Muonic Component of Air Showers Measured by the KASCADE-Grande Experiment

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***Abstract*. The KASCADE-Grande experiment consists of a large array of scintillators for the detection of charged particles from extensive air showers in the primary energy range 10^{16} eV – 10^{18} eV. In combination with the detectors of the KASCADE array it provides the means to investigate the composition in the expected transition region of galactic to extragalactic cosmic rays and the possible existence of a second knee in the total energy spectrum at E $\sim 10^{17}$ eV caused by heavy primaries.**
For the goals described it is indispensable to reconstruct the shower sizes with highest accuracy. The reconstruction of the muonic component as well as the muon lateral distribution will be discussed and the precision and systematic uncertainties in the reconstruction of the muon number will be studied based on Monte Carlo simulations.

***Keywords*: muonic component, lateral distribution, KASCADE-Grande**

I. Introduction and Experimental Setup

The combined KASCADE and KASCADE-Grande Experiment [1], located on the site of the Forschungszentrum Karlsruhe (110 m a.s.l.), consists of various detector components [2] for measuring the particles of extensive air showers in the primary energy range from 10^{16} eV – 10^{18} eV. The measurement at the upper part of that energy range is possible due to a large scintillator array, the Grande array, covering a collecting area of approximately 0.5 km^2. The 37 Grande stations located on a hexagonal grid with an average mutual distance of 137 m measure the total number of *charged particles* in an air shower.
With the colocated KASCADE array the *muon component* of the extensive air shower can be measured separately from the electronic one. Using an appropriate lateral distribution function, one can derive the total muon number of air showers from the muon signals measured locally with the KASCADE array. This method can be applied even in cases where the core is located in the KASCADE-Grande array, but not in the KASCADE array itself (Fig. 1, left). Subtracting the estimated number of muons from the total number of charged particles measured with KASCADE-Grande yields the total number of shower electrons [3]. The scintillators of the KASCADE detector array cover an area of 200 × 200 m^2 and are housed in 252 stations on a grid with 13 m spacing. While the inner stations of the KASCADE array are only equipped with liquid scintillators measuring primarily electrons and gammas, the outer stations are also containing plastic scintillators underneath a shielding[1] of 10 cm

[1]corresponding to 20 radiation lengths, muon threshold: 230 MeV.

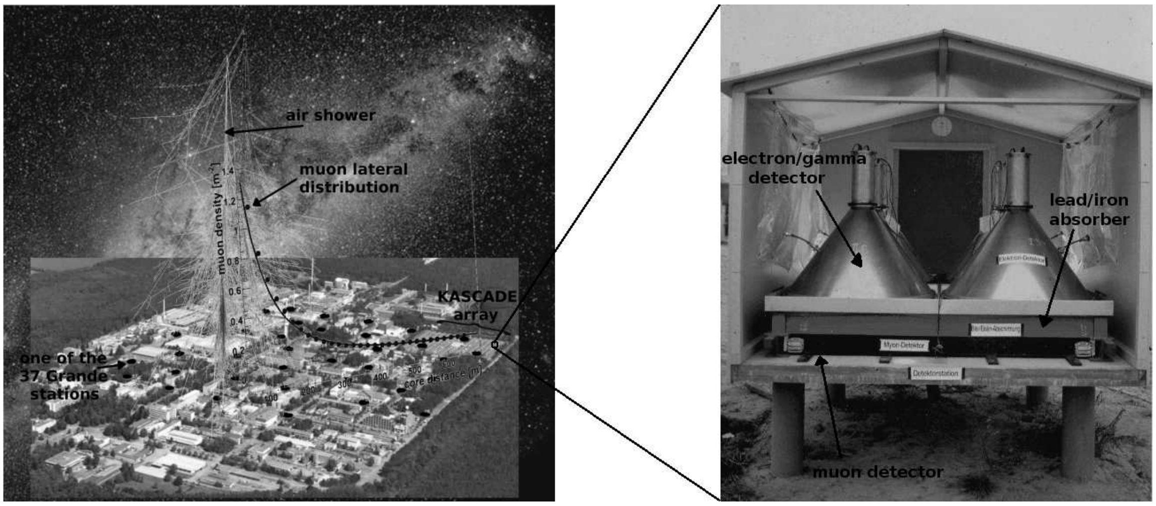


Fig. 1: *Left:* An air shower with the core located in the Grande array. Although the KASCADE detector field is far away from the core, non-zero muon densities can be measured there. *Right:* Detector station of the KASCADE-array equipped with electron/gamma and separate muon detectors.

