

1 Muon track reconstruction and veto performance 2 with D-Egg sensor for IceCube-Gen2

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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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†A footnote may follow.

3 **1. IceCube Gen2**

4 The neutrino observatory IceCube at the geographic South Pole is a cubic kilometer array
 5 of photosensors which is able to detect the faint Cherenkov light produced by secondaries from
 6 interactions of neutrinos with the glacial ice. So far, the experiment yielded a plethora of science
 7 results, among them the discovery of a neutrino flux of most likely extraterrestrial origin. Currently
 8 after 6 years of data-taking with the detector in full operation the precise measurement of this flux
 9 is still limited by statistics. To overcome the statistical limitations and to improve the effective
 10 area for neutrino events in the regime beyond 10 PeV, an extension of the IceCube array has been
 11 proposed. A further crucial taskset of an extended IceCube array is the discovery of a neutrino
 12 point source in the sky.
 13 Several geometries of the extended array which is furtheron called IceCube Gen2 - or short Gen2
 14 - have been proposed. The here used geometry is optimized to avoid corridors for background
 15 cosmic ray muon events and thus follows a more complex grid design than IceCube itself. The
 16 geometry features a string spacing of 240 and 120 additional strings with each 80 optical sensors.
 17 The proposed geometry is shown in 1. The geometry shows a larger extension in the x-y plane
 18 than in depth, thus the detector is assymmetric. The geometry is optimiued for the reconstruction of
 horizontal muon tracks, since these have the highest contribution to the point-source sensitivity.

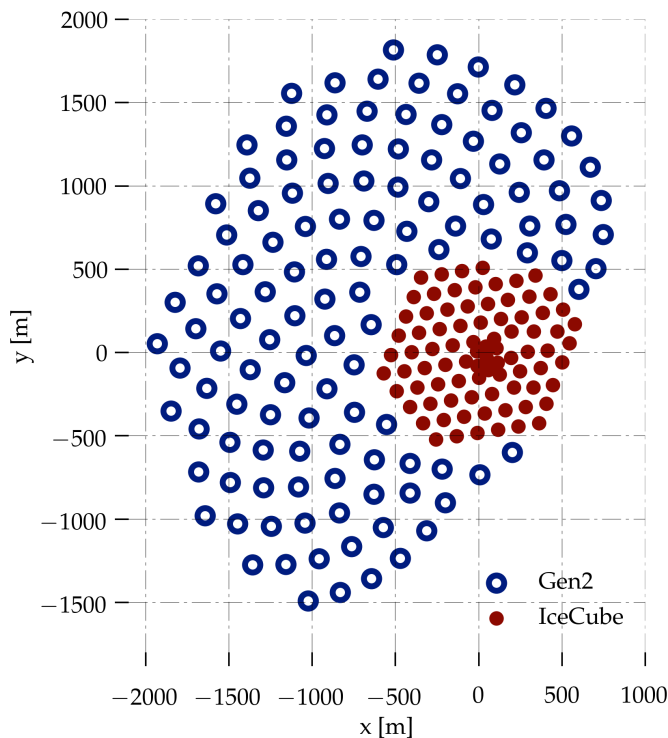


Figure 1: A proposed geometry for IceCube-Gen2 which is used for this study. Additionally to the 86 strings of IceCube, which can be seen as the hexagonal shape marked with the red dots, 120 new strings with each 80 sensors are arranged in a complex grid geometry to avoid “corridors” for background muons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

19

20 **2. Sensors for IceCube-Gen2**

21 Due to high drill costs at the South Pole, it is desirable to deploy sensors with a larg photocath-
 22 ode area to keep the cost for the average cm^2 photocathode as low as possible. Several different

23 designs are under study:

- 24 • The PDOM, which is basically the same as the IceCube optical sensor, however with a PMT
25 with a higher quantum efficiency. It features a single 10" PMT which is facing downwards
26 and a improved readout.
- 27 • The mDOM, which is a KM3Net inspired multi PMT design with XX X" PMTs allowing
28 it for a 4π acceptance angle. It features the largest photocathode area of the new sensor
29 designs, however its diameter is slightly larger and thus larger holes has to be drilled.
- 30 • The D-Egg, which follows basically the design of the PDOM, however includes another
31 PMT facing upwards. The PMTs are 8", so the total diameter of D-Egg is slightly smaller
32 than the one of the PDOM and it has about 1.48 of its photocathode area for a Cherenkov
33 weighted spectrum.

