THE EXTENSIVE AIR SHOWER EXPERIMENT KASCADE - FIRST RESULTS

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ABSTRACT

The extensive air shower (EAS) experiment KASCADE has started its operation at the laboratory site of the Forschungszentrum Karlsruhe, at 49° N, 8° E, 110 m above sea level.
It consists of an extended ($200 \times 200 m^2$) array of electron detectors and muon detectors as well as of a compact and complex central detector system. The latter contains a dense scintillator matrix, muon tracking detectors, a scintillator trigger layer, and as its main part a large ($16 \times 20 m^2$) hadron calorimeter. The principal aims of the KASCADE project are the determination of the energy spectrum and of the chemical composition in the ultra high energy (UHE) range around the *knee* in the primary cosmic ray spectrum.
The main advantage of the new installation lies in the simultaneous measurement of a large number of observables for each individual event. This is achieved by the combination of various detection techniques for electrons, muons, and hadrons in extensive air showers and is supplemented by detailed simulation work on air shower properties and detector response. In multiparameter analyses the effects of intrinsic fluctuations of shower parameters can be considerably reduced.
Both the event reconstruction and especially the interpretation of the results depend on model predictions. Air shower event simulations (e.g. with the CORSIKA code) in the UHE range have to rely on extrapolations of the hadronic interactions to higher energies and into the forward angle region not covered in collider experiments. Different interaction models give quite different observables at ground level. Therefore, it seems very important to test the results of these calculations experimentally. Especially the central detector system of KASCADE enables a variety of such model tests.
Data taking with a large part of the experiment has started in 1996. First (preliminary) results on air shower properties like lateral particle distributions, on details of the hadronic shower core, on electron and muon size spectra, and on the energy dependence of the primary composition have been deduced from a subset of data.

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INTRODUCTION

Since several decades one central topic of UHE cosmic ray studies has been the investigation of the *knee* in the primary spectrum. This distinct change in spectral index of the charged particle flux at observation level is generally believed to reflect a change in the energy spectrum of the primary cosmic rays around $(3-5)\times10^{15}$ eV. A variety of models for the sources, the acceleration schemes, and the transport of cosmic rays have been proposed to produce such a structure but are still under debate (Erlykin and Wolfendale 1997, and references therein).
The detailed knowledge of the chemical composition around the *knee* would be very important for understanding these problems. However, all methods for the conversion of particle densities (measured at ground level) to primary energy must rely on the validity of the high energy interaction models used in extensive air shower simulations. These models are based on accelerator data and contain extrapolations in energy and rapidity which follow our present theoretical understanding of hadronic interactions. A systematic study has been started to investigate the influence of different interaction models on observables predicted by air shower simulation codes (Knapp et al. 1997, Heck et al. 1997, and references therein). It seems mandatory, however, to search for methods to test the model predictions experimentally.
In the energy range above 10^{14} eV direct measurements on top of the atmosphere are sparse and the data lack statistical accuracy due to the steeply decreasing flux and to limited detector area and exposure time. At ground level, the EAS particles are sampled with a typical detector coverage far below 1%. The intrinsic fluctuations of the particles in the showers can be very large. Therefore, it is very difficult, in general, to obtain reliable information about the primary particles from ground based experiments.
The basic concept of KASCADE is to measure a large number of observables for each individual event with good accuracy and high sampling. We have achieved a detector coverage of more than 1% for electrons and about 2% for muons in the EAS, combined with a precise measurement of hadrons in the shower cores using a large iron sampling calorimeter.

EXPERIMENT

KASCADE (KArlsruhe Shower Core and Array DEtector) is located on the laboratory site of the Forschungszentrum Karlsruhe, Germany (at 8° E, 49° N, 110m above sea level). The experiment consists of several, nearly independent parts. Its layout is shown in Figure 1. The experimental arrangement has already been described in some detail (Klages et al. 1997) and only a brief review is given here.

The Detector Array

Detectors for the measurement of the electrons and the muons outside the core region of EAS are housed in 252 detector stations forming a detector array of $200\times200m^2$. A station contains liquid scintillation detectors for the electron/photon component on top of a thick (20 r.l.) lead/iron absorber plate. Below the shielding muons are detected by $3.2m^2$ plastic scintillation detectors. The supply and the electronic readout of the detectors in the stations is organized in 16 clusters. Each cluster acts as a small independent air shower array.

