Snowmass2021 - Letter of Interest

Atmospheric ν_τ Appearance in the Deep Underground Neutrino Experiment

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
■ (RF5) Rare Processes and Precision Frontier: Charged Lepton Flavor Violation

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Abstract:
Much progress has been made in the simulation of oscillated atmospheric neutrino ($\nu_{\rm atm}$) Honda fluxes at the Deep Underground Neutrino Experiment (DUNE) sitting at the Homestake Site. There are great opportunities to probe rich physics with these $\nu_{\rm atm}$s such as studying oscillatory effects not easily observable when utilizing DUNE's baseline neutrino beam, including but not limited to the study of ν_τ charged-current cross sections near threshold and their associated complex final states generated by multihadron τ decays. Such information would be highly useful for understanding aspects of CP-violation, lepton universality, mixing matrix unitary, nonstandard interactions, as well as helping achieve greater sensitivities to rare processes such as baryon number violating dinucleon decays and $n \to \bar{n}$, which could potentially mimic τ decays. Here, we call for the coordination and support of groups within DUNE pursuing this particularly powerful extension of the DUNE Physics program which could potentially access a total of ~ 800 $\{\nu_\tau, \bar{\nu}_\tau\}$ appearance events (~ 500 through τ hadronic decay channels) with proper reconstruction.

The Deep Underground Neutrino Experiment (DUNE) promises a fundamental leap forward in the understanding of neutrino (ν) properties [1;2]. The heart of the experiment will consist of a broadband beam of neutrinos produced at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, captured first by a near detector [3–5], then flung some 1300km away to Lead, South Dakota, into a set of gargantuan far detectors at the Homestake mine site some $1500\,\mathrm{m}$ underground. There, at long-baselines, a full set of $4 \times 10\,\mathrm{kt}$ liquid argon time projection chambers (LArTPCs) will allow for high-precision oscillation measurements, promising to extract parameters such as δ_{CP} over a decade of operation; such a measurement requires adequate knowledge of ν_τ appearance events. LArTPC detectors promise exquisite topological and kinematical reconstruction capabilities [6–10], and the current effectiveness of their reconstruction algorithms are already ground breaking while being in their relative infancy [11]; this being said, there is much to be improved in such reconstruction [12;13] over the next preparatory decade, particularly with respect to particle identification and fine-grained reconstruction of high multiplicity topologies.

While the long-baseline oscillation program will always be the definitive focus of DUNE, the all-encompassing design of the experiment allows for many to participate in other ground breaking physics searches (some semi-parasitically), including studies involving atmospheric neutrinos (ν_{atm}s). Of particular interest to our group are those pertaining to lepton universality, of which cross sections for charged-current (CC) ν_τ appearance via recognized τ decays could be a strong indicator. Such studies promise to serve as powerful probes of both the Standard Model (SM) and beyond SM (BSM) non-standard interactions (NSIs). Such studies could also better inform other BSM searches to take place within DUNE, such as intranuclear baryon number violating modes like neutron-antineutron transformation ($n \to \bar{n}$), which can share signal/background candidate topologies via multihadron τ decays near CC-production thresholds. Of course, presently, the expected sensitivities of DUNE physics searches are relegated to Monte Carlo (MC) simulation studies, albeit rather complex and powerful ones, many of which utilize the full stack of detector simulation and reconstruction software [14].

Due to these, the need for the DUNE Collaboration to conduct massive MC studies illuminating the expected ν_{atm} spectra, rates, oscillated flavors, interaction types, topologies, and associated reconstructed energy and angular resolutions to these has become apparent. Models of ν_{atm} flux have been developed by the Bartol [15] and Honda [16] groups, the latter of which has become the go-to solution for most theorists and experimentalists due to the calculations' comprehensive nature and associated validation; secondarily, Honda is in the unique position of having calculated expected fluxes at the Homestake site most important for DUNE. The `GENIE` MC Neutrino Event Generator [17] has become an indispensable framework in incorporating such fluxes into active experiments, including DUNE. However, both Honda fluxes and `GENIE` generator tools have previously not allowed for an easy, reliable, and accurate assessment of oscillation effects on neutrino flavor in DUNE; here, we briefly summarize some progress to inform the community on this developing front.