34 In this proceeding, we are presenting reconstruction results for the D-Egg, for a study about the
35 mDOM we are referring to[]. As very similar to the current design of the IceCube optical module,
36 we compare our results with the PDOM, however as this study focuses on the D-Egg a more precise
37 study to understand the behaviour of the PDOM in more detail might be necessary.

38 A graphic of the D-Egg is shown in 2. The two Hammaatsu RS-5912 high quantum efficiency
39 PMTs are enclosed in a highly transparent glass housing, which is optimized for transparency in
40 the near ultraviolet. The high voltage for the PMTs is generated on two boards, and the final design
41 will feature a board for readout electronics as well. For a more detailed description of D-Egg we
refer to [].

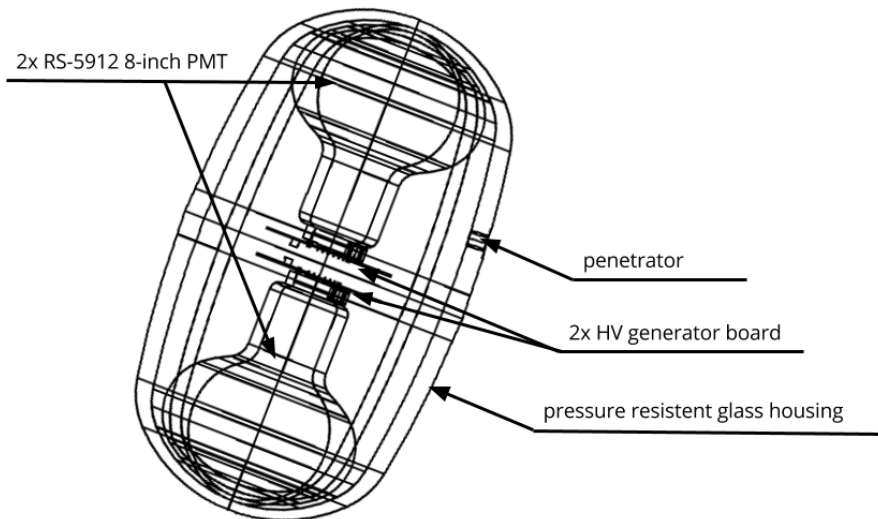


Figure 2: A schematic of the D-Egg design. It features two 8" PMTs enclosed in a highly transparent glass housing, Its diameter is slightly smaller than that of the current IceCube optical module.

43 3. Simulation

44 We simulated muons from an $E^{-1.4}$ power-law spectrum in the energy range of 10TeV to
 45 10PeV with a full 4π angular distributions. The muons were injected at a cylinder surface from
 46 somewhat outside the detector and then propagated through the ice. The injection surface is shown
 47 in ???. The light emerging by catastrophic energy losses of the muons as well as the smooth
 48 Cherenkov light were simulated with direct photon propagation. The simulation features a bulk
 49 ice model, and the hole ice which is the closest to the strings has been simulated. As the direct
 50 propagation is time consumption, the detector simulation for D-Egg and PDOM are sharing the
 51 same photon simulation as input. For a further increase in simulation efficiency, several simplifi-
 52 cations were made. Consequently, the effects of glass and gel and the module geometry are not
 53 simulated individually, instead the photons are weighted with the angular sensitivity of the module
 54 as well as the wavelength dependent quantum efficiency. The efficiency of the photocathode is
 55 assumed to be the same over the whole area. To further increase the efficiency of the simulation,
 56 the modules are oversized and the number of propagated photons is decreased accordingly.

