ELSEVIER Nuclear Physics B (Proc. Suppl.) 75A (1999) 228–233

NUCLEAR PHYSICS B
PROCEEDINGS SUPPLEMENTS

Test of high–energy hadronic interaction models using the hadronic shower core measured with the KASCADE calorimeter*

J.R. Hörandel for the KASCADE–Collaboration†
Universität und Forschungszentrum Karlsruhe, P.O. Box 3640, D–76021 Karlsruhe, Germany

The fine segmented hadron calorimeter of the KASCADE experiment allows to study the hadronic component of extensive air showers. Several hadronic observables are compared with predictions of air shower simulations, using the interaction models VENUS, QGSJET and SIBYLL with the objective to test the hadronic interaction models. Results of the comparison are presented.

1. Introduction

To investigate cosmic rays in the PeV region and above, one is forced to use indirect measurements, observing extensive air showers (EAS) induced in the atmosphere. To interpret the secondary particles at ground level, the measured data are compared with results from Monte Carlo calculations, describing the development of the EAS in the atmosphere and the response of the individual detectors.

One of the principle goals of the investigations is to estimate the mass and the energy of the primary particle. Starting with a given energy and mass of the primary, the development of the EAS in the atmosphere was calculated using the program CORSIKA [1] with different hadronic interaction models. The response of the secondary particles in the detectors at ground level are simulated to obtain the energy deposit and arrival time of each particle in the individual detectors. To reconstruct observables from the detector signals, the same procedures are used for measured and simulated data and comparing simulations and measurements we estimate the primary's mass and energy.

The particle interactions within the detectors are well studied at accelerators. In contrast to the latter, our knowledge of the high–energy hadronic interactions in the atmosphere above a few TeV is very poor. The cosmic–ray energies are much higher than the corresponding CMS energies at colliders, and the forward kinematic range important for EAS physics cannot be investigated in detail. Hence, in the simulation chain the hadronic interaction models in air shower calculations are the weakest point. The question of validity of the interaction models is especially important concerning the origin of the *knee*. The latter could be related to astrophysical or particle physics reasons.

Mostly soft hadronic interactions are important for the EAS development. Due to the energy dependence and the absolute value of the parameter α_S of the strong interaction, the interactions cannot be evaluated by QCD calculations via perturbation theory. Instead, one is obliged to use phenomenological descriptions. In the program CORSIKA, different hadronic interaction models are at the users disposal. In the following, the results of VENUS, QGSJET and SIBYLL calculations are compared with measurements in order to test the models.

2. Experimental setup

The interaction models are tested by investigating individual hadrons in the core of EAS. The fine segmented hadron calorimeter of the KASCADE experiment allows to distinguish two hadrons and to determine their energies separately with an energy threshold of 50 GeV in a distance of at least 40 cm [2]. At this energy the reconstruction efficiency for hadrons amounts

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*and "Energy deposition of 10 TeV hadrons in the KASCADE calorimeter" presented by J. Engler

†For the full author list see J.H. Weber, "Estimation of the chemical composition in the knee region from the muon/electron ratio in EAS", these Proceedings.

