29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Search for Diffuse Flux of Extraterrestrial Muon Neutrinos using AMANDA-II Data from 2000 to 2003

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The detection of extraterrestrial neutrinos would confirm predictions that hadronic processes are occurring in high energy astrophysical sources such as active galactic nuclei and gamma-ray bursters. Many models predict a diffuse background flux of neutrinos that is within reach of the AMANDA-II detector. Four years of experimental data (2000 to 2003) have been combined to search for a diffuse flux of neutrinos assumed to follow an E^{-2} energy dependence. Event quality cuts and an energy cut were applied to separate the signal hypothesis from the background of cosmic ray muons and atmospheric neutrinos. The preliminary results of this four-year analysis will be presented.

1. Introduction and Motivation

Currently most of the information on the universe comes from photons, however the detection of cosmic neutrinos would provide a new picture of distant regions of space. Neutrinos travel in straight lines, undeflected by magnetic fields. They interact rarely, making detection challenging. However, if detected, the direction of an extraterrestrial neutrino would point to the particle's origin. Many theoretical models predict that neutrinos originate in hadronic processes within high energy astrophysical sources such as active galactic nuclei and gamma-ray bursters.

This analysis searches for neutrinos from unresolved sources. This search for a diffuse flux of extraterrestrial neutrinos assumes an E^{-2} energy spectrum. Although other models will be assumed in future work, this energy spectrum assumption is based on the theory of particle acceleration in strong shocks [1]. Protons experience first-order Fermi acceleration and interact with protons and photons. The resulting pions are thought to decay into neutrinos that keep the same energy spectrum as the primary [2].

The AMANDA-II detector is a collection of 19 strings buried in the ice at the South Pole [3]. A total of 677 optical modules are attached to these strings between the depths of 1500-2000 m. Each optical module consists of a photomultiplier tube surrounded by a pressure-resistant glass sphere. AMANDA-II has been operating since 2000.

Downgoing muons created when cosmic rays interact in the atmosphere trigger the AMANDA-II detector at the rate of 80 Hz. This saturates any possible extraterrestrial signal that might be seen from the Southern Hemisphere. Hence, upgoing events travelling from the Northern Hemisphere to the detector are selected for this analysis. In this way, the Earth acts as a filter against cosmic ray muons [4]. Sky coverage is restricted to 2π sr. However, above the PeV range, the field of view is reduced due to neutrino absorption in the Earth [3].

Muons, created from interacting muon neutrinos, travel long distances in the ice while emitting Cherenkov light. The muon tracks are reconstructed from the detection times with a median space angle resolution of 2^o [3] when events from the highest cut selection are used. All neutrino flavors can cause hadronic or electromagnetic cascades which appear as a spherical point source of light, however they will not be considered here.

2. Backgrounds

The analysis involved the simulation of several different classes of background events. Monte Carlo simulation of neutrinos in the ice was performed assuming an E^{-1} spectrum. The spectrum was reweighted to model an E^{-2} extraterrestrial neutrino signal with a ν_μ test flux of $E^2 dN/dE = 1\times10^{-6}$ GeV cm^{-2} s^{-1} sr^{-1}. Atmospheric neutrinos were simulated by reweighting the neutrino events to a steeper $E^{-3.7}$ spectrum. This spectral dependence is common to both atmospheric muons and neutrinos because they are both produced by cosmic ray interactions in the atmosphere.

Sixty-three days of downgoing atmospheric muons were simulated with CORSIKA [5]. Downgoing atmospheric muons can reach AMANDA depth, however they cannot penetrate the Earth from the other hemisphere. In contrast, atmospheric neutrinos from the Northern Hemisphere can reach the detector. Hence, atmospheric muons can be rejected with directional cuts, but atmospheric neutrinos cannot be distinguished from signal in this way. However, because the signal has a harder energy spectrum, both atmospheric muons and neutrinos can be separated from signal by energy-based cuts.

