Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B (Proc. Suppl.) 196 (2009) 183–186
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
www.elsevier.com/locate/npbps

The Constant Intensity Cut Method applied to the KASCADE-Grande muon data

J.C. Arteaga-Velázquez [a*†], W.D. Apel[b], F. Badea[b], K. Bekk[b], M. Bertaina[c], J. Blümer[ba], H. Bozdog[b], I.M. Brancus[d], M. Brüggemann[e], P. Buchholz[e], E. Cantoni[cf], A. Chiavassa[c], F. Cossavella[a], K. Daumiller[b], V. de Souza[a‡], F. Di Pierro[c], P. Doll[b], R. Engel[b], J. Engler[b], M. Finger[b], D. Fuhrmann[g], P.L. Ghia[f], H.J. Gils[b], R. Glasstetter[g], C. Grupen[e], A. Haungs[b], D. Heck[b], J.R. Hörandel[a§], T. Huege[b], P.G. Isar[b], K.-H. Kampert[g], D. Kang[a], D. Kickelbick[e], H.O. Klages[b], Y. Kolotaev[e], P. Łuczak[h], H.J. Mathes[b], H.J. Mayer[b], J. Milke[b], B. Mitrica[d], C. Morello[f], G. Navarra[c], S. Nehls[b], J. Oehlschläger[b], S. Ostapchenko[b¶], S. Over[e], M. Petcu[d], T. Pierog[b], H. Rebel[b], M. Roth[b], H. Schieler[b], F. Schröder[b], O. Sima[i], M. Stümpert[a], G. Toma[d], G. Trinchero[f], H. Ulrich[b], W. Walkowiak[e], A. Weindl[b], J. Wochele[b], M. Wommer[b], J. Zabierowski[h]

[a]Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany
[b]Institut für Kernphysik, Forschungszentrum Karlsruhe, D-76021 Karlsruhe, Germany
[c]Dipartimento di Fisica Generale dell'Università,10125 Torino, Italy
[d]National Institute of Physics and Nuclear Engineering, P.O. Box Mg-6, RO-7690 Bucharest, Romania
[e]Fachbereich Physik, Universität Siegen, 57068 Siegen, Germany
[f]Istituto di Fisica dello Spazio Interplanetario, INAF, 10133 Torino, Italy
[g]Fachbereich Physik, Universität Wuppertal, 42097 Wuppertal, Germany
[h]Soltan Institute for Nuclear Studies, PL-90950 Lodz, Poland
[i]Department of Physics, University of Bucharest, Bucharest, Romania

The constant intensity cut method is a very useful tool to reconstruct the cosmic ray energy spectrum in order to combine or compare extensive air shower data measured for different attenuation depths independently of the MC model. In this contribution the method is used to explore the muon data of the KASCADE-Grande experiment. In particular, with this technique, the measured muon number spectra for different zenith angle ranges are compared and summed up to obtain a single muon spectrum for the measured showers. Preliminary results are presented, along with estimations of the systematic uncertainties associated with the analysis technique.

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, a 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 EAS data measured with the KASCADE-Grande experiment. The muon content of the EAS is a

*corresponding author, e-mail: arteaga@ifm.umich.mx
†now at: Instituto de Física y Matemáticas, Universidad Michoacana, Morelia, Mexico
‡now at: Univ. São Paulo, Instituto de Fisica de São Carlos, Brasil
§now at: Dept. of Astrophysics, Radboud University Nijmegen, The Netherlands
¶now at: University of Trondheim, Norway

doi:10.1016/j.nuclphysbps.2009.09.033

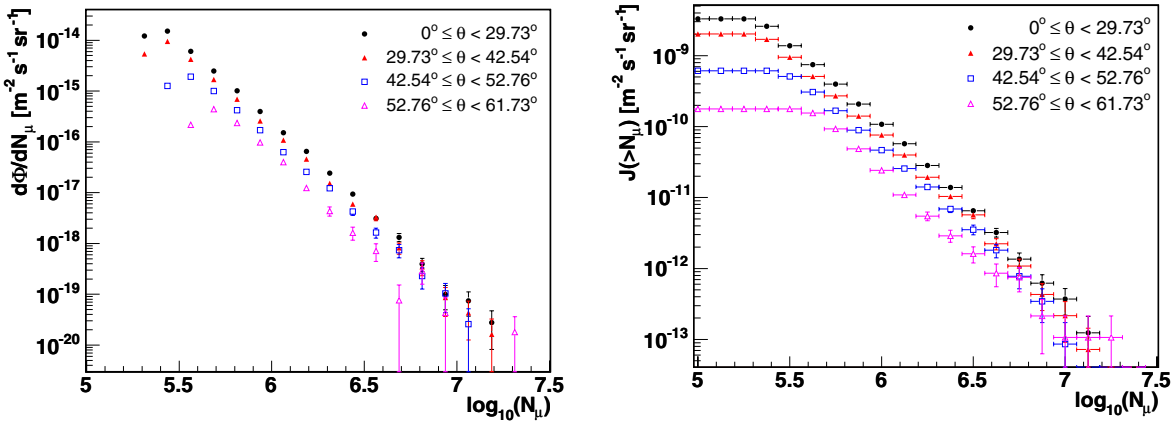

Figure 1. Differential (left) and integral (right) muon number spectra obtained from the KASCADE-Grande data. The vertical error bars represent statistical uncertainties.

