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Measurement of the atmospheric lepton energy spectra with AMANDA-II

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Abstract: Extragalactic objects such as active galactic nuclei (AGN) and gamma-ray bursts (GRB) are potential sources for the ultra-high energy cosmic ray flux. Assuming hadronic processes in these sources, a diffuse neutrino flux might be produced together with the charged cosmic ray component. To measure this diffuse extraterrestrial neutrino flux is one of the main goals of the Antarctic Muon and Neutrino Detector Array (AMANDA-II). The neutrino spectrum, based on a four year data set (2000-2003), is presented. The spectrum agrees with the atmospheric neutrino flux predictions. Upper limits to isotropic extraterrestrial contributions are derived.

Introduction

The search for extraterrestrial neutrino sources is the driving force behind the construction of large neutrino telescopes. Though all three neutrino species should arrive at Earth in equal number, muons from muon neutrinos have a distinct signature in the detector (a long path emitting Cherenkov light) that makes them a desirable focus for this analysis. The drawback of this signature is the existence of a large background of atmospheric muons entering the detector from the upper hemisphere. Atmospheric muons are suppressed by selecting only upgoing events as potential signal candidates. Muons from neutrinos produced in the atmosphere dominate even in this sample.

The search for extraterrestrial muon neutrinos within the data sample can be performed by multiple approaches, for instance by selecting local coincidences with proposed steady neutrino sources (AGN) or local and temporal coincidences with GRBs. Since the energy spectrum of extraterrestrial neutrinos is expected to be significantly harder than the atmospheric neutrino spectrum, another approach relies directly on the reduction of the atmospheric neutrino background by energy selection [1]. The analysis described here is based on the reconstruction of the energy spectrum of atmospheric muon neutrinos. Data taken with the AMANDA-II detector between 2000 and 2003 provide 2972 upgoing muons with a lifetime of 807 days. The criteria used for the selection of events are described in [2]. In addition a zenith angle veto at 10 degrees below the horizon is applied.

Unfolding of the energy spectrum

In this analysis, the problem of determining the energy spectrum from the observed detector response is solved by applying a regularized unfolding method. The underlying Fredholm integral equation of first kind is reduced to a matrix equation system. The kernel is determined with Monte Carlo methods. Statistically insignificant contributions to the kernel are suppressed by regularization [3, 4]. The observables used must be correlated to the neutrino energy. In total, eight observables are found to satisfy these conditions. Because the unfolding algorithm used for this calculation, RUN [3], allows only three input variables, six observables are combined into one energy-sensitive variable by a neural network application [4, 5]. In Figure 1, the Gaussian response of this variable to mono-energetic muons from the simulation is shown. The unfolded neutrino energy spectrum is compared to the flux expectations from [6, 7] in Figure 2. The error bars in the plot comprise both statistical and systematic uncertainties. The theoretical uncertainty of the atmospheric neutrino flux contributes with 25% to the total systematic error

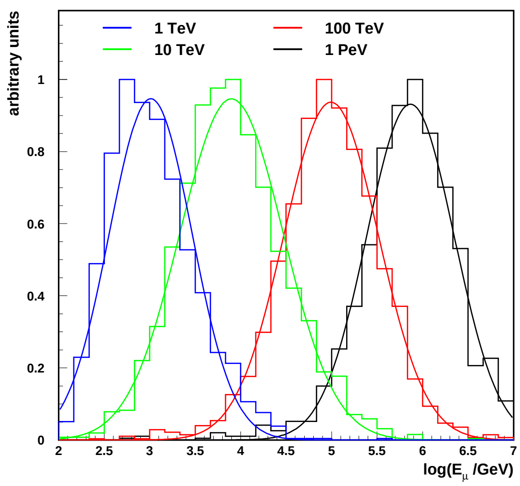

Figure 1: Neural network output for simulated mono-energetic muons fitted with Gaussian distributions.

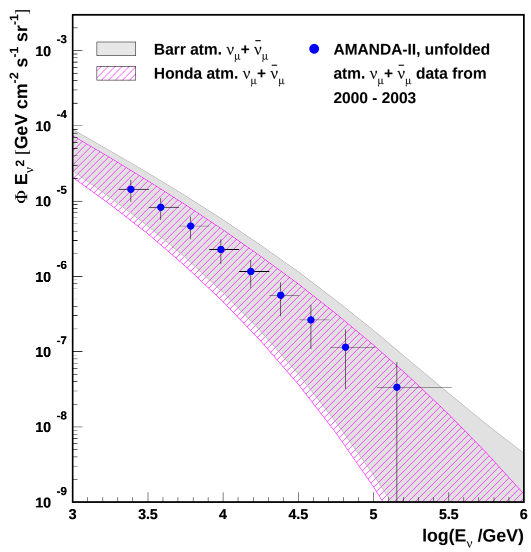

Figure 2: Comparison of the unfolded energy spectrum with flux expectations according to Ref.[6, 7]. The shaded bands show the range between the horizontal (upper border) and vertical flux (lower border).

of 30%. For a detailed error discussion see [5]. Good agreement is observed when the unfolded four-year neutrino spectrum is compared to the unfolded data from 2000 analysed in [4, 5] (Figure 3).

