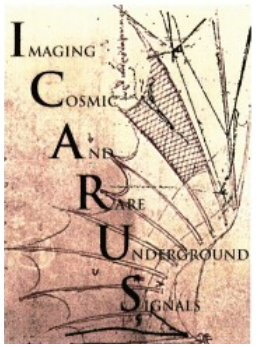
The Fermilab Short-Baseline Neutrino (SBN) Program

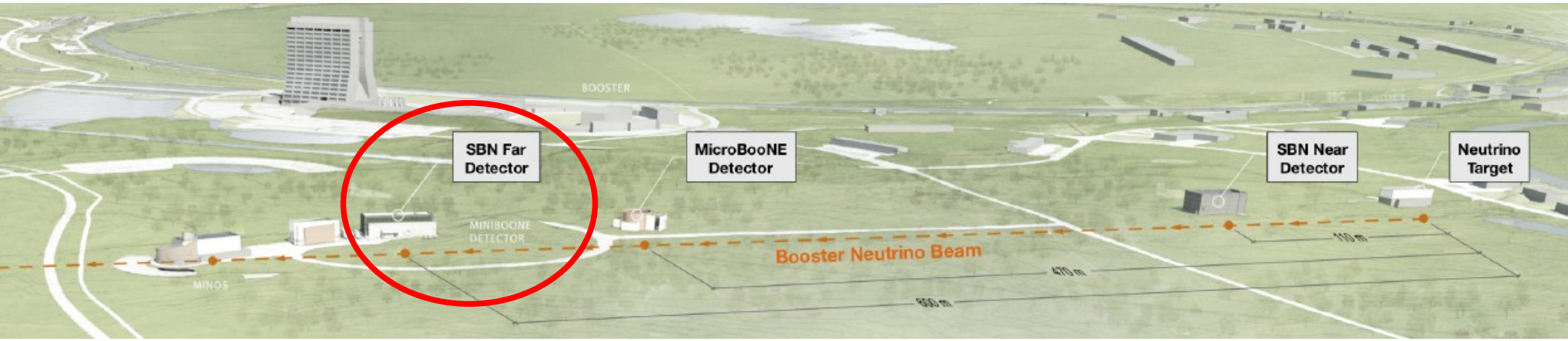
Chris Marshall, University of Rochester

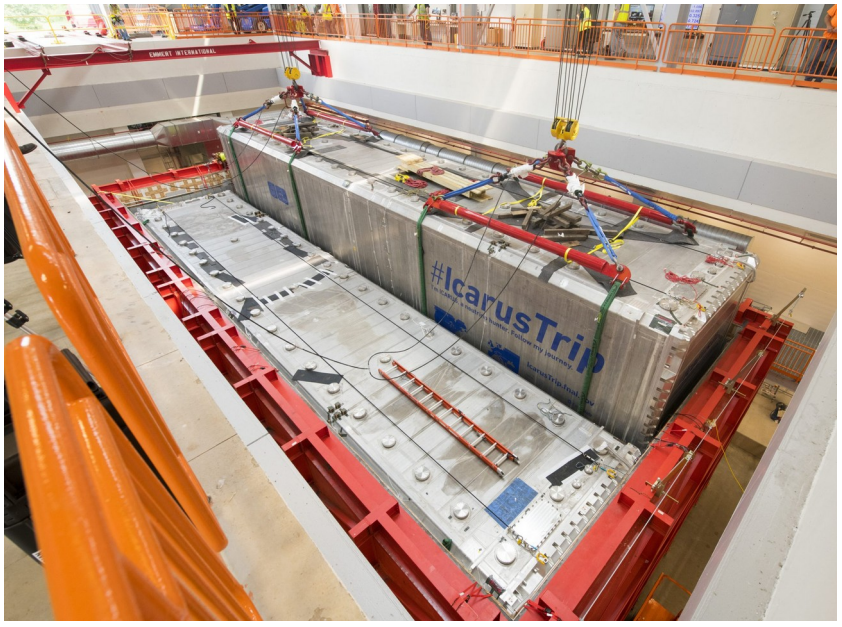
Symposium on Neutrino Physics and Beyond

19 February, 2024



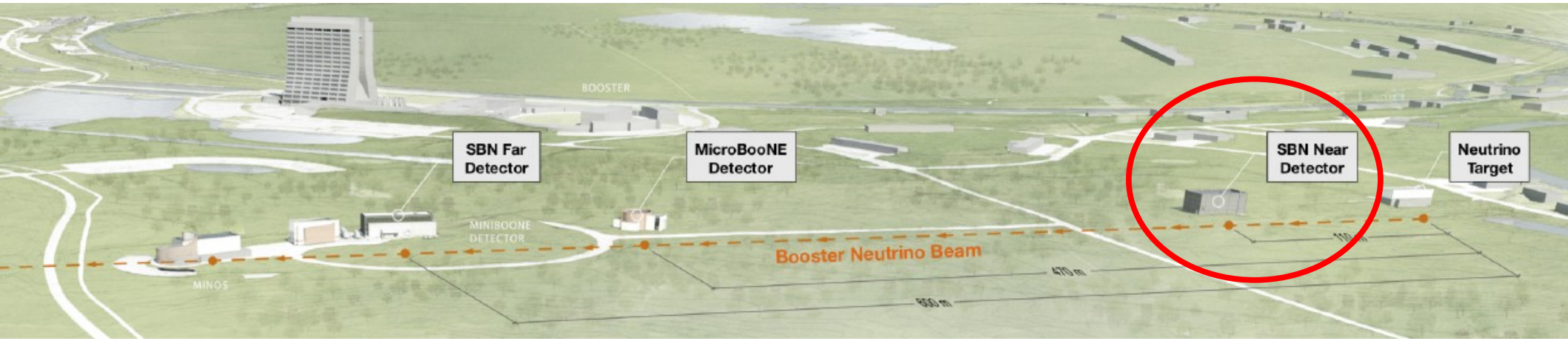
The SBN program: Far Detector





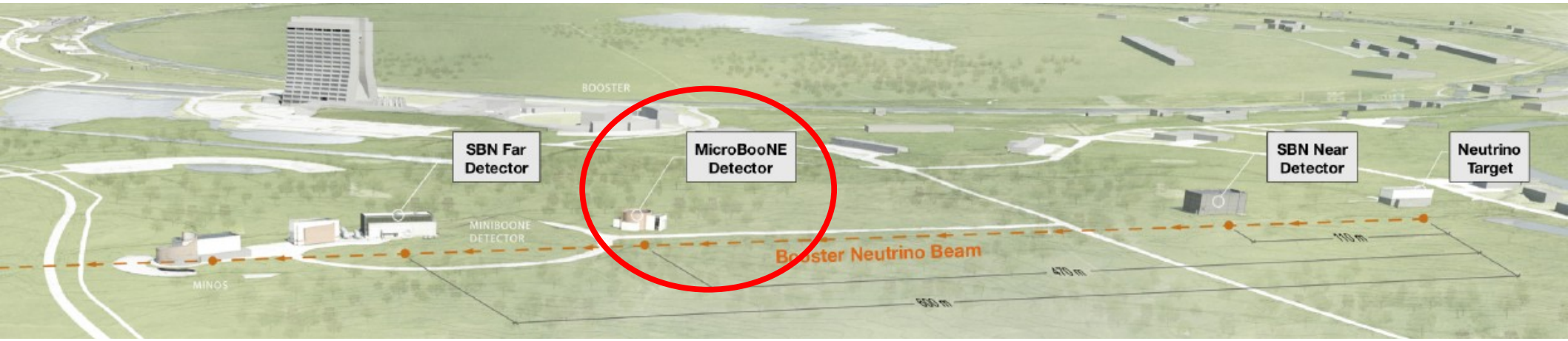
- ICARUS: 476t active mass, 600m from neutrino source
- Three-view wire-readout LArTPC, with PMTs for scintillation signal
- Operated at Gran Sasso 2010-2014, moved to Fermilab in 2017
- Taking physics-quality data since June 2022

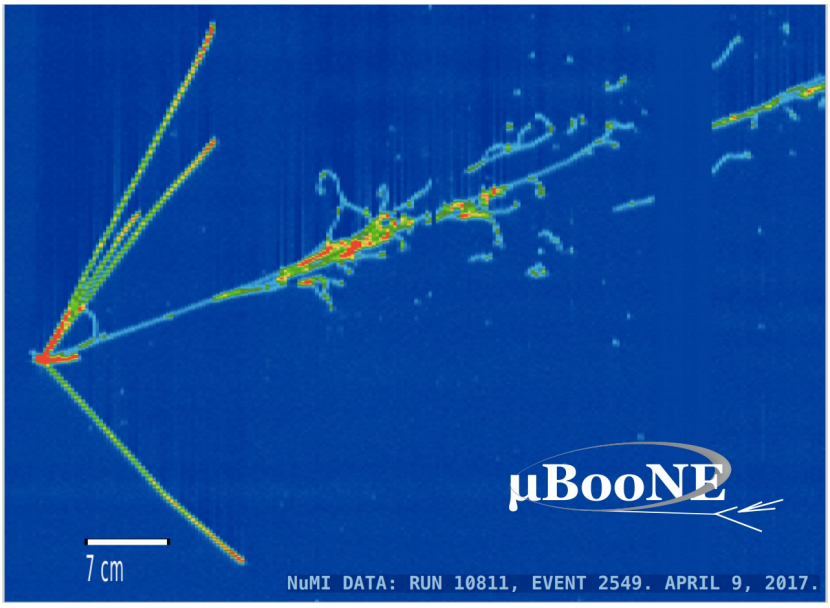
The SBN program: Near Detector



- SBND: 112t active mass LArTPC, 110m from neutrino source
- Three-view wire-readout LArTPC, with PMTs for scintillation signal
- Assembled 2018-2022, lowered into cryostat April 2023
- Physics run expected ~April 2024

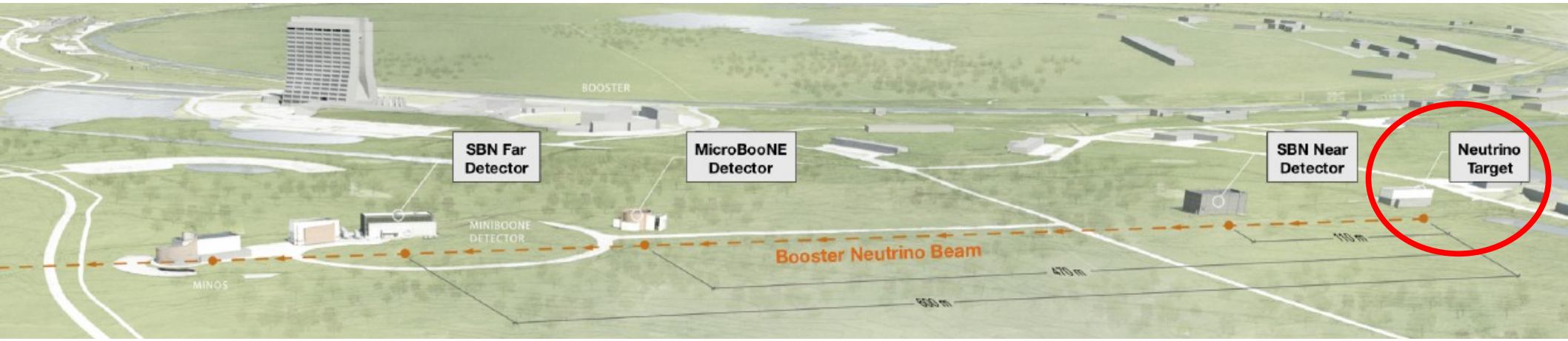
MicroBooNE completed its physics run in 2021

