The Angular Resolution Of The IceCube Neutrino Observatory

DESY Summer Student Programme, 2016

Samuel T. Spencer

University of Durham, United Kingdom

Supervisor

Jakob van Santen

September 5, 2016

Abstract

We present a method for testing the angular resolution of neutrino cascade events in IceCube using atmospheric muon data. We demonstrate that the detector has an angular resolution of order 30 degrees at neutrino energies of 10TeV, and discuss the possible implications for future research.

Contents

1 Introduction

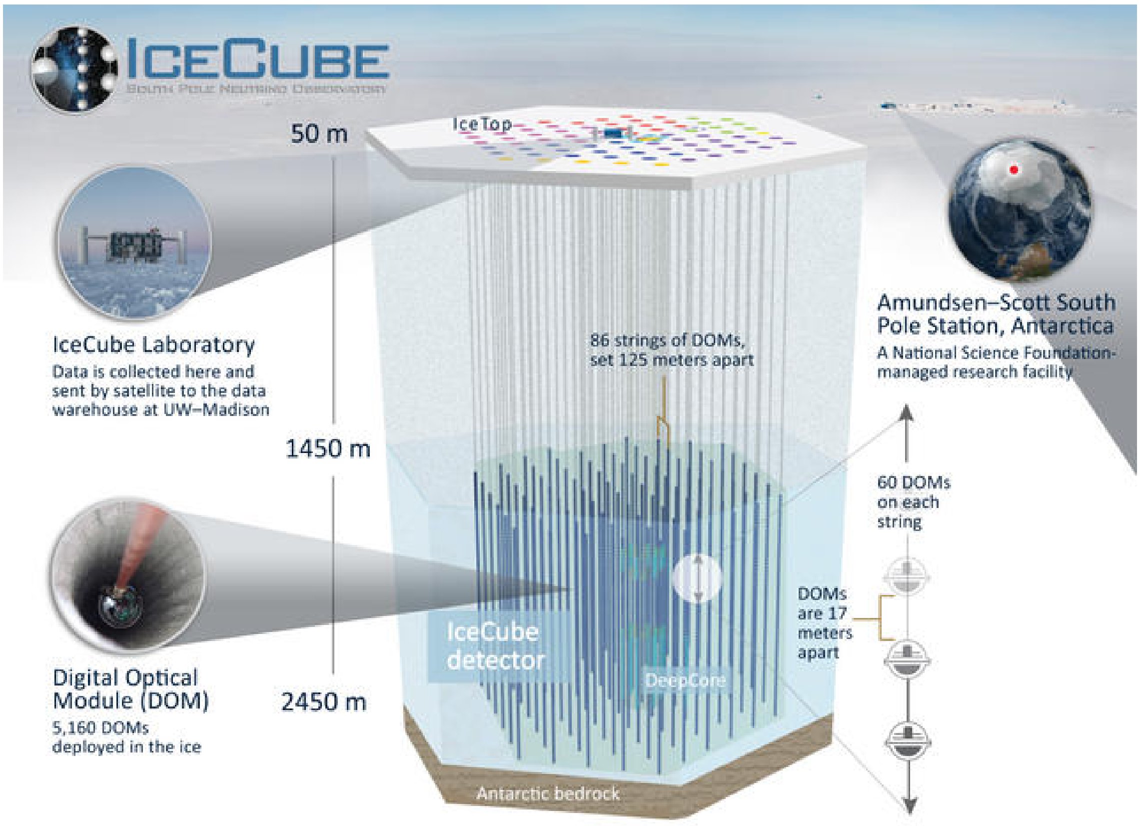

Figure 1: Graphic showing the IceCube 86 detector, used to generate the two datasets used in this report . Image courtesy of the IceCube Collaboration.

The IceCube neutrino observatory is a particle detector built into a cubic kilometer of ice located near the geographic south pole. The current configuration [1] of this instrument consists of 5160 Digital Optical Modules (DOMs); these contain downward-facing photomultipliers which detect the Cherenkov light emitted when charged particles travel through the ice at speeds higher than the local speed of light. Research highlights for the collaboration so far include the first ever detections of PeV energy astrophysical neutrinos [2], constraining the flux of cosmic neutrinos to greater precision than ever before [3], and the first measurements of cosmic ray anisotropy in the southern sky [4].

