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Electron shower size spectra reconstructed with KASCADE-Grande data

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Abstract: KASCADE-Grande, located at Forschungszentrum Karlsruhe, is a multi-detector experiment for the measurement of extensive air showers induced by primary cosmic rays in the energy range of $10^{14} - 10^{18}$ eV. With its 0.5 km^2 large field detector, in combination with the muon detectors of the KASCADE array, it allows the reconstruction of both the total electron and muon numbers, which are important observables for estimating the mass and the energy of the primary particles. In this work we will present the status of the electron size spectrum as well as the 2-dimensional ($N_e - N_\mu$) shower size spectrum after 626 days of effective data taking.

Introduction

The field array of the original KASCADE [1] experiment consists of 252 detectors stations placed on a grid of $200 \times 200\,\mathrm{m}^2$. Due to the low flux of cosmic rays in the order of $10^{-10}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ for energies above $10^{17}\,\mathrm{eV}$, the collective area of KASCADE is not sufficient for investigations in this energy range. Thus, the Grande array [2], with its 37 detector stations organised in 18 hexagonal trigger cells of 7 stations each, is the natural extension of KASCADE over an area of approximately $0.5\,\mathrm{km}^2$, suitable for detection of primary particles up to energies of $10^{18}\,\mathrm{eV}$. Each station consists of 16 scintillation detectors ($80 \times 80 \times 4\,\mathrm{cm}^3$), arranged in a 4×4 grid, with a total surface of $10\,\mathrm{m}^2$ sensitive to the charged particles of the shower. With the present set-up Grande measures densities up to 800 charged particles/m^2, while the muon component of the shower is estimated from the $622\,\mathrm{m}^2$ muon detectors of the KASCADE array, with an energy threshold for muons of $230\,\mathrm{MeV}$. Full efficiency for the coincident KASCADE-Grande array is reached with a 7 out of 7 stations coincidence (0.5 Hz) at $\log(N_e) \approx 6.3$ (corresponding roughly to a primary energy of

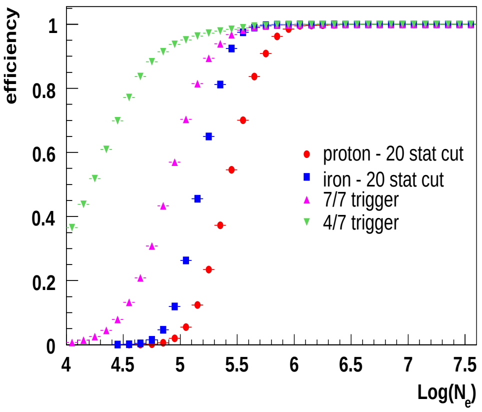

Figure 1: Reconstruction efficiency for showers between 10^{14} and 10^{18} eV, with zenith angles smaller than $40°$. Requiring a 7/7 trigger at Grande with muon number successfully reconstructed by KASCADE, a full efficiency is reached at $N_e = 2 \times 10^6$. Applied data quality cuts require at least 20 active Grande detector stations, for which case the efficiency is plotted for proton and iron.

few times 10^{16} eV) as shown in Fig. 1, where primary iron reach for a bit smaller electron number full efficiency. This is due to the fact that we trigger to charged particles, where also muons contribute, in particular for small showers.

KASCADE-Grande main goals are the investigation of the position of the expected iron knee and the nature of the second knee.

Shower reconstruction

Analysis of Grande array data provides information on core position, arrival direction and the total number of charged particles (N_{ch}) in the shower [3]; the information on muon densities comes instead from the KASCADE array.

The lateral distribution of electrons has been studied through detailed CORSIKA [4] simulations and is described best in case of KASCADE-Grande by a modified NKG-function [5]:

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

where the normalisation factor $C(s)$ depends on the shower age s. From simulations, values of $\alpha = 1.5$, $\beta = 3.6$ and $r_0 = 40\,\mathrm{m}$ were found as optimum for the radial distances relevant for Grande.

For the lateral distribution of muons, a modified Lagutin function [6]:

$$\rho_\mu = N_\mu \frac{0.28}{r_0^2} \left(\frac{r}{r_0}\right)^{p1} \cdot \left(1 + \frac{r}{r_0}\right)^{p2} \cdot \left[1 + \left(\frac{r}{10 \cdot r_0}\right)^2\right]^{p3}$$

is used, with $r_0 = 320\,\mathrm{m}$ and p1, p2, p3 respectively -0.69, -2.39 and -1, also found by simulation.

