New Background Rejection Methods for the GZK Neutrino Search with IceCube

THE ICECUBE COLLABORATION[1]
[1] *see special section in these proceedings*

Abstract: The detection of cosmogenic (GZK) neutrinos with IceCube requires the ability to discriminate very rare and energetic signal events from an abundant background of cosmic ray induced muons. High energy cosmic ray air showers produce high numbers of muons densely packed around the shower core trajectory. These bundles of muons emit large amounts of Cherenkov light in the ice that constitutes the detection volume. We present several techniques to improve background rejection while keeping a large fraction of the GZK neutrino signal. The differences in the light distributions around a neutrino-induced muon track and a muon bundle are exploited. The photon hit-time pattern in the detector differs slightly for the two event types and is used for identification of muon bundles. The surface array, IceTop, is used to tag the background with high efficiency but limited zenith range. The efficiency of this method was studied using data from the partially completed detector.

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1 Introduction

Ultra High Energy Cosmic Rays (UHECRs) with energies above 10^{11} GeV have been observed by several experiments[1, 2]. The origin of UHECRs remains unknown, though there may be indications of a correlation of incoming directions with the close-by extra-galactic source distribution [3]. The elucidation of the origin has been longed for from the first detection. UHECRs interact with cosmic microwave background photons and necessarily generate neutrinos with energies in excess of 10^7 GeV through secondary pion decays (GZK effect). Therefore, the detection of such Extremely High Energy (EHE) neutrinos can shed light on the UHECR origin.

The IceCube detector [4], completed in Dec. 2010, instruments a huge volume of $1\ \mathrm{km}^3$ ultra transparent glacial ice and is suitable to search for rare EHE neutrino events.

The GZK neutrino flux prediction depends on the cosmological source evolution, the source injection spectra and the cosmic ray composition [5]. The expected GZK neutrino event rate in IceCube is about one event per year [5, 6].

The main background for EHE neutrino search comes from muon bundles induced by cosmic ray interactions in the atmosphere. While bundles are much more abundant compared to the expected neutrino signal, their flux decreases steeply with increasing energy. Therefore signal, expected to have a harder energy spectrum, may emerge from the background above a certain critical energy. In addition, muon multiplicity in bundles increases with the primary cosmic ray energy, which leads to more pronounced background-event signatures and to increasing rejection efficiency. Another difference between neutrinos and muon bundles is their arrival direction. While the muon bundle rate decreases with increasing zenith angle, near horizontal directions are favored for GZK events because of the increase of the neutrino cross section at high energies.

The energy and arrival direction information has been used in several EHE neutrino searches [7, 8] producing the best upper limit for EHE neutrinos in the relevant energy range around 10^9 GeV.

In this paper we present methods which are being developed to achieve higher signal efficiency and high-multiplicity muon bundle background rejection using the characteristic differences between the two.

2 Muon Bundle Rejection Techniques

In Extensive Air Showers (EAS), more than thousands of muons can be generated and reach the IceCube detector

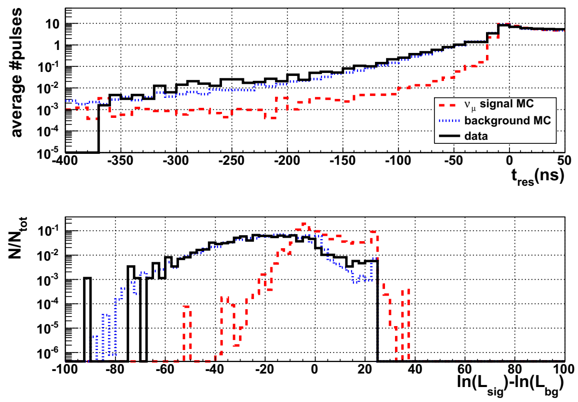

Figure 1: Top: Average number of recorded pulses as a function of the time residual for events with 10,000 <NPE< 30,000. Bottom: negative time residual likelihood ratio distribution for the same events. Dashed red: ν_μ signal simulation, dotted blue: background simulation, black: experimental data.