PII S0920-5632(99)00251-0

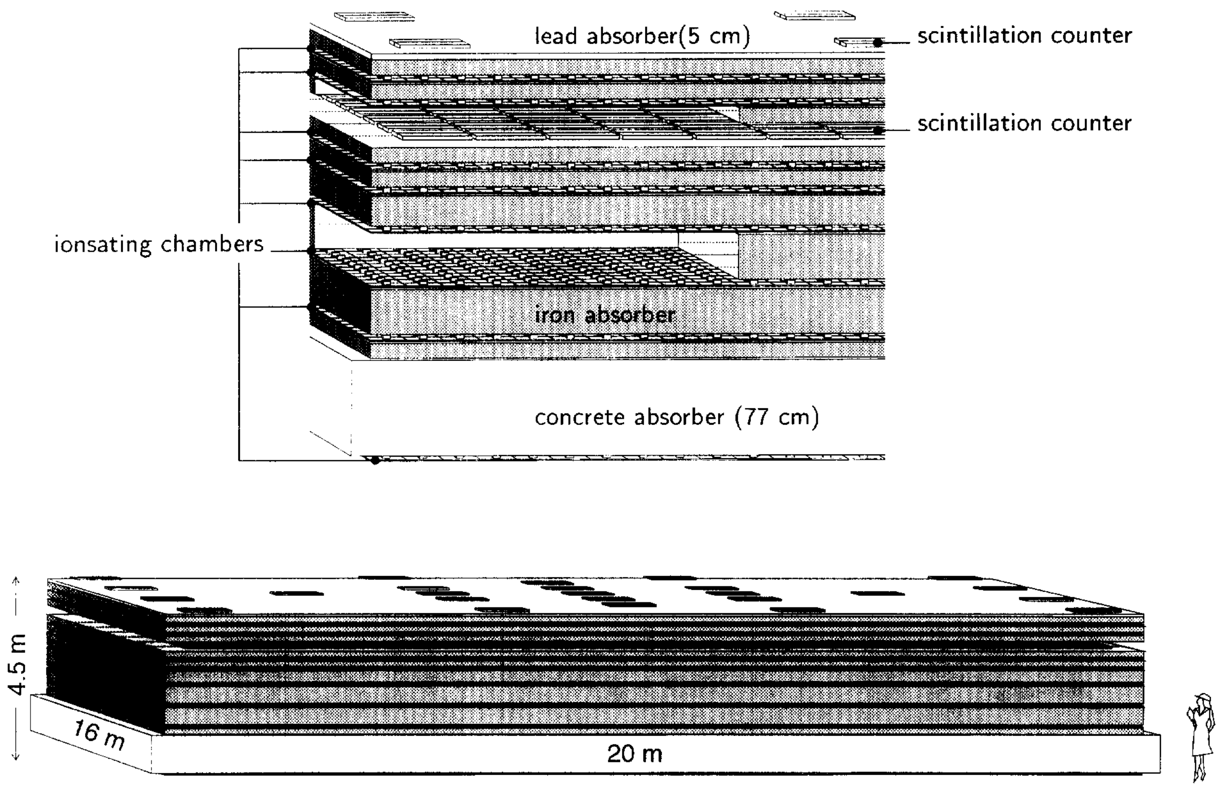

Figure 1. Schematic view of the KASCADE central calorimeter. Top: detailed sketch, bottom: total view.

to 50% growing to nearly 100% for an energy of 100 GeV. For showers in the PeV range, the number of not found hadrons typically amounts to 10% and is nearly constant with energy.

The calorimeter consists of iron slabs with increasing thickness from 12 cm up to 36 cm, as sketched in Figure 1. Between the absorber slabs, seven layers of liquid ionisation chambers are interspersed. Below the third iron layer, scintillation counters for fast–trigger purposes are located. A 5 cm lead absorber on top of the first iron layer serves to suppress electromagnetic punch–through. A last layer of ionisation chambers is situated below the concrete ceiling, which acts as a tail catcher. The total depth of the calorimeter for vertical protons amounts to 11.5 interaction lengths ensuring a reasonable shower containment up to 25 TeV. At this energy on average 97.5% of the energy are deposited in the calorimeter.

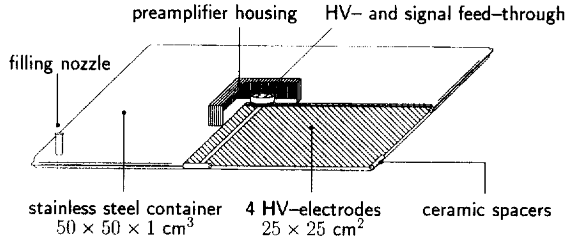

Figure 2. Sketch of a liquid ionisation chamber.

