A direct measurement of the muon component of air showers by the KASCADE-Grande Experiment

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

[†]*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76021 Karlsruhe, Germany*
[*]*Institut für Kernphysik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany*
[‡]*Dipartimento di Fisica Generale dell'Università, 10125 Torino, Italy*
[§]*National Institute of Physics and Nuclear Engineering, 7690 Bucharest, Romania*
[¶]*Fachbereich Physik, Universität Siegen, 57068 Siegen, Germany*
[‖]*Istituto di Fisica dello Spazio Interplanetario, INAF, 10133 Torino, Italy*
[**]*Fachbereich Physik, Universität Wuppertal, 42097 Wuppertal, Germany*
[††]*Soltan Institute for Nuclear Studies, 90950 Lodz, Poland*
[‡‡]*Department of Physics, University of Bucharest, 76900 Bucharest, Romania*
[xi]*now at: Universidad Michoacana, Morelia, Mexico*
[xii]*now at: Universidade de São Paulo, Instituto de Física de São Carlos, Brasil*
[xiii]*now at: Dept. of Astrophysics, Radboud University Nijmegen, The Netherlands*
[xiv]*now at: University of Trondheim, Norway*

***Abstract*. The muon component of atmospheric air showers is a very relevant information in astroparticle physics due to its direct relation to the primary particle type and dependence on the hadronic interactions. In this paper, we study the muon densities measured by the KASCADE-Grande experiment and illustrate its importance in composition studies and testing of hadronic interaction models. The data analysed here was measured by the KASCADE-Grande detector and lies in the $10^{16} - 10^{18}$ eV energy range. The measured muon density is compared to predictions of EPOS 1.61 and QGSJet II hadronic interaction models.**

***Keywords*: Muon Density, Composition and Simulation test.**

I. INTRODUCTION

Cosmic rays with energy range between 10^{16} and 10^{18} eV have the potential to reveal interesting astrophysical phenomena occurring in the Universe. This might be the energy range in which a transition in the predominance of the particle flux from galactic to extragalactic sources is happening what could be followed by changes in the primary cosmic abundance. If such a transition is not occurring in this energy range, galactic sources would have an acceleration power beyond the predictions of conservative theories.

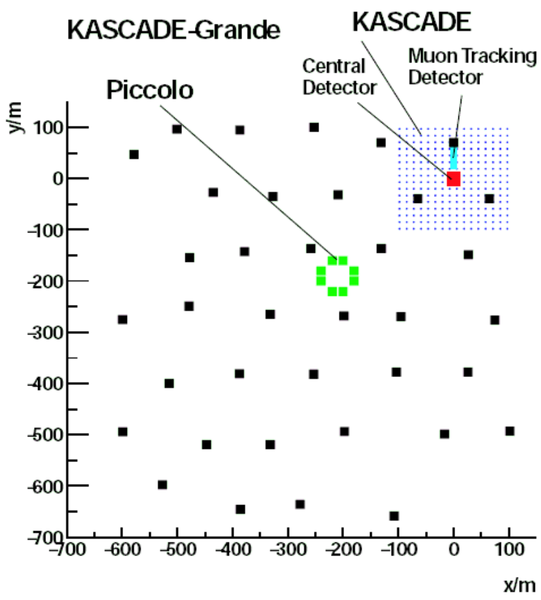

Fig. 1: Representation of the KASCADE-Grande detectors.

The KASCADE-Grande experiment (see figure 1) has been set up to measure primary cosmic rays in this energy range in order to help in the understanding

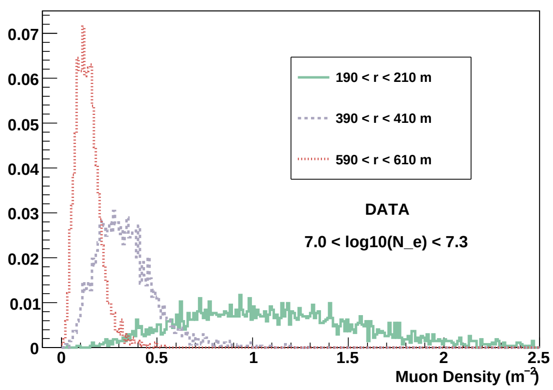

Fig. 2: Distribution of the density of muons for three distances from the shower axis.