lead and 4 cm iron, which allows the measurement of muons separately from electrons and gammas (Fig. 1, right). These muon detectors consist of four plastic scintillators per station. The scintillators are of 3 cm thickness and their surface area is 90×90 cm^2. The light is coupled out by wavelength shifters and read out by 1.5 inch photomultipliers. The energy resolution has been determined to about 10% at 8 MeV, the mean energy deposit of a MIP[2].

II. Reconstruction of the Muon Number

As described in the previous chapter the local muon densities can be measured even in cases where the shower core is located in the KASCADE-Grande array, but not in the KASCADE array itself. For these purposes the energy deposits in the muon detectors must be converted to particle numbers by means of a conversion function, the so-called LECF[3]. The LECF is derived from simulated air showers based on CORSIKA [4] and a detailed GEANT [5] detector simulation. It has been determined based on two primaries (H and Fe) and three different simulated energies, 3×10^{16} eV, 1×10^{17} eV and 3×10^{17} eV. The average energy deposit in the KASCADE muon detectors per shower muon at a distance r (in meter) from the shower core is given by the following LECF:

$$\frac{E_{\rm dep}}{muon}(r) = \left(7.461 + {\rm e}^{(1.762 - 0.017 \cdot r)} + 0.0003 \cdot r\right)\ {\rm MeV} \quad (1)$$

For small radii up to approximately 160 m the energy deposit per muon decreases in order to correct the high energetic electromagnetic punch through close to the shower core. At larger radii the deposited energy per muon reaches a constant value of approximately 7.6 MeV (Fig. 2).

For most analyses it is convenient not only to know the local muon densities given by the LECF but also the total number of muons in the shower disk. Assuming the locally detected muons fluctuate according to a poisson distribution, one can derive the total muon number $N_\mu^{\rm rec}$ from a maximum likelihood estimation, which yields:

$$N_\mu^{\rm rec} = \sum_{i=1}^{k} n_i \,/\, \sum_{i=1}^{k} \Big(f(r_i) \cdot A_i \cdot \cos(\theta)\Big)\ , \quad (2)$$

where n_i is the number of particles measured at a core distance r_i (in meter) in one of the k muon detectors within an area A_i (in square meters), θ is the zenith angle (in degree) of the air shower, and f is an appropriate

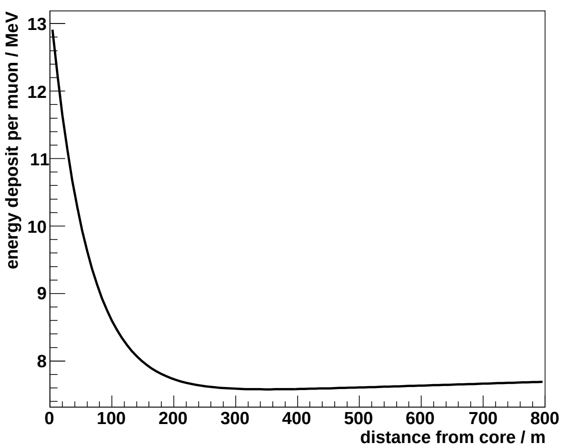


Fig. 2: Average energy deposit per muon in a KASCADE muon detector as a function of the distance of this detector from the shower core (muon LECF according to Eq. 1).

