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Muon track reconstruction and veto performance with D-Egg sensor for IceCube-Gen2

The IceCube Gen2 Collaboration
http://icecube.wisc.edu/collaboration/authors/icrc17_gen2

E-mail: `achim.stoessl@icecube.wisc.edu`

The planned extension of IceCube, IceCube-Gen2, a cubic-kilometer sized neutrino observatory, aims at increasing the rate of observed astrophysical neutrinos by up to a factor of 10. The discovery of a high energy neutrino point source is one of its primary science goals. Improving the sensitivity of the individual modules is a necessity to achieve the desired design goal of IceCube-Gen2. A way of improving their sensitivity is the increase of photocathode area. The proposed module called the D-Egg will utilize two 8" Hamamatsu R5912 photomultiplier tubes (PMTs), with one facing upwards and one downwards. These PMTs have an increased quantum efficiency and their sensitivity is comparable to the 10" PMT used by IceCube. This essentially leads to an increase in sensitivity by almost a factor of 2 with a full 4π solid angle acceptance. A simulation study is presented that indicates improvement in angular resolution using current muon reconstruction techniques due to the new sensor design. Since the proposed module is equipped with an upward facing PMT, further emphasis will be set on the development of new reconstruction techniques that exploit this geometry, as well as an improvement of veto probability for incoming muon tracks, which is crucial for neutrino astronomy in the Southern sky.

Corresponding author: A. Stoessl[*]
International Center for Hadron Astrophysics,Graduate School of Science,Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba-shi, Chiba, 263-8522 JAPAN

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[*] Speaker.

1. IceCube Gen2

The neutrino observatory IceCube at the geographic South Pole is a cubic kilometer array of photosensors which is able to detect the faint Cherenkov light produced by secondaries from interactions of neutrinos with the glacial ice[1]. So far, the experiment has yielded a plethora of science results, among them the discovery of a neutrino flux most likely of extraterrestrial origin[2]. After 6 years of data-taking, with the completed detector, a precise measurement of the extraterrestrial neutrino flux is still limited by statistics. To overcome the statistical limitations and to improve the effective area for neutrino events in the energy regime beyond 10 PeV, an extension of the IceCube array has been proposed[4]. A further crucial task set to an extended IceCube array is the discovery of a neutrino point source in the sky.
Several geometries of the extended array, called IceCube Gen2 - or Gen2, have been proposed. The geometry considered throughout this work is optimized to veto background cosmic ray muon events more efficiently and thus follows a more complex grid design than IceCube itself. The proposed geometry is shown in figure 1. The design features a string spacing of 240 m and includes 120 additional strings with 80 optical sensors each. The geometry shows a larger extension in the x-y plane than in depth. It is optimized for the reconstruction of horizontal muon tracks, since these have the highest contribution to the point-source sensitivity[5].