It is also possible that two downgoing muons from independent cosmic ray interactions may occur in the detector within the same detector trigger window. If this occurs, the software will have to guess one incidence direction for the pattern of light produced by two different tracks. The resulting reconstructed direction may be upgoing. These events, known as coincident muons, were simulated for 826 days of livetime.

3. Analysis Optimization and Sensitivity

The 2000 to 2003 search encompassed 807 days of detector livetime. As will be described below, the number of optical modules recording photons was used as an energy-related observable to distinguish extraterrestrial neutrinos from atmospheric backgrounds [6]. Analysis cuts were optimized by studying the signal and background Monte Carlo. In order to satisfy blindness requirements, the Monte Carlo and data were checked for agreement with events triggering less than 80 optical modules (NChannel < 80), hence leaving the high energy data unbiased.

The analysis began with 7.1×10^9 data events which triggered the detector during this time. Most of these were downgoing muons. All data events underwent an initial track reconstruction in which the software picked a direction of the particle based on the pattern of light the detector recorded. All events with reconstructed zenith angles between 0^o (travelling straight down) and 80^o degrees (just above the horizon) were removed.

More computer-intensive track reconstructions were performed on the remaining events. Although zenith angle cuts required the events to be upgoing, many downgoing atmospheric muons were misreconstructed as upgoing and remained in the sample. To separate these events from the expected atmospheric and extraterrestrial neutrino signals, events were removed if they did not show the signature of a muon neutrino in the detector. Long muon tracks smoothly emit Cherenkov light. High quality events cause many hits that arrive close to the calculated time for unscattered photons. These hits must be spread evenly along the the track and the log likelihood that the track is upgoing rather than downgoing must be high. As the requirements for these parameters were tightened, the number of data events began to look increasingly like the atmospheric and extraterrestrial signal Monte Carlo and less like the downgoing atmospheric muon simulation (see figure 1). The quality cuts were optimized to reject the single and coincident muon backgrounds while preserving the expected signal. Quality cut level 11 was chosen to define the sample used for analysis. After a zenith angle cut at 80^o degrees, 7,769,850 data events remained in the low-energy (NChannel < 80) sample, but the event quality cuts reduced this to 2207 data events.

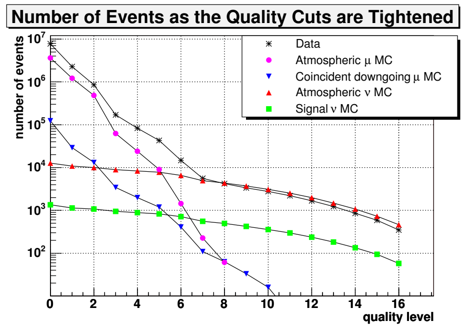

Figure 1. Above: Number of events as the quality cuts are tightened for 807 days of detector livetime. Cuts become increasingly tighter to the right. The quality cuts were aimed at removing the downgoing atmospheric muons and coincident atmospheric muons from the data. Only events with less than 80 optical modules triggered are shown.

The Feldman-Cousins method for calculating the average upper limit was applied [7]. The Model Rejection Factor is defined as the average upper limit divided by the number of predicted signal events [8] for a ν_μ signal test flux $E^2 dN/dE = 1\times10^{-6}$ GeV cm^{-2} s^{-1} sr^{-1}. Using the simulation of signal and background, the Model Rejection Factor was calculated as a function of the number of optical modules hit in the detector. The minimum Model Rejection Factor, which indicates the best placement of the NChannel cut to separate signal from background, occurs for NChannel ≥ 100 (see figure 2). Above this cut, the expected background of 16.2 atmospheric neutrinos leads to an average upper limit of 8.19. Dividing this by the expected signal for the given test flux (86.3 events) leads to a final sensitivity on the ν_μ flux of $1\times10^{-6} \times 8.19/86.3$ GeV cm^{-2} s^{-1} sr^{-1}, or 9.5×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}. The sensitivity (multiplied by three for oscillations) is shown in figure 3 in relation to several other models and analyses. The signal Monte Carlo events that populate the final data set have true neutrino energies between 13 TeV and 3.2 PeV (90% region).

