First Results from HNL Searches in IceCube

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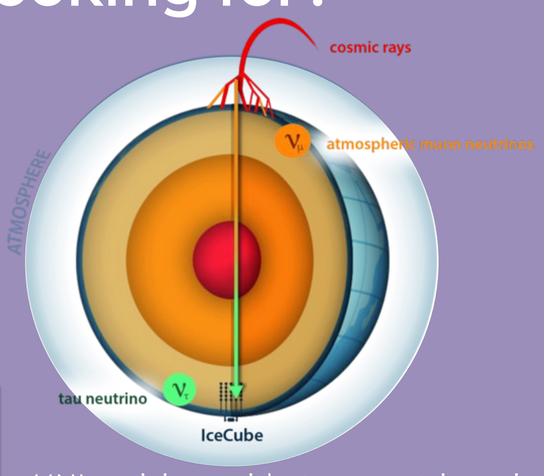
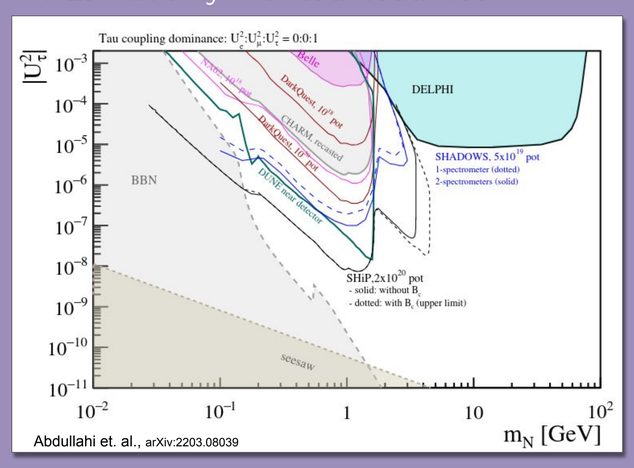
What are we looking for?

Muon neutrinos oscillate as they traverse the earth, resulting in a sizeable tau neutrino flux. This flux peaks in the 10-100 GeV range, where IceCube's DeepCore sub-detector is sensitive.

Presented here are results of a search for upscattering of those neutrinos to Heavy Neutral Leptons (HNLs), assuming the HNLs mix only with tau neutrinos.



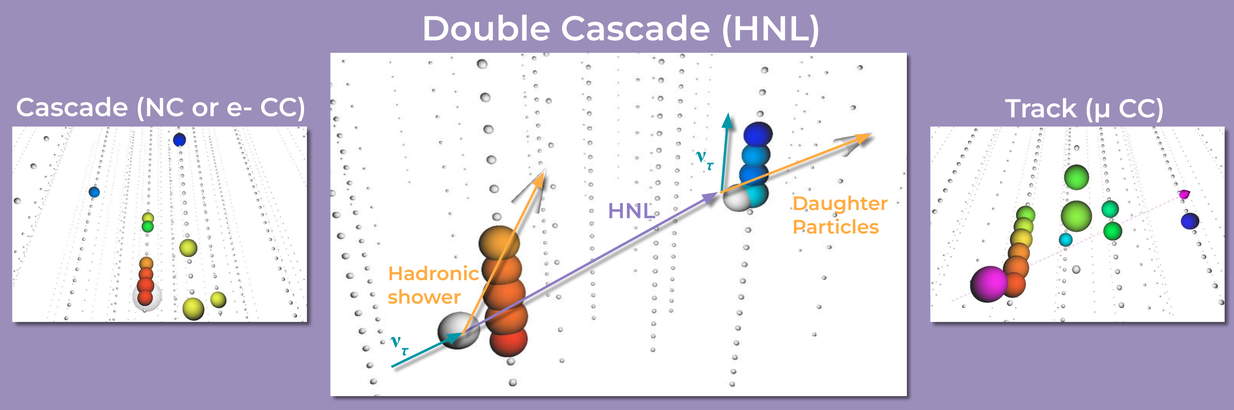


HNL mixing with tau neutrinos is least constrained, making this avenue most fruitful for future exploration.

