PROCEEDINGS OF SCIENCE

Beyond the Standard Model physics prospects at DUNE

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The *Deep Underground Neutrino Experiment* (DUNE) is an international project for neutrino physics and proton-decay searches, currently in the design and construction stages. Once built, DUNE will consist of two detectors exposed to the world's most intense neutrino beam. The near detector will record neutrino interactions near the beginning of the beamline, at Fermilab. The other, much larger, detector, comprising four 17-kton liquid argon time projection chambers (LArTPCs), will be installed at a depth of 1.5 km at the Sanford Underground Research Facility in South Dakota, about 1300 km away from the neutrino source. The unique combination of the high-intensity neutrino beam with DUNE's high-resolution near detector system and massive LArTPC far detector enables a variety of probes of BSM physics, either novel or with unprecedented sensitivity, from the potential discovery of new particles (sterile neutrinos or dark matter), to precision tests of the three-flavour neutrino mixing paradigm, or the detailed study of rare processes.

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1. Introduction

The *Deep Underground Neutrino Experiment* (DUNE) [1] is a next-generation, long-baseline neutrino oscillation experiment under construction in the United States by an international collaboration. Figure 1 illustrates the basic layout of the experiment. Two state-of-the-art neutrino detectors will be exposed to a high-intensity ν_μ (or $\overline{\nu}_\mu$) beam. The so-called *near detector* (ND) will record neutrino interactions at Fermilab, close to the source of the neutrino beam. The much larger *far detector* (FD) will be built at a depth of 1.5 km at the Sanford Underground Research Facility (SURF), in South Dakota, USA, 1300 km away from Fermilab. DUNE has a very rich scientific programme that includes the detailed study of neutrino mixing [2, 3], searches for phenomena beyond the Standard Model (BSM) [4] and astroparticle physics [5].

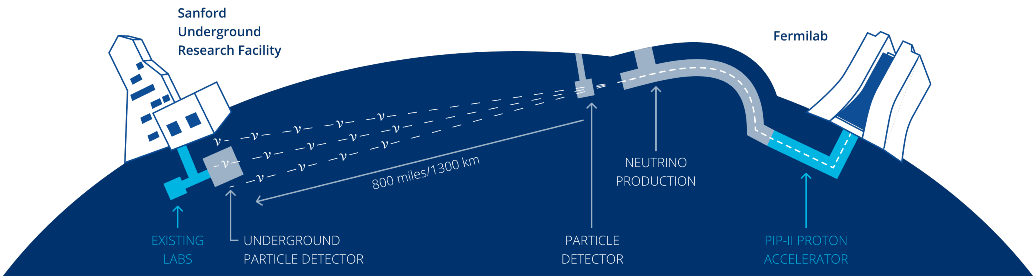

Figure 1: Sketch of the basic configuration of the *Deep Underground Neutrino Experiment* (DUNE).

The high-intensity, wideband muon-neutrino beam will be generated guiding 60–120 GeV protons onto a graphite target to produce mesons. These will be subsequently focused by magnetic horns into a long decay pipe where they will disintegrate producing an intense neutrino flux aimed underground towards SURF. The polarity of the focusing magnets can be reversed to produce a beam dominated by either muon neutrinos or muon antineutrinos. The beam will cover a broad range of neutrino energies, peaking at ~ 2.5 GeV.

The DUNE ND [6] will be built in a shallow underground hall located 574 m downstream from the neutrino beam origin. It will consist of three different components: a 150-tonne LArTPC (ND-LAr); a magnetized, gaseous argon time-projection chamber surrounded by an electromagnetic calorimeter (ND-GAr); and a magnetized beam monitor (SAND). They will serve important individual and overlapping functions in the primary mission of the ND: the precise characterization of the neutrino beam energy and composition, as well as vastly improving knowledge of cross sections and particle yields for neutrino scattering processes in the few-GeV energy region. The two argon TPCs (ND-LAr and ND-GAr) will move laterally to sample the beam at off-axis angles to better constrain flux uncertainties.