The Central Detector System

The main part of the central detector system (Figure 2) is the large segmented hadron calorimeter. It consists of an $20\times16m^2$ iron stack (4,000 tons) with 8 horizontal gaps. 10,000 ionization chambers filled with the room temperature liquids tetramethylsilane (TMS) or tetramethylpentane (TMP) are used as active detectors in the gaps to measure energy, impact point, and direction of individual hadrons in 40,000 electronic channels. In the third gap from the top a layer of 456 scintillation detectors with a size of $0.45m^2$ is used for triggering the central detector, but also for muon detection. In addition, arrival times of individual hadrons and muons in the air showers are measured.

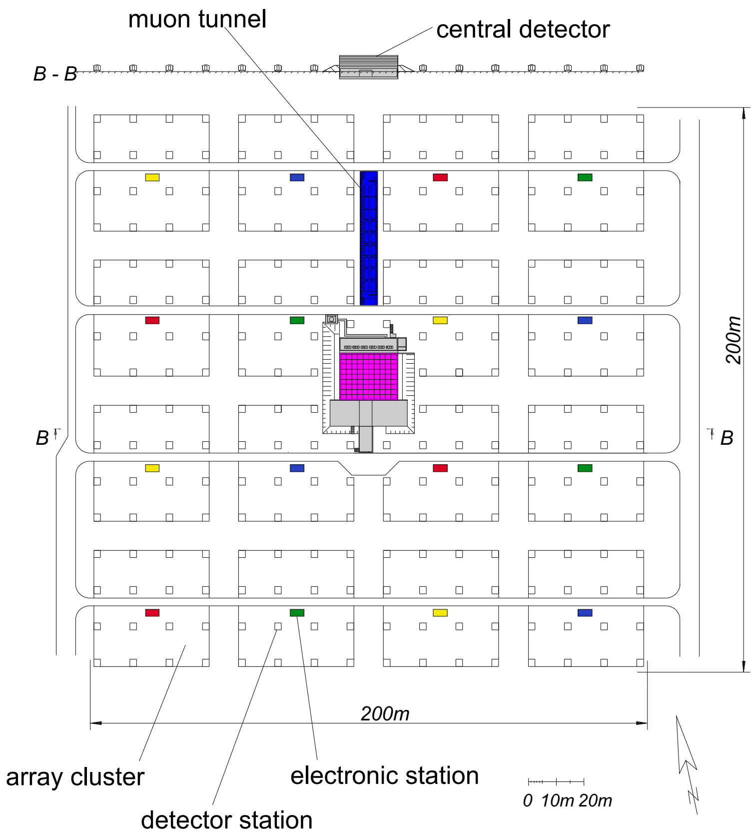

Fig. 1: Schematic layout of KASCADE.

Below the iron stack two layers of multiwire proportional chambers (MWPCs) are used for the measurement of muon tracks. They cover a total area of $122m^2$. These detectors allow detailed studies of structures in the muon lateral distributions in EAS cores.
50 scintillation detectors of the same type as in the trigger layer are placed on top of the calorimeter. They are used for triggering and for the measurement of small central showers. These "low energy" events allow to test the predictions of the shower simulations and to compare the experimental results with data from direct measurements.

The Muon Tunnel

North of the central detector a 50m long and 5.5m wide tunnel has been added to the experiment. Here $600m^2$ of streamertubes will be used in three layers for the tracking of muons. These detectors will enable the determination of the mean muon production height by triangulation, especially for showers with energies above 10^{16} eV.

Data Correlation

The 16 clusters of the array, the streamertube muon detector, and the 4 parts of the central detector system are 21 independent experiments, which can be started, run, read out, and stopped (in principle) independently. To correlate the data from all parts of KASCADE synchronized signals are distributed from a central clock system. By use of these "time labels" online event building is performed on a central work station.

OBSERVABLES

The main strength of KASCADE lies in the large number of experimental quantities which can be measured simultaneously for each event. This enables multidimensional analyses for the reconstruction of the energy and the mass of the primary.

