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

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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 R5912-100 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.

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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[3]. 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 as well as the point source sensitivity, an extension of the IceCube array has been proposed[4]. The proposed geometry for IceCube-Gen2 considered in this work is shown in figure 1. 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].

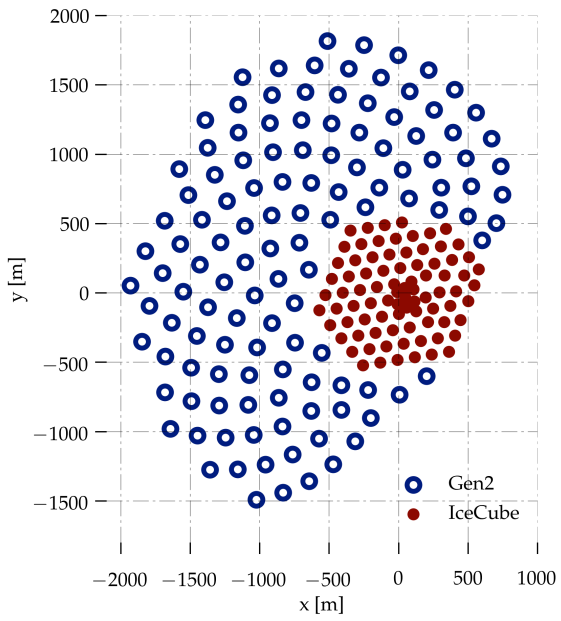

Figure 1: A proposed geometry for IceCube-Gen2 which is used for this study. In addition to the 86 strings of IceCube, which can be seen as the hexagonal shape marked with the red dots, 120 new strings with each 80 sensors are arranged in a complex grid geometry to optimize the veto power for incoming 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

Several different sensor designs for IceCube-Gen2 are under investigation, however relevant for this study are the following two proposed designs:

- 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 more photocathode area than the PDOM for a Cherenkov weighted spectrum.

A third design is worh mentioning in this context[9], since it exploits the idea of multiple sensors even further. 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. The high drill costs can be reduced by drilling holes with a smaller diameter, and thus as the diameter of the D-Egg is 10% smaller than the diameter of the PDOM, about 20% of the fuel cost can be saved during deployment. A graphic of the D-Egg with its dimensions is shown in figure 2. The two Hammaatsu R5912-100 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. 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.

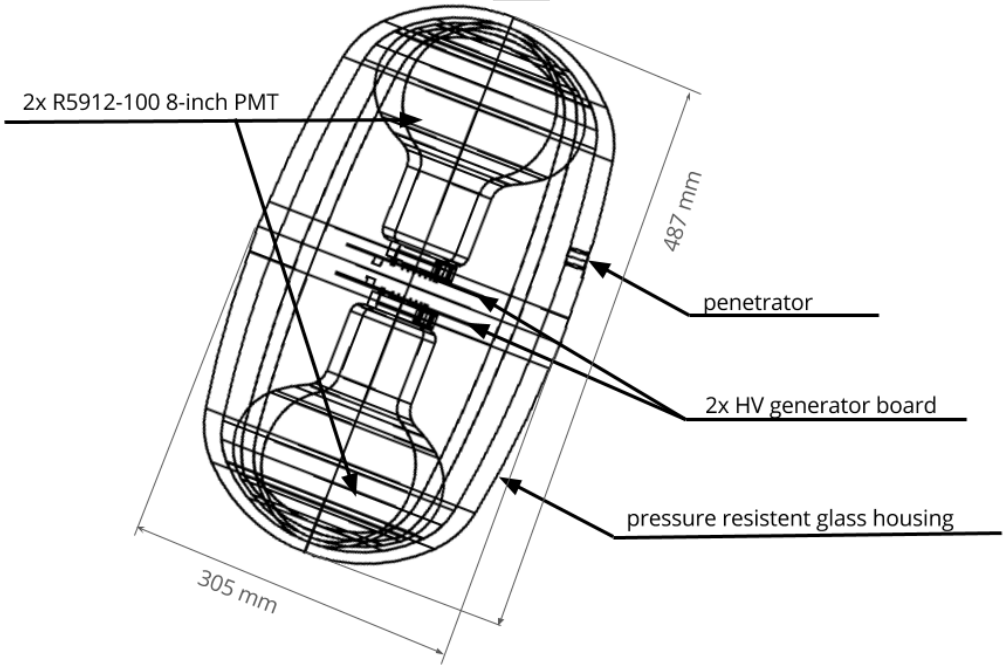

Figure 2: A schematic of the D-Egg design. It features two 8" PMTs enclosed in a highly transparent glass housing, Its diameter is 10% smaller then that of the current IceCube optical module.

