ICARUS at Fermilab
Status and Perspectives

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for the ICARUS Collaboration

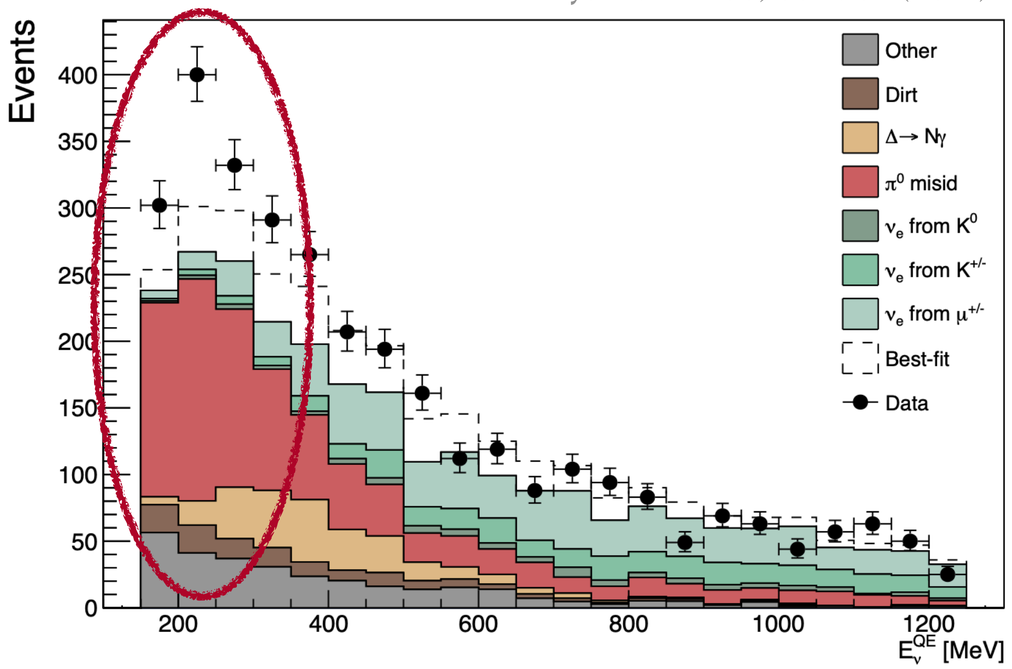
TAUP August 29 2023

The Short Baseline Neutrino Program

Main goal: address the anomalous results from past neutrino experiments (LSND, MiniBooNE), which could be explained by the possible existence of at least one **sterile neutrino**.

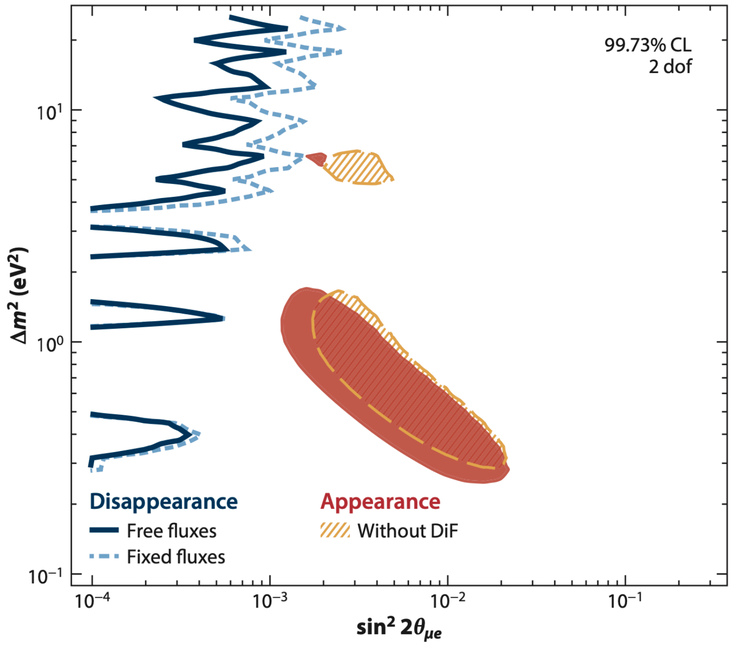
The Short Baseline Neutrino (SBN) Program will make precision measurements while providing a development platform for liquid argon time projection chambers (LArTPC) useful for future experiments (DUNE).

Phys. Rev. D 103, 052002 (2021)



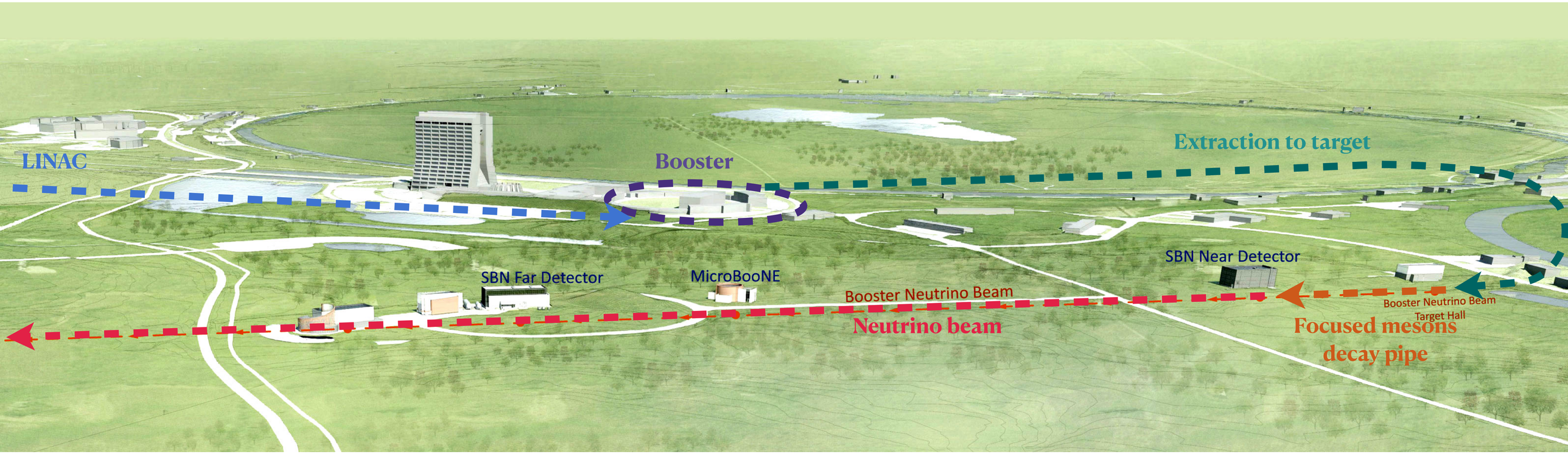
MiniBooNE's neutrino mode energy distribution. Best fit to neutrino mode data assuming 2-neutrino oscillations

Figure adapted from JHEP 08, 010 (2018)



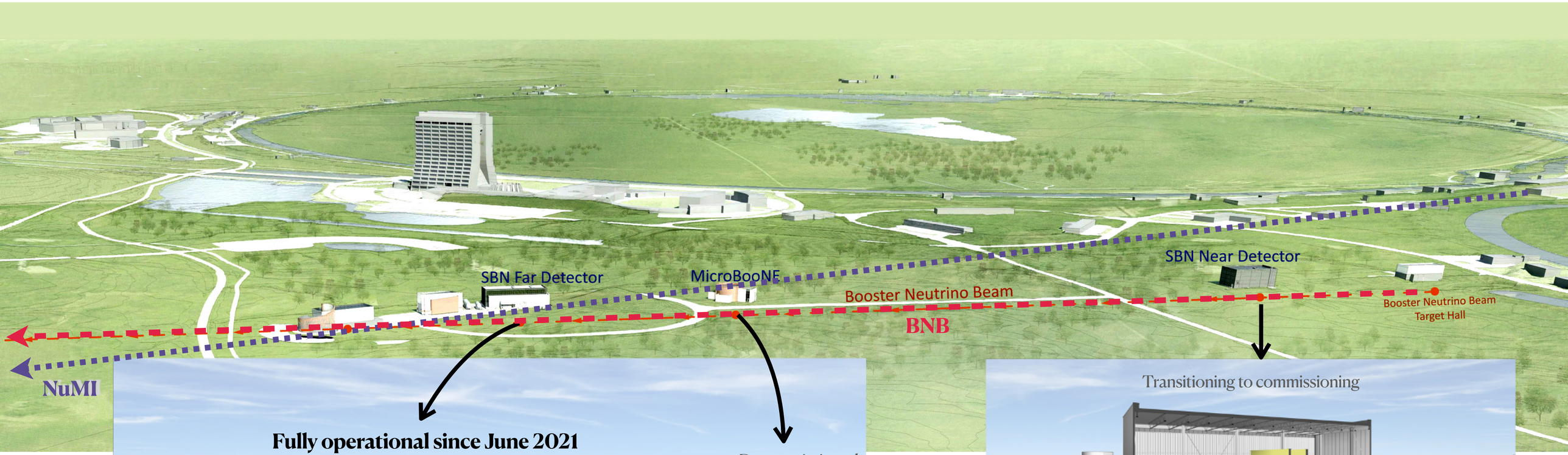
MiniBooNE's allowed oscillation parameter regions with simplified 2-neutrino oscillations model.

