The sensitivity of KASCADE-Grande to the cosmic ray primary composition between 10^{16} and 10^{18} eV

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***Abstract*. The goal of the KASCADE-Grande experiment is the study of the cosmic ray energy spectrum and chemical composition in the range 10^{16} - 10^{18} eV detecting the charged particles of the respective Extensive Air Showers. The observables here taken into account for discussion are the measured electron size (N_e) and muon size (N_μ). It is crucial to verify: the sensitivity to different chemical components, the data reproducibility with the hadronic interaction model in use as a function of the electron size and the athmospheric depth, the consistency with the results obtained by other experiments sensitive to composition in overlapping energy regions. The analysis is presented using KASCADE as reference experiment and using QGSjetII as hadronic interaction model.**

***Keywords*: KASCADE-Grande, sensitivity, interaction model.**

I. Introduction

The KASCADE-Grande experiment is located at Forschungszentrum Karlsruhe (Germany). It consists of an array of 37 scintillator modules 10 m^2 each (the Grande array) spread over an area of 700 x 700 m^2, working jointly with the co-located and formerly present KASCADE experiment [1], made of 252 scintillation detectors, 490 m^2 sensitive area spread over 200 x 200 m^2. The extension from KASCADE to KASCADE-Grande is meant to increase the experimental acceptance of a factor $\sim$10, the achieved accuracies showing there is no significant loss in resolution for the present analysis (see [2]). For each recorded EAS the charged particle size N_{ch} is measured through Grande, the reconstruction procedure being fine tuned over the whole experimental area (see [2]), and the muon size N_μ is obtained from KASCADE, the reconstruction and accuracy of the muonic component being described in [3]. The electron size is obtained subtracting the muon from the charged particle density. As to validate the experimental results and verify the applicability of the interaction model in use for data interpretation[1] it is first of all important to achieve an accurate event reconstruction, the next step is to test the sensitivity of the extended apparatus to observables, to verify the data reproducibility with the hadronic interaction model in use and to test the consistency of this reproducibility with the former KASCADE data. For this aims, in the following analysis, the total number of electrons N_e and the total number of muons N_μ of each recorded event are considered and the distribution of N_μ/N_e is studied in different intervals of ${N_e}^2$ and zenith angle (athmospheric depth).

[1]Both for energy measurements and composition studies.
[2]Corresponding to different energy intervals (see IV).

TABLE I: The results for the chi square minimization on the selected experimental data using just one chemical component.

chemical element	protons (p)	Helium (He)	Carbon (CNO)	Silicium (Si)	Iron (Fe)
χ^2/ν	6798.09	404.59	26.44	17.20	10.44

II. The features of the analysis

KASCADE-Grande data are chosen, at first, in an electron size range providing full reconstruction efficiency (see [5]) and high statistics: 6.49 $\leq$ Log(N_e) $<$ 6.74 in 0° $\leq \theta <$ 23.99° (see figure 1). The same event selection is made on the simulated QGSjetII [4] data sets at disposal for each cosmic ray primary[3]. The experimental distribution of the observable N_μ/N_e is taken into account and fitted with a linear combination of elemental contributions from simulations, expressed as follows:

$$F_{sim}(i) = \sum_j \alpha_j f_{sim,j}(i) \quad (1)$$

where F_{sim}(i) is the total theoretical fraction of simulated events falling in the channel i of the distribution considered as a histogram, $f_{sim,j}$(i) is the fraction for the single chemical component j, Σ_j is the sum over the different components and α_j is the fit parameter representing the *relative abundance* of the component j. The fit parameters fulfill the conditions

$$0. < \alpha_j < 1., \forall j \quad (2)$$

and

$$\sum_j \alpha_j = 1. \quad (3)$$

The fit is performed through the minimization of the following Chi Square function:

$$\chi^2 = \sum_i \frac{(F_{exp}(i) - F_{sim}(i))^2}{\sigma(i)^2} \quad (4)$$

where F_{exp}(i) is the fraction of experimental events falling in the histogram channel i and σ(i) is the error on the theoretical expression (1).

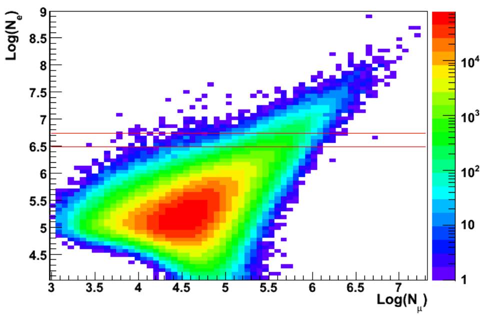

Fig. 1: The KASCADE-Grande data as they appear in the observables N_e and N_μ. The considered selection lies between the lines.

