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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/icecubegen2_2017

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The planned extension of IceCube, 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 thereby 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 photo cathode area. The proposed module D-Egg will utilize two 8" Hamamatsu R5912 photomultiplier tubes (PMT). The increased quantum efficiency of the used PMT yields a comparable sensitivity to the 10" PMT used by IceCube, which essentially leads to an increase of sensitivity almost by a factor of 2 with a full solid angle acceptance as the PMTs are facing upwards and downwards. A simulation study is presented that indicates improvement in angular resolution of 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 exploiting 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[**?**]. So far, the experiment yielded a plethora of science results, among them the discovery of a neutrino flux of most likely extraterrestrial origin[1, **?**, **?**]. Currently after 6 years of data-taking with the detector in full operation, the precise measurement of the extraterrestrial neutrinos 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[**?**]. A further crucial task set of an extended IceCube array is the discovery of a neutrino point source in the sky.
Several geometries of the extended array, which is further on called IceCube Gen2 - or short Gen2, have been proposed. The here utilized geometry is optimized to avoid corridors for background cosmic ray muon events and thus follows a more complex grid design than IceCube itself. The geometry features a string spacing of 240 m and includes 120 additional strings with 80 optical sensors each. The proposed geometry is shown in figure 1. The geometry shows a larger extension in the x-y plane than in depth. The geometry is optimized for the reconstruction of horizontal muon tracks, since these have the highest contribution to the point-source sensitivity[].

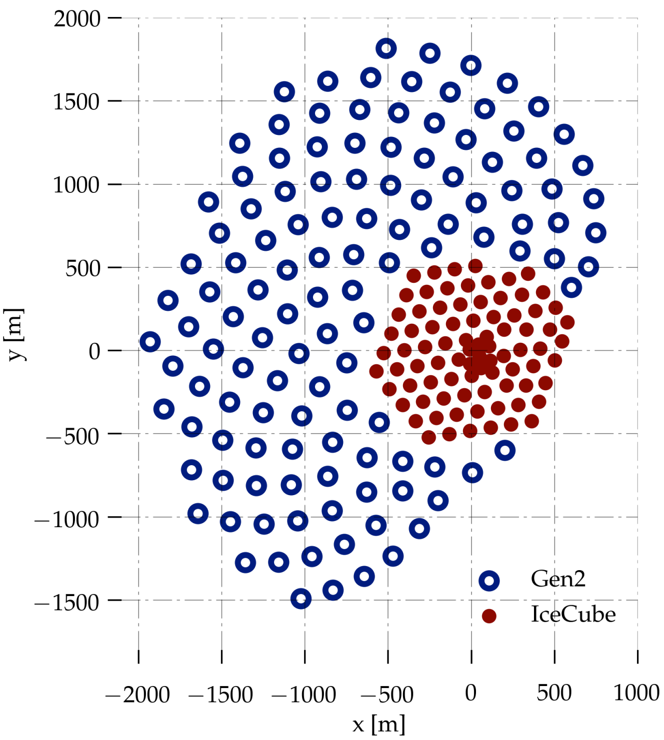

Figure 1: A proposed geometry for IceCube-Gen2 which is used for this study. Additionally to the 86 strings of IceCube, which can be seen as the hexagonal shape marked with the red dots, 120 new strings with each 80 sensors are arranged in a complex grid geometry to avoid "corridors" for background muons with comparatively sparse instrumentation. The extension of IceCube to larger positive x-values is prohibited due to the runway of the South Pole Station.

2. Sensors for IceCube-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[], which is basically the same design as the IceCube optical sensor[], however with a PMT with a higher quantum efficiency. It features a single 10“ PMT which is facing downwards and a improved readout.
- The mDOM[], which is a KM3Net[] inspired multi PMT design with 24 3” PMTs allowing it for a 4π acceptance angle. It features the largest photocathode area of the new sensor designs, however its diameter is slightly larger and thus larger holes in the glacial ice have to be drilled.
- The D-Egg, which follows basically the design of the PDOM, however includes another PMT facing upwards. The PMTs are 8“, so the total diameter of D-Egg is slightly smaller than the one of the PDOM and it has about 1.48 of its photocathode area for a Cherenkov weighted spectrum.

