29th International Cosmic Ray Conference Pune (2005) **5**, 111–114

Sensitivity of AMANDA-II to UHE Neutrinos

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The sensitivity of the AMANDA-II detector to ultra high energy (UHE) neutrinos (energy greater than 10^6 GeV) is derived using data collected during the year 2000. Due to absorption of UHE neutrinos in the earth, the signal is concentrated at the horizon and has to be separated from the background of large muon-bundles induced by cosmic ray air showers. This analysis leads to a sensitivity for an E^{-2} all neutrino spectrum (assuming a 1:1:1 flavor ratio) of 3.8 x 10^{-7} $cm^{-2}s^{-1}$ sr^{-1} GeV for an energy range between 1.8 x 10^5 GeV and 1.8 x 10^9 GeV. Sensitivities for five years of data taking and the future IceCube array are given.

1. Introduction

AMANDA is a large volume neutrino telescope with the capability to search for neutrinos from astrophysical sources [1]. In a previous publication [2] it was shown that neutrino telescopes are able to search for UHE neutrinos (neutrinos with energy greater than 10^6 GeV). UHE neutrinos are of interest because they are associated with the potential acceleration of hadrons by AGNs [3, 4, 5], are produced by the decays of exotic objects such as topological defects [6] or z-bursts [7] and are guaranteed by-products of the interaction of high energy cosmic rays with the cosmic microwave background [8].

Above 10^7 GeV the Earth is essentially opaque to neutrinos [9]. This, combined with the limited overburden above AMANDA (approximately 1.5 km), means that UHE neutrinos will be concentrated at the horizon. The background for this analysis consists of bundles of down-going, high energy muons from atmospheric showers. The muons from these bundles can spread over areas as large as 10^4 m^2. Separation of signal from the background takes advantage of the fact that signal events have a higher light density than background events, which causes multiple hits in multiple channels. Using this as well as the differences in geometrical acceptance and hit topology it is possible to remove almost all background while retaining a high sensitivity to signal. A previous analysis was performed using the inner ten strings of AMANDA (called AMANDA-B10) [2]. This analysis uses all nineteen strings of AMANDA (called AMANDA-II, for description see [1]). Although the effective area of AMANDA-II is approximately the same as AMANDA-B10 for this analysis, the larger number of optical modules (OMs) offer improved background rejection leading to an improved sensitivity.

2. Experimental and Simulated Data

AMANDA-II collected 6.9 x 10^8 events between February and November of 2000, with an integrated lifetime of 173.5 days after retriggering and correcting for dead time and periods where the detector was unstable. Of this data 20% was used to develop selection criteria, while the rest, with a lifetime of 138.8 days, is set aside for the final analysis. Two sets of cosmic ray air shower background events were generated using CORSIKA [10]. One set uses composition and spectral indices from [11], i.e. the spectra follows approximately E^{-3}. In the other set, the statistical error and CPU time were reduced by biasing the Monte Carlo generation in both energy and composition (see [2] for a full description). The UHE neutrinos were generated with energies between 10^3 GeV and 10^{12} GeV using ANIS [12]. For more details on AMANDA simulation procedures see [1, 2].

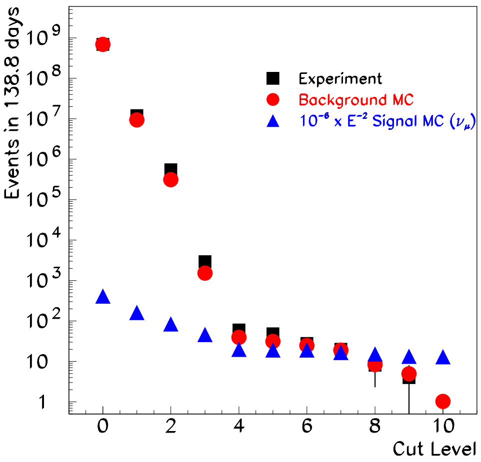

Figure 1. The number of events passing the cuts as a function of cut number. The values for the experimental data are estimated from a 20% subsample. Errors are statistical. The background MC has been scaled by a factor of 1.24 so that the event rate agrees with the experiment at level 0. The signal MC is shown with a lower energy threshold of 10^5 GeV.