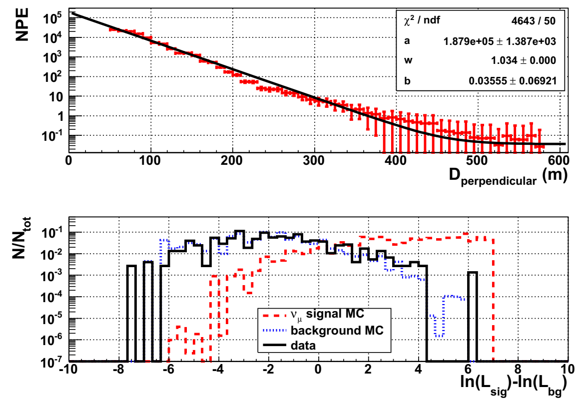

Figure 2: Top: Distribution of detected light perpendicular to a simulated neutrino-induced single muon track (red markers) and the fitted μ function (black) for an event with 100,000 NPE. Bottom: light distribution likelihood parameter ratio distribution for events with $10{,}000 < \text{NPE} < 30{,}000$.

depth, under an ice overburden of about 1500 m. Most of these muons are concentrated in a dense core, but some may have relatively high transverse momenta p_t and are therefore separated from the core of the bundle at the depth of IceCube by a distance $\propto p_t/E_\mu$. Multiple scattering and deflection due to the Earth's magnetic field can increase the separation for near-horizontal events [9]. Observing the separation of single muons within the bundle core is not possible in IceCube as the photon scattering length in ice is too short and the detector's string spacing is too large for this purpose. However, differences in the light distribution around the bundle core compared to that around a single muon can be used to distinguish the two event classes.

2.1 Early Photon Hit Times

The application of a single muon hypothesis track reconstruction [10] to a muon bundle event gives the location and direction of the bundle axis. For each detected Digital Optical Module (DOM) pulse and a given reconstructed track we define the time residual t_{res} as the difference between the measured pulse time and the expected arrival time of an unscattered Cherenkov photon from the single track hypothesis. In the muon bundle case, the light generated by outlying muons may result in pulses with negative t_{res} values, indicating photon arrival times inconsistent with the single track hypothesis. We exploit the density of negative t_{res} pulse distribution by means of a likelihood analysis where signal and muon bundle background hypotheses are compared. The distribution of number of pulses with negative t_{res} values for simulated signal and background, compared to experimental data events for the IceCube 40 string configuration is shown in Fig. 1 (top). The observable NPE refers to the total Number of Photo-Electrons collected in an event by the IceCube DOMs. The resulting likelihood parameter distributions are shown in Fig. 1 (bottom).

2.2 Perpendicular Light Distribution

The amount of detected light at perpendicular distances from a single muon track is a function of the muon energy, ice properties and the detector noise level due to DOM electronics. Its parameterization is described in [11] and is given by

$$\mu(d,\theta,E) = a(\theta,E)\,\omega^{-d/d_0} + b_{\mathrm{noise}} \qquad (1)$$

with d: DOM-track distance, θ: string axis-track opening angle, E: energy of the track and $d_0 = 1\ \mathrm{m}$. Parameter a (in units of NPE) represents the light normalization and is dependent on energy of the track in IceCube, the dimensionless parameter ω describes the shape of the falling light curve and b_{noise} (in units of NPE) gives the expected noise level of the DOMs. Parameters a and ω are both dependent on ice properties which vary with depth [12]. However, it is difficult to resolve the dependency as for each event light is emitted and detected at different ice depths and the dependency is averaged in the fitted parameter values.

Examples for the detected light distribution around a single muon neutrino event and the fitted $\mu(d,\theta,E)$ function are given in Fig. 2 (top). The radial spread of the muons inside the bundle can be up to $\sim$ 50 m, so the perpendicular light distribution at small distances is flatter around a bundle compared to a single muon track. The amount of detected light at larger distances is higher for a single muon track compared to a bundle. This could be because muons in the bundle range out and do not reach the clearest ice at the bottom of the detector and because of large stochastic energy losses in the single muon case. These differences appear mostly in the value of the fitted ω parameter. For

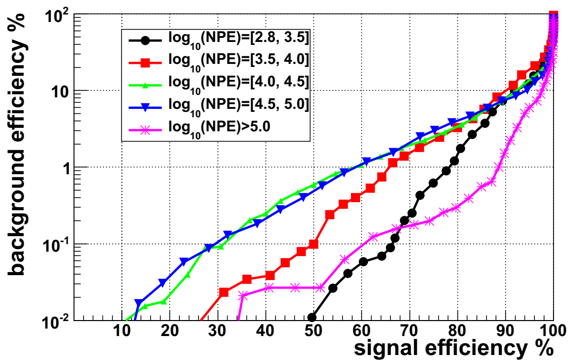

Figure 3: Combined $\Delta\ln(L)$ cut signal efficiency vs. background efficiency. For a signal cut efficiency of 90% the background rejection efficiency ranges from 90%-98% for neutrino energies of $10^{6.5}-10^{11}$ GeV. The curves refer to samples of events with increasing amount of light detected with the IceCube 40 string detector.