57 The noise introduced by the PMT and the glass housing is simulated in the same way for D-Egg and
 58 PDOM, however the absolute values are scaled by the photocathode area. Further simplifications
 59 are made in the PMT and sensor simulation. The PMT simulation is done as for the PMT used in
 60 IceCube, as they are very similar in their behaviour. The benefit of this is that the same simulation
 61 chain can be used for D-Egg as well as for the IceCube DOMs. As the readout electronics for the
 62 D-Egg is not yet finalized, we assume a perfect readout with an infinitesimal small binning in time.
 63 This means that each photoelectron which comes out of the PMT simulation yields an SPE pulse
 64 which charge is determined by the weight assigned to the simulated photoelectron by the PMT
 65 simulation. The ideal conversion also implies that there is no calibration step for IceCube-Gen2
 66 in the simulation.

67 So far, no trigger has been developed for Gen2, thus we are using a simple multiplicity trigger
 68 which is based on the simulated PMT pulses.

69 However as the as the IceCube-Gen2 array as shown in 1 includes also the IceCube array, we have
 70 simulated IceCube to our best knowledge and in a comparabIceCube-Gen2 le way to the IceCube
 71 simulations.

72 4. Muon reconstruction

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

78 The reconstructions are chained: LineFit provides a seed for SPEFit and MuExAngular provides a
 79 seed for Spline-reco, which does not use SPEFit as a seed. To compare the accuracy of the recon-
 80 struction results, we looked at the distributions of the opening angle Ψ between the simulated and
 81 reconstructed track. The median of this distribution is used as a figure of merit. An example Ψ

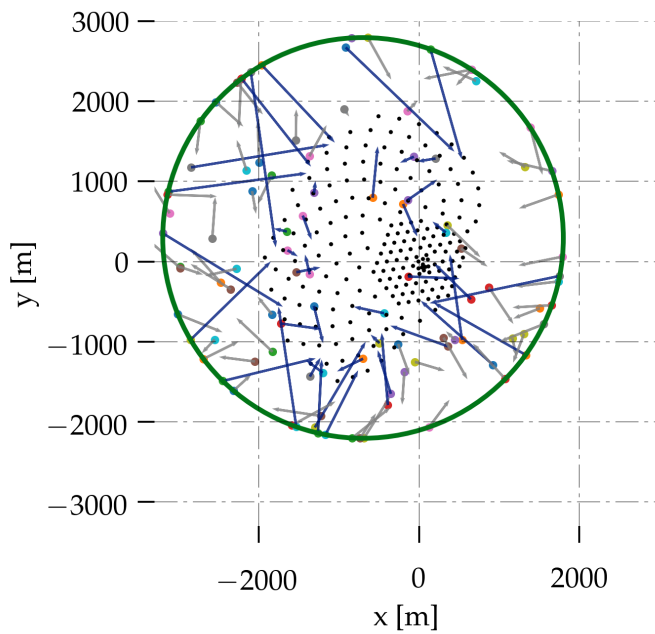


Figure 3: The sampling surface of the simulation is indicated by the cylinder, respectively box, in the two plots. Muons are injected from this surface and propagated through the ice. To avoid biases, we chose a rather large cylinder, resulting in many tracks not hitting the instrumented volume. Tracks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

82 distribution is showed in 4.

83 Studied where two different effects:

- 84 1. As the D-Egg has a 1.48 times larger photocathode for the expected Cherenkov spectrum
- 85 we in principle expect a general all-over higher performance than the PDOM just due to the
- 86 increased photocathode area.
- 87 2. Due to the segmentation of D-Egg, which has an additional upward facing PMT, we espe-
- 88 cially expect an increase in performance for down-going events.