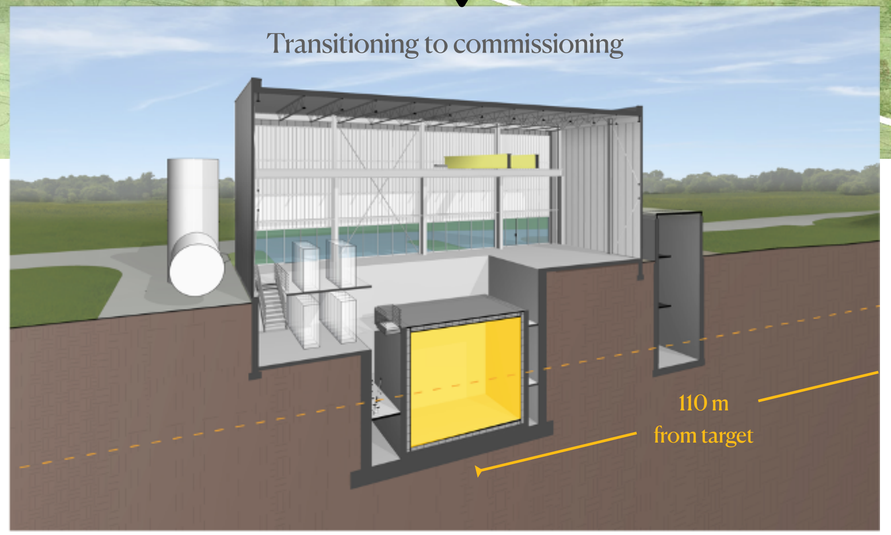
The Short Baseline Neutrino Program



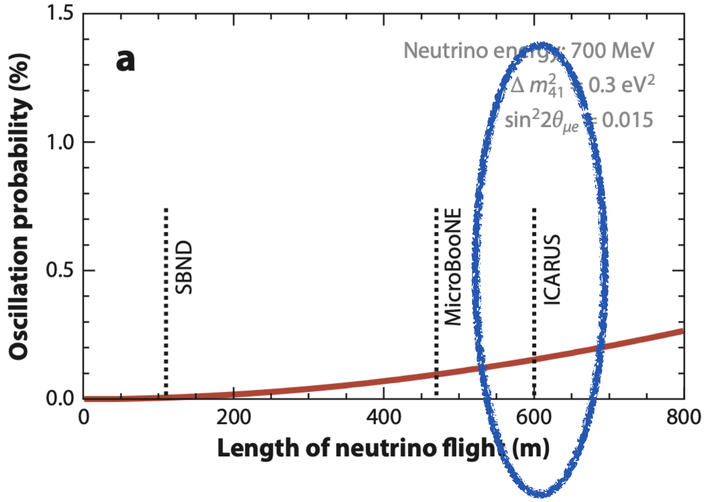
The 3 SBN detectors share the same nuclear target and similar technologies: liquid argon time projection chambers (LAr TPCs). The detectors are strategically placed to look for neutrino oscillations at short baselines and low energy range along Fermilab's **Booster Neutrino Beam** (BNB).

The Short Baseline Neutrino Program

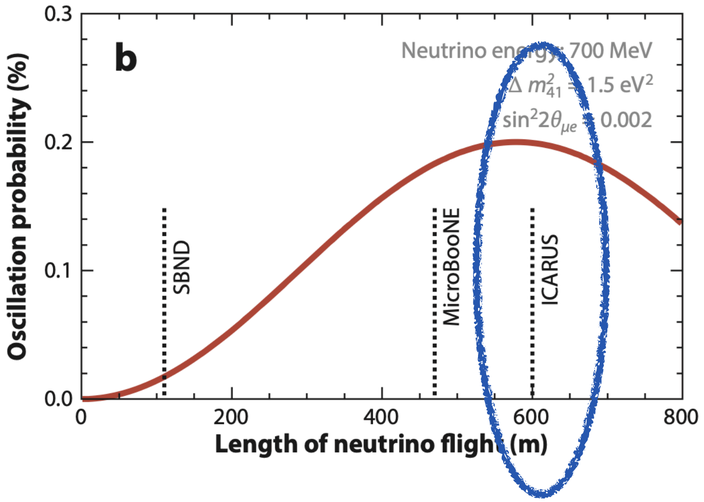




The Short Baseline Neutrino Program

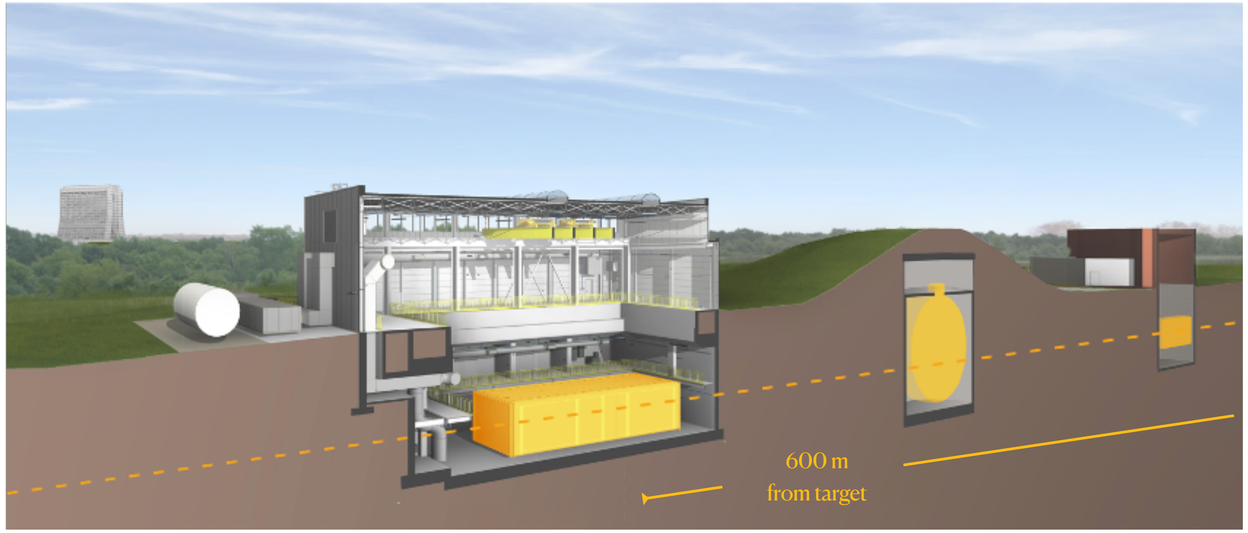


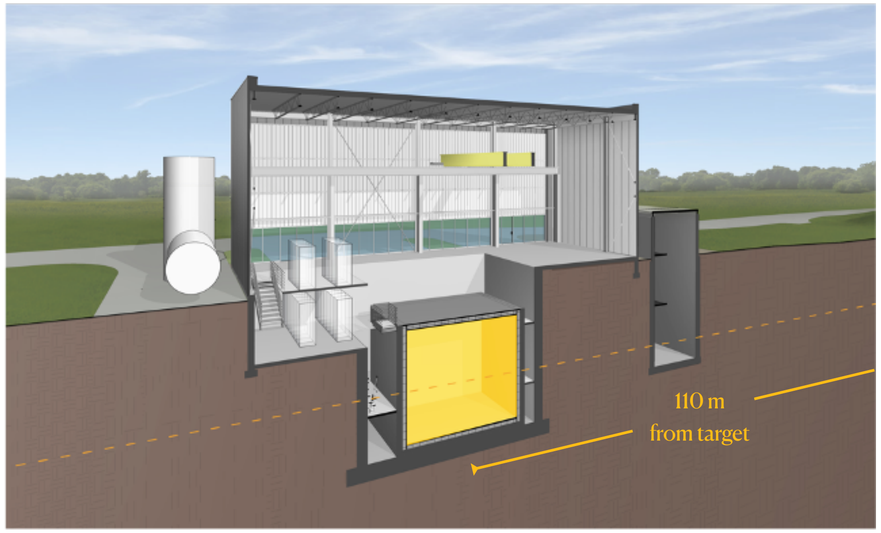
Annu. Rev. Nucl. Part. Sci. 2019 DOI 10.1146



The far detector plays a fundamental role on searching for sterile neutrinos at the eV scale using same beam as MiniBooNE.

ICARUS will **measuring the oscillated neutrino fluxes**, essential for performing simultaneous appearance and disappearance fits.





ICARUS Detector

The detector first operated at the Gran Sasso underground Laboratory (Italy), collecting data from the LNGS beam for 3 years.

Upgraded for on-surface operations before moving to Fermilab (USA) in 2018.

