Solving the Sterile Neutrino Puzzle with ICARUS

On Behalf of the ICARUS Collaboration

Justin Mueller

Colorado State University

July 20, 2020

DOE Report Number: FERMILAB-SLIDES-20-046-ND

Neutrino Oscillations

- The mismatch between the leptonic flavor basis (ν_e, ν_μ, and ν_τ) and the neutrino mass basis (ν_1, ν_2, and ν_3) results in a probability for a neutrino to be created in one flavor and detected as another

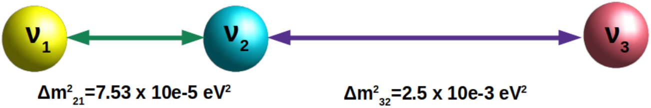
Two Flavor Approximation

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

L = Length of baseline

E = Energy of neutrino

$$\sin^2(\theta_{12}) = 0.3, \sin^2(\theta_{23}) = 0.5, \sin^2(\theta_{13}) = 0.02$$

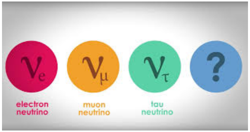


The Short-Baseline Neutrino Anomaly

- In the past 20 years four anomalies have been observed in short baseline neutrino experiments
- These anomalies are potential hints for a fourth and non-weakly interacting ("sterile") neutrino

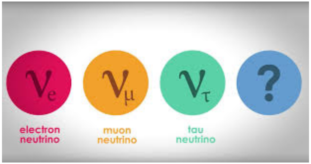
Experiment	Source	Channel	Significance
LSND	μ^+ Decay-at-Rest accelerator	$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$	3.8 σ
MiniBooNE	Short-baseline accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 σ
		$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$	2.8 σ
Reactors	β decay	$\overline{\nu_e}$ disappearance	3.0 σ
GALLEX/SAGE	e- capture	ν_e disappearance	2.8 σ

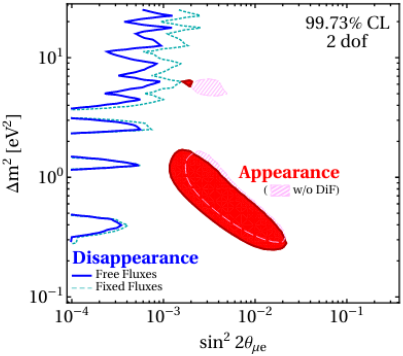
- These can be explained by a sterile neutrino driving short-baseline oscillations with $\Delta \mathrm{m}^2 \sim 1\mathrm{eV}^2$ with a small $\sin^2(2\theta)$



Sterile Neutrinos

- Adding to the mystery, there is so far no evidence in ν_μ disappearance measurements (MINOS/MINOS+, NOvA, IceCube)
- We need a definitive search of the parameter space indicated by these anomalies

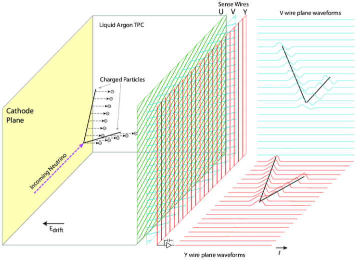




M. Dentler et al., JHEP 08:010 (2018)

Liquid Argon Time Projection Chambers (LArTPCs)

- The ν-Ar interaction produces charged particles which ionize the argon along tracks
- The electrons that are freed are caused to drift by an applied electric field
- The electrons produce induction signals as they pass the first two wire planes and are collected on the last wire plane

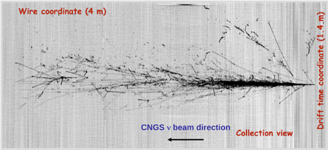


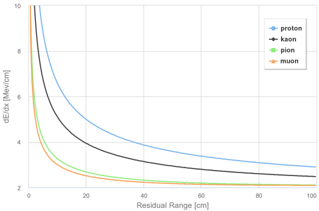
Note: ICARUS has a different wire plane geometry, but this demonstrates the LArTPC concept.

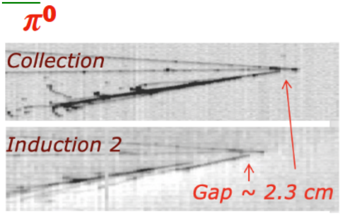
Why LArTPCs?

LArTPCs are characterized by

- Low thresholds: proton detection is possible!
- High spatial resolution: very useful for background rejection and particle identification
- Excellent calorimetry: allows for more precise neutrino energy estimation as well as particle identification via dE/dx







Note: dE/dx plots show the theoretical model

ICARUS (Imaging Cosmic and Rare Underground Signals)

- Two modules: each 19.6m x 3.6m x 3.9m
- Each module has two TPCs with 1.5 meter drift lengths
- Three readout wire planes (2 induction, 1 collection) per TPC, $\sim$ 54000 wires at 0, $\pm$60 degrees with 3 mm spacing
- 360 PMTs for trigger and timing
- Bottom, side, and top (to be installed) CRT systems for cosmic ray rejection
  - ICARUS previously searched for sterile ν oscillations in the ν_e appearance channel in the CNGS beam