Neutrino events detected by IceCube fall into two broad categories: 'cascades' are caused by ν_e charged-current weak interactions with the ice, along with neutral current weak interactions of all flavours. Alternatively, 'tracks' are generally muons created by ν_μ charged current interactions, but which pass selection as neutrino events based on the position and angle of the track (from which one can infer the existence of the neutrino as only they can penetrate through the entire Earth) [5]. Simulations suggest [5] that the ability of the current 'Icetray' software suite to reconstruct the energy of cascades is relatively good compared the ability to reconstruct the energy of tracks, since in cascades the entirety of

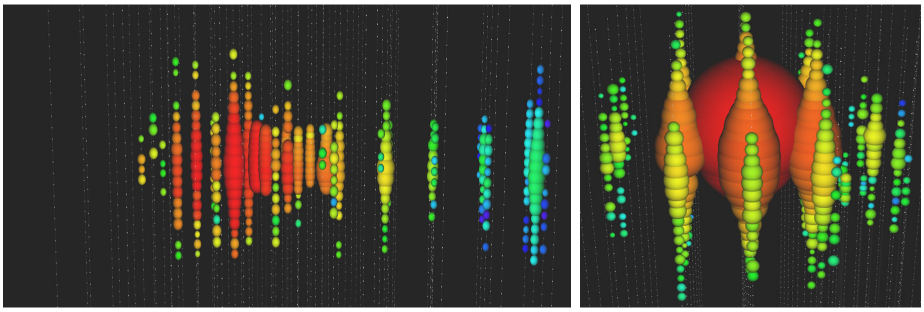

Figure 2: Left: A neutrino track event in the detector. Right: A neutrino cascade event in the detector. Images courtesy of the IceCube collaboration.

the energy lost by the neutrino is generally contained within the detector. In contrast, these simulations suggest that the ability of the reconstruction software to infer the direction of a neutrino in a track event is superior when compared to a cascade event, since the trajectory of the resultant muon is clear. Quantifying the angular resolution of cascade events is of key importance; both as a first step towards point source resolution (in the same vein as HESS), and in determining the physics behind the production of neutrinos. Even demonstrating that IceCube has a 20° angular resolution at sufficiently high energies would be significant, since this would aid searches for neutrinos originating in gamma-ray bursts [11].

When it comes to testing the ability of IceCube to reconstruct the angle of incoming neutrinos in cascade events with real data rather than simulation, one has the problem that a calibrated source of neutrinos that could be fired into the detector at varying angles does not exist. However, there exists a large (nearly isotropic) flux of atmospheric muons which we posit can be used as an effective substitute. Whilst studies have been performed to quantify the angular resolution of the detector using muon data before, most notably in [6], these studies focused entirely on track events. This report presents, for the first time, an approach to quantify the angular resolution of neutrino cascade events using muon data.

2 Theory

2.1 Reconstruction Methods

With a Cherenkov light detector, one can not measure the energy of a particle directly. Instead, in IceCube, we reconstruct the energy of a particle in the ice using the relation

$$q_j = \Lambda_{ji} E_i + \rho_j \tag{1}$$

where q is a vector containing the charges detected by the DOMs (which is what is actually measured), Λ is the 'response matrix', E is the proposed energy deposited by the particles, and ρ is a vector representing the noise in the detector. The response matrix and noise vector cannot be determined analytically, and must instead be constructed numerically though a mixture of Monte-Carlo simulations and testing of the ice using the calibration LEDs built into the detector [7].

