Physics Potential of the IceCube Upgrade

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Abstract. The IceCube Neutrino Observatory is a cubic-kilometer Cherenkov detector at the South Pole. The planned Upgrade project, which consists of seven new strings, will be deployed with densely spaced optical modules to improve the neutrino detection capability at a few GeV level. The goal of IceCube Upgrade is to provide world-leading sensitivity to neutrino oscillations and to take unique measurements of tau neutrino appearance with high precision. It also serves as a R&D platform for the future IceCube-Gen2 experiment. The newly designed DOMs will provide improved detection efficiency and directional resolution for Cherenkov photons. Furthermore, new calibration devices will be introduced which will provide a better understanding of the ice properties, thereby reduce the detector systematic uncertainties. The resulting calibration improvement from the Upgrade will be applied to the entire archival data of IceCube collected for more than 10 years, with an expected improvement of the angular and spatial resolution of the detected astrophysical neutrino events. The Upgrade can be regarded as the first stage in the development of IceCube-Gen2, the next-generation neutrino telescope at the South Pole.

1. Introduction

The IceCube Upgrade is a proposed project which aims to improve the existing IceCube/DeepCore detector through new columns of optical sensors (called strings) with dense instrumentation of new/refurbished optical modules together with newly designed calibration devices. Figure 1 shows the proposed geometry of the IceCube Upgrade [1]. It consists of an instrumented volume of ∼2 Mtons with filled arrays of photosensors at a depth between 2150 m and 2425 m, which is referred to as the physics region, which is chosen such that the glacial ice is the clearest and the atmospheric muon background is low. The seven new strings will increase the light yield in existing denser region of the DeepCore detector. By decreasing the distance between IceCube strings even further to ∼20 m and vertical distance between optical modules to ∼3 m, the energy threshold can be reduced to as low as a few GeV level resulting in an improvement of the ability to reconstruct these events, thereby more accurate measurements of atmospheric neutrinos. As a consequence, IceCube will be able to perform measurements of atmospheric neutrino oscillations with world-leading sensitivities. Furthermore, studies show that the Upgrade can improve the sensitivities to dark matter searches, which could not be further discussed due to limited space.

1.1. The IceCube Upgrade Detector

The Upgrade will make use of two types of newly designed optical modules: the Dual optical sensors in an Ellipsoid Glass for Gen2 (D-Egg) [3] and the Multi-PMT Digital Optical Module (mDOM) [2]. PDOM, which is the optical module used in DeepCore, will also be refurbished and
The new optical modules have designs based on the successful DOM design used in IceCube, with improvements made to increase quantum efficiency and directional sensitivity. The PDOM is a high quantum efficiency DOM that is used in DeepCore [6]. Similar to the standard IceCube DOM, the PDOM contains a single downward facing 10” PMT. The PDOM also has improved electronics compared to the regular IceCube DOMs. The D-Egg contains two 8” PMTs, with one facing upwards and the other facing downwards [3]. This design provides additional directional sensitivity, enabling better atmospheric muon background rejection, and also allows for more accurate directional reconstruction. Its design is also optimized for the detection of UV Cherenkov photons as more Cherenkov photons are expected due to the inverse wavelength dependence of the Cherenkov radiation. The mDOM is made up of 24 3” PMTs. Its directional sensitivity and dynamic range are also increased compared to the single-PMT designs of the current IceCube DOMs. The mDOM has better directional coverage, with an almost isotropic sensitivity, allowing more accurate reconstruction of neutrino direction [2].

The new optical modules are expected to significantly enhance the resolution of reconstructed quantities and extend the science capability of the Upgrade array.