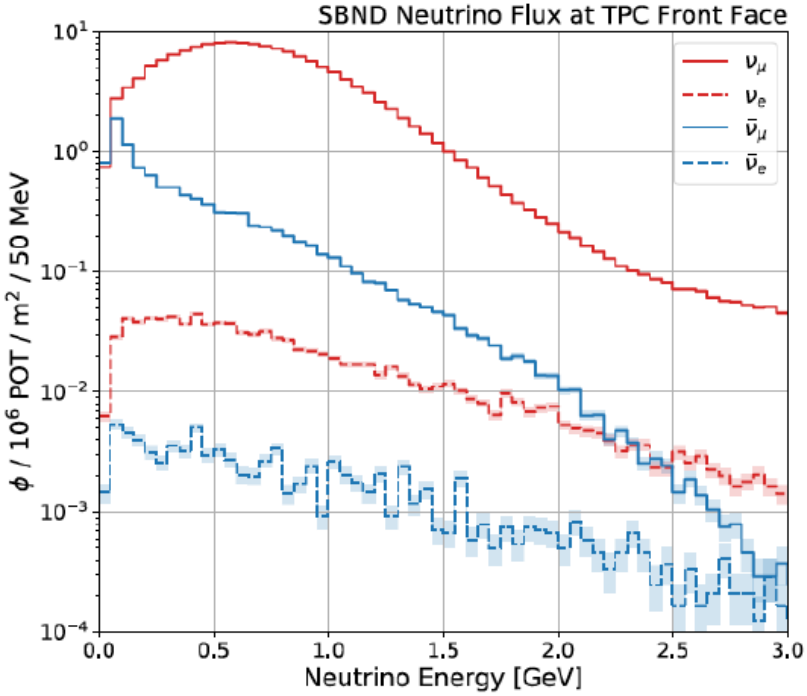




- 89t LArTPC operated from 2015-2021
- Successful physics program, has already produced ~50 publications and counting
- https://microboone.fnal.gov/documents-publications/

The SBN program: Booster beam



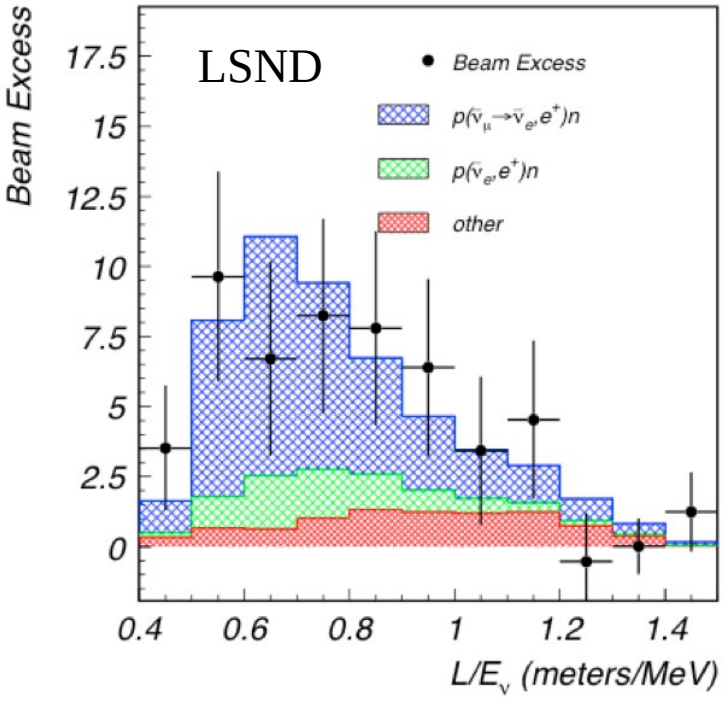


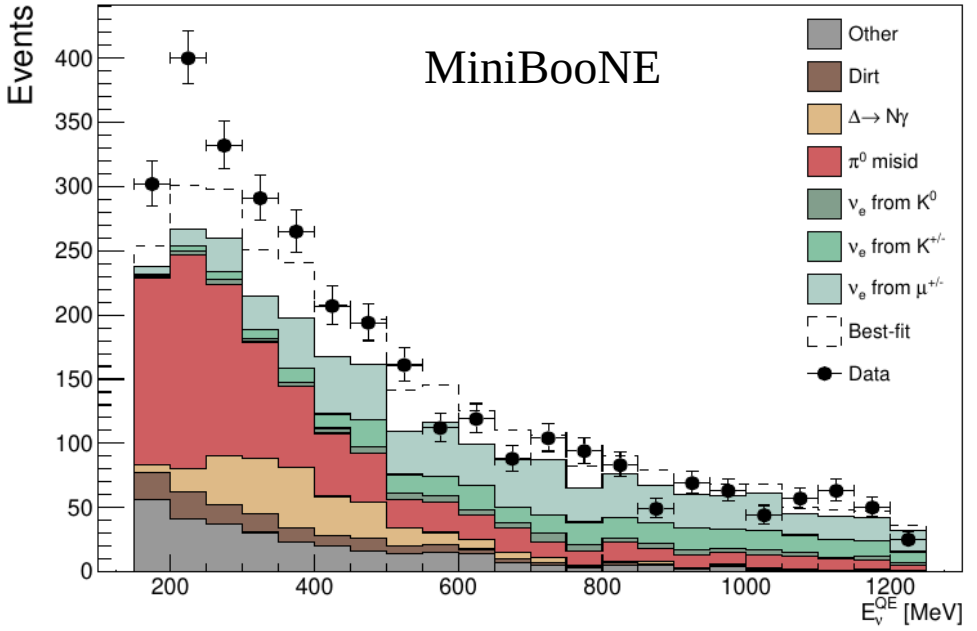
- Conventional neutrino beam using 8 GeV protons from Fermilab Booster
- Flux peaks at ~0.6 GeV, mean neutrino energy ~0.8 GeV
- High-purity ν_μ beam with ~6% $\bar{\nu}_\mu$ and ~0.5% ν_e+$\bar{\nu}_e$ contamination

SBN goals

- Science
  - Search for neutrino oscillations at $O(\Delta m^2) \sim 0.1\text{-}10\ eV^2$
  - Measure ν-Ar interactions
  - Search for physics beyond the Standard Model
- Technology
  - Deploy LArTPC technology, develop software & analysis tools, gain experience analyzing neutrino LArTPC data
- SBN is highly synergistic with DUNE program
  - Common LArTPC detector technology
  - ν-Ar cross section program → better models for DUNE
  - Resolve the sterile neutrino question

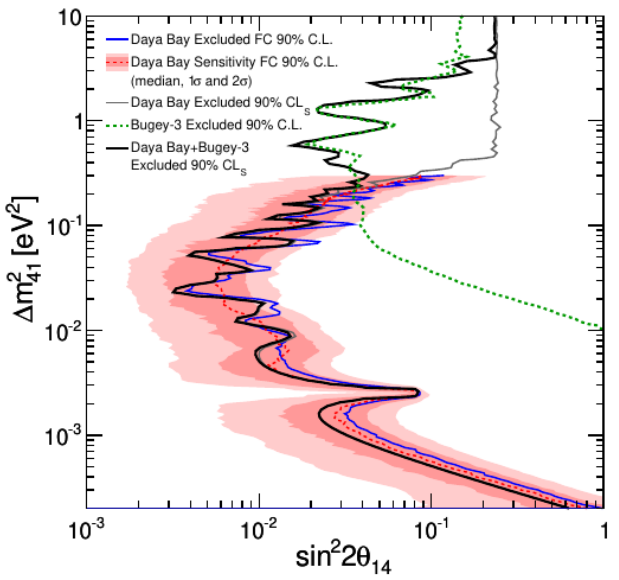
Sterile neutrinos: motivation

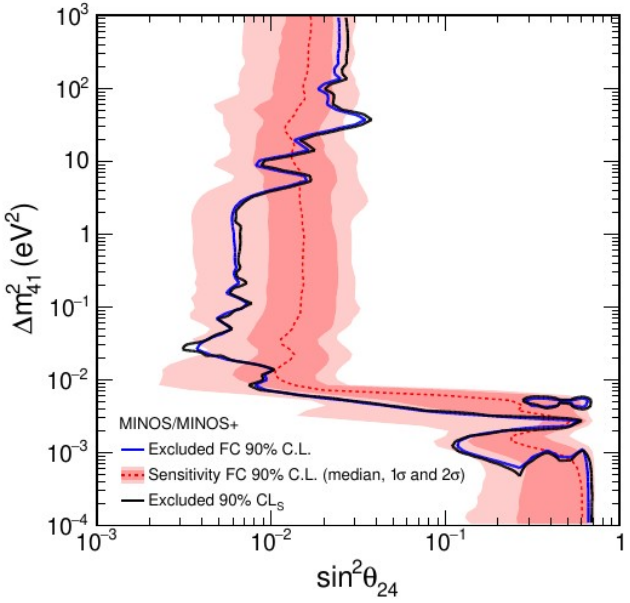


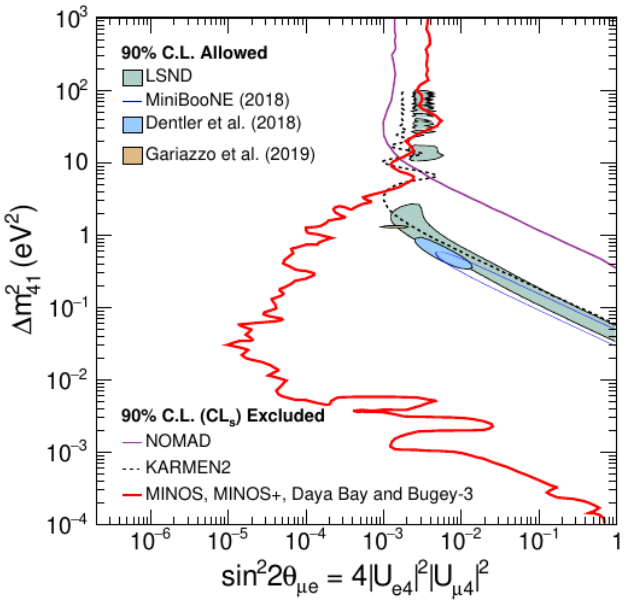


- LSND and MiniBooNE: anomalous results that could be explained by $\nu_\mu \to \nu_e$ appearance via O(eV^2) sterile neutrino(s)

