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The Air-Shower Experiment KASCADE-Grande

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KASCADE-Grande is an extensive air shower experiment at the Forschungszentrum Karlsruhe, Germany. Main parts of the experiment are the Grande array spread over an area of $700 \times 700\,\mathrm{m}^2$, the original KASCADE array covering $200 \times 200\,\mathrm{m}^2$ with unshielded and shielded detectors, and additional muon tracking devices. This multi-detector system allows to investigate the energy spectrum, composition, and anisotropies of cosmic rays in the energy range up to 1 EeV. An overview on the performance of the apparatus and first results will be given.

1. Introduction

Even 50 years after its discovery, the knee in the cosmic ray energy spectrum (a steepening of the spectrum around $4 \cdot 10^{15}\,\mathrm{eV}$) is still of considerable interest. Due to the low intensities, at present the knee region is only accessible by the detection of extensive air showers (EAS) induced by the primary cosmic-ray particles. Whereas this measurement method circumvents statistical problems, one has to rely on the results of simulations and the description of high energy hadronic interactions while reconstructing the properties of the primary particles. On the other hand, a thorough analysis of EAS data offers the opportunity of testing and improving the validity of these high energy interaction models.

The KASCADE-Grande experiment [1], located on the site of the Forschungszentrum Karlsruhe (Germany), is especially designed to measure EAS in the energy range between 0.5 PeV and 1 EeV. The installation consists of the original KASCADE [2] experiment and the newly added Grande array, covering an effective area of $0.5\,\mathrm{km}^2$.

The major goal of KASCADE-Grande is the observation of the 'iron-knee' in the cosmic-ray spectrum at around 100 PeV, which is expected

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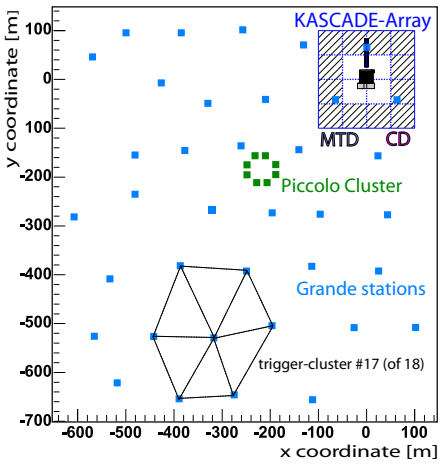

Figure 1. Layout of the KASCADE-Grande experiment: The KASCADE array, the distribution of the 37 stations of the Grande array, the small Piccolo cluster for fast trigger purposes, and the muon tracking (MTD) and central detector (CD) are shown. The outer 12 clusters of the KASCADE array consist of μ- and e/γ-detectors, the inner 4 clusters of e/γ-detectors, only.

following the KASCADE observations where the positions of the knees of individual mass groups suggest a rigidity dependence [3]. The capability of KASCADE-Grande will allow to reconstruct the energy spectra of various mass groups similar to KASCADE, which in addition will lead to hints to the energy range where the transition from cosmic rays of galactic to extragalactic origin occurs. The validity of hadronic interaction models used in CORSIKA [4] Monte Carlo simulations of ultra-high energy air showers will be also tested with KASCADE-Grande. Investigations of the radio emission in air showers continue at the site of KASCADE-Grande with promising results paving the way for this new detection technique (see LOPES contribution at this conference [5]).

2. The Set-Up

The existing multi-detector experiment KASCADE (located at 49.1°N, 8.4°E, 110 m a.s.l.), which takes data since 1996, was extended to KASCADE-Grande in 2003 by installing a large array of 37 stations consisting of $10\,\mathrm{m}^2$ scintillation detectors each, with an average spacing of 137 m (fig. 1 and tab. 1). The stations comprise 16 photo-multipliers each providing a high dynamic range from 1/3 to 30000 charged particles per station for the reconstruction of particle densities and timing measurements. The signals are amplified and shaped inside the Grande stations, and after transmission to a central DAQ station digitized in peak sensitive ADCs. KASCADE-Grande provides an area of $0.5\,\mathrm{km}^2$ and operates jointly with the existing KASCADE detectors. Grande is electronically subdivided in 18 trigger clusters and read out and jointly analysed with KASCADE for showers fulfilling at least one of these 7-fold coincidences (fig. 1). The joint measurements with the KASCADE muon tracking devices are ensured by an additional cluster (Piccolo) close to the center of KASCADE-Grande for fast trigger purposes. Piccolo consists of $8 \times 10\,\mathrm{m}^2$ stations equipped with plastic scintillators. Besides these Grande triggered events (0.5 Hz) the original KASCADE data acquisition is continued with a trigger rate of $\approx$ 4 Hz. While the Grande detectors are sensitive to charged particles, the KASCADE array detectors measure the electromagnetic component and the muonic component

Table 1
Compilation of the KASCADE-Grande main detector components.

