STERILE NEUTRINO SEARCHES AT FERMILAB

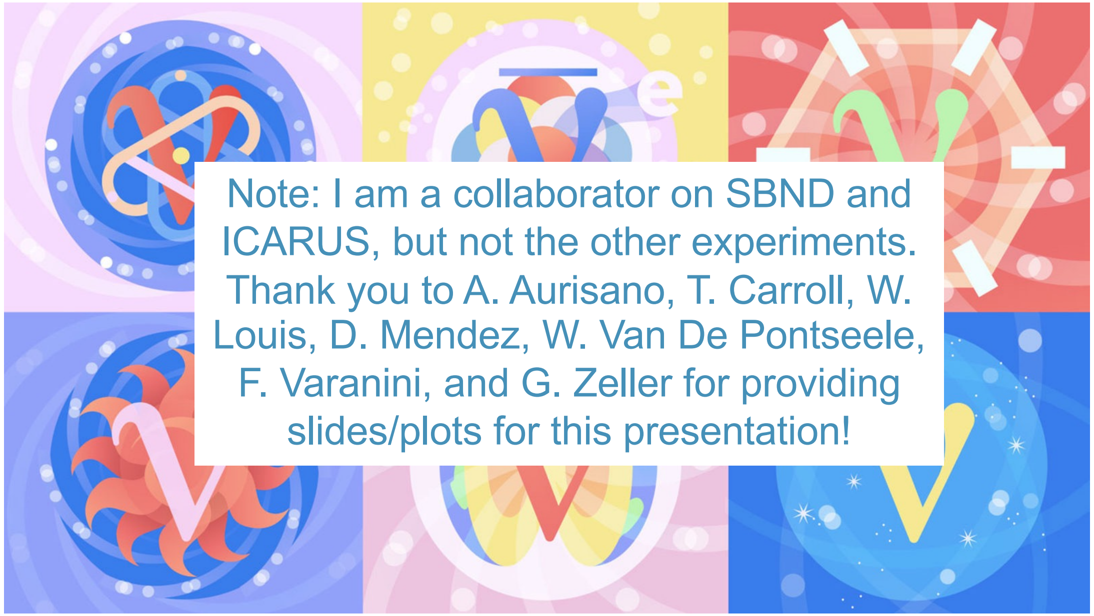
ELIZABETH WORCESTER
(BNL)

FERMILAB 54TH ANNUAL
USERS MEETING

AUGUST 5, 2021

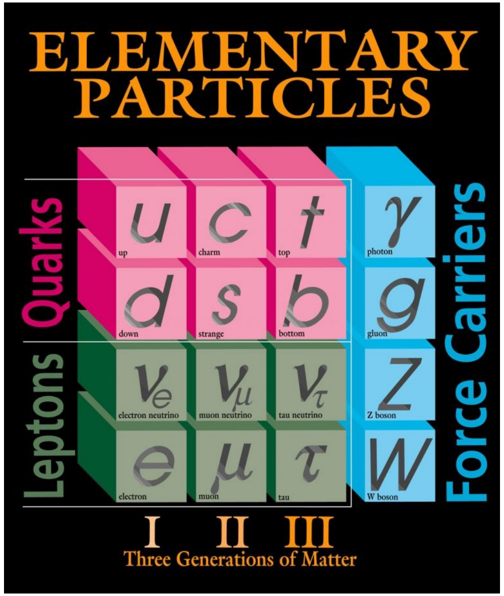
OVERVIEW

- Introduction to neutrino oscillation, sterile neutrinos, and Fermilab neutrino experiments
- MiniBooNE
- MINOS+
- Short Baseline Neutrino Program:
  - MicroBooNE status
  - SBN sensitivity projections
  - SBND installation status
  - ICARUS commissioning status & analysis plans



Note: I am a collaborator on SBND and ICARUS, but not the other experiments. Thank you to A. Aurisano, T. Carroll, W. Louis, D. Mendez, W. Van De Pontseele, F. Varanini, and G. Zeller for providing slides/plots for this presentation!

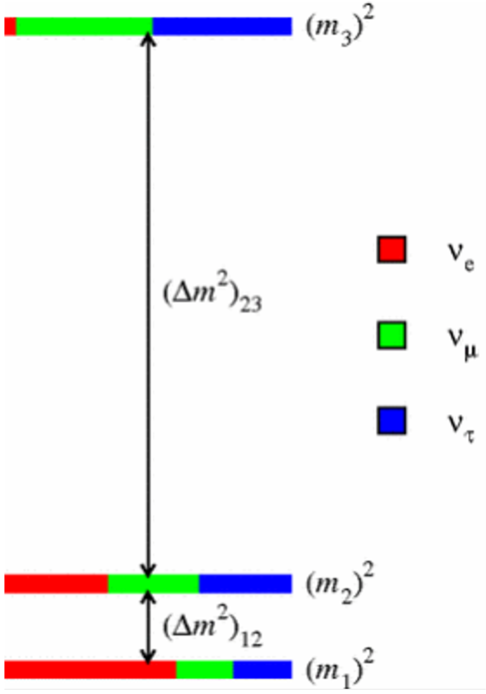
THREE-FLAVOR NEUTRINO OSCILLATION



- Measurements of the Z boson at LEP tell us there are three flavors of neutrino with SM weak interactions
- Neutrinos have mass, which implies neutrino mixing and neutrino oscillation

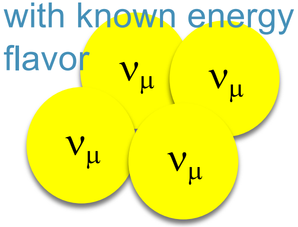
$$|\nu_\alpha\rangle = \sum_k \overset{\text{PMNS}}{U_{\alpha k}} |\nu_k\rangle$$

- All three flavors (ν_e, ν_μ, ν_τ) have been observed and their mixing is mostly consistent with two mass differences and a 3x3 mixing matrix ("PMNS matrix")
- The two mass differences and the three mixing angles of the PMNS matrix have all been measured by observing neutrino oscillation



MEASURING OSCILLATION PARAMETERS

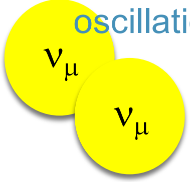
Source of neutrinos with known energy and flavor



$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

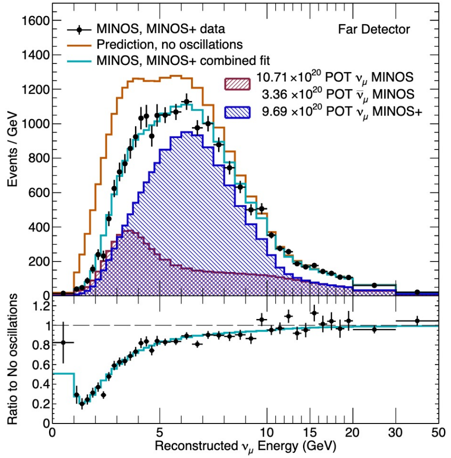
Two-flavor oscillation probability

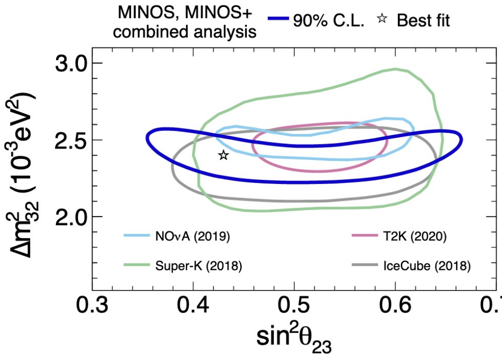
Different flavor composition after oscillation