Existing (shaded) and anticipated (outlined) limits are shown on the left. For this preliminary study, we investigate nominal mixings of $|U_{\tau 4}^2| > 10^{-3}$. Future work will expand the sensitivity to lower couplings.

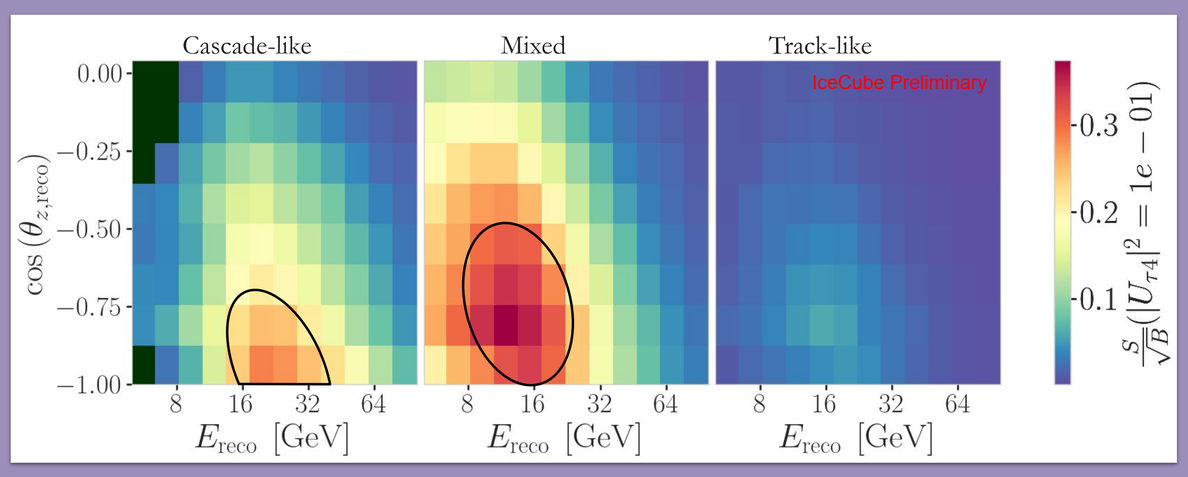
Signal definition and Reconstruction

Low energy IceCube events can create three distinct light patterns, determined by the underlying physics. The HNL signature is a double-cascade pattern, with no light between the cascades.



The low overall light yield per event, and the fact that the first cascade carries majority of visible energy makes distinguishing double cascades unfeasible with existing tools. Instead, we use FLERCNN[1, 2], an existing CNN-based reconstruction for low energy events in IceCube.

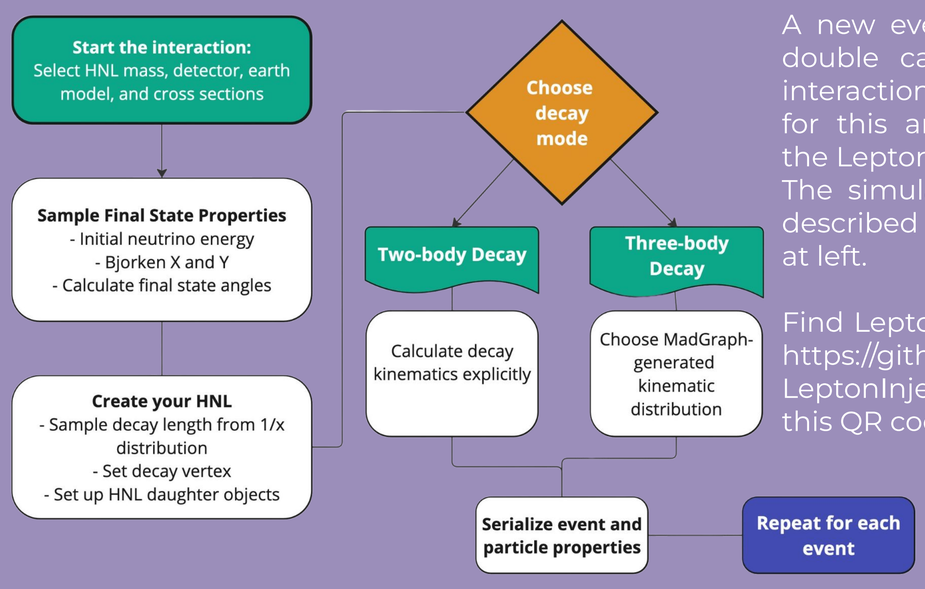
FLERCNN assigns each event a particle identification score, classifying events on a spectrum of cascade-like to track-like. HNLs, with their double-cascade shape, are expected mostly in the "mixed" category, with some falling into the cascade-like category as a result of the low light yield of the second cascade.