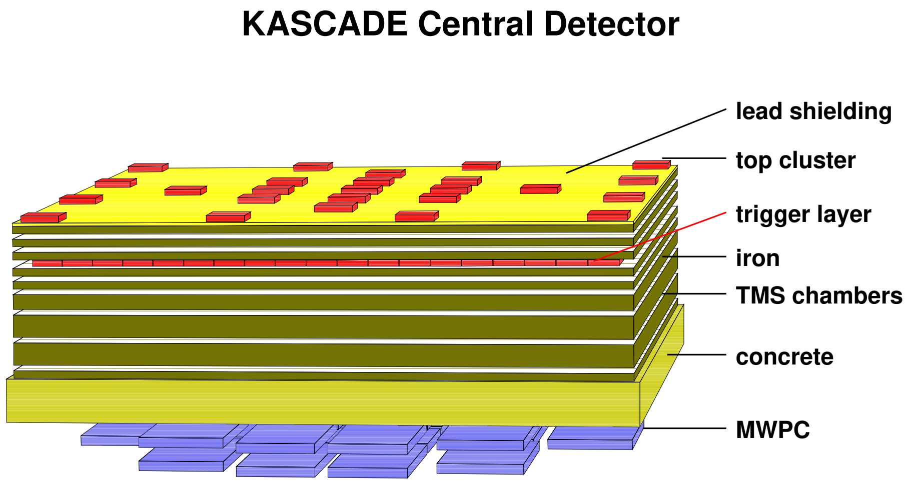

Fig. 2: The central detector system.

The most straightforward measurements are the absolute time of the event, the core position, and the zenith and azimuth angles. The number of electrons in the shower is determined together with the shape of the electron lateral distribution. The density of muons is measured both in the shower core and in the outside regions. The number of hadrons in the shower core, the individual hadron energy, and the lateral distribution of the energetic hadrons are important observables measured by the calorimeter. Arrival times of hadrons, muons, and electrons are studied by the trigger layer of the central detector and by the array detectors. The pattern of muons in the shower cores are investigated in detail by the multiwire proportional chambers. For higher energy events the determination of the mean muon production height (reflecting the longitudinal shower development) and of the slope of the muon lateral distribution is possible. With the detector array details of the electron distributions like (delayed) subshowers, asymmetric events, multiple cores or very narrow events can be studied.

Reconstruction Accuracy

To estimate the accuracy of the reconstructed shower parameters, a large effort has been put into the understanding of the detector response to air showers. Numbers are given below which have been determined by extensive simulations of air shower events followed through the KASCADE detectors and through the reconstruction codes. The quoted (relative) errors are valid for shower sizes $N_e \geq 10^5$, which corresponds to about 10^{15} eV at observation level. For these events the hadron number is measured to 8% and the muon number in the core to 12% if the core falls inside the central detector. The shower disk is measured by the detector array with an error of 7% in the number of electrons and 16% for the muon number. The core position is known to about 2.5 m and the shower direction with an accuracy of 0.3°. With the additional constraints from the other parameters mentioned above the determination of the mass and of the energy of the primary cosmic ray particles will be possible in a less ambiguous way than in previous experiments.

STATUS AND FIRST MEASUREMENTS

The detector array is fully operational. In the central detector system the top cluster, the trigger layer and the MWPCs are installed and working. The hadron calorimeter is nearly fully equipped with ionization chambers and in operation. Installation of the streamertube detectors in the muon tunnel has started.

Data taking with a large part of the experiment is performed routinely since 1996. The hardware has been running smoothly during many months. More than 5×10^7 extensive air shower events have been registered until July 1997 and are presently being analyzed. In the analyses, detector performance and consistency of the reconstruction procedures are thoroughly tested. Details can be found in a number of KASCADE contributions to this conference (KASCADE Collaboration 1997).

Trigger Conditions and Data Taking

At the present stage of the experiment, data taking is initiated by various different trigger sources. In each cluster of the detector array a trigger is generated and distributed, if half of the electron detectors in the cluster have fired within 300 nsec. In the central detector system, a multiplicity of **n** of the 50 scintillation detectors on top of the calorimeter is used to trigger the whole experiment on low energy ($\geq 10^{13}eV$) central showers. Two different trigger modes are provided simultaneously by the scintillator trigger layer : a muon density trigger based on a multiplicity of **m** out of 456 detectors and a (single) hadron trigger based on an energy deposit of more than 300 MeV in one detector. Both triggers are used for all parts of KASCADE. The total trigger rate of the experiment amounts to about 2 events per second.

DATA ANALYSES AND FIRST RESULTS

In the analysis procedures for the KASCADE data the reconstruction of the shower parameters is started independently for the various detector parts of the experiment. These individual results are stored on data summary tapes (DSTs) and are combined in multiparameter analyses afterwards. At the present stage only preliminary results for some observables can be presented. Most of these use the muon number in the radius range from 40m to 200m, derived from the array muon detectors, as common estimator for the energy of the primary particle. This estimator, according to shower simulations with the CORSIKA code, depends only slightly on the mass of the primary and on the high energy interaction models used - with the exception of SIBYLL which will be discussed in more detail later.

Size Spectra

The conversion of the energy deposits in the electron and muon detectors of the KASCADE array to electron and muon numbers are done by lateral energy correction functions (LECFs) to account for the effects of shower electrons, photons, hadrons, and muons in both types of detectors.