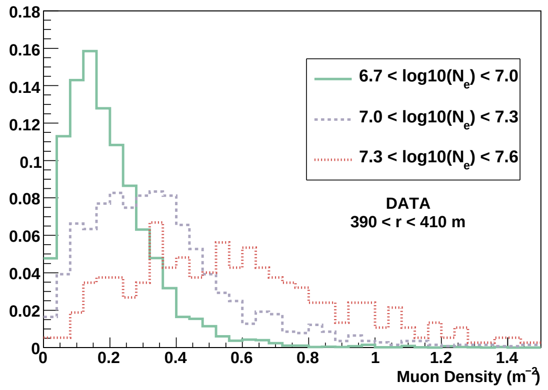

Fig. 3: Distribution of the density of muons for three cuts in the total number of electrons.

of these questions. The experiment is located at the Forschungszentrum Karlsruhe, Germany, where, beside the existing KASCADE [1] array, two new detector set ups (Grande and Piccolo) have been installed. The experiment is able to sample different components of extensive air showers (electromagnetic, muonic and hadronic) with high accuracy and covering a surface of 0.5 km^2. For an overview of the actual setup of the KASCADE-Grande Experiment see ref. [2].

In this article we present studies of the muon component of the shower. Muons are the messengers of the hadronic interactions of the particles in the shower and therefore are a powerful tool to determine the primary particle mass and to study the hadronic interaction models.

II. Reconstruction

The main parameters used in this study are the density of muons and the total number of electrons in the shower for which the reconstruction accuracy is going to be discussed below. For the reconstruction accuracy of the shower geometry see ref. [3].

The density of muons is directly measured by the KASCADE 622 m^2 scintillators. These detectors are shielded by 10 cm of lead and 4 cm of iron, corresponding to 20 radiation lengths and a threshold of 230 MeV for vertical muons. The error in the measurement of the energy deposit was experimentally determined to be smaller than 10% [1].

For each shower, the density of muons is calculated as follows. The muon stations are grouped in rings of 20 m distance from the shower axis. The sum of the signals measured by all muon stations inside each ring is divided by the effective detection area of the stations. Therefore the muon density as a function of the distance from the shower axis is measured in a very direct way. No fitting of lateral distributions is needed in these calculations.

The total number of electrons in the shower is reconstructed in a combined way using KASCADE and KASCADE-Grande stations. A lateral distribution function (LDF) of the Lagutin type can be fitted to the density of muons measured by the KASCADE detector [4]. After that, using the fitted function, the number of muons at any distance from the shower axis can be estimated. The KASCADE-Grande stations measure the number of charged particles. The number of electrons at each KASCADE-Grande stations is determined by subtracting from the measured number of charged particles the number of muons estimated with the LDF fitted to the KASCADE stations.

At this stage, the number of electrons at each KASCADE-Grande station is known. Finally, a modified NKG [5] function is fitted to this data and the total number of electrons is determined in the fit.

Quality cuts have been applied to the events in this analysis procedure. We have required more than 19 KASCADE-Grande stations with signal. The showers used in all analysis along this paper were reconstructed with zenith angle between 0 and 42 degrees. The same quality cuts were applied to the simulated events used for reconstruction studies and to the data presented in the following section. After the quality cuts, the total number of electrons can be estimated with a systematic shift smaller than 10% and a statistical uncertainty smaller than 20% along the entire range considered in this paper [3].

Figure 2 shows the measured density of muons at three distances from the shower axis for events with a total number of electrons (N_e) in the range $7.0 < Log10(N_e) < 7.3$ ($\approx 10^{17}$ eV). Similar plots were obtained for other N_e ranges.