As there is an inherent statistical randomness involved in the detection of the light, we cannot solve equation (1) directly, and must instead maximize the likelihood of E. In assuming the charges in the DOMs are Poisson distributed, the likelihood $\mathcal{L}$ for a charge q resulting in a number of detected photons k is given by

$$\mathcal{L}_j = \frac{q_j^{k_j}}{k_j!} e^{-q_j} \tag{2}$$

which substituting in equation (1) becomes

$$\mathcal{L}_j = \frac{(\Lambda_{ji} E_i + \rho_j)}{k_j!} exp(-\Lambda_{ji} E_i - \rho_j) \tag{3}$$

[5]. In practice, it is easiest to find the most likely charge distribution by taking the logarithm of $\mathcal{L}$ (due to the large numbers involved). One then sets the derivative of the sum over all the DOMs' $log(\mathcal{L})$ to zero in order to find the most probable q vectors. Equation (1) can then be inverted (subject to the constraint of positive energy) using numerical linear algebra techniques [5] [7] in order to obtain the most probable E for every DOM. One can then infer the direction of an incoming muon track by repeatedly applying the energy reconstruction at different incident track angles and again maximizing the likelihood [7] function.

Currently, all of this analysis is performed on tracks seen in IceCube using an algorithm called Millipede. Similarly, the algorithm used to reconstruct cascades in IceCube is called Monopod, and this is a modified version of Millipede designed to take test the hypothesis of a single cascade event. As muons can be seen in the detector to create both tracks and cascades, we posit that by isolating the track and the cascade events in a real muon detection, one can create a sample of neutrino-like cascades for which the true incident angle is known. These isolated muon cascades could therefore be a useful substitute for neutrino-induced cascades.

2.2 Determining angular error

There are two methods for determining the angle between two vectors in spherical polar co-ordinates, such as the directional vectors fitted to the track and cascade in this report. The first method is using the Haversine formula, given by:

$$hav\left(\frac{d}{r}\right) = hav(\phi_2 - \phi_1) + cos(\phi_1)cos(\phi_2)hav(\lambda_2 - \lambda_1) \tag{4}$$

where the Haversine, $hav(\theta) = sin^2(\frac{\theta}{2})$, $\frac{d}{r}$ is the central angle between the two vectors, and ϕ and λ are the longitudes and latitudes of the two vectors.

Alternatively, one may use the conversion functions for spherical polar co-ordinates on the unit sphere

$$x = sin(\phi)cos(\lambda) \tag{5}$$

$$y = sin(\phi)sin(\lambda) \tag{6}$$

$$z = cos(\phi) \tag{7}$$

and find the angle between the vectors using the conventional cartesian scalar product formula (as the choice of a zero angle is an arbitrary one when taking the difference between two vectors). Our initial investigations focused on using the Haversine formula, however we discovered that this does occasionally cause numerical precision errors when the Haversine of an angle is close to one, and as such we later used the cartesian conversion.

3 Method

3.1 Datasets Used

The results presented in this report come from four datasets. The first two, derived from four years of IceCube muon data from 2012-2015 (using the IceCube86 detector configuration), differ only in the extent of cuts applied to data. The LOWCUT data sample consists of those fully reconstructed events during this period with a cosine of the zenith angle less than 0.1 (i.e. down going in the detector), with a track length of more than 600m and a fitted cascade energy greater than 30 TeV. The GOFCUT data consists of the LOWCUT sample with further cuts to ensure the muon has high stochastic losses along the track, and requires than the peak energy in the event was a factor of at least ten higher than the median, with a normalized median energy greater than 0.2. Additionally the cascade fit must include more than 40 DOMs and the standard deviation of the cascade energy must be less than 30TeV.

In our final two datasets, one (SIMULATED) consisted of simulated muons generated using CORSIKA [8], and the other (NUE) of simulated ν_e generated with NEUTRINO-GENERATOR [11]. The simulated Muon set had the same cuts applied to it as the LOWCUT sample, whereas the simulated Neutrino set did not include the cut on track length (since neutrinos are uncharged and do not directly produce tracks). In all our datasets, we mandated that the Monopod fit must fall within the detector, and as such not have any single detector co-ordinate with a magnitude greater than 400m. Additionally, we also excluded DOMs from the analysis which were saturated with charge in order to improve the quality of the fits.

3.2 Causal Hit Selection

Our first approach to separating cascades and tracks was to use a position vector fitted to the cascade to seed a causal hit selector. This retains all observed photons within the radius of a sphere expanding from the position vector at the speed of light, and discards the rest. Similarly, acausal hit selectors pass the inverse events. We can then apply a Monopod fit to the causal energy depositions and a Millipede fit to the track, and use the aforementioned techniques to find the angle between the resulting two directional vectors.