[2]Minimum Ionizing Particle.
[3]Lateral Energy Correction Function.

lateral distribution function.
In case of the KASCADE-Grande Experiment the lateral distribution of muon densities ρ_μ is fitted with a function based on the one proposed by Lagutin and Raikin [6] for the electron component:

$$\rho_\mu(r) = N_\mu \cdot f(r), \text{ with}$$
$$f(r) = \frac{0.28}{r_0^2}\left(\frac{r}{r_0}\right)^{p_1} \cdot \left(1+\frac{r}{r_0}\right)^{p_2} \cdot \left(1+\left(\frac{r}{10\cdot r_0}\right)^2\right)^{p_3}. \quad (3)$$

The parameters $p_1 = -0.69$, $p_2 = -2.39$, $p_3 = -1.0$ and $r_0 = 320$ m are based on CORSIKA simulations using the interaction model QGSJet 01. Both proton and iron primaries were simulated at energies of 10^{16} eV and 10^{17} eV and then the average of the fit results is taken. Since the muon densities are very low, except for the highest energy showers, stable fits on the shower-by-shower basis are only obtained if the lateral distribution function is kept constant and only the muon number N_μ is taken as a fit parameter.
Substituting the lateral distribution function f from Eq. 3 into Eq. 2 yields a formula for calculating the total muon number of the KASCADE-Grande event.

III. Reconstruction Accuracy

The muon number is reconstructed based on the local muon densities measured only on the small area of the KASCADE detector field. The measured densities are typically very small and subject to large fluctuations. The reconstruction of the total number of muons is strongly affected by these uncertainties.

The to some extent *directly measured* muon density distribution and the lateral distribution function f (Eq. 3) with the muon number N_μ set to the *reconstructed* mean muon number $\overline{N_\mu^{\rm rec}}$ (Eq. 2) in each muon size bin are shown in Fig. 3. The measured densities are in general well described by the lateral distribution function. This means a good conformity between *directly measured* sizes and *reconstructed* ones. Only in case of relatively small and large core distances one can see deviations due to the fixed shape of the lateral distribution function which does not account for the primary energy or the zenith angle of the air shower.

The reconstruction quality has been tested based on CORSIKA simulations using the interaction model QGSJet II. Different primaries (H, He, C, Si and Fe) in equal abundances, with an E^{-3} power law spectrum, zenith angles up to $40°$ and cores scattered over the Grande array were considered in the simulations. The full detector response was also simulated (GEANT [5] detector simulation) and the usual reconstruction techniques were applied to the resulting data. The mean deviation of the reconstructed muon number $N_\mu^{\rm rec}$ from the true muon number $N_\mu^{\rm tru}$ as a function of the true muon number itself or the distance of the shower core to the centre of the KASCADE array are shown in Fig. 4. In the latter case, only events with muon numbers above $\log_{10} N_\mu^{\rm tru} \geq 5.0$ are taken into account, that

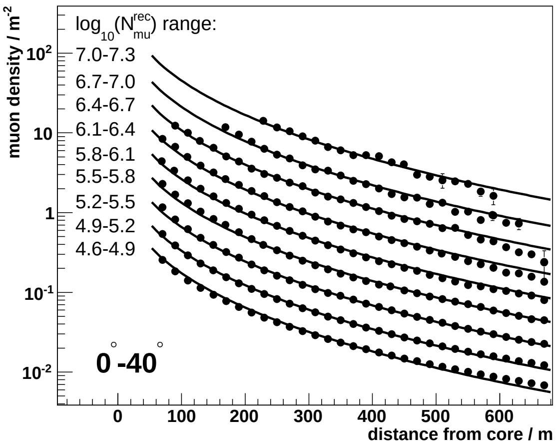
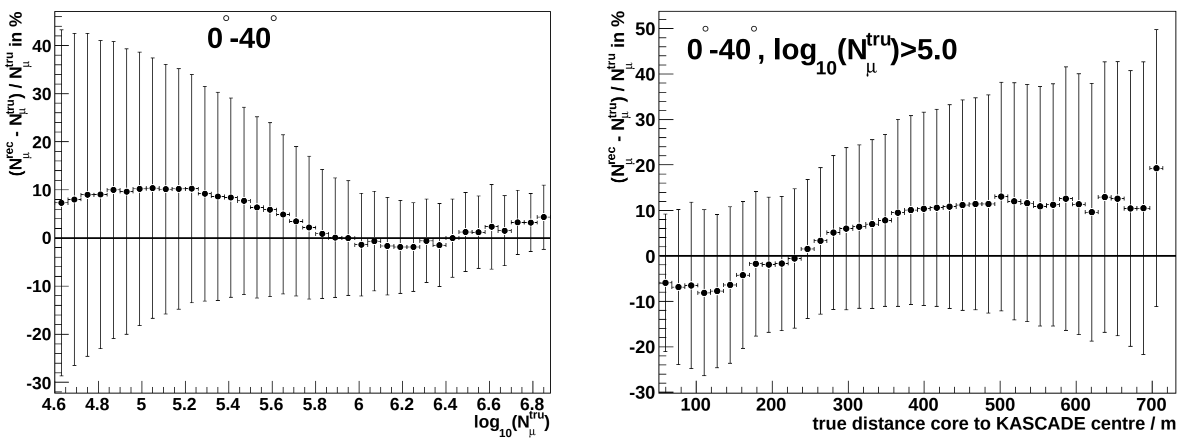


