Extending IceCube Low Energy Neutrino Searches for Dark Matter with DeepCore

THE ICECUBE COLLABORATION[1],

[1]*See special section in these proceedings*

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Abstract: The cubic-kilometer sized IceCube neutrino observatory in the glacial ice at the South Pole offers new opportunities for low-energy neutrino physics and astrophysics, in particular for indirect dark matter searches. An efficient veto against atmospheric muons at an early stage of an analysis is an important tool for background rejection. For low energies, this can be achieved by using the DeepCore in-fill array of IceCube as a fiducial volume and the surrounding IceCube detector as an active muon veto. We present newly developed veto techniques for dark matter searches with DeepCore. The effective use of DeepCore and the application of these vetos are discussed, drawing on the example of two recent IceCube indirect dark matter searches for signals from the Sun and the Galactic Center, respectively.

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Keywords: IceCube, DeepCore, Dark Matter, Southern Hemisphere.

1 Introduction

A flux of neutrinos from Weakly Interacting Massive Particle (WIMP) [1] annihilations may be detected in large neutrino telescopes such as IceCube [2]. IceCube searches for WIMP signals from self-annihilating or decaying dark matter in the galactic halo [3] and Galactic Center [4], as well as for signals from neutrino annihilation from large celestial bodies, such as the Sun [5]. IceCube's in-fill array "DeepCore" [6] increases the low-mass WIMP sensitivity and allows the search for low-energy neutrino source candidates in the southern equatorial sky. These promising analysis prospects present new challenges to reduce the down-going atmospheric muon background. Here we report on the technical details of new analysis and muon-veto techniques that have been developed for dark matter analyses using DeepCore data.

IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole between depths of 1450 m and 2450 m. Detector construction started in 2005 and finished in 2010. Neutrino reconstruction relies on the optical detection of Cherenkov radiation, via digital optical modules (DOMs), emitted by secondary particles produced in neutrino interactions in the surrounding ice or the nearby bedrock. The completed IceCube detector consists of 86 strings with 60 DOMs each. 78 strings have a horizontal spacing of 125 m and a vertical spacing between DOMs of 17 m. In addition, the detector contains 8 strings optimized for low energies that are clustered around the center most string of IceCube. These strings feature DOMs with higher quantum efficiency photo multiplier tubes and have reduced vertical DOM spacing. The spacings are 10 m for the uppermost 10 DOMs (*DC-veto region*) and 7 m for the remaining 50 DOMs (*DC-fiducial region*). Both regions are separated by the main dust layer, which is located at a depth of about 2050 m. The horizontal distance between DeepCore strings is less than 75 m. Together with the 12 adjacent IceCube strings they form the DeepCore subarray that is optimized for neutrino energies below 100 GeV.

The work described here uses the 79-string configuration of IceCube (see figure 1). During this data taking period, DeepCore consisted of 6 densely instrumented strings together with 7 surrounding standard IceCube strings.

2 Methods for Efficient Event Selections

IceCube is optimized for the detection of high energy neutrinos from a few hundred GeV up to several PeV. DeepCore increases IceCube's sensitivity for neutrinos below 100 GeV and allows the detection of neutrinos with energies down to the order of 10 GeV. Newly developed veto methods against atmospheric muons, that are described here, significantly improve the sensitivities of analyses focused on low-energy events in the Southern Hemisphere. This turns IceCube into an efficient 4π detector for indirect dark matter searches.

Several methods for efficient background rejection and signal selection have been developed in order to achieve this goal. These methods include energy dependent event selection splitting, veto techniques against atmospheric muon background, and the selection of neutrino induced muon tracks starting inside a fiducial volume. In order to apply these techniques, the detector volume is divided into a fiducial and a veto volume. For the 79-string configuration of IceCube the fiducial region is chosen as the DC-fiducial volume, as shown in figure 1.

2.1 Event Selection Splitting

Indirect dark matter analyses with IceCube search for neutrinos originating from WIMPs with masses ranging from ~ 10 GeV to ~ 10 TeV. Within this mass range, signal events can have very different event topologies in the detector. To accommodate all expected event topologies in