Sterile neutrinos: antimotivation



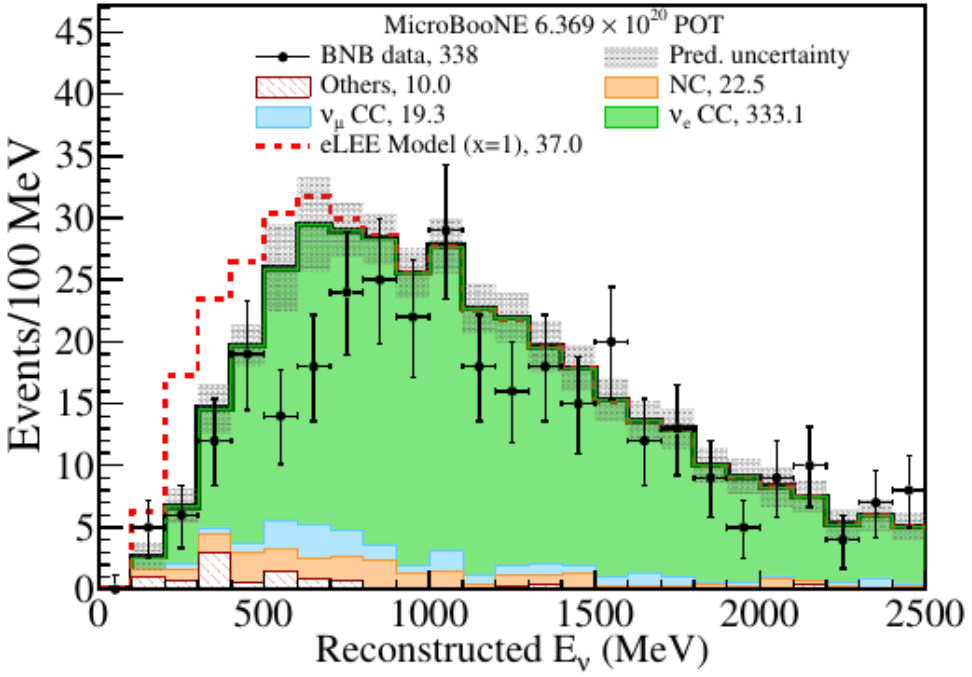


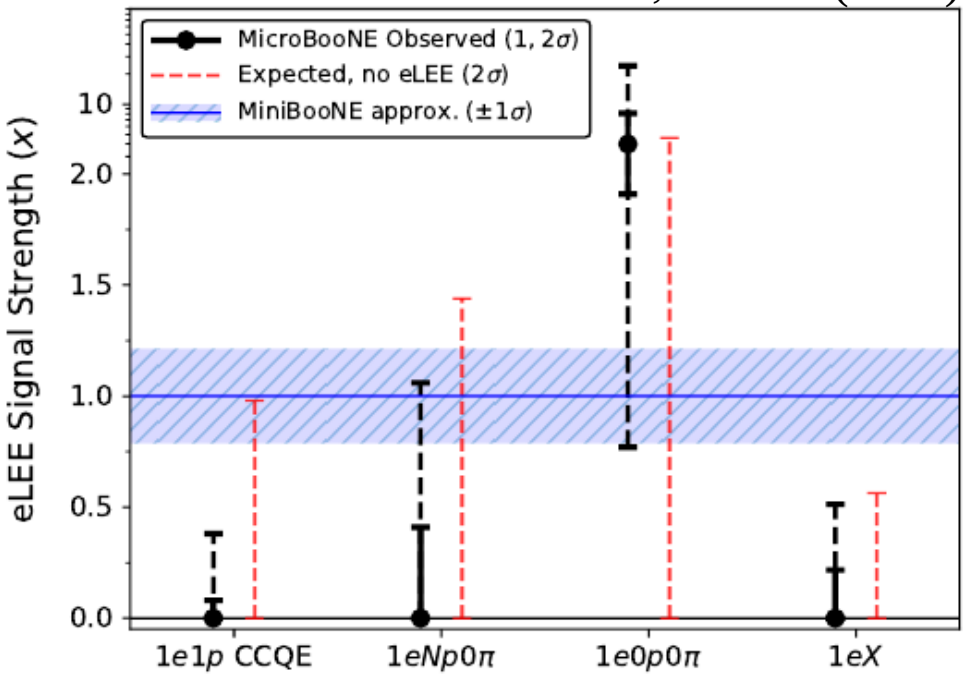


- Searches for ν_μ or $\bar{\nu}_e$ disappearance over similar L/E by MINOS/MINOS+, Daya Bay, Bugey-3, PROSPECT are consistent with Standard Model expectations, and exclude the LSND/MiniBooNE allowed regions

MicroBooNE LEE search results

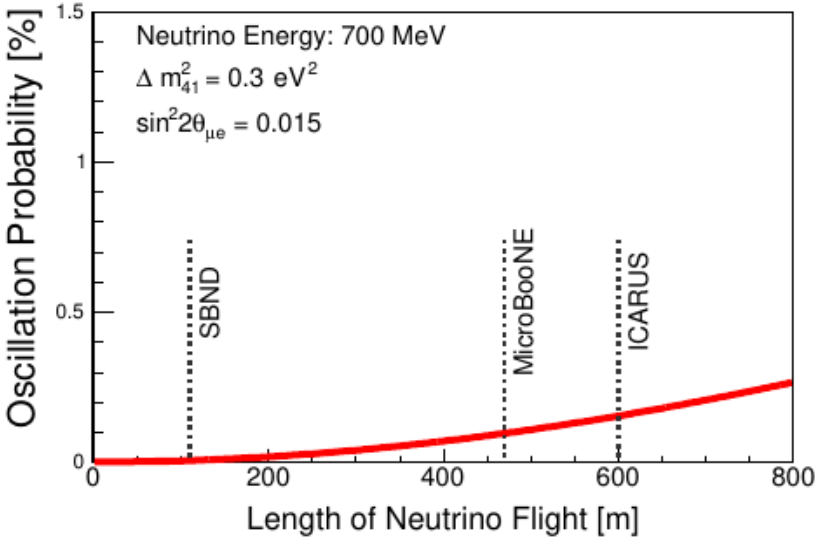
PRL 128, 241801 (2022)

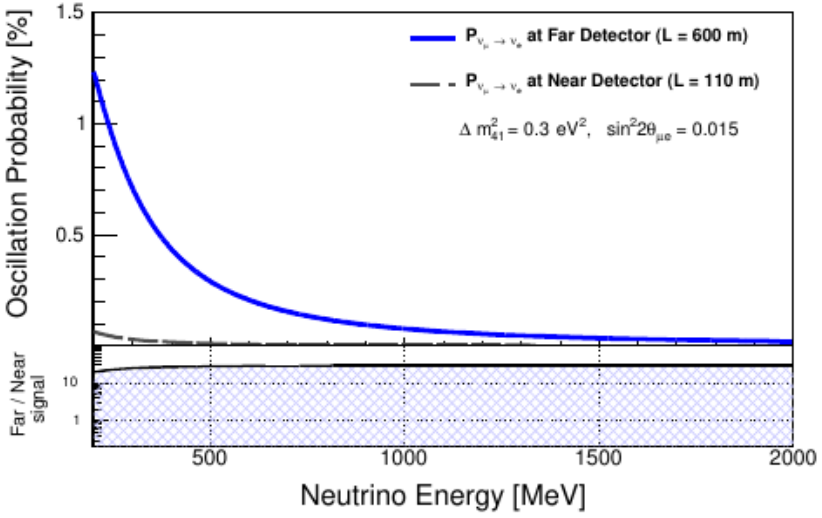




- MicroBooNE can separate e/γ, and search specifically for LEE-like signal coming from ν_e CC
- Results across four different channels are consistent with no LEE

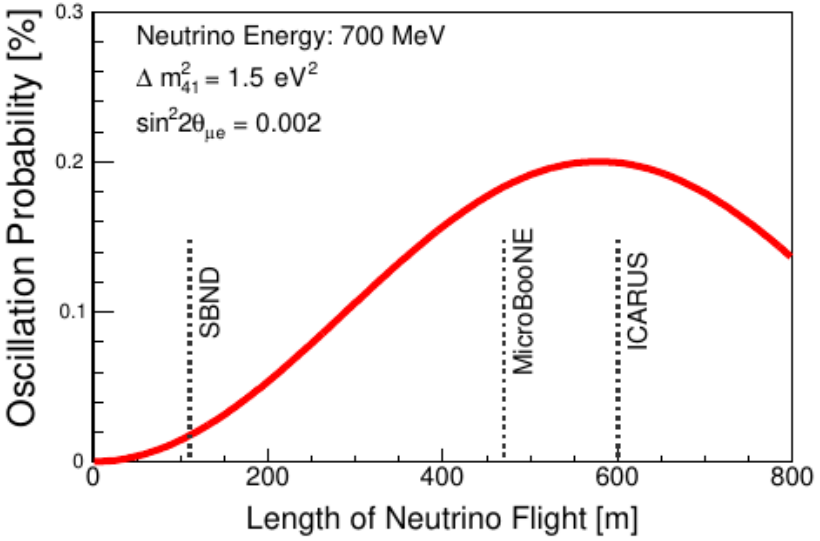
SBN changes the game with two detectors

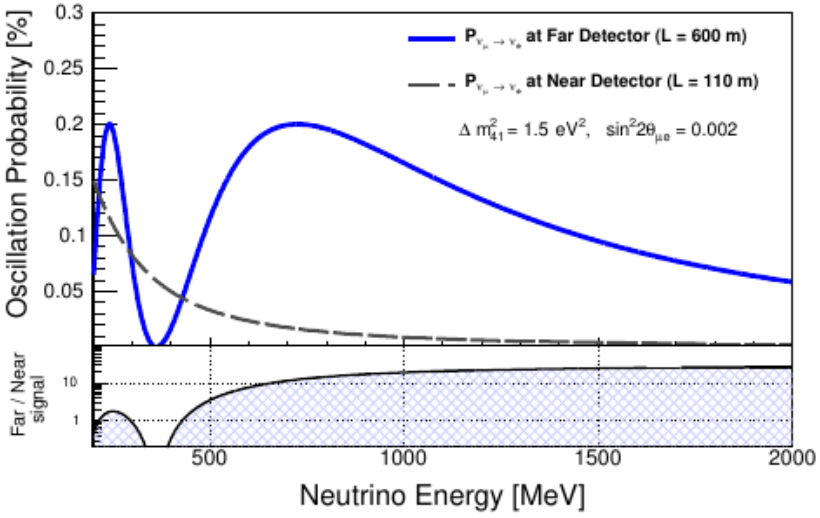




- LSND and MiniBooNE anomalies are data compared to tuned model predictions of (large) backgrounds
- SBN deploys two functionally identical detectors, similar to long-baseline experiments
- Much, much less sensitive to flux and cross section uncertainties
- Very high statistics: O(200k) CC events per year in FD, and O(2M) in ND

SBN changes the game with two detectors





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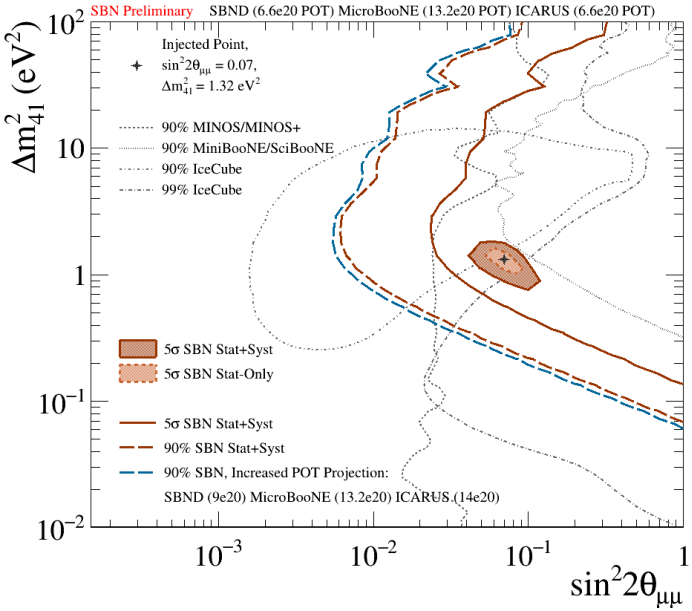
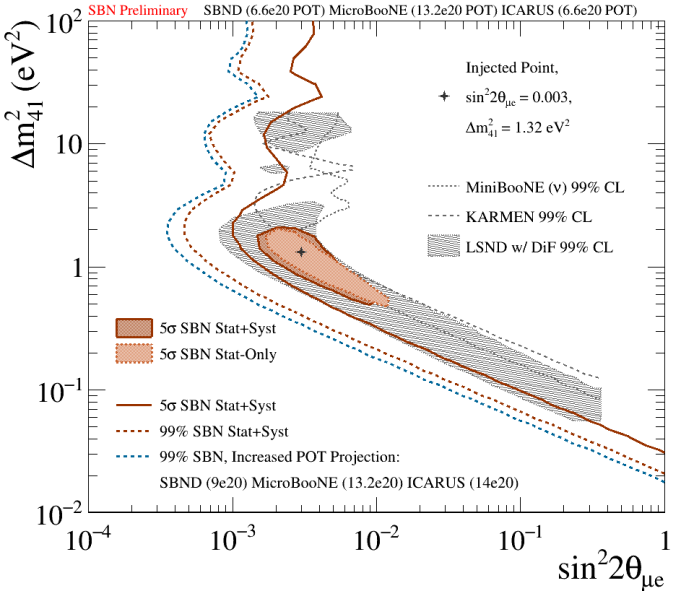
5σ discovery sensitivity, or exclusion of MiniBooNE/LSND

