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Analysis of atmospheric muons with AMANDA

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Abstract. In underground neutrino telescopes, the down-going atmospheric muon intensity exceeds that of up-going neutrino-induced muons by several orders of magnitude. Even a small fraction of atmospheric muons reconstructed as up-going represents the major background source for any neutrino analysis. A detailed study of atmospheric muon intensity is therefore of importance as it can also be used to check the detector efficiency and probe the involved physics. For this purpose, the atmospheric muon flux was generated with CORSIKA and, using various propagation codes, was calculated for AMANDA at South Pole and Fréjus underground detector locations. The comparison between simulated muon intensity at AMANDA depth and experimental determination is discussed and compared with Fréjus.

1 Introduction

In all neutrino telescopes, the down-going atmospheric muon flux exceeds by several orders of magnitude that of up-going neutrino-induced muons. Atmospheric muons are generated in the decay of charged pions and kaons, which are produced in the interactions of cosmic rays in the high atmosphere (Gaisser, T., 1990). A small fraction of high energy atmospheric muons has its origin in the decay of charmed mesons. Even with a very efficient event reconstruction procedure, the number of misreconstructed muon tracks, i.e. atmospheric muons reconstructed as up-going, represents the main background source for the detection of neutrino-induced muons. The large atmospheric muon flux can be used to study the detector response and possible systematic effects, which are of interest for any neutrino analysis.

The atmospheric muon flux at the location of the experiment is sensitive to the primary cosmic ray intensity and composition, the physics of the first interaction and the air shower development in the atmosphere and to the muon propagation through the ice.

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AMANDA (**A**ntarctic **M**uon **A**nd **N**eutrino **D**etector **A**rray) is located at the Amundsen-Scott geographic South Pole Station, it was completed in the austral summer 1999/2000. Since then it consists of 677 optical modules (OMs) deployed along 19 strings, most of them at depths between 1500-2000 m below the surface of the polar ice cap (Wischnewski, R., 2001).

The aim of the present analysis is to show the preliminary results on the detector sensitivity and Monte Carlo (MC) quality investigations with respect to atmospheric muon detection, and to check for systematic effects which are not clear from the limited up-going neutrino sample.

For this purpose a MC simulation of the complete chain, from the primary interaction to the detector response is done according to the best available knowledge. This means that, differently to a previous publication (Andrés, E., et al., 2000), the pure proton spectrum with a spectral index of 2.67 assumed in the BASIEV MC (Boziev, S.N., et al., 1989) is replaced by the measured primary spectra and chemical composition (Wiebel-Sooth, B., 1998). Moreover we apply a different data unfolding procedure. Primary interaction and shower development are now calculated within the CORSIKA frame using QGSJET generator (Heck, D., et al., 1998). This allows to use the systematic study of Chirkin, D., et al. (1999) for estimating the uncertainties due to the first interaction model. In order to look for systematic effects, the muon propagation through the ice is calculated using three independent programs (see sect 2). The detector response is simulated by using a modeling of the detector which includes much more details on ice properties and instrument functionality compared to Hundertmark, S., et al. (1999).

The analysis is based on the sub-array AMANDA -B10 [1] and the 1997 data sample.

The 500 m string-length makes the detector sensitive to the factor of ~ 2 muon intensity difference from the top to the bottom. In order to get for this systematic study a better correlation between the zenith angle and the distance to the

[1]The first 10 strings completed during austral summer 1996/1997 containing 302 OMs