The DUNE FD [7] will consist of four gigantic LArTPCs, each with an argon mass of about 17 kilotonnes. The LArTPC technology provides a three-dimensional measurement of the trajectory and energy-loss pattern of the detected particles. The full imaging of events will allow the study of neutrino interactions and other rare events over a wide range of energies with unprecedented resolution, and the huge mass of the FD will grant the collection of a vast number of events, with sufficient statistics for precision studies.

Some of DUNE's key scientific goals are the determination of the neutrino mass ordering, the definitive observation of charge-parity (CP) symmetry violation for more than 50% of possible true values of the charge-parity violating phase (δ_{CP}), and the precise measurement of other neutrino mixing parameters [2, 3]. In addition, DUNE provides enormous opportunities to probe BSM phenomena traditionally difficult to reach in neutrino experiments, from precision measurements that may uncover deviations from the present three-flavor mixing paradigm and unveil new interactions and symmetries, to the potential discovery of new particles beyond those included in the SM. These searches can be classified into three broad categories: non-standard short-baseline and long-baseline neutrino oscillations, beam-induced BSM phenomena at the ND and BSM searches at the FD. In the following, we briefly discuss an example of each category; for more details, we refer the reader to [4, 6].

2. Non-standard neutrino oscillations: sterile neutrino mixing

The existence of sterile neutrinos (i.e., right-handed neutrinos, which are singlets under the SM gauge group) is a common prediction in many extensions of the SM put forward to explain the origin of neutrino masses. The potential mixing of sterile neutrinos with the active ones can distort the standard oscillation probabilities, as shown in Figure 2. DUNE will be 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, DUNE provides, compared to previous experiments, 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.

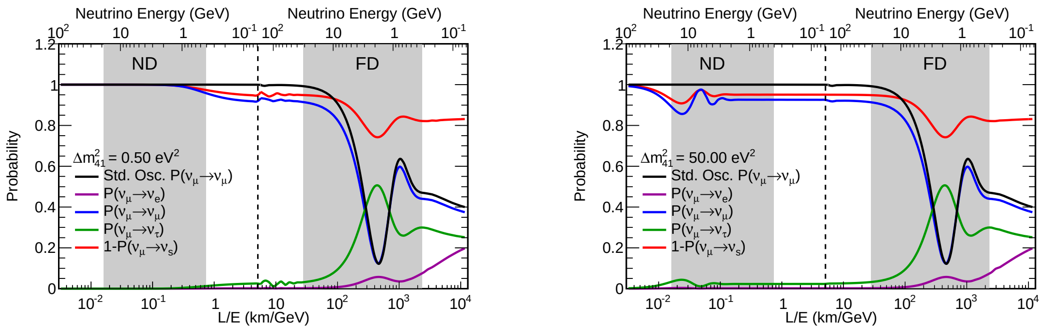

Figure 2: Regions of L/E (gray-shaded areas) probed by the DUNE detectors compared to 3-flavor and 3+1-flavor (that is, including one sterile state) neutrino disappearance and appearance probabilities. The top axis shows true neutrino energy, increasing from right to left. The left plot shows the probabilities assuming mixing with one sterile neutrino with $\Delta m^2_{41} = 0.05$ eV^2, corresponding to the slow-oscillations regime. The right plot includes mixing with one sterile neutrino with $\Delta m^2_{41} = 50$ eV^2, corresponding to the rapid-oscillations regime. Figure taken from [4].

