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Long-Baseline Accelerator Probes for Light Sterile Neutrinos

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Most results from experiments measuring solar neutrinos, atmospheric neutrinos, and neutrinos produced by accelerators and in nuclear reactors, are well-described by oscillations between three distinct neutrino types: the electron, muon, and tau neutrinos. However, several anomalies have puzzled and baffled the neutrino physics community. For example, the Liquid Scintilator Neutrino Detector (LSND) experiment reported a $3.8\,\sigma$ excess of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam over a short baseline [1]. In addition, MiniBooNE reported a $4.8\,\sigma$ excess in electron antineutrino appearance [2] compatible with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations in the 0.01 to $1\,\mathrm{eV}^2$ range of Δm^2_{41} values. Both of these excesses have been interpreted as evidence for oscillations between the known active neutrinos and eV-scale *sterile neutrinos*, which do not couple to other matter through known Standard Model interactions. Additional neutrino flavors may clarify the origin of neutrino mass, provide dark matter candidates [3], and explain core collapse in supernovæ [4, 5]. These strongly compel searches for sterile neutrinos.

In long-baseline (LBL) experiments, like MINOS/MINOS+, NOvA, T2K, and OPERA, with $(E/L)_{LBL} \sim 0.001$ GeV/km at the Far detector, searching for sterile neutrinos with $\Delta m^2{}_{41} = 1$ eV^2 through an excess appearance of electron antineutrinos consistent, for instance, with the LSND best-fit point, is very difficult as $(E/L)_{LSND} \sim 1$ GeV/km and the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability preferred by LSND corresponds to a very small 0.3% effect. However, LBL experiments can be powerful probes for sterile neutrino oscillations through looking for disappearance of the beam neutrino flux between the Near and Far detectors. This results from the quadratic suppression of the $\theta_{\mu e}$ sterile mixing angle measured in appearance experiments, $\left(\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2, \text{ for a } 3+1 \text{ model}\right)$, with respect to its disappearance counterparts, $\theta_{\mu\mu} \approx \theta_{24}$ for LBL experiments $\left[\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)\right]$, and $\theta_{ee} \approx \theta_{14}$ for reactor experiments $\left[\sin^2 2\theta_{ee} = 4|U_{e4}|^2\left(1-|U_{e4}|^2\right)\right]$. These disappearance effects have not been observed despite an extensive number of probes [6–9], and are in strong tension (4.7σ) with appearance results when a global fit of all available data is carried out [10].

Future LBL experiments will primarily probe light sterile neutrino mixing by searching for deficits of neutral-current (NC) interactions measured at the Far detector with respect to the Near detector prediction, as well as through deficits from similar measurements of charged-current (CC) muon and electron interactions. Since NC cross-sections and interaction topologies are the same for all three active neutrino flavors, the NC spectrum is insensitive to standard neutrino mixing. However, oscillations into a fourth light neutrino would induce an energy-dependent depletion at the FD, as the sterile neutrino would not interact in the detector volume. Furthermore, if sterile neutrino mixing is driven by a large mass-square difference $\Delta m^2_{41} \sim 1\,\mathrm{eV}^2$, the CC spectrum is distorted at energies higher than the energy corresponding to the standard oscillation maximum. Assuming a 3+1 model with one sterile neutrino, the LBL NC disappearance probability to first order in small mixing angles is given by:

$$\begin{aligned}1 - P(\nu_\mu \rightarrow \nu_s) \approx 1 &- \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}\\ &- \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}\\ &+ \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin\Delta_{31},\end{aligned} \tag{1}$$

where $\Delta_{ji} = \frac{\Delta m^2_{ji} L}{4E}$. The relevant oscillation probability for ν_μ CC disappearance is the ν_μ survival probability, similarly approximated by:

$$\begin{aligned} P(\nu_\mu \to \nu_\mu) \approx 1 &- \sin^2 2\theta_{23} \sin^2 \Delta_{31} \\ &+ 2 \sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31} \\ &- \sin^2 2\theta_{24} \sin^2 \Delta_{41}. \end{aligned} \tag{2}$$

