Non-standard neutrino interactions in IceCube

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Abstract. Neutrinos interact weakly with matter mediated by the W and Z bosons. For example, neutrino interactions with electrons in the earth interferes with the propagation of neutrinos, producing a measurable effect called the "MSW effect"[2]. These types of interactions are the "standard interactions" of neutrinos in standard matter. Some non-standard model theories predict the existence of heavy TeV-scale bosons. Recent ATLAS results have 3.4 sigma significance for a resonance in the diboson channel around 2 TeV [1], which could be caused by non-standard bosons interacting with matter. The neutrino interaction rate in matter would then fluctuate from the standard prediction due to interactions with these bosons in addition to the standard W and Z. Like the MSW effect, the fluctuation of neutrinos detected compared to those produced on the opposite side of the earth would be measurable. This analysis aims to measure this effect in the IceCube experiment using the event selection from the DeepCore three-year muon disappearance result. Because of the wide range of neutrino energies it can observe IceCube has the potential to set world leading limits for this measurement. The limits that can be set on the NSI parameters from interactions of muon neutrinos with non-standard bosons will be discussed.

1. Introduction
The standard model of particle physics is a theoretical framework that unifies the electro-weak and strong forces, used for decades to predict the behavior of fundamental particles and leading to the discovery of particles such as quarks, gluons and the W, Z and Higgs bosons. However, this model is unsatisfying because it fails to unify the electro-weak and strong forces with the gravitational force. Subsequently many 'grand unified theories' have been proposed to remedy this problem. One prediction of some of these 'non-standard' models are the existence of heavy TeV-scale bosons[6]. Particle physicists search for direct evidence of these particles with experiments like the Large Hadron Collider(LHC)[1].

Neutrinos can also be used to search for indirect signals for the existence of these TeV-scale particles. If these bosons mediated interactions with standard matter, then neutrinos could interact more strongly with these particles than the standard model predicts, and these interactions can potentially be flavor violating. These type of interactions are referred to as the neutrino 'non-standard interactions'(NSI)[6].

Neutrinos are produced in the atmosphere by the decay of particles, such as pions, kaons, and muons, produced in cosmic-ray interactions. By using these atmospheric neutrinos the Super-Kamiokande experiment was able to measure the disappearance of muon neutrinos produced in the atmosphere, and provide the first conclusive evidence for neutrino oscillations[4]. Neutrinos

1 http://icecube.wisc.edu
interact in flavor eigenstates and travel in mass eigenstates, meaning that a certain flavor of neutrino that is produced at the source may interact later as a different flavor. These neutrino oscillations are the only currently detected physics beyond the standard model.

This oscillation signal from atmospheric neutrinos is seen predominately at energies below 100 GeV. The signal predicted for the dominant muon neutrino NSI $\epsilon_{\mu\tau}$ has a smaller magnitude than the oscillation effect, but can be seen over a larger range of energies as seen in Figure 1. Therefore the optimal method for searching for an $\epsilon_{\mu\tau}$ NSI signal is to use a large range of neutrino energies, with the distinct signal of the combined effect of the NSI and oscillations in the low energy region, and the larger constraint of the high energy region where the NSI effect dominates.

2. The IceCube Detector
IceCube is a 1 km$^3$ detector embedded in the ice at the geographic south pole. The detector consists of 86 strings, each with 60 10-inch photo-multiplier tubes enclosed in glass spheres, called digital optical modules (DOMs). Of those strings 78 are separated by a distance of approximately 125m with DOMs on each string separated by 17m. An additional infill extension, DeepCore, consists of 8 strings separated by about 75m with DOMs on each string separated by 7m. Neutrino events are detected in the IceCube detector when neutrinos interact in the ice, producing particles that travel faster than the speed of light in the ice. These particles interact to produce light in the form of Cherenkov radiation that is detected by the DOMs. The number of such interactions, and therefore the distance over which the light is distributed, is dependent on the energy of the particles. Therefore more closely spaced DOMs will observe more light from lower energy events. For that reason the DeepCore extension extends the full range of the IceCube detector from PeV energies down to neutrino energies of about 10 GeV.

3. Neutrino Oscillations in IceCube
IceCube can measure neutrino oscillation parameters by looking for a deficit of neutrinos traveling through the earth and interacting in the detector. The survival probability for a muon neutrino with a certain energy $E_\nu$ traveling a certain distance $L$ through the earth can be calculated using the simple two-neutrino approximation

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2(\Delta m_{32}^2 L / 4E_\nu),$$

where $\theta_{23}$ is the mixing angle and $\Delta m_{32}^2$ is the mass difference. Because the largest disappearance signal is seen for neutrinos that travel the largest distance through the earth, the signal in IceCube peaks around 30 GeV, but the signal is measurable up to about 100 GeV as shown in Figure 1. In 2015 IceCube published a paper using the full three-neutrino survival probability calculation, which constrains the neutrino oscillation parameters to levels comparable with dedicated neutrino oscillation experiments [3]. This analysis uses 5174 events from three years of data taken with the full IceCube detector.