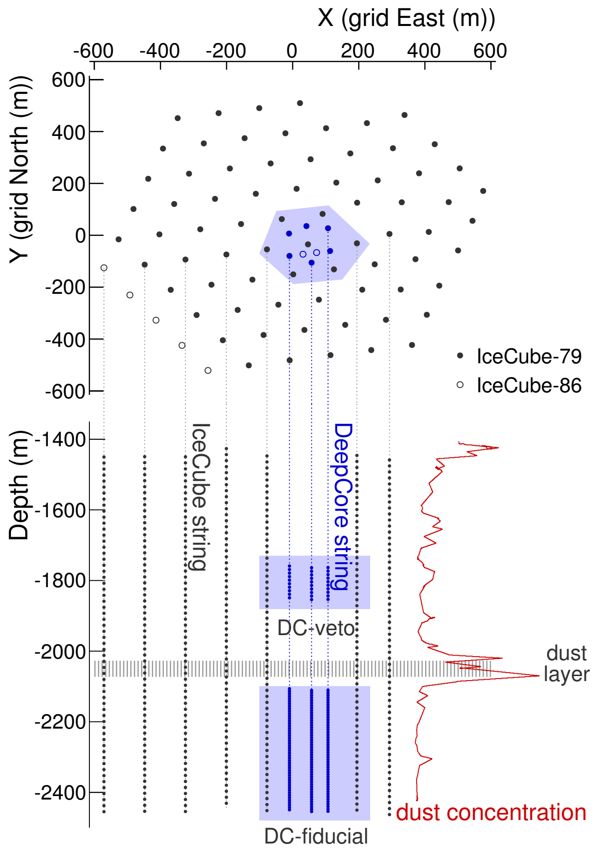

Figure 1: Top and side view of the IceCube detector (black) and its DeepCore subarray (blue). Strings constituting the IceCube 79-string configuration (solid) and the last deployed strings completing the IceCube detector (circles) are indicated. Also shown is the main dust layer within the detector and a dust concentration profile as measured with a dust logger [7].

a single analysis, the full dataset may be split into multiple event selections.

Signal-efficient event selection for low-mass WIMP signals and high-mass WIMP signals is only feasible by imposing different selection criteria. This motivates splitting the event selection into a Low Energy (LE) and a High Energy (HE) event sample, which are treated independently to get the best signal sensitivity for each of the samples. Using DeepCore, the split into a LE and HE event selection can be realized in the following way: events with a larger number of hits inside the DC-fiducial region than outside are assigned to selection LE. Additionally, the number of outside hits must be less than seven. This ensures that events with a long lever arm and therefore good angular resolution are assigned to the HE selection. The step is well motivated by looking at the event topology of the two classes of muon events that are selected for each event sample. The HE selection, defined as the complement of LE, contains high energy events with no containment requirement. Associated muon tracks have accurate track reconstructions and good quality parameters. This is used to separate true up-going muon-like events from mis-reconstructed atmospheric muons, which will exhibit lower quality parameter values. The LE selection consists of shorter track-like

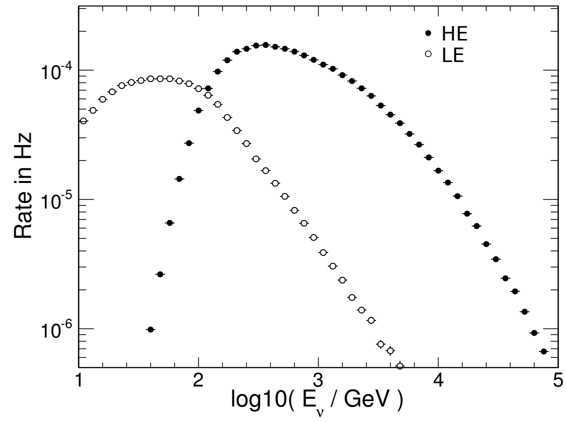

Figure 2: True neutrino energy (E_ν) distributions from simulation for the atmospheric neutrino event rate at cut level 4 of [5]. The low-energy event selection (LE) and high-energy event selection (HE) show a clear separation in E_ν around 100 GeV.

events with, in general, lower track reconstruction quality, but good containment. In this context, creating two independent data samples by splitting the original data set is an obvious choice for a hybrid detector. Figure 2 shows the clear separation into a low and high energy event sample around 100 GeV for atmospheric neutrinos after applying the split criteria.

2.2 Atmospheric Muon Vetos

IceCube observes a continuos stream of atmospheric muon, which are observed as down-going events and are the main background for low energy neutrino full-sky IceCube analyses. A good way to veto down-going atmospheric muons is to search for neutrino induced muon tracks starting within a fiducial volume. In this section, we discuss several such veto methods that have been developed and applied in recent dark matter searches with the IceCube-79 string configuration, detailed in Refs. [4, 5]. Events detected in IceCube consist of recorded photo multiplier tube responses from DOMs that triggered - *hit DOMs*. In the context of this article a hit DOM is denoted simply as a hit. Most reconstructions and variables used for analyses are computed using a subset of hits that has undergone cleaning to reduce the number of random hits. These subsets are defined by different cleaning algorithms based on time windows within the event and requirements on the topology of the hits. Among all veto methods to be described below, only the first uses a subset of hits, while later described veto methods consider all hits in an event.

