The Constant Intensity Cut Method applied to the KASCADE-Grande Muon Data

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1. Introduction

When confronting extensive air shower (EAS) data collected at different zenith angles, it is important to have a common energy scale and to correct for the atmospheric attenuation effect on the shower. One way to do it is through the use of the constant intensity cut method (CIC), which is based on the assumption of isotropy of the cosmic ray flux [1]. Isotropy implies that the arrival frequency of cosmic rays depends only on the primary energy and not on the arrival direction. In this way, the common energy scale is provided by the measurement of the intensity of cosmic rays. With this scale, the attenuation length of the EAS in the atmosphere can be easily extracted studying the behavior of the EAS size with the zenith angle at a constant intensity. With the attenuation length, the atmospheric effects on the shower size can be taken into account and comparisons can be performed.

In this work, the CIC method is employed to reconstruct a preliminary muon spectrum from vertical EAS data measured with the KASCADE-Grande experiment. The muon content of the
EAS is a key parameter to study the composition of the primary cosmic rays, their hadronic interactions and the energy spectrum, therefore, detailed analyses of this component, like the one performed here, become crucial in cosmic ray research. The way in which the CIC method is performed here, become crucial in cosmic ray reconstruction of the primary cosmic rays, their hadronic interactions and the energy spectrum, therefore, detailed analyses of this component, like the one performed here, become crucial in cosmic ray research. The way in which the CIC method is performed here, become crucial in cosmic ray reconstruction of the systematic uncertainties associated with the construction efficiency of the detector, to estimate the main systematics uncertainties, will be presented after a brief description of the experiment and the simulations.

2. The experiment and MC simulations

KASCADE-Grande is an air-shower experiment involved in the quest of the knee of the heavy component in the primary cosmic ray spectrum [2]. For energy and composition studies, the experiment measures simultaneously the electron($N_e$) and muon ($N_\mu$) sizes of air showers with energies in the range $E = 10^{16} - 10^{18}$ eV using a ground array of muonic and electromagnetic plastic scintillator detectors [2]. Reconstruction techniques of $N_e$ and $N_\mu$ are found in [3].

Monte Carlo (MC) simulations of EAS were employed in this work to study the performance of the experiment, to find the triggering and reconstruction efficiency of the detector, to estimate the systematic uncertainties associated with the reconstruction of $N_\mu$ and to select the best quality cuts as described in [4]. The MC simulations included both the development of the EAS and its interaction with the detectors. The parameters of the simulated showers were reconstructed with the same algorithm employed with the experimental data [3,4]. The development of the EAS was simulated with CORSIKA [5] and its primary collision, with the hadronic interaction model QGSJET II [6]. Cosmic ray events with energies $E = 10^{10} - 10^{18}$ eV were sampled from a differential spectrum described by a power law distribution with spectral index $\gamma = -2$. The EAS were generated for the zenith angle interval $\theta = 0^\circ - 70^\circ$. Several primaries with equal abundances (H, He, C, Si and Fe) were used. The flux was considered to be isotropic.

3. Muon size spectra

The analysis was performed over a sample of quality data events with $\theta \leq 61.7^\circ$ collected with KASCADE-Grande during the period December 2003 - July 2007. The selection of events was done on the basis of several quality cuts [4].

The muon size spectra reconstructed from the KASCADE-Grande quality data are shown in Fig. 1 for different zenith angle intervals with constant solid angle. In each graph, the EAS core position and the shower size using a correction function.
the integral spectra, CIC method. All begins with the calculation of attenuation effects in the atmosphere need to be taken into account. That is done applying the correction function: All)