NuFit 5.0

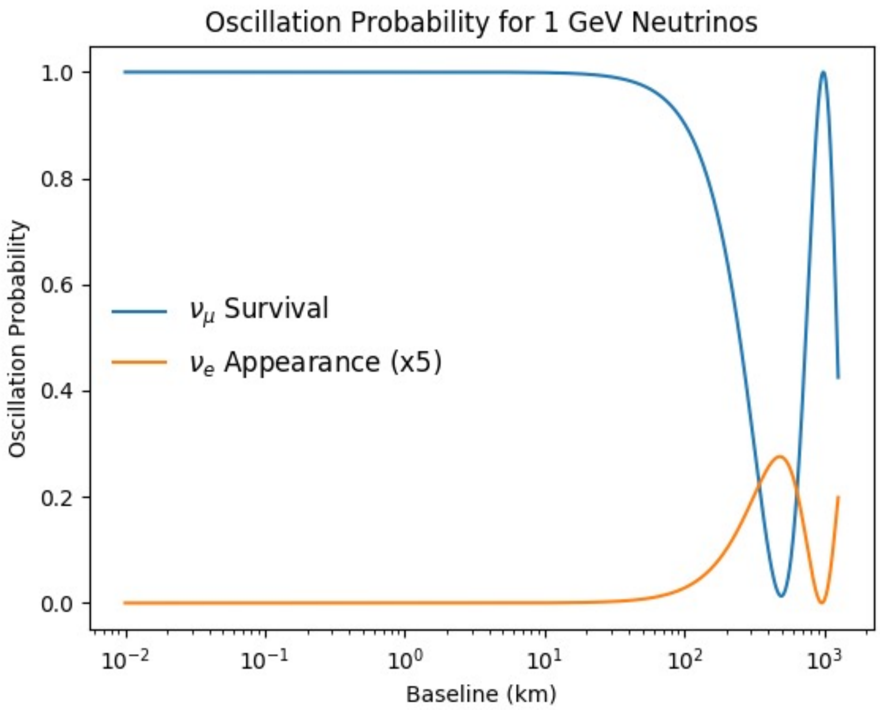
	Normal Ordering (best fit)	
	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$
$\delta_{\mathrm{CP}}/^\circ$	195^{+51}_{-25}	$107 \to 403$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$





MINOS/MINOS+ 3-flavor oscillations
Phys.Rev.Lett. 125 (2020) 13, 131802

WHY STERILE NEUTRINOS?

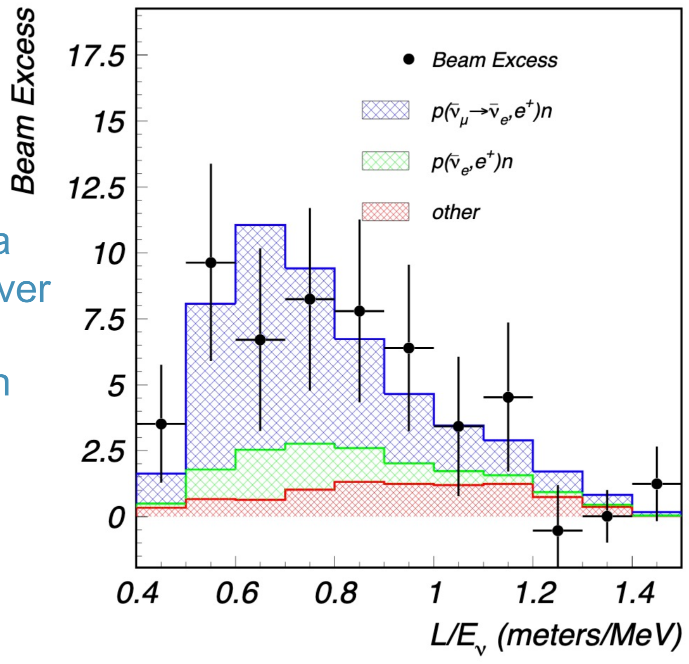


- Oscillation probability depends on mixing angle, mass splitting, and L/E
- Based on the already-measured oscillation parameters, we do not expect to see muon neutrino oscillation at small values of L/E
  - i.e.: ν_μ survival probability should be ~1 and ν_e appearance probability should be ~0 for order 1 GeV neutrinos with baselines < 100 km
  - Any evidence for ν_μ disappearance or ν_e appearance at these L/E values would require a larger mass splitting, which would require at least 1 additional neutrino mass state

WHY STERILE NEUTRINOS?

LSND Collaboration, Phys.Rev.D 64 (2001) 112007

3.8 sigma excess over SM prediction



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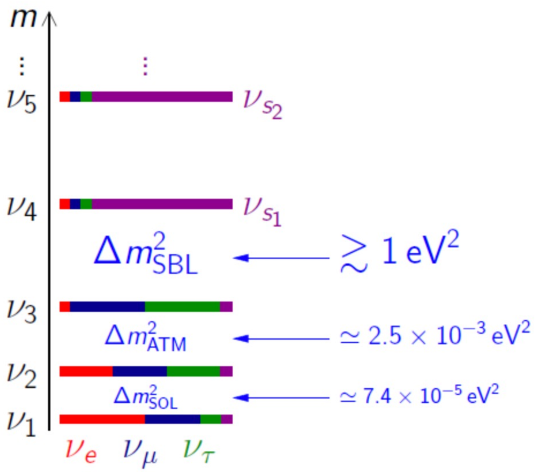
  - Any evidence for ν_μ disappearance or ν_e appearance at these L/E values would require a larger mass splitting, which would require at least 1 additional neutrino mass state
- Several experiments have observations consistent with ν_e appearance at L/E ~ 1 (+other anomalies)

STERILE NEUTRINO MODEL

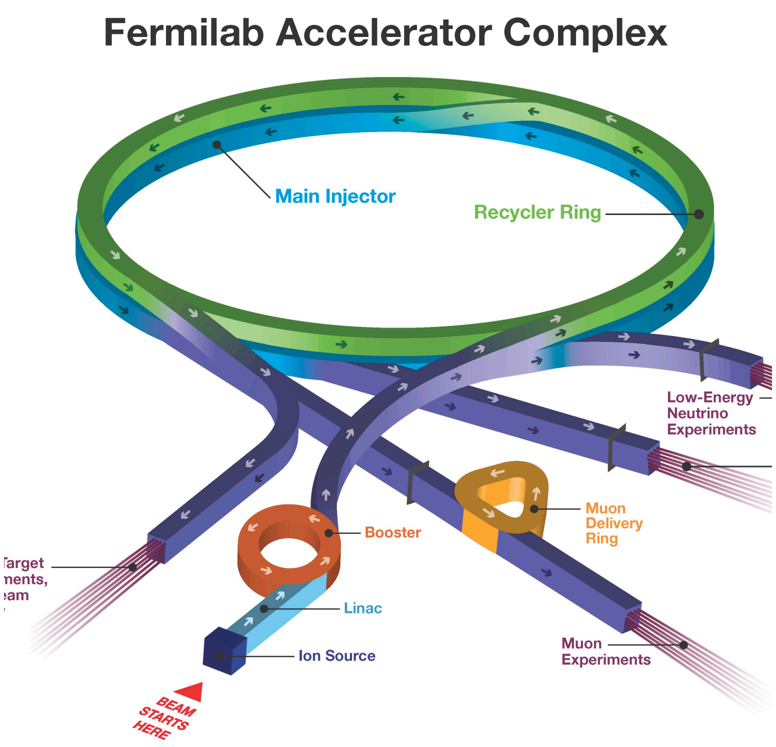
- 3 neutrino model → 3 + x neutrino model, where there are x additional, “sterile” neutrinos
- Sterile neutrinos mix with standard neutrinos (allows for additional oscillation), but do not have weak charge, (consistent with # of neutrinos from LEP/astrophysics)
- “3+1” model is simplest scenario; while this model is nearly excluded by data, we often quote sterile neutrino parameters in a simplified “2 flavor” version of this model
  - $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$ (ν_e appearance)
  - $\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$ (ν_μ disappearance)
  - $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$ (ν_e disappearance)

2 independent matrix elements



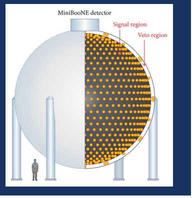
Other possible explanations for these anomalies proposed by theory community; differing levels of hadronic activity can distinguish these possibilities