Honda calculates four-type $\{\nu_{e,\mu}, \bar{\nu}_{e,\mu}\}$ atmospheric production, all in logarithmically spaced energy bins from 0.1-$10,000\,\mathrm{GeV}$; currently, solar-maximum (minimum ν_{atm} count) flux files are utilized up to $100\,\mathrm{GeV}$, but can be easily interchanged with solar-minimum (maximum ν_{atm} count) flux files and extended in energy. Using default CC and NC `GENIE` cross sections across all neutrino flavors and a realistic earth density profile [18], oscillation studies currently occur outside of `GENIE`, and can be completed either via proprietary, direct oscillation calculations followed by logarithmic interpolation of newly outputted Honda six-type $\{\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}\}$ logarithmic tables, or via complex event reweighting schemes using CAFAna on large MC samples of single flavors. The former of these can be interleaved together with the latter to correct known spectral shape issues within `GENIE`; the latter works well with reconstructed events coming from reweightable nuclear model configurations within `GENIE`. One can see in Fig. 1 the expected ν_{atm} spectra resulting from the proprietary method of oscillations with nominal NuFit [19] best-fit oscillation parameters. The expected counts (the integrals of these spectra) are shown in Tab. 1.

Per $10\,\mathrm{kt{\cdot}yr}$	Total	Charged-Current	Neutral-Current
ν_e	746.760	538.930	207.830
$\bar{\nu}_e$	188.833	113.893	74.939
ν_μ	756.522	527.679	228.842
$\bar{\nu}_\mu$	216.493	126.104	90.389
ν_τ	234.757	14.176	220.581
$\bar{\nu}_\tau$	92.519	5.148	87.371

Table 1: Expected ν_{atm} interaction counts per $10\,\mathrm{kt{\cdot}\,yr}$ in the DUNE far detector at the Homestake site using the oscillated and logarithmically interpolated Honda solar-maximum flux files from 0.1-$100\,\mathrm{GeV}$ of initial energy. These originate from the numerical integrals of the curves shown in Fig. 1, and characterize the nominal *minimal* ν_{atm} counts expected for the far detector.

The solar-maximum counts of the proprietary method have been confirmed with parallel CAFAna analyses. Production altitude is currently not taken into account, though this is expected to be a small effect and will be fully implemented

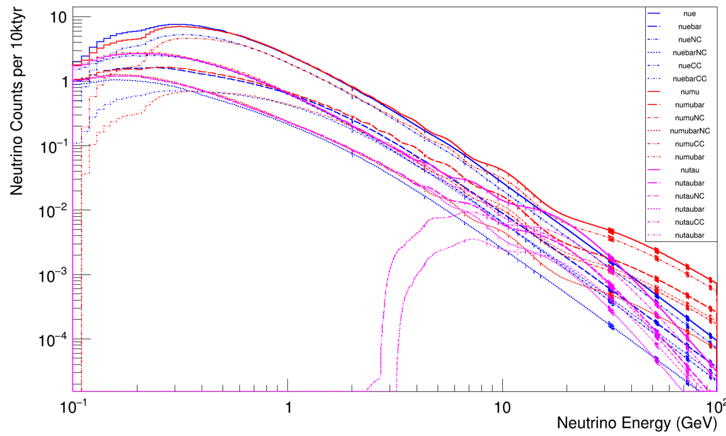

Figure 1: Predictions of logarithmically interpolated, oscillated $\nu_{\rm atm}$ spectra from GENIE when using Honda solar-maximum Homestake site fluxes alongside the default Bodek-Ritche relativistic nonlocal Fermi gas nuclear model of Fermi motion. We predict a rate of $\sim$ 20 CC-$\{\nu_\tau, \bar{\nu}_\tau\}$ total interactions per $10\,$kt$\cdot$yr in the DUNE far detector; thus, we would expect to observe $\sim$ 13 events via hadronic decays of the τ lepton. Detector reconstruction effects will lead to regions of uncertainty around all of these curves, and deviations from those regions could signal new physics.