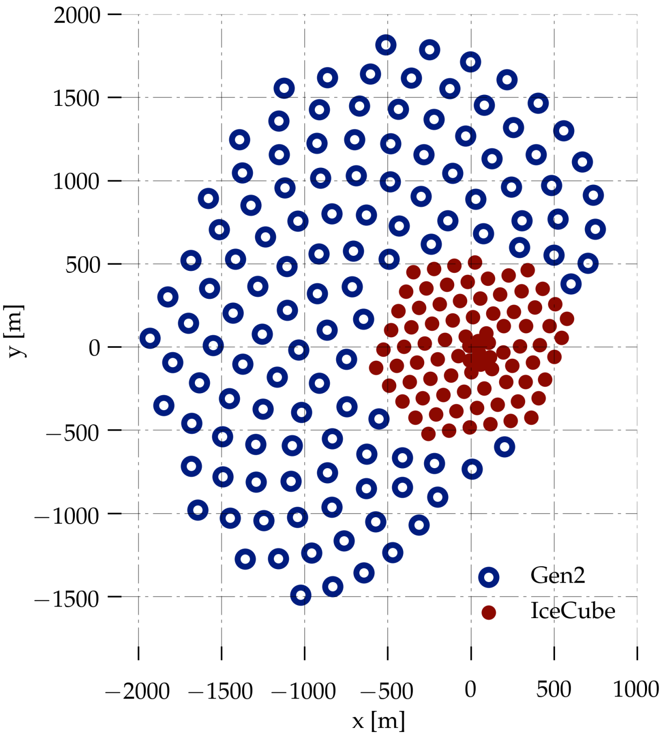

Figure 1: A proposed geometry for IceCube-Gen2 which is used for this study. In addition to the 86 strings of IceCube, which can be seen as the hexagonal shape marked with the red dots, 120 new strings with each 80 sensors are arranged in a complex grid geometry to optimize the veto power for incoming muon tracks. The extension of IceCube to larger positive x-values is prohibited due to the runway of the South Pole Station.

2. The D-Egg sensor for Gen2

Due to high drill costs at the South Pole, it is desirable to deploy sensors with a large photocathode area to keep the cost for the average cm^2 photocathode as low as possible. Several different designs are under study:

- The PDOM[7], which is basically the same design as the IceCube optical sensor[6], however with a PMT with a higher quantum efficiency. It features a single 10“ PMT which is facing downwards and a improved readout.
- The D-Egg[8], which follows the design of the PDOM, however includes another PMT facing upwards. The PMTs are 8“, so the total diameter of the D-Egg is slightly smaller than the PDOM and it has about 1.48 of its photocathode area for a Cherenkov weighted spectrum.

Other sensor designs for Gen2 are also under investigation, but are not the focus of this study[9]. In this proceeding, we investigate the performance of the D-Egg using several existing reconstruction methods developed for IceCube and compare the results against the benchmark PDOM performance. A graphic of the D-Egg is shown in figure 2. The two Hammaatsu RS-5912 high quantum efficiency PMTs are enclosed in a highly transparent glass housing, which is optimized for transparency in the near ultraviolet. The high voltage for the PMTs is generated on two boards, and the final design will feature a board for readout electronics as well.

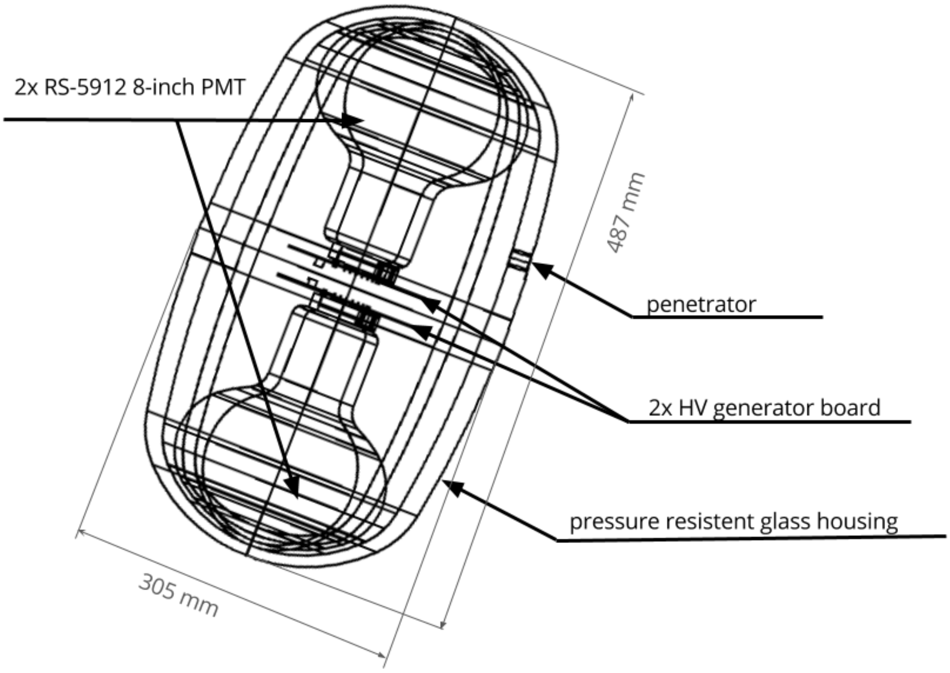

Figure 2: A schematic of the D-Egg design. It features two 8” PMTs enclosed in a highly transparent glass housing, Its diameter is slightly smaller then that of the current IceCube optical module.

