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Search for Neutrino-Induced Cascades with AMANDA data taken in 2000-2004

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Abstract: The Antarctic Muon And Neutrino Detector Array (AMANDA) is a Cherenkov detector deployed in the Antarctic ice cap at the South Pole [1]. The charged-current interaction of high-energy electron or tau neutrinos, as well as neutral-current interactions of neutrinos of any flavor, can produce isolated electromagnetic or hadronic cascades. There are several advantages associated with the cascade channel in the search for a "diffuse" flux of astrophysical neutrinos. The energy resolution of AMANDA allows us to distinguish between a hard astrophysical spectrum and a soft atmospheric spectrum. In addition, the flux of atmospheric electron neutrinos is lower by an order of magnitude relative to atmospheric muon neutrinos, while the background from downward-going atmospheric muons can be suppressed due to their track-like topology. The low background in this channel allows us to attain 4π acceptance above energies of ~ 50 TeV. We present the analysis of AMANDA data collected during 2000-2004. Compared to our previous analysis, this data set is a factor of five larger, resulting in a correspondingly improved sensitivity for the flux of astrophysical neutrinos.

Introduction

There are several theoretical predictions that cosmic neutrinos are produced by accelerated protons within high-energy astrophysical objects such as Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB). Neutrinos can propagate in straight lines through the universe as they are not effected by magnetic fields of the galaxy and essentially do not interact with particles on the way to the earth. They are expected to be produced in the source with a ratio $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$ but due to flavor-mixing during propagation a $1 : 1 : 1$ ratio is expected at the detector. However, due to the very small cross-section neutrinos are also difficult to detect. In order to perform a search for galactic and extragalactic neutrinos, the AMANDA telescope was installed in the antarctic ice cap at the geographical South Pole and has been operating since 2000. It consists of 677 optical modules (OM) which are attached to 19 strings and buried at depths from 1500 m to 2000 m under the ice surface. Each optical module contains a photomultiplier suited to register Cherenkov light emitted by a charged particle which is produced in the neutrino interaction. The signature of a charged-current interaction of ν_e and ν_τ is an electromagnetic and a mainly lower energetic hadronic cascade. Via neutral-current interaction, neutrinos of any flavor can produce isolated hadronic showers. This analysis is focused on a search for neutrinos from unresolved sources (diffuse flux) which have a cascade-like signature in the AMANDA detector. The muon-like events are the main background for this analysis. In the cascade channel the direction of the incoming neutrino is poorly reconstructed, however, the energy resolution of the detector for cascade reconstruction is $\mathcal{O}(\log(\mathrm{E}_\nu)) = 0.18$. By removing track-like events, one can eliminate most of the background from atmospheric muons. In addition, the flux of atmospheric electron neutrinos is much lower than the flux of muon neutrinos.

Experimental data and MC simulation

The experimental data used in this analysis were collected between 2000 and 2004. After excluding bad and unstable runs from the analysis we end up with a lifetime of 1000.1 days, where in total 8.8×10^9 triggered events were recorded. The main contribution are muons from meson decays in the atmosphere.

The atmospheric muon background was simulated with CORSIKA [2]. To reach large statistics for the high energy part of the background spectrum with acceptable computing time, about 5000 days of downgoing atmospheric muons were generated with energies above 5 TeV. For comparison a smaller sample of standard CORSIKA events was produced.

The cascades were simulated with ANIS [3] generating all three neutrino flavors (ν_e, ν_τ and ν_μ) at energies between 100 GeV and 100 PeV assuming an E^{-1} energy spectrum. The resulting muons were further propagated using MMC (see [4] for details). The signal spectrum was reweighted afterwards to a hypothetical E^{-2} flux of ν_e. Atmospheric ν were simulated by reweighting the same neutrino events to a steeper $\sim E^{-3.7}$ spectrum [5].

Analysis Optimization

The analysis consists of several filter levels including reconstruction of the cascade vertex and energy as well as a few quality cuts to select high quality events. The reconstruction algorithms based on the likelihood minimization method are described in [4, 6]. The vertex resolution of cascade-like events is about 4 m. Quality cuts were performed using the likelihood values L_{vertex} and L_{energy}, given by reconstruction algorithms.

In order to reduce events with a mis-reconstructed vertex, the cut on the vertex likelihood function has been applied, $L_{\text{vertex}} < 7.1$. The cut on the energy likelihood L_{energy} was performed as function of the reconstructed energy. Another energy-dependent cut was applied on the radial distance of the reconstructed vertex position ρ_{xy}. For $E_{\text{reco}} < 1.25$ TeV this cut was set such that only events with the reconstructed vertex position within a 100 m radius from the detector center (fiducial volume of AMANDA) were used in the analysis. Taking into account that the higher energetic events are often reconstructed at distances outside of the detector and the fact that the anticipated background is rather small for these energies, we allow an energy dependent increase of the volume above $E_{\text{reco}} > 1.25$ TeV.

