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Search for a diffuse flux of non-terrestrial muon neutrinos with the AMANDA detector

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Over the past decade, many extragalactic source types have been suggested as potential sources for the ultrahigh energy cosmic ray flux. Assuming hadronic particle acceleration in these sources, a diffuse neutrino flux may be produced along with the charged cosmic ray component. In the presence of a high background of atmospheric neutrinos, no extragalactic neutrino signal has been observed yet. In this paper, a new analysis to investigate with the Antarctic Muon And Neutrino Detector Array (AMANDA-II) a possible extragalactic component in addition to the atmospheric neutrino flux is presented. The analysis is based on the year 2000 data. Using an unfolding method, it is shown that the spectrum follows the atmospheric neutrino flux prediction [1] up to energies above 100 GeV. A limit on the extraterrestrial contribution is obtained from the application of a confidence interval construction to the unfolding problem.

1. Introduction

Neutrino-astrophysics has enlarged over the last years the knowledge of neutrinos and their properties. Current experiments are able to measure the neutrino flux from the sun as well as the flux that is produced by cosmic rays interacting with the atmosphere. The aim of high energy neutrino experiments such as AMANDA [2, 3, 4] is to observe an extraterrestrial component of the neutrino spectrum. The AMANDA detector, located at the geographical South Pole, uses the ice as the active volume.
Due to the high atmospheric neutrino flux at energies $E_\nu > 50$ GeV, a non-atmospheric component has not yet been observed. The atmospheric flux decreases roughly with $E_\nu^{-3.7}$ as opposed to the extragalactic contribution, which is expected to be around 1.7 powers flatter, E_ν^{-2}. Thus, it is predicted that an additional contribution should become dominant at higher energies. The exact energy at which the extraterrestrial flux exceeds the prediction of the atmospheric one is not known due to the uncertainties in the source properties which would determine the normalization of the neutrino flux.
The diffuse neutrino flux presented is measured with a combination of a neural network and a regularized unfolding [5] as described in [6]. Since the measured neutrino flux corresponds with the expectation of the atmospheric neutrino flux up to an energy of 100 TeV, the question of additional constituents and their exclusion has to be investigated. This paper describes how an upper limit to the neutrino flux from extraterrestrial sources can be obtained. It is shown how the unified approach of Feldman & Cousins can be applied to an unfolding problem to set a 90% confidence belt. Taking into account the statistical behavior of individual events, the probability density functions are calculated using large MC statistics. Finally, a limit on the diffuse muon neutrino and antineutrino flux from extragalactic sources is presented. This limit gives the most restrictive estimate of an upper bound of the neutrino flux among currently existing experiments.

2. Method to obtain a 90% confidence belt

The neutrino energy spectrum is dominated by the background of atmospheric neutrinos. By means of MC studies of atmospheric neutrinos the number of events per energy interval can be estimated. The lower energy threshold of examined events for a potential neutrino signal can be optimized [7]. This leads to a limit on the non-atmospheric neutrino flux using the number of measured events above the optimized threshold. The probability P to measure n events in a certain energy bin for a given mean signal μ is calculated by using large MC statistics. P is also called probability density function, pdf. Its calculation is described in the following paragraph.

For the year 2000, 21 different signal contributions ranging from 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} to 10^{-6} GeV cm^{-2} s^{-1} sr^{-1} are used. The signal contribution μ is equal to the flux ϕ multiplied by E^2. Each signal contribution μ is represented by 1000 one-year MC experiments which are altogether equivalent to a data taking of 21000 years. The energy is reconstructed using a combination of neural network and regularized unfolding [6]. The resulting energy distribution is evaluated for each of the 1000 MC experiments per fixed signal contribution, resulting in 21000 energy distributions using all 21 signal contributions. After applying an energy cut the event rate in the remaining bins are summed up and histogramed. The normalized histograms give the searched pdfs. In figure 1 the pdf for two different signal contributions is shown.

