

# Cosmic ray energy spectrum based on shower size measurements of KASCADE-Grande

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**Abstract.** The KASCADE-Grande (Karlsruhe Shower Core and Array DEtector and Grande array), located on site of the Forschungszentrum Karlsruhe in Germany, is designed for observations of cosmic ray air showers in the energy range of  $10^{16}$  to  $10^{18}$  eV. The measurement of the all-particle energy spectrum of cosmic rays is based on the size spectra of the charged particle component, measured for different zenith angle ranges and on the "Constant Intensity Cut" method to correct for attenuation effects. The all-particle energy spectrum, calibrated by Monte-Carlo simulations, is presented and systematic uncertainties discussed.

**Keywords:** cosmic rays; KASCADE-Grande; constant intensity cut method.

## I. INTRODUCTION

The energy spectrum and composition of primary cosmic rays around  $10^{17}$  eV are very important since they might be related to the existence of extragalactic cosmic ray sources, which might have a significantly different elemental composition from the one observed at lower energies [1]. The aim of KASCADE-Grande is the examination of the iron-knee in the cosmic ray energy spectrum, i.e. the end of the bulk of cosmic rays of galactic origin. It is expected at around  $10^{17}$  eV following previous KASCADE observations [2]. KASCADE-Grande will allow investigations in detail

about the elemental composition giving the possibility to distinguish between astrophysical models for the transition region from galactic to extragalactic origin of cosmic rays. The KASCADE-Grande array covering an area of  $700 \times 700$  m<sup>2</sup> is optimized to measure extensive air showers up to primary energies of 1 EeV [3]. It comprises 37 scintillation detector stations located on a hexagonal grid with an average spacing of 137 m for the measurements of the charged shower component. Each of the detector stations is equipped with plastic scintillator sheets covering a total area of 10 m<sup>2</sup>. The stations contain 16 scintillator sheets read-out by photo-multipliers providing a dynamic range up to about 10000 charged particles per station for the reconstruction of particle densities and timing measurements. The timing accuracy of Grande stations allows an excellent angular resolution [4]. Grande is electronically subdivided in 18 hexagonal trigger clusters formed by six external and one central stations. A trigger signal is build when all stations in a hexagon are fired, and its total rate is about 0.5 Hz. Full efficiency for the shower size is reached at the number of charged particles of around  $10^6$ , which approximately corresponds to a primary energy of  $10^{16}$  eV, so that a large overlap for cross-checks with measurements of the original KASCADE experiment is attained. The limit at high energies is due to the restricted area of the Grande array.

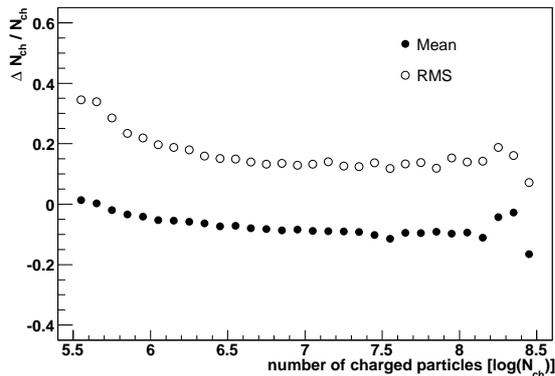


Fig. 1: Reconstruction accuracy of the number of charged particles obtained by Monte-Carlo simulations. The closed and open circles represent the values of mean and Root Mean Square, respectively.

## II. RECONSTRUCTION ACCURACY

The primary energy of cosmic rays is reconstructed by the observed electron and muon numbers at ground. While the Grande detectors are sensitive to all charged particles, the KASCADE detectors measure separately the electromagnetic and muonic components due to the shielding above the muon counters. Therefore, the shower core position, the arrival direction, and the total number of charged particles in the shower are reconstructed from Grande array data, whereas the total number of muons is extracted from the data of the KASCADE muon detectors. Performing CORSIKA air shower simulations [5] including the detector response of the Grande array, the parameters were optimized for the lateral density distribution of KASCADE-Grande [4], and well reconstructed with sufficient accuracies for the further physics analysis. Figure 1 shows the accuracy of the reconstructed number of charged particles obtained by Monte-Carlo simulations. The accuracy could be confirmed by combining information of KASCADE with Grande reconstruction on a subsample of commonly measured events (Ref. [4]). In order to avoid misreconstruction effects of shower core positions on the border of the Grande array, a fiducial area of about  $0.2 \text{ km}^2$  centered in the middle of the Grande array is chosen. The statistical uncertainty of the shower size is of the order of 20% for the total number of charged particles. Above a threshold of  $10^6$  charged particles, the reconstruction accuracies of the core position and the arrival direction are better than 8 m and  $0.5^\circ$ , respectively, for zenith angles below  $40^\circ$ .

