Atmospheric Neutrino and Muon Spectra Measured with the AMANDA-II Detector

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Abstract

AMANDA is a large neutrino telescope designed to measure the flux of high energy neutrinos from astrophysical sources. The background for such measurements consists of down-going atmospheric muons and up-going atmospheric neutrino-induced muons. A new method to reconstruct the muon and neutrino energy spectra based on neural networks and regularized unfolding has been developed. The atmospheric muon spectrum has been used as a cross-check on the method and the atmospheric neutrino spectrum has been measured up to 100 TeV.

1. Introduction

The Antarctic Muon And Neutrino Detector Array (AMANDA) detects neutrinos indirectly via the Cherenkov radiation emitted by leptons induced in charge current interactions. The detector uses the ice of the Antarctic glacier as detector medium [1,11]. The charged particle flux at the detector is dominated by down-going atmospheric muons. A unique neutrino signature is an upward moving muon, which allows the neutrinos to be extracted from the overwhelming amount of atmospheric muon background.

In this analysis the energy spectrum of up-going neutrino-induced muons in the detector is unfolded with respect to the neutrino energy. The down-going muon flux is measured with large statistics and thus used as a cross-check for the method.

2. The Method

The energy reconstruction of an event in the AMANDA detector is performed in two steps [5]. First, a neural network is used to reconstruct the single muon energy. A good choice of independent energy correlated variables consists of a set of six direct observables, such as the number of hit OMs. The observables are linearly normalized and used as input for a standard back-propagation multilayer perceptron (MLP). Various MLP topologies have been tested on Monte Carlo (MC) simulation data. A 6-6-3-1 network topology shows the best performance. The resolution of monoenergetic isotropically simulated muons in the detector is shown in Figure 1. The mean of $log_{10}(E_{reco})$ deviates by less than 10% from the same quantity of the simulated events. The energy resolution can be estimated from the width to be 0.5 in logarithm of the energy. This is comparable to other energy reconstructions for AMANDA data [7,2]. The energy reconstruction is only reliable in the range between 500 GeV and a few PeV. Below 500 GeV the radiative energy loss processes do not dominate, above a few PeV almost all OMs show a signal and the detector saturates. For this analysis only energies up to 100 TeV are relevant.

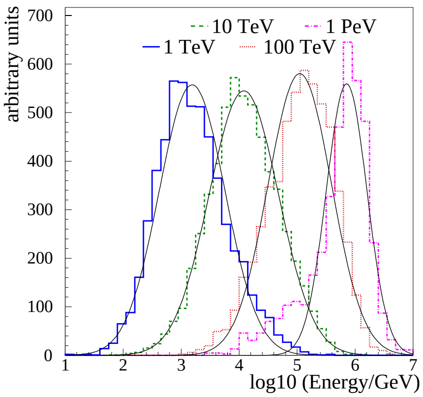


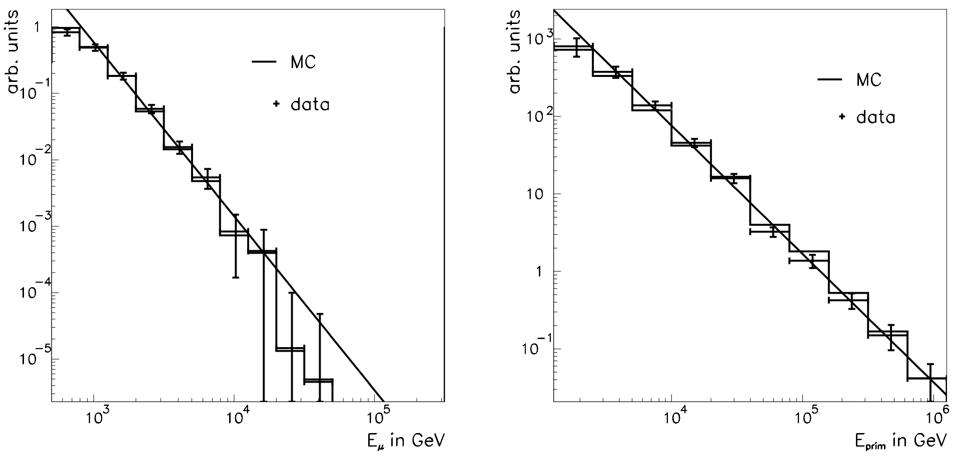
Fig. 1. The distribution of reconstructed energies for simulated muons with an energy of 1 TeV, 10 TeV, 100 TeV and 1 PeV in the AMANDA detector.

Secondly, the distribution of reconstructed single energies is a convolution of the physical energy spectrum with the limited acceptance and finite resolution of the detector. To account for this an unfolding algorithm is applied to recover the physical energy spectra. The method of regularized unfolding [3] is stable enough even for the case of small statistics and large covariances.

3. Muon Spectra

In this analysis the events recorded in the year 2000 are investigated. The effective livetime is 197 days and amounts to more than one billion triggers. As a cross-check of the method a subset of 2.5×10^4 triggered events was reconstructed and the spectrum was unfolded with respect to the muon energy at the surface. In Figure 2(a) a power law is fitted to the resulting muon energy spectrum with a differential spectral index of $\gamma = -3.72 \pm 0.17$ (stat.) which agrees with atmospheric muon flux predictions [4,9]. As a further cross-check the deconvolution kernel of the primary hadron spectrum is reconstructed. Figure 2(b) shows the resulting energy spectrum and a fitted differential spectral behavior of $\gamma = -2.70 \pm 0.04$ (stat.) in the energy range between 1 TeV and 1 PeV is in agreement with [12].