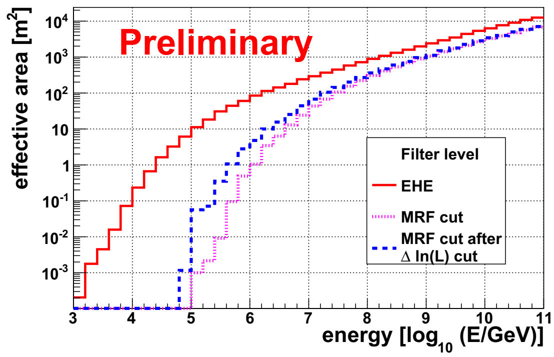

Figure 4: ν_μ effective areas for a simple analysis using a combined $\Delta\ln(L)$ cut on MC simulation of IceCube 40 string configuration. Full red: IceCube EHE events filter level, dotted purple: MRF cut calculated on filter level event sample, dashed blue: MRF cut calculated after applying a combined $\Delta\ln(L)$ cut.

signal and background events in a GZK neutrino search the obtained 2-dimensional distributions of fitted ω versus a values occupy different areas of the phase space. A likelihood parameter comparing signal and muon bundle background hypotheses is constructed and its distributions for the IceCube 40 string configuration simulated and experimental data events are shown in Fig. 2 (bottom).

2.3 Results

The bundle rejection observables described in sections 2.1 and 2.2 were combined in a single likelihood parameter. Background vs signal efficiency is shown in Fig. 3 as a function of a cut on the combined likelihood ratio $\Delta\ln(L)$ defined as $\ln(L_{\rm sig}) - \ln(L_{\rm bg})$. In order to assess the strength of the combined $\Delta\ln(L)$ observable, a cut was set at a fixed $\Delta\ln(L)$ value which gives signal passing rates of $88\% - 97\%$ depending on NPE range. A signal selection NPE threshold was then calculated using the MRF technique [14] on simulated and experimental data that passed both the EHE event filter (NPE > 630) and the combined $\Delta\ln(L)$ cut. The resulting effective areas are shown in Fig. 4.

3 IceTop Veto on Cosmic Ray Showers

An EAS event in the IceCube detector may be preceded by hits recorded in the surface detector IceTop. Therefore another promising technique to discriminate muon bundles from EHE neutrinos is to use IceTop to veto muon bundles. IceTop uses the same DOMs as IceCube to detect the electromagnetic and muonic part of EAS. For the IceTop veto the electromagnetic part plays only a minor role. Inclined EAS are mostly tagged by detection of high p_t muons far away from the shower core.

An efficient IceTop veto against high energy EAS will improve the signal efficiency in a GZK neutrino search. The three main parameters determining the EAS veto efficiency are:

Primary Energy and Composition: The higher the primary energy of the EAS, the higher the probability to see a signal in IceTop, as the number of secondary particles and the lateral extension increases. A higher veto probability for heavier primary particles is expected due to more secondaries.

Distance to IceTop: The shorter the distance of the shower core from IceTop, the higher the probability to detect the event by IceTop. The distance of the shower core can be up to several km, depending on the geometrical hit position in IceCube. This parameter is closely related to the inclination.

Inclination: With increasing inclination the air shower propagates through more atmosphere where the electromagnetic shower component gets attenuated more than the hadronic component. Thus for near-horizontal showers we expect IceTop to detect mainly muons.

Single tank hits in IceTop are used to establish the IceTop veto [13]. These IceTop hits have to be within the time window of several μs of a high energy event that triggered IceCube. In order to find hits in coincidence with the air shower front, we reconstruct the shower front in time and space. Here the center of gravity of the IceCube event and the direction from the track reconstruction are used. A planar shower front is a good approximation to find coincident hits and can be corrected by a parameterization of the shower front curvature. Fig. 5 shows the principal idea of the IceTop veto.