## III. DATA ANALYSIS

KASCADE-Grande has started combined data acquisition with all detector components since the end of 2003. The data presented here were taken from December 2003 to March 2009. It corresponds to the effective measuring time of 987 days, where all components

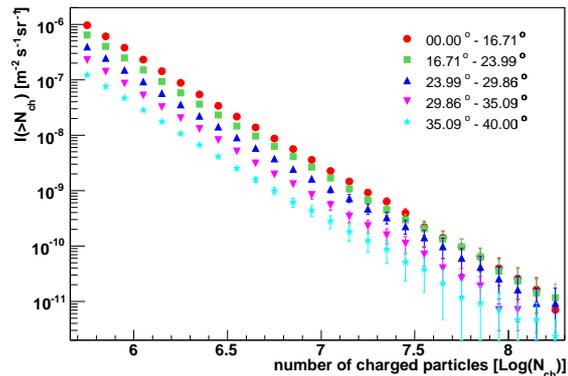


Fig. 2: Integral shower size spectra of the number of charged particles for different zenith angle ranges.

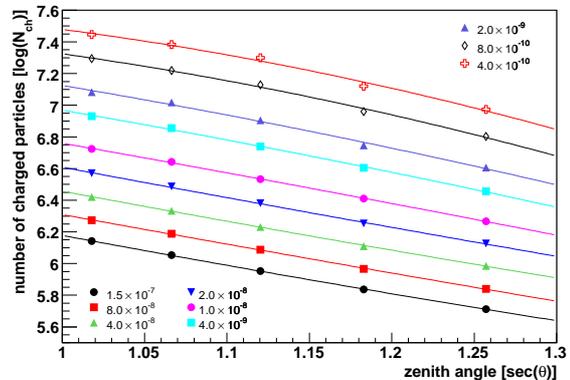


Fig. 3: The number of charged particles resulting from the constant intensity cuts as a function of the zenith angle. The unit of each flux (symbol) is  $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$ .

of KASCADE and KASCADE-Grande were operating without failures in data acquisition. In this analysis, all showers with zenith angles smaller than  $40^\circ$  have been analyzed. After some quality cuts approximately 10 million events are available for the physics analysis. As the first step to determine the all-particle energy spectrum, the constant intensity cut method was introduced. This method assumes that cosmic rays arrive isotropically from all directions, i.e. the primary energy of a cosmic ray particle corresponds to a certain intensity regardless of its arrival direction. In KASCADE-Grande, an isotropic distribution is assumed in the considered energy range up to  $10^{18} \text{ eV}$ , so that it allows us to apply the constant intensity method to the integral shower size spectra for different zenith angular bins (Fig. 2).

Above a certain shower size, the intensity should be constant due to the assumption of the uniform intensity distribution when binned in  $\cos^2\theta$ . For a given intensity, the number of charged particles is calculated for each zenith angle range. The intensity cut is mostly located in between two neighboring points of the distributions, and thus the exact values of the corresponding shower size are estimated by interpolation between these two

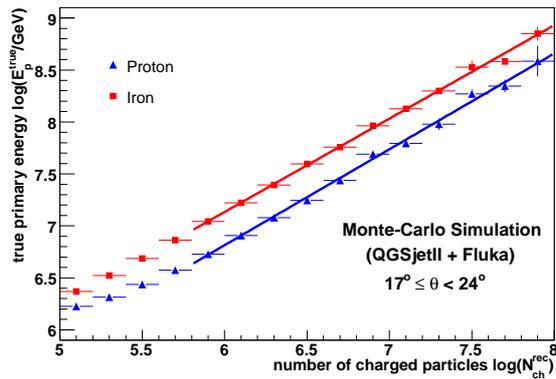


Fig. 4: The true primary energy as a function of the number of charged particles for proton and iron components. The lines show the applied fits to the points.

points. From the values of  $N_{ch}$  we obtain the attenuation curves (Fig. 3). It represents how the number of charged particles for a given intensity attenuates through the atmosphere with increasing zenith angle, i.e. with increasing atmospheric depth. Each curve is individually fitted by a second-degree polynomial function, where the reference angle  $\theta_{ref}$  of  $20^\circ$  is chosen by the mean value from a Gaussian fit to the measured zenith angle distribution. Due to a negligible variation of the fit parameters only one value is used to correct the number of charged particles event by event for the attenuation in the atmosphere. The zenith angle dependence of the number of charged particles was therefore eliminated by using informations from the measurements only.