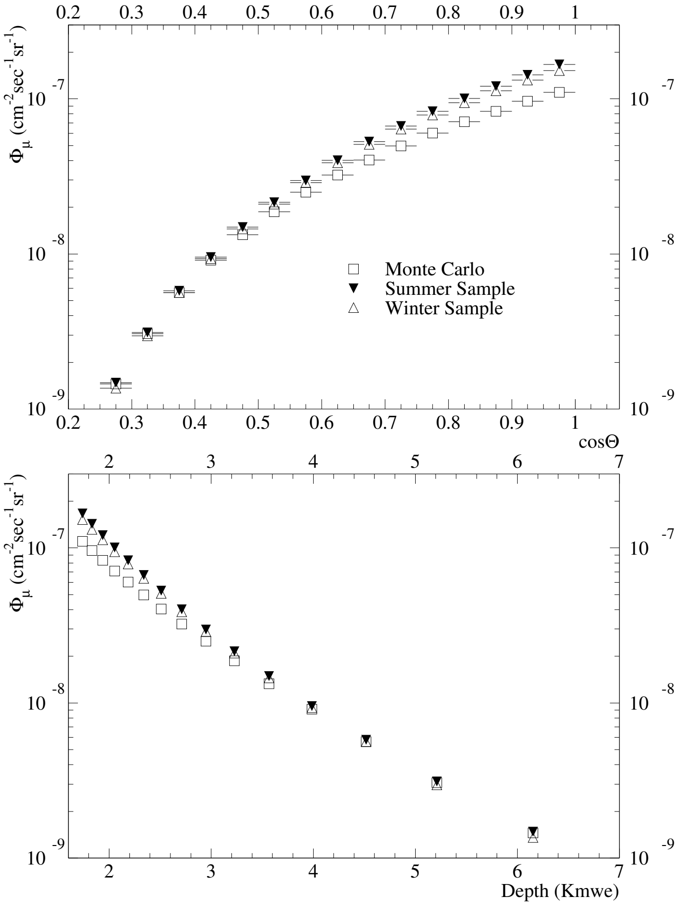

Fig. 1. Unfolded $cos\Theta$ and depth-intensity distributions compared with MC prediction. The result is obtained using MUDEDX propagation code in the simulation and for the unfolding procedure. The statistical error bars are inside the symbols.

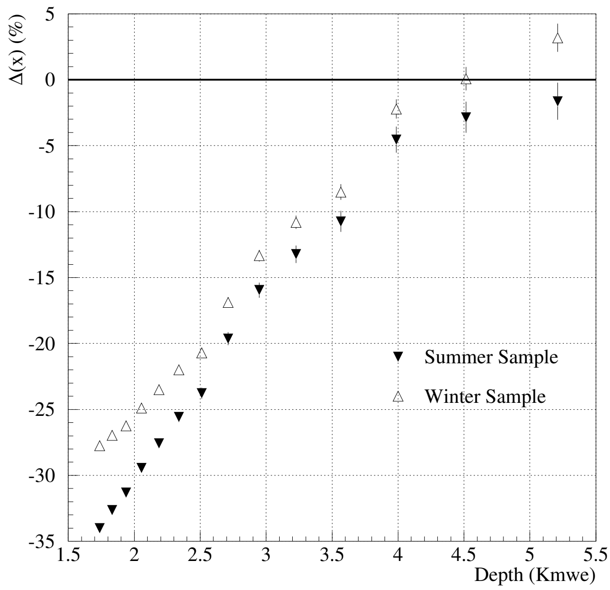

Fig. 2. Deviation between MC and unfolded data as a function of depth. The result is obtained using MUDEDX propagation code in the simulation and for the unfolding procedure.

surface, the detector has been divided in 3 equivalent parts, each containing approximately 100 OMs. In the present analysis only the bottom part has been considered [2].

2 The Data

The experimental data set is taken from 2 different days, one from the early winter (15^{th} April) and the other from the midwinter (21^{st} August), in order to check for systematics due to the time in the year. The experimental dead-time corrected counting rate, with a trigger multiplicity of 16 OMs hit in a 2 μs window, is $\sim$ 100 Hz.

The simulated data consist of 5×10^9 primaries, according to spectrum and mass composition from recent measurements (Wiebel-Sooth, B., 1998) and the relative extensive air showers production as simulated by CORSIKA, where the atmospheric muons are produced and propagated to the Earth's surface. A version of CORSIKA valid up to 90° and the atmospheric conditions from April 1997 were used for the simulation.

The generated atmospheric muons are then propagated to the ice from the surface to the AMANDA detector. Three muon propagation codes have been used, to check for systematic differences. These codes are: MUDEDX (Lohmann, W., et al., 1985), PROPMU (Lipari, P., et al., 1991) and MMC (Chirkin, D., et al., 2001) and are described below.

