Cosmic Ray Measurements with KASCADE-Grande

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Abstract: The detection of high-energy cosmic rays above a few hundred TeV is realized by the observation of extensive air-showers. By using the multi-detector setup of KASCADE-Grande energy spectrum, elemental composition, and anisotropies of high-energy cosmic rays in the energy range from below the knee up to 1 EeV are investigated. The most distinct feature of the spectrum, the knee, is thought to be the beginning of the end of the galactic origin of cosmic rays. As the highest energies (above the ankle) are most probably of extragalactic origin, between 10 PeV to 1 EeV one expects the transition of galactic to extragalactic origin. KASCADE-Grande is dedicated to explore this transition region. The estimation of energy and mass of the high-energy primary particles is based on the combined investigation of the charged particle, the electron, and the muon components measured by the detector arrays of Grande and KASCADE.

Keywords: KASCADE-Grande, 10-1000PeV, spectrum and composition

1 KASCADE-Grande

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 us to investigate the energy spectrum, composition, and anisotropies of cosmic rays in the energy range up to 1 EeV. The estimation of energy and mass of the primary particles is based on the combined investigation of the charged particle, the electron, and the muon components measured by the detector arrays of Grande and KASCADE.

The multi-detector experiment KASCADE [1] (located at 49.1°n, 8.4°e, 110 m a.s.l.) was extended to KASCADE-Grande in 2003 by installing a large array of 37 stations consisting of $10\,\mathrm{m}^2$ scintillation detectors each (fig. 1). KASCADE-Grande [2] provides an area of $0.5\,\mathrm{km}^2$ and operates jointly with the existing KASCADE detectors. 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. For results of the muon tracking devices see ref-

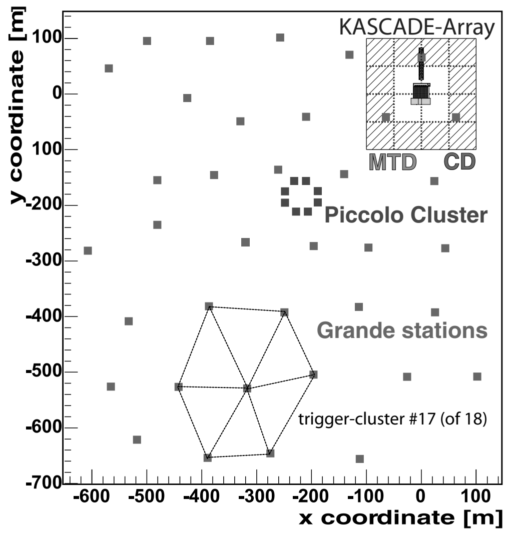

Figure 1: Layout of the KASCADE-Grande experiment: The original KASCADE, the distribution of the 37 stations of the Grande array, and the small Piccolo cluster for fast trigger purposes are shown. The outer 12 clusters of the KASCADE array consist of μ- and e/γ-detectors, the inner 4 clusters of e/γ-detectors,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

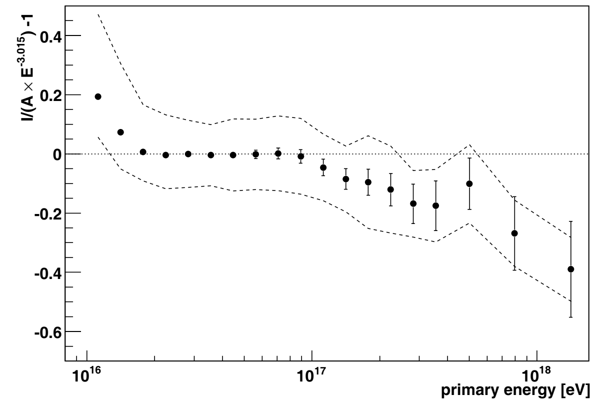

Figure 2: The all-particle energy spectrum obtained with KASCADE-Grande. The residual flux after multiplying the spectrum with a factor of $E^{3.015}$ and normalized with A is displayed as well as the band of systematic uncertainty.

erences [3, 4]. While the Grande detectors are sensitive to charged particles, the KASCADE array detectors measure the electromagnetic component and the muonic component separately. These muon detectors enable to reconstruct the total number of muons on an event-by-event basis also for Grande triggered events.

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. A core position resolution of $\approx 5\,\mathrm{m}$, a direction resolution of $\approx 0.7°$, and a resolution of the total particle number in the showers of $\approx 15\%$ is achieved. The total number of muons (N_μ resolution $\approx 25\%$) is calculated using the core position determined by the Grande array and the muon densities measured by the KASCADE muon array detectors. Full efficiency for triggering and reconstruction of air-showers is reached at primary energy of $\approx\ 10^{16}$ eV, slightly varying on the cuts needed for the reconstruction of the different observables [2].

The strategy of the KASCADE-Grande data analysis to reconstruct the energy spectrum and elemental composition of cosmic rays is to use the multi-detector set-up of the experiment and to apply different analysis methods to the same data sample. This has advantages in various aspects: One would expect the same results by all methods when the measurements are accurate enough, when the reconstructions work without failures, and when the Monte-Carlo simulations describe correctly and consistently the shower development and detector response.