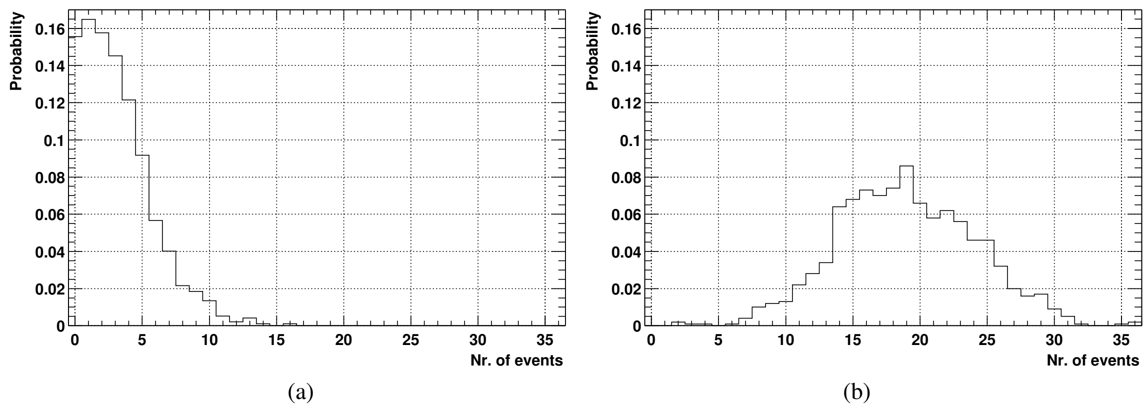
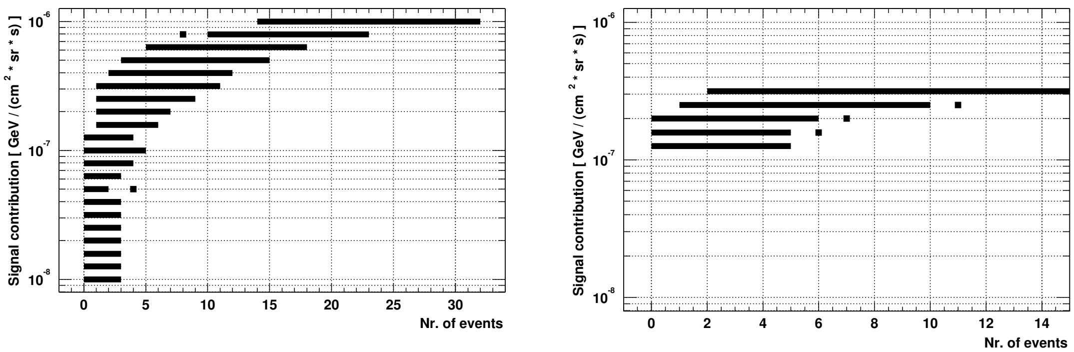


Figure 1. Probability density function for two different signal contributions. (a) : $2.0 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}, (b) : 10^{-6} GeV cm^{-2} s^{-1} sr^{-1}.

For generating a 90% confidence belt the method described in the unified approach by Feldman and Cousins [8] is applied using the probability density functions described above. After reconstruction and unfolding of the energy, confidence belts for different energy cuts are compared and the confidence belt for an energy cut resulting in an energy range of 100 TeV $< E <$ 300 TeV shows the best performance. The resulting confidence belt for this cut is illustrated in figure 2(a).

For data taken by AMANDA in the year 2000 optimized point source cuts [9] and a zenith veto at 10 degrees below the horizon have been applied. The resulting sample consists of 570 neutrino events. With the method described above the energy is determined. Inspecting the energy distribution of the data leads to 0.36 events in the energy range of 100 TeV $< E <$ 300 TeV. Since the event numbers used for building the confidence belt displayed in figure 2(a) are integer, a limit for 0.36 events can only be derived using further interpolation methods. To avoid this and to get a higher resolution the number of MC events have been enlarged by a factor of 10. This is done in the interesting signal contribution region from $1.26 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} to $3.16 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}. With the resulting confidence belt presented in figure 2(b) a definite limit of $2.0 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} can be assigned to a event rate of 0.36.



(a) (b)

Figure 2. Confidence belt in the signal contribution range of (a) : 10^{-8}GeV cm^{-2} s^{-1} sr^{-1} up to 10^{-6}GeV cm^{-2} s^{-1} sr^{-1} and (b) : $1.26 \cdot 10^{-7}$GeV cm^{-2} s^{-1} sr^{-1} up to $3.16 \cdot 10^{-7}$GeV cm^{-2} s^{-1} sr^{-1}.

3. Discussion

From the possible error contribution the systematic uncertainties are dominating. The main contribution to the systematic error is made by the uncertainty of the atmospheric neutrino flux 25%, [10].