89 These two effects have been studied with the help of 5 different types of simulations, where all sim-
 90 ulation share the same simulated photons, but then branch in different detector simulations. These
 91 are the simulation for PDOM and D-Egg, as well as D-Egg where we masked the lower or upper
 92 PMT respectively and additionally a simulation for D-Egg where the photocathode area is scaled
 93 down by a factor of 0.67 to match the photocathode area of PDOM. The last dataset then is used to
 94 study the effect of segmentation only. The first check which is done, asks for similar behaviour of
 95 the two PMTs. As the simulation has up-down symmetry, we expect the same performance for
 96 the datasets with only pulses in the upper or lower PMT. The result for the reconstructions LineFit
 97 and SPEFit can be seen in 5, due to the implementation of spline-reco which requires look-up ta-
 98 bles for the expected photon distribution this test was not performed for Spline-reco as these tables
 99 are only available for the full D-Egg. In this figures, several things can be seen: Firstly, all recon-
 100 structions perform best for more horizontal events. This is due to the fact that the Gen2 geometry
 101 as shown in 1 is elongated more in the x and y dimension than in the z dimension, which means
 102 that more horizontal track cross a larger instrumented volume. Also as the string spacing is 240m,
 103 vertical tracks have a lower light yield if they enter the dectector in between strings. For upgoing
 104 muons, if only the lower PMT of D-Egg is used as reconstruction input, it can be seen that the

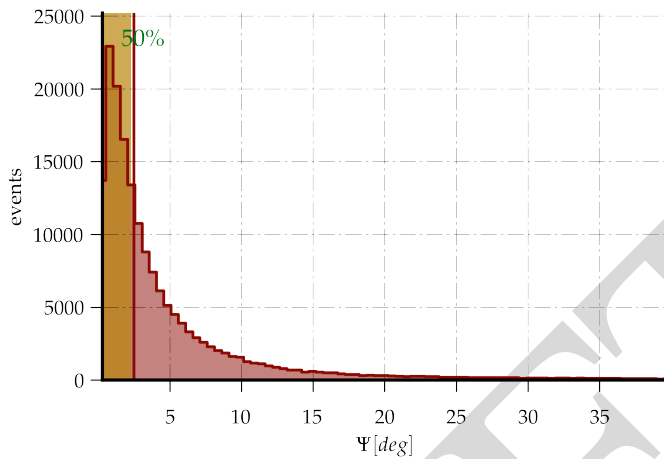


Figure 4: The Ψ distribution integrated over all simulated muon angles and energies. The line indicates the median of the distribution.

105 performance is slightly better than for the upper PMT only, and vice versa for downgoing muons.
 106 For this plot, the D-Egg’s photocathode area has been scaled down by a factor of 0.67 to match
 107 the photocathode area of the PDOM, as described earlier. Due to the scaling factor both modules
 108 have the same photocathode area and thus perform very similar. For LineFit, a slight difference
 109 can be seen for upgoing muons, where the PDOM performs better on the several percent level. For
 110 the reconstruction SPEFit, this advantage can not be seen anymore, yet the D-Egg reconstruction
 111 yields a higher accuracy. We attribute this due to the fact that SPEFit is only using the first pulse
 112 recorded by each PMT and the doubling of PMT thus increases the number of pulses available to
 113 the reconstruction as well.

114 The improvement of the reconstruction SPEFit by D-Egg is shown in more detail in 6 and can be
 115 quantified by an improvement of about 5% for downgoing tracks due to the segmentation of D-Egg
 116 alone.