Unfortunately, we found that this approach repeatedly returned median angular errors of order 3 degrees for all of our muon datasets (the test sample taken from the GOFCUT dataset shown in Fig. 3 had a median angular error of 2.96 degrees and a standard deviation of 0.57 degrees), far better than expected for neutrino events. We believe that this was a result of residual Cherenkov light from the incident muon being entangled with the cascade, and as such breaking the cascade's symmetry. This provided an Monopod

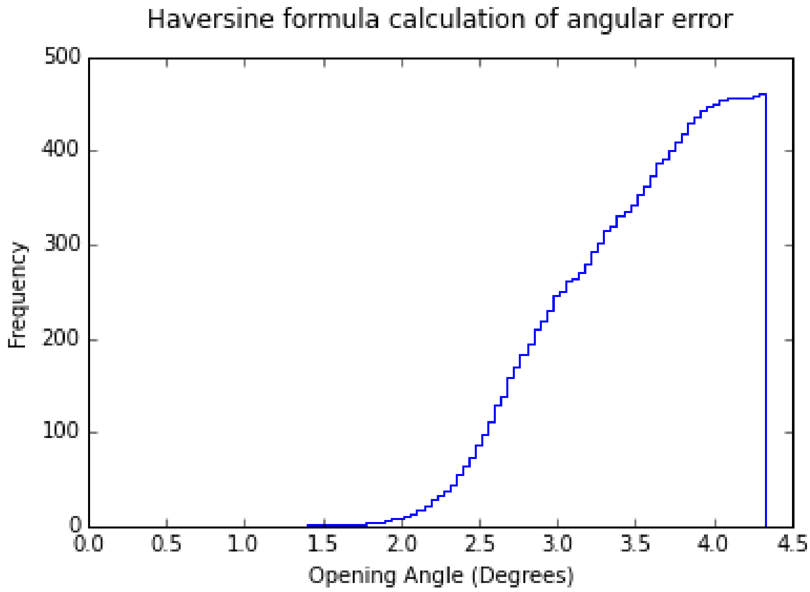

Figure 3: Cumulative histogram showing the results of the Haversine formula calculation of the angular error from a test sample of 461 muon events from 2014 data, which has been fitted using causal hit selection.

with a preferential direction on which to seed the directional reconstruction, and as such accounts for the discrepancy between these results and the expectation from the literature for neutrinos [5]. As such, we investigated alternative methods of separating the track and the cascade.

3.3 Removal of Residual Muon Track Light

Given the disagreement between our initial results and the simulations of [5], we opted to modify the Monopod fitting routine (developed for neutrino events) to account for additional Cherenkov light that might be emitted by the high energy incoming muon, which might be incorrectly fitted as being part of the particle cascade. This light would not be present in a neutrino event as the incident neutrino would be uncharged.

In order to remove this light, instead of using a causal hit detector to separate the cascade and the track, we removed all energies detected along the track within a 150ns (approximately 100m) window around the most energetic event in the vector representing E for our Monopod reconstruction. Additionally, the q vector that resulted by applying (1) to this E was then passed to the monopod cascade reconstruction as an addition to its ρ term by modifying the source code of the fitting routine.

4 Results and Discussion

4.1 Neutrino Simulation

As an initial test of our code, we found the opening angle between a Monopod fit to our simulated Neutrino cascades, and the true incident angle of the neutrino (found by selecting the most energetic neutrino from the simulation Monte-Carlo tree). The final sample consisted of 52366 events, with a median angular error of 32.2 degrees and a standard deviation of 33.7 degrees. As expected, and demonstrated in Fig. 5, the angular error shows an energy dependence, with superior angular resolution at higher energies. These results are in reasonable agreement with the findings of [5].