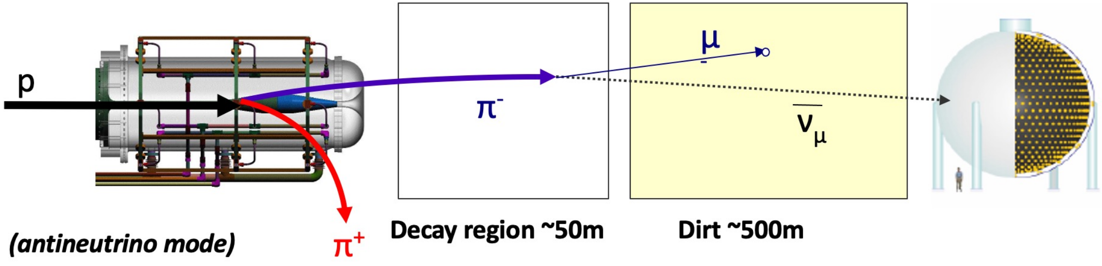
FERMILAB NEUTRINO EXPERIMENTS

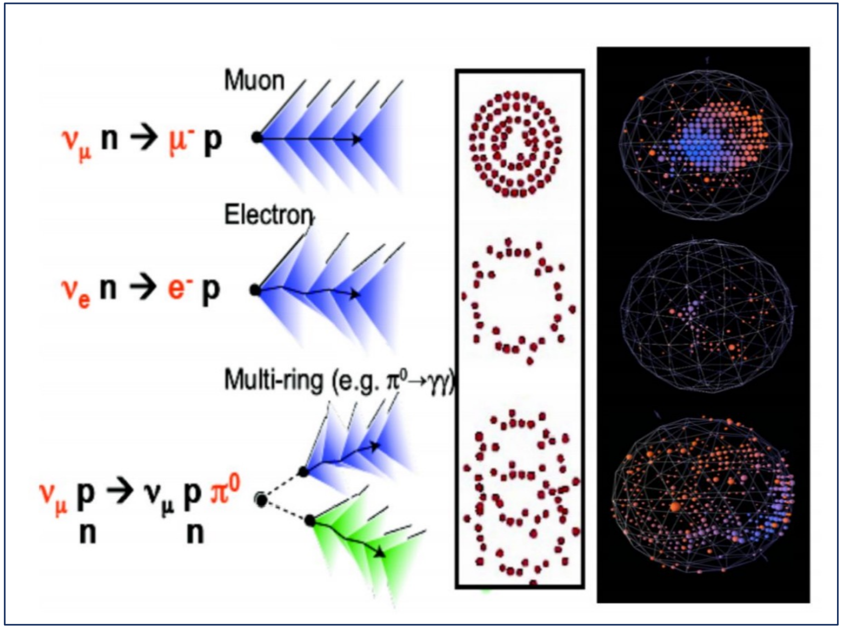


- Proton accelerator complex feeds multiple horn-focused neutrino beamlines
- Booster Neutrino Beam (BNB):
  - Neutrino energy ~700 MeV
  - **MiniBooNE**, **SBN** (**SBND, MicroBooNE, ICARUS**)
- NuMI Beam:
  - Wideband, tunable beam, neutrino energy peaks between 3 and 12 GeV depending on tune
  - MINERvA
  - MINOS/**MINOS+**, NOvA (off-axis), FDs in Minnesota
- LBNF Beam:
  - Future wideband beam
  - DUNE, FD in South Dakota

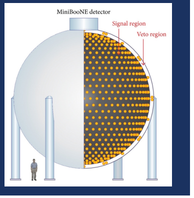
MINIBOONE EXPERIMENT





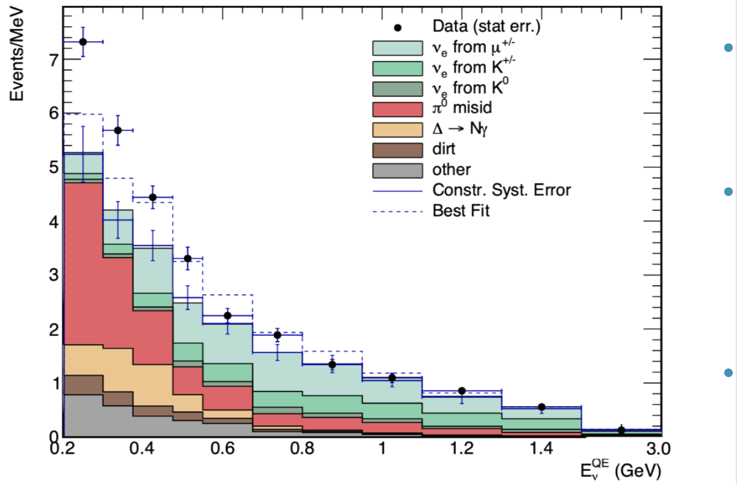


- Designed to test LSND signal: search for $\nu_\mu \rightarrow \nu_e$ appearance at L/E ~ 1 (~500m/~500MeV)
- 800t mineral oil Cherenkov detector
- 17 years of operation in Fermilab's Booster Neutrino Beam (3×10^{21} POT)!

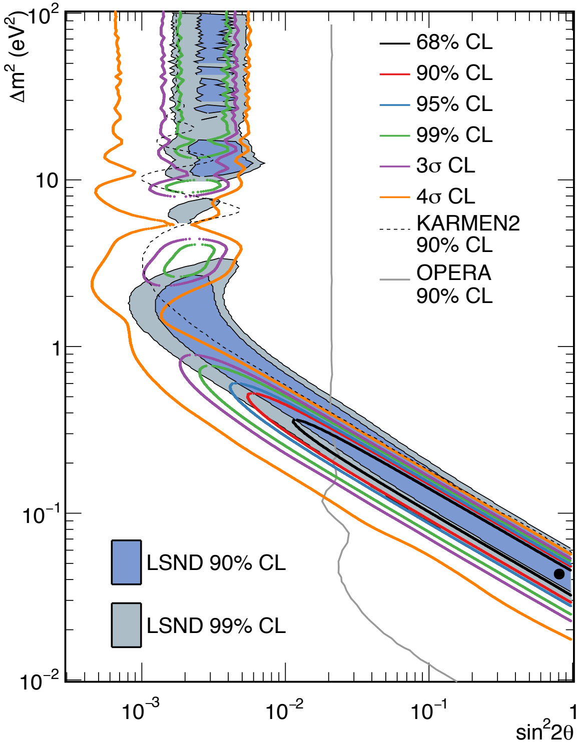


MINIBOONE RESULTS

PRD 103, 052002 (2021)

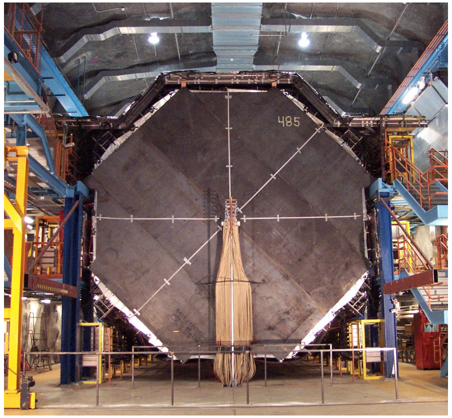


- MiniBooNE observes an excess of events over SM expectation at low energies (LEE)
- The excess events could be due to electrons, single gammas, or low-mass e^+e^- pairs
- The significance of the excess observed by LSND is 3.8σ and by MiniBooNE is 4.8σ, for a combined significance of 6.1σ
- LSND & MiniBooNE prefer consistent region of parameter space for 3+1 sterile neutrino model assumption

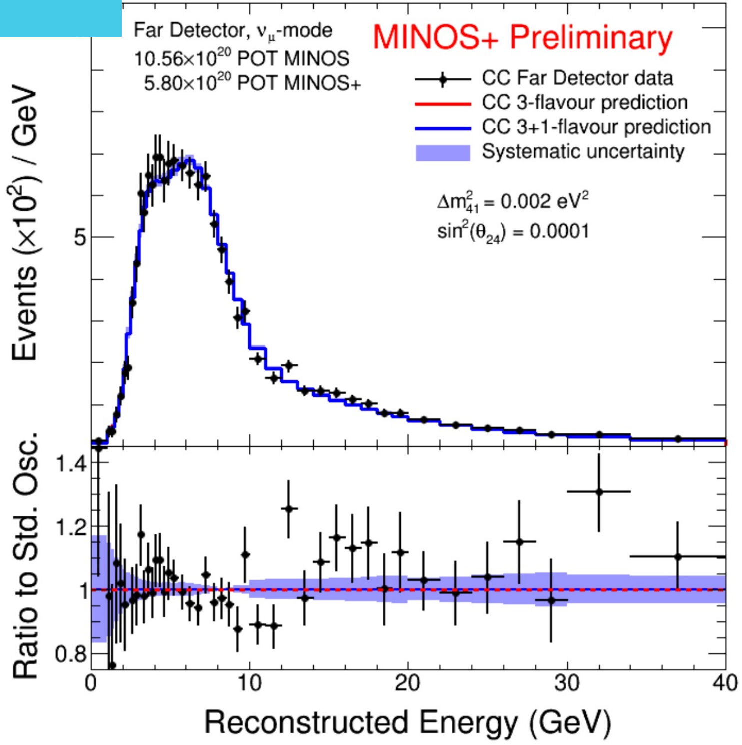


MINOS+

- MINOS was a long-baseline experiment that ran in the NuMI beam from 2005-2013; MINOS+ continued operating the experiment with the NuMI medium energy tune (simultaneous with NOvA operations) from 2013-2016
- Functionally equivalent tracking sampling calorimeters (ND+FD)
- Baseline of 735 km → L/E at far detector ~150-250 km/GeV

