The Energy Spectrum of Primary Cosmic Rays Reconstructed with the KASCADE-Grande Muon Data

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***Abstract*. A detailed analysis based on the Constant Intensity Cut method was applied to the KASCADE-Grande muon data in order to reconstruct an all-particle energy spectrum of primary cosmic rays in the interval $2.5 \times 10^{16} - 10^{18}$ eV. To interpret the experimental data, Monte Carlo simulations carried out for five different primary nuclei (H, He, C, Si and Fe) using the high-energy hadronic interaction model QGSJET II were employed. For each case, the derived all-particle energy spectrum is presented. First estimations of the main systematic uncertainties are also shown.**

***Keywords*: Ground arrays, cosmic ray energy spectrum, muons**

I. Introduction

One of the main goals of the cosmic ray research is the measurement of the primary energy spectrum, which encloses important keys about the origin, acceleration and propagation of cosmic rays. This task can be done directly or indirectly, depending on the energy of the primary particle. At high energies, above 10^{15} eV, where direct detection is not feasible, the energy spectrum must be determined indirectly from the measured properties of the extensive air showers (EAS) that cosmic rays induce in the Earth's atmosphere. Depending on the experimental apparatus and the detection technique, different sets of EAS observables are available to estimate the energy of the primary cosmic ray [1]. In ground arrays the total number of charged particles in the shower and the corresponding density at observation level are more commonly employed [1], [2]. However, the muon content is also at disposal for this enterprise [3]. One reason in favor of this observable is that, in an air shower, muons undergo less atmospheric interactions than the charged component (dominated by electromagnetic particles for vertical EAS) and present in consequence less fluctuations. Another reason is that, according to MC simulations, the muon shower size (N_μ) grows with the energy of the primary particle following a simple power law. Although these advantages, the muon number as an energy estimator is expected to be limited by the hadronic-interaction model, the experimental error and the uncertainty in the primary composition, among other things. In this work, the KASCADE-Grande muon data is used as a tool to derive the energy spectrum for cosmic rays in the range from 2.5×10^{16} to 10^{18} under different composition scenarios. The method is explained and the main systematic uncertainties behind the calculations are presented.

II. Description of the detector and the data

The KASCADE-Grande experiment was conceived as a ground-based air shower detector devoted to the search of the *iron knee* in the cosmic ray spectrum [4]. KASCADE-Grande, with an effective area of $0.5\,\mathrm{km}^2$,

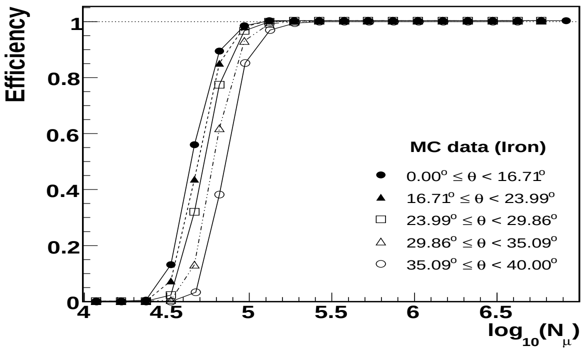

Fig. 1: KASCADE-Grande triggering and reconstruction efficiency shown as a function of the muon number for different zenith angle intervals. The efficiency was estimated from MC simulations assuming a pure iron composition.

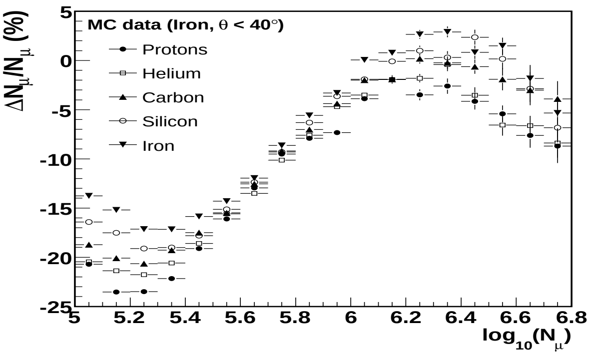

Fig. 2: Average values of the muon correction functions plotted versus the total muon number. Results for different primaries are displayed.