Detector Particles	sensitive area [m^2]
Grande	
charged	370
Piccolo	
charged	80
KASCADE array e/γ	
electrons	490
KASCADE array μ	
muons ($E_\mu^{\mathrm{thresh}} = 230\,\mathrm{MeV}$)	622
MTD	
muons ($E_\mu^{\mathrm{thresh}} = 800\,\mathrm{MeV}$)	3×128
MWPCs/LSTs	
muons ($E_\mu^{\mathrm{thresh}} = 2.4\,\mathrm{GeV}$)	3×129
LOPES 30 antennas	
radio emission	$> 5 \cdot 10^5$

separately. The muon detectors enable the reconstruction of the lateral distributions of muons on an event-by-event basis also for Grande triggered events. Further muon detector systems at a muon tracking detector (MTD) and at the Central Detector of KASCADE allow to investigate the muon component of EAS at three different threshold energies [6].

3. Update on KASCADE data analysis

The data of KASCADE have been used in a composition analysis showing the knee at 3–5 PeV to be caused by a steepening in the light-element spectra [3]. Since the applied unfolding analysis depends crucially on simulations of air showers, different high energy hadronic interaction models (QGSJet01 [7] and SIBYLL [8]) were used. The results have shown a strong dependence of the relative abundance of the individual mass groups on the underlying model. In a recent update of the analysis we applied the unfolding method with a different low energy interaction model (FLUKA [9] instead of GHEISHA [10]) in the simulations. While the resulting individual mass group spectra do not change significantly, the overall description of the measured data improves by using the FLUKA model [11]. In addition data over a larger range of zenith angle were analysed. The new results are completely consistent, i.e. there is no hint of any severe problem in applying the unfolding analysis method to KASCADE data [11].

KASCADE allows to correlate various observables of the electromagnetic, muonic, and hadronic component which is used for detailed consistency tests of hadronic interaction models. Recently [12], predictions of air shower simulations using the hadronic interaction model EPOS 1.61 [13] has been investigated revealing that the predictions of EPOS are not compatible with KASCADE measurements. Most likely, EPOS does not deliver enough hadronic energy to the observation level and the energy per hadron seems to be too small. Thus, simulating a specific primary particle, comparatively lower electron and higher muon numbers are obtained at the observation level, e.g. when the mass composition of cosmic rays is derived from measured values this effect leads to a much lighter mass composition.

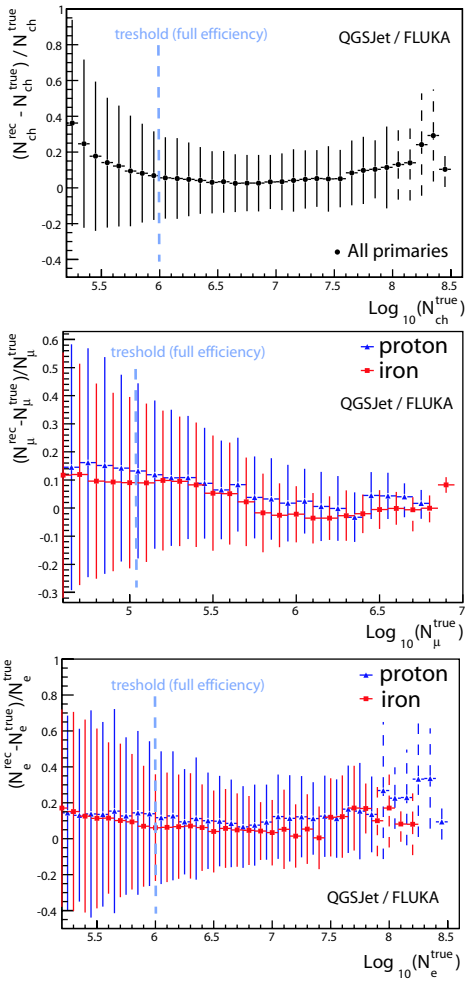

Figure 2. Charge particle, muon number, and electron number reconstruction resolution of KASCADE-Grande.