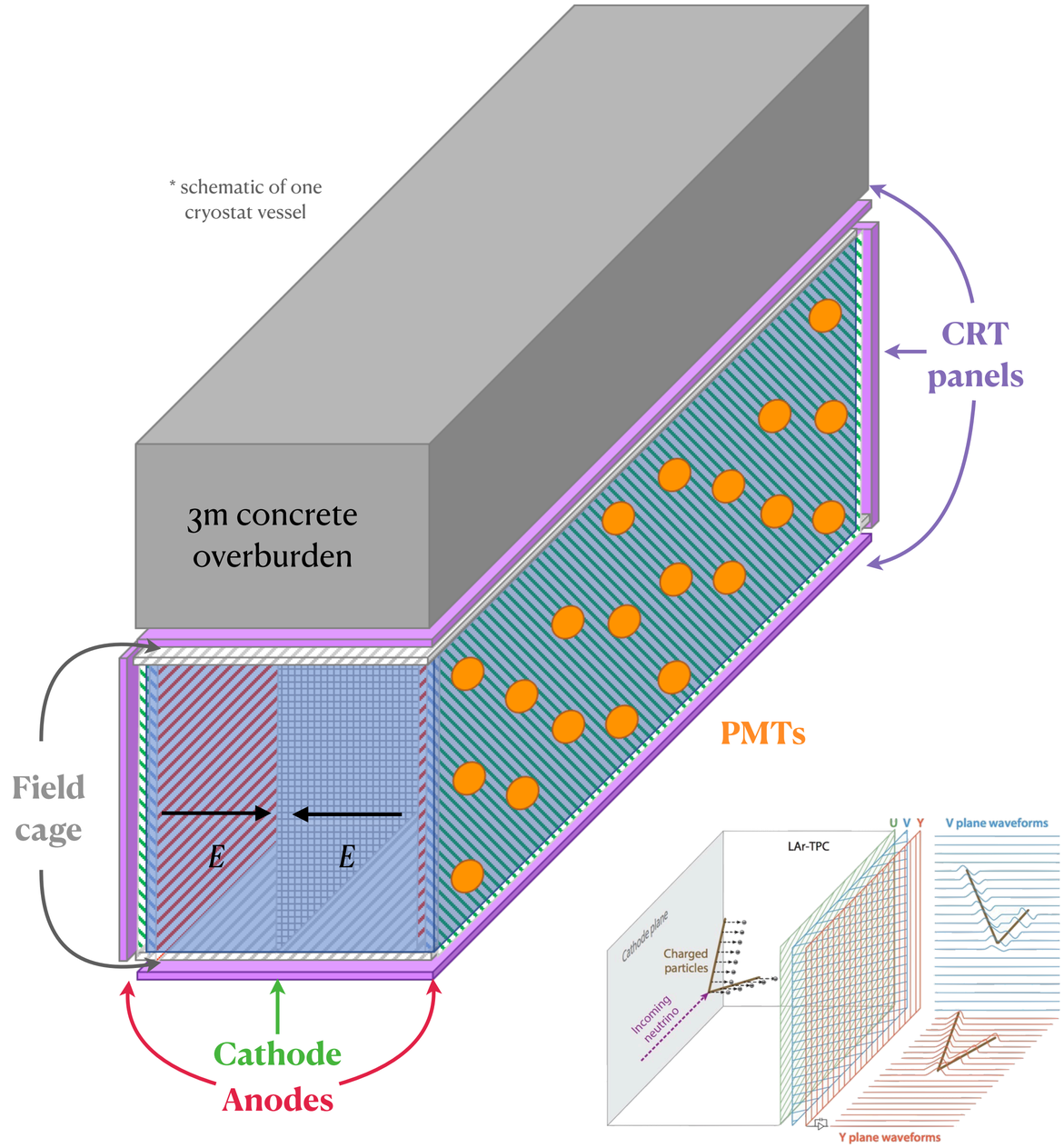
ICARUS Detector

Liquid Argon Time Projection Chamber

2 modules each containing 2 TPCs (4 TPCs total):
one central cathode is shared by **two anodes**.
Wire pitch = 3mm.

Field cage maintains 500 V/m drift field.
drift velocity = 1.6 mm/ms

Event characterisation: identification of final state particle and reconstruction of their kinematics.
Low energy threshold: recognise low hadronic energy events .



ICARUS Detector

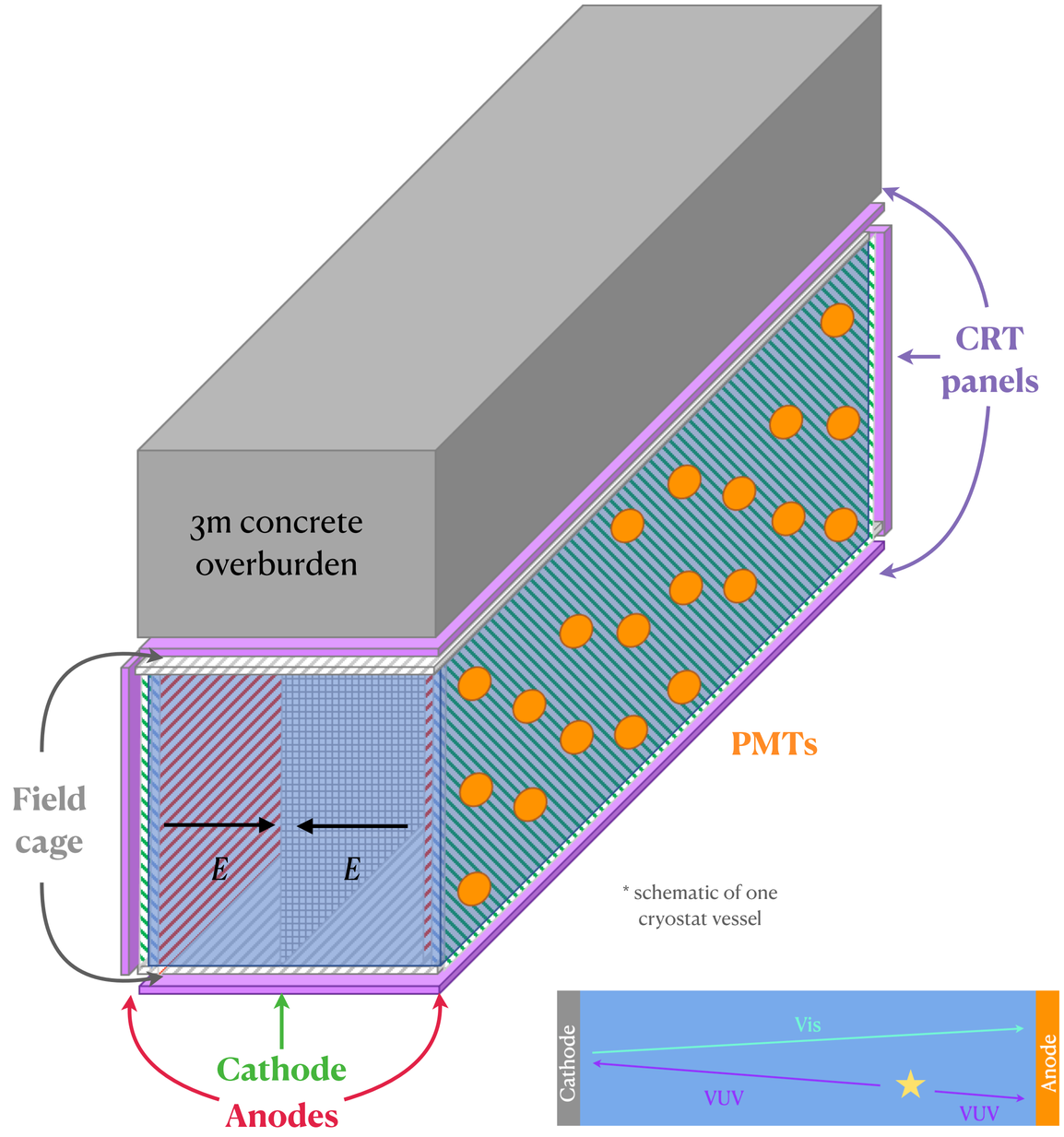
Photon and cosmic detection

Photo multiplier tubes (PMTs) located behind anodes complements 3D tracking and timing.

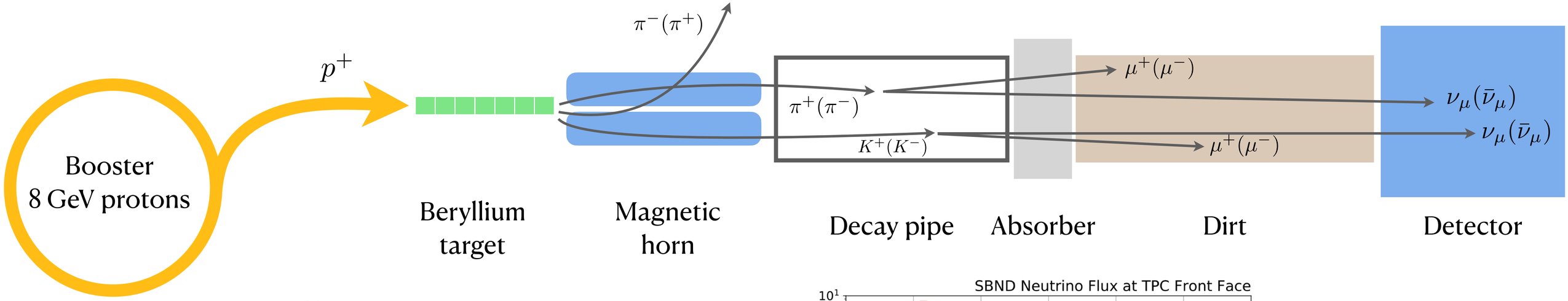
Cosmic ray tagger (CRT) gives full coverage with extruded scintillator strips planes for discriminating incoming and outgoing charged particles.

Overburden for further cosmic ray background reduction.

Thursday, session 7B, M. Cicerchia
Study of Cosmic Ray in the ICARUS T-600 detectors



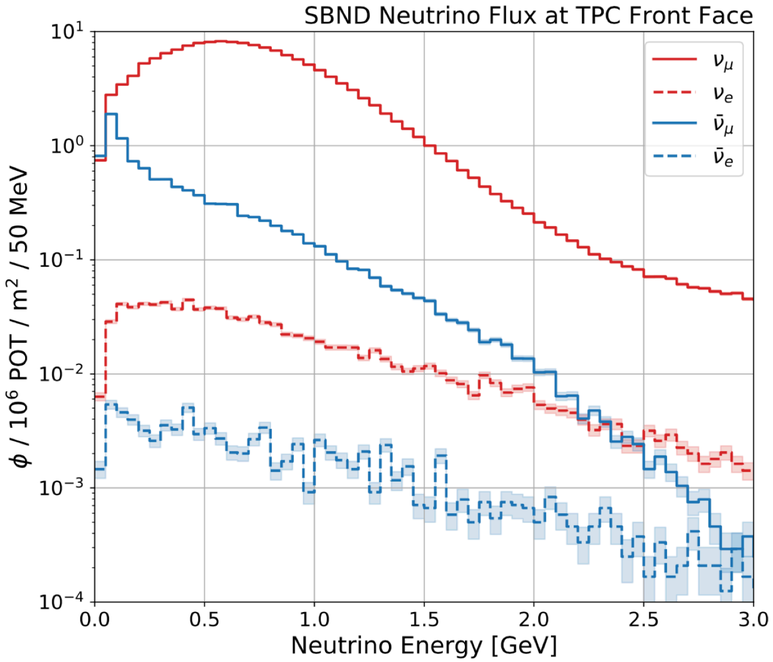
Neutrino Flux

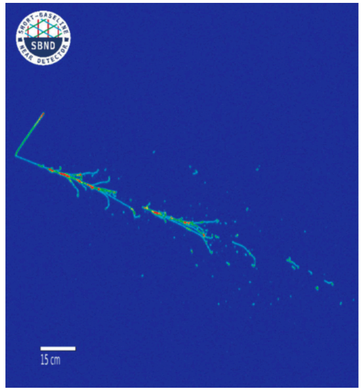


Mean ν_μ energy is about 0.8 GeV
at the near detector (SBND)
Beam composition:
ν_μ (93.6%)
$\bar{\nu}_\mu$ (5.9%)
$\nu_e + \bar{\nu}_e$ (0.5%)

Plan to collect BNB and NuMI data[1] until FNAL's accelerator complex long shutdown (Summer 2027).