4. Conclusions

With the cuts established and sensitivity determined, the high energy data can be studied. Limits obtained from the analysis of the complete data set will be presented at the conference.

The sensitivity of this four-year analysis is improved by a factor of nine over the limit previously set for one year of experimental data (1997). Limits are closing in on the Waxman-Bahcall bound. In the future, several other models for extraterrestrial neutrino production will also be tested.

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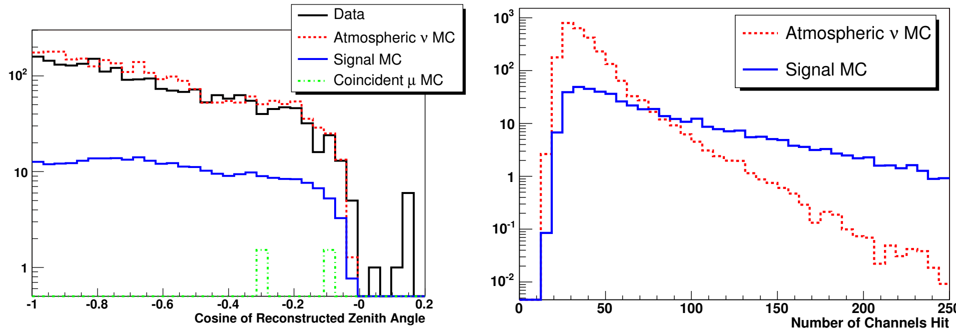

Figure 2. Left: Reconstructed zenith angle. The cosine of the zenith angle is shown for all low energy data and Monte Carlo. The number of events for 807 days of livetime is shown on the y-axis before the energy cut. After quality cuts, the data and predicted background show good agreement. At this high quality level, the downgoing atmospheric muons and coincident downgoing muons are nearly entirely removed. Right: Number of channels (optical modules) hit for a signal test flux of 1×10^{-6} GeV cm^{-2} s^{-1} sr^{-1}. This energy related variable is used to separate signal neutrinos from the atmospheric ν_μ background.

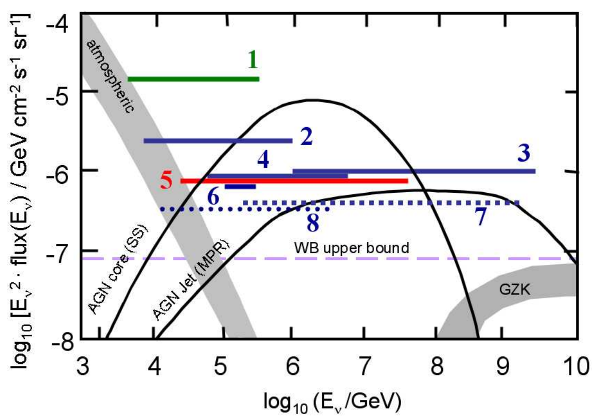

Figure 3. All-flavor neutrino limits and sensitivity on an $E^2\frac{dN}{dE}$ plot. Neutrino oscillations are assumed. (1) The MACRO ν_μ analysis for 5.8 years (limit multiplied by three for oscillations) [9]. (2) The AMANDA-B10 ν_μ analysis from 1997 (multiplied by three for oscillations) [10]. (3) AMANDA-B10 ultra-high energy neutrinos of all flavors 1997 [11]. (4) AMANDA-II all-flavor cascade limit from 2000 [12]. (5) Baikal cascades 1998 - 2003 [13]. (6) The preliminary results of the 2000 AMANDA-II ν_μ analysis (multiplied by three for oscillations). The limit is derived after unfolding the atmospheric neutrino spectrum. (7) The sensitivity for AMANDA-II ultra-high energy neutrinos of all flavors 2000. (8) 2000 to 2003 AMANDA-II ν_μ sensitivity (multiplied by three for oscillations).

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