4. Performance of KASCADE-Grande

Basic shower observables like the core position, angle-of-incidence, and total number of charged particles are provided by the measurements of the Grande stations [14]. A core position resolution of ≈ 10 m, a direction resolution of $\approx 0.7°$, and a resolution of the total particle number in the showers

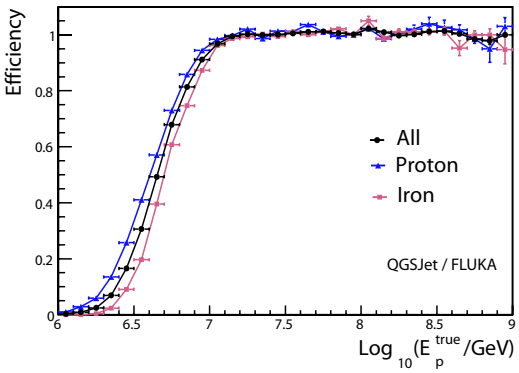

Figure 3. Reconstruction and Trigger Efficiency of KASCADE-Grande.

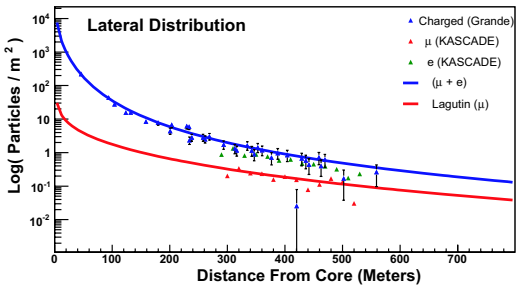

Figure 4. Example of the lateral distribution measured for a single event by the KASCADE-Grande experiment.

of $\approx 10\%$ is reached (fig. 2, where the error bars display the spread of the distributions). The total number of muons (N_μ resolution $\approx 20\%$, fig. 2) is calculated using the core position determined by the Grande array and the muon densities measured by the KASCADE muon array detectors. In particular this possibility to reconstruct the total muon number for Grande measured showers is the salient feature of KASCADE-Grande compared to other experiments in this energy range. In addition, a common fit to the energy deposits with the relative muon to electron ratio as an additional free parameter enables an estimate of the total electron number with a resolution in the order of 15% (fig. 2).

Full efficiency for triggering and reconstruction of air-showers is reached at a primary energy of $\approx 2 \cdot 10^{16}$ eV (fig. 3).

These main characteristics of the experiment are studied with detailed CORSIKA simulations including the full simulation of the detector responses to the incident particles. In addition to Monte Carlo simulations the precision of the reconstruction is also evaluated exploiting the unique feature of the KASCADE-Grande experiment of having two independent samplings of the same event by the KASCADE and the Grande arrays. Selecting showers with cores located in a region accessible for both arrays provides a set of events that are independently reconstructed by both arrays. We can thus compare the Grande results to those obtained by the KASCADE array. By that method the simulated accuracies are well confirmed [14,15]. An example of the particle densities of a single event is shown in figure 4. The particle densities measured by Grande detectors are those sampled by each single station, while for the KASCADE array the mean densities calculated in 20 m intervals of the core distance are shown. Another example of the reconstruction showing the good performance of the Grande measurements is shown in fig. 5, where average lateral distributions of the charged particle densities for vertical EAS in different intervals of the reconstructed shower size (charged particles) are displayed.

Additional sensitivity for composition estimates and interaction model tests is provided by muon density measurements and muon tracking at different muon energy thresholds [16]. The MTD measures the incidence angles of muons in EAS. These angles provide sensitivity to the longitudinal development of the showers [17,18]. The complementary information of the showers measured by the central and the muon tracking detectors is predominantly being used for a better understanding of the features of an air-shower and for tests and improvements of the hadronic interaction models underlying the analyses.

5. First Analyses

In the following some examples of first analyses based on the presently available data set of KASCADE-Grande are given.

The estimation of energy and mass of the pri-

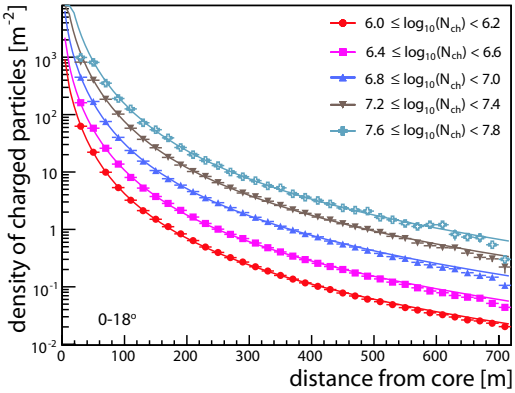

Figure 5. Measured average lateral distributions of the charged particle density.

