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Shower Size Reconstruction at KASCADE-Grande

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The KASCADE-Grande experiment consists of a large scintillator array for the detection of charged particles from extensive air showers in the primary energy range $10^{16} - 10^{18}$ eV. In combination with the KASCADE muon detectors it provides the means to investigate the possible existence of an iron knee and the change in composition due to extragalactic cosmic rays expected to become more dominant in that energy range. The performance of the apparatus and shower reconstruction methods will be presented on the basis of detailed Monte Carlo simulations. After approximately one year of data taking we present lateral distributions of the charged shower component and the reconstructed 2-dimensional shower size spectrum.

1. Experimental Setup

The combined KASCADE and KASCADE-Grande Experiment [1], located on the site of the Forschungszentrum Karlsruhe (110m a.s.l.), consists of various detector components [2] for measuring the particles of extensive air showers in the primary energy range from $10^{14} - 10^{18}$ eV. The measurement at the upper part of that energy range is possible due to a large scintillator array covering an area of approx. 700×700 m^2. It comprises 37 stations located on a hexagonal grid with an average distance of 140 m to each other for the measurement of the charged shower component. Each of the detector stations is equipped with 16 4 cm thick plastic scintillator sheets covering a total area of 10 m^2 per station. With the present setup the upper limit of the dynamic range will be reached at approx. 6000 MIPs. For details about readout and calibration see [3].

The muon component of EAS is reconstructed from the 192×3.2 m^2 muon detectors of the KASCADE array which are located under an iron/lead absorber, resulting in a muon threshold of 230 MeV and suppressing punch-through of the electromagnetic component efficiently above 40 m core distance. The muon number ($E_{kin} > 300$ MeV) of an air shower is therefore reconstructed from a relatively local measurement on the 200×200 m^2 field as described in [5].

2. Shower Reconstruction

For describing the lateral distribution of electrons in a hadronic induced air shower especially at large core distances ($r < 800$ m) a slightly modified NKG-function is used [4]:

$$\rho_e = N_e \cdot C(s) \cdot \left(\frac{r}{r_0}\right)^{s-\alpha} \cdot \left(1 + \frac{r}{r_0}\right)^{s-\beta}$$

with the normalization factor $C(s) = \Gamma(\beta - s)/(2\pi r_0^2 \Gamma(s - \alpha + 2)\Gamma(\alpha + \beta - 2s - 2))$, the shower size N_e and the so-called shower age s. Performing CORSIKA [7] air shower simulations, the parameters $\alpha = 1.5$, $\beta = 3.6$ and $r_0 = 40$ m were found as optimum for the radial distances relevant for the Grande array (opposite to the common parameters $\alpha = 2$ and $\beta = 4.5$ with $r_0 = 89$ m used for the KASCADE array at $r < 300$ m).

To describe the average arrival time $\bar{t}$ and the time spread σ_t of the shower electrons a Linsley-function has been adapted to the time distributions of pure CORSIKA simulations:

$$\bar{t} = 2.43\text{ns} \cdot (1 + \frac{r}{30\text{m}})^{1.55} \qquad \text{and} \qquad \sigma_t = 1.43\text{ns} \cdot (1 + \frac{r}{30\text{m}})^{1.39}$$

The parameters were found to depend only weakly on the primary particle properties and to first order approximation the measured arrival time of the first out of N particles inside a detector is given by $\bar{t}_{1.ofN} = \bar{t}/\sqrt{N}$.

Since the functions above are coupled via the particle number and the core distance in shower disc coordinates, they are fitted simultaneously to the data in a combined negative-log-likelihood/χ^2 minimization. For the calculation of the expected particle density in a Grande station a contribution from the previously reconstructed muon lateral distribution function ρ_μ (for functional form see [5]) is taken into account. Thus, the 7 free parameters of the global fit are the core position and the shower direction (including a time offset), as well as the electron number ($E_{kin} > 3$MeV) and shower age.