3. Simulation

We simulated muons from an $E^{-1.4}$ power-law spectrum in the energy range of 10 TeV to 10 PeV with a full 4π angular distribution. The muons were injected at a cylindrical surface enclosing the detector and then propagated through the ice. The light emerging by stochastic energy losses of the muons as well as the smooth Cherenkov light were simulated and the photon propagation is handled by the software clsim[]. The simulation features a bulk ice model which means that the ice is homogenous throughout the detector. As the direct propagation is time consumptive, the detector simulation for D-Egg and PDOM are sharing the same photon simulation as input. To further increase the simulation efficiency, several simplifications were made. Consequently, the effects of glass and gel and the module geometry are not simulated individually, instead the photons are weighted with the angular sensitivity of the module as well as the wavelength dependent quantum efficiency. The efficiency of the photocathode is assumed to be constant over the whole area. To further increase the efficiency of the simulation, the size of the modules is scaled up and the number of propagated photons is decreased accordingly.

The noise introduced by the PMT and the glass housing is simulated in the same way for D-Egg and PDOM, however with absolute values scaled by the photocathode area. Further simplifications are made in the PMT and sensor simulation. The PMT simulation is done as for the PMT used in IceCube, as they are very similar in their behavior. The benefit of this is that the same simulation chain can be used for D-Egg as well as for the IceCube DOM and PDOM. As the readout electronics for the D-Egg is not yet finalized, we assume a perfect readout with an infinitesimal small binning in time. This means that each photoelctron which is produced by the PMT simulation yields an SPE pulse with a charge determined by the weight assigned to the simulated photoelectron by the PMT simulation. The ideal conversion also implies that there is no calibration step for IceCbube-Gen2 in the simulation. So far, no trigger has been developed for Gen2, thus we are using a simple multiplicity trigger which is based on the simulated PMT pulses.

However as the IceCube-Gen2 array as shown in figure 1 also includes the IceCube array, we have simulated IceCube to our best knowledge.

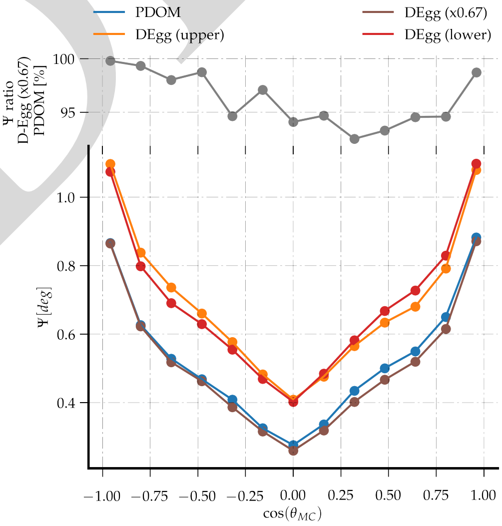

Figure 3: The results of the SPEFit reconstruction for both sensors, D-Egg and PDOM binned in the cosine of the simulated muon direction. The D-Egg effective area is scaled down by a factor of 0.67 to match the PDOM effective area. Muons with a cosine of -1 are entering the detector from below, those with 1 from above respectively.