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. The IceCube array, as part of IceCube-Gen2 has been simulated to our best knowledge.

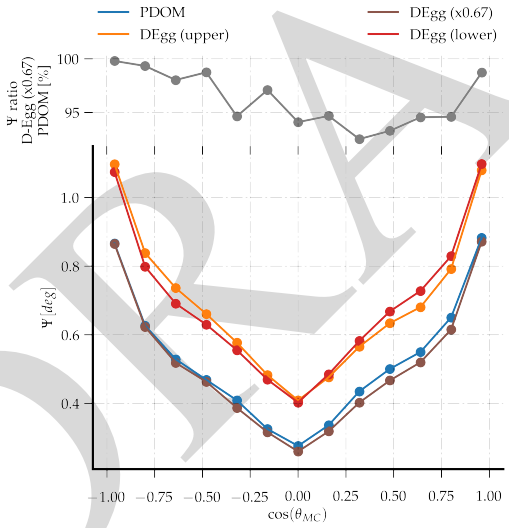

Figure 3: The results of the SPEFit reconstruction for both sensors, D-Egg and PDOM binned in the cosine of the simulated muon direction. The D-Egg effective area is scaled down by a factor of 0.67 to match the PDOM effective area. Muons with a cosine of -1 are entering the detector from below, those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

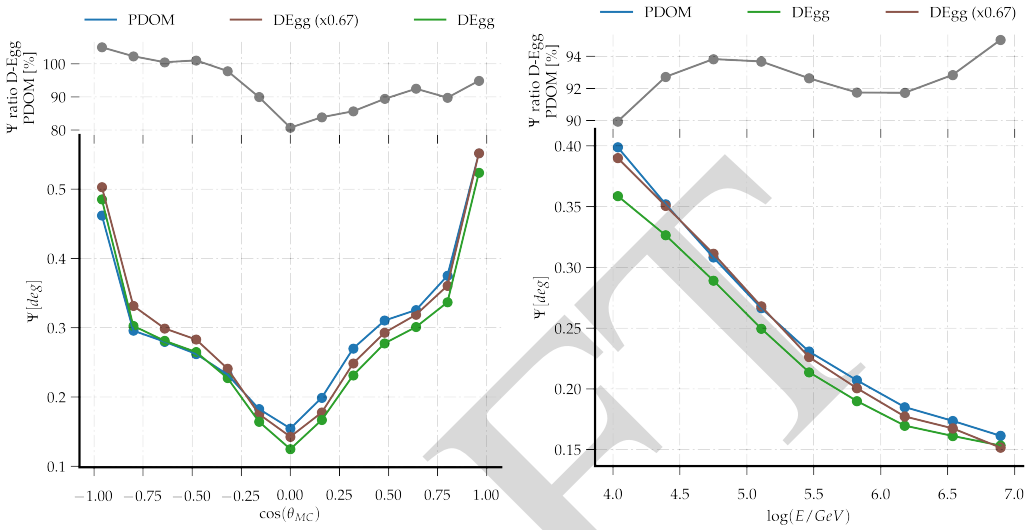

Figure 4: The results of the reconstruction SPLINE-RECO , binned in the cosine of the simulated muon direction on the left and binned in the logarithm of the muon energy on the right. Muons with a cosine of -1 are entering the detector from below, those with 1 from above respectively.

- 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. 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. 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 only as we here compare to the scaled-down version. 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.

The performance SPLINE-RECO 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. However it seems that most of the gain results from the larger photcathode area of D-Egg.

5. Likelihood improvements for segmented sensors

Figure 4 shows that the increase in reconstruction performance for the D-Egg seems to be attributed mostly to its larger total photocathode area. Thus, we investigate the details of the SPLINE-RECO reconstruction, which is developed for IceCube and not optimized for segmented sensors, and thus it may not exploit the full potential of highly segmented detector configuration. Developed for IceCube, the here used likelihood is not optimized for segmented sensors, and thus it does not exploit their full potential. The likelihood is given by:

$$L = \prod_{j=1}^{N_{DOM}} N \cdot p_j(t_j) \cdot (1 - P_j(t_1))^{N-1} \tag{5.1}$$

In the above equation, N stands for the number of hits on a certain optical module, p_j and P_j are the time residual pdf and cdf for the hit DOM and t_j is the time of the first hit of the given DOM. Contours of this likelihood function can be seen in figure 5. This simplified 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 120 m distance with an expectation of 20 photoelectrons, and 1σ likelihood contours are indicated. The likelihood developed for the IceCube DOM 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. Extending equation 5.1 and rewriting it including the arrival times of late photons can improve 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.