2. Science capability of the Upgrade

2.1. Precision measurements of $\nu_\mu$ disappearance and $\nu_\tau$ appearance

As mentioned before, the increased light yield with the Upgrade can lead to a more accurate event reconstruction in an energy range lower than the main energy range of DeepCore from $O(10 \text{ GeV})$ to a few GeV range. A consequence from this is an increase in reconstructable events, especially in the few GeV range (see figure 2 in [1] for details). Furthermore, a significant improvement in sensitivities for measuring $\nu_\mu$ disappearance and $\nu_\tau$ appearance is expected. Since the neutrino oscillation probabilities is dependent on $L/E$, with a decrease in $E$ and $L$ equal to the Earth’s diameter, the Upgrade can probe the first oscillation minimum for $\nu_\mu$ and $\nu_\tau$. However, a decrease in $E$ also decreases the energy range for reconstructable events, which can affect the precision of the measurements. Therefore, the determination of the oscillation parameters requires a careful analysis of the data, including the effects of background and systematics.
the first oscillation maximum for $\nu_\tau$ which are at approximately 25 GeV with an even higher precision compare to existing DeepCore, resulting from a much increased event rates and better reconstruction capabilities at the energy range relevant to oscillations. Figure 2 shows the Upgrade sensitivity projections for $\nu_\mu$ disappearance and $\nu_\tau$ appearance [1]. With one year of data-taking, the Upgrade will have the most precise measurement of $\nu_\tau$ normalization (where a value of 1 represents unitarity of the PMNS matrix). The enhanced sensitivity in oscillation analyses in the Upgrade is the result of both a larger signal sample and improved reconstruction performance in these events. Additional improvements of the shown results is expected from the new calibration devices [4]. Several new devices and strategies have been studied for the calibration of the ice [5] which will further improve the shown projected sensitivities.

2.2. Neutrino Mass Ordering (NMO) measurements in combination with JUNO
A study was performed on combined measurements of two future multi-purpose neutrino oscillation experiments, JUNO and the Upgrade. In the joint fit between the two experiments, tension occurs between their preferred mass-squared differences $\Delta m^2_{31}$ within the wrong mass ordering, allowing the latter to be excluded at high significance ($>5\sigma$) on a timescale of a few years, even under circumstances that are unfavorable to the experiments’ individual sensitivities. Figure 3 shows the time needed to obtain a significance of $5\sigma$ in a combined analysis of JUNO and the Upgrade at each true point of $\sin^2 \theta_{23}$. It is shown as a function of JUNO’s energy resolution since it is crucial to distinguish between the rapid small-amplitude variations of the $\nu_e$ energy spectrum. It shows the most favorable scenario is located in the lower right hand corner for both true mass ordering. For true IO it would take less than 3 years of measurement to reach the $5\sigma$ significance.
Figure 3. Time required for the combined analysis of JUNO and IceCube Upgrade to obtain a 5σ sensitivity of the NMO as a function of the true mixing angle $\sin^2 \theta_{23}$ and JUNO’s energy resolution, for true NO on the left and true IO on the right. The yellow square marks our nominal values about the two parameters. Solid contours trace parameter combinations for which the required time in years.

3. Towards the future IceCube-Gen2

The next-generation of neutrino telescope, IceCube-Gen2, is currently under development with the aim to expand the high energy limit up to EeV scale. It will consist of $\sim$8 km$^3$ of instrumented ice and an array of $\sim$1,000 optical sensors at the South Pole, which serves as an extension of the current IceCube detector. The neutrino point source sensitivity will be greatly enhanced with the IceCube-Gen2 detector. While the Upgrade will deliver compelling science on its own, as described in the previous sections, it will be also used for R&D of the future IceCube-Gen2. For example, the Upgrade is responsible for testing of prototype instrumentation for a full-scale development of the large IceCube-Gen2 array. Newly developed deep-ice drilling technology at the South Pole will improve the existing IceCube infrastructure for the next generation neutrino telescopes. Furthermore, in-situ sensitivity study of new sensors, current studies of narrow hole sensor design for significant cost reduction, and verification of large geometrical scale calibration techniques will be tested. IceCube-Gen2 is expected to fully operate by the end of next decade. As we enter a new era of multi messenger astronomy, it will enable us to resolve many unanswered questions about the evolution of the universe.

References

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