Veto I: First, an attempt is made to classify an event as starting track inside the fiducial volume, based on the hit times only. This simple veto does not rely on a track reconstruction and is defined in the following way: the first n hits of an event are required to occur inside the fiducial volume. By adapting n to the chosen fiducial volume, backscattering from a starting event into the veto volume is accounted for. For the DC-fiducial region, defined above, $n = 4$ is found to be optimal.

Veto II: A second veto method, *RTVeto*, aims to tag atmospheric muons within the veto region. Faint muon tracks penetrating the detector may be identified by the sporadic clusters of hits they leave when traversing the

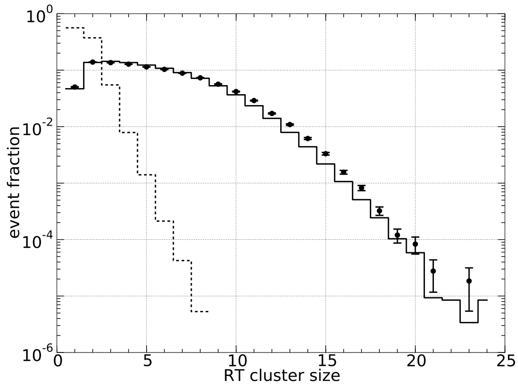

Figure 3: The size of the RT clusters found by RTVeto for atmospheric muon background simulation (solid line) and signal simulation (dashed line). Data is show in black dots.

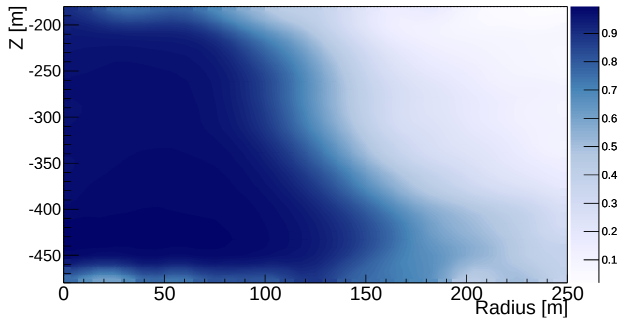

Figure 4: Fraction of signal per bin as a function of radial distance and z, defined as $f_s/(f_s+f_b)$. f_s is the two dimensional probability density function of signal in this plane. f_b is the corresponding probability density function for background, determined from data.

veto region. These clusters of hits are likely to be causally connected. For a given DOM, the algorithm checks whether there are other hits within a specific time and distance in space (RT-condition). If a hit is found that fulfills the RT-condition[1], it is added to the kept set of DOMs (cluster). Furthermore, each added DOM in the cluster is also checked for additional hits that fulfill the RT-condition. We test each hit DOM in the veto region, which has a hit prior to the time of the first fiducial hit, against this condition. If a cluster of at least three hits is found that fulfill the RT-condition (an RT-cluster), the event is rejected. This cut rejects more than 80% of atmospheric muons while keeping 90% of signal neutrino events starting within the fiducial region. This is illustrated in figure 3, which shows the distribution of RT-cluster sizes for data, muon background, and signal.

Veto III: The third veto method is based on the vertical position z of the first hit and the radial distance in the xy-plane of the reconstructed vertex position[2]. The vertex is determined by a reconstruction that uses the likelihood of a muon to produce or not produce hits in the DOMs along the reconstructed track up-stream of an assumed starting point. Maximizing this likelihood gives the location of the interaction vertex. A cut can then be applied to reject background events with high z positions and a reconstructed vertex at the periphery of the fiducial region. This veto, applied in sequence after the previously described veto methods, removes more than 70% background while retaining 90% signal. Figure 4 shows the fraction of signal per bin as a function of radial distance and z. The signal fraction is calculated as $f_s/(f_s+f_b)$, where f_s and f_b are the two dimensional probability density functions of signal and background in this plane, respectively.

Veto IV: Like the previous veto method, the *ConeHitsVeto* relies on a reconstructed track hypothesis and vertex. In this algorithm, a cone is defined around the reconstructed track direction beginning at the reconstructed staring point of the track. The cone is searched for the presence of hits at times earlier with respect to the reconstructed starting time of the track. The presence of too many hits, n_{cone}, inside the cone is evidence of a faint muon, and these events are rejected. To avoid events rejected due to random hits, n_{cone} is optimized with respect to the opening angle, time-window and the veto region. Since the optimal opening angle is in most cases found to be rather small (typically 20° - 30°), this veto method relies to a high degree on an accurate track reconstruction to be efficient.

Veto V: There are two classes of faint incoming muon tracks that, while still producing hits in the veto region, are extremely hard to identify with the veto techniques discussed above. Either the incoming muon produces fewer hits along its path in the veto region than the threshold value of the veto or the hits are too far apart and at some distance from the muon track. To examine suspect hits in the veto region the likelihood for the reconstructed track hypothesis is computed given the hits in the veto region as input. The value of the likelihood indicates how likely the veto hits are compatible with the reconstructed track hypothesis and thus how likely the hits are associated with an incoming muon track. If the likelihood is normalized correctly by taking into account the number of hits considered for the likelihood calculation a threshold value on the normalized likelihood, independent of the number of hits, can be found to reject incoming muon tracks.