Upper limits to additional contributions to the neutrino flux

Two properties of the unfolded spectrum in Figure 2 should be noted. First, the variable binning with a width of about half of the resolution was optimized by Monte Carlo to obtain the best sensitivity to an E^{-2} contribution of extraterrestrial neutrinos. The bins are statistically correlated to each other. This is taken into account in the error calculation. However, it is not obvious which kind of probability density function (pdf) the flux errors obey and how upper limits to additional contributions to the atmospheric neutrino flux have to be derived. Therefore, a confidence belt construction [8] has been applied to the unfolding problem. The second remark concerns the 2000-2003 data quality. During this period, small changes in the detector properties, such as the photomultiplier high voltage, resulted in different detector response in the observables used in this analysis.

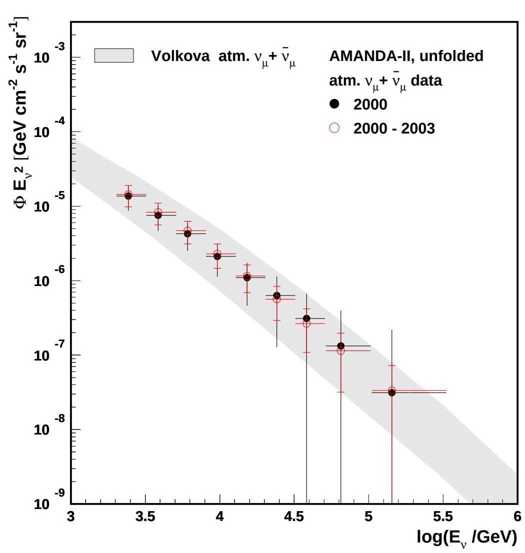

Figure 3: Comparison of the unfolded energy spectrum for 2000 and 2000-2003.

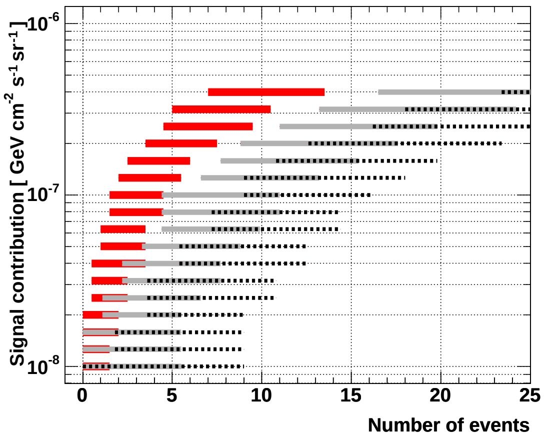

Figure 4: The unified approach of Feldman and Cousins has been applied to the unfolding problem by calculating individual probability density functions. 90% Feldman-Cousins confidence belts of three unfolding energy bins: 50 to 100 TeV (black dotted), 100 to 300 TeV (gray) and 300 TeV to 1 PeV (red) are displayed.

Since only the logarithm of these variables enters the unfolding procedure, these systematic effects concern only the low energy portion of the spectrum ($E < 2$ TeV).
Assuming a diffuse signal energy spectrum with an energy dependence of E^{-2}, the unfolded response for 17 different signal contributions between 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} and $4 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} has been calculated. For each signal contribution, the complete Monte Carlo and analysis chain has been applied. Finally, 1,000 Monte Carlo experiments each containing the equivalent of four years of AMANDA-II data have been used for each of the 17 signal contributions. The energy distributions of all 17,000 Monte Carlo experiments have been reconstructed. After applying an energy cut, the statistical weights, which corresponds to the weighted number of events, for a fixed signal distribution are summed, histogrammed and normalized to get the individual pdf. Using the pdfs for each signal contribution the Feldman-Cousins approach is applied. The resulting confidence belts are shown in Figure 4. The upper limit is obtained from the confidence belt by reading off the flux value that corresponds to the