Each ionisation chamber consists of four independent electronic channels with a size of 25 × 25 cm^2 as shown in Figure 2. They are inserted in a stainless steel box and positioned by ceramic spacers. A ceramic feed–through allows to apply high voltage to the electrodes and to read out their signals independently ensuring the fine segmentation. The chambers are filled either with room temperature liquid tetramethylsilane (TMS) or tetramethylpentane (TMP). These liquids show electron conduction, which allows to detect excess electrons emitted in the ionisation process.

The electrons and muons are detected in an array of 252 stations of scintillation counters. The muon detectors are positioned directly below the electron scintillators and are shielded by slabs of lead and iron corresponding to 20 radiation lengths in total. A detailed description can be found in [3].

3. Energy calibration

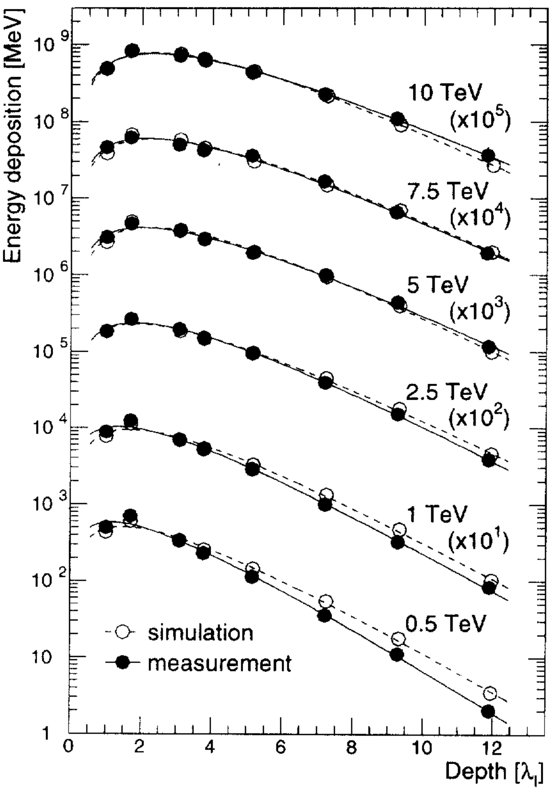

Figure 3. Experimental transition curves of single hadrons compared to simulated transition curves using the FLUKA code.

It is not possible to test the absolute amount of energy deposition due to the lack of calibration possibilities at accelerators. We, therefore, use a two step calibration procedure. Firstly, each ionisation chamber is calibrated with the signal of throughgoing muons. The second step is an indirect calibration using detailed detector simulations. We determine the longitudinal and lateral profiles of energy deposition and compare the measured distributions with simulation results, using the GEANT [4] package with the FLUKA [5] code.

As an example, the longitudinal development of single hadrons from 0.5 TeV up to 10 TeV in the calorimeter is shown in Figure 3. At the highest energies, the simulations reproduce the experimental data quite well. At lower energies the cascades seem to enter deeper into the absorber. However, this is probably an artifact caused by instrumental effects. At these energies the energy deposition in a chamber is low and still in the MeV region where the amplifier noise cannot be neglected. In the simulation it is taken into account as a mean value with a Gaussian distribution. This may not be realistic enough to simulate the data correctly. Consequently, the slight differences should not be taken as major discrepancies. At the lowest energies measurements of the transition curves with a prototype calorimeter have shown good agreement with FLUKA calculations [6].

4. Measurements and simulations

From October 1996 up to May 1998 about $7 \cdot 10^7$ events were collected. In $4 \cdot 10^6$ events we reconstructed at least one hadron. Events accepted for the present analysis had to fulfill the following requirements: At least three hadrons with a threshold energy of 50 GeV have been reconstructed. The zenith angle of the shower was less than 30°, and the shower core was located inside the calorimeter. After this cuts 28000 events remained for the further analysis.

