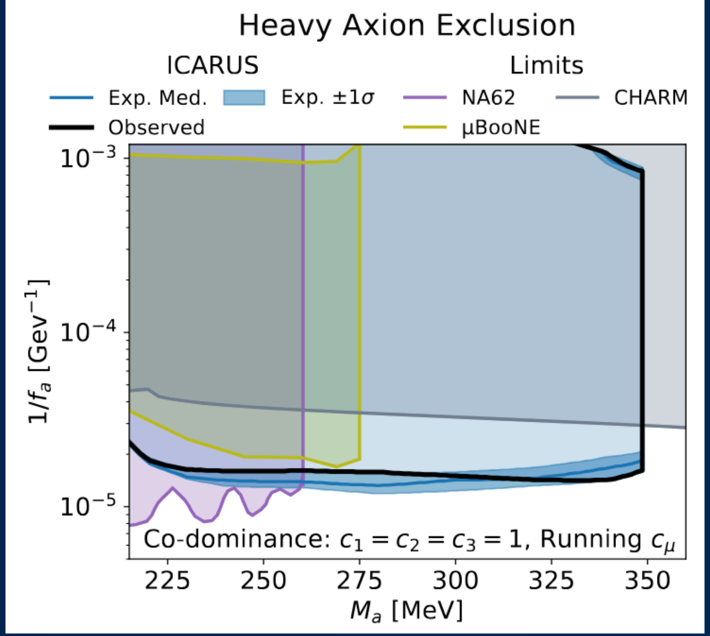
- ICARUS has also searched for long lived particles produced from kaon decay in the NuMI beam
- 9 candidate events compatible with expectations from ν_μCC background
- No significant signal





doi:10.48550/arXiv.2411.02727





doi:10.48550/arXiv.2411.02727

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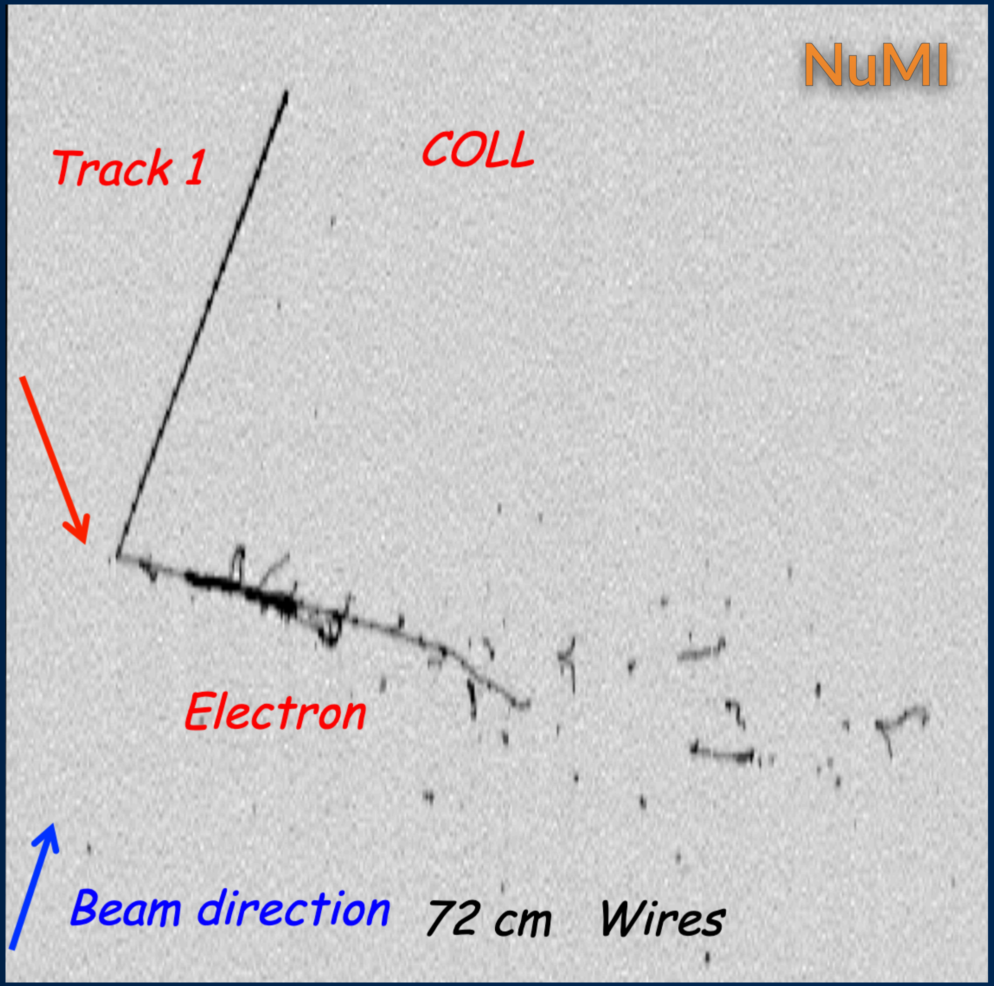
ICARUS Perspectives

