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# The muon component of air showers measured by the KASCADE-Grande Experiment

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**Abstract:** KASCADE-Grande is a multi detector setup for the investigation of extensive air showers in the $10^{16} - 10^{18}$ eV energy range. With the Grande array it is possible to reconstruct the shower core position, the arrival direction and the total number of charged particles in the shower. The Grande array measures in coincidence with the original KASCADE muon array consisting of 622 m$^2$ shielded scintillators. The data of the combined measurements are used to extract information from the muonic and eletromagnetic parts of the shower independently. In this paper, the muon density in a ring from 380 to 400 m distance from the shower axis is studied and compared to predictions of hadronic interaction models. We report first results of these muon measurements at KASCADE-Grande which indicates the primary composition evolution.

## Introduction

The KASCADE-Grande experiment [1] has been set up to measure primary cosmic rays in the energy range from $10^{16}$ to $10^{18}$ eV. Its main goal is to study the expected knee of the iron component. These observations would confirm the hypothesis that explains the proton knee of the primary cosmic rays spectrum at a few PeV and determine the astrophysical mechanism which operates in this energy range.

The experiment is located at the Forschungszentrum Karlsruhe, Germany, where, beside the existing KASCADE [2] 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 ac-

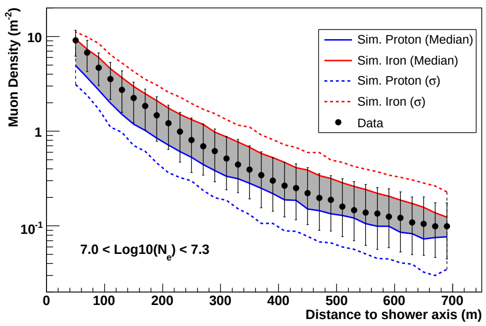


Figure 1: Density of muons as a function of the distance from the shower axis. Only showers with zenith angle below 40° were used. Error bars represent one sigma of the data distribution. See text for details.

tual setup of the KASCADE-Grande Experiment see ref. [3].

In this article we present studies of the muon component of the shower. The energy deposited by muons can be measured by the KASCADE stations separately from the electromagnetic component with a threshold of $E_\mu > 230$ MeV for vertical muons. 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.

Figure 1 shows the density of muons as a function of the distance from the shower axis for events with total number of electron ($N_e$) in the range $7.0 < Log10(N_e) < 7.3$. The density of muons is calculated for each shower as the sum of the signal measured by all stations in rings of 20 m divided by the effective detection area of the stations. Similar plots were obtained for other $N_e$ ranges.

In the same plot, two limits for iron and proton simulations are also shown. The shaded area was determined by taking the median of the iron (full red line) and proton (full blue line) simulation. The dashed lines represents the simulation limits when the $16^{th}$ quantile of the proton (dashed blue line) distribution and the $84^{th}$ quantile of the iron (dashed red line) distribution were taken. It represents the one sigma ($\sigma$ ) limit of the simulation.

For all the studies in this paper we have used the CORSIKA [4] simulation program with FLUKA [5] and QGSJetII [6] hadronic interaction models. 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.

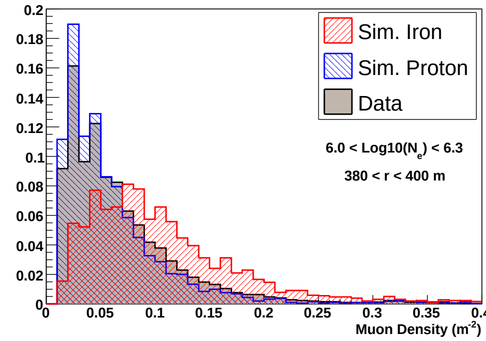


Figure 2: Density of muons in a ring from 380 to 400 m distance from the shower axis. See text for details.

In the following, the density of muons in the ring from 380 to 400 m distance from the shower axis is going to be studied in more details. This distance range has 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.

The evaluation of the density of muons in the ring from 380 to 400 m is going to be determined as a function of the total number of electrons in the shower and a comparison to simulations is going to be shown.

## Reconstruction Accuracy

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. [7].

The density of muons is directly measured by the KASCADE 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% [2].

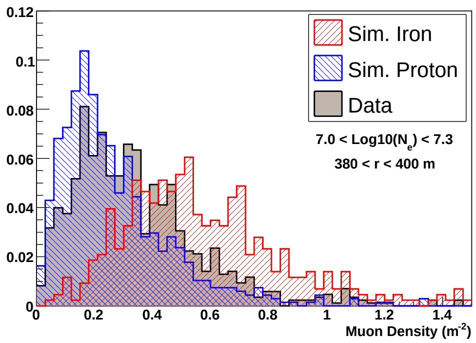


Figure 3: Density of muons in a ring from 380 to 400 m distance from the shower axis. See text for details.