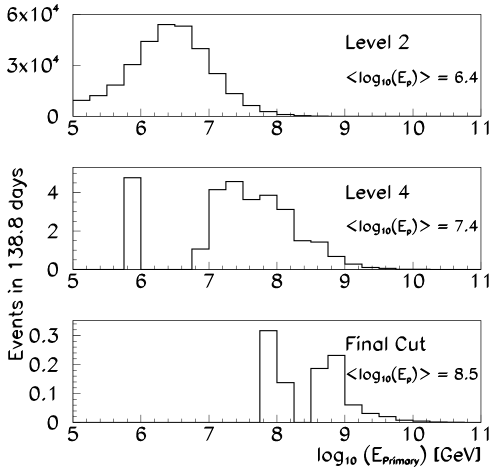

Figure 2. The distribution of primary energy for simulated background at three different cut levels. The data shown is from the biased CORSIKA simulation and demonstrates the removal of lower energy background events by this analysis.

3. Method

Twenty percent of the data from 2000 (randomly selected from February to November) was used to test the agreement with background MC. Following a blind analysis procedure this 20% will be discarded and the developed selection criteria will be applied to the remaining 80% of the data. Final cut values will be chosen by optimizing the model rejection factor [13] for an E^{-2} spectrum.

This analysis exploited the differences in light deposition caused by bundles of many low energy muons and single high energy muons. A muon bundle with the same total energy as a single high energy muon spreads its light over a larger volume, leading to a lower light density in the array. Both types of events have a large number of hit channels, but for the same number of hit OMs, the muon bundle has a lower total number of hits (NHITS). It also has a majority of OMs with a single hit, while the signal generates more multiple hits. The number of secondary hits is increased by the tendency of bright signals to produce afterpulses in the photomultiplier tube. The large amount of light deposited by high energy muons is also utilized in the reconstruction. The reconstruction algorithms used by the AMANDA Collaboration are optimized for the reconstruction of low energy muon bundles (from primaries with energies less than approximately 10^4 GeV), which makes them inaccurate for reconstructing the direction and energy of single high energy muons. However, loose cuts may be placed on the zenith angle based on the expectation that signal will come primarily from the horizontal direction, while background will come from the vertical, down-going direction. Single, high energy muons will also have distinct time residual distributions. The cylindrical geometry of the AMANDA-II array is also used to separate signal from background by estimating arrival direction. Down-going muon bundles will travel along the vertical strings of OMs in AMANDA-II. This, combined with asymmetries in the physical location of strings in the AMANDA-II array, pulls the center of gravity of hits away from the physical center of the array. Light from a single high energy muon will pass through a horizontal cross section of the array striking multiple strings, which pulls the center of gravity of hits closer to the physical center of the array.

Applying cuts on NHITS and the fraction of hit OMs with exactly one hit (F1H) reduced the data samples by a factor of 10^3 relative to retrigger level. At this point the data sets are split into a ”high energy” and a ”low energy” sample according to the energy deposited inside the array. A neural net trained on F1H, the closest distance between a reconstructed track and the detector center, and the radial distance from the center of the detector to the center of gravity of hits (RDCOG) served as an estimate of this energy selection value.

The average energy of signal neutrinos in the ”high energy” subset is 10^8 GeV. The energy deposited inside the array by these neutrinos is much greater than the energy deposited by a typical background event. This allows the application of simple selection criteria to separate signal from background events. Loose cuts on reconstruction variables, F1H and number of hit channels are sufficient to reduce the background expectation to less than 1 event for 138.8 days in this subset.

The ”low energy” subsample consists of neutrinos with an average energy of less than 2 x 10^6 GeV. As the energy deposited inside the array by a typical background bundle of muons begins to approach the energy deposited by a single astrophysical neutrino, more refined selection criteria which depend on subtleties of the distribution of hit times must be utilized. The production of afterpulses by signal events, combined with the inaccurate reconstruction of signal direction means that UHE neutrino events have an excess of hits with a large time residual relative to the reconstructed track. A cut based on the timing of hits has been devised to take advantage of this. Additionally, for the low energy subsample it is possible to take some advantage of differences in hit topology and multiplicity. Cutting on NHITS, the moment of inertia of the hits and the F1H of a subset of OMs helps to effectively separate signal from background. All these cuts, combined with cuts on reconstruction variables reduced the background by a factor of 10^8 relative to retrigger level.