Future Analyses

- Starting analyses on ν_e from BNB and NuMI
  - These analyses will complement our ν_μ disappearance search
- With SBND online and taking data we are getting closer to a joint SBN oscillations analysis



ICARUS

Summary

- ICARUS is in an exciting position to explore new physics
- With our BNB data we are progressing towards a ν_μ disappearance result
  - Single detector search making good progress
  - SBN joint analysis will provide most sensitive short baseline oscillation measurement
- NuMI beam provides excellent opportunity to measure neutrino-argon cross sections
  - These results will pave the way for physics with DUNE
- Additional analyses with ICARUS improve constraints on BSM physics
- And much more to come!

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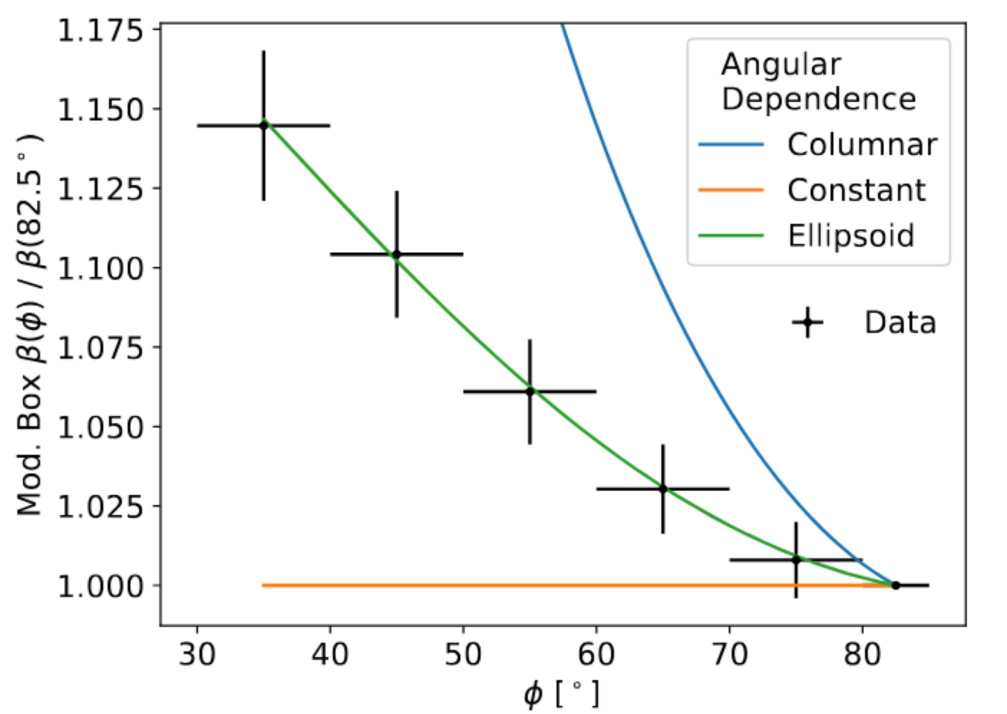
Ellipsoidal Modified Box Model

Detector Physics



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$$\frac{dQ}{dx} = \frac{\log\left(\alpha + \mathscr{B}(\phi)\frac{dE}{dx}\right)}{\mathscr{B}(\phi)W_{\text{ion}}}$$

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

α: 0.904 ± 0.008 $\quad R$: 1.25 ± 0.02

β_{90}: 0.204 ± 0.008 (kV/MeV)(g/mL),

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