Snowmass2021 - Letter of Interest

BSM Neutrino Oscillation Searches with 1-100 TeV Atmospheric Neutrinos at IceCube

Thematic Areas: (check all that apply □/■)

■ (NF01) Neutrino Oscillations
■ (NF02) Sterile Neutrinos
■ (NF03) BSM
■ (NF04) Neutrinos from Natural Sources
■ (NF08/TF11) Theory of Neutrino Physics

Contact Information:
Ben Jones (University of Texas at Arlington)[ben.jones@uta.edu]

Authors:

Carlos A. Argüelles (Harvard University) [carguelles@fas.harvard.edu]
Janet M. Conrad (Massachusetts Institute of Technology) [conrad@mit.edu]
Ben Jones (University of Texas at Arlington)[ben.jones@uta.edu]

On behalf of the IceCube[1] and IceCube-Gen2[2] collaborations.

Abstract:

The IceCube South Pole Neutrino Observatory has accumulated a large sample of atmospheric neutrino events in an energy range spanning 100 GeV-100 TeV. In this LOI we summarize the contributions of the high energy part of this sample to BSM neutrino physics to date, and outline prospects and plans for its extension and continued exploitation during the coming Snowmass period.

[1] https://icecube.wisc.edu/collaboration/authors/snowmass21_icecube
[2] https://icecube.wisc.edu/collaboration/authors/snowmass21_icecube-gen2

1 Sterile Neutrinos and BSM Oscillation Physics at IceCube

High-energy atmospheric neutrinos form the dominant contribution to the upward-going flux at neutrino telescopes in an energy range spanning approximately 100 GeV-100 TeV[1;2]. Over eight years of full-detector operation, the IceCube Neutrino Observatory has collected over 300,000 up-going track-like events in this energy range, using a highly efficient event selection with greater than 99.9% purity[3]. This sample has been put to use for one of the world's most sensitive searches for sterile-neutrino-induced muon-neutrino disappearance from new mass states in the range $0.1 \leq \Delta m^2/\mathrm{eV}^2 \leq 10$, the regime of mass splittings suggested by appearance anomalies from short baseline neutrino experiments[3;4]. The IceCube dataset provides a strong exclusion of much of the relevant parameter space at 99% CL.

IceCube's unique atmospheric muon-neutrino sample is especially powerful for certain beyond-standard-model physics searches for several reasons. These include:

- Very strong statistical precision, with 300,000 reconstructed events in the muon-neutrino channel (this is orders of magnitude larger than the typical sample size collected by most operational neutrino detectors);
- Oscillations strongly impacted by matter effects[5–10]. This feature is especially prominent for eV-scale sterile neutrinos, which create a matter-induced resonance around 1 TeV[11], the peak of the IceCube spectrum, but is also advantageous in searches for non-standard interactions[12];
- Coverage of four to five orders of magnitude in energy, and baselines from tens of kilometers to the diameter of the Earth, offering an especially "broadband" search for new physics;
- High-energy reach, that providing unparalleled access effects with positive dependencies on energy - for example, the Standard Model Extension of Lorentz violation[13], or decoherence models with positive energy exponents in the Von-Neumann equation[14].

Some of the challenges associated with these searches are that the IceCube detector is constructed with sparse photocathode coverage[15], and in a naturally occurring medium with uncertain optical properties[16;17]; that the neutrino beam is produced in very high energy and very forward collisions in the atmosphere[1] that are imperfectly understood based on lower energy terrestrial collider data[18]; and that high-energy muons are not contained by the detector, leading to unavoidable energy smearing[19]. Nevertheless, uncertainties associated with these sources have been controlled in the present generation of analyses, using a diverse array of in-ice calibration constraints, atmospheric air-shower modeling, air density measurements from IR sounding satellites, and more. Systematic uncertainties are presently believed to be controlled at the level of 1-2% per bin, commensurate with what is required to effectively employ the statistical power of the 8-year muon neutrino sample for BSM searches[3].