EAS simulations were performed with the program CORSIKA, versions 5.2 and 5.62. We calculated 2000 proton and iron induced showers for SIBYLL and 7000 p and Fe events for QGSJET.

For VENUS 2000 showers were generated, each for p, He, O, Si and Fe primaries. The showers were distributed in the energy range 0.1 PeV up to 31.6 PeV according to a power law with an index of -2.7. All secondary particles at ground level are passed through a detector simulation program using the GEANT package to determine the signals in the individual detectors.

5. Results

The cosmic-ray mass composition is poorly known above 0.5 PeV. Therefore, the interaction models can be tested only by comparing their predictions for the extreme primary masses, namely protons and iron nuclei. If the measured observables lie in between these predictions, the corresponding model is compatible with the data, otherwise we have to exclude it.

When comparing measurements and simulations, it is necessary to divide the data into intervals of fixed shower size. For our investigations we use shower size parameters of all three components, i.e., the number of electrons and muons as well as the hadronic energy sum. For the muonic shower size we use a muon number obtained by integration of the muon lateral distribution in the range from 40 to 200 m. Simulations show that this value N'_μ is a reasonably mass independent energy estimator. We investigated several hadronic observables [7], some of them are discussed in the following.

Firstly, the relation between the electromagnetic and hadronic component is presented in Figure 4. Plotted is the number of hadrons with an energy threshold of 50 GeV versus the number of electrons N_e as measured by the scintillator array. The measured data are compared with results for proton and iron induced showers calculated with the models VENUS and QGSJET. The energy range corresponds to approximately 0.2 PeV up to 20 PeV. Within this range QGSJET is compatible with our measurements. VENUS generates a steeper increase than the measurements indicate, and especially for higher energies the data are significant below the predictions. Similar discrepancies for VENUS show up in other observables, when electrons and hadrons are compared with each other.

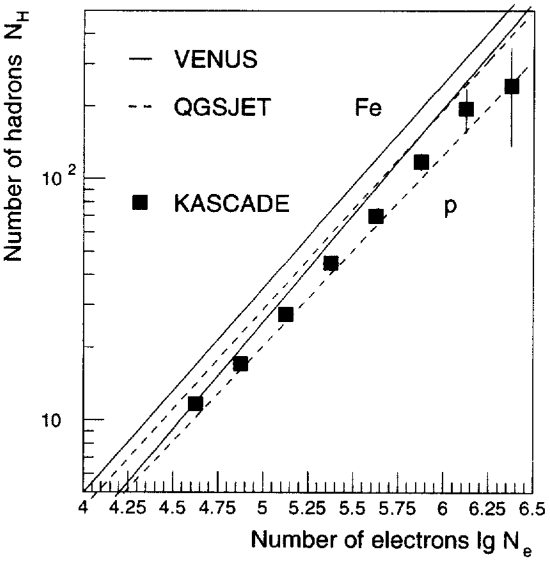

Figure 4. Number of hadrons ($E_H > 50$ GeV) versus number of electrons.

A second example is presented in Figure 5. The graph shows frequency distributions of the energy of each hadron normalized to the energy of the most energetic hadron in the shower. The measurements are compared with predictions for primary protons and iron nuclei, calculated with the models QGSJET and SIBYLL for two muon size intervals corresponding to approximately 3 PeV and 10 PeV. The upper two graphs show the low energy bin below the *knee*. The measured data are in between the range given by the QGSJET model in contrast to the SIBYLL predictions, which are not able to describe the measurements. Like in this example, SIBYLL cannot reproduce the measurements in other observables, especially when grouping the data into muon shower size bins. This might be due to a wrong muon number as generated by SIBYLL [8].