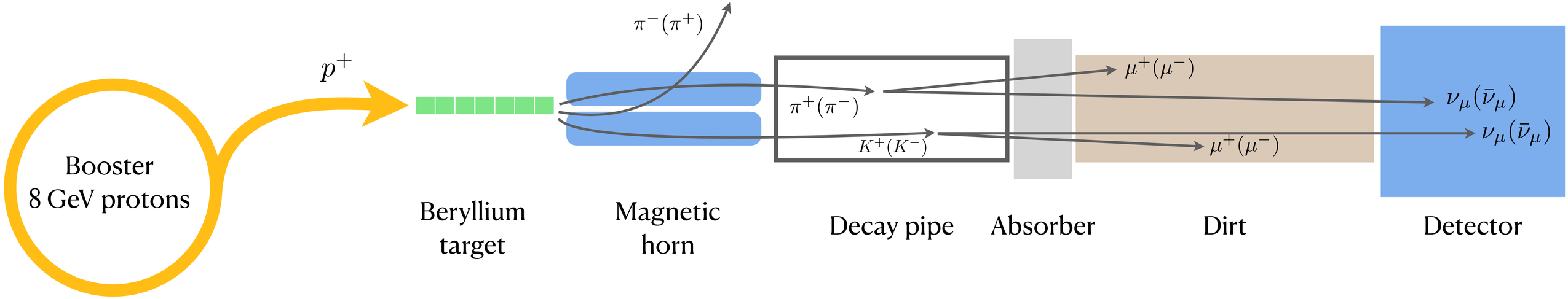
[1] Quantified in protons on target (POT).





Simulated ν_e interaction in SBND

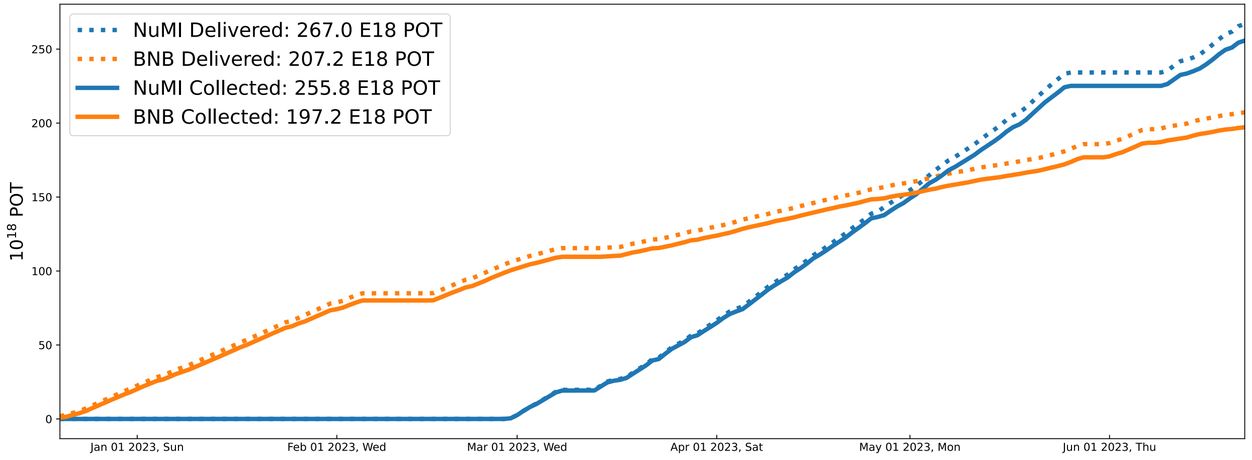
Neutrino Flux



ICARUS began operations on surface in early 2020, and physics data taking in Summer 2022.

Commissioning data is used to understand detector performance and simulation tuning for physics analysis[1].

Working on analysis of physics data collected collected over the last year: BNB and NuMI with >95% efficiency.

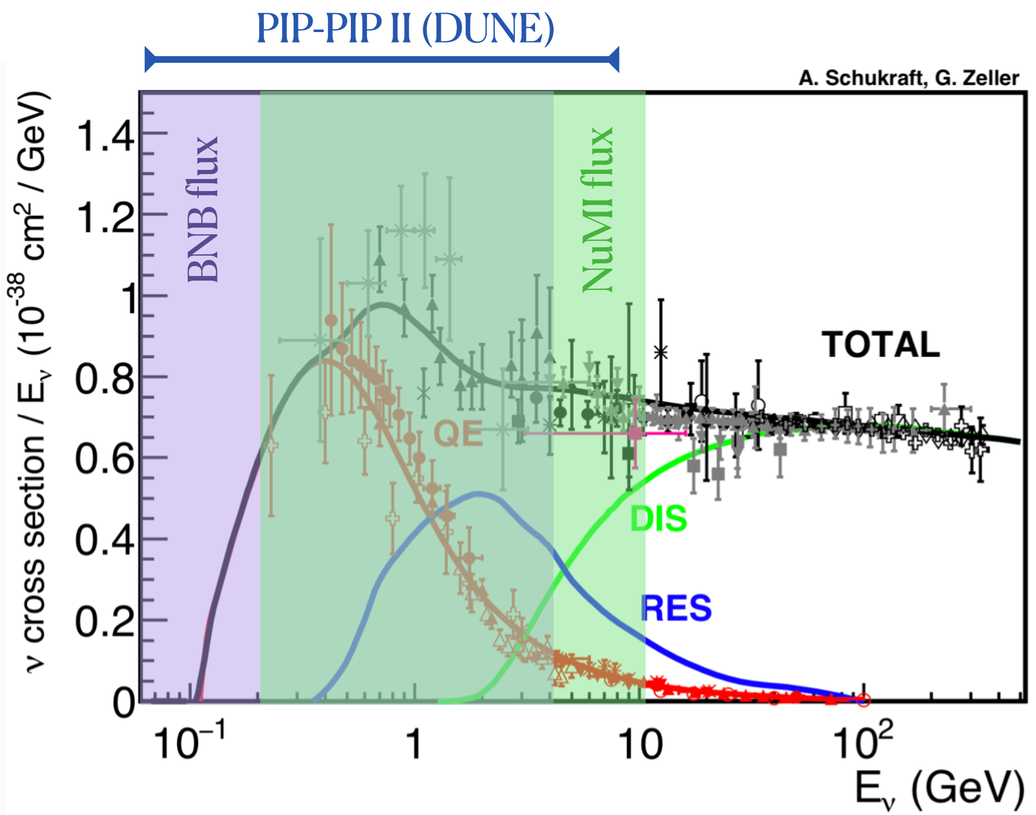


Neutrino beam data collection performance for Run II.

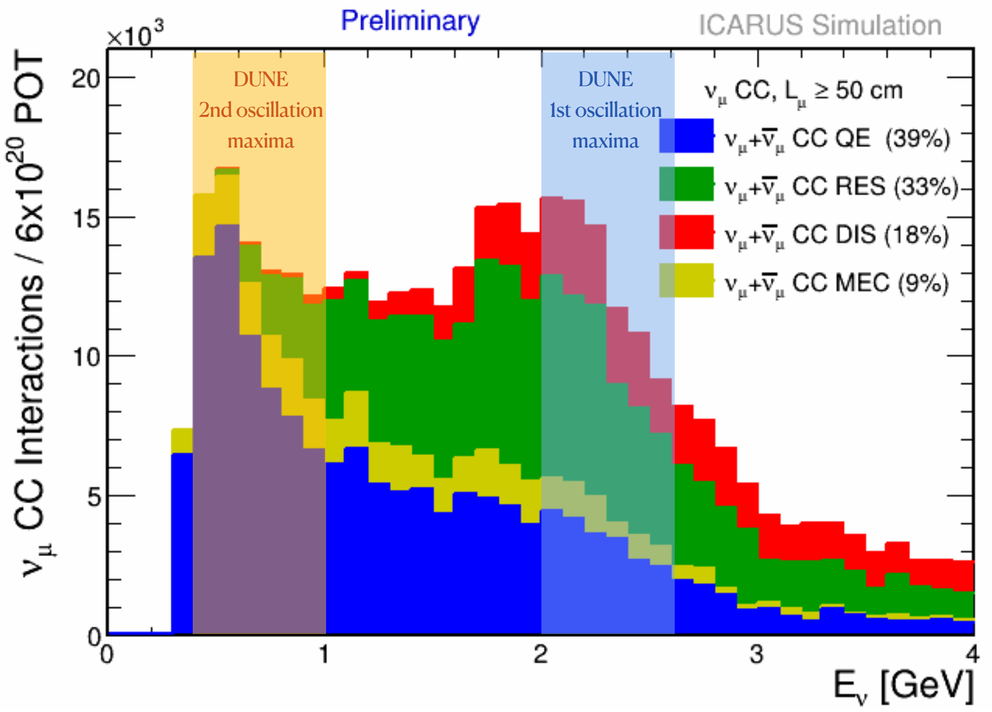
[1] ICARUS at the Fermilab Short-Baseline Neutrino Program: Initial Operation.

