Journal of Instrumentation

PAPER

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To cite this article: A. Trettin and on behalf of the IceCube collaboration 2021 *JINST* **16** C09005

*J*inst

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *July 30, 2021*
ACCEPTED: *August 26, 2021*
PUBLISHED: *September 8, 2021*

VERY LARGE VOLUME NEUTRINO TELESCOPE 2021
MAY 18–21, 2021
VALENCIA, SPAIN

Sensitivity of a search for eV-scale sterile neutrinos with 8 years of IceCube DeepCore data

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ABSTRACT: Several anomalies in reactor and accelerator neutrino experiments motivate the search for sterile neutrinos with squared mass splittings at the eV-scale. We present an analysis that probes the elements $U_{\mu 4}$ and $U_{\tau 4}$ of the extended $(3+1)$ neutrino mixing matrix using an 8 year data sample from IceCube's DeepCore sub-array containing atmospheric neutrinos between 5 and 300 GeV. We show the expected sensitivities of the analysis to $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ under the assumption of mass splittings between 1 and $100\,\mathrm{eV}^2$, and to $|U_{\mu 4}|^2$ for mass splittings below $1\,\mathrm{eV}^2$. We specifically discuss how we overcame the challenges of efficiently calculating neutrino oscillation probabilities in the presence of very fast neutrino oscillations involving large Δm^2.

KEYWORDS: Analysis and statistical methods; Neutrino detectors; Cherenkov detectors

https://doi.org/10.1088/1748-0221/16/09/C09005

Contents

1 Introduction

The IceCube South Pole Neutrino Observatory [1] is a km^3-scale neutrino telescope located at the geographic South Pole. It consists of 5160 Digital Optical Modules (DOMs) arranged on vertical strings at depths between 1450 m and 2450 m that are capable of detecting Cherenkov emissions from highly relativistic charged particles travelling through the Antarctic ice. The DeepCore sub-array of IceCube consists of 8 strings optimized for the detection of neutrinos with energies as low as 5 GeV within its volume. In the energy range below 100 GeV, oscillations of atmospheric neutrinos can be observed.

Some experimental anomalies from reactor and accelerator experiments [2–4] suggest that there could be a fourth neutrino mass eigenstate with a mass splitting of $O(1)$ eV^2 beyond the three eigenstates known from the Standard Model. To be consistent with independent constraints from particle accelerator data [5], this fourth neutrino flavor would have to be "sterile,“ i.e. non-interacting with respect to the weak force, and could therefore be only indirectly observed through its effect on neutrino oscillations. Extending the PNMS matrix by a fourth row and column to accommodate the additional sterile state adds three mixing angles $(\theta_{14}, \theta_{24}, \theta_{34})$ and two CP-violating phases $(\delta_{14}, \delta_{24})$ to the neutrino oscillation parameters. We study the sensitivity of an analysis measuring $|U_{\mu 4}|^2 = \sin^2\theta_{24}$ and $|U_{\tau 4}|^2 = \sin^2\theta_{34}\cos^2\theta_{24}$, where δ_{24} is included as a nuisance parameter and matter effects from Earth's mantle and core are taken into account.

2 Analysis

For this sensitivity study, Monte Carlo (MC) events are binned in reconstructed energy and zenith angle as shown in figure 1. The histograms are furthermore split into three channels by a particle identification (PID) score that corresponds to their signature in the detector, resulting in *cascade*, *mixed* and *track* channels. The *track* channel consists of >80% charged-current ν_μ events, while the *cascade* channel has a larger fraction of other flavors and interactions. Since the primary oscillation effect being observed is ν_μ disappearance, most of its sensitivity is due to the track channel. The MC events are weighted according to atmospheric flux, cross-sections, oscillation probabilities and detector effects to minimize a χ^2-loss function modified to account for uncertainties due to limited MC statistics.

2.1 Sterile neutrino oscillation signature

Figure 1 shows the expected significance of the difference in bin counts in the *track* channel of the analysis histogram due to a change in θ_{24} from 0° (no sterile mixing) to $\theta_{24} = 15°$ assuming 8 years of live time. The left panel shows the effect at $\Delta m^2_{41} = 0.1\,\mathrm{eV}^2$ and the right panel at $\Delta m^2_{41} = 1\,\mathrm{eV}^2$. In the upper right corner of the left panel we can see that the highest oscillation minimum in energy and zenith angle from the sterile neutrino oscillation pattern becomes apparent, which makes it possible to fit the value of Δm^2_{41}. In the right panel we see that the sterile neutrino oscillation pattern is fully averaged so that the analysis becomes insensitive to the value of Δm^2_{41}.