The main air-shower observables of KASCADE-Grande, shower size and total number of muons, could be reconstructed with high precision and low systematic uncertainties and are used in the following for the data analysis.

2 The all-particle energy spectrum

In a first step of the analysis, we reconstructed the all-particle energy spectrum. Applying various reconstruction methods to the KASCADE-Grande data the obtained all-particle energy spectra are compared for cross-checks of the reconstruction, for studies of systematic uncertainties and for testing the validity of the underlying hadronic interaction models. By combining both observables and using the hadronic interaction model QGSJet-II, a composition independent all-particle energy spectrum of cosmic rays is reconstructed in the energy range of 10^{16} eV to 10^{18} eV within a total uncertainty in flux of 10-15%.

Despite the overall smooth power law behavior of the resulting all-particle spectrum, there are some structures observed, which do not allow to describe the spectrum with a single slope index. Figure 2 shows the resulting all-particle energy spectrum multiplied with a factor in such a way that the middle part of the spectrum becomes flat [5]. The power law index of $\gamma = -3.015 \pm 0.010$ is obtained by fitting the range of $\log_{10}(E/eV) = 16.2 - 17.0$. There is a clear evidence that just above 10^{16} eV the spectrum shows a 'concave' behavior, which is significant in respect to the systematic and statistical uncertainties. Another feature in the spectrum is a small break at around 10^{17} eV. Applying a second power law above 10^{17} eV an index of $\gamma = -3.24 \pm 0.08$ is obtained. With a statistical significance of 7.75 sigma the two power laws are incompatible with each other. Even taking into account worst scenarios for the systematic uncertainties or applying more stringent procedures to calculate the significance a 5 sigma effect is kept. This slight slope change occurs at an energy where the rigidity dependent knee of the iron component would be expected (KASCADE QGSJet based analysis as-

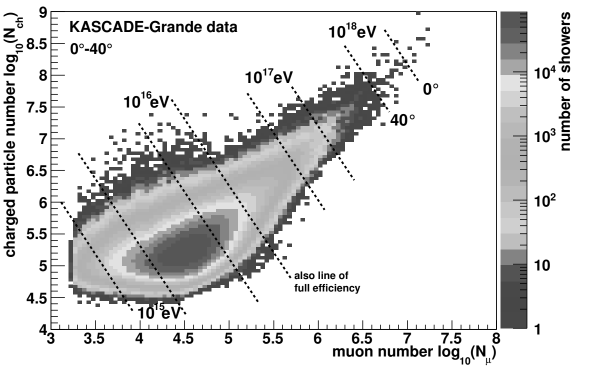

Figure 3: Two-dimensional distribution of the shower sizes charged particle number and total muon number as measured by KASCADE-Grande. All quality cuts are applied, i.e. these data are the basis for the mass composition studies.

signs the proton knee to an energy of $3 - 4 \cdot 10^{15}$ eV). Despite the fact, that the discussed spectrum is based on the QGSJet-II hadronic interaction model, there is confidence that the found structures of the energy spectrum remain stable. Tests with EPOS as well as investigations of the spectra of the pure (and independently obtained) observables shower size and total muon number, confirmed the structures [5].

3 Composition

A conclusion on the origin of the found structures in the all-particle spectrum is not possible without investigating the composition in detail in this energy range. The basic goal of the KASCADE-Grande experiment is the determination of the chemical composition in the primary energy range $10^{16} - 10^{18}$ eV. Like for the reconstruction of the energy, again several methods using different observables are applied to the registered data in order to study systematic uncertainties. However, the influence of predictions of the hadronic interaction models has a much larger influence on the composition than on the primary energy. As it is well known from KASCADE data analysis [6] that the relative abundances of the individual elements or elemental groups are very dependent on the hadronic interaction model underlying the analyses the strategy is to derive the energy spectra of the individual mass groups. The structure or characteristics of these spectra are found to be much less affected by the differences of the various hadronic interaction models than the relative abundance. The present goal is to verify the structure found in the all-particle energy spectrum at around 100 PeV in the individual mass group spectra and to assign it to a particular mass.

The main observables taken into account for composition studies at KASCADE-Grande are the shower size (N_{ch}, or the subsequently derived electron number N_e) and the muon shower size (N_μ). Figure 3 displays the correlation

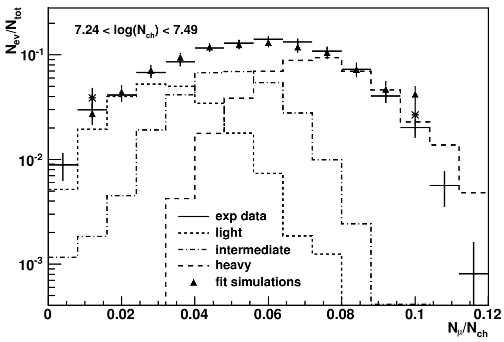

Figure 4: Shower size ratio distributions for a certain bin in charged particle number. Shown is the measured distribution as well as the simulated ones for three primary mass groups and the resulting sum.

of these two observables, i.e. this distribution is the basis of the composition analysis with KASCADE-Grande data.