The distribution in Fig. 5 is used to fix the size of the veto time window to 400 ns covering the coincidence peak. For comparison, we take a background time window of the

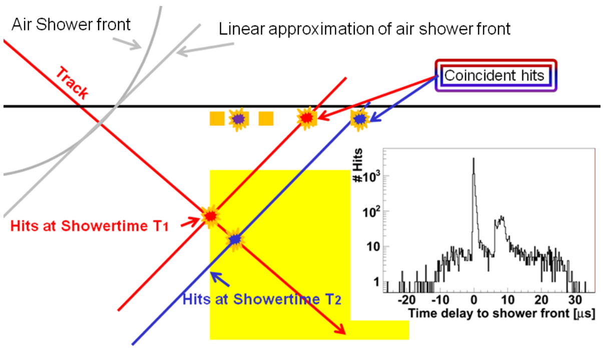

Figure 5: Sketch illustrating the veto principle. The right plot shows the IceTop hit distribution over time relative to the shower front. The sharp peak at $T = 0$ in the plot is caused mainly by coincident IceTop hits. The second peak after the shower front has passed is caused by after-pulses of the photomultipliers.

same length before the shower front reaches IceCube so that only hits from uncorrelated cosmic ray showers are included. The upper plot of Fig. 6 shows the time window selection strategy. The lower plot shows the number of events as a function of hits for both the random and real coincidence time windows. The ratio of the number of events in the real coincidence time window over the number of events in the random coincidence time window for a given number of hits gives the probability of the event to have correlated hits. Due to the low statistics of the available test data (10% of IceCube data taken in 2010 with 79 string configuration), no detailed systematic analysis of the veto efficiency is possible yet. The random coincident background is following Poisson statistics and is independent of the coincident hits. We assume that our data contains exclusively cosmic ray induced events and neglect all other background contributions. Estimates of the veto efficiency have to take into account the full dependences on energy, inclination, and distance to IceTop. All events with an NPE value exceeding 10^5 in the IceCube 2010 test data fulfill the 99.99% coincidence probability (5 hits in the coincidence time window). We conclude that the high veto efficiency at very high energies makes the IceTop veto a powerful instrument for GZK and diffuse neutrino searches.

4 Possible Future Improvements

Other variables are under investigation with the aim of further improving the sensitivity to EHE neutrinos. The longitudinal distribution of the amount of detected photons has been found to differ between a single muon derived from a neutrino and muon bundles [15]. The observed distribution along muon bundles is rather smooth while the one around single muons fluctuates much more and exhibits DOMs that detect very low PE values, which do not exist in the bundle case. It is important to separate EHE neutrinos passing far away from the detector center from the abundant lower energy muon bundles passing well within the fiducial detector volume since both of them yield similar NPE. Time-over-threshold of the recorded charge for each DOM was found to be a good proxy for the distance of light source from the DOM. This information will be used in a future EHE neutrino search as well as utilizing the IceTop veto power.

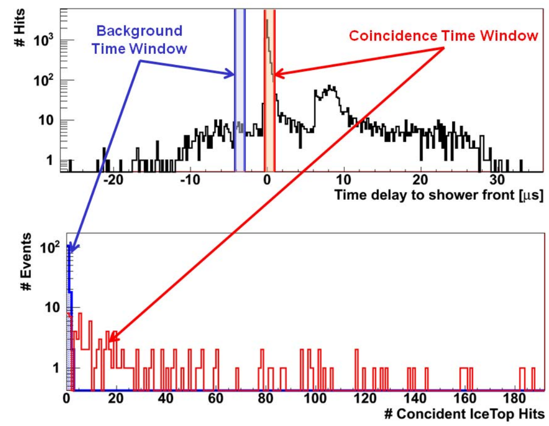

Figure 6: Top: Illustration of the chosen coincidence time windows for events with NPE > 30,000. The background time window contains hits due to background from uncorrelated cosmic ray showers. Bottom: The number of events in the background time window falls steeply as a function of IceTop hits. The distribution for events in the coincidence window is significantly flatter, indicating a preliminary veto efficiency higher than 85% for NPE > 30,000.

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