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Non-standard neutrino interactions in IceCube

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Non-standard neutrino interactions (NSI) may arise in various types of new physics. Their existence would change the potential that atmospheric neutrinos encounter when traversing Earth matter and hence alter their oscillation behavior. This imprint on coherent neutrino forward scattering can be probed using high-statistics neutrino experiments such as IceCube and its low-energy extension, DeepCore. Both provide extensive data samples that include all neutrino flavors, with oscillation baselines between tens of kilometers and the diameter of the Earth. DeepCore event energies reach from a few GeV up to the order of 100 GeV - which marks the lower threshold for higher energy IceCube atmospheric samples, ranging up to 10 TeV. In DeepCore data, the large sample size and energy range allow us to consider not only flavor-violating and flavor-nonuniversal NSI in the $\mu - \tau$ sector, but also those involving electron flavor. The effective parameterization used in our analyses is independent of the underlying model and the new physics mass scale. In this way, competitive limits on several NSI parameters have been set in the past. The 8 years of data available now result in significantly improved sensitivities. This improvement stems not only from the increase in statistics but also from substantial improvement in the treatment of systematic uncertainties, background rejection and event reconstruction.

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1. Introduction

1.1 Neutrino oscillations in IceCube and DeepCore

The IceCube Neutrino Observatory is an ice Cherenkov detector located at the South Pole. It consists of 5160 light detectors, so-called Digital Optical Modules (DOMs), that have been deployed along 86 strings within a cubic kilometer of glacial ice [1]. When neutrinos interact with matter inside or close to the instrumented volume, IceCube detects Cherenkov light produced by charged secondary particles. Being optimized for the detection of cosmic neutrinos, the lowest energy at which individual events can be reconstructed in IceCube is $\sim$100 GeV. DeepCore is IceCube's low energy extension, consisting of a more densely instrumented volume at the detector center (see Fig. 1). For events occurring within this region, the energy threshold is lowered to approximately 5 GeV [2]. Atmospheric neutrinos in DeepCore are a great probe for matter effects on neutrino oscillation [3], as they cover the energy range from approximately 5 GeV to 300 GeV. Depending on the angle at which they traverse the Earth, oscillation baselines range between a few km for down-going trajectories and $O(10^4\,\mathrm{km})$ for up-going trajectories, crossing the entire Earth. Event samples of atmospheric neutrinos contain neutral current (NC) and charged current (CC) interactions of all neutrino flavors.

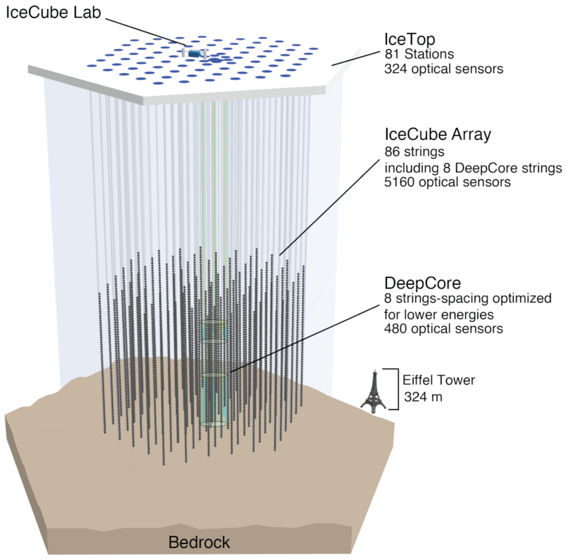

Figure 1: Layout of the IceCube Neutrino Observatory and its low energy extension, DeepCore (highlighted in green). Each dot represents a DOM, deployed within 1 km^3 of glacier inside the Antarcic ice sheet at depths between 1450 and 2450 m

1.2 Non-standard neutrino interactions

IceCube's sensitivity to neutrino oscillations allows us to probe matter effects from a number of beyond the standard model (BSM) scenarios, including non-standard neutrino interactions (NSI). We test for NC forward scattering between neutrinos of all flavors and charged fermions in Earth matter (up- and down-quarks, electrons), assuming the existence of a new heavy mediator particle. This is well motivated from theory, as NSI come up in a multitude of neutrino mass models [4]. By effectively introducing new degrees of freedom to neutrino oscillations, NSI effects might resolve tensions that are currently observed in measurements of standard oscillation parameters, such as δ_{CP} [5].

In an approach that is mostly independent from the underlying model and the mediator mass, the NSI-induced change to the matter potential can be parametrized with five effective coupling parameters:

$$H_{\text{mat}} = \sqrt{2}G_F N_e(x)\begin{pmatrix} 1+(\epsilon^{\oplus}_{ee}-\epsilon^{\oplus}_{\mu\mu}) & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & (\epsilon^{\oplus}_{\tau\tau}-\epsilon^{\oplus}_{\mu\mu}) \end{pmatrix}$$

The three flavor violating off-diagonal parameters, $\epsilon^{\oplus}_{e\mu}$, $\epsilon^{\oplus}_{e\tau}$ and $\epsilon^{\oplus}_{\mu\tau}$, are complex-valued. Subtracting $\epsilon^{\oplus}_{\mu\mu} \times \mathbb{1}$ yields two real-valued lepton universality-violating diagonal parameters, $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}$ and $\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu}$, thereby reducing dimensionality without observable consequences.

