IMPROVING RECONSTRUCTION OF GEV-SCALE NEUTRINOS IN ICECUBE-DEEPCORE BY DIRECT EVENT SIMULATION

BY SARAH NOWICKI[1]

Sarah Nowicki <snowicki@ualberta.ca>, Department of Physics, University of Alberta, Edmonton, AB, Canada T6G 2G7, http://icecube.wisc.edu

NEUTRINOS AND THE ICECUBE OBSERVATORY

Detection of the weakly interacting neutrino is a challenging area of study that has emerged as one of the most exciting in modern particle physics. The discovery of a non zero neutrino mass through measurements of neutrino oscillations [1,2] has provided a truly intriguing scenario for particle physicists where extensions to the existing Standard Model [3] are necessary.

The IceCube Neutrino Observatory (see Fig. 1) is a cubic-kilometre-scale Cherenkov detector, instrumenting the deep glacial ice sheet near South Pole Station, Antarctica [4]. More than 5000 sensitive light detectors, known as photomultiplier tubes (PMTs), are deployed in a nearly hexagonal 3D array in some of the most optically pristine ice in the world [5]. Each of the PMTs is integrated into a digital optical module (DOM) comprising a glass pressure housing with on-board autonomous power and data acquisition [7]. The DOMs are distributed vertically along a cable or 'string', with 60 DOMs per string.

The detector is designed with DOM spacing according to specifically targeted physics goals. To detect cosmic neutrinos from high-energy astrophysical processes, the primary IceCube array of 78 strings has an average inter-string spacing of 125 m and 17 m vertically between DOMs, optimizing the sensitivity to energies beyond the TeV-scale. At the centre of IceCube a denser infill array (DeepCore) has been deployed [8], optimized to detect atmospheric neutrinos between ~5 and 100 GeV. DeepCore largely facilitates IceCube's particle physics program, in particular measurements of atmospheric neutrino oscillations.

SUMMARY

Real-time event simulation, to include a full description of the natural ice, holds the potential to improve event reconstruction in the IceCube Neutrino Observatory.

ICECUBE EVENTS AND RECONSTRUCTION

When a neutrino undergoes a charged-current interaction with an atom in the ice within or near the IceCube detector array, a charged lepton of the same flavour is produced. These leptons will then emit their energy, including production of Cherenkov photons, as they traverse the detector. The topology of the particle's charge deposition is characteristic of the flavour and interaction type. As shown in Fig. 2, the detected neutrino interactions have two distinct types: 'cascades', related to electron-type, most tau-type and neutral-current interactions where an approximate spherical charge-deposition is observed; and 'tracks', related to muon-type charged-current interactions. The light generated in the energy deposition is then detected by the IceCube DOMs. At high energies, beyond the TeV scale, where many thousands of photons are detected, the event characteristics are largely evident by eye. Energies relevant for studies of neutrino oscillations however, 0 (10 GeV), result in only tens of detected photons on average. In either case, reconstruction of the event characteristics is crucial to extracting the physics of interest.

IceCube event reconstruction is in general concerned with the extraction of two key parameters of the neutrino: its energy and direction. The existing standard IceCube reconstructions predict the amount and timing of the deposited charge in the detector for a given event hypothesis. This expectation for the photon distribution relies on a tool known as 'photon look-up tables' [9]. These tables consist of pre-generated templates describing photon detection probabilities for a fixed event type in a given location of the detector.

Scaling and/or a superposition of these templates is used to predict the charge amplitudes for any event hypothesis. The glacial ice that makes up the detector medium is modelled in discrete, horizontal layers, each with its own scattering and absorption coefficients. The photon look-up tables are therefore specific to the assumed ice model. Advanced study of the ice has demonstrated the

1. Sarah Nowicki received 2nd place in the CAP Best Student Poster Presentation competition at the 2018 CAP Congress at Dalhousie U.