To test the reconstruction procedure and to estimate its uncertainties, air showers generated by the CORSIKA package using the interaction models QGSJET01 [8] and FLUKA2002.4[9] were used as input for a detailed GEANT3.21-based [6] simulation of the installation. In total, approx. 200000 proton and iron showers were generated using a E^{-2} spectrum in the energy range $10^{15} - 10^{18}$eV and zenith angles 0°-18°. The output has then been analysed in the same way as for the measurement and the resulting spatial and directional resolution (68 % confidence level) is shown in Figure 1 (upper row) as function of shower size and for different primaries. In addition, there was a smaller data set from an updated simulation code including instrumental effects from electronics like photomultiplier responses and cable delay uncertainties whose results are plotted as open symbols. Above a threshold of 10^6 electrons corresponding to 100 % trigger efficiency the resolution is better than 12 m and 0.6° respectively and nearly independent from the primary particle.

The accuracy of the estimated electron and muon number is shown in the lower panel of figure 1. Here, the average difference between the reconstructed and true logarithmic shower sizes (systematic deviation) have been plotted together with the spread of this quantities (statistical uncertainty). As can be seen, the statistical uncertainty for both is around 25 % at threshold and decreases slightly with shower size whereas the systematic deviation for the electrons decreases from 0 to -10 % and thus stays always well below the statistical accuracy of the experiment. The systematic overestimation of the muon component is currently under investigation [5].

