



Point source analysis for cosmic neutrinos beyond PeV energies with AMANDA and IceCube

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Abstract: The Antarctic neutrino telescope AMANDA-II, part of the IceCube observatory, can be used for searches for cosmic point sources of neutrinos with a wide range of energy. The highest of these energy bands spans from about 10^5 to 10^{10} GeV. Several source models predict a significant neutrino flux in this part of the spectrum, for example from active galactic nuclei. Since the interaction length of neutrinos with energies above $5 \cdot 10^4$ GeV is smaller than the diameter of the Earth the observable area lies mainly in the southern sky, in contrast to point source searches at lower energies. Nonetheless, the low atmospheric muon background at these energies makes such an analysis feasible, and it would comprise some interesting source candidates. We present the methods and sensitivity of this analysis as applied to data collected with the AMANDA-II detector during the year 2004. We comment also on the status of an equivalent analysis being developed for data from IceCube in its nine string configuration of 2006.

Introduction

Active galactic nuclei (AGN), and blazars in particular, are promising sources of high energy neutrinos detectable with the Antarctic Neutrino Telescope AMANDA-II, part of the IceCube observatory. Being candidates for the production of an observed flux of charged particles with energies up to a few hundred EeV, there is reason to expect a measurable neutrino flux beyond PeV energies from this class of objects. Additionally, theoretical models for several of these extra-galactic sources predict their neutrino spectra to be peaked in the PeV to EeV energy range, as for example presented in [7], [8].

An analysis with the aim to find neutrino point sources in this very high energy range is different from other point source analyses, as for example [1]. The usual approach to reduce the background of atmospheric muons is by selecting up-going neutrinos only, i.e. neutrinos which have traversed the Earth before interacting in the ice or bedrock near the detector. This effectively lim-

its the accessible neutrino spectrum due to the increase of neutrino cross section with energy. For multi-PeV neutrinos, the interaction length is much smaller than the diameter of the Earth and thus prevents most of the up-going neutrinos in this energy range from reaching the detector. On the other hand, down-going neutrinos from the southern sky high above the horizon have only the ice above the detector as target material and hence a significantly reduced interaction probability. Thus, a dedicated ultra high energy neutrino analysis must utilize a zenith angle band around the horizon, where the sensitivity of a standard search is limited by atmospheric muons. At higher energies, these muons form a much smaller background due to their soft spectrum. Bringing part of the sky in the southern hemisphere into the field of view also gives the possibility to observe candidate objects not included in other neutrino searches, thus enlarging the angular window where AMANDA-II is sensitive to point source signals.

Source Candidates

The main class of objects which are expected to emit a comparatively large flux of neutrinos at ultra high energies are blazars, particularly the GeV-blazars detected by EGRET and the TeV-blazars discovered by various air Čerenkov telescopes. The analysis is also sensitive to the galactic center as a possible source, lying in a region less than 30° above the horizon. The third EGRET catalog contains 39 confirmed AGN gamma ray sources with declinations between $+20^\circ$ and -30° [6]. The strongest sources have gamma ray fluxes of the order of 10^6 photons $\text{cm}^{-2} \text{s}^{-1}$, integrated for energies above 100 MeV.

In the final analysis, we will select a subset of these objects to avoid reducing the statistical significance by trial factors. As a first approach to find a suitable classification and identify the blazars with the highest potential as neutrino point sources, we extrapolate each gamma ray flux distribution to higher energies. The flux distribution is approximated with a power law $F(E) = F_0 \cdot E^{-\Gamma}$ where E is the photon energy and F_0 the flux normalization, making use of the spectral index Γ as measured by EGRET. For our current purposes of comparing the candidates we assume a direct correlation between photons and neutrinos. We calculate the integrated photon flux $F_I = \int_{E_{th}}^{\infty} F(E) dE$ with $E_{th} = 100$ TeV as the lower energy threshold for this analysis. The resulting maximum values for individual sources lie in the order of 10^{-10} photons $\text{cm}^{-2} \text{s}^{-1}$.