4. Muon reconstruction

The simulated dataset was reconstructed with a set of algorithms. In this study we focus on the reconstruction algorithms SPEFit and SPLINE-RECO[]. The algorithms operate on the recon-

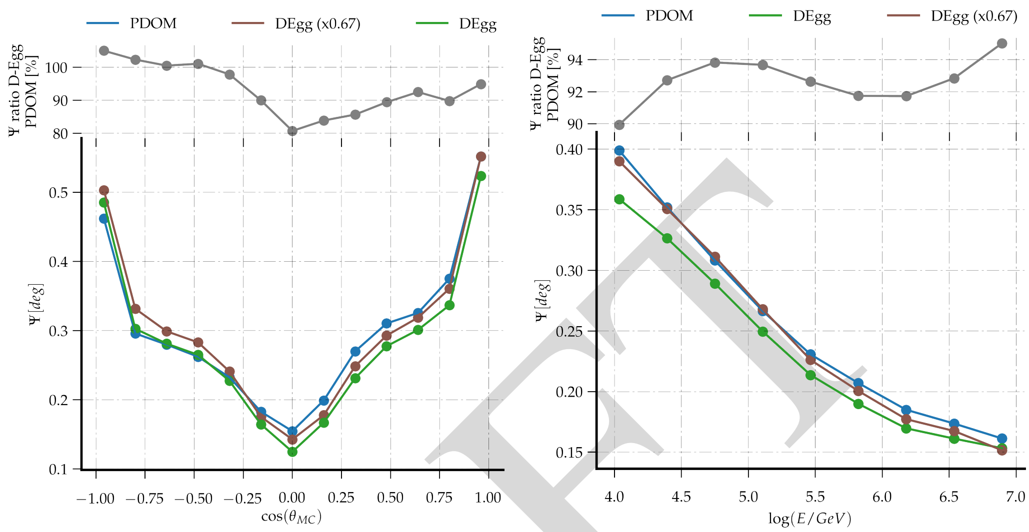

Figure 4: The results of the reconstruction Spline-reco, binned in the cosine of the simulated muon direction on the left and binned in the logarithm of the muon energy on the right. Muons with a cosine of -1 are entering the detector from below, those with 1 from above respectively.

structed pulses, each using a different method. While SPEFIT uses a simple analytical ice-model and a likelihood with one term per optical module, where only the first registered pulse is considered, SPLINE-RECO is capable of constructing a likelihood with a pdf obtained from tabulated values, and thus is able to also include more complicated models for the glacial ice. Further on, SPLINE-RECO attributes the fact that besides the smooth light from the muon track also localized stochastic losses will occur. This is especially important for high energy tracks.
To compare the accuracy of the reconstruction results, we looked at the distributions of the opening angle Ψ between the simulated and reconstructed track. The median of this distribution is used as a figure of merit. No quality cuts have been applied, yet we restrict ourself to tracks which traverse the instrumented volume.
We aim to investigate the impact of the increased photocathode area and segmentation on the reconstruction independently. As such, we work with different types of D-Egg simulation:

- Simulation of the D-Egg “as is” as described in section 3.
- The same as above, however the effective photocathode area is scaled down by a factor of 0.67 to match the photocathode area of the PDOM
- Simulation of the D-Egg where either the upward or downward facing PMT is disabled.

All types of simulations share the same simulated photons, but then branch in different detector simulations. First, the behavior of the two individual PMTs is studied. As the simulation has up-down symmetry, we expect the same performance for the datasets with only pulses in the upper or lower PMT. The results for the SPEFIT reconstructions is shown in figure 3. Because SPLINE-RECO requires look-up tables for the expected photon distribution, this test was not performed for SPLINE-RECO as these tables are only available for the full D-Egg. All reconstructions perform best for more horizontal events due to the fact that the Gen2 geometry, as shown in figure 1, is elongated more in the x and y dimension than in the z dimension. This means that horizontal tracks cross a larger instrumented volume. Also as the string spacing is 240 m, vertical tracks have a lower light yield if they enter the detector in between strings. For up going muons, if only the lower PMT of D-Egg is used as reconstruction input, it can be seen that the performance is slightly better than for the upper PMT only, and vice versa for down-going muons. For this plot, the D-Egg's photocathode area has been scaled down by a factor of 0.67 to match the photocathode area of the PDOM, as described earlier. Due to the scaling factor, both modules have the same photocathode area and thus perform very similar. The SPEFIT reconstruction yields a higher accuracy for the D-Egg sensor, which we quantify to be about 5% in the horizontal and downward region due to the segmentation of the D-Egg. We attribute this to the fact that SPEFit uses only the first pulse recorded by each PMT, and the doubling of PMT thus increases the number of pulses available to the reconstruction, especially for the downward region.