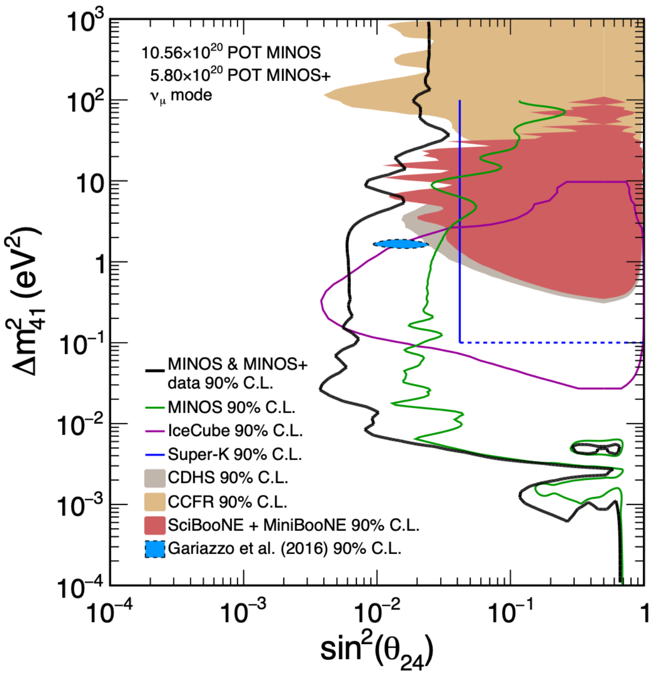


ν_μ CC



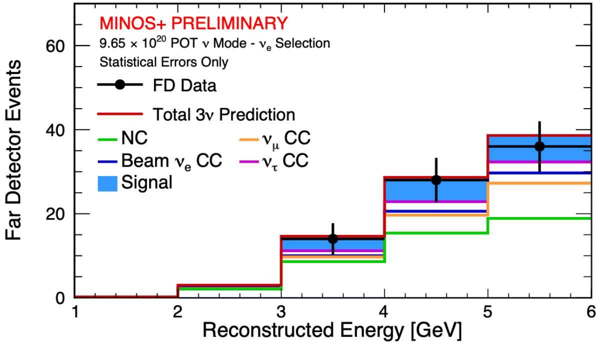
MINOS+ RESULTS

ν_μ Disappearance



P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. Lett. **122**, 091803 (2019)

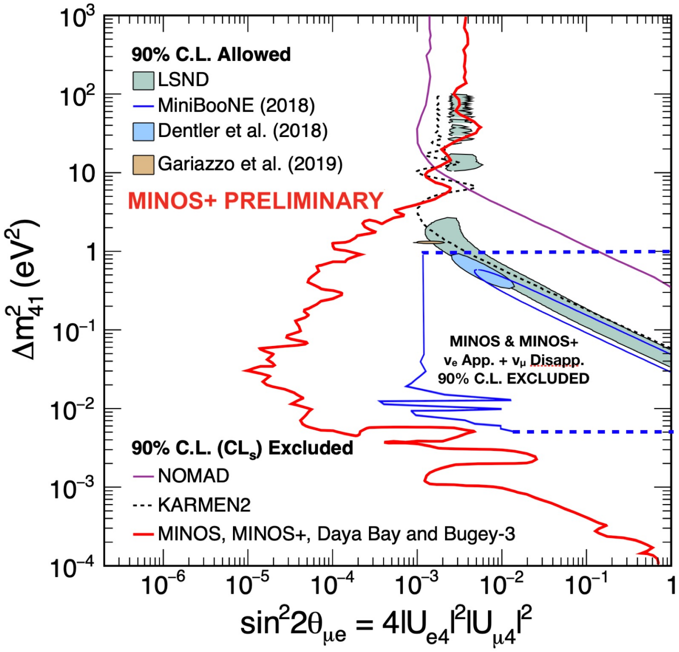
ν_e Appearance



Results consistent with 3 neutrino paradigm and significantly constrain 3+1 sterile neutrino model parameters.

Combined Analysis

MINOS, MINOS+, Daya Bay, Bugey-3

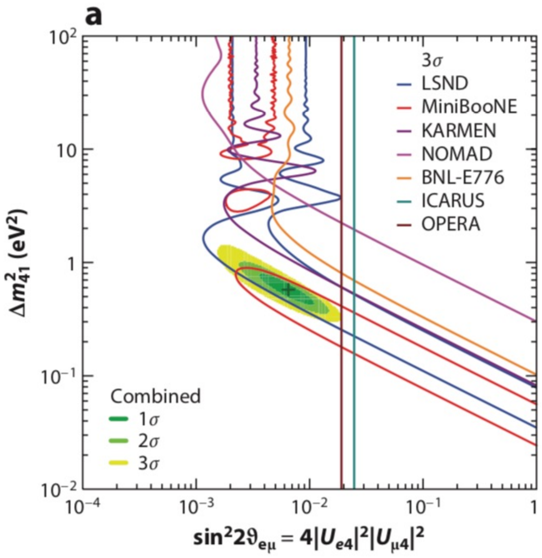


GLOBAL STERILE NEUTRINO FIT

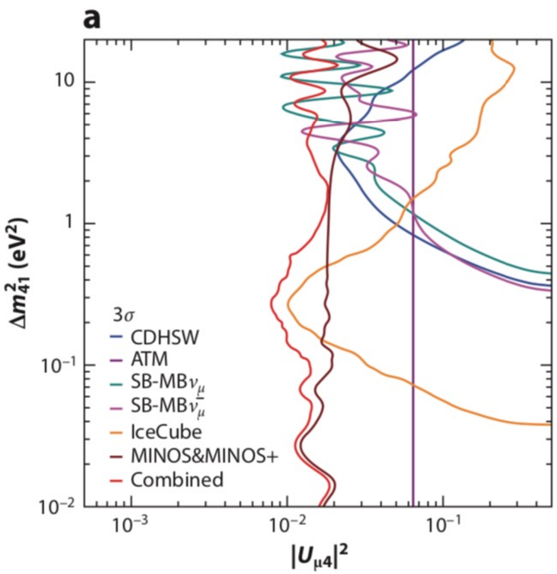
Annu. Rev. Nucl. Part. Sci. 2019 DOI 10.1146

Many more inputs: gallium experiments, reactor flux and oscillation experiments, atmospheric neutrinos, solar neutrinos, other accelerator-based experiments…