[2]a cylinder with 135 m height and 60 m radius with center at 1842.5 m depth, corresponding to min surface energy $E_{min} \simeq$ 600 GeV

3 Analysis

The same off-line analysis chain has been used for experiment and MC. After a hit cleaning, which rejects isolated noise hits, a maximum likelihood reconstruction procedure (Andrés, E., et al., 2000) is applied in order to determine the direction of the muons which have passed through the detector array and, in particular, through the bottom part under consideration.

Quality cuts, based on reconstruction estimation and geometrical considerations, are applied to the data samples. To take into account the detector response as well as possible, a Bayesian unfolding technique (D'Agostini, G., 1995) is used in the reconstructed $cos\Theta$ variable. The data unfolding is performed for each of the considered propagation codes in the MC chain. With this unfolding procedure the angular and depth-intensity distributions are determined. As expected, for this technique the unfolded spectrum depends on the detector efficiency but not on the different MC and propagation codes used in the unfolding procedure.

Sample	Deviation Δ	
	shift (%)	slope % /kmwe
MUDEDX	-27	11
PROPMU	-48	8
MMC	-16	14

Table 1. Comparison between different muon propagation codes: result of linear fit on $\Delta(x)$ (Fig. 2) in the depth interval 2-4 kmwe, yielding the shift at 2 kmwe and the slope

The unfolded $cos\Theta$ and depth-intensity distributions for the two considered data samples, and using MUDEDX, are shown in Fig. 1. If our knowledge about the physical processes and the detector sensitivity in this chain was perfect, an agreement between MC and unfolded data would be expected. A $\sim$ 10% difference in the overall muon intensity between the two experimental data samples is in agreement with the observed seasonal variations (Bouchta, A., et al., 1999).

Fig. 2 shows the observed deviation $\Delta(x) \equiv \frac{(I_{MC}-I_{Data})}{I_{Data}}$, as a function of depth, of the two considered data samples, with respect to the simulation using MUDEDX. A similar deviation has been observed using also the other propagation codes in the unfolding procedure. In this figure we expect a horizontal line if the unfolded spectrum agrees with the Monte Carlo expectation. CORSIKA produces, at sea-level, a spectrum with spectral index 2.73 (Chirkin, D., et al., 1999). This is in agreement with the direct measurements of muon energy spectrum at the surface. The simulated spectrum is therefore significantly too flat and its intensity is too small. It should be noted, that Fig. 2 shows the results without any simplifying assumption about the muon energy loss.

The deviation $\Delta(x)$ was determined for each of the three considered propagation codes included in the MC chain. A linear fit was done in the depth range $2-4$ kmwe. The fitted shift (at 2 kmwe) and the slope have been determined and are shown in Table 1. We see that the size of the observed deviations depend strongly on the muon propagation code. MUDEDX (Lohmann, W., et al., 1985) is based on Lohmann tables and was optimized for fixed-energy experiments. It requires, as an input, the energy scale at which cross sections are evaluated. PROPMU (Lipari, P., et al., 1991), also based on Lohmann tables, was specifically designed for underground applications. Its stochastic processes give rise to smaller fluctuations and higher survival probability (for $E < 1$ TeV) with respect to the other propagation codes. MMC (Chirkin, D., et al., 2001), based on formula collection from Rhode, W. et al. (1999), has a totally different approximation and tracking algorithms and it simulates energy losses taking into account the correct energy dependence of loss parameters.

4 Uncertainty Sources

In order to start a discussion on the observed deviations we can make use of a simplified model. If the muon energy loss is written as $\frac{dE}{dx} = a_{eff} + b_{eff} \cdot E$, the minimal energy for a muon to reach the detector is given by

$$E_{min}(x) \simeq \left(\frac{a_{eff}}{b_{eff}}\right) \cdot \left(e^{b_{eff} \cdot \rho \cdot x} - 1\right) \tag{1}$$

with ρ the material density [3]. Since the integral muon energy spectrum is roughly

$$I_\mu(E > E_{min}) = I_o \cdot sec\,\theta^\star \cdot E_{min}^{-\gamma}, \tag{2}$$

the measurement of the muon spectral index γ and of the effective energy loss parameter b_{eff} are highly correlated. Since the obtained integral muon spectrum is too flat (i.e. the muon range is too large) we can conclude that the effective energy loss has to be too small also.

