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Studies of the cosmic ray spectrum and large scale anisotropies with the KASCADE-Grande experiment

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Abstract. KASCADE-Grande is an air shower observatory devoted to the detection of cosmic rays in the $10^{16} - 10^{18} eV$ energy range. For each event the arrival direction, the total number of charged particles (N_{ch}) and the total number of muons (N_{μ}), at detection level (i.e. 110 m a.s.l.), are measured. The detection of these observables, with high accuracy, allows the study of the primary spectrum, chemical composition and large scale anisotropies, that are the relevant informations to investigate the astrophysics of cosmic rays in this energy range. These studies are of main importance to deeply investigate the change of slope of the primary spectrum detected at $\sim 4 \times 10^{15} eV$, also known as the knee, and to search for the transition from galactic to extra-galactic cosmic rays.

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The two-dimensional (N_{ch} vs N_{μ}) spectrum is the basis for the cosmic-ray chemical composition studies. EAS and detection fluctuations prevent the measurement of the primary mass on an event by event basis, nevertheless the precision obtained by the KASCADE-Grande experiment allows to separate events into mass groups. A search for anisotropies in the arrival directions of primary cosmic rays has been performed using the East-West analysis technique with the events detected by the Grande array. First harmonic modulation has been derived from the distributions (in sidereal, solar and anti-sidereal times) of the counts difference from the East and West sectors.

In this contribution we present and discuss the latest experimental results.

1. Introduction

To unveil the origin, nature, propagation and acceleration mechanism of galactic cosmic rays, high resolution measurements with high statistics of the energy spectrum, chemical composition and arrival directions are needed. Due to the low fluxes, at high energies ($E > 1PeV$), cosmic rays must be studied by means of extensive air showers (EAS) experiments and the characteristics of the primary particles are inferred indirectly.

The energy of the primary cosmic ray that originated the EAS can be obtained either from the total number of charged particles or from the muon number or from a combination of these two observables. In both cases the absolute energy scale depends on the hadronic interaction model used in the EAS development simulation.

The primary chemical composition studies are based on the detection of different EAS parameters[1]: the atmospheric depth of the shower maximum (available to fluorescence light detectors), the correlation between the muon and electron numbers at observation level (that can be detected in various ways, mainly by scintillation counters). The interpretation of these data requires full EAS simulations that are necessarily based on hadronic interaction models founded on the extrapolation of the accelerator measurements, performed at lower energies. Data of the LHC experiments will cover the energies of the knee, thus in the near future (tuning the hadronic interaction models with these data) we can expect great improvements of the situation. Nevertheless shower development fluctuations almost prevent an event by event detection of the nature of the primary particle.

The measured and expected amplitude of large scale anisotropies, for energies below $10^{16}eV$, are at the level of $10^{-4} \div 10^{-3}$. The significance of the measurements depends on the number of events in the data set, so long duration data taking are required. At the same time the counting rate variations induced by atmospheric effects (i.e. pressure and temperature) are bigger than those expected by cosmic rays anisotropies and so the arrays stability plays a crucial role in such analysis. To take into account the instabilities induced by atmospheric and instrumental effects the analysis performed by the KASCADE-Grande collaboration uses the East-West technique[2].

2. The Experiment

The KASCADE-Grande detector (located at 49.1° N, 8.4° E, $110ma.s.l.$) was the successor of the KASCADE experiment[3] and incorporated the original electromagnetic detectors and muon devices of KASCADE to a bigger system of detectors, called Grande, composed of a $700 \times 700m^2$ array with $37 \times 10m^2$ scintillator stations regularly spaced by an average distance of $137m$ [4]. A smaller array, named Piccolo, was also added and was used to coordinate the KASCADE and Grande triggers. The layout of the experiment is presented in figure 1.

The Grande array was used to sample the density of charged particles of the shower front at ground level and to measure the particle arrival times of the EAS. The core position, the number of charged particles (N_{ch}) and the arrival direction of the shower were extracted from the Grande data through an iterative fit and a careful modeling of the EAS front. To reconstruct

the arrival direction of the shower from the arrival times a fit was applied assuming a curved shower front as suggested by CORSIKA/QGSJET II simulations. On the other hand, to obtain the core position and the shower size from the density of charged particles of the EAS at ground a modified NKG lateral distribution function was fitted by means of a maximum-likelihood procedure[4].