In contrast to the reconstructions LineFit and SPEFit, Spline-reco uses an event hypothesis which includes the stochastic energy loss of muons. As the number and intensity of these losses increase with the energy of the muon, this reconstruction is especially valuable for very high energy events (>= 100 TeV). The performance of the reconstruction is shown in figure 4. The D-Egg exhibits up to 15% higher accuracy in reconstruction especially in the horizontal region, which is important to point source searches[]. The reconstruction in the down-going region yields more accurate results with D-Egg as well. Comparing the results as a function of the true muon energy E_{MC}, the Spline-reco reconstruction gains due to the higher photoelectron yield, which is shown for the two sensor modules in figure 4.

5. Veto performance

An effective method to select an all flavor neutrino sample with high purity and full sky acceptance is the implementation of a veto: Using the outer strings and top and bottom layer of optical modules, incoming tracks can be tagged and removed from such a sample. The method has been proven successful and lead to the discovery of the extraterrestrial neutrino flux[2].

So far, the method has not yet been extensively studied for IceCube-Gen2. We are here applying the method to the simulated dataset for D-Egg, however adapted to the geometry of IceCube-Gen2, the parameters of the veto might not yet be optimal. Despite the fact, we see a general reduction of the survival probability of muon tracks for D-Egg by about 10% as it is shown in figure 5. The gain in the likelihood to veto a muon track is observed in the energy range up to about several hundred TeV. However at this point it must be noted that this study runs into a statistical limit, due to the fact that it is very unlikely for high energy tracks to pass any veto at all.

6. Likelihood improvements for segmented sensors

Since the increase in reconstruction performance for the D-Egg seems to be attributed mostly due to the fact that it has a larger total photocathode area, as it is shown in figure 4, we investigate the SPLINE-RECO reconstruction. Developed for IceCube, it is not optimized for segmented sensors, and thus it does not exploit their full potential. This can be seen in figure 6. This simple

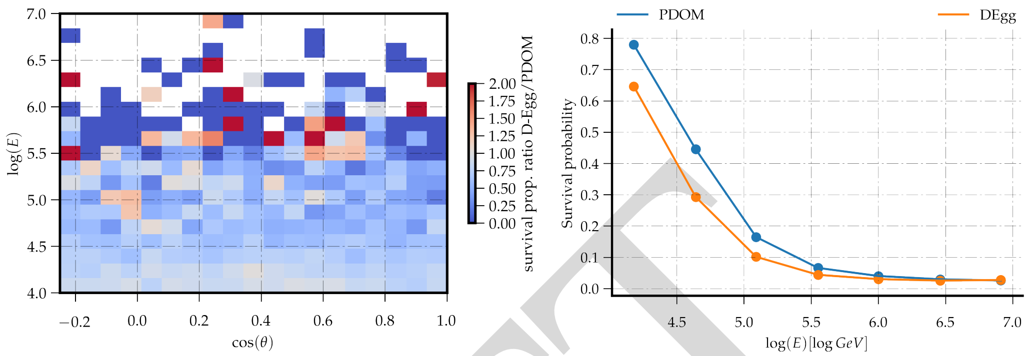

Figure 5: The cosine zenith angle-energy matrix for the probability of an event surviving the veto has been calculated for both D-Egg and PDOM. The ratio of these two matrices is shown on the left side, where the blue colors indicate a lower survival probability if the detector was equipped with D-Egg sensors and the red colors if it was equipped with PDOM sensors respectively. The zenith integrated energy dependence of the survival probability is shown on the right.

