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Search for sterile neutrinos in low-energy double-cascade events with the IceCube Neutrino Observatory: A first expected sensitivity

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Sterile neutrinos are a well motivated facet of the new physics landscape. From their role in the mechanism through which Standard Model (SM) neutrinos acquire mass, to their potential explanation of anomalies in oscillation experiments and even as Dark Matter candidates, these hypothetical particles are thought to play a central part in the near future of particle physics. Many models of sterile neutrinos exist, in some of which they are allowed to decay to SM particles. If the sterile neutrino production and subsequent decay happens inside the IceCube detector, this would lead to a double-cascade signature similar - but not identical - to the one known from tau neutrino charged current interactions. However, the lifetime of the sterile neutrino is potentially much longer than that of the tau lepton, depending on its mass. This opens the possibility for a spatial resolution of a double cascade topology at atmospheric neutrino energies, as opposed to searches for high energy tau neutrinos from astrophysical sources. We present the results of a first study of the IceCube-DeepCore detector sensitivity to such a signal. The strategy is to study the topology of such double-cascade events in simulation and design a classifier that helps us isolate a sample of signal events over the background from SM processes. We study the sensitivity as a function of the signal parameters to determine in what conditions could IceCube see such a signal. Scanning the two-dimensional tau-sterile mixing parameter and sterile neutrino mass phase-space, we conclude that with the current state of the analysis, this search will have to wait for the IceCube Upgrade or a major improvement in the analysis tools in order for a signal to be isolated from the very large neutrino background.

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As a predictive model, the SM of particle physics has been very successful for the vast majority of all ever observed phenomena. However, a series of yet unexplained observations have led the physics community to consider extensions to the current model that would help understand what we currently call "anomalies". One of these extensions considers the existence of a massive fourth neutrino that would not be charged under any of the SM gauge groups. This so-called "sterile" neutrino may be the reason of the LSND and MicroBooNE anomalies [1, 2], it could play a role in the mechanism under which SM neutrinos acquire mass [3] and it could also be a Dark Matter (DM) candidate under certain assumptions on its mass and density [4]. We present an analysis to search for a yet unobserved sterile neutrino, or Heavy Neutral lepton (HNL), that mixes with the three SM neutrinos through an extended PMNS matrix. Fig. 1 shows the existing constraints in the phase-space of the τ-sterile mixing parameter and the sterile neutrino mass. Following [5], we investigate the sensitivity of the IceCube detector to such a signal in the yet unexplored region between the results of the CHARM and the DELPHI collaborations. Recent works have also started to explore this region using different strategies [6, 7].

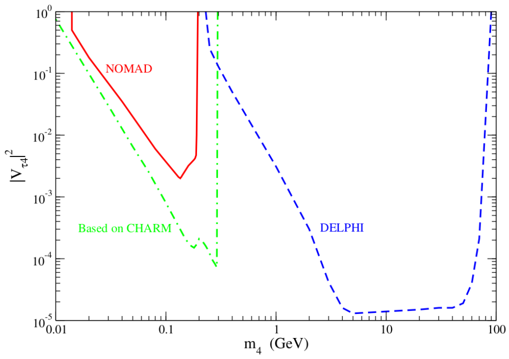

Figure 1: Current constraints in the phase-space of the τ-sterile mixing parameter and the sterile neutrino mass [8].

The IceCube Neutrino Observatory is a neutrino telescope burried within the ice of the South Pole. It consists of an array of digital optical modules (DOM's) that capture the Cherenkov light emitted by superluminal particles propagating in the ice. Using the light captured by each DOM, one can reconstruct the experimental signature of the event. In particular, we will focus on what we call a "double-cascade" event. The SM predicts the existence of such events when a boosted tau lepton is produced in the charged-current (CC) interaction of a tau neutrino. The tau propagates for a certain distance before it decays, allowing for the separation between the DIS cascade and the second cascade made of the decay products of the tau. In the near future, the detector core will be upgraded [9] to a denser array, allowing for a higher sensitivity to low energy signals. The aim of this work is to probe the $U_{\tau 4}$ mixing parameter, which means that we must somehow target ν_τ-ν_4 up-scatterings. Atmospheric neutrinos are mostly of electron and muon flavors so in order to have a decent flux of ν_τ, we must restrict ourselves to atmospheric neutrinos produced in the Northern hemisphere that have a larger probability to have oscillated to the τ flavour. This production mechanism is sketched in Fig. 2. Similarly to a SM ν_τ CC interaction, the first DIS scattering of the ν_τ onto a nucleus of the ice initiates a hadronic cascade in the detector. After production, the HNL propagates over some distance and decays to SM particles. This forms the

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second cascade of this so-called "double-cascade" event. As opposed to a ν_τ CC interaction, the two cascades are not connected through a track because the HNL is electrically neutral. The main advantage of this signature over the SM ν_τ CC double-cascade event is that there is no need for a highly energetic boosted ν_τ to obtain two well spatially-separated cascades. The larger lifetime of the HNL allows for a double-cascade signature at much lower energies, which justifies targeting atmospheric neutrino events.