These functions have been derived from Monte Carlo simulations of the detector response to a large number of shower events simulated by CORSIKA. The resulting particle lateral distributions are fitted to a NKG function (r=79m) for electrons and to a *Greisen* function (r=320m, slope parameter taken from simulations) for muons. Only shower events with a reconstructed core position clearly inside the fiducial area of the experiment ($r \leq 91m$) are used in the first analysis of the size spectra. These spectra are accumulated for different angular bins in such a way that the atmospheric thickness increases by a nearly constant amount for each bin. The differential flux as a function of the electron size of the

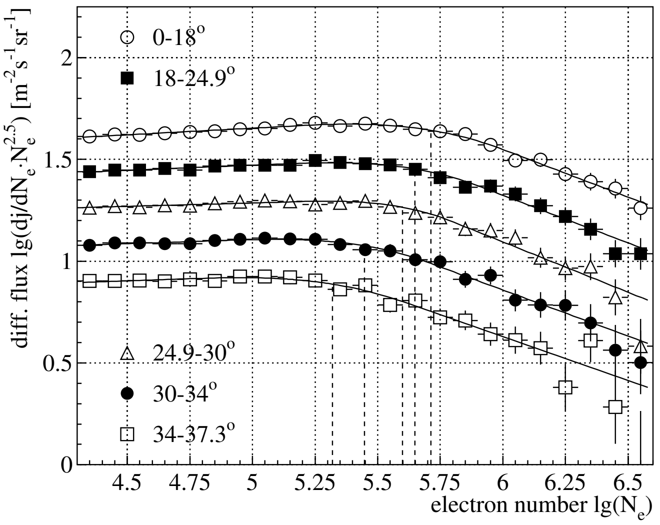

Fig. 3: N_e spectra for various zenith angle bins.

showers is shown in figure 3 multiplied by a factor $N_e^{2.5}$ to emphasize the change in slope in the *knee* region. It is evident from the figure that there remain structures in all spectra which we would attribute to statistical fluctuations.

These structures hamper the determination of the spectral indices above the *knee*, which depend strongly on the upper end of the fit region. We need better statistics in the high energy part of the spectra to clarify the situation. The fitted position of the *knee* is plotted in figure 4 as a function of zenith angle. As expected for a fixed energy phenomenon the corresponding shower size becomes smaller with increasing depth, although the decrease seems slower than predicted by simulations of shower development curves.

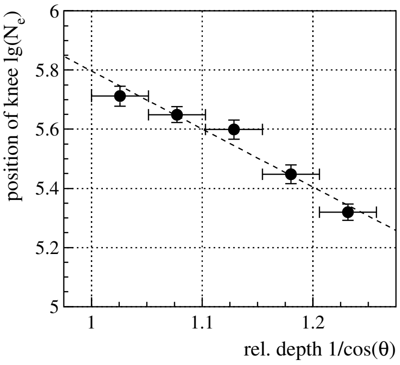

Fig. 4: Position of the knee N_e^k vs. relative atmospheric depth.

The muon size spectra show a less pronounced change in slope than the electron spectra. Also in these distributions the fluctuations at the high energy part of the spectra prohibit an unambiguous determination of the spectral indices above the *knee*. The position of the bend in the muon spectra is in good agreement with the electron results according to CORSIKA simulations using VENUS and assuming a rather light composition at the *knee*.

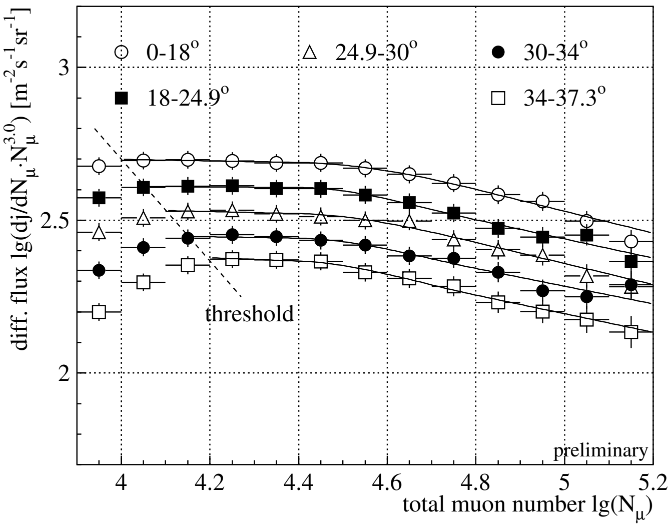

Fig. 5: N_μ spectra for various zenith angle bins.