In this proceeding, we are presenting reconstruction results for the D-Egg. As very similar to the current design of the IceCube optical module, we compare our results with the PDOM, however as this study focuses on the D-Egg a more precise study to understand the behavior of the PDOM in more detail might be necessary.
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. For a more detailed description of D-Egg we refer to [].

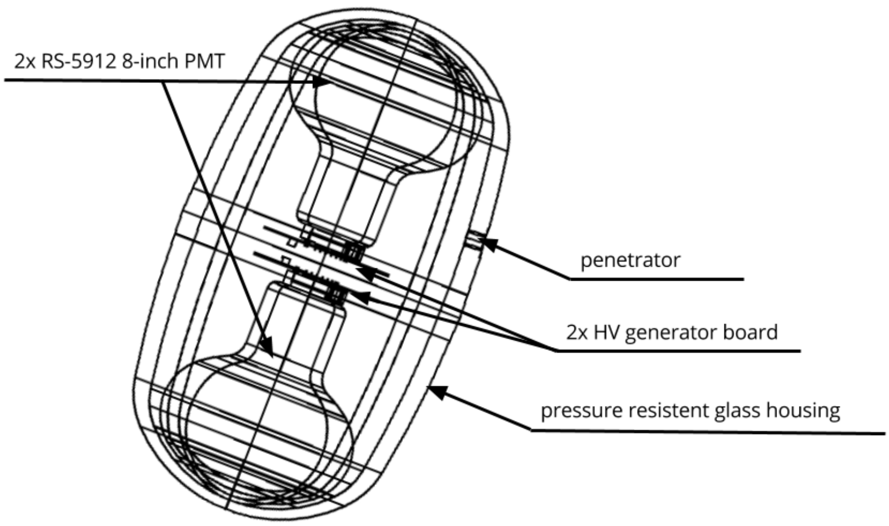

Figure 2: A schematic of the D-Egg design. It features two 8” PMTs enclosed in a highly transparent glass housing, Its diameter is slightly smaller then that of the current IceCube optical module.

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 cylinder surface from somewhat outside the detector and then propagated through the ice. The injection surface is shown in figure 3. The light emerging by catastrophic energy losses of the muons as well as the smooth Cherenkov light were simulated with direct photon propagation. The simulation features a bulk ice model, and the hole ice which is the closest to the strings has been simulated. As the direct propagation is time consumptive, the detector simulation for D-Egg and PDOM are sharing the same photon simulation as input. For a further increase in 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 the same over the whole area. To further increase the efficiency of the simulation, the modules are over sized 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 the absolute values are 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 which charge is 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 as the IceCube-Gen2 array as shown in figure 1 includes also the IceCube array, we have simulated IceCube to our best knowledge and in a comparable way to the IceCube simulations.

4. Muon reconstruction

The simulated dataset was reconstructed with a set of algorithms: LineFit, SPEFit, MuExAngular and Spline-reco[]. The reconstructions are operating on the reconstructed pulses, each using a different method. While LineFit is minimizing the χ^2 of a fitted track hypothesis, SPEFit is using a likelihood fit with an analytical ice model. FIXME MuExAngular. Spline-reco is using a likelihood fit with a pdf obtained from tabulated values for a bulk-ice model.

