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In-ice self-veto techniques for IceCube-Gen2

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The discovery of astrophysical high-energy neutrinos with IceCube opened the window to neutrino astronomy. With the IceCube-Gen2 high-energy array, an extension that will surround the existing IceCube deep ice detector, the detection rate of cosmic neutrinos will be increased by about an order of magnitude.

The main background of neutrino telescopes such as IceCube consists of muons that are produced by cosmic-ray particles in the atmosphere. A successful method to distinguish neutrinos from this background selects only events that start inside the detector. This can be accomplished by defining a veto layer in the outer region of the detector and considering the amount and timing of Cherenkov light detected in this region.

For the IceCube-Gen2 high-energy array the definition of the veto has to be optimized and new techniques will be introduced, as the geometry will be different and the distances between the optical modules will be larger than in IceCube. In this contribution we present the results of a data-driven analysis that uses real IceCube data to estimate the expected veto energy threshold. In addition, a new veto technique has been developed with the aim of lowering the energy threshold of the current veto procedure. A study of the veto efficiency for different detector geometries of IceCube-Gen2 will be presented as well.

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1. Introduction

The IceCube neutrino telescope is the first detector that successfully identified a flux of high-energetic astrophysical neutrinos. However, the statistics are limited, and it has not yet been possible to identify the sources of these neutrinos. To obtain more astrophysical neutrinos, a major upgrade, IceCube-Gen2, is in planning, that will increase the detection volume by an order of magnitude [1]. The main background for neutrino telescopes are muons produced by cosmic ray showers in the atmosphere. An effective method for the reduction of this background is the application of a veto against incoming tracks. This can be done by the installation of surface veto hardware like air shower arrays or air cherenkov telescopes. Another approach that does not depend on additional hardware for an alternative detection technique is the application of self-veto algorithms, which has been successfully done for IceCube. Transferring these filters to a detector that is less densely instrumented and bigger, will influence the performace of the veto. Therefore, the algorithms have to be adapted to the expanded geometry. In addition, new developments can increase the veto power.

2. IceCube-Gen2

IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole [2] between depths of 1450 m and 2450 m, completed in 2010. The reconstruction of neutrino direction, energy and flavor relies on the optical detection of Cherenkov radiation emitted by charged particles produced in the interactions of neutrinos in the surrounding ice or the nearby bedrock. A large number of results obtained using the IceCube detector (e.g.[3, 4, 5, 6]) have proven the scientific value of a Cherenkov neutrino telescope in the Antarctic ice sheet. However, the energy range and the event rate is limited by IceCube's current configuration and volume. To obtain a higher rate of events, an upgrade to the existing detector is in its planning phase (see Figure 1). One part of this upgrade is the extension of the current in-ice geometry by adding strings around the existing detector. The volume of this high-energy extension will be a factor of ten higher than the current detector, so the rate of high-energy neutrino events will increase by an order of magnitude. The goal is to obtain a much larger sample of events in order to investigate the sources of the high-energy neutrinos observed by the IceCube detector.

In the current planning, 120 new strings will be added around the existing configuration (IC86). Three layouts are under consideration, called sunflower, edge-weighted and banana geometry (see Figure 2). For the edge-weighted geometry, the string spacing is 240 meters for the inner strings and 125 meters for the outer strings. For the banana geometry, strings are separated by 235 meters. For the sunflower geometry, three different string spacings (200, 240 and 300 meters) are considered.

In contrast to IC86, the proposed geometries are not arranged in a hexagonal grid. Instead, a spiral geometry was chosen. This will improve the directional reconstruction of tracks, as no azimuthal directions will be preferred by certain planes in the grid. The most important difference between the current IceCube configuration and Gen2 is the increased string spacing, ranging from 200 to 300 meter, which decreases the total amount of light that will be received in each event. This will influence not only the resolution on reconstructed energy and direction, but also the efficiency of filters to select events which start inside the detector. The new strings are planned to carry 80

DOMs each, 20 more than the existing strings. Six of the additional DOMs will be placed above and 14 below the region covered by IC86.