[3]p,He, C, Si, Fe. (simulated with an energy spectrum γ = 3)

A. *The fit with a single chemical component*

A chi square minimization is performed at first with the use of a single chemical component. This shows to give not a good description of the data, as it can be seen in table I, summarizing the results for the chi square minimization with single elements (see also figure 2 as example).

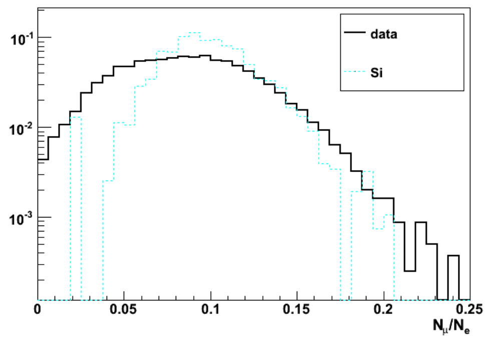

Fig. 2: The distributions (normalized to 1) of the KASCADE-Grande data in 6.49 $\leq$ Log(N_e) $<$ 6.74 (0° $\leq \theta <$ 23.99°) and of QGSjetII Silicium in the same selection range.

B. *The fit with two chemical components*

The experimental selection is then fitted with a combination of a light and a heavy chemical component that, at a qualitative glance, seem necessary to describe well the tails of the experimental histogram. Indeed, performing a minimization with two components steps up the fit, as it can be seen in table II and figures 3 and 4. It can be observed that Iron seems necessary to describe well the right tail of the experimental distribution, while Helium seems not to fit well on the left tail. Moreover, the shapes of the fits suggest the requirement of a third element in the middle.

TABLE II: The results for the chi square minimization on the selected experimental data using two chemical components.

chemical elements	p + Fe	He + Fe
α_p	0.41 $\pm$ 0.02	–
α_{He}	–	0.49 $\pm$ 0.02
α_{Fe}	0.59 $\pm$ 0.02	0.51 $\pm$ 0.02
χ^2/ν	3.51	1.48

C. *The fit with three chemical components*

The fit is then performed with a combination of three elements: Protons, Helium and Iron are chosen, matching the light elements with the heaviest element.

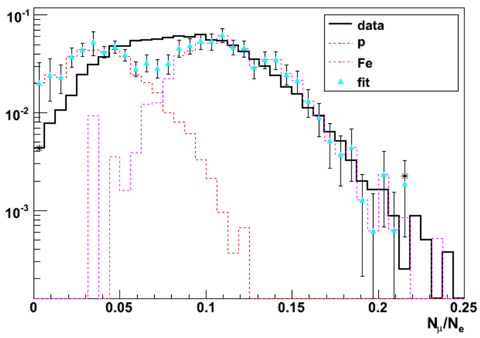

Fig. 3: The KASCADE-Grande data in 6.49 $\leq$ Log(N_e) $<$ 6.74 ($0° \leq \theta < 23.99°$) described by Protons and Iron primaries. Here and in the next pictures, the experimental plot is normalized to 1 and every simulated component is normalized to its relative abundance. Each tail of the experimental distribution (>2·RMS and <2·RMS) is treated counting the events in a single bin: the star indicates the total experimental value the fit must be compared with in that bin.

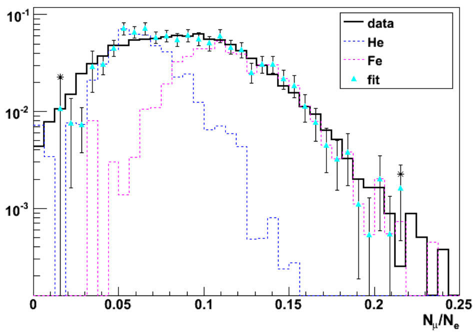

Fig. 4: The KASCADE-Grande data in 6.49 $\leq$ Log(N_e) $<$ 6.74 ($0° \leq \theta < 23.99°$) described by a Helium and Iron primaries.

It can be seen that a three elements combination is well fitting the data (see table III and figure 5). It is possible to use also another combination: Protons, Carbon and Iron (see table III and figure 6). These results show that the theoretical model describes well the shape and the tails of the experimental distribution.