Adding the smaller contributions as the uncertainty of the ν_μ to μ cross section (ca. 10%) to this value and including a maximal contamination by atmospheric neutrinos of the data set (7%), a total systematic error of 30% has to be applied.
This leads to a limit for the AMANDA data of the year 2000 of

$$\phi \cdot E^2 = 2.6 \cdot 10^{-7} GeV\ cm^{-2}\ s^{-1}\ sr^{-1}.$$

4. Conclusions

Fig. 3 shows the calculated spectrum and limit in the context of different muon neutrino and anti-neutrino flux predictions. The unfolded neutrino spectrum (circles) is complementary to the Frejus data [11] (squares) which are at lower energies. The black dashed lines in this figure show the horizontal and vertical atmospheric neutrino flux. The upper line represents the horizontal flux, while the prediction for the vertical flux is given with the lower line. The atmospheric flux spectrum above an energy of E $>$ 100 GeV is parameterized according to Volkova [1]. Below this energy the parameterization is given according to Honda et al. [12]. The reconstructed flux contains events from the lower hemisphere except events very near to the horizon and is in good conformity with the atmospheric prediction. In addition to the unfolded flux, an upper limit on the extragalactic neutrino signal of $2.6 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} is given. The limit clearly gives restrictions on model 1 (StSa) [13], assuming neutrino production in $p\gamma$ interactions in AGN cores. This model with the parameterization as given in [13] can be excluded. Model 2 (MPR-max, [14]) represents the maximum neutrino flux from blazars in photo-hadronic interactions and lies within the sensitivity range of AMANDA. In this context, an upper bound on the flux from these sources were estimated in [14], which is indicated in the figure as the shaded region (Model 3, MPR-bound). The horizontal line represents the limit for sources that are optically thick to $n\gamma$ interactions, $\tau_{n\gamma} >> 1$, the lower bound of the shaded region gives the bound for

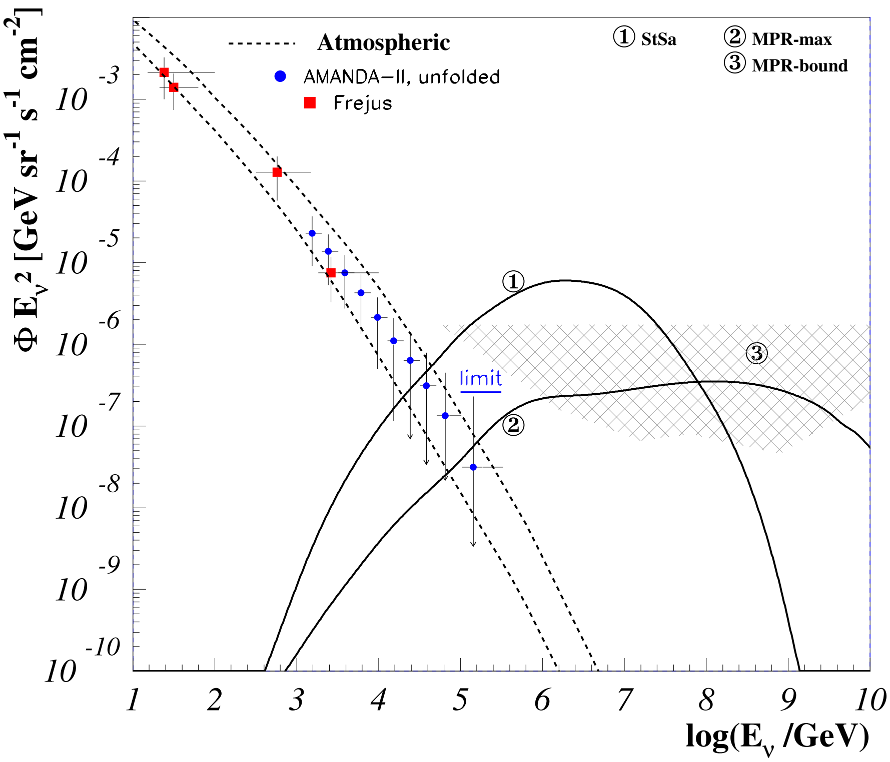


Figure 3. Reconstructed neutrino spectra and resulting limit for the year 2000 data compared with different flux models

optically thin sources ($\tau_{n\,\gamma} < 1$). In future analyses with a larger data set in AMANDA, it should be possible to set limits lying within the shaded regions, so that the opacity of the sources can be constrained.

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