Snowmass 2021 Letter of Interest: Neutrino Frontier

ICARUS in the Next Decade

Topical Group(s):

☑ (NF1) Neutrino oscillations
☑ (NF2) Sterile neutrinos
☑ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
☑ (NF5) Neutrino properties
☑ (NF6) Neutrino cross sections
☐ (NF7) Applications
☐ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
☑ (NF10) Neutrino detectors
☑ (Other) Instrumentation, Cosmic (CF1 - Dark Matter)

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Abstract: Over a period of more than 25 years the ICARUS collaboration has developed the liquid argon Time Projection Chamber technology that has enabled an era of precision large scale neutrino experiments. The ICARUS detector has been transported from Europe to the US and is in the commissioning phase as the far detector for the Short-Baseline Neutrino (SBN) program at Fermilab. Here we summarize the status and physics goals for that program and outline the potential for science and technology development with the ICARUS detector in the next decade.

ICARUS at SBN: The possible existence of neutrino oscillations mediated by additional "sterile" neutrino flavors with Δm^2~1 eV^2 hinted by LSND [1] and other experiments at reactors, accelerators and using radioactive neutrino sources [2], remains an open question in neutrino physics. The tension between these observed anomalies and the negative results from neutrino disappearance searches in the corresponding parameter region [3] and cosmological data [4] calls for a definitive clarification.

The ICARUS-T600 LAr-TPC (476 t active mass) at Fermilab is expected to collect more than half a million ν_μ CC events from the Booster Neutrino Beam (BNB) at 600 m from target and more than one million ν_μ CC from the 6° off-axis NuMI beam at ~800 m from target in its proposed data taking period. Comparison of the recorded events at the Booster beam with the corresponding sample collected by the smaller but similar SBND detector at 110 m from target, will confirm or exclude a sterile neutrino interpretation of the LSND result at ~5 σ C.L. by studying both the ν_μ to ν_e oscillation appearance and the ν_μ disappearance with about three years of data taking [5].

In addition to the physics program described in the SBN program proposal, a new opportunity has arisen. The claim of the observation of sterile neutrinos in the reactor Neutrino-4 experiment [6] shows an oscillatory pattern with a characteristic period of 1.4 m for E = 4 MeV neutrino energy and best fit parameters Δm^2~7.25 eV^2 and $\sin^2 2\theta \sim 0.26$. The principle of muon-electron universality predicts equality between the ν_e and ν_μ mass matrix, so the ICARUS experiment could provide a definitive verification of Neutrino-4 result with sensitive disappearance tests in both ν_μ and ν_e channels.

The Neutrino-4 L/E oscillation-like signal for ν_μ events can be observed by ICARUS at the BNB, as a function of the neutrino energy E, averaged over the 50 m of the pion decay tunnel, which is relatively short compared to the 600 m distance to the detector. ICARUS is expected to collect ~118,000 contained quasi-elastic ν_μ CC events with an average energy of 800 MeV for 6.6 x 10^{20} pot in three years exposure. Fig. 1 shows the results of a study that uses current knowledge of the BNB beam but without accounting for the small uncertainty due to the detector energy resolution. The expected disappearance oscillatory signature is evident, with statistical errors far smaller than for Neutrino-4, confirming the possibility to unambiguously observe the Neutrino-4 like signal with ICARUS at the BNB. The range of L/E values that can be explored by ICARUS overlaps with, and potentially extends, the Neutrino-4 range of 1.0 to 2.5 m/MeV.

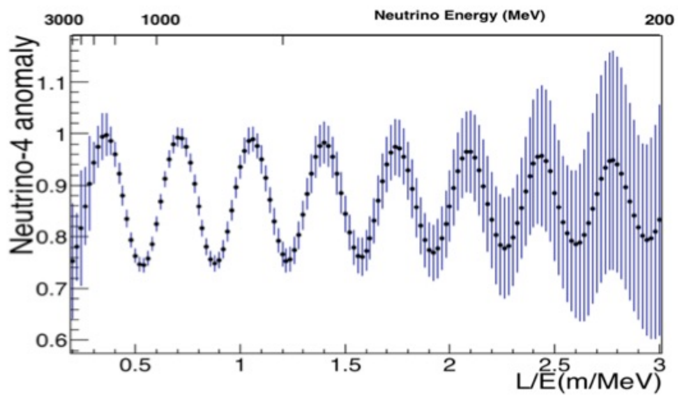

Fig. 1 Expected ratio of survived to initial ν_μ CC events as a function of L/E (lower axis, 0.02 m/MeV bins) and neutrino energy, E (upper axis).

In addition to sterile neutrino analyses with the BNB, ICARUS would also detect neutrinos from the NUMI beam. While in the BNB, muon neutrinos from pion production are dominant, whereas at the off-axis location of ICARUS with respect to the NuMI target kaons are the primary source of neutrinos, which leads to a much larger contribution of the ν_e signal that are produced mostly in the first ~100 m length of the NuMI decay tunnel at ~750 m from ICARUS. The integrated NuMI ν_e and anti-ν_e rates, 4.3% of the ν_μ CC rate, are ~20,000 events/year and 16,400 events/year for positive and negative beam focusing respectively, with a neutrino energy distribution similar to the previously described BNB case. CC-QE interactions are about one half of all charged current events, resulting in ~7300 reconstructed events per year for positive focusing, sufficient to verify conclusively the Neutrino-4 observation from another neutrino source.