A combined analysis of the preliminary electron and muon size spectra gives an estimate of the primary energy where the bend occurs: $(3 \pm 1) \times 10^{15} eV$. Furthermore, a first attempt has been made to investigate the hadron size spectrum for all EAS events with the shower core inside the hadron calorimeter. Naturally, due to the limited size of the detector, this analysis of the hadron number in the shower cores still lacks statistical accuracy at higher energies. However, a slight bend in the N_h spectrum is observed at about the position where the *knee* would be expected.

Lateral Distributions

KASCADE enables the determination of details of the lateral distribution for electrons, muons, and hadrons - for large EAS on an event-by-event basis, for smaller showers at least for samples of events with similar properties. Simulations predict for all shower components steeper distributions for light primaries and at higher energies. Examples of data are shown in figure 6 for the distribution of electrons and in figure 7 for the distribution of muons ($\geq 0.3 GeV$) containing about 10.000 EAS within a narrow energy and zenith angle bin. It can be seen that the average electron distribution in EAS is well described by the *NKG* function in the radius range from 10m to about 100m whereas for larger distances the agreement is less good. The muon density data show very good agreement with the shape of a *Greisen* function in the range from 40m to 200m where the muon detectors of the array provide reliable results. The slope parameters fitted to these average lateral distributions are very close to the mean values of the individual slope parameters which were kept fix (from simulations) during the reconstruction. This shows that the predictions of CORSIKA (using VENUS or QGSJET as interaction model) of the muon lateral distributions are reliable. Similar distributions are measured by the MWPCs below the calorimeter with a muon threshold of 2 GeV.

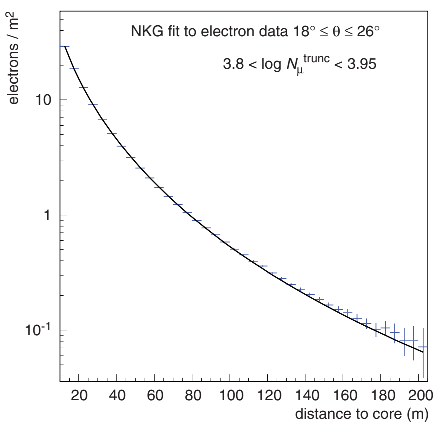

Fig. 6: Lateral distribution of electrons (10,000 events).

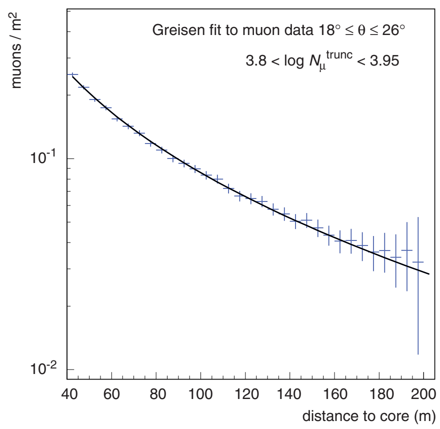

Fig. 7: Lateral distribution of muons (10,000 events).

The lateral distributions of hadrons are measured by the calorimeter up to a core distance of about 100m. In addition, for each individual hadron above the threshold of 50 GeV the energy is determined. In this way, lateral distributions can be analyzed for various shower parameters and hadron thresholds. First results show that these distributions become steeper with increasing hadron energy.

During the reconstruction of the individual hadrons the longitudinal development of the energy deposition is studied. No significant deviation from simulations using the FLUKA code is found up to 10 TeV hadron energy. In figure 8 the measured distribution of hadronic energy in the cores of EAS in a narrow range of shower (muon) size is compared to predictions of CORSIKA using the QGSJET interaction model for proton and iron induced showers.

It can be seen that the lateral distribution is well within the range predicted by the simulations using this model. The statistical errors of the hadron data are still rather large. Due to the fact that for each individual hadron its energy and impact point can be determined the hadrons enable a variety of tests of interaction models. In figure 9 the energy spectrum of the hadrons measured in the cores of EAS within a narrow muon size bin is compared to the predictions of CORSIKA (folded with the detector efficiency) using SIBYLL for proton and iron primaries. It shows, that the predictions of this model are in disagreement with the data. A more detailed investigation indicates that the SIBYLL code produces too few muons whereas the hadronic and electromagnetic parts of the EAS seem to be in better agreement with the corresponding data. This finding is very surprising and shows the strength of the KASCADE approach of multiparameter observations.

