Large Extra-Dimension Searches, LoI

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The main motivation for introducing extra space-time dimensions was to alleviate the so called hierarchy problem, i.e. the large difference between the electroweak and the GUT [1, 2] or the Planck energy scales [3–5]. More interestingly, models with large extradimensions can also accommodate non-zero neutrino masses. Since right-handed neutrinos are singlets under the Standard Model (SM) gauge group, they are one of the candidates to experience extra space-time dimensions and therefore to collect an infinite number of Kaluza-Klein excitations after compactification (integration of the Lagrangian density for the right-handed fields over the extra space time dimensions) [6, 7]. The remaining SM fermions are restricted to a four-dimensional brane. In this way, the Yukawa couplings between the right-handed and the active neutrinos are suppressed by the volume factor after compactification of the extra dimensions. In this context, neutrinos acquire a Dirac mass that is naturally small and thus provides an alternative to the usual seesaw mechanism for the generation of the neutrino masses while avoiding the need for large energy scales.

It is phenomenologically appealing to consider an asymmetric case where one of the extra dimensions is *large* with respect to the others, effectively reducing the problem to be five dimensional. In what follows we consider the specific model for Large Extra Dimensions (LED) from Ref. [8], which condenses the seminal works and provides estimates for constraints from oscillation neutrino experiments. This model considers three bulk right-handed neutrinos (experiencing extra space-time dimensions) coupled to the three active brane neutrinos. After compactification of the effective extra dimension, from the four dimensional (brane) point of view, the right-handed neutrino appears as an infinite tower of sterile neutrinos or Kaluza-Klein modes ($n = 0, 1...\infty$). Since the active neutrinos couple to the sterile neutrino states through the Yukawa couplings, they mix and Dirac neutrino masses $m_i^{(n)} = \lambda_i^{(n)}/R$ are generated, where $\lambda^{(n)}$ is the eigenvalue of the $n \times n$ neutrino mass matrix and R is the compactification radius. The free parameters describing neutrino oscillations in the LED model are the three Dirac masses m^D and R, however, one can parametrize the degrees of freedom in terms of the absolute neutrino mass scale m_0 and R [9], with $m_0 \equiv m_1^D$ ($m_0 \equiv m_3^D$) for normal (inverted) neutrino mass ordering.

The sterile-active mixings and the new oscillation frequencies modify the three flavor active neutrino oscillations [10, 11], therefore distorting the neutrino event energy spectrum. Departures from the standard oscillations due to the existence of LED can then be probed at neutrino oscillation experiments [8, 12–17]. The measured mass-squared differences and mixing angles constrain the parameter space of the LED model i.e. the absolute mass scale m_0 and the radius of compactification R. The mostly active case corresponds to $n = 0$ where the standard three neutrino oscillations are recovered in the limit $R \to 0$. The mostly sterile case then corresponds to $n \gg 1$ and oscillations will appear smeared at large baselines over neutrino energy factor (so at the far detector of a long baseline accelerator neutrino experiment) since a large n implies large oscillation phases, at the same time the active-sterile mixing is suppressed [8, 12]. This helps to fix the maximum number of KK modes to a finite value and makes the LED model pretty testable at neutrino oscillation experiments, in particular at long-baseline accelerator neutrino facilities.