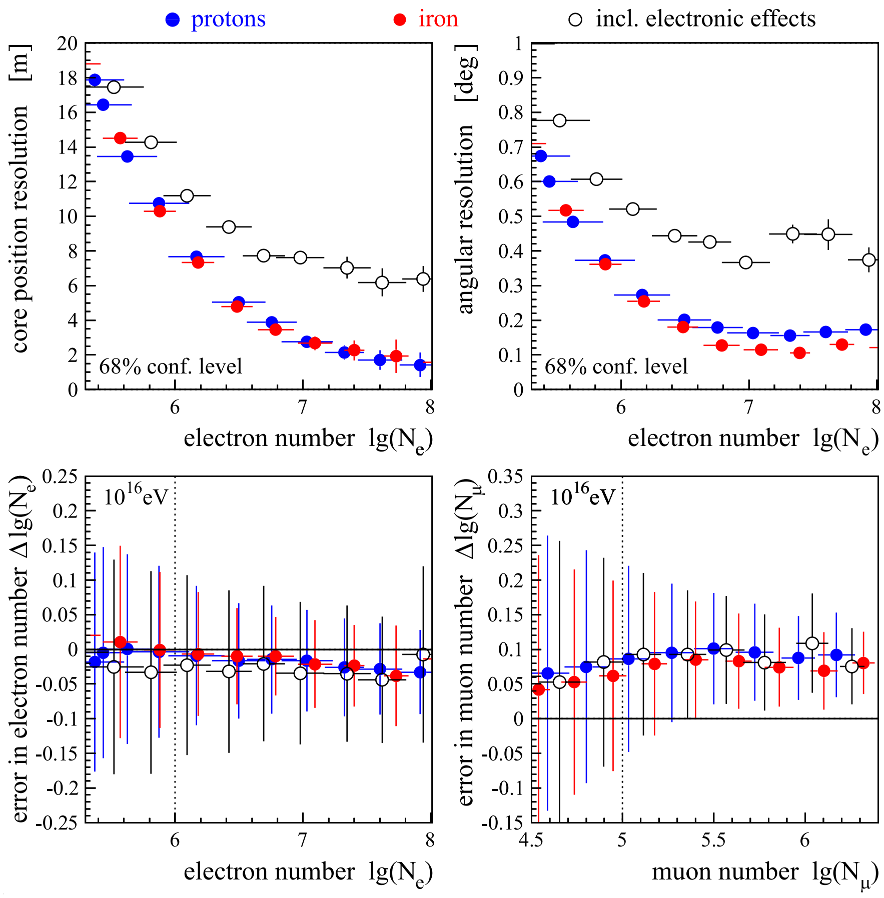

Figure 1. Reconstruction accuracy of core position (upper left) and shower direction (upper right) as function of electron number. Systematic deviation of the reconstructed electron (lower left) and muon number (lower right) as function of the true electron and muon number. The errors bars indicate the statistical error of a single reconstruction. The individual symbols correspond to a given primary energy range with isotropic zenith angles from $0^\circ - 18^\circ$ for two different primary particles (p and Fe) and a data set with less statistics (open symbols) including additional electronic effects.

3. First Results

In order to investigate the variation of the mean lateral distributions with energy, the primary energy has been roughly estimated from a linear combination of electron and muon numbers deduced from CORSIKA simulations with fixed energies and five different primaries (0°-18°) by means of a linear regression analysis:

$$\lg(E_{est}/\mathrm{GeV}) = 0.313 \cdot \lg N_e + 0.666 \cdot \lg N_\mu + 1.24/\cos\vartheta + 0.580$$

The result of this analysis is displayed in Fig. 2 (left) for air showers above the experimental threshold of 10^{16}eV with the fit functions $\rho_e + \rho_\mu$ shown for comparison using the average fit parameters. The average age $\bar{s}$ of these distributions is found to increase significantly with energy ($\sigma_{\bar{s}} < 0.005$). This indicates that the composition gets heavier, i.e. more showers are starting higher in the atmosphere, with increasing energy. On the contrary, a constant composition would result in decreasing age parameters, because showers of increasing energy would get *younger* at given atmospheric depth. This has been confirmed independently also by a KASCADE array analysis [4].

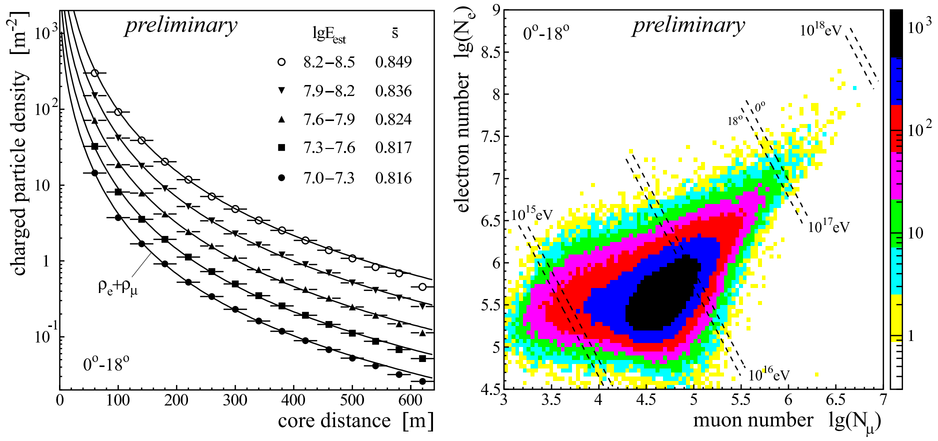

Figure 2. Measured lateral distributions of the charged particle component for 5 primary energy bins above the trigger threshold of 10^{16}eV (left). Reconstructed electron and muon number distribution of air showers measured by the KASCADE-Grande arrays (right). The dashed line pairs indicate average lines of constant energy derived from CORSIKA simulations for the extreme zenith angles.

In the last year more than 11 Mio. events triggered by the Grande array have been recorded. Fig. 2 (right) depicts the present data set in terms of the reconstructed particle numbers for zenith angles below 18°. Even though most of the triggered events are below the threshold, we have measured up to now nearly 400 events above 10^{17} eV (0°-18°). This is about the same number of events in that energy region as have been measured by the KASCADE array in one decade. In future, these events will be the basis of a sophisticated unfolding analysis according to [10] to disentangle the mystery about the predicted *iron knee* and the elemental composition above 10^{17}eV.

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