In the energy range above 10 PeV, as shown in the third graph, the data are outside the acceptable range also for the QGSJET simulation. It seems as if QGSJET produces correct distributions of the hadronic energy fraction below the *knee*, but there are discrepancies describing the data above. On the other hand, there exist ob-

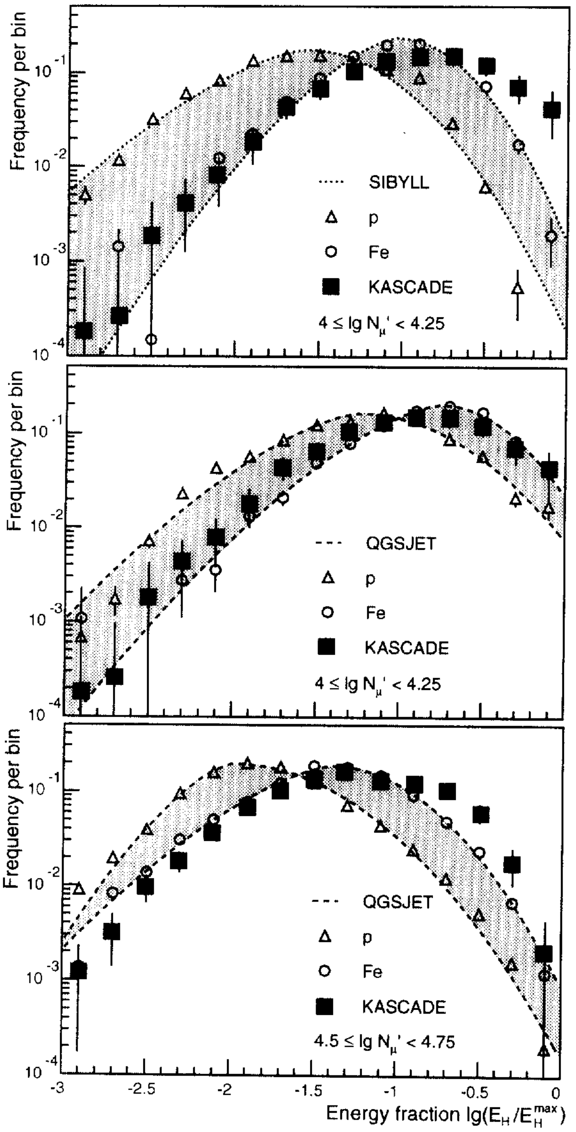

Figure 5. Frequency distributions of energy fraction for different interaction models and energy ranges. The curves connecting the simulated data points are fitted to guide the eye.

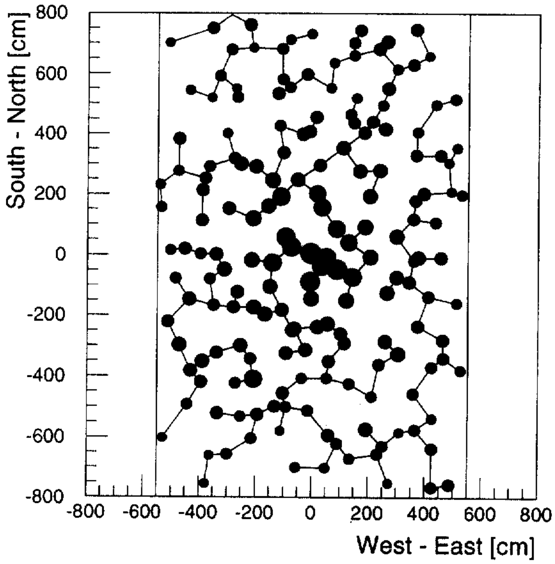

Figure 6. Spatial distribution of hadrons in the calorimeter for a shower induced by a 15 PeV proton. The distances between the hadrons are measured by a *minimum spanning tree*.

servables like the lateral distribution of hadrons or their differential energy spectrum for which the QGSJET predictions are compatible with the measurements below and above the *knee*. These inconsistencies need more detailed investigations, but may be a hint that the hadronic interaction models fail for energies above the *knee*.