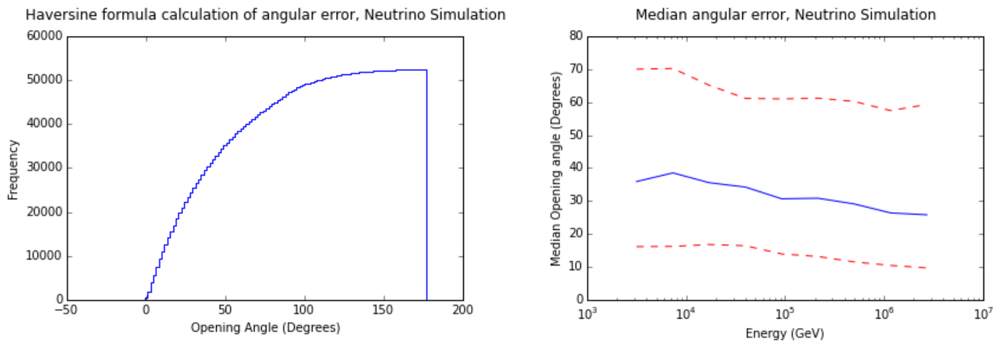

Figure 4: Left: Cumulative histogram showing the results of the Haversine formula calculation of the angular error in the Neutrino simulation. Right: Plot of median opening angle (blue line) against energy using 10 logarithmically spaced energy bins. 25 and 75 percentile lines are also shown (red dashed lines).

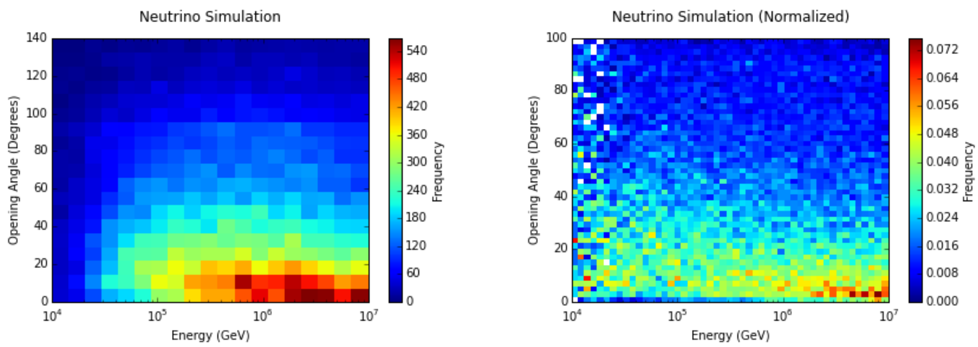

Figure 5: Left: 2D Histogram of opening angle and energy. Right: As left, but normalized by column in order to show energy dependence.

4.2 Muon Data and Simulation

Run	**Median**	σ	**Samples**
GOFCUT	43.6	60.0	787
LOWCUT	86.9	48.9	3228
SIMULATED	89.5	82.9	1315

Table 1:Table showing the angular errors for the various runs.

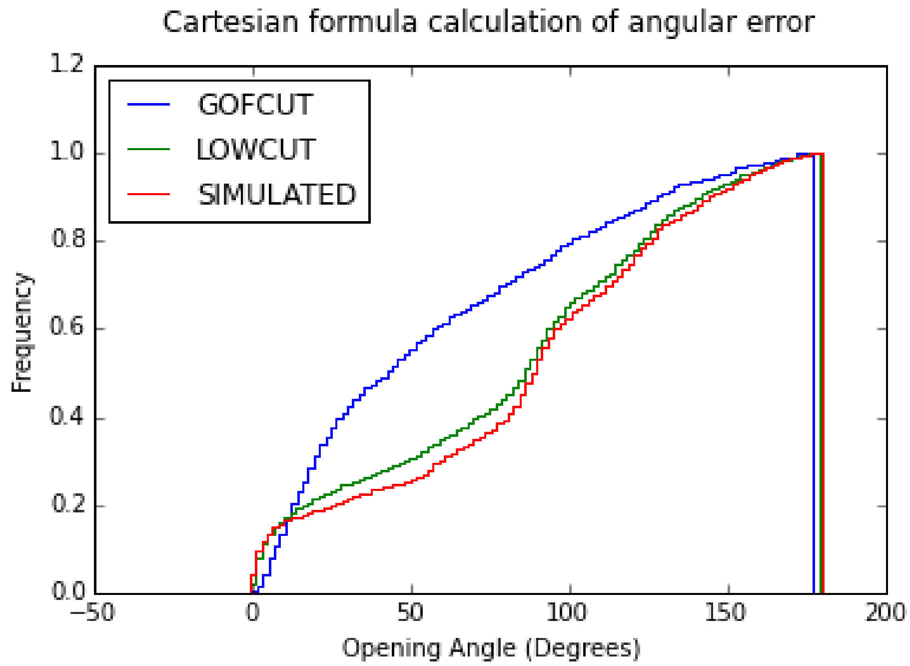

Figure 6: Cumulative histogram (normalized to unity) showing the various Muon run results.

