Multi-year Search for UHE Diffuse Neutrino Flux with AMANDA-II

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Abstract: AMANDA-II is a high volume neutrino telescope designed to search for astrophysical neutrinos. Data from 2000 - 2002 has been searched for a diffuse flux of ultra-high energy (UHE) neutrinos with energies in excess of 10^5 GeV. Due to absorption of UHE neutrinos in the earth, the UHE signal is concentrated at the horizon and has to be separated from the background of large muon-bundles induced by cosmic ray air showers. No statistically significant excess above the expected background is seen in the data, and a preliminary upper limit is set on the diffuse all-flavor neutrino flux of $E^2\ \Phi_{90\%\mathrm{CL}} < 2.4 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} valid over the energy range of 2×10^5 GeV to 10^9 GeV. A number of models which predict neutrino fluxes from active galactic nuclei are preliminarily excluded at the 90% confidence level.

Introduction

AMANDA-II 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 AMANDA-II is able to search for UHE neutrinos (neutrinos with energy greater than 10^5 GeV). UHE neutrinos are of interest because they are associated with the potential acceleration of hadrons by AGNs [3, 4], are produced by the interactions of exotic phenomena such as topological defects [5] or Z-bursts [6], and are guaranteed by-products of the interaction of high energy cosmic rays with the cosmic microwave background [7, 8].

Above 10^7 GeV the Earth is essentially opaque to neutrinos [9]. This, combined with the limited overburden above AMANDA-II (approximately 1.5 km, for a description of the AMANDA-II detector see [1]), 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 cosmic ray showers. The muons from these bundles can spread over cross-sectional areas as large as 200 m^2.

Experimental and Simulated Data

This analysis used AMANDA-II data collected between February 2000 and November 2002, with an integrated lifetime of 571 days after offline retriggering and correcting for dead time and periods where the detector was unstable. Of this data 20% from each year was used to develop selection criteria, while the rest, with a lifetime of 456.8 days, was set aside for the final analysis. Cosmic ray air shower background events were generated using CORSIKA [10]. The UHE neutrinos were generated with energies between 10^3 GeV and 10^{12} GeV using ANIS [11]. For more details on AMANDA simulation procedures see [1, 2].

Method

This analysis exploits the differences in light deposition from the background of bundles of many low energy muons and single UHE muons or cascades from UHE neutrinos. A muon bundle with the same total energy as a UHE neutrino 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 hits, but for the same number of hit optical modules (OMs), the muon bundle

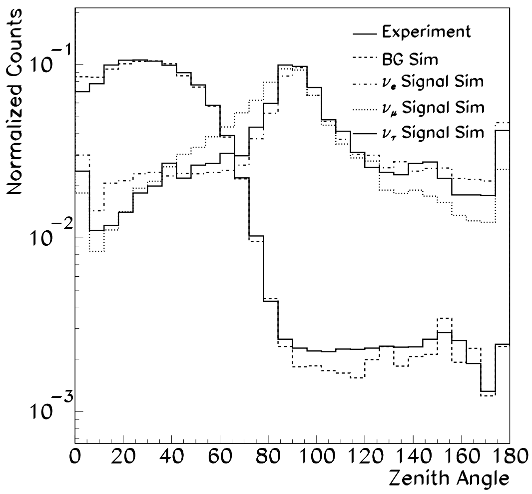

Figure 1: Reconstructed zenith angle for the experiment, background muon bundle and E^{-2} electron, muon, and tau neutrino signal simulations. The majority of signal events are expected at the horizon, while the background is primarily downgoing.

has a lower total number of hits (each OM may have multiple, separate hits in one event). Background muon bundles also have a higher fraction of OMs with a single hit, while the UHE neutrino generates more multiple hits. In addition to selecting on variables which correlate with energy, selecting on the reconstructed direction of the lepton track separates the primarily horizontal UHE neutrinos from down-going muon bundles (Fig. 1). Reconstruction algorithms optimized for cascade light deposition [1] are also used to select UHE neutrinos with an energy deposit from stochastic process (i.e. bremsstrahlung or e^+/e^- pair creation) many orders of magnitude brighter than the depositions from background muon bundles.

Systematic and Statistical Uncertainties

The sensitivity of AMANDA-II is determined from simulation. The dominant sources of uncertainty in this calculation are listed below.

Normalization of Cosmic Ray Flux: The average energy of simulated cosmic ray primaries at the penultimate selection level is 4.4×10^7 GeV. Estimates of the error in the normalization of the cosmic ray flux range from 20% [12] to a factor of two [13]. This analysis uses the more conservative uncertainty of a factor of two.

Cosmic Ray Composition: There is considerable uncertainty in the cosmic ray composition above the knee [13]. The difference between background passing rates at the penultimate selection level for iron- and proton-dominated spectra is 30%; this is taken as the uncertainty due to cosmic ray composition.

Detector Sensitivity The optical properties of the refrozen ice around each OM, the absolute sensitivity of individual OMs, and obscuration of OMs by nearby power cables can effect the detector sensitivity. Variations of these parameters can cause a 15% variation in the background and E^{-2} signal passing rate.

Neutrino Cross Section: The uncertainty in the standard model neutrino cross section is as large as a factor of two at high energies depending on the model assumed for the proton structure [14]. This causes a maximum variation in number of expected signal events for an E^{-2} spectrum of 8%.