2. NSI analyses in IceCube

IceCube NSI analyses are being performed on multiple data sets, varying in choice of methods and investigated NSI parameters. This is motivated by how the sensitivity to different NSI signatures depends on event types and energies.

The atmospheric neutrino flux at GeV to TeV energies is dominated by muon neutrinos [6]. Together with IceCube's capacity to discriminate ν_μ CC events from others (see Sec. 2.1), this renders our data sets most sensitive to effects on ν_μ oscillation probabilities, $P_{\mu\alpha}$[1].

The impact of individual NSI couplings on single oscillation probabilities differs between the energy ranges at which IceCube and DeepCore can resolve individual neutrino interactions (see Fig. 2). IceCube events have energies above 100 GeV, making them almost exclusively sensitive to $\epsilon^{\oplus}_{\mu\tau}$. Similarly, for DeepCore event energies of approximately 5 GeV to 100 GeV, dominant effects are observed for $\epsilon^{\oplus}_{\mu\tau}$[7]. Current DeepCore analyses, however, are able to constrain all effective NSI parameters.

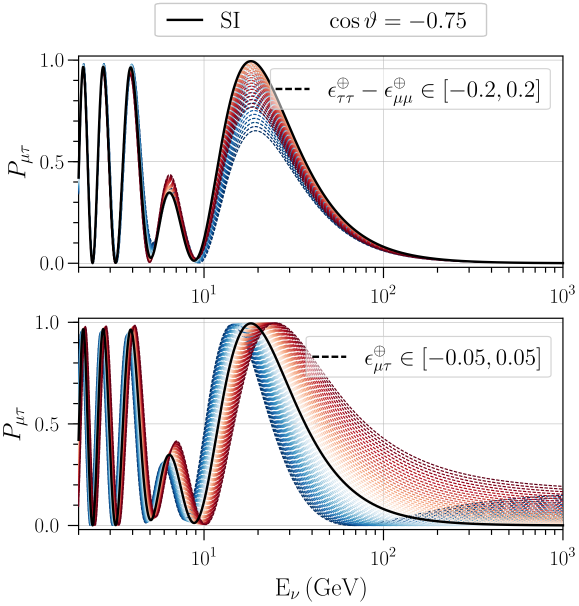

Figure 2: Examples of oscillation probabilities at different NSI hypotheses. Each panel shows $P_{\mu\tau}$ for different positive (in red) and negative (in blue) values of the individual NSI parameter together with the standard interaction oscillations (SI) case in black.

2.1 Analysis principle for DeepCore samples

In a typical DeepCore NSI analysis, binned data are compared to Monte Carlo (MC) simulated expectation templates, generated for a variety of NSI hypotheses. A metric based on the differences in event counts per bin is optimized or sampled to obtain the best-fitting NSI hypothesis and confidence intervals.

The binned quantities are the reconstructed energy of the events, the cosine of their zenith angle and their topology. The zenith angle corresponds to the oscillation baseline at which the neutrino

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[1] We use the term neutrinos for both neutrinos and antineutrinos and indicate arbitrary flavor as $\alpha \in [e, \mu, \tau.]$

traverses the Earth. The reconstructed event topology is based on a binned quantity, subdivided between more track-like and more cascade-like events. Track-like events are ν_μ CC interactions, with the secondary muon emitting light along its extended path through the detector. Any other neutrino interactions result in approximately spherical, cascade-like light deposition.

The analysis varies the NSI hypothesis being studied, as well as nuisance parameters for signal and background events, and detector characteristics [8]. Uncertainties in our understanding of the detector concern the efficiency of DOMs as well as the optical properties of the surrounding ice. Ice absorption and scattering characteristics differ between pristine glacial ice and the melted and re-frozen ice in which modules have been deployed. Signal nuisance parameters relate to the atmospheric flux of neutrinos, the oscillations they undergo and their interaction cross section.

3. Current prospects and results

While DeepCore samples allow for resolving the signatures of all NSI couplings at few GeV, analyses of IceCube events make use of the sensitivity of higher energy data to $\epsilon^{\oplus}_{\mu\tau}$ especially. A soon to be published analysis is based on the same data set as a recent sterile neutrino analysis [10], including ν_μ events at 500 GeV to 10 TeV from 7.5 years of IceCube data. Preliminary sensitivities to NSI imply globally competitive constraints on complex $\epsilon^{\oplus}_{\mu\tau}$ of -2.91 $\cdot$ 10^{-3} $\leq|\epsilon^{\oplus}_{\mu\tau}|\leq$ 2.93 $\cdot$ 10^{-3}.