3 Application to DM Searches

The veto methods described in the previous sections have been applied by two analyses searching for Dark Matter with WIMP masses in the range of 20 GeV and 10 TeV, using the 79-string configuration of IceCube.

During a recent analysis searching for dark matter in the Galactic Center [4] several of these veto methods were developed. Since the Galactic Center is above the horizon at the South Pole, a big effort was made to reject the down-going muon background. For this purpose the RTVeto (Veto II), the RZVeto (Veto III), and the LHVeto (Veto V) were developed. Vetos I and IV, which have been used in earlier analyses, were also used. The order in which the vetos are presented in section 2.2 is also the order in which they were applied in the analysis. Inspired by the event selection splitting described in section 2.1, two different multivariate cuts were made to define two final event selections. The two event selections result in flatter sensitivity in energy. With these methods sensitivities on the velocity averaged self-annihilation cross-section, $\langle\sigma_A v\rangle$, down to $3\cdot10^{-23}\,\mathrm{cm^3s^{-1}}$ for a 65 GeV WIMP mass were achieved.

1. For the RT condition a radius of 250 m and a time window of 1 μs between hits were applied in this work.
2. The vertex reconstruction is described in Ref. [8].

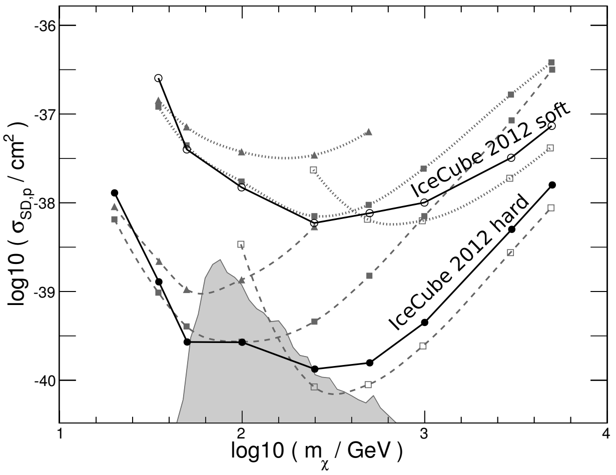

Figure 5: Sensitivities on $\sigma_{SI,p}$ from [5]. Hard channels are shown dashed and soft channels are shown dotted. The winter selection HE has empty square markers, the winter LE is shown with filled square markers, and the summer LE has filled triangle markers. The shaded region represents an allowed Minimal Supersymmetric Standard Model (MSSM) parameter space [9].

An earlier analysis searching for Dark Matter in the Sun [5] was able to set the most stringent limits to date on the spin-dependent WIMP proton cross-section for WIMPs annihilating into W^+W^- or $\tau^+\tau^-$ with masses above 35 GeV. It was also the first low energy analysis in IceCube that managed to expand the search to the southern sky and set limits on WIMPs with masses as low as 20 GeV. This was possible due to the development of the Hit-Time veto (Veto I) described above, an early version of the RZVeto (Veto III) and split datasets. For this particular analysis the data was divided into a down-going and an up-going dataset corresponding in time to the summer and winter dataset, respectively, depending on the position of the Sun in the sky at the South Pole. Furthermore, the winter dataset was divided into a HE selection and a LE selection as described in section 2.1 (see also figure 2). Figure 5 illustrates how the different selections compare to each other and also how they contribute to the final limit.

4 Conclusions

Introducing veto methods in analyses have been crucial to transform IceCube to a 4π detector and thus extending the field of view to the southern sky. We have presented veto methods intended for rejecting muon background while retaining low energy starting events inside a fiducial region. The methods have been developed for IceCube and especially to utilize the DeepCore subarray to detect low energy events. Furthermore, the importance of differentiating between different event topologies when developing an analysis has been discussed. Using the mentioned techniques together with DeepCore, two analyses [5, 4] have been able to set limits or computed sensitivities for WIMP masses which would have been beyond reach for IceCube without DeepCore.

Since the two mentioned analyses, using the IceCube-79 string configuration, are the first to apply these techniques, there is room for improvement. In future analyses using IceCube-86 string configuration fine-tuning the veto methods might be necessary due to slight changes in detector geometry.

Neutrino oscillation analyses have successfully used vetos [10] to reject down-going muon background. With efficient veto methods it is also possible to create down-going control regions which are not affected by neutrino oscillations. The veto methods developed for dark matter searches, presented here, might make it possible to create such control regions with an adequate neutrino purity.

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