Neutrino flux

Cross section and interaction models



Muon Neutrino



Measure nuclear effects and asses impact on final states and kinematics.

Perform precise cross-section measurements (for SBN program and long baseline).

Inform MC generators and discriminate between models (GENIE, GiBUU).

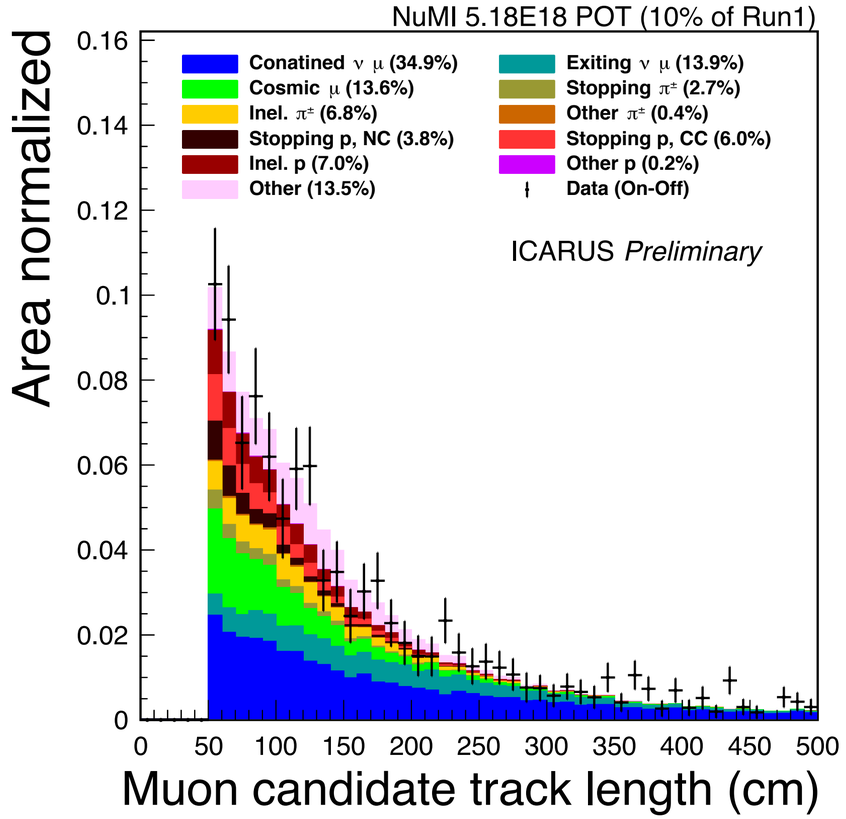
Event selection

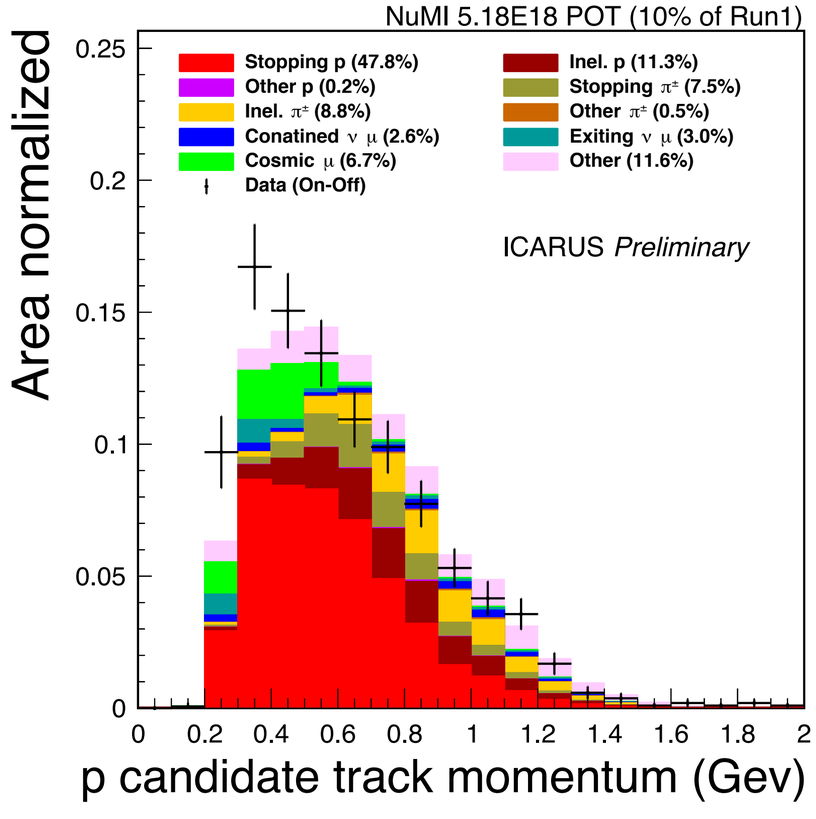
Cross sections and oscillations

Excellent particle identification and calorimetric energy reconstruction —> detector capable of discerning a wide variety of final states.

The far SBN detector have high statistics from muon and electron neutrino interactions from the **NuMI beam** for cross sections measurements.