We work on improving this first classification by using the parametrization of spectral energy distributions for blazars as presented in [4], with the plan to perform a more detailed study of flux predictions by individually fitting the observed EGRET spectra to the hadronic model used in [2]. In addition to the GeV blazars, the source list will include the galactic center and four TeV-blazars located in the chosen zenith band, as shown in Table 1.

Reconstruction Methods

The point source analysis for neutrinos beyond PeV energies we present here is developed for data from the AMANDA-II detector during the year

| Name | Dec [$^\circ$] | RA [$^\circ$] | z |
|-----------------|------------------|-----------------|-------|
| H 2356-309 | -30.62 | 359.75 | 0.165 |
| PKS 2155-304 | -30.22 | 329.50 | 0.116 |
| 1ES 1101-232 | -23.48 | 165.75 | 0.186 |
| M87 | 12.50 | 186.00 | 0.004 |
| Galactic center | -29.00 | 266.25 | 0.000 |

Table 1: TeV-blazar source list and the galactic center with information on declination (dec), right ascension (RA) and redshift (z).

2004. The detector consists of 677 optical modules (OMs) on 19 strings, most of which are deployed at depths between 1.5 and 2 km in the deep ice located at the Geographic South Pole. For this analysis we use the 540 OMs that show a stable performance. The analysis strategy is based on identifying tracks from neutrino-induced muons passing through the detector and emitting Čerenkov radiation.

To account for photon scattering in the ice, it is necessary to use likelihood algorithms to reconstruct particle tracks. An iterative maximum likelihood fit of the photon arrival times in the OMs finds the most probable muon track [3]. As a parametrization of the light propagation in ice we use an empirical model of the ice properties. The standard version of this likelihood approach includes only the timing information of the first photon hit in each photomultiplier. Monte Carlo simulations show, however, that the angular resolution of AMANDA-II with this reconstruction method degrades for higher energies. A high energy muon emits more photons per track length than one at lower energies. As photons are scattered independently in the ice, the order of arrival of multiple photons in one OM is not identical to their sequence of emission from the track. As a remedy for this we use an improved version of the likelihood fit. The likelihood is given by the probability that any of the detected photons in an OM arrives at the time of the first hit recorded in that OM and all other photons arrive at a later time [3]. This requires a numerical integration over the probability density function which is computationally expensive.

For this reason, it is not possible to run the improved fit iteratively for each event, but instead the

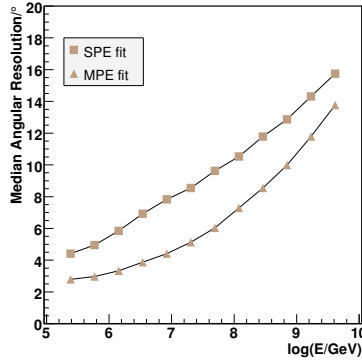


Figure 1: Median angular resolution in degrees as a function of primary neutrino energy from Monte Carlo simulation, reconstructed with the simple (SPE) and improved fit (MPE) accounting for multiple scattered photons. These resolutions are based on the discussed event sample with more than 140 hits and a one-photoelectron fraction smaller than 0.72.

track result of the standard likelihood fit is taken as the initial hypothesis for the improved likelihood maximization. In Monte Carlo simulations of a signal neutrino flux between 10^5 and 10^{10} GeV this method shows an improvement in median angular resolution. For an E^{-2} spectrum the angular resolution obtained with the improved fit is 3.87° , compared to 6.9° for the standard approach. The resolution as a function of primary neutrino energy for the standard fit and improved fit method is shown in Fig. 1. The whole analysis was performed using the IceCube software framework to simplify the use and exchange of tools and method implementations [5].

Event Selection

From the data collected with AMANDA-II in ca. 195 days of lifetime during 2004 we select events with a large light output that is likely to be caused by high energy events. We require at least 140 hits in the detector and a fraction of one-photoelectron hits smaller than 0.72. This results in a data sample of approximately $1.5 \cdot 10^7$ events. Standard cleaning procedures are applied to the sample to eliminate isolated hits and reduce electronically induced

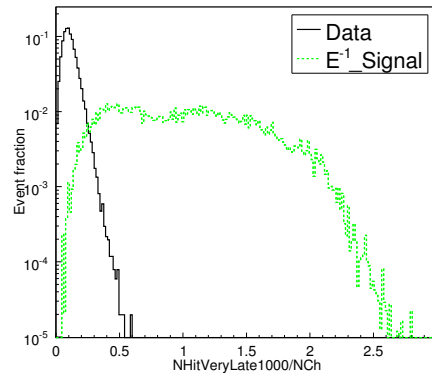


Figure 2: Ratio of late hits (hits occurring more than 1000 ns after the first hit in that OM) to the number of hit OMs for an E^{-1} signal spectrum and experimental data.

cross-talk.