The ICARUS detector will also be a sensitive probe of Beyond the Standard Model (BSM) physics topics, including low mass dark matter [7,8] and the Higgs portal [9] from the NuMI beam, as well as Boosted Dark Matters from the cosmogenic origin via their inelastic scattering signature described in Ref. [10]. The ability to detect the decay of long-lived dark sector particles produced in the NuMI target and absorber (only 110 m from ICARUS) will allow ICARUS to discover or extend the exclusion range for the dark scalar mass and mixing angle well beyond current limits from the CHARM, LHCb and E787/E949 experiments. ICARUS will explore BSM phenomena well ahead of future neutrino experiments, such as DUNE and Hyper-K, and serving as the lighthouse for significantly expanded physics opportunities at high intensity neutrino beam facilities. A related LOI, “Search for low mass dark matter at ICARUS detector using NuMI beam,” has been submitted to the Neutrino and Cosmic Frontier Topical Groups.

In addition to the BSM searches, a careful and detailed analysis of the events collected from the NuMI beam will be highly beneficial for the future LBNF-DUNE LAr program [11], allowing a precision study of detection efficiencies and kinematical selections in all neutrino channels and event topologies along with a rich program of cross section measurements.

Beyond the Current SBN Program: The current SBN program anticipates an exposure of 6.6x10^{20} POT in the Booster beamline to achieve the proposed science goals. However, the current long-term Fermilab accelerator operations plan indicates the potential for almost triple that exposure from both the Booster, and a similar factor for the NuMI beam, before the long shutdown associated with the LBNF program in 2025. A three times larger event sample would allow more detailed studies of the beam and the detector systematics in a data-driven way and possibly mitigate their impact on the sensitivity. Event selection would be further optimized both online and offline, leveraging the signal efficiency while reducing the residual background from cosmics and NC interactions, with a potential significant gain in sensitivity for the sterile neutrino search. In addition, the signature for the Neutrino-4 effect would be enhanced by enlarging the L/E coverage and extending the search to smaller mixing angles. Similar considerations apply to searches for the dark sector particles and other BSM phenomena. More broadly, the enhanced statistical precision and reduced systematic uncertainties would provide a precise test of the three-flavor paradigm in the few hundred MeV to few GeV energy range.

Technology Development: The addition of a magnetic field to large volume LArTPCs would allow the determination of the sign of the charge of ionizing particles on an event-by-event basis and improve the energy and momentum resolution at higher energies. The ICARUS collaboration intends to pursue a R&D program to investigate techniques to magnetize large volume LArTPCs such as is described in the work by C. Rubbia et al. [12] and will participate in the Instrumentation Frontier Topical Group during the coming year.

REFERENCES

[1] A. Aguilar-Arevalo et al. (LSND Collaboration), “Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam," Phys.Rev.D64, 112007 (2001), arXiv:hep-ex/0104049 [hep-ex].
[2] G. Mention et al., “The reactor antineutrino anomaly”, Phys.Rev.D83, 073006 (2011); W. Hampel et al. (GALLEX Collaboration), “Final results of the Cr-51 neutrino source experiments in GALLEX", Phys.Lett. B420, 114-126 (1998).
[3] M. Antonello et al. (ICARUS Collaboration), “Experimental search for the LSND anomaly with the ICARUS detector in the CNGS neutrino beam”, Eur. Phys. J. C (2013) 73:2345; N. Agafonova et al. (OPERA Collaboration), “Search for nm -> ne oscillations with the OPERA experiment in the CNGS beam”, JHEP 07 (2013) 004.
[4] N. Aghanim et al. (Planck Collaboration), “Planck 2018 results. VI. Cosmological parameters”, Astronomy & Astrophysics, 2020
[5] R. Acciarri et al., “A proposal for a three-detector short-baseline neutrino oscillation program in the Fermilab Booster neutrino beam”, arXiv:1503.01520
[6] A. Serebrov, “Observation of sterile antineutrino oscillation in Neutrino-4 experiment at SM-3 reactor”, Neutrino2020 conference
[7] B.Batell, M.Pospelov and A.Ritz, Phys. Rev. D80, 095024(2009)
[8] P.deNiverville, M.Pospelov and A.Ritz, Phys. Rev. D84, 075020(2011)
[9] B. Batell, J. Berger, A. Ismail, “Probing the Higgs portal at the Fermilab short-baseline neutrino experiments”, Phys.Rev.D100, 115039 (2019), arXiV::hep-ph/1909.11670
[10] A. Chatterjee, A. De Roeck, D. Kim, Z. Gh. Moghaddam, J.C. Park, S. Shin, L. H. Whitehead, and J. Yu, “Searching for boosted dark matter at ProtoDUNE.” Phys. Rev. D98(7):075027 (2018)
[11] B. Abi et al. (DUNE Collaboration), “Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: Physics”, arXiv:2002.03005 (2020)
[12] C. Rubbia et al., “A MgB_2 superconducting magnetic field in ICARUS as a major improvement of the TPC-LAr neutrino technology.” Unpublished.