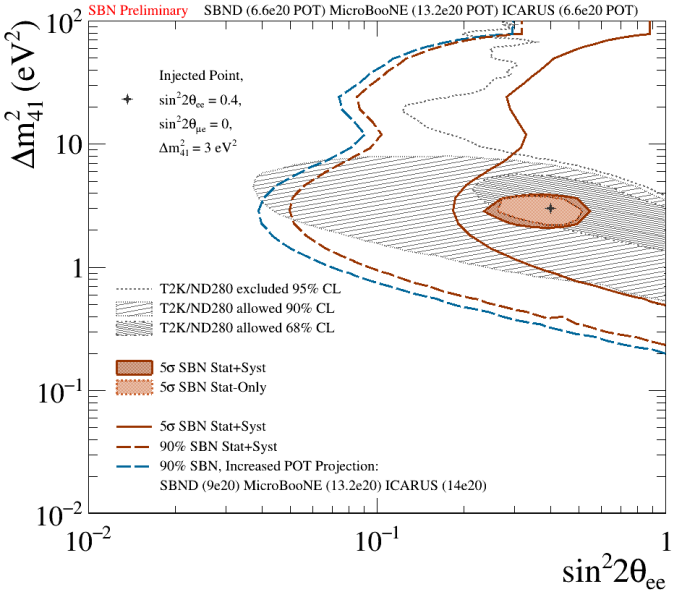
ν_μ disappearance



ν_e appearance

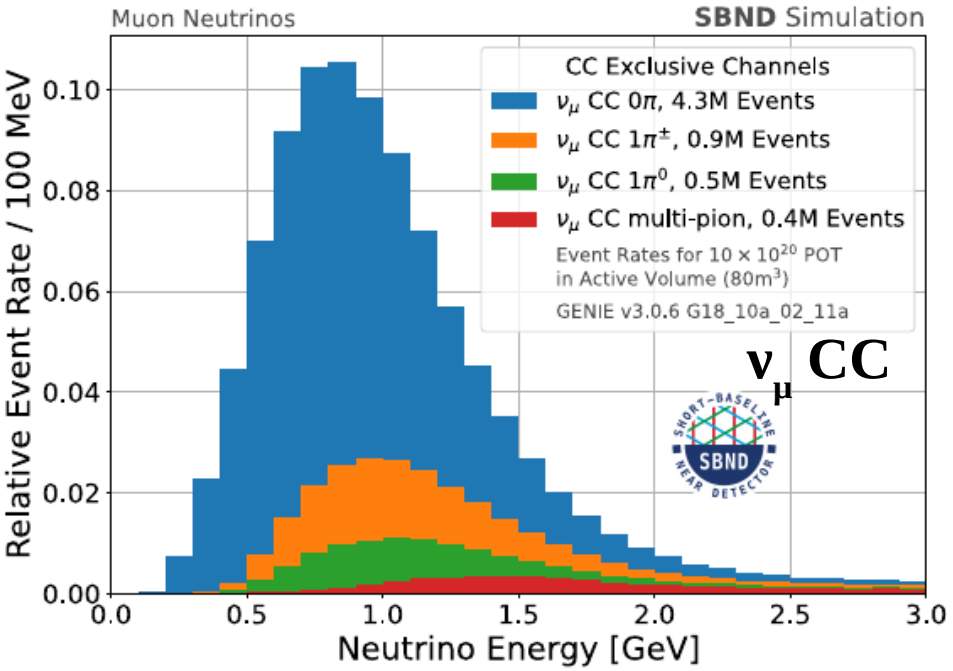


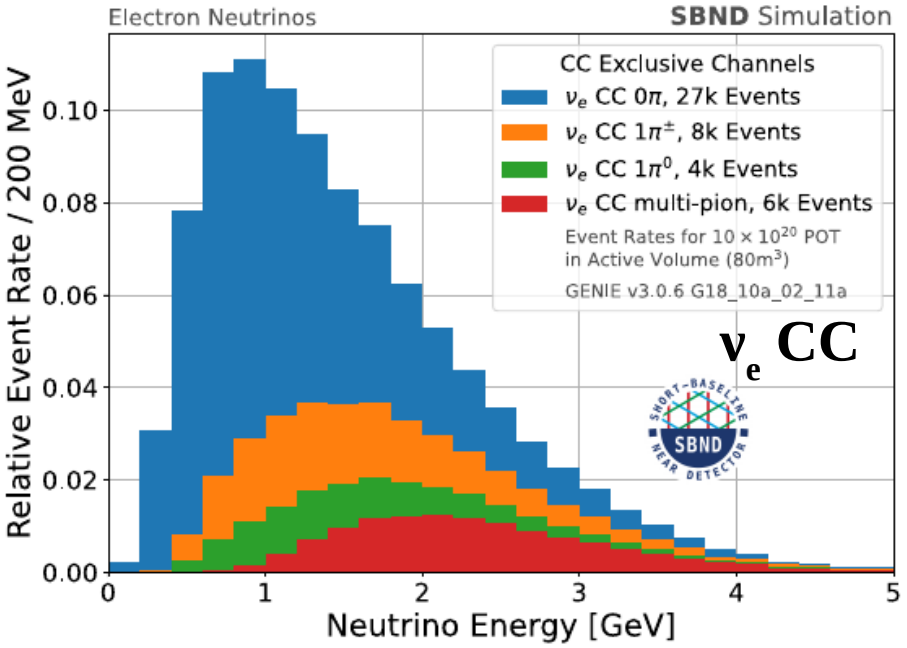
ν_e disappearance



- SBN is simultaneously sensitive to appearance and disappearance
- Discovery sensitivity over a broad range of parameter space, and world-leading exclusion sensitivity, covering all of MiniBooNE and LSND at 90% and most at 5σ

Neutrino interactions at SBND

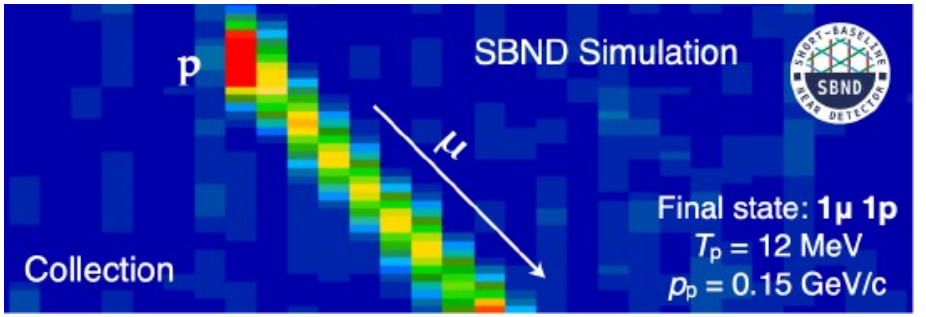


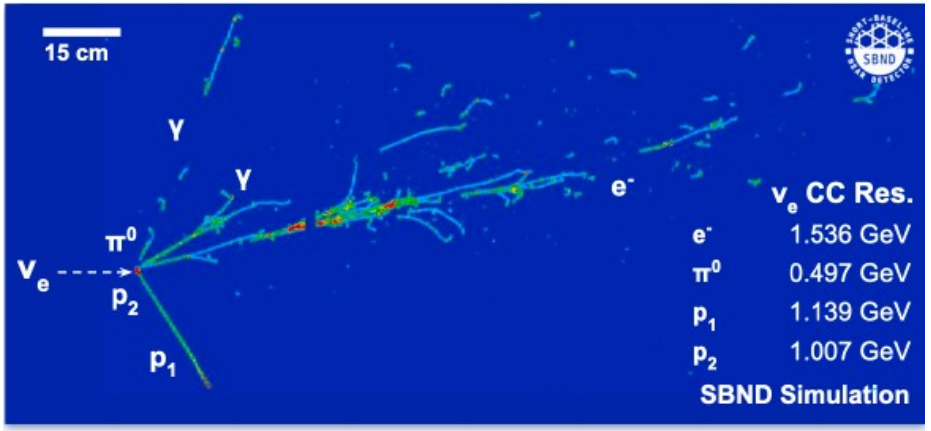


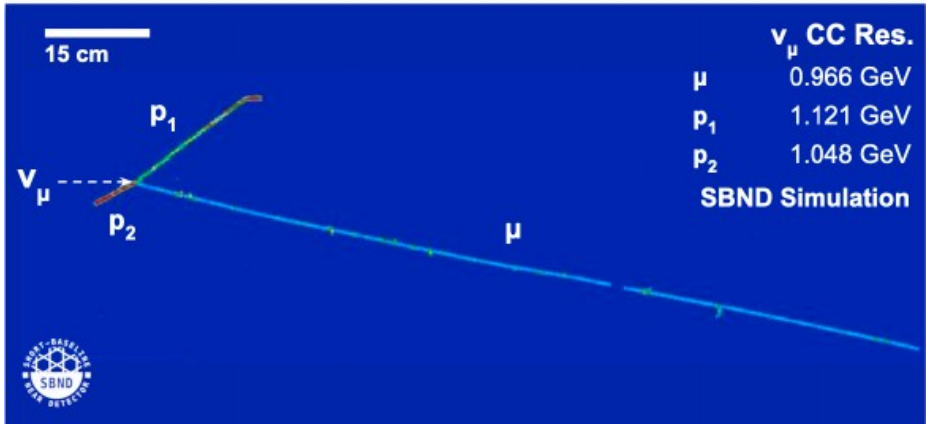
- SBND will collect a **huge** sample of ν-Ar interactions: ~2M ν_μ CC and ~15k ν_e CC events per year, equal to the entire MicroBooNE data set every ~3 months
- Peak energy is at the location of the 2nd oscillation maximum of DUNE