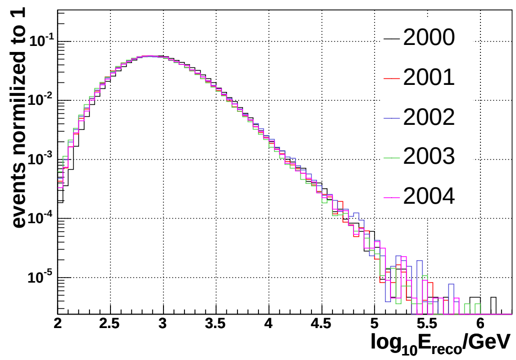

Figure 1: The reconstructed energy distribution of cascade candidate events for the five years (2000-2004) used in this analysis.

By this filter, the set of experimental data is reduced by a factor of 10^5. Fig. 1 shows the reconstructed energy of cascade candidates for the different years. Small variations arise from slightly different hardware configuration for different periods.

At the final filter level, two additional cuts were performed and optimized for the analysis. In addition to a cut on E_{reco} we introduced a discriminating parameter Q_{s} that involves the following set of three variables:

- vertex likelihood value L_{vertex},
- $\cos(\theta_\mu)$ taken from muon track likelihood reconstruction,
- radial distance, ρ^{60}_{xy}, between the vertex position of two likelihood vertex fits; the second fit is thereby not using hits within a 60 m sphere around the vertex position determined by the first fit.

The method to construct the discriminating parameter Q_{s} is described in more detail in [7]. The three distributions are shown in Fig. 2 for signal and background Monte Carlo and for experimental data. All distributions for data and background MC

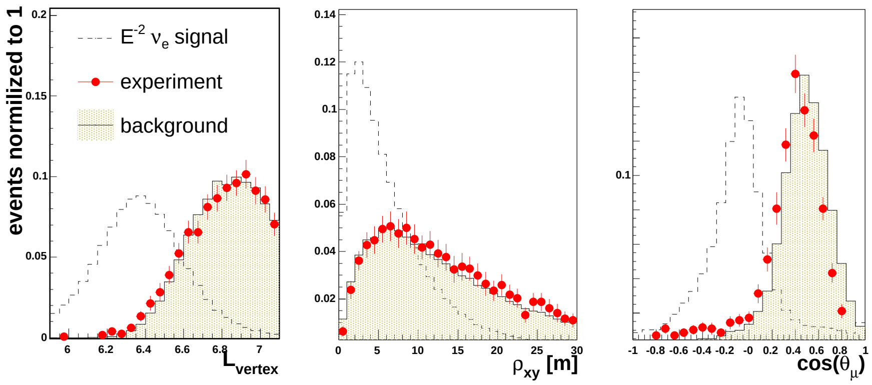

Figure 2: Distributions of the three variables used to construct the discriminating parameter Q_s for the experimental data, the background and the signal MC. Left: vertex likelihood distribution for signal and background. Middle: ρ_{xy}^{60} distributions (see text for details). Right: $\cos(\theta_\mu)$ distribution taken from the iterative muon likelihood reconstruction.

are in a good agreement apart some discrepancy in the $\cos(\theta_\mu)$ distribution. The reason for this could be an incorrect simulation of the ice properties and it needs to be taken into account in the systematic error. To maintain blindness we used only 20% of the experimental data to perform the final cut optimization. However, the optimization was done assuming the statistics of the full data sample i.e. the data were re-scaled by a factor of five. In Fig. 3 one sees the energy spectra for signal and background Monte Carlo and for experimental events which passed through the cascade filter. Here the background distribution was normalized to the experiment.

