Snowmass2021 - Letter of Interest

Follow up of anomalies measured in short baseline neutrino experiments

NF Topical Groups:

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (TF11) Theory of neutrino physics

Contact Information for corresponding authors:
Gianluca Petrillo (SLAC National Accelerator Laboratory) [petrillo@slac.stanford.edu]
Yun-Tse Tsai (SLAC National Accelerator Laboratory) [yuntse@slac.stanford.edu]

Authors: M. Convery, F. Drielsma, G. Petrillo, H. A. Tanaka, K. Terao, Y.-T. Tsai, T. Usher
SLAC National Accelerator Laboratory

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Abstract:

A number of anomalous measurements from neutrino experiments has perplexed the field for some time. While some of the results point to statistically significant departures from the expectations of "standard" particle physics, a satisfactory underlying explanation has remained elusive even as the possibility of exotic "sterile" neutrino states remains the most popular interpretation. The Short Baseline Neutrino (SBN) program at Fermilab is now coming into operation with the goal of definitively confirming the anomalies observed at MiniBooNE using the same neutrino beam. A positive result from this program would be a monumental development that would require follow up experiments, including extensions of the SBN program itself. At the same time, given the uncertainty in the underlying physics, qualitatively different experiments may also be needed to definitively identify and characterize the anomaly. Given the potentially wide scope and challenges in such a program, as well as the approaching time frame for results from SBN, it will be important to discuss and plan for this in the Snowmass process. Here we give a (non-exhaustive) summary of possibilities, options, and potential discussion points on this topic.

Short baseline anomaly. The neutrino community has been excited by the observation of several "anomalies" from experiments based on different neutrino sources (nuclear reactors [1], radioactive isotopes [2], and particle beams [3]). The experimental scenario is not crystalline yet, with prediction refinements changing the significance of the anomalies and with measurements reaching opposite conclusions [3–6]. In this fluid context, a class of highly predictive models which postulate the presence of new particles, called "sterile neutrinos", seemed to hold the potential to explain those anomalies. The new particles, mixing with the three neutrinos in the Standard Model (SM), alter the flavour of neutrinos, resulting into an increased or decreased number of neutrino interactions. Neutrino beam experiments have accumulated data which on one side confirms an increase of electron neutrino interactions even larger than those models could accommodate [3], and on the other side excludes the predicted decrease of muon neutrino interactions [7;8]. This scene strongly suggests either more complex oscillation scenarios, or different underlying physics, to model the existing observations. In addition, more complete observations will be required to inform and then test these new models [9].

The Short Baseline Neutrino (SBN) program [10;11] at Fermi National Accelerator Laboratory (FNAL) has been designed to definitively confirm or exclude the excess of ν_e interactions observed in the neutrino beam anomaly *and* the predicted and so far not observed decrease in ν_μ interactions, utilising a detection technology (liquid-argon time-projection chamber) which delivers rich information on the physics interaction topology, good particle energy resolution and particle type identification. The program is planned to collect 6.6×10^{20} protons on target in about three years, and will deliver its oscillation results some time half a decade from now.

The confirmation of an excess by SBN would be a ground-breaking development and should be considered as the onset of a broad experimental program to characterize it, attempt to reproduce it in different conditions and processes, and eventually provide comprehensive information for the development of the theory behind it.

Discussion. The task of extracting information about a truly sterile neutrino via quantum mixing is daunting: we never observe an interaction of such particle, not even indirectly, but rather we observe SM neutrinos, interacting in a standard way. An essential task after the confirmation of the excess is to test if the anomalous observations fit an oscillation pattern, supporting the hypothesis of neutrino mixing against other explanations, and at the same time pinning down the parameters regulating the phenomenon. The SBN program is equipped with three detection points (distance 110, 470 and 600 meters from the beam target) and with a beam covering roughly up to 2 GeV. These points, while located to maximize the sensitivity for the observation of an event excess, depending on the actual sterile neutrino mass might be able to cover just one oscillation period (fig. 1). It will be indispensable to test the "evolution of the excess" varying the baselines, L, and neutrino energies, E. In addition, we need to confirm whether this phenomenon occurs identically in particles and antiparticles. A difference could arise, in the case of a sterile neutrino oscillation, from new CP-violating phases. Such goals can be pursued by operating the SBN program with an antineutrino beam by reversing the horn current to focus negative pions, beyond the current run plan which includes exclusively neutrinos, and in parallel combining results from alternative sources, like reactor neutrino experiments, which test different L/E with electron *antineutrino* fluxes, as for example the Neutrino-4 experiment whose exciting results have been