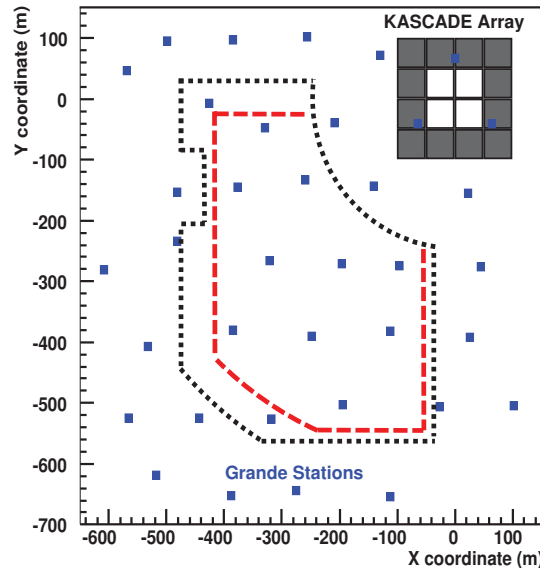


Figure 1. Layout of the KASCADE-Grande experiment. The KASCADE array and the distribution of the 37 stations of the Grande array are shown. The 192 muon detectors are placed in the outer 12 clusters of the KASCADE array (hatched area). The dashed line shows the fiducial area selected for the all-particle and heavy mass group spectra analysis. The dotted line indicates the area used for the measurement of the light mass group spectrum.

An important component of this experiment was the KASCADE muon array, composed by $192 \times 3.2m^2$ shielded scintillator detectors, which are sensitive to muons with threshold energy above $230MeV$ for vertical incidence. With the Grande information and the measurements of the shielded array of the lateral distribution of muons in the shower front, the muon size (N_μ) was reconstructed event-by-event at KASCADE-Grande. The procedure involved a maximum loglikelihood fit along with a Lagutin-Raikin distribution function[4].

Buried under several layers of soil, sand, iron and concrete, close to the center of the KASCADE array, was located the tunnel of the muon tracking detector (MTD), which was composed of streamer tubes grouped in modules[5]. This system was used to reconstruct the individual tracks of penetrating particles of a section of the EAS and to measure the muon pseudorapidities. By applying a triangulation procedure on the reconstructed tracks the muon production height of each event was also derived[6].

Systematic uncertainties for the core, N_{ch} and arrival direction of the EAS are studied directly[4] by comparing the results of the Grande and KASCADE reconstructions, which work independently. Comparisons were performed for a subset of data with cores located inside a common area for both detectors and shower sizes in the interval $\log_{10}N_{ch} = 5.8 \div 7.2$. Accuracies of the EAS core positions and arrival directions are found to be of the order of $\sim 5m$ and $\sim 0.7^\circ$, respectively. Meanwhile, for the total number of charged particles a resolution $\leq 15\%$ is achieved. Those values are in full agreement with expectations from Monte Carlo simulations.

The resolution on the N_μ EAS parameter is evaluated reconstructing simulated events, a

$\sim 20\%$ accuracy has been achieved. More details on the experimental setup and on the event reconstruction can be found in[4].

3. Results

3.1. All particle energy spectrum

The energy of the primary particle that originated the detected EAS is determined by the KASCADE-Grande experiment by means of the N_{ch} and N_{μ} observables[7], combining these two variables indeed we can lower the dependence from the chemical composition of the primary particles. This is obtained evaluating for each event the so called k parameter, that is essentially a measurement of the ratio between the muon and the charged particles numbers.

$$k = \frac{\log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_H}{\log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_H} \quad (1)$$

$$\log_{10}(N_{ch}/N_{\mu})_{H,Fe} = c_{H,Fe} \log_{10} N_{ch} + d_{H,Fe} \quad (2)$$

From its definition is clear that k is a number centered around zero (one) for proton (iron) generated events, if expressed as a function of N_{ch} for Monte Carlo events, assuming intermediate values for all other primaries. The values of the k parameters are tuned by a full EAS and detector simulation, the analysis reported in[7] is based on the QGSJetII-02[8] hadronic interaction model. Having calculated, for each event, the k parameter the primary energy is estimated from the N_{ch} value:

$$\log_{10}(E/GeV) = [a_H + (a_{Fe} - a_H) \cdot k] \log_{10}(N_{ch}) + b_H + (b_{Fe} - b_H) \cdot k$$

To take into account the shower evolution in atmosphere the parameters, $a_{H,Fe}, b_{H,Fe}, c_{H,Fe}, d_{H,Fe}$, contained in the k and E expressions are derived in five different angular intervals, whose upper limits are: $16.7^{\circ}, 24.0^{\circ}, 29.9^{\circ}, 35.1^{\circ}$ and 40.0° . The values of the parameters can be found in[7].

