Snowmass2021 - Letter of Interest

Sterile Neutrino Searches with Atmospheric Neutrinos

NF Topical Groups: (check all that apply ☐/■)

■ (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
☐ (RF4) Rare Processes and Precision Frontier: Baryon and Lepton Number Violating Processes

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Abstract:

Over the recent years, there has been a big effort in the area of Neutrino Physics to search for eV-scale sterile neutrinos. In this letter, we review sterile neutrino search possibilities with current and future experiments using atmospheric neutrinos and we point out some areas where coherent efforts will be needed to meet common challenges.

The three-flavor neutrino oscillation paradigm has been well established over the last three decades with observations from a number of solar, atmospheric, accelerator and reactor neutrino experiments. The last two unknown neutrino oscillation properties in the 3ν framework are the Neutrino Mass Ordering (NMO) and CP-violating phase.

However, there have been a few anomalous observations from Short-Baseline (SBL) accelerator experiments[1;2] and reactor neutrino experiments[3–5], which may be explained by invoking one or more sterile neutrinos. No anomalies are found in the Long BaseLine (LBL) MINOS/MINOS+[6;7] and atmospheric IceCube[8] data. Global data fits [9;10] show a strong tension and inconsistency between SBL appearance evidence and null results from disappearance experiments. A conclusive verdict on the existence of eV-scale neutrinos is much anticipated from the dedicated short-baseline accelerator[11;12] and reactor neutrino experiments[13;14]. The analyses of the Cosmic Microwave Background (CMB) data also finds strong tension with eV-scale sterile neutrinos[15;16]. Nevertheless, sterile neutrinos remain an attractive possibility in the theories of physics beyond the Standard Model. Therefore, it is worthwhile to look for hints of sterile neutrinos at different mass scales and go beyond eV-scale searches. Atmospheric neutrino data offer this opportunity thanks to a wide L/E accessible range and earth matter effects. Additionally, if sterile neutrinos are discovered via oscillation or non-oscillation experiments, an atmospheric sterile neutrino program can help to make precision measurements of the new model parameters and help break possible parameter degeneracies that may arise in fixed-baseline experiments.

The mixing matrix in the (3+1) model can be written as:

$$U \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} . \tag{1}$$

It may be parametrized as:

$$U = R_{34}(\theta_{34}) R_{24}(\theta_{24}, \delta_{24}) R_{14}(\theta_{14}) R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta_{13}) R_{12}(\theta_{12}, \delta_{12}). \tag{2}$$

In the (3+1) model, three new mixing angles (θ_{14},θ_{24} and θ_{34}) and two new CP-violating phases (δ_{24}, δ_{12}) are introduced in addition to the 3-flavor model parameters. The atmospheric neutrino fluxes span an energy range of 100 MeV to tens of PeV for the ν_e and ν_μ components. Figure 1 shows the atmospheric neutrino flux prediction obtained by Honda et. al[17]. The multiple oscillation channels and earth matter effects that can be probed with atmospheric neutrinos enable prospects for an exciting program that will test a diverse range of beyond standard model scenarios, such as sterile neutrinos, Non-Standard Interactions, Lorentz Invariance Violation, and invisible neutrino decays.

The current neutrino telescopes Super-K[18], DeepCore[19], ANTARES[20] have placed constraints on $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ at 1 eV^2 and over other Δm^2_{41} ranges. IceCube has put a strong constraint on $|U_{\mu 4}|^2$ using high energy events at the TeV scale[8].