As a last example, Figure 6 presents the spatial distribution of the individual hadrons in a 15 PeV proton induced shower core. The points show the impact coordinates at the top of the calorimeter and their size represents the corresponding energy in a logarithmic scale. To investigate the structure of the core a *minimum spanning tree* is constructed. For this objective all hadrons are connected by lines with each other and their distance is divided by the sum of their energies. The *minimum spanning tree* is that connection pattern which minimizes the total sum of weighted distances. Figure 6 shows the connecting lines for a particular shower core.

Frequency distributions of all distances in the *minimum spanning tree* are shown in Figure 7. Results are shown for showers in two muon size bins, corresponding to an energy below and above the *knee*. In the upper graph, below the *knee*, the KASCADE data are between the simulations for primary protons and iron nuclei, which means that QGSJET is compatible with the measurements. However, above the *knee*, as shown in the

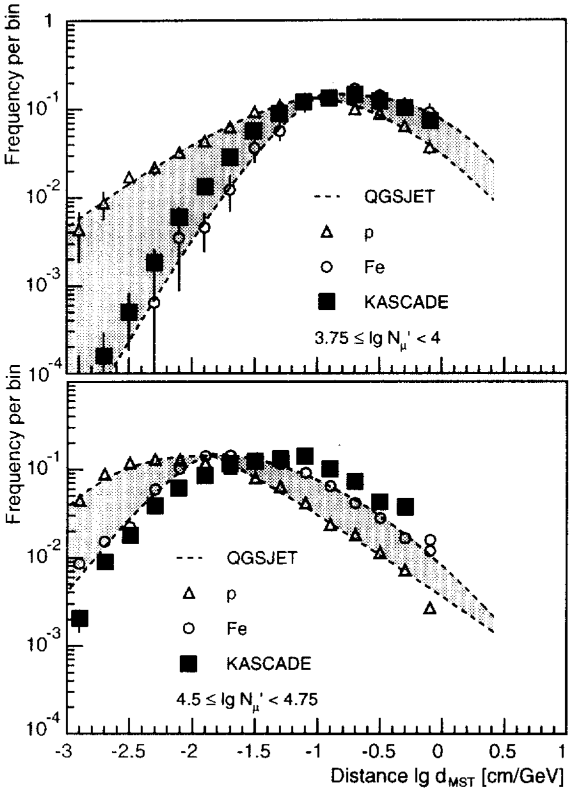

Figure 7. Frequency distributions of all distances in a *minimum spanning tree*. The curves connecting the simulated data points are fitted to guide the eye.

lower graph, a disagreement between data and simulations is observed. Further investigations are necessary to clarify the differences.

6. Conclusions

Several observables of the hadronic component of EAS have been investigated. The lateral distribution, the lateral energy density, the differential energy spectrum, the distance distribution, the number of hadrons and their energy sum, the maximum hadron energy, and the fraction of the energy of each hadron to the maximum hadron energy in each shower. All observables are investigated for five different thresholds of hadron energy from 50 GeV up to 1 TeV and the showers are divided into shower size intervals of all components, the number of electrons and muons as well as the hadronic energy sum. Out of these only a few examples have been discussed presenting the main findings.

The model SIBYLL has problems to describe the data, especially when they are classified according to the muon shower size. It is possible, that a new release [8] will fit the data better.

The model VENUS fits the data reasonable well, but there are deviations when binning the data in intervals of the electron number.

QGSJET describes the data well. Especially below the *knee* (E_0 < 5 PeV) compatibility between its predictions and measurements were found. Above the *knee* deviations in several observables are seen, which need further investigations. To sum up, it can be concluded that the results are a confirmation of the Gribov Regge theory, on which the models VENUS and QGSJET are based, and which is obviously able to describe the hadronic interactions in extreme forward region up to energies of at least 5 PeV.

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