$1\mu1p$



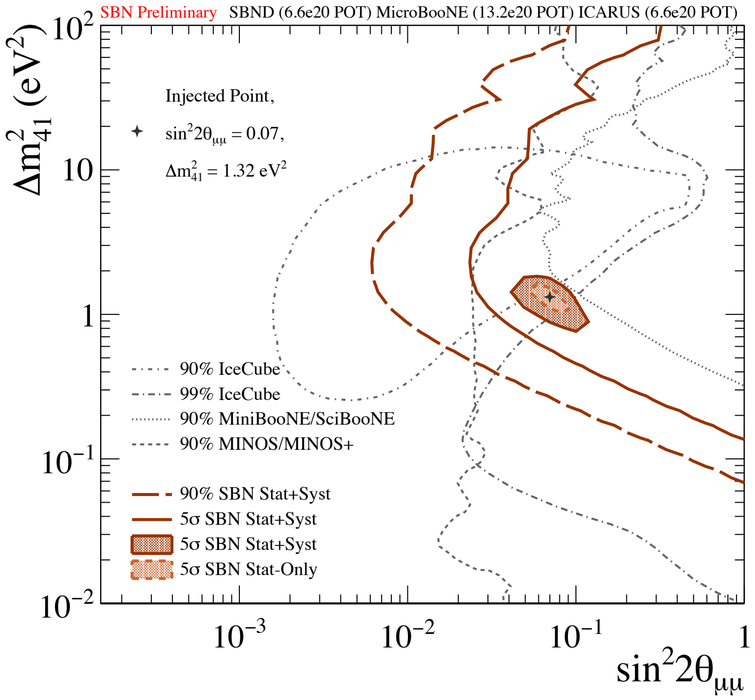


Blinding policy: 10% data

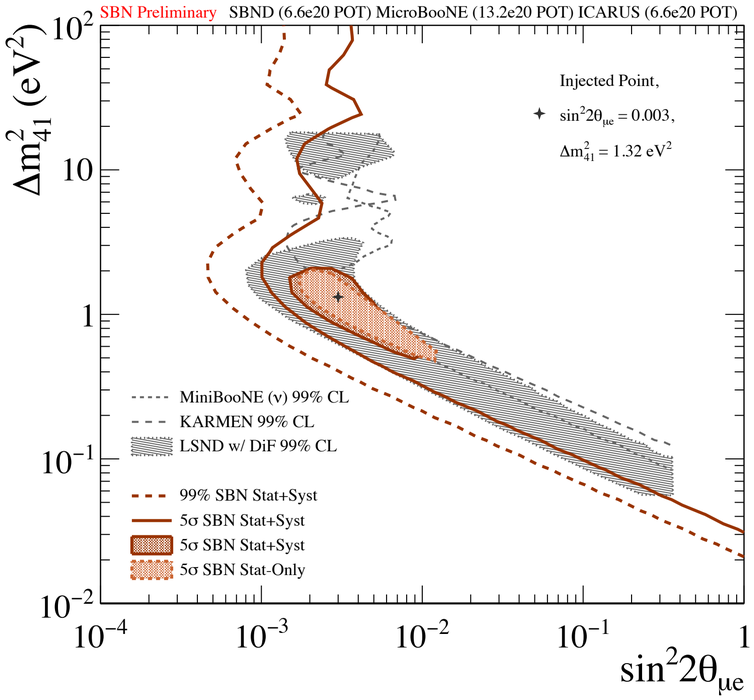
Neutrino Oscillations

Multi-detector search

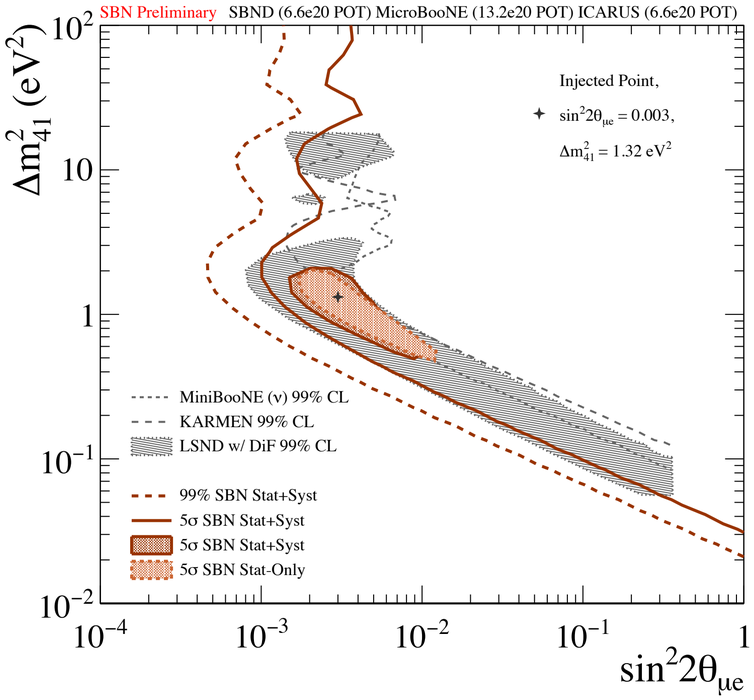
$\nu_\mu \rightarrow \nu_\mu$



$\nu_\mu \rightarrow \nu_e$



$\nu_e \rightarrow \nu_e$



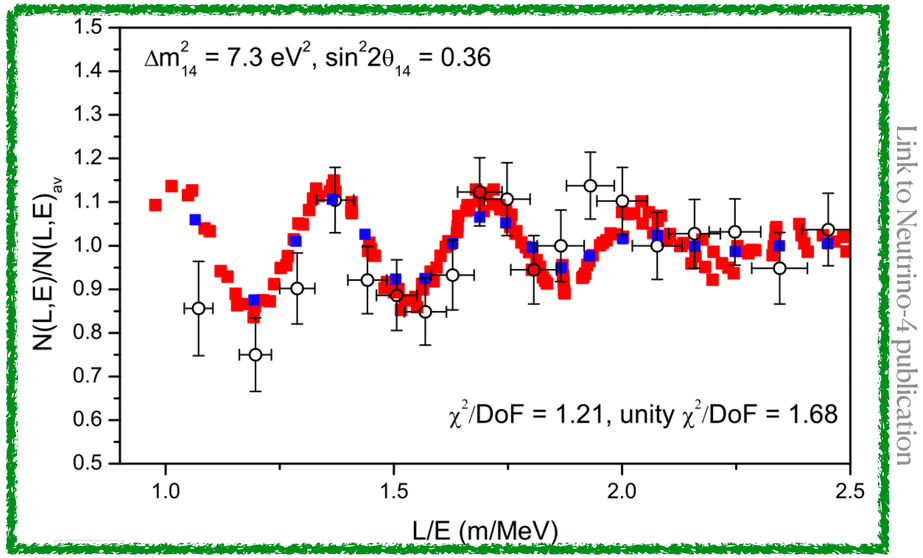
- Initial flux constrained by the near detector, oscillated measurements at far detector.
- LArTPC improves signal efficiency and shared technology decreases systematics.

Neutrino Oscillations

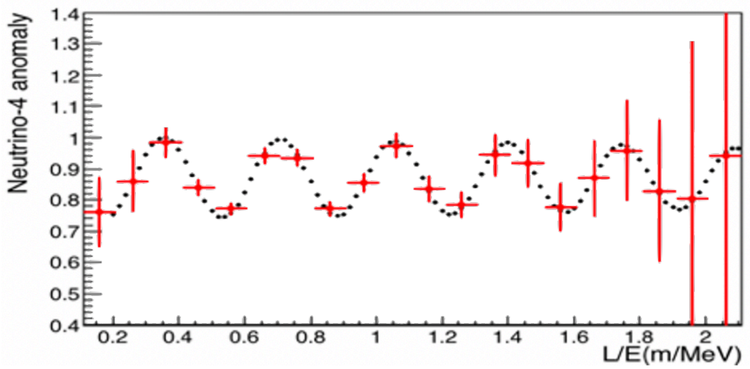
Neutrino-4 experiment reported reactor neutrino oscillations in the L/E range ~ [1,3] m/MeV.

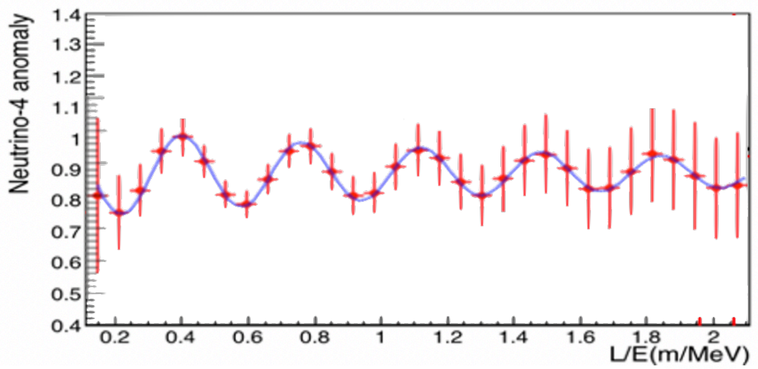
ICARUS is sensitive to the same L/E range and can probe these results with fully contained events.

- Fixed L but different E
- BNB ν_μ disappearance
- NuMI ν_e appearance



Link to Neutrino-4 publication





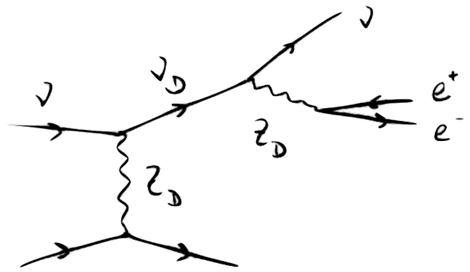
— Neutrino-4 prediction

+ expected oscillation pattern at ICARUS, stats only errors

Beyond the Standard Model Searches

Dark Neutrinos

[1] [2] [3]

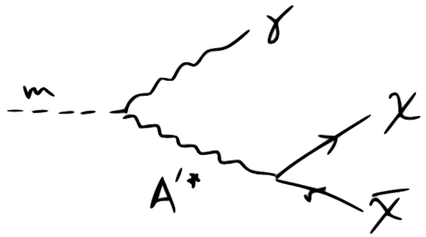


Light Dark Matter

[4]

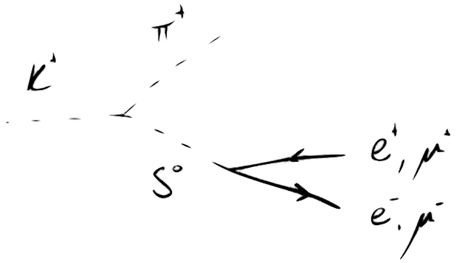
Milicharged Particles

[5] [6]



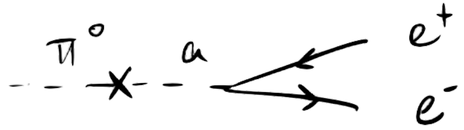
Higgs Portal Scalar

[15] [16] [17]



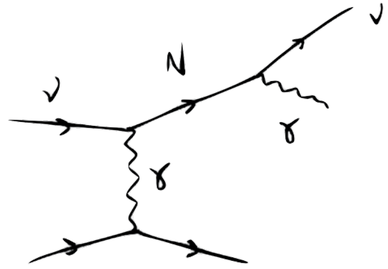
Axion-like Particles

[9] [10]



Transition Magnetic

[11] [12] [13] [14]



Alternative explanations to MiniBooNE's excess, and other BSM models:

Modifications to neutrino oscillations and new states

Diagram credit: Pedro Machado

Thursday, session 7B, J. Crespo-Anadón
Searches for BSM Physics in the SBND Neutrino Experiment

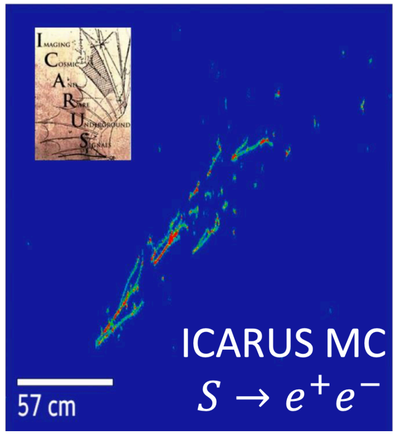
BSM searches

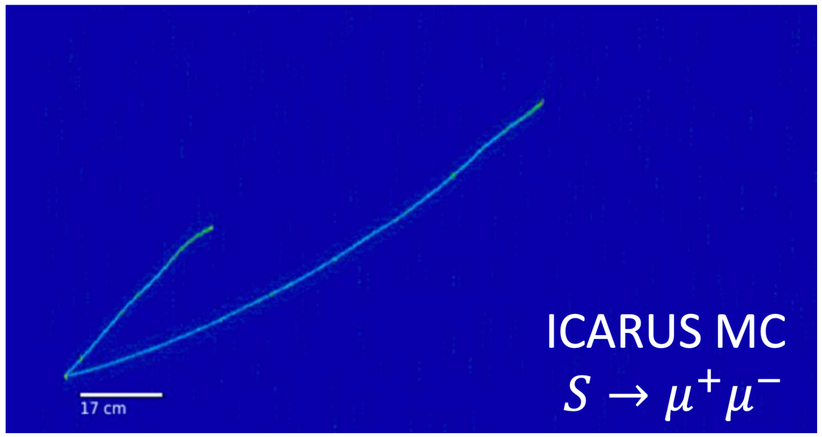
Higgs Portal

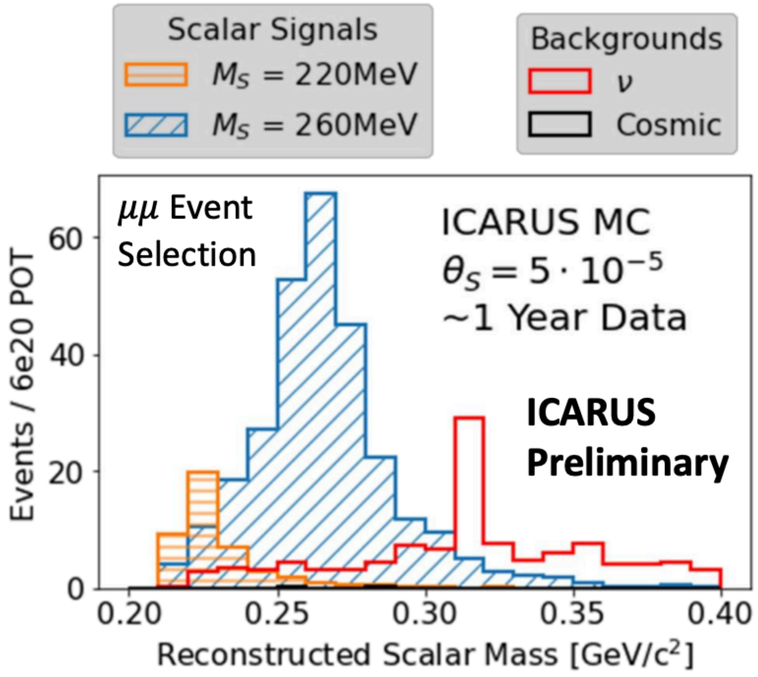
Developed selection for search of $\mu^+\mu^-$ pairs from kaon decays: it rejects most neutrino background events.