6. 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 muon 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[3].
The method has been applied and studied for IceCube-Gen2[11]. In the context of this proceedings we are investigating the impact of D-Egg on the efficiency of the veto algorithm. An important parameter of the current algorithm is the veto threshold, which is the charge required in the veto region to trigger the veto, which is currently set to 3 PE. Since the D-Egg has an upward facing PMT, we expect a higher performance for down-going cosmic ray muon tracks. Due to the D-Eggs

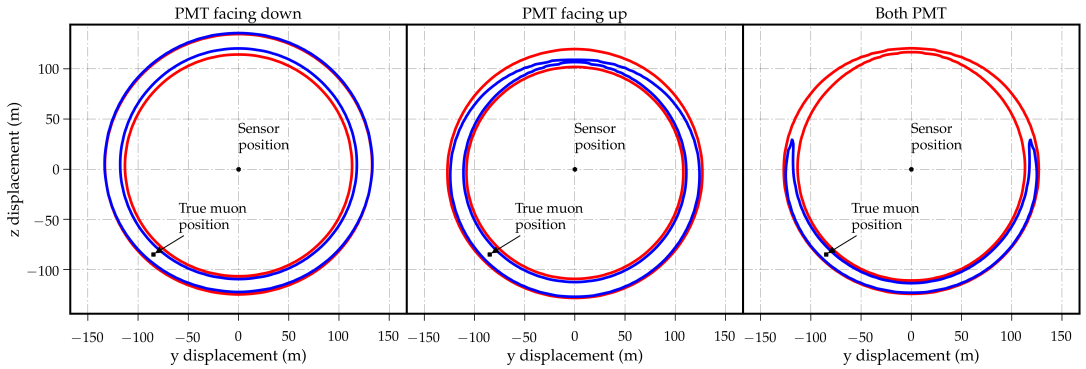

Figure 5: Likelihood contours of two different likelihoods for a single D-Egg sensor in case of a muon traversing the plane in orthogonal direction. The red contour results from the likelihood used in SPLINE-RECO, the blue contour is a proposed likelihood considering the timting of the late pulses in the arrival time distribuiton. On the left, the contours are shown for the lower PMT only. The contours are base on an Asimove test. The middle plot shows the situation for the upper PMT and on the right the combined contours of both PMTs are shown.

larger photo cathode, we also expect a higher probability to detect charge in the veto region at all. This is illustrated in figure 6: The distribution of collected charge for the upper 2 layers of modules of the IceCube-Gen2 sunflower geometry is significantly shifted for the use of D-Eggs to lower values, which results in a higher probabilty to veto incoming muons. Further impact of the use of D-Eggs in the veto region is currently under investigation.

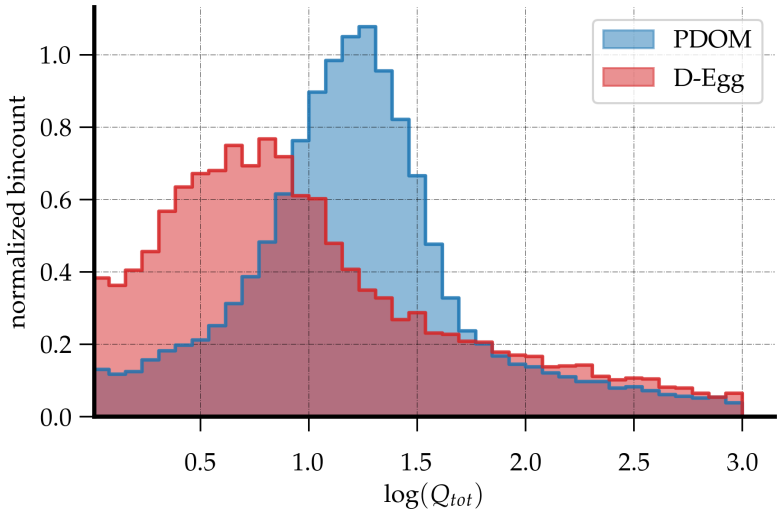

Figure 6: The collected charge in the upper layer of the IceCube-Gen2 array. The collected charge is shown for the uppermost 2 layers of optical modules. In the case of D-Egg, a much hihger contribution in the onset region around 3 PE has been found.

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). Despite with the advantage of higher segmentation, 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.
By studying why the higher segmentation only gives minor impact on reconstruction, 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. We studied the deposited charge in the upper layer of the IceCube-Gen2 array and find a significant increase in the low charge region around the 3 PE threshhold. 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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