Excellent final-state resolution with LArTPC detectors

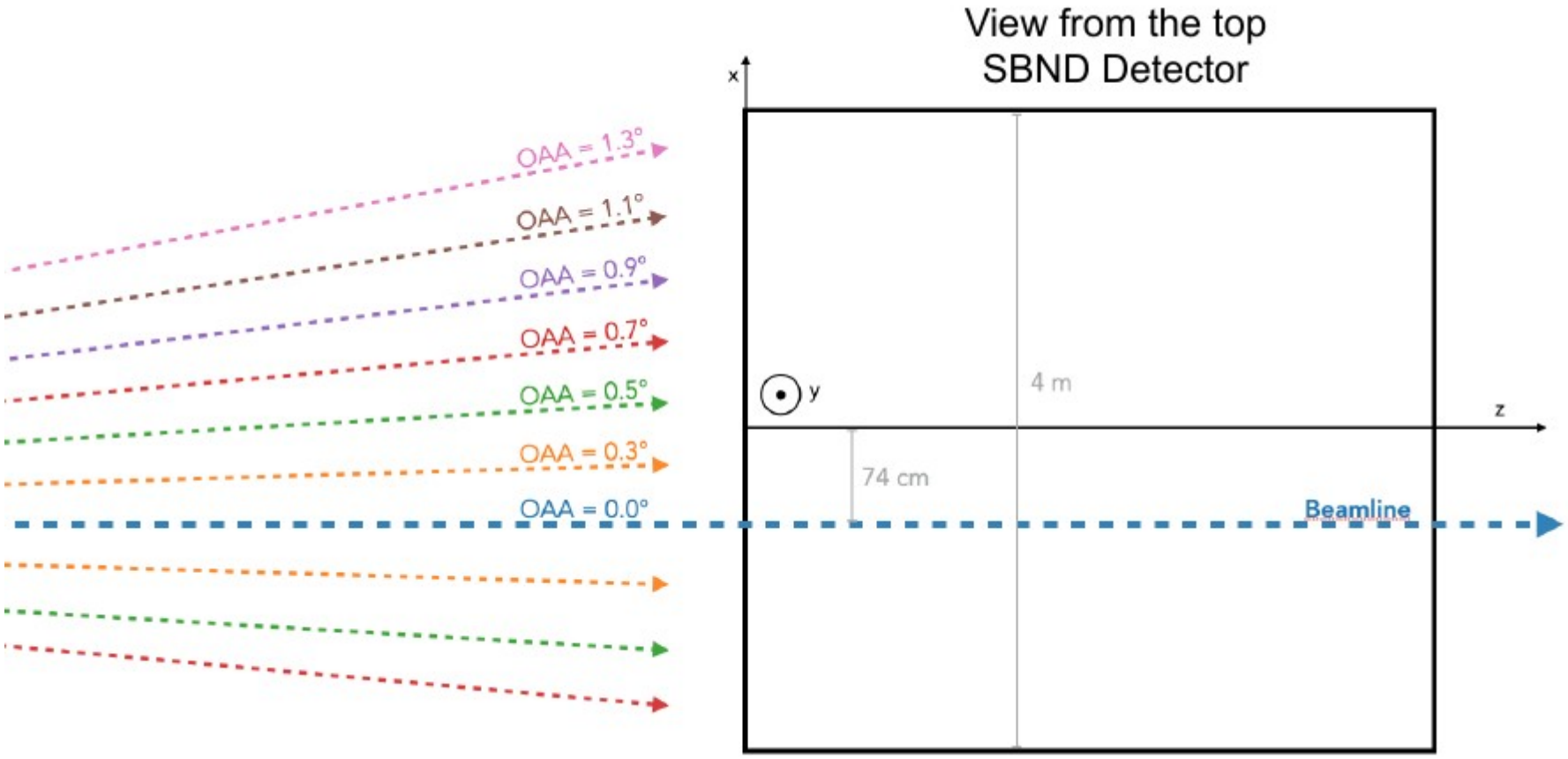
- Excellent detector for resolving exclusive final states:
  - Track/shower separation (e/μ)
  - e/γ separation from gap + dE/dx
  - p/$\pi^{\pm}$ separation from dE/dx
- SBND has same beam spectrum as MicroBooNE, similar detector, way higher statistics





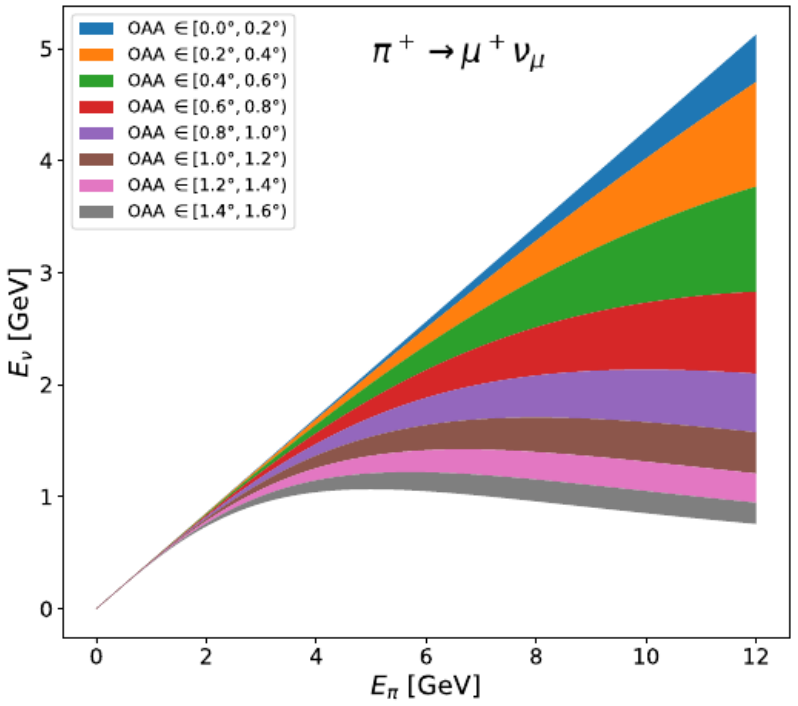


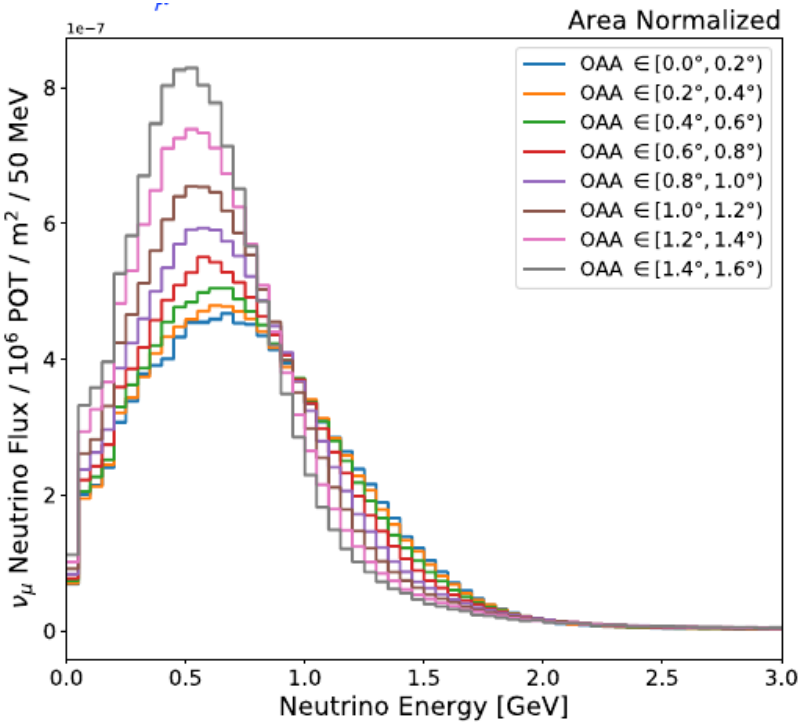
SBND-PRISM gives different neutrino flux distributions



- SBND is very close to neutrino source, and the flux changes appreciably across the 4m detector cross section

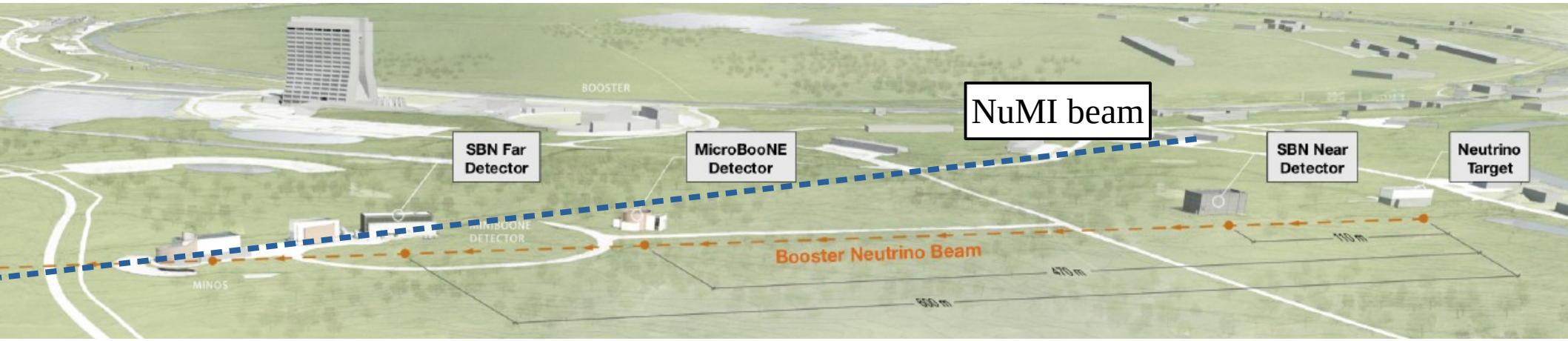
Pion decays give lower-energy neutrinos off axis





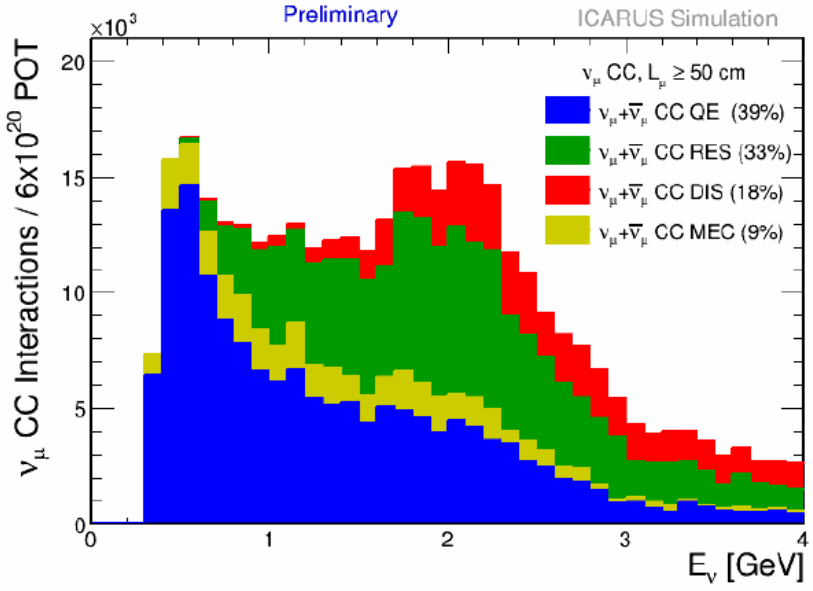
- Decay kinematics means that flux peak decreases as you move away from the beam center
- Gives some ability to study neutrino energy dependence of ν-Ar interactions

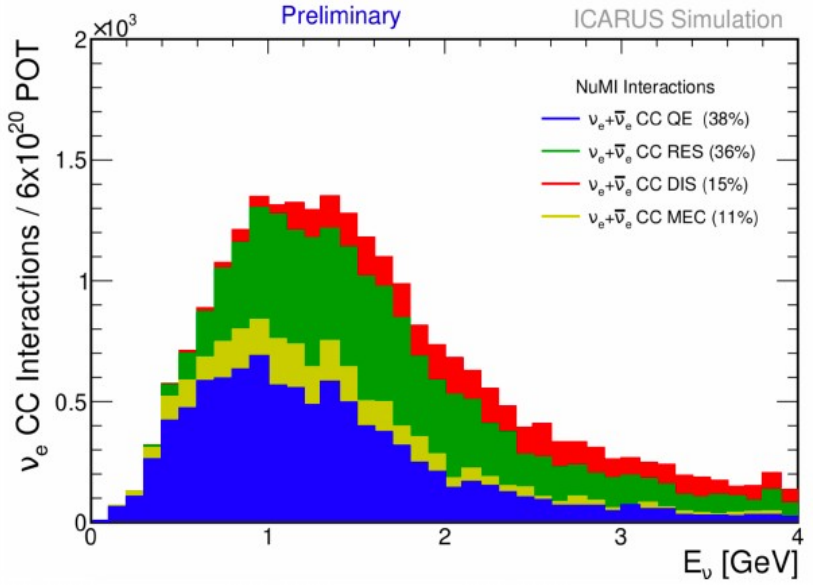
ICARUS also sees neutrinos from NuMI



- ICARUS is ~6° off-axis in the NuMI beam
- Beam center passes almost directly below ICARUS
- Far off-axis flux is enhanced in kaon decays
  - Higher energy neutrinos
  - Higher electron neutrino “contamination”

Neutrino interactions at ICARUS: NuMI beam

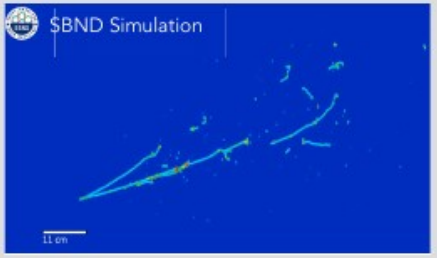




- ~400k ν_μ and ~20k ν_e CC events per year → very high ν_e rate compared to on-axis beams
- ν_μ flux is higher in energy than BNB → complementary to SBND cross section program
- ~Half of events have final-state pions → study the resonance, SIS, and DIS regions

Broad program of BSM searches at SBND using BNB...