The future neutrino telescopes and atmospheric experiments, such as KM3NeT[21], IceCube Upgrade[22], and INO-ICAL[23], are being built to primarily determine the Neutrino Mass Ordering using earth matter effects. Their setup is also suitable to further improve limits on the (3+1) model parameters. Most of these telescopes will have a fiducial volume of a few Mega-tons, which enables them to collect $\mathcal{O}(10^4)$ atmospheric neutrino events/year. These telescopes are sparsely instrumented in natural mediums such as sea water or continental ice, which is cost-effective and optimal for observing high energy neutrinos. The INO-ICAL experiment will use an RPC-based tracking detector with fine muon resolutions, enabling it to

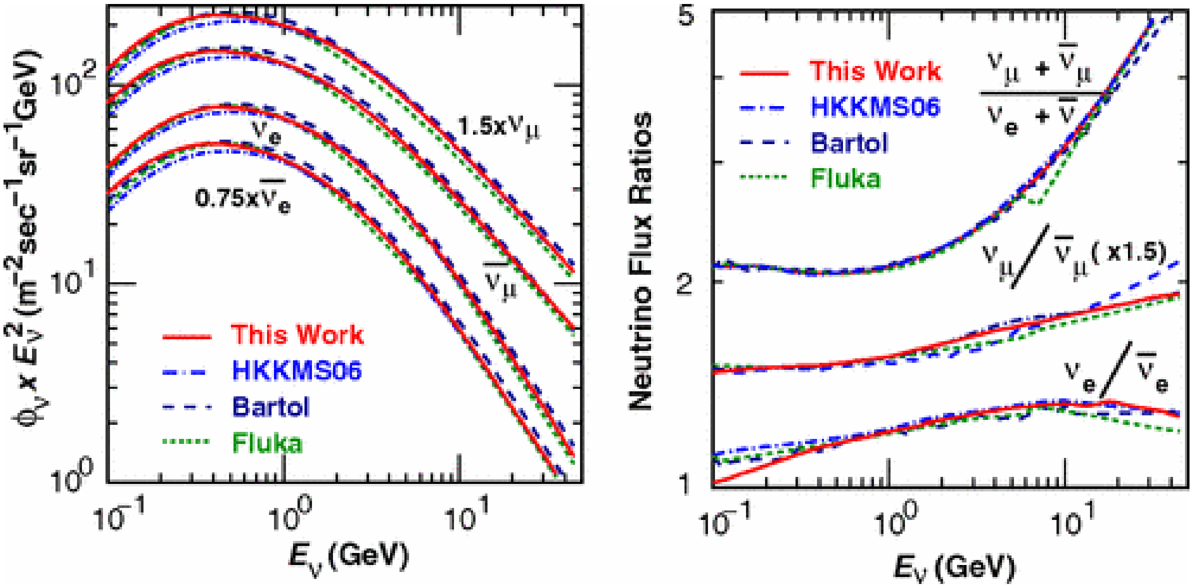

Figure 1: Atmospheric neutrino flux prediction by Honda, Bartol and Fluka groups.[17]

constrain sterile oscillation parameters[24]. Some of these experiments can constrain all three new mixing elements $|U_{e4}|^2$, $|U_{\mu4}|^2$, $|U_{\tau4}|^2$ simultaneously over a range of $\Delta m^2_{41} \approx 10^{-5} - 10^2$ eV^2[25].

The accelerator experiments Hyper-Kamiokande[26] and Deep Underground Neutrino Experiment (DUNE)[27] will also be excellent atmospheric neutrino experiments with fine energy/angle resolutions and detection efficiencies. They are capable of sterile neutrino searches with their neutrino beam data in the near and far detectors, the atmospheric data in the far detector, as well as their combination[28;29].

The atmospheric neutrino program poses many challenges. In order to make this program successful, a coherent effort on several frontiers is desired. The foremost effort would have to be dedicated to reducing uncertainties in the atmospheric flux predictions. For those detectors, which will observe neutrinos in the energy range 1-10 GeV, improved neutrino cross section models in the transition region and the Deep-Shallow inelastic scattering regime will be crucial. Advances in machine learning techniques to classify event topologies, neutrino energy, and direction reconstruction, as well as new atmospheric muon background rejection techniques would greatly benefit this program. On the computing front, efficient large detector Monte-Carlo productions to ensure sufficient statistics, and efficient calculation of neutrino oscillation probabilities in the (3+1) model with matter effects would be needed. With a wide variety of atmospheric neutrino detectors, a rich atmospheric sterile neutrino search program is foreseen. It will be an excellent complementary probe to SBL, LBL, and cosmology sterile neutrino search efforts.

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