As can be seen from figures 1 and 2, this analysis is effective at removing lower energy background events while retaining higher energy signal events.

4. Results and Outlook

Applying all the selection criteria leaves 1.0 ± 0.4 background MC event and 0 experimental events in the 20% sample. The expected sensitivity [14] for an E^{-2} all neutrino spectrum (assuming a 1:1:1 flavor ratio) is 3.8 x 10^{-7} cm^{-2} s^{-1} sr^{-1} GeV with ninety percent of the events between 1.8 x 10^5 GeV and 1.8 x 10^9 GeV (fig. 4). This sensitivity is nearly a factor of two improvement over the previous limit set using AMANDA-B10. The expected neutrino effective area (fig 3) is approximately the same as that of the previous analysis, but this analysis has increased background rejection which leads to an improved sensitivity.

Results from the analysis of the complete year 2000 data will be presented at the meeting. The AMANDA-II detector has been running since the beginning of 2000. Scaling this analysis to five years of AMANDA-II data results in an improvement of the sensitivity by a factor of 4. We expect additional improvements from the TWR system [15] installed at the end of 2002. The TWR system provides additional information which will increase AMANDA-II's sensitivity to high energy events. For the future, the IceCube detector expects a sensitivity of 4.2 x 10^{-9} cm^{-2} s^{-1} sr^{-1} GeV (for 10^5 GeV to 10^8 GeV) for three years of operation [16].

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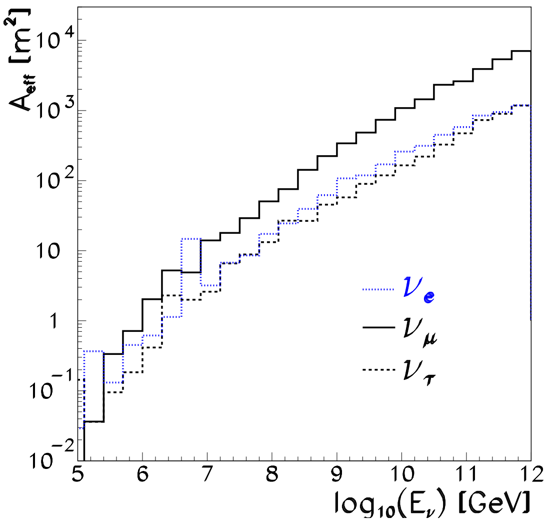

Figure 3. Effective area averaged over all angles after all selection criteria have been applied as a function of neutrino energy. The peak in the electron neutrino effective area just below 10^7 GeV is due to the Glashow resonance.

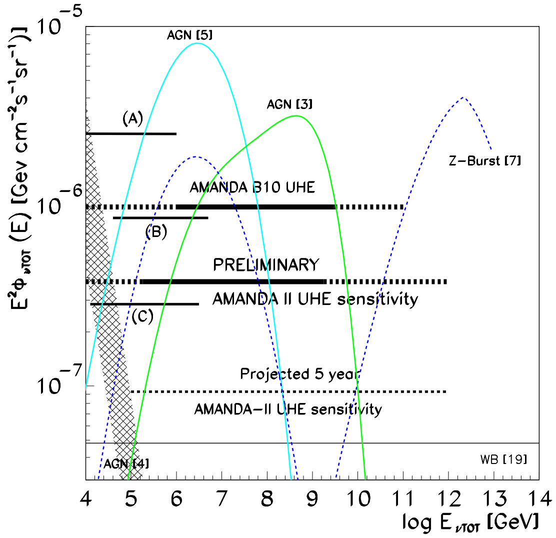

Figure 4. Limits on the flux of astrophysical neutrinos for an E^{-2} spectrum. Shown are the results from the AMANDA B10 diffuse (A) [17] and UHE analyses [2], the AMANDA-II cascade analysis (B) [1], the sensitivity of the three year AMANDA-II diffuse analysis (C) [18], and the expected sensitivities for the AMANDA-II UHE analysis and five years of AMANDA-II. Solid lines indicate the 90% CL limit setting potential for an E^{-2} spectrum. Also shown are the expected fluxes from a representative set of models.

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