Response of AMANDA-II to Cosmic Ray Muons

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Abstract

The high flux of down-going muon detected by the AMANDA-II neutrino telescope is used as a test beam to check the experiment systematics and to improve the knowledge of its response. This work shows the result of the effort to get a better understanding of AMANDA-II performance, an improved data filter and event reconstruction. The preliminary experimental down-going muon angular and depth intensities are compared with Monte Carlo prediction, other experimental results and theoretical calculations. A good agreement is found within systematic uncertainties.

1. Introduction

The main scope of a neutrino telescope is to detect muons generated by high energy cosmic neutrinos. These events can be separated from the atmospheric neutrino-induced muons mainly by using an energy cut, as they have a harder energy spectrum than atmospheric events. To ensure that detected muons are generated by neutrinos, the Earth is used as filter and only up-going muons are selected. Nevertheless, the large down-going atmospheric muon flux can be used to study the detector response and possible systematic effects, which are of interest for any neutrino analysis. Atmospheric muons are generated in the decay of charged π and K mesons, which are produced in the interactions of cosmic rays high in the atmosphere [8]. A small fraction of high energy atmospheric muons is produced in the decay of short-lived charmed mesons. These muons have a harder energy spectrum than muons from π and K and they dominate at $E_\mu > 100$TeV [11].

The aim of the present analysis is to show the capability of AMANDA-II to measure the known angular distribution of atmospheric muons. A preliminary analysis [6] showed a deviation between the Monte Carlo prediction and the experimental results. An overall improvement of the detector simulation, a refinement of the treatment of South Pole ice optical properties in the Monte Carlo and more efficient reconstruction algorithms have been achieved and now AMANDA-II is able to reproduce the down-going angular and the depth-intensity distributions

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as predicted by the simulation, within systematic uncertainties.

2. AMANDA-II and optical properties

AMANDA-II neutrino telescope is located at the Geographic South Pole. A full description of the detector and its operational principles can be found in [13]. The optical properties of the ice in which AMANDA-II is embedded were studied in detail, using the light emitters located on the strings and the down-going muon flux itself. This study shows the ice is not homogeneous [15], but it can be considered as made of several horizontal layers, laid down by varying climatological conditions in the past. Different concentrations of dust in the layers produce a modulation of the scattering and absorption lengths of light in the ice. At AMANDA-II depths and at λ=400 nm (corresponding to the maximum optical sensitivity) the average effective scattering length is 20 m and the average absorption length is 110 m, and their depth-variation ranges within a factor of two. An improved treatment of the optical properties in the simulation leads to a better detector description within systematic uncertainties in the absolute sensitivity. These include: $\sim$ 10% on the measured scattering and absorption lengths; $\sim$ 20% from the optical modules (OM) light collection efficiency; and $\sim$ 10% from the optical properties of the re-frozen ice surrounding the OMs, which affects their angular acceptance.

3. The analysis

In order to measure the atmospheric muon angular distribution it is necessary to evaluate the event trigger and reconstruction efficiencies as a function of zenith angle. To do that we use a Monte Carlo with the complete simulation chain, from the primary interaction in the atmosphere to the detector response, based on our best knowledge of physical processes involved.

The event generation is done using CORSIKA v6.020 with QGSJET01 interaction model, with Earth's curvature and the South Pole average atmosphere profile included. A multi-component primary cosmic ray energy spectrum and composition is taken from [14]. The generated muons are propagated to the Earth's surface and then through the ice, taking into account all relevant energy losses [5]. The muons passing through or near AMANDA-II are folded into the detector trigger simulation. At this stage the detector response is fully simulated in order to reproduce the experimentally detected events [9]. The Cherenkov photon propagation through the ice was modeled to create multidimensional tables of density and arrival time probability distributions of the photon flux. The spectral properties of OMs and glacial ice are included in the simulation of photon propagation. A detected event corresponds to a realization of a majority trigger of at least 24 hit channels within 2.5 μs. The event reconstruction chain is identical to