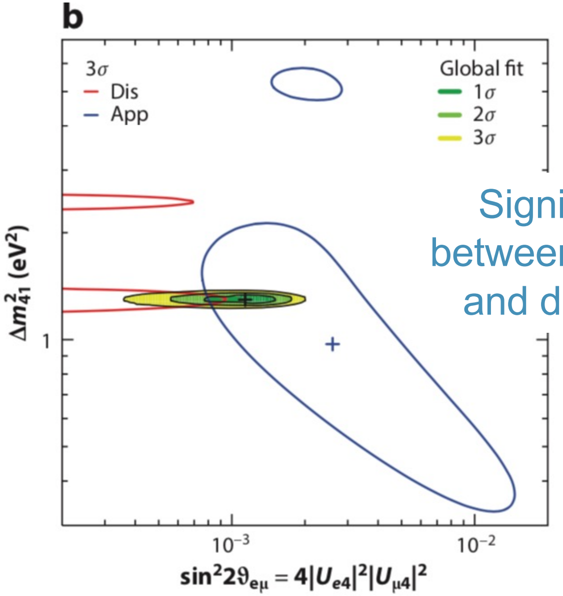
ν_e appearance



ν_μ disappearance

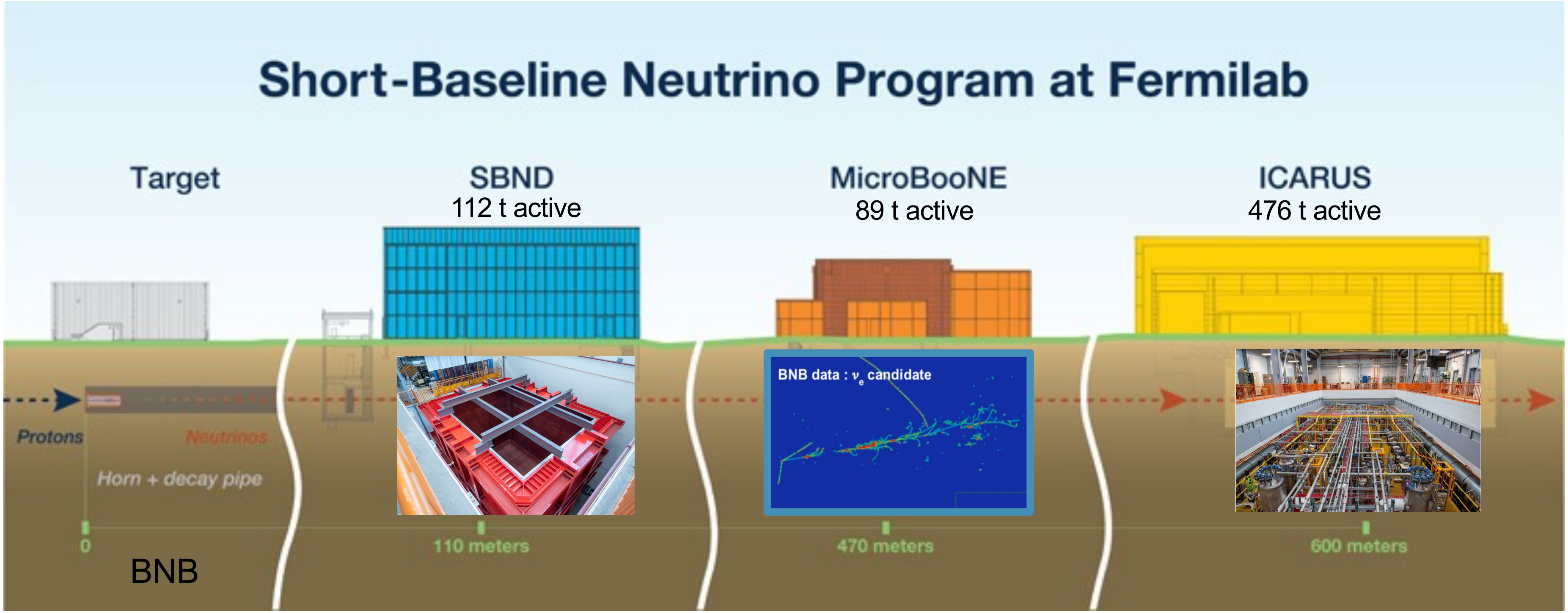


Combined



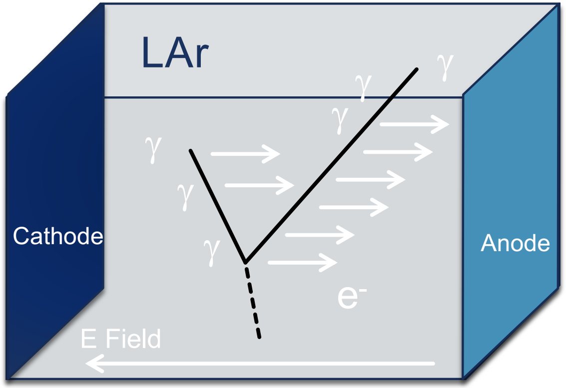
Significant tension between appearance and disappearance

SBN PROGRAM

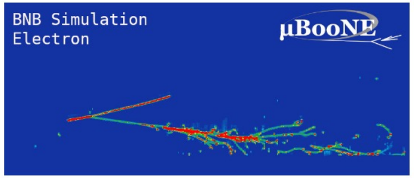


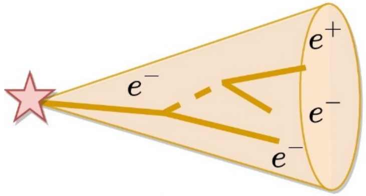
Installation in progress Taking data since 2015 Commissioning in progress

LIQUID ARGON TPC

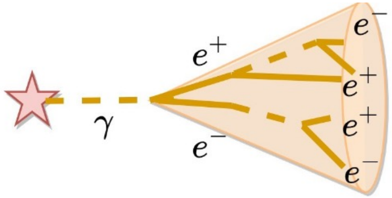


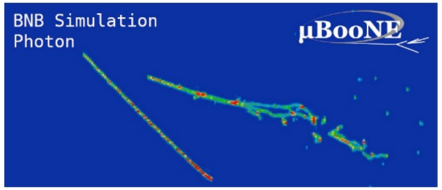
- Massive, homogeneous target for neutrino interactions with good tracking and calorimetric capability
- Ionization electrons drift to anode on a timescale of ms → 3D trajectory, energy
- Scintillation light (128 nm) detected promptly → time, energy





- Detailed images of particle trajectories
  - Significant information about complex final states
- Capability to distinguish electrons from photons:
  - Gap between vertex and shower start for photons (X_0 = 14 cm)
  - dE/dx at shower start (e^- vs e^+e^-)





MICROBOONE STATUS

- Currently the world's longest running liquid argon TPC (2015-present)
- Analysis of high statistics data and long-term operational experience is informing the future LAr neutrino program
  - 33 papers, 56 public notes so far!
- Physics run complete, R&D program now underway
- On the cusp of releasing a series of first results addressing the anomalies seen in prior short-baseline neutrino experiments

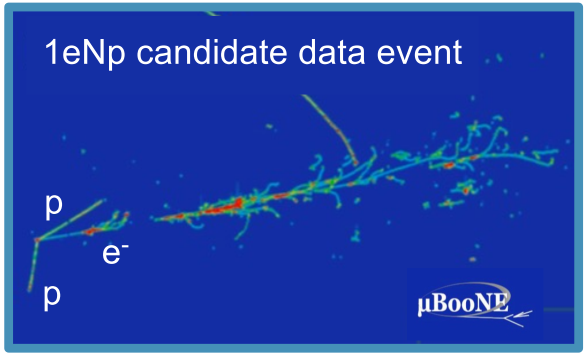
Upcoming analyses focusing on 6 final states:

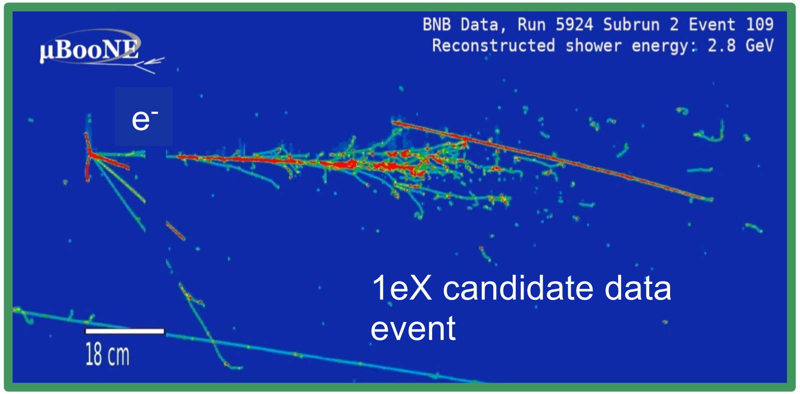
- **MiniBooNE-like ν_e final state** (1eNp, 1e0p)
- **Delta radiative decays**, the leading photon-based explanation for MiniBooNE (1γ1p, 1γ0p)
- **2-body ν_e quasi-elastic events** with high purity (1e1p)
- **Inclusive ν_e scattering** with high efficiency (1eX)

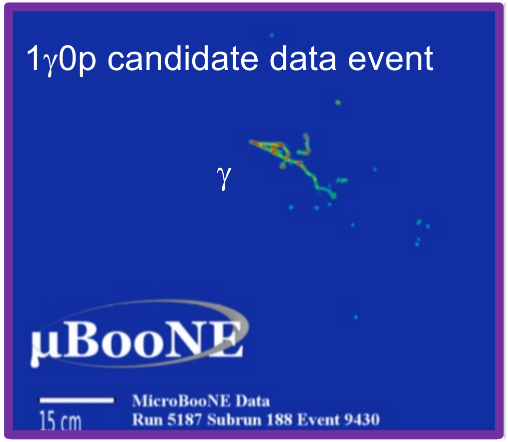
Future sterile-related analyses include: ν_μ disappearance, combined BNB + NuMI analysis in MicroBooNE, increased statistics (2x), combined SBN analysis with SBND and ICARUS

UPCOMING MICROBOONE RESULTS

- ν_e analyses:
  - MiniBooNE-like final state (Pandora, 1eNp, 1e0p)
  - restricting to quasi-elastic kinematics (Deep Learning , 1e1p)
  - all ν_e final states (Wire-Cell, 1eX)
- Single photon analysis:
  - targeting Delta radiative decay hypothesis (Pandora, 1γ1p, 1γ0p)