Dark Neutrinos

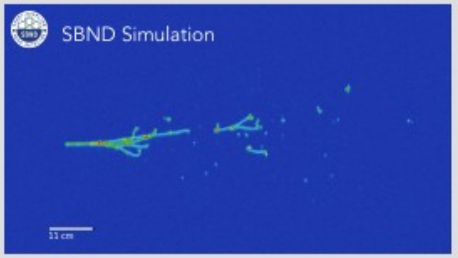


e+e- pair w/ or w/o hadronic activity

Transition Magnetic Moment

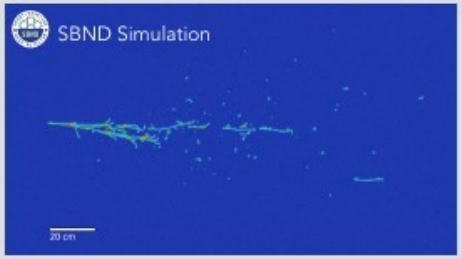
photon shower and hadronic activity

Axion-like Particles



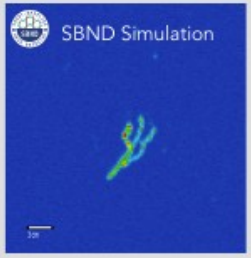
high-energy e^+e^-, $\mu^+\mu^-$

Heavy Neutral Leptons



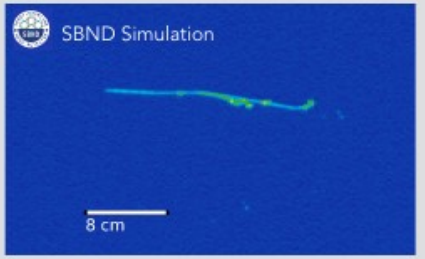
e^+e^-, $\mu^+\mu^-$, $\mu\pi$

Higgs Portal Scalar



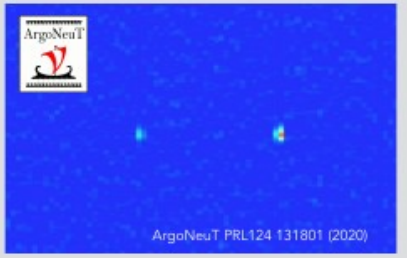
e^+e^-, $\mu^+\mu^-$, no hadronic activity

Light Dark Matter



electron scattering

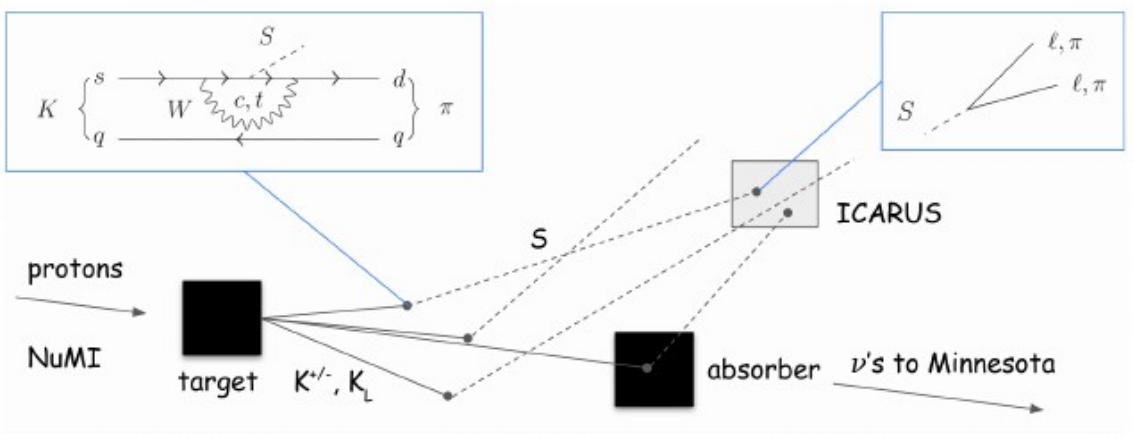
Millicharged Particles

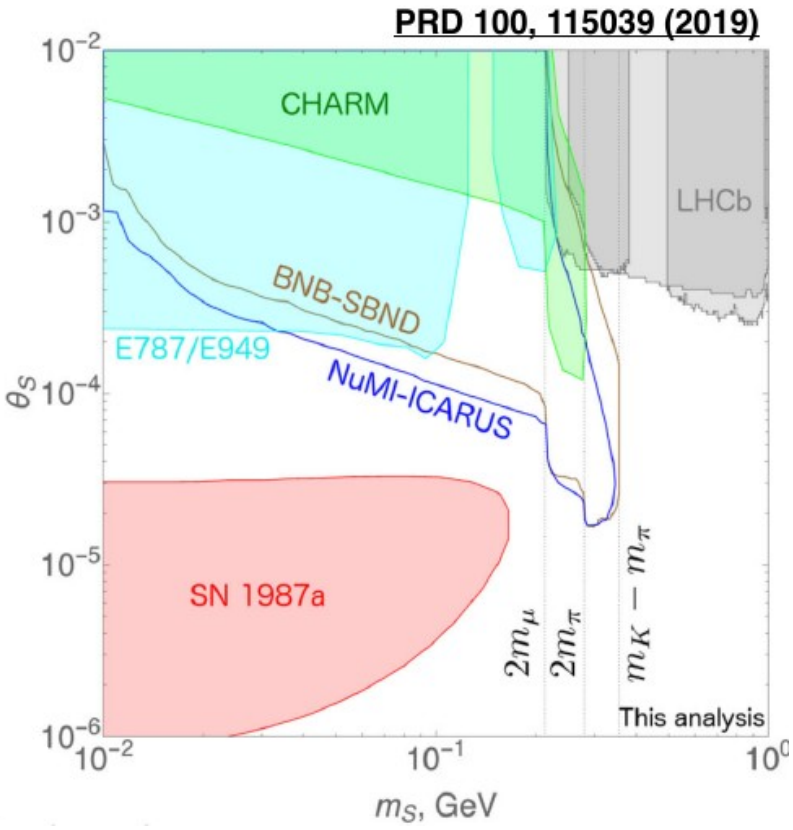


blips/faint tracks

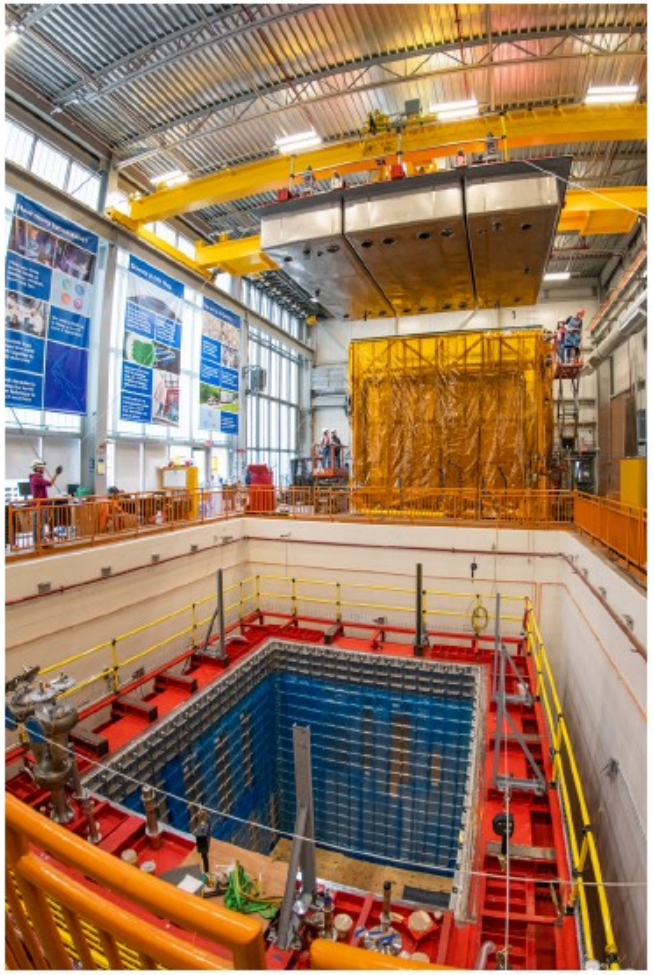
...and at ICARUS using NuMI

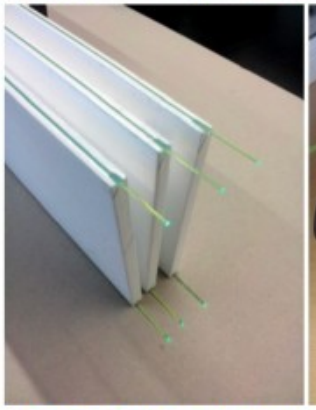
- Channels like kaon-coupled Higgs portal scalars have enhanced signal/background at far off-axis angles
- Also low mass DM, HNL in some phase space

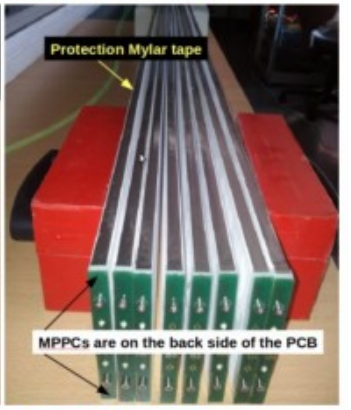




SBND status: cooling down!