The final cuts on the reconstructed energy were applied following the optimization method described in [8]. This cut was performed in order to separate the potential signal from the background. Both cuts Q_s and E_reco were chosen to result in the highest sensitivity to an astrophysical neutrino flux. The sensitivity is defined here as the average upper limit [9] which was obtained in an ensemble of identical experiments in absence of the signal. In Fig. 4, the average upper limit $\bar{\phi}$ is shown as a function of E_cut for $Q_\mathrm{s} > 0.92$. This procedure was repeated for a large range of Q_s values in order to obtain the optimal discriminating parameter and energy cut. To make a smooth background interpolation possible, the background

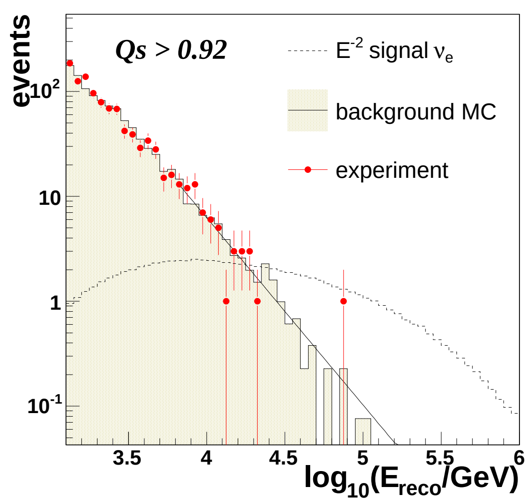

Figure 3: The reconstructed cascade energy distribution E_reco. Shown are experimental data as well as background and signal Monte Carlo simulation after application of all quality cuts and a cut on the discriminating parameter $Q > 0.92$. The smooth line is a result of the power-law fit to the background simulation.

distribution was fitted with a power-law function (see Fig. 3). For the discriminating parameter the optimal cut is at $Q_s > 0.92$. The energy cut obtained from the optimization is $\log(\mathrm{E}) > 4.65$. The corresponding sensitivity on the flux of ν_e is $2.7 \times 10^{-7}(\mathrm{E/GeV})^{-2}/(\mathrm{GeVs\,sr\,cm^2})$.

There is 1 event from the 20% experimental data subset passing this cut. We expect 1.3 background events from atmospheric muons. The expectation for the atmospheric ν_e and ν_μ which passed all cuts is 0.02 events for the 20% sample. No systematic uncertainties have been estimated yet, however, the uncertainties in the detector response and in the predictions of the atmospheric muon and neutrino fluxes are expected to be substantial.

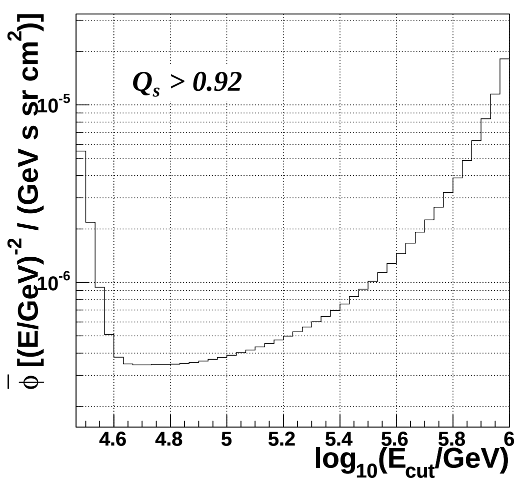

Figure 4: The average upper limit as a function of energy cut. The best sensitivity is reached for $\log(\mathrm{E_{cut}}) = 4.65$.

Results

Analyzing a 20% sub-sample of the 5 years AMANDA data, a search for cascade-like events was performed. The observed events from experimental data are statistically consistent with the background expectation. The expected number of signal events from a diffuse flux assuming a E^{-2} spectra and a strength of $10^{-7}(\mathrm{E/GeV})^{-2}/(\mathrm{GeVs\,sr\,cm^2})$ is 2.1 ν_e events, leading to a preliminary sensitivity on the ν_e flux of $2.7\times10^{-7}(\mathrm{E/GeV})^{-2}/(\mathrm{GeV\ s\ sr\ cm^2})$. Fig. 5 shows the effective areas after all selection cuts combined for neutrinos and anti-neutrinos. The effective area for tau neutrino is larger at high energy due to tau regeneration. Anti-electron neutrinos show a large increase in the effective area near 6.4 PeV due to the Glashow resonance.

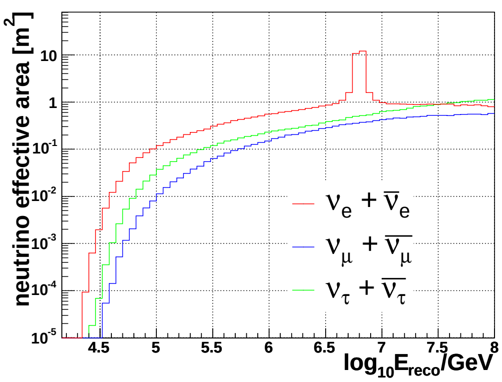

Figure 5: The effective neutrino areas for ν_e, ν_μ and ν_τ are shown as a function of neutrino energy after all selection criteria have been applied.

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