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

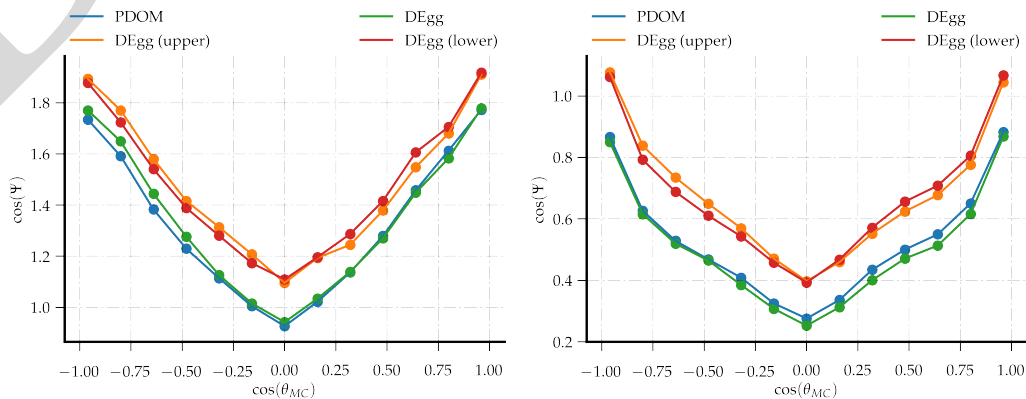


Figure 5: The results of two reconstructions LineFit and SPEFit, binned in the cosine of the simulated muon direction. Muons with a cosine of -1 are entering the detector from below, those with 1. from above respectively.

117 includes the stochastic energy loss of muons. As the number and intensity of these losses increase
 118

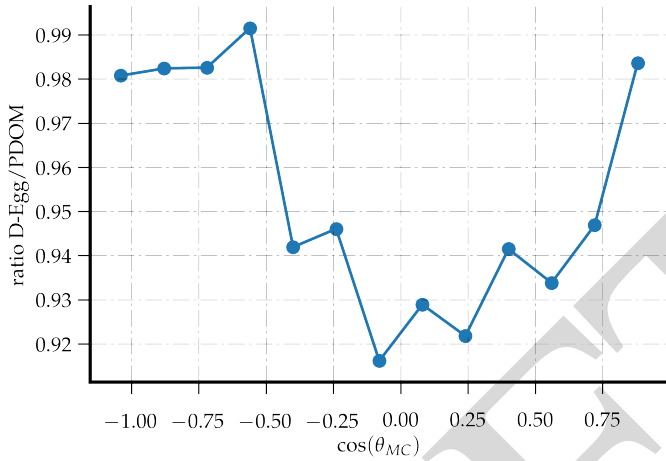


Figure 6: The ratio of the medians of the reconstruction SPEFit for both sensors D-Egg and PDOM, binned in the cosine of the simulated muon direction. Muons with a cosine of -1 are entering the detector from below, those with 1. from above respectively. The effective area of D-Egg is scaled down to match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

119 with the energy of the muon, this reconstruction is especially valuable for high energy events of
 120 several hundred TeV and more. The performance of the reconstruction is shown in 7. While
 121 performing similar to the PDOM, the D-Egg exhibits an up to about 15% higher accuracy in re-
 122 construction especially in the horizontal region, which is important to point source searches. The
 123 reconstruction in the down-going region is yielding more accurate results with D-Egg as well. Bin-
 124 ning not in zenith angle but in incoming muon energy, the reconstruction Spline-reco gains due to
 the higher light yield, which can is shown for the two sensor modules in ??