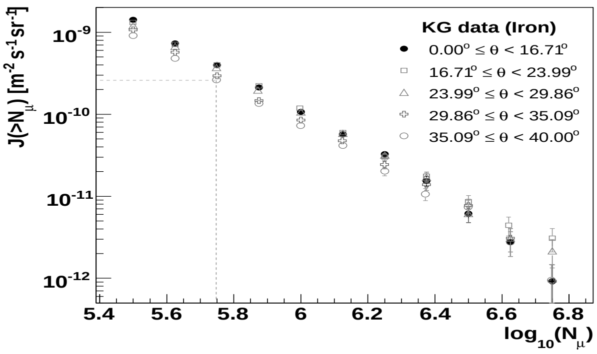

Fig. 3: Integral muon spectra obtained from the KASCADE-Grande data using the muon correction function for iron nuclei. The vertical error bars represent statistical uncertainties. In this figure, a CIC cut is represented by the horizontal line. The intersection of the CIC cut with a given integral flux defines a corresponding N_μ value, here indicated by the vertical line.

is composed by several types of particle detectors dedicated to study different components of the EAS. Important for this analysis is the $200 \times 200\,\mathrm{m}^2$ muon detector array integrated by $192 \times 3.2\,\mathrm{m}^2$ shielded scintillator detectors, which are sensitive to muons with energy threshold above $230\,\mathrm{MeV}$ for vertical incidence [4], [5], [6]. The muon array was implemented to measure the lateral distribution of muons in the shower front and to extract the muon shower size. The latter is performed, event by event, from a fit to the observed lateral muon densities [6].

The present analysis was based on a muon data set collected with the KASCADE-Grande array during the period December 2003 - February 2009 for zenith angles, θ, below 40°. In order to reduce the influence of systematic uncertainties in this data, a fiducial area of $370 \times 520\,\mathrm{m}^2$ located at the center of KASCADE-Grande was employed. Moreover various experimental cuts were imposed. As a result the effective time of observation of the selected data was approximately 754.2 days. For the conditions above described, full efficiency is achieved for $\log_{10}(N_\mu) > 5.1 - 5.4$, according to MC simulations. Here the lower threshold corresponds to the case of light primaries and/or vertical air showers (see, for example, Fig. 1).

The systematic uncertainties of the instrument and the reconstruction procedures were also investigated with MC simulations. The EAS events were generated with an isotropic distribution with spectral index $\gamma = -2$ and were simulated with CORSIKA [7] and the hadronic MC generators FLUKA [8] and QGSJETII [9]. MC data sets were produced for five different representative mass groups: H, He, C, Si and Fe. In each case the simulated data was weighted with a proper function to describe a steeper energy spectrum with $\gamma = -3$, which was chosen as reference for the purpose of this study.

III. The path to the spectrum

For the current analysis the experimental muon data was divided in five zenith angle intervals ($\Delta\theta$), each of them with the same value of acceptance. In addition, N_μ was corrected for systematic effects through a correction function, which was parameterized in terms of the zenith and azimuth angles, the core position and the muon size according to MC results. The precise magnitude of the corrections change with the primary mass, but on average they are under 25 % and tend to decrease with N_μ in the region of full efficiency (see Fig. 2). Along the paper muon correction functions were already applied to the data according to the primary composition assumed.

In order to reconstruct the all-particle energy spectrum, in a first step the CIC method was applied to the corrected muon data [2], [3], [10]. The objective was to extract a muon attenuation curve to correct the muon shower size at different atmospheric depths and convert it into an equivalent N_μ for a given zenith angle of reference to combine in this way muon data measured at different atmospheric depths. To start with, the integral muon spectra, $J(> N_\mu)$, were calculated for all $\Delta\theta$ bins. As an example, in Fig. 3 the integral fluxes derived with a N_μ correction function for iron nuclei were plotted. Unless otherwise indicated an iron primary composition will be assumed from now on to illustrate the procedure. Once the integral spectra were calculated, cuts at a fixed frequency rate or integral intensity were