TABLE III: The results for the chi square minimization on the selected experimental data using three chemical components.

chemical elements	p + He + Fe	p + CNO + Fe
α_p	0.15 $\pm$ 0.02	0.23 $\pm$ 0.02
α_{He}	0.31 $\pm$ 0.03	–
α_C	–	0.34 $\pm$ 0.03
α_{Fe}	0.54 $\pm$ 0.02	0.43 $\pm$ 0.02
χ^2/ν	0.68	1.14

III. Analysis on inclined showers

To check the consistency of the result at higher zenith angles, the same fits with three chemical components are performed on a higher angular interval of equal

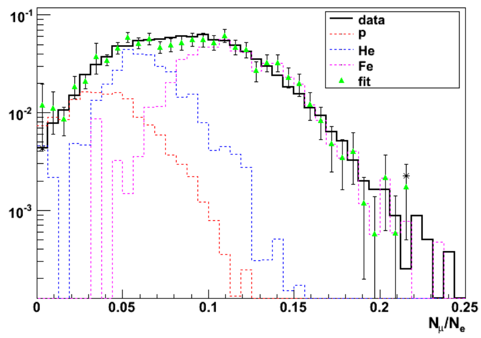

Fig. 5: The KASCADE-Grande data in 6.49 $\leq$ Log(N_e) $<$ 6.74 ($0° \leq \theta < 23.99°$) described by Protons, Helium and Iron primaries.

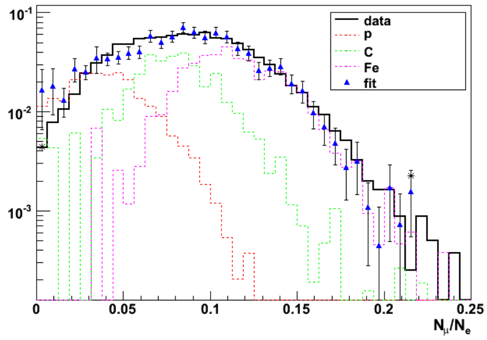

Fig. 6: The KASCADE-Grande data in 6.49 $\leq$ Log(N_e) $<$ 6.74 ($0° \leq \theta < 23.99°$) described by Protons, Carbon and Iron primaries.

acceptance, $29.86° \leq \theta < 40°$, in an electron size interval providing a similar number of events, 6.11 $\leq$ Log(N_e) $<$ 6.36. Also at higher angles, using three elements, it is found that the model reproduces the data, as it can be seen in table IV and figure 7.

TABLE IV: The results for the chi square minimization on the selected experimental data using p + He + Fe. Comparison between vertical and inclined showers.

angular bin	$0° \leq \theta < 23.99°$	$29.86° \leq \theta < 40°$
α_p	0.15 $\pm$ 0.02	0.17 $\pm$ 0.04
α_{He}	0.31 $\pm$ 0.03	0.31 $\pm$ 0.05
α_{Fe}	0.54 $\pm$ 0.02	0.52 $\pm$ 0.03
χ^2/ν	0.68	0.77

IV. Analysis at higher energies

Selecting the KASCADE-Grande experimental data for higher values of the electron size N_e means to chose showers that were generated by higher energy events (see [5]). Also in this case, it is found that the model reproduces the data, the minimization of the N_μ/N_e distribution with three chemical components still providing a good result, as it can be seen in table V and figure 8.

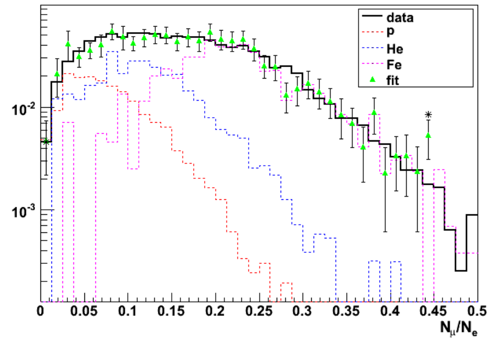

Fig. 7: The KASCADE-Grande data in $6.11 \leq$ Log(N$_e$) < 6.36 ($29.86° \leq \theta < 40°$) described by Protons, Helium and Iron primaries.