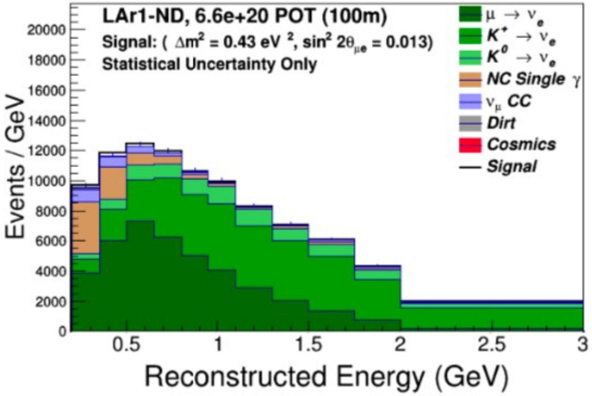




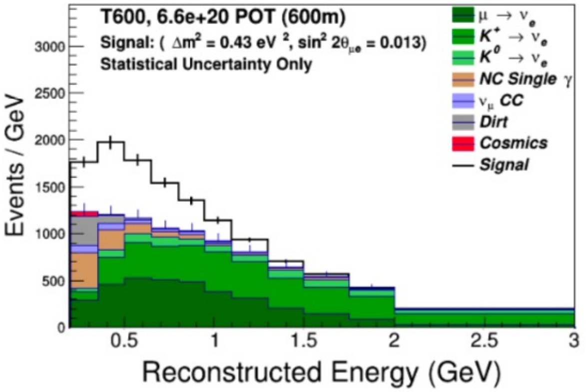


SBN SENSITIVITY PROJECTIONS

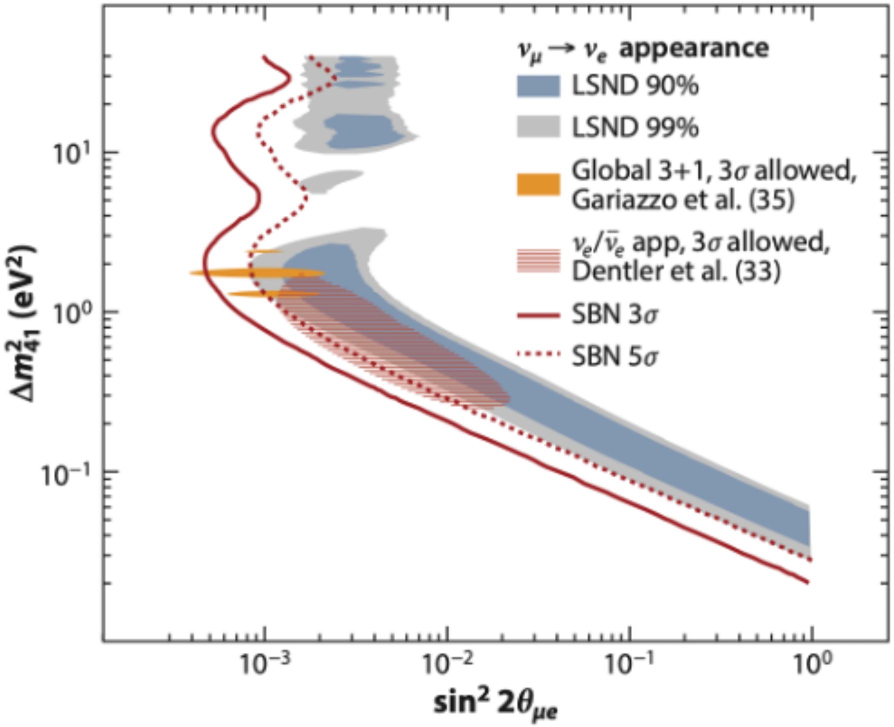
SBND (3 years BNB)



ICARUS (3 years BNB)



ν_e appearance



Annu. Rev. Nucl. Part. Sci. 2019 DOI 10.1146
(Reproduced from SBN Proposal assuming 6.6 E20 POT)

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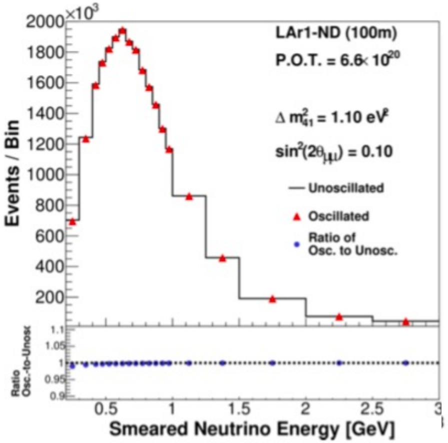
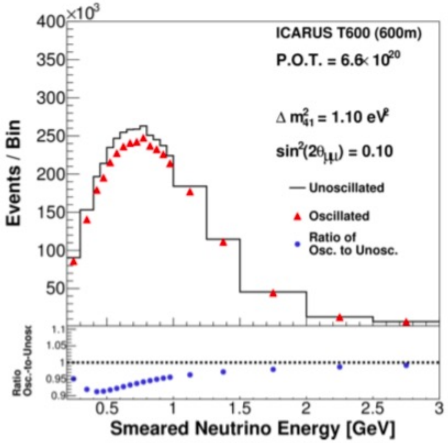
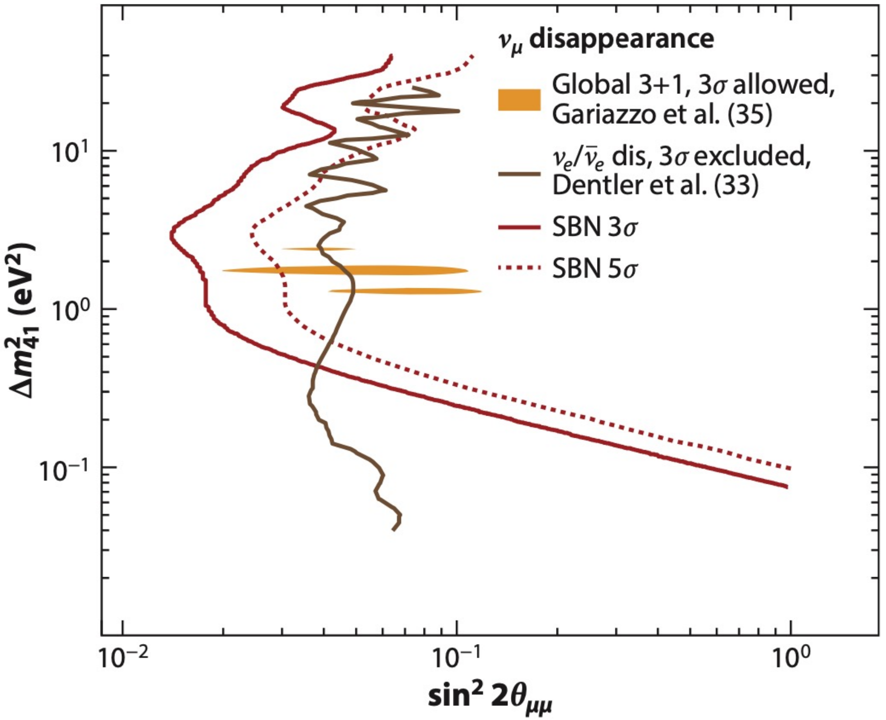


ICARUS
(3 years BNB)



ν_μ disappearance



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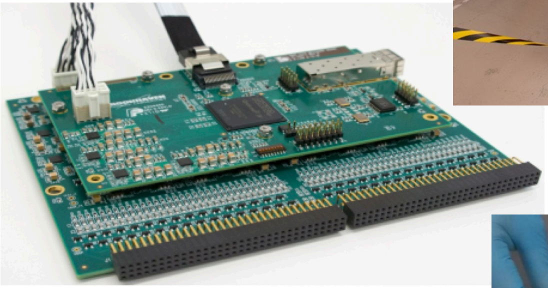
(Reproduced from SBN Proposal assuming 6.6 E20 POT)

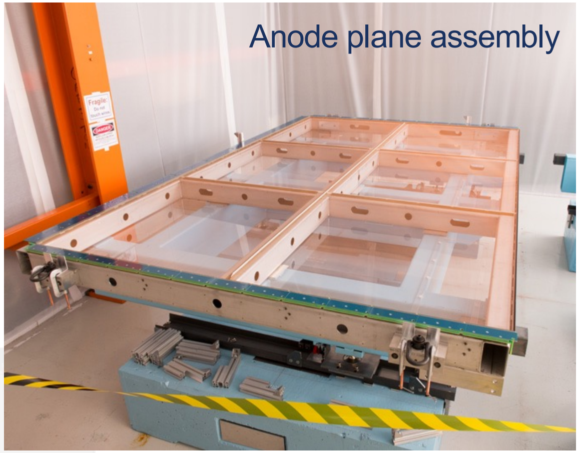
Not shown: MicroBooNE data (included in exclusion curves), ν_e disappearance sample, neutral current sample, joint appearance + disappearance fit, etc.

SBND INSTALLATION STATUS

CPA frame installed, CPA panel installation in progress. All other TPC components on site and ready for installation. Light collection module production in progress.