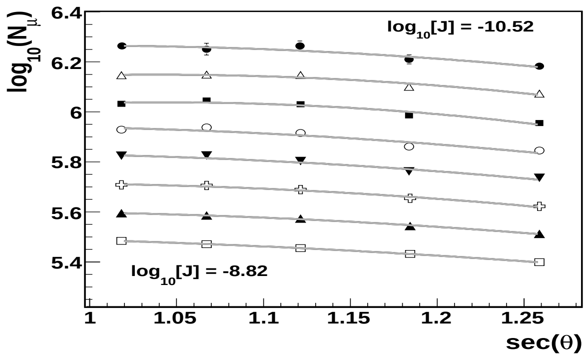

Fig. 4: Muon attenuation curves as extracted from several constant intensity cuts applied to the integral N_μ spectra of figure 3. From the bottom to the top, the CIC cuts decrease in steps of $\Delta\log_{10}[J/(m^{-2}s^{-1}sr^{-1})] \approx 0.24$.

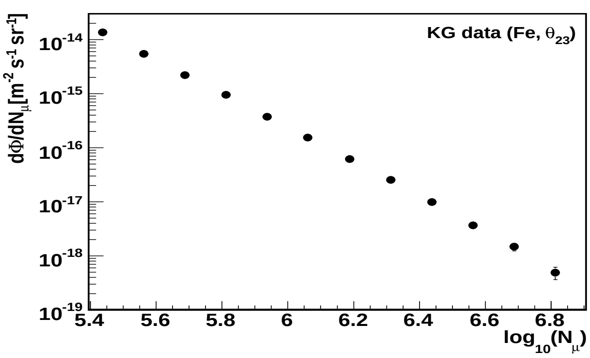

Fig. 5: The KASCADE-Grande muon spectrum obtained with the CIC method for $\theta_{ref} = 23.1°$. The muon correction function for iron nuclei was employed.

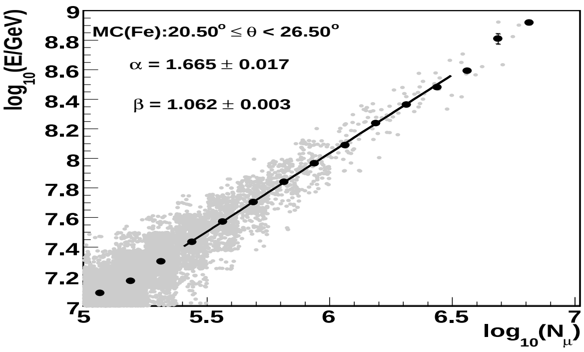

Fig. 6: Mean distribution of true energy vs muon number for iron nuclei and $\theta = 20.5° - 26.5°$ calculated with MC simulations. The fit with formula $\mathrm{E[GeV]} = \alpha \cdot N_\mu^\beta$ is shown.

applied covering only the region of maximum efficiency and statistics. Then from the intersection of each cut and the integral fluxes (see Fig. 3) a muon attenuation curve was built plotting the intersected muon numbers as a function of $\sec\theta$, as displayed in Fig. 4. This can be in principle done since, according to the CIC method (where isotropy of cosmic rays is assumed) all EAS muon sizes connected through a specific cut belong to showers of identical energy. A technical point should be mentioned before continuing, that linear interpolation between two adjacent points was used in order to find the crossing between a given cut and a certain spectrum. The uncertainty introduced by the interpolation procedure in the extracted value of N_μ was properly taken into account along with the statistical errors of the integral spectra.