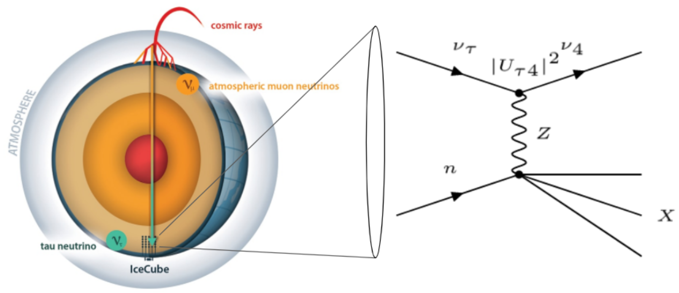

Figure 2: Sketch of the signal production mechanism. A fraction of the ν_e and ν_μ produced in collisions of cosmics rays with the atmosphere oscillate to the tau flavour before reaching the IceCube volume. The ν_τ then up-scatters to the sterile mass state ν_4 through mixing.

We select events using a DeepCore-based framework, motivated by the fact that we target atmospheric, hence low-energy events. The events are reconstructed assuming a simple double-cascade hypothesis. A fit is done to the following 9 event parameters: the primary vertex coordinates (x, y, z, t), the direction of the two cascades, taken equal (zenith θ, azimuth ϕ), the distance between the two cascades (L) and the energy of each cascade (E_0, E_1). Events are required to have a $\cos(\theta)$ smaller than 0.2 (mostly "up-going"). We require both cascades to have a reconstructed energy larger than 5 GeV, below which the reconstruction is not considered reliable. We also restrict the events sample to those with a reconstructed distance between the two cascades larger than 50 meters, distance below which the resolution is too bad (see Fig. 3 (left)). In Fig. 3 (right), one can see that even after the selection, the signal is drowned in the expected number of background events. To push further the signal-to-background discrimination, we make use of a boosted decision tree (BDT) algorithm. We feed the BDT with the following 10 variables: $\cos(\theta)$, E_0, E_1, L, the confinement and the asymmetry variables, the PID, and two different goodness-of-fit variables for the reconstruction algorithm. The confinement defines how much of the total energy in the event is contained within the two cascades. The asymmetry measures the energy difference between these two cascades. The PID (particle identification) quantifies the track-like or cascade-like topology of an event. The result of the BDT is shown in Fig. 4 (left). We require events to have a BDT score larger than -0.2.

Using the CLs technique, we compute the sensitivity of our analysis to the signal, i.e. the expected upper limit on the signal strength at 90% CL. This is shown in Fig. 4 (right). The upper limit is larger than unity for all scanned masses, meaning that we are not able to exclude the existence of such a signal. The IceCube detector will soon be upgraded with an even denser inner core. This will significantly improve the light collection, hence the reconstruction performance of low energy signals. We are currently working on expanding this sensitivity study to the upgraded detector, which we believe will bring this analysis down to the sensitivity threshold.

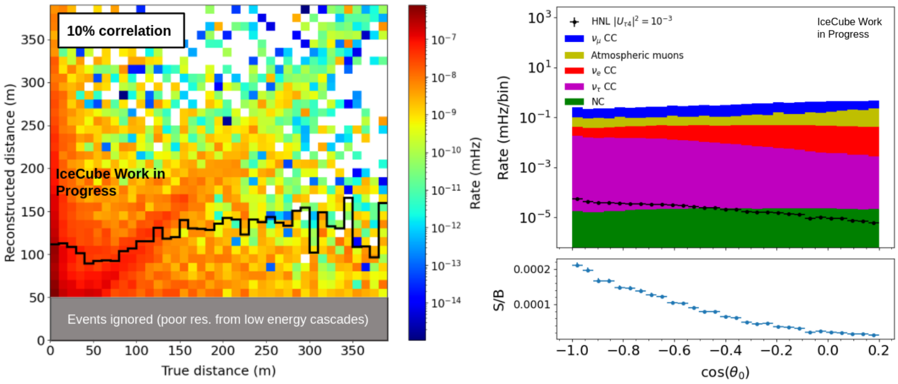

Figure 3: Left: Resolution of the distance between the two cascades. Right: Distribution of the cosine of the zenith angle of the two cascades for the background (stacked plain histograms), and the signal (black dots).

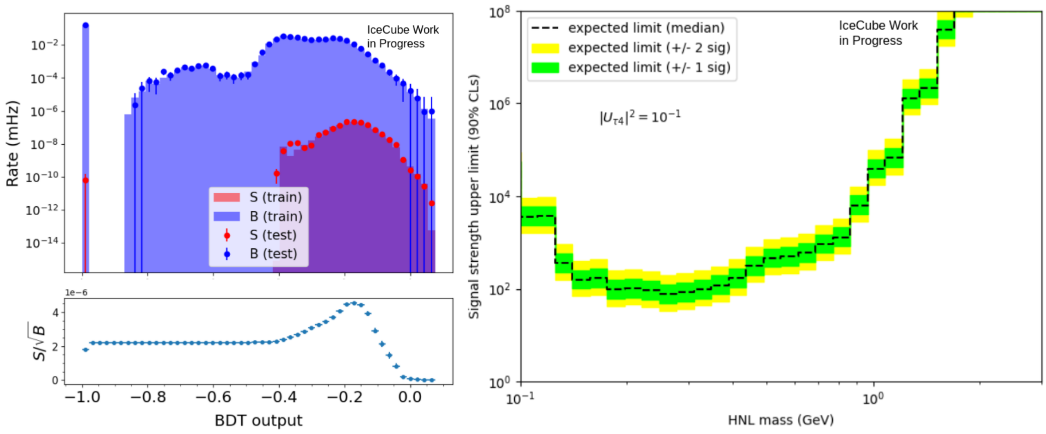

Figure 4: Left: Distribution of the BDT output for the background (blue) and the signal (red) and for the training and testing samples. Right: Expected upper limit (sensitivity) at 90% CL on the signal strength using the CLs technique.

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