Shown above is the anticipated HNL signal over square-root of background for 9.28 years of data. As expected, this study is background dominated.

1: arXiv:2107.02122v2, 2: https://github.com/jessimic/LowEnergyNeuralNetwork

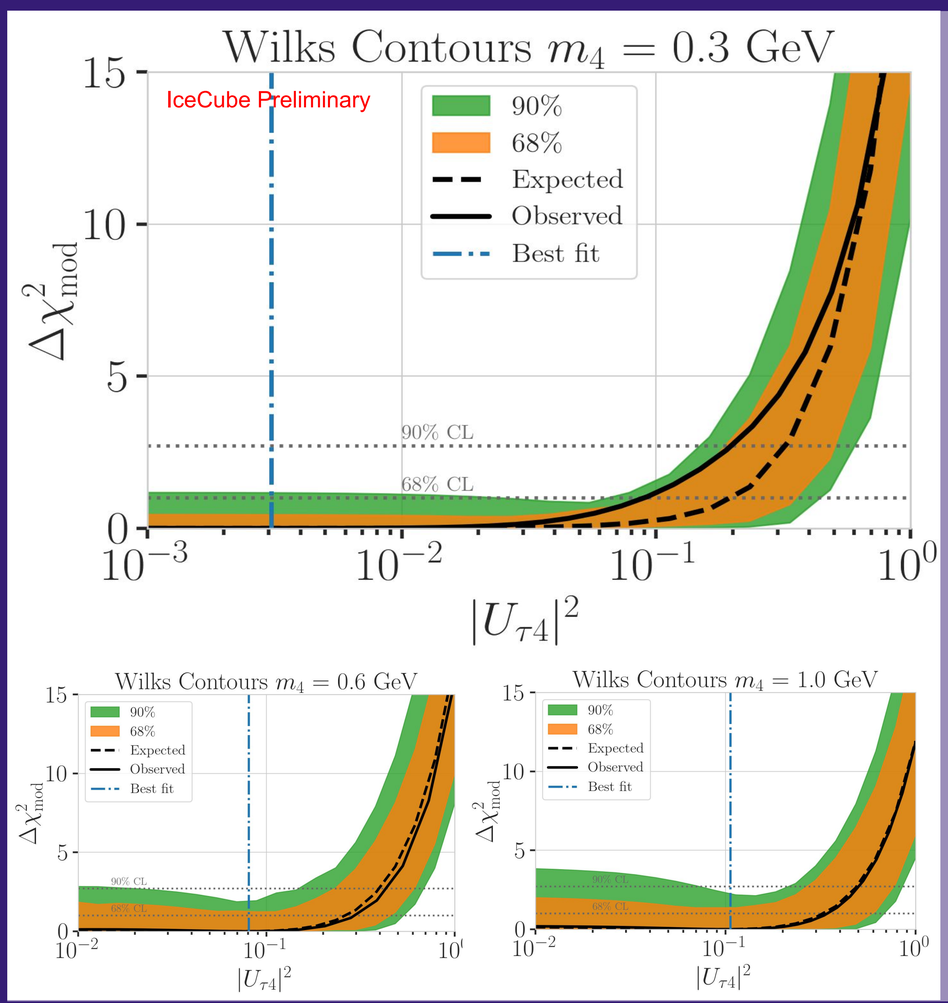
Simulation: LeptonInjector-HNL



A new event generator for double cascade neutrino interactions was developed for this analysis, based on the LeptonInjector package. The simulation workflow is described in the flowchart at left.