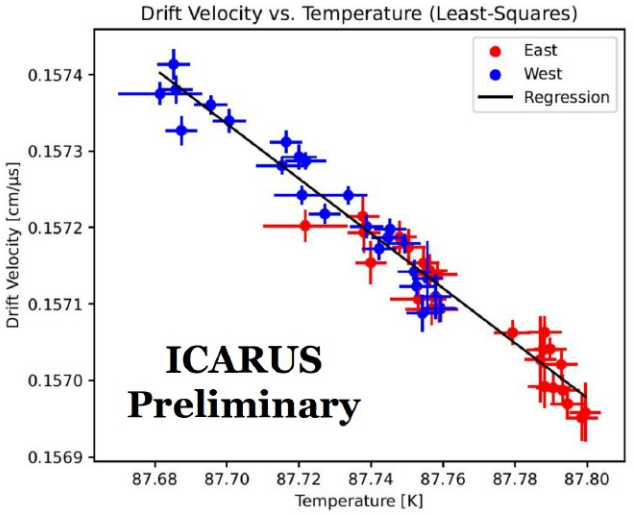


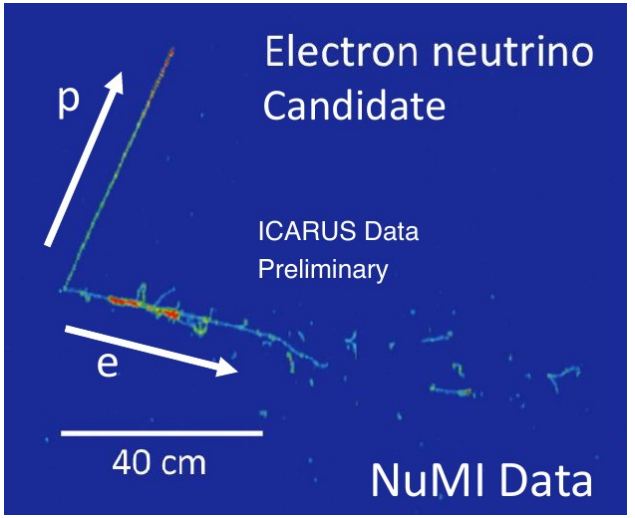




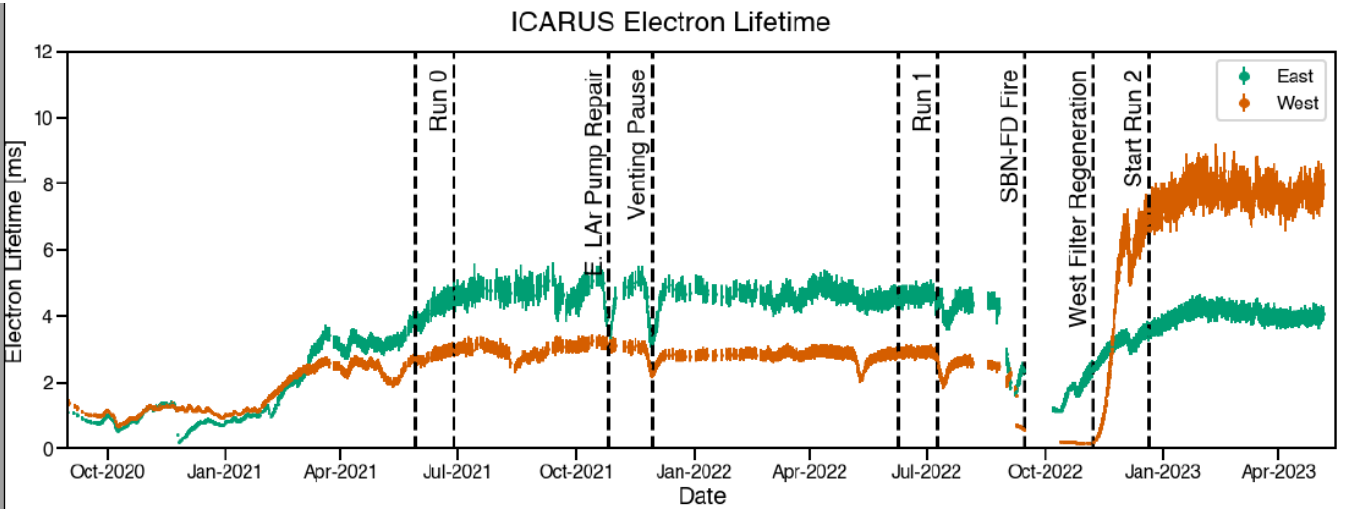
- SBND is installed, cooling down, preparing for LAr filling
- Commissioning with beam will begin when beam returns in next 1-2 weeks
- Physics-quality data expected by spring

ICARUS status: analyzing first data set, preparing for more!





arXiv:2301.08634



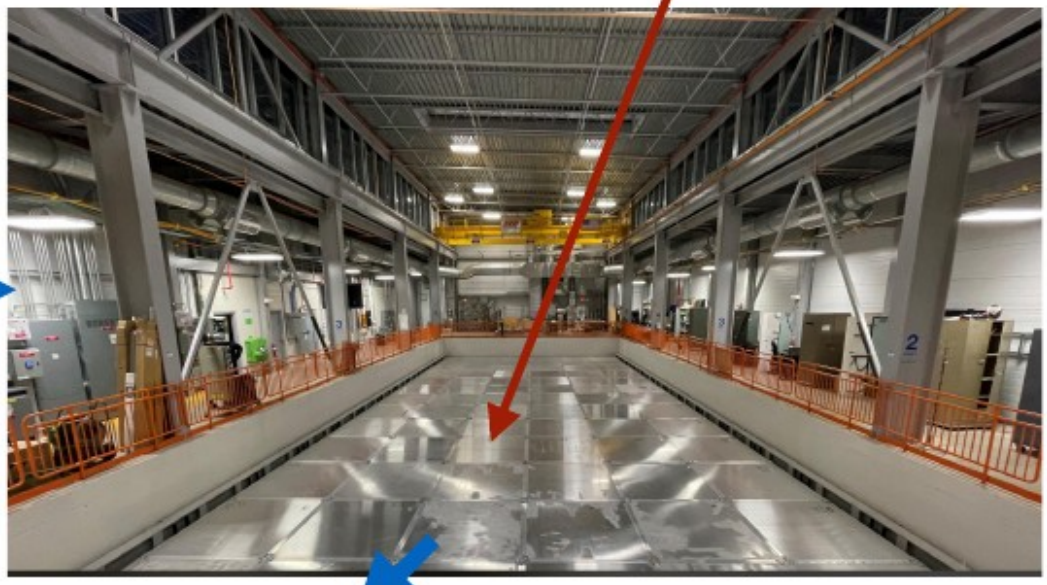
- Physics runs Jun-Jul 2022 and Dec 2022-Jul 2023 (NuMI in FHC mode)
- Running and ready for beam to return this month (with NuMI in RHC mode)
- Analyses of Run 1+2 in progress:
  - Higgs portal search
  - CC0π1p and 2+p cross sections
  - Oscillation search

Summary

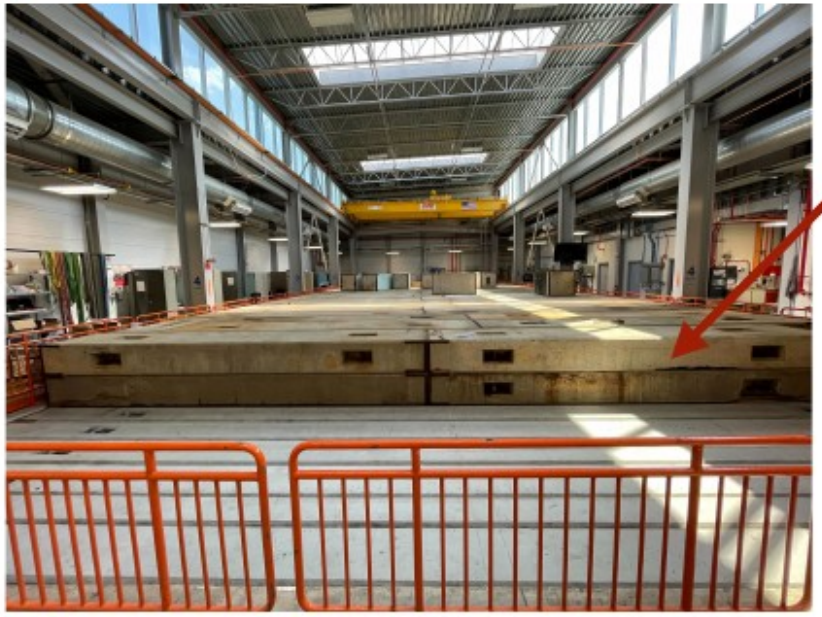
- Proper two-detector physics program begins in spring 2024 when SBND physics run begins
- Expect to run until 2027 LBNF shutdown, and collect ~12E20 POT in BNB
- MicroBooNE will continue to provide a steady stream of physics papers, with ICARUS and SBND joining the fun in 2024
- Stay tuned!