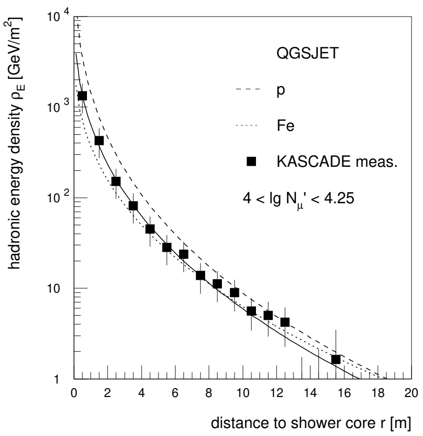

Fig. 8: Lateral distribution of the hadronic energy flux.

Model calculations indicate that spatial and energy distributions of energetic muons and hadrons in the shower cores are distinctly different for light and heavy primaries. In the simplified picture of superposition of many low energy showers in the case of a heavy primary this feature is very suggestive. In a "heavy" shower core the energy is distributed more evenly among the hadrons (see fig.10) and the spatial distribution of muons and hadrons is more uniform. These distributions can be studied in detail by the calorimeter and by the muon chambers below the central detector.

Investigations of the Primary Mass Composition

A number of different mathematical approaches are used to classify the patterns in the EAS cores. For the distribution of hadrons the method of the "minimum spanning tree" is applied, whereas for the hit pattern in the muon chambers

"multifractal moments" (A. Haungs et al. 1996) are being analysed.
With simulated data both methods show a sensitivity to primary mass. Figure 11 shows examples of "typical light" and "typical heavy" shower core hit patterns in the MWPCs below the calorimeter. This method of classification turns out to be a valuable additional parameter in the multiparameter event analyses using a neural network or other mathematical types of decision making. In the shower events shown in the figure, electron and muon size are quite similar, but the hadronic observables and the hit pattern in the MWPCs show substantial differences. This is again a demonstration of the discriminating power of multiparameter observations.
Simulations predict that at ground level the observable most sensitive to the primary mass in general is the muon/electron ratio. In many cases, this quantity is plotted for narrow zenith angle bins as a function of shower size N_e. This method of representation leads to an overestimation of the light components due to the steep energy spectrum and the larger electron size of showers induced by light primaries.

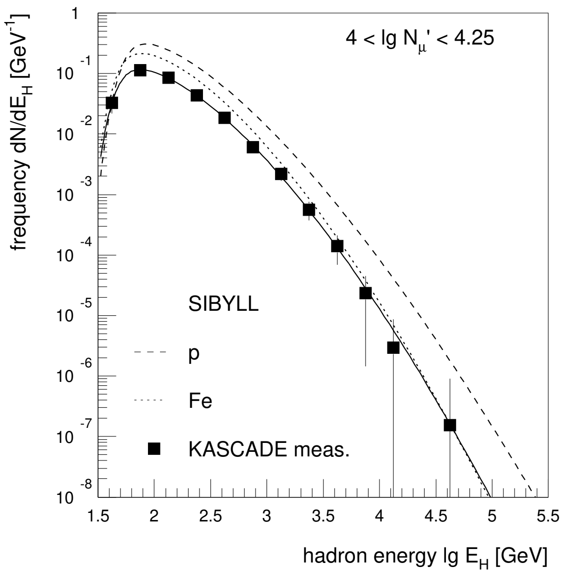

Fig. 9: Energy spectrum of hadrons in EAS cores, uncorrected for detector efficiency.

The muon size of showers at ground level is less dependent on the primary mass and zenith angle. Therefore, the muon size is a much better energy estimator, especially if the measured muon density is integrated in a limited radius range (40m to 200m), yielding the *truncated* muon size N_μ^{tr}. In figure 12 preliminary results for the ratio of the truncated muon size of the showers to the electron size are plotted and compared to simulated data from CORSIKA using the VENUS interaction model for proton and iron nuclei at 22° zenith angle. The results for the QGSJET model are quite similar.
The experimental data for this muon/electron ratio indicate a nearly constant mean mass of the primaries up to energies near the *knee* in the primary spectrum and a trend towards a heavier composition at the high energy end of the data. However, these results are clearly preliminary.

