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Simulating and searching for Heavy Neutral Leptons in IceCube

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Heavy Neutral Leptons (HNLs) are Standard Model (SM) singlets posited as an explanation for light neutrino masses. IceCube is uniquely capable of searching for an HNL in the hundreds of MeV to single GeV range by looking for atmospheric tau neutrinos upscattering to HNLs in the detector. The HNLs produced in IceCube would decay quickly, leading to Cherenkov radiation in both production and decay separated by a few meters, producing a "double cascade" signature in the detector. A simulation based on the most up-to-date calculations of HNL decay modes and cross-sections is required to explore the hundreds of MeV to single GeV parameter space for an HNL search. This work outlines the capabilities of the first HNL simulation for neutrino observatories, and presents sensitivities for IceCube's HNL search.

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1. Introduction

The discovery of neutrino oscillations, and the subsequent conclusion that neutrinos are massive, has led to an explosion of research on the nature of neutrino mass in recent years. To accommodate neutrino masses, we need to introduce fields beyond those of the Standard Model. Neutrino mass generating models that aim to explain the smallness of the neutrino masses via the see-saw mechanism require right-handed neutral fermions with masses above the neutrino mass scale. Such fermions are known as Heavy Neutral Leptons (HNLs).

Searches for HNLs have been performed over a variety of experimental setups, including collider experiments, beam-dump searches, and cosmological observations [1]. Despite this effort, a lack of an HNL event generator capable of supporting detailed detector geometries means that every researcher performing a search for HNLs needs to write their own model-specific generator.

These proceedings discuss the development of `LeptonInjector-HNL`, an extension of the LeptonInjector package [2] suitable to simulating HNL production and decay in the IceCube detector in the South Pole, and plans to generalize and publish the generator for use by scientists investigating a variety of double-cascade signals in ice or water Cherenkov detectors globally.

2. Motivation

While HNLs are a generic ingredient of neutrino mass generation mechanisms, the particulars of that new particle, its mass, and mixing with the active neutrino flavor, are largely unconstrained by theory. A light (eV-scale) sterile neutrino has been widely considered as a solution to neutrino oscillation anomalies [3]. This project considers sterile neutrinos at the MeV-GeV scale, commonly known as HNLs, whose detection would provide insight on the underlying theory of neutrino masses.

HNLs in this mass range have been studied in a variety of laboratory experiments and in cosmological probes via the sum of the neutrino masses and measurements of the effective number of neutrinos [1].

Recent bounds on HNLs can be seen in figure 1, where the region ruled out by Big Bang Nucleosynthesis (BBN) is shown in grey, and colored regions indicate the parameter space ruled out by laboratory experiments. We see that the parameter space for muon- and electron-neutrino dominated mixings is ruled out everywhere above a mixing strength on 10^{-5}, and mixing with the HNL below the 1 GeV scale is ruled out completely. Note, however, that the parameter space for a tau-neutrino dominated mixing is far less limited. The only parameter space completely ruled out is for HNL masses well below the GeV scale.

As first suggested by Coloma et al [5], IceCube has the potential to place limits in this parameter space by performing a search for double-cascade event topologies in the low-energy region.

3. Low-Energy Double Cascade Events in IceCube

The IceCube Observatory is a cubic-kilometer ice Cherenkov detector deployed deep inside the glacier at the South Pole [6]. It is buried between 1,450 and 2,450 meters below the surface, and consists of 5,160 digital-optical modules (DOMs) each containing a photomultiplier tube. These