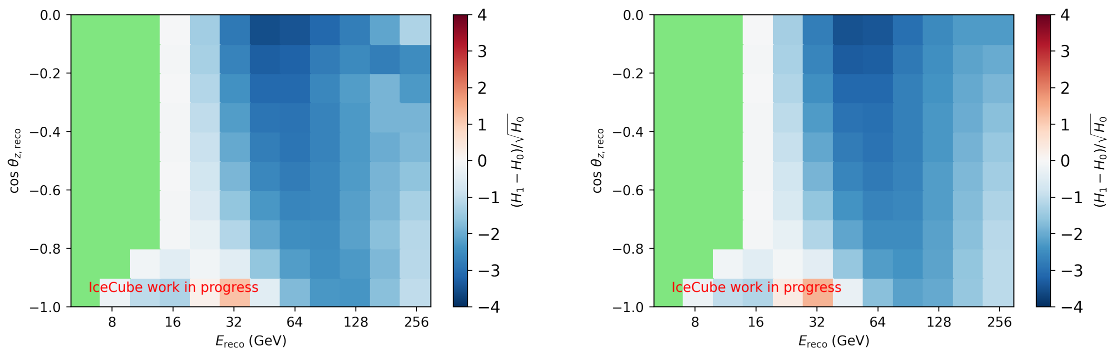

Figure 1. Significance of the difference in expected bin counts due to a change in θ_{24} from 0° (null hypothesis H_0) to 15° (alternative hypothesis H_1) in the *track* channel of the analysis binning at $\Delta m^2_{41} = 0.1\,\mathrm{eV}^2$ (left) and at $\Delta m^2_{41} = 1\,\mathrm{eV}^2$ (right). The green color indicates empty bins.

3 Computation of oscillation probabilities with `nuSQuIDS`

To calculate oscillation probabilities, we use the `nuSQuIDS` [6, 7] package. It calculates the evolution of state densities due to matter effects at a set of coarsely spaced *nodes*, interpolates the densities between them and extracts the probabilities with a trace operation involving only the vacuum part of the Hamiltonian. Because the operation after the initial overhead of calculating the state densities is very simple, it is more efficient than other analytical expressions when the number of evaluations is $\gtrsim 1000$ [8]. The nodes need to be spaced more densely in regions where the matter potential changes more rapidly and at lower energies as indicated in the left panel of figure 2. In addition, we apply a low-pass filter to the trace operation to smooth out rapid oscillations as shown in the right panel of figure 2. With this smoothing, we are able to calculate oscillation probabilities on a grid where the probability change in each bin is effectively negligible. The filter cut-off is optimized to remove only oscillation patterns that are too small to be resolved by the detector. In this configuration, we can compute oscillation probabilities for the entire MC set of $O(10^6)$ events in $\lesssim 3$ seconds, which is a factor of 400 speedup over an event-by-event calculation with `GLoBES` [9].

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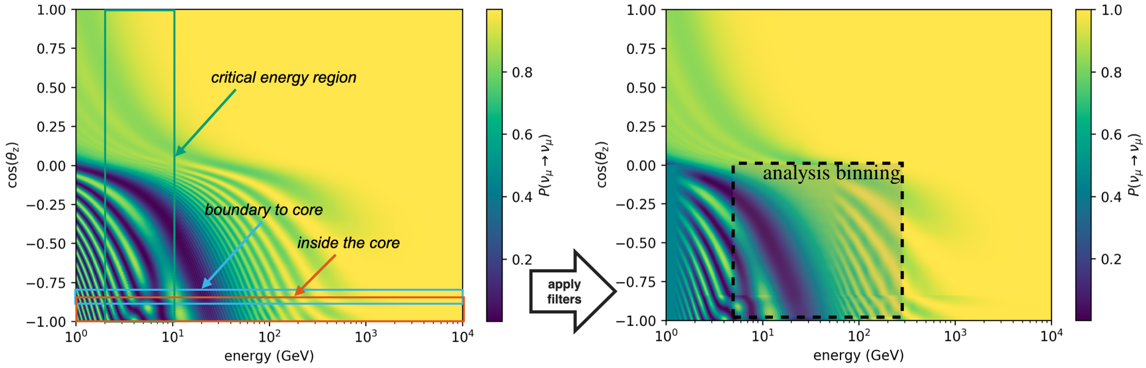

Figure 2. Muon survival probability without low-pass filtering (left) and with low-pass filtering below the horizon (right) in the presence of a sterile neutrino with $\Delta m^2_{41} = 0.1\,\text{eV}^2$ and $\theta_{24} = 15°$. The boxes in the left panel indicate where nuSQuIDS nodes are placed with increased density.