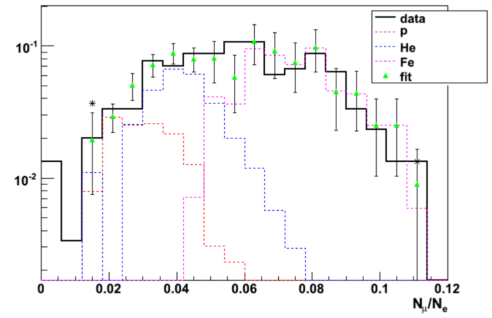

Fig. 8: The KASCADE-Grande data in $7.24 \leq$ Log(N$_e$) < 7.49 ($0° \leq \theta < 23.99°$) described by Protons, Helium and Iron primaries.

TABLE V: The results for the chi square minimization in a low and a high electron size interval, using p + He + Fe.

Δ Log(N$_e$)	$6.49 \leq$ Log(N$_e$) < 6.74	$7.24 \leq$ Log(N$_e$) < 7.49
α_p	0.15 $\pm$ 0.02	0.13 $\pm$ 0.02
α_{He}	0.31 $\pm$ 0.03	0.29 $\pm$ 0.04
α_{Fe}	0.54 $\pm$ 0.02	0.58 $\pm$ 0.04
χ^2/ν	0.68	0.83

V. Comparison with KASCADE data

Being the electron size range $6.11 \leq$ Log(N$_e$) $<$ 6.36 ($29.86° \leq \theta < 40°$) common to KASCADE and KASCADE-Grande data, the correspondent N$_\mu^{tr}$/N$_e$ distribution from KASCADE is taken into account. Applying the same analysis, it is found that three chemical components fit the data, as for KASCADE-Grande (see table VI and figure 9). Even with KASCADE data, the combination p + C + Fe is also fitting (see figure 10).

TABLE VI: The results for the chi square minimization on the selected data from KASCADE.

chemical elements	p + He + Fe	p + C + Fe
α_p	0.20 $\pm$ 0.03	0.33 $\pm$ 0.06
α_{He}	0.30 $\pm$ 0.04	–
α_C	–	0.26 $\pm$ 0.07
α_{Fe}	0.50 $\pm$ 0.03	0.41 $\pm$ 0.04
χ^2/ν	1.12	1.25

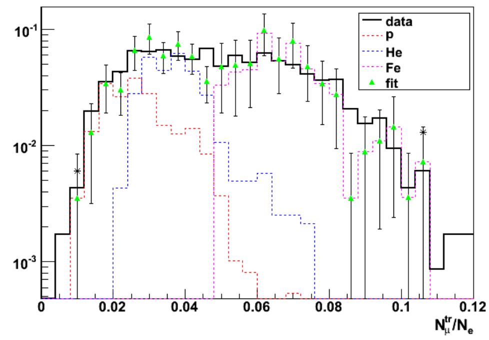

Fig. 9: The KASCADE data in $6.11 \leq$ Log(N$_e$) < 6.36 ($29.86° \leq \theta < 40°$) described by Protons, Helium and Iron primaries. Here the number of muons with distances to the shower core between 40 m and 200 m ("truncated") is considered.

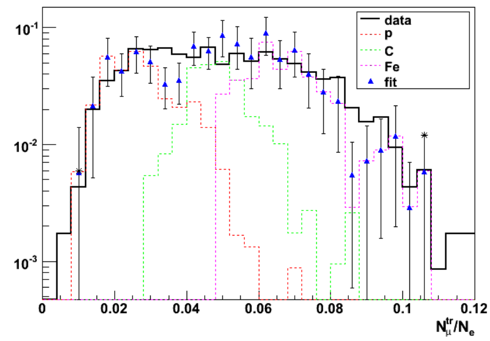

Fig. 10: The KASCADE data in $6.11 \leq$ Log(N$_e$) < 6.36 ($29.86° \leq \theta < 40°$) described by Protons, Carbon and Iron primaries.

VI. Conclusions

In this work it has been shown that, with the use of a method exploiting a chi square minimization of a linear combination of different simulated primaries, the KASCADE-Grande N$_\mu$/N$_e$ distributions are fitted using at least three elements. QGSjetII, the hadronic interaction model in use, can fairly reproduce the data and, in particular, the tails of the distributions, that represent a main constraint being related to the lightest and heaviest cosmic ray primaries. Finally, this kind of analysis, performed on the correspondent N$_\mu^{tr}$/N$_e$ distribution from KASCADE experiment, gives a consistent result, thus showing that, in the superposition energy region, KASCADE-Grande is fairly well reproducing KASCADE data.

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