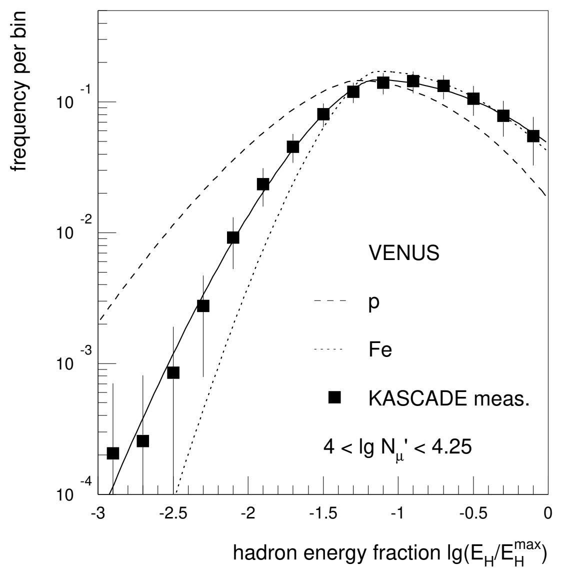

Fig. 10: Distribution of energy among the individual hadrons in EAS cores.

The errors shown are the statistical errors of the means of the distributions only and include no systematics in the present stage of the analyses. Better statistics and a very careful study of the overall (hardware and software) efficiencies are necessary before one can draw reliable conclusions from these measurements, especially if looking for mass distributions in narrow energy ranges as proposed by some models (Erlykin and Wolfendale 1997).
The data and the results shown so far have all dealt with one or two observables of the EAS only. The real strength of KASCADE however lies in the large number of observables which are determined for each individual event. At present, a variety of multiparameter data analyses

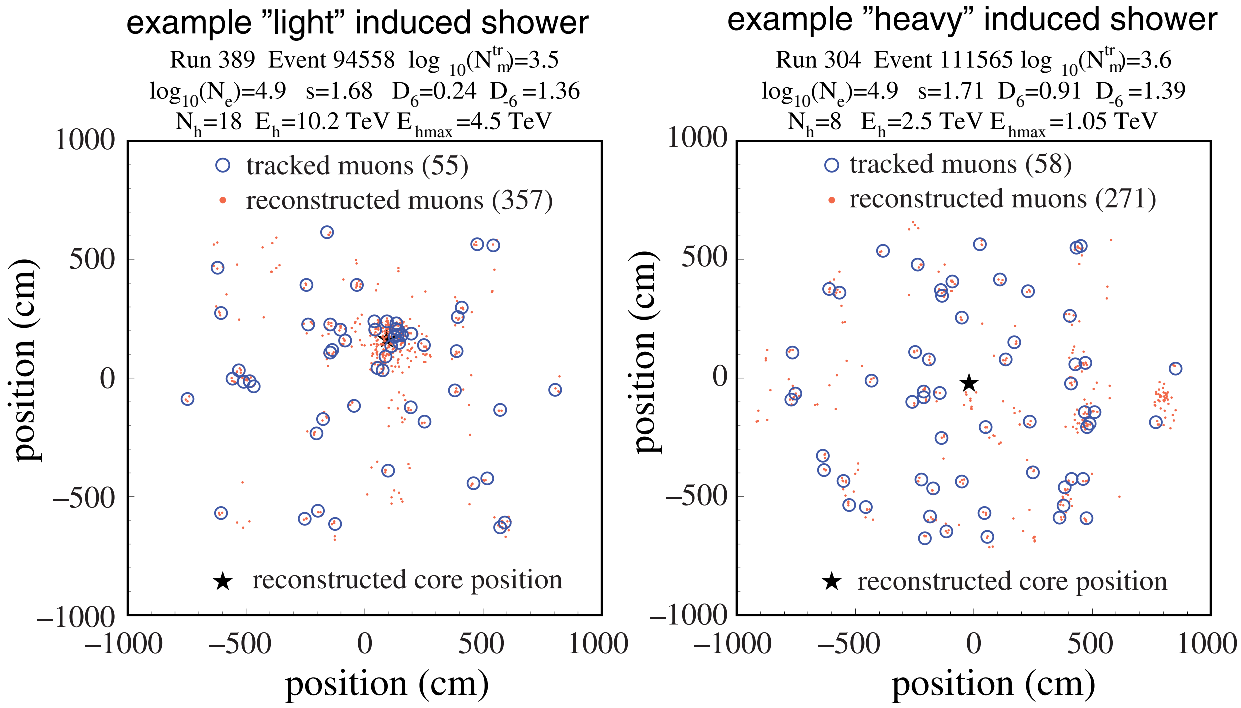

Fig. 11: Hit patterns in the cores of "typical light" and "typical heavy" EAS.