Status of ICARUS

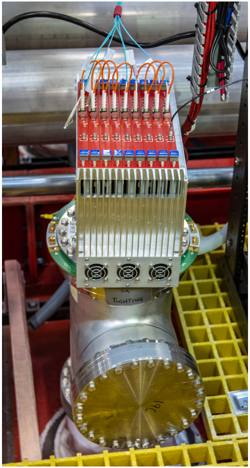
- Upgrades at CERN: new TPC readout electronics and photon detection system.
- ICARUS arrived at Fermilab in 2017 and was installed in 2018
- Began cooling down February 14, filling with LAr on February 24, and was completely filled on April 19
- Currently ICARUS is moving into the commissioning phase

Installation

One ICARUS module being lowered into the warm vessel

Top view of the installed ICARUS detector

Installation (Continued)

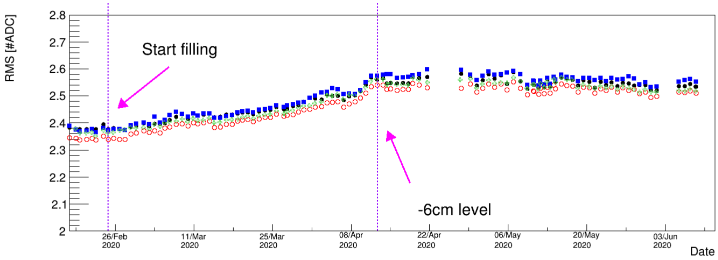


Fully connected TPC Mini-Crate

Side CRT installation

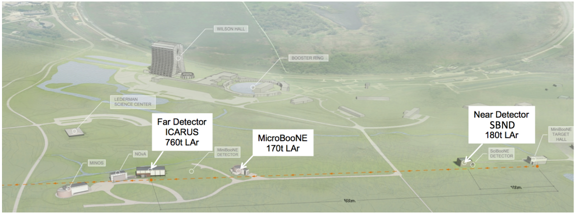
Commissioning

- We were able to take TPC data during the filling process!
  - Noise increase observed due to wire capacitance increase from LAr filling



Noise pictured is after coherent noise removal

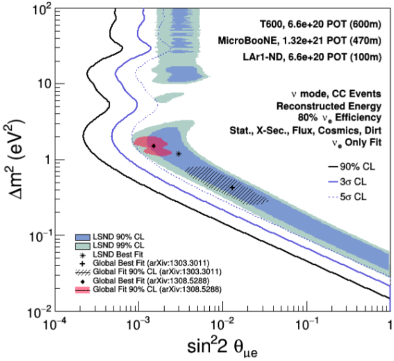
ICARUS and SBN

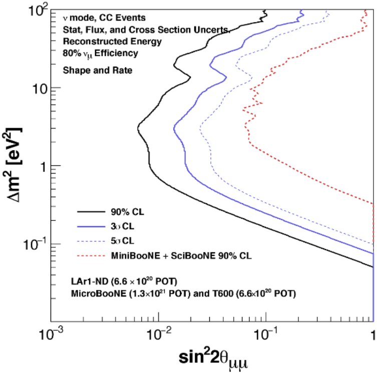


- The sterile neutrino search at ICARUS will proceed within the framework of the Short Baseline Neutrino Program (SBN)
  - The three detectors provide complementary roles in sampling the neutrino beam at varying distances
  - ICARUS serves as the far detector, MicroBooNE is positioned in the middle, and the Short Baseline Near Detector (SBND) serves as the near detector
- ICARUS will primarily be dedicated to the search for sterile neutrinos via measurements of the oscillated neutrino spectrum (ν_e appearance)

SBN Sensitivity

- ICARUS as part of the SBN program will be search for sterile neutrinos in both the ν_e appearance and ν_μ disappearance channels
- The 5σ exclusion region of SBN covers most of the parameter space allowed by short-baseline neutrino anomalies





arXiv:1503.01520

Summary

- The variety of neutrino anomalies at short-baselines is a potential hint for the existence of sterile neutrinos
- After extensive upgrades, ICARUS installation at FNAL has been completed
- ICARUS has been completely filled with LAr and is entering the commissioning phase at FNAL
  - Data taking for physics is expected by the beginning of next year
- The SBN oscillation program and search for sterile neutrinos will begin first with ICARUS data in the beginning of next year, then eventually SBND data when it becomes operational (expected first half of 2022).

Thank you

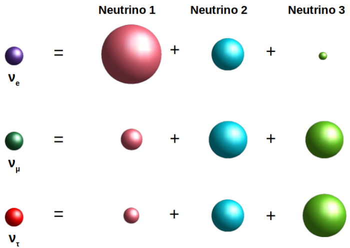
Questions?

Backup

Why Argon?

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Neutrino Oscillations



- Neutrinos are created in a leptonic flavor state (ν_e, ν_μ, or ν_τ)
- There are three discrete neutrino masses (ν_1, ν_2, and ν_3), but these do not correspond exactly to the flavor states
  - There exists a probability for a neutrino to be created in one flavor and be detected as another

Two Flavor Approximation

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

L = Length of baseline
E = Energy of neutrino

Neutrino Oscillations (Continued)

- The transformation is parameterized by three mixing angles (θ_{12}, θ_{23}, and θ_{13})
- Because of the mixing between neutrino states, there exists a probability for a neutrino to be created in one flavor and be detected as another

Two Flavor Approximation

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

L = Length of baseline
E = Energy of neutrino

N Neutrino Oscillation Probability

$$P_{\alpha \to \beta} = \delta_{\alpha\beta} - 4 \sum_{i<j} Re\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$+2 \sum_{i<j} Im\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$