Implementation of an active veto against atmospheric muons in IceCube DeepCore

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***Abstract*. The IceCube DeepCore [1] has been designed to lower the energy threshold and broaden the physics capabilities of the IceCube Neutrino Observatory. A crucial part of the new opportunities provided by the DeepCore is offered by the possibility to reject the background of atmospheric muons. This can be done by using the large instrumented volume of the standard IceCube configuration around DeepCore as an active veto region. By thus restricting the expected signal to those neutrino events with an interaction vertex inside the central DeepCore region, it is possible to look for neutrinos from all directions, including the Southern Hemisphere that was previously not accessible to IceCube. A reduction of the atmospheric muon background below the expected rate of neutrinos is provided by first vetoing events in DeepCore with causally related hits in the veto region. In a second step the potential starting vertex of a muon track is reconstructed and its credibility is estimated using a likelihood method. Events with vertex positions outside of DeepCore or with low starting probabilities are rejected. We present here these newly developed veto and vertex reconstruction techniques and present in detail their capabilities in background rejection and signal efficiency that have been obtained so far from full Monte Carlo studies.**

***Keywords*: high energy neutrino-astronomy, IceCube, DeepCore**

I. Introduction

The IceCube Neutrino Observatory [2] is currently being built at the geographic South Pole in Antarctica. After completion it will consist of ∼4800 digital optical modules (DOMs) on 80 strings instrumenting one cubic kilometer of ice at a depth between 1450 m and 2450 m. Each DOM consists primarily of a photomultiplier tube and read-out electronics in a glass pressure vessel. IceCube is designed to detect highly energetic neutrino-induced muons and cascades that produce Cherenkov radiation in the medium. Significant backgrounds to the signal, caused by muons from atmospheric air showers above the detector, limit the field of view to the Northern hemisphere for many studies that use neutrino events in IceCube. In addition to its nominal layout, the DeepCore extension to the observatory will lower the IceCube energy threshold from ∼100 GeV down to neutrino energies as low as 10 GeV. This improvement in the detector energy response is achieved by including 6 extra strings, deployed in a denser spacing, around a standard central IceCube string. Each of these strings will be equipped with 60 DOMs, containing Hamamatsu high quantum efficiency photo multiplier tubes (HQE PMTs). 50 of these DOMs will be placed in a dense spacing of ∼7 m in the lowest part of the detector where the ice is clearest and scattering and absorption lengths are considerably longer [3]. The remaining 10 modules are to be placed in a 10 m spacing at a depth from 1760 m to 1850 m. This position has been chosen in order to improve IceCube's capabilities to actively identify and reduce the atmospheric muon background to the central DeepCore volume, as described below. The HQE PMTs have a quantum efficiency that is up to 40% higher, depending on wavelength, compared to the standard IceCube PMTs, while their noise rate is on average

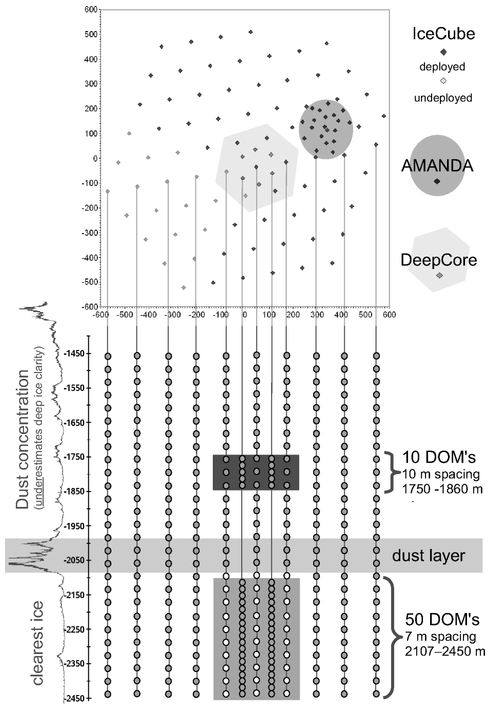

Fig. 1. Schematic view of the IceCube DeepCore

increased by about 35%. Together with the 7 neighboring IceCube strings DeepCore will consist of 13 strings and be equipped with 440 optical modules instrumenting a volume of ∼13 megatons of water-equivalent.