For all the methods it is crucial to verify the sensitivity of the observables to different primary particles and the reproducibility of the measurements with the hadronic interaction model in use as a function of sizes and the atmospheric depth. So far, in the composition analysis we concentrate on interpreting the data with the hadronic interaction model QGSJet-II (and FLUKA as low energy interaction model).

Four methods of composition studies at KASCADE-Grande are discussed in the following:

- **Charged particle – muon number ratio** [7]: The total number of charged particles N_{ch} and the total number of muons N_μ of each recorded event are considered and the distribution of N_μ/N_{ch} is studied in different intervals of N_{ch} (corresponding to different energy intervals) and zenith angle. The experimental distribution of the observable N_μ/N_{ch} is taken into account and fitted with a linear combination of elemental contributions from simulations, where we distinguish three groups: light, medium and heavy primaries. By this way the means and the widths of the distributions as two mass sensitive observables are taken into account (see as an example figure 4). The width of the data distribution is in all ranges of N_{ch} so large that always three mass groups are needed to describe them. Using the Monte Carlo simulations the corresponding energy of each mass group and shower size bin is assigned to obtain the spectra of the individual mass groups.

- **The Y-cut method** [8]: Here, the shower ratio $Y_{CIC} = \log N_\mu / \log N_{ch}$ between the muon and the charged particle numbers, both corrected for atmospheric attenuation by the Constant Intensity Cut method (CIC), is used as parameter to separate the KASCADE-Grande data into different mass groups. MC simulations performed with CORSIKA on the

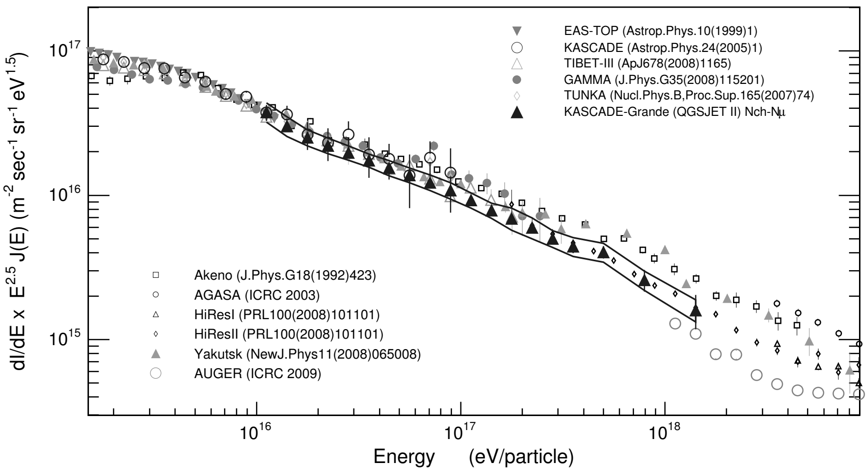

Figure 5: Comparison of the all-particle energy spectrum obtained with KASCADE-Grande data based on the QGSJet-II model to results of other experiments.

framework of FLUKA/QGSJET-II are employed to obtain the expected Y_{CIC} distributions as a function of the energy for different cosmic ray primaries as a basis for the separation. Then the Y_{CIC}-parameter is used to divide the KASCADE-Grande data into electron-rich and electron-poor events, i.e. generated by light and heavy primaries.

- **The k-parameter method** [9]: Using the above mentioned reconstruction of the energy spectrum by correlating the size of the charged particles N_{ch} and muons N_{μ} on an event-by-event basis, the mass sensitivity is minimized by means of a parameter $k(N_{ch}, N_{\mu})$. On the other hand, the evolution of k as a function of energy keeps track of the evolution of the composition, and allows an event-by-event separation between light, medium and heavy primaries. Using k as separation parameter for different mass groups, where the exact values of k have to be determined with help of simulations, directly the energy spectra of the mass groups are obtained.

- **The Gold-unfolding method** [10]: This method is based on the unfolding of the two-dimensional shower size spectrum (fig. 3) in a similar way as it was developed for the KASCADE data analysis [6]. Due to the fact that the accuracies in reconstructing the shower sizes for KASCADE-Grande are not as high as in case of KASCADE, for comparing both results, primary masses are combined to light (H), medium (He+C+Si) and heavy (Fe) spectra. The resulting individual mass group spectra can be combined to provide a solution for the entire energy range from 1 PeV to 1 EeV.

Summarizing, by these first composition studies it is seen that at least three primary elements are needed to describe the experimental data over the entire energy range accessible by KASCADE-Grande, i.e. up to 1 EeV. In addition, it was found that QGSJet-II, the hadronic interaction model in use, can fairly well reproduce the data and, in particular, provides a consistent solution on the elemental composition, independent of the method in use. One has to remark, that using another hadronic interaction model would probably lead to significant changes in the relative abundances of the elemental groups as different models predict different shower sizes for a certain energy and mass of the primary cosmic ray. But, we are confident that the obtained spectral form for the heavy and light component of the cosmic ray spectrum will be reliable.

Results and details of all these analyses will be presented at the 32^{nd} International Cosmic Ray Conference.

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