ICARUS Installation and Current Status

September 2020



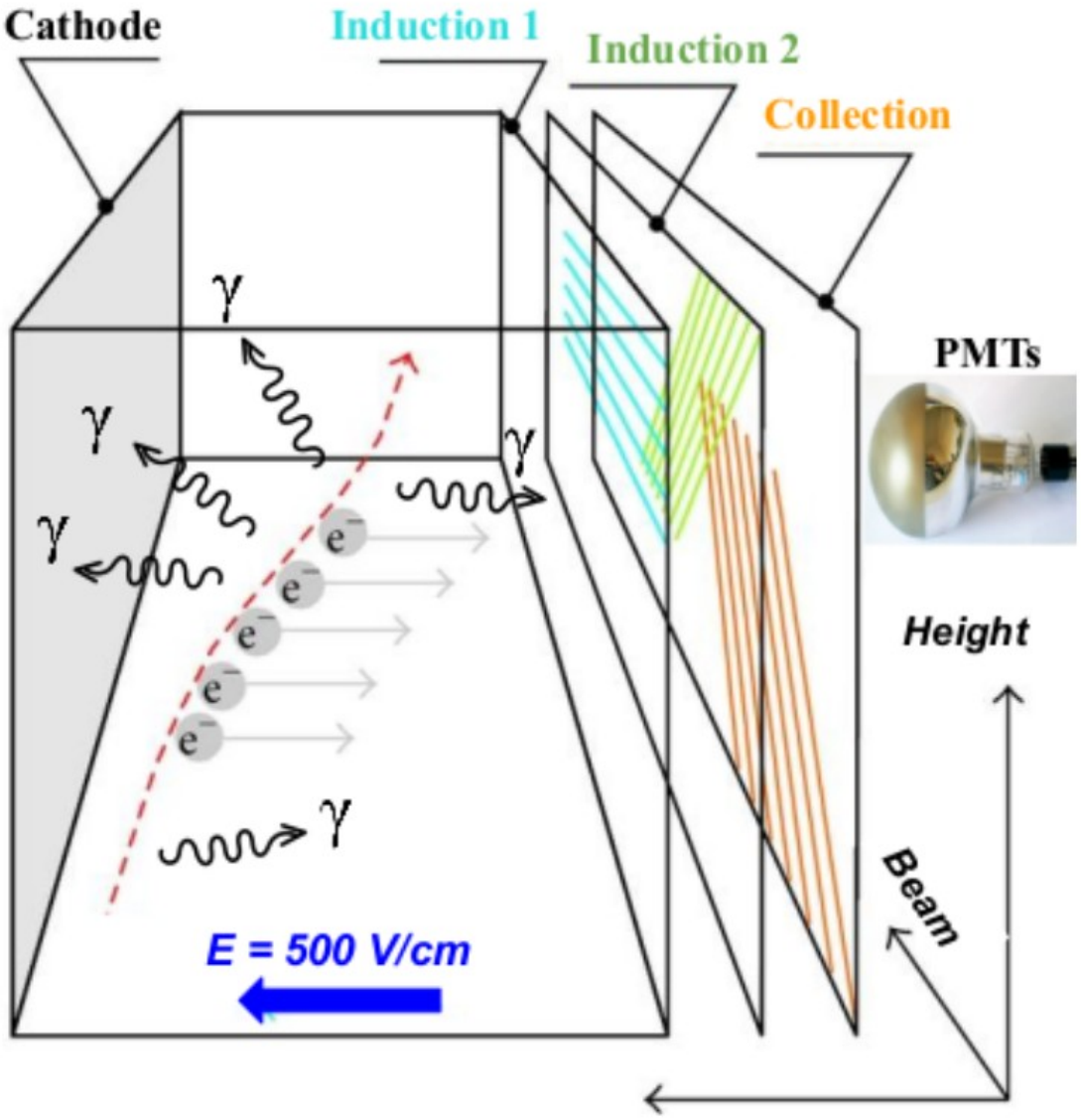
December 2021



May 2022

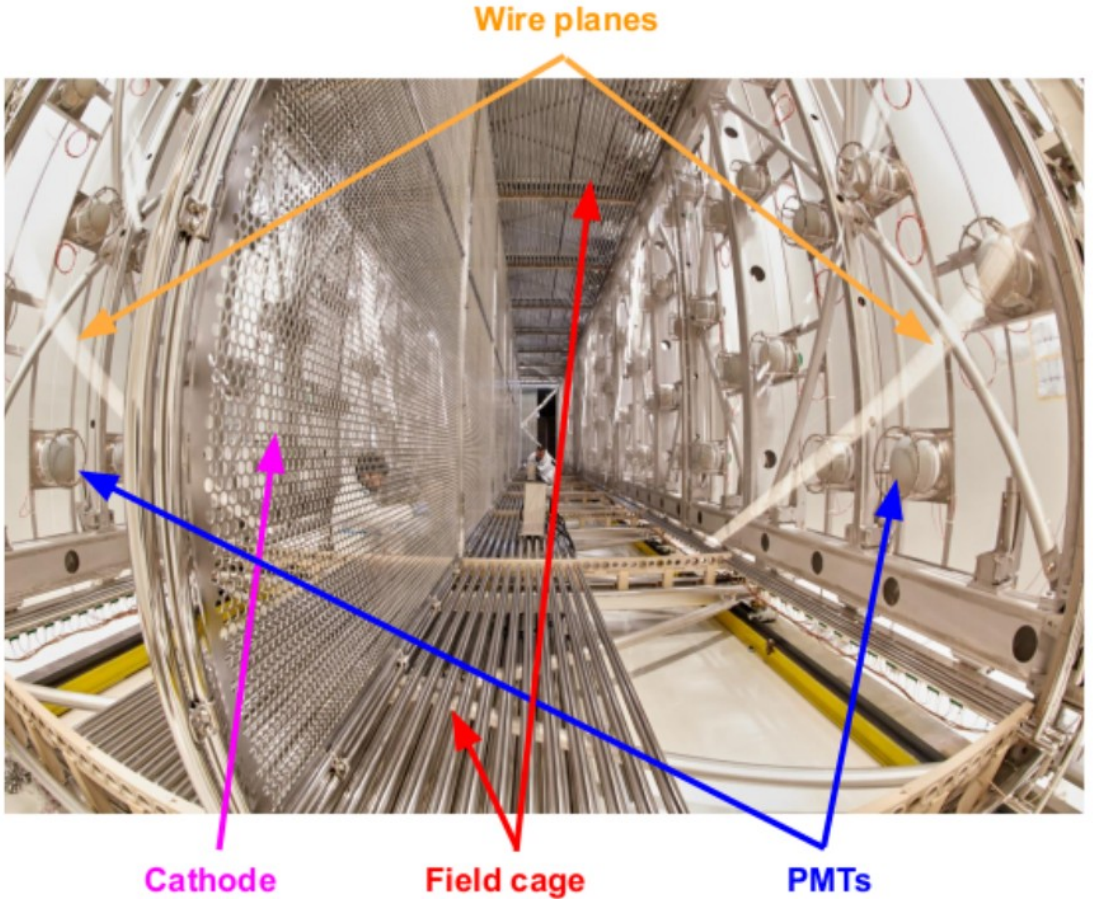
LArTPC principle

- Charged particles produce ionization charge and scintillation light
- Charge is drifted to anode in 500 V/cm electric field
- Two inductive wire planes and one collection plan record charge signals
- PMTs behind the wire planes measure scintillation light, with prompt component τ ~ 6 ns used for event timing

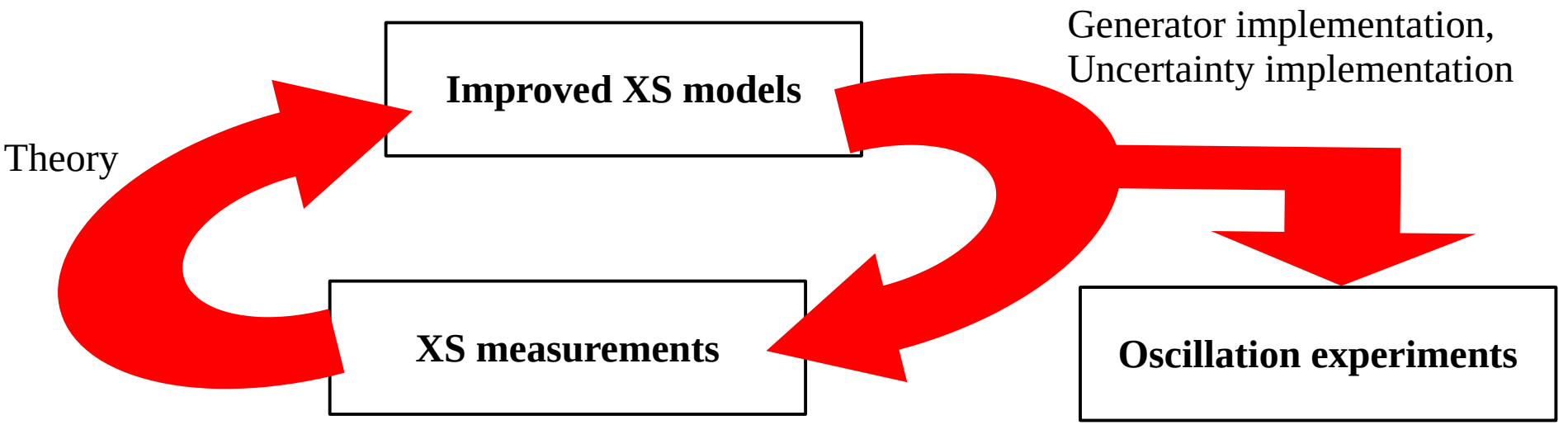


LArTPC in ICARUS

- ICARUS has two cryostats, each with a central cathode and two anode planes
- Photo shows the PMTs, field cage, cathode, taken during the detector refurbishment at Fermilab



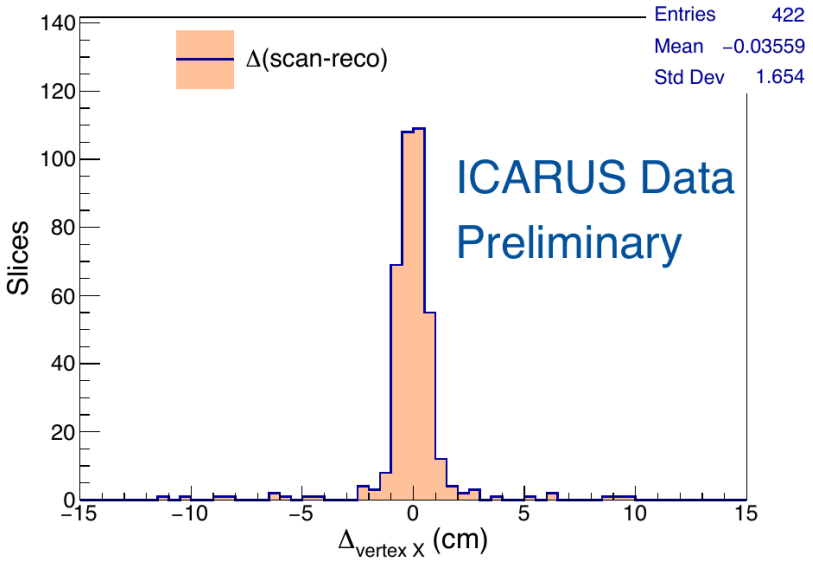
Neutrino interactions for neutrino oscillation experiments

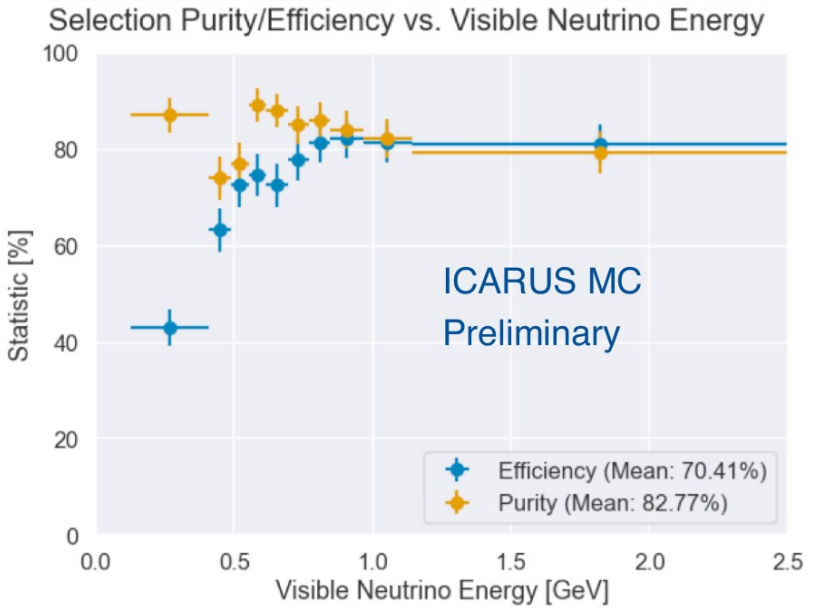


- Improving neutrino MC generators is an extremely complicated task, generally requires:
  - Neutrino XS measurements
  - Theory work
  - Generator & uncertainty implementation
- This process takes years → DUNE needs ν-Ar data and ν-Ar theory now!

ICARUS reco performance

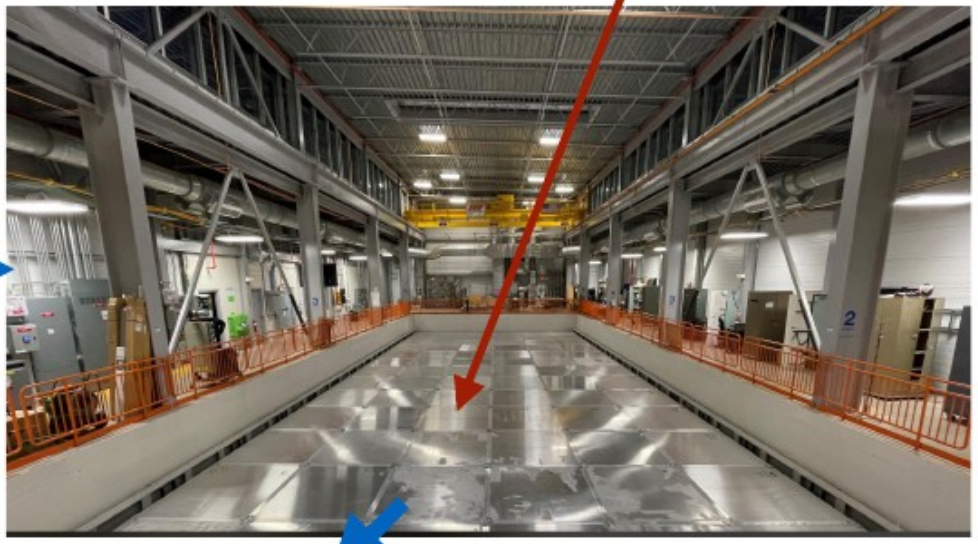
- For 1μ1p events, algorithmic reconstruction using Pandora toolkit is ~80% efficient
- Vertex reconstruction gives resolution of ~1cm compared to organic neural network (hand scanning)
- Cosmic backgrounds are largely mitigated by requiring two tracks



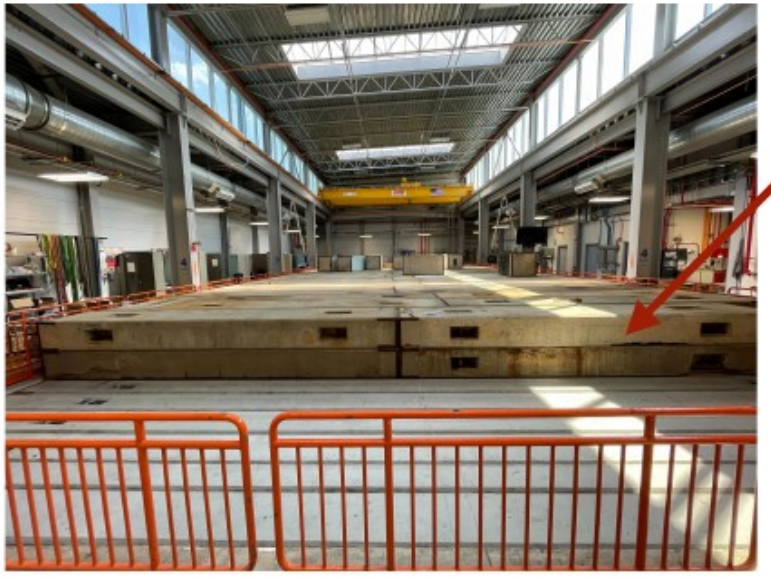


ICARUS Installation and Current Status

September 2020



December 2021



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