(Chilingarian et al. 1997) are in preparation. The methods used in these approaches must be trained and/or tested extensively by the use of simulated data. Therefore, the results are still dependent on the validity of the shower simulations. Stringent tests of the transport codes and of the interaction models used in the simulations are of prime importance.
In a first attempt to put more information together in a mass dependent analysis all measured hadronic observables have been used. They were analysed by comparison to simulated data from the CORSIKA code with VENUS or QGSJET including the full simulation of the detector response. A preliminary result is presented in figure 13. The reconstructed energy scale is taken from the truncated muon size of the EAS. These combined results indicate a trend to a slightly heavier composition at higher energies for both models used in this hadron analysis. The lowest

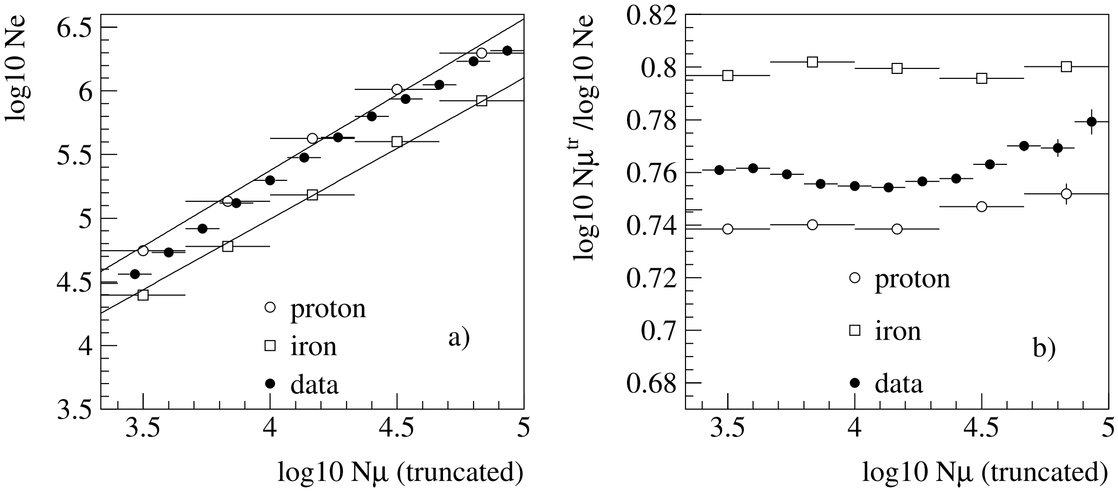

Fig. 12: Muon/electron ratio in EAS for zenith angles from 18° to 26° (preliminary).

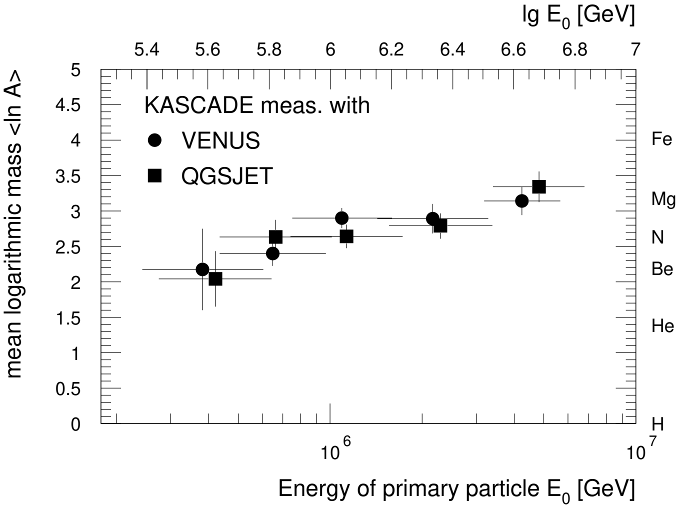

Fig. 13: Energy dependence of the mean primary mass from hadronic observables (preliminary). The (truncated) muon size of the EAS has been converted to an approximate energy scale.

energy bin may be affected by threshold and efficiency problems as can be seen from the large error bars. If this points are disregarded then at least the QGSJET results are in agreement with the electron/muon data. A different analysis has been performed using the muons measured by the MWPCs below the calorimeter, the hit pattern in the shower cores and the electron size of the EAS in a neural network trained by simulated data. The results show a quite similar behaviour as the calorimeter and the array data. A multivariate analysis is in preparation.

CONCLUSIONS AND OUTLOOK

KASCADE is now successfully in operation taking multiparameter data from EAS with an energy threshold of a few times $10^{14} eV$ at a rate of 2 events/sec. Data analyses have started and the preliminary results look very promising. Tests of interaction models are possible by the use of correlations in the data. In all components, changes in the slopes of the spectra have been observed but need further close investigation. First indications of the energy dependence of the mass composition can be deduced from the data. Better statistics and a thorough discussion of systematic errors are necessary and should be achieved in the near future.

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