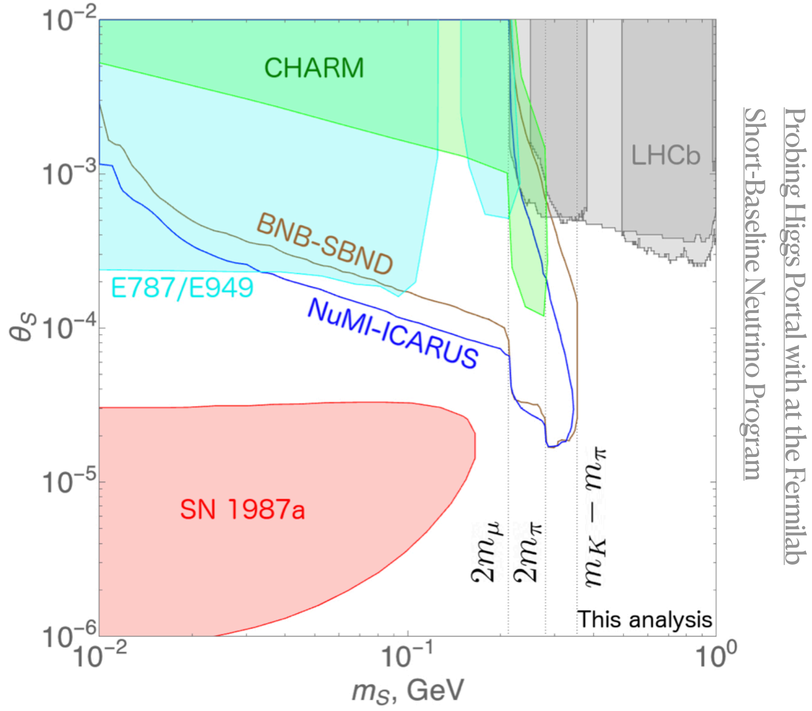
Ongoing work on e^+e^- decays and forward scattered electrons.

ICARUS has the potential to constrain the scalar mass vs mixing angle space.









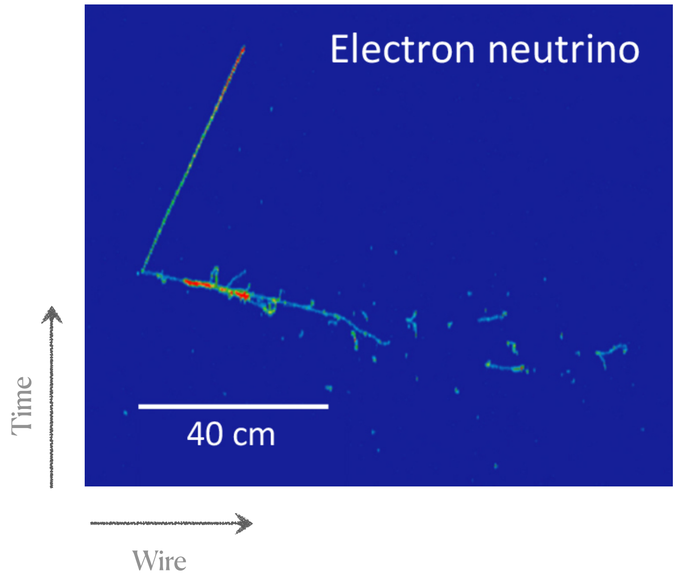
Probing Higgs Portal with at the Fermilab Short-Baseline Neutrino Program

Summary

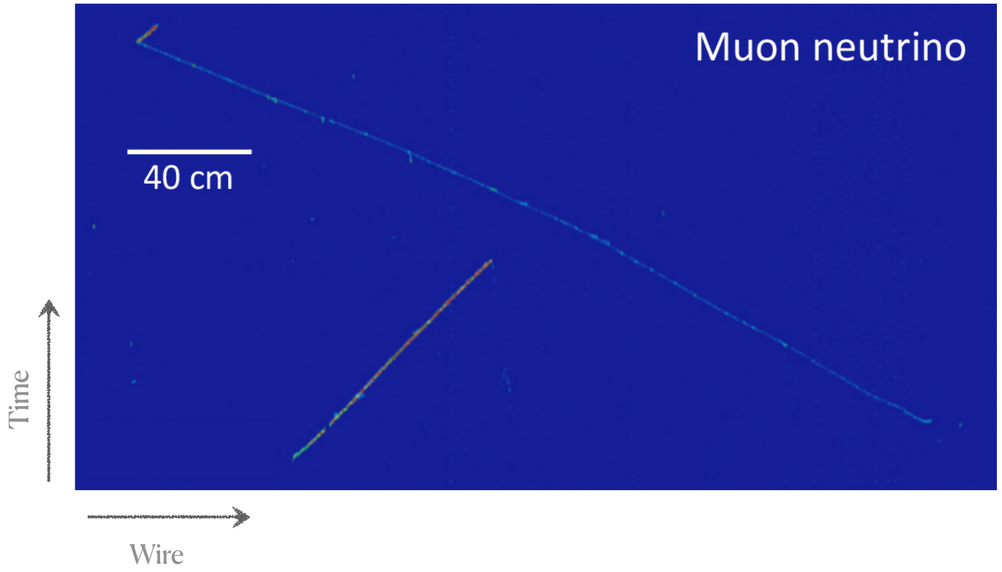
The Short Baseline Neutrino program at Fermilab has sterile neutrino oscillations and other beyond the standard model searches

- ICARUS will use BNB to measure oscillated neutrino flux in support of the SBN program.
  - It will individually probe Neutrino-4 claims.
- NuMI beam will allow
  - Precise cross-section measurements
  - Search of other BSM physics
- ICARUS will continue to collect neutrino data for the foreseeable future.