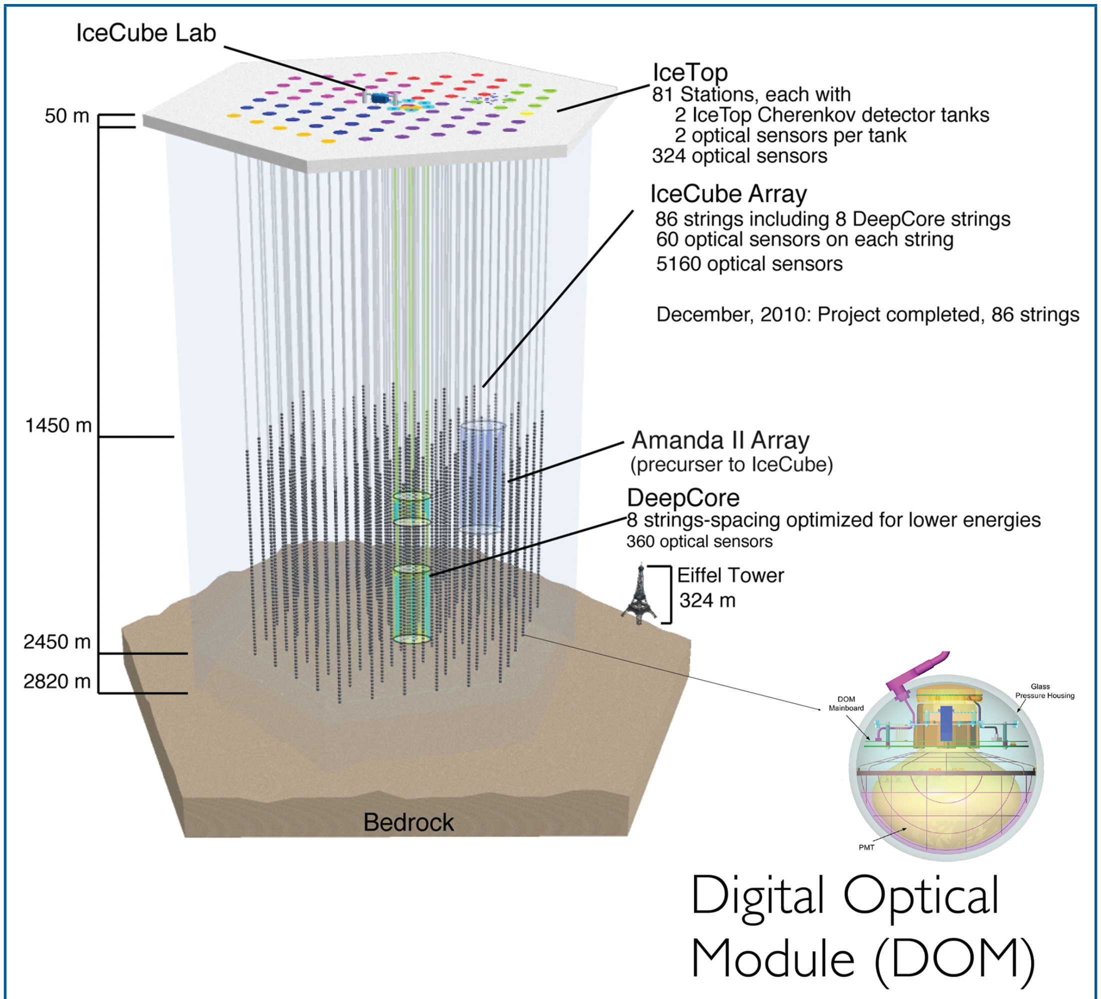

Fig. 1 Artist's concept of the IceCube Neutrino Observatory [6]. IceCube is composed of three primary detector arrays. The primary in-ice array, targeting astrophysical neutrino measurements, instruments more than a cubic-kilometre of the glacial ice sheet 1.5 km below the surface at South Pole Station. The DeepCore array extends the scientific reach of IceCube to neutrinos near 5 GeV. IceTop, deployed at the surface above the IceCube array, operates as a large-scale cosmic-ray air shower detector for the facility. Credit: IceCube Collaboration.