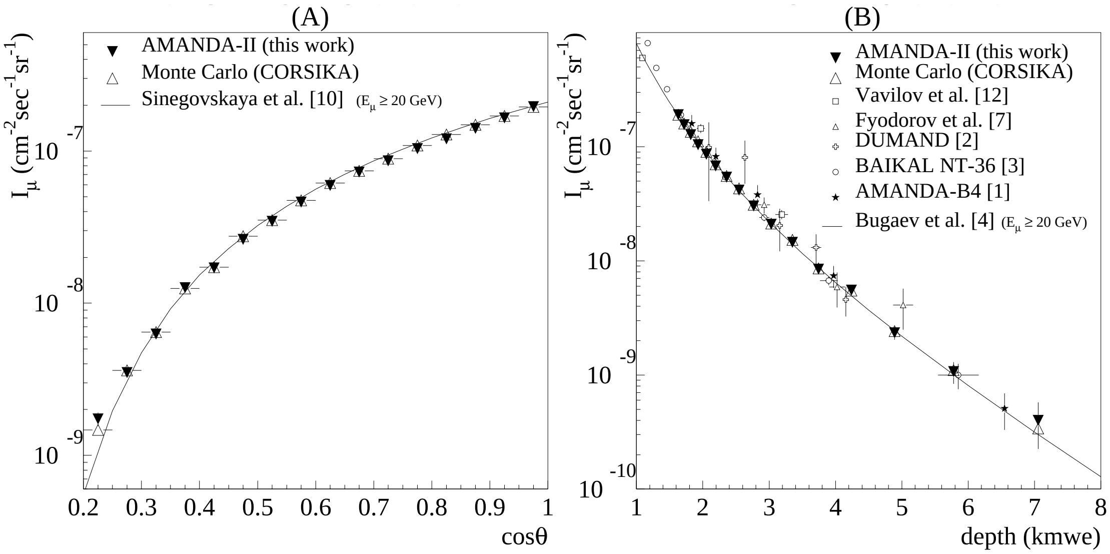

Fig. 1. Preliminary muon angular (A) and vertical depth intensity (B). AMANDA-II unfolded data are normalized to the vertical Monte Carlo point. See text for details.

the one used for experimental data. After a cleaning procedure that removes the OMs which are dead or have odd transient behavior, a time calibration, which takes into account the signal propagation time through the cables, and a time likelihood reconstruction are performed.

Due to the limited reconstruction resolution, additional cuts are used to improve the event sample quality for both experimental and simulated data. In particular, a good likelihood value of the reconstruction, a smooth hit distribution along the reconstructed track and a relatively long distance between the first and the last hit along the track are required. After these cuts the average angular resolution ranges from $\delta\theta \sim 1.5^\circ$ at $\cos\theta = 1$ to $\delta\theta \sim 2.4^\circ$ at $\cos\theta = 0.2$.

With this resolution we can derive the true experimental angular distribution at AMANDA-II depth by simply calculating the detector acceptance at each zenith angle bin with the Monte Carlo detector response simulation, and using it to unfold the measured data, neglecting the inter-bin correlations, given the proper bin choice. About 10 hours of experimental data from the year 2000 are used here.

4. The results

Figure 1-A shows the preliminary unfolded muon angular distribution, compared with the Monte Carlo true distribution and with the prediction from [10] calculated for AMANDA-II depth. The unfolded result gives the muon event intensity per angular bin. In order to compare it with theoretical calculations we need to convert it into intensity averaged over the muon multiplicity at the detector depth. This is evaluated using the Monte Carlo event simulation. Due to

the flatness of the ice surface around the South Pole, each zenith angle corresponds to a specific ice thickness. Thus, the angular distribution can be easily converted into slant-depth distribution. Taking into account the dependence of sea-level muon intensity versus zenith angle, the unfolded muon intensity at a given slant-depth is converted into vertical depth intensity. Figure 1-B shows the muon vertical depth intensity for Monte Carlo and experimental data. A comparison with similar underwater measurements is shown along with the prediction from [4]. Distributions in figures 1-A and 1-B have been converted to intensities relative to underwater depths, accounting for the lower ice density ($\rho_{\rm ice} = 0.917 \rm g/cm^3$). The errors in the figures are only statistical.

In the figures we choose to normalize the unfolded data to the most vertical point of Monte Carlo prediction. The simulated true distributions are in agreement with theoretical calculations, but the unfolded data exceed it by $\sim 30\%$. Nevertheless the shapes agree within statistical errors. The excess derives from an equivalent deficit of the simulated trigger rate with respect to the experimental one. Such a difference is attributed to the overall uncertainty in the optical properties of all transparent media as discussed in section 2.

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