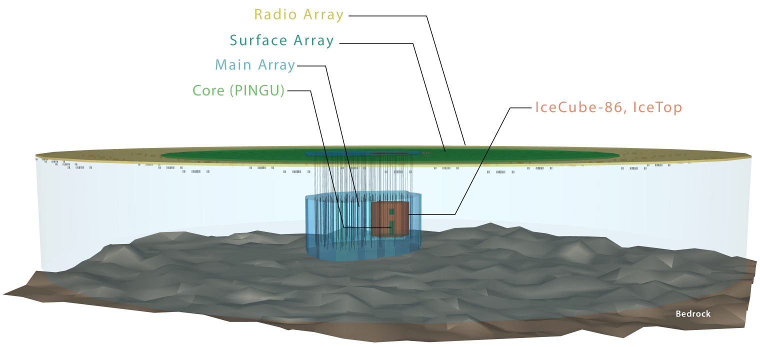

Figure 1: Schematic view of IceCube-Gen2. The detector includes the main array and densely instrumented core, as well as a large surface array and an array of radio detectors.

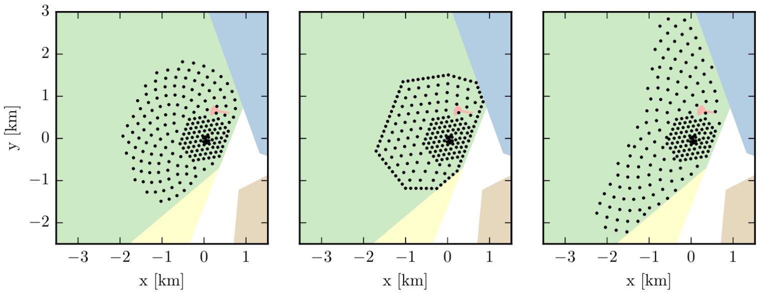

Figure 2: Different layouts for the high-energy in-ice extension. Left: sunflower geometry, center: edge-weighted geometry, right: banana geometry

3. The HESE filter

The trigger rate of IceCube is about 2.5 kHz. Of these events, only few per year can be identified as astrophysical neutrinos. The observation of a cosmic neutrino flux requires effective filters that select most of the signal events while removing a large fraction of the background. In IceCube this has been achieved in the High-Energy Starting Event (HESE) analysis [3]. The HESE filter was designed to identify high-energy events with an interaction vertex inside the detector volume. This way only neutrinos will be selected, as incoming muons will emit light while entering the detector. If the first light of an event is recorded at the edge of the detector, the filter rejects this event, producing a neutrino sample of high purity.

For the HESE filter a certain part of the detector is defined as a veto region. Figure 3 shows the IceCube detector with the veto region indicated by a grey band. A layer of 90 meters at the top of the detector is included to classify down-going atmospheric muons. To identify muons entering the side of the detector, the strings at the edge of the detector are also included. At the depth of 2000 m - 2100 m, the scattering and absorsorption lenghs of light are significantly decreased due to a dust layer in the ice [7]. As muons could enter the detector undetected here, the DOMs in the bottom of this region are also included in the veto layer. Additionally, DOMs in the bottom 10 meters of the detector are included.

The following procedure is applied to identify starting events. The earliest possible time window of 3μs is selected that includes at least 250 photo electrons (pe). If during this time window, the number of hits N inside the veto layer is larger than three, or the total charge Q of these hits exceeds 3 pe, the event is tagged as an incoming track. As low-energy background muons can pass the veto layer while depositing less than three hits, an overall charge threshold $Q_{tot} > 6000$ pe is applied. Low-energy muons passing very close to one of the DOMs can deposite a very high charge and thus surpass the threshold. To avoid these balloon events from falsely entering the selection, DOMs are excluded from the calculation of the total charge if they contribute more than 50% of the total charge.