With the attenuation curves finally at disposal, one can calculate the equivalent muon number of an EAS for a zenith angle of reference, θ_{ref}. This angle was chosen to be the mean of the measured zenith angle distribution, which was found around $23.1°$. Event by event, the equivalent EAS muon size for the selected atmospheric depth was estimated through the formula:

$$N_\mu(\theta_{ref}) = N_\mu(\theta)\exp\left[P(\theta_{ref}) - P(\theta)\right], \qquad (1)$$

where $P(\theta)$ is a fit, with a second degree polynomial in $\sec\theta$, to the attenuation curves (see Fig. 4). In the above equation $P(\theta)$ is the closest curve to a given $N_\mu(\theta)$ data point. In Fig. 5 the equivalent muon spectrum for θ_{ref} as calculated with the CIC method is presented.

In a final step, to derive the energy spectrum from the above data a conversion relation from muon content into primary energy was invoked. The calibration formula was obtained from MC simulations by fitting the mean distribution of true energy versus N_μ for data with zenith angles around θ_{ref}. The fit was done with a power law relation, $\mathrm{E[GeV]} = \alpha \cdot N_\mu^\beta$, for the N_μ interval of full efficiency and high statistics (see Fig. 6). To test the reconstruction method the same analysis was applied to the MC data. Differences between the magnitude of the true and the estimated MC energy spectra were found. At $E \approx 10^{17}$ eV, they are smaller than 30%. Deviations are due to fluctuations in the reconstructed energy, which are bigger for light primary masses. They vary in the range of $18 - 29$ % at 10^{17} eV. That defines our energy resolution at this energy scale.

IV. Results and Conclusions

The all-particle energy spectrum reconstructed from the KASCADE-Grande muon data is displayed in Fig. 7 for different primary composition assumptions. Measurements of the original KASCADE experiment [5] are also shown for comparison. It can be seen that the KASCADE data points are found inside the region that covers the KASCADE-Grande results, showing agreement between both experiments. Total uncertainties are also presented in the same figure. They take into account the following sources: 1) the influence of the energy resolution distribution, 2) uncertainties in the N_μ correction functions and 3) the energy conversion relation, both arising from the fits to MC data, 4) uncertainties in the estimation of the equivalent muon number, 5) a small shift observed in the estimated energy, which is introduced by the analysis, 6) uncertainties in the primary spectral index ($\gamma = -3 \pm 0.5$) and 7) the effect of selecting another reference angle θ_{ref}, using for example 10 and $30°$. Each of these contributions introduces a

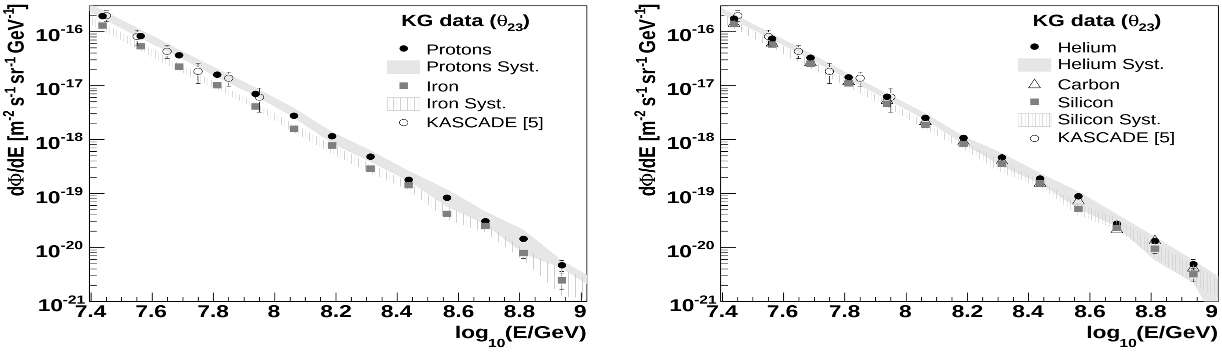

Fig. 7: The all-particle energy spectrum derived from the KASCADE-Grande muon data assuming different primary compositions. The bands for the total uncertainties (energy resolution plus systematic errors) are displayed (except for Carbon). Vertical error bars represent statistical uncertainties.

TABLE I: Percentual contributions to the total uncertainty (energy resolution and systematics) of the energy spectrum around 10^{17} eV. Sources are enumerated as described in the text. At the same energy scale, the average energy systematic uncertainty and energy resolution are also shown. The muon attenuation length is presented in the last column.