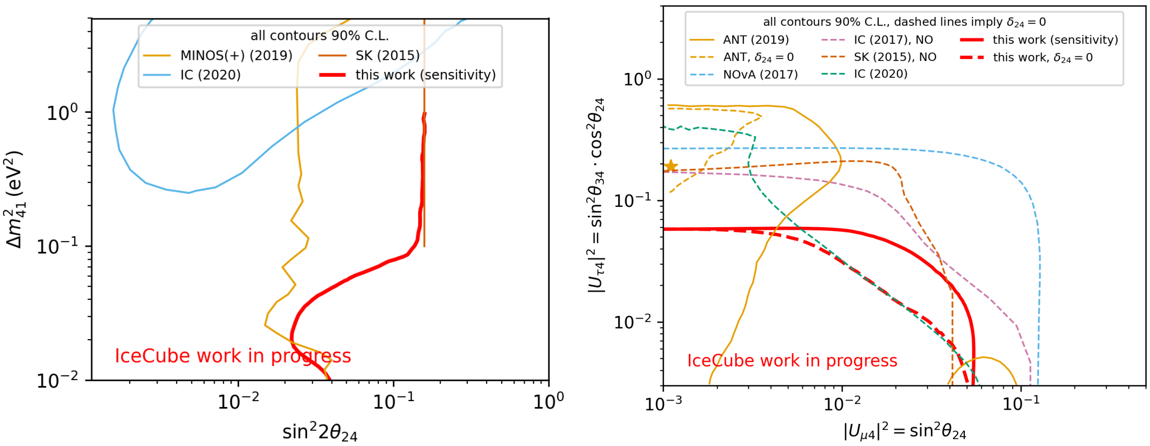

Figure 3. Projected sensitivity of this analysis for small (left) and large (right) mass splittings compared to 90% confidence limits from [10, 11, 15–19]. Dashed lines show results where the sterile phase δ_{24} was fixed to zero. The best fit point of the ANTARES result [18] is marked with a star. It prefers a large sterile mixing, resulting in the distinct shape of the contour. The IC (2020) contour in the left panel is closed.

4 Projected sensitivities

We present sensitivities of the analysis assuming 8 years of live time, in which we expect ≈ 250000 neutrino events. In the right panel of figure 3, we fit pseudo-data with a template assuming $\Delta m^2_{41} = 1\,\text{eV}^2$. At this mass splitting, fast oscillations are averaged out and the analysis becomes indifferent to the value of Δm^2_{41} while fitting θ_{24} and θ_{34}. In the left panel of figure 3, we assume $\theta_{34} = 0$ for mass splittings $\Delta m^2_{41} < 0.1\,\text{eV}^2$. The sensitivity to θ_{24} increases substantially and begins to be competitive with the MINOS/MINOS+ result [10] at some points. For mass splittings $\Delta m^2_{41} > 0.1\,\text{eV}^2$, the sensitivity is roughly constant, similar to the SuperK analysis [11]. Both contours include systematic uncertainties from the atmospheric flux (calculated with MCEq [12]), cross-sections, atmospheric muons and detector effects. The angle θ_{14} and phase δ_{14} are assumed to be zero because the analysis does not have significant sensitivity to $|U_{e4}|^2$ below the limits already set by reactor experiments [13] and the normalization of the PNMS matrix [14].

5 Conclusion

We present an analysis using atmospheric neutrino data from IceCube's DeepCore sub-array that is expected to have a high sensitivity to the sterile mixing magnitude $|U_{\mu 4}|$ and $|U_{\tau 4}|$. To make this analysis computationally practical, we have optimized our software configuration with `nuSQuIDS` and added low-pass filtering to average out unresolvably fast oscillations induced by the presence of an eV-scale sterile neutrino. For sterile mass splittings above 1 eV^2, these rapid oscillations are fully averaged out and we are able to produce limits on $|U_{\mu 4}|$ and $|U_{\tau 4}|$ that are valid even if the true mass splitting is larger than the 1 eV^2 assumed in the fit. For sterile mass-splittings below 0.1 eV^2, the sterile oscillation pattern begins to be resolvable and the sensitivity of the analysis increases to be competitive with accelerator experiments.

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