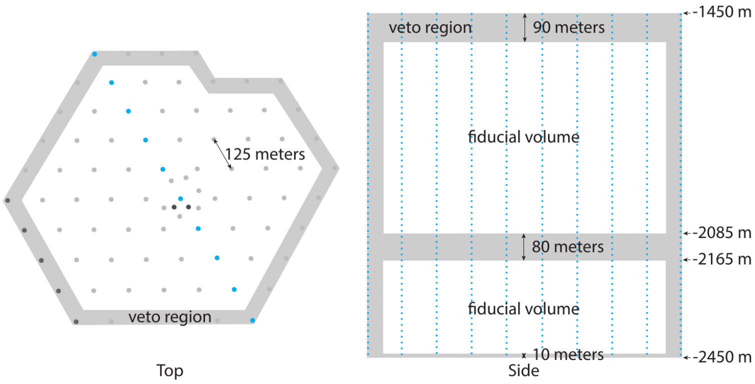

Figure 3: Top and side view of the IceCube detector. The veto region for the HESE veto is indicated as a gray area.

4. Performance of the HESE veto for Gen2

The HESE filter was designed and optimized for the dimensions and layout of IceCube. How the filter performes for a different geometry is a question that has to be addressed. One approach would be to use full simulations of the proposed detector layouts. However, the simulation of enough statistics for each geometry is computationally expensive. Another disadvantage is that systematic uncertainties will be included in the simulation.

Instead, a data-driven approach has been investigated in order to evaluate the passing rate for a detector with a string spacing of Gen2. To do that, one year of data taken by IC86 was processed as described in the following. First, IceCube strings are removed from the geometry in order to mimic the wider string spacing (250m) of Gen2. The geometry before and after the removal of the strings is shown in Figure 4.

Data form 2011 were used for this analysis. Before any string removal, the veto is applied for the full detector in order to select the events. Only events crossing the veto region are included, so that the sample consists of entering tracks only. After this, strings are removed from the geometry according to the new geometry and the veto is applied the same way as for the full detector.

Figure 5 displays the passing number as a function of the total charge deposited in IC86, which is a variable highly correlated to the energy. The blue points represent all the entering tracks in the sample and the green squares show the passing events in the sparse (250 m) detector. For comparison, the rate of passing events for the full detector are shown as red triangles. This was calculated by defining a second veto layer at the edge of the fiducial volume and counting the incoming events that are not rejected by the second veto. The dashed lines are the exponential fit to the data.

This study implies that applying the veto in the current configuration to a detector with increased string spacing will lead to an energy threshold (20000 pe) that is a factor of 3 higher compared to the corresponding threshold for IceCube (6000 pe).

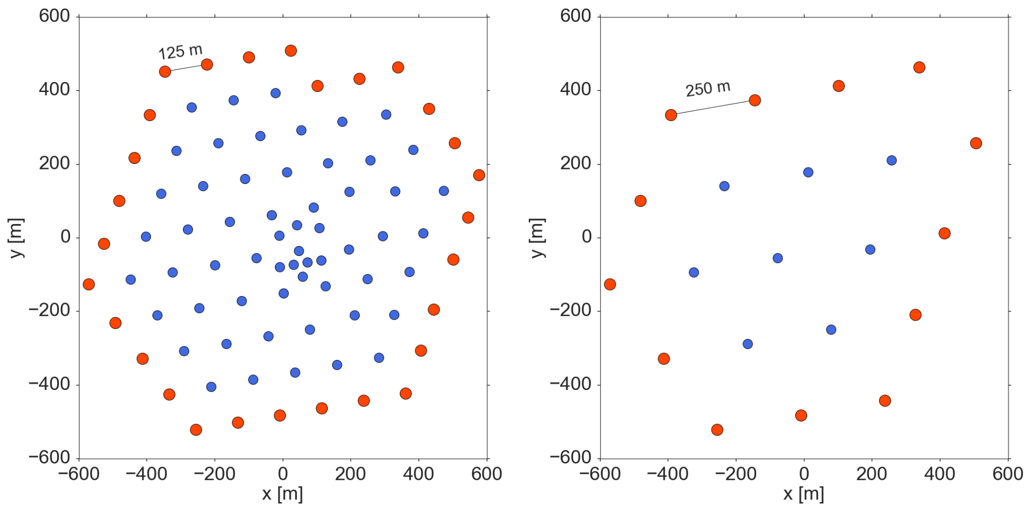

Figure 4: Left: top view of the IceCube detector. Strings that are completely used as veto are marked as red dots. Right: Top view of IceCube, after removal of strings from data to resemble a detector of increased string spacing.