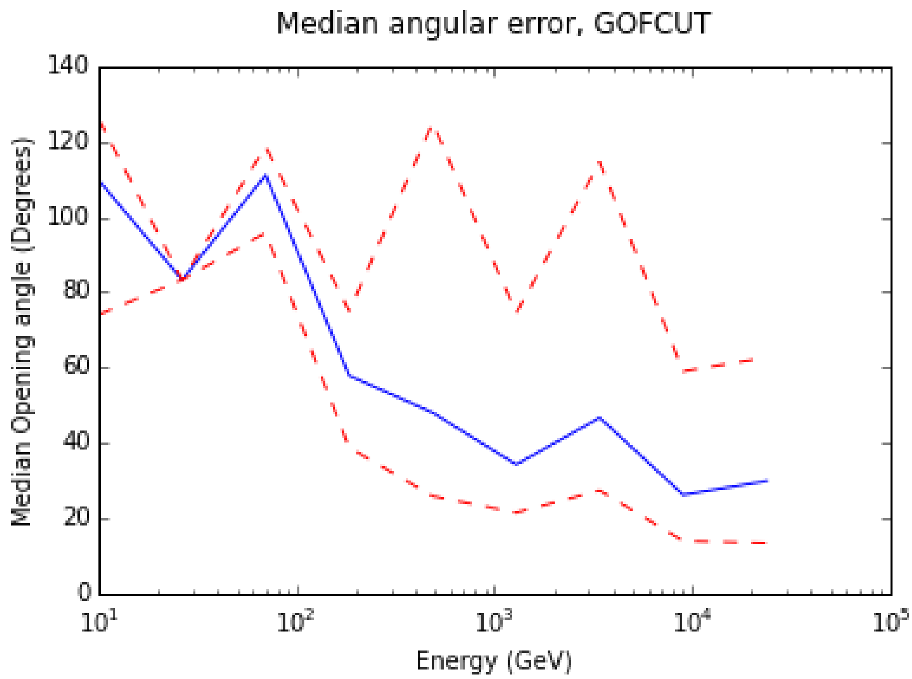

Figure 7: Median angular error (blue line) as a function of energy for the GOFCUT run in 10 logarithmically spaced energy bins. 25 and 75 percentile lines are also shown (red dashed lines).