example illustrates the likelihood space for a single module, placed in the middle of the individual figures. A muon track crosses the plane of the figure orthogonal in FIXME distance, and 1σ likelihood contours are indicated. The current used likelihood is shown with the red color. As it can be seen, it is rather agnostic to the direction of the individual PMT and imposes only very small constraints on the likelihood contour. As a reason, we suspect the importance of the late photons in the arrival time distribution, which are not well considered in the current approach, as it focuses on the unscattered photons from the Cherenkov cone of the track. However if their timing is considered, these late, scattered photons can contribute significantly to constraining the likelihood, as it is illustrated in the example. The IceCube-Gen2 collaboration is currently working on a reconstruction implementing this approach, yet it is not production ready at the time of this work.

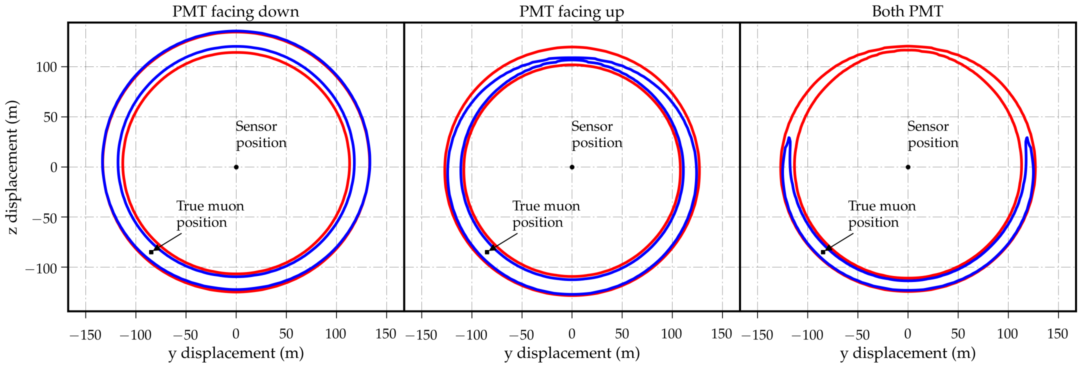

Figure 6: Likelihood contours of two different likelihoods for a single D-Egg sensor in case of a muon traversing the plane in orthogonal direction. The red contour results from the likelihood used in SPLINE-RECO , the blue contour is a proposed likelihood considering the timting of the late pulses in the arrival time distribuiton. On the left, the contours are shown for the lower PMT only. The middle plot shows the situation for the upper PMT and on the right the combined contours of both PMTs are shown.

7. Summary

For the first time, we present a study of muon track angular resolutions with current reconstruction techniques used by IceCube. We compare a new sensor design, the D-Egg, to an improved sensor based on the current IceCube design (PDOM). However advantegous, the performance of the D-Egg is increased by no more than 20% for the angular resolution in comparison with the PDOM. We attribute most of this increase to the increased photocathode area, which is increased by 48% compared to the PDOM.

Studying the reason of the found minor impact of segmentation, we find the reason in the likelihood of the SPLINE-RECO reoncstruction: By not considering the timing of the late pulses properly, the information in the late part of the arrival time distribution of the photons in the individual sensors is lost. Including the timing information of the late pulses in the likilhood we can improve the reconstruction in such a way, that it is able to identify the directionality of a muon track with only a single sensor in the best-case scenario.

Besides the improvement in angular resolution, we show that the veto performance for the current implementation of the IceCube veto can be improved by using D-Eggs as well. Our result indicates an reduction of 10% of overall survival probabiltiy for cosmic ray muons, most of it coming from energies up to several 100 TeV. It has to be noted, that we think the veto efficiency can be increased significantly as the current veto code was adapted to the Gen2 geometry, though no specific adaptions were made to incorporate the fact of segmented sensors.

In conclusion, we find that we are on a good track to improve the current IceCube reconstruction and veto techniques to exploit the full potential of new approaches in sensor design for IceCube-Gen2 and encourage further, more detailed studies to follow.

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