Finally, the disappearance of ν_e CC is described by:

$$\begin{aligned} P(\nu_e \to \nu_e) \approx 1 &- \sin^2 2\theta_{13} \sin^2 \Delta_{31} \\ &- \sin^2 2\theta_{14} \sin^2 \Delta_{41}. \end{aligned} \tag{3}$$

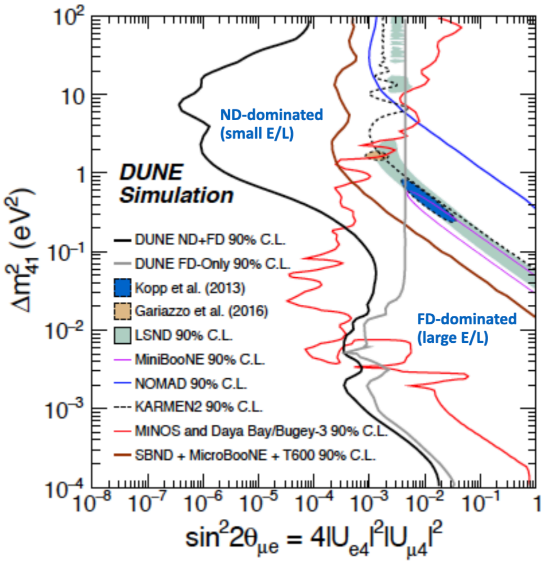

Figure 1. DUNE 90% C.L. sensitivities to $\theta_{\mu e}$ (solid black and solid grey lines) using CC muon and electron disappearance channels at the Near and Far detectors. A comparison with limits and allowed regions from previous and current experiments, and with the sensitivity from the future Short-Baseline Neutrino program, is shown. Regions to the right of the contours are excluded.

Present LBL accelerator experiment results on sterile neutrinos, such as from MINOS/MINOS+, T2K, NOvA, and OPERA [6–9], have established strong tension with indications from short-baseline (SBL) experiments. This tension largely excludes a pure sterile neutrino oscillation solution for global data, a conclusion that remains valid for models with additional sterile states [10, 11]. Along with atmospheric neutrino searches [12–15], LBL sterile probes also contribute to constraining the $\theta_{\mu\tau} \approx \theta_{34}$ angle in regions of parameter space with small sterile mass-square splitting, inaccessible to SBL experiments. Future LBL experiments, like DUNE [16, 17], HyperK [18], or ESSnu [19], will utilize megawatt-level neutrino beams, sampled by Far detectors with higher resolution and/or large fiducial masses. These improvements over present experiments will not only enable more sensitive light sterile probes, but also open additional channels for such probes, such as LBL electron neutrino disappearance and appearance. This allows a single LBL experiment like DUNE to probe the LSND and MiniBooNE allowed regions, as shown in Fig. 1 [16, 17]. Furthermore, the highly-capable Near detectors to be used by future experiments will collect neutrino interaction samples unprecedented in size, contributing sensitivity to similar regions of parameter space probed by SBL experiments. To successfully enable these searches, it is essential to conduct simultaneous two-detector analyses including SBL oscillations at the Near detector, as well as improve external constraints on the neutrino flux independent of potential sterile mixing, such as concurrent muon flux measurements from beam monitoring devices [20, 21] and hadroproduction measurements [22, 23]. Finally, interpretation of the precise measurements of standard oscillation at these new facilities will benefit from complementarity of new physics probes at LBL, SBL, atmospheric, and reactor experiments [24–27]. The sensitivity of LBL experiments to light sterile mixing over a broad range of mass splittings, as well as access to 3-flavor-independent checks of unitarity of the mixing matrix through the NC disappearance channel [27, 28], further strengthens the case to conduct light sterile neutrino searches at future LBL neutrino facilities.

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