DeepCore will improve the IceCube sensitivity for many different astrophysics signals like the search for solar WIMP dark matter and for neutrinos from Gamma-Ray Bursts [4]. It also opens the possibility to investigate atmospheric neutrino oscillations in the energy regime of a few tens of GeV [5]. An additional intriguing opportunity offered by DeepCore is the possibility to identify neutrino signals from the southern hemisphere. Such a measurement requires a reduction of the atmospheric muon background by more than a factor 10^6 in order to obtain a signal (atmospheric neutrinos) to background rate better than 1. A first step toward achieving this reduction is implicit in the design of DeepCore. Background events which trigger DeepCore with a minimum number of hits in the detector volume must pass through a larger overburden resulting in a order of magnitude decrease to the atmospheric muon rate. Two additional steps are then performed to attain the remaining 10^5 rejection factor. The first is a veto of DeepCore events with causally related hits in the surrounding IceCube volume, reducing the background rate by 10^2 to 10^3. Then we apply a vertex reconstruction algorithm based on a maximum-likelihood method that determines the approximate neutrino interaction vertex. By rejecting events with a reconstructed vertex outside the central DeepCore volume a full 10^6 background reduction can be achieved.

II. Triggering DeepCore

The first reduction of the atmospheric muon background rate, with respect to IceCube, is achieved by applying a simple majority trigger (SMT) to the DeepCore region, based on number of channels registering a hit in coincidence with a neighbor DOM. The trigger hit coincidence requirement, also known as hard local coincidence (HLC), is such that each channel is accompanied by at least one more hit on one of the four closest neighboring modules within a time window of ±1000 ns. The rate of atmospheric muons triggering DeepCore is largely dependent on the multiplicity that is required. In this study we applied a trigger requirement of 6 HLC hits (SMT6), which translates to an average neutrino energy of approximately 10 GeV.

Table I shows the approximate detector rates for the trigger level and after application of the veto algorithm. The background events, muons from cosmic ray air showers, are simulated using CORSIKA [6]. In this study only the most energetic muon is propagated through the full detector simulation. This is a conservative approach since the other muons could only improve the veto efficiency. The signal rate given here is the rate of neutrinos produced in atmospheric air showers and has been determined following the flux calculations of the Bartol group [7]. Neutrino oscillation effects, that

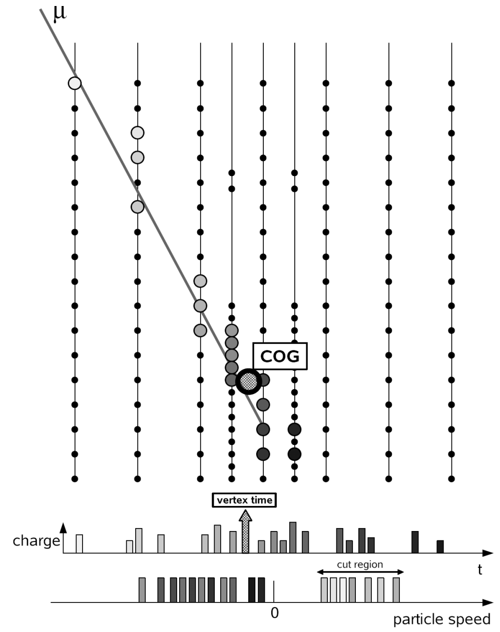

Fig. 2. Scheme of the veto principle: Illustration of the DeepCore hit center of gravity (COG), vertex time and particle speed per hit.

are expected to have an influence on the atmospheric neutrino rate for energies <50 GeV have not been taken into account yet. Since the goal is to identify starting muon tracks specifically, the signal is restricted to those events with a simulated interaction vertex within the DeepCore volume. The efficiencies given in Table I relate to events that fulfill this requirement and have a DeepCore SMT6 trigger. The background rejection factors refer to the expected main IceCube trigger rate, build up from an IceCube only SMT8 trigger, a String Trigger which requires 5 out of 7 aligned modules on a string to be fired in a trigger window of 1500 ns, as well as the DeepCore SMT6 trigger itself. From Table I it is apparent that applying the SMT6 trigger gives a background rate which exceeds the signal by a factor $\sim 10^5$. This sets the challenge for the performance of the veto algorithms to be applied.

III. The veto algorithm

DeepCore is surrounded by more than 4500 DOMs that can be used as an active veto volume to reject atmospheric muons. If hits in the surrounding standard IceCube array are consistent with a particle moving downwards with v=c the event is rejected. In contrast to the triggering, this veto algorithm, as well as, following reconstructions, makes use of all hits in the detector, including hits on DOMs without HLC (a mode called soft local coincidence, or SLC). To reduce the amount of dark noise hits, we rejectany hits that are isolated from others by more than 150 m in distance and by more than 1000 ns in hit time. To determine whether or not to reject an event we initially compute the average hit PMT position and an approximate start time (vertex time) of the DeepCore fiducial volume hits (see Fig.