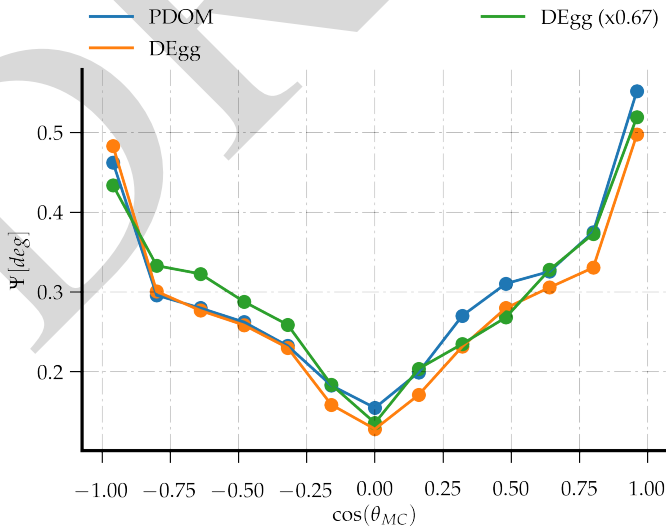


Figure 7: The results of the reconstruction Spline-reco, binned in the cosine of the simulated muon direction. Muons with a cosine of -1 are entering the detector from below, those with 1. from above respectively.

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126 **5. Veto performace**

127 An effective method to select an all flavor neutrino sample with high purity and full sky accep-
 128 tance is the implementation of a veto: Using the outer strings and top and bottom layer of optical
 129 modules, incoming tracks can be tagged and removed from such a sample. The method has been
 130 proven succesful and lead to the discovery of the extraterrestrial neutrino flux[1].

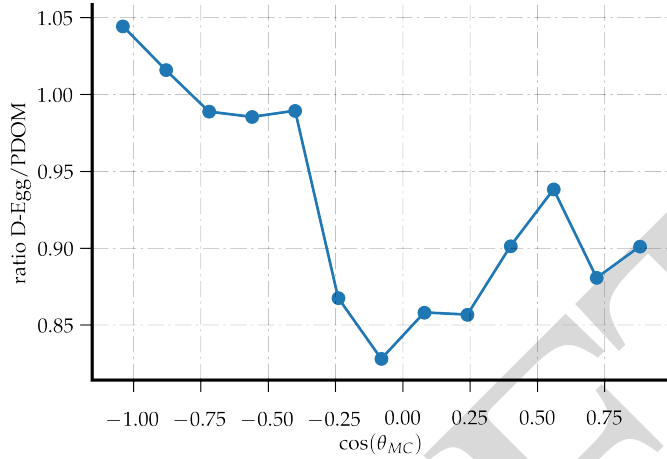


Figure 8: The ratio of the medians of the reconstruction SPEFit for both sensors D-Egg and PDOM, binned in the cosine of the simulated muon direction. Muons with a cosine of -1 are entering the detector from below, those with 1. from above respectively.

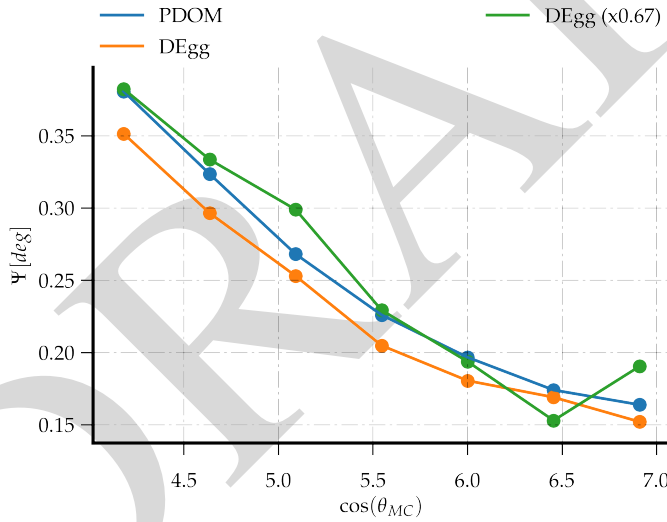


Figure 9: The results of the reconstruction Spline-reco, binned in the logarithm of the muon energy.