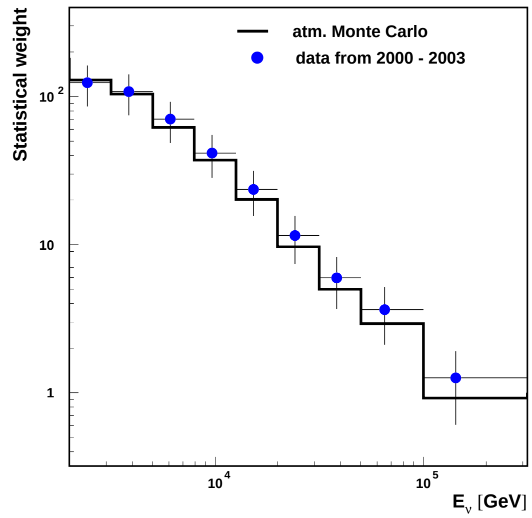

Figure 5: Statistical weight of the unfolded data.

statistical weight of the unfolded data (Figure 5). The statistical weight between 300 TeV and 1 PeV is 0.005. The error bars can be used to calculate an upper limit. Assuming normal distribution for the pdfs, the 90% upper limit on the sum of atmospheric plus extraterrestrial flux is given by 1.28 times the standard deviation. By subtracting the atmospheric portion (gained by fitting the Volkova prediction [9] to the unfolded spectrum) from the total upper limit, an upper limit on the extraterrestrial contribution can be calculated, see [4]. In Figure 6 the unfolded neutrino spectrum (blue circles) for data from 2000-2003 as well as the resulting upper limits are shown. The upper limits obtained by the Feldman-Cousins procedure (blue lines) are compared to those upper limits (pink lines) obtained by using the normal distributed pdf and the atmospheric fit. Since the upper limits obtained from the two different methods are in agreement, this is a good indication that the statistic errors in the procedure have been treated properly. The upper limits derived by calculating the individual pdfs in combination with the Feldman-Cousins approach deliver slightly more restrictive bounds. The resulting limits are compared with different flux models (see Figure 6). MPR-max represents the maximum neutrino flux from blazars in photohadronic interactions. An upper bound on the flux

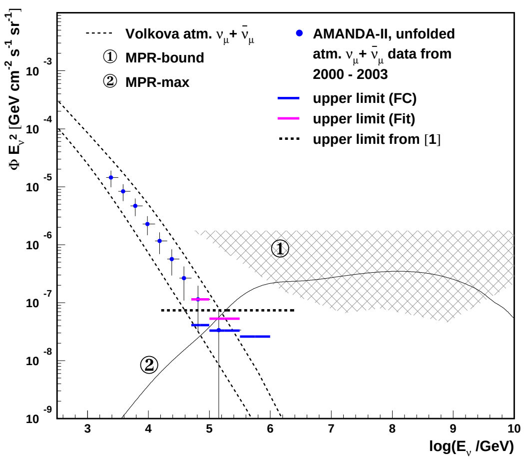

Figure 6: Reconstructed neutrino spectrum and resulting upper limits (blue and pink lines) for data from 2000-2003. The results are compared with different flux models [10] and the result from [1]. For the FC upper limit we added a bin from 300 TeV to 1 PeV which is not shown in Figures 2, 3 and 5 as only 0.005 events were observed in this range and the corresponding flux value is out of the displayed flux range.

from AGN was estimated in [10], which is indicated in the figure as shaded region (MPR-bound). The upper border of that region represents the limit for sources that are optically thick to $n\gamma$ interactions, $\tau_{n\gamma} \gg 1$. The bound for optically thin sources ($\tau_{n\gamma} < 1$) is given by the lower bound of the shaded region.

Conclusion

The energy spectrum of atmospheric muon neutrinos has been reconstructed with a regularized unfolding method in the energy range between 1 TeV and 300 TeV. In this energy range, no flattening of the spectrum is observed, as would be expected if a significant extraterrestrial neutrino contribution was presented. Upper limits to additional contributions of $\phi \cdot E^2 = 4.1 \cdot 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} to the energy bin between 50 TeV and 100 TeV, $\phi \cdot E^2 = 3.3 \cdot 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} between 100 TeV and 300 TeV and $\phi \cdot E^2 = 2.6 \cdot 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} between 300 TeV and 1 PeV are obtained. This is presently the most restrictive upper limit in this energy range and at the given energies well below the theoretical upper bound by Mannheim et al. [10]. This upper limit restricts the parameter range of the source models for AGN classes with flat luminosity distributions (FRII) [11]. A comparison of these upper limits to the upper limits obtained with independent methods in AMANDA-II [1] shows good agreement. All results shown here are preliminary.

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