Figure 3 shows the density of muons at 400 m from the shower axis for events with total number of electrons (N_e) in the range $6.7 < Log10(N_e) < 7.0$, $7.0 < Log10(N_e) < 7.3$ and $7.3 < Log10(N_e) < 7.6$. Similar plots were obtained for other distances from the shower axis.

Figure 2 and Figure 3 show the general expected

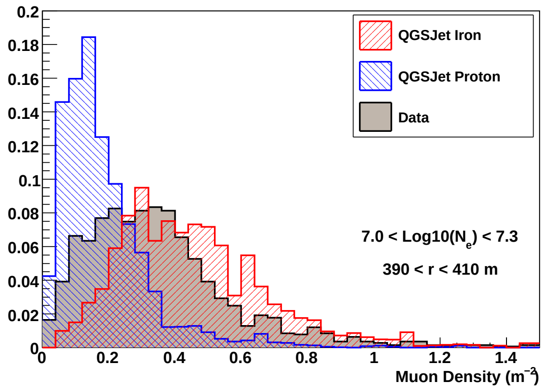

Fig. 4: Measured distribution of the density of muons at 400 m compared to the predictions of QGSJet II.

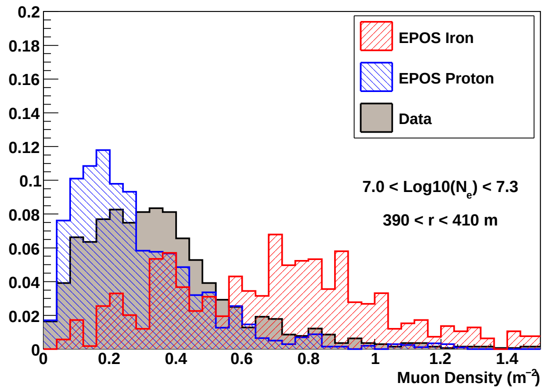

Fig. 5: Measured distribution of the density of muons at 400 m compared to the predictions of EPOS 1.61.

trend: a) decrease of the muon density with increasing distance from the shower axis and b) increase of the muon density with increasing total number of electrons. In the next sections we explore these relations in order to show the capabilities of the KASCADE-Grande experiment for a composition study and for tests of the hadronic interaction models.

We present data for $7.0 < Log10(N_e) < 7.3$ and $390 < r < 410\ m$, these cuts have been chosen in order to minimize the fluctuation of the signal and the reconstruction inaccuracy and to maximize the number of showers for which we have data, however the same conclusions would be drawn for all parameter cuts.

III. Simulation

For all studies in this paper we have used the CORSIKA [6] simulation program with the FLUKA [7] option for low energy hadronic interactions. Two high energy hadronic interaction models were used EPOS 1.61 [8] and QGSJet II [9]. No thinning is used [6].

CORSIKA showers are simulated through the detectors and reconstructed in the same way as the measured data, such that a direct comparison between data and simulation is possible.

Figures 4 and 5 show the comparison of the measured density of muons to values predicted by QGSJet II and EPOS 1.61. For both hadronic interactions models we show the limiting cases of proton and iron nuclei as primary particles. It can be seen in figures 4 and 5 that the data lie well within the proton and iron limits for QGSJet II and EPOS 1.61. These graphics are going to be further discussed in the next sections.

IV. Analysis

Figure 6 shows the mean muon density as a function of the distance from the shower axis compared to the predictions of QGSJet II and EPOS 1.61. Both hadronic interaction models include the data within the proton and iron limits for the entire range of distances from 100 to 750 meters. For distances further than 750 meters the statistics is not enough for a conclusion.

Interesting to note is also the slope of the LDF. Considering an equal probability trigger for protons and iron primaries as a function of distance from the shower axis, one should expect the LDF to be parallel to pure composition primaries. Note that the LDF of simulated proton and iron shower are parallel. However the measured LDF is not parallel to the QGSJet II nor to the EPOS 1.6 curves. That shows that the slope of the LDF can not be well described by neither models.