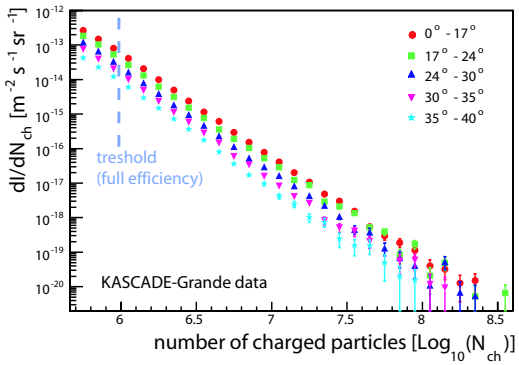

Figure 6. KASCADE-Grande shower size (total number of charged particles) spectra for different zenith angular ranges.

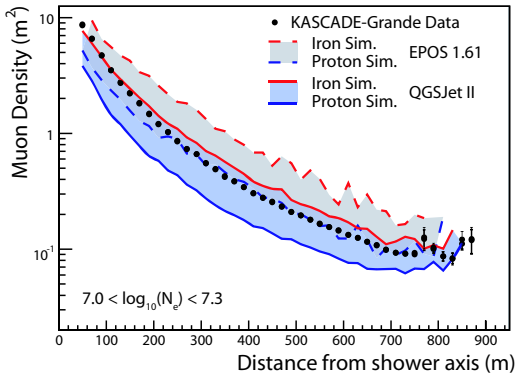

Figure 7. Example of a measured muon lateral distribution compared with predictions for two primaries by two hadronic interaction models.

mary particles will be based on a combined investigation of the charged particle, electron, and muon components measured by the detector arrays of Grande and KASCADE.

Figure 6 shows the differential shower size spectra for various zenith angular ranges, where the shower size here describes the number of charged particles. These spectra will be the basis for the reconstruction of the all-particle energy spectrum of cosmic rays. The idea is to apply the constant intensity cut method (equal intensity in different zenith angular ranges means equal energy) to correct for the attenuation of the shower size with increasing zenith angle. In a next step the conversion of size to primary energy will be done using Monte Carlo simulations for only one specific zenith angle [19].

In addition to the total number of charged particles for each event the total muon number (N_μ) [20] and the particle density at 500 m core distance ($S(500)$) [21] are also reconstructed and the according spectra determined. Applying the same reconstruction method the obtained all-particle energy spectra will be compared for cross-checks, for studies of systematic uncertainties and for testing the validity of the underlying hadronic interaction model.

As well as the total muon number, KASCADE-Grande allows to reconstruct the muon density at a certain distance to the shower core, which gives sensitivity to changes in the elemental composition [22] and to test the hadronic interaction models. Fig. 7 displays the measured lateral muon densities distribution for one bin in shower size (electron number) and compares it with expectations for primary iron and protons in the same shower size range for two interaction models. This example shows that there is a large discrepancy in the available models which hampers a simple estimate of mass composition. Correlation of many observables and detailed cross-checks of the models will help to solve the threefold problem of the reconstruction of the unknown primary energy, the primary mass, and to quantify the characteristics of the hadronic interactions in the air-shower development.

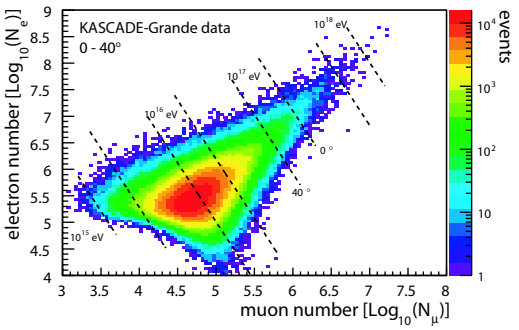

Figure 8. Two dimensional shower size (electron vs. muon number) spectrum of the KASCADE-Grande experiment.

At the KASCADE experiment, the two-dimensional distribution shower size (electrons) - number of muons played a fundamental role in reconstruction of energy spectra for single mass groups. In figure 8, where the two dimensional shower size spectrum electron number vs. muon number reconstructed by KASCADE-Grande is displayed, we illustrate the capability of the experiment to perform an unfolding procedure as in KASCADE.

6. Conclusions

KASCADE-Grande is fully efficient at energies above $2 \cdot 10^{16}$ eV, thus providing a large overlap with the KASCADE energy range. Due to the fact that for KASCADE-Grande a wealth of information on individual showers is available, tests of the hadronic interaction models and anisotropy studies will be possible in addition to the reconstruction of energy spectrum and composition.

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