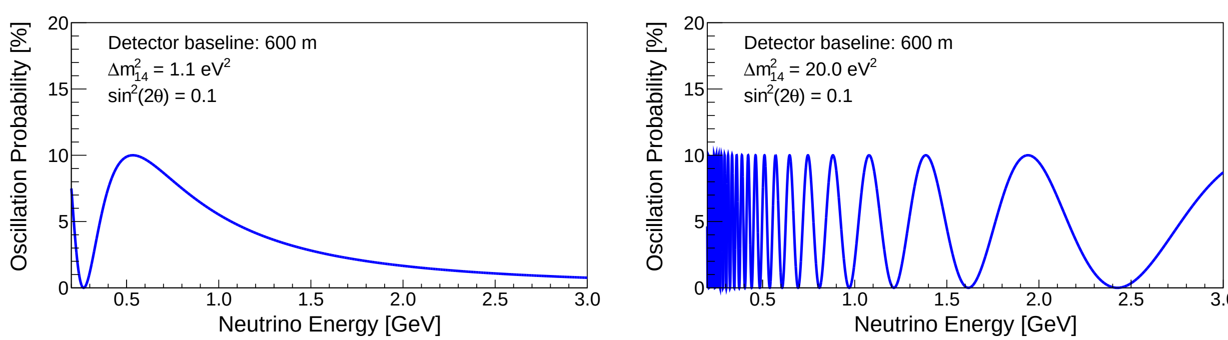

Figure 1: Shape of the probability of oscillation into ν_e of a ν_μ from FNAL BNB beam at SBN far detector location (distance: 600 meters) as function of the energy of the observed ν_e, as predicted by a minimal oscillation model with a single sterile neutrino, for the two sterile neutrino mass parameters $\Delta m^2_{14} = 1.1$ and 20.0 eV^2 [reproduction from ref. [10] p. 18].

recently reported[12]. Long baseline experiments measuring atmospheric and accelerator-produced neutrinos, such as IceCube Neutrino Observatory[7], MINOS[8], and T2K[13], together with ongoing and planned experiments, complement the survey of L and E. Additional information may come from detectors close to the target of neutrino beams, like at the Spallation Neutron Source facility at the Oak Ridge National Laboratory, which produces neutrinos from pion decay-at-rest, or like at an hypotetical off-axis location close to BNB at FNAL. Also important would be the contribution from a multi-baseline experiment like the developing DAEδALUS[14] project. Further, the modern design of the PRISM configuration of DUNE near detectors is desirable; it slides the near detector and can measure the neutrino beams at a variety of off-axis angles, allowing different peaks of E. This will allow a direct handle on the neutrino energy to more definitively understand the E_ν-dependence of the underlying physics.

Further studies on hadron production via fixed-target experiments and improvements in beam line simulation would reduce uncertainties in the neutrino flux predictions, allowing more sensitive and precise measurements. We note that the possibility of short baseline neutrino oscillations may complicate the utility of flux measurements using "standard candles" like $\nu - e$ elastic scattering. The quest may benefit from muon-based neutrino beams which may offer better control over the flavor content and energy spectrum and allow additional flavor transitions to be studied, which would require a substantial investment[15].

Measurements of ν_τ appearance from atmospheric and accelerator-produced neutrinos would test the unitarity of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix, thereby constraining additional neutrino states. Precise neutral weak current measurements, albeit challenging, can also contribute to unitarity constraints by highlighting a deficiency of events.

Apart from the interpretation of sterile neutrinos, the anomaly may come from the production of unknown particles in the beam line. Neutrino detectors placed off-axis of BNB and the DUNE-PRISM mechanism of the DUNE near detector, as discussed above, will also provide opportunities for exotic particle searches, complementing the detectors placed on-axis on neutrino beams[16].

A broad scrutiny of possible underlining theories is pivotal. Heavy neutral lepton searches, with the mass spanning from eV to MeV scale, in multiple fixed-target and neutrino experiments would contribute to our understanding of hypothesized particles explaining the anomaly and possibly their properties. The fruitful ongoing and proposed projects on dark sector particle searches, utilizing electron and proton beams, will explore a significant swath of parameter space. In addition, joint analyses between cosmology and all the related experiments would also shed light on the puzzle.

Summary. A confirmation of the anomalies observed in connection with neutrino interactions will trigger an even wider amount of questions on their nature. This is a great time for a discussion in the community to lay out a comprehensive strategy to answer them by exploring all the possibilities, from the most popular to the less obvious, and considering ideas for new experiments, extensions of the running ones, and tuning of the ones being planned. While in this Letter we have just scratched the surface of the topic with a few seeds of ideas, our purpose is to stress the importance of and encourage such broad discussion.

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