2 Future Prospects

Here we advocate that the powerful eight-year sterile neutrino searches at IceCube should be considered as the tip of an iceberg[3] of uniquely enabled BSM high-energy oscillation searches within the capabilities of the IceCube Neutrino Observatory. Given eight years of extant statistics and the high efficiency and purity of our event selections, statistical power in the existing muon-neutrino sample is now expected to accumulate slowly. However, several important directions remain to be explored, and now occupy our focus:

Utilization of IceCube's cascade samples: Track-like events from up-going muon-neutrino events are a natural first step for sterile neutrino searches at IceCube because the target volume for interactions stretches far below the detector, through the 10-100 km range of muons in this energy range. The cost is

[3]Intended.

that the original energy of the neutrino at interaction is unknown, leading to a wide smearing between true neutrino energy and reconstructed muon energy at the detector. This smearing obscures the compellingly sharp matter-induced-resonance feature of sterile neutrino oscillations at IceCube. Cascade events from electron- and tau-neutrinos, on the other hand, are compact — this means that the interaction must be in or very near to the fiducial volume to be detected, but the probability of full containment is high. Thus, while the statistical precision is reduced, calorimetric energy measurement enables much more precise bump- or dip-hunting searches (notably, both bumps and dips in the cascade channel are possible sterile neutrino signatures at IceCube, depending on mixing angles). Information from combined fits to both channels can yield flavor-dependent information on sterile neutrino mixing angles beyond θ_{24}. Particularly notable is that use of the cascade channel at IceCube can access the elusive ν_τ sector[20;21] needed to constrain unitarity of the extended PMNS matrix. The first generation of cascade-based sterile neutrino samples are now under development and will come to maturity during the coming Snowmass period.

Searches for diverse BSM physics in both cascade and track samples: Sterile neutrinos are only one form of novel oscillation effect that can be probed by IceCube. Searches are under development for the oscillation signatures associated with anomalous decoherence (a possible hallmark of quantum gravity / spacetime foam models)[14], violations of Lorenz invariance (LV)[13;22–24], neutrino-matter non-standard interactions (NSI)[25–27], and neutrino decay[28–31]. Preliminary projections show that IceCube is expected to set the worlds strongest limit on the NSI parameter $\epsilon_{\mu\tau}$ with the present track sample, and carve out sensitivity to vast new parameter space in decoherence and Lorentz violation models for operators with positive energy dependencies. Extension to the cascade sample also adds additional flavor information, for all these mosels. Non-oscillation based BSM searches are also made possible by consideration of the details of event topology, for example, double-bang signatures of neutral heavy leptons[32;33], or production of two-track trident events from Z' production[34;35], or exotic signatures of black hole evaporation[36–38].

Improved calibration constraints from the IceCube upgrade: In the present generation of analyses, the scales of statistical precision and systematic uncertainty are comparable. Notably, an indistinct but persistent feature at the $\sim$2-sigma level is present in the 8-year sterile neutrino analysis, which could be a tentative hint of new physics, or else a small systematic effect. One especially difficult source of uncertainty relates to knowledge of depth-dependent South Pole ice properties. The IceCube upgrade is an infill array of densely packed optical modules that will enable study of the ice stratigraphy with a new precision, and these constraints can be used in both existing and forthcoming analyses. This will reduce the scale of systematic uncertainty, potentially generating new insights into the observed effects and enabling more precise searches based on detailed event topology. The small upgraded volume will also have a lower energy threshold, potentially enabling new measurements in the range jointly covered by Hyper-Kamiokande and IceCube.

3 Conclusion

IceCube has collected multiple unique samples of high-energy atmospheric neutrinos that can be exploited for BSM neutrino oscillation searches. The recent powerful high energy sterile neutrino search using 8 years of reconstructed up-going muon neutrinos is an example of the power of these samples. This analysis represents the beginning of a much wider program of BSM oscillation physics at IceCube, which will continue to grow over the coming Snowmass period along orthogonal axes of increased reach in flavor space (utilization of cascade samples), more expansive coverage of BSM models (decoherence, Lorentz violation, non-standard interactions, neutrino decay, and more), and improved control of systematic uncertainties (via the IceCube upgrade). We particularly encourage our theoretical colleagues to continue to engage with this compelling physics program, including proposing and developing new ideas and models, and re-interpreting our datasets (provided via detailed data releases) in new and enlightening ways. The BSM oscillation physics program at IceCube is strong, unfinished, and being pursued with enthusiasm and vigor.

References

[1] T. K. Gaisser, R. Engel, and E. Resconi, *Cosmic Rays and Particle Physics* (Cambridge University Press, 2016), 2nd ed.

[2] M. Aartsen et al. (IceCube), Eur. Phys. J. C **75**, 116 (2015), 1409.4535.

[3] M. Aartsen et al. (IceCube) (2020), 2005.12943.

[4] M. Aartsen et al. (IceCube) (2020), 2005.12942.

[5] E. K. Akhmedov, Sov. J. Nucl. Phys. **47**, 301 (1988).