The all-particle energy spectrum is then measured in the five different angular bins. As shown in[7] these spectra are slightly shifted, indicating that the EAS evolution in atmosphere is not correctly described by the simulations. Nevertheless these differences are inside the experimental uncertainties and thus we mediate them to obtain the all particle energy spectrum measured in zenith angle range from 0° to 40° . The residuals of the all-particle energy spectrum multiplied by a factor, in such a way that the middle part of the spectrum becomes flat, are shown in figure 2.

The measured spectrum cannot be described by a single power law: a hardening around $10^{16}eV$ and a steepening at $\log_{10}(E/eV) = 16.92 \pm 0.10$ are observed. The statistical significance of the steepening is 2.1σ , here the change of the spectral slope is from $\gamma = -2.95 \pm 0.05$ to $\gamma = -3.24 \pm 0.08$. The same spectral features are meanwhile confirmed by the Tunka-133[9] and Ice-Top[10] experiments.

This procedure relies on the EAS simulation and thus depends on the high-energy hadronic interaction model used. To evaluate the systematic effects introduced in the all-particle spectrum measurement[11] the same procedure has been repeated using events simulated with the SIBYLL2.1[12], EPOS1.99[13] and QGSJetII-04[14] hadronic interaction models.

Applying the energy calibration functions, obtained by each model, to the measured data the all-particle energy spectra for the five zenith angle bins are obtained for the four previously mentioned models. Different sources of uncertainty affect the all-particle energy spectrum: the total systematic uncertainty is $\sim 20\%$ at the threshold ($E = 10^{16}eV$) and $\sim 30\%$ at the highest energies ($E = 10^{18}eV$) almost independently from the interaction model used to interpret the data. The final all-particle spectrum of KASCADE-Grande is obtained (see figure 3) by combining the spectra for the individual angular ranges. In general the shape of the energy

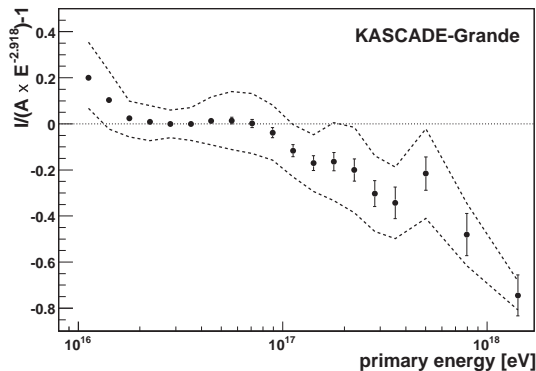


Figure 2. The all-particle energy spectrum obtained with KASCADE-Grande. The residual intensity after multiplying the spectrum with a factor of $E^{2.918}$ is displayed as well as the band of systematic uncertainty.

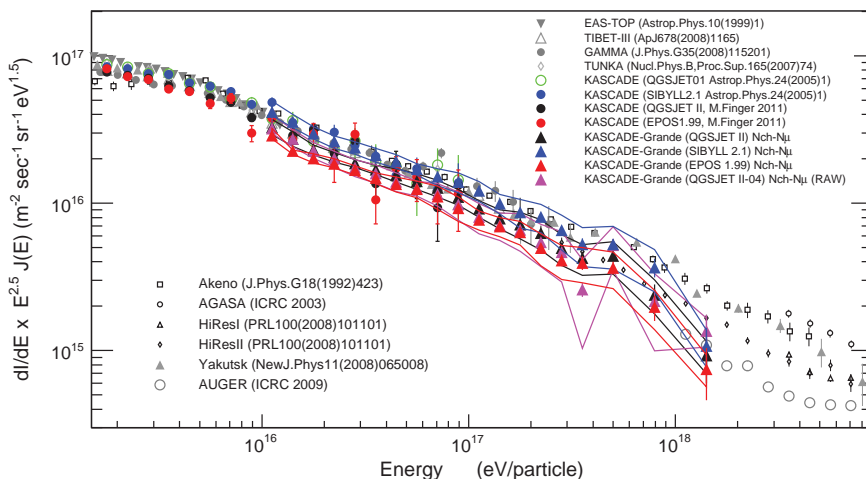


Figure 3. Comparison of the all-particle energy spectrum obtained with KASCADE-Grande data based on SIBYLL2.1 (blue), QGSJetII-02 (black), QGSJetII-04 (pink) and EPOS1.99 (red) models to results of other experiments. The band denotes the systematic uncertainties in the flux estimation

spectrum is very similar for all models, however, a shift in flux is clearly observed which amounts to $\sim 25\%$ increase in case of SIBYLL2.1 and $\sim 10\%$ decrease in case of EPOS1.99. The features seen in the spectrum are not an artifact of the hadronic interaction model used to interpret the data but they are in the measured data. In the overlapping region, KASCADE-Grande data are compatible inside the systematic uncertainties with KASCADE data interpreted with the same model.