complexity of this natural medium [10], including calibration measurements that have identified a tilt in the modelled layers across the detector volume and a directional anisotropy in the scattering and absorption properties [11]. Describing these ice model elements in the photon look-up tables requires increasing their dimensionality, limiting both the ability to produce and utilize the tables on large-scale computing clusters. In addition, the optical properties of the re-frozen ice near the DOMs may differ substantially from the surrounding medium. The characterization of the re-frozen ice and its incorporation into the event reconstruction remains an outstanding challenge.

RECONSTRUCTION BY DIRECT SIMULATION

One path to overcoming the challenges encountered in IceCube event reconstruction is to directly simulate the event hypothesis on the fly utilizing the most advanced ice models. This method, called DirectReco, removes several assumptions built into the predictions obtained using the photon look-up tables and proves particularly useful in evaluating the impact of systematic uncertainties associated with the ice model. The DirectReco algorithm is based on several existing reconstructing tools that compare the expected and observed charges in a given DOM via a maximum likelihood calculation. One of the inherent limitations in this method, however, is the statistical fluctuations that can arise when comparing the DirectReco charge predictions to those from the photon look-up tables, that are derived by averaging the effect of nearly 75 million photons. This limitation is mitigated by re-simulating an event many thousands of times, ultimately producing statistics of similar order to those in the photon look-up tables. At the final stage, a modified Poisson

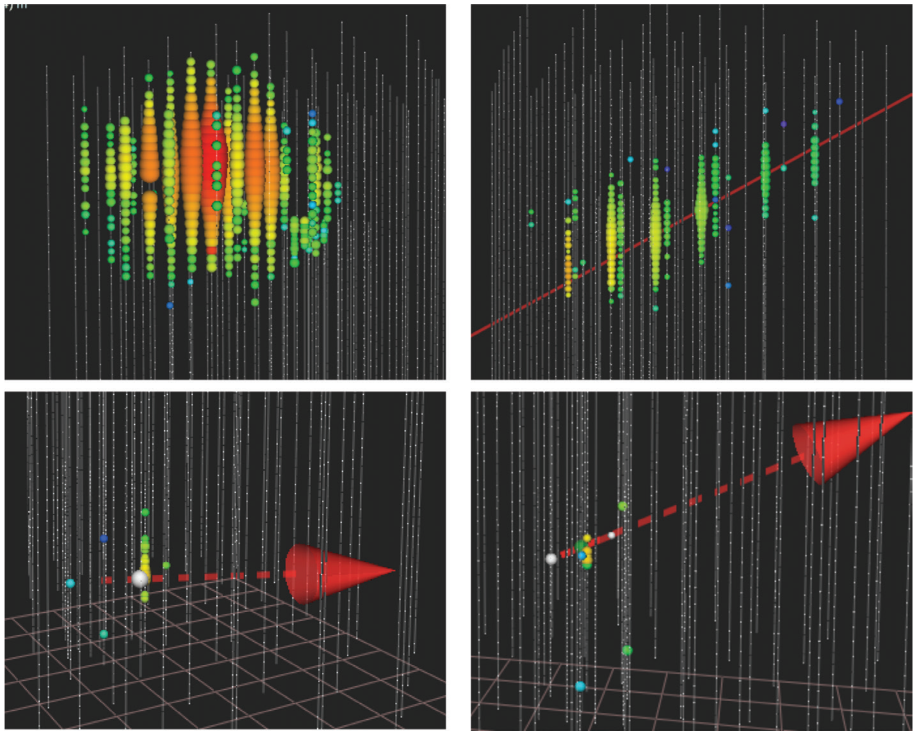

Fig. 2 Examples of IceCube events. (Top) High energy event displays: (Left) an ~1 PeV cascade-type; and (Right) an ~340 TeV muon-type. (Bottom) Low energy event displays: (Left) 30 GeV cascade-type; and (Right) 30 GeV muon-type.

