Snowmass2021 - Letter of Interest

[Physics Beyond the Standard Model in DUNE]

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
☐ (Other) *[Please specify frontier/topical group(s)]*

Contact Information:

Name (Institution) [email]: Ryan Patterson* (CalTech) [rbpatter@caltech.edu], Elizabeth Worcester* (BNL) [etw@bnl.gov] *DUNE Physics Coordinator
Collaboration (optional): DUNE

Authors: DUNE Collaboration

Abstract: Official DUNE LOI describing the Beyond-the-Standard-Model physics sensitivity of the experiment. The deep underground location of the far detector facilitates sensitivity to nucleon decay and other rare processes. Using both the far and near detectors, DUNE can probe a rich and diverse BSM phenomenology including searches for dark matter, sterile neutrino mixing, nonstandard neutrino interactions, CPT violation, new physics enhancing neutrino trident production, and baryon number violating processes.

The Deep Underground Neutrino Experiment (DUNE) is a next-generation, long-basline neutrino oscillation experiment, designed to be sensitive to ν_μ to ν_e oscillation. The experiment consists of a high-power, broadband neutrino beam, a powerful precision near detector (ND) complex located at Fermi National Accelerator Laboratory, in Batavia, Illinois, USA, and a massive liquid argon time-projection chamber (LArTPC) far detector (FD) located at the 4850 ft level of Sanford Underground Research Facility (SURF), in Lead, South Dakota, USA. The deep underground location of the FD facilitates sensitivity to nucleon decay and other rare processes. DUNE can probe a rich and diverse BSM phenomenology including searches for dark matter, sterile neutrino mixing, nonstandard neutrino interactions, CPT violation, new physics enhancing neutrino trident production, and baryon number violating processes. This Letter of Interest briefly summarizes the more quantitative conclusions presented in [1, 2]. The DUNE collaboration anticipates that a number of more detailed LOIs on BSM sensitivity in a DUNE-like experiment will be submitted by individuals.

Experimental results in tension with the three-neutrino-flavor paradigm, which may be interpreted as mixing between the known active neutrinos and one or more sterile states, have led to a rich and diverse program of searches for oscillations into sterile neutrinos [3, 4]. DUNE is sensitive over a broad range of potential sterile neutrino mass splittings by looking for disappearance of charged-current and neutral-current neutrino interactions over the long distance separating the ND and FD, as well as over the short baseline of the ND. With a longer baseline, a more intense beam, and a high-resolution large-mass FD, compared to previous experiments, DUNE provides a unique opportunity to improve significantly on the sensitivities of the existing probes, and greatly enhance the ability to map the extended parameter space if a sterile neutrino is discovered. A generic characteristic of most models explaining the neutrino mass pattern is the presence of heavy neutrino states, additional to the three light states of the Standard Model (SM) of particle physics [5–7]. These types of models, as well as those of light sterile neutrinos, imply that the 3×3 Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix is not unitary due to mixing with additional states. DUNE can constrain the parameters describing non-unitarity [8, 9] with precision comparable to that from present oscillation experiments.

Non-standard interactions (NSI), affecting neutrino propagation through the Earth, can significantly modify the data to be collected by DUNE as long as the new physics parameters are large enough [10]. Leveraging its very long baseline and wide-band beam, DUNE is uniquely sensitive to these probes. DUNE can substantially improve the bounds on, for example, the NSI parameter $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$ and the non-diagonal NSI parameters.

Charge, parity, and time reversal symmetry (CPT) is a cornerstone of our model-building strategy. Using beam neutrinos, DUNE can improve the present limits on Lorentz and CPT violation by several orders of magnitude [11–18], contributing as a very important experiment to test these fundamental assumptions underlying quantum field theory. Atmospheric neutrinos are a unique tool for studying neutrino oscillations: the oscillated flux contains all flavors of neutrinos and antineutrinos, is very sensitive to matter effects and to both Δm^2 parameters, and covers a wide range of L/E. Studying atmospheric neutrinos in DUNE is a promising approach to search for BSM effects such as Lorentz and CPT violation.

Neutrino trident production is a weak process in which a neutrino, scattering off the Coulomb field of a heavy nucleus, generates a pair of charged leptons [19–27]. The high-intensity muon-neutrino flux at the DUNE ND will lead to a sizable production rate of trident events, offering excellent prospects to improve [28–30] on existing measurements. A deviation from the event rate predicted by the SM could be an indication of new interactions mediated by the corresponding new gauge bosons [31].

DUNE will perform a search for the relativistic scattering of light-mass dark matter (LDM) at the ND, as it is close enough to the intense beam source to sample a substantial level of dark matter (DM) flux, assuming that DM is produced. It is also possible that boosted dark matter (BDM) particles are created in the universe under non-minimal dark-sector scenarios [32, 33], and can reach terrestrial detectors. The DUNE FD is expected to possess competitive sensitivity to BDM signals from various sources in the current universe such as the galactic halo [32, 34–39], the sun [34, 38, 40–43], and dwarf spheroidal galaxies [39].

The excellent imaging, as well as calorimetric and particle identification capabilities, of the LArTPC technology implemented for the DUNE FD will facilitate searches for a broad range of baryon-number violating processes. Reconstruction of these events, which have final-state particle kinetic energy of order 100 MeV, is a significant challenge, made more difficult by final-state interactions (FSI), which generally reduce the energy of observable particles. The dominant background for these searches is from atmospheric neutrino interactions. For example, a muon from an atmospheric $\nu_\mu n \to \mu^- p$ interaction may be indistinguishable from a muon from $K^+ \to \mu^+ \to e^+$ decay chain from $p \to K^+\overline{\nu}$ decay, such that identification of the event relies on the kaon-proton discrimination.

Sensitivity to several of these processes has been studied using the full DUNE simulation and reconstruction analysis chain, including the impact of nuclear modeling and FSI on a Boosted Decision Tree (BDT)-based selection algorithm. With an expected 30% signal efficiency, including anticipated reconstruction advances, and an expected background of one event per $\mathrm{Mt \cdot year}$, a 90% confidence level (CL) lower limit on the proton lifetime in the $p \to K^+\overline{\nu}$ channel of 1.3×10^{34} years can be set, assuming no signal is observed for a $400\,\mathrm{kt \cdot year}$ exposure. Another potential mode for a baryon number violation search is the decay of the neutron into a charged lepton plus meson, i.e., $n \to e^- K^+$. The lifetime sensitivity for a $400\,\mathrm{kt \cdot year}$ exposure is estimated to be 1.1×10^{34} years. Neutron-antineutron $(n - \bar{n})$ oscillation is a baryon number violating process that has never been observed but is predicted by a number of BSM theories [44]. The expected limit for the oscillation time of free neutrons for a $400\,\mathrm{kt \cdot year}$ exposure is calculated to be 5.53×10^8 s.

DUNE will be a powerful discovery tool for a variety of physics topics under active exploration today, from the potential discovery of new particles beyond those predicted in the SM, to precision neutrino measurements that may uncover deviations from the present three-flavor mixing paradigm and unveil new interactions and symmetries. Its high intensity beam with flexible energy range, large mass far detector, and powerful near detector complex enable expanded physics opportunities [45] that complements those at the energy frontier experiments. Through the ample potential for BSM physics, DUNE offers an opportunity for strong collaboration between theorists and experimentalists and will provide significant opportunities for breakthrough discoveries in the coming decades.

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