The main background dominating the data sample after this first selection is intense muon bundles from energetic cosmic ray air showers, which can fake the signature of a single muon of higher energy. However, the light from intense muon bundles is expected to be distributed more evenly through the detector as it is emitted from multiple tracks instead of a single one as in the case of a signal event. A multi-PeV neutrino-induced muon emits significantly more photons through stochastic energy losses and Monte Carlo Simulations show that this leads to a higher fraction of very late hits. We define very late hits as hits occurring more than 1000 ns after the first hit in the same OM. These can be caused by scattered photons or afterpulses in the photomultipliers. Normalizing the number of OMs with very late hits to the number of hit OMs yields a useful basic discrimination variable between expected signal and background, see Fig. 2.

Due to the long computation time of the improved likelihood method, this selection is also motivated by reducing the number of events before reconstruction. Hence, choosing a cut value for the afterpulse fraction is based on the aim to keep approximately 20 % of the (background dominated) data. Monte Carlo simulations of signal and background show that this implies a signal passing rate of 94 % for an E^{-1} spectrum and 98 % for an E^{-2} muon-neutrino spectrum. Therefore we select events with

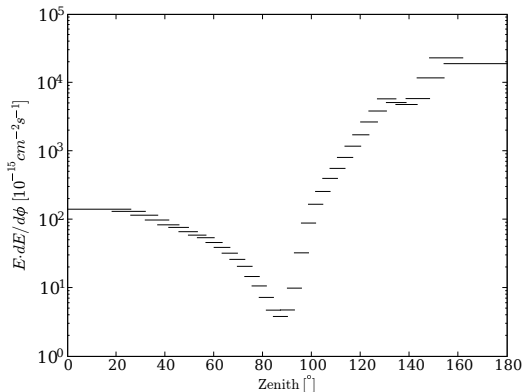


Figure 3: Preliminary sensitivity for this analysis for an E^{-1} flux of muon neutrinos in the energy range from 10^5 GeV to 10^{10} GeV vs. zenith angle. The upper limit is shown as a limit to the normalization constant Φ_0 of the differential flux $d\Phi/dE = \Phi_0 E^{-1}$. The horizontal lines indicate the width of the overlapping zenith bands where the cuts were independently optimized for sensitivity.

a fraction of OMs with very late hits larger than 0.16.

To estimate a sensitivity for this analysis, a number of background-signal discrimination variables have been examined. In a first iteration three variables sensitive to the light distribution in the detector and with respect to the track fit were chosen. These variables are the number of photons registered outside a 50 m cylinder around the track fit, the ratio of hit channels to the total number of hits and the ratio of late hits to the total number of hits. The cuts on these variables were optimized for sensitivity in different zenith bands, using the data as a background estimate. The achieved preliminary sensitivity versus zenith angle for this analysis can be seen in Fig. 3.

Conclusions and Outlook

Presented here is a dedicated analysis for the search for point-like sources of cosmic neutrinos beyond PeV energies. Our strategy enlarges the window for potential discoveries with AMANDA-II to parts of the southern sky and improves the methods for detecting neutrino events at the high-

est energies.

The concept of this analysis is currently being developed further with the aim to be applied to the data taken with IceCube in the nine string configuration of 2006. A preliminary study of reconstruction methods after a basic selection of high multiplicity hits shows an angular resolution of approximately 3° . Due to the asymmetric detector configuration the sensitivity of the analysis is not expected to improve much compared to the results presented here for AMANDA-II. A significant improvement of the sensitivity for point-like neutrino sources with extremely high energies can be expected with the 22-string configuration of IceCube in 2007.

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