Find LeptonInjector-HNL at: https://github.com/jybook/LeptonInjector-HNL, and at this QR code:

SCAN ME

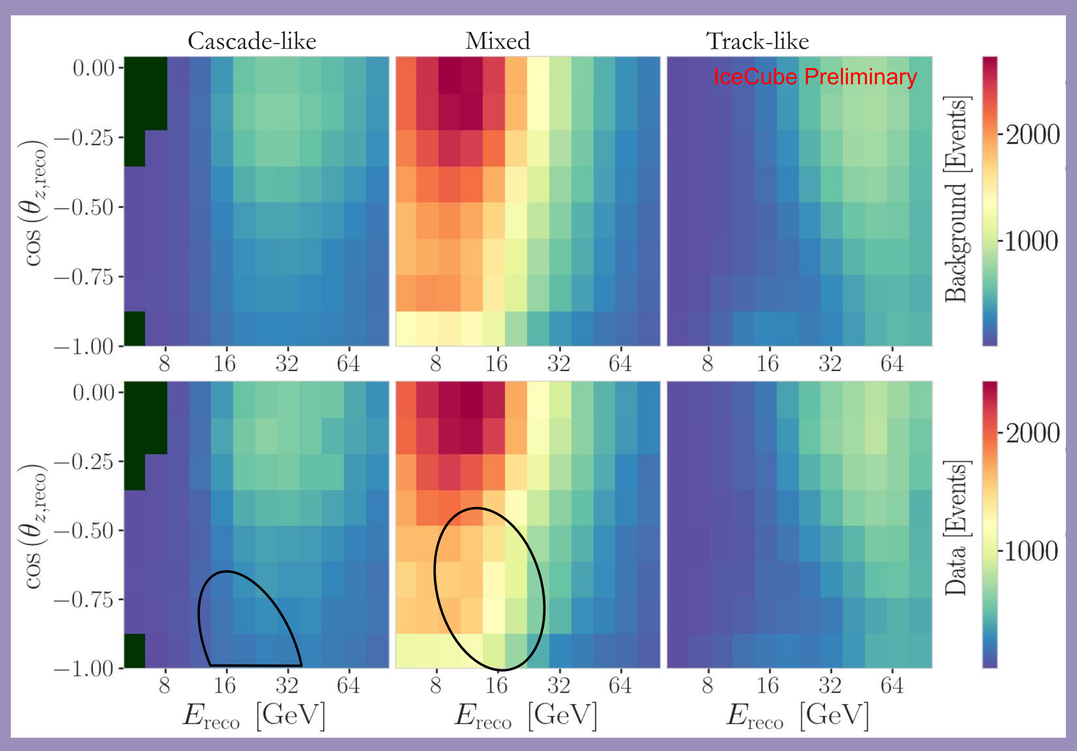


Results

The data are fit to the event expectation for three HNL masses: 0.3, 0.6, and 1.0 GeV.

The test statistic used is $\Delta\chi^2_{\mathrm{mod}}$ between a null hypothesis fit, and one where the mixing is fixed to a given value. Confidence intervals assuming Wilks' theorem are shown at left.

No significant evidence for an HNL was found.



The data collected is binned by particle identification score and shown in the plot at bottom right. Background expectation is also shown (right, top) for contrast. The ellipses indicate the regions with the largest predicted signal-to-background ratio.

Take-home message

The first search for HNLs in IceCube proves the viability of HNL searches in water Cherenkov experiments. Results are consistent with the null hypothesis.

HNL mass	$\lvert U_{\tau 4}\rvert^2$	68 % CL	90 % CL	NH p-value
0.3 GeV	0.003	0.09	0.19	0.97
0.6 GeV	0.080	0.21	0.36	0.79
1.0 GeV	0.106	0.24	0.40	0.63

Future improvements will allow IceCube to perform more sensitive analyses on ν_τ mixing with HNLs:

- Reconstruction of double-cascade morphology, reducing background.
- Enhancing simulation tools to broaden the HNL mass range investigated.
- The IceCube upgrade will lower the energy threshold from 10 GeV to 1 GeV, raising the anticipated statistics.