The analysis procedure develops in several steps. First, the total muon number and total number of charged particles are separately obtained fitting the respective lateral distributions. In a second step the contribution of muons to the densities of charged particles measured by Grande is taken into account: a likelihood fit compares for each detector the measured number of particles with the expected number given by the sum of electrons and muons estimated from the corresponding lateral distribution functions. The combined fit of the muonic and electromagnetic components is delivering in the final step the shower size N_e, the age parameter s, the muon size N_μ, the position of the shower core and the arrival direction of the shower. To test the reconstruction procedure and estimate the uncertainty, showers generated by CORSIKA, with the QGSJetII interaction model, have been used as input for a detailed GEANT [7] simulation of the apparatus. Approx. 260,000 proton and iron showers in the energy range of $10^{14} - 10^{18}\,\mathrm{eV}$, with zenith angles between $0°$ and $40°$, have been analysed with the same procedure used for real data. In order to reduce effects of misreconstructed shower cores at the edges of the Grande array, a fiducial area of $\approx 190,000\,\mathrm{m}^2$ centered in the middle of Grande has been chosen. The results for spatial resolution are shown as a function of the shower size in Fig. 2: above the threshold of 2×10^6 electrons the core resolution is better than $12\,\mathrm{m}$ and shows no significant dependence on the primary particle. The points mark the mean deviation from the true value in percent, while the error bars describe the spread of the distribution. Fig. 2, left part, displays the accuracy of the reconstructed electron number: the statistical uncertainty, expressed by the er-

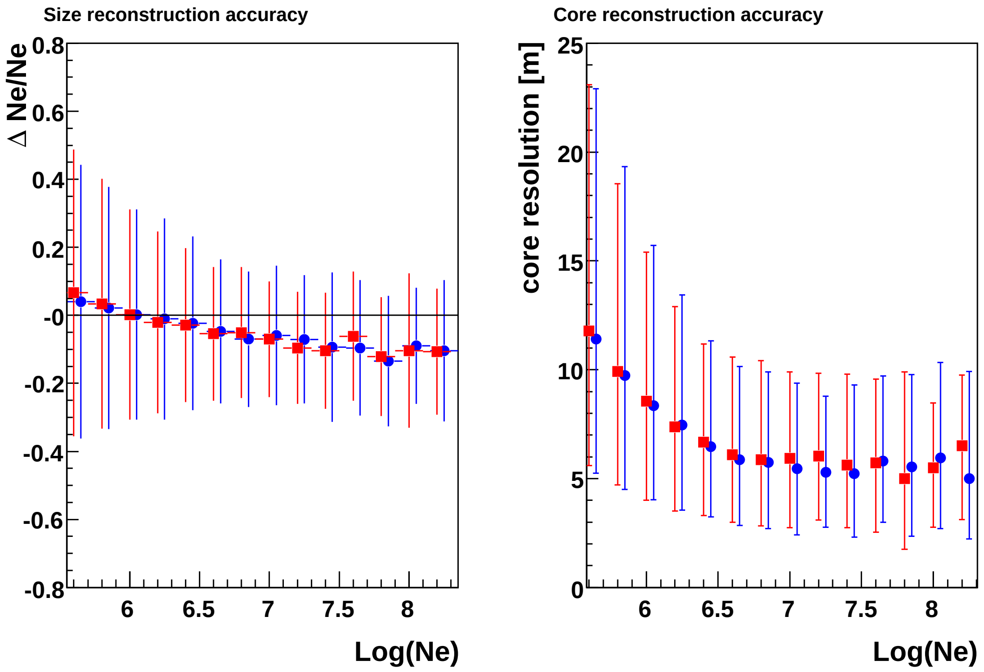

Figure 2: Left: reconstruction accuracy of the reconstructed electron number as function of the true electron number. The errors bars indicate the spread of the distribution (statistical error). Right: reconstruction accuracy of the core position. Showers between 10^{14} and 10^{18} eV with zenith angles smaller than $40°$ have been considered, corresponding to proton (circles) or iron (square symbol) primaries.

ror bars, is around 25% at threshold and decreases slightly with increasing shower size as expected, while the bias decreases from 0 to -15%. For details about the muon reconstruction see [8].