4. Non-standard Neutrino Interactions in Standard Matter
Non-standard neutrino interactions can be modeled as an additional term in the neutrino Hamiltonian, similar to the effect of the MSW term. The MSW effect is included in the neutrino Hamiltonian as a single potential that modifies the $\nu_e$ to $\nu_e$ component. Therefore it is affected by and affects any other process that affects the $\nu_e$ content, including standard oscillations. The potential $V_{CC}$ is proportional to the Fermi coupling constant $G_f$ and the density of electrons $n_e$

$$V_{CC} = \sqrt{2} G_f n_e.$$
Adding interactions with non-standard bosons to the Hamiltonian takes a similar form, but with additional components, as there are no current limits on the possible interactions that could be mediated by such bosons. Instead of a single flavor conserving term involving the $\nu_e$ to $\nu_e$ component, a term $\epsilon_{ij}$ scales all possible flavor violating and conserving $\nu_i$ to $\nu_j$ components in the $3 \times 3$ matrix. For the IceCube analysis we consider the non-standard interactions between neutrinos and d-quarks, so for this reason an additional factor of $n_d=3n_e$ (to account for the fact that d quarks are three times as abundant as electrons in the earth) is used instead of $n_e$ as in the case of the MSW effect. The total Hamiltonian is then

$$H_{3\nu} = \frac{1}{2E_\nu} U_{PMNS} M^2 U_{PMNS}^\dagger + V_{CC} \text{diag}(1,0,0) + V_{CC} \frac{n_d}{n_e} \epsilon,$$  \hspace{1cm} (3)$$

where

$$\epsilon = \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}. \hspace{1cm} (4)$$

Therefore adding the non-standard interaction terms adds an additional nine possible new terms to the Hamiltonian (allowing for the possibility that $\epsilon$ is not Hermitian). However,
for experiments like Super-Kamiokande and IceCube the terms that correspond to $\nu_\mu$ or $\nu_\tau$ interactions will dominate, because the atmospheric neutrinos are predominately $\nu_\mu$ that oscillate predominately into $\nu_\tau$ as they travel through the earth.

In a study by Super-Kamiokande in 2011\cite{7}, the NSI parameters $\epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ and $\epsilon_{\mu\tau}$ were studied using a two-neutrino approximation. Subsequently a phenomenological study predicted the sensitivity for these parameters using the IceCube one-year muon disappearance analysis\cite{8} and predicted the sensitivity of a future analysis using bins in both energy and zenith compared to the result from Super-Kamiokande. These limits are shown in Figure 3. As in the Super-Kamiokande study, we choose to only consider the dominant NSI terms, so the $\nu_e$ terms are set to zero, and the hermiticity of $\epsilon$ is also assumed, so the CP violating terms are neglected.

It can be shown\cite{6} that, to first order, the parameters $\epsilon_{\tau\tau}$ and $\epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ have an equivalent effect on the muon neutrino survival probability. The two-neutrino approximation can also behave strangely for small values of $\epsilon'$. Therefore the full three neutrino parameterization is used to calculate limits on the $\epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ and $\epsilon_{\mu\tau}$ parameters. This analysis uses the nuSQuIDS neutrino survival probability calculator\cite{5} because of the robust implementation of NSI and earth model effects.

Figure 3. Left: Predictions from the 2013 paper by Esmaili and Smirnov\cite{8} for IceCube sensitivity using data from the one year oscillation result\cite{9}(dashed line) and a projected future analysis using the DeepCore subdetector (DC) using a similar dataset but with both zenith and energy bins(solid line). These estimates are compared with the 2011 result from Super-Kamiokande\cite{7}(dotted line). Right: Current limits on the NSI parameters $\epsilon'$ and $\epsilon_{\mu\tau}$ using the event selection from the 2015 muon disappearance paper dataset. These limits are from simulation only and use no actual data. The sample was selected such that the reconstructed energy is between 6 and 56 GeV, with true energies less than 100 GeV. The distributions in energy and angle are shown in Figure 2. The analysis therefore also has the same energy and zenith resolution and systematics as in the 2014 muon disappearance paper\cite{3}.

To study the sensitivity to these parameters in IceCube, the study in this paper uses the event selection from the three-year muon disappearance result. These limits are from simulation only and use no actual data. The sample was selected such that the reconstructed energy is between 6 and 56 GeV, with true energies less than 100 GeV. The distributions in energy and angle are shown in Figure 2. The analysis therefore also has the same energy and zenith resolution and systematics as in the 2014 muon disappearance paper\cite{3}.
The contours are drawn with a Poisson likelihood test statistic with two degrees of freedom to compare with the Super-Kamiokande result, which drew contours with a Wilks’ Theorem assumption. Studies for this analysis show that actually the two physics parameters are strongly correlated for this event selection, and therefore there is effectively only one degree of freedom. The estimated constraints on the NSI parameters using this sample and the Wilks’ Theorem assumption are shown in Figure 3.

This result is comparable with the Super-Kamiokande limits for $\epsilon_{\mu\tau}$ over the full range of $\epsilon'$. The constraints on $\epsilon'$ are also stronger. Compared to the IceCube one year analysis the statistics for the low energy sample are about a factor of ten higher, but unlike the one year result there is no high energy sample. For that reason much of the sensitivity predicted in the phenomenological study for the $\epsilon_{\mu\tau}$ is lost. Figure 4 shows that the signal for $\epsilon_{\mu\tau}$ is largest in the region above 100 GeV. Therefore an extension of this study to include a sample of events above 100 GeV is planned.

5. Conclusions
Scientists predict the existence of physics beyond the standard model. Such physics could lead to a higher rate of neutrino interactions in standard matter. Experiments like IceCube and Super-Kamiokande, as well as future proposed experiments, have the potential to constrain these non-standard interactions (NSI) with greater precision than previous experiments.

The analysis presented here shows the potential power of the IceCube experiment to measure the NSI parameters using only a small sample of events in the lowest energy region, looking at the simulation used in the 2014 IceCube muon disappearance result. IceCube will continue to improve the constraints on the NSI in the future with larger datasets and by extending into the higher energy regions. With a full range of energies from 10 GeV to PeV energies IceCube has tremendous potential to produce world class limits on the NSI parameters.