TABLE I
BACKGROUND AND SIGNAL RATES AFTER DEEPCORE TRIGGER AND CAUSAL HIT VETO

	atm. μ (CORSIKA)	rejection	atm. ν_μ (Bartol)	eff.	atm. ν_μ upwards	atm. ν_μ downwards
main IceCube triggers	2279 s^{-1}	-	-	-	-	-
SMT6 (HLC, signal vertex in DC)	102 s^{-1}	$4.5 \cdot 10^{-2}$	$1.799 \cdot 10^{-3}$ s^{-1}	100%	$0.901 \cdot 10^{-3}$ s^{-1}	$0.895 \cdot 10^{-3}$ s^{-1}
Veto (SLC)	1.2 s^{-1}	$5.4 \cdot 10^{-4}$	$1.719 \cdot 10^{-3}$ s^{-1}	95.5%	$0.863 \cdot 10^{-3}$ s^{-1}	$0.856 \cdot 10^{-3}$ s^{-1}

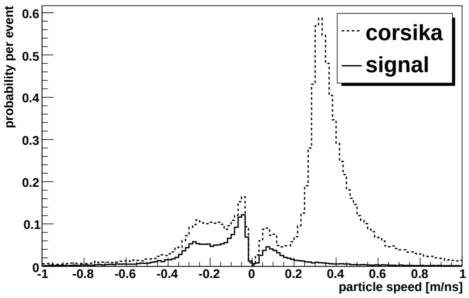

Fig. 3. Particle speed probabilities per event for atmospheric muons (dotted line) and muons induced by atmospheric neutrinos inside DeepCore (solid line).

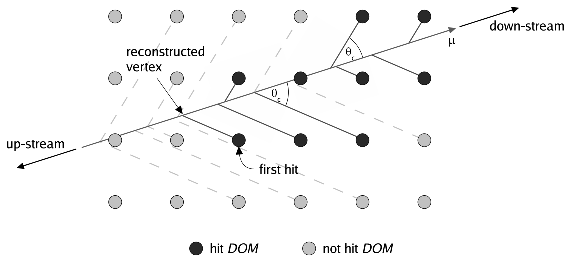

Fig. 4. Principle of the vertex reconstruction

2). The interaction position is determined by using the subset of those hit DOMs that have times within one standard deviation of the first guess vertex time. This has the benefit of reducing the contribution from PMT dark noise and, by weighting the DOMs by their individual charge deposition, a reasonable center of gravity (COG) for the event is computed. By making the assumption that roughly all light in the DeepCore volume originates from the COG a more thorough estimation of the vertex time is possible. For each individual hit the time light would have needed to travel from the COG to the hit module is calculated and subtracted from the original PMT hit time. The average of these corrected PMT hit times is then considered as the vertex time.

Each hit in the veto region gets assigned a particle speed, defined as the spatial hit distance to the DeepCore COG divided by the time difference to the DeepCore vertex time. This speed is defined to be positive if the hit occurred before the vertex time and negative if it appeared after. Causally related hits in the veto region are generally expected to have a speed close to the speed of the muon, which is very close to the speed of light in vacuum (0.3 m/ns). Smaller speeds occur for hits that have been scattered and thus arrive late. Larger speeds are in principle acausal, but since the vertex time represents the start of a DeepCore event, whereas the COG defines its center, the particle speeds for early hits are slightly overestimated. Late hits on the other hand have typically lower speeds. Fig. 3 shows the probability of the occurrence of a particular particle speed per event. The dotted curve describes the simulated muon background from air-showers (CORSIKA) and the solid curve the neutrino signal with an interaction vertex inside DeepCore and a flux according to Bartol the Bartol group [7]. The peak for the CORSIKA muons is slightly above +0.3 m/ns while muons induced by neutrinos in DeepCore mainly give hits with negative particle speeds. The peak at positive speeds close to zero is mainly due to early scattered light. By cutting out all events with more than one hit within a particle speed window between 0.25 and 0.4 m/ns we achieve an overall background rejection on the order of $5 \cdot 10^{-4}$ (see Table I).

IV. THE VERTEX RECONSTRUCTION

To achieve the remaining three orders of magnitude of background rejection, a second algorithm is used. The algorithm analyzes the pattern of hit in an event in conjunction with an input direction and position of a reconstructed track. From this it estimates the neutrino interaction vertex and calculates a likelihood ratio which is used as a measurement for the degree of belief that the track is starting at the estimated position.

As shown in Fig. 4, we trace back from each hit DOM to the reconstructed track using the Cherenkov angle of 41° in ice. This projection is calculated for all DOMs within a cylindrical volume of radius 150 m around the track and the DOMs are ordered according to this position. (Note that 150 m is large enough to contain virtually all photons produced by the track.) The projection of the first hit DOM in the up-stream direction defines the neutrino interaction (reconstructed) vertex. A reconstructed vertex inside IceCube indicates a potential starting (neutrino-induced) track.