4. Applying the CIC method

To combine the muon size spectra an obtain a single \( N_\mu \) flux for vertical showers (\( \theta \leq 42.5^\circ \)) the attenuation effects in the atmosphere need to be taken into account. That is done applying the CIC method. All begins with the calculation of the integral spectra, \( J(> N_\mu) \), for each zenith angle range. The respective graphs, obtained from the muon fluxes, are plotted in Fig. 1. Then a constant cut at a fixed frequency rate or intensity, \( J(> N_\mu) \), is applied inside the region of maximum efficiency and statistics. From the intersection between this cut and each integral flux a set of \( N_\mu \) values are obtained for every \( \Delta \theta \) (when necessary, linear interpolation was used between two adjacent points of the same graph). Under the assumption of an isotropic cosmic ray flux the extracted \( N_\mu \) values correspond to the same primary energy and the difference among them is due to the different distances that the EAS has to travel in the atmosphere when changing \( \theta \). From this data, the evolution of the muon size with the atmospheric depth is determined plotting \( \log_{10}(N_\mu) \) versus \( \sec(\theta) \). The resulting attenuation curves for several frequency cuts can be seen in Fig. 2. In the same plot, the results of the fit with the polynomial

\[
P(\theta) = a_0 + a_1 \cdot \sec(\theta) + a_2 \cdot \sec^2(\theta)
\]

are also displayed. In order to correct \( N_\mu \) for atmospheric effects, the mean attenuation curve, with \( \log_{10}[J/(m^{-2}s^{-1}sr^{-1})] = 10.44 \), was chosen. The correction was applied event by event in the following way:

\[
N_{\mu,\theta_{ref}} = N_\mu(\theta) \exp[P(\theta_{ref}) - P(\theta)],
\]

where \( a_0 = 6.69 \pm 0.13 \), \( a_1 = -0.49 \pm 0.19 \) and \( a_2 = 0.04 \pm 0.07 \). Here \( \theta_{ref} = 24.5^\circ \) is the angle of reference of the atmospheric depth selected to make the comparison and combine the spectra. This angle was chosen to be the mean of the \( \theta \) distribution of the vertical EAS data, since, for this work, only the \( N_\mu \) spectrum for \( \theta \leq 42.5^\circ \) will be estimated. In Fig. 3, the \( N_\mu \) spectra for \( \theta_{ref} = 24.5^\circ \) obtained after applying the CIC method to the vertical spectra of Fig. 1 can be observed. In the region of maximum efficiency, the experimental graphs for \( \theta_{ref} = 24.5^\circ \) are in good agreement inside a 3\( \sigma \) difference. Similar conclusions are derived when the CIC method is applied to the MC data. However, differences appear when confronting the experimental muon data and the MC simulations [4] and Fig. 4 is an example. There, the attenuation length (\( \Lambda_\mu \)), as extracted from a fit with the expression

\[
N_\mu = N_\mu^0 \exp[-X_o \sec(\theta)/\Lambda_\mu]
\]

to the attenuation curves, is plotted as a function of the muon size at \( \theta = 0^\circ \). In Eq. 3,
$X_0 = 1023 \text{ g/cm}^2$ is the average atmospheric depth for vertical showers. From Fig. 4, it can be observed that the experimental $\Lambda_\mu$ is bigger than the one obtained from MC simulations using CORSIKA/QGSJET II.

To finish, the single vertical muon size spectrum calculated with all data for vertical showers applying the CIC method is presented in Fig. 5 along with a first estimation of the main systematic uncertainties associated with the whole reconstruction technique. Here, errors from the parameters of the muon correction function, fluctuations, the CIC method itself, uncertainty in the spectral index (assuming $\gamma = -3$ instead of $-2$ in MC simulations) and the primary composition (working only with Protons or Iron nuclei) were evaluated. Statistical uncertainties in the integral spectra, the interpolation performed when applying the frequency cuts and the errors from the fit to the attenuation curves are considered inside the errors of the CIC method. At high energies, muon systematic uncertainties are of the order of 15% in the experiment.

5. Conclusions

The $N_\mu$ size spectrum for vertical EAS was reconstructed from KASCADE-Grande data using the CIC method. A first evaluation of the muon systematic uncertainties, after applying the full reconstruction procedure, was also performed. The results of this work show that the muon flux obtained with this technique can be used as a first step to reconstruct a primary energy spectrum. On the other hand, results for the attenuation length, as extracted with the CIC method, show that the CORSIKA/QGSJET II simulations do not reproduce the observed values of $\Lambda_\mu$.

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