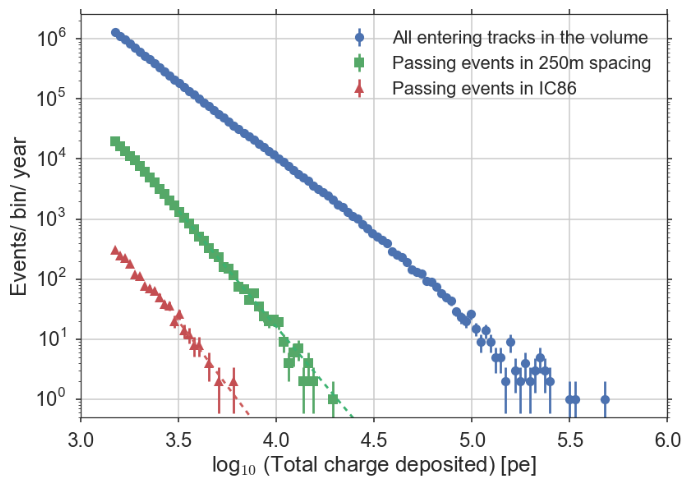

Figure 5: Number of background events passing the HESE filter before and after the removal of strings.

5. Development of new Veto

While a detector with a sparser grid can be evaluated using recorded data from IceCube, it is not possible to determine the effects of the increased size of Gen2 in this way. To investigate the efficiency of an in-ice self-veto for IceCube-Gen2, two sets of simulated data were generated. The background simulation made use of a parametrization of the in-ice muon flux, which was determined by simulating air showers and propagating the muons through the ice. The particle properties (energy, direction, position) were sampled from the predefined probability distributions, and then weighted to correspond to the primary cosmic-ray energy spectrum [8].

For the signal flux of atmospheric neutrinos, cascades were simulated uniformly throughout the detector volume. This provides a good approximation for neutrino induced interactions and is consistent with the position of the observed HESE events [3]. The simulated signal data set is weighted to the astrophysical neutrino flux, determined by IceCube:

$$E^2\phi(E) = 1.5 \cdot 10^{-8}\,(E/100\text{TeV})^{-0.3}\,\text{GeV}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1} \tag{5.1}$$

Figure 6 shows the energy distribution of the expected background and signal events. The ratio of the signal rate over the background rate shows how much the background has to be reduced to reach the level of the signal rate. At energies of 30 TeV and 100 TeV, the passing fraction of background should be smaller than 0.007% and 0.3%, respectively.

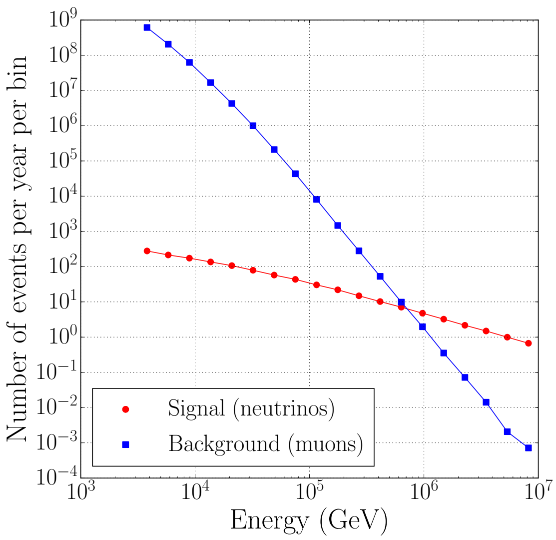

Figure 6: Predicted rates of signal and background events (single muons) in the sunflower 240 geometry as a function of the true energy before the muon enters the detector volume. The signal corresponds to the astrophysical neutrino flux of Equation 5.1. The plot shows the rates before the application of a veto.

To improve the background reduction for IceCube-Gen2, a new filter technique was developed as described in the following. As in the HESE procedure, balloon DOMs are removed from the events. Then a time window of 1 μs is shifted until it contains more than 10% of the total charge. The last hit of this time window is defined as a reference hit. If the number of causally connected hits that occur in the veto region before the reference hit exeeds a certain number N, the event will be identified as incoming particle and removed. A hit is considered to be causally connected to the reference hit if the condition $|\Delta x/c - \Delta t| < \Delta t_{\text{max}}$ is fulfilled, where Δx is the distance between the DOMs, Δt the time difference, and Δt_{max} an adjustable parameter.