The reconstructions are chained: LineFit provides a seed for SPEFit and MuExAngular provides a seed for Spline-reco, which does not use SPEFit as a seed. 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 merrit. An example Ψ distribution is shown in figure 4. No quality cuts have been applied, yet we restrict ourself to tracks

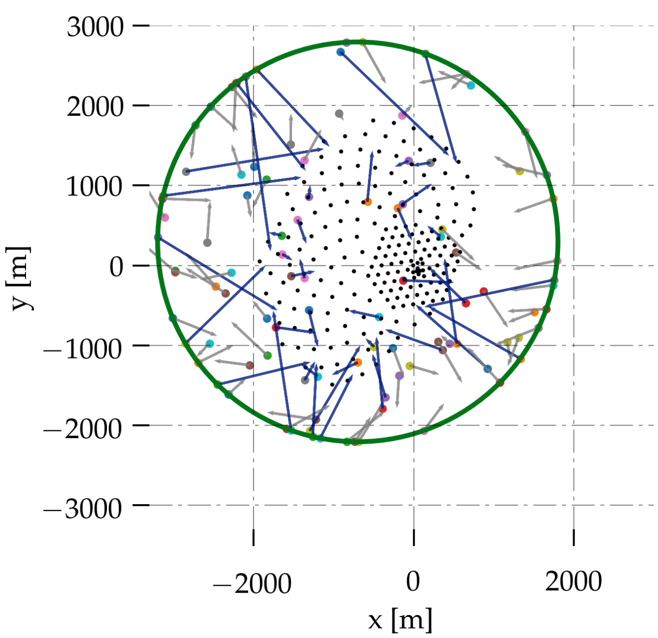

Figure 3: The sampling surface of the simulation is indicated by the cylinder. Muons are injected from this surface and propagated through the ice. To avoid biases, we chose a rather large cylinder, resulting in many tracks not hitting the instrumented volume. Tracks traversing the instrumented volume are shown in blue, while such which are not traversing the instrumented volume are of gray color.

which traverse the instrumented volume.
Studied where two different effects:

1. As the D-Egg has a 1.48 times larger photocathode area for the expected Cherenkov spectrum we expect a general all-over higher performance than the PDOM.

2. Due to the segmentation of D-Egg, which has an additional upward facing PMT, we especially expect an increase in performance for down-going events.

These two effects have been studied with the help of 5 different types of simulations, where all simulation share the same simulated photons, but then branch in different detector simulations. These are the simulation for PDOM and D-Egg, as well as D-Egg where we masked the lower or upper PMT respectively and additionally a simulation for D-Egg where the photocathode area is scaled down by a factor of 0.67 to match the photocathode area of PDOM. The last dataset then is used to study the effect of segmentation only. Firstly, 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 result for the reconstructions LineFit and SPEFit is shown in figure 5. Due to the implementation of spline-reco which 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. In this figures, several things can be seen: Firstly, all reconstructions perform best for more horizontal events. This is 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, which means that more horizontal track 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.

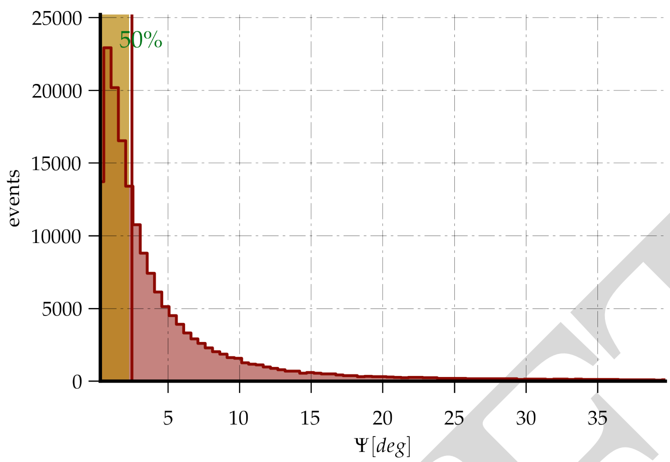

Figure 4: The Ψ distribution integrated over all simulated muon angles and energies. The line indicates the median of the distribution.

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. For LineFit, a slight difference can be seen for up-going muons, where the PDOM performs better on the several percent level. For the reconstruction SPEFit, this advantage can not be seen anymore, yet the D-Egg reconstruction yields a higher accuracy. We attribute this due to the fact that SPEFit is only using the first pulse recorded by each PMT and the doubling of PMT thus increases the number of pulses available to the reconstruction as well.
The improvement of the reconstruction SPEFit by D-Egg is shown in more detail in figure 6 and can be quantified by an improvement of about 5% for down-going tracks due to the segmentation of D-Egg alone.