A sample of 570 neutrino events has been selected from the raw data by applying optimized point source cuts [6] and a zenith veto at 10 degrees below the horizon. Comparison with MC background simulations predicts a contamination by misreconstructed down-going muons of less than 10% for this neutrino sample. A mixture of atmospheric neutrino and E^{-2} signal (MC) was used to calculate the deconvolution kernel of the neutrino energy spectrum. Different mixtures have



(a) (b)

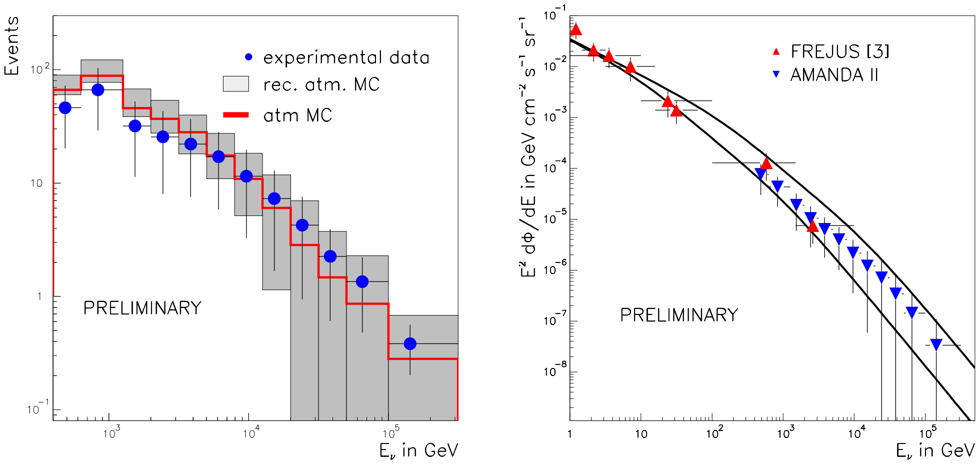
Fig. 2. Reconstructed down-going spectra (histogram: MC prediction, points: data, line: fitted power-law): (a) unfolded down-going muon spectrum on top of the surface, (b) unfolded primary hadron spectrum.

been used to confirm that the procedure is independent of any specific choice.

4. Neutrino Spectra

The unfolded energy distribution is presented in Figure 3(a). The boxes show the prediction of a pure atmospheric contribution. Figure 3(b) shows the corresponding fluxes and compares them with the high-energy data from the Fréjus experiment [4,9]. The lines show the horizontal and vertical atmospheric neutrino flux parameterizations according to Volkova [10]. The error bars give the statistical error from the unfolding procedure plus an overall systematic uncertainty. This includes uncertainties in the primary spectrum, the cross-sections of kaon and pion production, the muon range, the PMT efficiencies and the exact ice properties. The systematic errors due to the misreconstructed down-going muon background have so far not been included and the propagation of these errors through the deconvolution is not yet completed, thus a limit on non-atmospheric flux cannot be derived at present. For the first time, the spectrum is reconstructed up to 100 TeV and shows an overlap with the Fréjus results. The reconstructed fluxes are in agreement with current atmospheric flux parameterizations.

According to [8] atmospheric neutrinos can be used to probe a large neutrino mass splitting implied by the LSND experiment and discriminate among mass schemes with four neutrinos. A 2+2 neutrino scenario would predict a resonant $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) oscillation in case of an inverted (normal) mass hierarchy solution. The resonance should lead to a narrow three-dip-structure at 1 TeV. This should be-



(a) (b)

Fig. 3. Reconstructed neutrino spectra: (a) on filter level (solid: energy distribution of atmospheric neutrino expectation, boxes: unfolded energy distribution of atmospheric neutrinos (MC), points: reconstructed data), (b) reconstructed fluxes compared to Fréjus data.

come observable as a suppression in the neutrino spectrum between 400 GeV and 1100 GeV which is partly in reach of this analysis. The reconstructed spectrum in Figure 3(a) is slightly flatter than the atmospheric neutrino spectrum but agrees with the atmospheric expectation within the errors. The present results are not sensitive to these suppression effects.

5. References

1. J. Ahrens et al.,Phys. Rev. Lett. D66 (2003) 012005
2. The AMANDA Coll., Muon track reconstruction in AMANDA, to be submitted to NIM (2003)
3. V. Blobel, Proceedings of the 1984 CERN School of Computing, CERN
4. K. Daum et al., Zeitschrift für Physik C66 (1995) 417
5. H. Geenen, Diploma thesis, WU-D 2002-10, University of Wuppertal (2002)
6. T.Hauschildt and D. Steele, these proceedings (2003)
7. P. Miocinovic, Phd Thesis, University of California Berkeley (2001)
8. H. Nunokawa et al., hep-ph/0302039 (2003)
9. W. Rhode et al., Astroparticle Physics 4 (1996) 217
10. L.V.Volkova, Sov.J.Nucl.Phys., 31 (1980) 784
11. W. Wagner, these proceedings (2003)
12. B. Wiebel-Sooth, Phd Thesis, WUB-DIS 98-9, University of Wuppertal (1998)