Comparison of measured events reconstructed independently by both Grande and KASCADE confirms the values we obtained [3].

Size spectra

We present in this work a preliminary version of the shower size spectrum measured by KASCADE-Grande. Fig. 3 shows the spectra for six different zenith angular ranges, each corresponding to a change of the slant depth of $50\,\mathrm{g\,cm^{-2}}$, multiplied by ${N_e}^3$ in order to better appreciate possible features. The errors represent pure statistical uncertainty due to the number of events in each bin, there is no estimation of a systematic uncertainty yet, and no correction for the biases introduced by the reconstruction procedure is applied. Clearly, we are still missing statistics at the highest energies, i.e. at $N_e > 3 \cdot 10^7$, especially for inclined events, but the capability of the experiment can be determined.

The features appearing in the spectra at $\log(N_e) \geq 7.3$ are currently under investigation, in order to exclude possible effects of misreconstructed total muon number on the estimation of the shower size. The spectra are based on a data set of 1.9×10^6 well reconstructed events inside the fiducial area. The effective time of combined data taking with both KASCADE array and Grande is equivalent to 626 days. With the capability of reconstructing both, muon and electron numbers, it is possible to investigate the two-dimensional size spectrum like in KASCADE. In Fig. 4 the two-dimensional spectrum for zenith angles between $18°$ and $25°$ is shown. The dashed lines show an estimation of

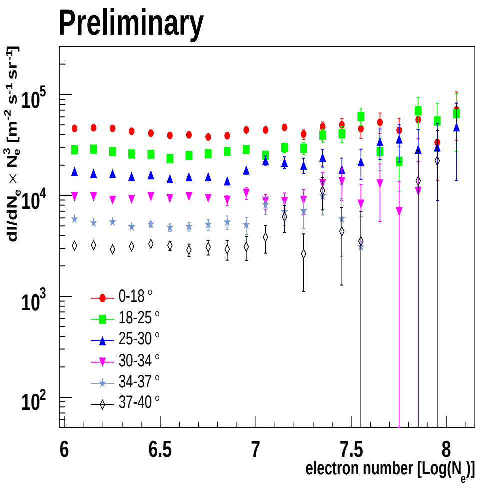

Figure 3: Differential shower size spectra for five different zenith angle ranges.

the primary energy based on simulations with the interaction model QGSjet01 [5].

Conclusions

In this paper, it has been shown that it is possible with the current setup of the KASCADE-Grande experiment to measure cosmic ray showers up to 10^{18} eV, although up to now only few events have been detected at these energies. Size spectra for different zenith angular ranges have been presented as well as an example of electron vs muon numbers distribution. At the moment the statistics are too small to make further concise statement of spectrum and mass composition for energies above 10^{17} eV, moreover the reconstruction procedure needs still some minimal refinements. In future the two-dimensional spectrum will be the starting point for the application of an unfolding analysis that will lead to the determination of spectra for different mass groups (as done for KASCADE [9]).

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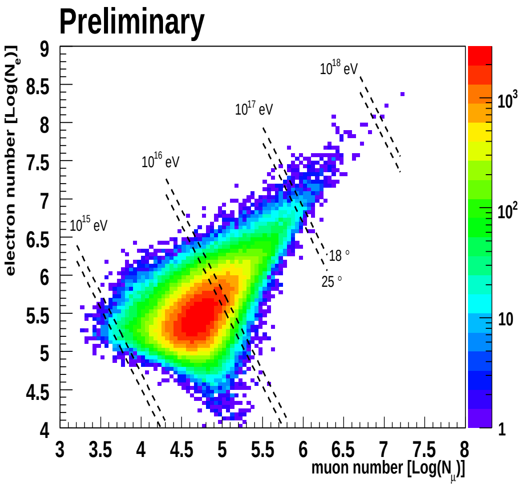

Figure 4: Reconstructed electron and muon number distribution of air showers measured by KASCADE-Grande in the zenith range $18° - 25°$. The dashed lines indicate average lines of constant energy derived from CORSIKA simulations

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