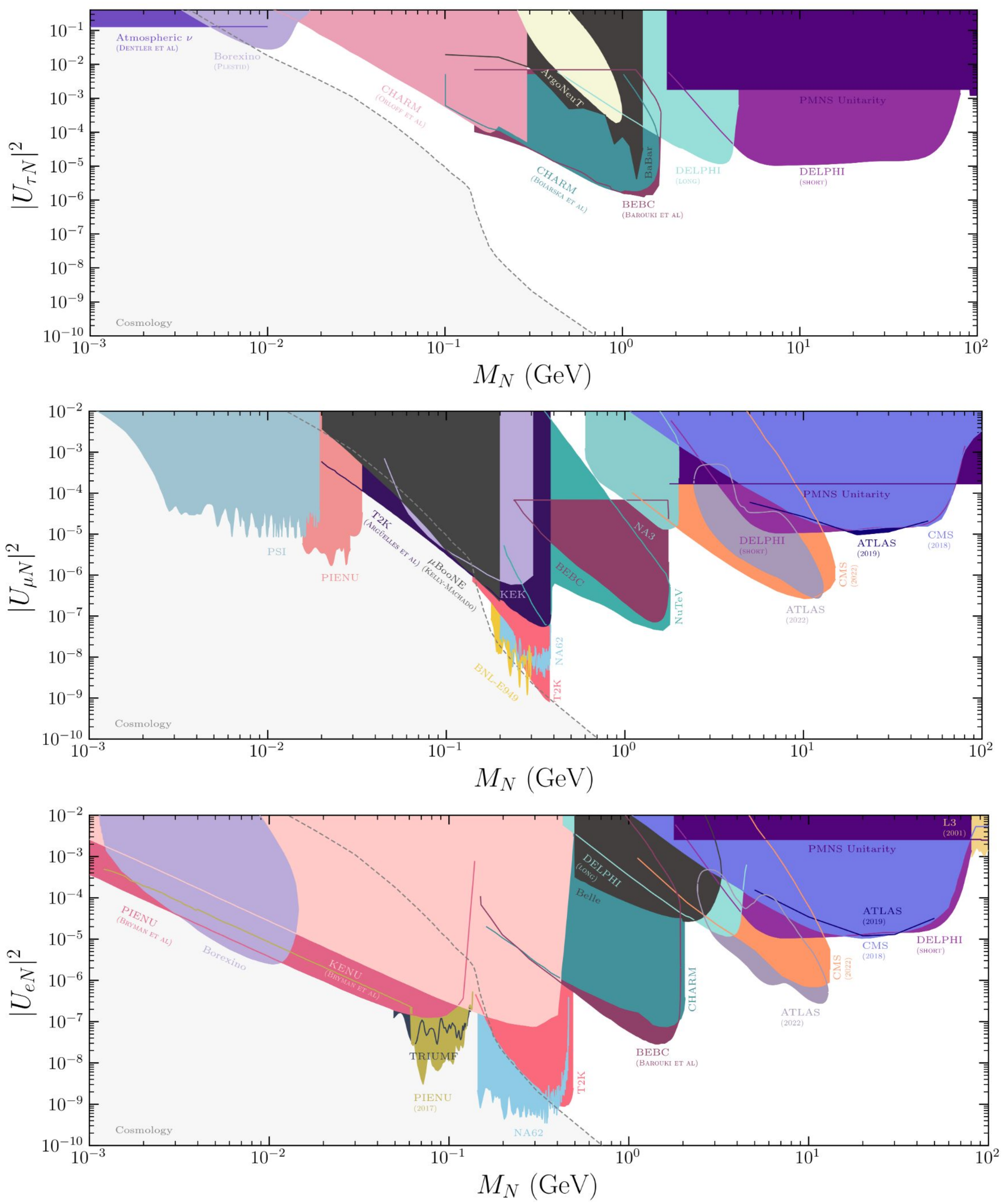

Figure 1: Figure from Fernandez-Martinez et al. [4]. Recent limits on HNL mixing with active neutrino flavors. While the parameter space for mixings above 10^{-5} is ruled out almost completely for electron-neutrino and muon-neutrino dominant mixings, the tau-neutrino dominated mixing has parts of the parameter space still unexplored.

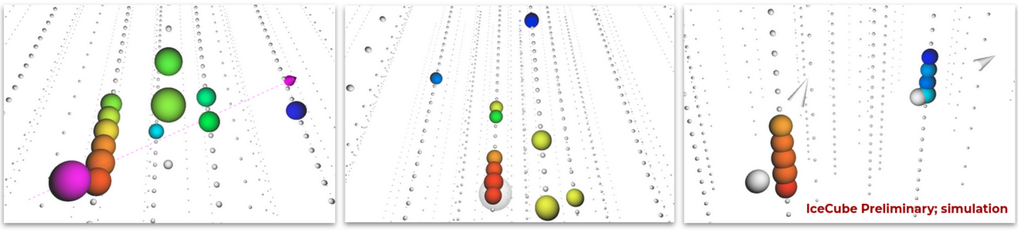

Figure 2: IceCube low-energy event morphologies from simulation. From left to right: track, cascade, double cascade. The magenta ball and arrow in the leftmost plot indicates the origin point and direction of the track, while the red to blue color scale of other bubbles indicates photon arrival time at each DOM, with red corresponding to earliest times. Bubble size corresponds with the amount of light recieved at each DOM.

DOMs are spaced along 86 vertical readout and support cables ("strings"), 78 of which are 125 meters apart. The other eight strings are more densely spaced, and concentrated at the middle of the array. This denser section is termed IceCube DeepCore [7]. The tighter spacing DOMs gives higher sensitivity to lower energy events, pushing detection thresholds down to the tens of GeV compared to hundreds of GeV in the main in-ice array.

There are three event morphologies distinguishable in IceCube - tracks, cascades, and double cascades - shown in figure 2. Tracks are caused by muons passing through the detector, or by charged-current muon-neutrino events occuring within it. Cascades are produced by neutral current neutrino events, and by charged-current electron neutrino events (as electrons stop quickly in ice). Double cascades can be produced by tau neutrinos or exotic signals.

A low-energy double-cascade event in IceCube would be the result of HNL production and decay, with the initial upscattering and subsequent decay to leptonic or mesonic final states each producing one burst of Cherenkov light. If resolvable, these double-cascades at low energies will be a clear hallmark of an HNL signal.