In contrast to the reconstructions LineFit and SPEFit, Spline-reco uses an event hypothesis which

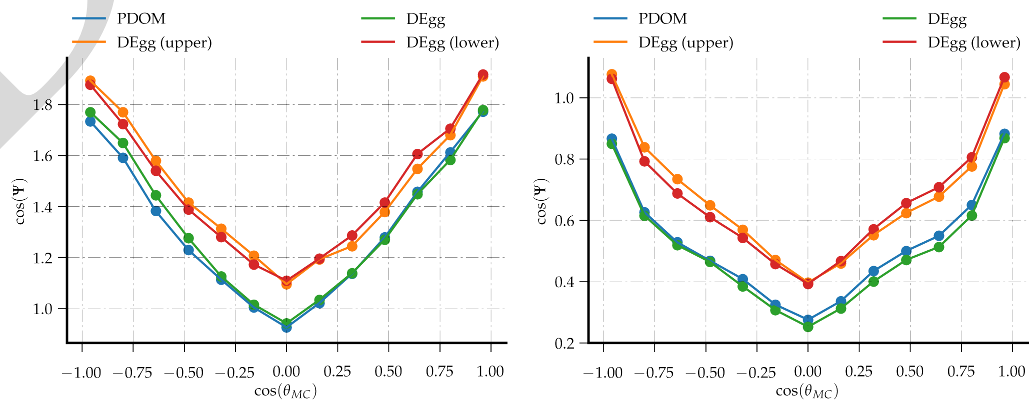

Figure 5: The results of two reconstructions LineFit and SPEFit, binned in the cosine of the simulated muon direction. Muons with a cosine of -1 are entering the detector from below, those with 1. from above respectively.

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 high energy events of

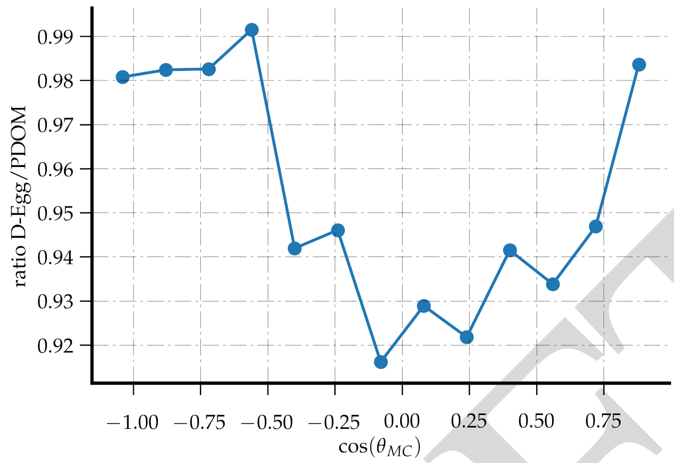

Figure 6: The ratio of the medians of the reconstruction SPEFit for both sensors D-Egg and PDOM, binned in the cosine of the simulated muon direction. Muons with a cosine of -1 are entering the detector from below, those with 1. from above respectively. The effective area of D-Egg is scaled down to match the effective area of PDOM to study the effect of segmentation.

several hundred TeV and more. The performance of the reconstruction is shown in figure 7. The D-Egg exhibits an up to about 15% higher accuracy in reconstruction especially in the horizontal region, which is important to point source searches[]. The reconstruction in the down-going region is yielding more accurate results with D-Egg as well. Comparing the results binned in true muon energy, the reconstruction Spline-reco gains due to the higher photoelectron yield, which is shown for the two sensor modules in figure 9