Statistical: Due to the very demanding computational requirements, background simulation statistics are somewhat limited. A statistical error of 1σ for a Poissonian distribution with $\mu = 0$ is assumed for each year at the final selection level. The signal simulation has an average statistical error of 5% for each neutrino flavor.

Summing the systematic errors of the signal simulation in quadrature gives a systematic uncertainty of 17%. Combining this with the statistical uncertainty of 5% per neutrino flavor gives a total uncertainty of 18%. Following a similar method for the background simulation, the systematic uncertainty is 105%, and the maximum background expectation is fewer than 2.1 events for three years. These

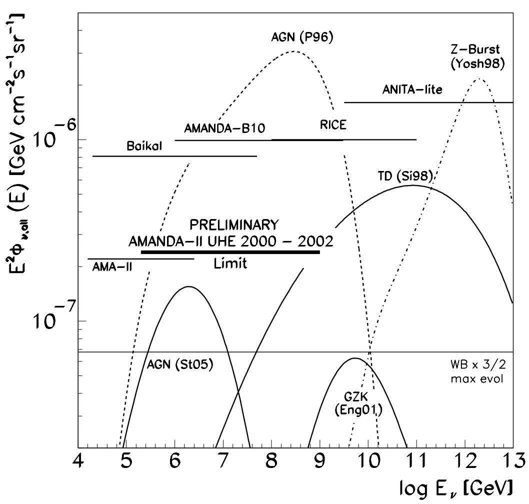

Figure 2: Preliminary all-flavor neutrino flux limit and sensitivity for 2000 - 2002 over the range which contains 90% of the expected signal with an E^{-2} spectrum. Also shown are several representative models: St05 from [4], P96 from [3], Eng01 from [7], Si98 from [5], Yosh98 from [6] and the Waxman-Bahcall upper bound [16]. Existing experimental limits shown are from RICE [17], ANITA-lite [18], Baikal [19], AMANDA-B10 [2] and AMANDA-II lower energy diffuse search [20].

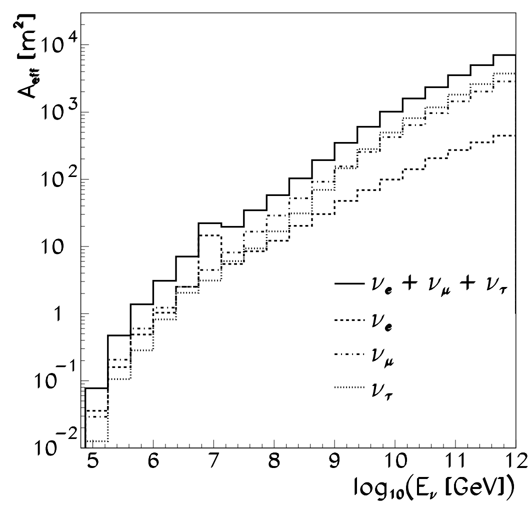

Figure 3: Angle-averaged neutrino effective area for 2000 - 2002 after application of all selection criteria. The peak at $\sim 10^7$ GeV in the ν_e effective area is due to the Glashow resonance.

uncertainties are included in the final limit using a method outlined in [15].

Results

The effective area after applying all selection criteria is shown in Fig. 3. After applying all selection criteria two events were found in the 456.8 days of data between 2000 - 2002. The background expectation for the same time period is fewer than 2.1 events, after including simulation uncertainties. This yields a 90% confidence level average event upper limit [21] of 4.74 and a preliminary upper limit on the all-flavor neutrino flux of

$$E^2\Phi_{90\%\mathrm{CL}} \leq 2.4 \times 10^{-7}\mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}} \quad (1)$$

with 90% of the E^{-2} signal found between the energies of 2×10^5 GeV and 10^9 GeV. This is the most stringent limit at these energy ranges to date (Fig. 2). A number of neutrino flux predictions are eliminated at the 90% confidence level (see Table 1).

Future Prospects

AMANDA-II hardware upgrades which were completed in 2003 should lead to an improvement of the sensitivity at ultra-high energies [22]. AMANDA-II is now surrounded by the next-generation IceCube detector which is currently under construction. The sensitivity to UHE neutrinos will further increase as the IceCube detector approaches its final size of 1 km^3 [23].

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Table 1: Flux models, the number of neutrinos of all flavors expected at the Earth at the final selection level and the preliminary MRFs for 456.8 days of livetime. A MRF of less than one indicates that the model is excluded with 90% confidence.

Model	ν_{all}	MRF
AGN [3]	20.6	0.23
AGN [24]	17.4	0.27
AGN [25]	8.8	0.54
AGN [26]	5.9	0.80
AGN RL B [27]	4.5	1.05
Z-Burst [28]	2.0	2.37
AGN [4]	1.8	2.63
GZK ν norm AGASA [29]	1.8	2.63
GZK ν mono-energetic [8]	1.2	3.95
GZK ν a=2 [8]	1.1	4.31
GZK ν norm HiRes [29]	1.0	4.74
TD [5]	0.9	5.27
AGN RL A [27]	0.3	15.8
Z-Burst [6]	0.1	57.4
GZK ν [7]	0.06	79.0

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