Electron neutrino candidate from NuMI beam

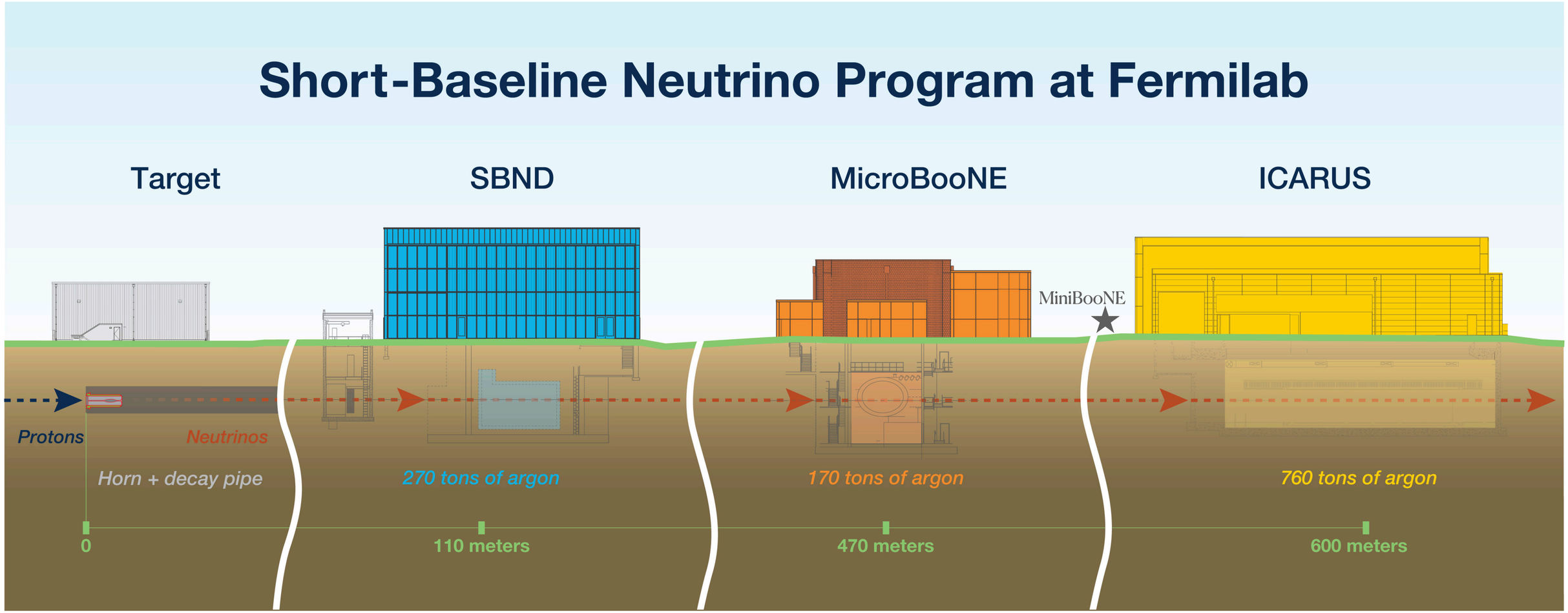


Muon neutrino candidate from BNB in one ICARUS TPC



Backup

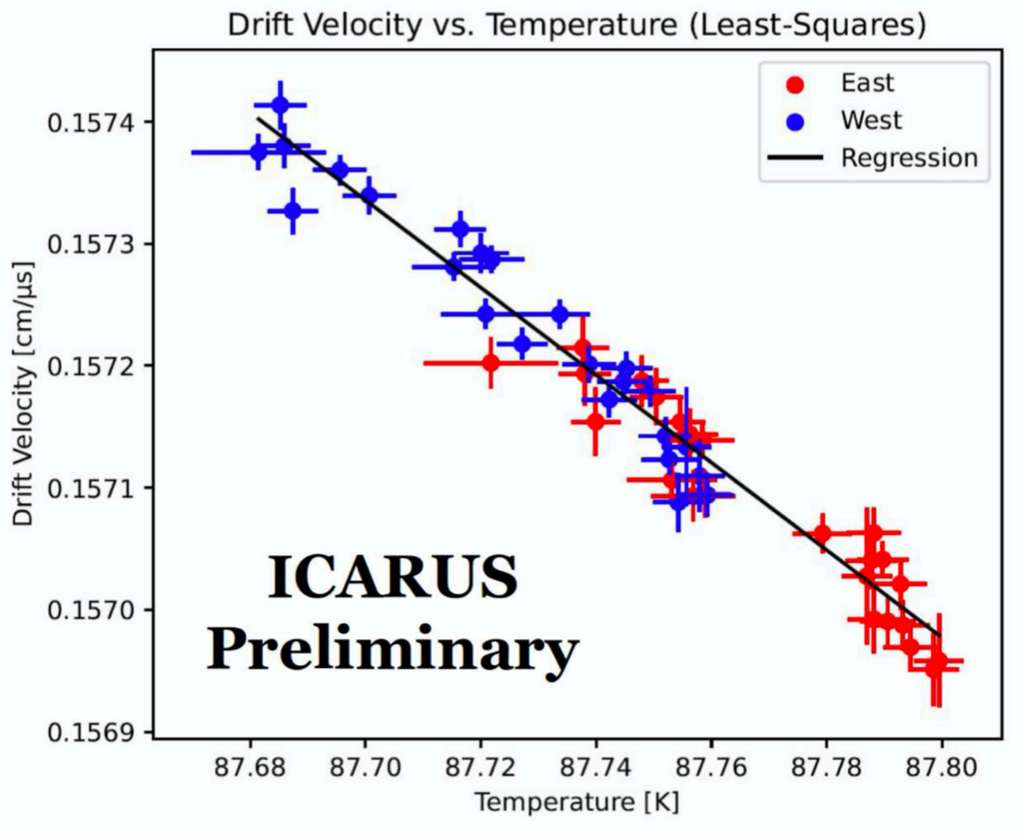
Short-Baseline Neutrino Program at Fermilab

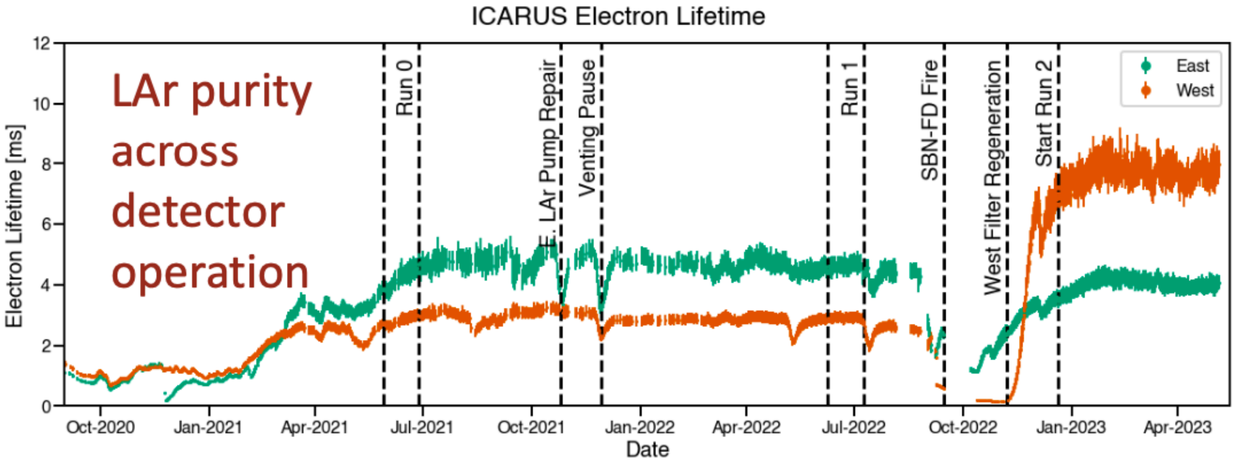


Detector assembly ongoing

Operating since October 2015

Transitioning from commissioning to stable operation

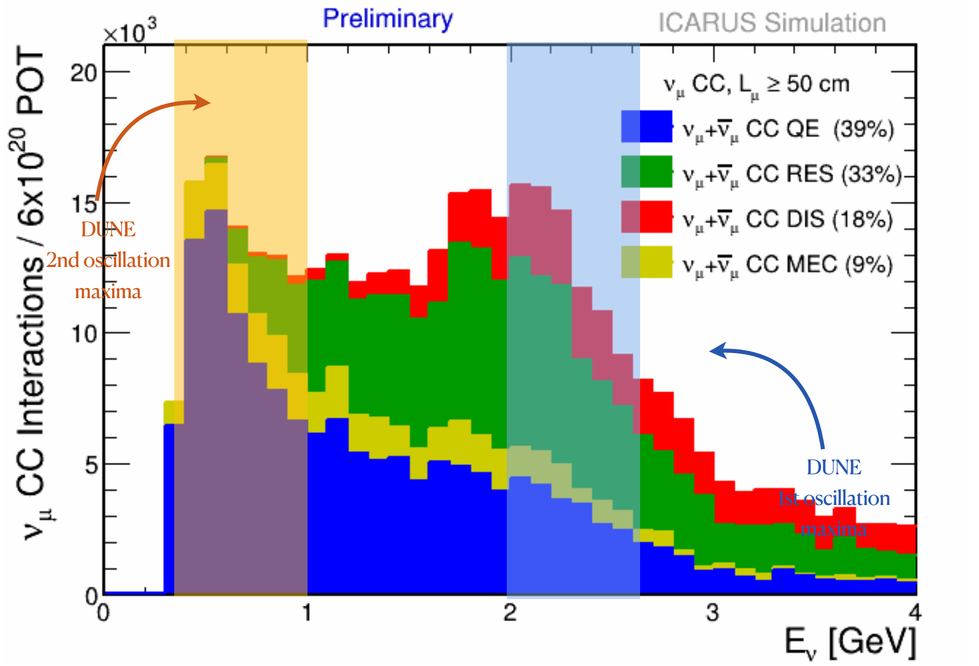

Drift Velocity vs. Temperature (Least-Squares)
East
West
Regression
ICARUS
Preliminary
Drift Velocity [cm/μs]
0.1574
0.1573
0.1572
0.1571
0.1570
0.1569
87.68
87.70
87.72
87.74
87.76
87.78
87.80
Temperature [K]


ICARUS Electron Lifetime
LAr purity across detector operation
Run 0
E. LAr Pump Repair
Venting Pause
Run 1
SBN-FD Fire
West Filter Regeneration
Start Run 2
East
West
Electron Lifetime [ms]
12
10
8
6
4
2
0
Oct-2020
Jan-2021
Apr-2021
Jul-2021
Oct-2021
Jan-2022
Apr-2022
Jul-2022
Oct-2022
Jan-2023
Apr-2023
Date

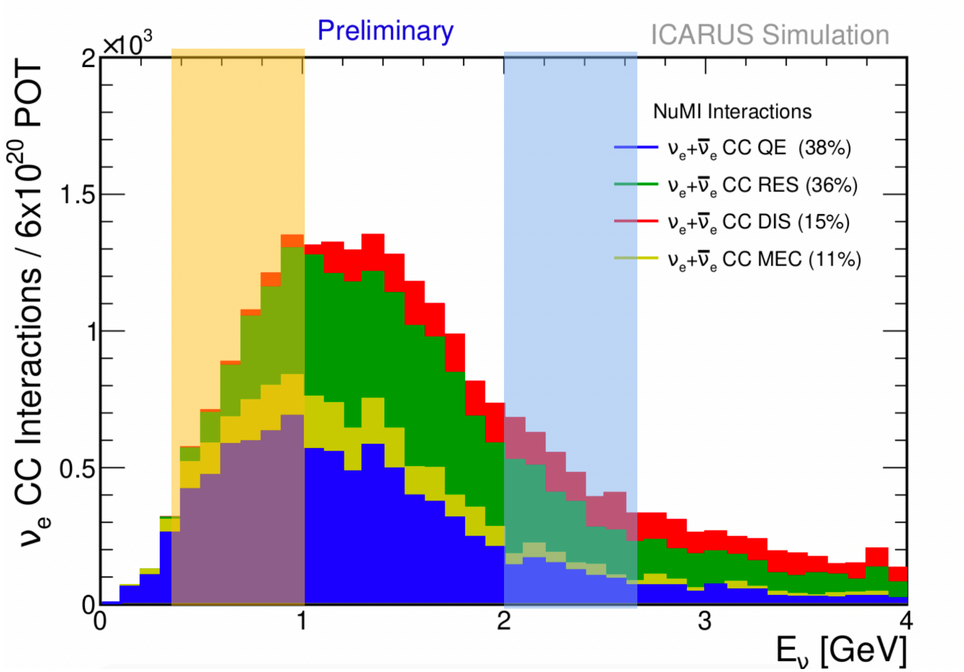
Event selection

Cross section and interaction models

Muon Neutrino



Electron Neutrino



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