This behavior can be due to various reasons. Systematic deviations in the muon cross sections, might add up, after the $\sim$ 500 stochastic interactions from the surface to the detector, to a resulting error of several percent. From this point of view we can investigate whether a numerical MC problem or, rather, the used parameterization of cross sections is the reason of the observed deviation. The differences within propagation codes support that conclusion. However, one has to note that using improved cross section formulations and increased numerical accuracy do not solve the problem.

The complete generation of secondary showers and their Cherenkov light is mandatory for a propagation code if we want to reproduce the response of an underwater and under-ice detector. This aspect was not a priority in the older codes and is being optimizing in the most recent ones.

The observed absolute deviation and its correlation with depth contain still uncertainties due to ice optical properties and to the absolute OM sensitivity (Wiebusch, C., et al., 2001). There is the possibility that the OM absolute and angular acceptance, or the photon scattering processes close to the OMs are not correctly modeled in the used MC. The uncertainties in the absolute OM sensitivity and in the ice optical properties are $\sim$ 10% and $\sim$ 15%, respectively (Wiebusch, C., et al., 2001). At this stage it is still not clear how the variation of the OM angular-dependent sensitivity would modify the observed deviations. This, however, would explain neither the differences observed between the MC predictions using different propagation codes, nor the very similar deviations observed by Fréjus experiment (Schröder, F., et al., 2001). Though detector effects not reproduced in the simulation have to be further investigated, there is the possibility that they are not the only reason for the observed deviations.

We can exclude a wrong muon spectrum at the sea level to explain the spectral deviation, since CORSIKA yields results compatible to surface measurements. To get agreement between data and MC a spectral index at the surface around

[3] for ice $\rho = 0.92\mathrm{g} \cdot \mathrm{cm}^{-3}$

3, instead of 2.7, would be required. Also the ice density is known well enough.

The picture changes, if we look now into the absolute deficit. Uncertainties in the all-particle primary flux absolute normalization at 1 TeV, on their spectral index and on the number of produces showers, amount $\sim 7\%$ for AMANDA detector (Wiebel-Sooth, B., 1998). This uncertainty seems to be too small to explain the observed deviations. Unknown is however the exact contribution of the particle production in forward direction. This effect has to be investigated.

Another possibility is suggested by the recent measurement of cosmic proton flux with AMS (AMS Coll., 2000) up to 200 GeV. The measured flux seems to be $\sim 30\%$ lower than the one usually used in calculations and simulations. If this measurement will be confirmed up to TeV energies, then, maybe, it is possible to explain the observed deviations.

5 Conclusions

The atmospheric muon flux has been generated with CORSIKA and, using different muon propagation codes, has been calculated for the South Pole and Fréjus underground detector locations.

A deviation of unfolded data with respect to the simulations, as a function of depth, is observed for each of the used propagation codes. We discussed the possible origin of these deviations.

The unknown detector effects, still not reproduced in our MC, and the uncertainties on the primary cosmic ray flux, seem not to explain completely the observed deviations. Moreover the compatibility with very similar observation in the Fréjus experiment (see Schröder, F., et al. (2001)), which, due to its larger depth, samples higher muon energies than AMANDA , seem to drive the attention on the muon propagation codes, unless the AMS proton flux measurement will be confirmed up to TeV energies.

So far the AMANDA detector needs further systematic investigations. Tests will be done in order to check if the observed deviations are depth-dependent or rather angular-dependent. This, in principle, could be done in AMANDA , by taking into account, separately, the other 2 detector parts, allowing for a better sensitivity to the sea-level muon intensity details and to the specific detector OM angular response.

Also the detailed study of stopping muons inside the detector can give some indications of the origin of the observed deviations.

Finally the analysis of the atmospheric muons in the larger AMANDA -II detector would certainly improve the angular sensitivity and the capabilities to check the new available muon propagation codes.

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