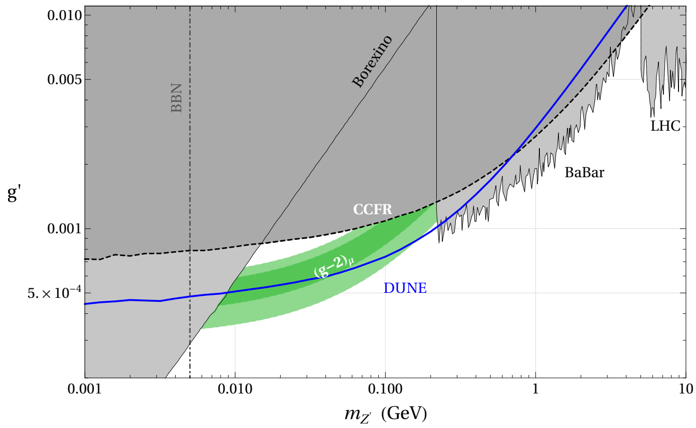

Figure 3: Projected DUNE sensitivity (solid blue line) and existing constraints (gray shaded area) in the $L_\mu - L_\tau$ parameter space. Shown in green is the region where the $(g-2)_\mu$ anomaly can be explained at the 2σ level. The DUNE sensitivity shown by the solid blue line assumes 6 years of data running in neutrino mode. Figure taken from [4].

3. BSM searches at the ND: neutrino tridents

Neutrino trident production is an electroweak process in which a neutrino, scattering off the Coulomb field of a heavy nucleus, generates a pair of charged leptons. The high-intensity muon-neutrino flux at the DUNE ND will lead to a sizeable production rate of trident events, offering excellent prospects to improve previous measurements [8]. A deviation from the event rate predicted by the SM could be an indication of new interactions mediated by the corresponding new gauge bosons. Of particular interest is the class of models that introduce a Z' neutral boson associated with a new $U(1)_{L_\mu - L_\tau}$ gauge symmetry, as it could explain the long-standing discrepancy between the theoretical calculation and the measurement of the muon $g-2$. The sensitivity of DUNE in the parameter space of the Z' mass and its gauge coupling g' is shown in Figure 3.

4. BSM searches at the FD: boosted dark matter

Thanks to its deep underground location and large active mass, as well as its excellent event imaging, particle identification and calorimetric capabilities, the DUNE FD will be a powerful instrument for the observation of rare events predicted by extensions of the SM, such as baryon-number-violating processes or dark matter (DM) interactions.

Conventional direct DM searches use the non-relativistic scattering of DM particles with nuclei of the detection medium, resulting in energy deposits well below the expected threshold energy of the DUNE FD. By contrast, typical energy deposits in association with a relativistic scattering of boosted DM would readily surpass the threshold. A possible mechanism to create relativistic DM in our universe is the boosted dark matter (BDM) scenario [9], which hypothesises two stable DM species, a heavier χ_0 and a lighter χ_1. When a pair of χ_0 annihilate into a pair of χ_1 in an astrophysical source, the mass gap between the two species allows the χ_1 to acquire a large boost factor and induce relativistic scattering signatures in terrestrial detectors. Figure 4 shows two such possible detection processes. The one on the left corresponds to the ordinary elastic scattering with

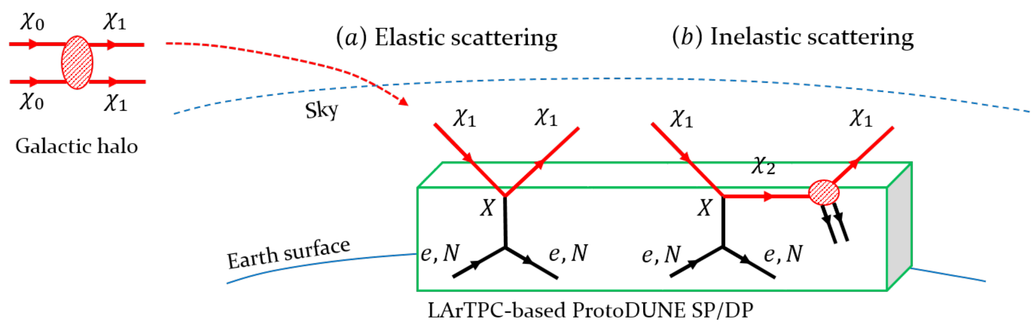

Figure 4: Sketch of the detection process of boosted dark matter in the DUNE FD. Figure taken from [10].

a visible target recoil; the process on the right assumes a non-minimal dark-sector scenario allowing the transition to a heavier unstable state (χ_2) which subsequently disintegrates back to χ_1 together with possibly visible secondary particles in addition to the primary target recoil.

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