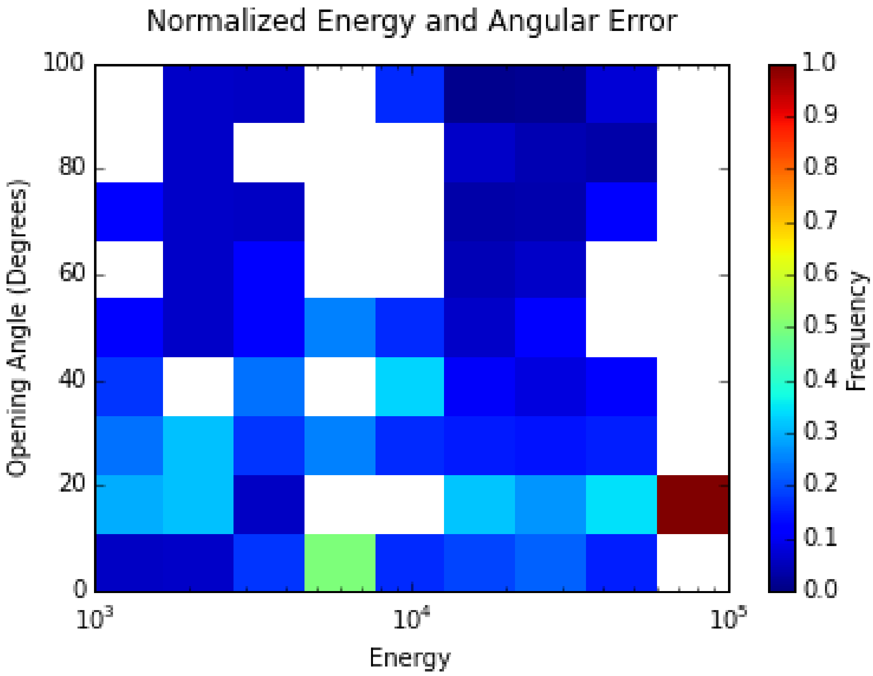

Figure 8: 2D Histogram (normalized by row) of Angular Error and Monopod Energy in the GOFCUT run.

From our results, it is clear that the best angularly resolved muons are those with high stochastic losses, and as such it is the GOFCUT dataset that we will focus on forthwith. That said, the agreement between our LOWCUT and SIMULATED muon datasets is very good, suggesting that CORSIKA is highly effective at simulating incoming muons. Whilst at first glance, the GOFCUT results (with their higher median) might appear in tension with the neutrino simulations, they are in fact consistent in angular error. The reason for this is the absence of muon events that pass GOFCUT selection with energies greater than 10^5 GeV. One possibility is an increase of the stopping power of the ice at such energies preventing down going muons of these energies from reaching the detector [10], but it is more likely that these muons flood the detector with light to the extent that they do not pass the statistical cuts necessary to determine the direction of the cascade well. Still, as can be seen in Fig. 8, our results show that angular errors between 10 and 20 degrees are possible for muons with energy of order 100TeV. As with the neutrino simulations, the muon angular error exhibits a clear energy dependence, consistent with expectations.

4.3 Result Verification

In order to verify whether our attempts to remove the muon track light from the cascade events were actually successful, we compared our results to a test muon run which used the same fitting routine as our data, but without the cascade light passed to the Monopod fitting routine. In doing this, we hoped that the angular error measured would significantly increase as Monopod would ,in theory, no longer have any light from which to seed the directional reconstruction. We also seeded the cascade reconstruction with a random number generator in this case and increased the number of monopod iterations to 10 in order to clearly highlight any potential bias. In order to seed a uniform distribution of points in spherical co-ordinates, one cannot simply generate a random distribution of zenith and azimuth angles over $[0, \pi]$ and $[0, 2\pi]$ respectively. This is because the Jacobian determinant in spherical co-ordinates has a ϕ dependence. Instead, where U and V are uniform random distributions of points over the range $[0, 1]$, one can generate a random distribution on the surface of a sphere by letting

$$\theta = 2\pi * U \tag{8}$$

$$\phi = arccos(2V - 1) \tag{9}$$

[9]. In performing this, we found that the median angular error from the test set with the most energetic event along the track removed was 47.2 degrees with a standard deviation of 48.5 degrees, whereas without this event removed the angular error deteriorated to a median of 100.0 degrees with a standard deviation of 48.5 degrees. Whilst the results are not as good with this random seed, the clearly show that removing the most energetic event along the muon track has a significant effect on the angular resolution, and as such demonstrates that the residual muon track light will have a minimal influence upon the directional reconstruction in the cascade.

