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# Primary energy reconstruction from the charged particle densities recorded at 500 m distance from shower core with the KASCADE-Grande detector

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**Abstract.** Previous EAS investigations have shown that for a fixed primary energy the charged particle density becomes independent of the primary mass at certain (fixed) distances from the shower axis. This feature can be used as an estimator for the primary energy. We present results on the reconstruction of the primary energy spectrum of cosmic rays from the experimentally recorded S(500) observable (the density of charged particles at a distance of 500 m to the shower core as measured in a plane normal to the shower axis) using the KASCADE-Grande detector array. The KASCADE-Grande experiment is hosted by the Karlsruhe Institute for Technology - Campus North, Karlsruhe, Germany, 110 m a.s.l. and operated by an international collaboration. The obtained primary energy spectrum is presented along with the result of another reconstruction technique presently employed at KASCADE-Grande.

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## 1 Introduction

Previous EAS investigations have shown that the charged particle density becomes independent of the primary mass at large but fixed distances from the shower core and that it can be used as an estimator for the primary energy (Hillas et al., 1971). A method was derived to reconstruct the primary energy spectrum from the particular value of the charged particle density, observed at such specific radial distances. The technique has been used by different detector arrays in order

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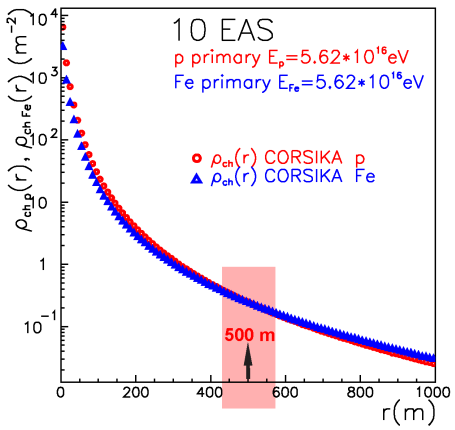


**Fig. 1.** Simulations show that, for the case of the KASCADE-Grande experimental layout, the particle density becomes independent of the primary mass at around 500 m distance from the shower core; this plot shows averaged simulated lateral distributions for different primary types with equal energy.

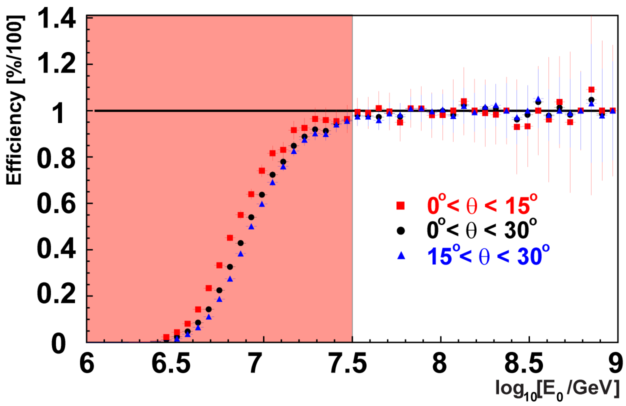


**Fig. 2.** S(500) reconstruction efficiency for different zenith angular ranges and for the entire shower sample (all quality cuts applied); the reconstruction efficiency exceeds 95% at $\log_{10}[E_0/\mathrm{GeV}]>7.5$.

to reconstruct the primary energy spectrum of the cosmic radiation (Dai et al., 1998; Edge et al., 1973; Nagano et al., 1984; Roth et al., 2003). In the case of the KASCADE-Grande array, detailed simulations (Brancus et al., 2005; Rebel et al., 2005) have shown that the particular distance for which this effect takes place is about 500 m (see Figs. 1 and 4), hence the notation S(500) for the charged particle density at 500 m distance from the shower core. The distance is measured in a plane normal to the shower axis and containing the shower core. The data recorded in the detector plane is projected on the normal plane taking into account the attenuation effects characteristic to inclined events.

The study has been performed for both simulated (Fig. 5) and experimental (Fig. 6) events, using identical reconstruction procedures (Sima et al., 2004). CORSIKA Monte Carlo EAS simulation tool (Heck et al., 1998) is used to simulate