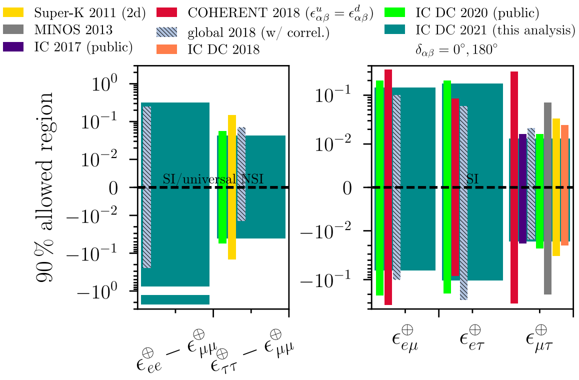

Figure 3: Limits on singly tested NSI couplings based on 3 years of DeepCore data, compared to earlier results [9].

3.1 Recent DeepCore results

A recently published analysis [9] was for the first time able to constrain all effective NSI parameters from a single IceCube sample, using the approach outlined in Sec. 2.1. It was based on three years of DeepCore data, including events of all flavors, from all zenith angles and with energies of 5.6 GeV to 100 GeV. In Fig. 3, the limits obtained from investigating all effective NSI parameters individually, while fixing all other NSI couplings to 0, can be found. This approach results in some model dependence, as it excludes any hypotheses with multiple non-zero NSI parameters. The reason why this approach is chosen is that keeping all NSI parameters free is not computationally feasible. In order to cover the full model space, a second part of the analysis was carried out using a different parametrization with three free parameters (generalized matter potential), yielding limits on the scale and structure of fully free NSI.

3.2 Upcoming 8 year DeepCore analysis

An analysis similar to the one performed in [9] is applied to 8 years of DeepCore data with an extended energy range with respect to earlier analyses of 5.6 GeV to 300 GeV. Preliminary sensitivities suggest significant improvement, specifically to the limits on $\epsilon^{\oplus}_{\mu\tau}$ (see Fig. 4), while sensitivity to the complex phases of flavor violating parameters remains low.

The improved sensitivity is not only due to the larger data set, but also to a multitude of refinements of the analysis tools and technique. An improved background rejection using Boosted Decision Trees (BDTs) results in a sample purity of 97% (compared to 95% in earlier DeepCore samples [3]), with ~3% of atmospheric muon events and negligible contribution of random noise hits of $< 0.03\%$ of the final sample. This is reached while keeping signal rates at ~1 mHz, improving upon earlier samples by approximately a factor of two.

A new reconstruction keeps the original approach of minimizing a tabulated likelihood, but reverses the process by starting at the individual modules and tracing photons back to their source. For topology classification, for the first time, BDTs are used. These measures result in an at least two times faster reconstruction and better resolution in all observable variables.

With the enhanced data set containing approximately $3 \cdot 10^5$ events, analysis techniques face unprecedented requirements in speed and optimization of computational resource usage. For SI analyses, these could be met through optimization of the established PISA tool [11]. For an NSI analysis of these data further revision of the analysis technique is required as the traditional approach through minimization of the parameter space is rendered computationally challenging due to the number and behavior of NSI parameters: fast and simple minimizers fail to resolve symmetries e.g. in the complex phases of flavor violating couplings. Additional complexity is introduced through the degeneracy of $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}$ with neutrino mass ordering (NMO) and vacuum-like oscillations behavior at $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} = -1$.

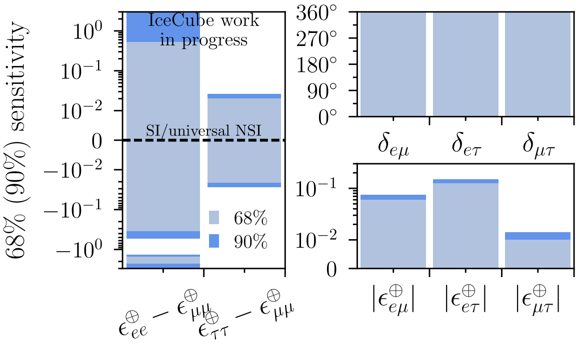

Figure 4: Preliminary sensitivities based on 8 years of DeepCore data to all NSI couplings, each evaluated singly.

Markov Chain Monte Carlo (MCMC) sampling of the parameter space in place of minimization has multiple advantages for this specific scenario: MCMC techniques are known to cope well with high dimensional space and yield the full parameter space profile and confidence limits in addition to the best fitting hypothesis. We use the emcee Python package [12], which allows for parallelization via openMPI. This promises to allow for simultaneous evaluation of all effective NSI parameter magnitudes.

3.3 On the horizon: The IceCube Upgrade

An IceCube low-energy extension, the IceCube Upgrade, consists of seven densely instrumented additional strings which will be deployed within the next several years [13]. Its increased sensitivity to low energy neutrinos owes to the increase in event rate as well as the Upgrade's capacity to observe individual events starting at ~1 GeV, resolving NSI signatures over a wider range. Calibration devices along the new strings will furthermore improve our understanding of detector systematics. As a result, the IceCube Upgrade will constitute a significant improvement in sensitivity to NSI effects.

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