In this algorithm, several parameters can be optimized to achieve a sufficient background rejection. One set of parameters concerns the selection of the reference hit: the size of the time window can be tuned as well as the fraction of the total charge that is required to be collected in this time window. Another set refers to the selection of hits in the veto layer: the maximal number of hits N_{max} and the causal constraint $(\Delta t)_{\text{max}}$. Finally, also the configuration of the veto layer itself, specifically the number of DOMs in top layer, can be optimized.

In Figure 7, the fraction of passing background events is plotted against the signal efficiency for different veto hits and time constraints. With a low number of allowed veto hits N_{min} and a high causal constraint $(\Delta t)_{\text{max}}$, the background can be reduced by 3 orders of magnitude while keeping more than 60% of the signal for energies larger than 200 TeV. Additionally, the expected number of signal events per year is shown for different geometries. This plot demonstrates that the performance of the edge-weighted layout is inferior to the sunflower geometries for every energy region.

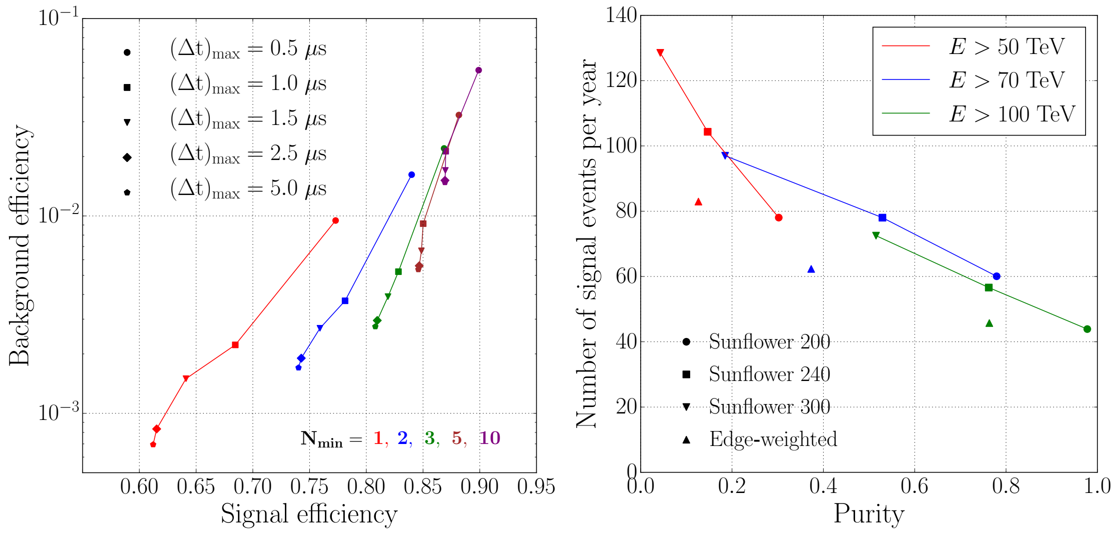

Figure 7: Left: Background vs. signal efficiency for different maximal hits in the veto layer N_{max} and different causal constraints Δt_{max}. The geometry configuration is sunflower 240 and a lower energy cut at $E > 200$ TeV is applied. Right: Expected signal events per year against the expected purity of the event sample for different detector geometries with lower energy cuts at 50 TeV, 70 TeV and 100 TeV. For each point, the parameters that maximize the purity are used for the veto. For both plots, the reference hit was chosen using a 1 μs time window that contains 10% of the total charge. The veto configuration includes the top 12 DOMs of GEN2 and the top 6 DOMs of IceCube.

6. Summary

Self-veto algorithms are a powerful technique for neutrino telescopes to filter the background of incoming atmospheric particles. They played a key role in the discovery of the flux of astrophysical neutrinos. We have shown that the application of the current IceCube filter to a detector with larger string spacing would increase the energy threshold by a factor of three. Therefore new filters have to be developed and optimized for a new detector geometry. These studies imply that the sunflower geometries will show a better performance with a in-ice self-veto than the edge-weighted layout.

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