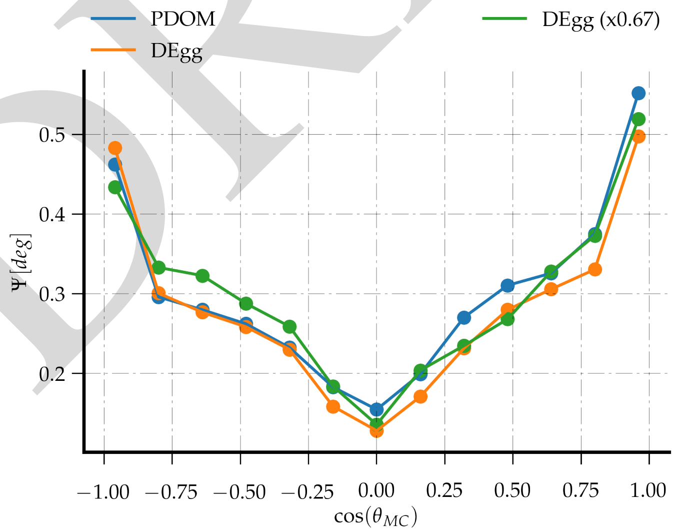

Figure 7: The results of the reconstruction Spline-reco, binned in the cosine of the simulated muon direction. Muons with a cosine of -1 are entering the detector from below, those with 1. from above respectively.

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[1].
So far, the method has not yet been extensively studied for IceCube-Gen2. We are here applying

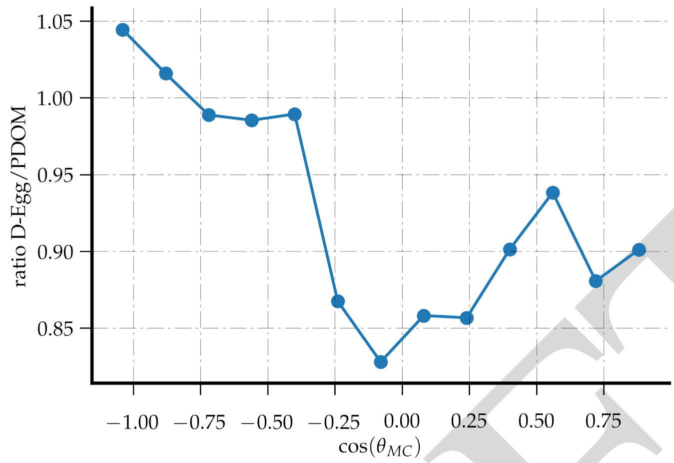

Figure 8: The ratio of the medians of the reconstruction SPEFit for both sensors D-Egg and PDOM, binned in the cosine of the simulated muon direction. Muons with a cosine of -1 are entering the detector from below, those with 1. from above respectively.

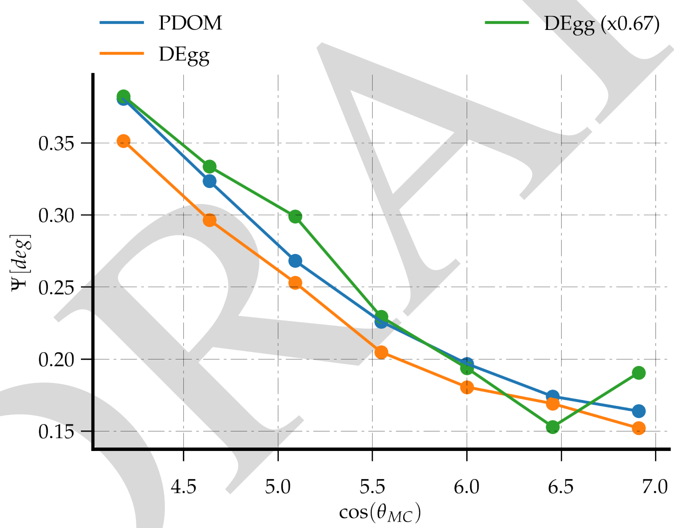

Figure 9: The results of the reconstruction Spline-reco, binned in the logarithm of the muon energy.