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

138 **6. Summary**

139 Since the discovery of an extraterrestrial neutrino flux, the IceCube collaboration made large
 140 efforts for a precise measurement of its energy spectrum and to unveil its sources.
 141 However, currently it seems that the statistical power of the dataset wich is acquirable within the
 142 livetime of IceCube might not be large enough to answer the most urgent questions.
 143 Especially in the regime of PeV events only about 3-4 events per decade are expected with the

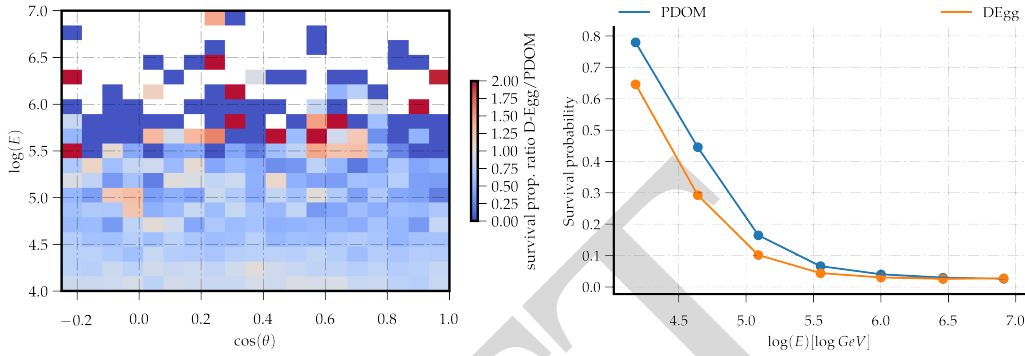


Figure 10: The cosine zenith angle/energy matrix for the probability of an event surviving the veto has been calculated for both D-Egg and PDOM. The ratio of these two matrixes is shown on the left side, where the blue colors indicate a lower survival probability if the detector was equipped with D-Egg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

144 current design of IceCube. The future of neutrino observatories thus demands for detectors with a
 145 a larger effective area and at the same time the desire is to keep the cost per cm^2 phot cathode as
 146 low as possible.

147 The IceCube Gen2 array is a proposed extension of current IceCube, which is planned to be ca-
 148 pable of gaining enough data to answer the above mentioned questions. Since the planning and
 149 construction of KM3Net, sensors with multiple PMTs instead of a single large-aperture PMT seem
 150 to be a promising approach.

151 We took the general idea but simplified it by using current IceCube technology to develop D-Egg,
 152 which is a design with 2 8-inch PMTs with a full 4π acceptance. In this proceeding, we studied the
 153 performance of this sensor in comparison to an upgraded DOM design, designated as PDOM for a
 154 dataset of simulated muons coming from all directions in the sky with energies between 10TeV and
 155 10PeV. We investigated the angular resolution for 3 different reconstructions LINEFIT , SPEFIT
 156 and SPLINE-RECO for the D-Egg as well as the PDOM and a version of D-Egg which has been
 157 shrunk to match the Cherenkov weighted phot cathode area of PDOM. We were able to show
 158 that there is an overall gain of up to about 4-8% by the segmentation alone for the reconstruction
 159 SPEFIT . However for the sophisticated reconstruction SPLINE-RECO , the gain in reconstruc-
 160 tion performance seems to be caused mainly by the increased phot cathode area, yet it is up to
 161 about 15% in the for points source searches important horizontal region. This result is consistent
 162 with this study[], where the same approach in simulation was used. As this approach includes
 163 many simplifications, especially for the actual geometry of the individual sensors, we can not ex-
 164 clude the possibility that the fact that we do not see significant improvement of the performance of
 165 SPLINE-RECO is solely attributed to the simplicity of the simulation approach, yet we think it
 166 is not likely.

167 We also studied the veto performace where we see a slight advantage for the D-Egg sensor to ener-
 168 gies up to about several 100TeV of about 10% This contribution is the first to discuss muon angular
 169 resolutions for D-Egg and the results indicate that it might be a valuable asset to the development
 170 of a next generation neutrino observatory in the Antarctic, however a more precise performance

171 estimate with a more accurate simulation will be worth studying.

172 **References**

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- 175 [2] Aartsen, M.G. et al., *Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube*
176 *Data*, *Physical Review Letters*, 113:101101, Sep 2014
- 177 [3]