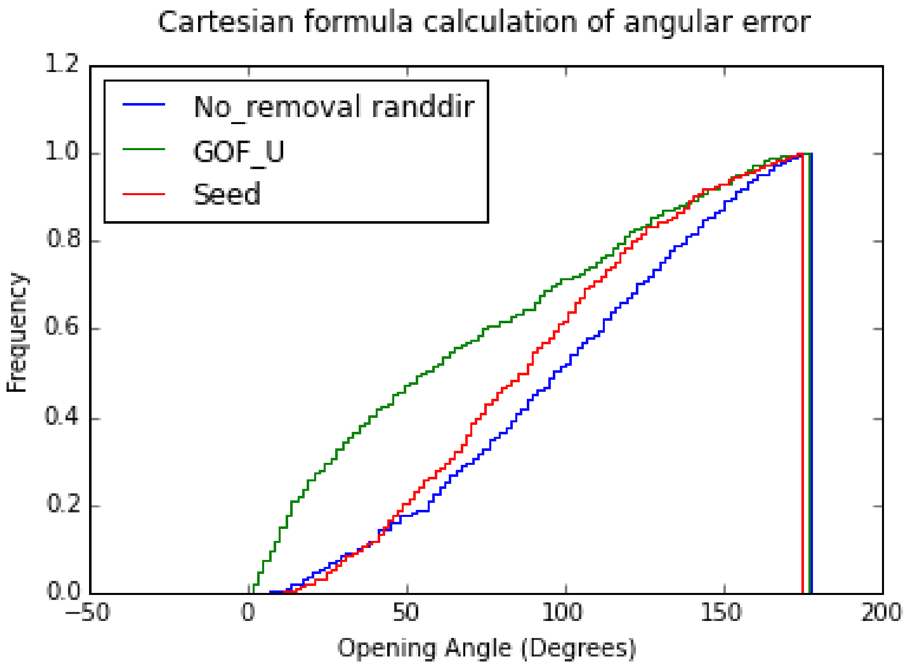

Figure 9: Cumulative histogram (normalized to unity) with 461 events showing the verification test run results from data both with (green) and without (blue) the largest energy deposition along the track removed. The angle between the detector axis and the random seed vector is also shown (red).

5 Conclusions

Whilst a 20 degree angular resolution would be considered unusable for conventional telescopes, our evidence that such detections are possible with IceCube is a clear step towards true point source detection in neutrino astronomy. Additionally, it opens the possibility of conducting studies using data from Gamma-Ray Bursts combined with astrophysical neutrino detections in order to constrain the acceleration methods in such events further by using timing arguments. Furthermore, the method used here to verify the angular resolution of neutrino detectors using muon events could easily be replicated on future neutrino telescopes (such as Km3net or IceCube Gen-2) to verify their angular resolutions.

Acknowledgements

The author thanks J. van Santen for patient advice and guidance throughout the project, and H.P. Bretz for help with the muon simulations. Additionally, the author is grateful to DESY for the opportunity to perform this research, and financial support; in particular G. Maier and K. Vaschen for organizing the Zeuthen summer student program.

References

[1] The Ice-Cube Gen 2 Collaboration (2014) *'IceCube-Gen2: A Vision for the Future of Neutrino Astronomy in Antarctica'*. Available at: https://arxiv.org/abs/1412.5106

[2] The IceCube Collaboration (2013) *'Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector'*. Science **342** Issue 6161

[3] The IceCube Collaboration (2013) *'Probing the Origin of Cosmic-Rays with Extremely High Energy Neutrinos Using the IceCube Observatory'* Phys. Rev. **D88** 112008

[4] The IceCube Collaboration (2010) *'Measurements of the Anisotropy of Cosmic Ray Arrival Detections with IceCube'* Available at: 'http://arxiv.org/abs/1005.2960'.

[5] The IceCube Collaboration (2014) *'Energy Reconstruction Methods in the IceCube Neutrino Telescope'* JINST **9** P03009

[6] The IceCube Collaboration (2014) *'Observation of the cosmic-ray shadow of the Moon with IceCube'* Phys. Rev. D **89** 102004

[7] Hallen, B. (2013) *'On the Measurement of High-Energy Tau Neutrinos with IceCube'* Available at: 'https://www.rwth-aachen.de/global/show_document.asp?id=aaaaaaaaaapwhzq'

[8] Heck, D. et al. (1998) *'CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers'* Available at: https://web.ikp.kit.edu/corsika/physics_description/corsika_phys.pdf

[9] Weisstein, Eric W. *'Sphere Point Picking'* Available at: http://mathworld.wolfram.com/SpherePointPicking.html

[10] Olive, K.A. et al. (2015) *'The Review of Particle Physics'* Chin. Phys. C **38** 090001

[11] The IceCube Collaboration (2016) *'An All-Sky Search for Three Flavors of Neutrinos from Gamma-Ray Bursts with the IceCube Neutrino Observatory'* Astrophys. J. **824** no. 2 115