In order to determine the energy conversion relation between the number of charged particles  $N_{ch}$  and the primary energy  $E_p$ , Monte-Carlo simulations were used. Extensive air showers were simulated using the program CORSIKA with QGSjetII [6] and FLUKA as hadronic interaction models, including full simulations of the detector response. The simulated data sets contain air shower events for five different primary mass groups: proton, helium, carbon, silicon and iron. For the simulation, events for the zenith angle ranges of  $17^\circ \leq \theta < 24^\circ$ , i.e. around the reference angle, are selected to reduce systematic effects. The relation of the primary energy as a function of the number of charged particles is shown in Fig. 4. Assuming a linear dependence  $\log E_p = a + b \cdot \log N_{ch}$ , the correlation between the primary energy and the number of charged particles is obtained, where the fit is applied in the range of full trigger and reconstruction efficiencies. The fit yields  $a = 1.28 \pm 0.08$  and  $b = 0.92 \pm 0.01$  with a reduced  $\chi^2$  of 1.42 for proton, and  $a = 1.74 \pm 0.07$  and  $b = 0.90 \pm 0.01$  with a reduced  $\chi^2$  of 0.98 for iron. The same procedure is also performed for helium, carbon and silicon to examine the dependence of the calibration on the assumed primary particle type, where the fit parameters are also in between above values. Using these

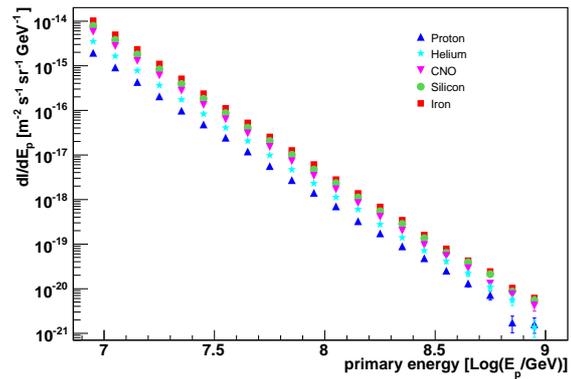


Fig. 5: All-particle energy spectrum reconstructed from KASCADE-Grande shower size for five different primary particle type assumptions together with its statistical uncertainties.

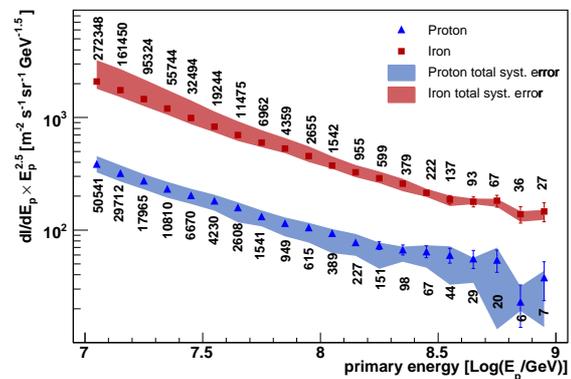


Fig. 6: The reconstructed energy spectrum for proton and iron, together with statistical error bars (vertical lines) and uncertainties (energy resolution and systematics) (bands). The numbers indicate the events per bin for the points.

correlations the all-particle energy spectrum is obtained. The reconstructed energy spectra for the assumption of five different primary particle types are shown in Fig. 5.