3.2. Energy spectra of individual mass groups

The k parameter previously defined can also be used to separate the events in samples generated by two different primary mass groups. To emphasize the features of the heavy elements we selected the electron-poor events with $k_{ep}(E) \geq (k_C(E) + k_{Si}(E))/2$, i.e. events with a k value

greater than the mean value of the expectations for C and Si primaries (QGSJetII-02[8] based simulation). The spectra of these event samples are shown in figure 4, the band indicates changes of the spectra when the cut is varied by one standard deviation in the $k_{ep}(E)$ definition.

The reconstructed spectrum of the electron-poor events shows a distinct knee like feature at about $8 \times 10^{16} eV$ [16]. Applying a fit of two power laws to the spectrum interconnected by a smooth knee[15] results in a statistical significance of 3.5σ that the entire spectrum cannot be described with a single power-law. The change of the spectral index is $\Delta\gamma = -0.48 \pm 0.05$ from $\gamma = -2.76 \pm 0.02$ to $\gamma = -3.24 \pm 0.05$ with the break position at $\log_{10}(E/eV) = 16.92 \pm 0.04$. The spectrum of the electron-rich events (corresponding, with this cut definition, to light and medium mass primaries) is compatible with a single power law with slope index $\gamma = -3.18 \pm 0.01$. A recovery to a harder spectrum at energies greater than $10^{17} eV$ cannot be excluded by this analysis.

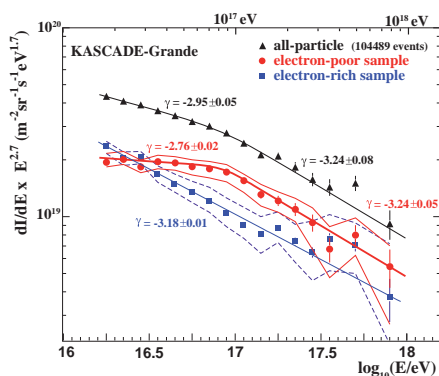


Figure 4. Reconstructed energy spectrum of the electron-poor and electron-rich components together with the all-particle spectrum for the angular range $0^\circ - 40^\circ$. The error bars show the statistical uncertainties; the bands assign systematic uncertainties due to selection of the subsamples.

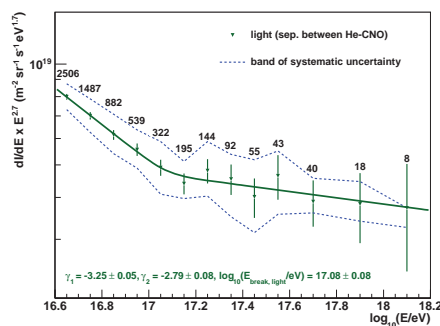


Figure 5. The reconstructed energy spectrum of the light mass component of cosmic rays. The number of events per energy bin is indicated as well as the range of systematic uncertainty. The error bars show the statistical uncertainties.

To increase the statistics and deeply investigate this possible hardening of the light primaries spectrum a larger fiducial area has been defined, essentially accepting events at larger distances from the muon detector (i.e. from the KASCADE array, see figure 1). The main effect of this event selection is that the 100% efficiency is reached at higher energies, that is not a problem for this analysis aimed to study a possible spectral feature at energies greater than $10^{17} eV$. In order to emphasize features of the light mass group we redefine the cut on the k parameter as $k_{er}(E) \leq (k_C(He) + k_C(E))/2$ (again a simulation based on the QGSJetII-02 hadronic interaction model is used). The obtained spectrum is shown in figure 5; a hardening, or ankle-like feature, is clearly observed[17]. Fitting this spectrum with the same function used for the all-particle and heavy mass groups primary spectra we obtain a change of the spectral index from $\gamma = -3.25 \pm 0.05$ to $\gamma = -2.79 \pm 0.08$ at an energy of $\log_{10}(E/eV) = 17.08 \pm 0.08$. The measured number of events above the bending is $N_{meas} = 595$. Without the bending we would expect $N_{exp} = 467$ events above this ankle-like feature. The Poisson probability to measure at least N_{meas} events above the bending, if N_{exp} are expected, is $P \sim 7.23 \times 10^{-9}$, corresponding to a 5.8σ significance.