However, with low energy comes low light yield, and the different topologies become difficult to distinguish from one another. Doing so effectively necessitates specialized simulation and reconstruction tools. Current searches for HNLs in IceCube use tools which rely on the assumption that an HNL signal could appear as a cascade-like excess. However, searching for a double-cascade signal (even accurately assessing the discovery potential of such a search) requires custom tools such as `LeptonInjector-HNL`, outlined in the following section.

4. LeptonInjector-HNL

While some work has been done to simulate HNL production in accelerator experiments, there is not yet an HNL generator for neutrino observatories. `LeptonInjector-HNL`, an extension of the LeptonInjector package, is an HNL simulator for water-Cherenkov neutrino observatories, adaptable to a range of experiments and theoretical models [2].

The LeptonInjector-HNL workflow, as shown in figure 3, allows the user to simulate HNL events with a variety of geometrical configurations (a capability shared with the base LeptonInjector package) and physical parameters - notably, the mass of the predicted HNL, and its mixing with

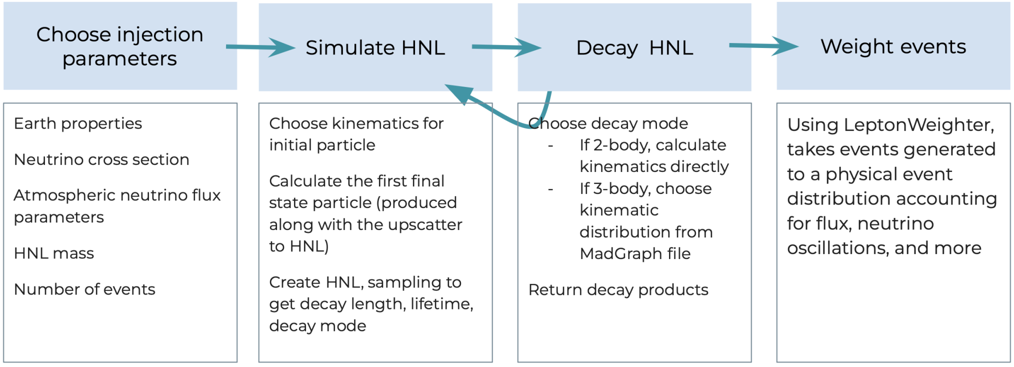

Figure 3: Flowchart describing the process of simulation procedure for HNL events with LeptonInjector-HNL.

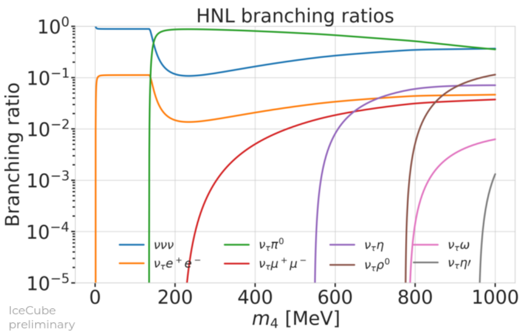

Figure 4: The HNL branching ratios as a function of mass as used in LeptonInjector-HNL.

the tau-neutrino. Additionally, the cross sections used for HNL production and decay are handled modularly, providing additional flexibility with the model tested.

LeptonInjector-HNL uses `Madgraph5` with `Feynrules`[8] to model the three-body decay modes, and computes two-body decay modes directly. Figure 4 shows the branching ratios of HNLs generated as a function of mass.

The utility of LeptonInjector-HNL can be seen in figure 5, which shows the decay length of HNLs at various masses, and energies, as a function of its mixing with the tau neutrino.

5. Future Outlook

For `LeptonInjector-HNL` to reach its full potential as a dynamic event generator relevant to a variety of experiments, it will be made open-source, and compatible with other open-source tools like Prometheus, a neutrino telescope simulator for ice and water Cherenkov experiments [9]. Furthermore, its discovery ability within IceCube will be realized only when a double-cascade specific reconstruction is developed. A graphnet-based reconstruction for double-cascades in IceCube is currently underway [10].

With these pieces put together, `LeptonInjector-HNL` is the first event generator built specifically for double-cascade scenarios in neutrino telescopes, and presents the potential for new searches for HNLs.

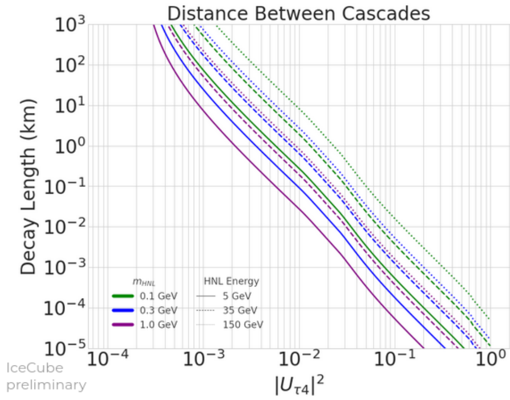

Figure 5: The HNL decay length for a sample of masses and energies, as a function of mixing with the tau neutrino.

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