#### IV. SYSTEMATIC UNCERTAINTY

The energy resolution is estimated from the difference between simulated energy and derived energy, where the derived energy is obtained by applying the measured attenuation correction to the Monte-Carlo simulation. The energy resolutions for proton and iron are about 31% and 15% over the whole energy ranges, where the uncertainties of the reconstructed number of charged particles give the largest contribution. In addition, the systematic uncertainties on the reconstructed energy spectrum are investigated considering various possible contributions. Firstly, the fit of the attenuation curve was performed in order to correct the zenith angle dependence of the number of charged particles. Each fit parameter has an associated error and it effects on the

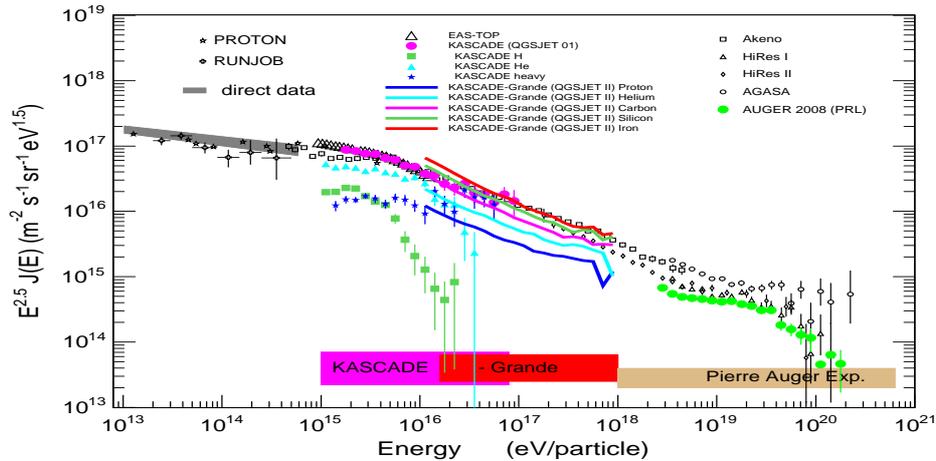


Fig. 7: All-particle energy spectrum in comparison with results of other experiments. The lines represent the KASCADE-Grande spectrum for the calibration assuming five different primary mass groups.

determination of the energy spectrum. The fit parameters are correlated with each other, so that the propagation of errors is used to calculate the systematic uncertainty induced by the attenuation fit. This uncertainty is estimated to be less than 2% for both proton and iron in the full energy range. Secondly, for the correlation of  $N_{ch}$  with  $E_p$  a power law fit was applied. As the same procedure above, the estimated systematic uncertainties due to the fit of the energy calibration contribute with 1% for proton and 3% for iron to the total uncertainty. The shower fluctuations are another source of systematic uncertainties, which is basically caused by the nature of the development of extensive air showers. The influence of these fluctuations on the reconstructed primary energy spectrum is estimated by using simulation data. For the calibration a spectral index of  $\gamma = -3$  is used in the simulations. By varying this spectral index, i.e. varying the effect of fluctuations on the reconstructed spectrum, the systematic uncertainty is estimated. The systematic deviation due to the shower fluctuation is evaluated by this procedure to be about 15% and 4% for proton and iron, respectively. Uncertainties due to a possible misdescription of the attenuation in the Monte-Carlo simulation are estimated by using two different reference zenith angles, together with the corresponding correlation of  $N_{ch}$  and  $E_p$ . The systematic uncertainties of 14% for proton and 11% for iron on the energy estimation are obtained for varying the reference angle from  $10^\circ$  to  $30^\circ$  for the calibration. All these individual systematic contributions were considered to be uncorrelated, and combined thus in quadrature to obtain the total systematic uncertainty (Fig. 6), where the composition dependence was not taken into account. The systematic uncertainty (i.e. sum in quadrature of all terms discussed above except the energy resolution) in the energy scale is of the order of about 20% for proton and 12% for iron at the primary energy of  $10^{17}$  eV. The uncertainties on the

flux for proton and iron are 32% and 21%, respectively, at energies of  $10^{17}$  eV. Further checks are currently being performed to reduce the systematic uncertainties on the energy estimation.

## V. CONCLUSION

The air shower experiment KASCADE-Grande measures cosmic rays in the energy range of  $10^{16}$ - $10^{18}$  eV. The multi detector setup of KASCADE-Grande allows us to reconstruct charged particles, electron and muon numbers of the showers separately with high accuracies. In the present contribution the reconstructed all-particle energy spectrum by means of the shower size measurements of the charged particle component by Grande array is presented by using the hadronic interaction model QGSjetII. The resulting spectrum is shown in Fig. 7 in comparison with results of other experiments. The obtained intensity values have been shown to depend on the nature of the primary particle as expected for an observable dominated by the electromagnetic components. Such values, inside the systematic uncertainties, are consistent with other KASCADE-Grande analysis based on different observables and methodologies. Their combination is a basic tool to provide an unbiased measurement of the primary energy spectrum and first indications on average primary composition [7].

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