Due to the large distance between neighboring strings, atmospheric muons may leak through the veto, producing their first hit deep inside the detector and thus

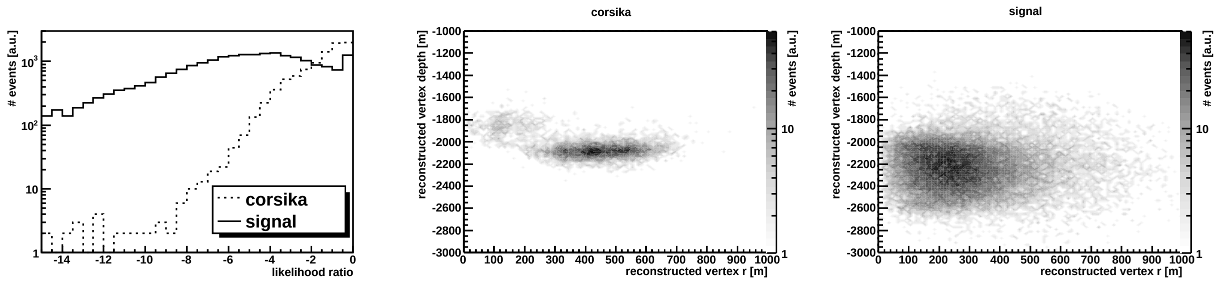

Fig. 5. Distributions of the cut parameters of the vertex reconstruction: Likelihood ratio (left), position of the reconstructed vertex (right).

mimicking the signature of a starting track. Therefore it is necessary to quantify for each event the probability of actually starting at the reconstructed vertex. To determine this starting likelihood, one first selects all DOMs without a hit and with a projection on the assumed track up-stream of the first hit DOM. The probability that each of these DOMs did not receive a hit is calculated assuming two track hypotheses: a track starting at the reconstructed vertex and a track starting outside the detector volume. Under the assumption of an external track $p(\text{noHit}|\text{Track})$ is calculated. Here, for each DOM the probability of not being hit (in spite of the passing track) depends on track parameters (energy of the light emitting particle, position and direction of the track) and ice properties. The probability is calculated from the expected number of photoelectrons, taken from *Photorec* tables of the *Photonics* project [8], assuming Poisson statistics:

$$p_\lambda(\text{noHit}) = p_\lambda(0) = \frac{\lambda^0}{0!}e^{-\lambda} = e^{-\lambda}. \qquad (1)$$

λ is the expected number of photoelectrons. Under the assumption of a starting track $p(\text{noHit}|\text{noTrack})$ is calculated, which is equal to the probability of a noise hit and can therefore be calculated from measured noise rates.

The likelihood for the full, observed pattern of hit DOMs may now be constructed as the product of the individual hit probabilities. A track is classified as starting in the detector according to the probability given by the ratio of the likelihoods. For a clearly starting track this ratio is a negative number, and the larger the value the higher the starting probability for the track.

To select tracks starting inside the detector, cuts are applied on the position of the reconstructed vertex and on the likelihood ratio. Preliminary studies indicate that the remaining background rejection needed can be achieved if the event is required to have a likelihood ratio smaller than -6 with the position of the reconstructed vertex below a depth of 2050 m and within a radius of 260 m around the center of DeepCore. The distributions of the cut parameters are shown in Fig. 5. With the given cuts, the combined veto has a background rejection power of at least six to seven orders of magnitude. The volume defined by this radius and depth cut is larger than the densely instrumented DeepCore volume and thus there is still some room for improvement of the rejection power, although at the cost of maximal effective volume.

V. Summary and Outlook

We have presented the methods developed thus far to reduce the rate of background muon events within the IceCube DeepCore detector. Utilizing the instrumented standard IceCube volume around DeepCore as an active veto to identify and reject atmospheric muon events improves the possibility of detecting neutrino induced muons and cascades independent of direction. The rate of atmospheric muons is mainly reduced in a two step process. First, a veto algorithm is applied against DeepCore events with causally related hits in the surrounding IceCube region. Second, applied to the veto surviving events, a cut has been defined, using a likelihood ratio, to determine the probability that the event had a starting vertex within the fiducial region of the detector. Monte Carlo studies indicate that both methods together are suitable to reduce the background muon rate by more than the factor of 10^6 needed to obtain a signal (atmospheric neutrinos) to background ratio of > 1. IceCube and DeepCore are currently under construction and will be finished in 2011. The fully deployed DeepCore detector will provide an effective volume of several megatons of water equivalent for neutrino events with an energy above 10 GeV and a starting vertex in DeepCore. The exact volume will depend on the required signal-to-noise ratio and the individual analysis strategies.

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