Composition	$\Phi \pm$ tot. $\pm$ stat. 10^{-18}[m^{-2} s^{-1} sr^{-1} GeV^{-1}]	(1) [%]	(2) [%]	(3) [%]	(4) [%]	(5) [%]	(6) [%]	(7) [%]	ΔE/E [%] $\pm$syst. $\pm$ res.	Λ_μ [g/cm^2]
H	$2.75^{+1.09}_{-0.21} \pm 0.07$	$+35$	$^{+2}_{-1}$	± 1	$^{+3}_{-1}$	$+11$	$^{+13}_{-7}$	$^{+8}_{-0}$	$^{+9}_{-8} \pm 29$	1136 ± 115
He	$2.52^{+0.53}_{-0.20} \pm 0.07$	$+19$	$^{+1}_{-0.4}$	$^{+1}_{-0.4}$	$^{+2}_{-1}$	-3	$^{+6}_{-5}$	± 5	$^{+6}_{-12} \pm 26$	1111 ± 112
C	$2.29^{+0.23}_{-0.229} \pm 0.06$	$+9$	$^{+0.2}_{-2}$	$^{+0.2}_{-1}$	$^{+1}_{-2}$	-2	$^{+2}_{-6}$	$^{+3}_{-10}$	$^{+6}_{-13} \pm 19$	1137 ± 121
Si	$1.88^{+0.20}_{-0.35} \pm 0.06$	$+6$	$^{+2}_{-3}$	$^{+0.4}_{-0.1}$	± 2	-3	$^{+4}_{-1}$	$^{+7}_{-18}$	$^{+5}_{-15} \pm 20$	1056 ± 146
Fe	$1.58^{+0.36}_{-0.26} \pm 0.05$	$+22$	$^{+0.5}_{-0.1}$	$^{+0}_{-0.1}$	$^{+1}_{-4}$	$+2$	$^{+2}_{-0.1}$	$^{+1}_{-16}$	$^{+4}_{-13} \pm 18$	1123 ± 182

modification in the estimated energy of the events, which is propagated to the flux. The differences between the reference spectrum and the modified ones were interpreted as the corresponding uncertainties. They were added in quadrature to get the total error. In cases (2), (3) and (4) usual error propagation formulas were employed to find the energy uncertainty of the events. (1) and (5) were estimated from MC simulations. In the case of (1), the energy of an event was assigned in a probabilistic way using the energy resolution distributions per energy bin obtained with MC simulations. In (6) MC relations employed in the whole analysis were recalculated with simulations characterized by the new spectral indexes. Finally, for (7) both the equivalent N_μ and the energy calibration formula were estimated for the new values of θ_{ref}. The resulting uncertainties (energy resolution (1) and systematics (2)-(7)) for the energy and the spectrum around 10^{17} eV are presented in table I. In general, for the interval $\log_{10}[\mathrm{E/GeV}] = 7.4 - 8.3$ from all the estimated contributions to the total uncertainty of the flux the biggest one is related to composition ($\lesssim$ 50%). The second most important contribution ($\lesssim$ 35%) comes from (1). The uncertainties associated to (6) and (7) together occupy the third place ($\lesssim$ 31%), but sometimes they can be as important as (1). For light primaries (5) can become the next influent source ($\lesssim$ 12%). The rest contributions, (2)-(4), are always the smaller ones (added they are $\lesssim$ 12%). Both the energy and flux total uncertainties change with the value of E. They tend to increase near the energy threshold and in the high-energy region, where statistics decreases. These first estimations are very encouraging. They show that muons can be used in KASCADE-Grande as a tool to reconstruct the primary all-particle energy spectrum. More work is to come in order to improve the reconstruction method. Plans are also underway to investigate the muon attenuation length, Λ_μ. Some values extracted from the N_μ attenuation curves are shown in Table I for $E \approx 10^{17}$ eV. A good agreement is seen among the experimental attenuation lengths under the assumption of different primary masses at this energy.

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