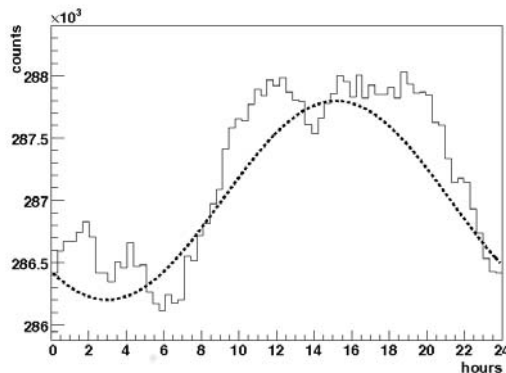


Figure 6. Sidereal time distribution of the number of counts ($\theta < 40^\circ$ and $\text{Log}N_{ch} > 5.2$) in 20 minute intervals obtained applying the East-West method. The dashed line shows the calculated first harmonic.

Comparing the two previous observations it is important to notice that the knee in the heavy component occurs at a lower energy compared to the bending in the spectrum of the light primaries. Therefore the steepening of the heavy spectrum and the recovery of the light component are not due to a bias in the reconstruction or separation procedures. It is worth pointing out that the slope of the heavy mass spectrum above the knee-like feature is very similar to the slope of the light mass spectrum before the ankle-like feature. The slope index of the light mass group spectrum above the ankle-like feature is $\gamma \sim -2.7$ and this can be interpreted as an indication of an injection of a new (extragalactic) population of high energy cosmic-rays[17].

3.3. Large Scale Anisotropies

The search for large scale anisotropies has been performed through a differential method, the so called East-West[2] method, based on the counting rate differences between East-ward and West-ward directions. This method allows to remove counting rate variations caused by atmospheric and instrumental effects. The used data set contains 10^7 events recorded between December 2003 and October 2011. To ensure reconstruction quality, a cut on the zenith angle θ and on the number of charged particles at observation level (N_{ch}) was applied: $\theta < 40^\circ$ and $\text{Log}(N_{ch}) > 5.2$.

Figure 6 shows the modulation in sidereal¹⁷ time obtained using the East-West method. The amplitude of the first harmonic calculated in sidereal time is $(0.28 \pm 0.08) \times 10^{-2}$ with a 0.2% Rayleigh probability of being due to background fluctuation (i.e. $\sigma = 3.5$) at median energy $3.3 \times 10^{15} \text{eV}$. The 99% C.L. upper limit on the amplitude is 0.47×10^{-2} , derived according to the distribution drawn from a population characterized by an anisotropy of unknown amplitude and phase as derived by Linsley[18].

To investigate a variation of the amplitude and phase of the first harmonic with primary energy we have performed the same analysis in intervals of the number of charged particles. The results are shown in table 1, in none of the bins the amplitude of the harmonic is statistically significant and so we have calculated the upper limits at 99% confidence level. The N_{ch} limits of the intervals used for the harmonic analysis are converted to primary energy and the median energy of the events in each bin is defined as representative energy.

¹⁷ sidereal time: Common time scale among astronomers which is based on the Earth's rotation measured relative to the fixed stars.

$\log_{10}(N_{ch})$	E (PeV)	$A_{sid} \times 10^{-2}$	Phase	U.L. $\times 10^{-2}\%$
5.2-5.6	2.7×10^{15}	0.26 ± 0.1	225 ± 22	0.49
5.6-6.4	6.1×10^{15}	0.29 ± 0.16	227 ± 30	0.64
≥ 6.4	3.3×10^{16}	1.2 ± 0.9	254 ± 42	3.1

Table 1. Results of harmonic analysis through the East-West method for three intervals of N_{ch} .

4. Conclusions

The KASCADE-Grande experiment took data from January 2004 to end 2012, detecting EAS generated by primary cosmic rays in the $10^{16} - 10^{18}eV$ energy range. In this contribution we have shown the main results obtained so far by the experiment:

- (i) a measurement of the all-particle energy spectrum, showing that it cannot be described by a single slope power law. A hardening slightly above $10^{16}eV$ and a steepening at $\log_{10}(E/eV) = 16.92 \pm 0.10$ are detected.
- (ii) The measurement of the light and heavy primary mass group energy spectra. These spectra were obtained dividing the events in two samples on the basis of the ratio between the muon and the charged particles numbers. A steepening at $\log_{10}(E/eV) = 16.92 \pm 0.04$ in the spectrum of the electron poor event sample (heavy primaries) and a hardening at $\log_{10}(E/eV) = 17.08 \pm 0.08$ in the one of the electron rich (light primaries) one were observed. The slope of the heavy mass group spectrum above the knee-like feature is similar to the one of the light mass spectrum before the the ankle-like feature.
- (iii) Upper limits on the amplitude of large scale anisotropies in three N_{ch} bins.

Acknowledgments

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