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 applied, along with results and estimations of the main systematics uncertainties, will be presented together with 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_μ) 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_μ 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_μ and to optimize the selection 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 high-energy hadronic collision with the hadronic interaction model QGSJET II [6]. Cosmic ray events with energies $E = 10^{16} - 10^{18}$ eV were sampled from a differential spectrum described by a power law distribution with spectral index $\gamma = -2$, which was re-weighted to $\gamma = -3$ for specific studies. The EAS were generated for the zenith angle interval $\theta = 0° - 70°$. 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 $\theta < 61.7°$ collected with KASCADE-Grande during the period December 2003 - April 2007.

The muon size spectra reconstructed from the KASCADE-Grande quality data are shown in Fig. 1 for different θ intervals with constant solid angle. In each graph, N_μ was corrected, event by event, for systematic uncertainties arising from the reconstruction procedure. These uncertainties were estimated with MC simulations assuming a mixed composition. They were parameterized using a correction function. The uncertainties change with muon size, but on average they

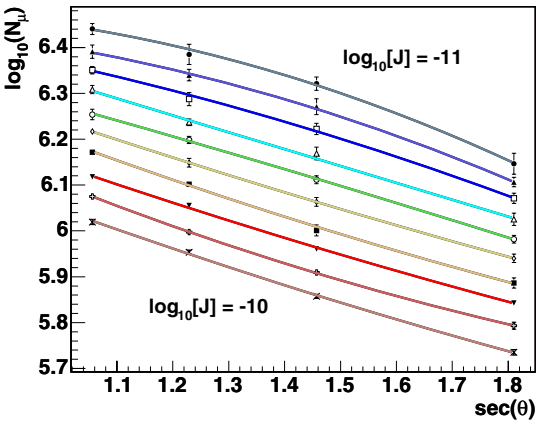

Figure 2. Muon attenuation curves obtained for several constant intensity cuts. The cuts increase from the bottom to the top in units of $\Delta \log_{10}[J/(\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1})] = -0.11$.

are smaller than 26 %.

4. Applying the CIC method

To combine the muon size spectra and obtain a single N_μ flux for the EAS, the attenuation effects in the atmosphere need to be taken into account. That is done by applying the CIC method. This starts 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 inside the region of full efficiency and sufficient statistics a constant cut at a fixed frequency rate or intensity, $J(> N_\mu)$, is applied. From the intersection between this cut and each integral flux a set of N_μ values is obtained for every $\Delta\theta$ (linear interpolation is used between two adjacent points of the same graph). Under the assumption of an isotropic cosmic ray flux the extracted N_μ values correspond to the same primary energy and the differences among them are due to the different distances that the EAS has to travel in the atmosphere when changing θ. From this data, the evolution of the muon size with 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

$$P(\theta) = a_0 + a_1 \cdot \sec(\theta) + a_2 \cdot \sec^2(\theta) \qquad (1)$$

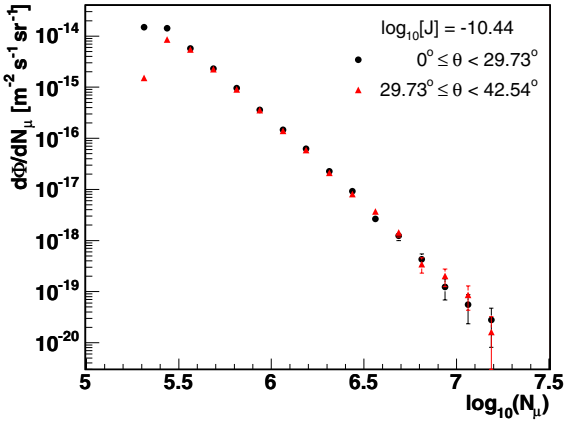

Figure 3. Muon size spectra for $\theta_{ref} = 24.5^o$ obtained with the CIC method and muon data from two zenith angle intervals.