in future work; parallel CAFAna analyses do contain such correlations. It is important to note that there are theoretical uncertainties in both methods associated with choices in particular nuclear models of Fermi motion and intranuclear cascades (some of which are stochastic in nature, and thus are *not* reweightable) within GENIE MC event productions, and how these *may* effect the interpretation of experimental observables through detector responses remains under active investigation within the DUNE HEP Working Group. Due to the nature of the cross section calculations inherently depending upon the chosen nuclear model (and leading to still larger uncertainty regions surrounding all shown curves in Fig. 1), interpretations of new physics will be challenging, especially with small data samples. Fully reconstructed detector simulations show the potential resolution of such searches for $\{\nu_\tau, \bar{\nu_\tau}\}$ appearances, as shown in Figs. 2 for CC interactions from hadronic calorimetry.

We hope that this letter further interests the broader community in supporting and pursuing these veins of inquiry. The far detector of DUNE shows great promise with the potential to observe ~ 800 CC-$\{\nu_\tau \bar{\nu}_\tau\}$ appearances over $400\,$kt$\cdot$yrs of operation; if one considers only reconstructing such interactions from hadronic activity due to multihadron decays of the τ, this expected number decreases by $\sim 35\%$ to ~ 500 events. There is much left to do within the DUNE Collaboration, including implementing fully consistent simulations of τ decays with polarization; reconstruction should be improved to better deal with expected multihadron final states from these decays, and the dependencies of these algorithms on nuclear model configurations is actively being pursued. Such progress will better enable our ability to definitively recognize such interactions as backgrounds for other rare processes, including intranuclear $n \to \bar{n}$. The accumulation of a high purity, high statistics ν_τ sample spanning a broad range of L/E, with well reconstructed kinematics, can lead to still greater improvements in our knowledge of neutrino properties, possibly acting as a portal beyond δ_{CP} onto lepton universality, BSM NSIs, sterile neutrinos, and mixing matrix unitarity.

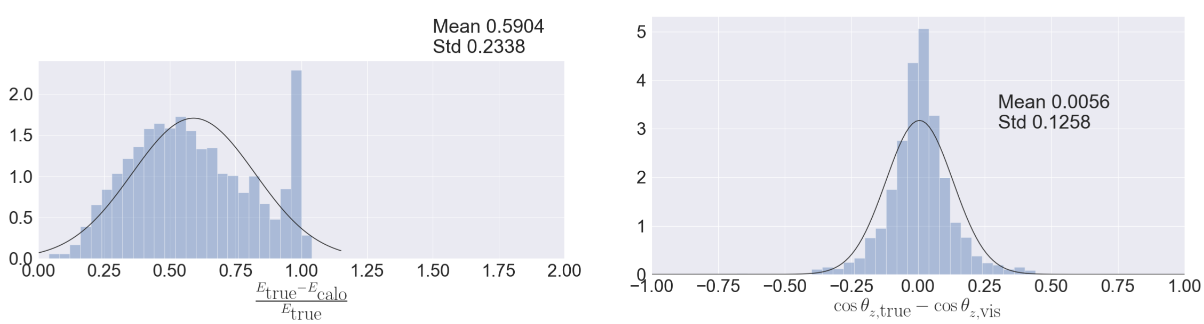

Figure 2: A few resolution plots for reconstructed energy and angles from hadronic activity are shown for the DUNE far detector when simulating atmospheric ν_τ CC-interactions using the default GENIE nuclear model configuration.

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