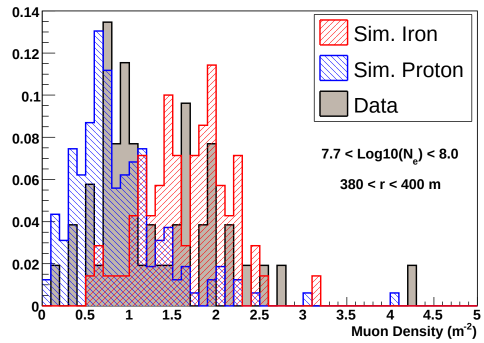


Figure 4: Density of muons in a ring from 380 to 400 m distance from the shower axis. See text for details.

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 [8]. 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. Latest, a modified NKG function is fitted to this data and the total number of electrons is determined in the fit. The accuracy of the reconstruction of $N_e$ can be seen in ref. [9].

Quality cuts have been applied to the events in this analysis procedure. We have required the zenith angle to be smaller than 40 degrees and the event should have more than 19 KASCADE-Grande stations with signal. 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 [9].

## Data Analysis

All showers measured by KASCADE-Grande which survived the quality cuts explained above have their muon density measured as a function of the distance from the shower axis. The distributions of the measured densities in a ring from 380 to 400 meters distance from the axis are shown in figure 3,4 and 5 in comparison with simulation.

We show the distributions for three cuts in total electron number: $6.0 < Log10(N_e) < 6.3$, $7.0 < Log10(N_e) < 7.3$ and $7.7 < Log10(N_e) < 8.0$ in figures 2, 3 and 4, respectively.

Figure 2 shows that the data could be better described by a proton dominant abundance at this $N_e$ selection. However, figures 3 and 4, with higher $N_e$ selections, show that the data could only be described if a mixed composition is considered. From the three figures it is clear that an enhancement of the heavy component occurs with increasing $N_e$.

Figure 5 shows the evolution of the median muon density as a function of $N_e$. Two limits for the simulation are shown. The shaded area shows the limits determined by the median values of the proton (full blue line) and iron simulations (full red line). These limits can be used to visualize the evolution of the primary composition.

The dashed lines delimit the one sigma range of the proton and iron simulations. For that, it was taken the lower one sigma limit ($16^{th}$ quantile) of the proton (dashed blue line) distribution and the

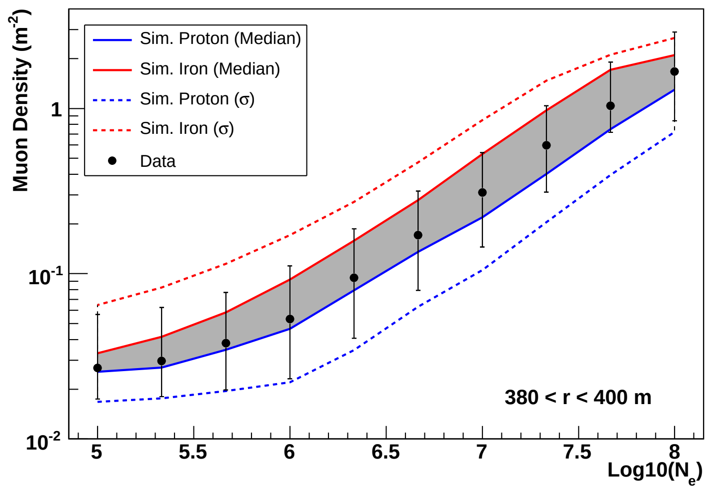


Figure 5: Muons density from 380 to 400 m distance from the shower axis as a function of total electron number. Error bars represent one sigma of the data distribution. See text for details.

upper one sigma limit ($84^{th}$ quantile) for the iron (dashed red line) distribution. These limits can be used to understand the fluctuations of the data when compared to the simulation. Note that a combined proton and iron composition shows about the same fluctuation of the data.

The change in slope seen in figure 6 for $Log10(N_e) < 6.0$ corresponds to the threshold of the experiment and the fact that both data and simulation shows the same behavior illustrates the good level of understanding of our detectors. For the highest $N_e$ values the simulations run out of sufficient statistics.

## Conclusions

The Grande array is in continuous and stable data taking since January 2004. In this article, we have briefly described the procedure used to measure the density of muons with the KASCADE array and studied its correlation with 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 model (QGSJetII) and the primary composition. The median and the fluctuation of the density of muons in a ring from 380 to 400 m distance from the shower axis lies within the limits of proton and iron simulations calculated by CORSIKA-QGSJetII in the range $6.0 < Log10(N_e) < 8.0$. We have also shown that this parameter can be used for composition studies. A preliminary evolution from more light to a more heavy composition with increasing $N_e$ was observed.

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