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 10. 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 has to 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. Summary

Since the discovery of an extraterrestrial neutrino flux, the IceCube collaboration made large efforts for a precise measurement of its energy spectrum and to unveil its sources.
However, currently it seems that the statistical power of the dataset winch is acquirable within the livetime of IceCube might not be large enough to answer the most urgent questions.
Especially in the regime of PeV events only about 3-6 events per decade are expected with the current design of IceCube. The future of neutrino observatories thus demands for detectors with

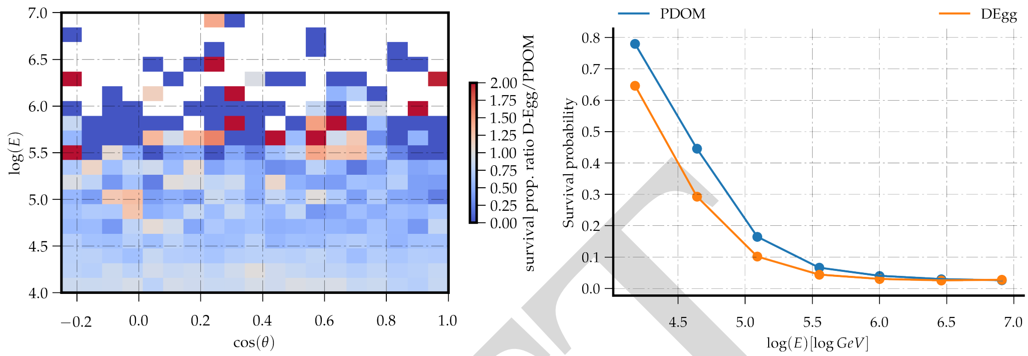

Figure 10: The cosine zenith angle-energy matrix for the probability of an event surviving the veto has been calculated for both D-Egg and PDOM. The ratio of these two matrices is shown on the left side, where the blue colors indicate a lower survival probability if the detector was equipped with D-Egg 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.

a a larger effective area and at the same time it is desirable to keep the cost per cm^2 photocathode area as low as possible.
The IceCube Gen2 array is a proposed extension of current IceCube, which is planned to be capable of gaining enough data to answer the above mentioned questions. Since the planning and construction of KM3Net, sensors with multiple PMTs instead of a single large-aperture PMT seem to be a promising approach.
We took the general idea but simplified it by using current IceCube technology to develop D-Egg, which is a design with 2 8-inch PMTs with a full 4π acceptance. In this proceeding, we studied the performance of this sensor in comparison to an upgraded DOM design, designated as PDOM, for a dataset of simulated muons injected from all directions in the sky with energies between 10 TeV and 1 0PeV. We investigated the angular resolution for 3 different reconstructions LineFit , SPEFit and SPLINE-RECO for the D-Egg as well as the PDOM and a version of D-Egg which has been shrinked to match the Cherenkov weighted photocathode area of PDOM. We were able to show that there is an overall gain of up to about 4-8% by the segmentation alone for the reconstruction SPEFit . However for the sophisticated reconstruction SPLINE-RECO , the gain in reconstruction performance seems to be caused mainly by the increased photocathode area, yet it is up to about 15% in the for point source searches important horizontal region. This result is consistency with[4], where the same approach in simulation was used. As this approach includes many simplifications, especially for the actual geometry of the individual sensors, we can not exclude the possibility that the fact that we do not see significant improvement of the performance of SPLINE-RECO is solely attributed to the simplicity of the simulation approach, yet we think it is not likely.
We also studied the veto performance where we see a slight advantage for the D-Egg sensor to energies up to about several 100TeV of about 10%This contribution is the first to discuss muon angular resolutions for D-Egg and the results indicate that it might be a valuable asset to the development of a next generation neutrino observatory in the Antarctic, however a more precise performance estimate with a more accurate simulation will be worth studying.

References

[1] Aartsen, M.G. et al., *Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector*. Science, 342(6161):1242856, December 2013

[2] Aartsen, M.G. et al., *Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data*, Physical Review Letters, 113:101101, Sep 2014

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