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

$$N_{\mu,\theta_{ref}} = N_\mu(\theta)[P(\theta_{ref})/P(\theta)], \qquad (2)$$

where $a_0 = 6.69 \pm 0.13$, $a_1 = -0.49 \pm 0.19$ and $a_2 = 0.04 \pm 0.07$. Here $\theta_{ref} = 24.5°$ 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 θ distribution of the more vertical EAS data. We restricted ourselves in a first step to $\theta < 42.5°$, due to an increasing reconstruction uncertainty in N_μ for more inclined EAS. In Fig. 3, the N_μ spectra for $\theta_{ref} = 24.5°$ obtained after applying the CIC method to the fluxes of Fig. 1 can be observed. In the region of maximum efficiency, the experimental graphs for $\theta_{ref} = 24.5°$ are in good agreement (see Fig. 3). 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 (Λ_μ), as extracted from a fit with the expression

$$N_\mu = N_\mu^\circ \exp[-X_\circ \sec(\theta)/\Lambda_\mu] \qquad (3)$$

to the attenuation curves for $\theta < 61.7°$, is plotted as a function of the muon size at $\theta = 0°$.

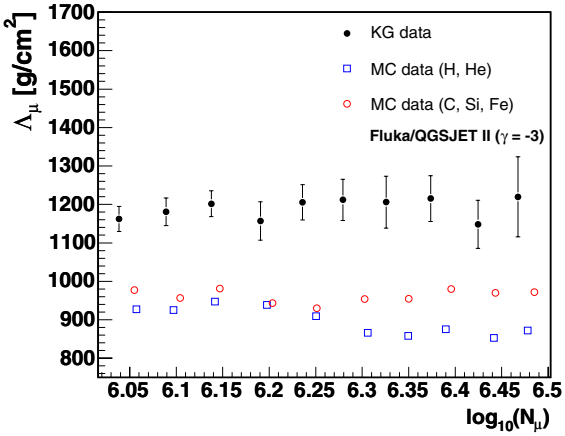

Figure 4. Muon attenuation length obtained from KASCADE-Grande data and MC simulations using CORSIKA and FLUKA/QGSJET II (assuming $\gamma = -3$ for the primary spectrum).

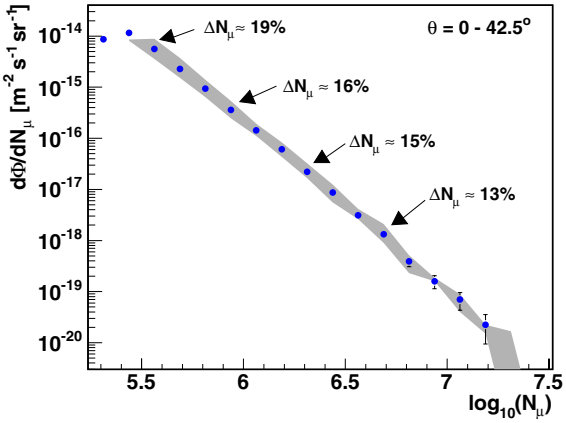

Figure 5. Single muon size spectra for $\theta_{ref} = 24.5°$ obtained with the CIC method and all KASCADE-Grande muon data for vertical showers. Systematic uncertainties are represented by the grey band.

In Eq. 3, $X_\circ = 1023\,\mathrm{g/cm^2}$ is the average atmospheric depth for vertical showers. From Fig. 4, it can be observed that the experimental Λ_μ is bigger than that obtained from MC simulations using CORSIKA/QGSJET II.

The obtained single N_μ spectrum calculated with all EAS data for $\theta < 42.5°$ 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 assumed in MC simulations and the primary composition (difference between pure proton and pure iron assumption) were evaluated. Statistical uncertainties in the integral spectra, the interpolation performed when applying the frequency cuts and the errors form 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_μ 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 Λ_μ.

6. Acknowledgements

One of the authors, J.C.Arteaga, acknowledges the partial support from the SEP-PROMEP and the Coordinación de la Investigación Científica of the Universidad Michoacana.

REFERENCES

1. D.M.Edge *et al.*,J.Phys.**A6** (1973). J.Alvarez-Muñiz *et al.*, Phys.Rev. **D66**, 123004 (2002).
2. A.Haungs *et al.*, KASCADE-Grande Coll., these proceedings, (2009).
3. F.Cossavella *et al.*, KASCADE-Grande Coll., Proc. of 30th ICRC Mexico **4**, 211(2008). J.van Buren *et al.*, KASCADE-Grande Coll., Proc. of 29th ICRC Pune **6**, 301(2005).
4. J.C.Arteaga *et al.*, KASCADE-Grande Coll., Proc. of 30th ICRC Mexico **4**, 203-206 (2008).
5. D.Heck *et al.*, Forschungszentrum Karlsruhe, Report FZKA 6019 (1998).
6. S.S.Ostapchenko, Phys.Rev. **D74** 014026.