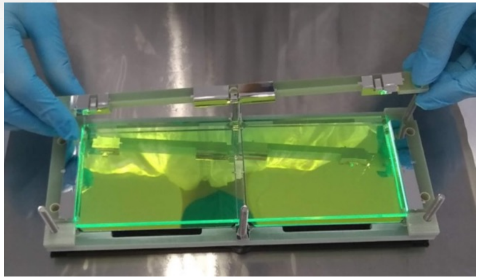
CE front-end motherboard



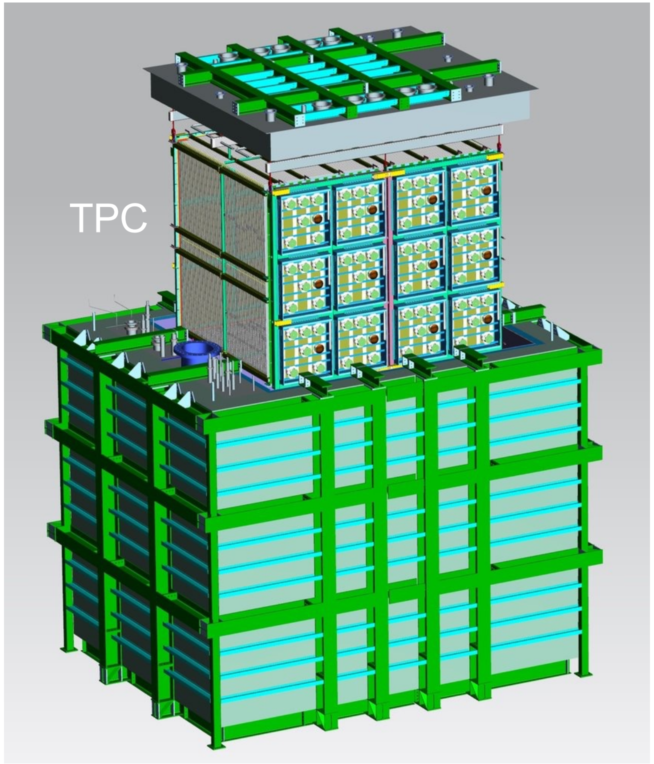


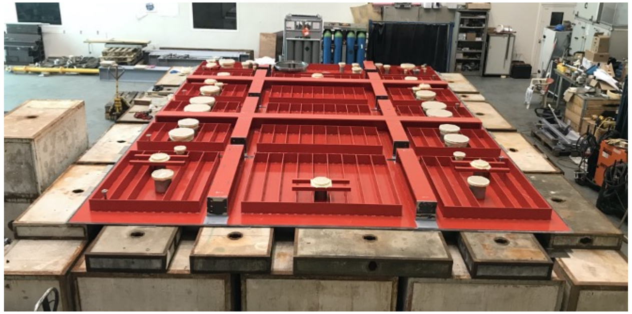
Anode plane assembly

X-ARAPUCA production

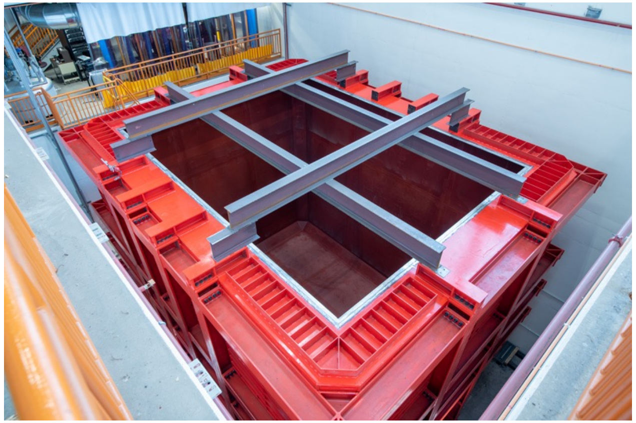


SBND INSTALLATION STATUS



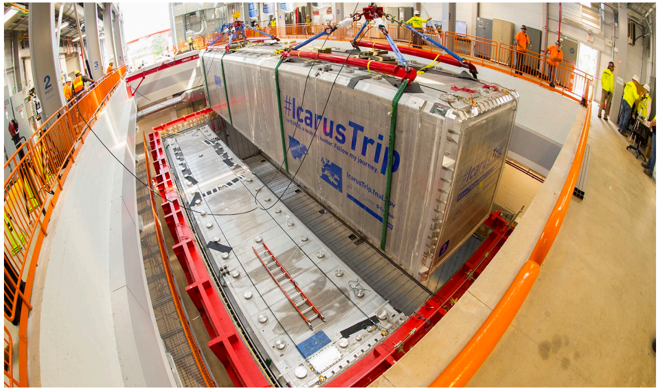


- Cryostat top fabricated
- Warm outer vessel already installed in the SBN-ND building
- Cyrogenics/cryostat installation in progress
- SBND ready for cold commissioning by end of 2022!

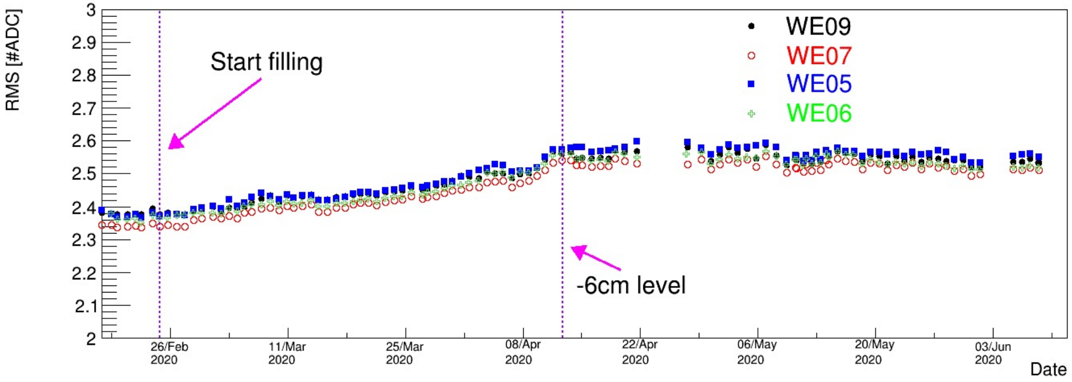


ICARUS COMMISSIONING STATUS

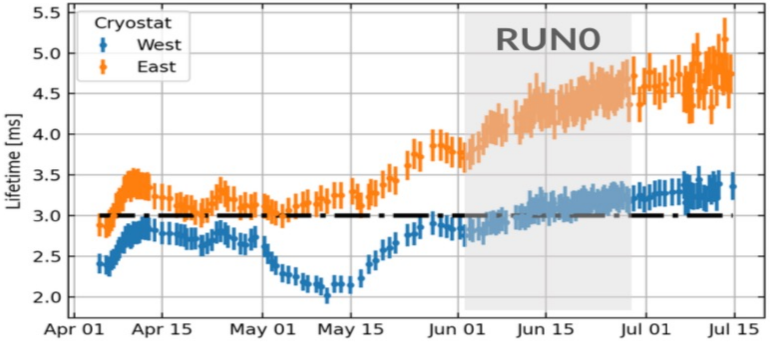
- ICARUS has been commissioning since 2020 and collecting neutrino data from the BNB and NuMI beams since March 2021
- Improvements in progress during summer shutdown: install top cosmic ray tagger, upgrade PMT HV, upgrade TPC readout electronics, upgrade cryogenic filters, continued development of analysis infrastructure, data processing, etc.
- First physics data collection will begin in October 2021!