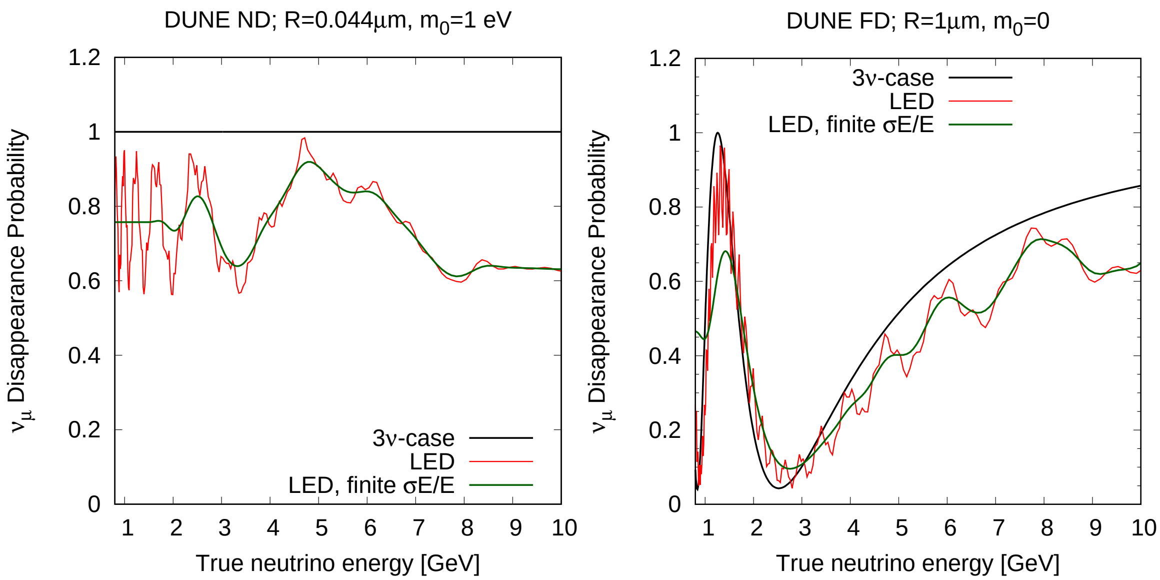

Figure 1. Muon neutrino disappearance probability at the DUNE near (far) detector baseline, 575m (1300km), is presented in the left (right) panel. The black line corresponds to the standard neutrino oscillation case, while the LED case is shown in red and dark green, where the finite detector energy resolution is also taken into account in the latter curve.

In the forthcoming precision era, new physics signals might emerge as subleading effects of the three neutrino paradigm or as a new oscillation phase(s). This last scenario is mainly motivated by results of short-baseline experiments which call for a new neutrino flavor state that has to be sterile, i.e. it cannot interact with the Standard Model gauge bosons. Although the unexpected results observed by some short baseline experiments seem compatible with a new, nonzero oscillation phase, several other experiments challenge this interpretation (see e.g. Refs. [18–20] for reviews). Several efforts are devoted to discover a sterile oscillation at the eV-mass scale or to completely rule out this hypothesis [21, 22]. Since the LED model predicts a large number of sterile states, it is worth testing this model in the same footing as it is being done for the $3 + 1$ scenario.

With respect to the standard three–neutrino oscillation case, the mixing predicted by the LED model has two striking features: a global reduction of survival probabilities, which is typically noticeable at high energies and an appearance of modulations and fast oscillations to Kaluza-Klein states [12, 23], as shown in Fig. 1. Variants of the most simple LED realization comprising bulk mass terms may also induce neutrino appearance at short baselines and perturb the typical LED pattern of masses and mixings [24]. Given the broad mass spectrum of Kaluza-Klein modes, a robust way of constraining these models comes from analyzing the shape of the measured neutrino energy spectrum. In particular, combining information from near and far detectors allows to probe lighter and heavier KK modes, providing a powerful test of the LED hypothesis.

Neutrino oscillation experiments with capabilities to detect neutrinos in a wide energy range, and with a good energy resolution, are more suitable to exploit the LED features. Current and future long-baseline neutrino experiments, and high energy atmospheric neutrinos experiments like IceCube [14], are therefore good candidates for this search [1]. In particular, the MINOS collaboration [23] was the first long-baseline experiment to constrain the LED compactification radius to $R < 0.45\,\mu$m at 90% of C.L [30]. Recently, forecast analyses have explored the DUNE capabilities to constraint the LED model [16]. An updated version including the most recent DUNE fluxes and efficiencies appear in Ref. [31]. In general, future high intensity beam experiments with higher resolutions and/or fiducial masses, like DUNE and HyperK, are expected to probe LED subleading oscillation effects allowed by current searches.

In summary, neutrino oscillations within the LED model considered here provide unique features that can be explored in parallel to the search for a sterile neutrino oscillation at the eV energy scale. Long–baseline experiments detecting neutrinos at high energies, and with a percent-level energy resolution, are good candidates for LED probes. In particular, sensitivity studies have shown the DUNE far detector potential to improve over the current MINOS limit. This potential improvement arises from the DUNE capabilities to reconstruct the main LED modulations at high energies, which were exploited in the sensitivity analysis by using spectral information. A similar sensitivity analysis at short baselines also provides complementary information [17]. Therefore, having a long-baseline experiment with two detectors is very suitable for exploring a large LED parameter space. In the case of DUNE, the near detector sensitivity to LED is only limited by the systematical errors due to its large statistics, thus, a two-detector analysis with realistic systematics is very promising for future LED searches.

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