[6] M. Chizhov, M. Maris, and S. Petcov (1998), hep-ph/9810501.

[7] P. Krastev and A. Smirnov, Physics Letters B **226**, 341 (1989), ISSN 0370-2693, URL http://www.sciencedirect.com/science/article/pii/0370269389912069.

[8] M. Chizhov and S. Petcov, Phys. Rev. Lett. **83**, 1096 (1999), hep-ph/9903399.

[9] E. K. Akhmedov and A. Smirnov, Phys. Rev. Lett. **85**, 3978 (2000), hep-ph/9910433.

[10] E. K. Akhmedov, Pramana **54**, 47 (2000), hep-ph/9907435.

[11] H. Nunokawa, O. Peres, and R. Zukanovich Funchal, Phys. Lett. B **562**, 279 (2003), hep-ph/0302039.

[12] J. Salvado, O. Mena, S. Palomares-Ruiz, and N. Rius, JHEP **01**, 141 (2017), 1609.03450.

[13] M. Aartsen et al. (IceCube), Nature Phys. **14**, 961 (2018), 1709.03434.

[14] T. Stuttard and M. Jensen (2020), 2007.00068.

[15] M. Aartsen et al. (IceCube), JINST **12**, P03012 (2017), 1612.05093.

[16] M. Aartsen et al. (IceCube), Nucl. Instrum. Meth. A **711**, 73 (2013), 1301.5361.

[17] M. Aartsen et al. (IceCube), JCAP **10**, 048 (2019), 1909.01530.

[18] G. Barr, T. Gaisser, S. Robbins, and T. Stanev, Phys. Rev. D **74**, 094009 (2006), astro-ph/0611266.

[19] M. Aartsen et al. (IceCube), JINST **9**, P03009 (2014), 1311.4767.

[20] M. Aartsen et al. (IceCube), Phys. Rev. D **93**, 022001 (2016), 1509.06212.

[21] M. Aartsen et al. (IceCube), Phys. Rev. D **99**, 032007 (2019), 1901.05366.

[22] M. Gonzalez-Garcia, F. Halzen, and M. Maltoni, Phys. Rev. D **71**, 093010 (2005), hep-ph/0502223.

[23] C. A. Argüelles, T. Katori, and J. Salvado, Phys. Rev. Lett. **115**, 161303 (2015), URL https://link.aps.org/doi/10.1103/PhysRevLett.115.161303.

[24] M. Bustamante, J. F. Beacom, and W. Winter, Phys. Rev. Lett. **115**, 161302 (2015), URL https://link.aps.org/doi/10.1103/PhysRevLett.115.161302.

[25] *Neutrino Non-Standard Interactions: A Status Report*, vol. 2 (2019), 1907.00991.

[26] M. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, and N. Song, Astropart. Phys. **84**, 15 (2016), 1605.08055.

[27] M. Aartsen et al. (IceCube), Phys. Rev. D **97**, 072009 (????), 1709.07079.

[28] M. Gonzalez-Garcia and M. Maltoni, Phys. Lett. B **663**, 405 (2008), 0802.3699.

[29] M. Bustamante, J. F. Beacom, and K. Murase, Phys. Rev. D **95**, 063013 (2017), 1610.02096.

[30] P. B. Denton and I. Tamborra, Phys. Rev. Lett. **121**, 121802 (2018), 1805.05950.

[31] A. Abdullahi and P. B. Denton, Phys. Rev. D **102**, 023018 (2020), 2005.07200.

[32] P. Coloma, P. A. Machado, I. Martinez-Soler, and I. M. Shoemaker, Phys. Rev. Lett. **119**, 201804 (2017), 1707.08573.

[33] P. Coloma, Eur. Phys. J. C **79**, 748 (2019), 1906.02106.

[34] S.-F. Ge, M. Lindner, and W. Rodejohann, Phys. Lett. B **772**, 164 (2017), 1702.02617.

[35] B. Zhou and J. F. Beacom, Phys. Rev. D **101**, 036010 (2020), 1910.10720.

[36] J. Alvarez-Muniz, J. L. Feng, F. Halzen, T. Han, and D. Hooper, Phys. Rev. D **65**, 124015 (2002), hep-ph/0202081.

[37] M. Kowalski, A. Ringwald, and H. Tu, Phys. Lett. B **529**, 1 (2002), hep-ph/0201139.

[38] K. J. Mack, N. Song, and A. C. Vincent, JHEP **04**, 187 (2020), 1912.06656.