Figure 7 shows the evolution of the mean muon density as a function of N_e. The calculations done with QGSJet II and EPOS 1.61 using proton and iron nuclei as primary particles bracket the data in the entire range of $5 < Log10(N_e) < 8$.

Nevertheless, both figures 6 and 7 show that EPOS 1.61 would require a very light primary composition in order to fit the data. On the other hand, QGSJet II could fit the data with an intermediate primary abundance between proton and iron nuclei.

Besides that, in figure 7 it is possible to analyse a possible transition of the primary component with increasing total number of electrons. The analysis done with both models show no abrupt change in the compositon in the entire energy range.

The change in slope seen in figure 7 for $Log10(N_e) < 6.0$ corresponds to the threshold of the experiment and the fact that both data and simulation show the same behavior illustrates the good level of understanding of our detectors.

V. Conclusions

The Grande array is in continuous and stable data taking since December 2003. The quality of the detector can be illustrated by the smooth data curve and small fluctuations in figures 6 and 7.

In this article, we have briefly described the procedure used to measure the density of muons with the KASCADE array and we have studied its correlation with

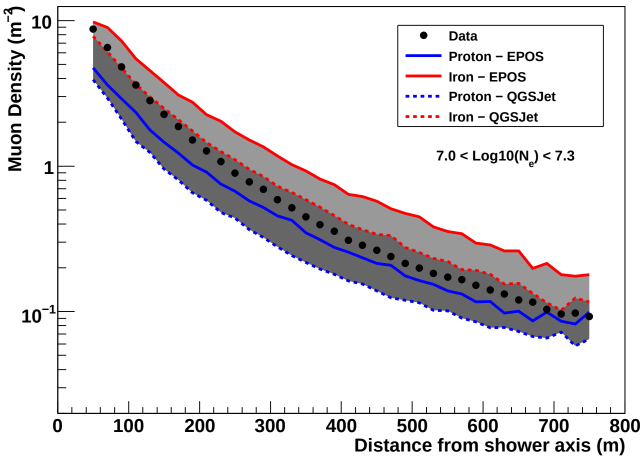

Fig. 6: Lateral distribution of muons compared to the predictions of QGSJet II and EPOS 1.61.

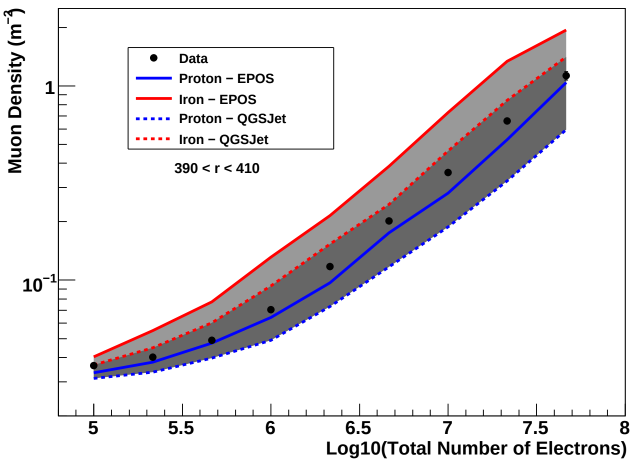

Fig. 7: Muon density as a function of the total number of electrons compared to the predictions of QGSJet II and EPOS 1.61.

the distance from the shower axis and the total number of electrons in the shower.

The density of muons in the shower is measured directly by the KASCADE detectors. We have used this data to study the hadronic interaction models QGSJet II and EPOS 1.61. The data taken with KASCADE-Grande confirms at higher energies the recent results published by the KASCADE [10] experiment. EPOS 1.61 would require a very light abundance of primary particles in order to fit the data. QGSJet II could fit the data with an intermediate primary abundance.

Figure 7 shows no abrupt change with increasing total number of electrons up to $Log10(N_e) = 7.5 \approx 5 \times 10^{17}$ eV. The mean primary mass estimation would depend on the hadronic interaction model used.

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