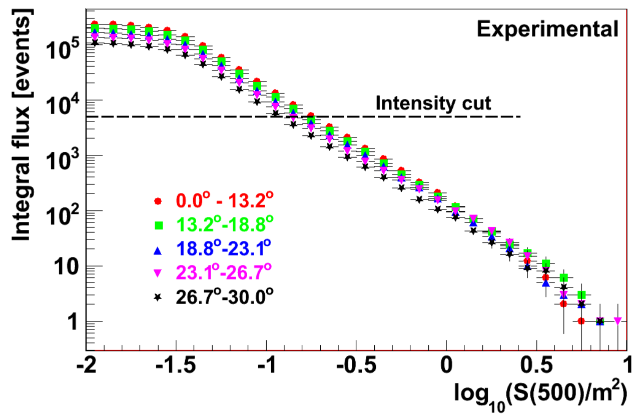


**Fig. 3.** Integral S(500) spectra; the horizontal line is a constant intensity cut at an arbitrarily chosen intensity; by assuming an exponential attenuation pattern the attenuation length of S(500) was evaluated to $\lambda(500) = 754 \pm 8\,\mathrm{g\,cm^{-2}}$.

air showers, with QGSJETII as model for high energy interactions (Kalmykov et al., 1997; Ostapchenko, 2006a,b).

The reconstruction begins with recording the energy deposits of particles in the KASCADE-Grande detector stations and the associated temporal information (arrival times of particles). Using appropriate Lateral Energy Correction Functions (LECF), the energy deposits are converted into particle densities. The LECF functions are dependent on the shower zenith angle (GEANT, 1993; Toma et al., 2006) and on the position of the station around the shower core (i.e. the LECF are dependent on the angle of incidence of particles in detectors). For every event, the obtained lateral density distribution is approximated by a Linsley (Linsley et al., 1962) Lateral Density Function (LDF) in order to evaluate the particle density at the radial range of interest, 500 m.

The described reconstruction is performed independently from the standard reconstruction applied at KASCADE-Grande - based on the $N_{ch}$-$N_{\mu}$ approach (Bertaina et al., 2009).

## 2 KASCADE-Grande

Historically, the KASCADE-Grande detector array (Haungs et al., 2003) is an extension of a smaller array (the KASCADE array, operated since 1996). KASCADE was designed to record air showers initiated by primaries with energies in the $10^{14}-10^{17}$ eV range (including the knee range). The extension of the original KASCADE array was guided by the intention to extend the energy range for efficient EAS detection to $10^{16}-10^{18}$ eV (Fig. 2). This energy range provides various interesting aspects: the expected transition from galactic to extragalactic cosmic rays and, in particular the question whether there exists a further “knee” in the energy spectrum.

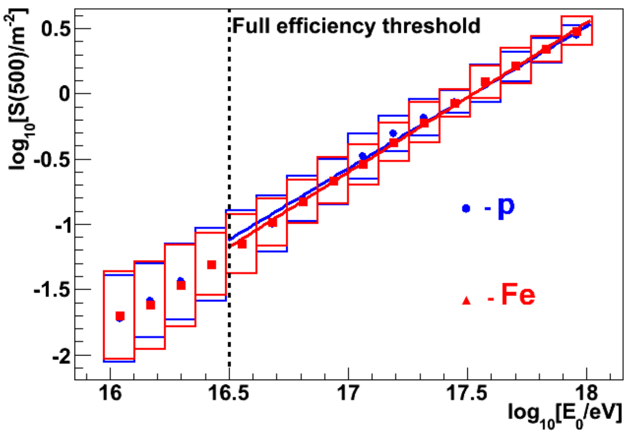


**Fig. 4.** The dependence of S(500) on the primary energy $E_0$ for two different primaries (showers in fairly equal proportions for the two masses); the box-errors are the errors on the spread; the errors on the mean are represented with bars and are dot-sized; straight lines represent power law fits.

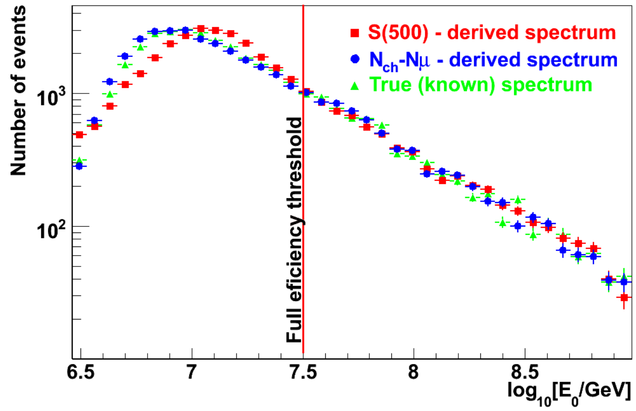


**Fig. 5.** Comparison between the true (known) energy spectrum of primaries (five masses in fairly equal proportions) used in the simulated shower sample and the result of the reconstructions: the described reconstruction based on S(500) and the result of the standard KASCADE-Grande approach based on the $N_{ch}-N_\mu$ approach.