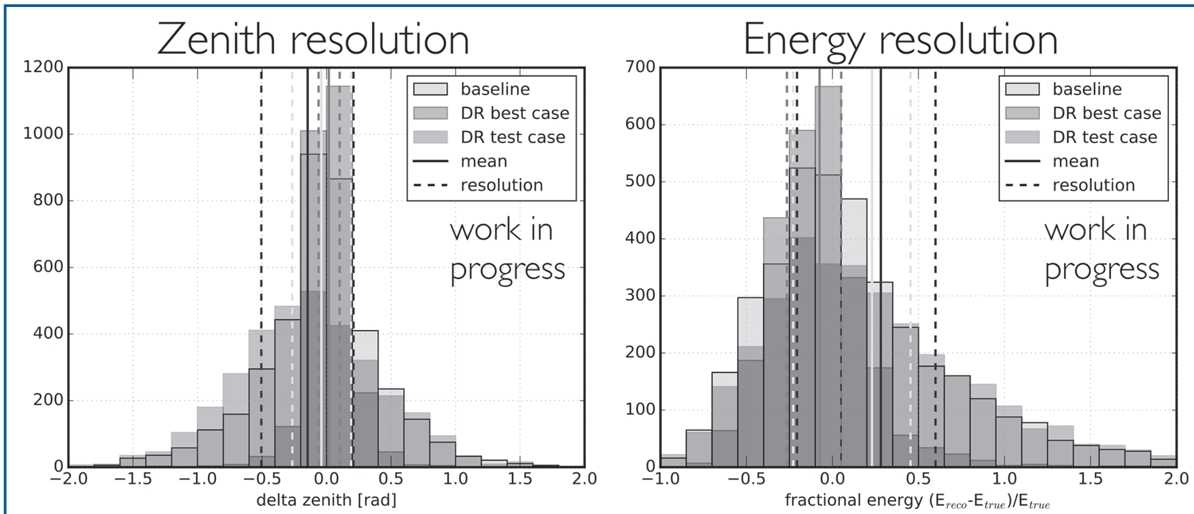

Fig. 3 Initial benchmark test of the DirectReco algorithm for 'low-energy' IceCube DeepCore simulation events. The reconstructed neutrino parameters for the zenith direction (Left) and energy (Right) are evaluated. Note that the current IceCube best reconstruction (baseline) is shown in yellow. DirectReco output, seeded with the event's true information, is shown in blue and represents a 'best case' output of the fitter at this stage of the development. Also shown in purple is the DirectReco result when seeded with the same values as those used in the baseline fit. The mean (solid vertical lines) and the 25 – 75% quantile (dashed vertical lines) for each of the distributions are shown in the related colours.

likelihood [12] is applied to account for any remaining statistical fluctuations in the reconstruction calculation.

To benchmark this method, ~4000 final analysis-level simulated events over the energy range of 1 GeV to 1 TeV were reconstructed with the DirectReco algorithm. Figure 3 shows the substantial improvement in the event reconstruction made possible with DirectReco, in particular for the resolutions of the reconstructed zenith angle and energy of the simulated neutrinos. Since these observables affect the sensitivity of IceCube to neutrino oscillation physics, DirectReco is expected to produce corresponding improvements to the constraints on oscillation parameters. The improvements to IceCube's constraints on neutrino oscillations will be discussed in a future publication.

One of the remaining long-term challenges for the DirectReco fitter in replacing the standard method using photon look-up tables is the time required to propagate sufficient photon statistics for the full event dataset. In particular, as steps are taken to optimize the resolution achieved with the DirectReco fitter through an iterative process, the event reconstruction time may dramatically increase. This remains a work in progress for the study, with the current mean reconstruction time of $0(100)$ s, similar to that of the current baseline reconstruction for the low-energy events.

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