TPC Noise (coherent noise removed)

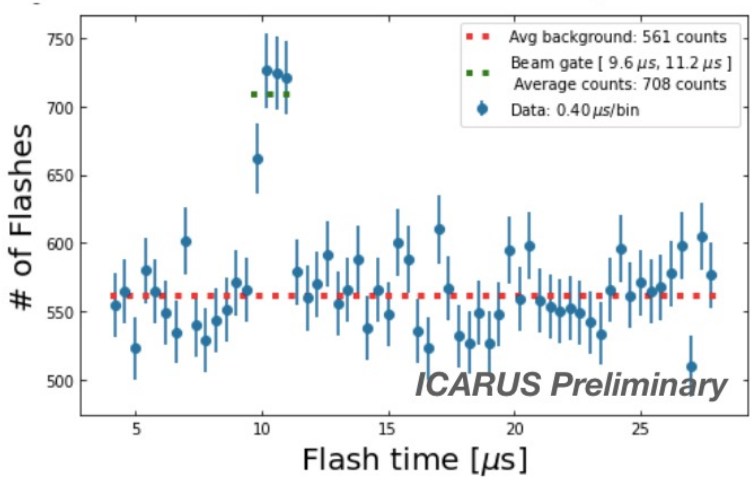


Electron Lifetime

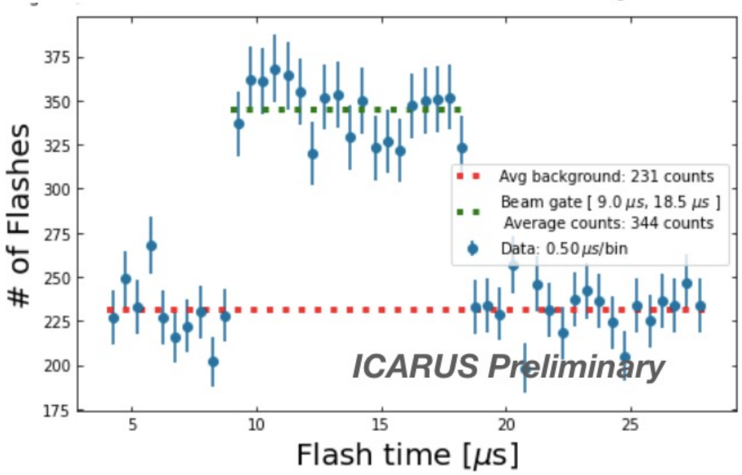


ICARUS FIRST NEUTRINO DATA

BNB SPILL WINDOW 1.6 μs

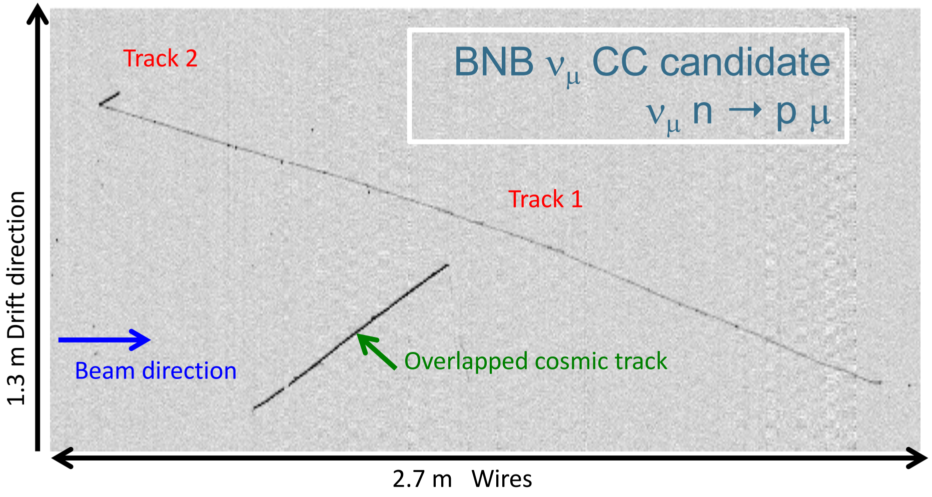


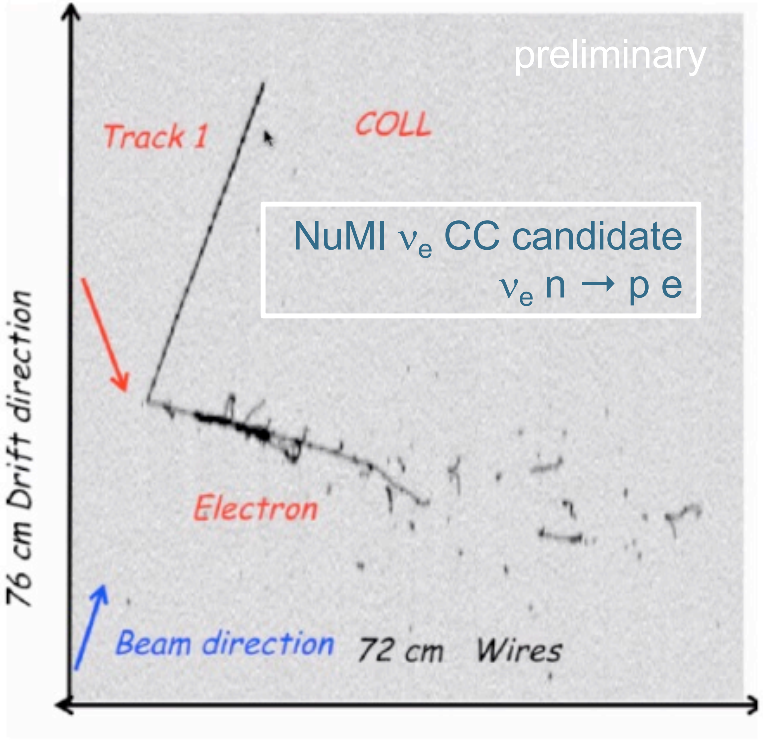
NuMI SPILL WINDOW 9.5 μs



Time of PMT light flashes shows excess over the cosmic background rate at the expected neutrino arrival time for both BNB and NuMI beams

ICARUS FIRST NEUTRINO DATA

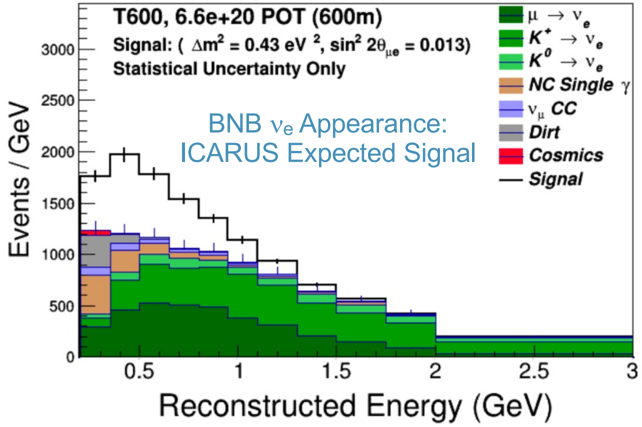


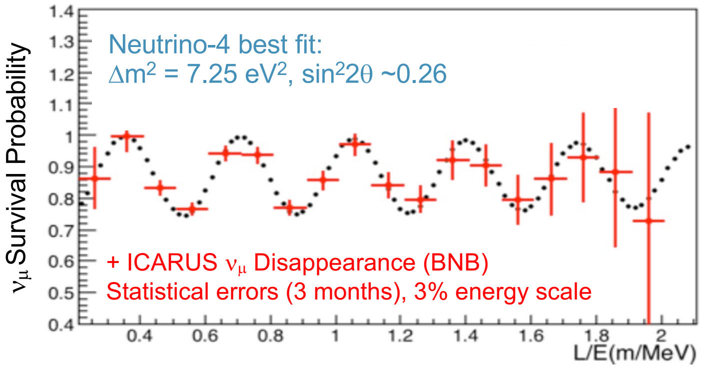


ICARUS was the primary BNB user during the full month of June 2021 (“run 0”):
27.8 $\times 10^{18}$ POT from BNB and 52.0 $\times 10^{18}$ POT from NuMI were collected

ICARUS STERILE NEUTRINO SEARCH PLANS

- ICARUS is the far detector for the SBN oscillation analysis: with 3 years of data the combined SBND and ICARUS analysis will be able to cover most of the allowed region of parameter space with 5σ sensitivity
- ICARUS will perform a single-detector oscillation analysis using data taken in the coming year (before SBND data is available)
  - Focus on **quasi-elastic-like** ν_μ CC and ν_e CC candidates to simplify analysis
  - **ν_μ disappearance (BNB)**: expect ~11,500 events in 3 months
  - **ν_e disappearance (NuMI)**: expect ~5,200 events per year
  - Combined analysis of these samples + beam-off samples provides significant sensitivity to potentially interesting areas of parameter space, including regions probed by the current generation of short-baseline reactor experiments





SUMMARY

Photo: R.Hahn

- Fermilab's experiments are central to understanding the longstanding mystery surrounding sterile neutrinos
- Significant non-Standard Model excesses observed in multiple experiments, but there is also significant tension among experimental results
  - **MiniBooNE** observes 4.8σ excess (6.1σ combined with LSND) consistent with eV-scale sterile neutrino
  - **MINOS+** results consistent with three flavor paradigm
  - Many other experiments around the world contribute to global picture
  - **MicroBooNE** analyses addressing LEE expected very soon
  - SBN program designed to study multiple appearance and disappearance channels and provide definitive answers
- **ICARUS** commissioning very successful with physics data coming this year
- **SBND** installation in progress, expect commissioning at the end of 2022
- Fermilab's neutrino experiments are also sensitive to a broad range of physics topics beyond the scope of this talk: precision three flavor oscillation, neutrino interaction/cross-section measurements, other BSM searches…
- Exciting times!