Fig. 3: Measured muon density distribution (dots) for zenith angles 0°–40° and different intervals of the reconstructed muon number. The lateral distribution function of Eq. 3 (curves) with the muon number N_μ set to the measured mean muon number $\overline{N_\mu^{\rm rec}}$ in each interval describes the data quite well.

means only muon numbers above full reconstruction efficiency[4]. In case of muon numbers above a threshold of $\log_{10} N_\mu^{\rm tru} \approx 5.6$, which corresponds to an energy of approximately 5×10^{16} eV, the systematic deviation of the reconstructed total muon number is smaller than 5% and to some extent constant in this range (Fig. 4a). Above the mentioned threshold, the statistical error (represented by the error bars, RMS) decreases from around 20% to 7% with increasing muon number. Showers below 100% efficiency are characterized by a rather large statistical uncertainty up to 40%. In Fig. 4b the dependence of the reconstructed accuracies on the distance of the core to the centre of the KASCADE array is shown. An increase of the statistical uncertainty with increasing distances from approximately 15% at 100 m to 30% at 700 m distance is observed. The under- or overestimation of the local muon densities by the lateral distribution function (discussed above, Fig. 3) in cases of small and large core distances results in an under- or overestimation of the total muon number in these distance ranges. The deviation of the reconstructed muon number from the true one starts from $\sim -7\%$ for small distances, gets zero for ~ 240 m distance and increases to $\sim +12\%$ for larger core distances. Taking into account the fact that quite small particle densities are measured across a small detection area far away from the shower core, one can draw the conclusion, that the reconstruction of the total muon number works surprisingly well. Furthermore the features of the accuracies are well understood and open the possibility to correct the reconstructed muon number to the true one using appropriate correction functions and to perform analyses based on these corrected muon numbers (see [7]).

[4] 100% reconstruction efficiency of muon number is obtained above $\log_{10} N_\mu^{\rm tru} \approx 5.0$.



(a) (b)

Fig. 4: Reconstruction quality tested based on Monte Carlo simulations. In case *a)* the deviation of the reconstructed to the true muon number is shown as a function of the true muon number, in case *b)* as a function of the distance of the shower core to the centre of the KASCADE array. In both cases the error bars represent the statistical uncertainty (RMS) in a single measurement.

IV. Conclusion

The reconstruction of the total muon number in the shower disk has been presented using the KASCADE scintillator array as a part of the KASCADE-Grande experiment. The procedure of converting the energy deposits to particle numbers was explained as well as the calculation of the total muon number using a maximum likelihood method. The reconstruction accuracies have been discussed and reveal a good reconstruction quality, despite the fact that the total muon number is reconstructed based on just a small fraction of radial detector coverage. Deviations between reconstructed and true shower sizes are well understood such that it is possible to derive correction functions allowing to correct the reconstructed muon number to the true one. Hence, KASCADE-Grande analyses taking into account the total muon number can be performed.

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