## 3 The constant intensity cut method

For a given event sample, an EAS observable could have different values for events induced by identical primaries but arriving from different zenith angles (due to EAS attenuation through the atmosphere). This is also the case for the S(500). One has to correct for this effect before performing an analysis simultaneously on all EAS events. This is achieved by applying the Constant Intensity Cut (CIC) method (Fig. 3) (Nagano et al., 1984). All reconstructed S(500) values are corrected for attenuation by bringing them to the value they would have at a chosen reference angle. For the present study the reference angle is considered to be 21°, since the zenith angular distribution for the recorded EAS sample peaks at this value. The CIC correction is derived from recorded experimental data and is independent from simulated studies.

## 4 Conversion to energy

For the experimental EAS sample, the total time of acquisition was 1173 days for a $500 \times 600\,\mathrm{m}^2$ fiducial area. The same quality cuts were used for both simulated and experimental events. Only those events are accepted for which the zenith angle is below 30°, the reconstructed shower core is positioned inside the detector array and not too close to the border, and the event is triggered by more than 24 Grande stations. A good quality of the fit to the Linsley distribution is a further important criterion.

A calibration of the primary energy $E_0$ with S(500) was derived from simulations (see Fig. 4). For the systematic contribution to the total error, several sources of systematic uncertainties have been identified: the spectral index of the simulated shower sample (which is different from the true one) is acting as a source of systematic uncertainty (<1% contribution), the S(500)$-E_0$ calibration (<1% contribution), the CIC method (<1% contribution), the statistical fluctuations in the simulated shower sample (7%) and the choise of a certain reference angle at which to perform the S(500) attenuation correction (7% contribution).

The energy resolution has also been evaluated from simulations by calculating the difference between the true and the reconstructed primary energy (applying CIC to the simulated data) and was found to be 22% for $E_0 = 10^{17}$ eV (for all primaries) with a slight decrease with increasing energy.

## 5 The correction based on a response matrix

Fluctuations may lead to the mis-reconstruction of an event (by under- or over-estimation) and when representing the energy flux as a histogram that particular event may be stored in the wrong (neighboring) energy bin. Thus in every energy bin of our spectrum we will have the data correctly belonging to that bin, but also data that was migrating from neighboring bins. As the energy spectrum is very steep (spectral index $\gamma \approx -3$) we expect that for a given energy bin, the mis-reconstructed events falling into it will be coming predominantly from lower energy bins thus affecting the spectral index of the reconstructed spectrum.

It is possible to account for the effect of fluctuations by calculating (from simulations) how many events migrate. Therefore a correction procedure is derived and applied to the experimental data. This is done with the help of a response matrix. The spectrum presented in Fig. 6 includes the result of this correction.

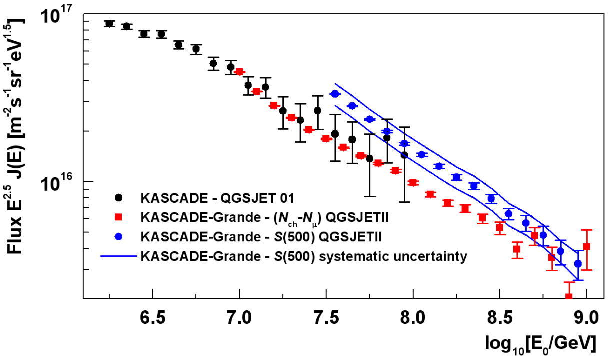


**Fig. 6.** Reconstructed experimental energy spectrum by KASCADE-Grande from S(500)/CIC, multiplied by $E^{2.5}$ together with the result of the standard reconstruction procedure (based on the $N_{ch} - N_{\mu}$ correlation) and the results of KASCADE towards lower energies; the continuous lines above and below the spectrum show the systematic uncertainties.

## 6 Results and conclusions

The primary energy spectrum has been reconstructed from the particle densities recorded in the stations of the KASCADE-Grande array at 500 m distance from the shower core, S(500). The CIC method was applied on the recorded S(500) spectrum in order to correct each shower for attenuation effects. Using a simulation-derived calibration between S(500) and $E_0$, the S(500) values are converted into primary energy. The S(500)-derived KASCADE-Grande spectrum is composition independent. An evaluation of the various uncertainty sources has been done and a correction based on a response matrix has been employed to account for the effects of the fluctuations on the spectral index of the reconstructed energy spectrum. The obtained all-particle primary energy spectrum (Fig. 6) shows a shift and a slightly different spectral index compared to an independent performed reconstruction approach based on the total number of charged particles and muon number (although such a shift is not visible when reconstructing simulated events with the two approaches - Fig. 5). Present and future investigations are directed towards understanding the origin of this difference. A possible cause could be the shape of the lateral density distribution for simulated events that appears to be different from the shape of the experimental one.

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